Heavy-ion and fixed-target physics in LHCb

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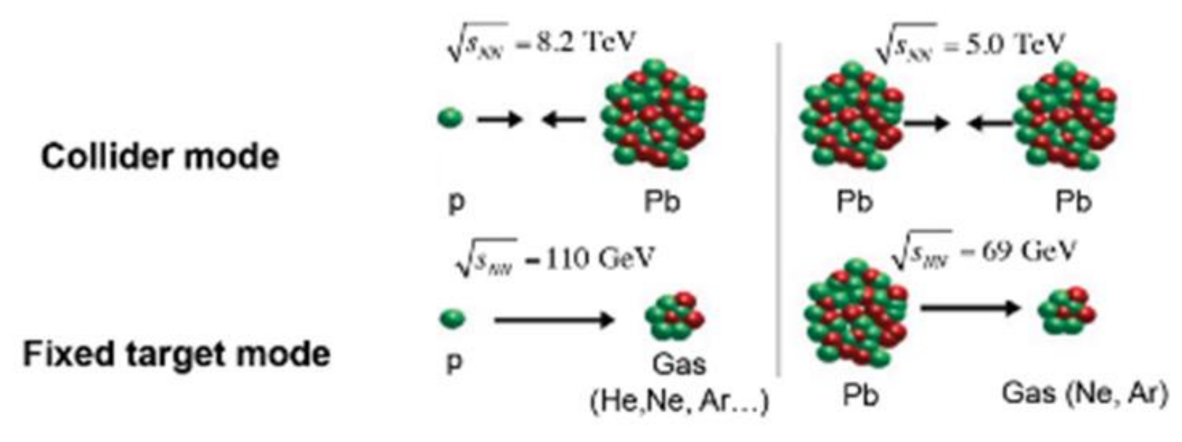
on behaf of the LHCb Collaboration

Outline

- **Introduction**
- **Heavy Ions in LHCb experiment:**
  - ➢ **Physics goals**
  - ➢ **Technical capabilities**
    - ➢ **Detector to study QCD phase space**
    - ➢ **Collider and Fixed target modes at the LHCb**
  - ➢ **Selected physics results**
- **Summary and Outlook**



INTRODUCTION

2. LHCb in Heavy Ion collisions

Perfect performance of the LHCb detector observed in p-p collisions studies allowed to start its exploration in heavy ion sector since the year 2013:

- **proton-lead ($\sqrt{s_{NN}}$ = 5 and 8 TeV):**
- **lead-lead, Xe-Xe ($\sqrt{s_{NN}}$ = 5 TeV)**
- **proton and lead ions at fixed targets Ar, He, Ne, at energies of $\sqrt{s_{NN}}$ ~ 0.1 TeV**

Synergy - from SPS to LHC physics within a single experiment

- ➢ **production cross-sections, forward –backward asymmetries, nuclear modification factors:**
  - ❖ **Observables - D_0 , J/Ψ, ψ(2S), Υ(nS), anti-protons, B-mesons, ...**

Physics-

- **EOS - hadronic matter at high densities and temperatures (QGP - ?)**
- **Nucleon and nuclear PDFs**
- **Dynamics of multi-nucleon interaction, hadronisation**
- **QED at high em field strengths**
- **...**

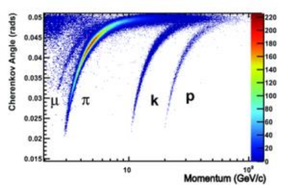
The LHCb experiment

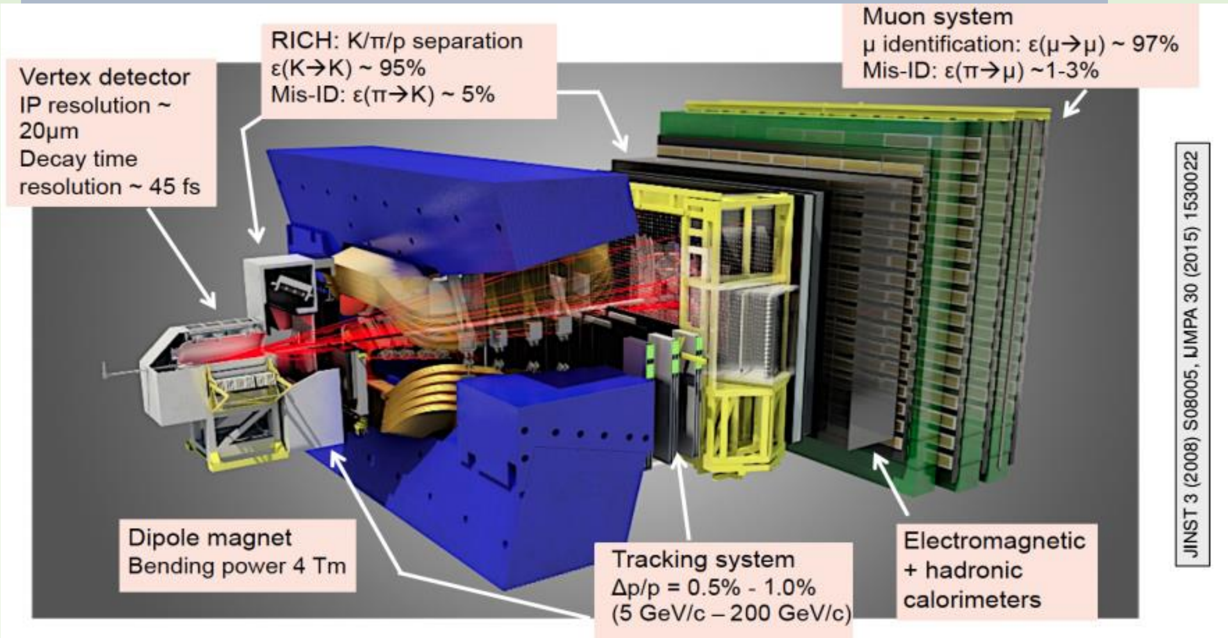
LHCb: The Large Hadron Collider Beauty Experiment for Precise Measurements of CP-Violation and Rare Decays

The LHCb detector – forward spectrometer with excellent characterisitics

- Acceptance $2 < \eta < 5$ & HERSCHEL $8 < |\eta| < 10$
- Momentum resolution about 0.5 %
- Track reconstruction efficiency > 96 % (pp-collisions)
- Impact parameter resolution: ~ 20 µm
- Decay time resolution: ~45 fs
- Invariant mass resolution: ~(10-20) MeV/c^2
- Ring-Imaging Cherenkov Detectors and Muon system - particle identification

  (Perfect ID efficiency)





The only LHC experiment fully instrumented at large η ($2<\eta<5$)

Techniques

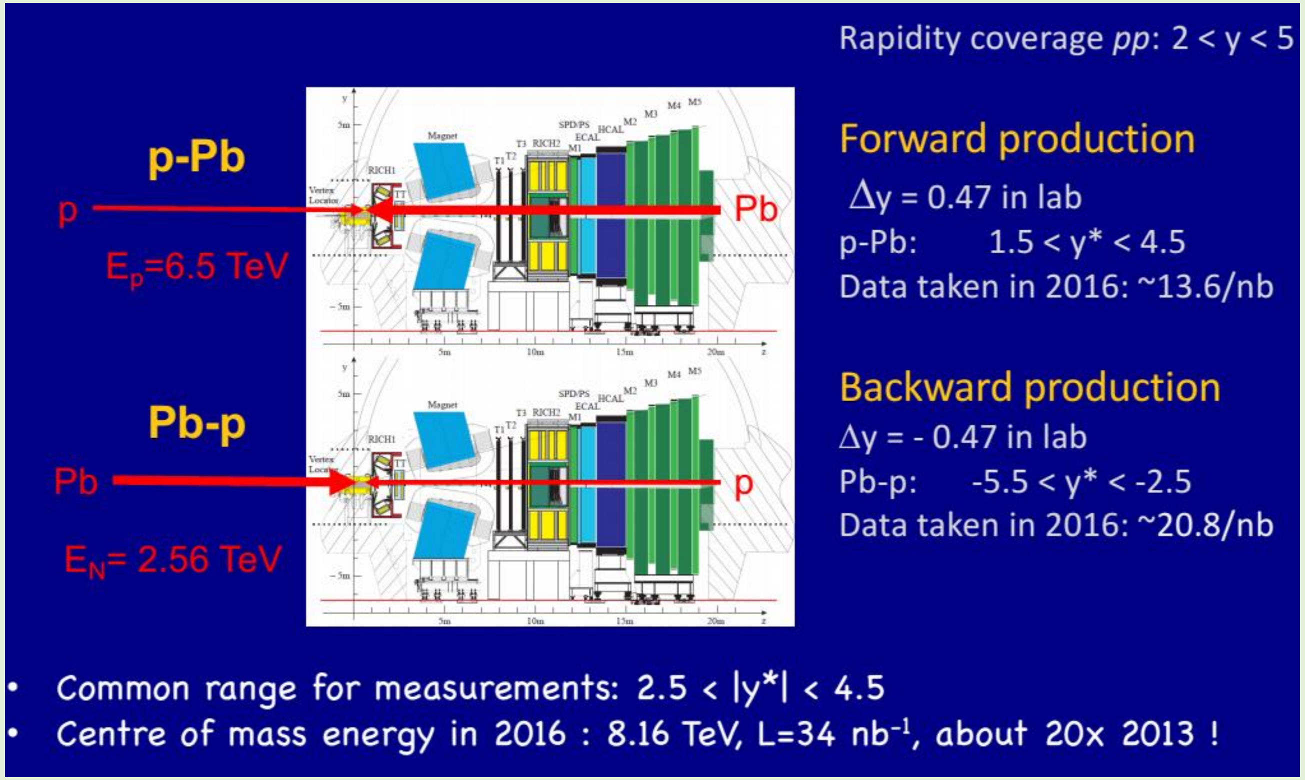
- ➢Detector for physics events reconstruction in search for the QGP
- ➢**Fixed target regime at the LHCb**

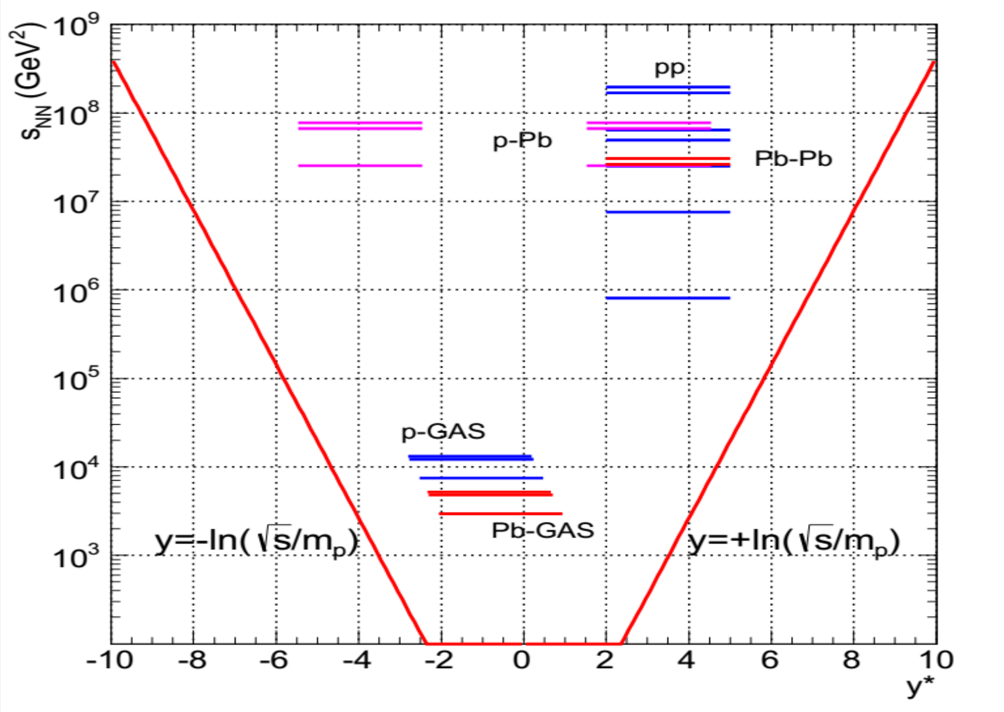
SMOG

Noble gas only
(very low chemical reactivity)

	He	Ne	Ar
A =	4	20	40

Forward-Backward Hadron Production in heavy ions collisions at LHCb.





The LHCb Acceptance

Giulia Manca, Bormio-2019

Measurement of hadrons production at FWD & BWD rapidity

- probes two x_B values: $x_{1,2} \approx e^{\pm y^*} \frac{M}{\sqrt{s}}$

$$x \simeq \frac{m_{J/\psi} e^{-y}}{\sqrt{s}}$$

With LHCb acceptance at 13 TeV pp collision, x down to 10^{-6}

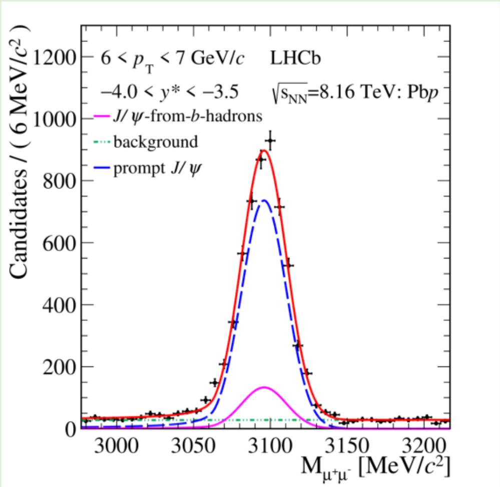
PbPb collision at 5 TeV, x>5•10^{-6}

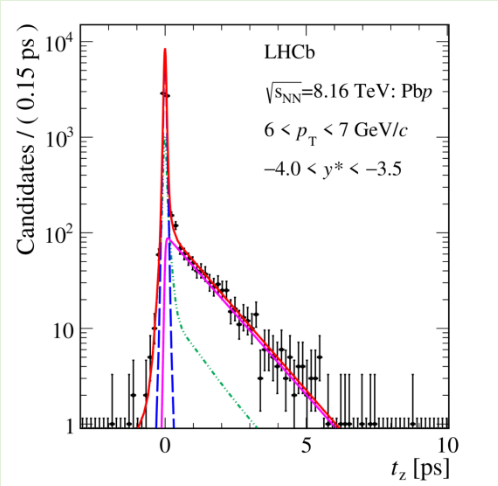
Selected LHCb results
Collider mode. p-A.

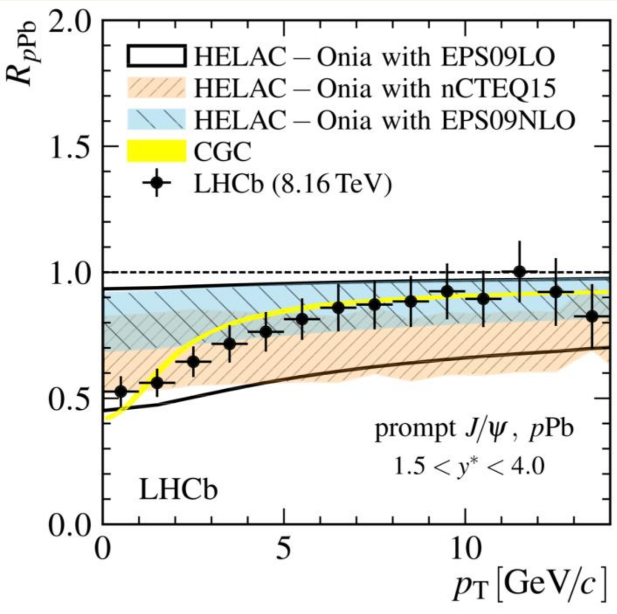
J/ψ production in p-Pb collisions at 8.16 TeV

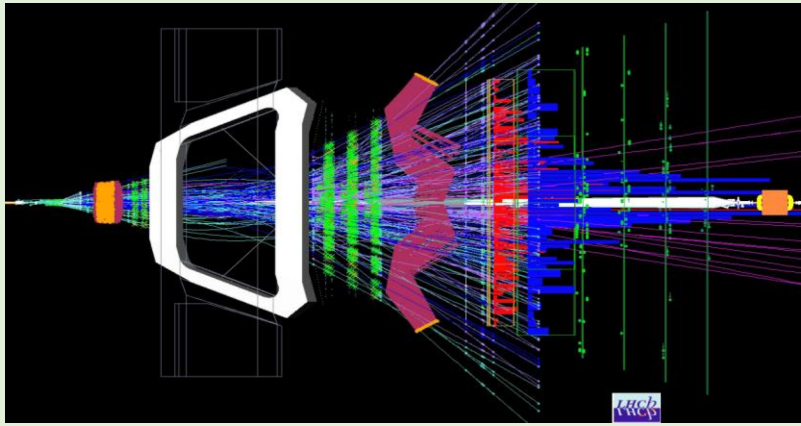
LHCb has **powerful vertexing tool (few tens fs in time) for separation prompt and delayed events)**

LHCb-PAPER-2017-014,PLB 774 (2017) 159.









Middle figure illustrates
Principle of separation:

- **'Prompt'** – from primary vertices
- **'non-prompt'-** from b-hadron decays

Nuclear Modification Factor

$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) \equiv \frac{1}{A}\frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*},$$

Observations: **Prompt production- strong suppression in p_T distribution at forward rapidity**.

Theories: nuclear PDFs EPJC77 (2017) 1 & Color Glass Condensate calculations;
PRD91(2015) no.11, 114005 accounting for observations coherent energy-loss ;
JHEP 1303 (2013) 122 accounting for rapidity dependence

Results constrain nPDFs in unexplored area at low-x,
PRL 121,052004(2018)

Heavy ions collisions:.
Selected LHCb results
Collider mode. p-A.

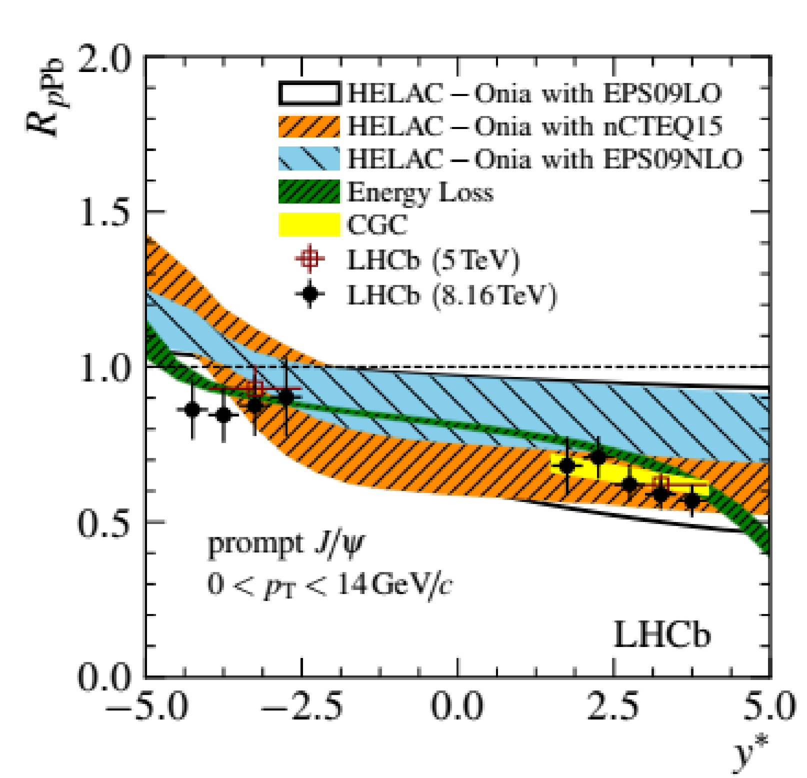
J/Ψ production in proton-lead @ 5 and 8.16 TeV

Comparison of ‘prompt’ – ‘non-prompt’ results:

Established significant difference in the FWD rapidity.

PLB 774 (2017) 159-178

Nuclear modification factor - prompt J/Ψ



Remarkable difference
For two cases!

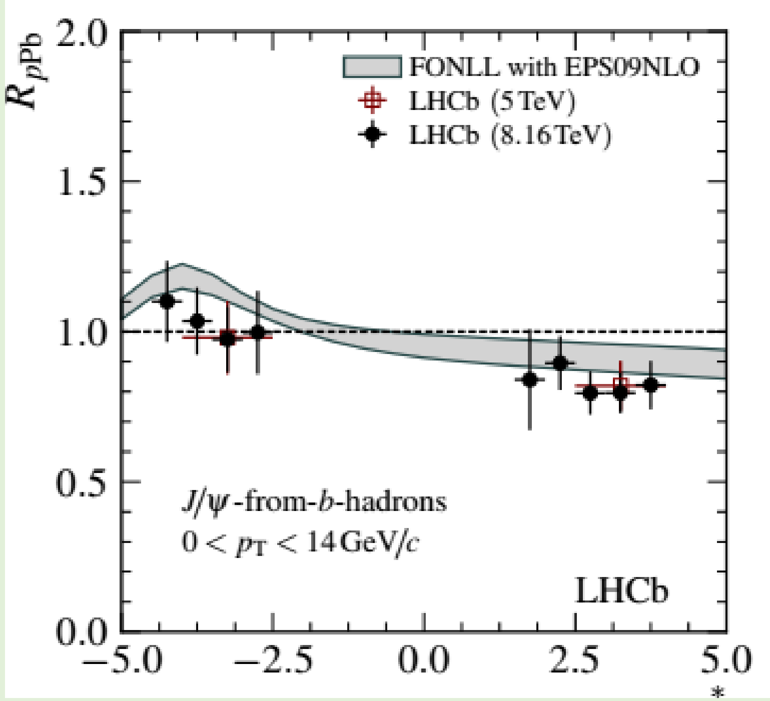
Illustration of the hot environment impact
or ‘cold’ nuclear matter effect ?

Theories:

- ‘prompt’ described by NLO nPDFs plus energy loss effects

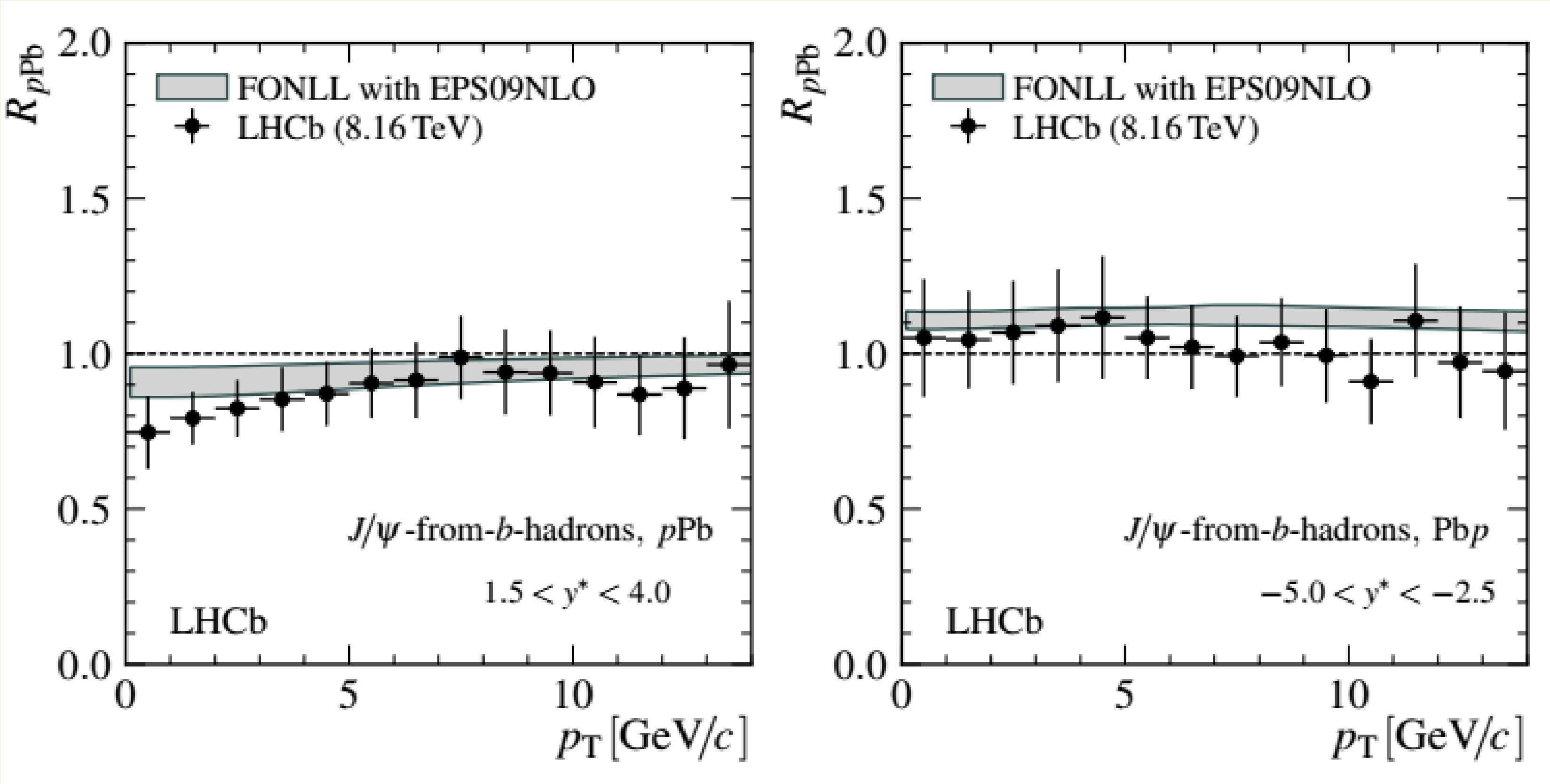
- ‘non – prompt ‘ described by effects of NLO nPDFs

Nuclear modification factor – J/Ψ from b



Consistent results for data at 5 and 8.16 TeV

Non-prompt J/ψ production in pPb collisions at 8.16 TeV (continue)



Suppression at forward rapidity, yet less than for ‘prompt’ J/ψ

first precise b-production measurement in pPb at low p_T

input for Pb-Pb phenomenology

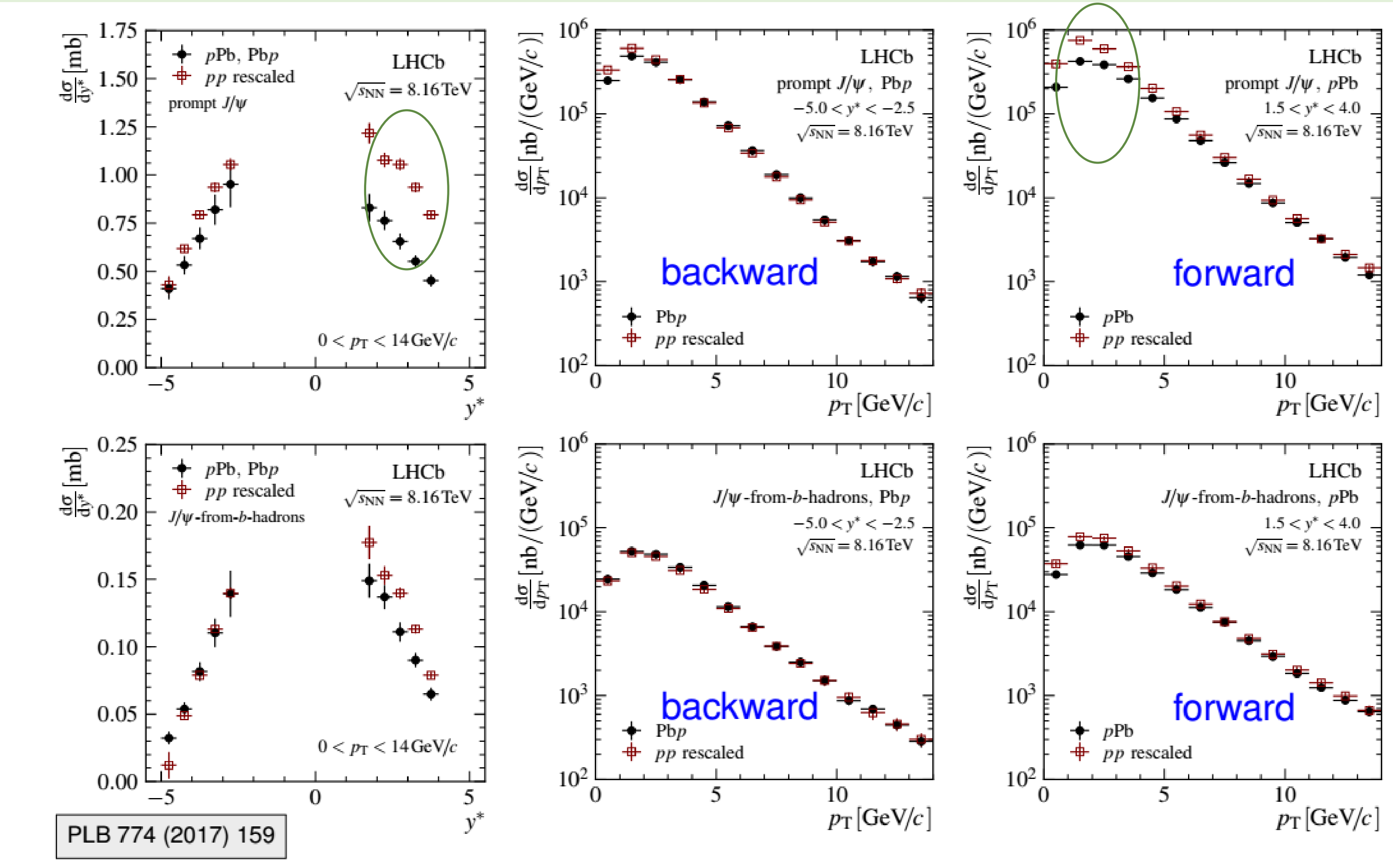
Constraining nPDFs at low-x, (PRL 121, 052004 (2018)

J/ψ from b-hadrons decays are approximated by effects of NLO nPDFs

J/Ψ production in proton-lead @ 8.16TeV (continue)

Comparison of 'prompt' – 'non-prompt' results wrt to p-p data:

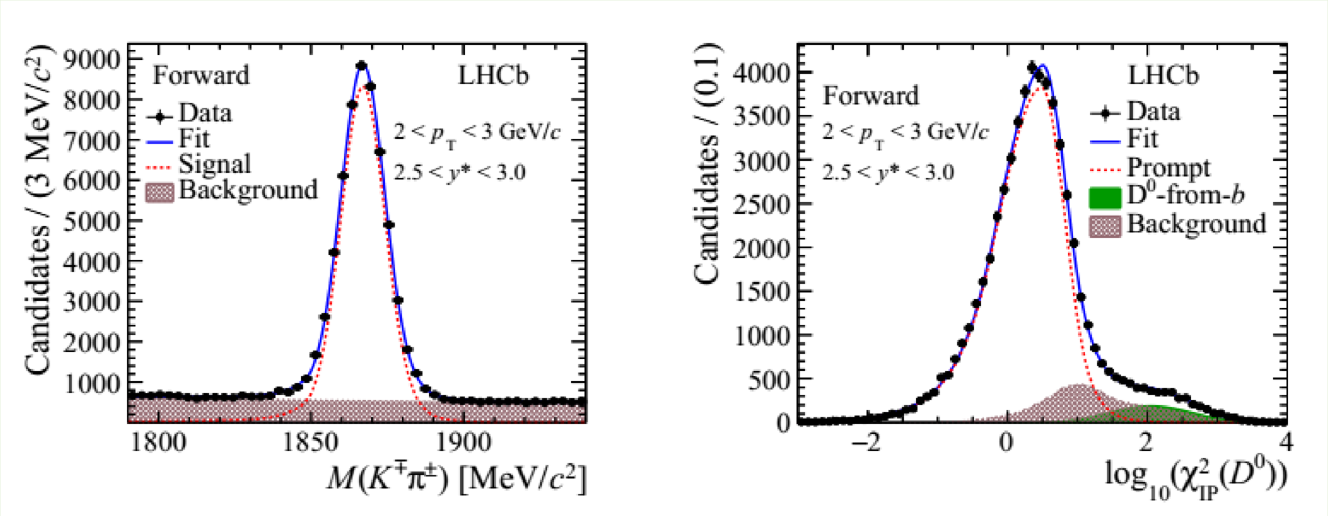
Established significant difference in the FWD rapidity



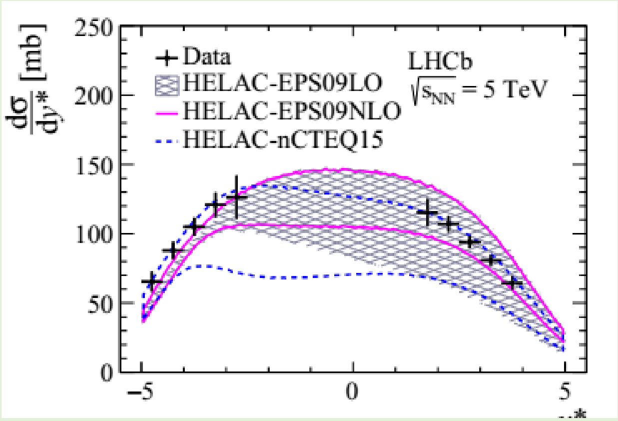
prompt J/ψ compared to $208 \times \sigma_{pp}$ (red)

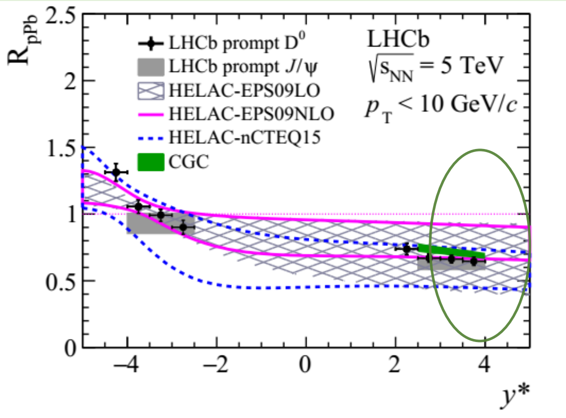
delayed J/ψ compared to $208 \times \sigma_{pp}$ (red)

D^0 production in pPb collisions at 5 TeV



The (left) $M(K^\mp\pi^\pm)$ and (right) $\log_{10}(\chi^2_{IP}(D^0))$ distributions and the fit result for the inclusive D^0 mesons in the forward data sample in the kinematic range of $2 < p\mathrm{T} < 3$ GeV/c and $2.5 < y* < 3.0$.





JHEP 10 (2017) 090

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Observations:

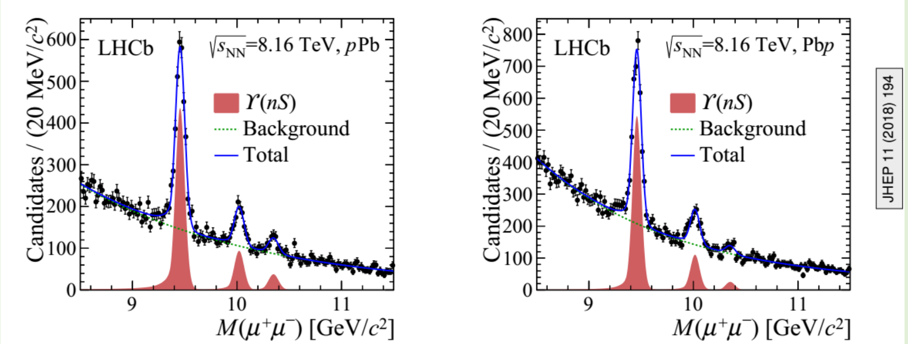
Strong suppression in the forward Rapidity(right bottom figure).
(Similar to **J/Ψ** results (previous slides)

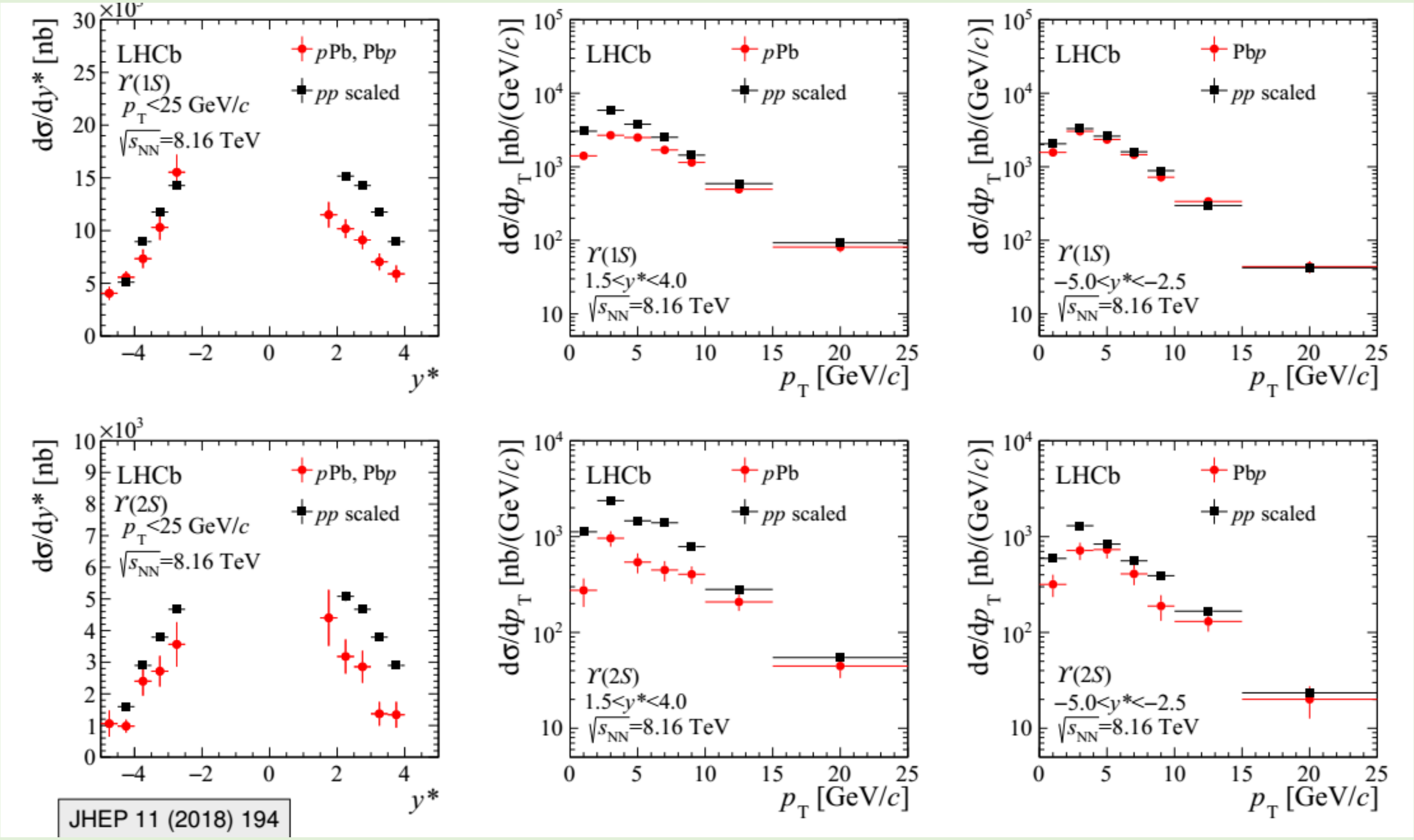
Theoretical description:

Nuclear PDFs & Color Glass Condensate calculations agree with observations (large theoretical uncertainties)

-> Contribution to constraining nPDFs at low-Bjorken *x*
(PRL 121, 052004 (2018))

ϒ-meson production in proton-lead @ 8.16TeV

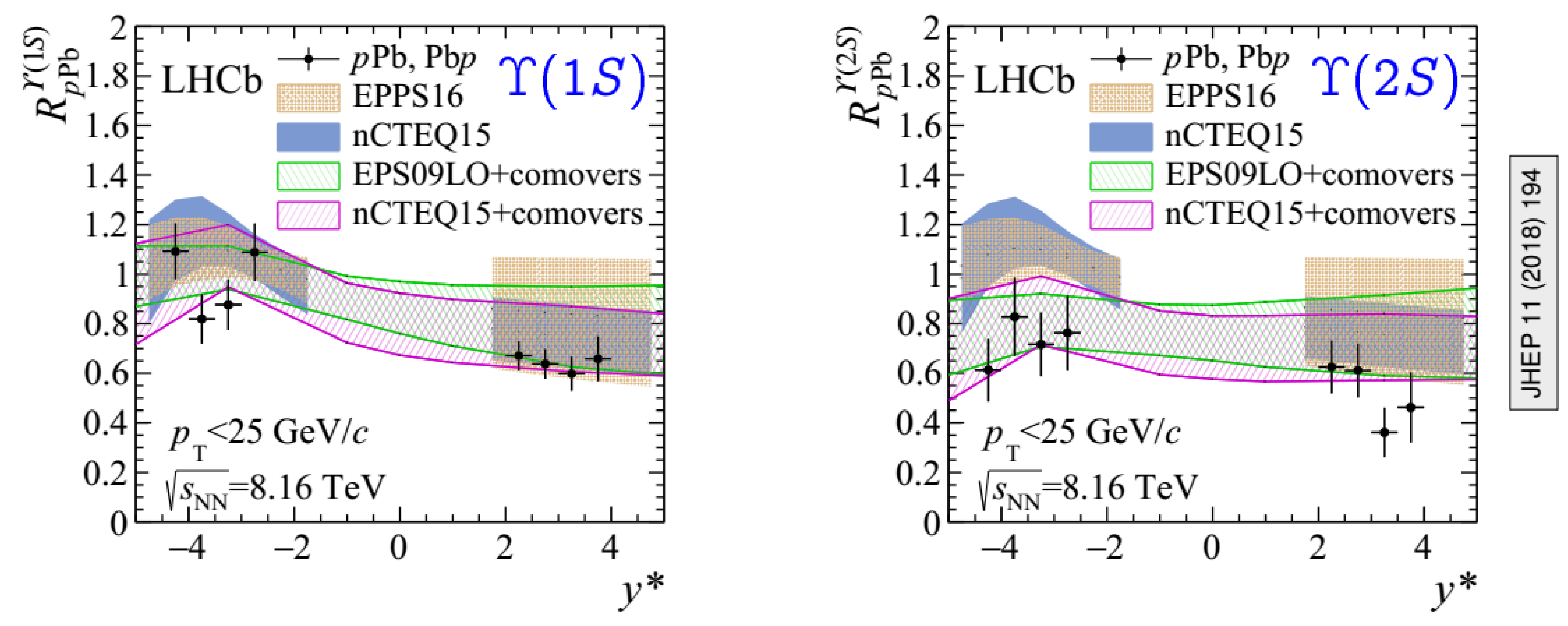




Observed:

Suppression of
2S- 3S- ϒ states
in forward hemisphere.
2S and 3S stronger suppression
Compared to 1S.

ϒ-meson production in proton-lead @ 8.16TeV/
Nuclear Modification Factors (NMF)



JHEP 11 (2018) 194

Results:

- **Strong suppression at forward rapidity.**
- **NMF for ϒ(1*S*) within theory and experiment uncertainties explained by nPDFs Comover-effects in the data for ϒ(2*S*) -?**

LHCb Internal Gas Target (SMOG)

JINST 9 (2014) P12005

Initial purpose for injection of noble gas in the VELO tank:

luminosity measurement from reconstructed vertices originated by

proton beam-gas nuclei interactions (1.2% precision !)

Since Run 2- internal gas target (SMOG):

Targets: **He, Ne or Ar with unique coverage of the high-x regime in the target nucleon.**

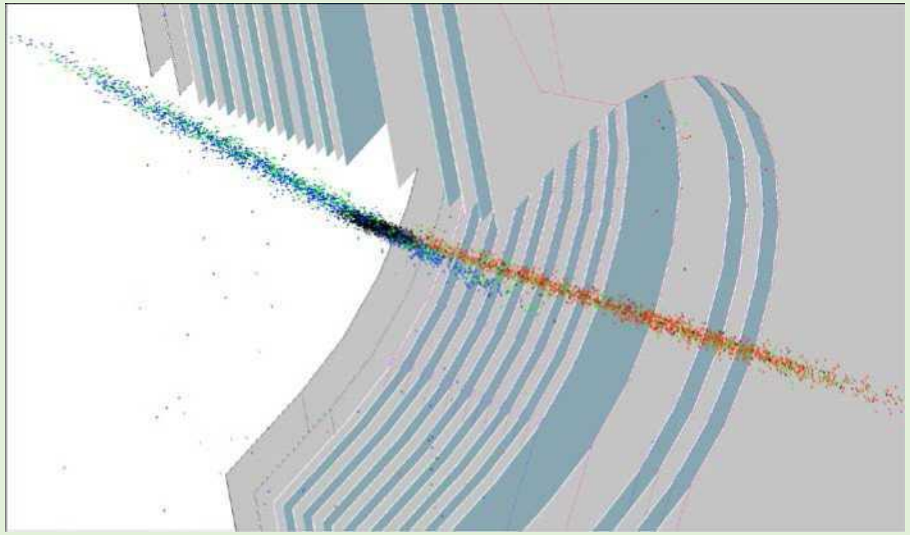
Collisions **at an energy scale of $\sqrt{s_{NN}} \sim 100$ GeV .**

Run 2 data allow for:

- studies particle production in the soft QCD regime, of particular relevance to cosmic ray physics

- collection samples of charmed mesons

- **to discriminate cold nuclear matter effects from the effect of deconfinment,**
- **to study nuclear PDFs at large x.**



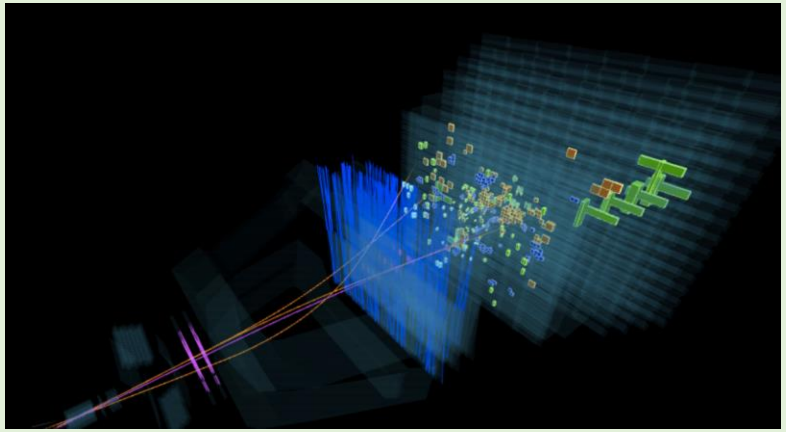
p + He->anti-p + X @ $\sqrt{s_{NN}} = 110$ GeV,
an input for cosmic rays physics

Phys. Rev. Lett. 121 (2018), 222001

J/ψ and D^0 production cross-sections in p-He @ $\sqrt{s_{NN}} = 86.6$ GeV and p-Ar @ $\sqrt{s_{NN}} = 110$ GeV

Phys. Rev. Lett. 122, 132002 (2019)

Fixed target regime at the LHCb

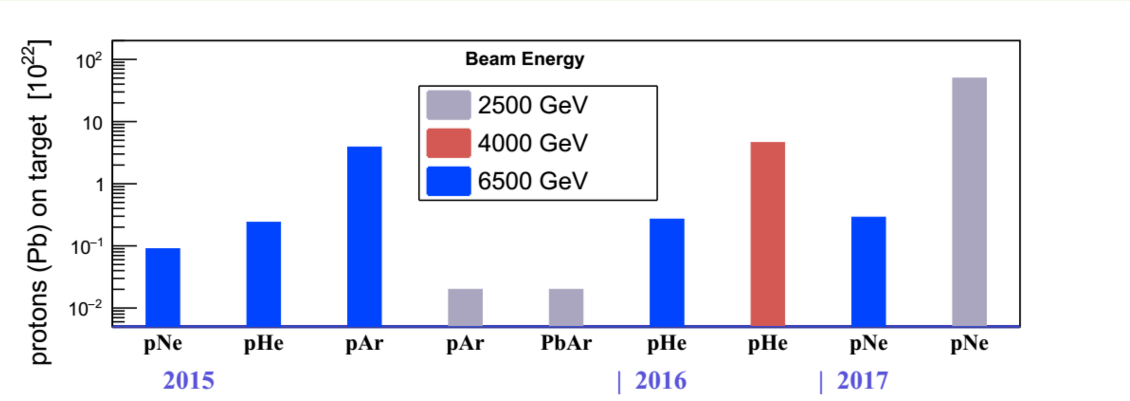


Fixed Target regime extends the LHCb physics programme.

QCD phase diagram may have interesting features observable at scattering TeV beams on fixed target.

For instance: J/ψ, and $\psi(2S)$ modification of cross-sections due to hard production and suppression by hadronic dissociation in QGP.

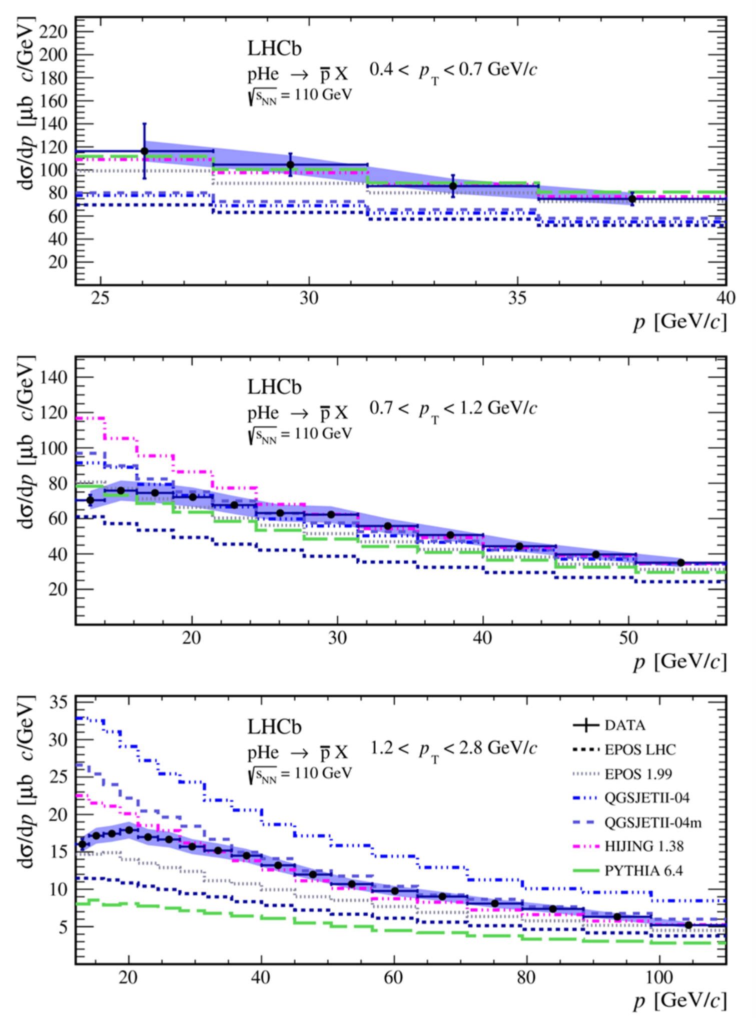
➢



Internal Gas-Target SMOG.
Acquired SMOG (see next slide) data sample sizes, given in terms of proton (or Pb) on target. The unit of 10^{22} corresponds to about 5/nb per 1 m of gas, at the nominal SMOG pressure.

Heavy ions collisions:.
Selected LHCb results
Fixed Target mode.

Prompt anti-p production in *p*He collisions @ $\sqrt{s_{NN}}$ = 110 GeV



Antiproton production cross-section as a function of momentum, integrated over various p_T regions.

► uncertainties **smaller than model spread**

differ by hadronisation & parton model+dynamics

► **EPOS LHC** tuned on LHC collider data **underestimates** *anti-p* production

► *LHCb EPOS /LHC*

= 1.08 ± *0.07(lumi)* ± *0.03*

► **unique and precise**

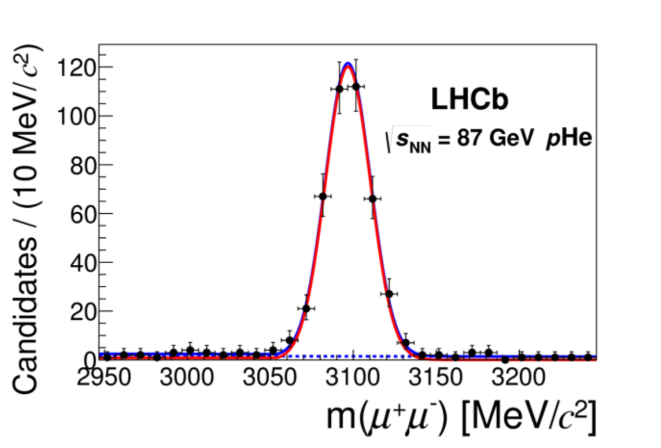
decisive contribution to shrink background uncertainties in dark matter searches in space

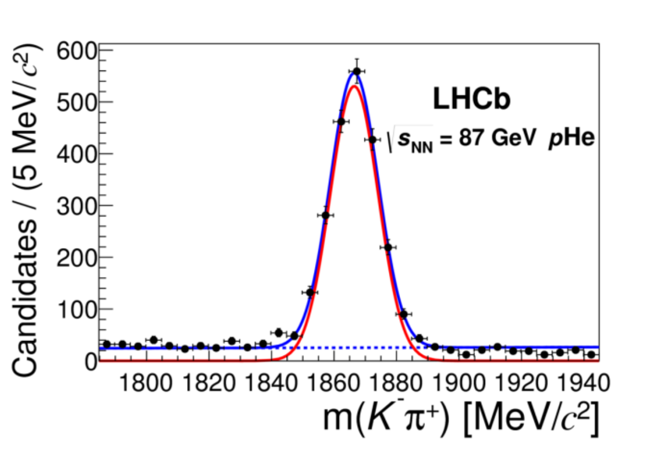
PRL 121 (2018) 222001

Heavy ions collisions:.
Selected LHCb results
Fixed Target mode.

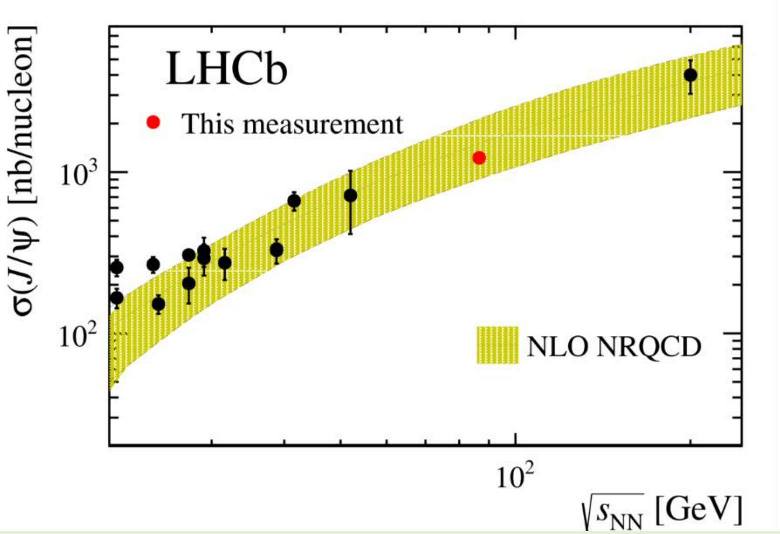
Production cross-sections

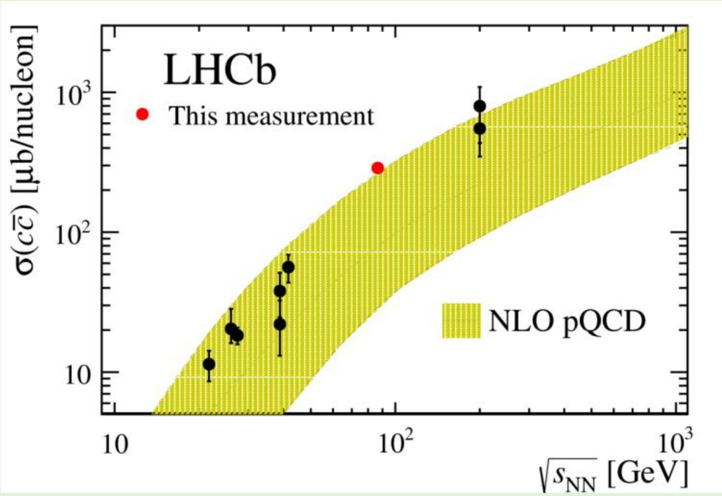
J/ψ, D^0 in pHe @ $\sqrt{s_{NN}}$ = 86.6 GeV
J/ψ, D^0 in pAr @ $\sqrt{s_{NN}}$ = 110 GeV





LHCb-PAPER-2018-022





Energy region between 20 GeV (SPS) and 200 GeV (RHIC)

Access nPDF anti-shadowing region and intrinsic charm content in the nucleon

Heavy ions collisions:.
LHCb Upgrade
Fixed Target mode.

The LHCb collaboration is presently considering several proposals to extend Heavy Ion Fixed Target programme

Upgrades with crystal target for c-quark MDM, EDM, polarised target further upstream & wire targets are under discussion

LHC ERA

HL-LHC ERA

3 fb-1		♦5 fb-1				50 fb-1		300 fb-1
2011-2012		2015-2018	LS2	2021-2023	LS3	2026-2029	LS4	2031-...

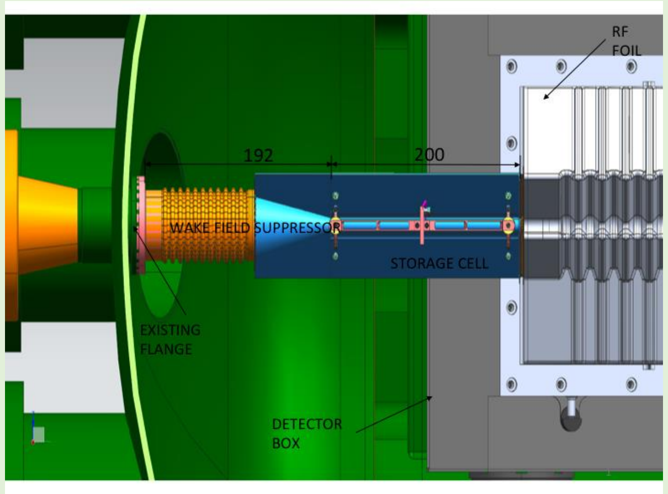
Run 1 Run 2 Run 3 Run 4 Run 5...

LHCb Upgrade I LHCb LS3 Consolidation LHCb Upgrade II

SMOG2?

OTHER TARGETS

Bent crystals? Polarised gas? Metal wires?



SMOG2: the injected gas inside a 20 cm long storage cell (1 cm in diameter) in front of the VELO.
-Up to two order of magnitude higher luminosity,
- Will operate also hydrogen, deuterium and noble gases

Summary and Outlook

- **LHCb has successfully joined the Heavy Ion Sector of research**
- **Superior technical features of the experimental setup allowed to obtain precise data on quarkonia production cross-sections in collider and fixed target modes.**
- **Double differential cross-sections for production of charm, strange and beauty hadrons are measured at 5, 8 and ~0.1 TeV in various combinations of HI collisions. The striking feature was observed – essential suppression of cross sections at low p_T & forward rapidity compared to p-p data.**
- **Interpretation of the obtained results has been performed in frames of existing theoretical approaches. The statistical and theoretical uncertainties have to be reduced for improving extraction of nPDFs.**
- **Fixed Target mode is unique for the experiments at LHC. Four proposals to extend this area of studies in the RUN3, Run4. are under discussion. The upgraded version of the current gas target (SMOG2) will allow to increase the instantaneous luminosity up to two orders of magnitude.**

Acknowledgements

The studies have been partially supported in frames of the NAS of Ukraine Targeted research program «Fundamental research on high-energy physics and nuclear physics (international cooperation)» and LIA IDEATE (STCU Project P9903).

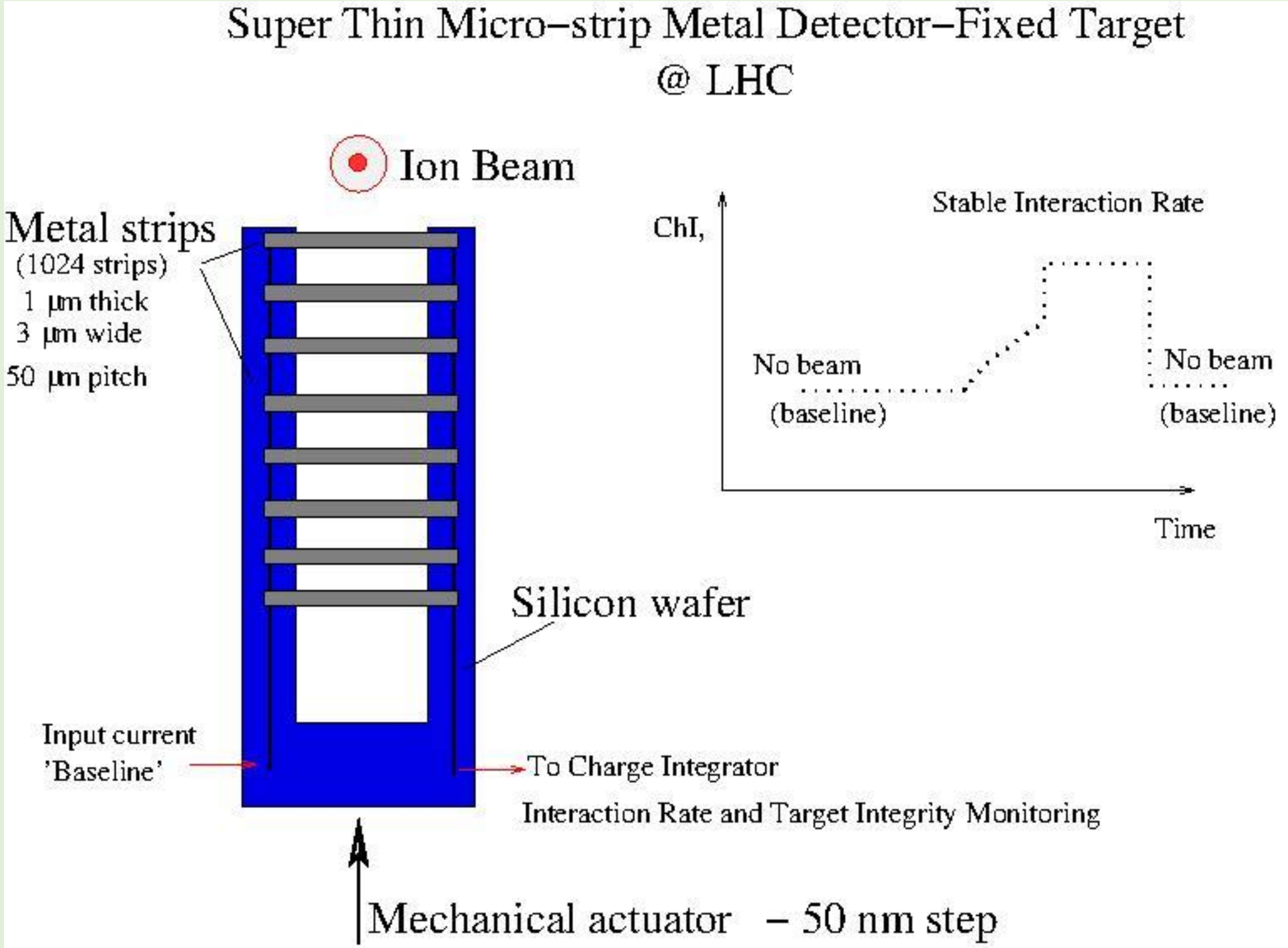
Thank you for your attention!

Welcome to Kyiv !

Techniques:

➢**Metal microstrip detector-target**

Superthin Wire Target - HOW-and When TO-DO it at LHCb ? VELO – VErtex Locator construction after (LS3 ?) upgrade



Metal Microstrip Detector –MMD-1024.

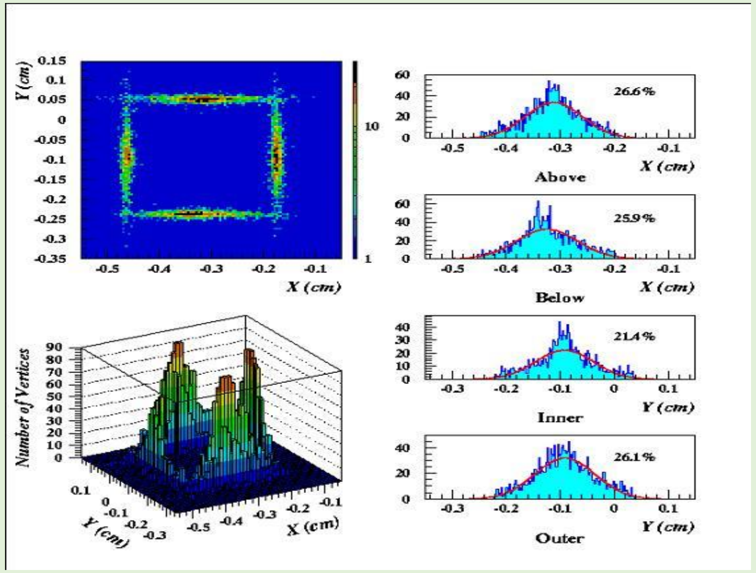
Nano-technologies evolve fast
– already nowadays- carbon nano-tubes, fullerene structures, graphenes, …
May become a nano-wire target components.

Techniques:

- **Metal microstrip detector-target**
- **Steering of the targets**

Equalization of the luminosities

Charge Integrated in Individual Targets -
data for the steering feedback system at HERA



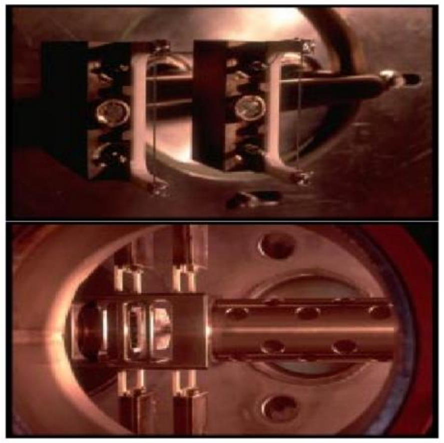
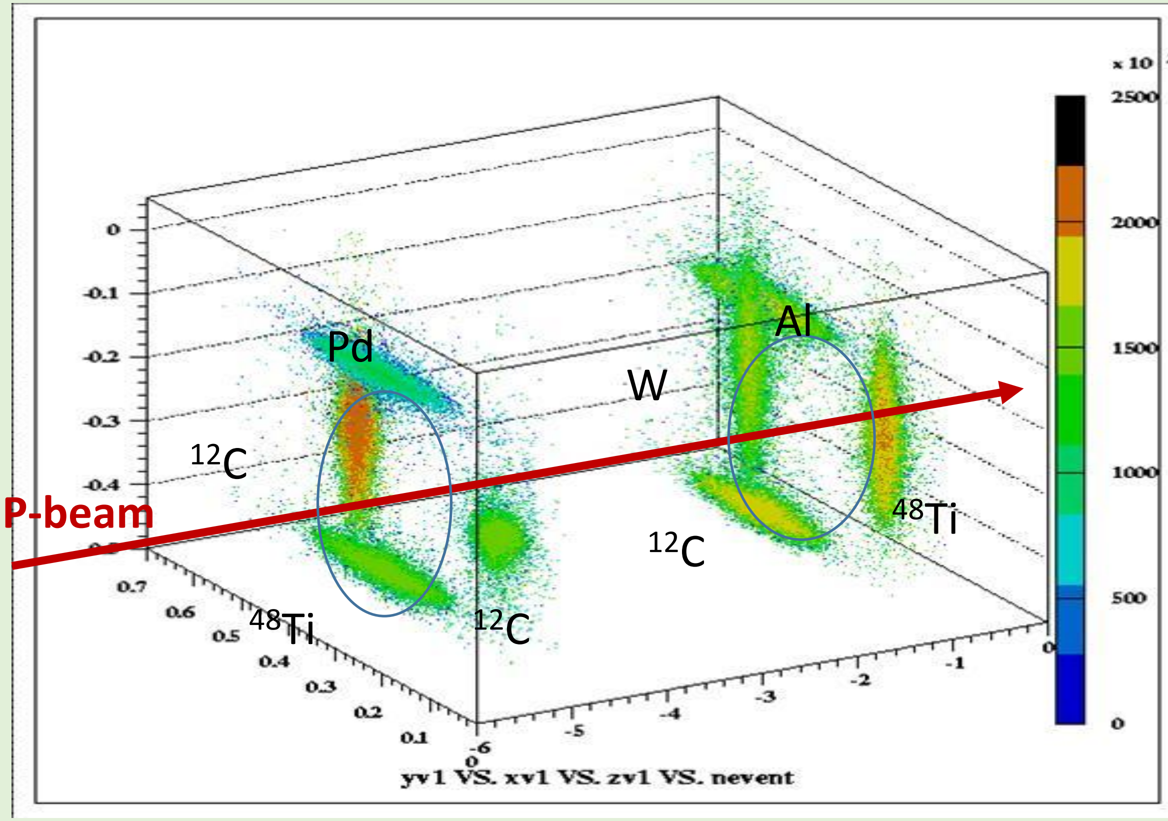


Figure 9: Targets mounted in the VDS vessel.

Wire	Charge Integrators %	Vertices %
Above	26.06 ± 0.08	26.6 ± 0.7
Below	24.26 ± 0.10	25.9 ± 0.7
Inner	23.49 ± 0.06	21.4 ± 0.7
Outer	26.20 ± 0.07	26.1 ± 0.7

Four targets



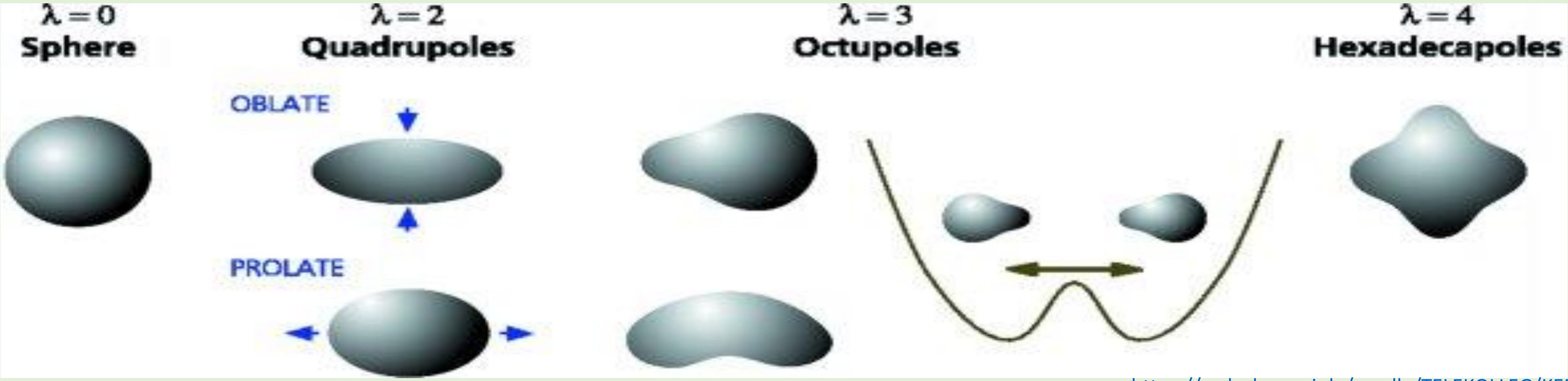
Eight targets

Proof of the principle – **Vertices are equally distributed over inserted targets.**

8 targets simultaneously could be handled providing 40 MHz interaction rate

http://dx.doi.org/10.1063/1.1291460

Impact of the ground state properties on Nuclear Modification Factor ?



https://web-docs.gsi.de/~wolle/TELEKOLLEG/KERN/index-s.html

- **Nuclei in ground state have different shape, angular momentum, …**
- **Nuclei with closed p-, n-shells (double-magic) are spherical**
- **Nuclear matter density distribution is not uniform**
- **Neutron-rich nuclei have large radius**
- **Neutron excess may create neutron nuclei in collisions ?**

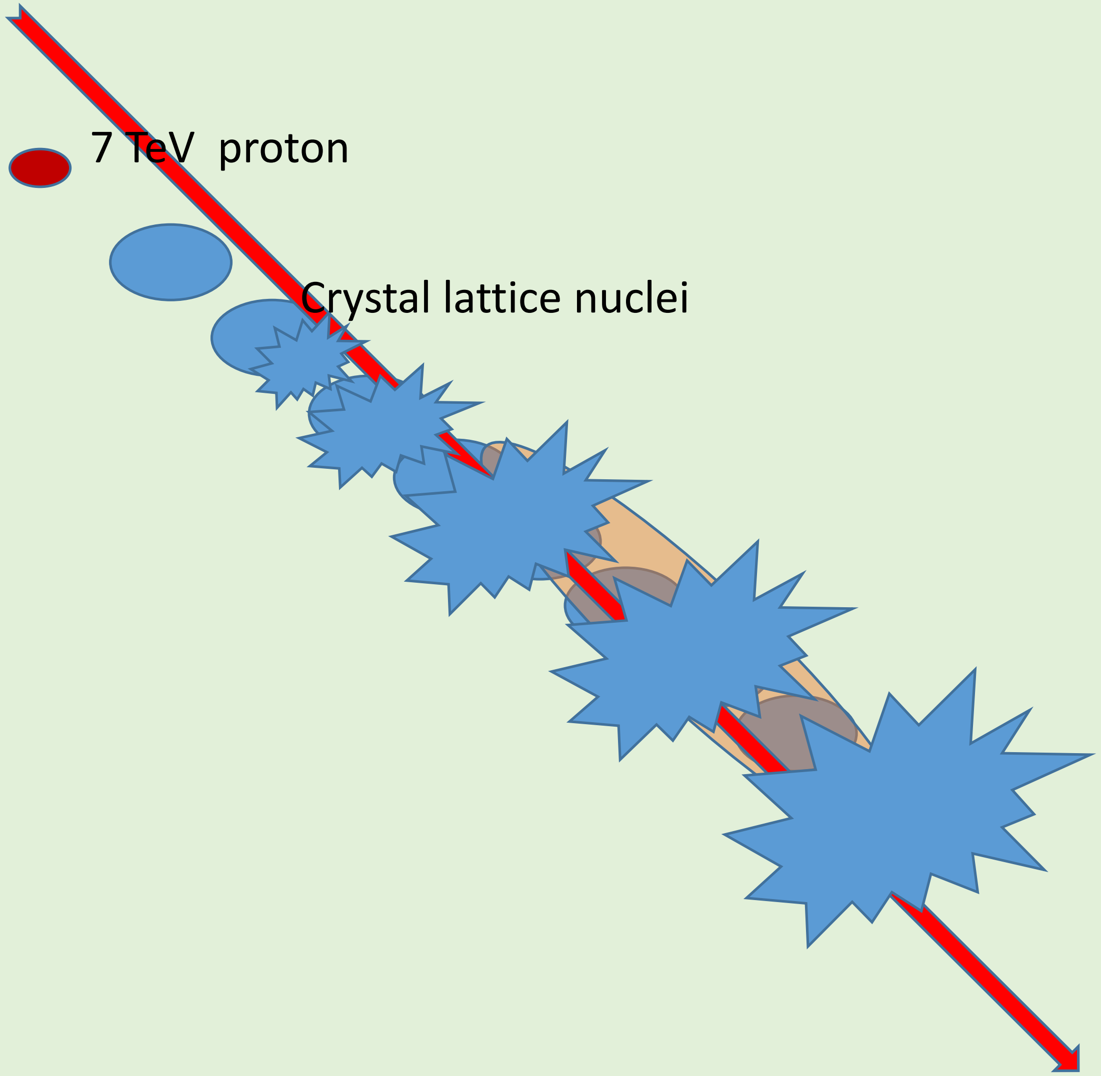
Different fixed targets
behave differently in collisions …

[Bullet Time | City Gallery Wellington]

Physics:

- **QCD at the ~100 GeV NN cms energy**

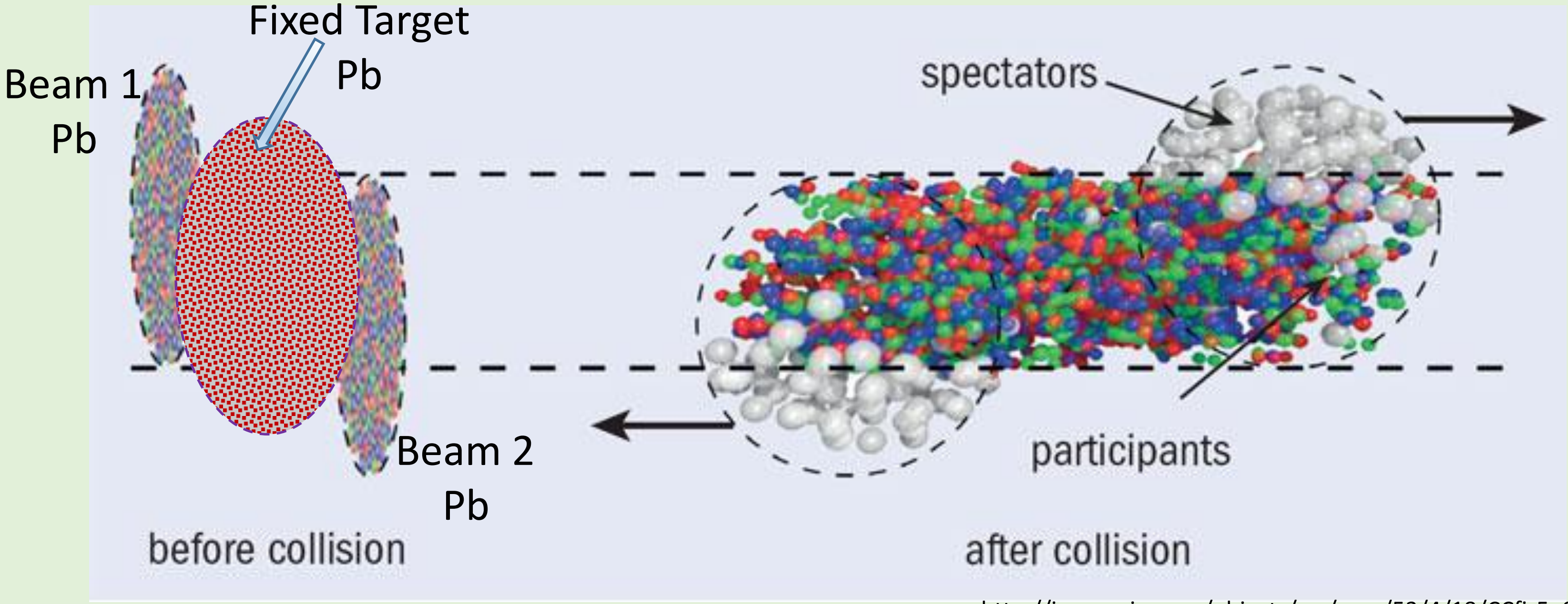
Crystalline Targets



Crystall structure – alligned atoms&nuclei – sequential scattering of high energy nucleus:

- **Cascade of nuclear interactions – Multiplicity of event– 10^{5-8} - ?**
- **Fusion to super heavy nuclei ?**
  - **Mass-spectrometry, gamma-rays analysis after irradiation**
- **Neutron rich or even neutron nuclei production ?**
- **Scattering at excited short-lived nuclei - new RBF ?**
- **…**

Three-nuclei interaction
– two nuclei from LHC beams
and one from the LHCb Microstrip Target



http://images.iop.org/objects/ccr/cern/53/4/18/CCfir5_04_13.jpg

Events with three nuclei interaction !

- **Intriguing opportunity with metal microstrip target – never explored in earlier experiments !**
- **Might be very interesting phenomenon – what is the interaction energy of three nucleons (two from LHC beams and one from the fixed target) ?**
- **What will be the Equation of State ?**
- **Which temperatures and densities of the hot matter part might be ?**