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The present issues are dedicated to the 110-th anniversary of great scientist M.M. Bogolyubov, founder and first director of BITP

CONTENTS

Editorial Foreword 541

Experiment

Aushev V. Charm and Beauty Production Cross-Section Measurements in Deep Inelastic Electron-Proton Scattering at HERA 543

Bozzo E., Amati L., O'Brien P., Götz D. The Transient High-Energy Sky and Early Universe Surveyor 548

Cieśla K., Staszewski R., Chwastowski J.J. On the Centrality Determination with Forward Proton Detectors 554

Dittert D. Electromagnetic Radiation from Au + Au Collisions at $\sqrt{s_{NN}} = 2.4$ GeV Measured with HADES 560

Fionda F. Quarkonium Production Measurements with the ALICE Detector at the LHC 566

Fraenkle F.M. The Neutrino Mass Experiment KATRIN 573

Gornushkin Yu. Study of Tau Neutrino Production in Proton Nucleus Interactions 577

Harabasz S. Exploring Baryon Rich Matter with Heavy-Ion Collisions 583

Horváth D. Tests of the *CPT* Invariance at the Antiproton Decelerator of CERN 589

Van Hulse C. Central Exclusive Production at LHCb 595

Kovalenko O. Neutral Meson and Direct Photon Measurements with the ALICE Experiment 602

Lymanets A. The Silicon Tracking System of the CBM Experiment at FAIR 607

Nosek T. Results on Neutrino and Antineutrino Oscillations from the NOvA Experiment 613

Pugatch V. Heavy-Ion and Fixed-Target Physics in LHCb 619

Rostomyan T. Status of the MUSE Experiment 624

Rymbekova A. Study of the Polarized Gluon Structure of a Proton via Prompt-Photon Production in the SPD Experiment at the NICA Collider 631

Schever M. Status of the Jiangmen Underground Neutrino Observatory 635

Schmidt M. The PANDA Detector at FAIR 640

Valiño I. The Pierre Auger Observatory: Studying the Highest Energy Frontier 646

Vorobel V. Latest Results from Neutrino Oscillation Experiment Daya Bay 653

Authors Index 660

УКРАЇНСЬКИЙ ФІЗИЧНИЙ ЖУРНАЛ

НАЦІОНАЛЬНА АКАДЕМІЯ НАУК УКРАЇНИ
ІНСТИТУТ ТЕОРЕТИЧНОЇ ФІЗИКИ
ім. М.М. БОГОЛЮБОВА НАН УКРАЇНИ

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ЗАСНОВАНИЙ У КВІТНІ 1956 р.
КИЇВ

ЗМІСТ

Вступ 541

Експеримент

Аушев В. Вимірювання поперечних перерізів утворення кварків charm та beauty в електрон-протонних зіткненнях на HERA 543

Боццо Е., Аматі Л., Обраєн П., Гьотц Д. Перехідне високоенергетичне небо і топографія раннього Всесвіту 548

Чєшла К., Сташевскі Р., Хвастовскі Й.Й. Про визначення центральності за допомогою детекторів протонів, розсіяних вперед 554

Діттерт Д. Електромагнітне випромінювання в зіткненнях Au + Au при енергії 2,4 ГеВ, в дослідах на HADES 560

Фіонда Ф. Вимірювання продукування кварконія за допомогою детектора ALICE на LHC 566

Френкле Ф.М. Експеримент KATRIN для вимірювання маси нейтрино 573

Горнушкін Ю. Дослідження продукування тау-нейтрино в протон-ядерній взаємодії 577

Гарабаш С. Дослідження баріонної матерії в зіткненнях важких іонів 583

Хорват Д. Тести *CPT* інваріантності на антипротонному уповільнювачі ЦЕРНу 589

Ван Гулсе Ш. Центральне ексклюзивне продукування на LHCb 595

Коваленко О. Вимірювання нейтральних мезонів та прямих фотонів в експериментах ALICE 602

Лиманець А. Кремнієва трекінгова система експерименту CBM на комплексі прискорювачів FAIR 607

Носек Т. Осциляції нейтрино та антинейтрино. Експеримент NOvA 613

Пугач В. Фізика важких іонів та фіксованої мішені в експерименті LHCb 619

Ростомян Т. Статус експерименту MUSE 624

Римбекова А. Дослідження поляризованої структури протона за допомогою фотонародження в експерименті SPD на колайдері NICA 631

Шевер М. Стан Підземної Обсерваторії Нейтрино в Жіангмені 635

Шмідт М. Детектор PANDA на прискорювачі FAIR 640

Валіно І. Обсерваторія Пьєра Оже вивчає границі найвищих енергій 646

Воробел В. Новітні результати з експерименту нейтринних осциляцій DAYA BAY 653

Авторський покажчик 660

EDITORIAL FOREWORD

Issues 7 and 8 of the Ukrainian Journal of Physics (V. 64, Nos. 7 and 8, 2019) contain original papers presented at the conference on New Trends in High-Energy Physics, organized by the Bogolyubov Institute for Theoretical Physics (BITP), National Academy of Sciences of Ukraine and held in Odessa on May 12–18, 2019, https://indico.bitp.kiev.ua/event/1/. The present issues are dedicated to the 110-th anniversary of great scientist M.M. Bogolyubov, founder and first director of BITP. They collect experimental (No. 7) and theoretical/phenomenological (No. 8) papers. As guest editors, we made sure that the submitted papers, presented and discussed at the Conference, have undergone regular submission procedures and passed peer review by experts.

We thank all participants for coming to Odessa and making the Conference successful. We acknowledge the authors of the present publication for their valuable contributions, marking new trends in high-energy physics.

The Conference Program and pdf versions of all talks presented at the Conference are available at the Conference site: https://indico.bitp.kiev.ua/event/1/.

The next conference of this series is scheduled to be held in Kyiv by the end of June 2021.

László JENKOVSZKY and Rainer SCHICKER,
Guest Editors

“New Trends” in Odessa. Credit: A. Burgazli

M.M. Bogolyubov
21.08.1909–13.02.1992

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CHARM AND BEAUTY PRODUCTION CROSS-SECTION MEASUREMENTS IN DEEP INELASTIC ELECTRON-PROTON SCATTERING AT HERA

The open charm and beauty production cross-sections in the deep inelastic ep scattering (DIS) at HERA from the H1 and ZEUS Collaborations are combined. Reduced cross-sections are obtained in the kinematic range of negative four-momentum transfer squared of a photon $2.5 \leq Q^2 \leq 2000$ *GeV*^{2} *and the Bjorken scaling variable* $3\times10^{-5} \leq x_{Bj} \leq 5\times10^{-2}$*. The different charm- and beauty-tagging methods are used for the heavy-flavor production study in DIS. The combined method accounts for the correlations of systematic uncertainties, as well as statistical uncertainties among the different datasets. Perturbative QCD (pQCD) calculations are compared to the measured combined data. A NLO QCD analysis is performed using these data together with the combined inclusive deep inelastic scattering cross-sections from HERA. The running charm- and beauty-quark masses are determined as* $m_c(m_c) = 1.290^{+0.046}_{-0.041}(exp/fit)^{+0.062}_{-0.014}(model)^{+0.03}_{-0.031}(parametrization)$ *GeV and* $m_b(m_b) = 4.049^{+0.104}_{-0.109}(exp/fit)^{+0.090}_{-0.032}(model)^{+0.001}_{-0.031}(parametrization)$ *GeV.*

Keywords: charm and beauty production, deep inelastic interaction, electron-proton scattering, quark mass, perturbative QCD, combined cross-sections.

1. Introduction

Measurements of open charm and beauty productions in the deep inelastic ep-scattering at HERA provide the important input for tests of quantum chromodynamics (QCD). HERA collected about 0.5 fb^{-1} of the integrated luminosity by each experiment. Measurements at HERA have shown that the heavy-flavor (HFL) production in DIS proceeds predominantly via the boson-gluon-fusion process, i.e. $\gamma g \to q\bar{q}$. Therefore, the cross-section depends on the gluon distribution in the proton, as well as the heavy-quark mass. This mass provides a hard scale for the applicability of pQCD. At the same time, other hard scales are also present in this process such as the transverse momenta of the outgoing quarks and the virtuality, Q^2, of the exchanged photon. The presence of several hard scales complicates the calculation of the HFL production in pQCD. We used different approaches to cope with the multiple scale problem. In our study, the massive fixed-flavor-number scheme (FFNS) and the variable-flavor-number scheme (VFNS) are used.

The ZEUS and H1 detector systems at the HERA electron-proton collider were general purpose detectors. They have a similar structure and consist of tracking systems (including high-resolution silicon vertex detectors) surrounded by electromagnetic and hadronic calorimeters and muon detectors. This provides almost 4π coverage of the collision region.

In this report, a H1 and ZEUS combination of the charm and beauty quark productions is presented

[4]. This analysis is an extension of the previous combination of charm cross-section measurements in DIS, including new charm and beauty data. A single consistent dataset of reduced charm and beauty cross-sections from both detectors is obtained. All correlations are included. This dataset covers the kinematic range of boson (photon) virtualities $2.5 \leq Q^2 \leq \leq 2000$ GeV^2 and the Bjorken scaling variable in the region $3 \times 10^{-5} \leq x_{Bj} \leq 5 \times 10^{-2}$.

For these measurements, different flavor tagging methods are used: the full reconstruction of D or $D^{\star\pm}$ mesons, which is sensitive to the charm production; the lifetime of heavy-flavored hadrons and their semileptonic decays. This allows the measurement of charm and beauty cross-sections simultaneously. These methods show the dependences on sources of systematic uncertainties for different regions of the heavy-quark phase space. The simultaneous combination of charm and beauty cross-section measurements reduces all uncertainties. The combined charm cross-sections of the previous analysis [1] are superseded by the new results presented in this paper. The measured combined beauty cross-sections are presented for the first time. In general, this paper sums up almost 20 years of HFL researches at HERA.

The new data are analyzed using QCD methods for determining the running charm and beauty quark masses at the NLO calculations in the minimum-subtraction (MS) scheme. The FFNS is used for pQCD calculations for the corrections of measurements to the full phase space and in the QCD fits. In this scheme, heavy quarks are always treated as massive. The number of active flavors in the PDFs, n_f, is set equal to 3. In this model, heavy quarks are produced only in the hard-scattering ep process. In all FFNS heavy-quark calculations presented in this paper, the default renormalization scale μ_r and factorization scale μ_f are set to $\mu_r = \mu_f = \sqrt{(Q^2 + 4m_Q^2)}$, where m_Q is a pole or running mass. Predictions from different variants of the VFNS are also compared to the data. In the VFNS, heavy quarks are treated as massive at small Q^2 up to $Q^2 \approx O(m_Q^2)$ and as massless at $Q^2 \gg m_Q^2$, with interpolation prescriptions between the two regimes.

2. Combined Cross-Sections and QCD Analysis

The data have been obtained from both the HERA I (in the years 1992–2000) and HERA II (in the years 2003–2007) data-taking periods. The combination includes measurements based on using different HFL-tagging techniques: the reconstruction of particular decaying D mesons, the inclusive analysis of tracks exploiting the lifetime information and the reconstruction of electrons and muons from heavy-quark semileptonic decays.

A total of 209 charm and 57 beauty data points are combined simultaneously to obtain 52 charm and 27 beauty cross-section data-sets. A χ^2 value of 149 for 187 degrees of freedom is obtained in the combination, indicating a good consistency of the input data. There are 167 sources of correlated uncertainties in total. These are 71 experimental systematic sources, 16 sources due to the extrapolation procedure (including the uncertainties on the fragmentation fractions and branching ratios), and 80 statistical charm and beauty correlations.

The experiments at HERA typically measure the so-called reduced cross-section,$\sigma_{\rm red}$, which is closely related to the double-differential cross-section in the kinematic quantities Q^2 and x. The combined reduced cross-sections $\sigma_{\rm red}^{\rm cc}$ are shown as functions of x_{Bj} in bins of Q^2 together with the input H1 and ZEUS data in Fig. 1. As we can see, the combined cross-sections are significantly more precise than any of the individual input data-sets for the charm and beauty productions. This is illustrated in Fig. 2, where the charm measurements for $Q^2 = 32$ GeV^2 are shown. The uncertainty of the combined charm cross-section is 9% on the average and reaches values of about 5% or better in the region 12 GeV$^2 \leq \leq Q^2 \leq 60$ GeV^2. The uncertainty of the combined beauty cross-section is about 25% on the average and reaches about 15% at small x_{Bj} and 12 GeV$^2 \leq Q^2 \leq \leq 200$ GeV^2.

Theoretical predictions of the FFNS in the MS running mass scheme are compared to the combined reduced cross-sections $\sigma_{\rm red}^{\rm cc}$ and $\sigma_{\rm red}^{\rm bb}$, as we can see in Figs. 3 and 4, respectively. In these calculations, the running quark masses are set to the world average values [2] of $m_c(m_c) = 1.27 \pm 0.03$ GeV and $m_b(m_b) = 4.18 \pm 0.03$ GeV.

The charm cross-sections of the current analysis agree well with the previous measurements, but have considerably smaller uncertainties. The observed changes in the χ^2 values are consistent with an improvement in the data precision. The tension observed between the central theory predictions and

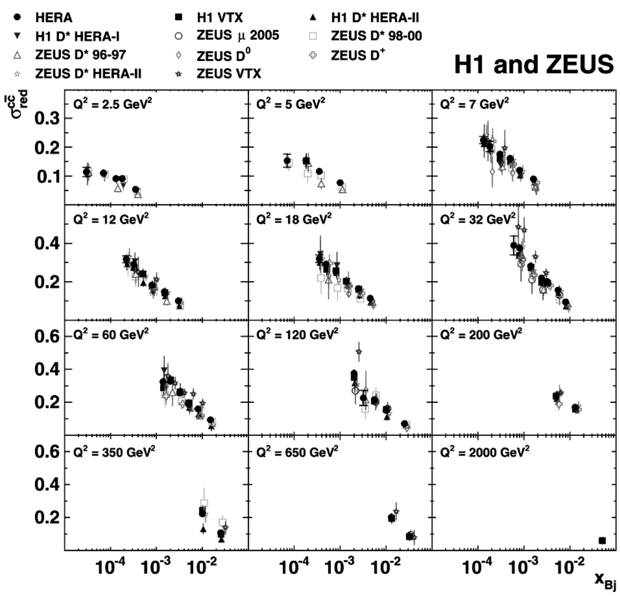

Fig. 1. Combined measurements of the charm production cross-sections, $\sigma_{\rm red}$, (full circles) as functions of x_{Bj} for different values of Q^2. The inner error bars indicate the uncorrelated part of the uncertainties, and the outer error bars represent the total uncertainties. The input measurements with their total uncertainties are also shown by different markers. For a better visibility, the individual input data are slightly displaced in x_{Bj} toward larger values

the charm data ranges from $\sim 3\sigma$ to more than 6σ, depending on the prediction. The NLO FFNS calculations provide the best description of the charm data. For the beauty cross-sections, a good agreement of theory and data is observed within the larger experimental uncertainties. The effect of the PDF uncertainties on the χ^2 values is negligible.

The combined charm and beauty data are used together with the combined HERA inclusive DIS data [3] to perform a QCD analysis. In our QCD analysis, we determined simultaneously the running heavy-quark masses $m_c(m_c)$ and $m_b(m_b)$. We investigated the x_{Bj} dependence of the reduced charm cross-sections. We used the XFITTER programme, in which the scale evolution of partons is calculated through DGLAP equations at NLO (using the QCDNUM programme). The theoretical FFNS predictions for the HERA data are obtained using the OPENQCDRAD programme interfaced in the XFITTER framework. The number of active flavors is set to $n_f = 3$ at all scales. For the heavy-quark contributions, the scales are set to $\mu_r = \mu_f = \sqrt{(Q^2 + 4m_Q^2)}$.

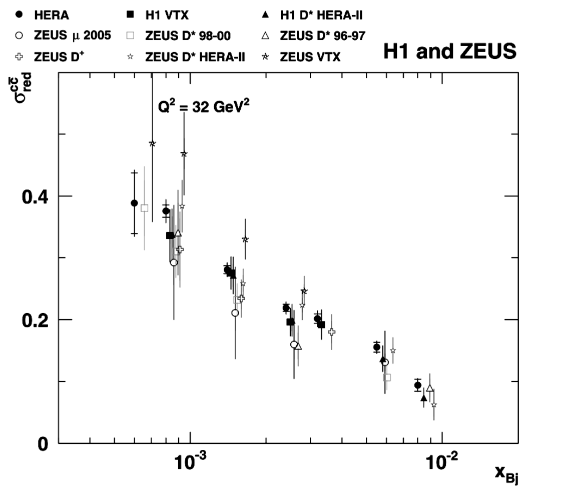

Fig. 2. Reduced cross-sections as a function of x_{Bj} at $Q^2 = 32$ GeV^2 for the charm production. The combined cross-sections (full circles) are compared to the input measurements shown by different markers. For the combined measurements, the inner error bars indicate the uncorrelated part of the uncertainties and the outer error bars represent the total uncertainties

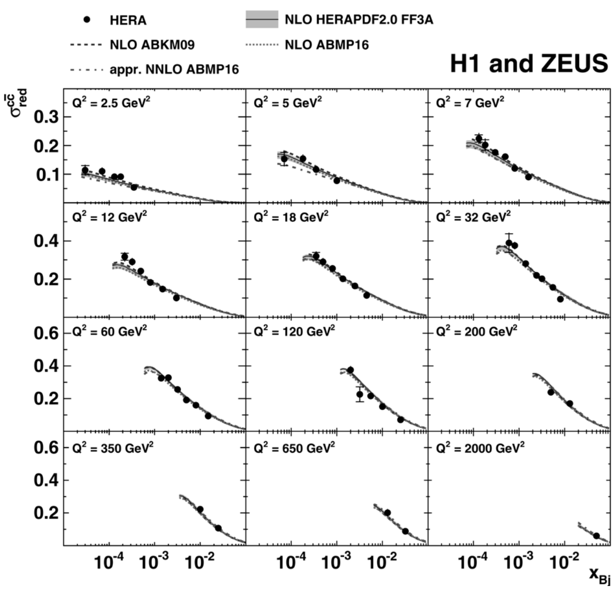

Fig. 3. Combined reduced charm cross-sections, $\sigma^{\rm cc}_{\rm red}$ (full circles) as functions of x_{Bj} for given values of Q^2, compared to the NLO QCD FFNS predictions based on the HERAPDF2.0 FF3A (solid lines), ABKM09 (dashed lines), and ABMP16 (dotted lines) PDF sets. The approximate NNLO prediction using ABMP16 (dash-dotted lines) is also shown. The shaded bands on the HERAPDF2.0 FF3A predictions show the theory uncertainties obtained by adding PDF, scale, and charm-quark mass uncertainties in quadrature

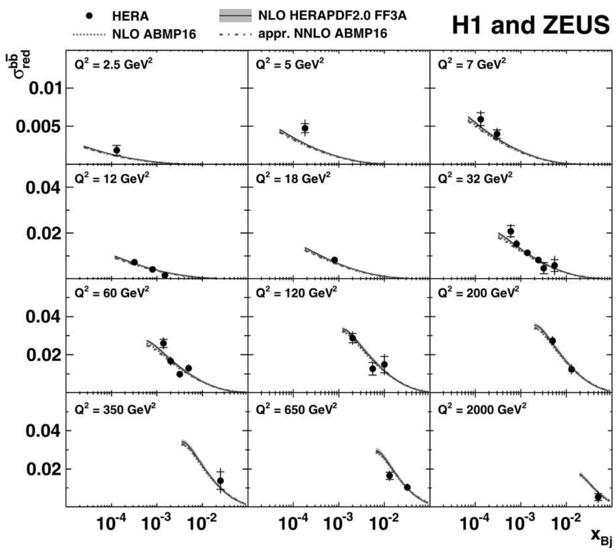

Fig. 4. Combined reduced beauty cross-sections $\sigma_{\rm red}^{\rm bb}$ (full circles) as functions of x_{Bj} for the given values of Q^2 , compared to the NLO QCD FFNS predictions based on the HERAPDF2.0 FF3A (solid lines), ABKM09 (dashed lines), and ABMP16 (dotted lines) PDF sets. The approximate NNLO prediction using ABMP16 (dashed-dotted lines) is shown as well. The shaded bands on the HERAPDF2.0 FF3A predictions show the theory uncertainties obtained by adding PDF, scale, and beauty-quark mass uncertainties in quadrature

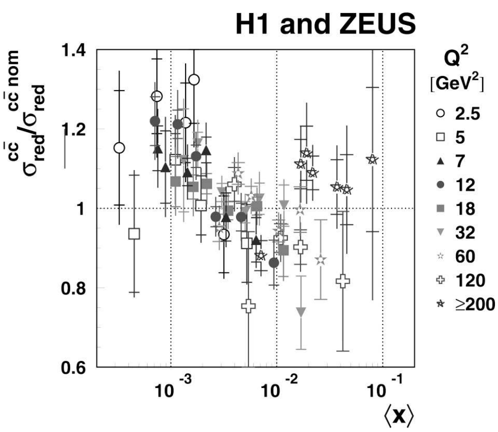

Fig. 5. Ratio of the combined reduced cross-sections, $\sigma_{\rm red}^{\rm cc}$, to the respective NLO FFNS cross-section predictions, $\sigma_{\rm red}^{\rm nom}$ based on HERAPDF-HQMASS, as a function of the partonic average x for different values of Q^2

The c and b-quark masses are left free by fitting. The running heavy-quark masses are fitted simultaneously with the PDF parameters. The fit yields a total $\chi^2 = 1435$ for 1208 degrees of freedom. The smaller uncertainties of the new combination reduce the uncertainty of the charm-quark mass determination with respect to the previous result. The beauty quark mass determination improves the previous result based on a single dataset. The running quark masses are determined (in GeV) as:

$$m_c(m_c) = 1.290^{+0.046}_{-0.041}(\exp/\mathrm{fit})^{+0.062}_{-0.014}(\mathrm{model})^{+0.03}_{-0.031}(\mathrm{param}),$$

$$m_b(m_b) = 4.049^{+0.104}_{-0.109}(\exp/\mathrm{fit})^{+0.090}_{-0.032}(\mathrm{model})^{+0.001}_{-0.031}(\mathrm{param}).$$

The model uncertainties are dominated. A better description of the charm data can be achieved, if $x_{Bj} \leq 0.01$ are excluded from the fit. Alternative NLO and NNLO QCD calculations, including those with low-x resummation, do not provide a better description of the combined heavy-quark data.

Since, in LO QCD, the heavy-quark production proceeds via the photon-gluon-fusion, at least two partons are present in the final state. The x of the incoming parton is different from x_{Bj} measured at the photon vertex. The x of the gluon is equal to

$$x = x_{Bj}\left(1 + \frac{\hat{s}}{Q^2}\right),$$

where $\hat{s}$ is the invariant mass of the heavy-quark pair. In Fig. 5, the ratio of the measured reduced cross-sections to the NLO FFNS predictions based on HERAPDF-HQMASS is shown. More detailed studies of the x slope tension showed that it can not be solved by varying the gluon density, or adding higher orders, or resumming $\log(\frac{1}{x}$ terms, within the respective pQCD frameworks.

3. Conclusions

The results of measurements of charm and beauty production reduced cross-sections in the deep inelastic ep scattering by the H1 and ZEUS experiments at the HERA collider are combined for the first time (beauty) and significantly reduced uncertainties (charm) than those previously published. Next-to-leading and approximate next-to-next-to-leading order QCD predictions are compared to the data. Calculations are found to be in a good agreement with the charm data. The NLO calculations in the fixed-flavor-number scheme provide the best description of

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the heavy-flavor data. The beauty data have larger experimental uncertainties. These data are well described by all QCD predictions. The new combined data are subjected to a NLO QCD analysis in the fixed-flavor-number scheme using the MS running-mass definition. The running heavy-quark masses are determined from combined data. The simultaneously determined parton density functions are found to agree well with HERA-PDF2.0 FF3A. The QCD analysis reveals some tensions, at the level of 3σ, in describing simultaneously the inclusive and heavy-quark HERA DIS data. The measured reduced charm cross-sections show a stronger x_{Bj} dependence than that obtained in the combined QCD fit of charm and inclusive data, in which the PDFs are dominated by the fit of the inclusive data.

The work was supported by the Ministry of Education and Science of Ukraine

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В. Аушев

ВИМІРЮВАННЯ ПОПЕРЕЧНИХ ПЕРЕРІЗІВ УТВОРЕННЯ КВАРКІВ CHARM ТА BEAUTY В ЕЛЕКТРОН-ПРОТОННИХ ЗІТКНЕННЯХ НА HERA

Р е з ю м е

Наведено комбіновані значення перерізів утворення c та b кварків в глибоко-непружних електрон-протонних взаємодіях на колайдері HERA, виміряних колабораціями ZEUS і H1. Параметри визначено в діапазоні віртуальності обмінного фотона $2{,}5 \leq Q^2 \leq 2000$ ГеВ^2 та значення змінної Бйоркена $3 \cdot 10^{-5} \leq x_{Bj} \leq 5 \cdot 10^{-2}$. Використано різні методи тагування c та b кварків, які спираються на всебічне дослідження важких ароматів. При комбінуванні обчислювались статистичні та систематичні невизначеності для різних наборів даних. Для обчислень використовувалась пертурбативна КХД в різних порядках наближення і результати обчислень порівнювались з виміряними даними. Визначено поточні значення мас c та b кварків, які становлять: $m_c(m_c) = 1{,}290^{+0{,}046}_{-0{,}041}(\exp/\mathrm{fit})^{+0{,}062}_{-0{,}014}(\mathrm{model})^{+0{,}03}_{-0{,}031}(\mathrm{param})$, $m_b(m_b) = 4{,}049^{+0{,}104}_{-0{,}109}(\exp/\mathrm{fit})^{+0{,}090}_{-0{,}032}(\mathrm{model})^{+0{,}001}_{-0{,}031}(\mathrm{param})$.

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THE TRANSIENT HIGH-ENERGY SKY AND EARLY UNIVERSE SURVEYOR

The Transient High-Energy Sky and Early Universe Surveyor (THESEUS) is a mission concept developed in the last years by a large European consortium and currently under study by the European Space Agency (ESA) as one of the three candidates for next M5 mission (launch in 2032). THESEUS aims at exploiting high-redshift GRBs for getting unique clues to the early Universe and, being an unprecedentedly powerful machine for the detection, accurate location (down to ∼arcsec) and redshift determination of all types of GRBs (long, short, high-z, under-luminous, ultra-long) and many other classes of transient sources and phenomena, at providing a substantial contribution to multi-messenger time-domain astrophysics. Under these respects, THESEUS will show a strong synergy with the large observing facilities of the future, like E-ELT, TMT, SKA, CTA, ATHENA, in the electromagnetic domain, as well as with next-generation gravitational-waves and neutrino detectors, thus greatly enhancing their scientific return.

Keywords: THESEUS, space mission concept, ESA, M5, gamma-ray bursts, cosmology, gravitational waves, multi-messenger astrophysics.

1. Introduction

The main feature of the modern astrophysics is the rapid development of multi-messenger astronomy. At the same time, relevant open issues still affect our understanding of the cosmological epoch (a few millions years after the "big-bang"), at which first stars and galaxies start illuminating the Universe and reionizing the inter-galactic medium.

In this context, a substantial contribution is expected from the Transient High Energy Sky and Early Universe Surveyor (THESEUS [1]), a space mission concept developed by a large European consortium including Italy, UK, France, Germany, Switzerland, Spain, Poland, Denmark, Czech Republic, Ireland, Hungary, Slovenia, ESA, with Lorenzo Amati (INAF-OAS Bologna, Italy) as a lead proposer. In May 2018, THESEUS was selected by ESA for a Phase 0/A study as one of the three candidates for the M5 mission within the Cosmic Vision programme. The end of phase A and a down-selection to one mission to be implemented is expected for mid-2021. The launch of the selected M5 mission is planned for 2032. Details on the THESEUS science objectives, mission concept, and expected performances are reported in [1] and [2].

2. Scientific Objectives

THESEUS is designed to vastly increase the discovery space of high energy transient phenomena over the entirety of cosmic history (see Fig. 1).

Because of their huge luminosities, mostly emitted in the X and gamma-rays, their redshift distribution extending at least to $z \sim 9$ and their association with explosive death of massive stars and star forming regions, GRBs are unique and powerful tools for investigating the early Universe: SFR evolution,

[1] https://www.isdc.unige.ch/theseus

physics of re-ionization, galaxies metallicity evolution and luminosity function, first generation (pop III) stars. THESEUS will obtain a statistical sample of high-z GRBs, which allow us, in turn, to [1]:

• measure independently the cosmic star-formation rate, even beyond the limits of current and future galaxy surveys;

• directly (or indirectly) detect the first population of stars (pop III);

• obtain the number density and properties of low-mass galaxies (even JWST and ELTs surveys will be not able to probe the faint end of the galaxy luminosity function at $z > 8$–10);

• evaluate the neutral hydrogen fraction;

• measure the escape fraction of UV photons from high-z galaxies;

• study the early metallicity of ISM and IGM and its evolution.

Through a carefull design optimization, a mission capable to substantially increase the rate of identification and characterization of high-z GRBs can also provide a survey of the high-energy sky from soft X-rays to gamma-rays with an unprecedented combination of a wide Field of View (FoV), source location accuracy, and sensitivity below 10 keV. For this reason, THESEUS will provide a substantial contribution also to the time-domain astrophysics, in general, and, in particular, to the newly born and fastly growing field of multi-messenger astrophysics. For instance, THESEUS will be able to provide the detection, accurate location, characterization, and redshift measurements of the electromagnetic emission (short GRBs, possible soft X-ray transient emission, kilonova emission in the near-infrared) from gravitational-wave sources like NS-NS or NS-blackhole (BH) mergers [2].

THESEUS will be an unprecedentedly powerful machine for the detection, accurate localization (down to ∼arcsec), and redshift determination of all types of GRBs (long, short, high-z, under-luminous, ultra-long) and many other classes of transient sources and phenomena. THESEUS will also provide a substantial contribution to the multi-messenger time-domain astrophysics. The mission capabilities in exploring the multi-messenger transient sky can be summarized as follow:

• Localize and identify the electromagnetic counterparts to sources of gravitational radiation and neutrinos, which may be routinely detected in the late '20s/early '30s by next generation facilities like aLIGO/aVirgo, eLISA, ET, or Km3NET;

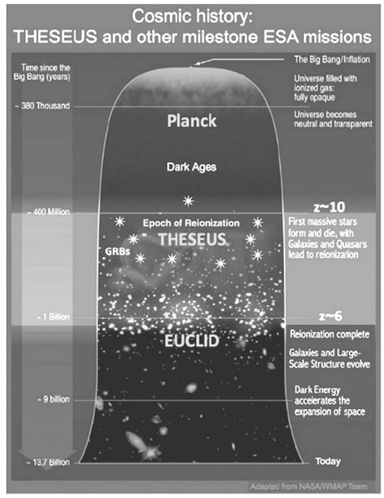

Fig. 1. Gamma-ray bursts in the cosmological context and the role of THESEUS (adapted from a picture by the NASA/WMAP Science team)

• Provide real-time triggers and accurate (∼1 arcmin within a few seconds, ∼1 arcsec within a few minutes) localizations of both high-energy transients for follow-up with next-generation optical-NIR (E-ELT, JWST, if still operating), radio (SKA), X-rays (ATHENA), TeV (CTA) telescopes, as well as to LSST sources;

• Provide a fundamental step forward in the comprehension of the physics of various classes of transients and fill the present gap in the discovery space of new classes of transient events.

In the field of gravitational wave source, THESEUS capabilities will permit us to:

• detect short GRBs over a large FoV with arcmin localization;

• detect the kilonovae and provide their arcsec localization and characterization;

• detect weaker isotropic X-ray emissions.

3. Mission Concept and Payload

THESEUS will be capable to achieve the exceptional scientific objectives summarized above thanks to a smart combination of the instrumentation and mission profile. On its board, the mission will carry two large-FoV monitors, a 1-sr FoV in the region of soft X-rays (0.3–5 keV) with unprecedented sensitivity and arcmin location accuracy and a several-sr FoV from

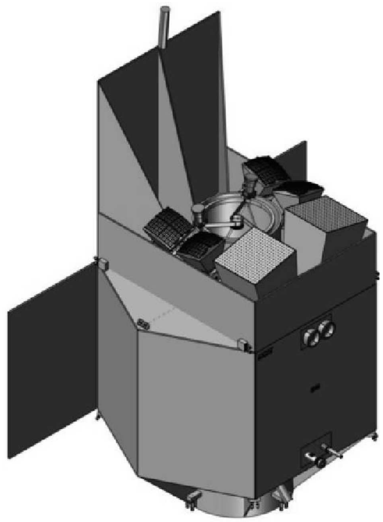

Fig. 2. Sketch of the THESEUS spacecraft and payload accommodation. The IRT is placed in the middle of the optical bench and is clearly visible with 4 SXI squared cameras, as well as the two XGIS rectangular cameras (credits: ESA)

Fig. 3. Sketch of THESEUS inside the VEGA fairing (credits: ESA)

2 keV up to 20 MeV, with additional source location capabilities of a few arcmin from 2 to 30 keV. Once a GRB or a transient of interest is detected by one or both the monitors, the THESEUS spacecraft will autonomously slew quickly to point, within a few minutes, an on-board near infra-red telescope (70 cm class operating from 0.7 to 1.8 μm) toward the direction of the transient, so to catch the fading NIR afterglow or, e.g., the kilonova emission, localizing it at a 1 arcsec accuracy and measuring its redshift through photometry and moderate resoluton spectroscopy.

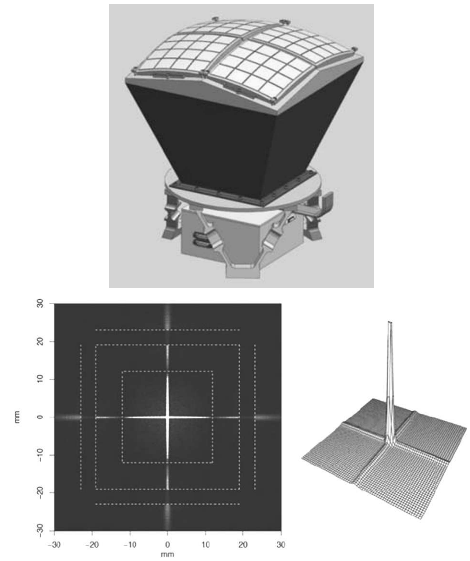

Fig. 4. Top: sketch of one SXI camera. Left: the SXI point spread function

The detailed description of THESEUS can be found in [1]. A sketch of the THESEUS spacecraft, showing also the accommodation of all payload elements, is presented in Fig. 2. This sketch is a result of the Concurrent Design Facility (CDF) study performed by ESA at the end of the phase 0 before the kick-off of phase A (end of 2018). It is expected that THESEUS will be injected into a low equatorial orbit (<6 deg. inclination, ∼600 km altitude) with a VEGA-C launcher (see Fig. 3). We provide a short description of the THESEUS payload, comprising the SXI, XGIS, and the IRT instruments, in the following subsections.

3.1. The soft X-ray imager

The soft X-ray Imager (SXI) comprises a set of four sensitive lobster-eye telescopes observing in the 0.3–5 keV energy band and providing a FoV of ∼1sr. The expected source location accuracy is 0.5–1 arcmin. A few details of the instrument are provided in Fig. 4. The SXI is being developed by a UK-led consortium.

3.2. X- and gamma-ray imaging spectrometer

The X- and Gamma-rays Imaging Spectrometer (XGIS) comprises 2 coded-mask cameras using bars of Silicon diodes coupled with CsI crystal scintillators (see Fig. 5). The instrument is operating in the 2 keV–10 MeV energy band, providing the imaging capabilities only in the 2–30 keV energy range. It operates as a collimated instrument between 30–150 keV and as an all-sky monitor at higher energies. Depending on the operating mode, the XGIS can achieve a FoV as large as ∼2–4 sr and provides a source location accuracy of about 5 arcmin. In order to optimize the detection of high-energy transients and GRBs, in particular, the FoV of the XGIS partly overlaps with that of the SXI (see Fig. 6). The XGIS is being developed by an Italy-led consortium.

3.3. Infrared telescope

The InfraRed Telescope (IRT) is a 0.7 m class IR telescope operating between 0.7–1.8 μm. A design based on a off-axis Korsch model is presently (see Fig. 7) assumed, resulting in a FoV of 15×15 arcmin and providing both imaging and moderate resolution spectroscopy capabilities (up to $R = 500$). The IRT is being developed by a France-led consortium.

4. THESEUS Performances

4.1. Early Universe with GRBs

THESEUS will have the ideal combination of the instrumentation and the mission profile for detecting all types of GRBs (long, short/hard, weak/soft, high-redshift), localizing them from a few arcmin down to arsec, and measuring the redshift for a large fraction of them (see Fig. 8).

In addition to the GRB prompt emission, THESEUS will also detect and localize, down to 0.5–1 arcmin, the soft X-ray short/long GRB afterglows, NS-NS (BH) mergers, and many classes of galactic and extra-galactic transients. For several of these sources, the IRT will provide a characterization of the associated IR counterpart, including a location within 1 arcsec and, possibly, the redshift.

The impact of the THESEUS measurements for shedding light on the study of the early Universe exploiting GRBs is represented in Fig. 9, where we show the expected number per year of GRBs detected, localized, and such, for which a redshift measurement is achieved. The THESEUS expected performance is compared to the present situation, which is a result of the large efforts coordinated between Swift, Konus-WIND, Fermi/GBM, and several on-ground robotic/large telescopes.

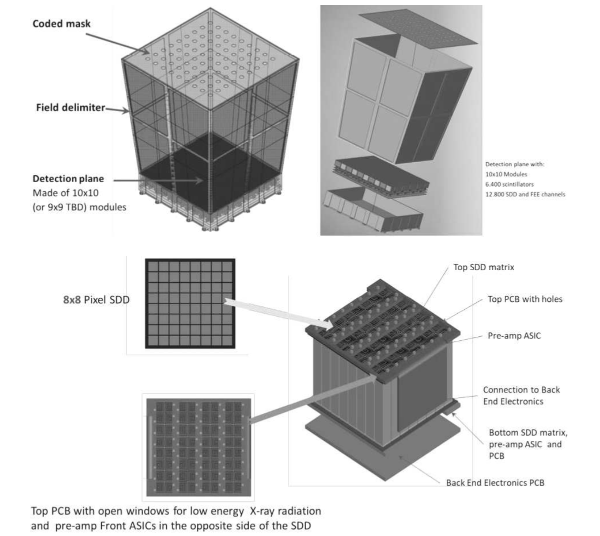

Fig. 5. Top: sketch of one XGIS camera. Bottom: details of one of the 100 modules comprised within the focal plane of each XGIS camera

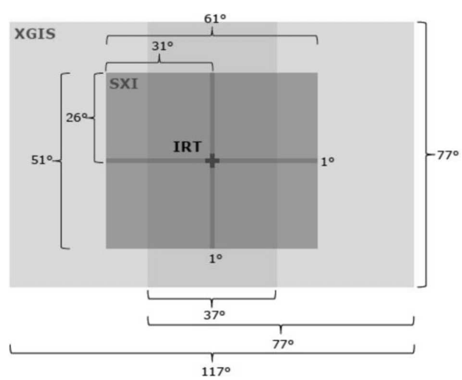

Fig. 6. Combined THESEUS instruments FoV (credits: ESA)

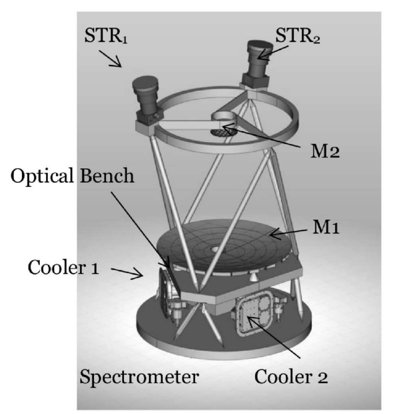

Fig. 7. The IRT assembly (credits: ESA)

4.2. Multi-messenger and time-domain astrophysics

As anticipated in a few of the previous sections, THESEUS will be capable of monitoring a number of different expected gravitational wave source counterparts in the electromagnetic (EM) domain, including:

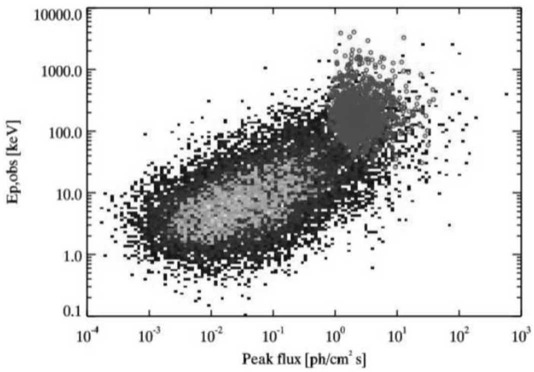

Fig. 8. GRB distribution in the peak flux – spectral peak energy (E_{P}) plane according to the most recent population synthesis models and measurements ([1]). For all shown GRBs, THESEUS will be able to provide the detection, accurate location, characterization, and measurement of the redshift. The low-E_{P} – low peak flux region is populated by high-redhsift GRBs (shown in dark blue, blue, ligt blue, green, yellow), a population unaccessible by current facilities, while the high E_{P} region highlighted with red points shows, where the shortest GRBs will lay

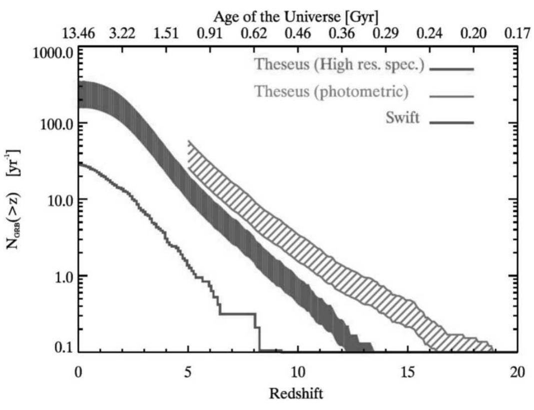

Fig. 9. Yearly cumulative distribution of GRBs with redshift determination vs. redshift for Swift and THESEUS. These predictions are conservative, as they reproduce the current GRB rate as a function of the redshift. However, thanks to its improved sensitivity, THESEUS can detect a GRB of $E_{\mathrm{iso}} = 10^{53}$ erg (corresponding to the median of the GRB radiated energy distribution) up to $z = 12$. Our currently poor knowledge of the GRB rate-star formation rate connection does not preclude the existence of a sizable number of GRBs at such high redshifts, in agreement with recent expectations on Pop III stars

• NS-NS/NS-BH mergers: for these events, THESEUS is expected to detect the collimated EM emission from short GRBs, as well as their afterglows (the currently estimated event rate is of $\lesssim$1 yr^{-1} for the GW detectors of the second generation, but up to $\sim$20 yr^{-1} for the third generation detectors such as the Einstein Telescope). THESEUS is also expected to detect the NIR and soft X-ray isotropic emissions from macronovae, as well as from off-axis afterglows and, for NS-NS, to identify newly born magnetars spinning down in the millisecond domain (the rate of GW detectable NS-NS or NS-BH systems is estimated at dozens-hundreds yr^{-1}).

• Core collapse of massive stars: for these events, THESEUS is expected to detect the emission from long GRBs, LLGRBs, as well as ccSNe (in these cases, the prediction on the energy released in GWs is much more uncertain, and the estimated rate of events is of $\sim$1 yr^{-1}).

• Flares from isolated NSs: for these events, THESEUS is expected to be able to detect the typical emission from, e.g., the Soft Gamma Repeaters (although the associated GW energy content is estimated to be only $\sim$0.01%–1% of the EM emission).

THESEUS will be able to detect, localize, characterize, and measure the redshift for NS-NS/NS-BH mergers thorugh the following channels:

• collimated on-axis and off-axis prompt gammaray emission from short GRBs;

• NIR and soft X-ray isotropic emissions from kilonovae, off-axis afterglows, and, for NS-NS, from newly born ms magnetar spindown.

THESEUS will thus beautifully complement the capabilities of the next generation of GW detectors (e.g., Einstein Telescope, Cosmic Explorer, further advanced LIGO and Virgo, KAGRA, *etc.*) by promptly and accurately localizing e.m. counterparts to GW signals from NS-NS and NS-BH mergers and measuring their redshift. These combined measurements will provide unique clues on the nature of the progenitors, on the extreme physics of the emission and, by exploiting the simultaneous redshift (from e.m. counterpart) and luminosity distance (from the GW signal modeling) of tens of sources, fully exploit the potentialities of the multi-messenger astrophysics for cosmology.

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4.3. Time-domain astronomy and GRB physics

The unique capabilities of THESEUS will also allow us to provide relevant contributions to the more general field of the time-domain astronomy and, of course, to the GRB science. As a few examples, THESEUS will provide the astrophysical community with:

• survey capabilities of transient phenomena similar to the Large Synoptic Survey Telescope (LSST) in the optical range: a remarkable scientific sinergy can be anticipated;

• substantially increased detection rate and characterization of subenergetic GRBs and X-ray flashes;

• unprecedented insights in the physics and progenitors of GRBs and their connection with peculiar core-collapse SNe.

5. Conclusions

THESEUS, under study by ESA and a large European collaboration with strong interest by international partners (e.g., US) will fully exploit GRBs as powerful and unique tools to investigate the early Universe and will provide us with unprecedented clues to the GRB physics and subclasses. This mission will also play a fundamental role for the GW/multi-messenger and time domain astrophysics at the end of the next decade, also by providing a flexible follow-up observatory for fast transient events with multi-wavelength ToO capabilities. THESEUS observations will thus impact on several fields of astrophysics, cosmology, and even fundamental physics and will enhance importantly the scientific return of next-generation multi-messenger (aLIGO/aVirgo, LISA, ET, or Km3NET) and e.m. facilities (e.g., LSST, E-ELT, SKA, CTA, ATHENA)

In addition, the THESEUS scientific return will include the significant observatory science, e.g., studying thousands of faint to bright X-ray sources through the unique simultaneous availability of broad band X-ray and NIR observations.

THESEUS will be a really unique and superbly capable facility, one that will do the amazing science on its own, but also will add a huge value to the currently planned new photon and multi-messenger astrophysics infrastructures in the 2020 s to >2030 s.

1. L. Amati, P. O'Brien, D. Götz, *et al.* The THESEUS space mission concept: Science case, design and expected performances. *Adv. in Space Research* **62**, 191 (2018).
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ПЕРЕХІДНЕ ВИСОКОЕНЕРГЕТИЧНЕ НЕБО І ТОПОГРАФІЯ РАННЬОГО ВСЕСВІТУ

Р е з ю м е

Перехідне високоенергетичне небо та топографія раннього Всесвіту (THESEUS) – це концепція космічної місії, яка розроблена в останні роки великим європейським консорціумом і наразі вивчається Європейським космічним агентством (ЄКА) як один з трьох можливих кандидатів на чергову місію M5 (запуск у 2032 р.). THESEUS має на меті експлуатувати GRB з високим червоним зміщенням для отримання унікальних підказок від раннього Всесвіту і, будучи безпрецедентною потужною машиною для виявлення точного розташування (до ∼арксекунди) і визначення червоного зміщення всіх типів GRB (довге, коротке, з високим z, нижче світлових, наддовге) та багато інших класів перехідних джерел і явищ, має на меті зробити істотний внесок у багаточастотну астрофізику часової області. У цьому відношенні THESEUS покаже сильну синергію з великими проектами спостереження майбутнього, такими як E-ELT, TMT, SKA, CTA, ATHENA в електромагнітній області, а також з детекторами нового покоління для спостереження гравітаційних хвиль і нейтрино, що значно підвищує їхню наукову результативність.

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ON THE CENTRALITY DETERMINATION WITH FORWARD PROTON DETECTORS

The forward proton detectors, already installed at the Large Hadron Collider, are studied in the context of heavy-ion collisions. The potential of such detectors in measuring the nuclear debris coming from the spectator fragments is presented. The geometric acceptance of the forward proton detectors for different debris is estimated. The impact of experimental conditions and the Fermi motion on the acceptance is studied. A possibility of the collision impact parameter reconstruction from the measurement of nuclear fragments is discussed.

K e y w o r d s: heavy-ion physics, impact parameter, forward detectors.

1. Introduction

The Large Hardon Collider [1] is equipped with forward proton detectors designed to register protons scattered in diffractive or electromagnetic interactions. Such protons are scattered at very low angles, and this requires detectors to be installed very far away from the interaction point. In addition, with the use of the Roman Pot technology, they can be placed very close to the beam. The LHC physics programme is not entirely devoted to studies of proton-proton interactions. The machine may also accelerate the heavy-ion beams. This resulted in many measurements of proton-lead and lead-lead collisions [2].

A sketch of an typical heavy-ion collision is shown in Fig. 1. It is quite obvious that the impact parameter of a collision has usually a non-zero value. This means that only a part of nucleons belonging to the one nucleus interacts with a part of nucleons of the other one. Nucleons actively participating in the interactions are called participants, in contrary to the spectators.

The time scale of a ultrarelativistic heavy-ion collision is much shorter than the time scale of the interactions within the nuclei. The spectators are mostly left intact and are scattered into the beampipe escaping the central detector acceptance, similar to the forward protons. This paper tries to answer whether and to what extent the forward proton detectors installed at the LHC can be used with heavy-ion beams.

2. Forward Proton Detectors

Several systems of forward proton detectors are currently installed at the LHC, including: AFP [3], ALFA [4], CT-PPS [5], and TOTEM [6]. All of them are installed about 200 m away from their corresponding interaction points. The ALFA detectors approach the beams vertically, the AFP and CT-PPS horizontally, while TOTEM has both types of the detectors. This work takes the AFP detectors as an example. However, similar results could also be expected for other horizontal detectors.

The AFP (ATLAS Forward Proton) detectors [3] are a subsystem of the ATLAS experiment. They consist of four detector stations – two on each outgoing beam, with the near stations placed at 205 m and the far stations at 217 m away from the interaction point. Each AFP station includes four planes of 3D

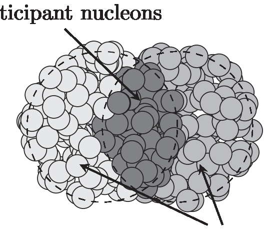

Fig. 1. Schematic diagram of an ultrarelativistic collision of two heavy nuclei (a view along the motion axis)

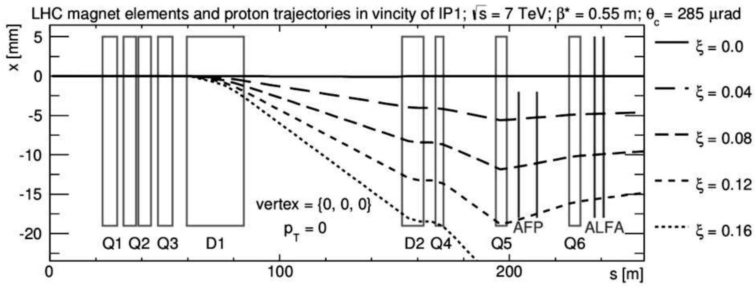

Fig. 2. Trajectories of forward protons in the LHC magnetic lattice. s is the distance from the interaction point along the nominal optics, x is the horizontal coordinate of a trajectory with respect to the nominal orbit, ξ is the relative energy loss of a forward proton

Silicon pixel tracker sensors [7], the far stations are additionally equipped with quartz Cherenkov time-of-flight detector [8] (not important in the current study). The use of the Roman Pot mechanism allows the AFP detectors to be horizontally inserted into the accelerator beampipe.

Since the AFP detectors are located at some distance from the interaction point, the scattered protons, before being registered by them, travel through magnetic fields of several LHC magnets, confront Fig. 2. The Q1–Q3 quadrupole magnets are responsible for the final focusing of a beam, providing the high luminosity of the collisions. As for two dipole magnets, D1 separates the outgoing and the incoming beams, and D2 accommodates them within the beampipes. The Q4 and Q5 quadrupole magnets are used to match the interaction region optics to the optics of the rest of the machine.

As a result of the interaction, the forward protons produced in pp interactions (e.g., in diffractive processes) have slightly different kinematics, than the beam protons. They are scattered at a very small angle and often lose some part of their energy. Small scattering angles mean a very steep distribution of forward proton transverse momenta. Thus, the forward proton trajectory and the position in the detectors are primarily determined by the proton energy. The transverse momentum leads to a moderate smearing of the scattered proton position at the detector. The forward proton relative energy loss is defined as $\xi = 1 - E_{\text{proton}}/E_{\text{beam}}$. The higher its value, the larger is the forward proton trajectory curvature in the magnetic fields. An example of various trajectories is illustrated in Fig. 2, where also the positions of the LHC magnets and AFP detectors are shown. The kinematic range in which the measurements are possible can be described by the value of the geometric acceptance treated as a function of the relative energy loss and transverse momentum of the forward proton, p_T. The acceptance calculated using the MAD-X program [9] for the design LHC optics [10] is shown in Fig. 3. One can see that the AFP detectors can register protons with relative energy loss between 2% and 12% and less than 3 GeV of the transverse momentum.

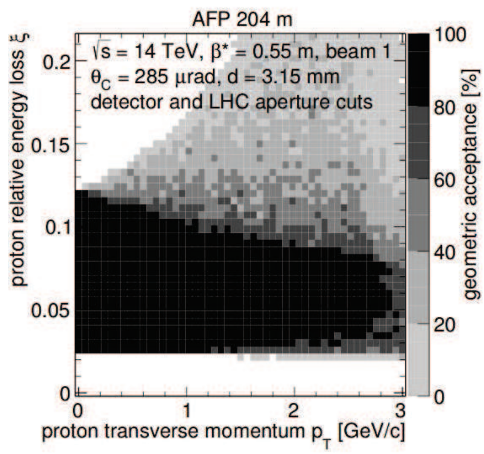

Fig. 3. Geometric acceptance of the AFP detectors for forward protons

3. Acceptance for Nuclear Spectator Fragments

Before the ultrarelativistic heavy-ion collision, both participating and spectating nucleons are parts of the nucleus, interacting with each other. During an interaction, the spectators are, in a sense, peeled away from participants, and their ensemble is left in a very

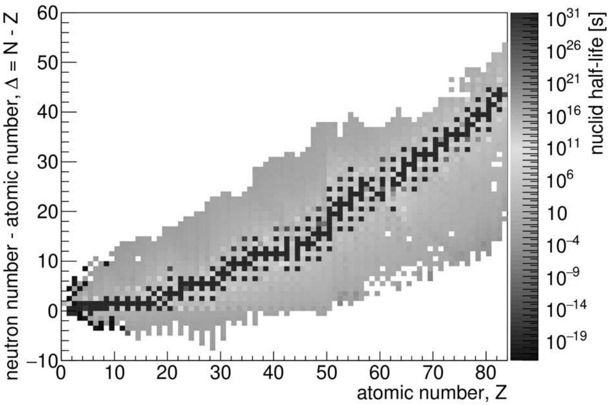

Fig. 4. Half-life time of the known nuclei

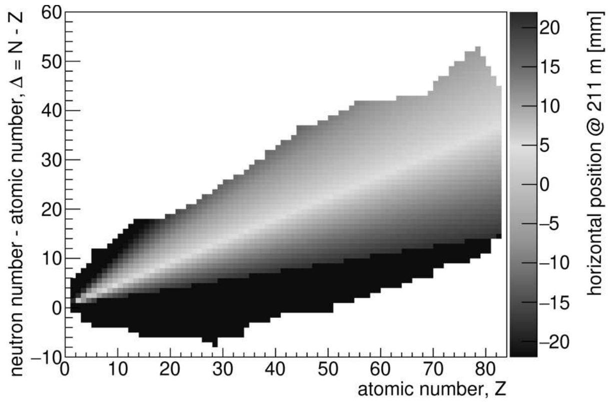

Fig. 5. Horizontal position of the nuclei at the distance of 211 m from the ATLAS interaction point

peculiar state which subsequently decays into lighter fragments. In the calculations of the geometric acceptance of the detectors for the spectator fragments, it is assumed that all nuclei lighter than the projectiles can possibly be produced.

Since the AFP detectors are positioned far away from the interaction point, it is necessary to check whether and which produced fragments can hit a detector before the decay. For a Pb beam at the LHC with magnets set as for 6.5 TeV proton optics, the proper time between the production and reaching a detector is about 0.3 ns. The half-life time of the known nuclei, as a function of the atomic number Z and the difference between the number of neutrons and the atomic number Δ is shown in Fig. 4. We can see that a vast majority of known nuclei could reach the detectors before the decay.

The nuclear fragment transport simulation was preformed using the MAD-X program, assuming the beam of fully ionized ^{208}Pb ions accelerated to the energy of 2.56 TeV per nucleon. The LHC optics corresponding to the LHC Run 2 heavy-ion operations [10] was used. Trajectories of ions different from Pb were simulated by scaling their momenta to the momentum of a lead ion that would have same trajectory in the magnetic filed as the tracked one. This scaling procedure is possible due to the dependence of the trajectory observed in the magnetic field on the ratio of the particle momentum to its charge.

Without introducing the spreads originating from the beam emittance and internal motion of nucleons, a nucleus with a given A and Z will hit the AFP detectors at a well-defined position. Dipole magnets bend the beam trajectory in the horizontal direction, so the x-coordinate of a fragment trajectory plays the major role in this consideration. It should also be noted that, for the safety reasons, the detectors are positioned at some distance with respect to the beam. An additional dead material of the Roman Pot floor has also been taken into account in the calculations.

Predicted horizontal positions of all nuclei at 211 m from the interaction point (in the middle between the near and far stations) are shown in Fig. 5. The position of ^{208}Pb ($\Delta = 44$) and all nuclei with the same Δ/Z ratio is equal to zero. Nuclei containing less neutrons per proton are deflected outside the LHC ring, similarly as the forward protons, and can be registered in the AFP detectors. Nuclei with more neutrons per proton are deflected toward the LHC center and escape the detection. Nuclei with Δ/Z ratio very different from that of lead can be lost in the LHC and not reach the AFP detectors.

Neglecting the internal motion of the nucleons within a nucleus, the energy of each nucleon is the same and equal to the energy of the beam divided by the mass number of the beam particles: $E_N = E_{\mathrm{beam}}/A_{\mathrm{beam}}$. Assuming that the spectator fragments are left intact during the collision, the energy of a spectator with mass number A will be equal to $A \cdot E_N$. The internal motion of nucleons is introduced by applying the Fermi-gas model of a nucleus. In the rest frame of a nucleus, the density of nucleon states is given by $dn \sim p^2dp$. In the simulation, the absolute value of the momentum of each nucleon was randomly drawn from a quadratic distribution between zero and the Fermi momentum of 250 MeV. Then the momentum of a given fragment was calculated as a vector sum of the momenta of all its nucleons and the Lorentz-transformed into the laboratory frame.

For the beam emittance value of 1.233 μm [10], the lead beam angular spread is 24 μrad at the interaction point, and the interaction vertex distribution has the transverse and longitudinal spreads of 13 μm and 5.5 cm, respectively. The horizontal width of the beam at 211 m from the interaction point, σ_x, is 134 μm. This width is an usual unit of distance between the detector and the beam. The distance between the edge of a sensor and the center of the beam is assumed to be 3 mm. It covers about 19 σ_x and a 0.5-mm-long distance between the active sensor edge and the outer wall of the Roman Pot floor.

The result of studies of the influence of various factors on the positions of the selected ions at the distance of 211 m away from the interaction point is shown in Fig. 6. One can observe that the effects of the beam spreads and those due to the transverse component of the Fermi motion are small. The position smearing is dominated by the longitudinal Fermi motion magnified by the Lorentz boost. This effect is stronger for the lighter nuclei.

Figure 7 shows the acceptance to detect a given nuclear fragment as a function of its Z and Δ at a distance of 211 m away from the interaction point. The results were averaged over the distributions of the momenta and the Gaussian spatial and angular spreads of the LHC beam. However, the AFP detectors were not designed for measurement of the nuclear debris, and their acceptance covers a significant part of the nuclei spectrum. As one can observe, for a given Z, especially for heavier nuclei, more than a half of known nuclei can be potentially detected. This range of accepted masses decreases linearly with decreasing value of Z.

4. Centrality Determination

To study how the measurements of fragments can be used to retrieve information about a central state, a simulation of Pb–Pb collisions using the DPMJET Monte Carlo generator [11] was performed. For each event, the generator reports a list of produced particles, including the spectators. Figure 8 shows the distribution of produced fragments.

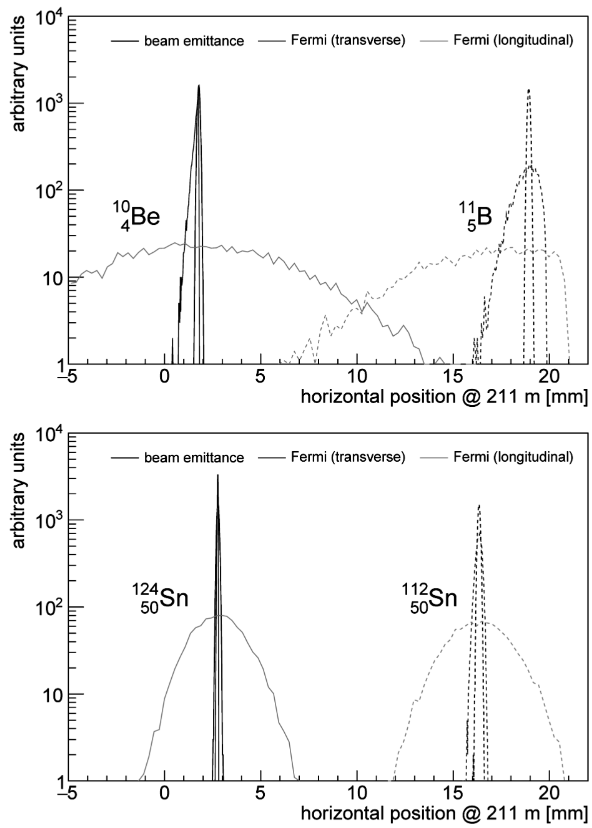

Fig. 6. Effects of the beam emittance and the Fermi motion on the fragment position in the AFP for selected light (top) and heavy (bottom) nuclei

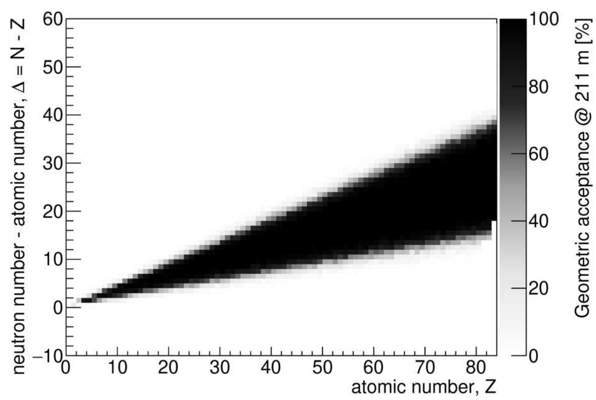

Fig. 7. AFP acceptance for nuclear fragments

Each event is generated with a known random value of the impact parameter. Figure 9, *a* shows the correlation between the impact parameter value and the sum of the mass numbers of all produced frag-

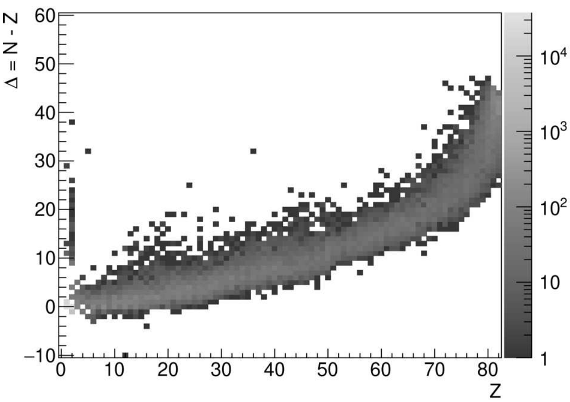

Fig. 8. Multiplicity of the nuclear fragments produced in Pb–Pb collisions simulated using DPMJET

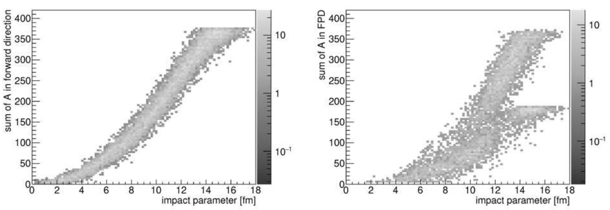

Fig. 9. Correlation between the collision impact parameter and the sum of mass numbers of: all produced fragments (left), fragments produced within the acceptance of forward proton detectors (right)

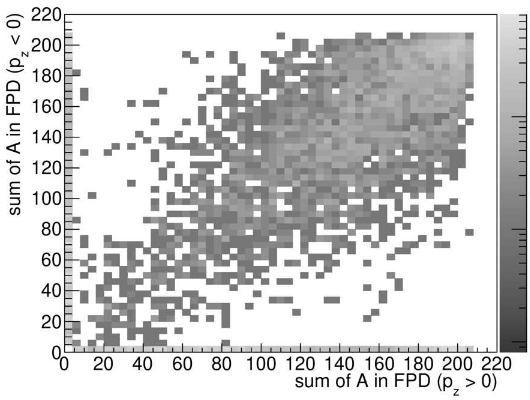

Fig. 10. Correlation between the sum of masses of fragments produced within the acceptance of forward proton detectors on the sides with positive and negative longitudinal momenta

ments. One can observe a strong dependence between these two variables – the more peripheral the event, the more the spectators are produced. Calculating this plot, the acceptance of forward proton detectors was not considered. Figure 9, b shows the same correlation. But here, the sum runs only over the frag-

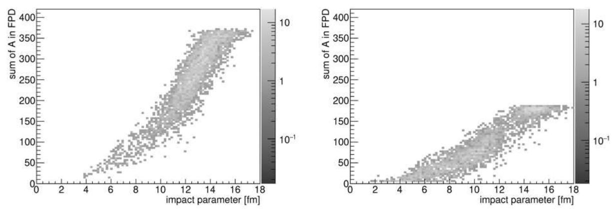

Fig. 11. Correlation between the collision impact parameter and the sum of mass numbers of fragments produced within the acceptance of forward proton detectors for double-tag (left) and single-tag (right) (see text)

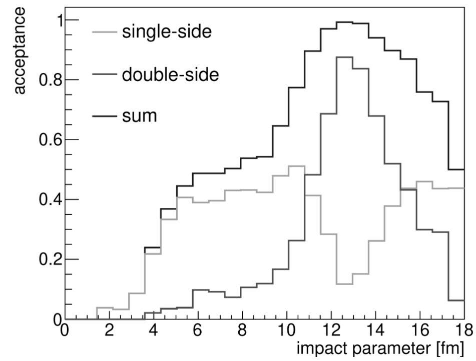

Fig. 12. Acceptance for events with nuclear fragments measured in forward proton detectors

ments within the acceptance of the forward proton detectors[1]. One can notice that the correlation persists. However, it is not as strong as in the previous case. The correlation has two components – one similar to the original one and the another one with ΣA scaled down.

The initial state of the Pb–Pb collision is, in the first approximation, symmetric with respect to the p_z sign. In a particular event, fluctuations of the shape of ions and those related to the spectator fragmentation can break this symmetry leading to a two-component picture. Indeed, this can be observed from Fig. 10 showing the correlation between the sum of A measured on the two sides. Two types of events can be distinguished – events with fragments on both sides (double-tag) and only one side (single-tag). For double-tag events, the ΣA of the fragments measured on both sides are correlated. The width of this correlation reflects the correlation between the impact parameter and the measurements on each side.

[1] For the results based on the DPMJET simulation, the acceptance of the forward proton detectors is taken into account in an approximate way based on their A/Z ratio.

Figure 11 shows the correlations between the collision impact parameter and the sum of A for measured fragments of the two types of events separately. A correlation between the two variables is visible in both cases, which shows that the proposed method can be used for the centrality determination.

Figure 12 shows the probability that a given event will be of either type as a function of the impact parameter. For the most central events (small impact parameter), the probability of observing any fragment in the forward detectors is zero. In such collisions, only the lightest fragments can be produced, which will escape the detection. With increasing value of the impact parameter, the probability of observing the single-tag events increases. However, at about 12–14 fm it drops down, which corresponds to a peak in the probability for double-tag events.

5. Conclusions

The presented study shows that the existing forward proton detectors at the LHC provide an interesting possibility of detecting the nuclear debris originating from the collision of two heavy ions. One of the possibility is a measurement of the centrality of Pb–Pb collisions. Different centralities result in different signals generated by the produced nuclear fragments. Such measurement would be independent of and complementary to the other commonly used methods. A direct measurement of the number of spectator fragments and, hence, the determination of the number of participants could be possible, if several forward detectors providing thus a much larger acceptance are used [12]. The present work shows that one can get information about the centrality even with the limited acceptance of the already existing detectors. More details can be found in [13].

The measurements of spectators using the Roman Pot detectors could be considered also for proton-ion and lepton-ion interactions. However, this topic requires dedicated studies.

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ПРО ВИЗНАЧЕННЯ ЦЕНТРАЛЬНОСТІ
ЗА ДОПОМОГОЮ ДЕТЕКТОРІВ ПРОТОНІВ,
ЩО ВИЛІТАЮТЬ УПЕРЕД

Р е з ю м е

Вивчаються детектори протонів, що вилітають уперед, які вже встановлені на великому Адронному Колайдері, для дослідження зіткнень важких іонів. Демонструються можливості таких детекторів для вивчення продуктів поділу ядер – фрагментів спектаторів. Дана оцінка геометричного аксептансу детекторів протонів, що вилітають уперед, у випадку різних продуктів поділу. Вивчається вплив на аксептанс умов експерименту та руху Фермі. Обговорюється можливість реконструкції параметра зіткнень за допомогою вимірювання ядерних фрагментів.

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ELECTROMAGNETIC RADIATION FROM Au + Au COLLISIONS AT $\sqrt{s_{NN}} = 2.4$ GeV MEASURED WITH HADES

We present results of low-mass dielectron measurements from Au + Au collisions at $\sqrt{s_{NN}} = 2.4$ GeV *with HADES. The focus lies on the extraction of the effective temperature from the differential dilepton spectra and the analysis of the azimuthal anisotropy of virtual photons.*

Keywords: HADES, dielectrons, effective temperature, azimuthal anisotropy.

1. Introduction

The matter created in heavy-ion collisions at relativistic energies is rather compressed than heated, reaching net baryon densities of a few times normal nuclear matter density and moderate temperatures below 70 MeV/$k_{\rm B}$. Such matter is commonly described as the resonance matter consisting of a gas of nucleons and excited baryonic states, as well as contributions from mesonic excitations. Due to the compression in the inital phase of the collision, the hadron properties are substantialy modified. To understand the microscopic structure of baryon-dominated matter, HADES systematically measures virtual photons, that decay into dileptons, from elementary and heavy-ion collisions. These electromagnetic probes access the entire space-time evolution of a fireball and leave the collision zone without further interactions. Moreover, in contrast to real photons, they carry an additional information through their invariant mass. Thus, they provide the unique information about the various stages of the collision.

In Au + Au at $\sqrt{s_{NN}} = 2.4$ GeV, HADES observed a strong excess radiation which is remarkably well described assuming the emission out of a thermalized system [1]. Thus, the results imply strong medium effects beyond a pure superposition of individual nucleon-nucleon (pp, np) collisions.

The total yield of dileptons in the low-mass region up to 1 GeV/c^2 is related to the fireball lifetime [2]. The inverse slope of the invariant mass spectra provides information about the temperature in the system averaged over the whole space-time evolution of the collision [3,4]. To gain a further insight, the dependence of those temperatures on the virtual photon transverse momentum and rapidity and on the event centrality can be studied. Furthermore, the shapes of the spectra can be confronted with model calculations to obtain the understanding of the processes occurring in low-energy heavy-ion collisions such as the establishment of a local thermal equilibrium and the restoration of the chiral symmetry at high densities leading to modifications in the low-mass in-medium vector meson spectral function [2,5–8]. Using a coarse-grained transport calculation to describe the fireball evolution leads to a good agreement with the experimental data in the region $M_{ee} > 0.3$ GeV/c^2 [9,10].

This approach implies a locally equilibrated system for which the corresponding thermodynamic parameters can be extracted [2]. However, non-equilibrated transport-calculations also describe the data points without significant deviations.

In addition, the observables related to the collectivity of a system, e.g., the flow, are used to describe the macroscopic properties of nuclear matter. The collective flow consists of a radial flow, which affects the thermal spectra of the outgoing particles, and anisotropic flow, which affects the spatial orientation of the particle momenta. The azimuthal anisotropy is especially useful to disentangle early and late emission sources, because the effective temperature results from the superposition of all fireball stages with decreasing the temperature T, but increasing the flow β_T over time (see Eq. 4). The azimuthal anisotropies, on the other hand, are actually small in the early phases of the fireball evolution, where the flow is not yet fully developed and grow larger for the later phases. Thus, the elliptic flow does not show this implicit time dependence, and the combined dependence of the elliptic flow of dileptons on their transverse momentum and their invariant mass provides a rich landscape of structures, which allows one to set the observational window on specific stages of the fireball evolution [11].

2. Data Analysis and Signal Extraction

HADES at SIS18 (GSI, Darmstadt, Germany) is a fixed-target experiment. The spectrometer provides a large acceptance between 18° and 85° in the polar angle, as well as a nearly full azimuthal coverage. Figure 1 shows a 3D view of HADES with the main components of the detector. The Ring Imaging CHerenkov detector (RICH), the Time of Flight (TOF) and RPC detector, as well as the Pre-Shower detector, are mainly used for the particle identification, while four planes of low-mass MDCs in combination with a superconducting toroidal magnet are used to determine the particle tracks and momenta. In order to reduce the background from the photon conversion in a detector material, all tracking detectors are designed as light as possible. About 7 m behind the spectrometer, the Forward Wall is placed. It is used to reconstruct the event plane and to determine the centrality of a collision by measuring the spectator nucleons.

In twelve runs between 2002 and 2019, HADES collected data from various experiments at beam energies of 1–3.5 GeV. The size of the collision system ranged from elementary $p + p$ collisions over light- ($\mathrm{C}+\mathrm{C}$) and medium-sized ($\mathrm{Ar}+\mathrm{KCl}$) collision systems to the large $\mathrm{Au}+\mathrm{Au}$ system. In the two runs performed in 2014, also the pion-induced reactions were investigated. Before the most recent run ($\mathrm{Ag}+\mathrm{Ag}$ @ $\sqrt{s_{NN}}$ = 2.55 GeV completed in March 2019), the major detector upgrades including the RICH detector and a new electromagnetic calorimeter were conducted. In this work, the results of analysis of the data taken from the $\mathrm{Au}+\mathrm{Au}$ run at

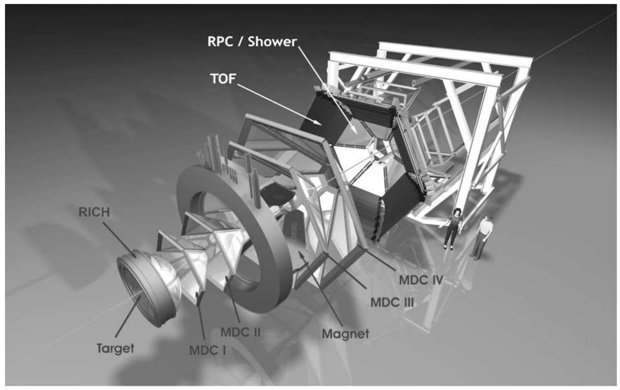

Fig. 1. 3D view of the HADES setup

2.4 GeV [1] in 2012 will be presented. In the five-week beamtime (overall 557 hours) with beam intensities between 1.2–1.5 $\times 10^6$ ions/s, the total of 7.3 billion events were collected and stored in 138 TB of data [13, 14].

After choosing only the events with a reaction vertex inside the target, rejecting the pile-up events and using a high-multiplicity trigger that selects 47% of the most central events along with event quality selection criteria, a clean sample of about 2.6×10^9 events were left to analyze.

Dileptons are very rare due to low branching ratios, e.g., $\Gamma_{ee}/\Gamma = (4.72 \pm 0.05) \times 10^{-5}$ in the case of a ρ-meson [15]. Thus, a very precise particle identification is crucial for reliable measurements. To separate the leptons from the hadronic background, the hard cuts in one or two dimensions can be applied on various observables. However, a better performance can be achieved, by considering the correlations between all the observables simultaneously, i.e., by using Multivariate Analysis (MVA) methods. They allowed us to identify single leptons with a very high purity of at least 98% and a good efficiency. In order to take the step from the reconstructed single electron signal to the dilepton spectra, the electron-positron pairs have to be build. It is not possible to identify electrons and protons from the same vertex. Instead, all possible unlike-sign pair combinations are calculated event-by-event (Fig. 2, black circles). This leads to a large contribution of wrong pair-

[1] A center-of-mass energy of $\sqrt{s_{NN}} = 2.42$ GeV corresponds to a beam energy of $E_{\mathrm{beam}} = 1.23A$ GeV and a center-of-mass rapidity of $y_{\mathrm{mid}} = 0.74$.

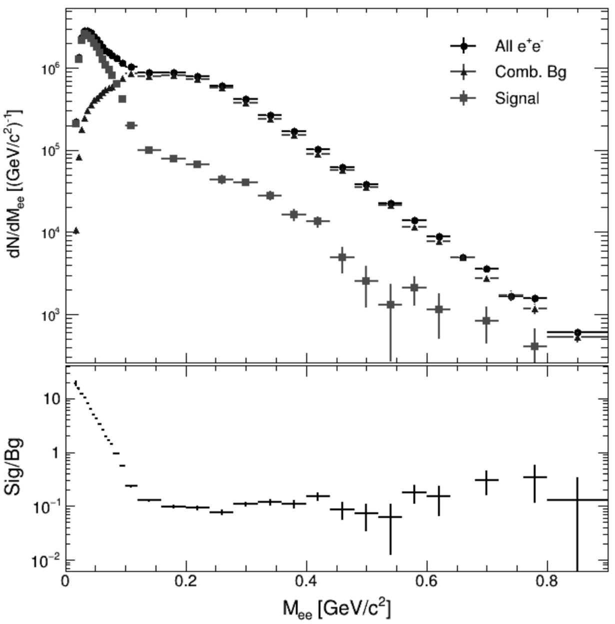

Fig. 2. Resulting dilepton spectrum and signal-to-background ratio

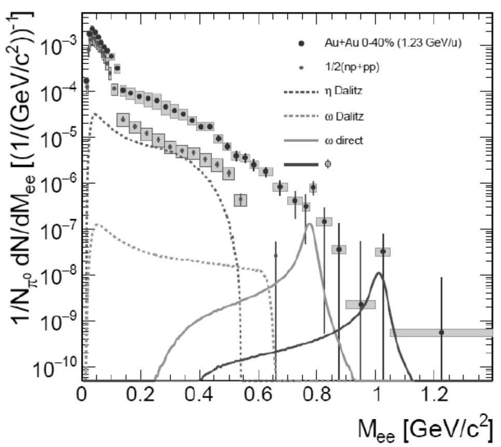

Fig. 3. Efficiency corrected dilepton spectrum is shown alongside a simulated cocktail of contributions from first chance collisions and the freeze-out stage [17]

ings to the final spectra. This so-called combinatorial background has to be subtracted from all pairs to obtain the true signal pairs (Fig. 2, blue triangles). As usual, two types of fake lepton pairs are distinguished, namely, the uncorrelated and correlated backgrounds. The former one stems from the pairing of leptons, originating from different mother particles, which is the largest contribution to the combinatorial background. Due to the random combination of two different decays, it is structureless. In the case of a two-photon decay or a Dalitz decay with the subsequent photon conversion of a neutral meson, it can happen that the paired leptons have different mother particles, but share their grandparent. The correlation of these pairs leads to a background contribution with a bump-like structure. While the uncorrelated background can be reproduced using the event mixing, the correlated background, which is dominant in the low-mass region, is handled using a same-event like-sign technique. The signal is a result of subtracting the combinatorial background from all e^+e^- combinations (Fig. 2, red squares). The signal-to-background ratio (bottom panel of Fig. 2) is $\sim 10\%$ for the invariant masses above 0.15 GeV/c^2.

3. Anisotropy Analysis

The flow coefficients v_1 (directed flow), v_2 (elliptic flow), v_3 (triangular flow), *etc.* are defined as the Fourier coefficients of the azimuthal angle expansion [16]:

$$\frac{dN}{d\Delta\Phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos(n\Delta\Phi), \quad \Delta\Phi = \Phi_{ee} - \Psi_{\mathrm{EP}}. \tag{1}$$

To extract the $\Delta\Phi$ of dileptons, the difference of the azimuthal angle of the dilepton pair (Φ_{ee}) and the angle of the event plane (Ψ_{EP}), which is determined using the information of the spectator hits in the Forward Wall, is calculated. This subtraction is necessary due to the correlation between the directed and elliptic flow components and the collision geometry. Furthermore, a correction factor accounting for the event plane angle resolution has to be applied [18]. The anisotropy coefficient v_2^{sig} of the signal pairs is then calculated from [19]:

$$v_2^{\mathrm{sig}} = \frac{1}{r} v_2^{\mathrm{tot}} - \frac{1-r}{r} v_2^{\mathrm{bg}}, \tag{2}$$

where r is the mass-dependent signal-to-background ratio, and v_2^{sig}, v_2^{tot}, and v_2^{bg} represent the flow coefficients for the signal pairs, all pairs, and the combinatorial background pairs. The latter ones are determined using different methods, namely, the same-event like-sign geometric mean background, mixed-event unlike-sign background and making an assumption that the combinatorial pairs, being built from the same single particles as signal pairs, have also the same orientation with respect to the reaction plane. To obtain a final value for the azimuthal anisotropy, the mean of the different methods is calculated. Their standard deviation is used to determine the systematic uncertainty. The statistical uncertainties are taken from the same-event like-sign geometric mean background for the lowest mass region, where the correlated background from π^0-Dalitz decays is dominant, and from the mixed-event background in the mass regions above.

4. Results

Figure 4 shows the effective slope parameter T_{slope} as a function of the invariant mass of the dielectron pairs, resulting from the fit:

$$\frac{1}{p_T}\frac{dN}{dp_T} \propto m_T K_1\left(\frac{m_T c^2}{k_\text{B} T_{\text{slope}}}\right), \tag{3}$$

with $m_T = \sqrt{M_{ee}^2 + p_T^2 c^2}$ and the assumption of a pure Boltzmann nature of the source. Since only a small fraction of the dilepton yield is lying outside of the HADES acceptance, which can be verified by comparing the rapidity spectra to different model calculations, this assumption is justified and is valid to apply a thermal fit without prior extrapolation to the unmeasured rapidity. Utilizing the good agreement between the shapes of the model fits and the experimental p_T spectra, a parametrization of the slopes from the model provides a further quantitative information. From

$$k_\text{B} T_{\text{slope}} = k_\text{B} T_{\text{kin}} + \frac{1}{2} M_{ee} c^2 \langle \beta_T \rangle^2, \tag{4}$$

where T_{kin} and $\langle \beta_T \rangle$ in the case of dileptons can be interpreted as the properties of their source averaged over four-volume, rather than of the freeze-out hypersurface, the values $T_{\text{kin}} = 65$ MeV/k_B, $\langle \beta_T \rangle = 0.19$ for the coarse-grained (CG) approach plus cocktail and $T_{\text{kin}} = 74$ MeV/k_B, $\langle \beta_T \rangle = 0.05$ for Hadron String Dynamics (HSD) can be extracted. Extrapolating those model fits to the zero invariant mass results in $T_{\min} = 61$ MeV/k_B and $T_{\min} = 69$ MeV/k_B, respectively. However, more precise experimental data are needed to decide for one model or another one. Contrary to hadrons [22, 23], the slope parameter is not dependent on the invariant mass, but stays rather constant over the whole mass range. This is due to the very low transverse velocity $\langle \beta_T \rangle$, indicating that the majority of dileptons is emitted at an early phase, thus not carrying the full $\langle \beta_T \rangle$ established at the freeze-out.

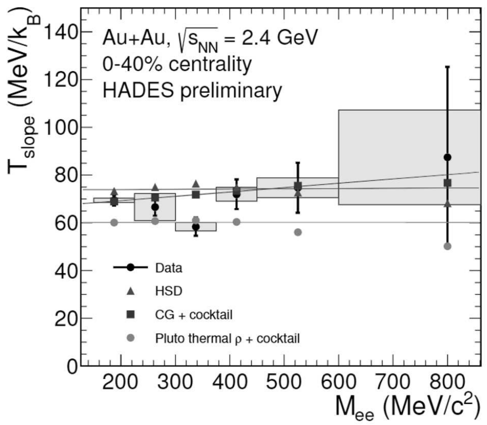

Fig. 4. Fitted slope parameters of the p_T-spectra in experimental data and model calculations of HSD [20], freeze-out meson cocktail combined with the in-medium ρ-spectral function [2] (denoted as CG), and the same cocktail combined with simple thermal ρ simulated using the Pluto event generator [21]. Solid curves represent the parametrization in Eq. 4, fitted to the model points [24]

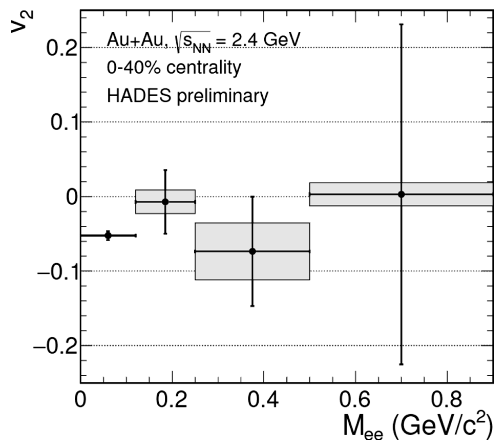

Fig. 5. v_2 coefficient of signal dileptons as a function of the invariant mass [24]

The second Fourier harmonic of the azimuthal anisotropy as a function of the invariant mass is shown in Fig. 5. The value in the lowest mass region $\left(0 \le M_{ee}\ [\text{GeV}/c^2] \le 0.12\right)$, where the dilepton spectrum is dominated by π^0-Dalitz decays, is in a good agreement with the elliptic flow seen in charged pions (see Fig. 6). A negative sign of v_2

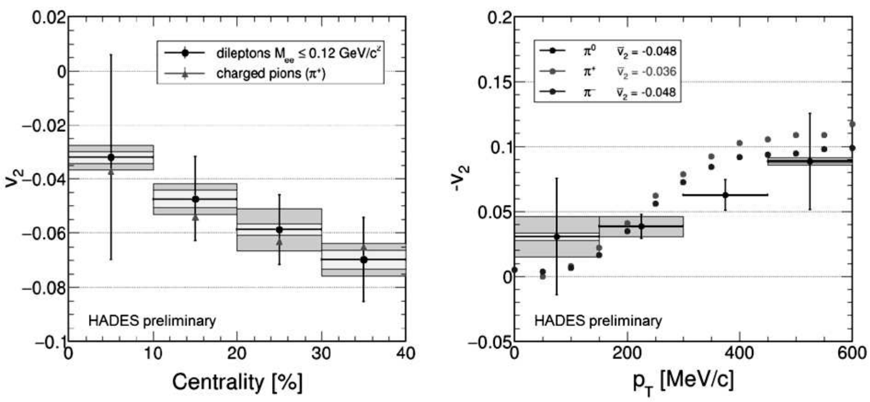

Fig. 6. v_2 of dileptons below 0.12 GeV/c^2 and charged pions as functions of the centrality and transverse momentum

means that the majority of the particles is ejected perpendicularly to the event plane. This out-of-plane flow can be explained by the passing spectator nuclei shadowing the collision center. This shadowing effect reduces the mean free path of particles that are emitted into the reaction plane, which leads to a squeeze-out of ejectiles perpendicularly to the reaction plane. At masses above the π^0-region, the azimuthal anisotropy seems to decrease and indeed is consistent with zero. Recalling the cocktail contributions shown in Fig. 3, it becomes apparent that the physics background contribution in those mass regions is at the level of at most 10% from η-decays, thus much lower than the 90% pion contribution in the first mass bin, meaning that those dileptons are mostly stemming from an early phase before the build-up of the flow. This is consistent with the observed very low transverse velocity discussed above. An alternative explanation of the vanishing azimuthal anisotropy is given by the penetrating nature of dileptons, which therefore do not experience the shadowing effect of the spectator matter [25]. More insights will be provided with the new set of data collected in March 2019, and that data are awaiting for theory interpretations. Figure 6 shows a comparison between v_2 of dileptons below 0.12 GeV/c^2 and charged pions. In the left panel, the centrality-dependent elliptic flow is plotted. As the collision gets more peripheral, more spectator nucleons are shielding the collision zone resulting in a stronger, i.e. more negative, flow. The values from the dileptons from π^0-decays and the charged pions are in a very good agreement. The same is true for the transverse-momentum-dependent flow coefficients shown in the right panel.

5. Conclusions

The results from the dilepton analysis in Au + Au collisions at 2.4 GeV show a clear evidence for the penetrating nature of the electromagnetic probes. The very low transverse velocity indicates that the majority of dileptons is ejected before the freeze-out, where the full transverse velocity seen in hadrons would have build up. The same is true for the creation of a flow in the system. Thus, the dileptons, which do not stem from hadronic decays show little or no azimuthal anisotropy. However, both methods would profit from higher statistics, as it is not possible up to now to definitely rule out one of the models with the inverse slope analysis or extract the azimuthal anisotropy with higher precision. In the most recent HADES beamtime with Ag + Ag at $\sqrt{s_{NN}} =$ = 2.55 GeV, conducted in March 2019, ∼15 billion events were collected, and the first low-level analysis promises high statistics and a very good data quality. Moreover, a newly installed electromagnetic calorimeter allows one to directly detect neutral mesons, making it possible to further determine the physics background in the dilepton spectra. In addition, the effects of the system size can be investigated. Combining the presented Au + Au data with the recently measured Ag + Ag run, as well as Ar + KCl at $\sqrt{s_{NN}} = 2.6$ GeV, will help one to draw a more complete picture.

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Д. Діттерт
від імені Колаборації HADES

ЕЛЕКТРОМАГНІТНЕ ВИПРОМІНЮВАННЯ
В ЗІТКНЕННЯХ Au + Au ПРИ ЕНЕРГІЇ 2,4 ГеВ,
В ДОСЛІДАХ НА HADES

Р е з ю м е

Представляємо результати вимірювання діелектронів малих мас у зіткненнях Au + Au при енергії 2,4 ГеВ у дослідах на HADES з метою отримання ефективної температури з диференційного спектра ділептонів, а також для аналізу азимутальної анізотропії віртуальних фотонів.

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QUARKONIUM PRODUCTION MEASUREMENTS WITH THE ALICE DETECTOR AT THE LHC

In (ultra-)relativistic heavy-ion collisions, the strongly interacting matter is predicted to undergo a phase transition into a plasma of deconfined quarks and gluons (QGP), and quarkonia probe different aspects of this medium. However, the medium modification of the quarkonium production includes also the contribution of cold nuclear matter effects (CNM), such as the shadowing or nuclear break-up in addition to QGP effects. Proton–nucleus collisions, where no QGP is expected, are used to measure cold nuclear matter effects on the quarkonium production. The vacuum production of quarkonia is modeled in proton–proton (pp) collisions, which are used as the reference for both heavy-ion and proton–nucleus collisions. Besides serving as a reference, the results in pp collisions represent a benchmark test of QCD-based models in both perturbative and non-perturbative regimes. The ALICE detector has unique capabilities at the LHC for measuring quarkonia down to the zero transverse momentum. Measurements are carried out at both central and forward rapidities in the dielectron and dimuon decay channels, respectively. In this contribution, the latest quarkonium measurements performed by the ALICE Collaboration during the LHC Run-2 period for various energies and colliding systems will be discussed.
Keywords: QGP, quarkonium,relativistic heavy-ion collisions, cold nuclear matter effects.

1. Physics Motivations

Quarkonium measurements represent an important tool for the investigation of the interaction of heavy quarks with the hot and energy-dense medium created in heavy-ion collisions, known as Quark–Gluon Plasma (QGP) [1], and provide an important insight about its properties. In the original prediction by Matsui and Satz [2], it was argued that quarkonium states could melt in a deconfined medium, since the binding energy between the quark and antiquark is screened due to the presence of free color charges. This implies that the quarkonium production in heavy-ion collisions should be suppressed as compared to binary-scaled *pp* collisions. However, it is also argued that the large production cross-section of heavy quarks in the hot thermalized medium leads to the (re)generation of quarkonia via the statistical recombination at the phase boundary [3] or through the coalescence of charm quarks [4]. Models including (re)generation describe the majority of charmonium measurements from LHC Run-1 (2009–2013), showing already the evidence that the (re)generation is the dominant production mechanism of J/ψ in heavy-ion collisions at LHC energies [5]. Measurements of the bottomonium production, for which the contribution from the (re)generation could be small due to the much smaller beauty production cross-section, and the comparison with the corresponding charmonium results can further shed light on the quarkonium production mechanisms in large systems. Furthermore, if heavy-flavor quarks thermalize in the QGP, regenerated quarkonium states could inherit their flow and then participate in the collective motion of the QGP.

The study of the quarkonium production in proton–nucleus collisions is relevant to quantify cold nuclear matter (CNM) effects. Mechanisms such as a modification of the parton distribution functions in nuclei, the presence of a Color Glass Condensate (CGC), and coherent energy loss of the $c\bar{c}$ or $b\bar{b}$ pair in the medium have been employed to describe the

J/ψ and Υ production obtained in proton–nucleus collisions from the LHC Run-1 [6–8].

In elementary *pp* collisions, the production of a quarkonium state can be understood as the creation of a heavy-quark pair ($q\bar{q}$) followed by its binding into a state with given quantum numbers. The first step is well described by perturbative quantum chromodynamics (QCD), while the second step is inherently non-perturbative. Currently, none of the existing models is able to satisfactorily describe simultaneously all aspects of the quarkonium production in *pp* collisions. Therefore, more differential measurements represent a powerful tool for adding further constraints to quarkonium production models, improving significantly our understanding of quarkonium production mechanisms in elementary hadronic collisions.

2. Quarkonium Measurements in ALICE

The ALICE detector [9] has unique capabilities to measure the quarkonium production down to the zero transverse momentum (p_{T}) in two rapidity ranges [1]: at mid-rapidity ($|y| < 0.9$) with the central barrel through the dielectron decay channel and at forward rapidity ($2.5 < y < 4$) with the muon arm through the dimuon decay channel.

The main tracking detectors in the central barrel are the Inner Tracking System (ITS) and the Time Projection Chamber (TPC). The ITS provides the primary and secondary vertex information, the latter is useful to separate the non-prompt J/ψ contribution (from beauty-hadron decays). The TPC provides the excellent particle identification for particles with intermediate momenta, in particular, for electrons up to about 10 GeV/c, based on the measurement of their specific energy loss.

The forward muon spectrometer includes a dipole magnet with an integrated field of 3 T·m, five tracking stations comprising two planes of cathode pad chambers each, and two trigger stations consisting of two planes of resistive plate chambers each. The latter allows one to trigger on events with at least a pair of opposite-sign track segments in the muon trigger system, each with a p_{T} above a specific threshold. A system of absorbers is used for filtering out hadrons.

[1] The rapidity ranges are quoted in the "laboratory" reference frame ($y = y_{\mathrm{lab}}$) which is coincident with the center-of-mass reference frame (y_{cms}) in *pp* and Pb–Pb collisions, but not in *p*-Pb collisions because of the asymmetric beam conditions.

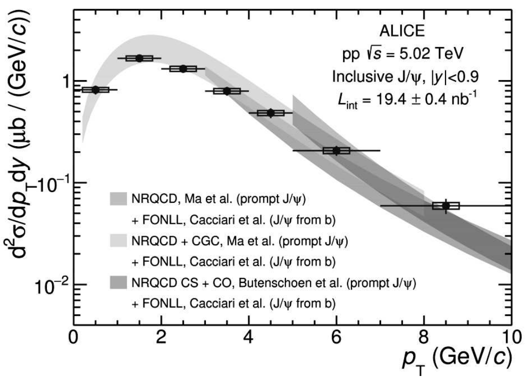

Fig. 1. p_{T}-differential inclusive J/ψ cross-section measured at mid-rapidity in *pp* collisions at $\sqrt{s} = 5$ TeV compared to prompt J/ψ NRQCD calculations added to predictions of non-prompt J/ψ from FONLL (see [10] and references therein)

3. Results: Selected Highlights

3.1. pp collisions

An extensive study of quarkonium production cross-sections in *pp* collisions has been performed by the ALICE Collaboration at several center-of-mass energies.

In Fig. 1, the inclusive J/ψ cross-section measured at mid-rapidity at $\sqrt{s} = 5$ TeV (see [10] and references therein) is compared to different sets of Non-Relativistic QCD (NRQCD) calculations of the prompt J/ψ production.

The model from Ma *et al.* is coupled to a CGC description of the low-x gluons in the proton and can predict the prompt J/ψ cross-sections down to $p_{\mathrm{T}} = 0$. In all cases, the non-prompt J/ψ component calculated from Fixed-Order Next-To-Leading-Logarithm (FONLL) predictions is added to the prompt J/ψ contribution.

The agreement between all models and data is good in the measured p_{T} range. It is worth noting that the uncertainties on the data points are significantly smaller than the model uncertainties, especially at low p_{T}. The ψ(2S)-to-J/ψ cross-section ratio, measured at the forward rapidity as a function of p_{T} in *pp* collisions at $\sqrt{s} = 13$ TeV, is compared to NLO NRQCD calculations in Fig. 2 (see [11] and references therein). In the ratio, many of the systematic uncertainties cancel for both data and model.

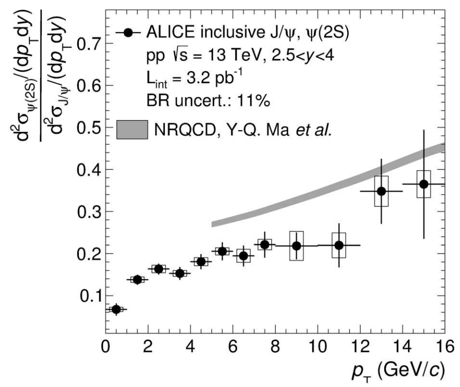

Fig. 2. ψ(2S)-to-J/ψ cross-section ratio as a function of p_{T} in *pp* collisions at $\sqrt{s} = 13$ TeV measured at the forward rapidity as compared to NLO NRQCD calculations (see [11] and references therein)

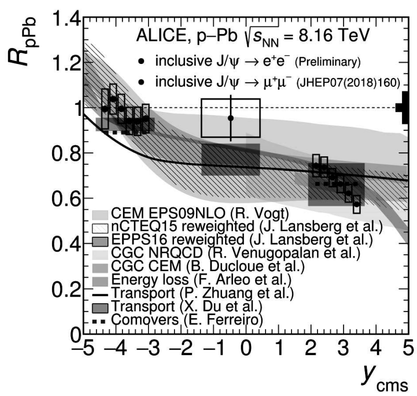

Fig. 3. $R_{p\text{-Pb}}$ as a function of y_{cms} of the J/ψ in *p*-Pb collisions at $\sqrt{s}_{\mathrm{NN}} = 8.16$ TeV. The results are compared to several theoretical predictions (see [13] and references therein; for the model of Du *et al.* see [14])

From the comparison, it is clear that there are still tensions between data and models. Similarly, discrepancies are observed for polarization measurements performed in *pp* collisions at $\sqrt{s} = 8$ TeV at the forward rapidity [12].

3.2. p-Pb collisions

The nuclear effects on the quarkonium production in *p*-Pb collisions are estimated via the p_{T} and rapidity differential nuclear modification factor defined as

$$R_{p\text{-Pb}}(y_{\mathrm{cms}}, p_{\mathrm{T}}) = \frac{\mathrm{d}^2\sigma^{\mathrm{onium}}_{p\text{-Pb}}/\mathrm{d}y_{\mathrm{cms}}\mathrm{d}p_{\mathrm{T}}}{A_{\mathrm{Pb}}\,\mathrm{d}^2\sigma^{\mathrm{onium}}_{pp}/\mathrm{d}y_{\mathrm{cms}}\mathrm{d}p_{\mathrm{T}}},$$

where the *p*-Pb production cross-section of a given quarkonium state, $\mathrm{d}^2\sigma^{\mathrm{onium}}_{p\text{-Pb}}/\mathrm{d}y_{\mathrm{cms}}\mathrm{d}p_{\mathrm{T}}$, is normalized to the corresponding quantity for *pp* collisions times the atomic mass number of a Pb nucleus ($A_{\mathrm{Pb}} = 208$). The p_{T}-integrated $R_{p\text{-Pb}}$ of inclusive J/ψ, measured in *p*-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV, is shown in Fig. 3 as a function of the center-of-mass rapidity, y_{cms}. Measurements in the dimuon channel are performed by taking data in two configurations of the beams with either protons or Pb ions going toward the muon spectrometer, corresponding to forward and backward rapidities, respectively. For the mid-rapidity measurement, the data corresponding to the two configurations can be combined due to the symmetry of the central barrel detector. The nuclear modification factor is compatible with unity at backward and mid-rapidities. In contrast, a suppression is visible at the forward rapidity. It is compared to several theoretical models which attempt to describe the prompt J/ψ production (see [13] and references therein; for the model of Du *et al.* see [14]). The results of calculations based on shadowing only show a good agreement with data, when the nCTEQ15 or EPPS16 set of nuclear parton distribution functions (nPDF) are adopted (Lansberg *et al.*), while using the EPS09 set of nPDF leads to a slightly worse agreement at the forward y_{cms} (Vogt). Calculations based on a CGC approach coupled with various quarkonium vacuum production models are able to reproduce the data in their domain of validity, corresponding to the forward-y_{cms} region (Venugopalan *et al.*; Ducloue *et al.*). The model of Arleo *et al.*, based on the calculation of the effects of parton coherent energy loss, gives a good description of the results for both backward-y_{cms} and forward-y_{cms} rapidities. Finally, models including a contribution from the final state interactions of the $c\bar{c}$ pair with the partonic/hadronic system created in the collision (Zhuang *et al.*; Du *et al.*; Ferreiro) can also reproduce the trend observed in the data. In the latter set of models, the nuclear shadowing is included, and it is the mechanism that plays a dominant role in determining the values of the nuclear modification factors.

The $R_{p\text{-Pb}}$ for ψ(2S) as a function of y_{cms} is shown in Fig. 4, where it is compared to the corresponding J/ψ result. At the forward rapidity, J/ψ and ψ(2S) show a similar suppression, while, at the backward rapidity, ψ(2S) is significantly more suppressed than J/ψ. Contrary to the J/ψ case, only models that include final state interactions with the surrounding medium are able to reproduce ψ(2S) results.

The ALICE Collaboration has also measured long-range correlations between forward-$y_{\rm cms}$ and backward-$y_{\rm cms}$ inclusive J/ψ and mid-rapidity charged hadrons, in p-Pb collisions at both $\sqrt{s}_{\rm NN} = 5.02$ and 8.16 TeV [15]. The data indicate persisting long-range correlation structures at $\Delta\phi \sim 0$ and $\Delta\phi \sim \pi$, reminiscent of the double ridge previously found in charged-particle correlations at mid- and forward rapidities [16]. The corresponding $v_2^{J/\psi}$, obtained by combining data of the two collision energies, is shown in Fig. 5. In heavy-ion collisions, this coefficient is related to the azimuthal anisotropy of the final-state particle momentum distribution and is sensitive to the geometry and the dynamics of the early stages of the collision. The results in p-Pb collisions are compared to $v_2^{J/\psi}$ measurements performed in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [17]. The positive v_2 coefficients observed in Pb–Pb collisions for $p_{\rm T}{}^{J/\psi}$ below 3–4 GeV/c are believed to originate from the recombination of charm quarks thermalized in the medium and are described fairly well by the transport model. In p-Pb collisions, the $v_2^{J/\psi}$ is compatible with zero at low $p_{\rm T}$, and this is in line with expectations, since no QGP is expected to be produced in which charm quarks could thermalize. Even assuming such scenario, the amount of produced charm quarks is small compared to that in heavy-ion collisions. Therefore, the contribution from the recombination should be negligible. However, at high-$p_{\rm T}$, J/ψ v_2 is comparable to the magnitude of the flow observed in central Pb–Pb collisions. It is worth noting that, in Pb–Pb collisions, the measured $v_2^{J/\psi}$ coefficients exceed substantially the theoretical predictions for $p_{\rm T}^{J/\psi} > 4$ GeV/c, where the main contribution to $v_2^{J/\psi}$ is expected to come from the path-length dependent suppression inside the medium. These intriguing results point to a common underlying mechanism, not included in current calculations, at the origin of the comparable magnitude of the $v_2^{J/\psi}$ at a high transverse momentum in both systems.

3.3. Pb–Pb collisions

The nuclear modification factor, for a quarkonium state in a given centrality class i of the Pb–Pb collision, is calculated as

$$R^1_{\rm Pb-Pb}(y, p_{\rm T}) = \frac{{\rm d}^2 N^{\rm onium}_{{\rm Pb-Pb},i}/{\rm d}y{\rm d}p_{\rm T}}{\langle T^i_{\rm AA}\rangle\ {\rm d}^2\sigma^{\rm onium}_{pp}/{\rm d}y{\rm d}p_{\rm T}},$$

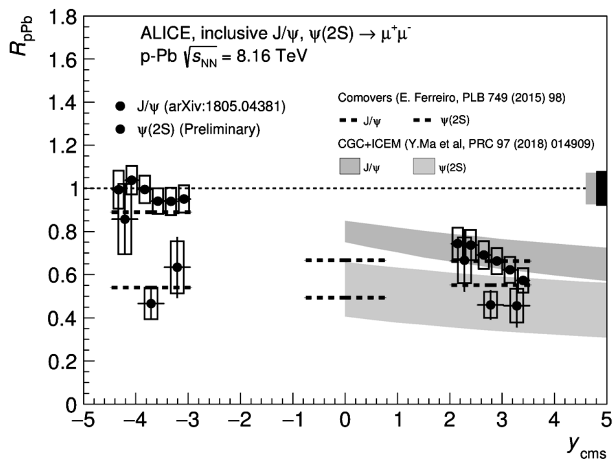

Fig. 4. $R_{p\text{-Pb}}$ as a function of $y_{\rm cms}$ for ψ(2S) and J/ψ in p-Pb collisions at $\sqrt{s}_{\rm NN} = 8.16$ TeV. The results are compared to different theoretical models (see references on the plot)

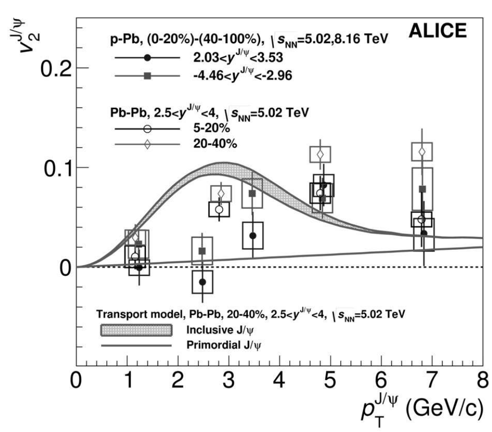

Fig. 5. Combined $v_2^{J/\psi}$ coefficients in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ and 8.16 TeV compared to results in central and semicentral Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV and to the transport model calculations for semicentral Pb–Pb collisions (see [15] and references therein).

where ${\rm d}^2 N^{\rm onium}_{{\rm Pb-Pb},i}/{\rm d}y{\rm d}p_{\rm T}$ is the corrected yield of the studied quarkonium state in Pb–Pb collisions, $\langle T^i_{\rm AA}\rangle$ is the nuclear overlap function, and ${\rm d}^2\sigma^{\rm onium}_{\rm pp}/{\rm d}y{\rm d}p_{\rm T}$ is the corresponding cross-section in pp collisions at the same center-of-mass energy. Figure 6 shows $R_{\rm AA}$ as a function of the centrality, for J/ψ measured at the forward rapidity in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, in the transverse momentum range $0.3 < p_{\rm T} < < 8$ GeV/c [18]. The $p_{\rm T}$ region below 0.3 GeV/c was excluded in order to reduce significantly the contribution from the photo-production

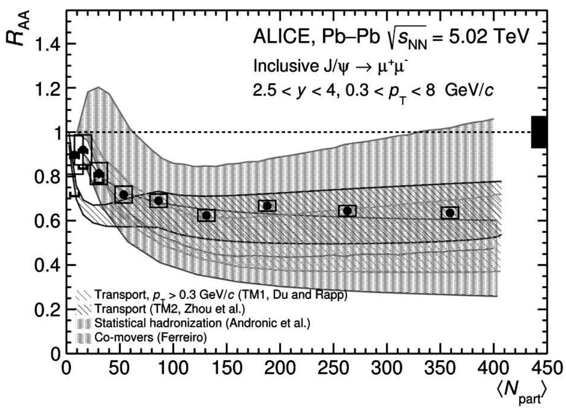

Fig. 6. Centrality dependence of inclusive J/ψ R_{AA} for $0.3 <$ $< p_T < 8$ GeV/c measured in Pb–Pb collisions at $\sqrt{s_{NN}} =$ $= 5.02$ TeV and comparison with theoretical models (see [18] and references therein)

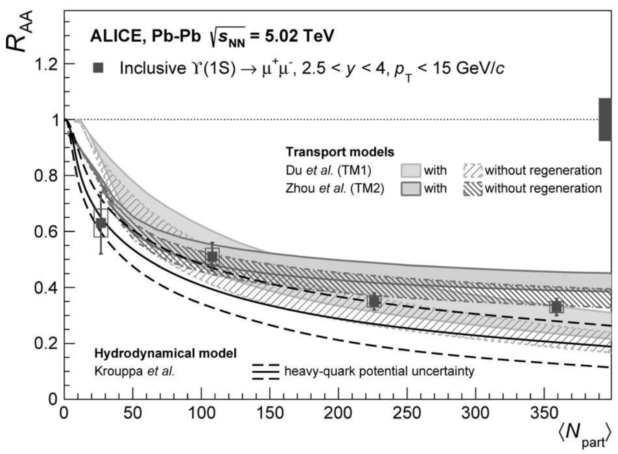

Fig. 7. Inclusive $\Upsilon(1S)$ R_{AA} as a function of the centrality measured at the forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared to theoretical model calculations (see [20] and references therein)

of J/ψ, which could influence the R_{AA} in peripheral collisions [19]. The results are compared to several theoretical models. The statistical hadronization model assumes that J/ψ are created, like all other hadrons, only at the chemical freeze-out according to their statistical weights. Transport models are based on a thermal rate equation, which includes the continuous dissociation and regeneration of J/ψ, both in the QGP and in the hadronic phase. Finally, in the "co-mover" model, J/ψ are dissociated via interactions with the partons/hadrons produced in the same rapidity range, and the regeneration term is included

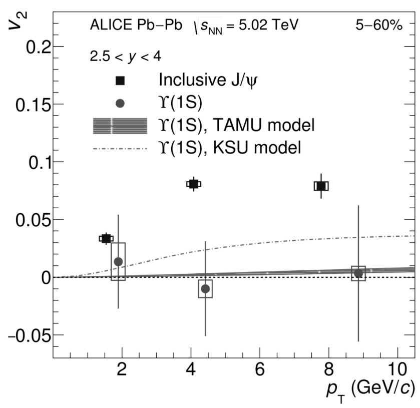

Fig. 8. The $\Upsilon(1S)$ v_2 coefficient as a function of p_T measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 5–60% centrality interval compared to that of inclusive J/ψ and to theoretical calculations (see [21] and references therein)

as well. The data are described by the various calculations, the latter having rather large uncertainties. These are related to the choice of the corresponding input parameters, and in particular, the nucleon-nucleon $c\bar{c}$ production cross-section ($d\sigma_{c\bar{c}}/dy$), as well as the set of nPDF.

The centrality dependence of the nuclear modification factor for $\Upsilon(1S)$ measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is shown in Fig. 7 along with several theoretical model calculations [20]. Both transport and dynamical model calculations reproduce qualitatively the observed centrality dependence. However, current uncertainties on both model and data prevent a firm conclusion regarding the contribution from the regeneration in the bottomonium sector. Furthermore, more precise measurements of the feed-down contribution from higher-mass bottomonia to the $\Upsilon(1S)$ are needed for a correct interpretation of results. Further information about the interplay between the regeneration and suppression in the bottomonium sector can be provided by elliptic flow measurements. The v_2 of $\Upsilon(1S)$, obtained by combining data samples recorded by ALICE during the 2015 and 2018 LHC Pb–Pb runs at $\sqrt{s_{NN}} = 5.02$ TeV, is shown in Fig. 8 in three p_T intervals [21] and is compared to the inclusive J/ψ v_2, measured in the same centrality and rapidity ranges. The $\Upsilon(1S)$ results are compatible with zero and with the small positive values predicted by the available theoretical models within uncertainties. Furthermore, the $\Upsilon(1S)$ v_2 is found to be lower by about 2.6σ compared to the one of the inclusive J/ψ in the centrality 5–60% and for $2 < p_T < 15$ GeV/c. This observation, coupled to the different measured centrality and p_T dependences of the $\Upsilon(1S)$ and J/ψ suppression, provides a further evidence that, unlike $\Upsilon(1S)$, the J/ψ production has a significant regeneration component.

4. Conclusions and Future Perspectives

Selected quarkonium measurements in pp, p-Pb, and Pb–Pb collisions performed by the ALICE Collaboration are presented. In pp collisions, NRQCD predictions coupled with CGC fairly describe the data in a wide range of momentum and rapidity. However, some tensions between data and models are still present. In p-Pb collisions, theoretical models are in fair agreement with quarkonium results, in particular, for $\psi(2S)$, models that include final state effects are able to describe the data. The positive v_2 measured for J/ψ is comparable with a similar measurement in Pb–Pb collisions for $p_T > 44$ GeV/c. The latter exceeds theoretical predictions in Pb–Pb collisions at high p_T, where the v_2 originates from the path-length suppression inside the medium. This intriguing observation points to a common mechanism at the origin of v_2 in both systems at high transverse momentum, besides what is currently included in the models. An extensive y and p_T-differential studies of the J/ψ suppression in Pb–Pb collisions indicate that, at LHC energies, a significant contribution to the J/ψ yields originates from the regeneration mechanism. However, for a better discrimination among the models, an improved precision is needed for both data and theoretical predictions. $\Upsilon(1S)$ is found to be more suppressed than J/ψ. Currently, the comparison with models does not allow us to quantify the contribution from the regeneration. A large elliptic flow for J/ψ, measured at low p_T, suggests the thermalization of charm quarks within the medium. On the contrary, the $\Upsilon(1S)$ v_2 is found to be compatible with zero and with values predicted by models, suggesting a negligible contribution from the regeneration mechanism in the bottonomium sector.

A significant improvement regarding the quarkonium measurements is expected for Run-3 (starting in 2021) and Run-4, when a major upgrade of the ALICE detector is foreseen [22]. A high-statistics minimum bias sample ($L_{\rm int} = 10$ nb^{-1}) will improve significantly mid-rapidity quarkonium measurements at low transverse momenta. Furthermore, a new Muon Forward Tracker (MFT) will be installed at the forward rapidity enabling the reconstruction of secondary vertices in this rapidity range, needed to measure the contribution of charmonia coming from beauty-hadron decays.

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ВИМІРЮВАННЯ ПРОДУКУВАННЯ КВАРКОНІЯ ЗА ДОПОМОГОЮ ДЕТЕКТОРА ALICE НА LHC

Р е з ю м е

Передбачається, що в (ультра)релятивістських зіткненнях важких іонів сильно взаємодіюча речовина проходить фазовий перехід до плазми кварків та глюонів (КГП), а кварконій може бути джерелом інформації щодо властивостей цієї матерії. Проте модифікація середовища, де продукується кварконій, включає також вплив холодної ядерної речовини (CNM) як екранування ядерного (брейкап) розвалу на додаток до ефектів КГП. Протон-ядерні зіткнення, в яких не очікуються утворення КГП, служать для визначення впливу холодної ядерної речовини на продукування кварконія. Вакуумне продукування кварконія моделюється в протон-протонних зіткненнях, які служать еталоном як для зіткнень важких іонів, так і для протон-ядерних зіткнень. Окрім калібровки, результати зіткнень протонів служать також орієнтиром для моделей, основаних на КХД як в пертурбативній, так і в непертурбативній областях. Детектор ALICE має унікальні для LHC можливості для вимірювання кварконіїв аж до нульового значення поперечного імпульсу. Вимірювання було виконано як для центральних, так і для передніх бистрот в каналах розпаду, відповідно, діелектрона та дімюона. В даній роботі представлено новітні вимірювання продукування кварконія Колаборацією ALICE на LHC під час Сеансу-2 при різних енергіях та для різних систем.

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THE NEUTRINO MASS EXPERIMENT KATRIN

The KArlsruhe TRItium Neutrino (KATRIN) experiment is a large-scale experiment with the objective to determine the effective electron antineutrino mass in a model-independent way with an unprecedented sensitivity of 0.2 eV/c^2 at 90% C.L. The measurement method is based on the precision β-decay spectroscopy of molecular tritium. The experimental setup consists of a high-luminosity windowless gaseous tritium source, a magnetic electron transport system with differential cryogenic pumping for the tritium retention, and an electrostatic spectrometer section for the energy analysis, followed by a segmented detector system for the counting of transmitted β-electrons. The first KATRIN neutrino mass measurement phase started in March 2019. Here, we will give an overview of the KATRIN experiment and its current status.

Keywords: neutrino mass, tritium β-decay, spectrometers.

1. Introduction

The absolute neutrino mass scale is one of the big open questions in particle physics, astrophysics, and cosmology. Cosmological observations and neutrinoless double β-decay experiments provide an indirect access to the absolute neutrino mass scale, but are model-dependent. A model-independent direct method to determine the neutrino mass is the precise investigation of weak decays such as the β-decay.

In the nuclear β-decay, the neutron in an atomic nucleus decays into a proton, thereby emitting an electron (e^-) and an electron antineutrino ($\overline{\nu}_e$). The energy released in the decay is divided between the e^- and $\overline{\nu}_e$ in a statistical way. The energy spectra of the electron is given by the well-known Fermi theory of β-decay [1]:

$$\frac{dN}{dE} \propto p(E+m_e c^2)(E_0-E)\sqrt{(E_0-E)^2 - m^2_{\overline{\nu}_e} c^4} \quad (1)$$

with the electron energy E, the endpoint energy E_0, the electron mass m_e, and the effective electron antineutrino mass $m^2_{\overline{\nu}_e} = \sum |U_{ei}|^2 \; m(\nu_i)^2$. This is the incoherent sum of neutrino mass eigenstates and is therefore insensitive to the phases of the neutrino mixing matrix (in contrast to the neutrinoless double β-decay). As one can see in Eq. 1, it is the square of the neutrino mass $m^2_{\overline{\nu}_e}$ that enters, as a parameter. Its effect on the shape of the spectrum is significant only in a very narrow region close to E_0. The current upper limit on the neutrino mass of 2 eV/c^2 [2] was determined from investigating the tritium β-spectrum near the endpoint of 18.6 keV by the experiments in Mainz [3] and Troitsk [4].

2. KATRIN Experiment

The **KA**rlsruhe **TRI**tium **N**eutrino (KATRIN) experiment [5] is a next-generation, large-scale experiment to determine the effective mass of an electron antineutrino by investigating the tritium β-decay kinematics with a sensitivity of 0.2 eV/c^2. The experiment was executed at the Karlsruhe Institute of Technology (KIT) in Germany. The measurement setup (see Figure 1) has an overall length of $\approx$ 70 m. Molecular tritium is injected into a windowless gaseous tritium source (b), where it decays with an activity of 10^{11} Bq, thus providing a sufficient number of β-decay electrons close to the endpoint energy E_0. The activity of the source is monitored at the rear section (a). Tritium is removed from the beamline in the differential pumping section (c) and the cryogenic pumping section (d), while electrons from the source are magnetically guided toward the spectrometer section. Both a pre-spectrometer and a main spectrometer are operated as electrostatic retarding high

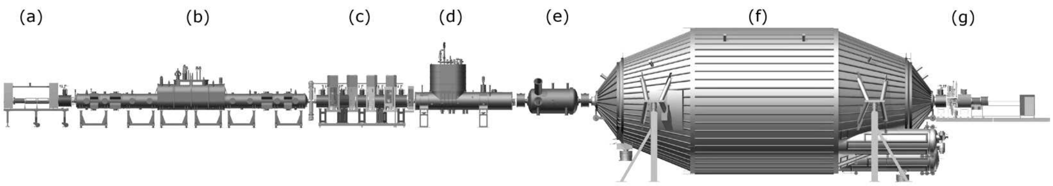

Fig. 1. The KATRIN experimental setup with its main components: rear section (a); windowless gaseous tritium source (WGTS) (b); differential pumping section (DPS) (c); cryogenic pumping section (CPS) (d); pre-spectrometer; (f) main spectrometer (e); focal plane detector (g)

pass filters of the MAC-E filter (**M**agnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic Filter) type [6]. The pre-spectrometer (e) is operated as a pre-filter in order to reduce the flux of electrons into the main spectrometer (f) which performs the energy analysis of the β-decay electrons near the endpoint with the energy resolution $\Delta E = 0.93$ eV at 18.6 keV. The main spectrometer is equipped with a dual-layer wire electrode system for electrostatically shielding secondary electrons from the inner vessel surface and for the fine-tuning of a retarding potential. The transmitted β-decay electrons are counted in the detector system (g) with a segmented silicon detector [7].

2.1. Windowless gaseous tritium source

The windowless gaseous tritium source (WGTS) consists of a 10 m long tube 90 mm in diameter and is operated at a temperature of about 30 K by the circulation of two-phase neon. Molecular tritium (T_2) is injected into the center of the source tube and decays with an activity of 10^{11} Bq to provide a sufficient number of electrons close to the tritium endpoint energy E_0. The β-electrons are guided via an axial magnetic field of up to 3.6 T toward the spectrometer section. T_2 is collected via turbo-molecular pumps at both ends of the WGTS and is recirculated via an "inner loop" which removes contaminants (particularly, ^{3}He) and is capable to process 40 g of T_2 per day. A prototype system to investigate the performance of the temperature stabilization of a beam tube showed that the stringent thermal performance specifications (temperature stability ± 30 mK) could be met, and the temperature stability better by a factor of twenty was achieved [8]. The WGTS was delivered to KIT in September 2015 and integrated into the KATRIN beam line. The magnet system was successfully tested to the maximum field. Initial tests of the temperature stabilization confirmed the performance better than the specified one already observed at the prototype system.

2.2. Differential cryogenic pumping section

The task of the Differential Pumping Section (DPS) is to reduce the T_2 partial pressure by a factor of $>10^5$ and to guide β-electrons via a strong magnetic field of up to 5.6 T. The beam tube has four bends to avoid the beaming of T_2 molecules toward the spectrometers. In order to remove tritium ions, the DPS is equipped with electric dipole electrodes. The magnet system was successfully commissioned, and the installation of the beam tube is complete.

Any remaining T_2 that passes the DPS is trapped in the Cryogenic Pumping Section (CPS) by argon frost frozen on the 4 K cold beam tube. The argon frost forms a highly efficient, large-area, and radiation-immune surface. The feasibility of this approach was successfully tested in a test experiment called TRAP [9] which achieved a T_2 reduction factor of about 10^7. The CPS was delivered to KIT in July 2015 and was successfully cooled to the operational temperature of about 4 K. Simulations based on the performance of the initial cool-down indicate that the T_2 reduction factor could be two or more orders of magnitude better than specified.

2.3. Spectrometer section

The spectrometer section consists of two spectrometers of the MAC-E filter type: a pre-spectrometer and a much larger main spectrometer.

The pre-spectrometer is intended to be used as a pre-filter on a potential a few hundred Volts below E_0. The pre-filtering reduces the flux of β-electrons into the main spectrometer by many orders of magnitude and minimizes β-electron-induced background processes in the main spectrometer.

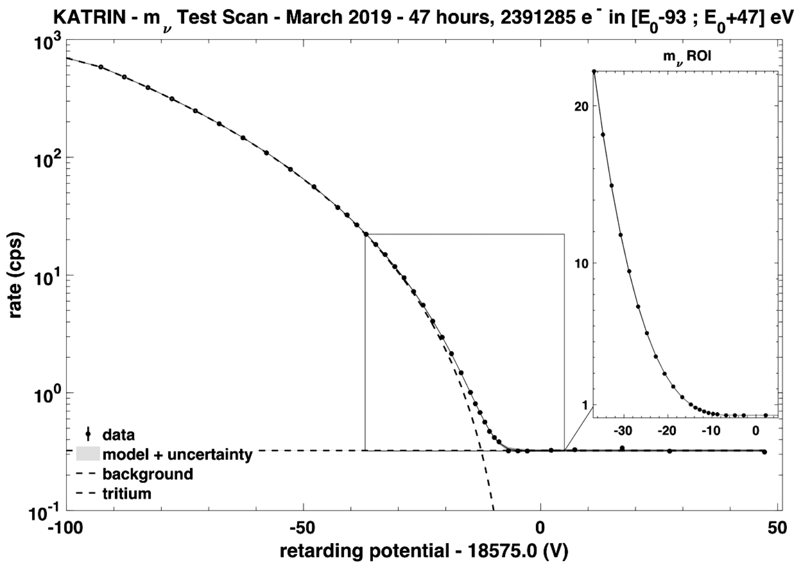

Fig. 2. Test scan of the tritium β-spectrum close to the endpoint

The purpose of the 10-m-diameter and 24-m-long main spectrometer is to analyze the energy of the β-decay electrons. It has an energy resolution of 0.93 eV at 18.6 keV. In order to reduce the spectrometer background rate, a double layer inner electrode system made of thin wires – mounted with submillimeter precision – is installed. The wire layers are put on a more negative potential with respect to the tank voltage in order to shield secondary electrons produced in the vessel wall. The absolute voltage of -18.6 kV needs to be stable on the 1 ppm level and is monitored with a high-precision voltage divider an independent calibration beam line [10]. The vacuum system of the main spectrometer is capable of reaching a pressure of about 10^{-10} mbar with one active non-evaporable getter pump [11]. After a recent baking of the spectrometer, a second getter pump was activated, and a pressure on the order of 10^{-11} mbar was achieved inside the main spectrometer.

2.4. Detector

Electrons that are able to overcome the potential barriers of the spectrometers are detected in a monolithic 148 pixel silicon PIN diode [7]. The energy resolution of the detector system is 1.4 keV (FWHM). The selection of materials, shielding, and an active veto are used to keep the intrinsic detector background at a low level of 1.2 mcps/keV.

3. Tritium Commissioning Measurements

The official inauguration of the KATRIN experiment took place on June 11th, 2018. In the following months, the tritium activity was increased step-by-step. The results of an initial test scan of the β-spectrum close to the endpoint are shown in Fig. 2. The plot shows the integral rate at the detector as a function of the main spectrometer retarding voltage. The spectrum is composed of two components: a voltage-independent background and the tail of the β-spectrum close to the endpoint.

The first KATRIN neutrino mass measurement phase started in March 2019 and concluded in May. The first results of this measurement phase are expected to be announced in September of this year.

4. Conclusions

Direct neutrino mass measurements are a model-independent way to determine the neutrino mass. A major improvement of the neutrino mass sensitivity by one order of magnitude is expected of the KATRIN experiment, which has completed its first neutrino mass measurement following its construction phase.

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ЕКСПЕРИМЕНТ KATRIN
ДЛЯ ВИМІРЮВАННЯ МАСИ НЕЙТРИНО

Р е з ю м е

Karlsruhe Tritium Neutrino (KATRIN) є широкомасштабним експериментом, метою якого є визначення маси електронного антинейтрино модельно-незалежним шляхом з безпрецедентною точністю 0,2 eB/c^2. Метод вимірювання базується на точній спектроскопії бета-розпаду молекулярного тритія. Експериментальна установка складається з безвіконного газовидного джерела молекулярного тритія високої світимості, магнітної електронної транспортної системи з диференційованою кріогенною помпою для затримки тритію, а також електростатичною спектрометричною секцією для контролю за енергією, за якою слідує сегментована система детекторів для підрахунку переданих бета-електронів. Перша фаза вимірювання маси нейтрино почалася у березні 2019 року. В роботі ми даємо огляд експерименту KATRIN та його сучасного стану.

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STUDY OF TAU NEUTRINO PRODUCTION IN PROTON NUCLEUS INTERACTIONS

In the DsTau experiment at the CERN SPS, an independent direct way to study the tau neutrino production in high energy proton-nucleous interactions was proposed. Since the main source of tau neutrinos is a decay of D_s mesons, the project aims at measuring the differential cross-section of this reaction. The experimental method is based on the use of high-resolution emulsion detectors for the efficient registration of events with short-lived particle decays. The motivation of the project, details of the experimental technique, and the first results of the analysis of the data collected during test runs, which prove the feasibility of the study are presented.

K e y w o r d s: tau neutrino, cross-section, nuclear emulsions.

1. Introduction

Tau neutrino is eventually the least studied elementary particle. Although its existence was predicted after the tau lepton discovery in 1975 [1], the first tau neutrinos were detected in the DONuT experiment 25 years later [2]. In 2015, somewhat more ν_τ appeared through $\nu_\mu \leftarrow \nu_\tau$ oscillations were detected by OPERA [3]. Super-Kamiokande (SK) and IceCube [4] also reported an evidence of the ν_τ presence in their data.

Given a poor statistics of registered tau neutrinos, their properties are not well studied. In particular, the cross-section of the tau neutrino charge current (CC) interaction is known [5] with much larger statistical and systematic uncertainties compared to the other neutrino flavors, as shown in Fig. 1. However, a precise measurement of this cross-section would allow testing of the Lepton Flavor Universality (LFU) in the neutrino scattering. LFU is a principal assumption of the Standard Model (SM) of particle physics, but its validity was questioned by recent results on the B decay asymmetry [6–8]. There is the expectation of a possible deviation of the cross-section of the ν_τ interaction as well [9]. The measurement of the ν_τ CC cross-section has impact on the current and future neutrino oscillation experiments. In the mass hierarchy measurements in the atmospheric Super-Kamiokande (SK) [10] and accelerator neutrino experiments (e.g., in DUNE [11] and HyperKamiokande [12]), ν_e flux measurement will have a background due to $\tau \to e$ decays. So, the systematic uncertainty of the ν_τ interaction cross-section will be a limiting factor in the oscillation analyses in these experiments [13, 14].

So far, the tau neutrino interaction cross-section was only measured in the DONuT [5], OPERA [18], and SK [17] experiments, though under rather different conditions. All the measurements have large statistical and/or systematic errors of 30–50% due to low statistics and experimental uncertainties. In a future experiment at CERN, SHiP [19], a rich neutrino program [20] is proposed with thousands of tau neutrino interactions detected, hence, providing a negligible statistical error of the cross-section measurement. The overall accuracy of the cross-section will be determined by the systematic errors, and, in particular, by the ν_τ flux uncertainty, which is to be studied by the DsTau experiment [34].

The dominant source (>90%) of ν_τ in an accelerator-based neutrino beam is leptonic decays of $D_s^\pm$ mesons produced in proton-nucleus interactions:

$$D_s^- \to \tau^- \overline{\nu}_\tau,$$
$$\tau^- \to X \nu_\tau,$$

producing ν_τ and $\overline{\nu}_\tau$ in every decay.

Conventionally, the differential production cross-section of charmed particles is approximated by a

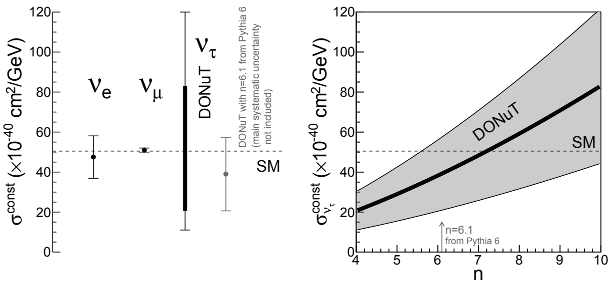

Fig. 1. Left: ν, $\overline{\nu}$ averaged energy-independent cross-section of the three neutrino flavors ([15] for ν_e, [16] for ν_μ, and for ν_τ [5]). The SM LFU prediction is indicated as a dashed horizontal line. For the DONuT result, since there is no measurement of the parameter n concerning the D_s double differential production cross-section (Eq. 1), the value is plotted in the empirical range of a parameter n given by the DONuT paper as in the right plot

phenomenological formula

$$\frac{d^2\sigma}{dx_{\rm F}\cdot dp_T^2} \propto (1-\mid x_F \mid)^n \cdot e^{-b\cdot p_T^2}, \tag{1}$$

where $x_{\rm F}$ is the Feynman x ($x_{\rm F} = 2p_Z^{\rm CM}\sqrt{s}$) and p_T is the transverse momentum, n and b are the parameters controlling the longitudinal and transverse dependences of the differential production cross-section, respectively. Although there were several measurements on charm particles [21–25], there is a lack of measurements on the D_s differential production cross-section in the proton interactions, especially concerning the longitudinal dependence represented by the parameter n. This has been the main source of the systematic uncertainty of the ν_τ cross-section measurements in DONuT [5].

Thus, a new measurement of the differential production cross-section of D_s is necessary for future precise tau neutrino measurements, as well as for the reevaluation of the DONuT result. In the DsTau experiment, a direct study of the tau neutrino production, namely, the measurement of $D_s \to \tau \to X$ decays following high-energy proton-nucleus interactions, is proposed. DsTau will provide an independent ν_τ flux prediction for future neutrino beams with accuracy under 10%. Then the systematic uncertainty of the ν_τ CC cross-section measurement can be made sufficiently low to test LFU in the neutrino scattering by future experiments [20].

In addition to the primary aim of measuring the D_s differential production cross-section in 2.3×10^8 proton interactions, a high yield of $\mathcal{O}(10^5)$ charmed particle pairs is expected. The analysis of those events can provide valuable by-products.

2. Overview of the Project

DsTau exploits a simple setup consisting of a segmented high-resolution nuclear emulsion vertex detector (a module) capable to recognize $D_s \to \tau \to X$ by their very peculiar double-kink topology as shown in the bottom part of Fig. 2. In addition, because charm quarks are created in pairs, another decay of a charged/neutral charmed particle from the same vertex will be observed with a flight length of a few millimeters. Such a "double-kink plus decay" topology in a short distance has a marginal background.

However, to register the events is a challenge. First, all the decays take place on a scale of millimeters: the mean flight lengths of D_s, τ, and pair-charms are 3.6, 2.1, and 4.2 mm, respectively. Second, although the kink angle at the τ decay vertex is easily recognizable (mean kink angle of 96 mrad), the one at $D_s \to \tau$ decays is rather small, 6.2 mrad. The expected signal features were studied making use of Pythia 8.1 [29]. The project aims to detect $\sim$1000 $D_s \to \tau \to X$ decays in 2.3×10^8 proton interactions with a tungsten target. State-of-the-art nuclear emulsion detectors with a nanometric-precision readout will be used to achieve this goal. The modern use of the emulsion detection technology is based on the high-speed high-precision automatic readout of emulsions developed during the last two decades and available today [26–28].

The DsTau module structure is shown in Fig. 2. The upstream part is named the *decay module*. The basic unit is made of a 500 μm-thick tungsten plate (target) followed by 10 emulsion films interleaved with 9 210 μm-thick plastic sheets which act as a decay volume for short-lived particles, as well as high-precision particle trackers. This structure (thickness of 5.4 mm) is repeated 10 times. Five additional emulsion films are placed most upstream of the module to tag the incoming beam protons. It is followed by the downstream part made of a repeated structure of emulsion films and 1-mm-thick lead plates for the measurement of the momenta of daughter particles through their Multiple Coulomb Scattering (MCS) measurement [30]. The entire detector module is 12.5 cm wide, 10 cm high, and 8.6 cm thick and consists of a total of 131 emulsion films.

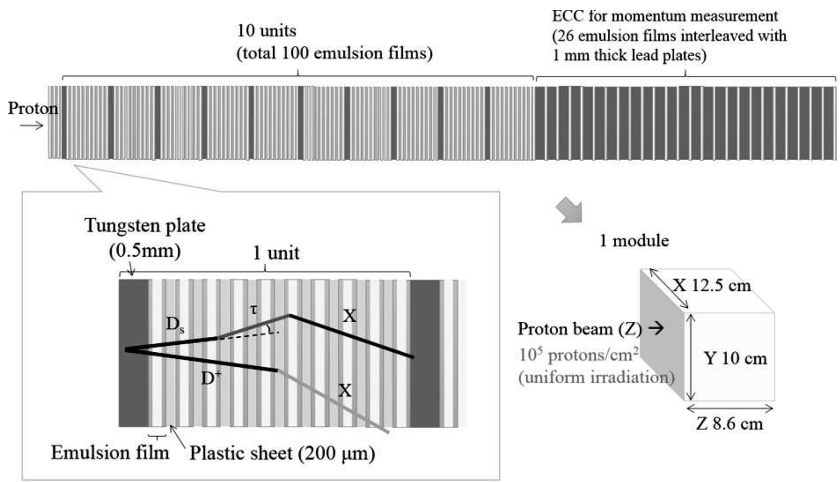

Fig. 2. Schematic view of the module structure. A tungsten target plate is followed by 10 emulsion films alternated by 9 plastic sheets acting as a tracker and a decay volume of 5.4 mm. The sensitive layers of emulsion detectors are indicated by green color. This basic structure is repeated 10 times, and then followed by a lead-emulsion structure for the measurement of the momenta of daughter particles. In the bottom part, the "double kink" topology of $D_s \to \tau \to X$ is shown

Once a charged particle passes through the emulsion layer, the ionization is recorded quasipermanently and then amplified and fixed by the chemical process. The trajectory of a charged particle can be observed on an optical microscope. The emulsion detector with 200 nm-diameter AgBr crystals and a 210 μm-thick base has a track position resolution of 50 nm [32] and an angular resolution of 0.34 mrad (projection). With this angular resolution, one can detect 2-mrad kink with 4σ confidence.

A key feature of the modern emulsion technique is the use of fast readout instruments, which allow extracting and digitizing the information on the tracks fully automatically. Emulsion detectors and automated readout systems have been successfully employed in several neutrino experiments such as CHORUS [33], DONuT [2, 5] and OPERA [3]. The latest scanning system, the HTS system [26, 27], allows the scanning of emulsion films at a speed of 5,000 cm^2 per hour per emulsion layer, which is $\mathcal{O}(100)$ faster than those used in OPERA.

The detection efficiency for the $D_s \to \tau \to 1$ prong events (85% of τ decays) was estimated by the PYTHIA 8.1 [29] simulation.

The following criteria were requested to be fulfilled: (1) the parent particle has to pass through at least one emulsion film (two sensitive layers), (2) the first kink daughter has to pass through at least two sensitive layers, and the kink angle is $\geq$2 mrad, (3) the flight length of the parent and the first kink daughter has to be <5 mm, (4) the second kink angle is $\geq$15 mrad and (5) the partner of the charm pair is detected with 0.1 mm $\leq$ flight length <5 mm (they can be charged decays with a kink angle >15 mrad or neutral decays). With these selection criteria, the detection efficiency was estimated to be 20%.

The main background to $D_s \to \tau \to 1$ prong events is hadron interactions that can mimic the decays of short-lived particles. Its probability was obtained by simulating 3×10^5 protons on the detector with the FLUKA [35] simulation. The criteria used for the charged charm or tau decay topology selection are applied to the interactions of secondary hadrons with only one charged daughter particle ($P > 2$ GeV/c). In addition to high-energy particles, a large part of interactions has associated nuclear fragments, which is a strong evidence of hadron interactions. Those are effectively rejected by requesting only one charged daughter. The total probabilities to account for background events such as a double kink with charged pair charm or with neutral pair charm are $1.3 \pm 0.4 \times 10^{-9}$ and $2.7 \pm 0.8 \times 10^{-9}$ per incident proton, respectively. The expected numbers of background events in the full statistics of DsTau (4.6×10^9 p.o.t.) are 6.0 ± 1.8 and 12.4 ± 3.7 for these 2-signal channels, respectively.

DsTau will provide the differential cross-section of D_s meson production and the following decay to a tau

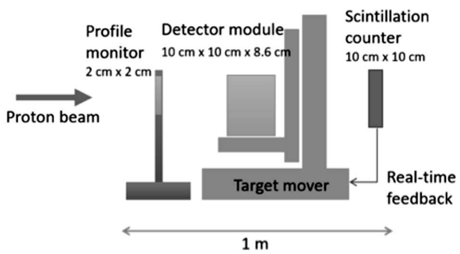

Fig. 3. Schematic of the DsTau setup. The detector module was moved in the plane perpendicular to the beam to provide uniform exposure at a density of 10^5 protons/cm^2

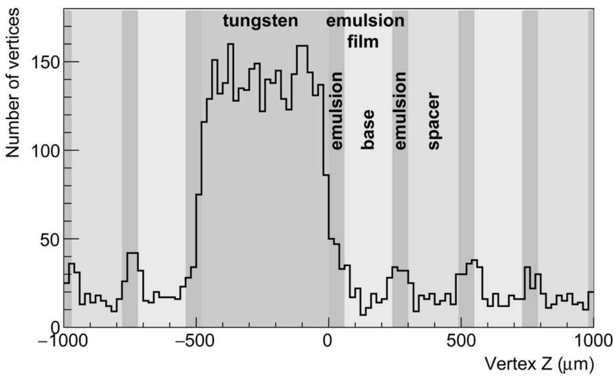

Fig. 4. Reconstructed vertex position distribution in Z. The correspondence with the detector structure is clearly visible

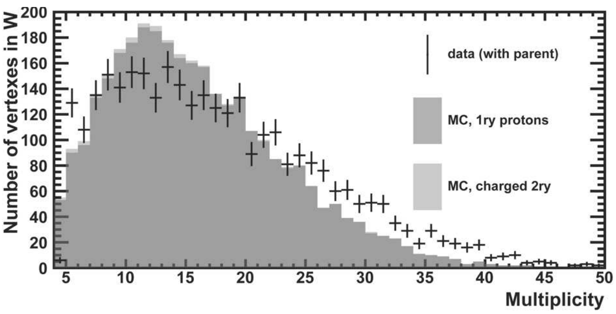

Fig. 5. Measured multiplicity of charged particles at the proton interaction vertices compared with the prediction from FLUKA simulations

lepton in the 400-GeV proton-nucleus interaction. It may be fit with the phenomenological formula, Eq. 1, and get the parameter n estimated, which is relevant for a re-evaluation of the tau neutrino cross-section measurement by the DONuT experiment. At the statistics of 1000 $D_s \to \tau \to X$ detected events, the relative uncertainty of the ν_τ flux will be reduced to below 10% [34].

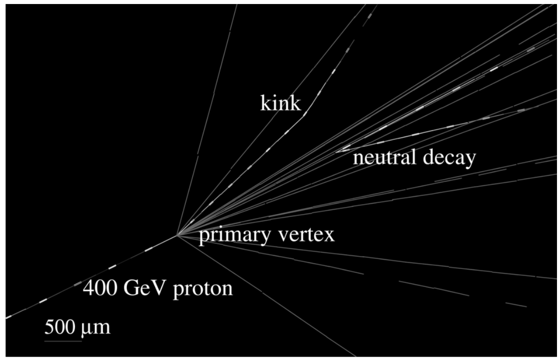

Fig. 6. A double charm candidate event with neutral 2-prong (vee) and charged 1-prong (kink) topologies. (tilted view) See the text about the details of event features

In order to collect 1000 $D_s \to \tau$ events, 230 millions of proton interactions are to be analyzed, which is another challenge from the point of view of the track density and the amount of data to be processed. The high proton density of 10^5 cm^2 at the upstream surface of an emulsion detector was chosen to maximize the number of interactions in a single module. The track density will then increase in the detector, yet not exceeding 10^6 cm^2 at the downstream part of the decay module, which is affordable for the emulsion detector readout and reconstruction. With this density, 6.25×10^5 proton interactions are expected in the tungsten target in a decay module. To accumulate 2.3×10^8 proton interactions in the tungsten plates, 4.6×10^9 protons on the target are needed. More than 368 modules with a total film area of 593 m^2 will be employed for this measurement.

3. Beam Exposure and Analysis Scheme

Two test beam campaigns were held at CERN SPS in 2016 and in 2017. In 2018, a pilot run was conducted aiming at the recording of 10% of the experimental data. A schematic view of the detector setup is shown in Fig. 3.

The proton beam profile was measured by a silicon pixel telescope. Each emulsion detector module was mounted on a motorized X-Y stage (target mover) to change the position of the module with respect to the proton beam, so to make the detector surface uniformly irradiated at a density of 10^5 tracks/cm^2.

The emulsion detector is both a detector and the data storage media at the same time. The automatic scanning systems read out the track information accumulated in the emulsion films during the exposure, digitize it, and transfer to the computers for the pattern recognition and track analysis like in case of any electronic detector. The output of the readout is the information on the track segments recorded in the top and bottom layers of a film (*microtracks*). A segment made by linking the microtracks on two layers in a film is called a *basetrack*, which is a basic unit of the track information from each emulsion film for the later processing. Each basetrack provides 3D coordinates $\mathbf{X} = (x, y, z)$, 3D vector $\mathbf{V} = (\tan\theta_x, \tan\theta_y, 1)$, and dE/dx parameter. The tracks are reconstructed by linking basetracks on different films making use of their position and direction.

The average basetrack efficiency measured with tracks is higher than 95%, which provides the track detection with efficiency >99%. The reconstructed tracks are then used to find vertices. To provide the efficient detection of small kinks of $D_s \rightarrow \tau$ decays, the analysis is performed in two stages: (1) scan the full module by a fast HTS system with relatively coarse angular resolution (2.5 mrad) and detect events that have two decays in a short distance, namely, the decays of τ and partner charm ($D^{\pm}$ and D^0); (2) perform a high-precision measurement around the τ decay candidates to find $D_s \rightarrow \tau$ small kinks. For this, the dedicated stations with a piezo-based Z axis are used providing a reproducibility of a single hit position measurement of 8 nm and angular measurements of 0.16 mrad (RMS).

Here, the first results acheaved at the first stage of the analysis are presented. Figure 4 shows the distribution of the Z coordinate (along the beam) of the vertices reconstructed in the detector. An enhancement of the vertices in the tungsten target is evident. One can even see the microstructure corresponding to the emulsion layers (of higher density) and plastic bases/spacers. Figure 5 shows the measured multiplicity of charged particles at proton interactions, compared with the prediction by FLUKA. A good agreement of the numbers of observed tracks and expected ones demonstrates a good efficiency of the track reconstruction.

With the data analyzed so far, several events with short-lived particle decays have been already recognized (See an example in Figure 6).

4. Conclusion and Outlook

The DsTau experiment is going to study the tau neutrino production following the high-energy proton interactions, which will provide necessary information for future ν_τ experiments. The SPSC recommended approving DsTau in April 2019.

The test of a beam in 2016–2017 and the pilot run in August 2018 were performed, and over 20 million proton interactions in the detector were registered. The emulsion scanning and analysis of these samples are ongoing, which would allow confirming the Ds detection feasibility and the re-evaluation of the ν_τ cross-section by refining the ν_τ flux. The full scale study scheduled for the next physics run at CERN SPS in 2021 and 2022. A large amount of the decays of charmed particles is expected to be recorded, as well providing a possibility of interesting by-product results.

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ДОСЛІДЖЕННЯ ПРОДУКУВАННЯ
ТАУ-НЕЙТРИНО В ПРОТОН-ЯДЕРНІЙ ВЗАЄМОДІЇ

Р е з ю м е

В рамках експерименту DsTau на прискорювачі SPS в ЦЕРНі нами запропоновано незалежний та прямий спосіб дослідження продукування тау-нейтрино в високоенергетичних зіткненнях протонів з ядрами. Зважаючи не те, що основним джерелом нейтрино є розпад Ds-мезонів, в проекті будуть вимірюватись диференційні перерізи цього процесу. Методика експерименту базується на застосуванні емульсійних детекторів для ефективної реєстрації подій розпаду короткоживучих частинок. Нами представлено мотивацію проекту, деталі експериментальної техніки, а також перші результати аналізу даних з перших пробних сеансів, що показали ефективність нашого експерименту.

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EXPLORING BARYON RICH MATTER WITH HEAVY-ION COLLISIONS

Collisions of heavy nuclei at (ultra-)relativistic energies provide a fascinating opportunity to re-create various forms of matter in the laboratory. For a short extent of time (10^{-22} s), matter under extreme conditions of temperature and density can exist. In dedicated experiments, one explores the microscopic structure of strongly interacting matter and its phase diagram. In heavy-ion reactions at SIS18 collision energies, matter is substantially compressed (2–3 times ground-state density), while moderate temperatures are reached ($T < 70$ MeV). The conditions closely resemble those that prevail, e.g., in neutron star mergers. Matter under such conditions is currently being studied at the High Acceptance DiElecton Spectrometer (HADES). Important topics of the research program are the mechanisms of strangeness production, the emissivity of matter, and the role of baryonic resonances herein. In this contribution, we will focus on the important experimental results obtained by HADES in Au + Au collisions at 2.4 GeV center-of-mass energy. We will also present perspectives for future experiments with HADES and CBM at SIS100, where higher beam energies and intensities will allow for the studies of the first-order deconfinement phase transition and its critical endpoint.

K e y w o r d s: heavy-ion collisions, HADES, vector meson dominance, dileptons, strangeness.

1. Introduction

When two heavy ions collide at relativistic energies, they form matter of high temperature (10^{12} K) and density ($< 3\rho_0$). The exact values and, thus, the detailed properties of the matter depend on the kinetic energy of the collision. While, at $\sqrt{s_{\rm NN}}$ of the order of hundreds GeV or of TeV, the properties of the matter resemble that, which prevailed in the Universe shortly after the Big Bang, with energies of few GeVs, thermodynamic conditions are similar to neutron star mergers (see, e.g., [1]). The scan of beam energies in between probes the phase diagram of a strongly interacting matter (search for a first-order phase transition and a critical point). Through the relation between a phase structure and symmetry patterns, it sheds light on the problems of quark confinement and hadron mass generation.

In this paper, we will present the results on the production of strange hadrons and dileptons in Au + Au collisions at $\sqrt{s_{\rm NN}} = 2.4$ GeV obtained by HADES. We will put them in context of earlier results on the dilepton production in nucleon-nucleon (*pp* and *np*) reactions at the same collision energy (per nucleon).

2. Experimental Setup

HADES is a fixed-target setup installed at SIS18 (*Schwerionen-Synchrotron* with rigidity 18 Tm) accelerator in Darmstadt, Germany [2]. It possess a six-fold symmetry defined by identical sectors covering nearly 60 degrees of the azimuthal angle each. Within the sectors, the particle tracking and momentum reconstruction are provided by the toroidal magnetic field generated by compact superconducting coils located between sectors and by four Multiwire Drift Chambers (MDCs): two upstream and two downstream to the magnetic field region. The tracking resolution for lepton pair invariant masses close to vector meson poles is of the order of few % ($\delta M = 15$ MeV/c^2 at $M = 780$ MeV/c^2).

Behind the tracking system, time-of-flight detectors are located. Above the polar angle of about 45 degree, a wall of plastic scintillator bars is mounted, at lower polar angles, Resistive Plate Chambers

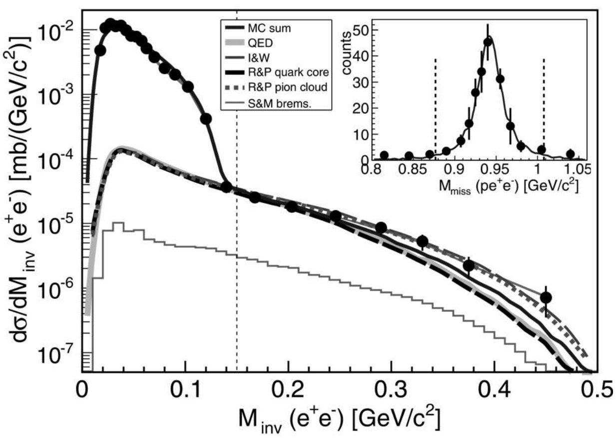

Fig. 1. e^+e^- invariant mass within the HADES acceptance. Experimental data (black dots) are corrected for the detection and reconstruction inefficiencies. Curves represent models, as discussed in the text

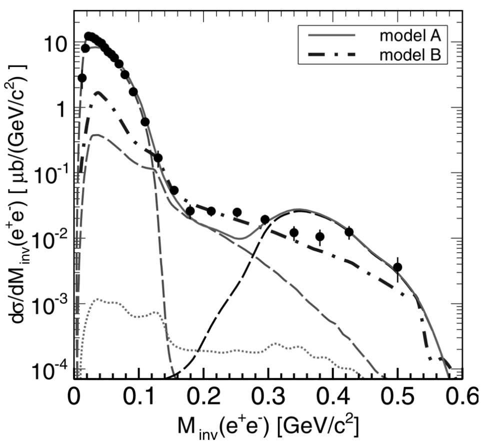

Fig. 2. Dielectron differential cross section as a function of the invariant mass of e^+e^- within the HADES acceptance. The data (black dots) are corrected for the detection and reconstruction inefficiencies. The simulated cocktail (curves) of the π^0 (dashed violet), η (dotted magenta), Δ (dashed red) Dalitz decays, ρ from the $\Delta - \Delta$ interaction process (dashed black) according to the model [4] and the sum (contributions from π^0, η, Δ and ρ – solid green curve) are displayed – model A. The dotted-dashed blue curve shows the bremsstrahlung contribution from [6] – model B

(RPCs) are installed, which have granularity necessary for high-multiplicity Au + Au events. After the proper calibration, the intrinsic time resolution of the scintillator wall is 150 ps and that of RPC – below 70 ps. Behind the RPC, an electromagnetic Pre-Shower detector is located, which contributes to the lepton identification. In each sector, it consists of two lead converter plates sandwiched between three wire chambers in the streamer mode.

The main role in the lepton identification task is played by a Ring Imaging Cherenkov (RICH) detector. It is placed in front of the tracking system in the field-free region. It consists of a single chamber filled with C_4F_{10} radiator gas, closed by a spherical mirror in the forward direction and separated from the photon detector by a CaF_2 window in the backward direction. The photon detector is an MWPC with aa planar CsI photocathode divided into pads in such a way that Cherenkov light emitted in the radiator and reflected from the mirror forms rings on the cathode plane, whose radii in terms of the number of pads are independent of the location. For C_4F_{10}, the threshold Lorentz γ for Cherenkov emission is 18. This translates to the threshold momenta for electrons of 0.01 GeV/c, for muons of 1.9 GeV/c, and for pions of 2.4 GeV/c. With the energy available for the particle production at $\sqrt{s_{\rm NN}} = 2.4$ GeV collisions, the very fact of the Cherenkov radiation emission discriminates between electrons and other particles.

The spectrometer is also equipped with a CVD (chemical vapor deposition) diamond t_0 detector placed in front of and a VETO detector behind the target. About 7 m downstream the target, a Forward Wall hodoscope is located. The Au target was split into 15 segments, each 20 μm thick, in order to reduce the conversion probability of real photons in the target.

3. Dileptons in $p + p$ and $n + p$

Collisions of single hadrons (nucleon-nucleon and pion-nucleon) allow for determining various resonance properties in elementary collisions, in particular the electromagnetic transition form factors. Via the Dalitz decays, they can be studied in the kinematic region $0 < q^2 < 4m_p^2$ (m_p is the proton mass), which is not accessible in annihilation experiments.

The analysis of the exclusive channel $pp \to ppe^+e^-$ with a kinetic energy of 1.25 GeV of the beam allowed HADES to measure, for the first time, the branching ratio of the decay $\Delta \to pe^+e^-$. It equals $(4.19 \pm 0.62 \pm 0.34) \times 10^{-5}$, where the former uncertainty is systematic, including the model dependence, and the latter is statistical [12].

Figure 1 shows the invariant mass distribution of dileptons from $p + p$ collisions after the cut on the

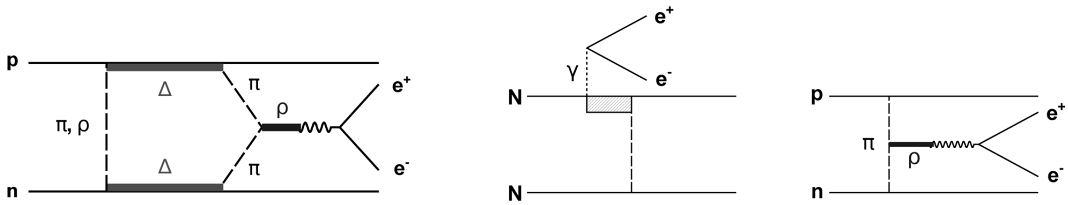

Fig. 3. Left: one of the diagrams contributing to the $\Delta - \Delta$ interaction in model A [4] of Fig. 2. Middle and right: diagrams contributing to the coherent sum in the bremsstrahlung description of [6]

proton missing mass indicated in the inset, compared to different models of the Δ form factor. The blue curve represents the sum of the following contributions: π^0 Dalitz decay, Δ Dalitz decay according to [5], and bremsstrahlung according to [6]. The cyan curve is the Δ Dalitz contribution in a description with a point-like $\gamma^* NR$ coupling ("QED-model") [7, 8], fixed from reactions with $q^2 = 0$. The two-component Iachello–Wan model [9–11], depicted with the dashed dark green curve, has the largest contribution. It parametrizes the electromagnetic interaction by a direct coupling and a coupling via a vector meson with dressed ρ propagator. The constituent quark model by Ramalho and Peña [5] describes the dominant G^*_M form factor with two contributions: quark core (quark-diquark S-wave) and pion cloud (photon directly coupling to a pion or to an intermediate baryon state). The two components are shown after scaling each of them up to the same yield as in the full model: quark core (dashed black curve) and pion cloud (dashed red curve). All model contributions are supplemented with the bremsstrahlung (shown also separately as a green histogram).

It should be noted that the quark-core contribution of the Ramalho–Peña model nearly coincides with the "QED-model," and both are not sufficient to describe the experimental data. An additional coupling in terms of the pion could/intermediate ρ meson seems to be necessary.

The role of a ρ meson is also highlighted by the np measurement [13]. It was performed by colliding a deuterium beam with a kinetic energy 1.25A GeV and selecting events with a quasifree neutron through the proton detection in a forward hodoscope. The cross-section distribution for the e^+e^- production over the pair invariant mass is shown in Fig. 2. It is compared to two model calculations. Model A includes hadronic sources, as well as $\Delta - \Delta$ interaction, as shown in the left-most panel of Fig. 3 (other

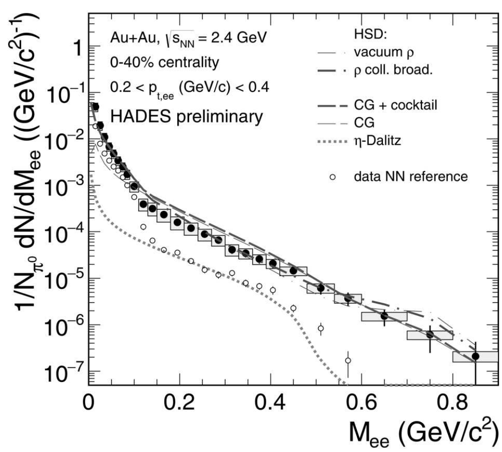

Fig. 4. Invariant mass distribution of e^+e^- from Au + Au collisions at $\sqrt{s_{\rm NN}} = 2.4$ GeV. It was corrected for the detection efficiency, extrapolated to 4π and the zero single-lepton momentum and normalized to the π^0 multiplicity. Similarly, the corrected normalized distribution from the reference pp and np reactions is shown as well. Curves represent theoretical model calculations: [18] (HSD), [16] (CG). The latter is accompanied by a cocktail of hadronic sources at the freeze-out (these sources are already included in the HSD calculation). The largest contribution to the cocktail above the π^0 mass, $\eta \to \gamma e^+e^-$, is shown separately

diagrams permuting incoming and outgoing propagators are also included). Model B contains only bremsstrahlung, described in [6] in terms of diagrams like shown in the middle and the right panel of Fig. 3 (with appropriate permutations). Model A underestimates the cross-section in the invariant mass region of 0.15–0.3 GeV/c^2. The bremsstrahlung contribution goes though the experimental points here. A full model adding all the contributions, perhaps coherently, would be needed. But the results indicate that the interaction via the pion exchange or annihilation of virtual pions with the subsequent emission of a ρ meson plays an important role in hadronic interactions.

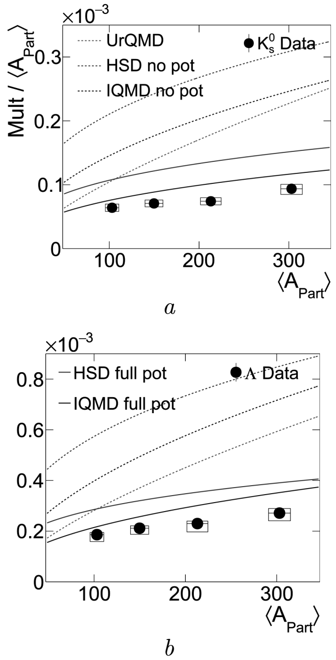

Fig. 5. Multiplicities per mean number of participants Mult/$\langle A_{\rm part}\rangle$, as a function of $\langle A_{\rm part}\rangle$ for K^0_s (a) and Λ (b) compared to various transport model calculations

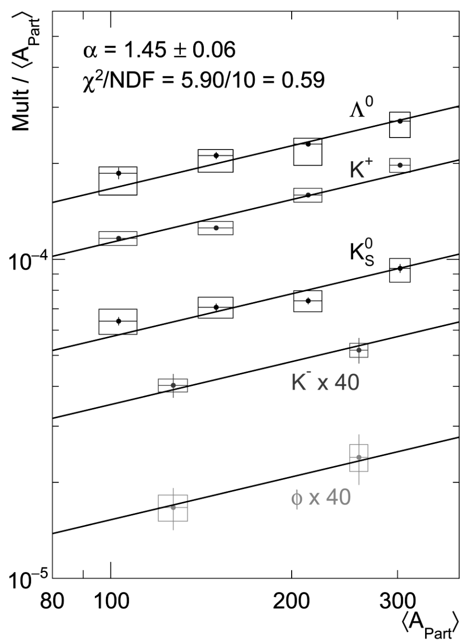

Fig. 6. Multiplicities per mean number of participants Mult/$\langle A_{\rm part}\rangle$ as a function of $\langle A_{\rm part}\rangle$. All hadron yields are fitted simultaneously with a function of the form Mult $\propto \langle A_{\rm part}\rangle^\alpha$ with the result: $\alpha = 1.45 \pm 0.06$

4. Dileptons in Heavy-Ion Collisions

In heavy-ion collisions, the dileptons are not scattered or reabsorbed through the strong interaction with hadronic matter. Thus, they can probe the interior and early stages of the evolution of a hot dense fireball. Their multiplicity will be ever-increasing with fireball's lifetime, and the spectra will take exponential shape with the slope reflecting the effective temperature of the system, which should be higher than the freeze-out temperature extracted from the spectra of hadrons that decouple in the late stage of the collision.

Figure 4 shows the invariant mass distribution of the radiation of dileptons at $\sqrt{s_{\rm NN}} = 2.4$ GeV, for a pair transverse momentum $p_{\rm t,ee}$ range of 0.2–0.4 GeV$/c$. It is compared to the spectrum from pp and np reactions which represents, after a proper normalization, first-chance collisions between nucleons participating in a heavy-ion reaction ("NN reference"). The excess amounts to the factor of 8–10 in the mass range above the π^0 mass, see also [14]. By comparing to the ρ spectra from the transport model HSD [18], where a ρ meson is treated as free or subject to the collisional broadening, one can note that the resonant structure completely disappears ("melts") in the experiment. This feature is captured by different implementations of the relatively novel approach of coarse-graining (CG) [15–17], where the explicit assumption of local thermal equilibrium is made. It is used to calculate the temperature and density of small space-time cells of a fireball (with transport models as the input). These are used to calculate the thermal dilepton emission using a vector meson (ρ dominating) spectral function. Coarse-graining approaches also make use of the vector meson dominance (VMD) assumption, according to which all the dilepton emission proceeds through an intermediate vector meson. Their validity is strengthened by the aforementioned findings in NN collisions.

At lower values of the invariant mass, all the models leave room for an improvement, and the higher statistics data with a higher signal-to-background ratio (main source of the systematic uncertainty) would be of great importance.

5. Strangeness Production in Heavy-Ion Collisions

Collision energies at SIS18 are below the strangeness production threshold in NN collisions. Therefore, the multiplicities and spectra of strange particles in heavy-ion reactions are sensitive to the mechanisms of energy accumulation and possibly to the equation of state of the strongly interacting matter.

Figure 5 shows the multiplicities of K^0_s and Λ as functions of the mean number of nucleons participating in the collision, $\langle A_{\rm part}\rangle$ in Au + Au at $\sqrt{s_{\rm NN}} = 2.4$ GeV [19]. It is compared to a number of transport models: UrQMD [21], IQMD [22], and HSD [23]. For HSD and IQMD, two versions of a simulation were done: with a repulsive K-N potential of 40 MeV at the nuclear ground state density ρ_0, which increases linearly with the density, and without such a potential. Turning on the potential brings the theory predictions closer to the experimental data, both in terms of the multiplicity values and of the α exponent in the power law Mult $\propto \langle A_{\rm part}\rangle^\alpha$. The large spread between the models themselves would result in the value of the potential strongly model-dependent.

The $\langle A_{\rm part}\rangle$ dependence of the multiplicities of all strange particles reconstructed in HADES (K^+, K^-, ϕ [20], K^0_s, and Λ [19]) is displayed in Fig. 6. Data for all the particles can be described by the power law with the same exponent. This does not reflect the hierarchy in NN thresholds for different strange particles and is not expected, if the energy for their production is accumulated in a sequence of isolated nucleon-nucleon collisions. Instead, we suggested in [19] that the total amount of strange quarks in a collision is produced according to the system size determined by the number of participating nucleons. Their distribution between hadrons is fixed at the freeze-out.

6. Conclusions

HADES provides the high-statistics and high-precision data on the particle production in Au + Au collisions at the relatively low energy $\sqrt{s_{\rm NN}} = 2.4$ GeV. In this contribution, a selection of results was presented, which suggests that the hot dense fireball created in such collisions is a much stronger correlated system, than it was assumed up to now. These correlations might allow for a faster thermalization of the system, a statistical redistribution of strange quarks among hadrons, and the melting of a ρ meson. These cannot be exactly reproduced by the conventional hadronic transport models. It remains to be rigorously studied on the ground of theory and phenomenology, if the correlations can be attributed to a "pion cloud" of hadron (or another formalism), whose effect is clearly visible in NN collisions. If the density-dependent repulsive effective K-N potential can be regarded as a proxy for the nontrivial hadron structure, then the improvement in the description of the Mult($\langle A_{\rm part}\rangle$) dependence for K^0_s and Λ could also be a manifestation of this structure.

7. Outlook

On the experimental side, the understanding of the effects observed in heavy-ion collisions requires more data with various colliding systems and beam energies. To this end, HADES measured Ag + Ag collisions at $\sqrt{s_{\rm NN}} = 2.4$ GeV and $\sqrt{s_{\rm NN}} = 2.55$ GeV in March 2019. The statistics of events at the former energy is slightly lower as in Au + Au at $\sqrt{s_{\rm NN}} = 2.4$ GeV, while it is a few times higher at the latter energy. Moreover, in Ag + Ag, the combinatorial background in the reconstruction of unstable particles is expected to be smaller, than in Au + Au. Therefore, it will very likely that the main physical results of Au + Au can be extended to Ag + Ag at both collision energies.

In the future FAIR (Facility for Antiproton and Ion Research) in Darmstadt, currently under the construction, the CBM (Compressed Baryonic Matter) experiment will collide heavy ions at energies of $\sqrt{s_{\rm NN}}$ from roughly 3 to 6 GeV. This will fill the gap in energy between the existing data of HADES and STAR at Relativistic Heavy-Ion Collider in Brookhaven. It will collect data with an unprecedented interaction rate of 10 MHz (0.5 MHz from day 1), which will allow for the studies of rare and penetrating probes, in particular, dileptons and multistrange particles and for the search of the critical point of the deconfinement phase transition. HADES at SIS100 will focus mainly on the e^+e^- and strangeness production in pp and pA collisions.

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ДОСЛІДЖЕННЯ БАРІОННОЇ МАТЕРІЇ В ЗІТКНЕННЯХ ВАЖКИХ ІОНІВ

Р е з ю м е

Зіткнення важких іонів при (ультра-)релятивістських енергіях дають чудову можливість для створення різних форм речовини в лабораторії. Короткий час (10^{-22} сек) може існувати речовина з екстремальними температурою та щільністю. В спеціальних експериментах вивчається мікроскопічна структура сильновзаємодіючої речовини і її фазова діаграма. В реакціях з важкими іонами при енергіях SIS18 речовина значно стискається (в 2–3 рази порівняно зі щільністю основного стану) при помірних температурах ($T < 70$ МеВ). Ці умови нагадують, наприклад, стан колапсу нейтронних зірок. Речовина при таких умовах власне вивчається на HADES (High Acceptance DIElectron Spectrometer). Важливими в рамках цієї програми є дослідження механізму продукування дивності, випромінювання матерії та роль в цьому баріонних резонансів. В даній роботі ми звертаємо увагу на важливі експериментальні результати, отримані на HADES у зіткненнях Au+Au при енергії в системі центра мас 2,4 ГеВ. Ми також представимо перспективи майбутніх експериментів з HADES та CBM при SIS100, де більш високі енергії та інтенсивності дозволять вивчати фазовий перехід першого роду деконфайнменту та відповідну йому критичну точку.

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TESTS OF *CPT* INVARIANCE AT THE ANTIPROTON DECELERATOR OF CERN

The Standard Model, the theory of particle physics is based on symmetries: both the structure of the composite particles and their interactions are derived using gauge invariance principles. Some of these are violated by the weak interaction like parity and CP symmetry, and even masses are created via spontaneous symmetry breaking. CPT invariance, the most essential symmetry of the Standard Model, states the equivalency of matter and antimatter. However, because of the lack of antimatter in our Universe it is continuously tested at CERN. We overview these experiments: measuring the properties of antiprotons as compared to those of the proton at the Antiproton Decelerator and also searching for antimatter in cosmic rays.

Keywords: Standard Model, CPT invariance, antiproton mass, antihydrogen, cosmic antimatter.

1. Introduction

The theory behind particle physics, called for historic reasons *the Standard Model*, developed half a century ago, is based on *gauge symmetries* [1]. Some of those, however, are violated, like the maximally broken parity symmetry or the tiny little CP-violation. And of course, there is the spontaneous symmetry breaking mechanism necessary to create masses for the elementary particles.

The fundamental particles of the Standard Model are fermions with half-integer and bosons with integer spins. The elementary fermions have three families, each consisting of a pair of quarks and a pair of leptons and all of them have antiparticles of opposite charges, but otherwise identical properties. The leptons can propagate, but the quarks are bound in hadrons: the baryons (like the proton and neutron) consist of three quarks and the antibaryons of three antiquarks, and the mesons (like the pion) are bound states of a quark and an antiquark.

The three basic interactions in the Standard Model are derived from local gauge invariances: the strong interaction from a local SU(3) and the electroweak one from a local U(1)⊗SU(2) gauge invariance with the *spontaneous symmetry breaking*. These interactions are mediated by elementary bosons, the strong interaction by the eight gluons carrying the colour charges of the quarks and antiquarks, the weak interaction by the three heavy weak bosons, $W^{\pm}$ and Z^0 and the electromagnetism by the γ photon. These bosons are virtual when they mediate the interactions, but they can also be emitted and observed experimentally, even the heavy weak bosons and the coloured gluons in high-energy collisions.

2. CPT Invariance

According to the well-known theorem of Emmy Noether, continuous symmetries of the Lagrangian lead to conservation laws. The conservation of the electric charge and of the fermion number is connected to the U(1) symmetry of the Dirac Lagrangian: that is a valid, non-breaking symmetry. The colour-SU(3) symmetry of quantum chromodynamics leads to the conservation of the colour charge. The ultimate symmetry of matter and antimatter is manifested by the CPT invariance, which makes it possible to treat free antiparticles as particles moving backward in space and time. This is a most important symmetry of Nature: the physical laws do not change when charge (C), space (P) and time (T) are simultaneously inverted:

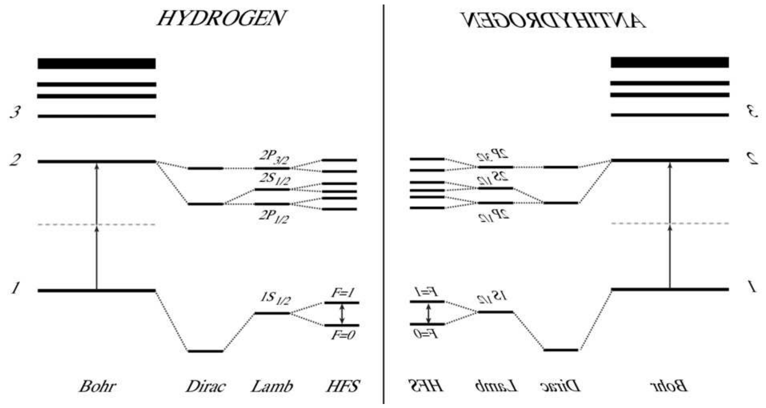

Fig. 1. Energy levels of hydrogen and antihydrogen. The 2S–1S transition offers extremely precise two-photon spectroscopy [3]

• charge conjugation (i.e. changing particles into antiparticles), $C\psi(r,t) = \overline{\psi}(r,t)$;

• parity change (i.e. mirror reflection), $P\psi(r,t) = \psi(-r,t)$, and

• time reversal, $T\psi(r,t) = \psi(r,-t)K$ where K denotes complex conjugation.

Time reversal is an *anti-unitary* operation due to the phase factor connecting time and energy in the state function. As a result, CPT is also anti-unitary, it conjugates the phase of the system while not changing the measurable properties. Using CPT invariance positron annihilation can be described as if an electron arrived, irradiated two or three photons and left backward in space and time.

CPT invariance is supported by all known theoretical and experimental evidence. Its role is so fundamental in quantum field theory that it is almost impossible to test experimentally: in the case of observing a small deviation one should suspect the violation of a conservation law rather than CPT violation. Giving up CPT invariance brings dire consequences: one may lose causality, unitarity or Lorentz invariance. Nevertheless, it seems to be grossly violated: according to the generally accepted Big Bang theory of cosmology, at the end of the radiation period particles and antiparticles should have been produced in exactly the same amounts, but we cannot see antimatter galaxies anywhere [2]. This badly necessitates testing the CPT invariance experimentally. To date the most precise one of such tests is the mass difference between the neutral kaon and anti-kaon as measured using kaon oscillation: the relative difference is less than 10^{-18}.

3. Antimatter Problems

In 1928 Paul M. Dirac tried to produce a linear equation for the hydrogen atom and got two solutions for the electron: an ordinary one and another one with positive charge and negative mass. Dirac first assumed the latter non-physical, but three years later Carl Anderson observed positively charged electrons, positrons in cosmic rays (both of them were awarded the Nobel Prize).

In addition to the mysterious lack of antimatter in our Universe, there are some other questions for antiparticles. Is it really true that particles and their antiparticles have exactly the same properties except for the sign of their charges? Could there be a tiny difference between particle and antiparticle to cause the lack of antimatter galaxies? Are there particles which are their own antiparticles (called Majorana particles)? In principle, the neutrinos can be Majorana-particles, although there are no signs of this in experiment. Could the dark matter of the Universe consist of such particles?

The above problems may point to a possible CPT violation, and so we are obliged – in spite of our belief in its validity – to test CPT invariance. The easiest way is to compare the properties of particles and antiparticles. In addition to the kaon-anti-kaon mass difference one can compare the spectroscopic properties of atoms and anti-atoms. It was shown [3] that the simplest and most precise such measurement with antiprotons should be to perform two-photon spectroscopy on antihydrogen atoms, $\overline{\mathrm{H}} = [\overline{\mathrm{p}}\mathrm{e}^+]$, the bound state of an antiproton and a positron, and that antihydrogen can be produced and confined in electromagnetic traps. The 1S–2S transition of antihydrogen (Fig. 1) seemed to be most eligible as it can be excited with two photons only and as a result of that it has a very long lifetime and consequently very narrow line width. Moreover, when applying two counter-propagating laser pulses one excludes the longitudinal Doppler-broadening of the line width, significantly increasing the precision of the measurement.

4. The Antiproton Decelerator of CERN

Antihydrogen atoms were first produced at the Low Energy Antiproton Ring (LEAR) at CERN and later also at Fermilab [4, 5]. Relativistic antiprotons collide in the storage ring with Xe atoms and produce electron-positron pairs. With a low probability the antiproton can pick up a fast positron forming an antihydrogen atom which is neutral and leaves the ring along a straight beam line. The positron and the antiproton of the antihydrogen atom are then separated and identified: the positron annihilates to two photons and the antiproton to several charged pions.

CERN, the joint European Particle Physics Laboratory has built the *Antiproton Decelerator, AD* facility (it is now called Antimatter Factory) in 1997-99 to study antimatter physics and to test the CPT invariance, mainly via producing and studying antihydrogen. At the moment there are six experiments: three to test CPT and another three to check antigravity, i.e. to measure the gravitational mass of the antiproton.

The Antiproton Decelerator works the following way. The Proton Synchrotron shoots protons with a 26 GeV$/c$ momentum onto an iridium target producing proton–antiproton pairs. From there the AD gets antiprotons of 3.57 GeV$/c$ momentum and slows them down to 100 MeV$/c$ (corresponding to 5.3 MeV kinetic energy) in four steps, in the first two steps with stochastic and then electron cooling [7]). The AD delivers $3 \ldots 4 \times 10^7$ antiprotons at 100 MeV$/c$ momentum to several experiments, which trap them in electromagnetic fields after suitable further deceleration, and using slow positrons make antihydrogen ($\overline{\mathrm{p}}\mathrm{e}^+$) atoms [6].

The antiprotons have to slow further down to keV energies in order to facilitate trapping. The ALPHA and ATRAP experiments prepare spectroscopy on trapped antihydrogen, ASACUSA and BASE compare the properties (mass, charge and magnetic moment) of protons and antiprotons at high precision, AEGIS and GBAR plan to measure the gravitational mass of antihydrogen, and ACE studied the effects of antiprotons on living tissue. The success of the AD experiments persuaded CERN to increase their efficiency by building a small storage ring ELENA (Extreme Low Energy Antiprotons) which will supply an order of magnitude higher number of slow antiprotons for trapping than the AD with the energy absorbers of the experiments. ELENA has been constructed and it will serve all AD experiments from 2020 on.

5. Antihydrogen Production

In order to produce antihydrogen, one has to confine both antiprotons and positrons in a trap, cool them to very low temperatures and then let them interact. The radiative recombination, ($\overline{\mathrm{p}}\mathrm{e}^+\gamma$), should produce deeply bound atoms, but it is hopelessly slow. At the moment all AD experiments produce $\overline{\mathrm{H}}$ atoms using the three-body recombination reaction [8]: $\overline{\mathrm{p}}\mathrm{e}^+\mathrm{e}^+ \to \overline{\mathrm{H}}\mathrm{e}^+$ where a second positron carries away the released energy and momentum. This reaction has a quite high cross section, but it produces highly excited $\overline{\mathrm{H}}$ atoms which then should be de-excited to make spectroscopy possible.

Another method [9] is investigated at the AD: $\overline{\mathrm{H}}$ production in collisions of antiprotons with positronium, the bound state of an electron and positron. This reaction has a high rate and results in not-too-highly excited $\overline{\mathrm{H}}$, but it is more complicated to prepare.

The first cold, confined $\overline{\mathrm{H}}$ atoms were produced by the ATHENA experiment at the AD, and its successor, the ALPHA (Antimatter Laser PHysics Apparatus) Collaboration made all steps leading from $\overline{\mathrm{H}}$ atoms confined in a trap, to their de-excitation and spectroscopy. At the same time the ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) Collaboration managed to produce and extract an $\overline{\mathrm{H}}$ beam from a trap.

6. $\overline{\mathrm{H}}$ Spectroscopy by the ALPHA Experiment

The ALPHA (Antimatter Laser PHysics Apparatus) Collaboration was the first and to date the only experiment to perform $2S$–$1S$ spectroscopy on antihydrogen [12]. The measurement was quite elaborate, developed gradually step by step in ten years:

1. 90,000 antiprotons were captured and cooled in a Penning trap.

2. Mixed them with 3 million cold positrons and 50,000 $\overline{\mathrm{H}}$ atoms were produced.

3. The remaining charged particles were removed by dropping the trapping potential.

4. 20 $\overline{\mathrm{H}}$ atoms were stored in an inhomogeneous magnetic field at $T = 0.54$ K temperature.

5. The $\overline{\mathrm{H}}$ atoms were kept trapped for 10 s in order to let them to undergo de-excitation to the $1S$ ground state.

6. The excitation $1S \rightarrow 2S$ was performed with two 243 nm photons (standing wave for 300 s) tuned around the resonance (appearance measurement).

7. A microwave irradiation removed the residual $1S$ atoms (disappearance measurement).

8. The trap was flushed by dropping the confining B field measuring the number of remaining $\overline{\mathrm{H}}$ atoms.

The 10 s waiting time was necessary to let the $\overline{\mathrm{H}}$ atoms de-excite to 1S, and at the same time short enough not to lose them from the trap as demonstrated by the ALPHA experiment earlier. Half the cold $\overline{\mathrm{H}}$ atoms can be confined depending on the spin polarization of the positron, and thus they can be flushed out by a microwave irradiation on resonance with the positron spin flip. This hyperfine transition was also studied when preparing the experiment [11]. At each step the antiproton annihilations were detected with checking the vertex positions of the events to make sure that they do not come from hitting the walls of the vessel. The last three steps made both an appearance and a disappearance measurement of the same reaction, and the results agreed with each other and also with the simulation assuming CPT invariance. At laser spectroscopy the laser power affects the result: that was also measured and the results normalized to the power of 1 W. At last, ALPHA has managed also to observe the 1S–2P Lyman alpha transition in antihydrogen [12].

Using 15000 $\overline{\mathrm{H}}$ atoms the ALPHA experiment [10] yielded 2 466 061 103 079.4 $\pm$5.4 kHz for the 1S–2S transition frequency of antihydrogen. Its precision is just one order of magnitude behind that of ordinary hydrogen: 2 466 061 103 080.3 $\pm$0.6 kHz. This means a confirmation of CPT on the level of 2×10^{-12}.

7. Antimatter Gravity Measurement

The negative mass of antiparticles in the Dirac theory keeps exciting the general public, although the masses of our everyday objects are mostly (about 95%) energy-related. Of course, this is also something that has to be checked experimentally as precisely as possible. Unfortunately, gravity is so much weaker than electromagnetism that it makes a measurement with charged particles hopeless. There are nice gravity measurements made with neutrons, but the problem with antineutrons is that they cannot be slowed down without fast annihilation. That leaves antihydrogen for such studies. Of course, CPT invariance does not prescribe identical acceleration in Earth's gravitational field for protons and antiprotons: that is a result of the weak equivalence principle.

Testing antimatter gravity is the main aim of two AD experiments, AEGIS and GBAR. AEGIS (Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy) is the largest AD collaboration (although still two orders of magnitude smaller than the largest LHC experiments). They are preparing to measure the gravitational falling of a beam of collimated $\overline{\mathrm{H}}$ atoms as compared to light using Moiré deflectometry. AEGIS will produce antihydrogen using the collisions of antiprotons with excited positronium atoms [13].

The GBAR (Gravitational Behaviour of Antihydrogen at Rest) Collaboration [14] plans to do an antihydrogen free-fall measurement. They plan to use such a dense positronium cloud that the antiprotons would pick up two positrons in two collisions to form an $\overline{\mathrm{H}}^{+}$ ion which then can be cooled in several steps down to the vicinity of 10 μK and they will move very slowly. Removing the excess positron via laser excitation they plan to let the neutral $\overline{\mathrm{H}}$ fall in the gravitational field of Earth and measure its acceleration. GBAR was the first AD experiment to use the slow antiprotons from ELENA in 2018. The ALPHA Collaboration has also constructed a free-fall apparatus for measuring antihydrogen gravity.

8. Antiproton Properties

The ASACUSA (Atomic Spectroscopy And Collisions Using Slow Antiprotons) Collaboration stopped antiprotons in helium gas and using laser spectroscopy measured the transition energies of antiprotons between atomic orbits determined the mass of the antiproton [15]. The method is based on the earlier observation that about 3% of antiprotons stopped in helium gas get captured in a metastable three-body bound state $[\overline{\mathrm{p}}\mathrm{He}^{+}\mathrm{e}^{-}]$. When a laser resonance excites its transition to a non-metastable state, the antiproton will immediately annihilate. The experiment managed to increase the relative precision of the measurements from year to year, reaching the order of 10^{12} (meaning a CPT-test of similar precision) using two-photon spectroscopy [16] and buffer-gas cooling [17]. The ASACUSA Collaboration has built a post-decelerator system (essentially a radio-frequency quadrupole accelerator cavity working the opposite way) which increased the trapping efficiency by orders of magnitude and made it possible to produce an extracted beam [18] of slow antihydrogen atoms.

The BASE (Baryon Antibaryon Symmetry Experiment) performed direct high-precision measurements of the charge-to-mass ratio [19] and the magnetic moment [21] of a single antiproton stored in a cryogenic Penning trap. Both of them are, of course, sensitive CPT-tests when compared to those of the proton. It is remarkable, that this method is not destructive: in all 2016 BASE used 18 antiprotons for their measurements [20]. The obtained charge-to-mass ratio agrees with the predictions of the Standard Model (i.e. CPT invariance) at the level of 10^{-10}. Moreover, assuming CPT invariance the above result helps to confirm the weak equivalence principle [20] in Earth's gravitational field on the level of 6.8×10^{-7}.

9. Antimatter in Space

To solve the problem of the lack of antimatter galaxies, CERN prepared a cosmic detector, the Alpha Magnetic Spectrometer (AMS2) with the leadership of Nobel laureate Samuel Chao-chung Ting. It has a 1200 kg permanent magnet and it was launched in 2011 from the USA. It is placed onto the International Space Station and checks antiparticles in cosmic rays and also searches for dark matter annihilation. So far it did not detect anti-helium atoms, but saw many high-energy positrons which could come from pulsars or dark matter.

10. Conclusion

The Antiproton Decelerator of CERN was built 20 years ago in order to test the validity of CPT invariance, the principle of matter-antimatter symmetry. The work of these two decades yielded many results, and the measured antiproton charge, mass, and magnetic moment, and the antihydrogen 1S–2S transition measurement all conform the validity of CPT and the Standard Model. The lack of antimatter galaxies seems to question CPT invariance, but the results of the AMS2 space detector also confirmed: no anti-helium atoms are seen in cosmic rays. Thus CPT invariance seems to be at absolute validity.

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ТЕСТИ *CPT* ІНВАРІАНТНОСТІ
НА АНТИПРОТОННОМУ УПОВІЛЬНЮВАЧІ ЦЕРНу

Р е з ю м е

Стандартна Модель теорії елементарних частинок базується на симетріях: як структура композитних частинок, так і їх взаємодія виводяться з принципів калібровної інваріантності. Деякі з них, як парність та *CP* симетрія, порушуються слабкою взаємодією, та навіть маси породжуються спонтанним порушенням симетрії. Згідно з *CPT* інваріантності – найсуттєвішої симетрії Стандартної Моделі – матерія та антиматерія еквівалентні. Проте, через відсутність антиматерії у Всесвіті, цю симетрію постійно вивчають у ЦЕРНі. Ми даємо огляд цих експериментів: вимірюємо властивості антипротонів у порівнянні з протонами на Антипротонному Уповільнювачі, а також шукаємо антиречовину в космічних променях.

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CENTRAL EXCLUSIVE PRODUCTION AT LHCb

The LHCb collaboration has measured central exclusive production of J/ψ, $\psi(2S)$, and Υ mesons as well as $J/\psi J/\psi$, $J/\psi\psi(2S)$, $\psi(2S)\psi(2S)$, and $\chi_c\chi_c$ meson pairs in proton-proton collisions. The analyses of Υ and charmonium pairs are performed at the centre-of-mass energies of 7 TeV and 8 TeV, and those of J/ψ and $\psi(2S)$ are done at 7 TeV and 13 TeV. The analysis at 13 TeV involves the use of new shower counters. These allow a reduction in the background by vetoing events with activity in an extended region in rapidity. The measurements of central exclusive production at LHCb are sensitive to gluon distributions for Bjorken-x values down to 2×10^{-6} (at 13 TeV). An overview of the LHCb results is presented and compared to existing measurements of other experiments and theoretical calculations.

K e y w o r d s: exclusive photoproduction, ultra-peripheral collisions, generalised parton distributions, parton distribution functions.

1. Introduction

The nucleon structure can be described in three dimensions in terms of the probability to find quarks and gluons as a function of their transverse position inside the nucleon and their longitudinal momentum fraction with respect to the nucleon momentum [1, 2]. The longitudinal direction coincides here with the direction of the probe used to investigate the nucleon. The corresponding probability distributions are called impact-parameter-dependent parton distributions. They are Fourier transforms of generalised parton distributions (GPDs) (see, e.g., Ref. [3]). These GPDs do not have a probabilistic interpretation. Instead, they represent probability amplitudes for a parton with longitudinal momentum fraction $x+\xi$ to be emitted from a nucleon and a parton with longitudinal momentum fraction $x-\xi$ to be absorbed by the nucleon. The nucleon stays intact, but receives a four-momentum transfer squared equal to $-t$. This is represented in Fig. 1, for quarks (left) and gluons (right).

Generalised parton distributions are accessible in exclusive reactions, such as the exclusive production of photons or vector mesons, involving a hard scale. The hard scale is necessary in order to factorise the process into perturbatively calculable parts and non-perturbative parts, which are the GPDs and meson distribution amplitudes in the case of exclusive meson production [4, 5]. Exclusive vector-meson production can be measured in deep-inelastic scattering, as illustrated in Fig. 1, left. The hard scale is provided here by the large virtuality, $Q^2 = -q^2 \gg 1$ GeV^2, of the photon exchanged between the lepton and the nucleon. There exists a multitude of such measurements at fixed-target experiments [6–13] and at lepton-proton colliders, by the H1 and ZEUS collaborations [14–17]. The former series of measurements are mainly sensitive to larger values of Bjorken-x, $x_{\rm B}$, with $\xi \approx x_{\rm B}/(2-x_{\rm B})$, and thus to quark GPDs, while the latter probe lower values of $x_{\rm B}$ down to 10^{-4}, where gluons dominate.

Alternatively, it is possible to use a (quasi-)real photon ($Q^2 \approx 0$ GeV^2) to investigate the nucleon, provided that the particle created in the final state has a large mass component. In the case of exclusive vector-meson production, such as J/ψ or Υ production, the large scale is then provided by the large mass of the meson valence quarks (charm or bottom quarks). The vector mesons originate, as illustrated in Fig. 1, right, from the splitting of the real photon into a quark-antiquark pair ($c\bar{c}$ or $b\bar{b}$). This pair interacts with a nucleon through the exchange of two gluons, and as a result a vector meson is formed in the final state. Quasi-real photopro-

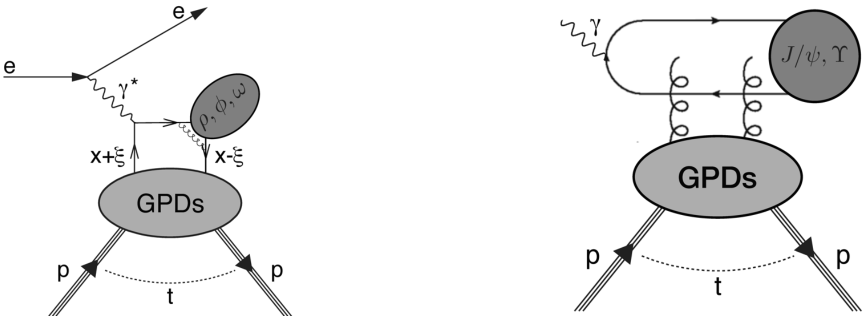


Fig. 1. Diagrams for exclusive production of vector mesons in deep-inelastic scattering (left) and in photoproduction (right). The figure on the left illustrates access to quark GPDs, while the figure on the right shows the diagram for gluon GPDs

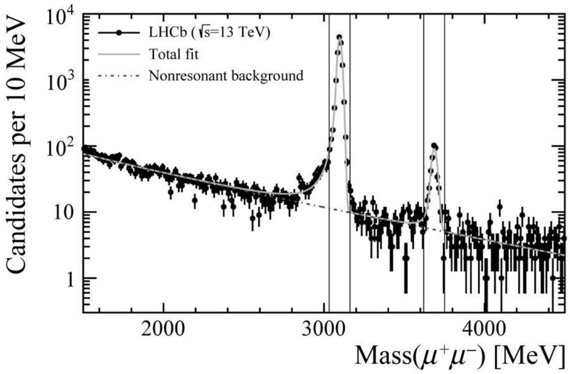
duction of vector mesons has been measured in electron-proton collisions by the H1 and ZEUS experiments [16, 18–21]. These measurements probe a photon-nucleon centre-of-mass energy ranging from 30 GeV to 300 GeV.

It is also possible to study photoproduction in ultra-peripheral collisions of protons and ions. In such reactions, the beam particles interact at a large enough distance from each other (in practice more than the sum of their respective nuclear radii) so that they interact through the exchange of colour-neutral objects. The flux of photons emitted by a beam particle is proportional to the square of its atomic charge, and hence photon emission by heavy ions is greater than for protons. There exist measurements of exclusively produced vector mesons in gold-gold collisions by the PHENIX experiment [22], in proton-antiproton collisions by the CDF experiment [23], in lead-lead and proton-lead collisions by the ALICE experiment [24–26] and in proton-proton and lead-lead collisions by the LHCb experiment [27–31]. The covered photon-nucleon centre-of-mass energy ranges from 34 GeV, for the PHENIX experiment, to 1.5 TeV, for the measurements performed by the LHCb collaboration. The very high energy available at the LHC offers the unique possibility to probe the GPDs down to Bjorken-x values of the order of 10^{-6}, i.e., two orders of magnitude lower than for the existing measurements in electron-proton collisions. At such low values of x_{B}, one might also be sensitive to saturation effects [32]. In addition, at such low x_{B}, the exclusive cross section can be approximated in terms of standard gluon parton distribution functions (PDFs) [33–36]. This cross section has a quadratic dependence on the gluon PDFs, and thus provides a higher sensitivity than inclusive measurements, where the dependence is only linear.

2. LHCb Measurements

In central exclusive production of vector mesons in ultra-peripheral collisions, the proton (or ion) emitting the real photon is to a good approximation not altered from its original trajectory, while the proton interacting through the two gluons undergoes a small change in momentum, but remains close to the beam line. The vector meson, in turn, is produced in the central region. At LHCb, this vector meson is generally reconstructed through its decay into a $\mu^+\mu^-$ pair. Hence, the experimental signature for exclusive vector-meson production is two oppositely charged muons in the LHCb detector, with large regions of rapidity, down to close to the beam line, devoid of particle activity. There exists a different process with the same final state, but where the oppositely charged muons originate from the interaction of photons emitted by the respective beam particles. This process is called the Bethe–Heitler process. This production mode of muons forms a continuum background to the exclusive production of vector mesons, and needs to be subtracted from the measured signal. Another source of background is the production of higher-mass vector mesons that decay into the vector meson under study without detection of the other decay products. Furthermore, the production of vector mesons where one or both of the interacting protons dissociate forms another background contribution.

The LHCb detector is a forward detector, covering a rapidity range between 2 and 5. The detector is fully instrumented for particle identification, and is capa-



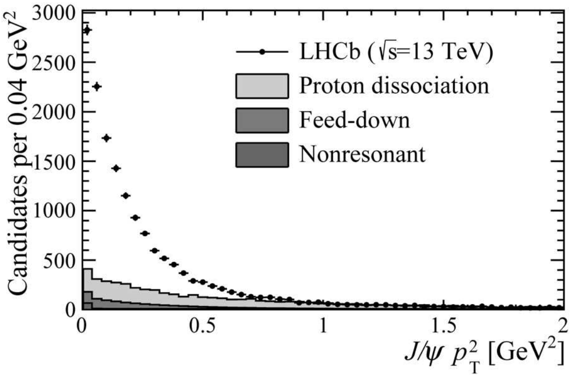


Fig. 2. Dimuon invariant-mass distribution (left) and dimuon squared-transverse-momentum distribution for muon pairs within the J/ψ invariant mass region (right) for data collected at $\sqrt{s} = 13$ TeV, and satisfying the selection requirement imposed by HeRSCheL. Different background contributions are indicated in both figures, while the vertical lines in the figure on the left indicate the selected range in invariant mass for the measurement of J/ψ and $\psi(2S)$

ble of detecting particles with transverse momenta as low as 200 MeV. The LHCb experiment is not instrumented with detectors around the beam line for the detection of protons emerging intact from the interaction or for products from proton dissociation that remain close to the beam line. However, the LHCb experiment is well suited for the measurement of exclusive processes. Firstly, the average number of interactions per beam crossing at the LHCb interaction point ranges only from 1.1 to 1.5, depending on running conditions. Secondly, besides the coverage in rapidity from 2 to 5 by the fully instrumented LHCb detector, the LHCb vertex locator is capable of detecting charged-particle activity for rapidities between –3.5 and –1.5. Also, for Run 2 of the LHC data-taking period (2015–2018), the LHCb experiment was additionally equipped with a series of five stations of scintillators, HeRSCheL [37], placed at –114 m to +114 m from the LHCb interaction point. This allowed for the detection of particle showers in a rapidity range between –10 and –5, and between +5 and +10, and hence for a supplementary reduction of the contribution from background processes.

Measurements of exclusive production of J/ψ and $\psi(2S)$ mesons have been performed by the LHCb experiment using data collected in proton-proton collisions at a centre-of-mass energy $\sqrt{s} = 7$ TeV [28], and part of the data collected at $\sqrt{s} = 13$ TeV [30], amounting to an integrated luminosity of respectively 929 ± 33 pb^{-1} and 204 ± 8 pb^{-1}. This data set allows one to access x_B down to 2×10^{-6}. Both the J/ψ meson and the $\psi(2S)$ meson are reconstructed through

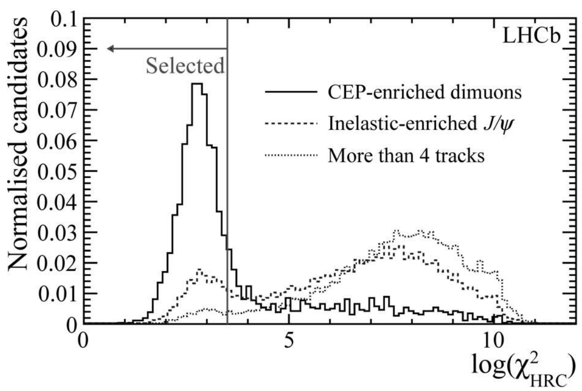


Fig. 3. The distribution, normalised to unit area, of the HeRSCheL discriminating variable χ^2_{HRC}. The continuous, black line corresponds to a sample highly enriched in exclusively produced muon pairs; the blue, dashed line represents the distribution for events enriched in inelastically produced J/ψ mesons, while the purple, short-dashed line contains events with more than four tracks

their decay into muons, which are required to lie in the LHCb detector acceptance, between 2 and 4.5 in rapidity. Furthermore, the transverse momentum squared of the dimuon pair, $p_T^2 \approx -t$, needs to be below 0.8 GeV^2. Finally, the absence of any other detector activity is required.

In Fig. 2, left, the dimuon invariant-mass distribution is shown, while in Fig. 2, right, the squared-transverse-momentum distribution of the muon pair with invariant mass in the J/ψ mass region is presented. The three sources of background contamination to the J/ψ signal are also shown. The back-

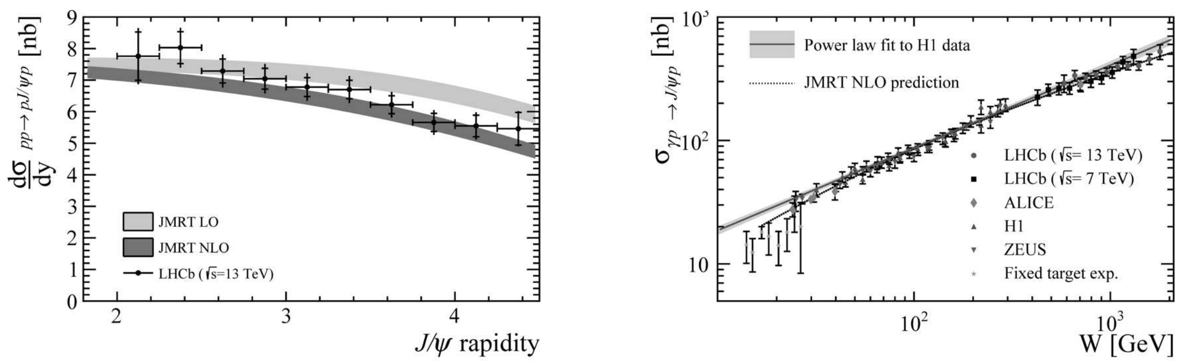


Fig. 4. Cross section differential in rapidity for exclusive J/ψ production (left) and exclusive J/ψ photoproduction cross section as a function of the photon-proton invariant mass (right). The leading-order (yellow band) and next-to-leading-order (green band and dotted line) JMRT calculations [34] are also indicated

ground contribution from the Bethe–Heitler process, labelled nonresonant background, is obtained from a fit to the dimuon mass distribution (see Fig. 2, left). The background from feed-down from exclusive production of $\psi(2S)$ and χ_c mesons is evaluated using $\psi(2S)$ and χ_c signals in experimental data and Monte-Carlo simulation. Finally, the contamination from events where at least one of the protons dissociates is evaluated for Run 1 through a fit of the dimuon transverse-momentum distribution, while for the data collected in Run 2, HeRSCheL has been used. The discriminating power of HeRSCheL is illustrated in Fig. 3. The figure represents distributions of a discriminating variable related to detector activity in HeRSCheL. The continuous, black line is the distribution for a very pure sample of exclusively produced pairs of muons, while the other lines indicate samples enriched in nonexclusive events. From the figure, it is clear that for exclusive events, the discriminating variable is located at low values, whereas for nonexclusive events, the variable extends to higher values. For the selection of exclusive events in Run 2, only events below the value indicated by the red, vertical line are selected. This results in a signal purity of 76% (73%) for J/ψ ($\psi(2S)$). For data collected in Run 1, the signal purity amounts to 62% (52%), where the contribution from proton-dissociative background is about twice as high.

The cross section differential in rapidity for exclusive production of J/ψ in proton-proton collisions at $\sqrt{s} = 13$ TeV is shown in Fig. 4, left. It is seen to decrease at larger values of rapidity. In addition to the experimental data points, theoretical predictions (JMRT) [34], which approximate the cross section in terms of standard gluon PDFs, are shown. There are predictions at leading order in α_S (yellow band) and at next-to-leading order in α_S (green band). The leading-order predictions fail to describe the data at higher rapidities, while the next-to-leading order calculations are in reasonable agreement with the data.

The exclusive vector-meson production cross section in proton-proton collisions is related to the photoproduction cross section through

$$\sigma_{pp\to p\psi p} = r(W_+)k_+\frac{dn}{dk_+}\sigma_{\gamma p\to\psi p}(W_+) + \\ + r(W_-)k_-\frac{dn}{dk_-}\sigma_{\gamma p\to\psi p}(W_-), \quad (1)$$

where r represents the gap survival factor, $k_\pm$ the photon energy, $dn/dk_\pm$ the photon flux, and $W_\pm^2 = 2k_\pm\sqrt{s}$ the photon-proton invariant mass squared. The subscript $+$ ($-$) corresponds to the situation where the downstream-going (upstream-going) proton is the photon emitter. As can be seen from Eq. (1), the photoproduction cross section appears twice in the expression. The reason resides in the ambiguity on the identity of the proton emitting the real photon. Since the photoproduction cross section corresponding to the low-energy solution W_- only contributes about one third of the time and it has been previously measured and parametrised by the H1 collaboration, this parametrisation is used to fix the low-energy photoproduction cross section, and extract the one at high photon-proton invariant mass. The resulting photoproduction cross section is presented in Fig. 4, right. The data points represented by the red circles are the result at $\sqrt{s} = 13$ TeV,

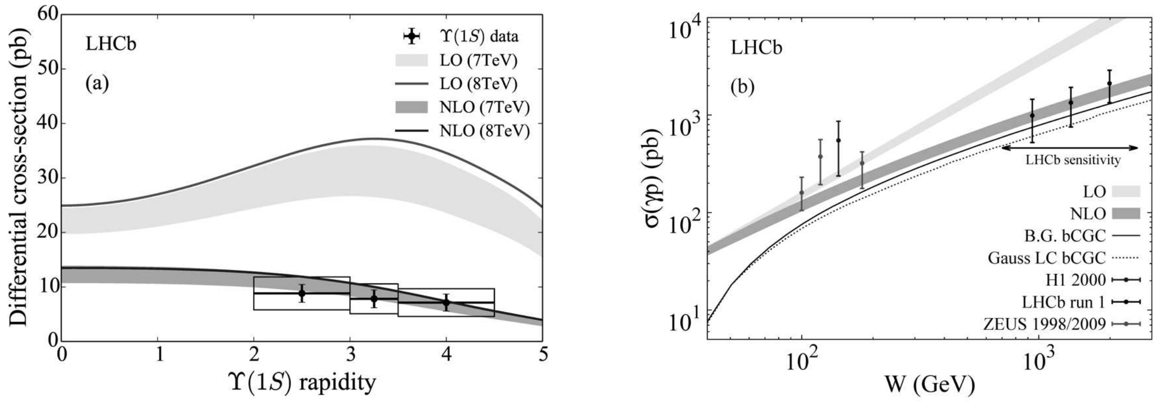


Fig. 5. Cross section differential in rapidity for exclusive $\Upsilon(1S)$ production (left) and exclusive $\Upsilon(1S)$ photoproduction cross section as a function of the photon-proton invariant mass (right). Next-to-leading-order (leading-order) JMRT calculations [34] at $\sqrt{s} = 7$ TeV are indicated by the blue (yellow) band and include uncertainties. The mean value of the next-to-leading-order (leading-order) calculations from JMRT [34] at $\sqrt{s} = 8$ TeV is indicated by the blue (red) line

while those indicated by the black squares are those at $\sqrt{s} = 7$ TeV. Also measurements from the H1 collaboration, from which the parametrisation is taken, the ZEUS and ALICE collaborations as well as from fixed-target experiments [38–40] are presented. The different data sets are in good agreement with each other. The parametrisation from the H1 collaboration is indicated in the figure by the blue band. It is seen to describe the data well at intermediate values of W, but fails at lower and higher values. Also the next-to-leading order JMRT calculations are shown, as indicated by the dotted line. They are in good agreement with the data, describing it well also at low and high values of W. Also for the proton-proton and photoproduction cross section of $\psi(2S)$ (not shown), the next-to-leading order predictions in α_S describe the data well, whereas the leading-order predictions fail to describe the data.

There exist also results from exclusive Υ production by the LHCb collaboration, using data collected in proton-proton collisions in Run 1 at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, corresponding to a respective luminosity of 0.9 fb^{-1} and 2.0 fb^{-1} [29]. The two data sets are combined in order to increase statistical precision. The data-selection procedure follows that of the measurement for exclusive J/ψ, with a p_T^2 restricted to below 2.0 GeV^2. Given the larger mass of the Υ meson, the lowest values in x_B reach down to 2×10^{-5}. The total proton-proton production cross section for $\Upsilon(1S)$ is determined to be $9.0 \pm 2.1 \pm 1.7$ pb, where the first uncertainty is statistical and the second systematic, while for $\Upsilon(2S)$ it is $1.3 \pm 0.8 \pm 0.3$ pb. For $\Upsilon(3S)$ production, an upper limit on the cross section of 3.4 pb at the 95% confidence level is determined. For the $\Upsilon(1S)$ resonance, the production cross section differential in rapidity and the photoproduction cross section as a function of W are also extracted. They are shown in Fig. 5. Also here, leading-order and next-to-leading order JMRT calculations are presented, and only the next-to-leading order calculations describe the data well. In the figure on the right, also results from the ZEUS and H1 collaborations are shown. These are not able to discriminate between the leading-order and next-to-leading order calculations.

The LHCb collaboration also published results of exclusive production of the charmonium pairs $J/\psi J/\psi$, $J/\psi\psi(2S)$, $\psi(2S)\psi(2S)$, $\chi_{c0}\chi_{c0}$, $\chi_{c1}\chi_{c1}$, and $\chi_{c2}\chi_{c2}$ [41]. These are potentially sensitive to glueballs and tetraquarks. In the framework of describing the exclusive cross section in terms of standard gluon PDFs, they are sensitive to the fourth power of these gluon PDFs. The measurements combine the data collected in proton-proton collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. The production cross sections are measured to be $\sigma(J/\psi J/\psi) = 58 \pm 10 \pm 6$ pb; $\sigma(J/\psi\psi(2S)) = 63^{+27}_{-18} \pm 10$ pb; $\sigma(\psi(2S)\psi(2S)) < 237$ pb; $\sigma(\chi_{c0}\chi_{c0}) < 69$ nb; $\sigma(\chi_{c1}\chi_{c1}) < 45$ pb; $\sigma(\chi_{c2}\chi_{c2}) < 141$ pb, where only an upper limit is determined for the four last pairs. These results are not corrected for proton dissociation, due to the limited statistical precision. Only for the production of pairs of $J/\psi J/\psi$ it is possible to estimate the contribution from central exclusive production, which amounts to about 42%, and thus to determine the cross section corrected for proton dissociation, which is 24 ± 9 pb.

3. Summary

Measurements of exclusive production of J/ψ, $\psi(2S)$, and $\Upsilon(nS)$, with $n = 1, 2, 3$, have been performed by the LHCb collaboration. These measurements are sensitive to gluon GPDs and PDFs. The cross sections are measured differentially in rapidity and the photoproduction cross section is extracted as a function of the photon-proton invariant mass. Comparisons to next-to-leading order JMRT calculations show good agreement with these data. Also cross-section measurements of pairs of charmonia have been performed. They are sensitive to the fourth power of the gluon PDFs and potentially to glueballs and tetraquarks. Although not discussed here, there are also preliminary measurements of Bethe-Heitler production in proton-proton collisions [42] and on exclusive χ_c production in proton-proton collisions [42], which is sensitive to the exchange of two gluon pairs. Furthermore there are preliminary results on exclusive production of J/ψ and $\psi(2S)$ in lead-lead collisions [31], which give access to nuclear GPDs and PDFs, and are sensitive to shadowing.

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ЦЕНТРАЛЬНЕ ЕКСКЛЮЗИВНЕ ПРОДУКУВАННЯ НА LHCb

Р е з ю м е

Колаборація LHCb вимірювала центральне ексклюзивне продукування мезонів J/ψ, $\psi(2S)$ і Υ мезонів, а також мезонних пар $J/\psi J/\psi$, $J/\psi\psi(2S)$, $\psi(2S)\psi(2S)$, $\chi_c\chi_c$ в протон-протонних зіткненнях. Аналіз пар мезонів Υ та шармонія виконано при енергіях в системі центра мас 7 та 8 ТеВ, а для J/ψ та $\psi(2S)$ – при 7 та 13 ТеВ. В аналізі при 13 ТеВ були задіяні нові лічильники, які зменшують фон, відсікаючи події з активністю в широкому інтервалі швидкостей. Виміри центрального ексклюзивного продукування на LHCb чутливі до глюонних розподілів для значень бйоркенівської змінної аж до $2 \cdot 10^{-6}$ при 13 ТеВ. Нами представлено огляд результатів LHCb та їх порівняння з існуючими вимірами в інших експериментах, а також з теоретичними розрахунками.

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NEUTRAL MESON AND DIRECT PHOTON MEASUREMENTS WITH THE ALICE EXPERIMENT

The ALICE experiment is designed to study the properties of the matter created in proton-proton and heavy-ion collisions at the LHC. Neutral mesons can be reconstructed in ALICE in a wide range of transverse momenta via two-photon decays. Neutral meson measurements in pp collisions give an opportunity to validate the NLO or NNLO pQCD calculations and to constrain the parton distribution functions and the parton fragmentation functions. Neutral meson spectra measured in pA and AA collisions allow us to test a modification of the parton distribution functions in nuclei and the parton energy loss in the hot matter created in AA collisions. The recent results from ALICE on direct photon measurements in the Pb–Pb, neutral pion and η meson productions in pp, p-Pb, and Pb–Pb collisions are presented.

Keywords: high-energy physics, neutral meson spectra, direct photons.

1. Introduction

ALICE experiment aims to explore properties of the hot ($T \sim 10^{12}$ K) and dense quark-gluon matter and to investigate the chiral symmetry restoration and the deconfinement mechanisms. The hard hadron production in pp collisions can be described by a convolution of the hard parton cross-section, parton distribution function (PDF), and fragmentation function (FF). The measurement of hadron spectra in a wide kinematic range for various collision energies provides a new input for PDF and FF parametrizations. The meson production in heavy-ion collisions allows studying several effects. The development of a collective flow can be studied at low $p_{\rm T}$ ($p_{\rm T} <$ < 3 GeV/c). The high-$p_{\rm T}$ ($p_{\rm T} > 5$ GeV/c) part of the spectra originates predominantly from the hard parton hadronization. At moderate $p_{\rm T}$, the π^0 and η mesons are mainly produced via the gluon fragmentation at LHC energies. As gluons show a larger energy loss in the medium than quarks, the comparison of the suppressions of the yields of light neutral mesons and heavier hadrons will provide an input for the understanding of the energy loss by the different partons. The difference in the suppression patterns of the π^0 and η meson yields can indicate the differences in the relative contributions of quarks and gluons. Neutral meson spectra also serve as an input for the direct photon analysis. Direct photons are defined as all photons that are not coming from the decays of particles. Photons do not interact strongly with the medium. They carry information on the properties of the matter at the space-time point of their emission. The high-$p_{\rm T}$ part of the direct photon spectrum is dominated by photons created in the hard scattering of the partons of incoming nucleons and can serve as a tool to constrain the models that describe the initial stage of a collision. The low-$p_{\rm T}$ part of the direct photon spectrum may contain photons from the thermal emission of the hot matter and probes its temperature and the velocity of the collective expansion.

2. Neutral Meson Measurements

The ALICE experiment is a general-purpose detector [1]. It consists of 17 separate subdetectors that are dedicated to specific goals. Neutral mesons are reconstructed via the two-photon decay channel. Photons in ALICE can be measured in an Electro-Magnetic Calorimeter (EMCal) [2] and a Photon Spectrometer (PHOS) [3] or by means of the Photon Conversion Method (PCM) based on the reconstruction of photons from e^+e^- pairs that are products of the photon conversion in the material of central barrel detectors [4].

The product the efficiency ε times the acceptance A for different methods of neutral meson reconstruction is shown in Fig. 1. The EMCal has the highest $A \cdot \varepsilon$

values, as it has a large acceptance and a high probability to measure photons. PHOS has a lower $A \cdot \varepsilon$ factor due to limited acceptance, but it has lower energy threshold for the signal and outperforms EMCal at low p_{T}. It is possible to combine the photons reconstructed with EMCal and PCM to form pairs (PCM-EMC method). In this case, the $A \cdot \varepsilon$ factor is approximately 10 times smaller than that of EMCal due to the small conversion probability of a photon. This method makes it possible to extend the measurement up to high p_{T}, because showers from different photons don't merge in a detector. The PCM efficiency is determined by the probability of the photon conversion, its $A \cdot \varepsilon$ factor is the lowest.

2.1. Transverse momentum spectra of neutral mesons in pp collisions

The ALICE experiment has measured π^0 and η meson spectra in pp collisions at several collision energies: $\sqrt{s} = 0.9, 2.76, 7, 8$ TeV [5–9], see Fig. 2. Neutral pion spectra were reconstructed up to $p_{\mathrm{T}} \sim 40$ GeV/c (for $\sqrt{s} = 2.76$ TeV). PYTHIA 8.2 [10] with Monash 2013 tune describes the data at high p_{T}, but shows a deviation from the data at moderate p_{T} at the higher energies. The NLO calculations [11–13] predict a 20–60% higher yield, and the difference increases with p_{T}. The situation with η meson is similar: PYTHIA 8.2 with Monash 2013 tune reproduces the data, whereas the NLO calculations predict a 50–100% higher yield at all colliding energies.

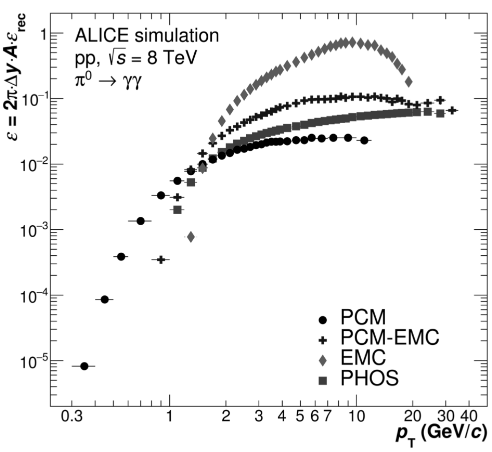


Fig. 1. Normalized correction factors ϵ for each reconstruction method for π^0 as a function of p_{T}. The factors contain the reconstruction efficiencies and the detector acceptances normalized per unit rapidity and full azimuthal angle

2.2. Transverse momentum spectra of neutral mesons in p-Pb collisions

ALICE has recently measured the π^0 and η yields in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [15]. Neutral pion and η spectra are well described by the Tsallis fits [16]. The NLO pQCD calculations [11, 17] scaled

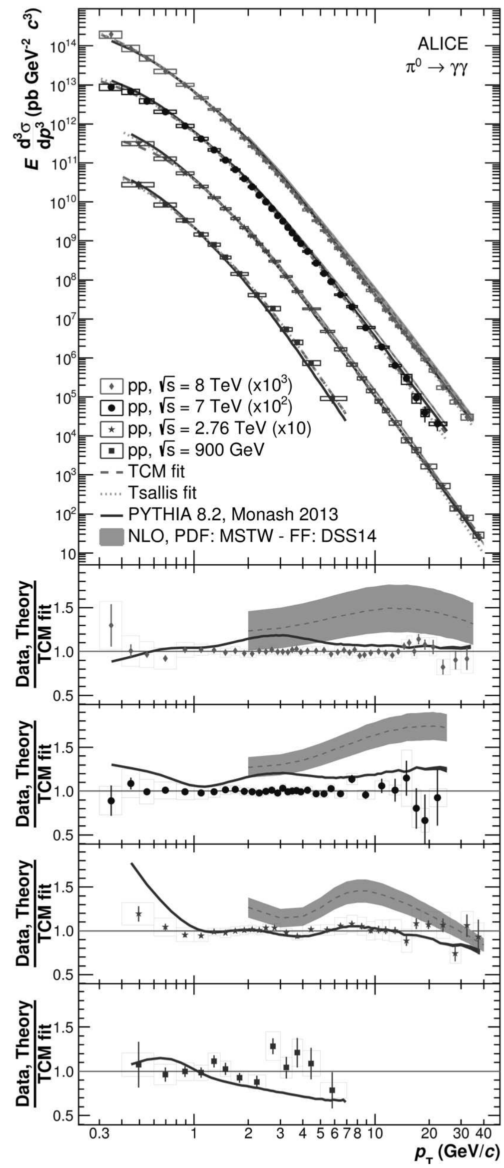


Fig. 2. Neutral pion spectrum at $\sqrt{s} = 0.9, 2.76, 7,$ and 8 TeV [5–9]. The spectrum is compared to the PYTHIA8 [10] event generator and NLO pQCD calculations. The ratios of data and predictions to the two-component model (TCM) fit [14] are shown on the bottom panels for each energy separately

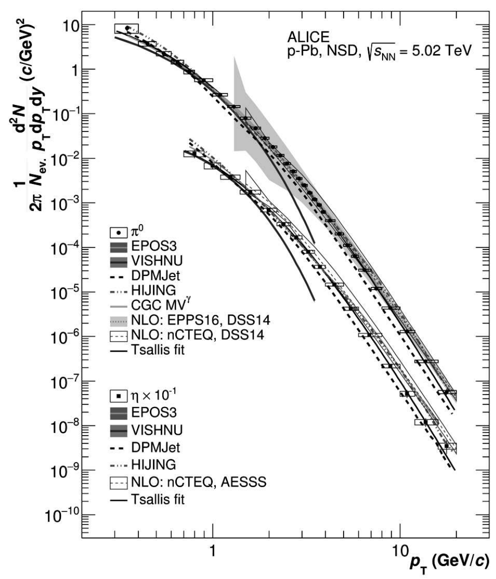


Fig. 3. Neutral pion and η spectra measured in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [15]. The data are compared to the scaled NLO pQCD calculations [11, 17] and to DPMJET [19], VISHNU [20], HIJING [21], EPOS [18], CGC [22] models

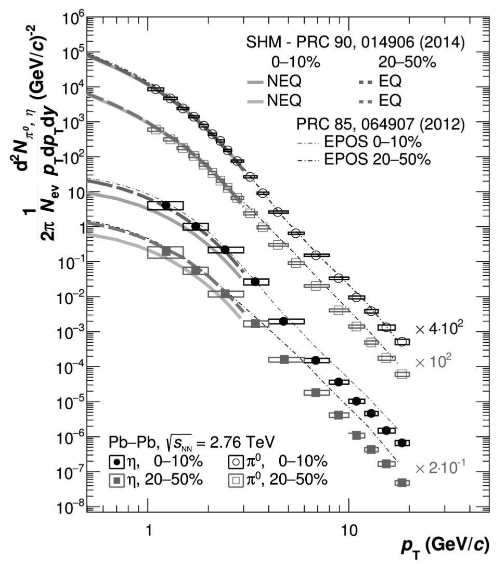


Fig. 4. Neutral pion and η spectra in two centrality classes measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [6]

with the number of binary nucleon-nucleon collisions reproduce the π^0 spectrum in the entire $p_{\rm T}$ range and overpredict the η spectrum at high $p_{\rm T}$. EPOS [18] Monte-Carlo reproduces the π^0 spectrum and η spectrum below 3 GeV/c, but overpredicts it at high $p_{\rm T}$. The hydrodynamic model VISHNU[20] provides a good description at low $p_{\rm T}$. The HIJING[21] and DPMJET [19] models fail to reproduce data for $p_{\rm T}$ larger than 4 GeV/c.

2.3. Transverse momentum spectra of neutral mesons in Pb–Pb collisions

The data collected in 2010 allowed the measurement of the spectrum of π^0 in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV in the range $0.6 < p_{\rm T} < 12$ GeV/c [6]. The neutral pion yield can be described by the Tsallis fits. Combining the datasets collected in 2010 and 2011 years allowed one to extend the range of the π^0 spectrum up to 20 GeV/c and to measure also the η meson spectra in narrower centrality classes [8], see Fig. 4. Two versions of the SHM model [23] reproduce the shape of the π^0 spectrum at low $p_{\rm T}$. For the η mesons, NEQ SHM underestimates the yield at the low-$p_{\rm T}$ region.

2.4. Nuclear modification factor in Pb–Pb collisions

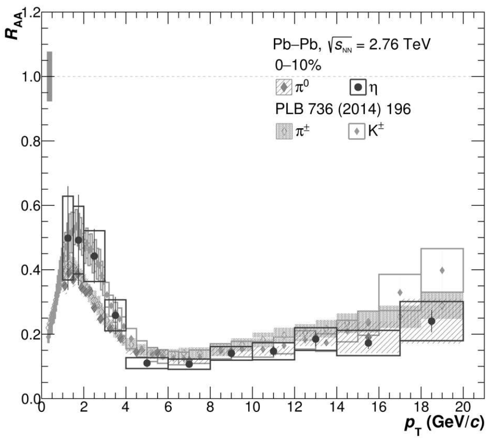
Figure 5 shows the nuclear modification factor defined as the meson yield in Pb–Pb collisions divided by the meson production cross-section in pp collisions at the same energy scaled with the nuclear overlap function. The value of $R_{\rm AA} = 1$ corresponds to the absence of medium effects. For Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, $R_{\rm AA} \sim 0.1$ at $p_{\rm T} \sim 7$ GeV/c was observed reflecting a strong energy loss by partons in the hot quark-gluon matter. The $R_{\rm AA}$ increases with $p_{\rm T}$. The nuclear modification factors for π^0 and η agree with those for $\pi^\pm$ and $K^\pm$. The right plot of Fig. 5 shows the centrality dependence of the nuclear modification factor in Pb–Pb collisions. The $R_{\rm AA}$ decreases, as the centrality increases, indicating that the medium effects are most prominent in the central collisions.

3. Direct Photons Measurements

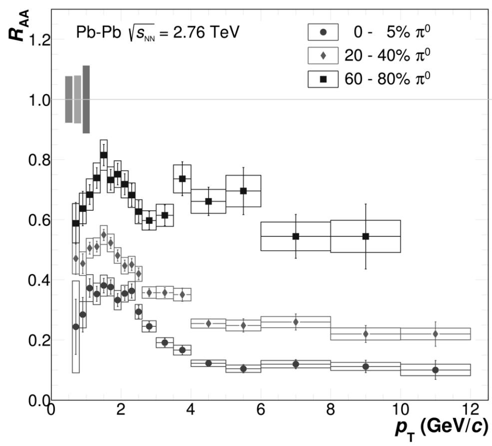
Direct photons are all photons that do not originate from the hadron decays. The yield can be calculated as

$$\gamma_{\rm \,direct} = \gamma_{\rm \,inc} - \gamma_{\rm \,decay} = (1 - 1/R_\gamma)\,\gamma_{\rm \,inc},$$

where $\gamma_{\rm \,inc}$ – the inclusive photon spectrum, $\gamma_{\rm \,decay}$ – the decay photon spectrum, $\gamma_{\rm \,direct}$ – the direct photon spectrum, and $R_\gamma = \gamma_{\rm \,inc}/\gamma_{\rm \,decay}$. It turns out that the ratio R_γ expressed as a double ratio $R_\gamma =$



a



b

Fig. 5. Nuclear modification factor of π^0, $\pi^{\pm}$, η, and $K^{\pm}$ mesons measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV in the centrality class 0–10% [8] (*a*). Centrality dependence of the π^0 nuclear modification factors in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV (*b*)

$= \frac{(N_{\gamma,\ \rm inc}/N_{\pi^0})_{\rm meas}}{(N_{\gamma\ \rm decay}/N_{\pi^0})_{\rm simulated}}$ cancels out the significant part of systematic uncertainties of the measurement. The value of R_γ greater than unity indicates the direct photon signal. The double ratio together with the direct photon spectrum were measured for three centrality classes in Pb–Pb at $\sqrt{s_{\rm NN}} = 2.76$ TeV [24], see Fig. 6. The pQCD calculations describe well the high $p_{\rm T}$ part [25]. There is a visible excess of direct photons compared to NLO pQCD predictions for $p_{\rm T} <$ < 4 GeV/c in the most central collisions, which can be attributed to the thermal emission of a hot matter. The low $p_{\rm T}$ part (below 2.2 GeV/c) of the spectrum was fitted with the exponential function. The

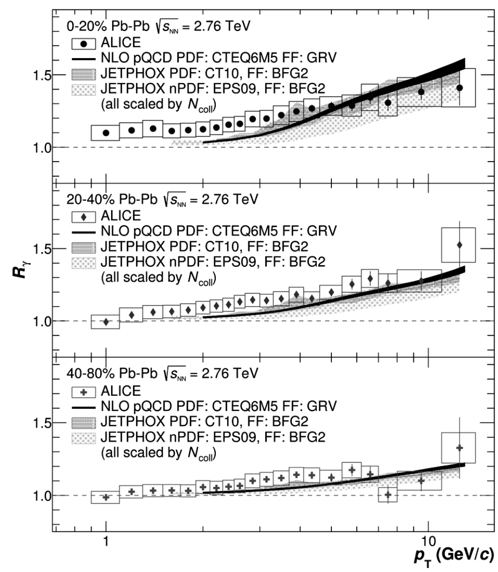


Fig. 6. The double ratio R_γ measured for three centrality classes in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV [24] compared to NLO pQCD (for the direct photon yield in pp collisions) and JETPHOX [26] predictions with various PDFs and FFs scaled by the number of binary collisions

inverse slope is found to be equal to $304 \pm 11^{\rm stat} \pm$ $\pm\, 40^{\rm sys}$ MeV. To convert the slope value to the temperature, however, one has to take the expansion of the system into account.

4. Summary

ALICE has measured the neutral meson spectra in a wide $p_{\rm T}$ range in pp collisions at $\sqrt{s} = 0.9$, 2.76, 7, and 8 TeV. The NLO calculations systematically predict a higher yield, especially at the highest collision energies. The neutral meson spectra measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV were used to calculate nuclear modification factors. The nuclear modification factor measured in Pb–Pb shows the strong suppression of the π^0 yield related to the parton energy loss in a hot quark-gluon matter. That can be explained by the final-state effect, as p-Pb data are consistent with unity, showing the absence of cold nuclear matter effects. The direct photon spectrum and the double ratio R_γ were measured in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV in three centrality classes. The double ratio R_γ in central Pb–Pb collisions exceeds the prompt photon pQCD predictions at $p_{\rm T} < 4$ GeV/c. The inverse slope of the direct photon spectrum in central Pb–Pb collisions is estimated to be $304 \pm 11^{\rm stat} \pm 40^{\rm sys}$ MeV.

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ВИМІРЮВАННЯ НЕЙТРАЛЬНИХ МЕЗОНІВ
ТА ПРЯМИХ ФОТОНІВ В ЕКСПЕРИМЕНТАХ ALICE

Р е з ю м е

Експеримент ALICE заплановано для вивчення властивостей речовини, що народжується в зіткненнях протонів та важких іонів на LHC. Нейтральні мезони можна відтворити в ALICE в широкому інтервалі поперечних імпульсів за допомогою двофотонних розпадів. Вимірювання нейтральних мезонів у зіткненнях протонів дають можливість перевірити пертурбативну КХД в NLO та NNLO наближеннях, а також уточнити функції розподілу та фрагментації партонів. Спектри нейтральних мезонів, виміряних у pA та AA зіткненнях, дозволяють перевірити модифікацію партонної функції розподілу в ядрі і втрату енергії партонів у гарячій речовині, що утворюється в AA зіткненнях. Нами представлено останні результати ALICE стосовно вимірювання прямих фотонів у Pb–Pb зіткненнях, продукування нейтральних піонів та η мезонів у зіткненнях pp, p-Pb та Pb–Pb.

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THE SILICON TRACKING SYSTEM OF THE CBM EXPERIMENT AT FAIR

The Compressed Baryonic Matter (CBM) experiment at FAIR (Darmstadt, Germany) is designed to study the dense nuclear matter in a fixed target configuration with heavy ion beams up to kinetic energies of 11 AGeV for $Au + Au$ collision. The charged particle tracking with below 2% momentum resolution will be performed by the Silicon Tracking System (STS) located in the aperture of a dipole magnet. The detector will be able to reconstruct secondary decay vertices of rare probes, e.g., multistrange hyperons, with 50 μm spatial resolution in the heavy-ion collision environment with up to 1000 charged particle per inelastic interaction at the 10 MHz collision rate. This task requires a highly granular fast detector with radiation tolerance enough to withstand a particle fluence of up to 10^{14} n_{eq}/cm^2 1-MeV equivalent accumulated over several years of operation. The system comprises 8 tracking stations based on double-sided silicon microstrip sensors with 58 μm pitch and strips oriented at 7.5° stereo angle. The analog signals are read out via stacked microcables (up to 50 cm long) by the front-end electronics based on the STS-XYTER ASIC with self-triggering architecture. Detector modules with this structure will have a material budget between 0.3% and 1.5% radiation length increasing towards the periphery. First detector modules and ladders built from pre-final components have been operated in the demonstrator experiment mCBM at GSI-SIS18 (FAIR Phase-0) providing a test stand for the performance evaluation and system integration. The results of mSTS detector commissioning and the performance in the beam will be presented.

K e y w o r d s: low-mass tracking system, double-sided silicon microstrip sensors, self-triggering readout.

1. Introduction

A number of research centers worldwide carry out or prepare research programs to shed light on the fundamental questions of the QCD physics, e.g., the origin of the mass of hadrons, structure of neutron stars, or evolution of the early Universe. They can be addressed in high-energy collisions of heavy nuclei in which a fireball of hot and dense nuclear matter is formed prior to the hadronization. The measurement of heavy-ion collision products thus gives an experimental access to the deconfined system of quarks and gluons in a wide range of temperatures and baryon densities. The Compressed Baryonic Matter (CBM) experiment [1] at the Facility for Antiproton and Ion Research (FAIR) is a fixed target spectrometer being designed to measure multiple observables, including rare probes, with statistics high enough to build multidifferential cross-sections.

The measurement of particle yields, momentum spectra, angular distributions, as well as fluctuations and correlations of hadrons, requires a set of detectors for the vertex reconstruction and tracking, particle identification, and calorimetry. Thus, two detectors located in the aperture of a superconducting dipole magnet, a Micro-Vertex Detector (MVD) operating in the vacuum closest to the target and a Silicon Tracking System will provide the precise vertex reconstruction and the momentum determination, respectively. The detector composition further downstream implements two configurations driven by the detection of charmed or strange particles and low-mass vector mesons decaying into di-leptons. In elctron-hadron configuration, a Ring Imaging Cherenkov counter (RICH) and Transition Radiation Detector (TRD) provide the electron identification and the electron-pion separation. A time-of-flight system consisting of resistive plate chambers (RPC) and a diamond start counter will identify fast hadrons. Elect-

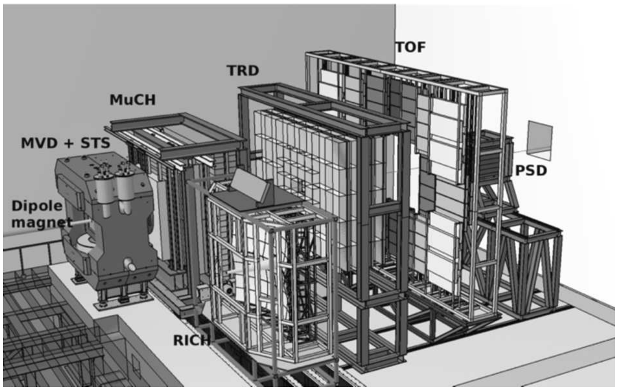

Fig. 1. CBM detector in the muon and electron-hadron configurations

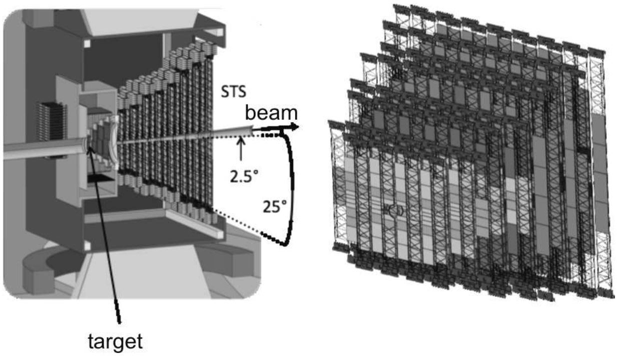

Fig. 2. Conceptual design of the STS consisting of eight tracking stations

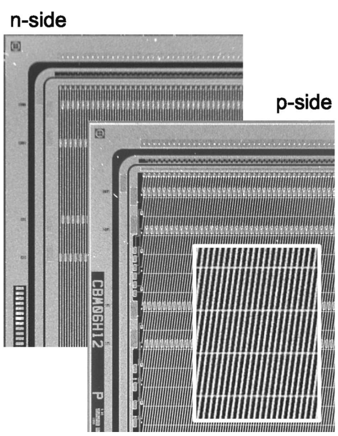

Fig. 3. Close-up of corners of a prototype sensor produced by Hamamatsu. Shown are strips on the p-side, oriented under a stereo angle with respect to the n-side strips. The horizontal lines are second-metal routing lines between short corner strips, allowing to read out the full sensor area from the staggered read-out pads at the top edge

rons and photons will be detected by the Electromagnetic Calorimeter (ECAL). The collision plane and centrality will be determined by the Projectile Spectator Detector (PSD). In the muon configuration, the RICH detector will be replaced by an instrumented absorber with muon tracking capability.

2. Silicon Tracking System

The STS consists of eight tracking stations located in the aperture of a dipole magnet with 1 T field, 30–100 cm downstream of the target. Its main mission is the momentum measurement for charged particles with a resolution of $\delta p/p < 2\%$ [2]. Therefore, a detector module must have the minimum amount of a material in the physical acceptance (polar angle 2.5–25°) with front-end electronics operating at the periphery of the stations. The system is required to have the track reconstruction efficiency >95% for tracks with momentum above 1 GeV. For this, the detector modules based on double-sided silicon microstrip sensors need to have hit the reconstruction efficiency close to 100% and the low-noise performance ensuring the operation with signal-to-noise ratio well above 10 during the whole detector lifetime.

The goal of the STS is to reconstruct up to 1000 charged particles created in the collision of gold ions with gold target at beam energies up to 11 AGeV at SIS-100 and up to 45 AGeV at a future SIS-300 synchrotron. Depending on the physics case, the interaction rate will range between 0.1 MHz and 10 MHz. In the latter case, a significant challenge is posed to the detector design and data acquisition system due to high radiation load and data rates generated by the collision products, as well as δ-electrons. The tracking stations will have to withstand radiation damage up to $10^{14}\,n_{\mathrm{eq}}/\mathrm{cm}^2$ within its planned operation.

In total, the STS stations will consist of 896 double-sided silicon sensors installed onto 106 carbon fibre ladders with the total area of 4 m^2 (see Fig. 2). The pre-final module components, their integration into detector modules and ladders as basic functional and structural units of the tracking stations are presented in the following sections.

3. Module Components

3.1. Sensors

Final protptypes of double-sided silicon microstrip sensors 320 μm in thickness have been produced in cooperation with Hamamatsu (Japan) [3]. The sensors

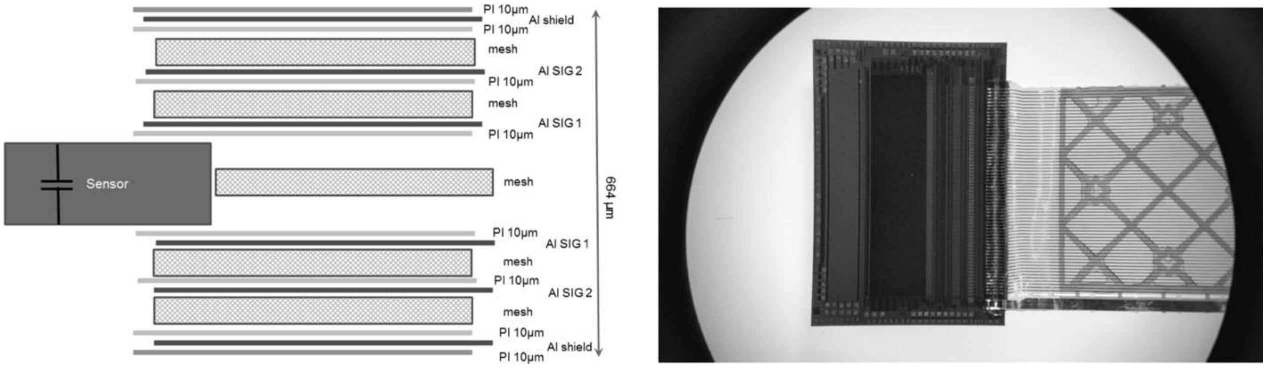

Fig. 4. Multilayer structure of microcables with two signal layers per side, shielding layers, and meshed spacers shown in the attachment to both sides of a microstrip sensor (left); photo of a single microcable layer attached to a readout chip (right)

feature four discrete sizes (62 mm width and 22, 42, 62 and 124 mm height). The wafer material is of the n-type. One prototype is shown in Fig. 3. The sensor layout has been optimized for the attachment of microcables by *TAB* bonding for read-out and bias connections, minimum trace resistance, and inter-strip capacitance. The sensors are segmented into 1024 strips per side at a strip pitch of 58 μm. The strips are read out through integrated *AC* coupling. The p-strips are arranged under a stereo angle of 7.5° with respect to the n-strips. The short corner strips are interconnected using a second metal layer in order to enable the full readout of the p-side from one sensor edge only, like with the simpler topology of the n side. The sensors are oriented with the strips vertically in the dipole magnetic field to be sensitive to the track curvature. They have been tested under the anticipated thermal operation conditions, –5 °C, and were shown to be radiation-tolerant up to twice the nominal lifetime in the experiment, 2×10^{14} 1-MeV $n_{\rm eq}$ cm^{-2}.

3.2. Microcables

In the STS module concept, the microcables are the important component to yield a low material budget. They are also central to the noise performance, because they allow one to have the readout electronics outside of the detector acceptance. A microcable is implemented as a stack of two signal layers per side with aluminum traces on a polyimide substrate with spacers inbetween and additional shielding layers on the outside (see Fig. 4). One stack is designed to read out 128 channels. Thus, 16 microcable stacks are required for the full readout of a sensor. The microcable structure aims at balancing the trace capacitance and series resistance based on the ENC contribution to the total noise seen by the preamplifier. A signal layer comprises 64 *Al* lines at 116 μm pitch, twice the strip pitch on the sensor. Two signal layers are stacked to match the read-out pitch. The thickness of aluminium and polyimide is 14 μm and 10 μm, respectively. Such a structure of a cable stack corresponds to 0.23% X_0 equivalent to 213 μm of silicon. The cables are produced in lengths up to 55 cm. The current pre-series production of microcables aims at maximizing the yields [4].

3.3. Front-end electronics

The readout chip STS-XYTER has been developed specifically for the STS. It is a mixed signal ASIC with data driven architecture [5]. Each channel has a fast branch for the time stamp generation with less than 5 ns resolution and a slow one for the amplitude measurement (see Fig. 5). The chip provides 128 independent channels with switchable signal polarity and two gain settings that makes it suitable for use with the STS and a further CBM sub-system, the muon detector with its GEM chambers. For the silicon detector read-out, the dynamic range of the integrated 5-bit ADC is 12 fC, which can be switched to 100 fC for the gas detectors. The design goal with STS-XYTER is to achieve a noise performance of 1000 e$^-$ with a power consumption that is estimated to be <10 mW/channel. This will ensure the matching with the STS detector module structure, where significant noise contributions are expected from the capacitance and the series resistance of the microca-

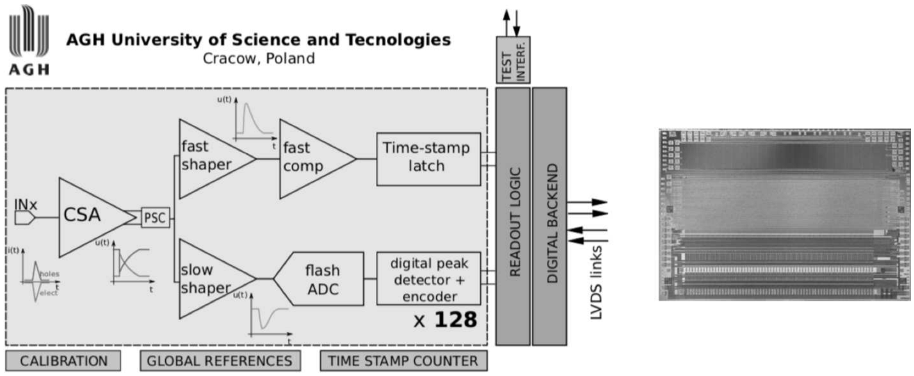

Fig. 5. Block diagram of the STS-XYTER architecture

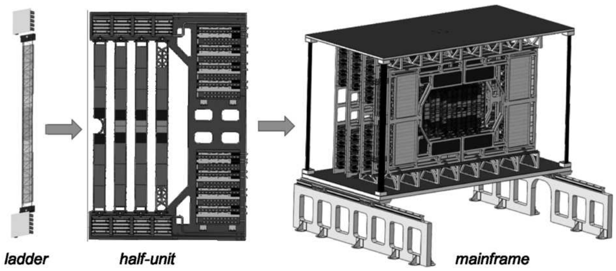

Fig. 6. System integration concept: from ladders to half-units mounted in the mainframe

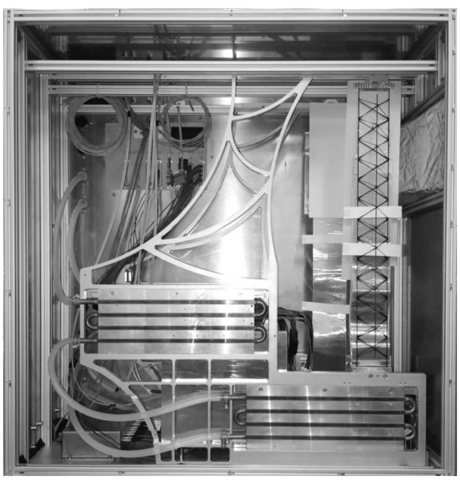

Fig. 7. mSTS detector modules mounted on the C-frames. Microcables running along the ladders and integrated cooling plates are visible

ble signal traces and sensor strips. The noise performance is addressed in the chip architecture using the double-threshold technique, where triggers generated by the fast branch are vetoed if no coinciding signal peak was detected. The chip is currently under production in its second iteration, compatible with the CERN GBT read-out protocol, using a 180 nm CMOS process.

4. System Integration

The current activities on the system integration focus on devising a detailed engineering solution for the assembly of a system from individual mechanical units and its installation in the magnet aperture taking the intersection of the active volume by the beam pipe and MVD vacuum vessel into account. A thermal enclosure will have to provide numerous interfaces for services, e.g., cooling, powering, and data cables in its side walls. The integration concept foresees a hierarchical mechanical structure of the STS (see Fig. 6), where modules are mounted onto the carbon fiber ladders. The so-called half-units will carry the ladders and the necessary infrastructure so that every half of a tracking station will be formed by two such units. The stations are thus separated into two halves for the maintainability and will be movable in order to allow for the replacement of broken modules. A system [6] cooling the plates with channels for circulating the cooling liquid integrated into the C-frames of half-units is devised to remove the power dissipated by the STS front-end electronics, amounting to about 42 kW.

5. mSTS at mCBM

As a part of the FAIR Phase-0 program, a long-term beam test campaign of CBM pre-final detector systems has been started at GSI in 2018 at SIS18 synchrotron (mini-CBM or mCBM) [7] with high-rate heavy-ion collisions and followed up by a beam campaign in March 2019. The goal was to operate the full system with complex hardware and software components and to optimize their performance before the final series production. The subsystems had common free-streaming readout with the data transport to the prototype online event selection system.

At the time of the beam test, the mSTS detector shown in Fig. 7 consisted of two C-frames equipped with four detector modules mounted on carbon fiber ladders using L-legs. All modules provided the full double-sided readout of sensors with 62×62 mm^2 dimensions using about 45 cm long stacked microcable. Each sensor side is read out by a front-end board (FEB) with 8 STS-XYTER ASICS. The FEBs are mounted on the cooling plates integrated into the C-frames [8]. The plates are cooled by the chilled water circulating inside them. Apart from front-end electronics, the C-frames carry the common readout boards (C-ROBs) based on CERN GBT and Versatile Link components [9]. The functions of the C-ROB are the data aggregation from the front-end boards and the further data transport via the optical interface, control of the front-end ASICs, clock distribution, and synchronization.

In future runs, the mSTS will concentrate on optimizing the system performance towards particle tracking in combination with other detectors and increasing the number of detector modules to 13. The mCBM operation is planned till 2022.

6. Summary and Outlook

The CBM experiment will measure rare probes in the heavy-ion collision environment. This will require a tracking system with hit position resolution better than 20 μm, fast detectors compatible with operation at an interaction rate up to 10 MHz, and radiation tolerance up to 10^{14} $n_{\rm eq}$cm^{-2}. The Silicon Tracking System based on double-sided silicon microstrip detector modules compatible with these requirements will provide the charged particle tracking and measure particle momenta with a resolution of $\delta p/p < 2\%$. For this, it requires a particularly low-mass design of the system. The signals from the double-sided sensors are read out via ultra-thin analog microcables by the front-end electronics located outside of the detector acceptance. Currently, the production readiness of the system components has been achieved, and the production phase has started. The feasibility of the detector concept has been demonstrated in the mCBM beam campaign.

The author expresses his gratitude to Prof. Dr. Hans Rudolf Schmidt for his help in the preparation of this contribution and colleagues from University of Tübingen and GSI Detector Laboratory for the fruitful work presented in it.

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А. Лиманецъ, для CBM колаборації

КРЕМНІЄВА ТРЕКІНГОВА
СИСТЕМА ЕКСПЕРИМЕНТУ CBM
НА КОМПЛЕКСІ ПРИСКОРЮВАЧІВ FAIR

Р е з ю м е

Експеримент CBM на прискорювальному комплексі FAIR (Дармштадт, Німеччина) розробляється для вивчення ядерної речовини з високою густиною в експериментальній установці на фіксованій мішені із струменем важких іонів з енергіями до 11 ГеВ/нуклон у системі $\mathrm{Au}+\mathrm{Au}$. Трекінг заряджених частинок із роздільною здатністю по імпульсу краще, ніж 2%, буде проводитись Кремнієвою Трекінговою Системою (КТС), розташованою у апертурі дипольного магніту. Детектор зможе реконструювати вторинні вершини розпадів рідкісних частинок, наприклад, гіперонів із кількома дивними кварками з точністю 50 мкм в оточенні продуктів зіткнення важких іонів, що породжує до 1000 заряджених частинок на кожне непружне зіткнення з частотою взаємодії до 10 МГц. Ця задача вимагає швидкого детектора із високою гранулярністю і радіаційною стійкістю, достатньою для роботи при еквівалентному флюенсі до $10^{14} n_{\rm eq}$/см^2, накопиченому за кілька років роботи. Система складається із 8 трекінгових станцій на основі двосторонніх кремнієвих мікростріпових детекторів із кроком 58 мкм і орієнтацією стріпів під стереокутом 7,5°. Аналогові сигнали із сенсорів зчитуються через багатошарові мікрокабелі довжиною до 50 см найсучаснішою електронікою на основі STS-XYTER ASIC із самозапускною архітектурою. Детекторні модулі із цією структурою матимуть кількість матеріалу від 0,3% до 1,5% радіаційної довжини, із збільшенням товщини в напрямку до периферії. Перші детекторні модулі та утворені з них "драбини" на основі компонентів, готових до серійного виробництва, тестувалися в ході демонстраційного експерименту міні-CBM на синхротроні SIS18 у GSI (Дармштадт, Німеччина) в рамках програми FAIR Phase-0. Експеримент являв собою тестовий стенд для оцінки роботи установки та системної інтеграції. Представлено результати запуску детектора та його робочі характеристики.

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RESULTS ON NEUTRINO AND ANTINEUTRINO OSCILLATIONS FROM THE NOvA EXPERIMENT

NOvA is a two-detector long-baseline neutrino oscillation experiment using Fermilab's 700 kW NuMI muon neutrino beam. With a total exposure of $8.85 \times 10^{20} + 12.33 \times 10^{20}$ protons on target delivered to NuMI in the neutrino + antineutrino beam mode (78% more antineutrino data than in 2018), the experiment has made a 4.4σ-significant observation of the $\bar{\nu}_e$ appearance in a $\bar{\nu}_\mu$ beam, measured oscillation parameters $|\Delta m^2_{32}|$, $\sin^2\theta_{23}$, and excluded most values near $\delta_{\mathrm{CP}} = \pi/2$ for the inverted neutrino mass hierarchy by more than 3σ.

Keywords: neutrino oscillations, long-baseline experiment, NOvA, Fermilab.

1. Introduction

NOvA is a long-baseline neutrino oscillation experiment designed to make measurements of the muon neutrino (ν_μ) disappearance and the electron neutrino (ν_e) appearance in Fermilab's NuMI (Neutrinos at the Main Injector) beam. Well tuned for the first oscillation maximum around a neutrino energy of 2 GeV over 810 km baseline, the experiment studies primarily four channels of oscillations: $\nu_\mu \to \nu_\mu$ or $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ or $\bar{\nu}_\mu \to \bar{\nu}_e$. They allow us to address several concerns of neutrino oscillations:

1. mass ordering, i.e. normal (NH) or inverted hierarchy (IH) of neutrino mass eigenstates,
2. direct CP violation (δ_{CP} phase) and
3. precise determination of θ_{23} and Δm^2_{32} neutrino mixing parameters.

This paper reports the 2019 NOvA combined analysis of 8.85×10^{20} POT (protons on target) neutrino data collected from Feb 2014 to Feb 2017 and 12.33×10^{20} POT antineutrino data collected from Jun 2016 to Feb 2019 [1]. Neutrino oscillation parametrization, fits, predictions, and interpretation of the results were done within the standard oscillation model of 3 active neutrino flavors of electron, muon, and tau neutrinos (ν_τ) [2].

2. The NOvA Experiment

The experiment consists of two large functionally identical detectors sitting 14.6 mrad off the beam axis 810 km apart. This off-axis configuration reduces the uncertainty on energy of incoming neutrinos and suppresses the higher-energy neutrinos background producing neutral current interactions (NC) misidentified as ν_e charged current (CC). On the other hand, it also results in a lower intensity than in the on-axis region, mitigated by the size of the detectors and beam power upgrades.

The detectors are finely grained and highly active (∼65% active mass) liquid scintillator tracking calorimeters, which allow for a precise analysis of the neutrino interactions events. They are designed to be as similar as possible aside from the size: the Far Detector (FD) is 14 kt and on the surface located in Ash River, Minnesota, the Near Detector (ND) is located underground in Fermilab, close enough to the neutrinos source to see a far greater flux with only 0.3 kt of mass. Both are constructed out of extruded PVC cells (3.9×6.6 cm in cross-section and 15.5/3.8 m in length for FD/ND) filled with scintillator and equipped with a wavelength shifting fiber connected to an avalanche photodiode (APD). They collect light produced by charged particles subsequently amplified by APDs. The cells alternate in horizontal and vertical orientations to allow for a stereo readout. More information on detectors can be found in Ref. [3].

The NuMI beam is created following the decay of charged pions and kaons produced by 120 GeV protons hitting a carbon target. These parent mesons are focused by two magnetic horns and decay in flight

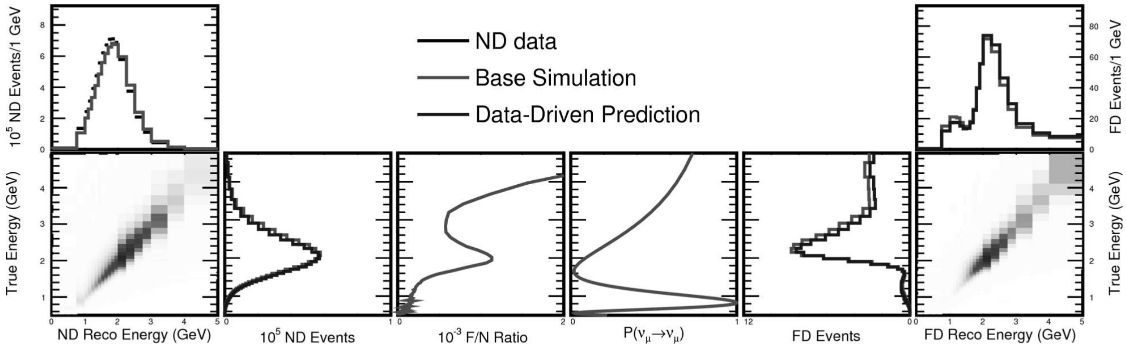

Fig. 1. Illustration of the NOvA's F/N technique. From left to right: reconstructed to true ν_μ energy translation, F/N ratio, $\nu_\mu \to \nu_\mu$ oscillation probability, true to reconstructed ν_μ energy restoration. Base simulation in red (light), ND data-driven corrected prediction in blue (dark)

through the chain $K^+, \pi^+ \to \mu^+ + \nu_\mu$, with the muon then decaying as $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$. By switching the polarity of the horns, the opposite charge sign particles can be focused, thus effectively selecting an antineutrino beam. The resulting neutrino events sample composition in range 1-5 GeV at ND is of 96% ν_μ, 3% $\bar{\nu}_\mu$ and 1% $\nu_e + \bar{\nu}_e$ in the case of neutrino beam and 83% $\bar{\nu}_\mu$, 16% ν_μ and 1% $\bar{\nu}_e + \nu_e$ in the case of antineutrino beam.

To identify and classify neutrino interactions, NOvA uses a method based on image recognition techniques known as Convolutional Visual Network (CVN), see Ref. [4]. CVN treats every interaction in the detector as an image, with cells being pixels and collected charge being their color. When trained with simulated events and cosmic data, CVN can extract abstract topological features of neutrino-like interactions with convolutional filters (feature maps [4]). With an input of calibrated 2D pixelmap (two views of horizontal and vertical event projections), the output is a set of normalized classification scores ranging over the hypotheses of beam neutrinos event (ν_μ CC, ν_e CC, ν_τ CC and NC), or cosmics. CVN has been used together with additional supporting PIDs: separate ν_e and ν_μ cosmic rejection boosted decision trees and muon track identification in ν_μ events.

NOvA's two identical detectors design enables us to employ data-driven predictions of FD observations. FD ν_μ and ν_e signal is predicted using ND ν_μ, whereas FD ν_e beam background is constrained using ND ν_e sample. This Far/Near (F/N) technique includes several steps (Fig. 1). First, the reconstructed neutrino energy spectrum is translated to the true energy using a simulated migration matrix. Second, the F/N ratio accounting for geometry, beam divergence, and detector acceptance is applied to create an unoscillated FD prediction. Then the FD spectrum is weighted by the oscillation probability for a given set of oscillation parameters. Finally, the true energy is smeared back again to the reconstructed energy via the migration matrix. As a reward, F/N technique significantly reduces both neutrino flux and cross section systematic uncertainties. The ND reconstructed energy spectra of ν_μ and $\bar{\nu}_\mu$ (the source of FD ν_μ and ν_e signals) can be found in Fig. 2.

3. Muon Neutrino and Antineutrino Disappearance

The muon neutrino disappearance channel is primarily sensitive to $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$, and the precision with which they can be measured depends on the ν_μ energy resolution. The energy of ν_μ is reconstructed as a sum of the energy of a muon and the remaining hadronic energy. The former is estimated from the range of the muon track, the latter from the sum of the calibrated hits not associated with the track. To get the best effective use of the energy resolution, the data binning is optimized in two ways. First, the energy binning has finer bins near the disappearance maximum and coarser bins elsewhere. Second, the events in each energy bin are further divided into four populations, or "quartiles", of varying reconstructed hadronic energy fraction, which correspond to different ν_μ energy resolutions. The divisions are chosen such that the quartiles are of equal size in the unoscillated FD simulation. The ν_μ ($\bar{\nu}_\mu$) energy resolution is estimated to be 5.8% (5.5%), 7.8% (6.8%), 9.9% (8.3%), and 11.7% (10.8%) for

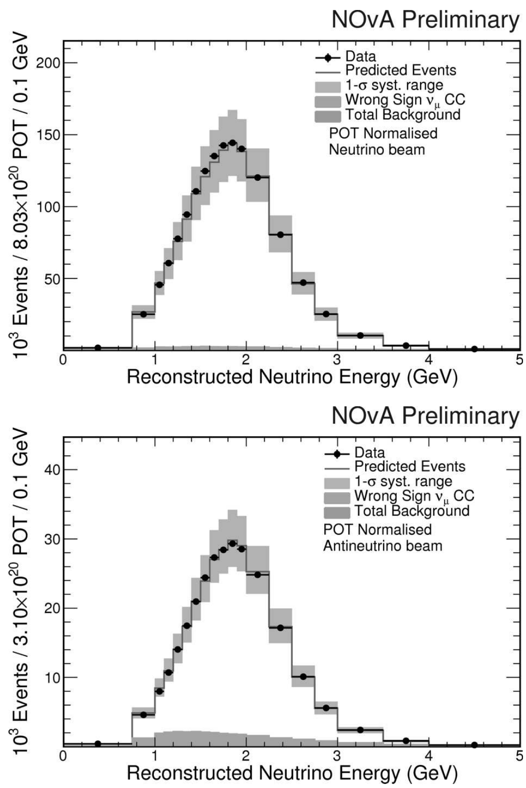

Fig. 2. ND selected ν_μ (top) and $\bar{\nu}_\mu$ (bottom) reconstructed energies in data (black dots) and simulation (band). Each bin is normalized by its width

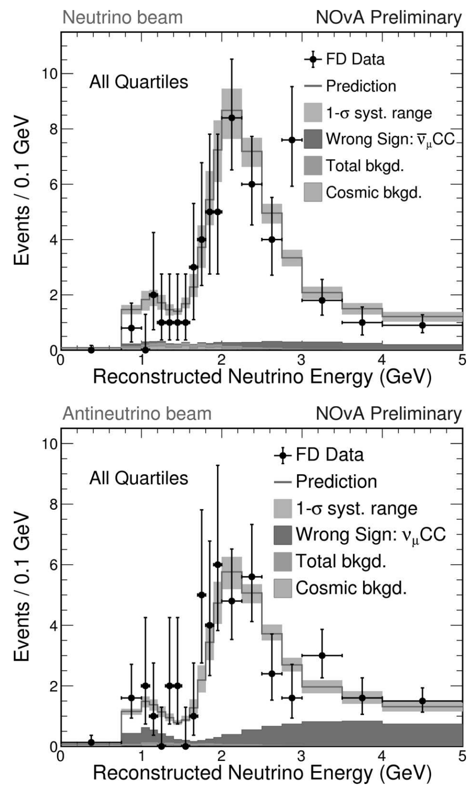

Fig. 3. FD data (black dots) selected ν_μ (top) and $\bar{\nu}_\mu$ (bottom) candidates reconstructed energies compared to the best fit prediction (line) with 1σ systematics uncertainty range. Summed over all quartiles of the hadronic energy fraction

each quartile, ordered from lower to higher hadronic energy fraction. The F/N technique is applied separately in quartiles, which has the additional advantage of isolating most of the cosmic and beam NC background events along with events of the worst energy resolution (4^{th} quartile).

The efficiency of the ν_μ ($\bar{\nu}_\mu$) CC events selection is 31.2% (33.9%) with respect to true interactions in the fiducial volume and the purity 98.6% (98.8%) in the FD samples. In total, there were 113 (102) ν_μ ($\bar{\nu}_\mu$) CC candidates observed in FD with an estimated background of $4.2^{+0.5}_{-0.6}$ ($2.2^{+0.4}_{-0.4}$). FD data and the best fit prediction can be seen in Fig. 3.

4. Electron Neutrino and Antineutrino Appearance

In order to maximize the statistical power of the ν_e selected events at FD, the sample is binned in both reconstructed energy and CVN score. There are two CVN bins of low and high purities (low and high PID), or "core" selection, and an additional "peripheral" bin. Events which fail the containment or cosmic rejection cuts, but do have a very high CVN ν_e CC score, may be added to the peripheral sample. Because the events on the periphery are not always fully contained, they are summed into a single bin instead of estimating their energy (up to reconstructed 4.5 GeV). The overall integrated selection efficiency of ν_e ($\bar{\nu}_e$) is 62% (67%). The purity of the final predicted FD samples depends on the oscillation parameters, but ranges from 57% (55%) to 78% (77%). The beam backgrounds are reduced by 95% (99%).

To estimate FD beam backgrounds, the F/N technique is used with the ND ν_e sample. It consists of the beam ν_e and ν_μ CC or NC interactions misidentified as ν_e CC. Since each of these components oscillates differently along the way to the FD, the sample needs to be broken down into them. In the case of neutrino beam, the ν_e component is constrained by inspecting the low-energy and high-energy ν_μ CC spectra to

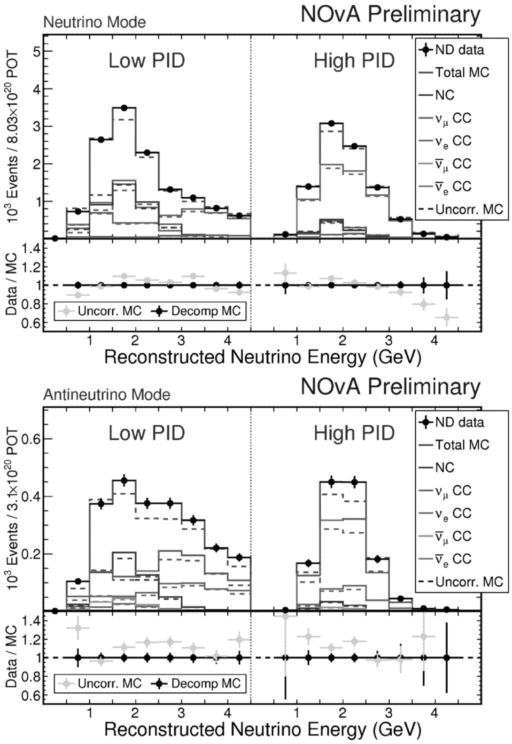

Fig. 4. ND selected ν_e (top) and $\bar{\nu}_e$ (bottom) reconstructed energy data (black dots), uncorrected simulation (dashed red) and data-driven correction (solid red). The selection is decomposed (broken down) into NC (blue), $\nu_\mu/\bar{\nu}_\mu$ CC (dark/light green) and $\nu_e/\bar{\nu}_e$ CC (light/dark magenta). Binned in two PID bins, which are correlated to lower and higher purities of $\nu_e + \bar{\nu}_e$

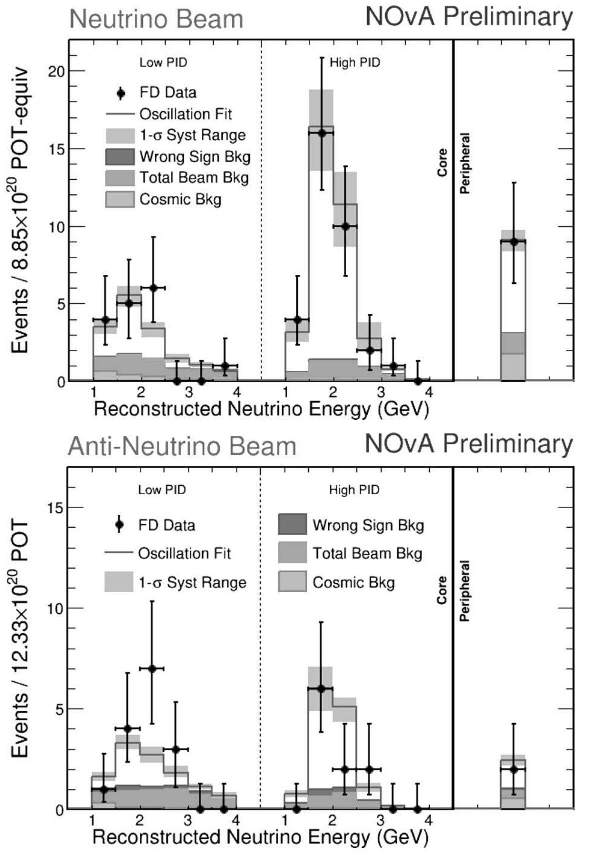

Fig. 5. FD data (black dots) selected ν_e (top) and $\bar{\nu}_e$ (bottom) candidates reconstructed energies binned in low and high PID bins and peripheral sample with energies up to 4.5 GeV. The best fit prediction (purple band) shows the expected background of wrong sign (green), other beam backgrounds (grey) and cosmics (blue) as shaded areas

adjust the yields of the parent hadrons that decay into both ν_μ and ν_e (track ν_μ and ν_e to their common parents). The ν_μ component is estimated from observed distribution of time-delayed electrons from the decay of stopped μ. The rest is attributed to the NC interaction. In the case of antineutrino beam, the simulated components are evenly and proportionally scaled to match ND data in each bin. ND selections and their breakdowns, or "decomposition", can be seen in Fig. 4. The high PID bin is dominated by the beam $\nu_e+\bar{\nu}_e$, the low PID bin has a significant admixture of ν_μ ($\bar{\nu}_\mu$) CC and NC events. The beam background of the FD peripheral bin is estimated from the high PID bin of the core sample.

There were 58 (27) ν_e ($\bar{\nu}_e$) candidates in the FD data with the total expected background of $15.0^{+0.8}_{-0.9}$ ($10.3^{+0.6}_{-0.5}$) events of 7.0 (5.3) beam $\nu_e + \bar{\nu}_e$, 0.7 (0.2) $\nu_\mu+\bar{\nu}_\mu$, 3.1 (1.2) NC events, 3.3 (1.1) cosmic-ray-induced events, 0.4 (0.3) others and 0.6 $\bar{\nu}_e$ (2.2 ν_e) from the wrong sign component of the ν_μ ($\bar{\nu}_\mu$) sample. The FD data and the best fit predictions can be seen in Fig. 5. The antineutrino data give a 4.4σ evidence of the $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam (an excess over predicted background).

5. Constraints on Oscillation Parameters

To obtain oscillation parameters, a simultaneous fit of joint $\nu_e + \nu_\mu$ and both the neutrino and antineutrino data was performed. Systematic uncertainties are incorporated as nuisance parameters with Gaussian penalty term, appropriately correlated between all the data sets. The leading systematics are worth a note: detector calibration (calorimetric energy scale), light production and collection model and muon energy scale (abs. + rel.) for the ν_μ disappearance; detector response and calibration, neutrino cross-sections and actual ND to FD differences for the ν_e appearance. Several oscillation parameters are taken as inputs from other measurements: solar parameters θ_{12} and Δm^2_{12}, the mixing angle θ_{13} and its uncertainty were taken from reactor experiments, all in Ref. [2]. The best fit is

$$\begin{aligned}&\Delta m^2_{32} = 2.48^{+0.11}_{-0.06} \times 10^{-3}\ \mathrm{eV}^2,\\&\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03},\\&\delta_{\mathrm{CP}}/\pi = 0.0^{+1.3}_{-0.4},\end{aligned} \tag{1}$$

which corresponds to NH and the uppper θ_{23} octant (UO, $\theta_{23} > 45°$). All confidence levels (C.L.) and contours are constructed following the Feldman–Cousins approach [7].

The 90% C.L. allowed region for a combination of Δm^2_{32} versus $\sin^2\theta_{23}$ in the $\Delta m^2_{32} > 0$ half-plane, together with other results from MINOS (2014) [8], T2K (2018) [9], IceCube (2018) [10] and Super–Kamiokande (2018) [11] overlaid is shown in Fig. 5. There is a clear consistency within all experiments despite that NOvA data asymmetrically point to UO and disfavor lower θ_{23} octant (LO, $\sin^2 < 0.5$) at about 1.6σ C.L.

Fig. 7 shows the 1, 2 and 3σ C.L. allowed regions for $\sin^2\theta_{23}$ versus δ_{CP} in both cases of NH and IH (mass ordering). It is worth noticing that the values of δ_{CP} around $\pi/2$ are excluded at $> 3\sigma$ C.L. for IH, similarly to the previous NOvA neutrino only analysis [5]. On the other hand, rather weak constraints on δ_{CP} itself allow all possible values $[0,2\pi]$ for the case of NH and UO. NH is preferred with 1.9σ significance.

6. Future Prospects

NOvA is expected to run till 2025 with about an equal total exposure of neutrino and antineutrino beams. Moreover, several accelerator upgrades to enhance the beam performance are planned for the next years. Based on these prerequisities and projected 2019 analysis techniques, there is a possibility of more than 3σ sensitivity to hierarchy resolution for 30–50% of all possible δ_{CP} (up to 5σ for favorable true values of oscillation parameters: NH and $\delta_{\mathrm{CP}} = 3\pi/2$). In addition, more than 2σ sensitivity to CP violation in the case of $\delta_{\mathrm{CP}} = \pi/2$ or $3\pi/2$ (maximal violation) is expected.

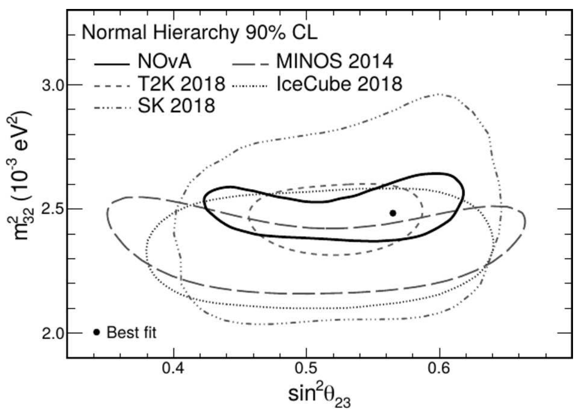

Fig. 6. Comparison of the allowed regions of Δm^2_{32} vs. $\sin^2\theta_{23}$ parameter space at the 90% confidence level as obtained by recent experiments

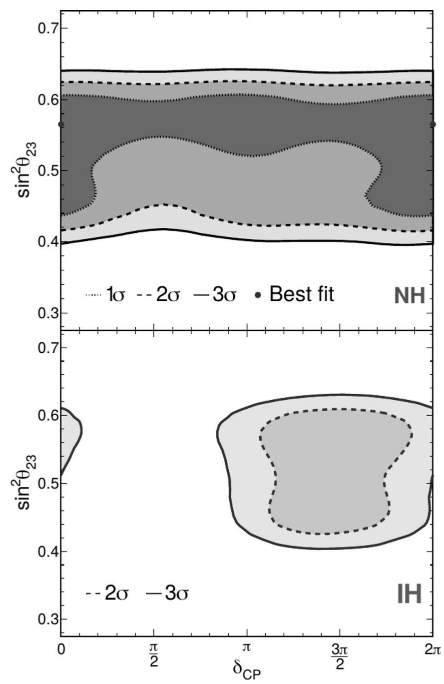

Fig. 7. 1, 2, and 3σ allowed regions of $\sin^2\theta_{23}$ vs. δ_{CP} neutrino oscillation parameter space consistent with the ν_e appearance and ν_μ disappearance data. The top panel corresponds to the case of normal hierarchy (NH) of neutrino masses ($\Delta m^2_{32} > 0$), the bottom one to the inverted hierarchy (IH, $\Delta m^2_{32} < 0$)

To further improve the neutrino oscillation analysis and to extend the reach of the experiment, NOvA started an intensive test beam program in early 2019. This should focus on the simulation tuning, systematics study and their reduction, validation and training of the reconstruction or machine learning algorithms.

7. Conclusions

New antineutrino data from NOvA (12.33×10^{20} POT in total) has been analyzed together with existing neutrino data (8.85×10^{20} POT). The measurements are well consistent with the standard oscillation model of 3 active neutrino flavors. NOvA observes 4.4σ evidence for the $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam. The results of joint analysis of neutrino and antineutrino and both ν_μ disappearance and ν_e appearance channels give the parameters estimates of $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$ and $\Delta m^2_{32} = 2.48^{+0.11}_{-0.06}\times10^{-3}$ eV^2, which are in a good agreement with other accelerator and atmospheric oscillation experiments. The data prefer θ_{23} upper octant at 1.6σ and the normal hierarchy of neutrino masses at 1.9σ and also disfavor the inverted hierarchy for $\delta_{\rm CP}$ around $3\pi/2$ at more than 3σ. NOvA plans to continue running till 2025 in both neutrino and antineutrino beam modes.

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ОСЦИЛЯЦІЇ НЕЙТРИНО
ТА АНТИНЕЙТРИНО. ЕКСПЕРИМЕНТ NOvA

Р е з ю м е

NOvA – експеримент з двома детекторами з подовженою базою для вимірювання нейтринних осциляцій за допомогою струменя мюонних нейтрино на 700 kW NuMi. З протонним струменем, спрямованим на мішень NuMi із загальною експозицією $8.85\times10^{20} + 12/33\times10^{20}$, в режимі нейтрино + антинейтрино (на 78% процентів більше антинейтрино, ніж у 2018 році), експеримент досяг достовірності 4.4σ появи $\bar{\nu}_e$ в пучку $\bar{\nu}_\mu$, було виміряно параметри осциляції $|\Delta m^2_{32}|$, $\sin^2\theta_{23}$, а також було виключено більшість значень, близьких до $\delta_{\rm CP} = \pi/2$ для зворотних нейтрино, більш ніж на 3σ.

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HEAVY-ION AND FIXED-TARGET PHYSICS IN LHCb

Selected results of the LHCb experiment on heavy ion collisions studied in the collider and fixed-target modes are presented. The clear evidence of the impact of the production mechanism (prompt/delayed, p-p or p-Pb systems) on the p_T *and rapidity distributions for* J/ψ, D^0 *and* $\Upsilon(ns)$ *species is demonstrated. The interpretation of the observations in frames of theoretical models is briefly discussed. Some original results, as well as prospects of fixed-target mode studies, are presented.*

K e y w o r d s: high-ehergy physics, heavy ions, LHCb experiment, nuclear modification factor, quark-gluon plasma.

1. Introduction

The LHCb Collaboration has started heavy ion studies in the year 2013, and many interesting observations have been reported. In this presentation, we shall discuss recent results on the charmonium and bottonium production cross-sections measured over the transverse momentum and rapidity. Physics goals include studies of the hadronic matter at high densities and temperatures, nucleon and nuclear PDFs, dynamics of the multinucleon interaction, hadronization, and QED at high electromagnetic field strengths. Charmonium and bottomonium states are considered as tools for the studies. It is assumed that their features are dependent on the properties of the QGP. One can expect their dependence on the interaction energy (collider or fixed-target mode), systems size (p-p, p-A, A-A), localization of the quarkonium production and direction of its emission (primary interaction region or displaced vertices, forward or backward emission), and different levels of a modification for the ground and excited states of the same probe, as well as on the centrality factor or multiplicity of events. To quantify the above-mentioned impacts, it is natural to compare differential production cross-sections measured in the proton proton scattering and in heavy ion collisions (p-A, A-A) at the same nucleon-nucleon cms energy. The normalized ratio of those cross-sections is defined as a Nuclear Modification Factor (NMF). The LHCb experiment operating in the collider and fixed-target modes allows one to measure the double differential production cross-sections for various hadronic probes as a function of the transverse momentum and the rapidity. The measured physical observables treated theoretically allow one to probe the structure of nuclei on the partonic scale. In this presentation, selected recent results on heavy ion collisions in the collider and fixed-target modes are presented for J/ψ, D^0, and $\Upsilon(ns)$ hadrons.

2. LHCb Detector

The LHCb detector [1] is a forward spectrometer with excellent characterisitics: accep$_T$ance $2 < \eta < 5$ (with HERSCHEL $8 < \eta < 10$), momentum resolution about 0.5%, track reconstruction efficiency >96%, impact parameter resolution ∼20 μm (decay time resolution: ∼45 fs), invariant mass resolution ∼15 MeV/c^2, and perfect particle identification efficiency in Ring-Imaging Cherenkov Detectors and the Muon system. LHCb is the only experiment at the LHC fully instrumented for the large-rapidity range. The proton-lead collisions were studied at two energies corresponding to the proton-nucleon center-of-mass energies $\sqrt{S_{NN}} = 5.02$ TeV and 8.16 TeV. Protons and lead ions at fixed targets (Ar, He, Ne) were studied at energies $\sqrt{S_{NN}}$ of ∼0.1 TeV. The directions of proton and lead beams were swapped during the data-taking period. The configuration with the protons traveling in the direction from the Vertex detector (VELO) to the Muon system is referred to as p-Pb collisions, the inverse configuration as Pb-p ones. The positive rapidity in the proton-nucleon center-of-mass system is defined

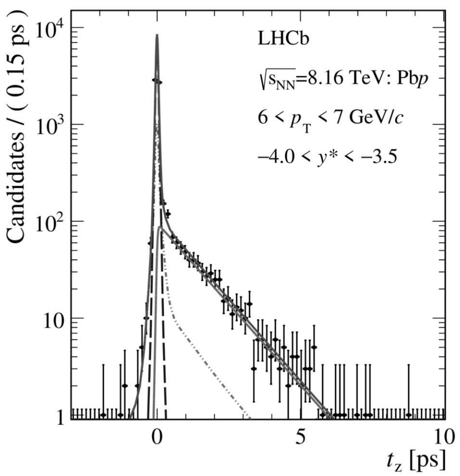

Fig. 1. Decay time distribution for J/ψ events from Pb-p collisions

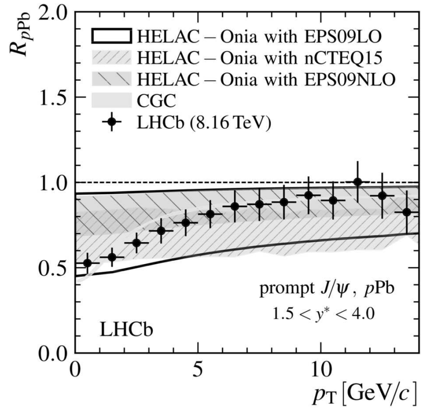

Fig. 2. NMF (experiment – black circles with error bars) as a function of p_T for prompt J/ψ in the rapidity range 1.5<y^*<4.0

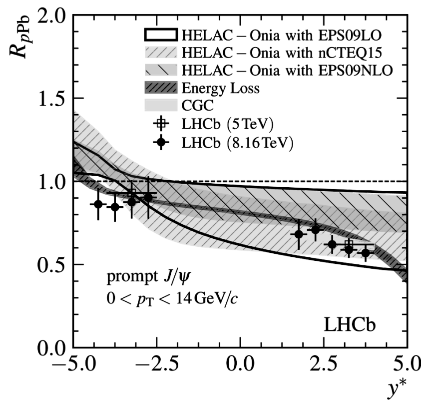

Fig. 3. Nuclear modification factor as a function of the rapidity for J/ψ from prompt events

by the direction of the proton beam. Thus, within a single experiment, the production cross-sections, forward-backward asymmetries, and nuclear modification factors were measured in a wide energy range for various hadronic states (J/ψ, D^0, $\Upsilon(ns)$, antiprotons, B mesons, and other hadrons).

3. Charmonium Production in Proton-Lead Collisions at $\sqrt{S_{NN}} = 5.02$ TeV and 8.16 TeV

Exploring the powerful vertexing tool of the detector, the double differential cross-sections were measured for prompt and delayed J/ψ mesons separated as illustrated in Fig. 1 [2]. The two components in the J/ψ decay time distribution (Fig. 1) correspond to the prompt J/ψ (narrow peak at zero time) and non-prompt J/ψ from the b-hadron falling exponentially with a time constant of beauty hadrons. The interpretation of the results in frames of different theoretical approaches is illustrated in Fig. 2, where the experimental values for the NMF (black circles with error bars) are shown as a function of p_T for prompt J/ψ in the rapidity range $1.5 < y^* < 4.0$. If there would be no impact of the media, the NMF at the level of unity should follow up the dotted line parallel to the x-axis. Instead, a strong suppression of the J/ψ production is well pronounced for p_T less than 10 GeV/c. The CGC theory [3] follows experimental points nearly ideally, while other calculations (HELAC) just reflect the general tendency with large uncertainties [2]. These results constrain nPDFs in unexplored area at low-x [4, 5]. The comparison of p_T, as well as rapidity distributions, has revealed significant differences for J/ψ mesons produced in p-p and p-Pb collisions. The data extracted from p-Pb collisions at 8.16 TeV for J/ψ originated from primary vertices (prompt events, forward rapidity region) demonstrated a reduction of the cross-section by twice for low p_T (<4 GeV/c). While, for the backward rapidity range, the cross-sections are close to be equal within statistical errors. The delayed events are characterized by a much less suppression even for the forward rapidity range y^*. These observations are consistent with data measured for J/ψ at a lower energy of 5 TeV. This is illustrated in Figs. 3 and 4 [2] which show the nuclear modification factor extracted from data measured at 5 TeV (open circles) and 8.16 TeV (filled circles) for J/ψ from prompt (Fig. 3) and from the decay of b-hadrons (Fig. 4). The remarkable dependence on the mechanism of production is clearly visible. The theoretical approach based on NLO nuclear PDFs accounting for the coherent energy-loss (black thick line) [6] follows well experimental data points for prompt J/ψ (Fig. 3). Non-prompt J/ψ are treated less satisfactorily with large uncertainties in frames of the calculations within the code FONLL with EPS09NLO [7] (Fig. 4). The production suppression at the forward rapidity for J/ψ from b-hadrons is less pronounced than for prompt J/ψ. These data allow one to constrain nPDFs at low-x [7]. Studies of the prompt D^0 meson production in pPb collisions at 5 TeV [8] have demonstrated similar observations. As an example, Figs. 5 and 6 show data for the prompt D^0 meson production in p-Pb collisions as a function of y^* (Fig. 5) and the Nuclear modification factor $R_{\text{p-Pb}}$ as a function of y^* (Fig. 6) with $\text{p}_T < 10$ GeV/c. The strong suppression in the forward-rapidity range (Fig. 6) was observed and well approximated by the theoretical description based on Nuclear PDFs and Color Glass Condensate assumptions. The data allow one to constrain nPDFs at low-Bjorken x [7].

4. Bottonium Production in Proton-Lead Collisions at 8.16 TeV

Comprehencive studies were performed for properties of bottonium states $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ produccd in p-p and p-Pb collisions [9]. The detailed analysis of p_T, as well as rapidity distributions, demonstrates the suppression of 1S and 2S states, with the 2S state being suppressed to a larger extent. Figures 7 and 8 show an example of such analysis for the nuclear modification factors $R_{\text{p-Pb}}$ for the $\Upsilon(1S)$ and $\Upsilon(2S)$ states (black dots with error bars) compared with different theoretical calculations (bands). $R_{\text{p-Pb}}$ (1S) is consistent with unity at negative y^*, while a significant (by $\sim$30%) suppression is observed for positive y^*. The nuclear modification factor for $\Upsilon(2S)$ is smaller than $\Upsilon(1S)$) especially in the backward region, which is consistent with the comovers models [10] and in agreement with other experiments [11]. Calculations are based on the comovers model of $\Upsilon(nS)$ production, which implements the final state interaction of the quarkonia states and a nuclear parton distribution function modification. For the $\Upsilon(1S)$ state, the nuclear modification factor is consistent with unity for $\text{p}_T > 10$ GeV/c, as predicted by the models. It is important to point out that the measurements of B^+, B^0, and $\Lambda^0{}_b$

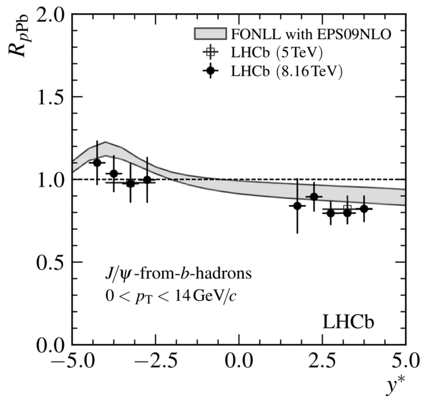

Fig. 4. Nuclear modification factor as a function of the rapidity for J/ψ from b-hadrons

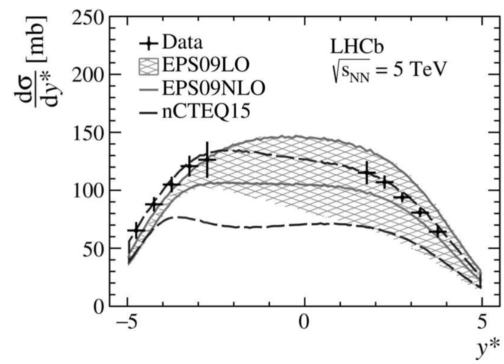

Fig. 5. Differential cross-section of the prompt D^0 meson production in p-Pb collisions as a function of y^*

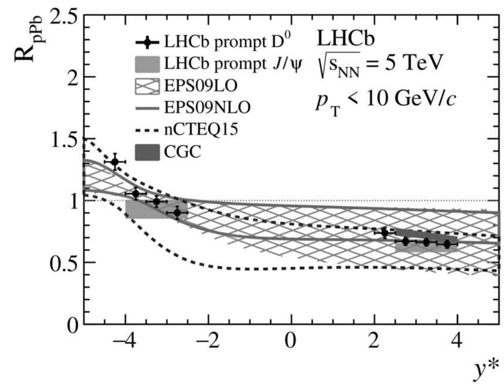

Fig. 6. Nuclear modification factor $R_{\text{p-Pb}}$ as a function of y^* for the prompt D^0 meson production with p_T<10 GeV/c

production in pPb collisions at 8.16 TeV [12] also indicated a significant nuclear suppression of the nuclear modification factors and forward-to-backward cross-section ratios at the positive rapidity.

5. Fixed-Target Mode Studies

The LHCb fixed-target program [13] includes, in particular, the study of the heavy-quark production in the large Bjorken x region, the test of the intrinsic charm content of the proton and cosmic rays physics relevant production of antiprotons. Below, some results obtained in this area are briefly presented. In particular, the antiproton production in proton-helium collisions and the charmonium production in proton-argon collisions are discussed. The prompt anti-p production in p-He collisions was thouroughly studied in a fixed-target mode at the energy $\sqrt{S_{NN}} = 110$ GeV exploring a He gas injected inside by the SMOG system [14]. These data are important for the interpretation of recent results on the antiproton fraction in cosmic rays. An increase of the antiproton fraction in cosmic rays might be a sign of the antimatter produced by the dark matter annihilation. The measured production cross-sections were interpreted in frames of the several models differing by hadronization, parton model, and dynamics. The shapes are well reproduced except at low rapidities, and the absolute yields deviate up to a factor of two [15]. The uncertainties (~10%) of experimental data are smaller than the spread of theoretical models. The results contribute to shrink background uncertainties in the dark matter searches in space [15, 16]. Among other important resuts obtained in a fixed-target mode exploring the SMOG system, the first measurement of the heavy flavor (J/ψ and D^0) production cross-section in p-He at $\sqrt{S_{NN}} = 86.6$ GeV and p-Ar at $\sqrt{S_{NN}} = 110$ GeV at the LHC were reported in [18]. The measurements were performed in the range of J/ψ and D^0 transverse momentum $p_T < 8$ GeV/c and the rapidity $2.0 < y < 4.6$. In this range, any substantial intrinsic charm contribution should be seen in the p-He results. The measurements show no strong differences between p-He data and the theoretical predictions which do not consider the intrinsic charm contribution. Future measurements with larger samples and more accurate theoretical predictions will permit one to perform more quantitative studies.

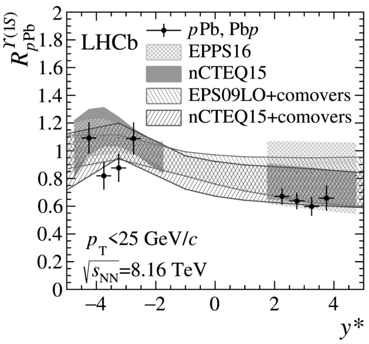

Fig. 7. Nuclear modification factor $R_{\text{p-Pb}}$ as a function of the rapidity y^* for $\Upsilon(1S)$ state

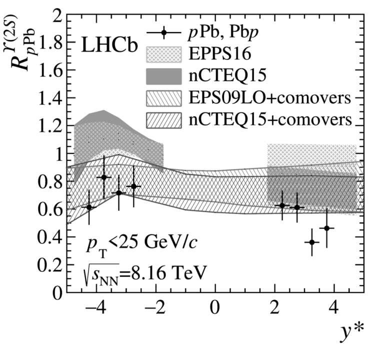

Fig. 8. Nuclear modification factor $R_{\text{p-Pb}}$ as a function of the rapidity y^* for $\Upsilon(2S)$ state

In view of the successful running in the fixed-target mode in Run2, it is decided to upgrade the system for the injection of a gas for Run3. The SMOG2 [19] will inject a gas inside a 20-cm-long storage cell (1 cm in diameter) in front of the vertex detector aiming to provide the instantaneous luminosity higher by up to two orders of magnitude. In addition to the noble gases, hydrogen and deuterium will operate as well. To extend the Heavy Ion Fixed Target program for Run4 and further, a crystal target, polarized target, and superthin wire targets were proposed and discussed. The LHCb fixed-target mode is unique for the experiments at LHC, and it is planned to extend this area of studies in the future RUN3 and Run4 data taking.

6. Summary and Outlook

Double differential cross-sections for the production of charm and beauty hadrons measured in the collider and fixed-target mode in various combinations of heavy ions collisions at 5, 8, and 0.1 TeV have been presented. The remarkable feature was observed in the collider-mode data: significant suppression of cross-sections at low transverse momenta and the forward rapidity in comparison with p-p data. The interpretation of the obtained results has been performed in frames of several theoretical approaches. The statistical and theoretical uncertainties have to be reduced for improving the extraction of nPDFs.

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В. Пугач, від імені Колаборації LHCb

ФІЗИКА ВАЖКИХ ІОНІВ
ТА ФІКСОВАНОЇ МІШЕНІ В ЕКСПЕРИМЕНТІ LHCb

Р е з ю м е

Представлено вибрані результати експерименту LHCb по зіткненням важких іонів, дослідженим в колайдерному режимі та з фіксованою мішенню. Спостережено незаперечний вплив механізму (миттєвого чи з затримкою, в p-p чи p-Pb системах) утворення мезонів J/ψ, D^0 або $\Upsilon(ns)$ на розподіли подій по p_T та бистротам. Коротко обговорюється інтерпретація спостережень у рамках теоретичних моделей. Представлено деякі оригінальні результати, а також перспективи досліджень в режимі фіксованої мішені.

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STATUS OF THE MUSE EXPERIMENT

The 5.6σ *difference in proton radii measured with* μp *atoms and with ep atoms and scattering remains an unexplained puzzle. MUSE will measure the* μp *and ep elastic scatterings in the same experiment at the same time. The experiment determines cross-sections, two-photon effects, form-factors, and radii and allows* μp *and ep to be compared with reduced systematic uncertainties. These data should provide the best test of the lepton universality in a scattering experiment to date, about an order of magnitude improvement over previous tests, a 7*σ *radius determination, and improved two-photon measurements.*

Keywords: proton radius puzzle, MUSE, elastic scattering, muon beam, TPE.

1. Introduction

In 2010, a Paul Scherrer Institute (PSI) experiment [1] reported that the proton charge radius determined from muonic hydrogen level transitions is 0.84184 ± 0.00067 fm, about 5σ off from the nearly order-of-magnitude less precise non-muonic measurements. This "proton radius puzzle" was confirmed in 2013 by a second muonic hydrogen measurement [2] of 0.84087 ± 0.00039 fm. Subsequent ep scattering results of 0.879 ± 0.008 fm [3] and 0.875 ± 0.010 fm [4] confirmed the puzzle. The situation has been discussed in review papers [5], in dedicated workshops [6–8], and in many talks. It is generally agreed that new data are needed to resolve the puzzle.

The MUon Scattering Experiment (MUSE) collaboration was formed in 2012 to uniquely attempt to resolve the "Proton radius puzzle" by simultaneously measuring the μp and ep elastic scattering cross-sections at the sub-percent level. MUSE alternates between positive vs. negative charged beams – all previous measurements are with negative leptons. Thus, MUSE directly compares μp to ep cross-sections and radii, provides the first significant μp scattering radius, and measures two-photon exchange effects (TPE) at the sub-percent level, rather than using the calculated corrections.

2. PSI Beam Line and $\pi M1$ Experimental Area

The PSI High Intensity Proton Accelerator (HIPA) primary protons strike the M production target and generate secondary $e^{\pm}$, $\mu^{\pm}$, and $\pi^{\pm}$ beams that are transported through the PiM1 channel to MUSE. Particle species are identified by timing relative to beam RF (Figure 1). The beam composition delivered to $\pi M1$ is shown in the Table.

Three different beam momenta are chosen to optimize both e and μ fluxes and RF time separation and provide redundant cross-sections as a check of the systematics. Figure 1 shows that the different particle species are 3–6 ns apart, much larger than the intrinsic timing width of ≈ 300 ps.

3. MUSE Detector Setup

MUSE is implemented as a set of detectors and cryotargets mounted on a moveable platform, so that

The measured $\pi M1$ beam composition

P, MeV/c	Polarity	e, %	μ, %	π, %
115	+	96.7	2.1	0.9
153	+	63.0	12.0	25.0
210	+	12.1	8.0	79.9
115	–	98.5	0.9	0.6
153	–	89.9	3.2	6.8
210	–	47.0	4.0	49.0

the PiM1 area can be shared. Figure 2 shows the experiment as represented in a Geant4 [9] simulation. The beam strikes the Beam Hodoscope (BH) detector and three Gas Electron Multiplier (GEM) chambers, passes through a central hole in the annular Beam Veto detector, enters the cryotarget vacuum chamber, strikes one of the targets (Liquid Hydrogen, Carbon, *etc.*), and then exits the vacuum chamber. Unscattered particles go through the Beam Monitor (BM), while scattered particles are detected by two symmetric spectrometers, each with two Straw-Tube Trackers (STT-s) and two planes of Scattered Particle Scintillators (SPS). The BH identifies particles through the RF timing; triggering depends on the particle type. Reaction identification (scattering vs. decays in flight) uses GEM and STT tracking along with the time of flight (TOF) from the BH to SPS. The BM can also be used to suppress Moeller events. More details are below.

3.1. Beam hodoscope

Purpose:

The BH provides timing information that, along with the RF signal, determines beam particle species for triggering and analysis. TOF from the BH to the SPS determines the reaction type, in particular, separates the muon decay from the muon scattering. TOF from the BH to the BM identifies backgrounds and determines μ and π momenta. The BH also measures the particle-separated beam fluxes.

Requirements:

The most stringent time resolution requirement is 100 ps needed for the reaction identification at the highest beam momentum; 80 ps has been achieved. High efficiency of 99% is needed to efficiently collect data and reject backgrounds; 99.8% has been achieved. A rate capability of ≈3.3 MHz is needed to obtain the adequate statistical precision; the use of multiple paddles allows rates up to 10 MHz.

Design:

Figure 3 shows a BH plane under construction. We use BC-404 scintillator paddles that are 10 cm long and ×2 mm thick. Six central 4 mm wide paddles are flanked on each side by 5 outer 8-mm wide paddles. The paddles are read out at each end by Hamamatsu S13360-3075PE SiPMs. A 6 μm gap between the paddles suppresses cross-talk. To minimize effects on the beam and to achieve the needed performance, we use 2–4 planes of BH depending on the beam momentum.

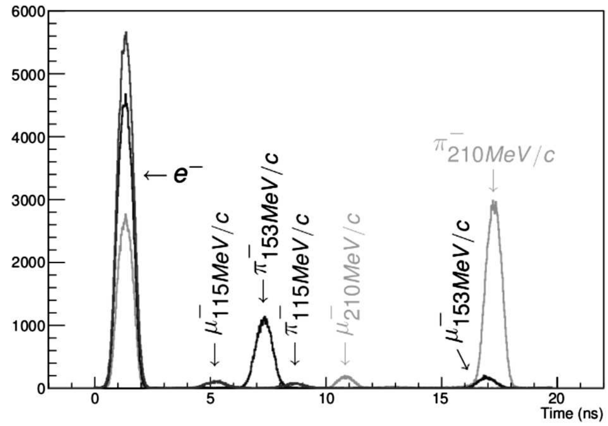

Fig. 1. Measured RF time spectrum for negative charge particles at 115, 153, and 210 MeV/c. The spectrum wraps around every ≈20 ns

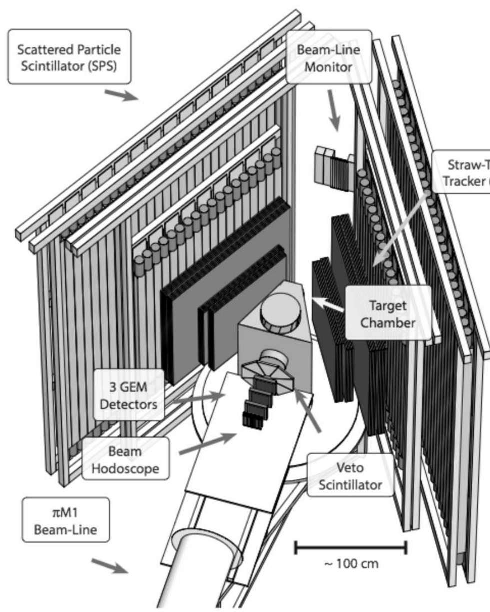

Fig. 2. MUSE detector setup implementation in GEANT4 simulation

The BH analog signal is amplified to produce a fast signal with a 1.2 (3.0) ns rise (fall) time and typically a few hundred mV peak. A Mesytec CFD sends an analog copy of the signal to a Mesytec QDC input, and the discriminated signal to a TRB3 TDC and the trigger, and an OR of all input signals to the Mesytec QDC gate.

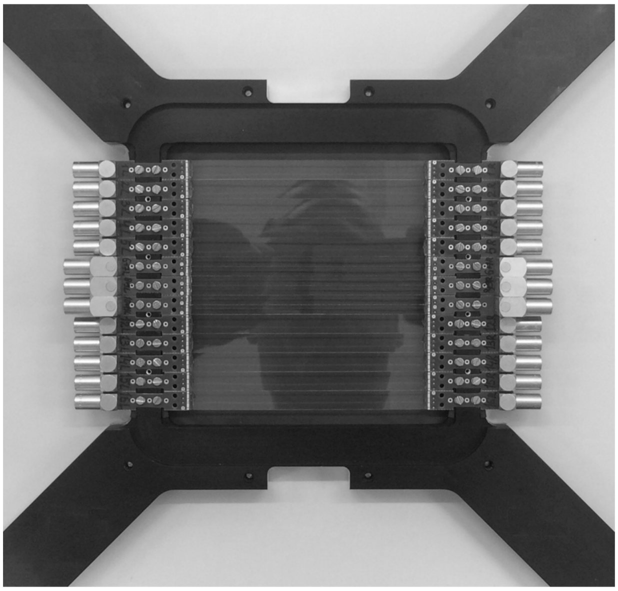

Fig. 3. BH plane with SiPM readout under construction

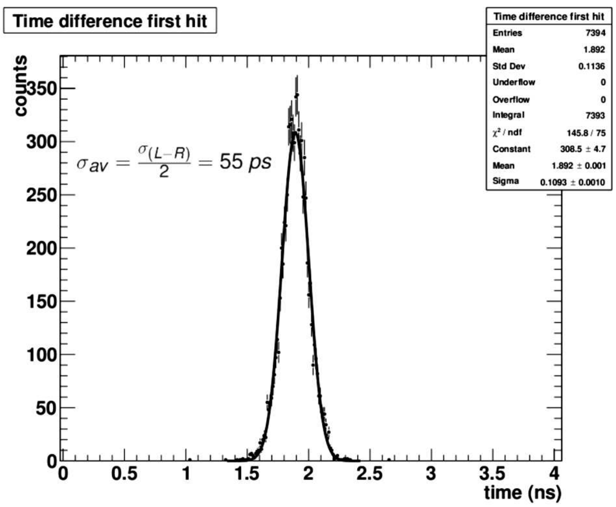

Fig. 4. The best obtained time resolution of a BH paddle

Status:

Five BH planes are built with all paddles meeting requirements. The best time resolution achieved is shown in Fig. 4.

3.2. GEM trackers

Purpose:

The GEMs measure beam trajectories so that precise scattering angles and reaction vertices can be determined. GEM chambers were chosen, as they are low-mass detectors, $\approx$0.5% of radiation length, which keeps the multiple scattering at a minimum, provide several MHz rate capability with $<$100 μm position resolution and high efficiency, $>$98%.

Requirements:

In addition to the performance characteristics given above, we require a read-out time $<$100 μs for the efficiency in obtaining data.

Detector design:

We use three 10×10 cm^2 GEMs, which were previously used in OLYMPUS [10]. The GEMs are read out using FPGA-controlled frontend electronics based on the APV-25 chip developed for CMS and digitized with the Multi-Purpose Digitizer (MPD) v4. There are readout strips in two directions, each with 400 μm pitch, much smaller than the amplified charge, which is distributed in a few mm wide cluster. Centroid weighting provides a resolution smaller than the pitch.

The GEM efficiency remains high at rate densities up to 2.5 MHz/cm^2. The expected rate density for MUSE is $\approx$3.3 MHz/5 cm^2 = 0.66 MHz/cm^2.

Current status:

The GEM system has been re-established for MUSE. We have implemented the new INFN/JLab DAQ readout software and VME controllers, which improve the read out speed along with low-noise operation and high efficiency reproduction. All requirements are now satisfed. The πM1 beam spot obtained by the GEMs is shown in Fig. 5.

3.3. Beam Veto

Purpose and requirements:

The Beam Veto detector is used to reduce the trigger rate, by vetoing some of the events that arise from beam particle decays in flight or the scattering upstream of a scattering chamber. The veto detector requires a high efficiency, $>$99%, and a 1-ns time resolution – 200 ps has been achieved.

Design:

The Beam Veto detector uses the same technology as the SPS (described in Section 3.7), with a modified geometry and only single-ended readout. Figure 6 shows the detector. The detector geometry is nearly annular, surrounding the beam. Four trapezoidal BC-404 scintillators are each read out with two Hamamatsu R13435 PMTs. The inner aperture roughly matches the target vacuum chamber entrance win-

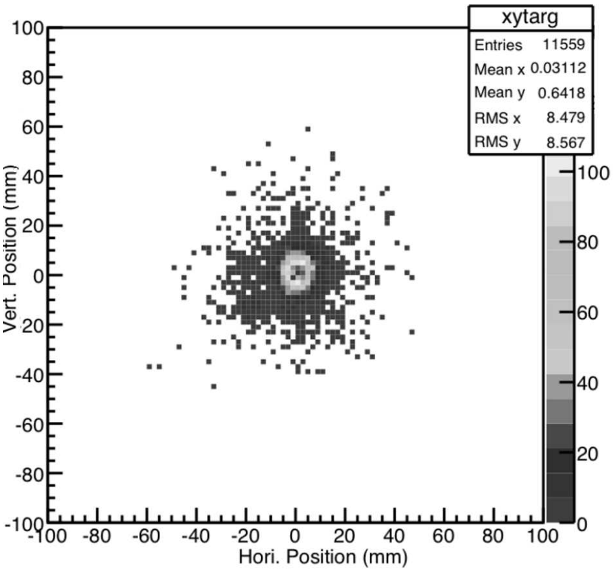

Fig. 5. The πM1 beam spot at the most upstream GEM detector

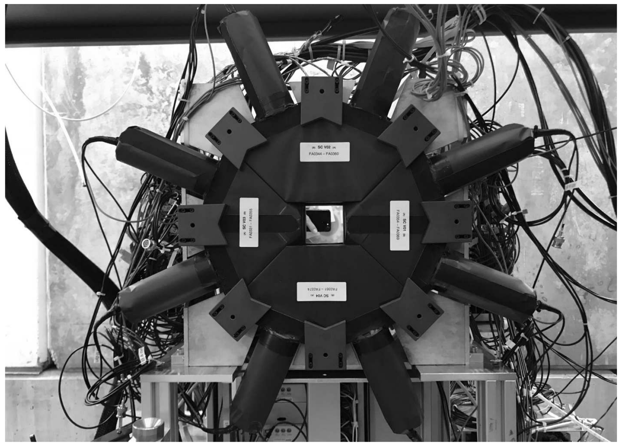

Fig. 6. Beam-Veto detector. The beam is pointing to us

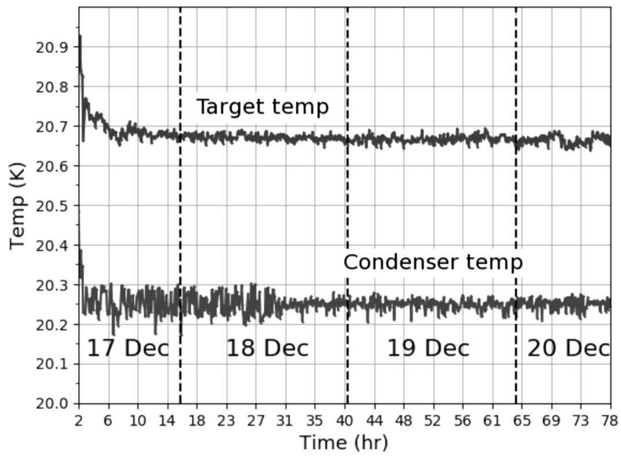

Fig. 7. Results of the first hydrogen cooldown, covering from 2 till 78 hours. Temperature stability assures the target density stability below the experimental requirements

dow. The outer extent of the detector, about 16 cm radius, was determined from simulations.

Status:

The Beam Veto detector was built, installed, and commissioned. All performance requirements have been achieved.

3.4. Liquid hydrogen target

Purpose and requirements:

A Liquid Hydrogen (LH_2) target is needed for the ep and μp scatterings. In practice this requires a target ladder that includes at least a full cell, an empty cell for background subtractions, a solid target for alignment, and an empty position. The LH_2 density must be stable, <0.1%, to precisely compare cross-sections measured at different times. The geometry of the target must be uniform at the sub-mm level for precise background subtractions.

Design:

Detailed final construction designs and the actual construction were performed by CREARE Inc. working with the collaboration. The target ladder is housed in a vacuum chamber with a 7-cm diameter entrance (7.8 cm wide by 35.6 cm high exit) window, made of 125-μm thick kapton. Scattered particles with $\theta = 20°–100°$ go through side windows 33.7 cm wide and 35.6 cm high, made of Mylar laminated on aramid sailcloth fabric, with an areal density of 368 g/m^2. The main target is a 280 mL LH_2 cell made of upper and lower copper end caps connected by a side wall of 4 wraps of 25 μm thick kapton. A cryocooler cools a condenser assembly so that the resulting LH_2 drips into the target cell. A lifting mechanism switches between ladder positions, lifting as well the cryocooler cold head and the condenser assembly.

Current status:

Filling the cryotarget with LH2 at 20.67 K takes about 2.5 h from the start of the cooldown. The target was operated steadily for over three days at a pressure of 1.1 bar with temperature constant at the 0.01 K level – see Fig. 7 – consistent with the mea-

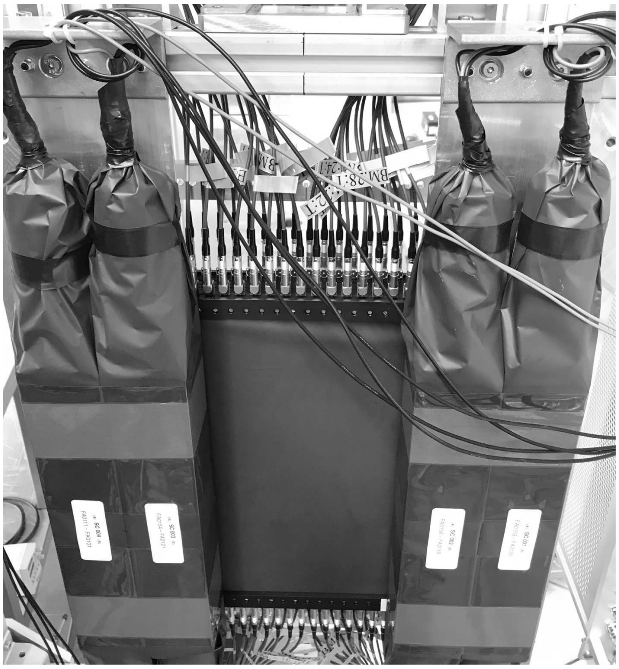

Fig. 8. Beam Monitor: The LEMO readout connectors of two offset planes are seen, continued with bigger BC-404 scintillators. The beam hits into the picture

surement uncertainty. This gives a target density of 0.070 g/cm^3 with stability <0.02%, better than experimental requirements.

3.5. Beam monitor

Purpose:

The BM provides a high-precision time measurement that determines the beam flux downstream of the target. TOF from the BH to BM determines a particle type and the background information for the RF-time only determination. TOF also determines μ and π momenta to <0.2%. The BM also detects forward Moller electrons, so it can suppress this background in the scattering data.

Requirements:

The BM comprises a central scintillator hodoscope similar to the BH of Subsection 3.1 and an outer hodoscope similar to the SPS of Subsection 3.7. The underlying technology and requirements are the same in both cases.

Design:

Figure 8 shows the BM. The central hodoscope of the BM comprises two offset planes of 16 paddles. We use 30 cm long $\times$ 12 mm wide $\times$ 3 mm thick BC-404 paddles, each read out at each end by 3 Hamamatsu S13360-3075PE SiPMs in series. The same readout electronics as for the BH is used. The outer hodoscope consists of four 30 cm long $\times$6 cm wide $\times$6 cm thick BC-404 scintillator paddles that are identical in technology to the SPS scintillators.

Status:

The BM was fully assembled, installed, and commissioned. Typical time resolutions of σ_T < 100 ps (Best: $\sigma_T = 59$ ps) were achieved, with $\geq$99.9% efficiency, exceeding performance requirements.

3.6. Straw-tube tracker

Purpose and requirements:

The STT tracks scattered particles. High resolution, <150 μm, and efficiency, >99.8%, are required for precise cross-sections.

Design:

The STT follows the PANDA straw chamber design [11] adapted to the MUSE geometry. We use the same straws, wires, end pieces, and feed-throughs as PANDA. Thin-walled, over-pressured straws allow for a significantly less straw material, while providing the mechanical stability. The straw spacing is 1.01 cm, and adjacent offset straw planes are 0.87 cm apart.

The symmetric beam left and right scattered particle detector systems include 2 chambers on each side of the beam, each with 5 vertical and 5 horizontal planes, to achieve a high tracking efficiency. The front chambers have 275 60-cm long vertical straws and 300 55-cm long horizontal straws, with an active area of 60×55 cm^2. The rear chambers have 400 90-cm long vertical straws and 450 80-cm long horizontal straws with an active area of 90×80 cm^2. The front (rear) chambers are 30 (45) cm from the target. There are 2850 straws in the system. The STT uses 90% Ar +10% CO_2 at a pressure of 2 bar. Straws operate at 1700 V. Frontend PASTTREC cards read out the straws, and are in turn read out by TRB3 TDCs.

Status:

All 4 chambers have been assembled at PSI and undergone initial performance tests. Figure 9 shows the STT being craned into the MUSE detector setup. In the initial tests, the straws operated reliably with approximately 90% efficiency, which yields $\approx$99% tracking efficiency for 5 planes. A preliminary analysis of

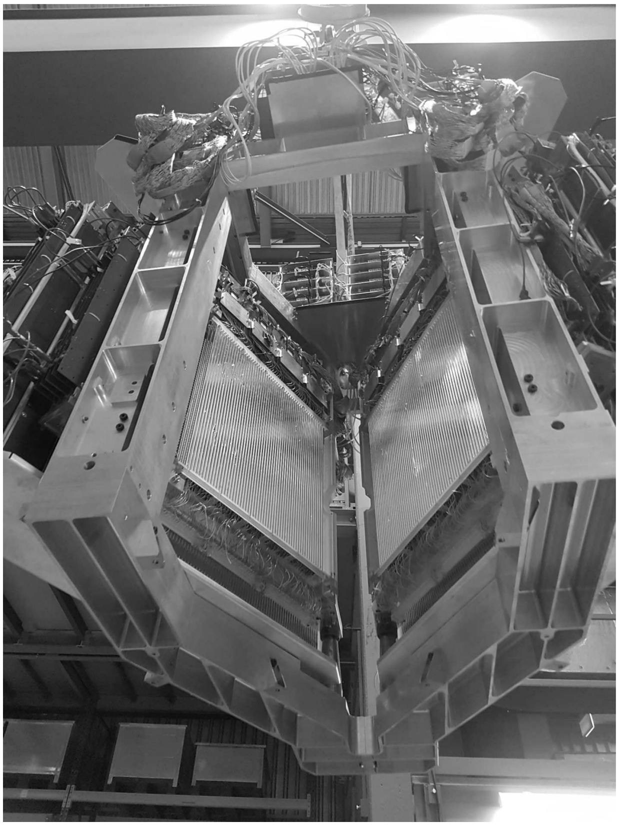

Fig. 9. Fully assembled STT detector being craned into the MUSE detector setup

the STT data yields a tracking resolution of approximately 115 μm, exceeding requirements.

3.7. Scattered particle scintillators

Purpose and requirements:

The SPS is a high-efficiency high-precision scintillator hodoscope that detects and times particles for the triggering and reaction identification. A time resolution of ≈100 ps is needed for the reaction identification. A uniform efficiency of >99% is needed so that the shape of the angular distribution is not altered.

Design:

The SPS design follows the JLab CLAS12 FTOF12 design by University of South Carolina. Symmetric left and right, front and rear hodoscope paddles are made of an Eljen Technology EJ-204 plastic scintillator, which has a high light output and a fast rise time. Hamamatsu R13435 PMTs are glued to each end of the scintillator. The front wall is roughly square and

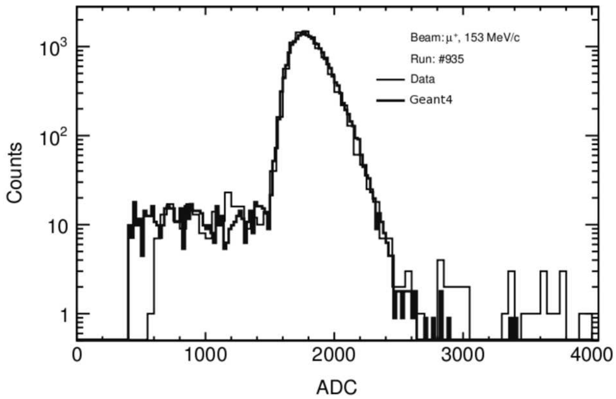

Fig. 10. SPS ADC spectra: Particles stopping or going through the bar are in peak; particles going out the side of the bar are in the low-energy tail

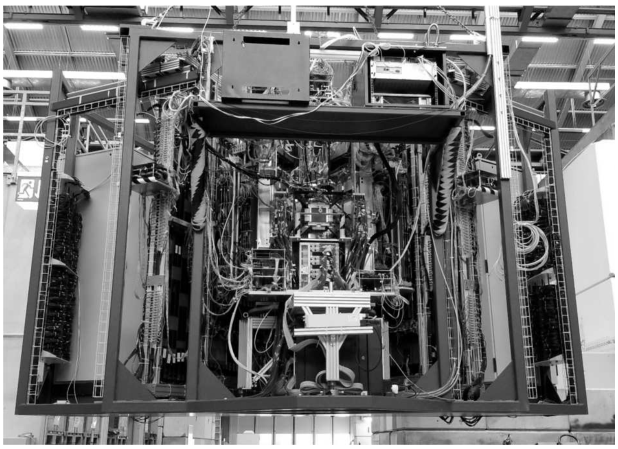

Fig. 11. MUSE Detector setup is being craned into the experimental area

covers $\theta \approx 20^\circ$–100°. The oversized back wall accounts for the multiple scattering in the front wall.

Status:

All 92 paddles are tested and installed. Average time resolutions of $\sigma_{\rm avg}$ = 52 ps ± 4 ps for the 220-cm long rear bars and 46 ps ± 4 ps for the 110-cm long front bars were obtained. Figure 10 shows that energy deposition in the scintillators modeled with Geant4 simulations agrees nicely with measurements.

The two-plane coincidence efficiency is well above 99.5%, except for e^+ (≥99%) due to the annihilation. We expect the cross-section systematic uncertainty from the SPS efficiency to be <0.1%.

3.8. Trigger, DAQ, and tracking

MUSE uses TRB3 FPGAs for the triggering. The primary scattered particle trigger logic is:

$$(e^{\pm}\ \mathrm{OR}\ \mu^{\pm})\ \mathrm{AND}\ (\mathrm{no}\ \pi^{\pm})\ \mathrm{AND}\ (\mathrm{scatter})\ \mathrm{AND}\ (\mathrm{no\ Veto}).$$

The MUSE DAQ uses a mix of VME modules for the charge determination and TRB3 TDCs for the timing. There are about 3000 TDC and 500 Q/ADC channels. Both the trigger and DAQ along with controls and basic analysis software are fully operational. The advanced analysis software development continues.

4. Conclusions

The data taken compared to simulations prove that MUSE is well suited to investigate the ($R_e - R_\mu = 0.034 \pm 0.006$ fm) 5.6σ Proton Radius Puzzle. By comparing the $p + e^{\pm}$ and $p + \mu^{\pm}$ scattering cross-sections, we will determine the absolute radius at the $\approx$0.005 fm level. All detectors are constructed and mounted on the MUSE platform. Production data runs are planned in 2019–2021.

We acknowledge the US National Science Foundation for supporting the MUSE experiment, with the additional support from the US Department of Energy, the Binational Science Foundation, and the Paul Scherrer Institute. Special thanks to Prof. Dr. Ronald Gilman for creating such a nice working atmosphere for me. Thanks to PSI for the great hospitality and the organizers of the "New Trends in High Energy Physics" for giving me opportunity to present this work.

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Т. Ростомян

СТАТУС ЕКСПЕРИМЕНТУ MUSE

Р е з ю м е

Різниця в 5.6σ у радіусах протона, виміряних з атомами μp і з атомами ep та в процесі розсіяння залишається нерозв'язаною головоломкою. В проекті MUSE буде вимірюватися пружне розсіяння μp і ep в тому самому експерименті одночасно. Експеримент визначає перерізи, двофотонні ефекти, форм-фактори та радіуси, і дозволяє порівнювати результати, отримані для μp і ep процесів зі зменшеною систематичною похибкою. Ці дані повинні забезпечити найкращий на сьогоднішній день тест універсальності лептона в процесі розсіяння, на порядок поліпшений у порівнянні з попередніми тестами, дати можливість визначити радіус з інтервалом надійності 7σ і забезпечити покращені двофотонні вимірювання.

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STUDY OF THE POLARIZED GLUON STRUCTURE OF A PROTON VIA PROMPT-PHOTON PRODUCTION IN THE SPD EXPERIMENT AT THE NICA COLLIDER

Photons produced in the hard scattering of partons, named prompt photons, provide information about the internal structure of hadrons. The NICA collider has the possibility to provide new data to study the production of prompt photons in non-polarized and polarized proton-proton collisions, which gives an access to spin-dependent parton distribution functions for gluons. Unpolarized and polarized physics with prompt photons and capabilities of the SPD detector in such measurements is discussed.

Keywords: polarized structure of a nucleon, prompt photons, gluons, SPD.

1. Prompt Photons

Prompt photons are photons produced in the hard scattering of partons. According to the factorization theorem, the inclusive cross-section for the production of a prompt photon in collisions of h_A and h_B hadrons can be written as follows:

$$d\sigma_{AB} = \sum_{a,b=q,\bar{q},g} \int dx_a dx_b f_a^A(x_a, Q^2) f_b^B(x_b, Q^2) \times$$
$$\times\, d\sigma_{ab\to\gamma X}(x_a, x_b, Q^2). \qquad (1)$$

The function f_a^A (f_b^B) is the parton density for h_A (h_B) hadron, x_a (x_b) is the fraction of the momentum of h_A (h_B) hadron carried by parton a (b), and Q^2 is the square of the 4-momentum transferred in the hard scattering process, and $\sigma_{ab\to\gamma X}(x_a, x_b, Q^2)$ represents the cross-section for the hard scattering of partons a and b [1].

The prompt-photon production in hadron collisions is the most direct way to access the gluon structure of hadrons. There are two main hard processes for the production of prompt photons: 1) gluon Compton scattering, $gq(\bar{q}) \to \gamma q(\bar{q})$, which prevails, and 2) quark-antiquark annihilation, $q\bar{q} \to \gamma g$.

Unpolarized measurements of the differential cross-section of the prompt-photon production in proton-proton(antiproton) collisions have already been performed by the fixed-target and collider experiments. Figure 1 shows the ratio of the measured cross-sections to one predicted by theory as a function of $x_T = 2p_T/\sqrt{s}$ [2]. One can see that, for the fixed-target results corresponding to $\sqrt{s} \sim 20$ GeV, there is a significant disagreement with theoretical expectations that is absent for the high-energy collider results. A new precise measurement could clarify the problem.

2. Spin Asymmetries

A measurement of the single transverse spin asymmetry $A_\gamma^N = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow}$ in the prompt-photon production at high p_T in polarized p-p and d-d collisions could provide information about the gluon Sivers function which is mostly unknown at the moment. The numerator of A_γ^N can be expressed as [3]

$$\sigma^\uparrow - \sigma^\downarrow =$$
$$= \sum_i \int_{x_{\min}}^{1} dx_a \int d^2\mathbf{k}_{Ta} d^2\mathbf{k}_{Tb} \frac{x_a x_b}{x_a - (p_T/\sqrt{s})e^y} \times$$
$$\times \Bigg[q_i(x_a \mathbf{k}_{Ta}) \Delta_N G(x_b, \mathbf{k}_{Tb}) \times \frac{d\hat{\sigma}}{d\hat{t}}(q_i G \to q_i \gamma) +$$
$$+ G(x_a, \mathbf{k}_{Ta}) \Delta_N q_i(x_b, \mathbf{k}_{Tb}) \frac{d\hat{\sigma}}{d\hat{t}}(G q_i \to q_i \gamma) \Bigg]. \qquad (2)$$

Here, $\sigma^\uparrow$ and $\sigma^\downarrow$ are the cross-sections of the prompt-photon production for the opposite transverse polarizations of one of the colliding protons, $q_i(x_a, \mathbf{k}_{Ta}) \times [G(x_a, \mathbf{k}_{Ta})]$ is the quark [gluon] distribution function with specified $\mathbf{k}_T$, and $\Delta_N G(x_b, \mathbf{k}_{Tb}) \times$

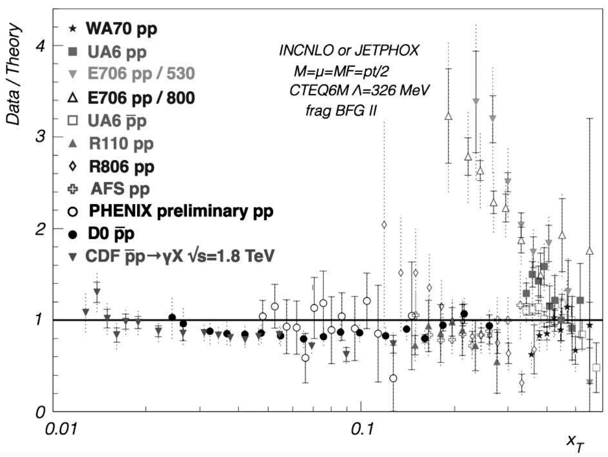

Fig. 1. Measured cross-sections of the prompt-photon production divided by those predicted by theory as a function of x_T [2]

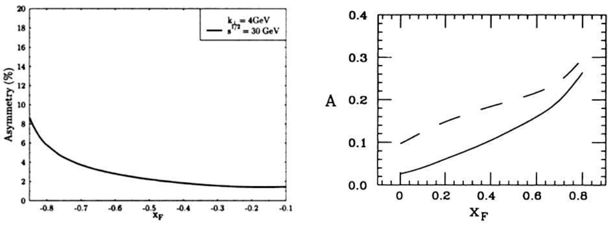

Fig. 2. Theoretical predictions for A_γ^N at $\sqrt{s} = 30$ GeV and $p_T = 4$ GeV/c for (left) positive [4] and (right) negative [5] values of x_F

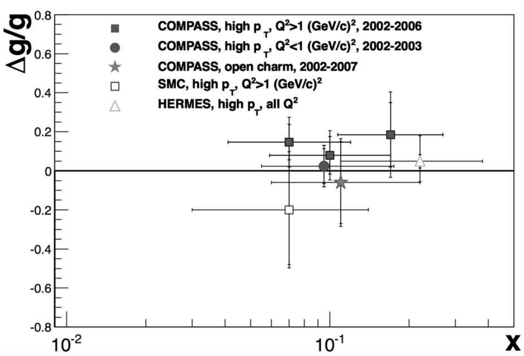

Fig. 3. A compilation of gluon polarization measurements from the open charm and high-p_T hadron production [8]

$\times\, [\Delta_N q_i(x_b, \mathbf{k}_{Tb})]$ is the gluon [quark] Sivers function, $\frac{d\hat{\sigma}}{dt}$ represents the corresponding gluon Compton scattering cross-section. Figure 2 shows theoretical predictions for A_γ^N at $\sqrt{s} = 30$ GeV and $p_T = 4$ GeV/c for positive [4] (left) and negative [5] (right) values of x_F. The study of the prompt-photon production at the large transverse momentum with longitudinally polarized proton beams could provide the access to the gluon polarization Δg via the measurement of the longitudinal double spin asymmetry A_{LL}^γ [6]. Assuming the dominance of the gluon Compton scattering process, the asymmetry A_{LL}^γ can be presented as [7]

$$A_{LL} \approx \frac{\Delta g(x_a)}{g(x_a)} \left[\frac{\sum\limits_q e_q^2 [\Delta q(x_b) + \Delta \bar{q}(x_b)]}{\sum\limits_q e_q^2 [q(x_b) + \bar{q}(x_b)]} \right] \times$$
$$\times\, \hat{a}_{LL}(gq \to \gamma q) + (a \leftrightarrow b). \qquad (3)$$

The second factor in the equation coincides to the lowest order with the spin asymmetry A_1^p well known from polarized DIS, the partonic asymmetry $\hat{a}_{LL}$ is calculable in perturbative QCD. Previous results for the gluon polarization show that the gluon polarization is consistent with zero: $|\Delta g/g| < \pm 0.2$ [8], while the A_1^p asymmetry is about 0.2 for $x \simeq 0.1$ [9].

Thus, under the given experimental conditions, it is possible to gain access to the gluon Sivers function, as well as to the gluon polarization (helicity).

3. The SPD Detector at NICA

The study of the gluon structure through the prompt-photon production is planned at the SPD experiment at the new accelerator complex NICA (Nuclotron-based Ion Collider fAcility) which is currently under construction at the Joint Institute for Nuclear Research (Dubna, Russia).

The possibility to have high-luminosity collisions (up to 10^{32} cm^{-2}s^{-1} at $\sqrt{s_{pp}} = 27$ GeV) of polarized protons and deuterons at the NICA collider allows studying spin- and polarization-dependent effects in hadron collisions.

The current design of the SPD setup foresees three modules: two end-caps and a barrel section. Each part has an individual magnetic system: solenoidal for the end-caps and toroidal for the barrel part of the setup. Main detector systems are the following: Range System (RS) (for muon identification), Electromagnetic calorimeter (ECal), PID/Time-of-Flight system, Main Tracker (TR), and Vertex Detector (VD).

Photons should be detected by the lead-scintillator electromagnetic calorimeter ("shashlyk"-type), which is placed inside the Range System and consists of three parts: the barrel one and two end-caps. Each part has a depth of about 12.5 X_0, which is sufficient to fully contain the highly energetic electromagnetic showers considered in this analysis. The energy resolution is planned to be about $5\%/\sqrt{E[\mathrm{GeV}]}$. The acceptance of the calorimeter in polar angle is between 2° and 178°.

4. Prompt Photons at SPD

The object-oriented C++ toolkit SPDroot based on the FairRoot framework [10] was used for the Monte-Carlo simulation of the detector response. The SPD setup description is based on the ROOT geometry while the transportation of secondary particles through a material of the setup, and the simulation of the detector response is provided by the GEANT4 code. The standard multipurpose generators like PYTHIA6, PYTHIA8, FRITIOF could be used for the simulation of primary interactions.

Energy deposition in a connected area in the ECal is called a cluster. If, in the course of extrapolation, the track does not rest against a cluster, such a cluster is considered as neutral, and vice versa. The main issue of the future analysis will be the correct identification of prompt-photon clusters.

The study of background contributions and possibilities of their suppression is almost the main task. On the experience of previous experiments, the main background components are:

• decay photons. Most of them (almost 96%) are coming from the decays of π^0 and η mesons;

• fragmentation photons produced in the process of fragmentation of color partons with large transverse momenta;

• photons produced in the other parts of the facility due to the interaction of particles with a material of the setup;

• neutral hadrons like n, K^0, *etc.* and their antiparticles that are identified in the calorimeter as neutral clusters;

• "charged" clusters in the ECal misidentified as "neutral" ones due to the inefficiency of the track finding and reconstruction algorithms;

• the so-called "double" clusters which are a result of the overlapping of showers produced by different particles in ECal. The special case is the clusters produced by energetic π^0 decays into two photons flying at a very small angle relative to each other.

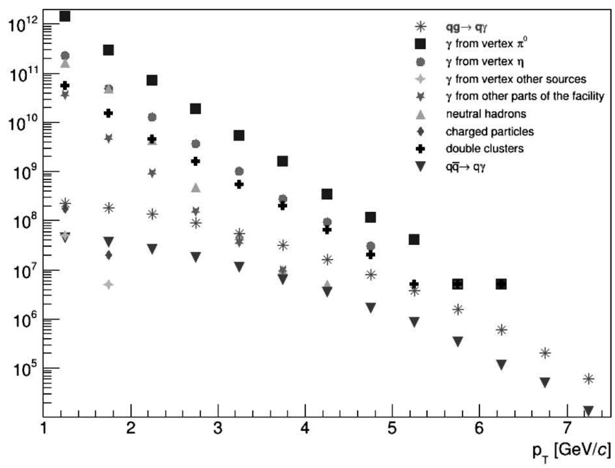

Fig. 4. Contributions of each background component for p-p collisions at $\sqrt{s} = 26$ GeV shown together with the prompt-photon production

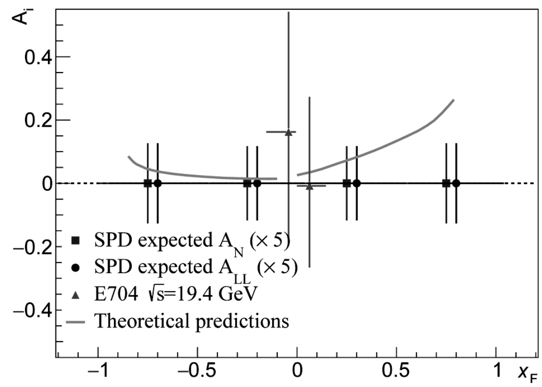

Fig. 5. Expected accuracy of A_N and A_{LL} asymmetries with $p_T > 6$ GeV/c as a function of the x_F-variable

The expected contributions of each background component mentioned above as a function of the transverse momentum p_T calculated with the use of the cluster energy and position are shown in Fig. 4 for p-p collisions at $\sqrt{s} = 26$ GeV.

As could be concluded from Fig. 4, the low p_T region is useless for any studies of prompt-photons due to a huge background. The signal-to-background ratio at $p_T = 1$ GeV/c is about 10^{-4}. Only at high values of the transverse momentum, it is possible to separate statistically the signal and the background. A reasonable cut on the transverse momentum of a photon has to be applied in order to maximize the accuracy of the planned measurements.

The background suppression process could be divided into two stages. At first, all photons from the reconstructed 2γ decays of π^0 and η mesons are rejected. After such rejection, the sample still contains an admixture of photons from 2γ decays. This residual admixture could be statistically subtracted basing on the Monte-Carlo information about properties of the SPD setup. The subtraction procedure can be illustrated by the following equation:

$$\sigma \sim N_{\mathrm{prompt}} = N_{\mathrm{single}\,\gamma} - N_{\pi^0,\eta} \times k, \tag{4}$$

where $N_{\mathrm{single}\,\gamma}$ is a number of candidates to be prompt-photons, N_{π^0} is a number of reconstructed 2γ decays of π^0 and η, and k is a factor to be determined from the Monte-Carlo procedure. The typical value of the k factor is 0.76.

To estimate the accuracy of the measurement of asymmetries, the signal and the background Monte-Carlo samples were produced. For the simulation of primary p-p collisions with $\sqrt{s} = 26$ GeV, the PYTHIA6 [11] generator with the standard settings was used. The estimation was performed for 10^7 s (one year) of data taking with an average luminosity 10^{32} s^{-1}cm^{-2}. 100% polarization of proton beams was supposed.

Using Eq. (4) and the cut $p_T > 6$ GeV$/c$ which removed most of the background and assuming that the relative accuracy $dk/k = 0.02$ could be achieved, the preliminary results on the expected accuracy of the A_N and A_{LL} asymmetries measurement in the SPD experiment were obtained. The results for four subranges of x_F-variable are shown in comparison with the E704 measurements [12] and the theoretical predictions [4, 5] in Fig. 5. The expected A_N and A_{LL} accuracies are multiplied by a factor of 5 and shown by the error bars in respect to zero values of asymmetries. The uncertainties related to polarization and luminosity measurements are not taken into account.

5. Conclusions

The study of the polarized and non-polarized gluon contents of a nucleon is one of the main physical tasks of the planned SPD experiment at the NICA collider. The prompt-photon production via the gluon Compton scattering is the most promising process for that. The precision measurement of the A_N and A_{LL} spin asymmetries with transversely and longitudinally polarized proton and deuteron beams provides the access to the gluon Sivers and helicity functions, respectively. The preliminary studies of the background conditions show that the accuracy for the asymmetries of about 2% could be achieved in the wide range of x_F.

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ДОСЛІДЖЕННЯ ПОЛЯРИЗОВАНОЇ СТРУКТУРИ ПРОТОНА ЗА ДОПОМОГОЮ ФОТОНАРОДЖЕННЯ В ЕКСПЕРИМЕНТІ SPD НА КОЛАЙДЕРІ NICA

Р е з ю м е

Фотони, утворені в жорсткому розсіянні партонів, так звані миттєві фотони, дають інформацію про внутрішню структуру адронів. Колайдер NICA зможе забезпечити нові дані про народження миттєвих фотонів в неполяризованих та поляризованих процесах фотонарождення, що, в свою чергу, дасть інформацію про спінові функції розподілу глюонів. В даній статті представлено фізику поляризації із миттєвими фотонами і можливості детектора SPD в таких експериментах.

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STATUS OF THE JIANGMEN UNDERGROUND NEUTRINO OBSERVATORY

The Jiangmen Underground Neutrino Observatory (JUNO) is a next generation multipurpose antineutrino detector currently under construction in Jiangmen, China. The central detector, containing 20 kton of a liquid scintillator, will be equipped with ∼18 000 20 inch and 25 600 3 inch photomultiplier tubes. Measuring the reactor antineutrinos of two powerplants at a baseline of 53 km with an unprecedented energy resolution of $3\%/\sqrt{E(MeV)}$*, the main physics goal is to determine the neutrino mass hierarchy within six years of run time with a significance of 3–4*σ*. Additional physics goals are the measurement of solar neutrinos, geoneutrinos, supernova burst neutrinos, the diffuse supernova neutrino background, and the oscillation parameters* $\sin^2\theta_{12}$*,* Δm^2_{12}*, and* $|\Delta m^2_{ee}|$ *with a precision <1%, as well as the search for proton decays. The construction is expected to be completed in 2021.*

Keywords: antineutrino detector, reactor antineutrinos, supernova neutrinos, proton decay, neutrino mass hierarchy.

1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton liquid scintillator (LS) detector currently under construction in the south of China close to Jiangmen. The LS is contained in a 35.4 m diameter acrylic sphere and monitored by ∼18 00 20 inch photomultiplier tubes (PMTs), allowing for an unprecedented energy resolution of $3\%/\sqrt{E(\mathrm{MeV})}$. A complementary system of 25 600 3 inch PMTs facilitates to use the concept of double calorimetry[1]. In order to reduce the external background and to track and veto cosmogenic muons, the Central Detector (CD) is submerged in a cylindrical water Cherenkov detector filled with ultra-pure water. The main goal of JUNO is to determine the neutrino mass hierarchy (MH) by measuring the oscillations of reactor antineutrinos emitted by two powerplants, Taishan and Yiangjian, with a final thermal power of 35.8 $\mathrm{GW_{th}}$ at a baseline of 53 km. Furthermore, measurements of the oscillation parameters $\sin^2\theta_{12}$, Δm^2_{12}, and $|\Delta m^2_{ee}|$ can be achieved with subpercentage precision. Numerous additional physics goals exist [2], of which measuring solar neutrinos and geoneutrinos are reviewed in the following. The Taishan Antineutrino Observatory (TAO) will be built and operated next to the Taishan power plant to reduce systematic effects in the reactor antineutrino spectrum measured by JUNO.

2. Neutrino Physics Programme at JUNO

2.1. Reactor Antineutrinos

To reach the primary goal of determining the neutrino mass hierarchy, JUNO aims at the detection of reactor antineutrinos based on the Inverse Beta Decay (IBD) of protons occuring in the LS in the CD, where the e-flavor antineutrino reacts with a proton producing a positron and a neutron according to

$$\bar{\nu}_e + p \rightarrow e^+ + n. \tag{1}$$

The IBD signature is the coincidence of a prompt and a delayed signal. The prompt signal stems from the energy loss and the subsequent annihilation of a positron taking place effectively instantaneously after its creation. Since the mass of a neutron is much larger than the mass of a positron, the energy of the

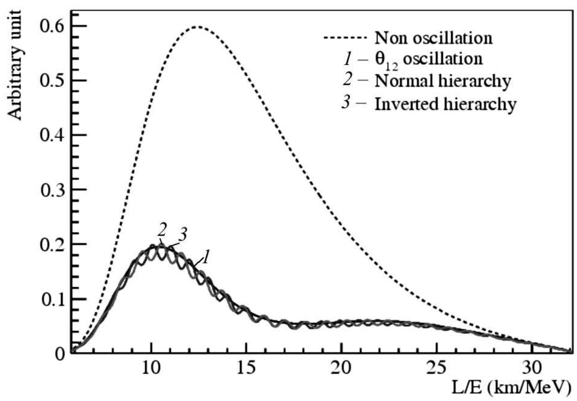

Fig. 1. Unoscillated reactor neutrino flux (dotted line) and the relative shape differences for the NH and the IH. From [2]

positron relates to the energy of an antineutrino. The delayed signal stems from the neutron being captured by hydrogen in the LS with a mean time of $\sim$200 μs after undergoing the thermalization. The neutron capture on protons emits a photon with an energy of 2.2 MeV.

The time coincidence of both the prompt and delayed signals, together with their vertex positions and the energy constraint, allows for the IBD signal detection and the background rejection. Several sources have to be considered for the background. The dominant background source is the cosmogenic isotopes ^{9}Li and ^{8}He, which are produced through the spallation by cosmogenic muons traversing through the detector. Their $(\beta^- + n)$-decay channel mimics the coincidence of the prompt and delayed signals of the IBD signature. Featuring a life time of 256 ms and 172 ms, respectively, 99% of the ^{9}Li and ^{8}He isotopes produce IBD-like signatures at a 3 m distance to the muon track [3, 4]. Therefore, the strategy for the muon veto includes a partial volume veto of the area of the liquid scintillator contained in a cylinder with a radius of 3 m around the muon track for a time of 1.2 s [5]. Other considerable background sources are the following:

- Accidental coincidences by natural radioactivity, mostly from the surrounding rock and the PMT glass.
- Fast neutrons produced by cosmogenic muons which travel through the surrounding rock or through the water at the corner of the detector. They can mimic the IBD signature by scattering off a proton and undergoing the subsequent neutron capture in the LS.
- Geoneutrinos produced in the radioactive decays of U and Th from inside the Earth. Causing the same signal like the reactor antineutrinos, their contribution to the reactor antineutrino energy spectrum is handled through the known β-decay spectra of U and Th.
- (α, n)-background originating from the α particles of the U and Th chain and reacting with ^{13}C in the LS and producing a neutron and ^{16}O. The IBD coincidence signature can be mimicked in the case where a neutron is fast enough or ^{16}O emits a photon during the deexcitation.

The expected rates of both the IBD reactor neutrino signal and the above-mentioned backgrounds are summarized in Table.

Expected signal and background rates per day with various selection cuts. From [2]

<table>
<tr><th>Section</th><th>IBD</th><th>Geo-νs</th><th>Accidental</th><th>^{9}Li/^{8}He</th><th>Fast n</th><th>(α, n)</th></tr>
<tr><td>–</td><td>83</td><td>1.5</td><td>$\sim 5.7 \times 10^4$</td><td>84</td><td>–</td><td>–</td></tr>
<tr><td>Fiducial volume</td><td>76</td><td>1.4</td><td rowspan="3">410</td><td>77</td><td rowspan="5">0.1</td><td rowspan="5">0.5</td></tr>
<tr><td>Energy cut</td><td rowspan="3">73</td><td rowspan="3">1.3</td><td rowspan="3">71</td></tr>
<tr><td>Time cut</td></tr>
<tr><td>Vertex cut</td><td>1.1</td></tr>
<tr><td>Muon Veto</td><td>60</td><td>1.1</td><td>0.9</td><td>1.6</td></tr>
<tr><td>Combined</td><td>60</td><td colspan="5">3.8</td></tr>
</table>

The neutrino MH is determined by relating the measured reactor antineutrino spectrum to the MH-dependent survival probabilities for antielectron neutrinos conditioned by neutrino oscillations. Here, the measured reactor antineutrino energy spectrum is represented by the prompt energy spectrum of the positrons produced in the IBDs. The antielectron neutrino survival probability is given by

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13} (\sin^2 \theta_{12} \sin^2 \Delta_{32} +$$

$$+ \cos^2 \theta_{12} \sin^2 \Delta_{13}) - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{12} \quad (2)$$

with $\Delta_{ij} = (\Delta m_{ij}^2 L)/(4E)$ and shown for both cases of the normal hierarchy (NH) and the inverted hierarchy (IH) in Fig. 1.

The χ^2-based analysis of the reactor antineutrino energy spectrum determines the neutrino mass hierarchy with a sensitivity $\Delta\chi^2$ by fitting the energy spectrum with the expected spectra both for the NH and IH. The obtained sensitivity depends both on the acquired amount of statistics and the energy resolution. Figure 2 shows the $\Delta\chi^2$-contour plot for different sensitivity levels depending on a variable energy resolution and a range of the number of IBD events included in the analysis. The latter is normalized to the expected number of events after 6 years of the data acquisition with 35.8 $\mathrm{GW_{th}}$ reactor power, corresponding to 100,000 IBD events. With this amount of detected events and the design energy resolution of $3\%/\sqrt{E(\mathrm{MeV})}$, the reachable sensitivity is expected to be 3–4σ, corresponding to 9–16$\Delta\chi^2$.

Additionally, JUNO will be able to improve the precision of the oscillation parameters $\sin^2\theta_{12}$, Δm^2_{12}, and $|\Delta m^2_{ee}|$ to the subpercentage level of 0.67%, 0.50%, and, 0.44%, respectively.

2.2. Solar neutrinos

The Sun is a powerful source of electron neutrinos. The neutrinos are produced in the nuclear fusion reactions and emitted with the energy of $\mathcal{O}$ (1 MeV). Their study yields the possibility to gain knowledge in the context of neutrino properties (e.g., the Mikheyev–Smirnov–Wolfenstein (MSW) effect [6]) as well as the Sun (e.g. the solar metallicity problem [7]).

The JUNO experiment is principally well suited for the detection of solar neutrinos via the electron scattering due to the low energy detection threshold, the high energy resolution, the high radiopurity, and the large mass. The focus lies on the neutrinos emitted from the ^{8}B and ^{7}Be chains.

Since a single energy deposition of the scattering electron is the event signature, the resulting experimental challenge is the rejection of the enormous background. Dominant background sources are natural radioactivity (^{210}Po, ^{210}Bi, ^{14}C and its pile-up, ^{85}Kr, and the ^{238}U- and ^{232}Th-chains [8]) and the cosmogenic isotopes ^{10}C and ^{11}C. The expected detection rates are $\sim 10^4$ events per day for ^{7}Be and $\sim$90 events per day for ^{8}B.

2.3. Geoneutrinos

While the Earth's surface heat flow has been measured to be (46 ± 3) TW [9], the contribution of the radiogenic heat in contrast to the primordial heat remains unclear till now. Therefore, knowledge of the absolute abundance of U and Th in the Earth is required. Their abundance is accessible through the antielectron neutrino flux caused by the radioactive β-decays from the ^{238}U and ^{232}Th chains.

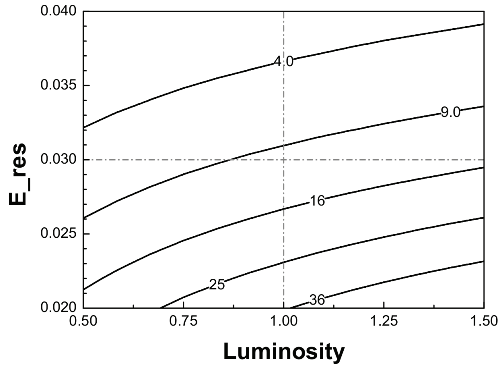

Fig. 2. Iso-$\Delta\chi^2$ contour plot as a function of the acquired statistics labeled as the luminosity and the energy resolution. The nominal luminosity marked by the vertical dotted line corresponds to a run time of 6 years and 100,000 IBD events. The design energy resolution is marked by the horizontal dotted line. From [2]

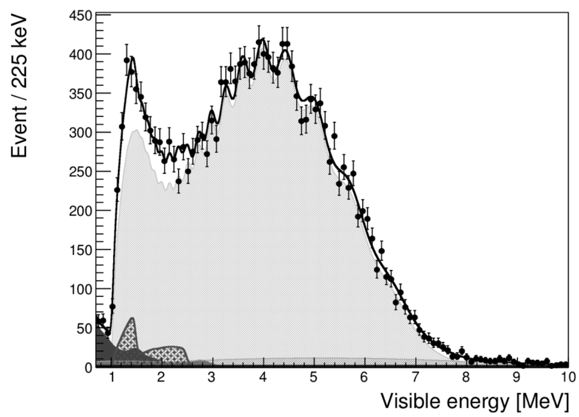

Fig. 3. Expected geoneutrino signal (grid shade) and background spectra for one year of measurement. Background contributions are the reactor antineutrinos (light grey), the cosmogenic isotopes ^{9}Li and ^{8}He (flat light grey), the accidental background (dark grey), and the (α, n)-background (small). The total sum for the best fit is indicated by the black line. From [2]

JUNO aims at measuring these so-called geoneutrinos expected with a rate of 400 events per year [2]. This would yield the world's largest sample of geoneutrinos in less than one year. The experimental challenge is the large background of reactor antineutrinos which can only be handled by the subtraction of both spectra. Further background sources are the cosmogenic isotopes ^{9}Li and ^{8}He, accidental background, and (α, n)-background. Figure 3 demonstrates the expected geoneutrino signal and background spetra for one year of measurements.

3. The JUNO Experiment

The JUNO experiment is located close to Jiangmen in China, at a distance of 53 km to both the Taishan and Yiangjian powerplants. The detector is built underground with an overburden of 700 m of a granite rock to reduce the amount of cosmogenic muons as the background source.

This section describes the following subsystems of the JUNO detector: the Central Detector (CD), the Water Pool (WP), the Top Tracker (TT), the Calibration System, activities and apparatus in the context of the LS purification, and the Taishan Antineutrino Observatory (TAO).

The central detector

The CD is an acrylic sphere with a diameter of 35.4 m containing 20 kton of LS. It is equipped with 18 000 20 inch Photo-Multiplier Tubes (PMTs) and 25 600 3 inch PMTs. The PMTs are mounted on a stainless steel truss surrounding the acrylic sphere with a distance of 1.8 m. The resulting photocoverage is 78%. A high quantum efficiency of $\sim$30% is required in order to reach the unprecedented design energy resolution of $3\%/\sqrt{E(\mathrm{MeV})}$. Out of the 18 000 20 inch PMTs, 5000 are dynode PMTs produced by *Hamamatsu Photonics K.K.*, the remaining PMTs are Micro Channel Plate PMTs and manufactured by the Chinese company *North Night Vision Technology Co. Ltd.* Shielding against the Earth's magnetic field is ensured by the compensation through electromagnetic coils.

The water pool and the top tracker

The CD is submerged into the cylindrically shaped WP containing 40 kton of ultra-pure water to provide shielding from the radioactivity of the surrounding rock and the PMT glass. The WP has a diameter of 43.5 m and is equipped with 2 400 20 inch PMTs to detect the Cherenkov light of muons traversing the JUNO detector. The TT is placed on the WP top. It was a part of the former Opera detector [10] and consists of three layers of a plastic scintillator with a spatial resolution of 2.6×2.6 cm^2 and a coverage of approximately 60% of the surface of the top of the WP. Together, the WP and the TT enable one to track cosmogenic muons providing the foundation for a partial volume muon veto.

Calibration

In order to achieve an energy scale uncertainty of less than 1%, the efficient calibration is of great importance. Four calibration systems are planned to be implemented to provide the basis for a thourough calibration. The first calibration system is the Automated Calibration Unit (ACU) which can be operated 1-dimensionally along the vertical axis in the center of the detector. The second calibration system is the Cable Loop System (CLS), and the third is the Guide Tube Calibration System (GTCS). Both CLS and GTCS can be operated 2-dimensionally, the first in a fixed vertical plane and the latter along a fixed longitude of the CD bound to a guide tube. The fourth calibration system, the Remotely Operated Vehicle (ROV), is steerable in all 3 dimensions and can move freely within the LS in the CD. Furthermore, the double calorimetry system including both the 20 inch and 3 inch PMTs provides an additional calibration strategy, especially with respect to the systematics of the large PMTs due to a multiplicity in the photo-electron detection.

LS purification

In order to prepare the mixing of the LS components and the online purification procedure for the filling of the JUNO CD, as well as to gain experience in the system cleanliness and leak-tightness, distillation, and stripping, pilot plants are currently tested at the Daya Bay Neutrino Laboratory [11].

The LS purification aims at decreasing the amount of radioimpurities primary due to ^{238}U, ^{232}Th, and ^{40}K. For ^{238}U and ^{232}Th, the abundances in the range of 10^{-15}–10^{-17} g/g are targeted. Simultaneously, the attenuation length in the wavelength interval 350–550 nm is improved to exceed 25 m for a wavelength of 430 nm. The gas stripping of the LS with steam and nitrogen extracts radioactive gases, in particular ^{85}Kr, ^{39}Ar, and ^{222}Rn.

The Taishan Antineutrino Observatory

In order to determine the neutrino MH from the oscillated reactor antineutrino spectrum measured by the JUNO detector, a precise knowledge of the unoscillated spectrum is required. The existing model for the energy-dependent reactor flux is subject, however, to both the anomalous bump observed in reactor antineutrino spectra at 5 MeV and a fine structure yet unknown [12]. Therefore, TAO will be placed in 30 m distance to a 4.6 GW_{th}-power core of the Taishan powerplant to measure the shape of the unoscillated reactor antineutrino reference spectrum for JUNO. The spherical detector will be filled with several tons of Gd–LS to detect the antineutrinos via the IBD reaction. Being equipped with Silicon Photomultipliers (SiPM) featuring a photo-electron (PE) detection efficiency of $\sim$50% at the full coverage, a light yield of 4500 PEs at an energy of 1 MeV will be reached, resulting in an energy resolution better than $3\%\sqrt{E(\mathrm{MeV})}$. The Gd-LS will be operated at –50 degree Celsius to reduce the SiPM noise [13].

4. Conclusion

JUNO is a 20 kton liquid scintillator detector currently under construction in the south of China, close to Jiangmen. The physics main goal is to determine the neutrino MH based on the detection of reactor antineutrinos at a baseline of 53 km reaching 3–4σ significance after 6 years of data taking with 35.8 GW_{th} reactor power. Therefore, an unprecedented energy resolution of $3\%/\sqrt{E(\mathrm{MeV})}$ based on a light yield of 1200 PE/MeV and an energy scale uncertainty <1% is required. Furthermore, the physics programme is extended to the detection of terrestrial and astrophysical neutrinos. The oscillation parameters $\sin^2\theta_{12}$, Δm^2_{12}, and $|\Delta m^2_{ee}|$ will be measured at a subpercentage precision level. The construction is expected to be completed in 2021.

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СТАН ПІДЗЕМНОЇ
ОБСЕРВАТОРІЇ НЕЙТРИНО В ЖІАНГМЕНІ

Р е з ю м е

Підземна Обсерваторія Нейтрино в Жіангмені (JUNO) є багатоцільовим детектором антинейтрино нового покоління, що споруджується в Китаї. Центральний детектор, що містить 20 кілотон рідинного сцинтилятора, буде оснащено трубками фотопомножувачів, 17 571 штук по 20 дюймів та 25 600 по 3 дюйми. У процесі вимірювання антинейтрино від двох реакторів з базою 53 км при безпрецедентній роздільній здатності по енергії $3\%/\sqrt{E}$ МеВ основною метою є визначення впродовж шести років роботи ієрархії мас нейтрино з точністю 3–4σ. Додатковими фізичними цілями є вимірювання сонячних нейтрино, геонейтрино, нейтрино від вибуху супернової, нейтринного фону дифузної супернової, параметрів осциляції $\sin^2\theta_{12}$, Δm^2_{12}, $|\Delta m^2_{ee}|$ з точністю <1%, а також пошуки розпаду протона. Планується закінчити конструкцію у 2021 році.

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THE PANDA DETECTOR AT FAIR

PANDA is a fixed-target experiment that is going to address a wide range of open questions in the hadron physics sector by studying the interactions between antiprotons with high momenta and a stationary proton target. The PANDA detector is currently under construction and will be situated in the HESR that is a part of the future FAIR accelerator complex on the area of the GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt. The key features of the detector are: the precise tracking in strong magnetic fields, excellent particle identification, and high-resolution calorimeters.

Keywords: FAIR, PANDA, antiprotons.

1. Introduction

1.1. Antiproton Production at FAIR

The future Facility for Antiproton and Ion Research (FAIR) is designed as an extension to the existing GSI Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany. A new linear accelerator (p-LINAC) that is currently under development will accelerate protons up to a kinetic energy of 70 MeV. After being further accelerated in the two synchrotrons SIS18 and SIS100, these protons will be extracted to collide with a nickel target. The antiprotons, that are created during this process, will be collected by the Collection Ring (CR) and further injected into the High Energy Storage Ring (HESR) where the PANDA detector will be located. In addition to NUSTAR, CMB, and APPA, it is going be one of the four excellent physical experiments at FAIR [2].

1.2. HESR & PANDA

The injection momentum of the antiprotons into the HESR will be 3.8 GeV/c. Inside the HESR, the beam momentum can be modified to values between 1.5 GeV/c and 15 GeV/c. One of the key features of the HESR is the stochastic cooling that can be applied over the full momentum range. In addition to that, the HESR can run in two different modes: a high-luminosity and a high-resolution mode. The important parameters of both modes are represented in the table below. The high-luminosity mode with an interaction rate of 20 MHz will not be available in the beginning, because it requires an additional synchrotron called Recycling Energy Storage Ring (RESR). The investigation of collisions between antiprotons and protons in PANDA will be used to answer open questions in the fields of nucleon structure, hadron spectroscopy, and nuclear physics.

Because of the forward boost of the created particles, PANDA will consist of two spectrometers: a target spectrometer designed as an onion shell detector around the interaction point and a forward spectrometer covering small polar angles. Both spectrometers have redundant detector systems for the tracking, particle identification (PID), and calorimetry. The complete PANDA detector including all sub-

Different operation modes of the HESR

Parameter	High Res.	High Lum.
Momentum [GeV/c]	1.5–15	1.5–15
Antiprotons	10^{10}	10^{11}
Luminosity [$\mathrm{cm}^2\,\mathrm{s}^{-1}$]	2×10^{31}	2×10^{32}
Resolution $\Delta p/p$	5×10^{-5}	1×10^{-4}

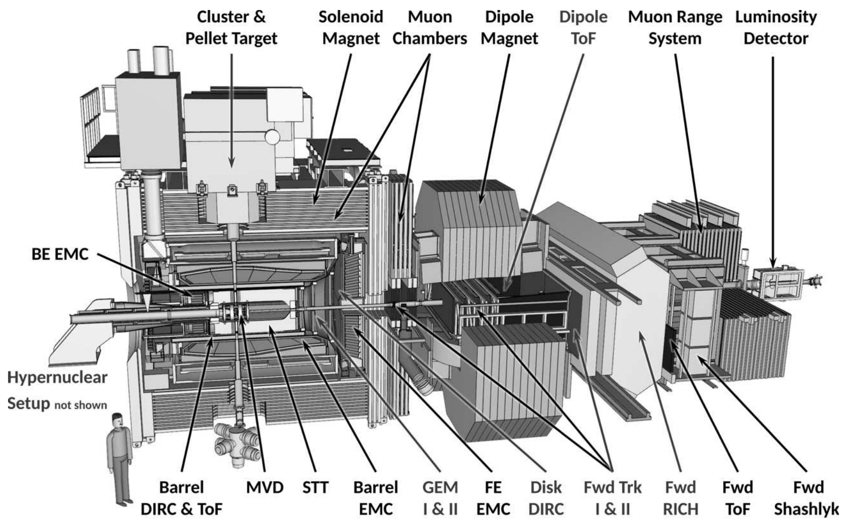

Fig. 1. The PANDA detector at FAIR including all detectors for phase *1* (black) and phase *2* (gray)

detectors is shown in Fig. 1. For most of the physical analysis, it is important to cover the full solid angle with all subdetectors.

1.3. Physics programs

The PANDA experiment is designed to cover a large amount of antiproton physics programs in order to answer many open questions related to the huge sector of hadron physics in the non-perturbative region [7]. This can be summarized as follows:

- Hadron spectroscopy: Production of exotic QCD states and exploring charm hadrons.
- Nucleon structure: Investigating the generalized parton structure and time-like form factors.
- Nuclear physics: Studying hadrons in nuclei and performing hypernuclear physics.

1.4. Time schedule

The time schedule of PANDA is divided into 3 phases. In the present phase 0, the subdetectors of PANDA are under development and tested in various other excellent High Energy Physics (HEP) experiments. With the availability of the PANDA hall in 2022, the installation of phase 1 subdetectors is going to start. In the year 2025, a proton beam will be used for commissioning the start setup of PANDA, whereas the first antiproton beam will be available in 2026. The measurements of phase 2 that includes all remaining subdetectors are going to be started around 2027. After running for a long-time period, further physical experiments with other possible setups can be performed, e.g., phase 3 that represents the high-luminosity mode. A complete overview over all phases is presented in Figure 2.

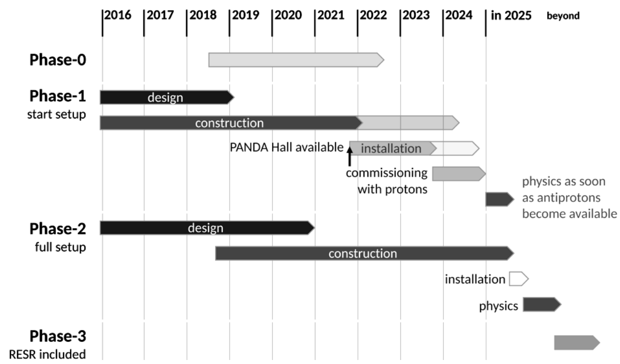

Fig. 2. The different phases of the PANDA detector

2. Proton Target

The proton target marks the interaction point (IP) and can be seen as the core component of a PANDA target spectrometer. Two targets are currently foreseen. The clusterjet target will be already installed in the first phase of PANDA. It creates small hydrogen clusters with a size of 10^3 to 10^5 atoms per cluster by expanding pre-cooled and compressed hydrogen into the vacuum of the beam pipe.

The pellet target creates small droplets of frozen hydrogen with pellet diameters between 10 and 30 μm in a triple point chamber. These pellets will be injected into the target tube with a falling speed of around 60 m/s. In total, a constant flow rate of 100,000 pellets per second can be achieved. Further targets are under development and can be installed in later phases.

3. Magnets

For the purpose of the momentum determination, two magnets will be installed in PANDA [3]. A solenoid magnet in a target spectrometer will create a field of around 2 T with a field inhomogenity of less than 2% over the full field map. Inside the iron yoke, drift tube chambers will be placed for PID and tracking of high energetic muons. The inner/outer diameter of the magnet will be 1.9 m/2.3 m. The length is given by 4.9 m, which leads to a total magnet weight of approx. 360 t.

In the forward spectrometer, a dipole magnet is going to create a magnetic field of 1 T. The length of the magnet is 2.5 m and has an overall weight of 240 t. It has a conical shape with an opening diameter of 1 m at the front- and 3 m at the backside. The key feature of this magnet is a short ramping speed of 1.25% per second and the possibility for a synchronized operation with the HESR.

4. Tracking

4.1. Micro Vertex Detector

The inner-most detector and the closest one to the target is the Micro Vertex Detector (MVD) [4]. It consists of four barrels around the interaction point and six disks in the forward direction. The inner barrel layers of the MVD contain hybrid pixels with a size of 100 μm $\times$ 100 μm, while the outer layers are made of double sided microstrips. The last two disks will be equipped with pixel and strip detectors.

A time resolution of 6 ns and a pixel resolution of 28 μm are achievable. From these values, a vertex resolution of 50 μm can be computed. This high vertex resolution is important to measure displaced vertices, e.g., to analyze different decay channels in the open charm sector.

4.2. Straw tube tracker

The Straw Tube Tracker (STT) [5] is placed in a cylindrical shape around the MVD and consists of 4,200 Al-Mylar drift tubes filled with a mixture of Ar/CO_2 gas. The readout can be done with ASICs combined with TDCs or with Flash ADCs (FADCs) instead. In total, 21 to 27 layers are planned to be installed, of which 8 layers are skewed by 3° for the purpose to reconstruct the longitudinal coordinate. The electron avalanche gain of these tubes is about 100. The inner/outer radius of the detector is 15 cm/42 cm. Each tube has a diameter of 1 cm and a length of 150 cm. Taking the spatial and time resolutions into account, a ϱ/ϕ plane resolution of 150 μm and a z resolution of 1 mm can be achieved. Currently, most of the tubes have been produced and already been mounted within an STT prototype.

4.3. Gas electron multiplier tracker

The Gas Electron Multiplier (GEM) tracker in the forward region of the target spectrometer is a combination of three stations. Two stations will be installed in phase 1 and the third one in phase 2. The foreseen large area GEMs were developed at CERN and are going to be produced in Poland. They contain a 50 μm kapton layer covered by thin copper layers with a thickness of 2 to 5 μm on both sides. The ADCs, that are planned for the readout, will allow for the cluster centroiding to calculate the precise particle position and to reach a position resolution of better than 100 μm.

4.4. Forward tracker

The forward tracker, containing similar straw tubes to the STT, assembled in three planar tracking stations, will be installed in the forward spectrometer to cover small polar angles up to $\pm 10°$ horizontally and $\pm 5°$ vertically. The momentum acceptance is larger than 3% of the beam momentum. This goal is achieved by adjusting the dipole field according to the beam momentum. For the position resolution, 0.1 mm per layer can be achieved, whereas the momentum resolution will be better than 1%.

5. Particle Identification

The envisaged physical programs of PANDA require excellent PID for all decay channels. Since PANDA does not comprise hadronic calorimeters, the PID of hadrons will be performed with four different detector methods: 2 Cherenkov detectors, a Time of Flight (ToF) system, the specific energy loss from the STT and MVD, and a muon detection system.

5.1. Barrel DIRC

One of the Cherenkov detectors based on the Detection of Internally Reflected Cherenkov Light (DIRC), is the Barrel DIRC [9] which will be mounted in a cylindrical shape around the STT. It is designed to separate $\pi^{\pm}$ and $K^{\pm}$ with a separation power of more than 3 s.d. in the polar angle range of 22° to 140° and the momentum range of 1.5 to 3.5 GeV/c.

The radius of the detector is 476 mm. It will consist of 16 fused silica bars and 128 Multichannel Plate Photomultiplier Tubes (MCP-PMTs), which adds up to around 10,000 channels to be read out with the DiRICH readout system. The MCP-PMT signal shape results in a time resolution of 100 ps.

5.2. Disc DIRC

Another Cherenkov detector called Disc DIRC [6] will be placed at the forward endcap of the PANDA target spectrometer, around 2 m away from the interaction point in the downstream direction. It will cover small polar angles between 5° and 22° and particle momenta of $\pi^{\pm}$ and $K^{\pm}$ between 0.5 and 4.0 GeV/c. As for the Barrel DIRC, the separation power will be larger than 3 s.d. The Disc and Barrel DIRC together will cover almost the full kaon phase space in the target region.

The Disc DIRC consists of four independent quadrants made of synthetic fused silica. The detector radius is approx. 1,200 mm. Currently, 96 MCP-PMTs are foreseen for the photon detection, which requires a readout of 30,000 channels with TOFPET ASICs from the company PETsys. The time resolution is similar to the one of the Barrel DIRC. For the reconstruction of the Cherenkov angle, the tracking information has to be taken additionally into account.

5.3. Barrel ToF

The Barrel ToF [1], also called SciTil detector, is required for the PID of low momentum particles below 1 GeV. A very good time resolution of better 100 ps is required for that purpose and can be achieved with a high photon yield. In total, 5,760 scintillator tiles with sizes around 90 mm × 30 mm × 5 mm have to be installed in the target spectrometer around the Barrel DIRC.

The scintillator material has not been finally chosen, but it will be either EJ-228 or EJ-232 from Eljen Technology. The photon signals will be detected with Silicon Photomultipliers (SiPMs) that can be read out in combination with PETsys TOFPET ASICs.

5.4. Forward ToF

In the forward spectrometer, PID is essential. Hence, a forward ToF system was developed. It does not require a start counter, but uses relative timing to the Barrel ToF. The baseline design of the Forward ToF is a wall of scintillator slabs. In the center of the detector, 20 slabs with the dimensions 1400 mm × × 5 mm × 2.5 mm will be used. On both sides, the width of each slap changes from 5 cm to 10 cm. BC-409, made by Saint-Gobain Crystals, will be used as a scintillation material. The photon detection will be done with 1-inch PMTs R4998 from Hamamatsu that are going to be mounted on both ends. The detector is going to be installed 7.5 m away from the interaction point.

5.5. Forward RICH

The PID detector with the largest distance to the interaction point is the forward Ring Imaging Cherenkov (RICH) that is placed behind the Forward ToF for phase 2. It contains two layers of aerogel with small refractive indices of $n_1 = 1.05$ and $n_2 = 1.047$ in order to obtain a better focusing of the Cherenkov ring. The setup is very simple, because it contains only one flat mirror and a Multi Anode PMT (MaPMT) array with a pixel size of 6 mm to determine the position of the photon hits. A separation of $\pi^{\pm}/K^{\pm}$ and $\mu^{\pm}/K^{\pm}$up to particle momenta of 10 GeV/c is realistic. The used MaPMTs are approx. 10 times less expensive than MCP-PMTs, but still have a long lifetime and a sufficient radiation hardness.

6. Energy Measurement

PANDA contains Electromagnetic Colorimeters (EMCs) in the target and a forward spectrometer with the goal to achieve a good energy and spatial resolution for photons from a few MeV up to 15 GeV in order to reconstruct almost all multiphoton and lepton-pair channels. Because of the hadronic interactions in PANDA, a high photon yield and the background suppression are required. For that purpose, the energy threshold of all calorimeters has to be set to a value around 10 MeV. The rate of a single crystal is given by 10^6 s^{-1}.

6.1. Target Calorimeter

The EMC in the target spectrometer [8] contains one barrel part, which will be installed around the Barrel ToF, and two flat parts at the forward and backward endcaps. It uses the 2nd generation of $PbWO_4$ crystals with improved light yield and better radiation hardness. In total, 15,744 crystals have to be installed in all parts. In order to increase the photon yield by a factor of four, the crystals have to be cooled to a temperature of (-25 ± 0.1) °C. The used material has the advantage of a small radiation length around 0.9 cm and and a Molière radius of 2.1 cm. The typical size of each crystal is 2.5 mm $\times$ 2.5 mm with a fixed length of 20 cm. For particles with energies above 100 MeV, a time resolution of better than 1 ns and a spatial resolution of less than 1.5 mm are feasible. The energy resolution is given by

$$\frac{\sigma(E)}{E} = 1\% \oplus \frac{2\%}{\sqrt{E[\mathrm{GeV}]}}. \tag{1}$$

Currently, 75% of all required crystals have been produced.

6.2. Forward calorimeter

The EMC in the forward spectrometer [10] is a shashlyk-type sampling calorimeter consisting of interleaved scintillators and lead absorbers. The photon readout is done with PMTs and FADCs that are used for the signal digitization. The active area of the calorimeter is given as 297×154 cm^2. The total energy resolution can be calculated to

$$\frac{\sigma(E)}{E} \leq 1.3\% \oplus \frac{2.8\%}{\sqrt{E[\mathrm{GeV}]}} \oplus \frac{3.5\%}{E[\mathrm{GeV}]}. \tag{2}$$

7. Muon Detector System

In the iron yoke of the target spectrometer and in the forward spectrometer, small Muon Drift Tubes (MDTs) with a wire and cathode strip readout will be used to detect created muons. Due to the low muon momenta, a large pionic background is expected. This effect can be minimized by using a multilayer range system. In PANDA, $12+2$ layers are installed in the barrel and $5+2$ layers in the endcap part. Between the target and forward spectrometer, muon filters will be installed for the background reduction. Behind the forward EMC, $16+2$ layers of muon chambers will be installed additionally. In total, the setup will contain 3,751 MDTs in all parts.

8. Luminosity Detector

The luminosity detector of PANDA will be placed around 11 m away from the target in the forward direction behind the forward spectrometer. It is going to measure the elastic scattering of antiproton-proton interactions. The main component is a silcon pixel detector that is mounted on five Chemical Vapour Deposition (CVD) diamond wafers with a thickness of 200 μm. Each wafer contains 10 High Voltage Monolithic Active Pixel Sensors (HV MAPS) with a pixel size of 80 μm $\times$ 80 μm. The active pixel sensor is based on the CMOS technology which allows the digital processing directly on a chip. The detector is able to attain a very high efficiency of approx. 99.5%.

9. Hypernuclear Setup

The hypernuclear setup is an alternative setup for physical studies in phase 2. It contains two targets: one passive primary target, made of a diamond wire on piezo motored wire holders, to produce Ξ baryons and one secondary active target for capturing them together with all track products in silicon microstrips and absorbers. High-purity germanium detectors at the rear will be used for gamma spectroscopy of the related decay products.

10. Data Acquisition

One of the outstanding features of PANDA is the triggerless data acquisition [12]. Because of the absence of a hardware trigger, the data from the Front End Electronics (FEE) have to be reduced by a factor of more than 1,000. This reduction will be achieved by a daisy chain of different event building and online reconstruction levels. First, the data from the FEE will be transmitted via data concentrators to a burst building network. From there, the remaining hits will be processed further in special compute nodes to perform the 1st and 2nd level selections, before the reduced data will be written to the PANDA storage. The time synchronization will be done with a dedicated PANDA development called SODAnet.

11. Simulation Framework

For the simulation and analysis, a dedicated framework called PandaRoot [11], that is based on ROOT, was developed. This framework includes the geometries of all PANDA subdetectors together with the important simulation parameters and passive volumes. Different particle generators can be used in or-

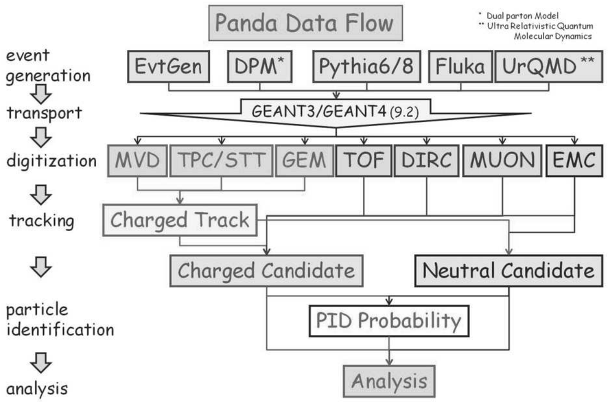

Fig. 3. The data flow in PandaRoot

der to simulate from dedicated probe tracks to specific physics channels. For the particle propagation through matter, it is possible to switch between the toolkits Geant3 and Geant4. The PandaRoot framework will additionally be used to reconstruct and analyze the acquired data of the final PANDA detector, as shown in Figure 3.

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М. Шмідт

ДЕТЕКТОР PANDA НА ПРИСКОРЮВАЧІ FAIR

Р е з ю м е

PANDA – експеримент з фіксованою мішенню, в якому передбачається розглянути широкий спектр відкритих питань адронної фізики шляхом дослідження взаємодії між антипротонами з великими імпульсами та стаціонарною протонною мішенню. Детектор PANDA наразі знаходиться на стадії будівництва і буде розміщений у HESR, що є частиною майбутнього комплексу прискорювача FAIR на платформі Центру Гельмгольца для дослідження важких іонів GSI у Дармштадті. Головні характеристики детектора: треки високої точності в сильному магнітному полі, чудова ідентифікація частинок, а також калориметри високої роздільної здатності.

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THE PIERRE AUGER OBSERVATORY: STUDYING THE HIGHEST ENERGY FRONTIER

We highlight the main results obtained by the Pierre Auger Collaboration in its quest to unveil the mysteries associated with the nature and origin of the ultra-high energy cosmic rays, the highest-energy particles in the Universe. The observatory has steadily produced high-quality data for more than 15 years, which have already led to a number of major breakthroughs in the field contributing to the advance of our understanding of these extremely energetic particles. The interpretation of our measurements so far opens new questions which will be addressed by the on-going upgrade of the Pierre Auger Observatory.

Keywords: astroparticle physics, high-energy cosmic rays, multi-messenger astrophysics, hadronic interactions.

1. Introduction

Over a century after the discovery of cosmic rays, there are still a number of open, fundamental questions about their nature, especially about those with energies above 10^{17} eV, referred to as ultra-high energy cosmic rays (UHECRs). The Pierre Auger Observatory [1], the largest ultra-high energy cosmic-ray detector built so far in the world, was conceived to unveil the most important questions, namely the origin, propagation, and properties of UHECRs, and to study the interactions of these, the most energetic particles observed in Nature. To achieve the scientific goals, the Observatory was designed as an instrument for the detection of air showers initiated by the cosmic rays in Earth's atmosphere. Measured properties of the extensive air showers (EAS) allow determining the energy and arrival direction of each cosmic ray and provide a statistical determination of the distribution of primary masses.

Apart from measuring UHECRs, the Pierre Auger Observatory is a multi-purpose observatory for the extreme energy Universe with multi-messenger observations. In fact, it has shown an excellent sensitivity to EeV neutrino and photon fluxes due to its vast collecting area and its ability to efficiently discriminate between those neutral particles and hadronic cosmic rays. The Auger Observatory also offers a unique window to study particle physics at the high-energy frontier, held by UHECRs, easily reaching centre-of-mass energies ten times larger than the Large Hadron Collider (LHC) at CERN. Observables from the EAS allow improving our understanding of hadronic interactions at the higher energies.

2. The Pierre Auger Observatory

The Auger Observatory is located in a vast, high area near the small town of Malargüe in western Argentina at the latitude of about 35.2° S and the altitude of 1400 m above the sea level. Completed in 2008, it is a hybrid detector that combines an array of particle detectors, the Surface Detector array (SD), to observe the secondary shower particles that reach the ground, and Fluorescence Detector (FD) telescopes to collect the ultraviolet-light emitted by nitrogen air molecules during the shower development in the atmosphere. The SD comprises 1660 water-Cherenkov detectors (WCDs) laid out on a triangular grid with 1500 m spacing, covering an area of about 3000 km^2. Nested within this array is a low-energy extension to the SD which is comprised of 61 identical detectors with half the grid-spacing, 750 m, covering an area of 23.5 km^2. The FD comprises 24 telescopes at four perimeter buildings viewing the atmosphere over the array. A single telescope has a field of view of $30° \times 30°$ with a minimum elevation of 1.5° above the horizon. Three additional telescopes, the High Elevation Auger Telescopes (HEAT), cover an elevation up to 60° to detect the low-energy showers in coincidence with the 750 m array. The hybrid technique developed in the Auger Observatory exploits the large aperture of the SD, operating continuously, as well as the nearly calorimetric measurement of the shower energy deposited in the atmosphere obtained with the FD which, by contrast, has its on-time limited to clear moonless nights ($\sim$13%). Thanks to the combination of the FD and SD measurements, the energy scale of the Observatory is set with the FD measurement with a good control over the associated systematic uncertainties. Given the fact that the atmosphere acts as a calorimeter for the FD, a comprehensive monitoring of the atmosphere, particularly of the aerosol content and the cloud cover, is undertaken accurately with a set of high-quality monitoring devices, as described in [1].

The Observatory setup is complemented by two more detector types. The Auger Muons and Infill for the Ground Array (AMIGA) enhancement consists of coupling WCD and buried scintillation detectors deployed in two superimposed hexagon grids: the 750 m array and an even denser array with a 433 m spacing covering an area of 1.9 km^2. AMIGA provides direct measurements of the muon content in air showers. The Auger Engineering Radio Array (AERA) complements the Auger Observatory with a 17 km^2 array of more than 150 radio-antenna stations, co-located with the 750 m array, that measures EAS with energies between 10^{17} eV and several 10^{18} eV via their radio emission in the 30–80 MHz frequency band. The Auger Observatory layout is shown in Fig. 1.

3. Latest Results

Collecting scientific data since 2004, the results of the Pierre Auger Observatory have dramatically advanced our understanding of UHECRs during the last decade. In this section, a brief review of the recent highlights is given.

3.1. Energy spectrum

The measurement of the cosmic-ray energy spectrum is one of the cornerstones of astroparticle physics, since it encodes the very important information about the mechanisms of CR generation and propagation. The distribution of their sources, propagation effects, transitions over the types of particles, and classes of sources shape the spectrum.

The cosmic-ray energy spectrum above $10^{16.5}$ eV up to its very end above 10^{20} eV has been measured at the Auger Observatory with unprecedented statistics [2]. Five independent and complementary data sets collected between 1 January 2004 and 31 August 2018 have been used, with a total exposure of approximately 80000 km^2 sr yr. The method to derive the spectra is unique in this energy region, because it is entirely data-driven and nearly free of model-dependent assumptions about hadronic interactions in air showers. Two of these data sets have allowed the recent extension of the flux measurement to lower energies. An extension down to $E > 10^{17}$ eV was made possible using the 750 m array, thanks to the implementation of a new algorithm at the

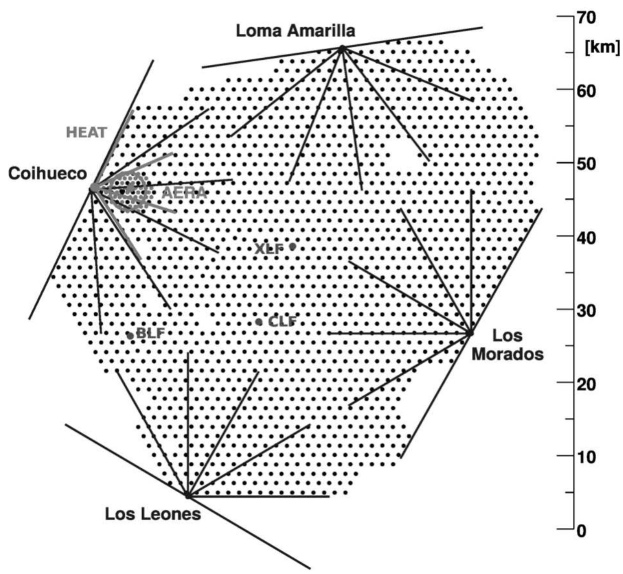

Fig. 1. Layout of the Pierre Auger Observatory. Black dots represent the WCD positions, blue and orange lines show the azimuthal field of views of the fluorescence telescopes. The location of the two laser facilities (CLF and XLF) for the monitoring of the atmospheric conditions are shown with red dots, and the area equipped with radio antennas (AERA) is marked with a light-blue circle

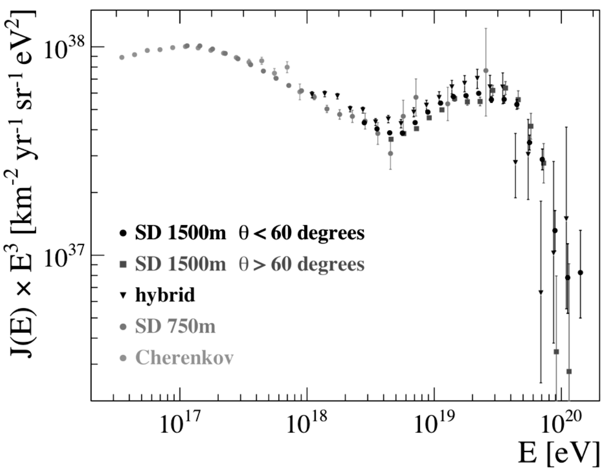

Fig. 2. Energy spectrum of cosmic rays measured using the Pierre Auger Observatory

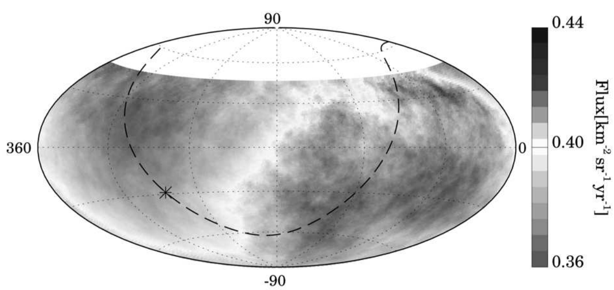

Fig. 3. Map of the CR flux above 8 EeV in equatorial coordinates, averaged on top-hat windows of 45° radius. The location of the Galactic plane is shown with a dashed line, and the Galactic centre is indicated with a star

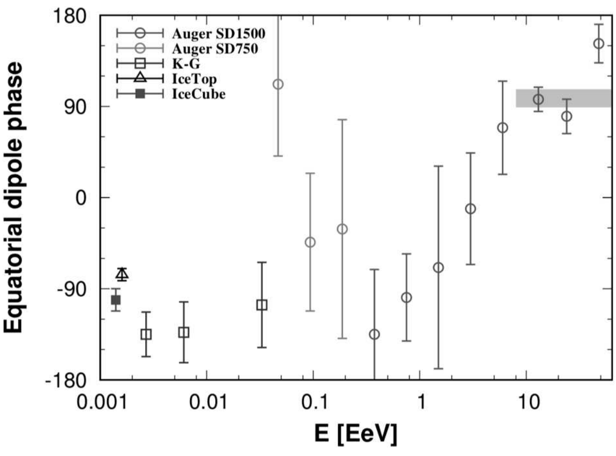

Fig. 4. Phase of the equatorial dipole amplitude determined with Auger Observatory data in different energy bins. Results from other experiments are also shown. Figure taken from [7]

WCD level [3]. This is the highest precision measurement near the region of the so-called *second-knee* or *iron-knee*, where previous experiments have shown a change in the spectral index. In addition, using for the first time events detected by HEAT in which the detected light is dominated by Cherenkov radiation, an extension of the spectrum down to $E > 10^{16.5}$ eV has been achieved [4]. Both new measurements allow studying the spectral features precisely around the *second-knee*. In total, the Auger spectrum spans over three decades in energy as shown in Fig. 2, where three relevant spectral features are observed: the softening in the spectrum at about 10^{17} eV (the *second-knee* region), the hardening at about $5{\times}10^{18}$ eV (the *ankle*), and a strong suppression of the flux at about 50×10^{18} eV.

3.2. Anisotropies

To understand the origin of UHECRs, the study of the distribution of their arrival directions has always been of capital importance, despite the difficulties that arise from the deflection they suffer due to the Galactic and extragalactic magnetic fields. Moreover, given the suggested trend towards a heavier composition with increasing energy that is inferred to happen above few EeV, only at the highest observed energies, the average deflections of CRs from an extragalactic source are expected to be smaller than a few tens of degrees, smearing point sources into *warm/hot* spots in the sky.

The Pierre Auger Collaboration has performed several anisotropy searches by using different techniques at different angular scales and by covering 85% of the celestial sphere. Among the various results, the observation of a large-scale anisotropy in the directions of CRs with energies larger than 8 EeV stands out (post-trial significance of 5.4σ) [5]. As shown in Fig. 3, the direction of the discovered dipole strongly favoured an extragalactic origin for the UHECR sources beyond the *ankle*. A new analysis was performed in [6] by splitting the events with $E > 4$ EeV into four energy bins, finding an indication at the 3.7σ level of growth of the dipolar amplitude with energy, expected from models, and consistent with the extragalactic origin in all bins. An update of this work by extending the study down to energies $\sim$0.03 EeV is presented in [7]. As shown in Fig. 4, the results suggest that the transition from the predominantly Galactic origin to the extragalactic one for the dipolar anisotropy is taking place somewhere between 1 and few EeV.

At higher energies, with more than 15 years of data and with an exposure exceeding 100000 km^2 sr yr, searches for an intrinsic anisotropy at small angular scales at energies exceeding 38 EeV have revealed an interesting possible correlation with nearby starburst galaxies, with a post-trial significance reaching 4.5σ in the most recent update [8]. A slightly weaker association (3.1σ) with active galactic nuclei emitting γ-rays is also found in events above 39 EeV. The region with the most significant flux excess is densely populated with different types of nearby extragalactic objects, with its centre at 2° away from the direction of Cen A, the nearest radio-loud active galaxy, at a distance of less than 4 Mpc.

3.3. Multi-messenger observations

The Pierre Auger Observatory has demonstrated capability to significantly contribute to Multi-messenger Astrophysics (MM) by searching for ultra-high energy (UHE) particles, particularly neutrinos and photons which, being electrically neutral, point back to their origin (see [9] for a recent review).

Given the non-observation of neutrino or photon candidates in data collected up to 31 August 2018, upper bounds on their diffuse fluxes were obtained [10, 11], allowing one to constrain the parameter space of cosmogenic neutrinos and photons. Scenarios assuming sources that accelerate only protons with a strong evolution with redshift are strongly constrained by the Auger Observatory results at more than 90% C.L.

In the MM context, the Auger Observatory can also search for neutrinos with energies above 100 PeV from point-like sources, monitoring a large fraction of the sky (from ∼−80° to ∼+60°) in the equatorial declination with peak sensitivities at declinations around −53° and +55°, unmatched for arrival directions in the northern hemisphere. An excellent sensitivity can also be obtained in the case of transient sources of order an hour or less, if they occur, when the source is in the field of view of the detection channels. The Auger Collaboration has performed several searches for UHE neutrinos following the detections of various types of transient astrophysical sources [12]. These include binary black hole (BBH) mergers, detected via gravitational waves (GWs) by the LIGO Scientific Collaboration and the Virgo Collaboration (LVC) instruments. Follow-up searches for the 21 events reported by LVC as BBH merger candidates till 2 June 2019 have been made, resulting in no candidates found in coincidence with any of them. As a consequence, the upper limit on a universal isotropic UHE neutrino luminosity as a function of the time after the merger was obtained, as shown in Fig. 5. Another source of interest is TXS 0506 + 056, a powerful blazar that was found to emit an energetic neutrino candidate event correlated to a gamma-ray flare, along with a burst of events earlier in the same direction [13]. This blazar is thus the first identified source of neutrinos in the hundreds of TeV range. The Auger Collaboration performed follow-up searches for UHE neutrinos from the direction of TXS 0506 + 056 during the periods of increased emission of high-energy photons and neutrinos, resulting in the non-observation of neutrino candidates. Regarding UHE photons, the search for point-like sources yielded no significant deviations from background expectations for Galactic sources and nearby extragalactic sources, the only targets accessible with photons in the EeV range.

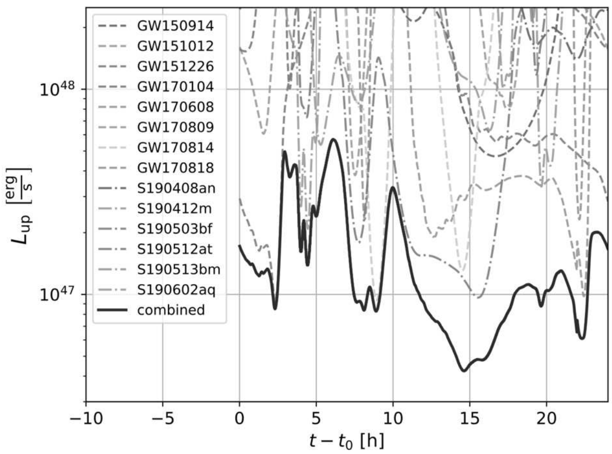

Fig. 5. A 90% C.L upper limit on the time-dependent universal isotropic luminosity (solid line), together with the contributions from the single sources (dashed lines). Sources not indicated here are above the L_{up}-range drawn

The prominent role of the Pierre Auger Observatory as a multi-messenger observatory at the EeV range made it both a triggering and a follow-up partner in the Astrophysical Multi-messenger Observatory Network (AMON) [14], which establishes and distributes alerts for cimmediate follow-up by subscribed observatories.

3.4. Particle Physics at UHE: measurement of the muon content in cosmic-ray showers

In the quest of understanding how particles interact with another ones at energies much higher than those attainable at human-made particle accelerators, the UHECRs entering Earth's atmosphere play a key role in providing such high-energy collisions. The showers analyzed by the Auger Collaboration come from atmospheric cosmic-ray collisions with centre-of-mass energies ten times higher than the collisions produced at the LHC. Using these showers, the Auger Collaboration found, for the first time, an excess in the number of muons that arrive at the ground from cosmic-ray showers in comparison with expectations from models using LHC data as input [15–17]. One of the most direct measurements demonstrating this excess at 10^{19} eV is shown in the top panel of Fig. 6. The level of discrepancy depends on the hadronic model, and only SYBILL 2.3 c predictions are barely compatible with data within systematic uncertainties. The results of the Auger Collaboration are included in a recent meta-analysis of muon measurements in air showers with energies from PeV up to tens of EeV performed by eight air-shower leading experiments [18]. They found the muon measurements seem to be consistent with simulations based on the latest generation of hadronic interaction models up to about 10^{16} eV. Above this energy, most experimental data show a muon excess with respect to model predictions that gradually increases with energy. This result may, therefore, suggest that our understanding of hadronic interactions at the higher energies is incomplete.

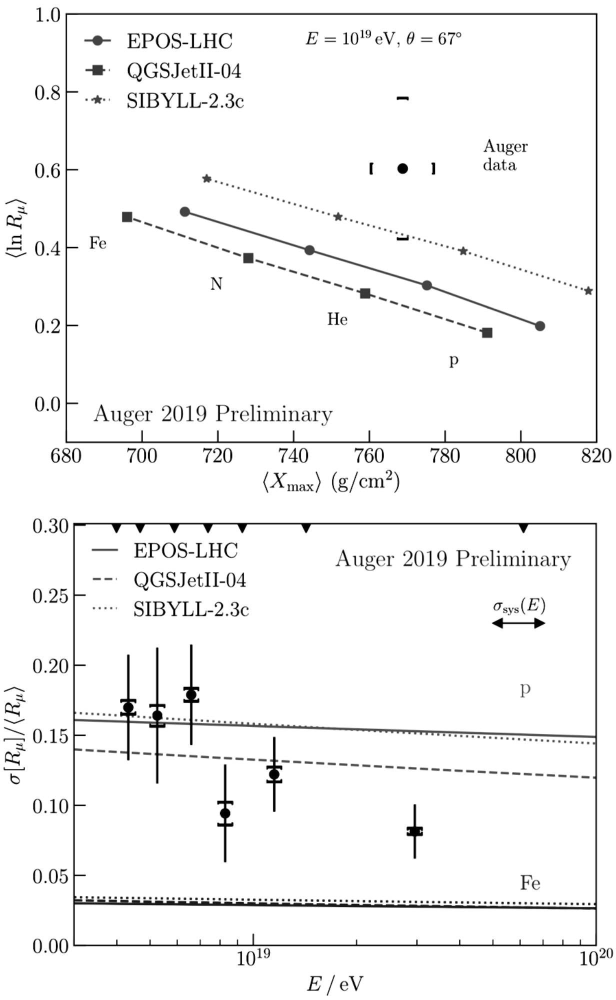

Fig. 6. Top: Average number of muons as a function of the depth of the shower maximum development. Bottom: Shower-to-shower fluctuations in the number of muons as a function of the primary cosmic-ray energy [17]

The measurement of shower-to-shower fluctuations in the number of muons in air showers allows one to constrain the available phase space for exotic explanations of the muon excess. In [17], the Pierre Auger Collaboration presents the first measurement of the fluctuations in the number of muons in inclined air showers with energies above 4×10^{18} eV. As shown in the bottom panel of Fig. 6, the observed fluctuations fall in the range of the predictions from air shower simulations with current models and, in fact, are compatible with the expectation from composition data [19]. As discussed in [17], this result suggests that the first high interaction in the shower is reasonably well described by models in this energy range. The likely explanation for the disagreement in the average value is that a small discrepancy in the particle production exists at all energies, which then is accumulated as the showers develop to create the deficit in the number of muons finally observed at the ground in simulations.

4. AugerPrime, the Observatory Upgrade

Despite a large number of valuable results as those described above, the many unknowns about UHECRs and hadronic interactions prevent the emergence of a uniquely consistent picture that would help us to understand the very complex astrophysical scenario

Fig. 7. Photograph of an upgraded station of the SD, featuring the SSD on top of the WCD

resulting from the Pierre Auger Observatory measurements. The understanding of the nature and the origin of the highest-energy cosmic rays remains an open science case that calls for an upgrade of the Observatory, called AugerPrime [20]. AugerPrime aims for the collection of a new information about the primary mass of the cosmic rays on a shower-by-shower basis from a high statistics sample of UHE events, by discriminating the electromagnetic and muonic components in air showers with SD-based observables.

The main element of the upgrade consists of 3.8 m^2 plastic scintillator detectors (SSD) on the top of each of the 1660 WCDs as illustrated in Fig. 7. The different sensitivity of the two detectors to the electromagnetic and muonic shower components is used to disentangle them. Other key elements of AugerPrime are an additional small photomultiplier (PMT) installed in the WCD for the extension of the dynamic range, and new SD electronics to process signals with higher sampling frequency and enhanced amplitude resolution. The upgrade will also be complemented by extending the FD measurements into the periods of a higher night-sky background, to increase the on-time of the FD about 50%. Finally, based on the AERA results, a new project for adding a radio antenna on the top of each WCD is now on-going [21]. The new detectors will operate together with the WCD+SSD, forming a unique setup to measure the properties of showers above $10^{17.5}$ eV.

The Engineering Array of 12 upgraded stations has been taking data in the field since late 2016. As of July 2019, over 300 SSDs have been deployed, of which 77 are operational, and the production of all the SSDs is nearing its end. The deployment of the AugerPrime should be completed in 2020. Operations and full data-taking are planned at least until 2025.

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І. Валіно

ОБСЕРВАТОРІЯ ПЬЄРА ОЖЕ
ВИВЧАЄ ГРАНИЦІ НАЙВИЩИХ ЕНЕРГІЙ

Р е з ю м е

Ми представляємо основні результати, отримані Колаборацією Pierre Auger, метою яких є пошук загадкових джерел космічних променів надвисоких енергій – частинок з найвищою енергією у Всесвіті. Обсерваторія постійно, вже впродовж 15 років, продукує якісні дані, які привели до низки відкриттів в області фізики частинок надвисоких енергій. Інтерпретація отриманих результатів породжує також нові питання, відповідь на котрі дасть нинішня модернізація (upgrade) Обсерваторії Pierre Auger.

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LATEST RESULTS FROM NEUTRINO OSCILLATION EXPERIMENT DAYA BAY

The Daya Bay Reactor Neutrino Experiment was designed to measure θ_{13}, the smallest mixing angle in the three-neutrino mixing framework, with unprecedented precision. The experiment consists of eight identically designed detectors placed underground at different baselines from three pairs of nuclear reactors in South China. Since Dec. 2011, the experiment has been running stably for more than 7 years, and has collected the largest reactor antineutrino sample to date. Daya Bay greatly improved the precision on θ_{13} and made an independent measurement of the effective mass splitting in the electron antineutrino disappearance channel. Daya Bay also performed a number of other precise measurements such as a high-statistics determination of the absolute reactor antineutrino flux and the spectrum evolution, as well as a search for the sterile neutrino mixing, among others. The most recent results from Daya Bay are discussed in this paper, as well as the current status and future prospects of the experiment.

Keywords: neutrino oscillation, neutrino mixing, reactor, Daya Bay.

1. Daya Bay Neutrino Experiment

The Daya Bay Reactor Neutrino Experiment was designed to measure θ_{13}, the smallest mixing angle in the three-neutrino mixing framework, with unprecedented precision [1]. The experiment profits from a rare constellation of a nuclear power station complex situated near Hong Kong and adjacent mountains. The reactors serve as the source of neutrinos, while the mountains provide a sufficient overburden suppressing cosmic muons – the strongest background source (see Fig. 1). The Daya Bay and Ling Ao nuclear power plant (NPP) reactors (red circles) were situated on a narrow coastal shelf between the Daya Bay coastline and inland mountains.

At the time of the measurement, the facility consisted of six pressurized water reactors (PWRs). The electron antineutrinos are emitted in the beta-decay of fission fragments released in the chain reaction. The antineutrino flux and the energy spectrum is determined by the total thermal power of the reactor, the fraction of each fissile isotope in the fuel, the fission rate of each isotope, and the energy spectrum of neutrinos from each isotope. All the reactors have the same thermal power 2.9 GW_{th} each and all together produced roughly 3.5×10^{21} $\tilde{\nu_e}$/s with energies up to 8 MeV making it one of the most intense $\tilde{\nu_e}$ sources on the Earth.

Two antineutrino detectors installed in each underground experimental hall near to the reactors (Hall 1 and Hall 2) measured the $\tilde{\nu_e}$ flux emitted by the reactors, while four detectors in the far experimental hall (Hall 3) measured a deficit in the $\tilde{\nu_e}$ flux due to oscillations in the location, where the neutrino oscillation effect is expected to be the strongest. Such configuration allows one to suppress the reactor-related uncertainty in the measured neutrino flux. The disappearance signal is most pronounced at the first oscillation minimum. Based on the existing accelerator and atmospheric neutrino oscillation measurements, this corresponded to the distance $L_f \approx 1.6$ km for the reactor $\tilde{\nu_e}$ with a mean energy of 4 MeV. The detectors were built and initially tested in a surface assembly building (SAB), transported to a liquid scintillator hall for the filling, and then installed in an experimental hall.

The detection of antineutrinos is based on the same principle as in the famous experiment of Reines and Cowan [2], who registered reactor antineutrinos in 1956. A sensitive part of the detector consists of a hydrogen-rich liquid scintillator doped with gadolinium (Reines and Cowan used Cd instead as the dopant). Antineutrino interacts via the inverse

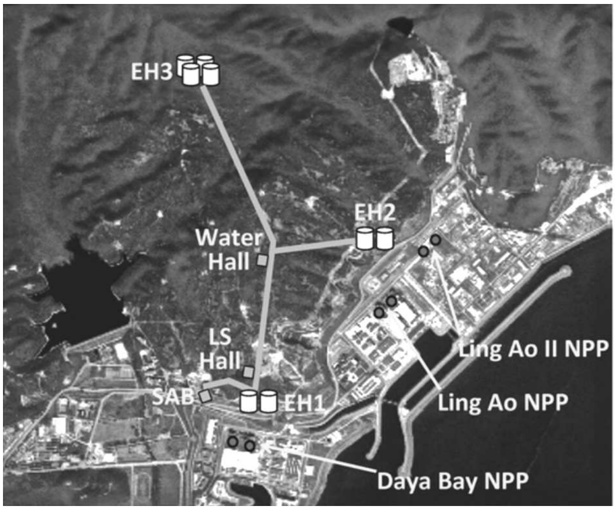

Fig. 1. Layout of the Daya Bay Neutrino Experiment

beta-decay (IBD)

$\tilde{\nu_e} + p \to e^+ + n$

with a proton (hydrogen) giving rise to a neutron and a positron. The positron deposits its kinetic energy to the scintillator, then annihilates on an electron, and generates two gamma rays, each 511 keV which together with the deposited positron kinetic energy cause a "prompt signal" within a few nanoseconds. The neutron is first moderated and then is captured on Gd typically 30 ns after the prompt signal. Consequently, a cascade of gamma quanta with a total energy of 8 MeV is emitted and generates a "delayed signal". The appearance of the two signals "prompt" and "delayed" is a signature of the antineutrino registration.

The Daya Bay antineutrino detector modules have an onion-like structure (see Fig. 2, left). The innermost volume is filled with 20 tons of the Gd-loaded liquid scintillator (GdLS) serving as the antineutrino target. The second layer – the gamma catcher – is filled with additional 20 tons of a normal liquid scintillator (LS) which can register most of the gamma energies from the neutron capture or positron annihilation. Neutrino interactions in the gamma catcher will not satisfy the trigger, since only the signal of the neutron-capture on Gd will trigger a neutrino event. The outer-most layer is normal mineral oil (MO) that shields the radiation from the PMT glass from entering the fiducial volume. The two inner vessels are fabricated of PMMA which is transparent for optical photons and chemically resistant against the used liquids, the outer-most 5 m by 5 m tank is made of a stainless steel and is equipped with 192 8-inch PMTs. Specular reflectors are located above and below the outer PMMA vessel to improve the light collection uniformity, while the vertical wall of the detector is black. Three automated calibration units are used to deploy radioactive sources (^{60}Co, ^{68}Ge, and ^{241}Am-^{13}C) and light-emitting diodes through narrow teflon-bellow penetrations into the GdLS and LS regions.

After the filling, the antineutrino detectors were installed in a 10 m deep water pool in each underground experimental hall, as shown in Fig. 2, right. The water shielded the detectors from γ-rays arising from the natural radioactivity and muon-induced neutrons, which were primarily emanated from the cavern rock walls. The pool was optically separated into two independent regions, the inner (IWS) and outer water shields (OWS). Both regions were instrumented with PMTs to detect the Cherenkov light produced by cosmogenic muons. A 4-layer resistive plate chamber (RPC) system was installed over the pool, which served in studies of muons and muon-induced backgrounds. The identification of muons which passed through the IWS, OWS, and RPC system enhanced the rejection of the background from neutrons generated by muon interactions in the immediate vicinity of the antineutrino detectors. Each detector (ADs, IWS, OWS) operated as an independently triggered system.

2. Results

2.1. Oscillation analysis based on n-Gd [3]

The presented results are from the analysis of data collected in the Daya Bay experiment with 6 detectors in 217 days (Dec/2011–Jul/2012), with 8 detectors in 1524 days (Oct/2012–Dec/2016), and with 7 detectors in 217 days (Jan/2017–Aug/2017). During 1958 days of operation, the Daya Bay experiment collected more than 3.5 millions inverse beta decays in the near halls and more than 0.5 million IBD have been detected in the far hall. The daily rate is $\sim$2500 IBD events in the near halls and $\sim$300 IBD in the far hall.

The distortion of the energy spectrum at the far hall relative to near halls was consistent with oscillations and allowed the measurement of $|\Delta m^2_{ee}|$. The

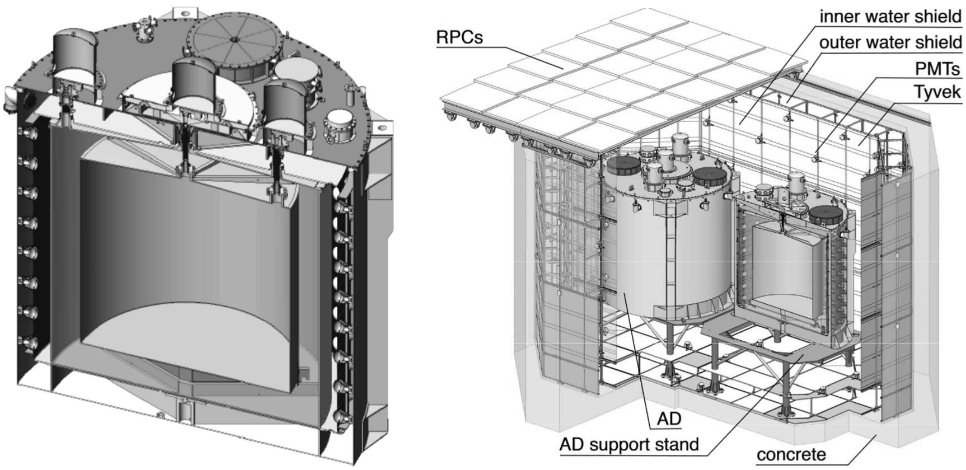

Fig. 2. Scheme of the antineutrino detector (AD) – left, and the near site detection view – right

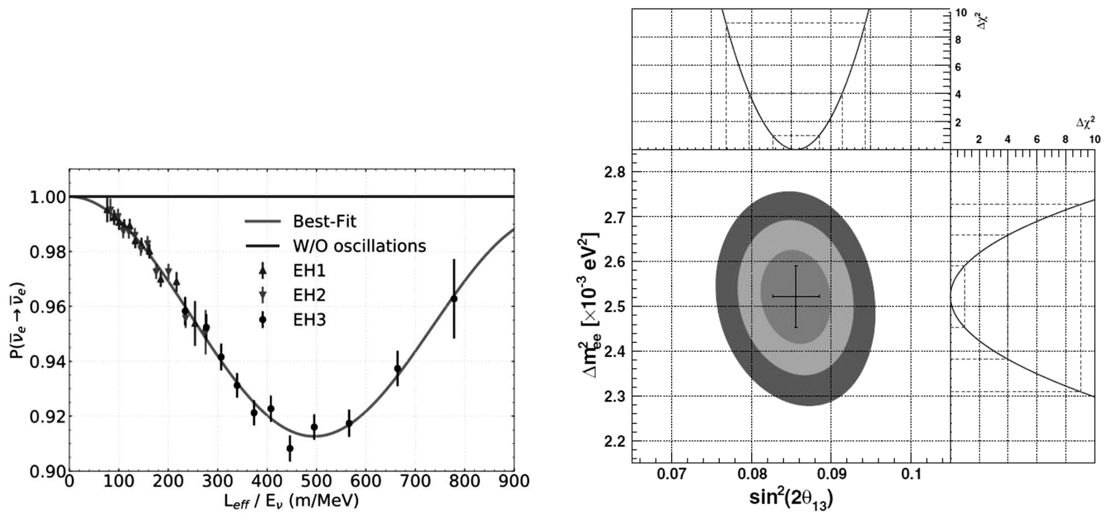

Fig. 3. Oscillation survival probability versus antineutrino proper time – left. The 68.3%, 95.5%, and 99.7% C.L. allowed regions for $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ – right

parameters of the three-flavor model in the best agreement with the observed rate and energy spectra were

$$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029,$$

$$|\Delta m^2_{ee}| = [2.522^{+0.068}_{-0.070}] \times 10^{-3} \ \ \mathrm{eV}^2,$$

$$\Delta m^2_{32}(NH) = +[2.471^{+0.068}_{-0.070}] \times 10^{-3} \ \ \mathrm{eV}^2,$$

$$\Delta m^2_{32}(IH) = -[2.575^{+0.068}_{-0.070}] \times 10^{-3} \ \ \mathrm{eV}^2.$$

The Δm^2_{32} values were obtained under the assumptions of normal (NH) and inverted (IH) mass orderings.

Figure 3 – left, shows the observed electron survival probability as a function of the effective baseline L_{eff} divided by the average antineutrino energy $\langle E_\nu \rangle$. Almost one full oscillation disappearance and reappearance cycle was sampled, given the range of L/E_ν values which were measured.

The confidence intervals for Δm^2_{ee} versus $\sin^2 2\theta_{13}$ are shown in Fig. 3 – right. The 1σ, 2σ, and 3σ 2-D confidence intervals are estimated using $\Delta\chi^2$ values of 2.30 (red), 6.18 (green), and 11.83 (blue) relative to the best fit. The upper panel provides the 1-D $\Delta\chi^2$ for $\sin^2 2\theta_{13}$ obtained by profiling $|\Delta m^2_{ee}|$ (blue line), and the dash lines mark the corresponding 1σ, 2σ,

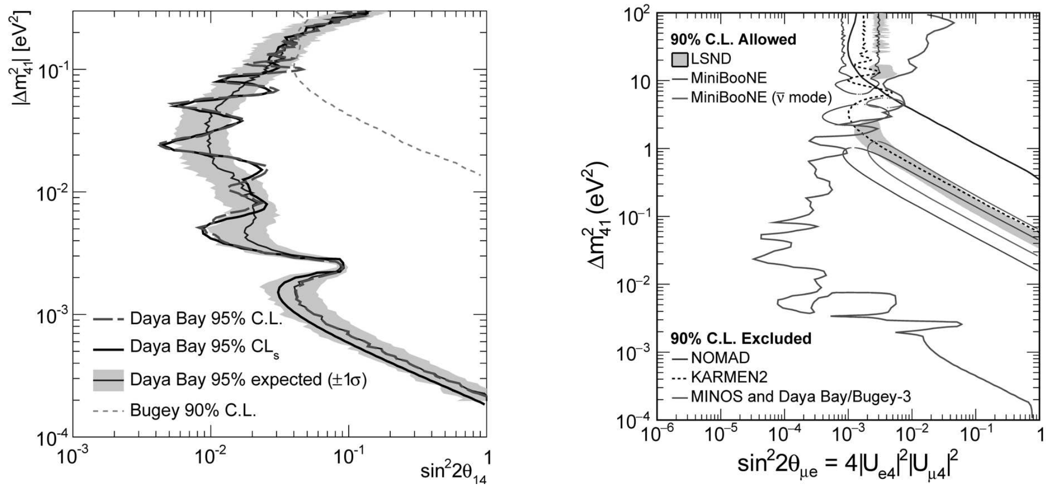

Fig. 4. Constraints for a sterile light neutrino provided by Daya Bay [13] – left, and the combined analysis of data from MINOS and Daya Bay/Bugey-3 [14] – right

and 3σ intervals. The right panel is the same, but for $|\Delta m^2_{ee}|$, with $\sin^2 2\theta_{13}$ profiled. The point marks the best estimates, and the error bars display their 1-D 1σ confidence intervals.

The Daya Bay results are compatible with the $\sin^2 2\theta_{13}$ results provided by other experiments: RENO [4], D-CHOOZ [5], T2K [6], MINOS [7], and $|\Delta m^2_{32}|$ values provided by RENO [4], T2K [6], MINOS [8], NOvA [9], Super-K [10], and IceCube [11]. While the accuracy of determination of $|\Delta m^2_{32}|$ is comparable with T2K and MINOS, the determination of $\sin^2 2\theta_{13}$ is more than twice more accurate than other results.

2.2. Oscillation analysis based on n-H [12]

The alternative analysis of data taken in 621 days and based on the events in which the neutron from IBD is captured on hydrogen results in

$$\sin^2 2\theta_{13} = 0.071 \pm 0.011.$$

The combination of the n-H and n-Gd results from 1230 days data gives the 8% improvement in precision:

$$\sin^2 2\theta_{13} = 0.082 \pm 0.004.$$

2.3. Search for Light Sterile Neutrino

The large statistics collected with the full configuration of eight detectors in the Daya Bay experiment allowed a new precise analysis with aim to search for a light sterile neutrino [13]. A relative comparison of the rate and energy spectrum of reactor antineutrinos in the three experimental halls yields no evidence of the sterile neutrino mixing in the $2 \times 10^{-4} < |\Delta m^2_{41}| < 0.3$ eV^2 mass range. The resulting limits on $\sin^2 2\theta_{14}$ shown in Fig. 4 – left, constitute the most stringent constraints to date in the $|\Delta m^2_{41}| < 0.2$ eV^2 region.

Searches for a light sterile neutrino have been independently performed by the MINOS and Daya Bay experiments using the muon (anti)neutrino and electron antineutrino disappearance channels, respectively. Results from both experiments are combined with those from the Bugey-3 reactor neutrino experiment to constrain oscillations into light sterile neutrinos [14]. The three experiments are sensitive to complementary regions of the parameter space, enabling the combined analysis to probe the regions allowed by the LSND and MiniBooNE experiments in a minimally extended four-neutrino flavor framework. Stringent limits on $\sin^2 2\theta_{\mu e}$ are set over six orders of magnitude in the sterile mass-squared splitting Δm^2_{41}. The sterile-neutrino mixing phase space allowed by the LSND and MiniBooNE experiments is excluded for $\Delta m^2_{41} < 0.8$ eV^2 at 95% CLs, see Fig. 4 – right.

2.4. Reactor antineutrino flux and spectrum anomalies [15]

Data collected in 1230 days were used to measure the IBD yield in four near detectors. The new av-

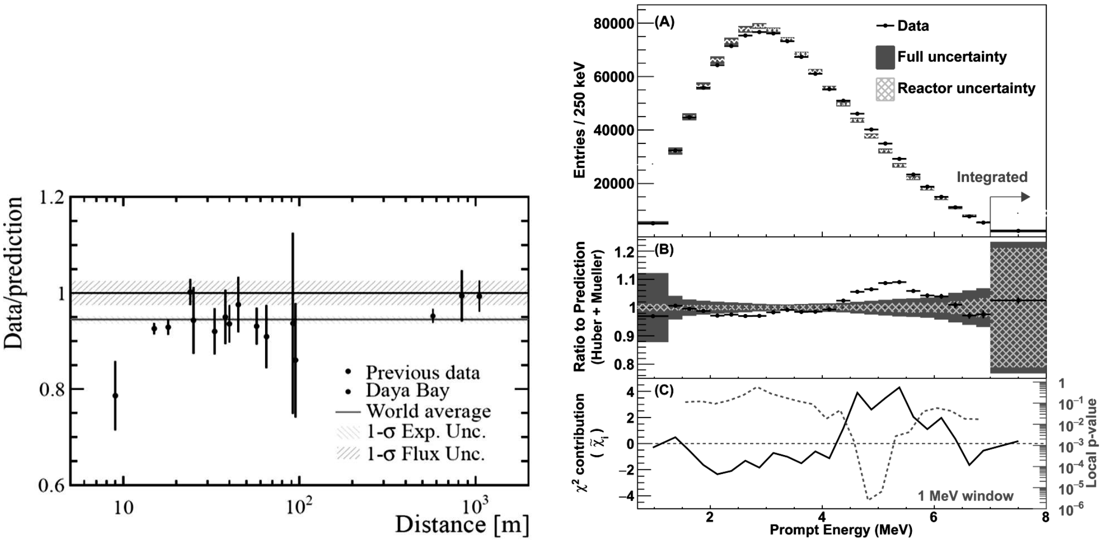

Fig. 5. Ratio of the measured antineutrino yield to the Huber–Vogel theoretical prediction vs. the distance from detector to detector – left. Comparison of the predicted and measured prompt energy spectra – right

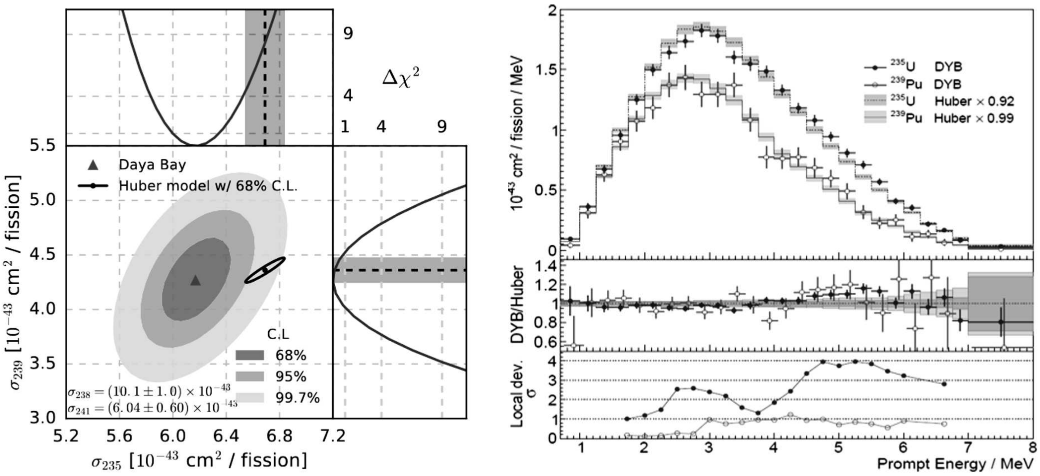

Fig. 6. Combined measurement of ^{235}U and ^{239}Pu IBD yields per fission σ_{235} and σ_{239} – left. Decomposition of the reactor anti-neutrino spectrum into two dominant contributions from ^{235}U and ^{239}Pu

erage IBD yield is determined to be $(5.91 \pm 0.09) \times \times 10^{-43}$ cm^2/fission, and the updated ratio of measured to predicted flux was found to be $0.952 \pm 0.014 \pm 0.023$ and $1.001 \pm 0.015 \pm 0.027$ for the Huber + Mueller and ILL + Vogel models, respectively, where the first and second uncertainties are experimental and theoretical model uncertainties, respectively. The tension with respect to the theoretical predictions is consistent with other experiments, see Fig. 5 – left. In particular, an excess of events in the region of 4–6 MeV was found in the measured spectrum, with a local significance of 4.4σ, see Fig. 5 – right.

2.5. Evolution of the reactor antineutrino flux and spectrum [16]

The data taken by the detectors in two near halls in 1230 days spanning multiple fuel cycles for each of the reactors were used for the investigation of the evolution of the antineutrino flux and spectrum. Weakly effective fission fractions values corresponding to the fission isotopes ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu for each detector were calculated using thermal power and fission fraction data for each core, which were provided by the power plant.

A decrease of the total IBD yield/fission with increase of the effective fission fraction F_{239} of ^{239}Pu (larger fuel burn-up) was clearly observed. Individual yields σ_{235} and σ_{239} from the main flux contributors ^{235}U and ^{239}Pu, respectively, were fitted, see Fig. 6 – left. The discrepancy in a variation of the antineutrino flux from ^{235}U with respect to the reactor fuel composition model prediction suggests a 7.8% overestimation of the predicted antineutrino flux from ^{235}U and indicates that this isotope could be the primary contributor to the reactor antineutrino anomaly.

2.6. Reactor antineutrino spectrum decomposition [17]

The analysis of 3.5 milions of events taken during 1958 days in four near antineutrino detectors allows the partial decomposition of the antineutrino spectra – see Fig. 6 – right. The IBD yields and prompt energy spectra of ^{235}U and ^{239}Pu are obtained using the evolution of the prompt spectrum as a function of the fission fractions. The analysis confirms the discrepancy between the measured spectrum shape and the prediction. The deviation is 5.3σ and 6.3σ in the energy interval 0.7–8 MeV and in a local energy interval of 4–6 MeV, respectively.

The comparison of the measured and predicted ^{235}U and ^{239}Pu IBD yields preferes an incorrect prediction of the ^{235}U flux as the primary source of the reactor antineutrino rate anomaly. The discrepancy in the spectral shape for ^{235}U suggests the incorrect spectral shape prediction for the ^{235}U spectrum. However, no such conclusion can be drawn for the ^{239}Pu spectrum due to a larger uncertainty.

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НОВІТНІ РЕЗУЛЬТАТИ
З ЕКСПЕРИМЕНТУ НЕЙТРИННИХ
ОСЦИЛЯЦІЙ DAYA BAY

Р е з ю м е

Експеримент з реакторними нейтрино DAYA BAY задумано для вимірювання Θ_{13} – найменшого кута в рамках тринейтринного змішування – з безпрецедентною точністю. Експериментальна система складається з восьми однакових детекторів, розміщених під землею на різних базових відстанях від трьох пар ядерних реакторів Південного Китаю. Починаючи від 2011 року, експериментальна система працює стабільно впродовж більш ніж 7 років та накопичила найбільше як на сьогодні даних про реакторні антинейтрино. DAYA BAY значно покращив точність Θ_{13} і виконав незалежні вимірювання ефективного розщеплення мас в каналі зникнення електронного нейтрино. DAYA BAY провів також інші точні експерименти, такі як вимірювання з високою точністю абсолютного потоку реакторних нейтрино і їхнього спектра, а також пошук змішування стерильних нейтрино. В даній роботі обговорюються новітні результати з DAYA BAY, а також сучасний стан та перспективи експерименту.

AUTHOR'S INDEX

Amati L., No. 7, 548
Aushev V., No. 7, 543
Ayala A., No. 8, 665

Babiarz I., No. 8, 750
Berezovskiy O.D., No. 8, 732
Bluhm M., No. 8, 766
Bozzo E., No. 7, 548

Catto S., No. 8, 672
Cavan E., No. 8, 683
Chudak N.O., No. 8, 732
Chwastowski J.J., No. 7, 554
Cieśla K., No. 7, 554
Cisek A., No. 8, 750

Dittert D., No. 7, 560

Fadin V.S., No. 8, 678
Fionda F., No. 7, 566
Fraenkle F.M., No. 7, 573

Götz D., No. 7, 548
Gürcan Y., No. 8, 672
Gkigkitzis I., No. 8, 683
Gorenstein M.I., No. 8, 745
Gorkavenko V.M., No. 8, 689
Gornushkin Yu., No. 7, 577

Harabasz S., No. 7, 583
Haranas I., No. 8, 683
Hentschinski M., No. 8, 665
Hernández L.A., No. 8, 665
Horváth D., No. 7, 589

Khalfan A., No. 8, 672
Kovalenko O., No. 7, 602
Kundrát V., No. 8, 725
Kurt L., No. 8, 672

Lebiedowicz P., No. 8, 695
Loewe M., No. 8, 665
Lokajíček M.V., No. 8, 725
Lukashevich S.A., No. 8, 702
Lymanets A., No. 7, 607

Machado M.V.T., No. 8, 705
Maksimenko N.V., No. 8, 702
Merkotan K.K., No. 8, 732
Minaiev P., No. 8, 710
Mishustin I.N., No. 8, 745
Motornenko A., No. 8, 745

Nachtmann O., No. 8, 695
Nicolescu B., No. 8, 672
Nosek T., No. 7, 613

Obikhod T.V., No. 8, 714
O'Brien P., No. 7, 548
Opyatyuk V.V., No. 8, 732

Petrenko I.A., No. 8, 714
Petronilo G.X.A., No. 8, 719
Potiienko O.S., No. 8, 732
Procházka J., No. 8, 725
Ptashynskiy D.A., No. 8, 732
Pugatch V., No. 7, 619

Redlich K., No. 8, 766
Rostomyan T.A., No. 7, 624
Rusov V.D., No. 8, 732
Rybczyński M., No. 8, 738
Rymbekova A., No. 7, 631

Santana A.E., No. 8, 719
Sasaki Ch., No. 8, 766
Satarov L.M., No. 8, 745
Schäfer W., No. 8, 750
Schever M., No. 7, 635
Schmidt M., No. 7, 640
Sharph I.V., No. 8, 732
Skalozub V., No. 8, 710, 754
Staszewski R., No. 7, 554
Stoecker H., No. 8, 745
Svintozelskyi V., No. 8, 760
Szanyi I., No. 8, 760
Szczurek A., No. 8, 695, 750
Szymański M., No. 8, 766

Trzebiński M., No. 8, 772

Ulhoa S.C., No. 8, 719

Valiño I., No. 7, 646
Van Hulse C., No. 7, 595
Voitenko V.V., No. 8, 732
Vorobel V., No. 7, 653
Vovchenko V., No. 8, 745

Włodarczyk Z., No. 8, 738
Wilk G., No. 8, 738

Yu E., No. 8, 672
Yushkevich T.V., No. 8, 732

Zamora R., No. 8, 665
Zelentsova T.M., No. 8, 732
Zharova O.V., No. 8, 732