"New Trends in High-Energy Physics"
Odessa - May 12-18, 2019

Quarkonium measurements with the ALICE experiment at the LHC

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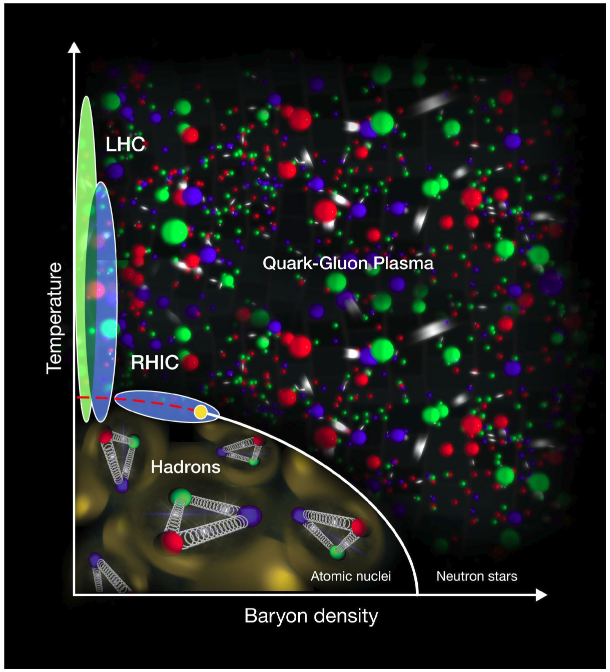
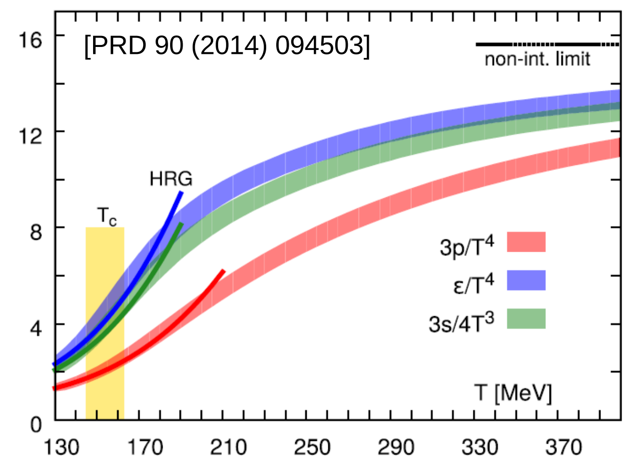
on behalf of the ALICE Collaboration

[1]University of Bergen, Norway

Introduction: the Quark Gluon Plasma



- State of nuclear matter in which quarks and gluons are not confined into hadrons
- Predicted by lattice Quantum ChromoDynamics (QCD) with a pseudo-critical temperature at zero baryon chemical potential ($\mu_B = 0$)



T_c **~ 155 MeV**

- Relativistic **heavy ion collisions (AA)** can create the conditions for the **phase transition from ordinary matter to the QGP**
- In order to interpret correctly results in **AA** collisions it's crucial to study:
  - **pp** collisions: reference system, basic production mechanisms, no QGP expected
  - **pA** collisions: quantify initial state effects
- **Heavy-Quarks (charm and beauty)**: produced in the initial hard partonic scatterings and experience the full evolution of the AA collision → relevant probes to study the properties of the hot and dense medium
  - focus of this talk → **Quarkonia**

Outline

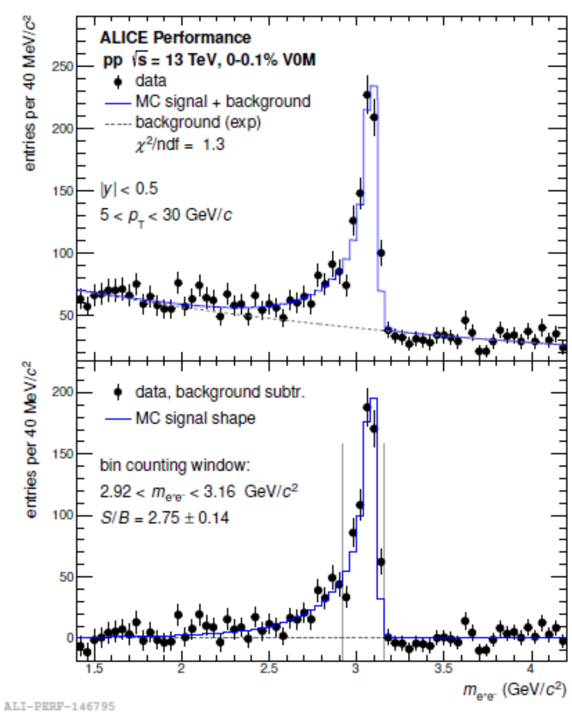
- Quarkonium measurements in ALICE
- pp collisions: baseline production
- p-Pb collisions: study Cold Nuclear Matter (CNM) effects
- Pb-Pb: study the properties of the hot and dense medium
- Conclusions and perspectives

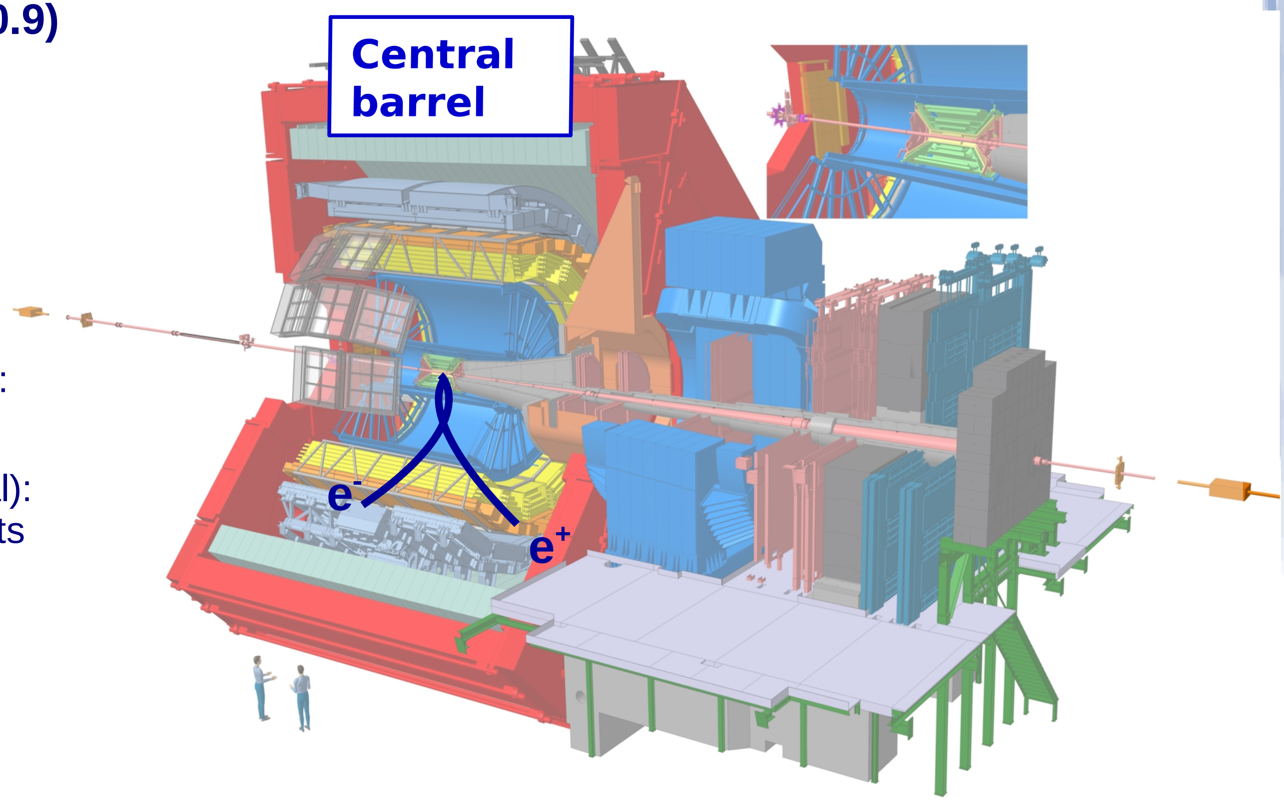
Quarkonium measurements in ALICE

Mid-rapidity measurements (|y| < 0.9)

- **Dielectron** decay channel

- Time Projection Chamber (TPC): tracking, PID via dE/dx
- Inner Tracking System (ITS): vertexing, tracking, triggering
- Transition Radiation Detector (TRD): electron ID, triggering
- ElectroMagnetic Calorimeter (EMCal): triggering, PID via E/p measurements





- Inclusive J/ψ measurements down to $p_T = 0$ → unique kinematic coverage at the LHC !

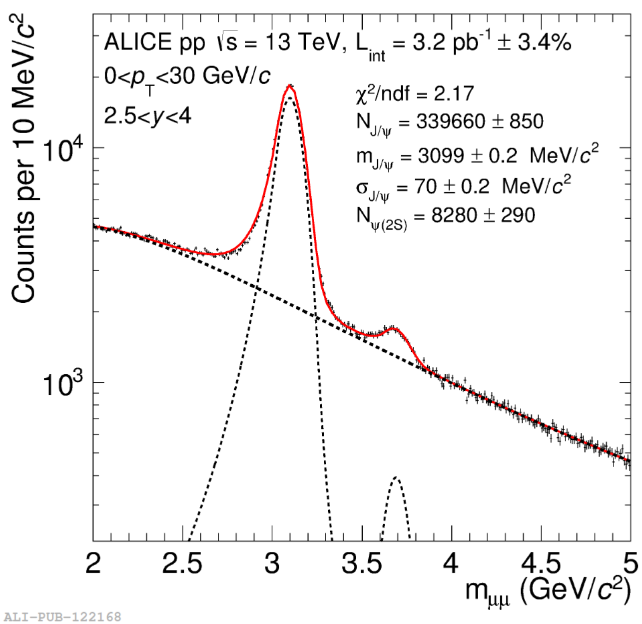
- Possibility to separate prompt and non-prompt J/ψ down to a few GeV/c thanks to Silicon Pixel Detectors (SPD) → access beauty hadron production down to very low p_T !

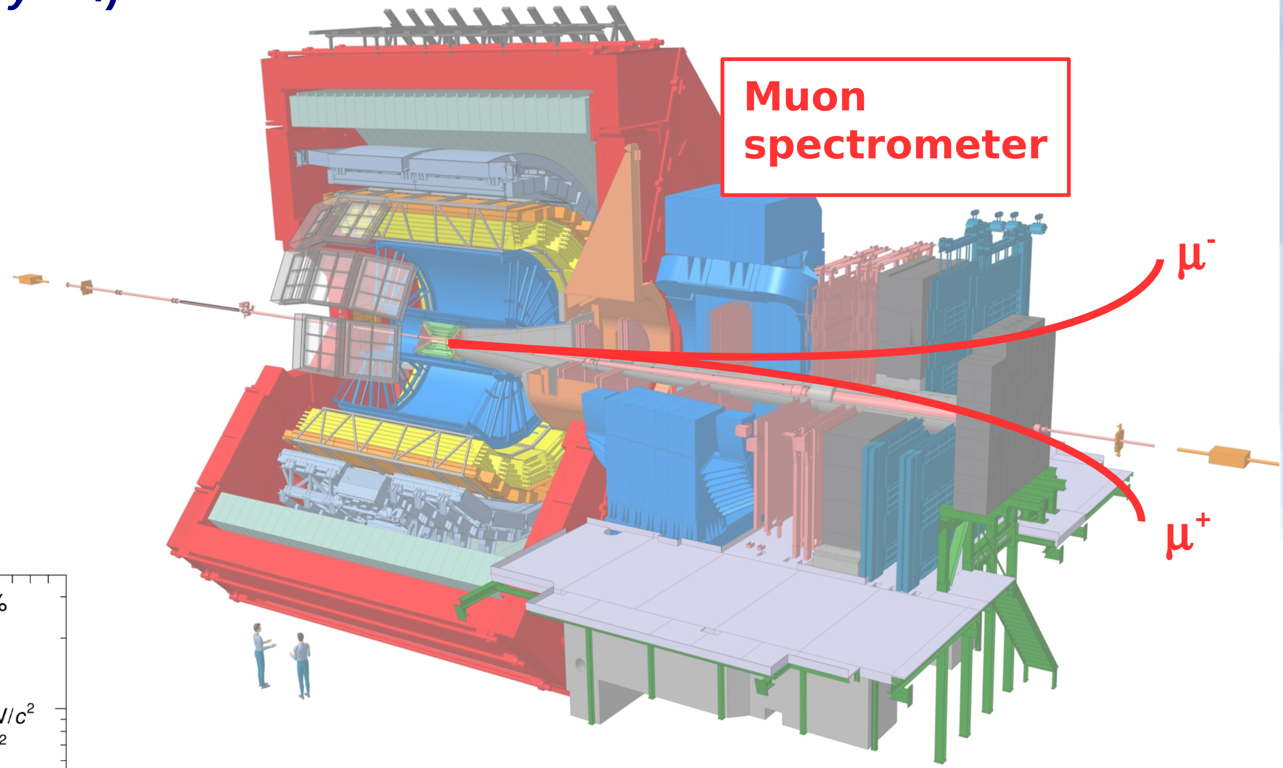
(*) Only detectors relevant for quarkonium analyses discussed here

Quarkonium measurements in ALICE

Fwd-rapidity measurements (2.5 < *y* < 4)

- **Dimuon** decay channel
- Muon spectrometer:
  - Dipole magnet
  - Front absorber 10 λ_I
  - 10 tracking planes (Cathode Pad Chambers)
  - 4 trigger planes (Resistive Plate Chambers)
  - Muon filter (7 λ_I)





- Several charmonia and bottomonia states measured:
  - J/ψ, ψ(2S), ϒ states
- Acceptance: down to p_T = 0 for all quarkonium species !

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Quarkonium measurements in ALICE

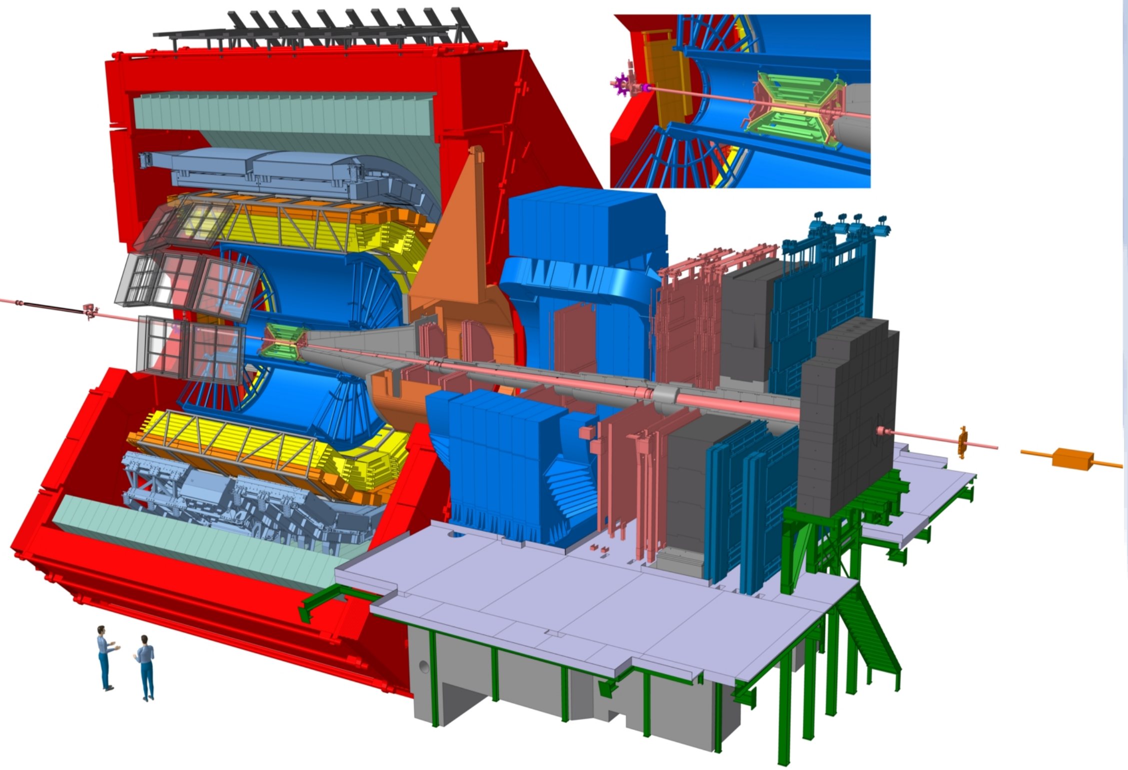
Minimum Bias trigger based on:

- Forward scintillator arrays (VZERO) (+Silicon Pixel Detector (SPD) in Run I)

In addition:

- trigger on **muon p_T** in the forward spectrometer
- trigger on energy deposition in the **EMCal** at mid-rapidity

System	Year	$\sqrt{s_{NN}}$ (TeV)
	Run I	
pp	2009–13	0.9, 2.76, 7, 8
p-Pb	2013	5.02
Pb-Pb	2010,11	2.76
	Run II	
pp	2015,17 2015–18	5.02 13
p-Pb	2016	5.02, 8.16
Xe-Xe	2017	5.44
Pb-Pb	2015 2018	5.02 5.02



Detectors used for **centrality / multiplicity** dependent analyses:

- VZERO
- SPD
- Zero Degree Calorimeters (important for centrality measurements in p-Pb)

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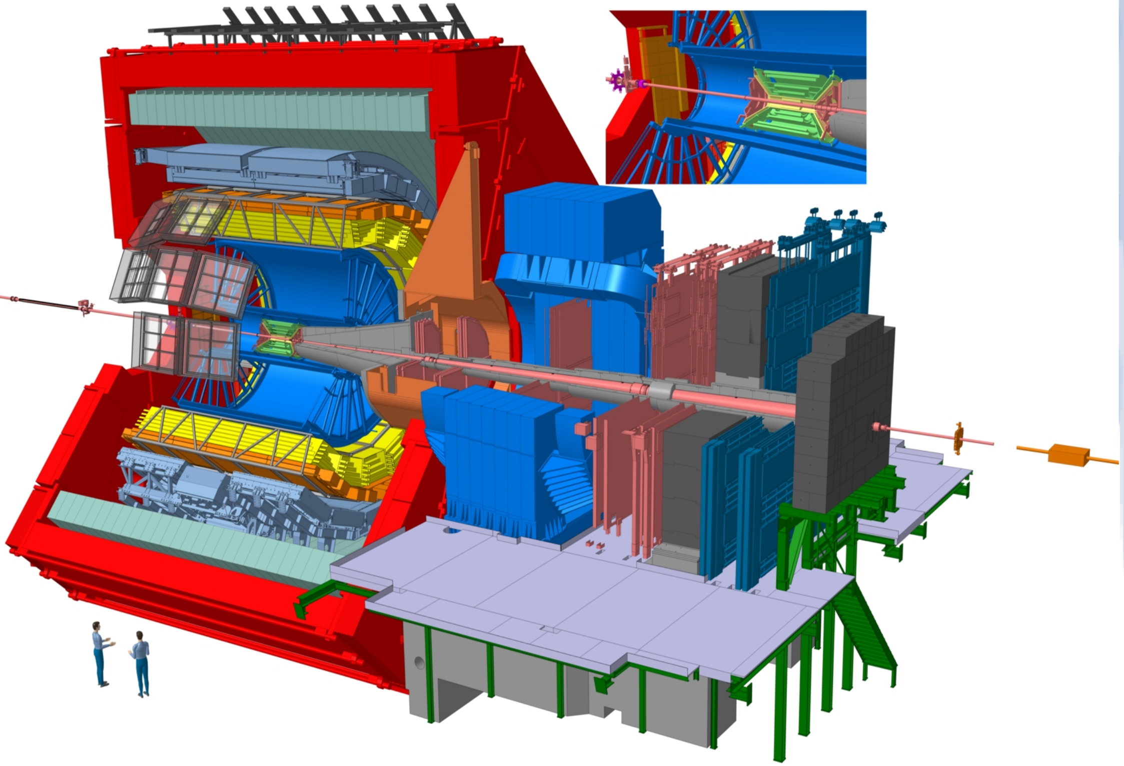
Focus on results based on Run II data



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Production mechanisms in pp collisions

- Important **baseline** for Pb-Pb and p-Pb systems to quantify nuclear matter effects

- **Benchmark test for QCD** based processes: “factorization theorem” can be employed to describe prompt quarkonium production:

  1) $q\bar{q}$ pairs produced by initial hard partonic scattering → pQCD applicable

     - gluon fusion processes dominant at the LHC → sensitivity to gluon PDFs

  2) Hadronization into a “colourless” bound state → non-perturbative process. Three main production models:

     - Color Evaporation Model (CEM) [Phys. Rev. D 12 (1975) 2007]
     - Color Singlet Model (CSM) [Phys. Lett. B 67 (1977) 217]]
     - Non-Relativistic QCD (NRQCD) [Phys. Rev. D 51 (1995) 1125]

  → more differential measurements based on several “observables” (e.g. cross-sections, polarization, quarkonium-hadron correlations, etc.) represent a powerful tool to constrain quarkonium production models

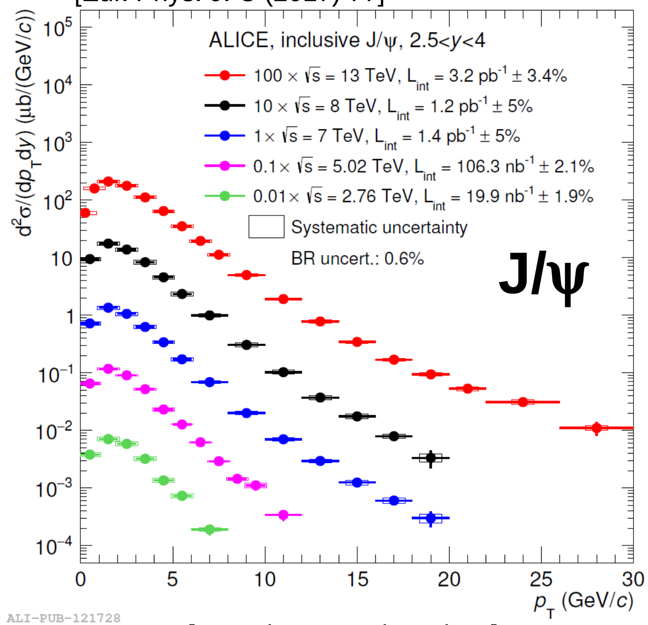
- Quarkonium studies as a function of multiplicity shed light on **Multiple Parton Interactions** (MPI)
  [relevant for heavy-flavour production at the LHC energies!]

Quarkonium cross sections

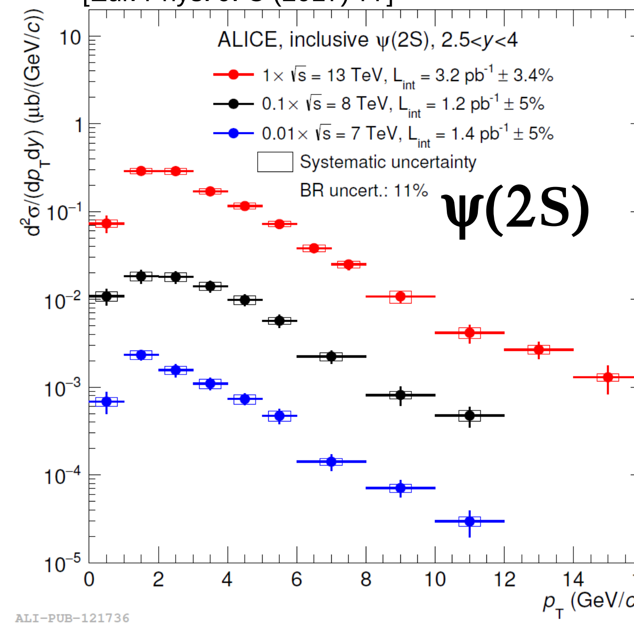
fwd-y

- Extensive and precise charmonium production measurements at several $\sqrt{s}$
  - Hardening of the p_T differential cross-sections with increasing energy

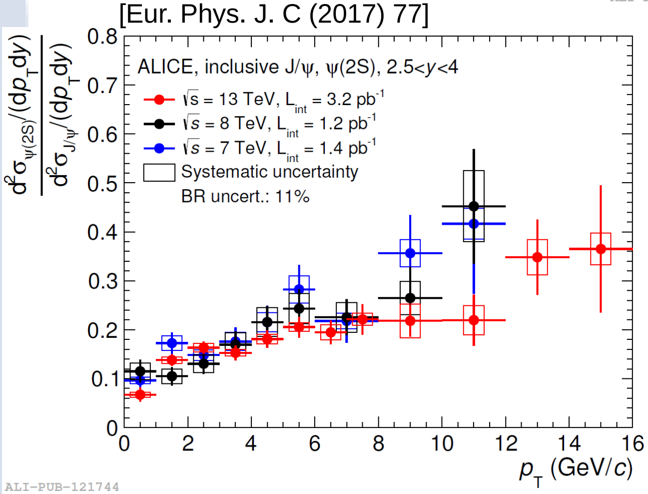
[Eur. Phys. J. C (2017) 77]



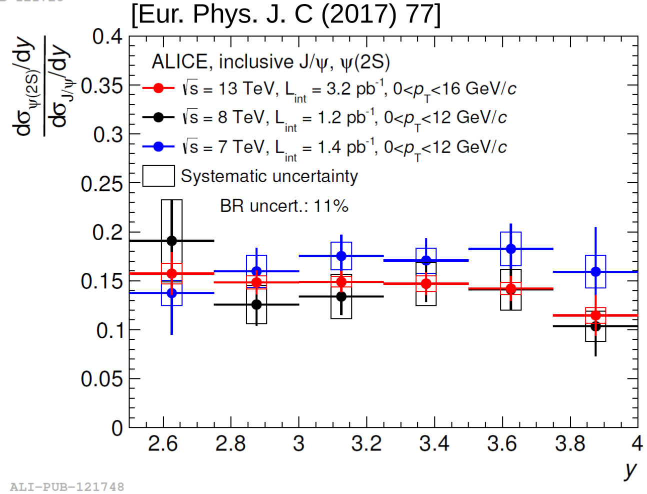
[Eur. Phys. J. C (2017) 77]



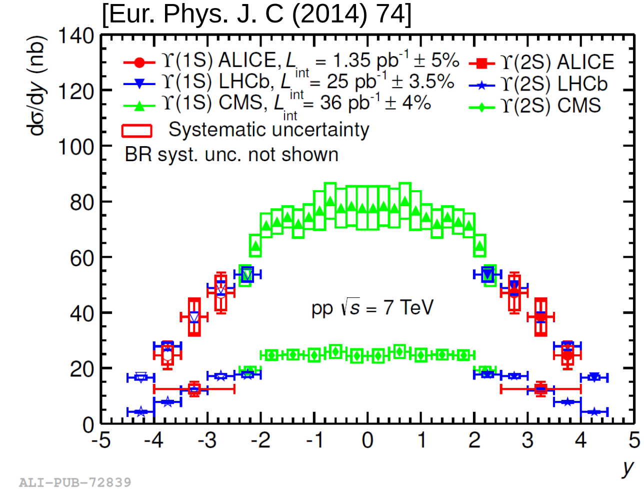
[Eur. Phys. J. C (2017) 77]



[Eur. Phys. J. C (2017) 77]



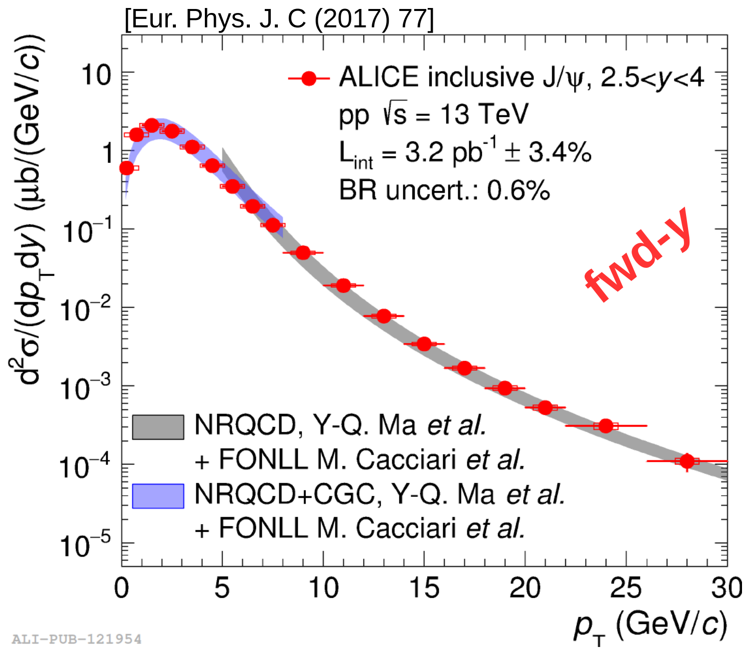
[Eur. Phys. J. C (2014) 74]

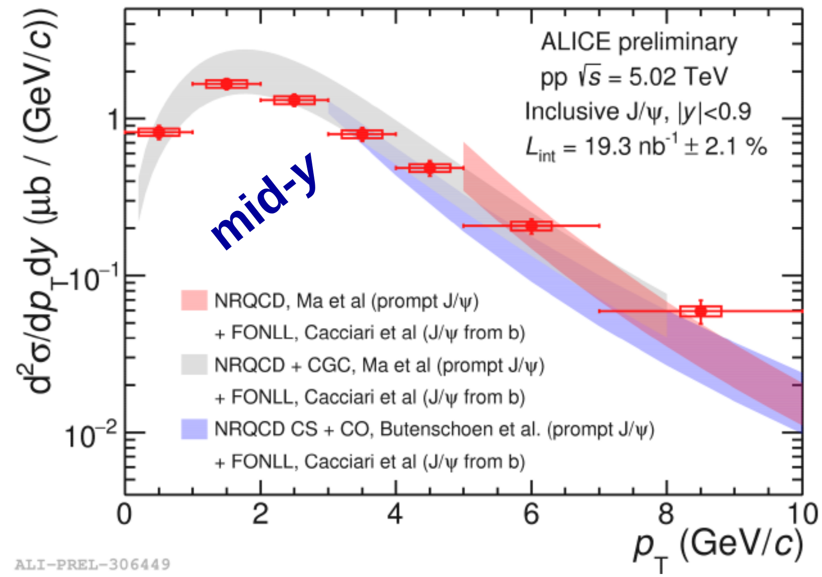


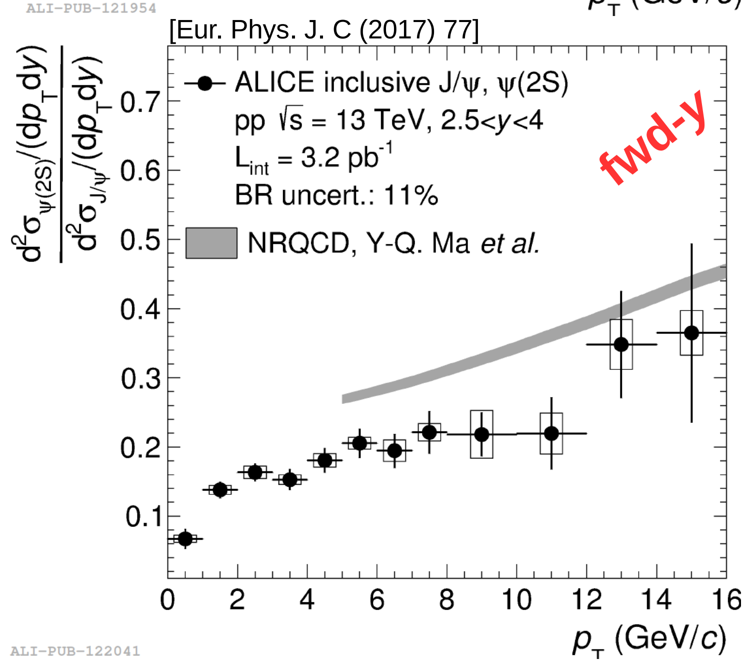
- ψ(2S) / J/ψ cross-section ratio shows:
  – an increasing trend with p_T
  – no significant dependence with rapidity and $\sqrt{s}$

- ALICE results are in good agreement with results from other LHC experiments

Quarkonium cross sections

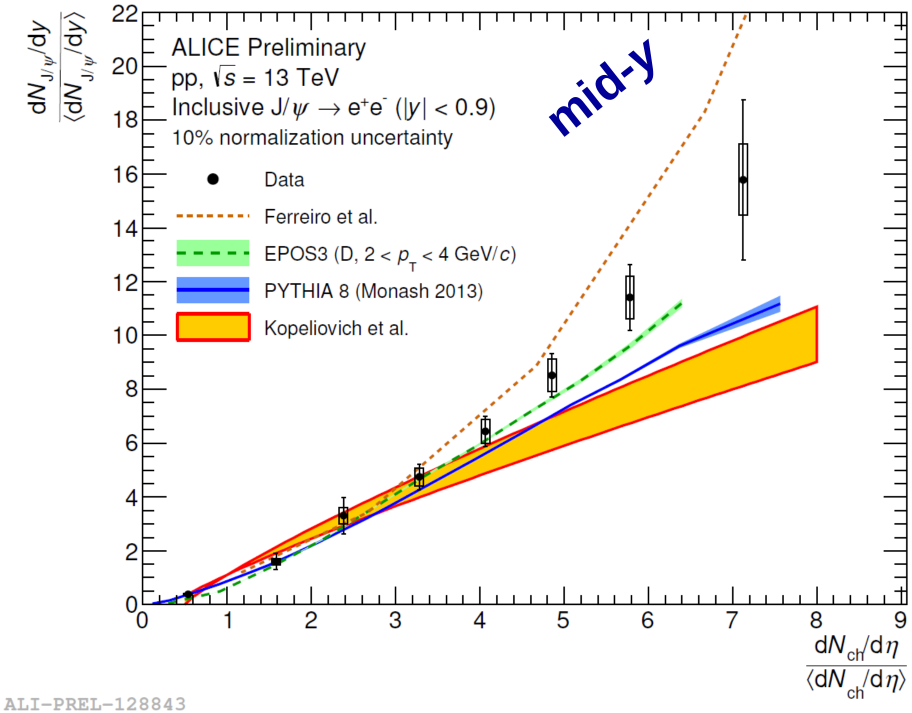


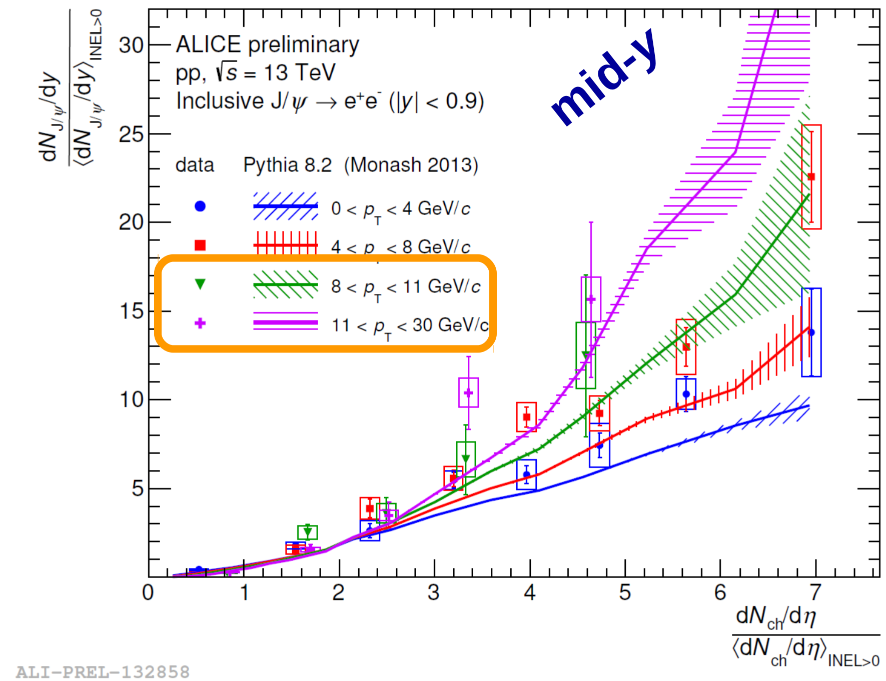




- ✔ NRQCD combined with FONLL is able to describe p_T spectra at both central and forward rapidity
  - ✔ NRQCD+CGC provides a good description down to p_T = 0
- ✔ tensions between models and data still visible in the ratio ψ(2S) / J/ψ

Quarkonia vs multiplicity



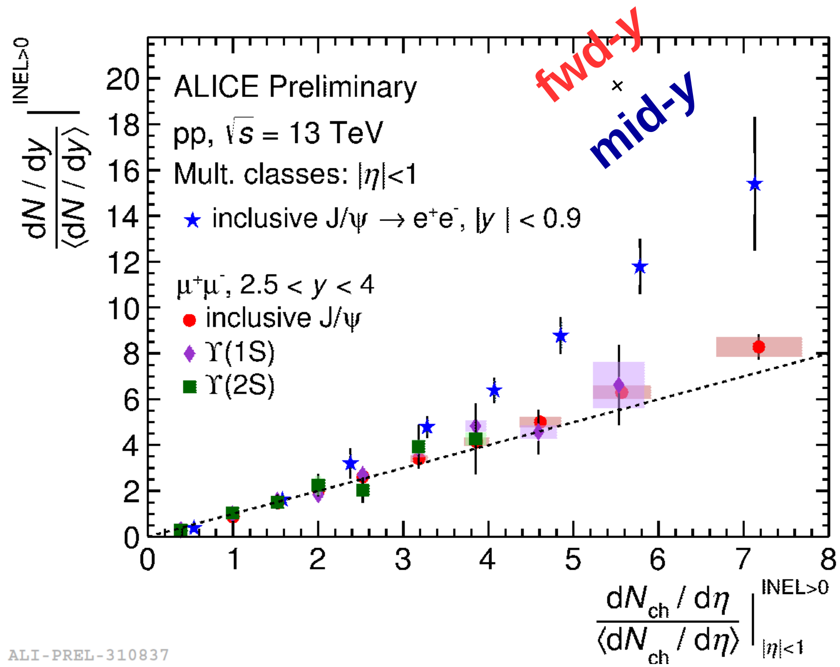


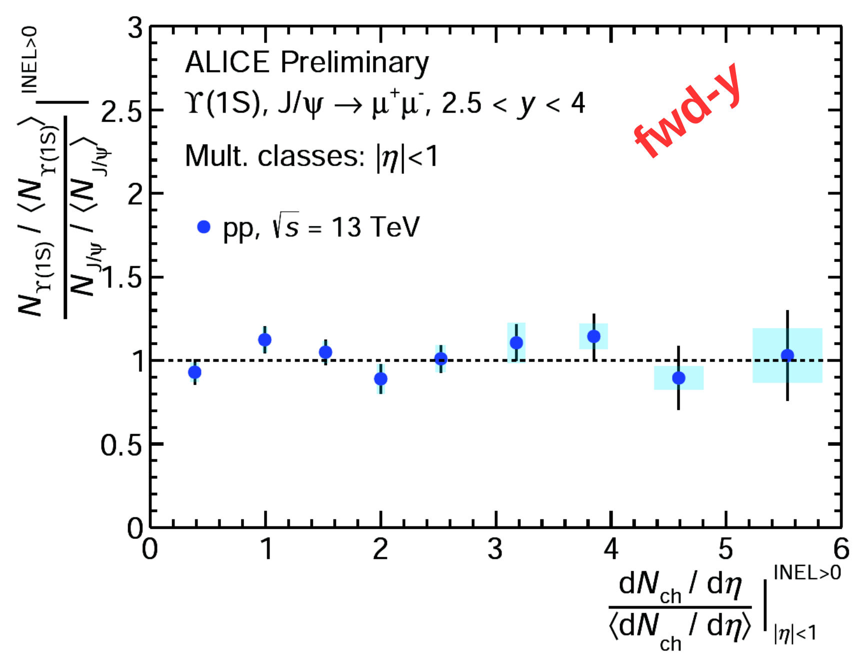
- Faster than linear increase observed for J/ψ at mid-rapidity
- Reproduced qualitatively well by models that include production of heavy-quarks in MPI (PYTHIA8 Monash2018, EPOS3)
- Percolation model overestimates the increasing trend at high multiplicity

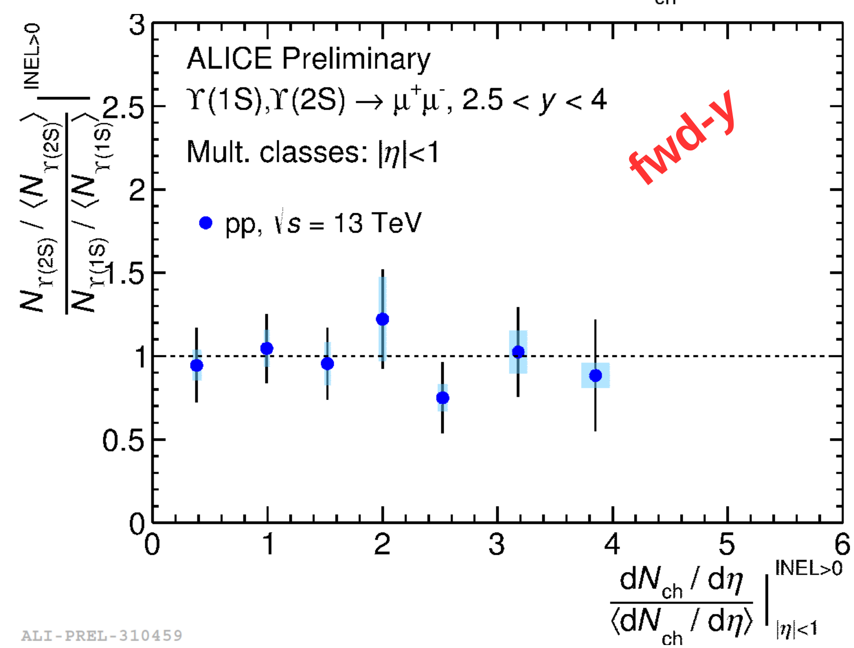
- **EMCAL** analysis significantly extends the p_T range (up to 30 GeV/c)
- Slope increases with the transverse momentum of J/ψ
  - described qualitatively well by PYTHIA8

Ferreiro, Pajares, PRC86 (2012) 034903
EPOS3, Werner et al., Phys.Rept.350 (2001) 93
PYTHIA8, Sjostrand et al., Comput.Phys.Comm.178(2008)
Kopeliovich et al., PRD88 (2013) 116002

Quarkonia vs multiplicity







- ✔ Linear increase observed for J/ψ, ϒ(1S) and ϒ(2S) at forward rapidity (*y*-gap between multiplicity and quarkonium measurements)
- ✔ No significant dependence on mass and heavy quark content observed

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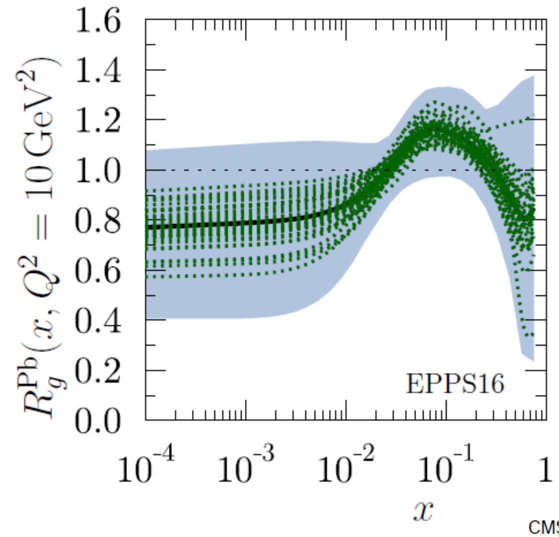
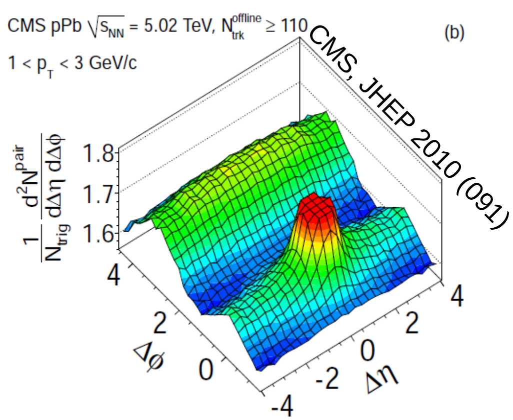
Production in p-Pb collisions

- **Cold Nuclear Matter (CNM)** effects:
  - (anti-)shadowing modifications for nuclear PDFs
  - gluon saturation, Colour Glass Condensate
  - parton energy loss
  - final state dissociation (absorption, comovers)

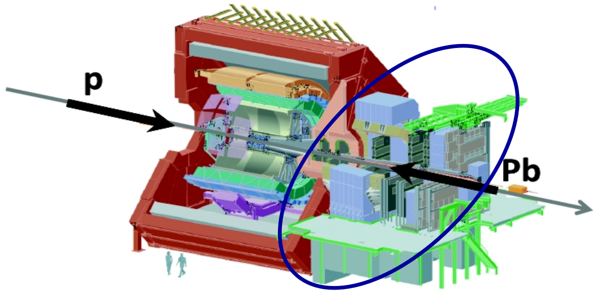


[EPJ C77 (2017) 163]

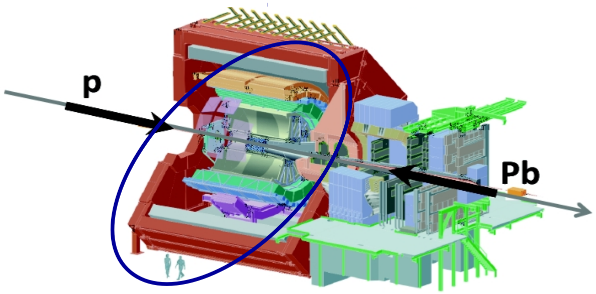


- Open questions: QGP formation in small systems ? Collectivity ?

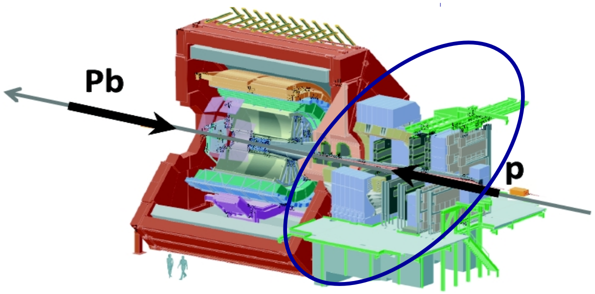
- Two beam configurations: p-Pb / Pb-p (two energies: $\sqrt{s_{NN}}$ = 5.02, 8.16 TeV)



Forward rapidity



Mid-rapidity



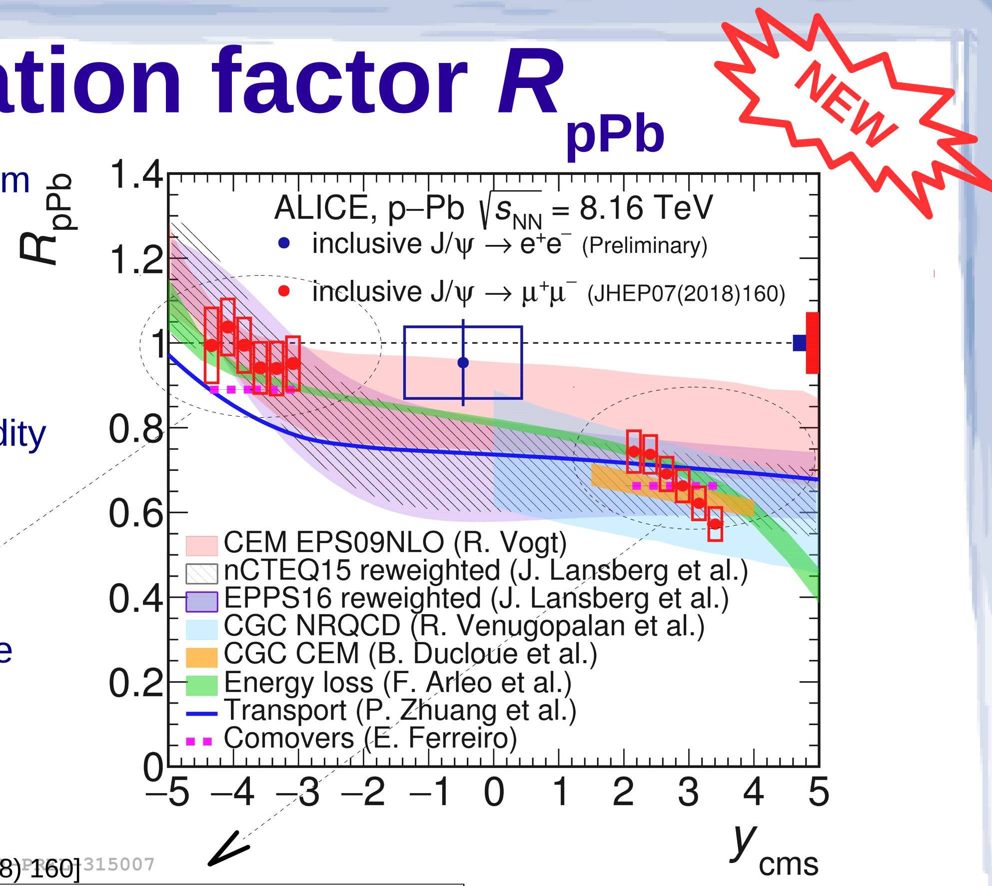
Backward rapidity

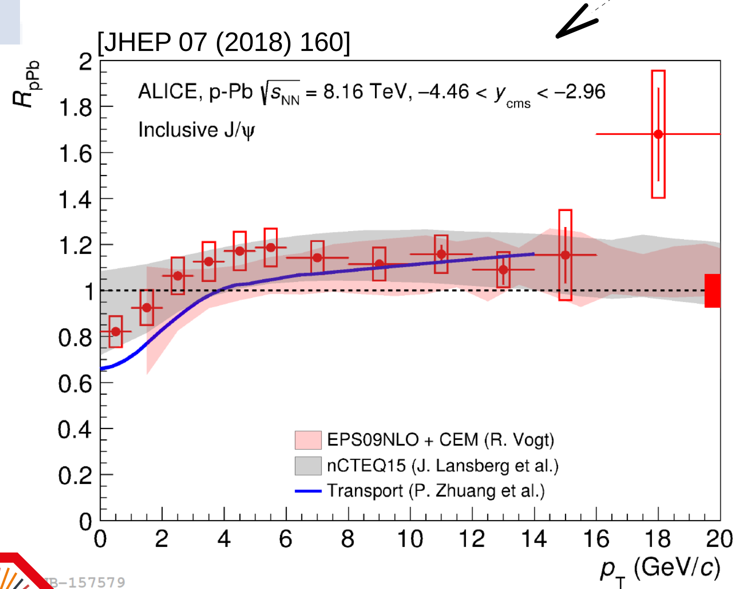
Nuclear modification factor R_{pPb}

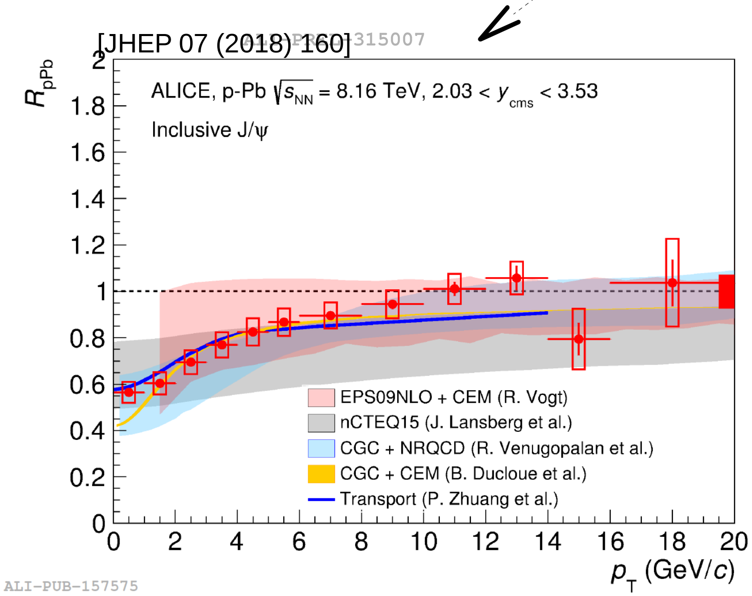
Nuclear modification factor R_{pPb} is used to quantify medium effects:

$$R_{pA}(y, p_T) = \frac{1}{A}\frac{d^2\sigma_{pA}/dydp_T}{d^2\sigma_{pp}/dydp_T}$$

- ✔ Stronger J/ψ suppression observed at forward rapidity
- ✔ R_{pPb} compatible with unity at backward and mid-rapidity within uncertainties
- ✔ Fair agreement between data and models within the current experimental and theoretical uncertainties







- ✔ Increase of R_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV with increasing p_T at both forward and backward rapidity
- ✔ p_T dependence fairly described by models

Nuclear modification factor R_{pPb}

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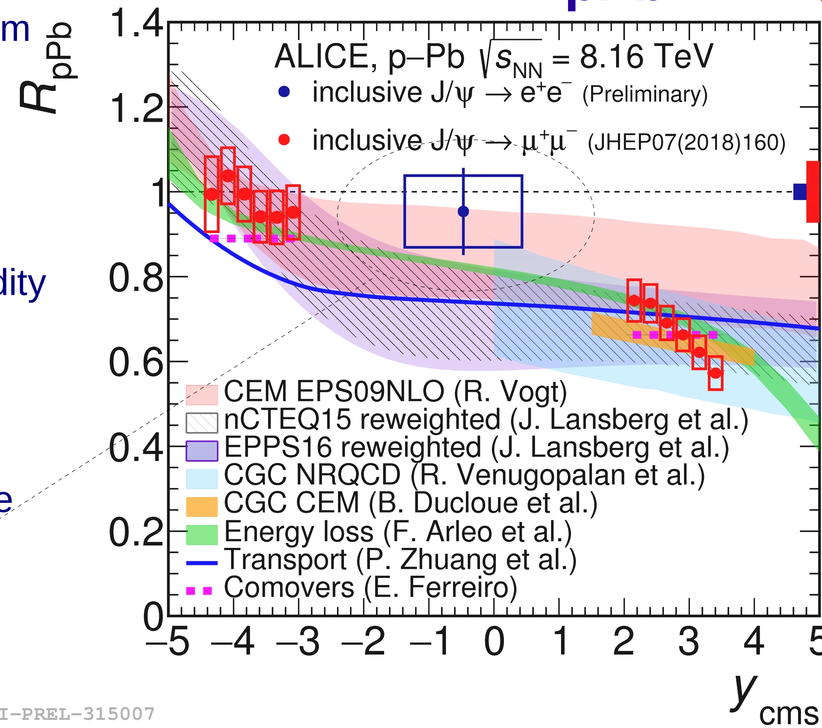
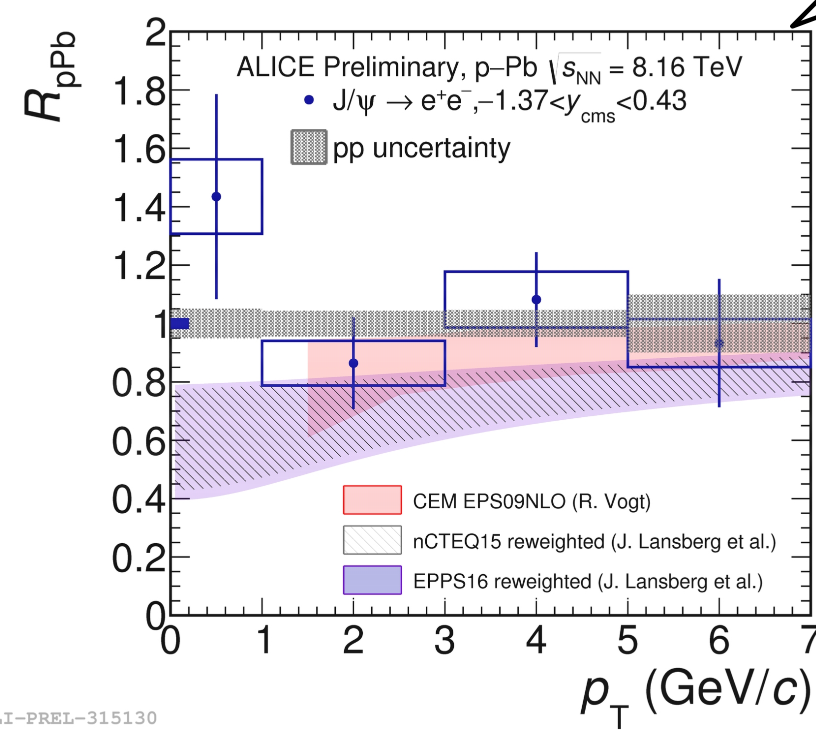
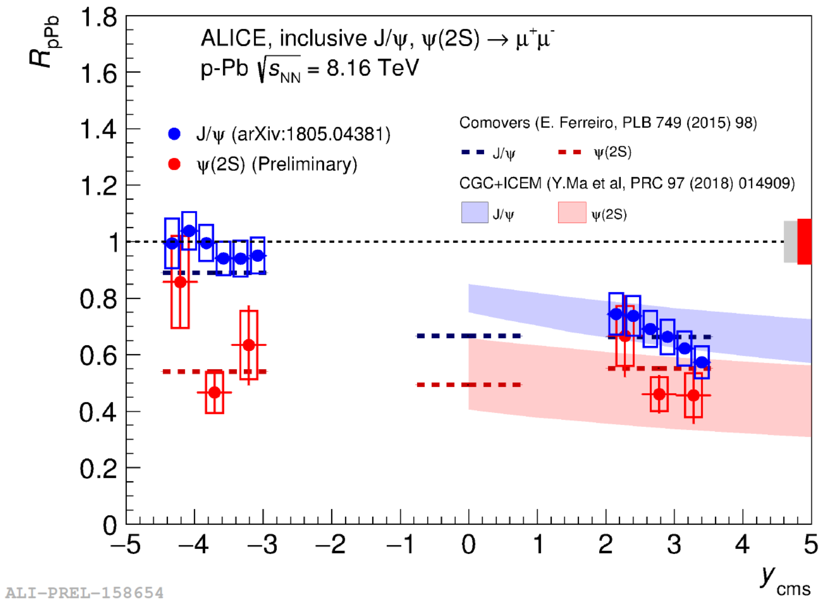
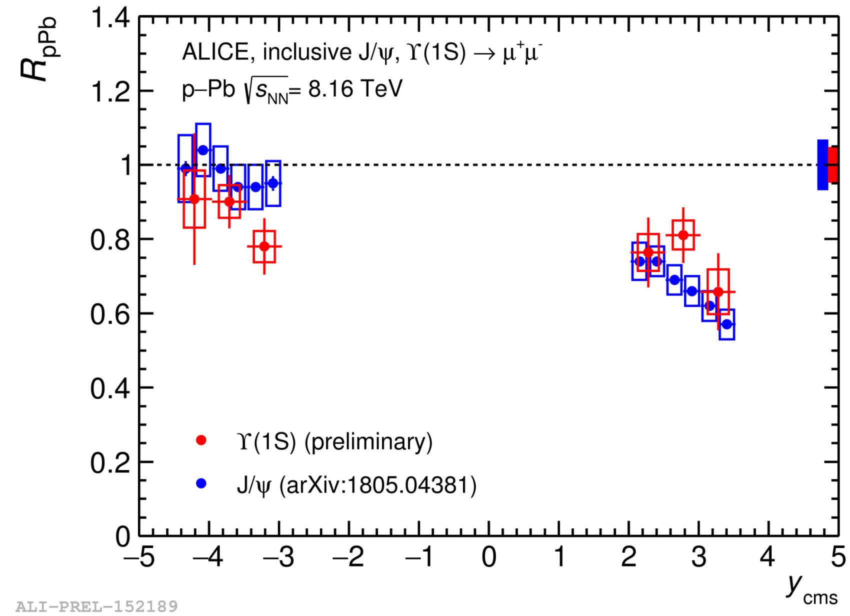




- ✔ R_{pPb} compatible with unity over the whole p_{T} range
- ✔ Data and models compatible within uncertainties
- ✔ Higher p_{T} reach expected thanks to TRD triggered data

Nuclear modification factor R_{pPb}





- ✔ Similar suppression observed for J/ψ and ψ(2S) at forward rapidity
- ✔ ψ(2S) suppressed significantly more than J/ψ at backward rapidity
  - ✔ Final state effects needed to explain ψ(2S) modification

- ✔ Similar suppression observed for J/ψ and Υ(1S) at both backward and forward rapidity

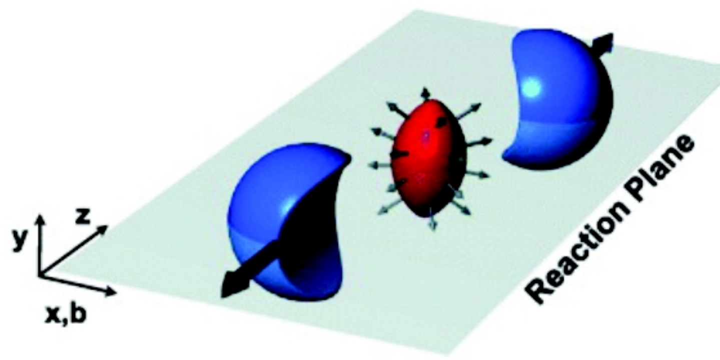
Azimuthal anisotropy (v_2)

- In a strongly interacting medium, pressure gradients convert any initial geometrical anisotropy into an anisotropy in the momentum space
  - anisotropy is quantified by the 2nd order coefficient v_2 of the Fourier expansion of the particle azimuthal angle distribution

$$\frac{dN}{d\varphi} = \frac{N}{2\pi}\left[1 + \sum_{n=1}^{\infty} 2 v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)\right]$$

$$v_2 = < cos2(\varphi_{part} - \Psi_{EP}) >$$

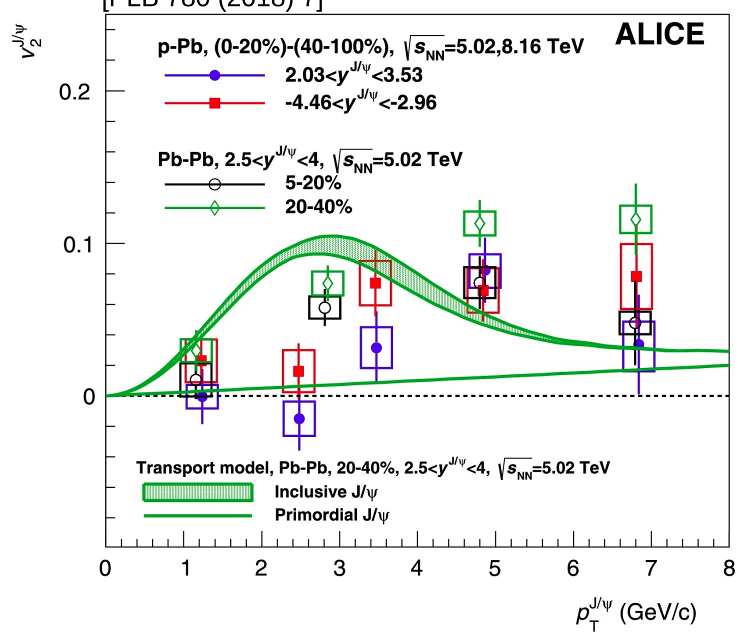
[Figure: Raimond Snellings New J. Phys. 13 (2011)]



- In heavy-ion collisions **non-zero v_2** indicates the **participation in the collective expansion** of the system

- J/ψ v_2 measured looking at l**ong-range angular correlations** between backward / forward rapidity J/ψ and charged hadrons produced at mid-rapidity (rapidity gap ~ 1.5)
- Non-zero v_2 observed for p_T > 3 GeV/c (~5σ significance)
  - Similar v_2 compared to Pb-Pb measurements → very intriguing result: **common underlying mechanism** (besides what's included in current calculations) at the origin of J/ψ v_2?
  - **Initial conditions** ?

[PLB 780 (2018) 7]



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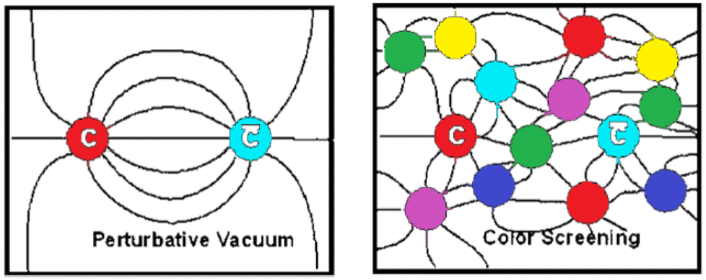
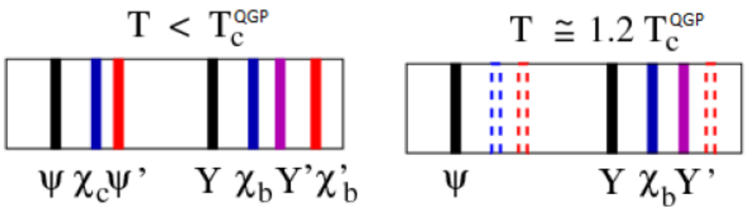
Quarkonium production as a probe of heavy-ion collisions

- Suppression of quarkonia by **colour screening** in a deconfined medium was originally proposed as a signature of the formation of QGP

  [Matui & Satz, Phys.Lett. B178 (1986) 416-422]

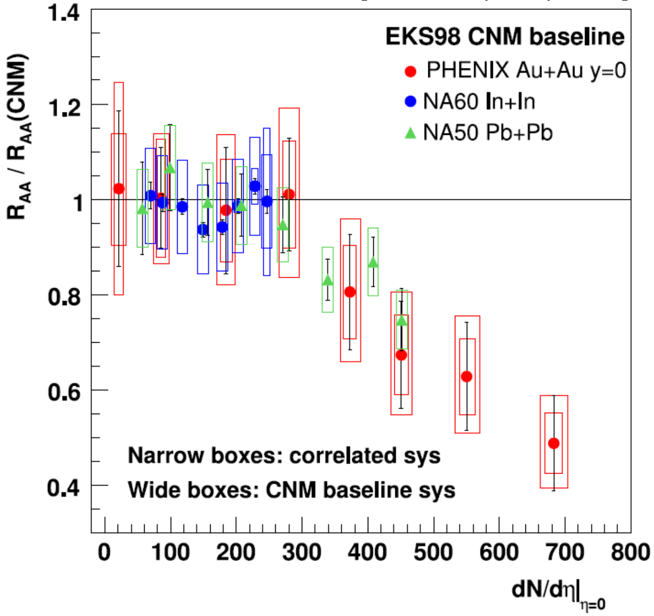


- Dissociation depends on the quarkonium binding energy (**sequential melting**) → quarkonia can be considered as a **"thermometer"** of the QGP



- J/ψ measurements from **RHIC** experiments showed **puzzling** features:
  - Slightly larger suppression at forward-*y* compared to mid-*y* [Phys. Rev. C 84, 054912]
  - similar suppression at RHIC and SPS

[EPJC 71 (2011) 1534]



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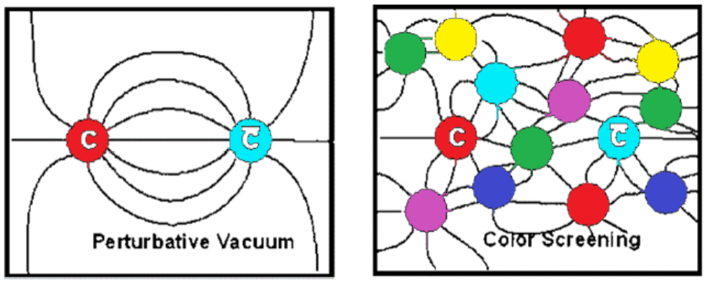

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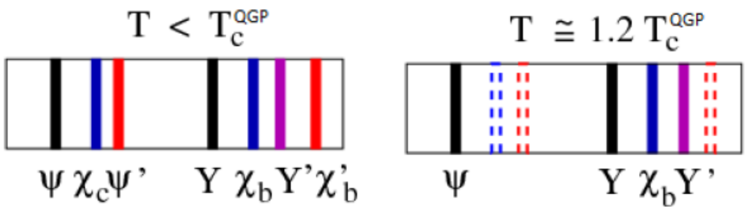

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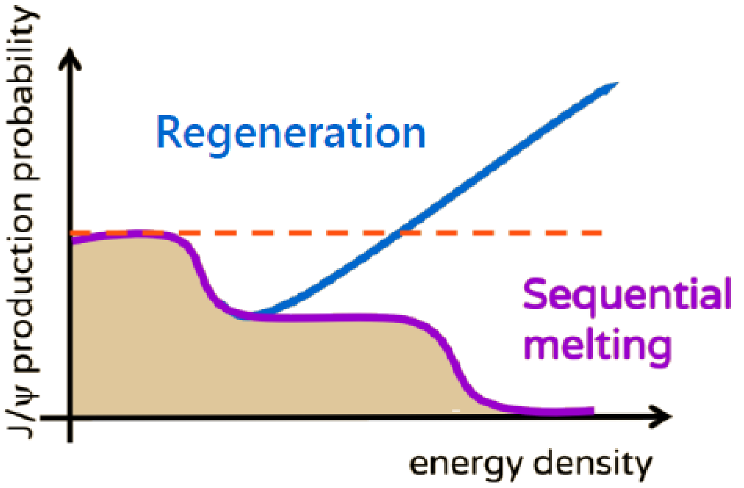


- Novel quarkonium production mechanism at the LHC energies → **recombination** phenomena from uncorrelated heavy quark pairs at the phase boundary

[P. Braun-Muzinger, J. Stachel, PLB 490(2000)196]
[R. L. Thews, M. Schroedter, J. Rafelski, Phys.Rev. C63 (2001) 054905]

Nuclear modification factor R_{AA}

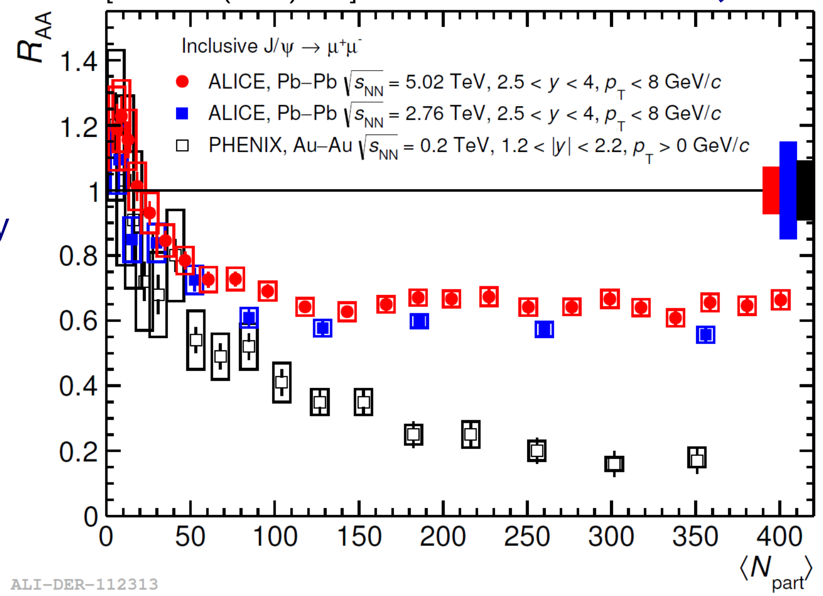
fwd-y × mid-y

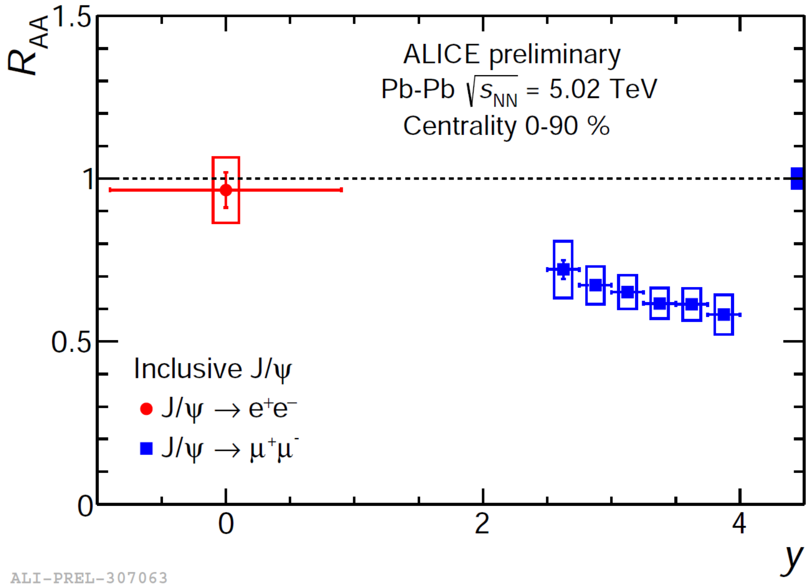
Nuclear modification factor in AA: $$R_{AA}(y,p_T) = \frac{1}{\langle N_{coll}\rangle}\frac{d^2N_{AA}/dydp_T}{d^2N_{pp}/dydp_T}$$

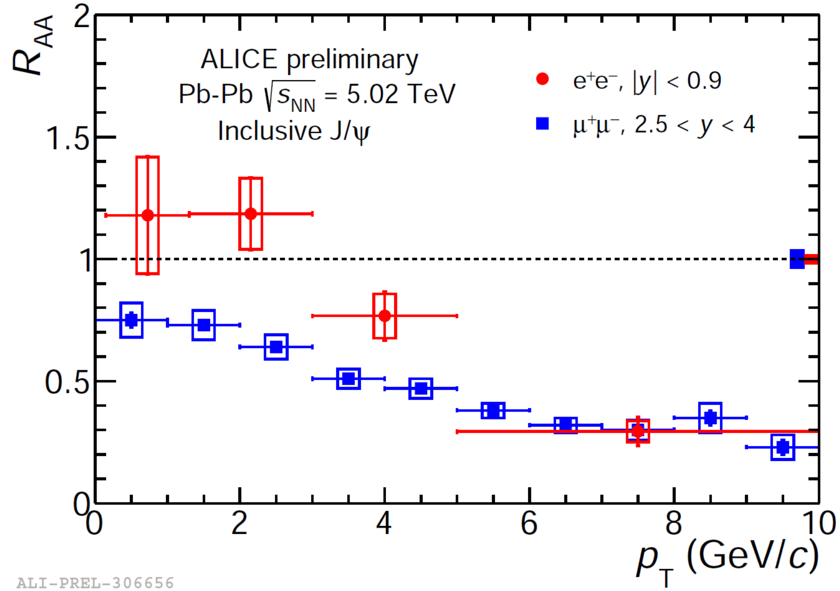
- Similar suppression observed in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV
- Less suppression at LHC energy compared to lower RHIC energy
- Weaker suppression at mid- compared to forward rapidity
  - Comparable suppression at high p_T
  - Increasing R_{AA} towards lower p_T, more pronounced at mid-y

Everything consistent with J/ψ regeneration scenario!

[PLB 766 (2017) 212]

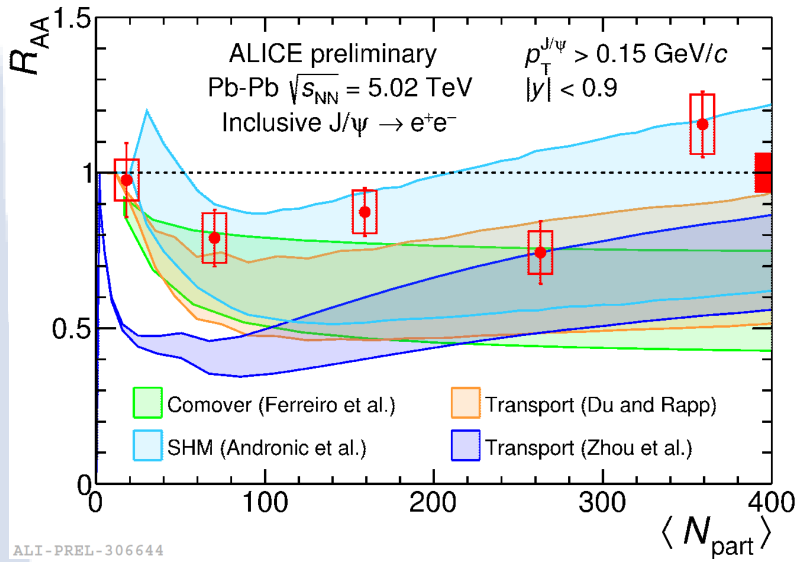


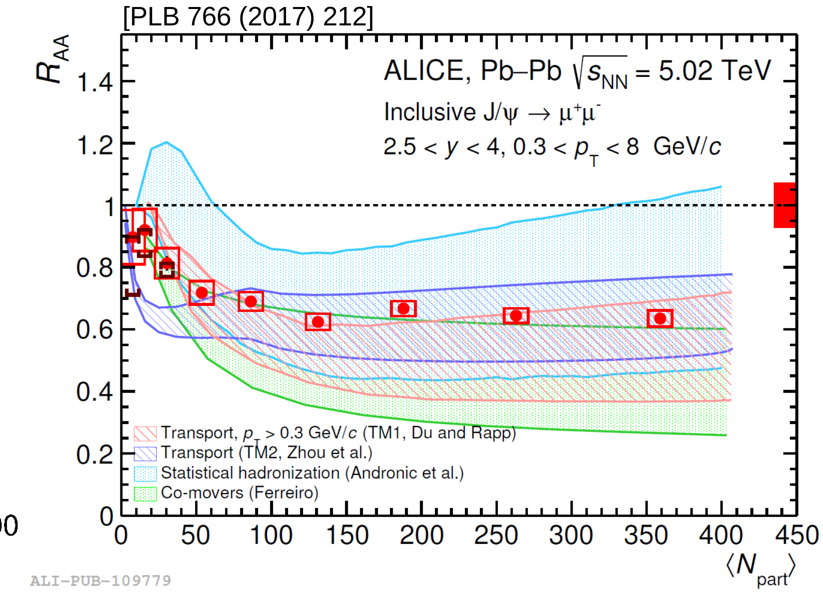




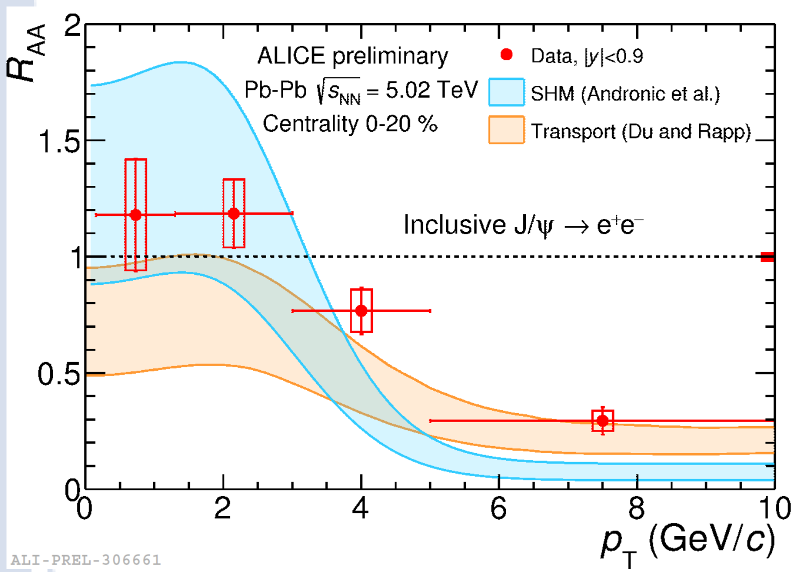
Nuclear modification factor R_{AA}

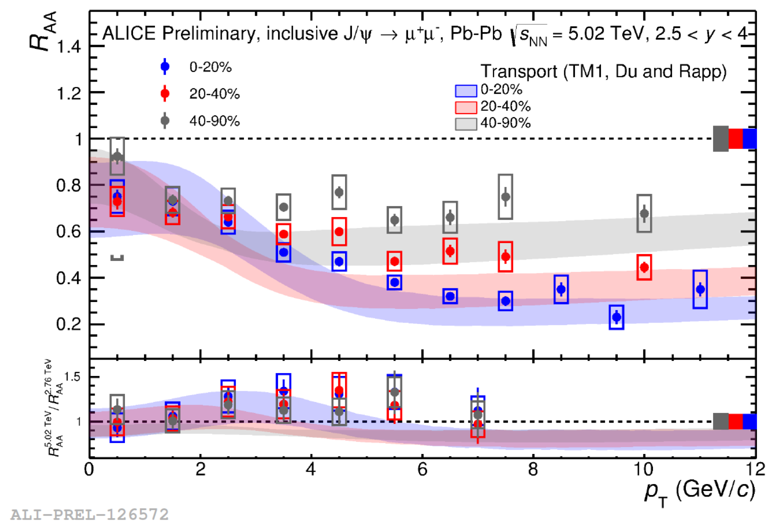
fwd-y × mid-y





- Models including recombination describe the centrality dependence of the data





- p_T dependence described qualitatively well by transport and statistical hadronization models

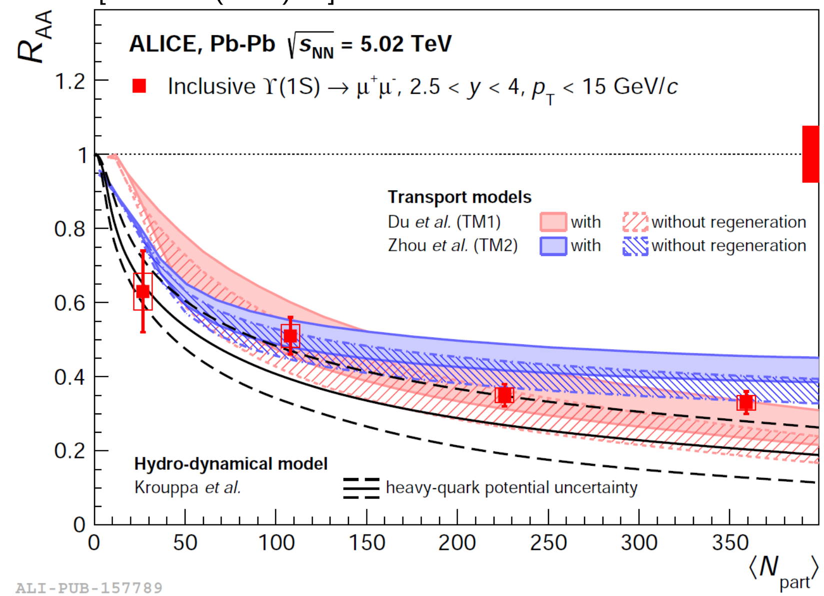
- **More precise measurements of σ_{cc} needed to improve discrimination among models**

Bottomonium R_{AA}

fwd-y

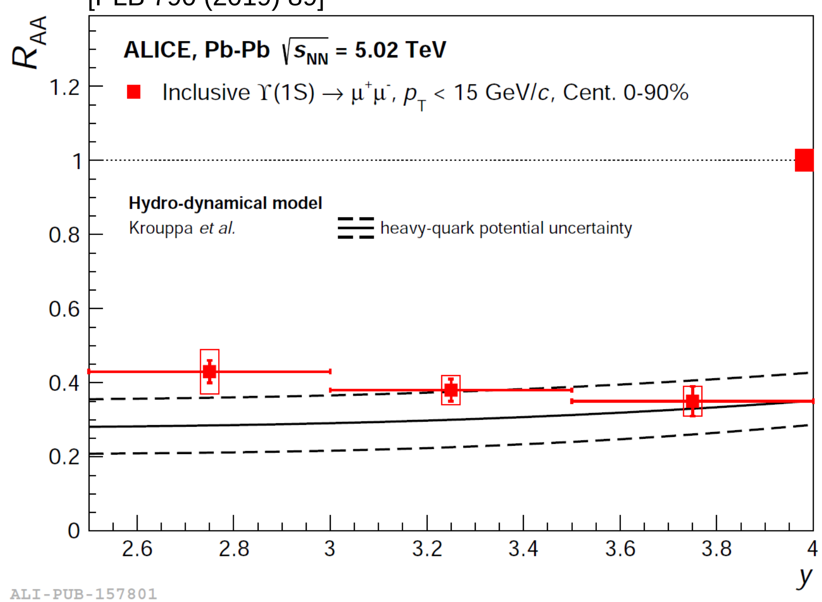
- Strong suppression of Υ(1S) seen towards central collisions
- models agree with the data within current uncertainties
  - no sensitivity to recombination component in the beauty sector
  - more precise measurements of feed-down fractions needed
- No significant dependence observed for Υ(1S) R_{AA} with rapidity and transverse momentum

[PLB 790 (2019) 89]

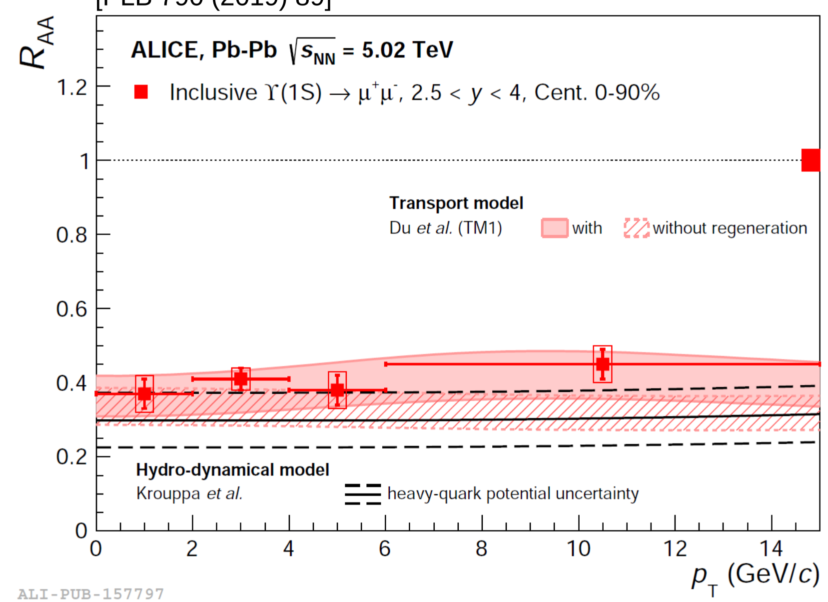


- $R_{AA}^{\Upsilon(2S)}/R_{AA}^{\Upsilon(1S)} = 0.28 \pm 0.12(\text{stat.}) \pm 0.06(\text{syst.})$ [p_T > 0]

[PLB 790 (2019) 89]

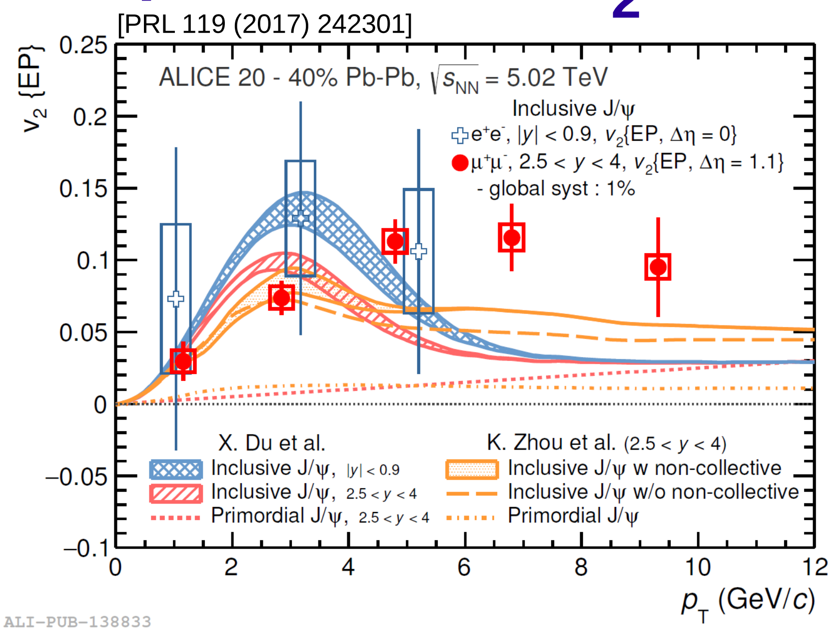


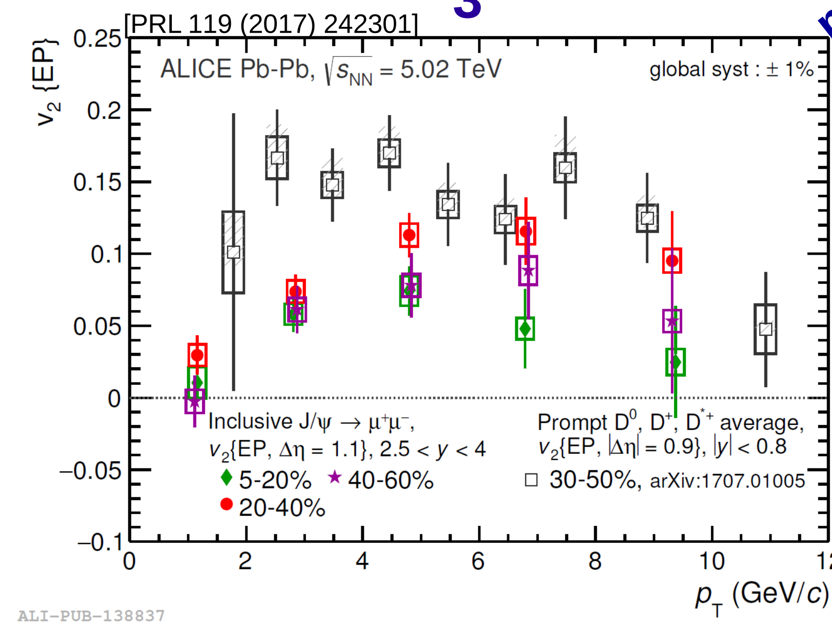
[PLB 790 (2019) 89]



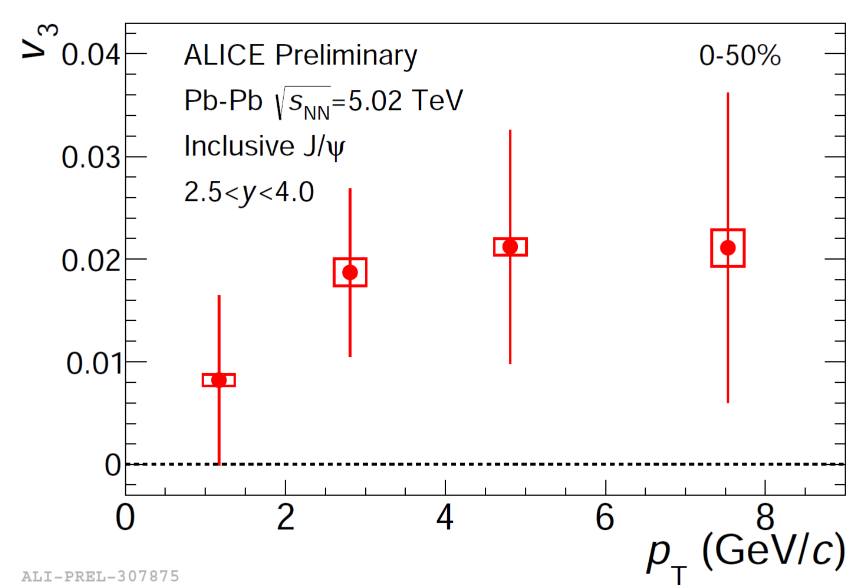
J/ψ elliptic (v_2) and triangular (v_3) flow

fwd-y × mid-y

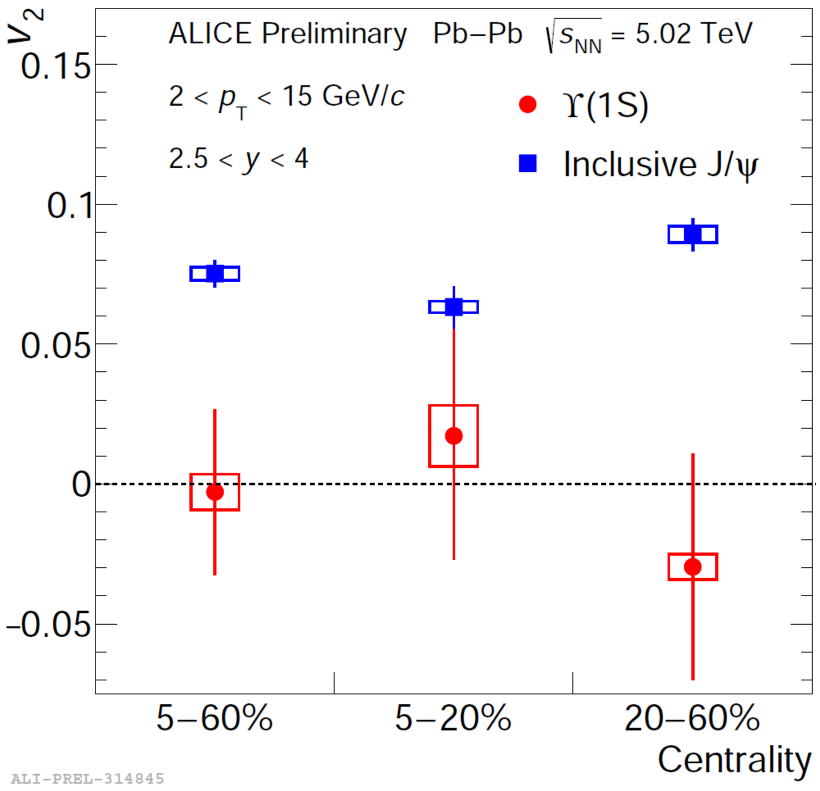


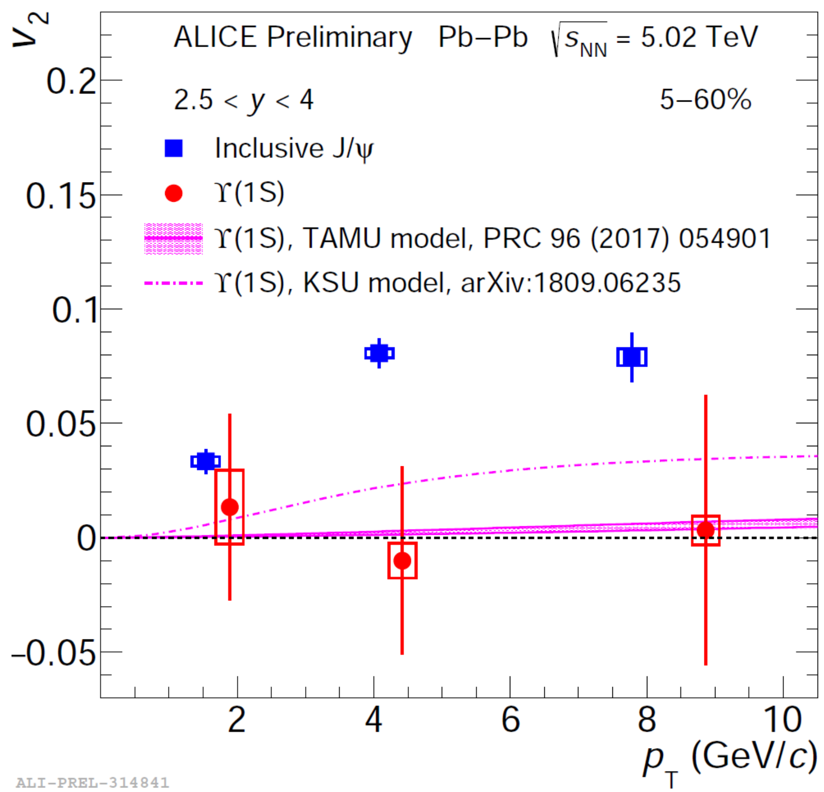


- Evidence of J/ψ v_2 > 0 at both central and forward rapidity
  - low p_T: J/ψ v_2 consistent with **hydrodynamic flow of charm quarks in QGP** → regenerated J/ψ inherit flow from deconfined (thermalized) charm quarks
  - high p_T: lower v_2 predicted by models
  - consistent with results of open-charm flow
- First observation of **positive J/ψ v_3** in Pb-Pb collisions (3.7σ significance)
  - v_3 sensitive to fluctuations of initial nucleon distributions in the overlap region



Υ(1S) elliptic flow





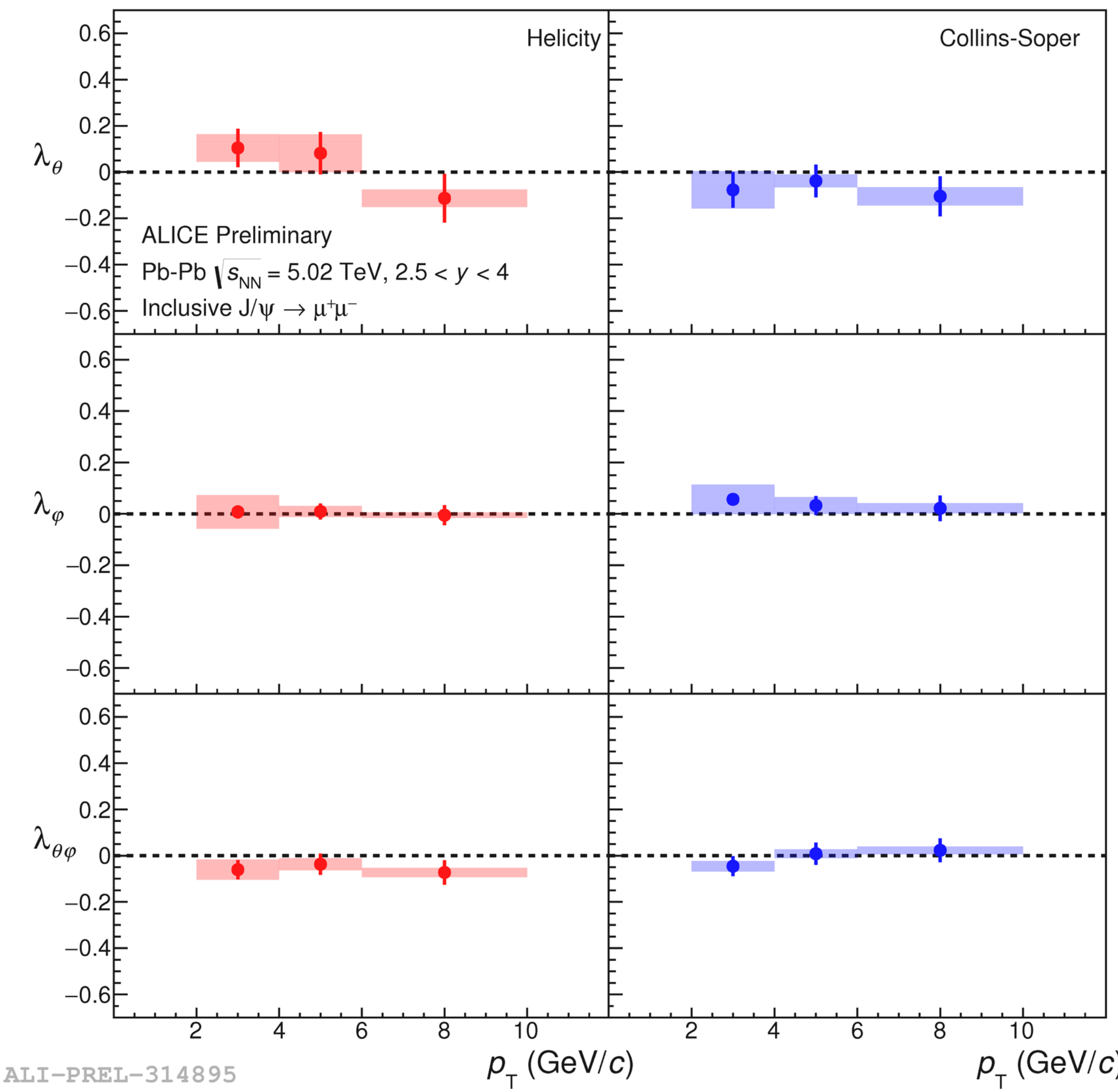
- Analysis based on Pb-Pb data collected in 2015 and 2018
- Υ(1S) v_2 compatible with zero and smaller than that of inclusive J/ψ (2.6σ significance excluding the lowest p_T bin)
  - different relative importance of production mechanisms (dissociation vs regeneration) for J/ψ and Υ(1S) ?
- Results compatible within uncertainties with values predicted by theoretical models:
  - Regeneration included in TAMU, but it gives no significant contribution to the Υ(1S) v_2
  - differences between TAMU and KSU arise from dissociation mechanism and medium properties implemented

J/ψ polarization in Pb-Pb collisions

NEW

First measurement in heavy-ion collisions at the LHC !

- polarization parameters studied through the angular distributions of leptons in the quarkonium rest frame
  - values close to zero in both Collins-Soper and Helicity frame



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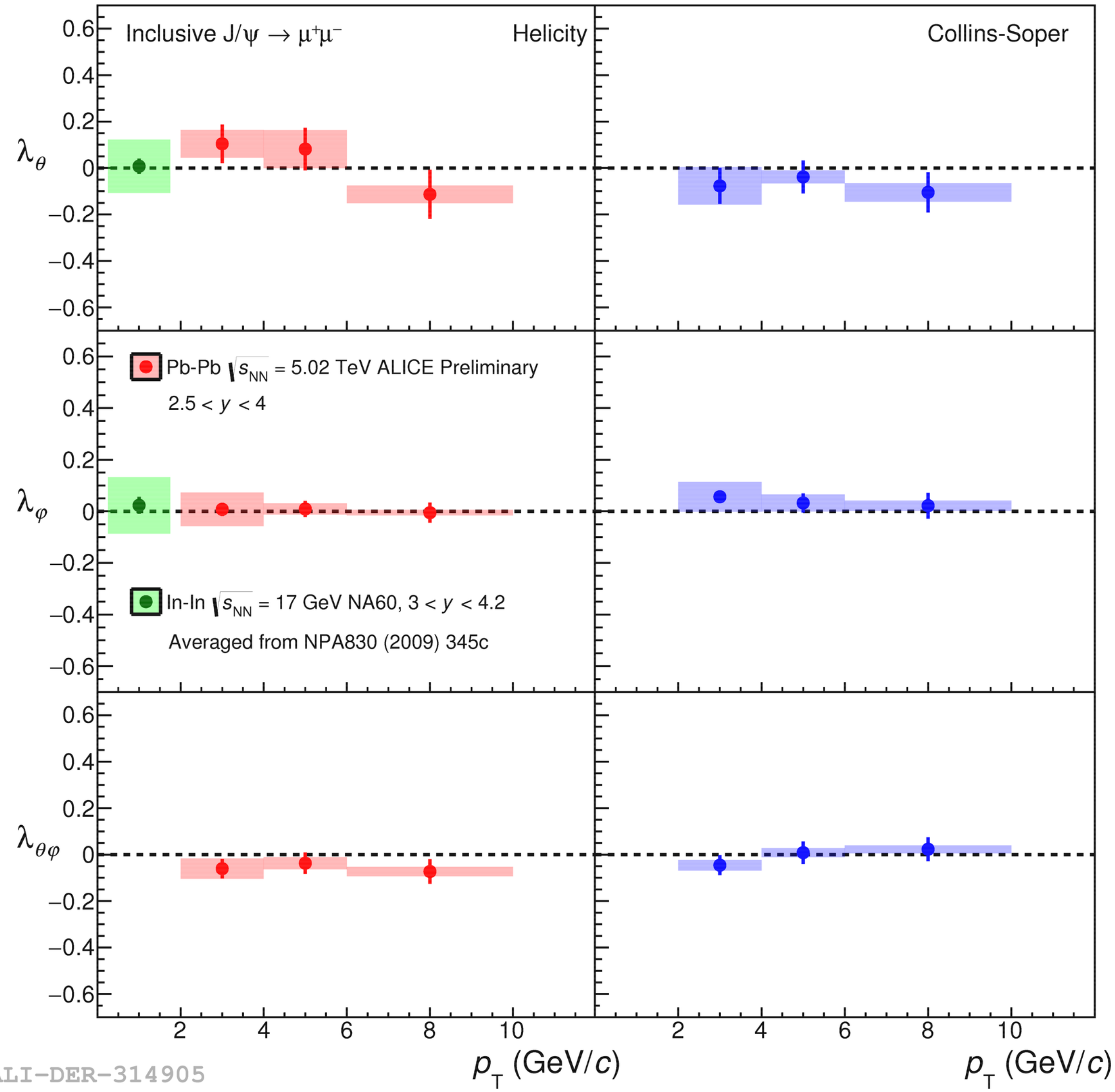

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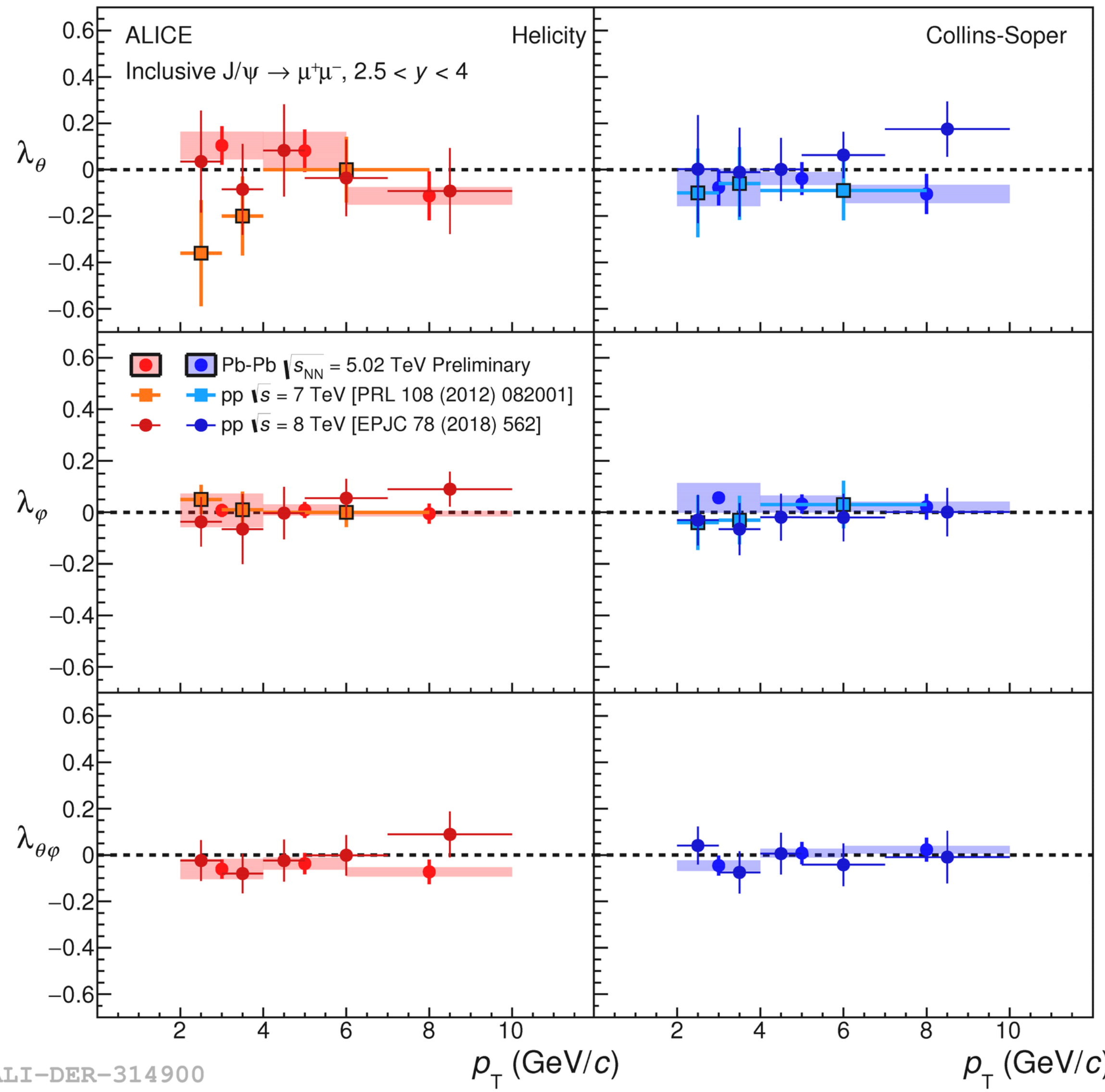
- Results compatible with other ALICE measurements in pp collisions at different $\sqrt{s}$



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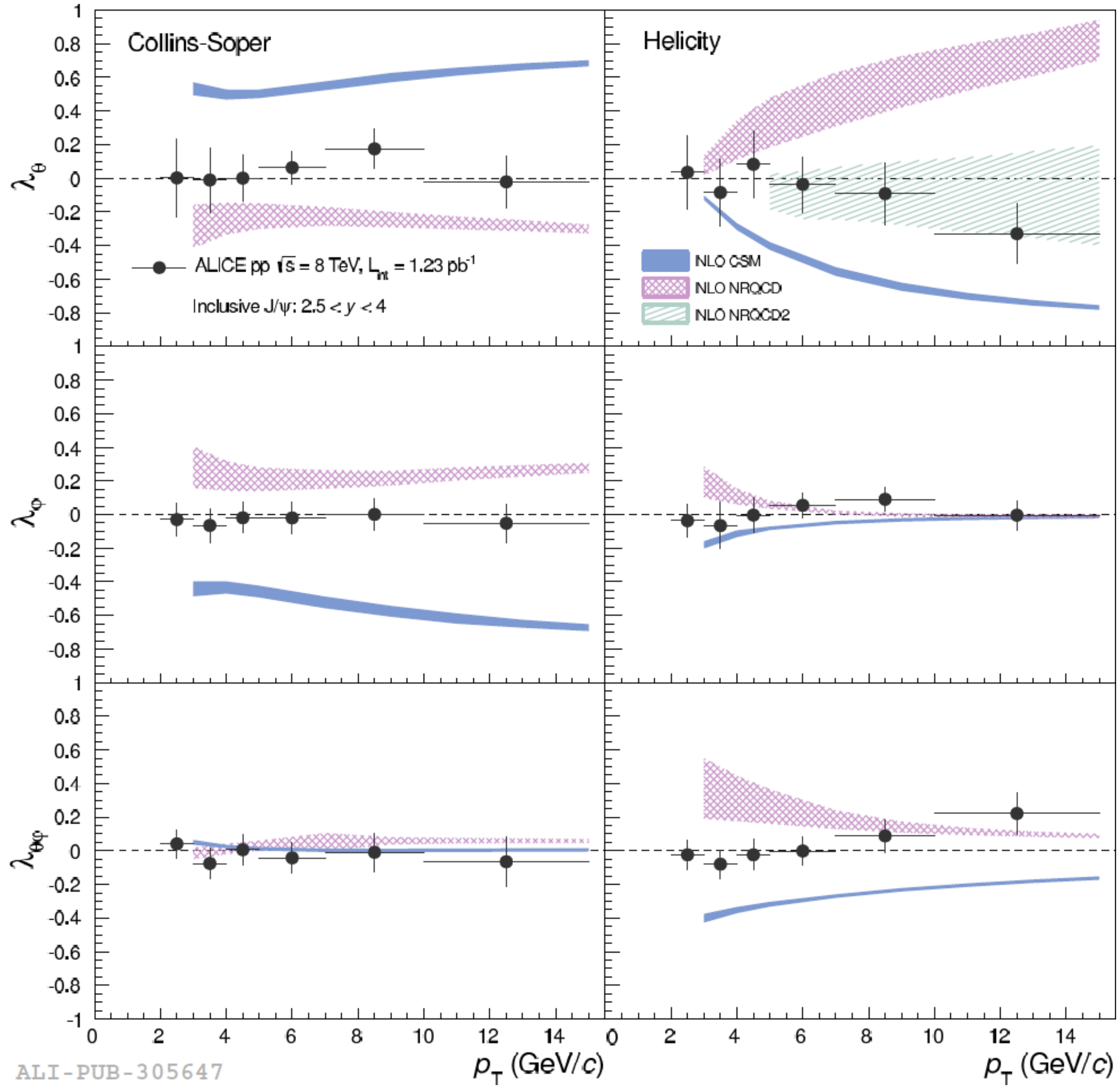
- Negligible polarization measured also by NA60 in In-In collisions at $\sqrt{s_{NN}}$ = 17 GeV
- Results compatible with other ALICE measurements in pp collisions at different $\sqrt{s}$
- Powerful tool for **constrain models** → currently none of them is able to describe observed measurements already in pp collisions

[Eur. Phys. J. C (2018) 78]



Outline

- ✔ Quarkonium measurements in ALICE
- ✔ pp collisions: baseline production
- ✔ p-Pb collisions: study Cold Nuclear Matter (CNM) effects
- ✔ Pb-Pb: study the properties of the hot and dense medium
- ✔ Conclusions and perspectives

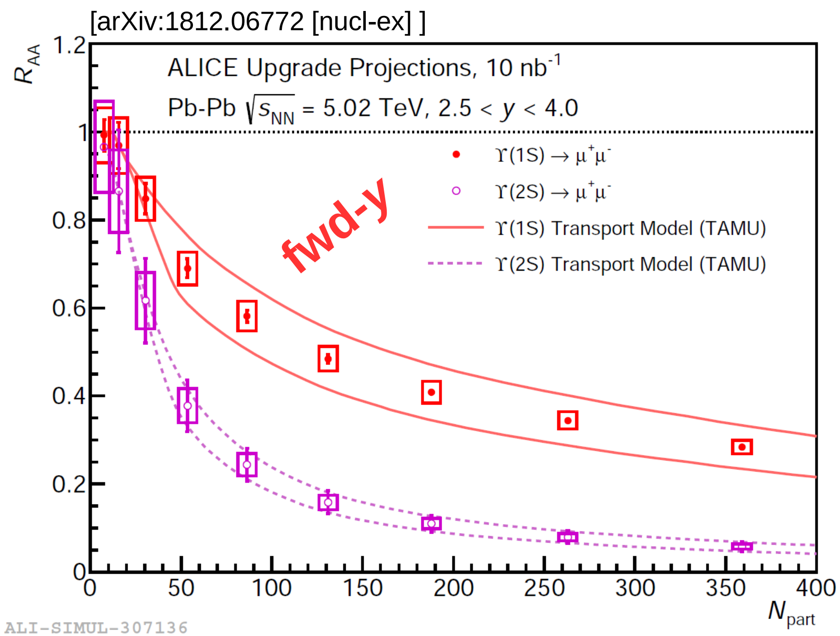
Conclusions

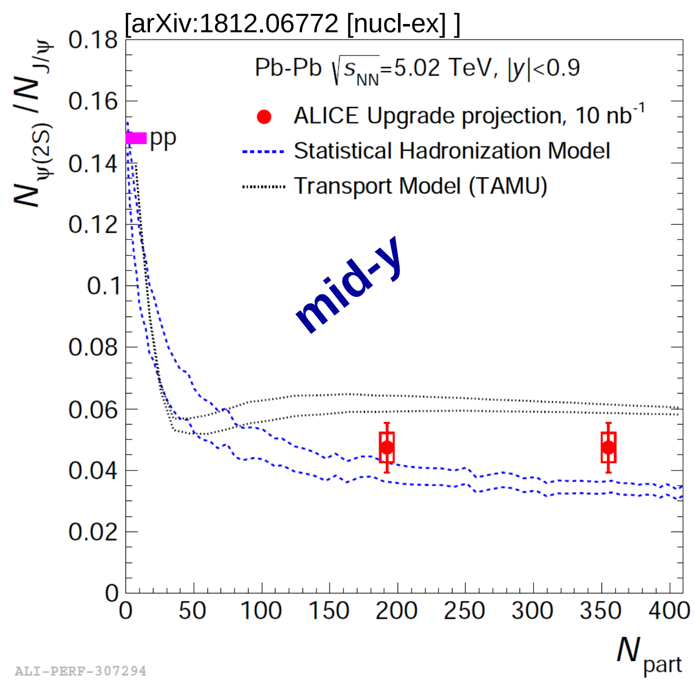
Impressive amount of quarkonium measurements provided by ALICE:

- **pp collisions:**
  - Fair description of the data provided by NRQCD(+CGC) in a wide range of momentum and rapidity
  - Some tensions still present between data and models (ψ(2S) / J/ψ ratio, J/ψ polarization)
  - Multiplicity dependence: models including HF-production in MPI describe qualitatively the observed trends
- **p-Pb collisions:**
  - Models are not able to describe consistently all quarkonium results
  - Final-state effects needed to describe the ψ(2S) suppression at backward rapidity
  - Positive elliptic flow v_2, comparable with Pb-Pb values → common underlying mechanism? Initial conditions ?
- **Pb-Pb collisions:**
  - J/ψ results at both mid- and forward rapidity consistent with significant contribution from regeneration mechanism → **Need higher precision on models (and data as well) for a better discrimination**
  - Strong suppression of Υ(1S) towards central Pb-Pb collisions; no significant dependence on y and p_T
  - Flow:
    - v_2 of J/ψ suggests thermalization of charm quarks within the medium; positive v_3 of J/ψ with 3.7σ significance observed
    - Υ(1S) v_2 compatible with zero and with values predicted by models
  - New polarization measurements in Pb-Pb compatible with zero and with pp results

Perspectives

- ALICE Upgrade foreseen for Run III-IV:
  - Continuous readout: high statistics minimum bias sample **(target for Pb-Pb: L_{int} = 10 nb^{-1})** → significant improvement for low p_T quarkonia at mid-rapidity
  - New Muon Forward Tracker (MFT) at forward rapidity → reconstruction of secondary vertices possible





- Improved precision for existing quarkonium measurements down to p_T = 0
- New measurements will become accessible

Stay tuned!

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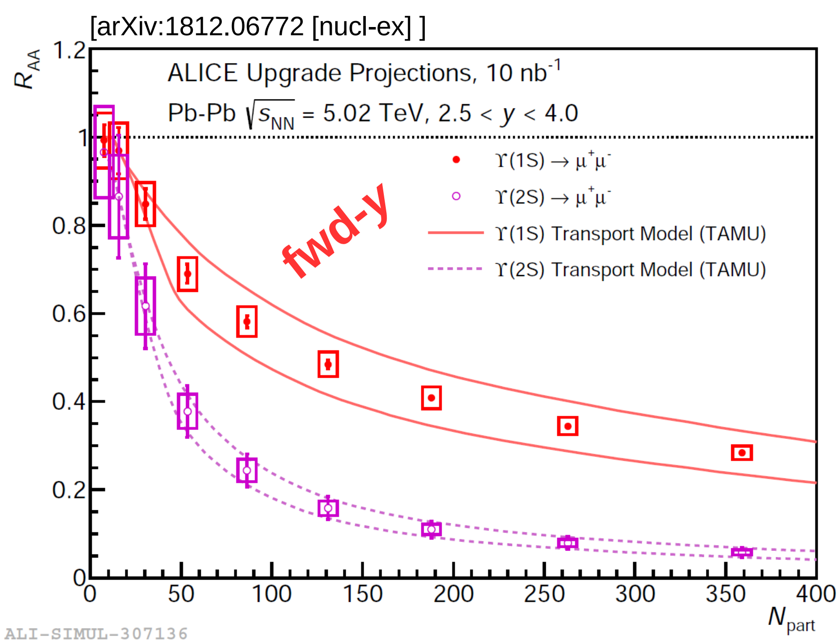
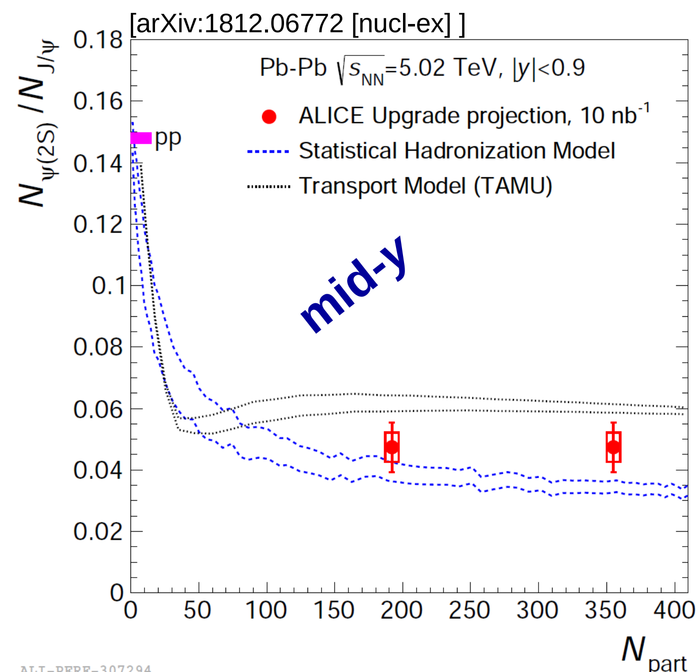




- Improved precision for existing quarkonium measurements down to p_T = 0
- New measurements will become accessible

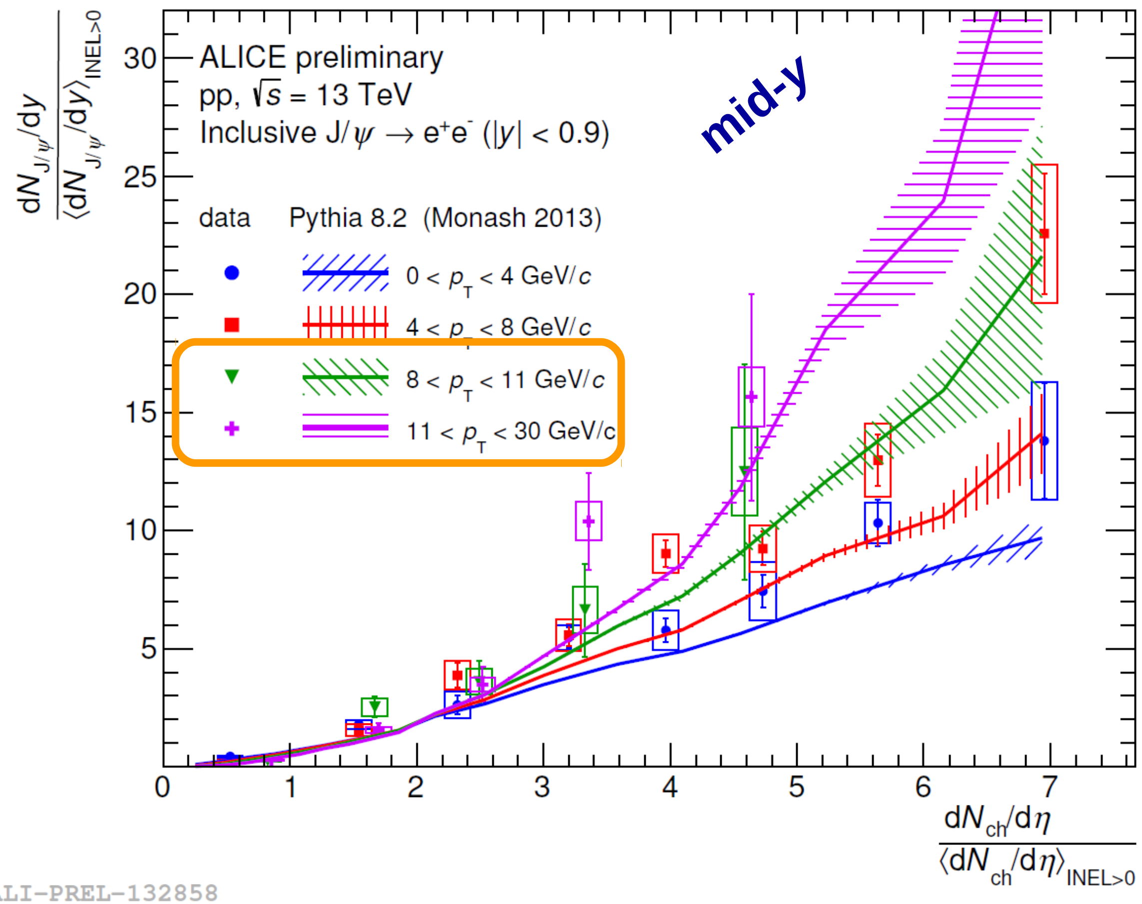
Stay tuned!

Дякую за увагу !

Thank you for your attention !

BACK-UP

Quarkonia vs multiplicity



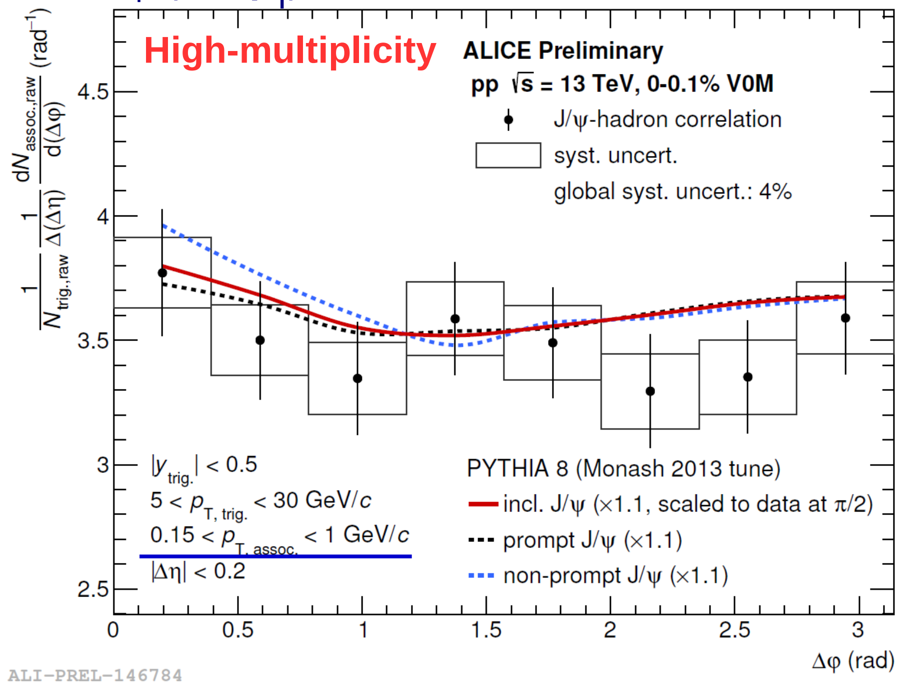
- **EMCAL** analysis significantly extends the p_T range (up to 30 GeV/c)
- PYTHIA8 calculations qualitatively describe the p_T dependent trends seen in data

- Faster than linear increase observed also in p_T bins
- Slope increases with the transverse momentum of J/ψ

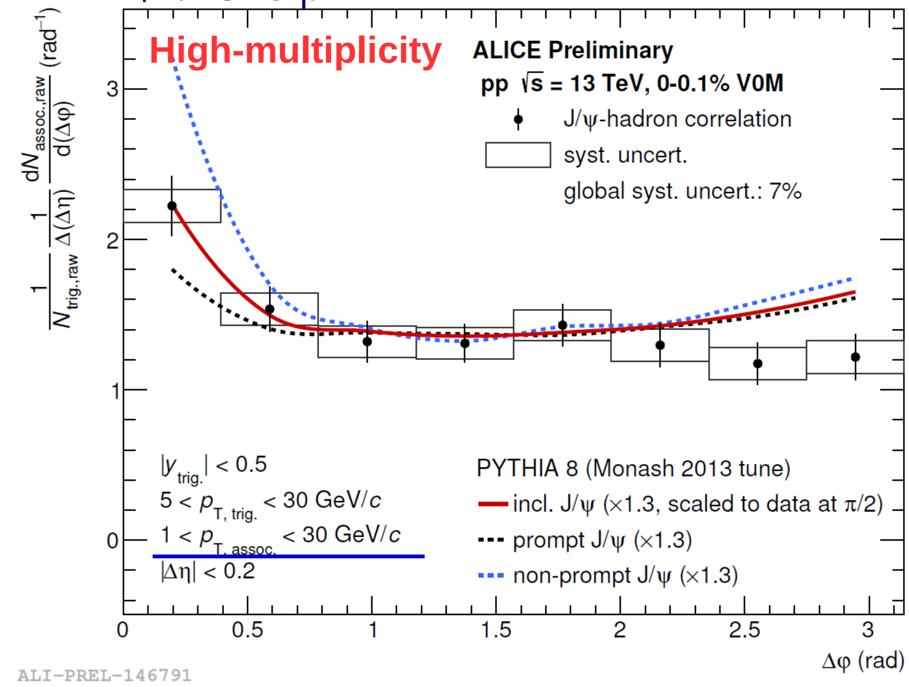
J/ψ-hadron correlations

mid-y

J/ψ-(**low-p_T**)-hadron correlations



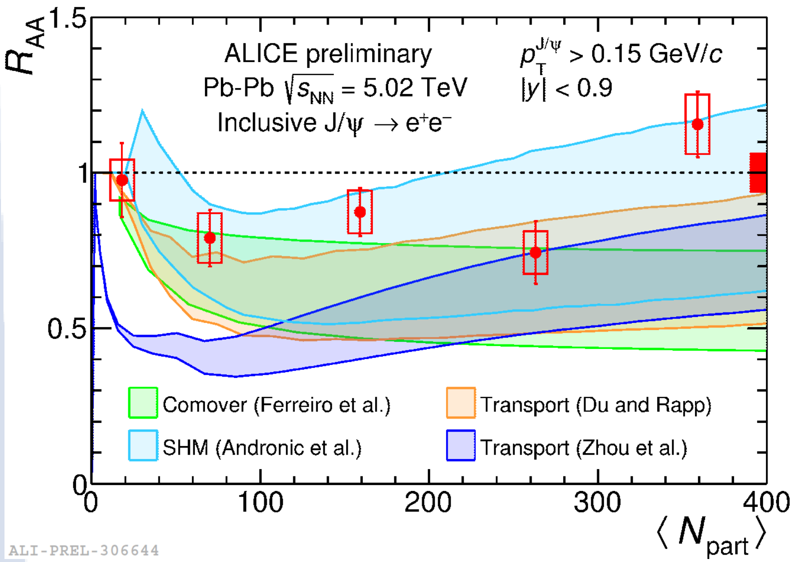
J/ψ-(**high-p_T**)-hadron correlations

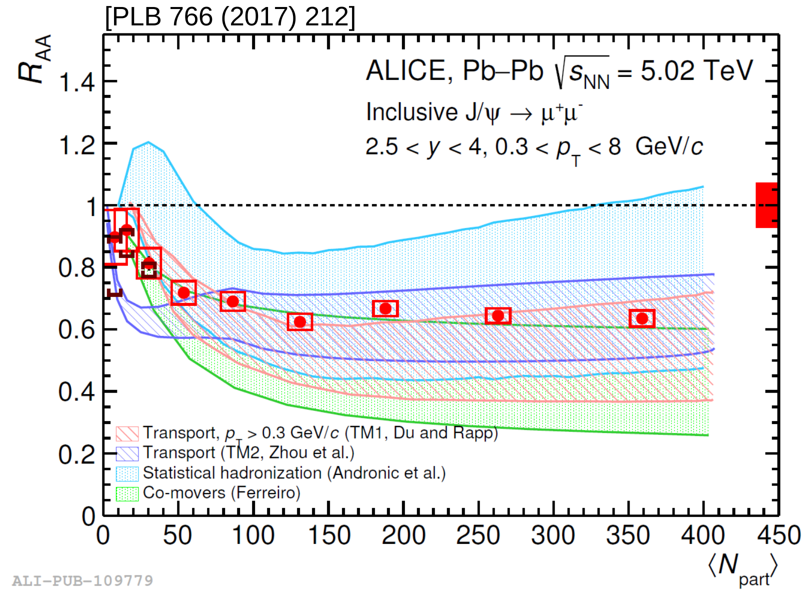


- ✔ Clear near side peak observed by correlating high-p_T J/ψ (p_T > 5 GeV/*c*) and hadrons with p_T > 1 GeV/*c*
- ✔ Qualitative good agreement observed with PYTHIA8 simulations
- ✔ Usage of full Run II statistics (gain of a factor ~100 expected for p_T (J/ψ) > 5 GeV/*c*) will improve significantly uncertainties allowing finer kinematic scan → **powerful tool to constrain models!**

Nuclear modification factor R_{AA}

fwd-y × mid-y

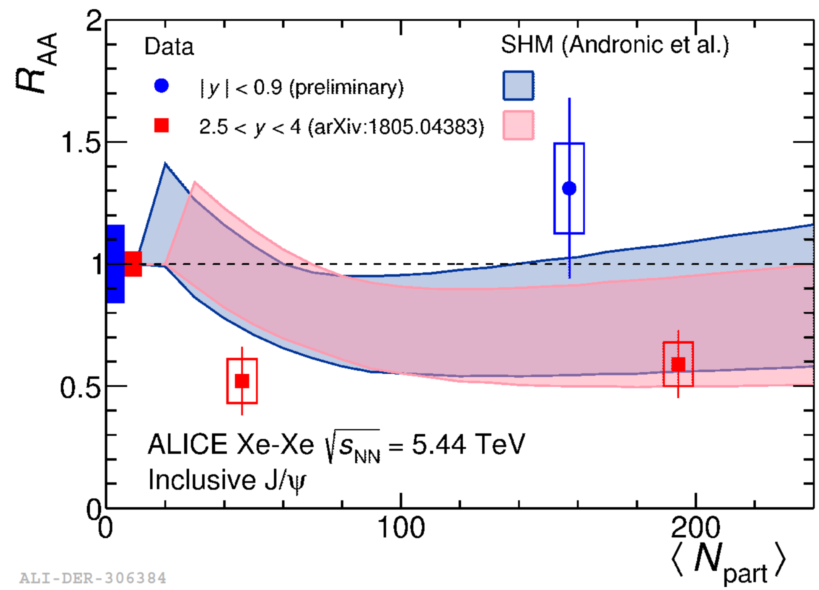




- Models including recombination describe the centrality dependence of the data

Xe-Xe collisions

- Study nuclear modification in a smaller collision system (same fireball volume with different shape at fixed ⟨N_{part}⟩)
- Large statistical uncertainties for measured R_{AA}
- Statistical hadronization model consistent with data; similar agreement observed also with transport model (not shown)

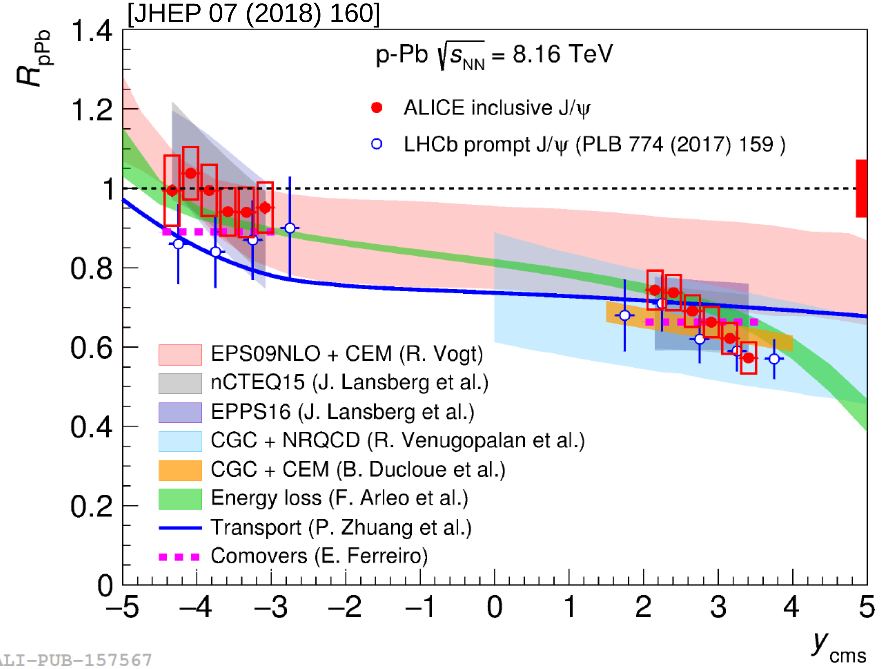


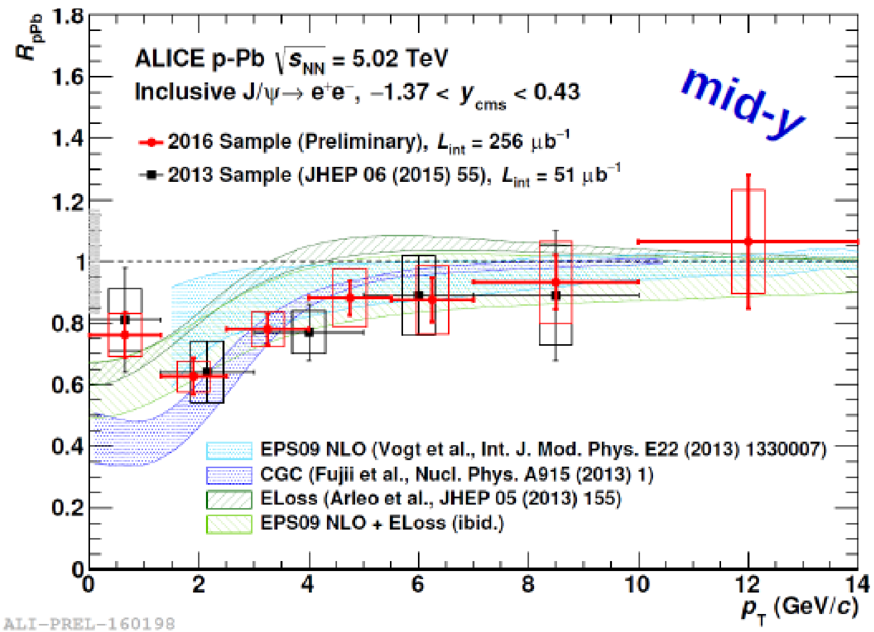
Nuclear modification factor R_{pPb}

Nuclear modification factor R_{pPb} is used to quantify medium effects:

$$R_{\mathrm{pA}}(y, p_{\mathrm{T}}) = \frac{1}{A}\frac{\mathrm{d}^2\sigma_{\mathrm{pA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}$$

- ✔ Stronger J/ψ suppression observed at forward rapidity
- ✔ R_{pPb} compatible with unity at backward rapidity
- ✔ Good agreement between ALICE and LHCb results
- ✔ Fair agreement between data and models within the current experimental and theoretical uncertainties





- ✔ Similar increasing trend of R_{pPb} at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV with p_{T} at mid-rapidity
- ✔ R_{pPb} consistent with unity for p_{T} > 5 GeV/c
- ✔ fair agreement with models within uncertainties

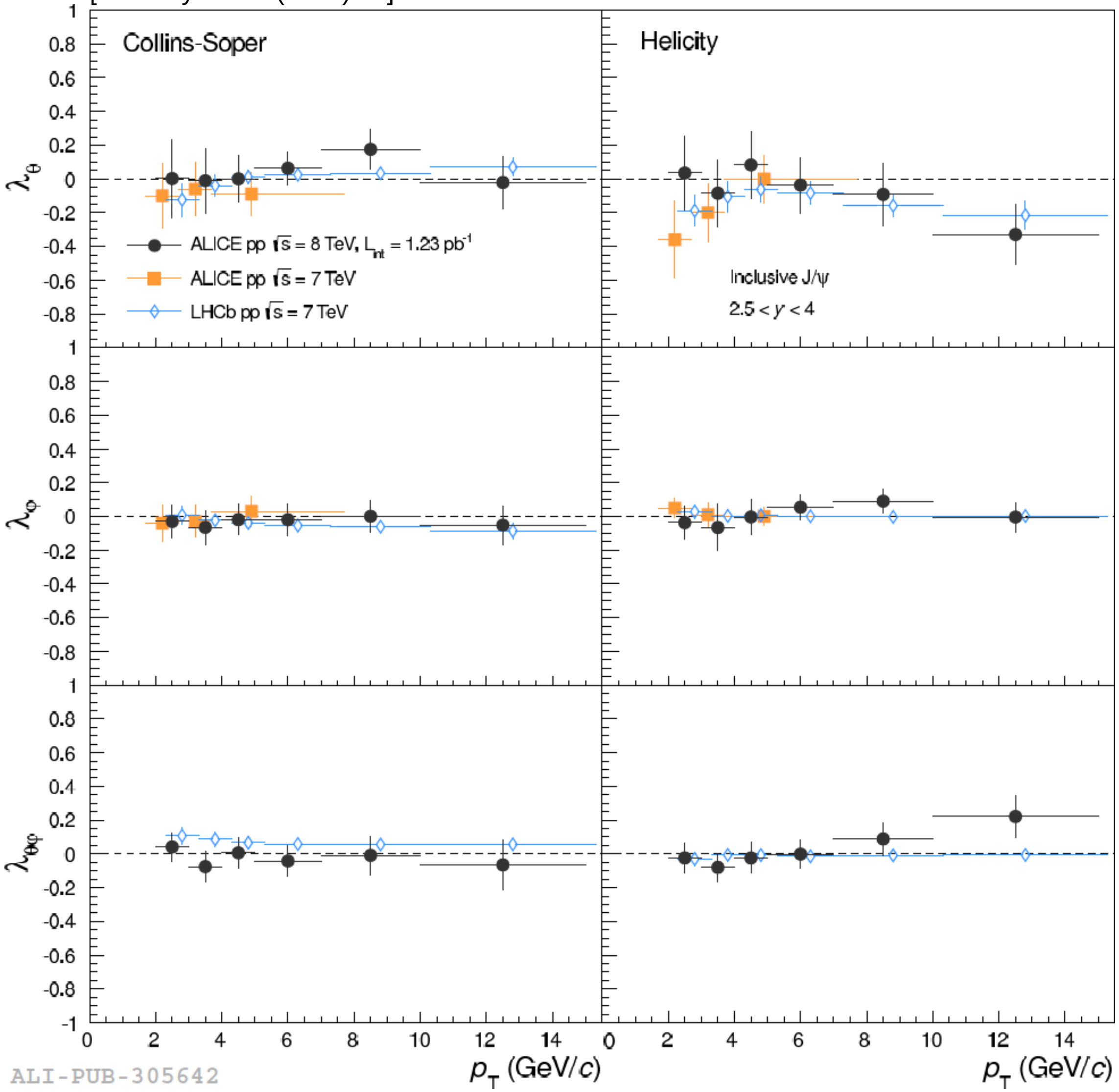
J/ψ polarization

fwd-y

- Polarization parameters studied through the angular distributions of leptons in the quarkonium rest frame
- Measurements performed in different polarization frames (Helicity and Collins-Soper)
- No significant J/ψ polarization observed
- Good agreement between ALICE and LHCb measurements at $\sqrt{s}$ = 7 TeV

$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}\left[1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\cos(2\varphi)+\lambda_{\theta\varphi}\sin(2\theta)\cos\varphi\right]$$

[Eur. Phys. J. C (2018) 78]



J/ψ polarization

fwd-y

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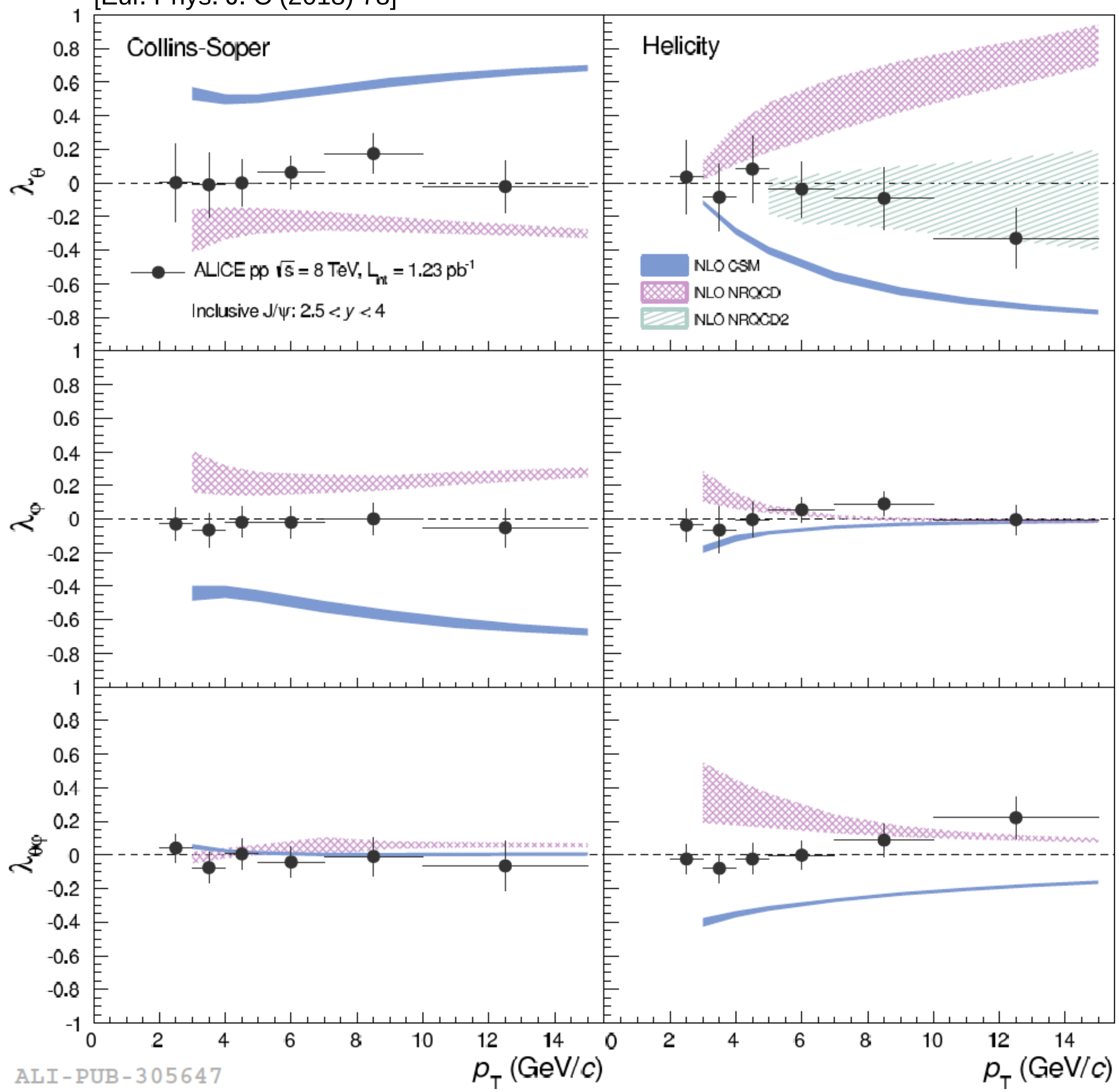
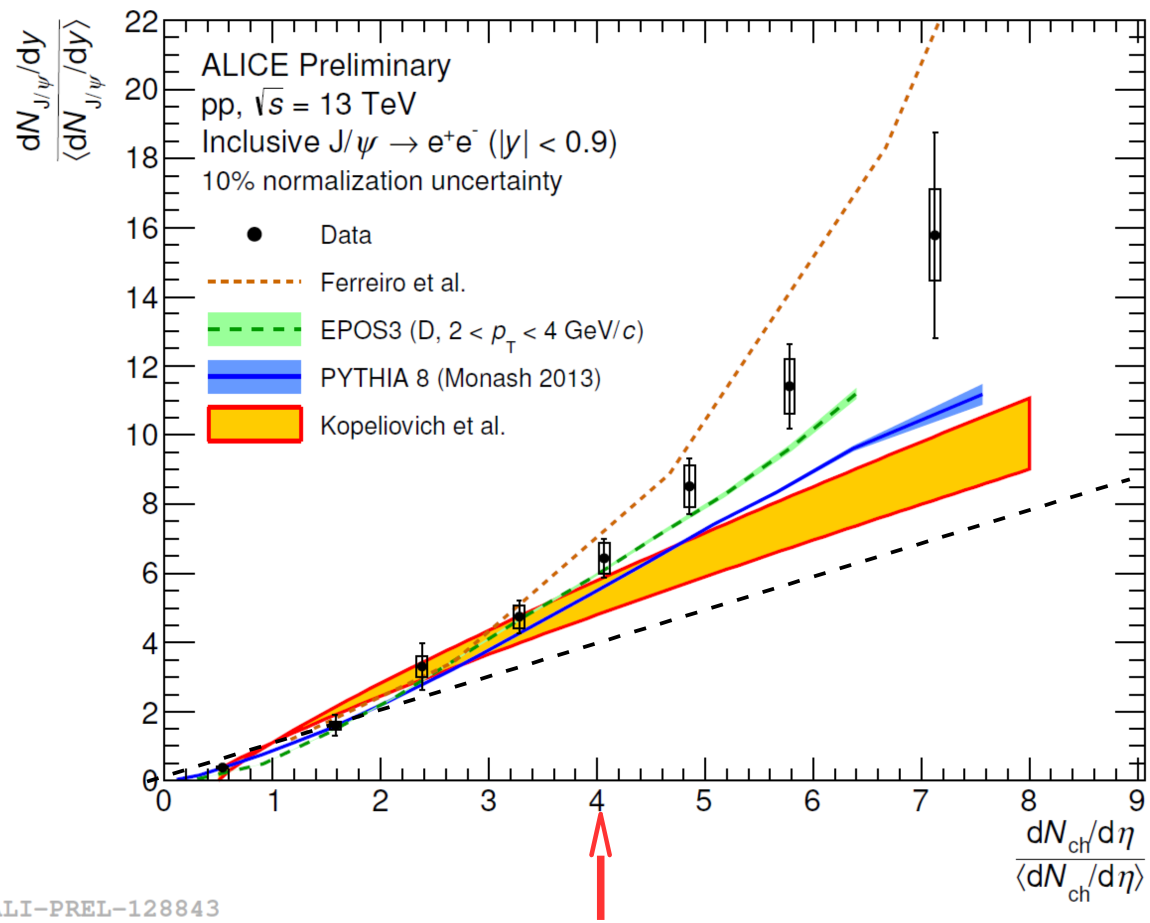


- Measurements performed in different polarization frames (Helicity and Collins-Soper)
- No significant J/ψ polarization observed
- Good agreement between ALICE and LHCb measurements at $\sqrt{s}$ = 7 TeV
- None of the models is able to describe simultaneously all measurements

Inclusive J/ψ yields vs multiplicity in pp at √s = 13 TeV



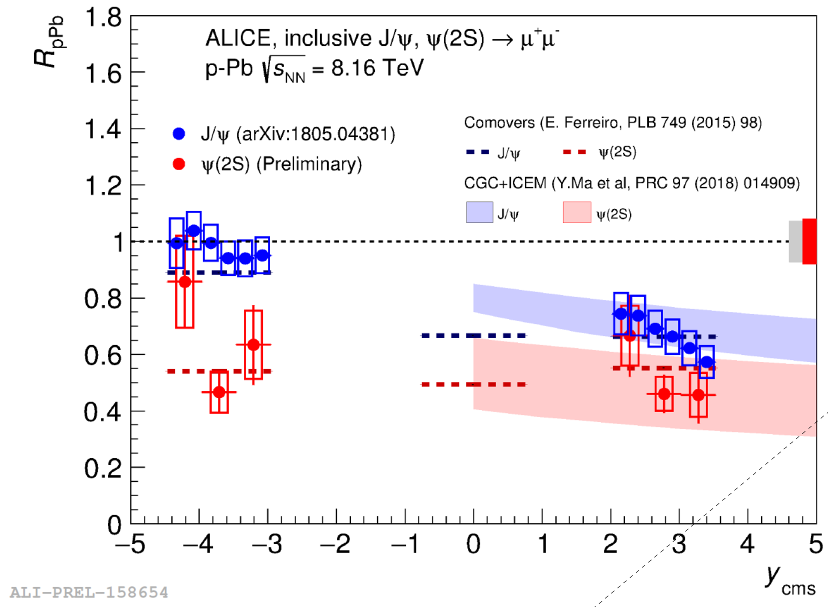
RUN I mult. reach for J/ψ

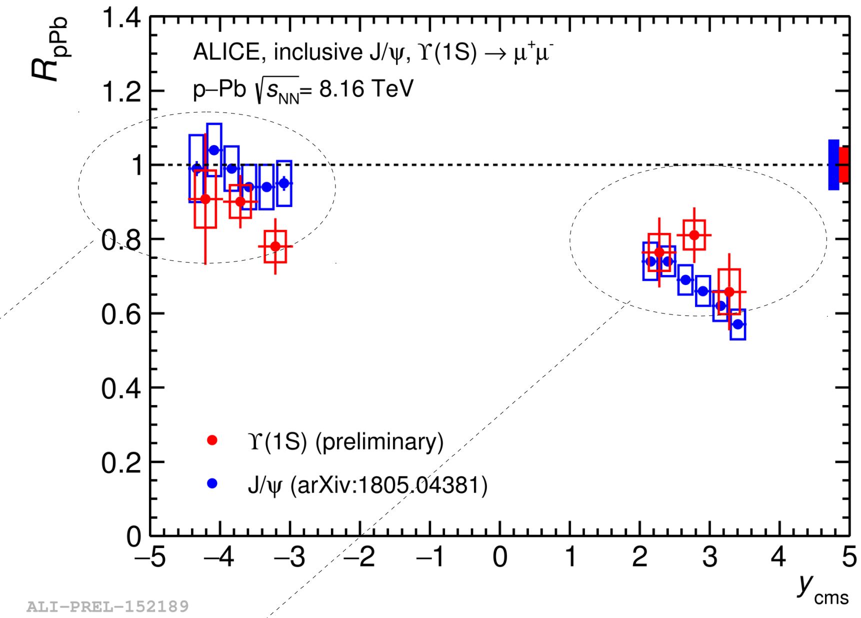
- ✔ **PYTHIA8 (Monash 2013)**
  - ✔ Initial hard processes
  - ✔ Hard processes in MPI
  - ✔ ISR / FSR
- ✔ **EPOS3**
  - ✔ Gribov-Regge formalism (MPI included)
  - ✔ Hydro evolution of the system
- ✔ **Kopeliovich et al.**
  - ✔ contributions of higher Fock states
- ✔ **Percolation model**
  - ✔ Soft sources stronger affected than hard sources with increasing density (multiplicity)

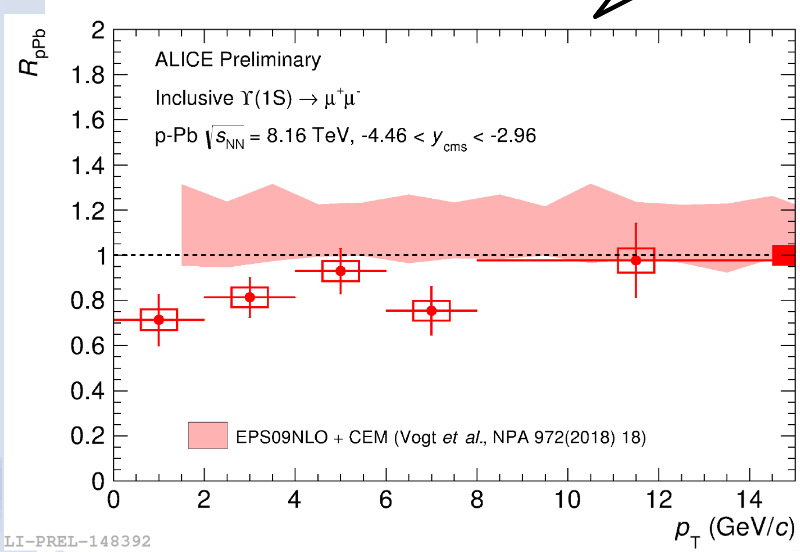
Ferreiro, Pajares, PRC86 (2012) 034903
EPOS3, Werner et al., Phys.Rept.350 (2001) 93
PYTHIA8, Sjostrand et al., Comput.Phys.Comm.178(2008)
Kopeliovich et al., PRD88 (2013) 116002

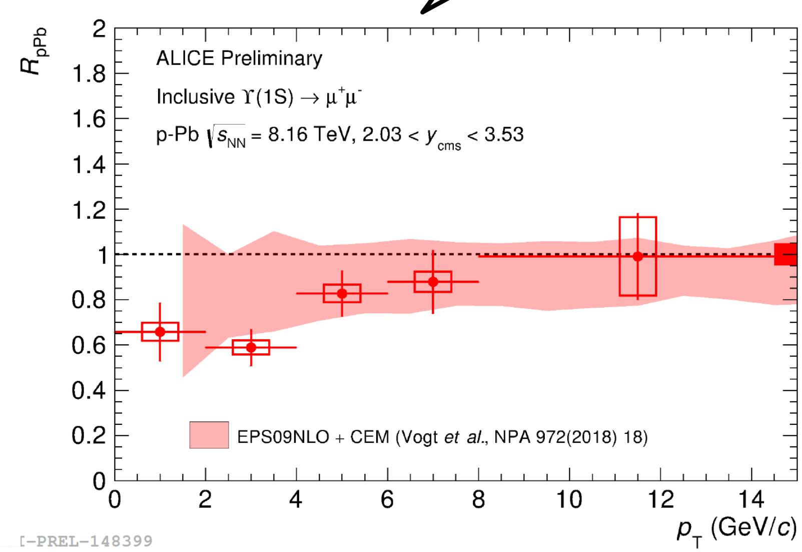
- ✔ Significantly higher multiplicities exploited thanks to high-multiplicity triggered data!
- ✔ Very similar trend observed for open and hidden HF measurements → confirmation of Run I results

Nuclear modification factor R_{pPb}





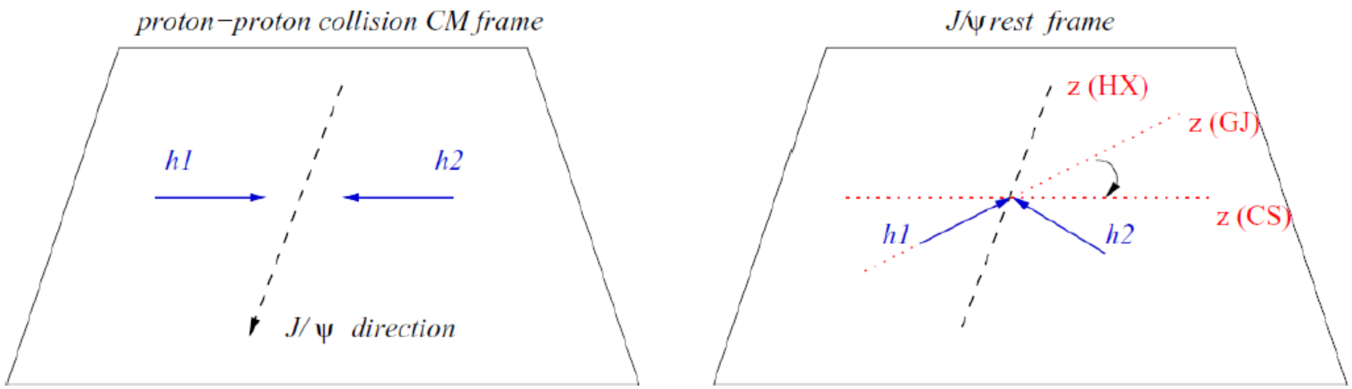




- ✔ Similar increasing trend at both backward and forward rapidity
- ✔ Model predicts almost no p_T dependence

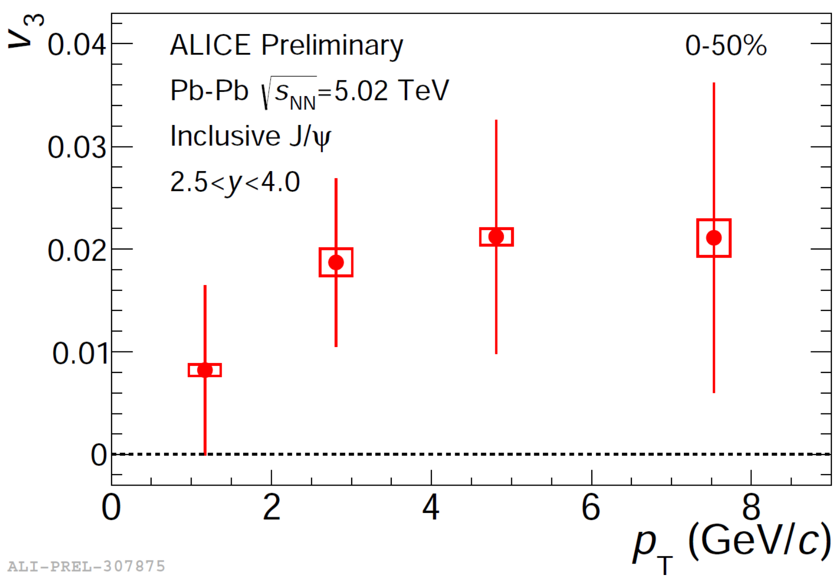
Polarization parameters

$$W(\cos\theta,\varphi) \propto \frac{1}{3+\lambda_\theta}\left[1+\lambda_\theta\cos^2\theta+\lambda_\varphi\sin^2\theta\cos(2\varphi)+\lambda_{\theta\varphi}\sin(2\theta)\cos\varphi\right]$$

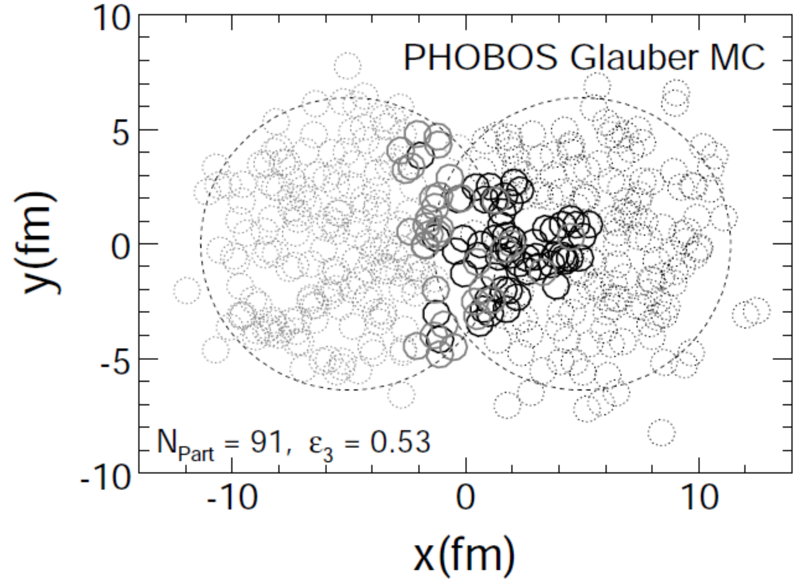


- **Helicity**: z-axis corresponds to the quarkonium flight direction in the center-of-mass of the colliding beams
- **Collins-Soper**: z-axis coincides with the bi-sector between the momenta of the two beams in the quarkonium rest frame

J/ψ triangular flow at forward-*y*



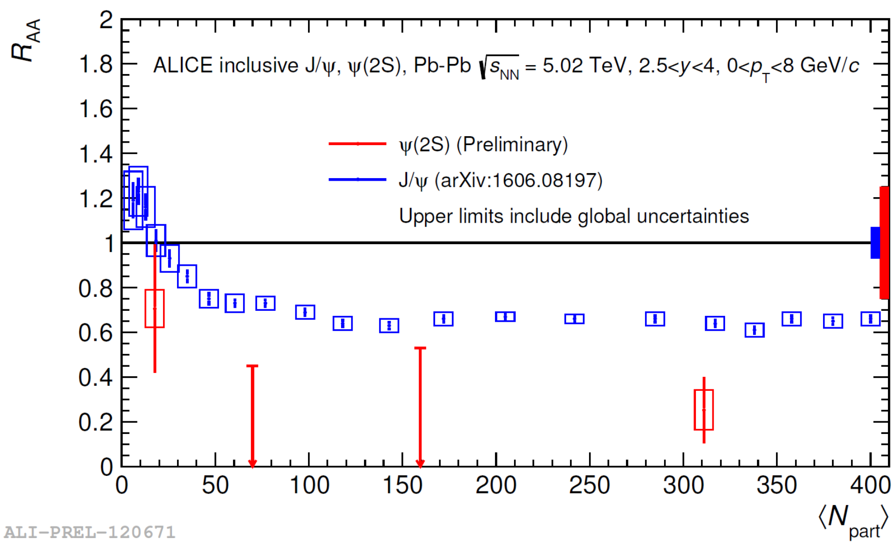
[PRC. 82. 039903]

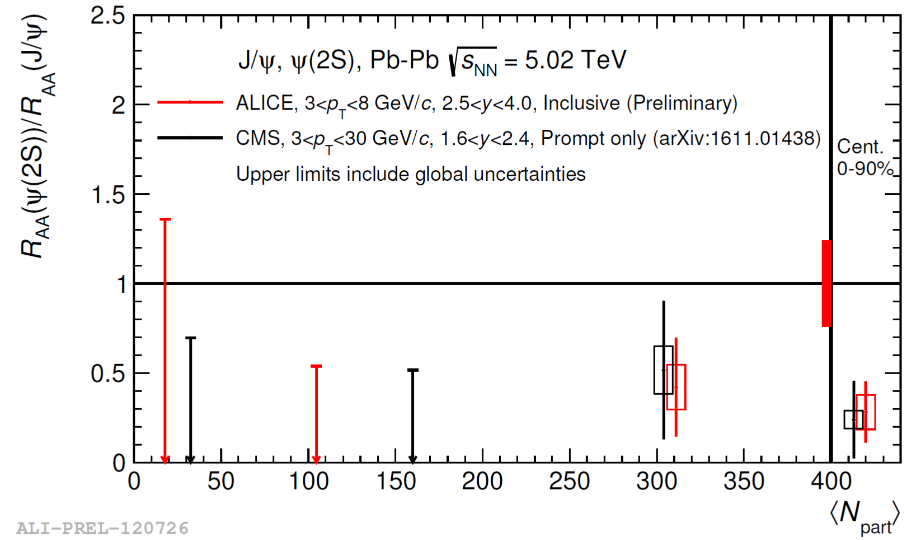


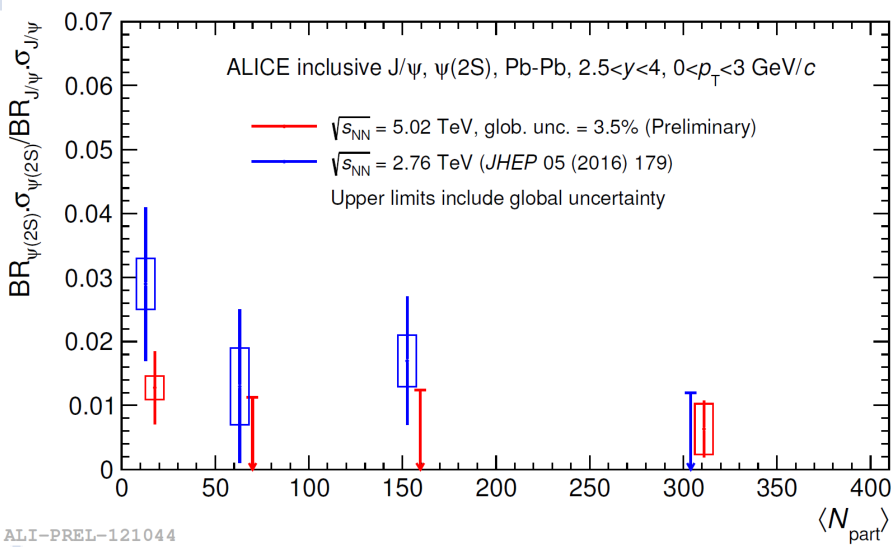
- First observation of **positive J/ψ v_3** in Pb-Pb collisions (3.7σ significance)
  - v_3 sensitive to fluctuations of initial nucleon distributions in the overlap region

FIG. 3: Distribution of nucleons on the transverse plane for a $\sqrt{s_{NN}} = 200$ GeV Au+Au collision event with ε_3=0.53 from Glauber Monte Carlo. The nucleons in the two nuclei are shown in gray and black. Wounded nucleons (participants) are indicated as solid circles, while spectators are dotted circles.

ψ(2S) in Pb-Pb collisions at 5.02 TeV







- ✔ ψ(2S) more suppressed than J/ψ towards more central collisions
- ✔ Results compatible with CMS
- ✔ More precise measurements expected thanks to 2018 Pb-Pb data