Quarkonium measurements at forward rapidity with ALICE at the LHC

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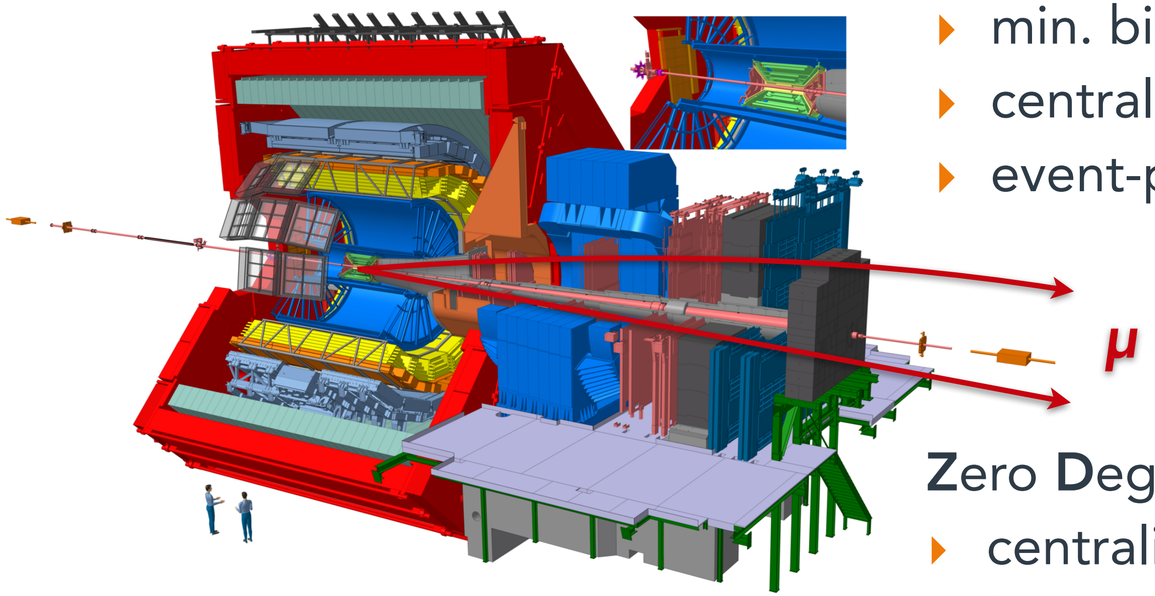
on behalf of the **ALICE collaboration**
EPS-HEP | Ghent 2019

A Large Ion Collider Experiment

Silicon **P**ixel **D**etector
- vertexing
- multiplicity

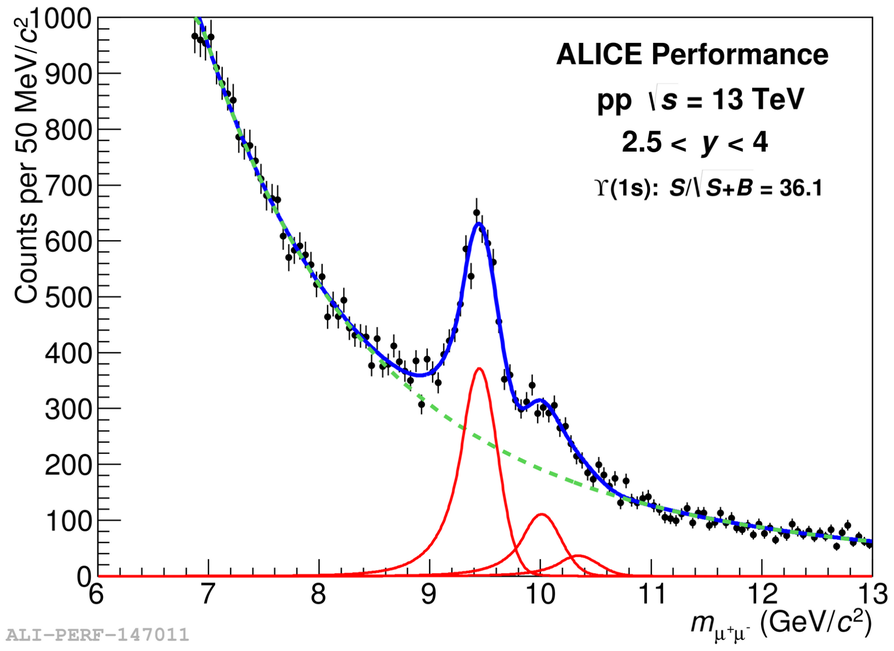
V0 detectors
- luminosity
- min. bias trigger
- centrality
- event-plane



Zero **D**egree **C**alorimeter
- centrality in p-Pb
- background rejection

Muon spectrometer (-4 < η < -2.5)
☛ trigger and tracking

Measurement of quarkonia at forward rapidity *via* **dimuon** decay channel, **down to p_T = 0**



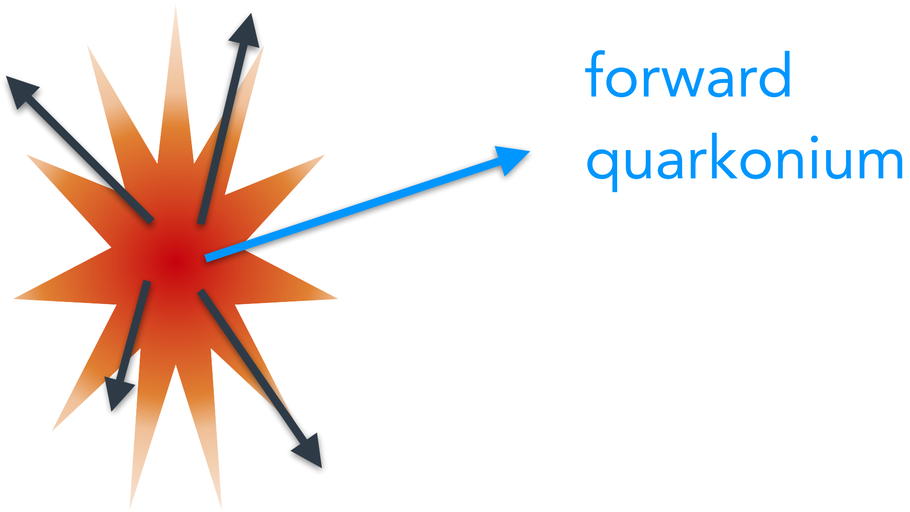
Event activity dependence

Physics motivations:

- test production mechanisms
- study the **role of multi-parton interactions in quarkonium production**
- observe potential *collective-like* effects in small systems

Correlation of forward quarkonium production with event activity at mid-rapidity

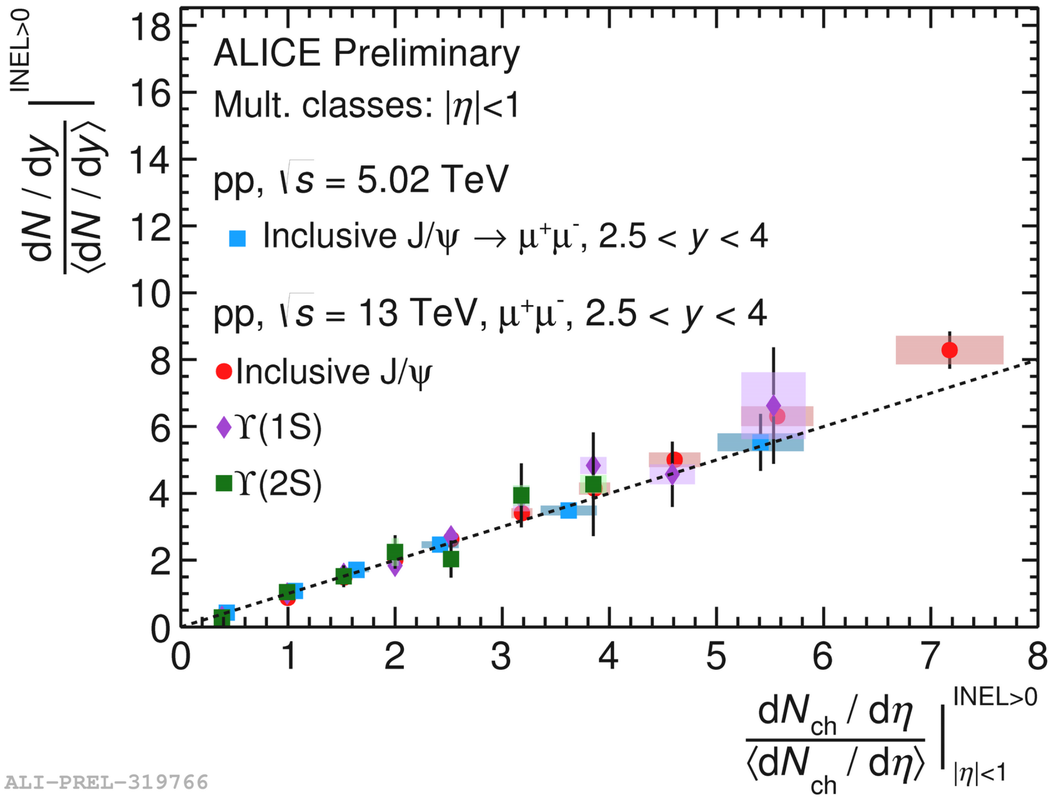
Presence of Cold Nuclear Matter effects in p-Pb to be taken into account



event activity in $|\eta| < 1$

Relative production yield

Dependence of self-normalised yield of quarkonium production on self-normalised charged-particle multiplicity density at mid-rapidity.



In pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV:

- **linear increase** with multiplicity
- independent of energy and quarkonium state

Relative production yield

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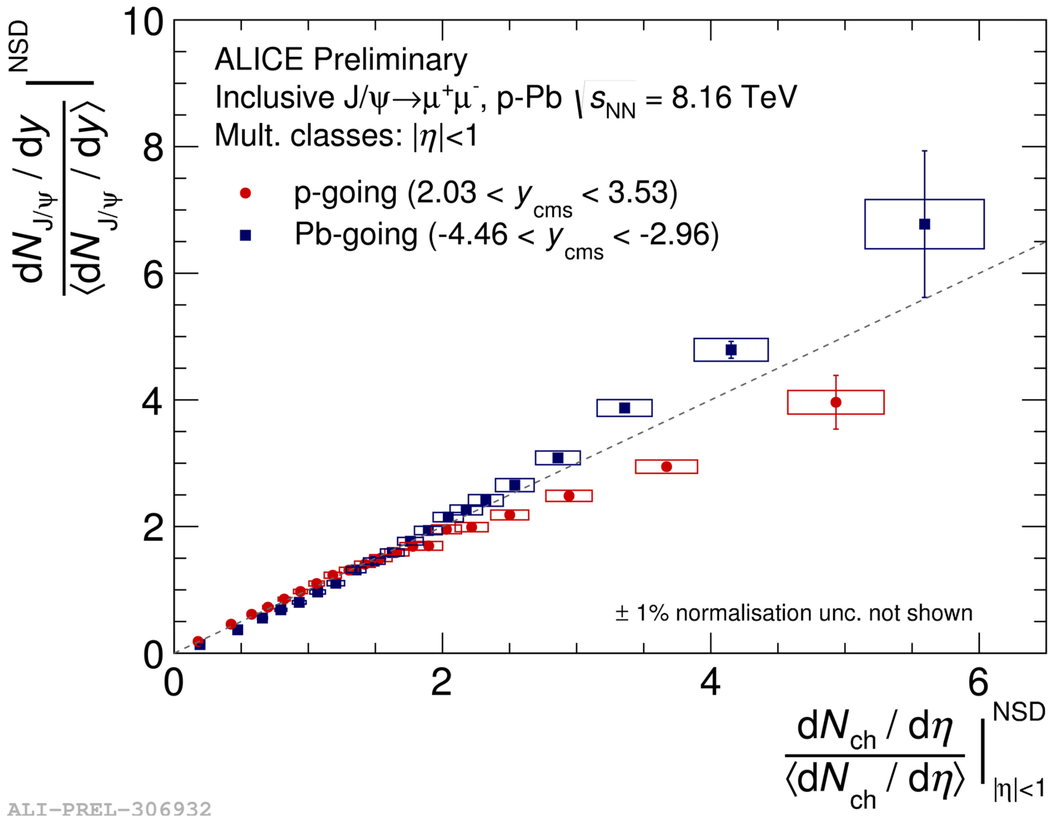


In pp collisions at $\sqrt{s}$ = 5.02 and 13 TeV:

- **linear increase** with multiplicity
- independent of energy and quarkonium state

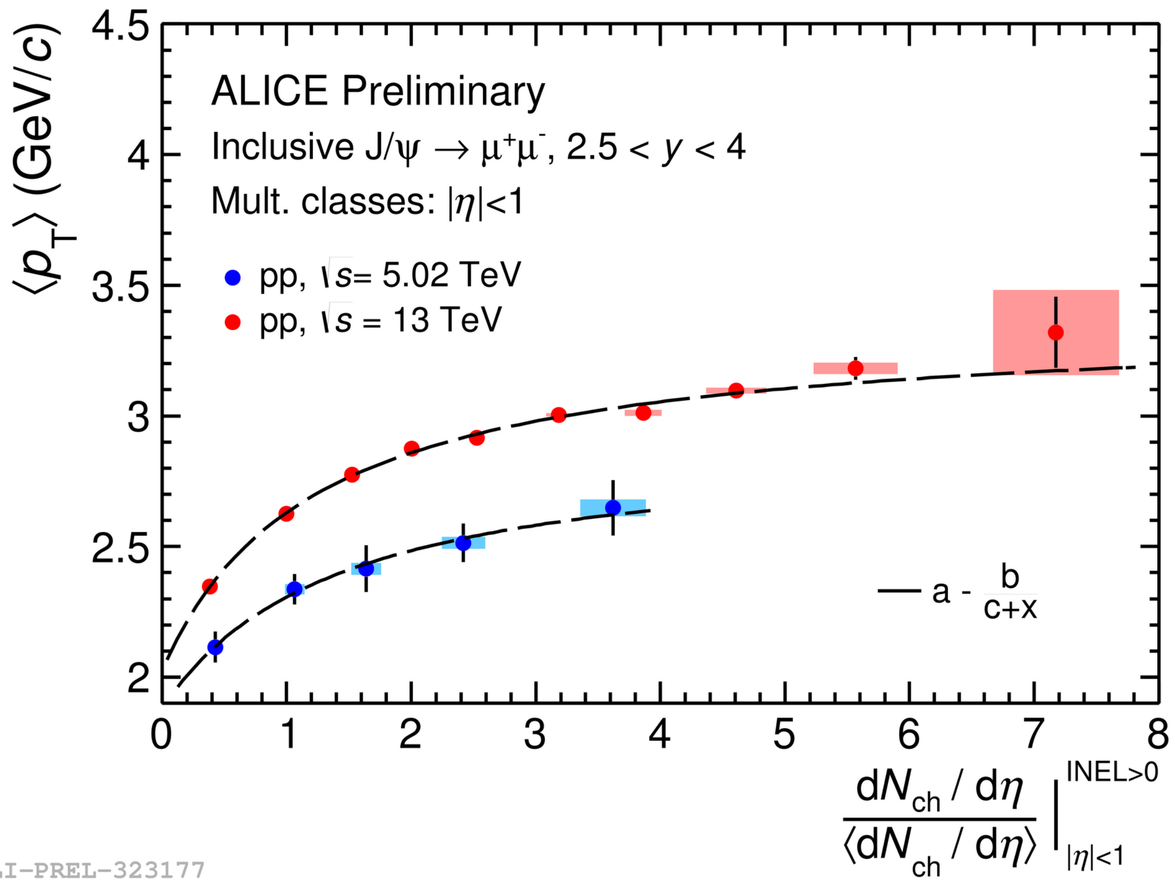
In p-Pb collisions at $\sqrt{s_{NN}}$ = 8.16 TeV:

- **continuous rising** at backward rapidity
- increase of forward yields **slows down** for high multiplicity classes

Mean transverse momentum

NEW !

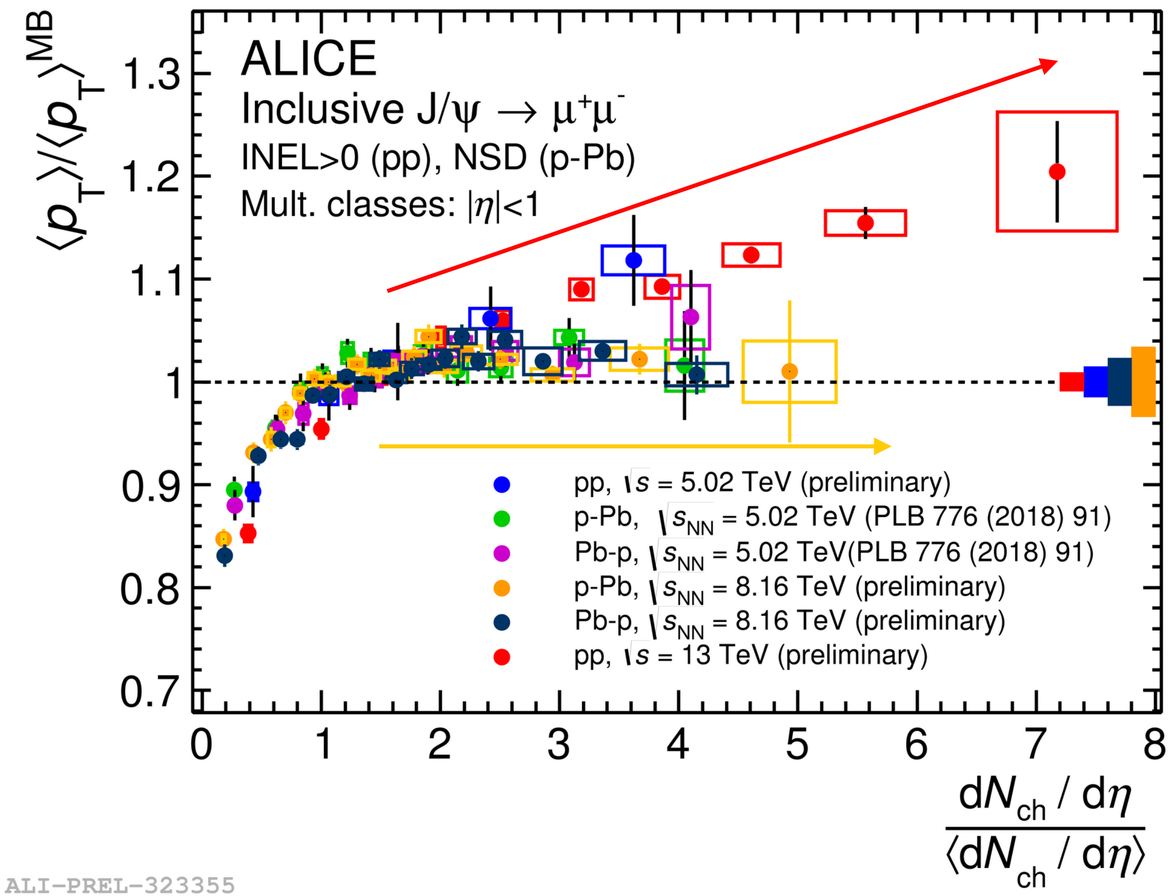
Dependence of J/ψ $\langle p_T \rangle$ on charged-particle multiplicity at mid-rapidity.



- increase of $\langle p_T \rangle$ in pp collisions: stronger in low multiplicity than in the higher region

Mean transverse momentum

Dependence of J/ψ $\langle p_T \rangle$ on charged-particle multiplicity at mid-rapidity.



- increase of $\langle p_T \rangle$ in pp collisions: stronger in low multiplicity than in the higher region

Relative $\langle p_T \rangle$ in *small systems*:

- increase in low multiplicity region
- saturation in p-Pb while a continuous rising is observed in pp

Quarkonium suppression

Originally proposed as a ***smoking gun* of the deconfinement** in heavy-ion collisions

- color screening in QGP ☛ suppression of quarkonium production [PLB 178 (1986) 416]
- different binding energies for quarkonia ☛ sequential melting [PRD 64 (2001) 094015]

Cold Nuclear Matter effects

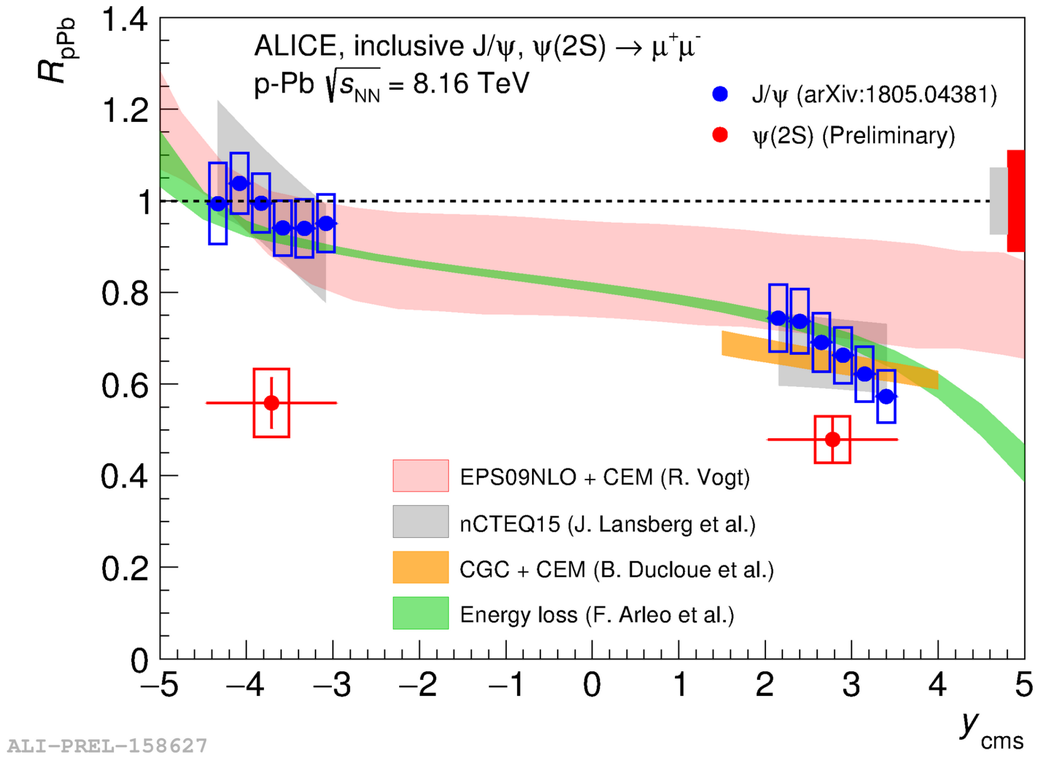
- modification of the PDF
- parton energy loss
- interaction with comovers

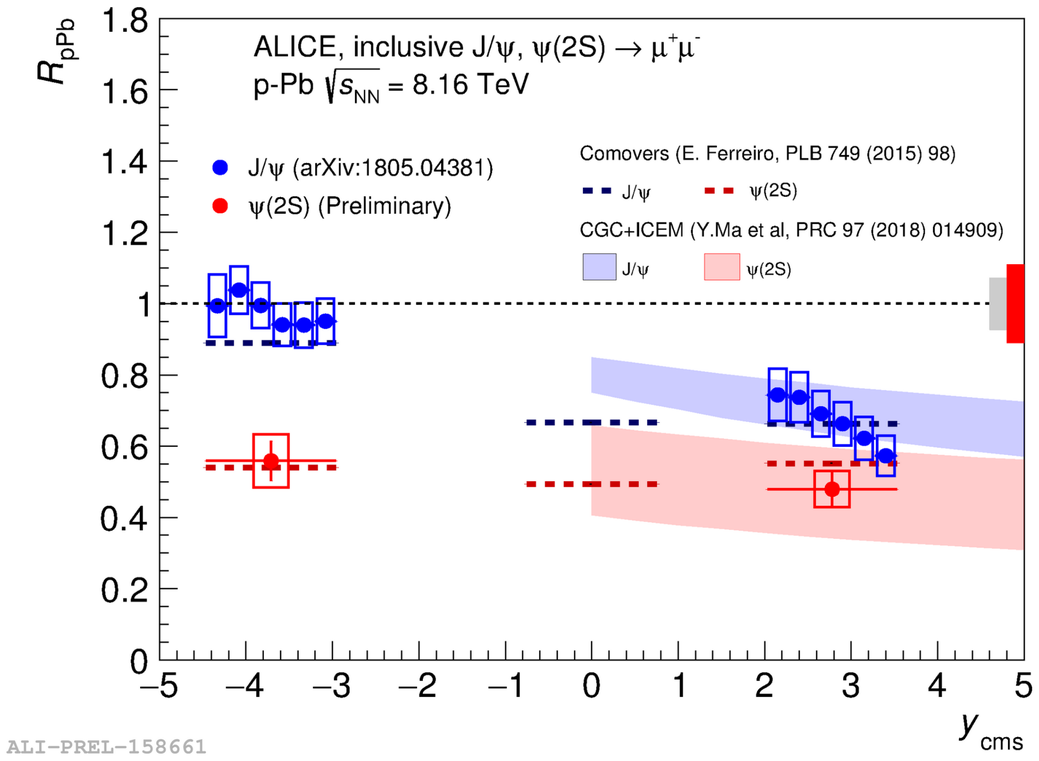
☛ **addressed in p-Pb** collisions

Regeneration [PLB 490 (2000) 196, PRC 65 (2001) 054905]

- statistical production of quarkonia *via* **(re)combination** of *thermalized* quarks in QGP or at hadronization stage
- significant enhancement expected for charmonium, little to no enhancement for bottomonium at LHC

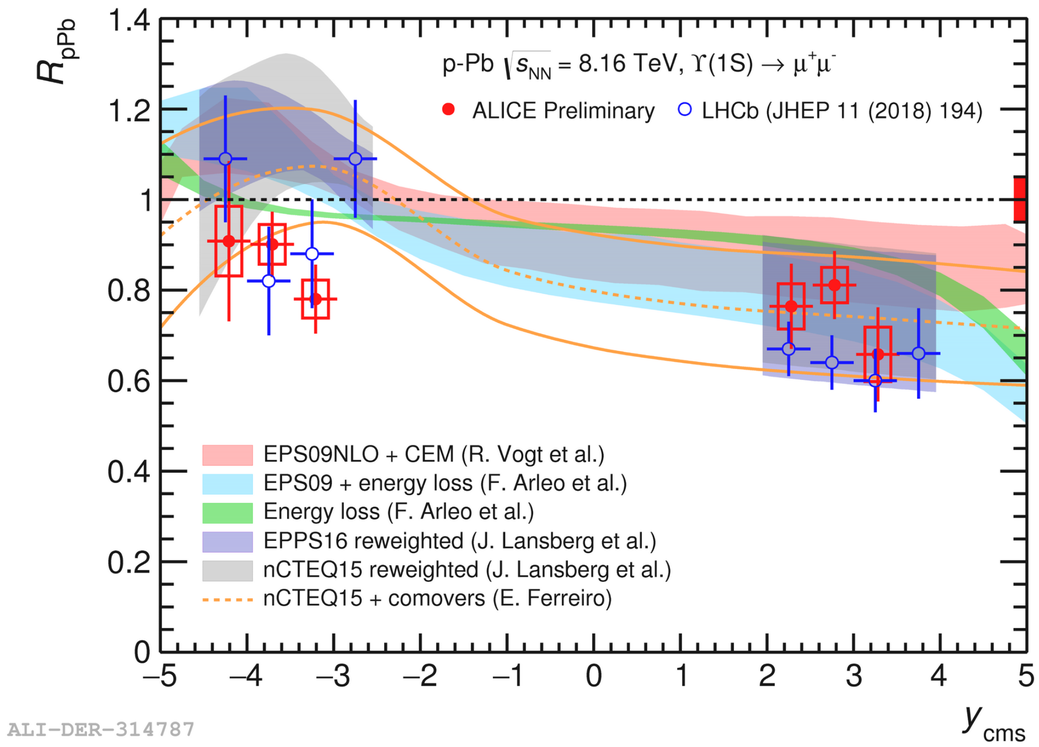
Charmonium R_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV

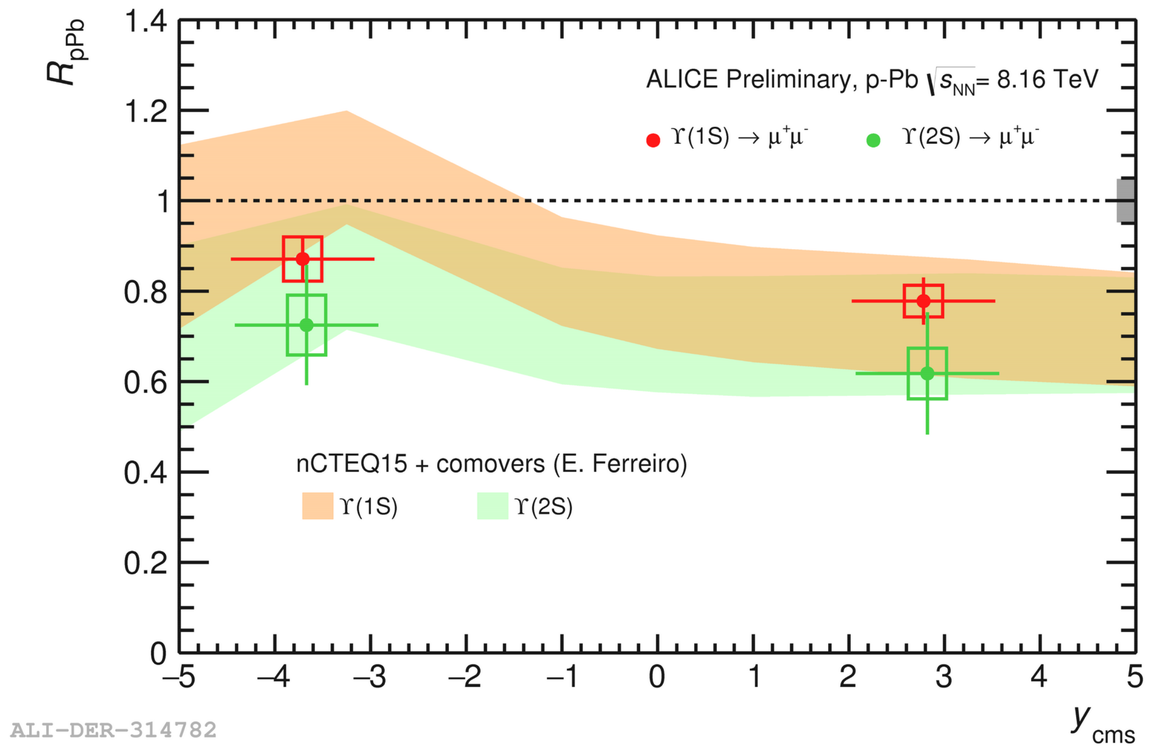




- J/ψ suppression trend can be explained by initial-state effect models only
- **stronger suppression for ψ(2S)**, especially at backward rapidity
  ☛ final-state effects needed to reproduce the suppression

Bottomonium R_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV



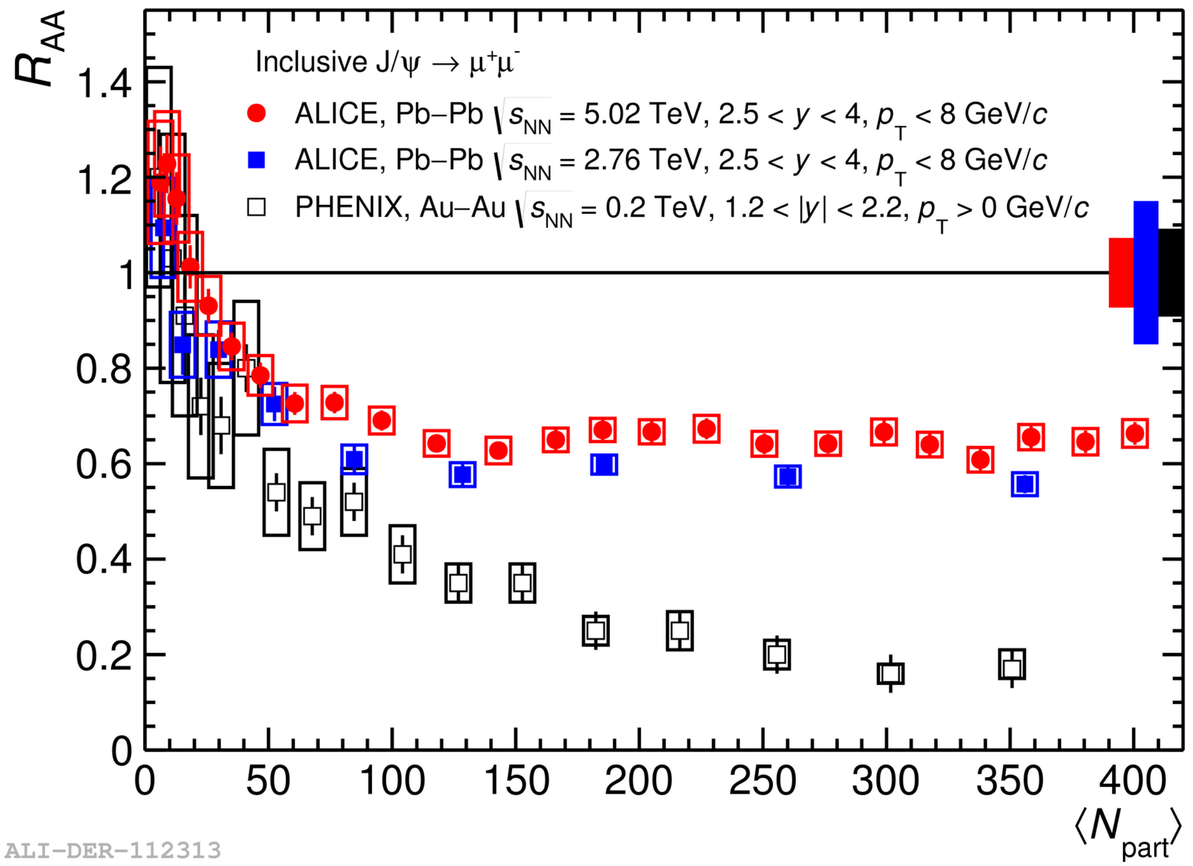


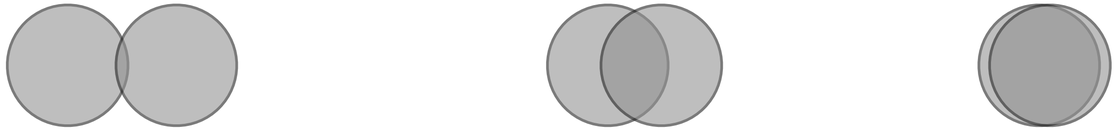
- Υ(1S) suppression compatible with LHCb results, stronger at forward rapidity
- *tension* of shadowing and energy loss models with data in the backward region
- Υ(2S) slightly more suppressed than Υ(1S), reproduced by shadowing + comovers

Inclusive J/ψ R_{AA}

PLB 766 (2017) 212

- **weaker suppression** with respect to RHIC
  ☛ interpreted as a large contribution of **regeneration** at LHC energies

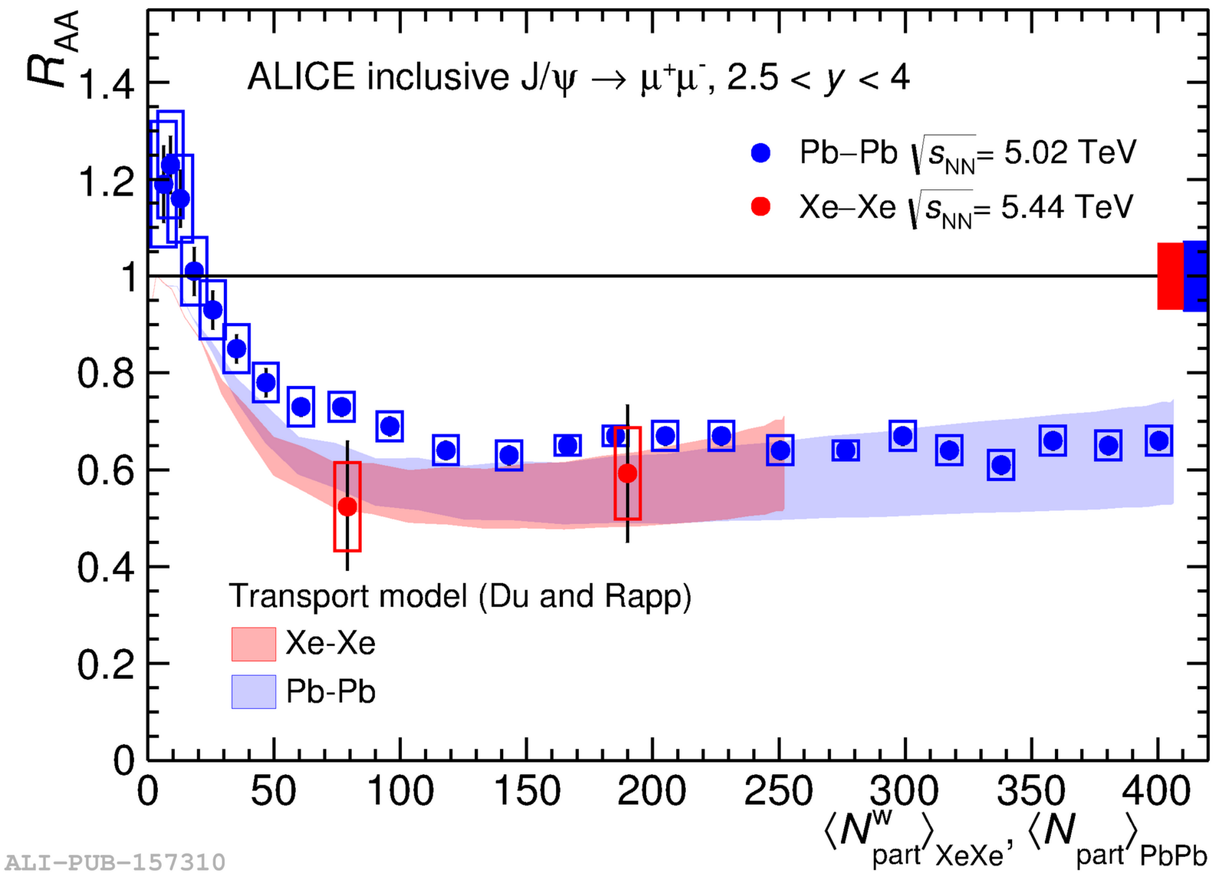


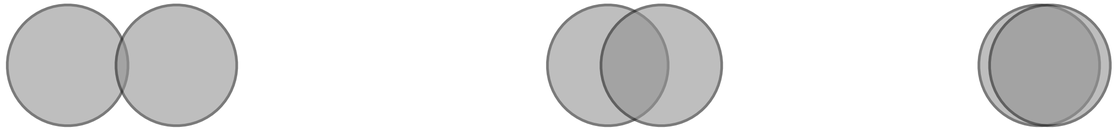


Inclusive J/ψ R_{AA}

- **weaker suppression** with respect to RHIC
  ☛ interpreted as a large contribution of **regeneration** at LHC energies
- similar magnitude in Xe-Xe and Pb-Pb collisions
- well described by Transport Model [NPA 943 (2015) 147] within uncertainties
- triple-differential (y, p_T, centrality) R_{AA} possible with new pp reference

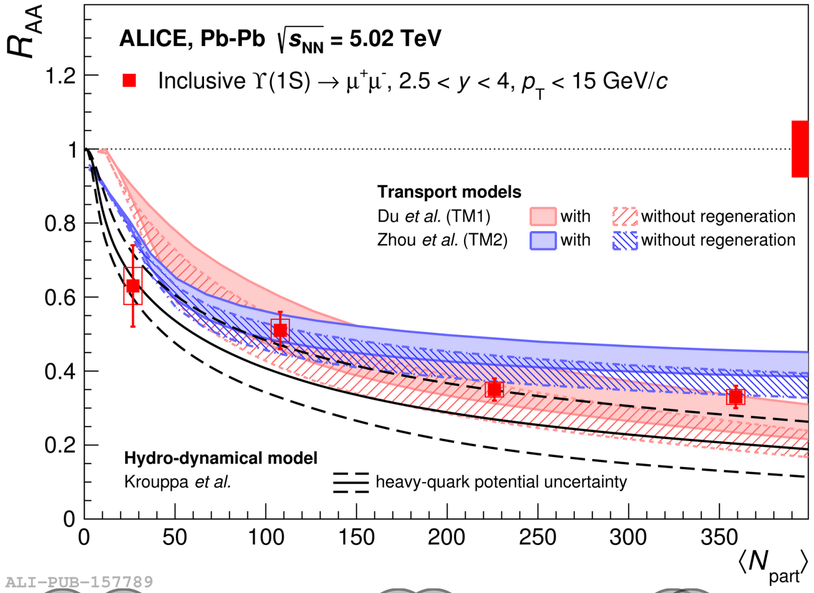
PLB 785 (2018) 419

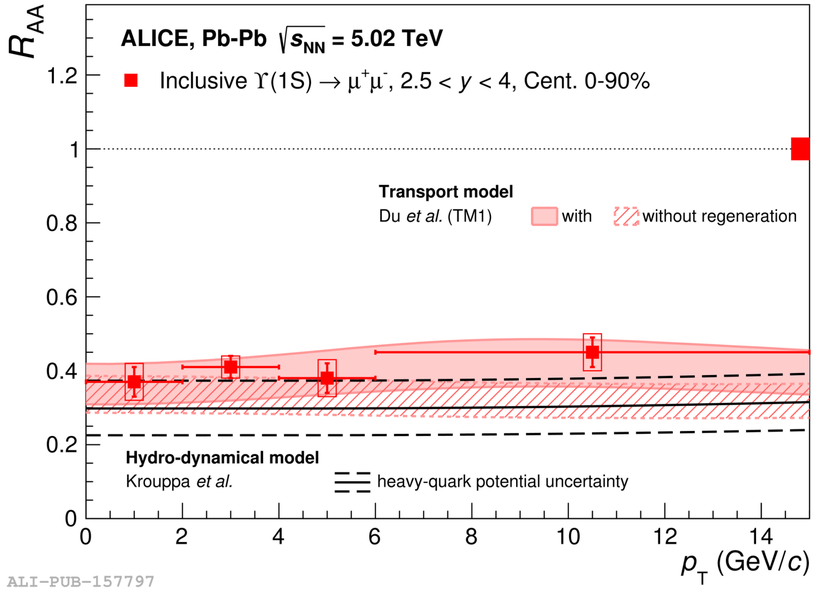


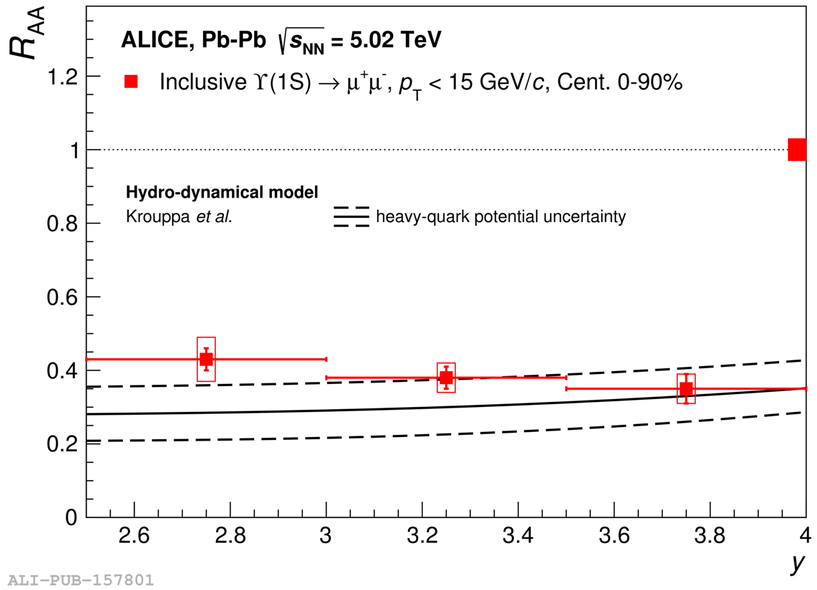


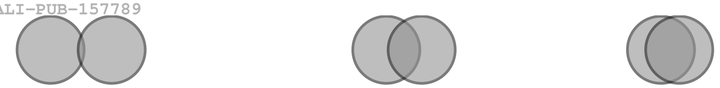
Upsilon R_{AA} at $\sqrt{s_{NN}}$ = 5.02 TeV

PLB 790 (2019) 89







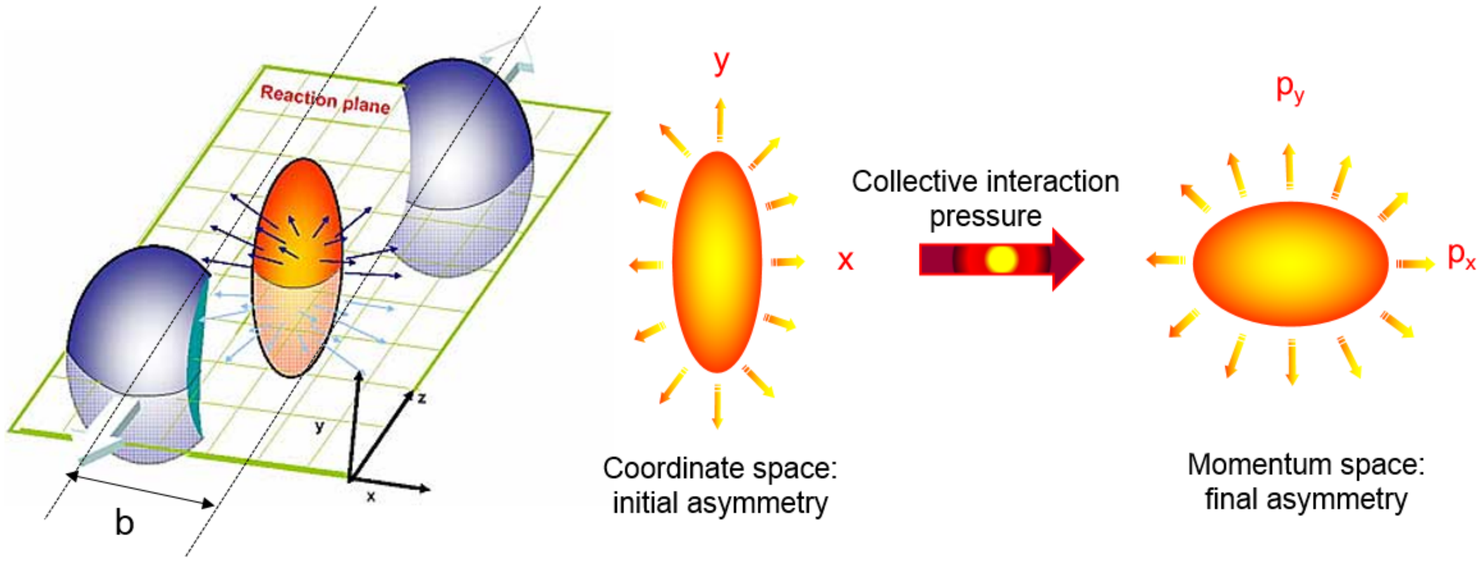


- Υ(1S) suppression increases with centrality, described by model predictions
- **Υ(2S) more suppressed** ☛ Υ(2S)/Υ(1S) R_{AA} ratio = 0.28 ± 0.12 (stat) ± 0.06 (syst)
- No significant dependence on p_T and rapidity
- More precise measurements to come with full Run 2 data

Azimuthal anisotropy

taken from arXiv:1611.01533

Motivation: study **transport properties of the medium** in non-central collisions *via* momentum distribution of the produced final-state particles.

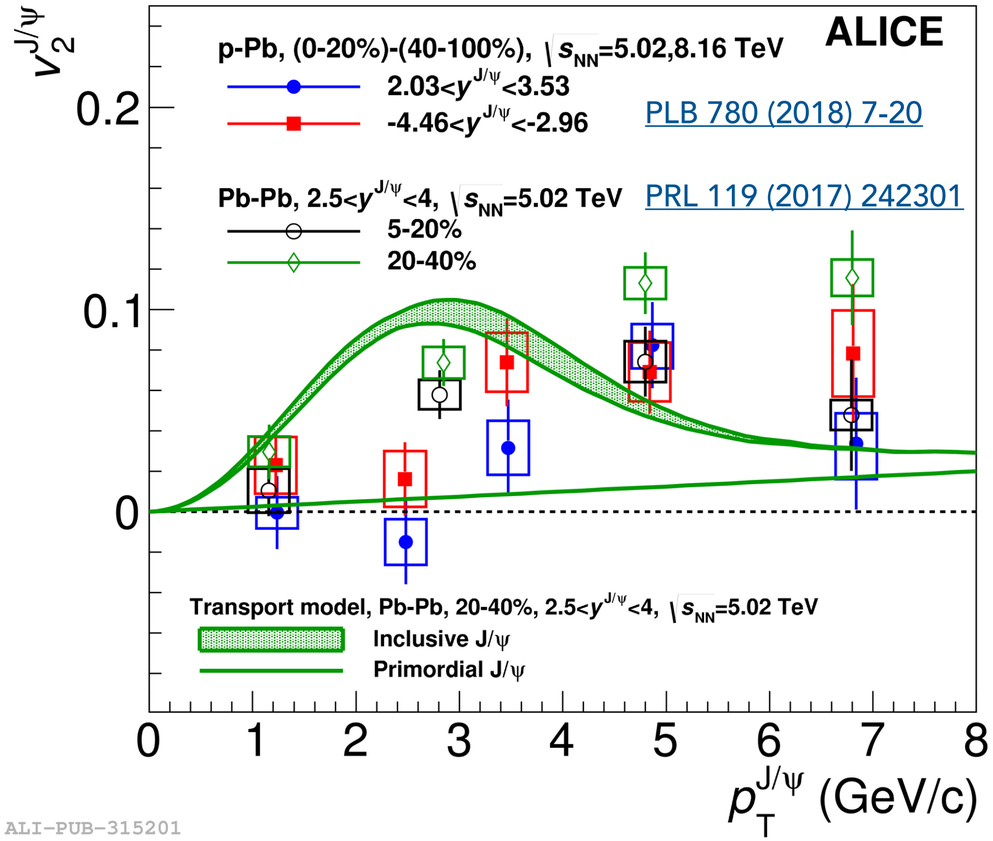


☛ evaluate the harmonic coefficients of the Fourier expansion of the azimuthal particle distribution:

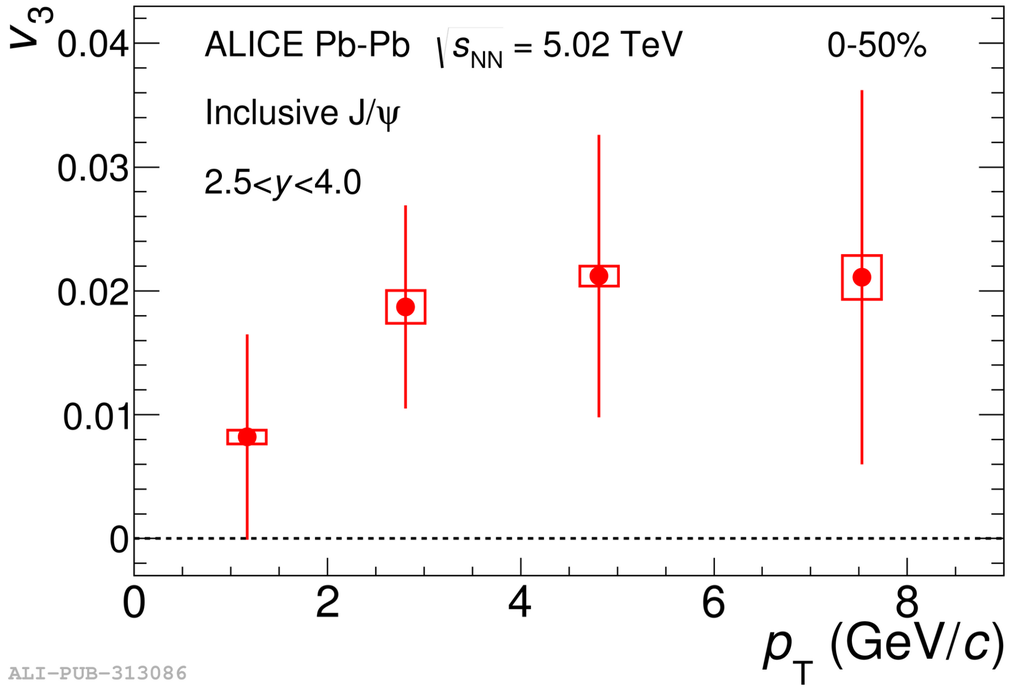
- v_2 ≡ **"elliptic flow"**
- v_3 ≡ **"triangular flow"**

Inclusive J/ψ flow

Positive v_2 in Pb-Pb and p-Pb for p_T > 3 GeV/c, underestimated by model at higher p_T



JHEP 1902 (2019) 012



- **first measurement of triangular flow** for J/ψ in Pb-Pb (2015 dataset)
- 3.7σ significance for a positive v_3

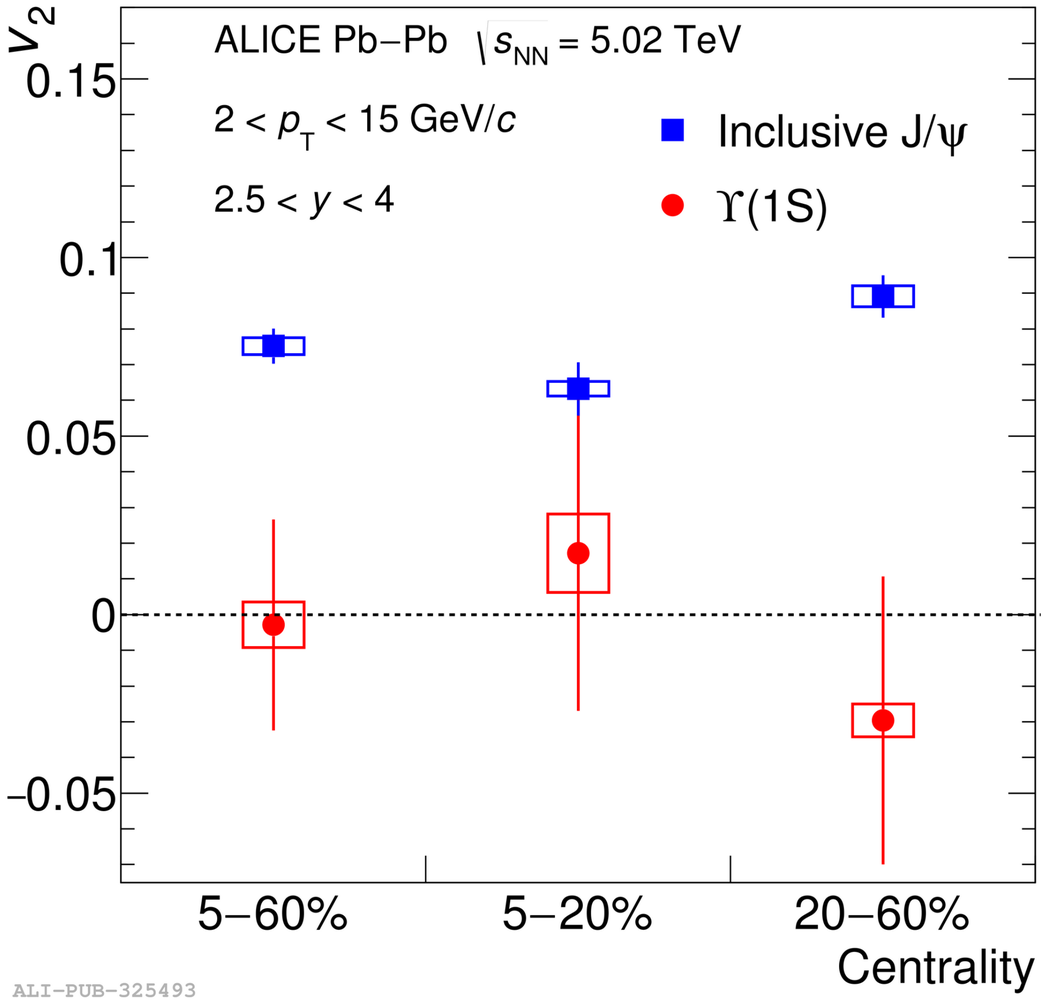
Υ(1S) elliptic flow

NEW !

arXiv:1907.03169

First measurement of Υ(1S) elliptic flow

- **v_2 compatible with zero** (a non-zero flow is measured for all other hadrons !)
- 2.6σ lower than J/ψ v_2 in $2 < p_T < 15$ GeV/c



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ALICE

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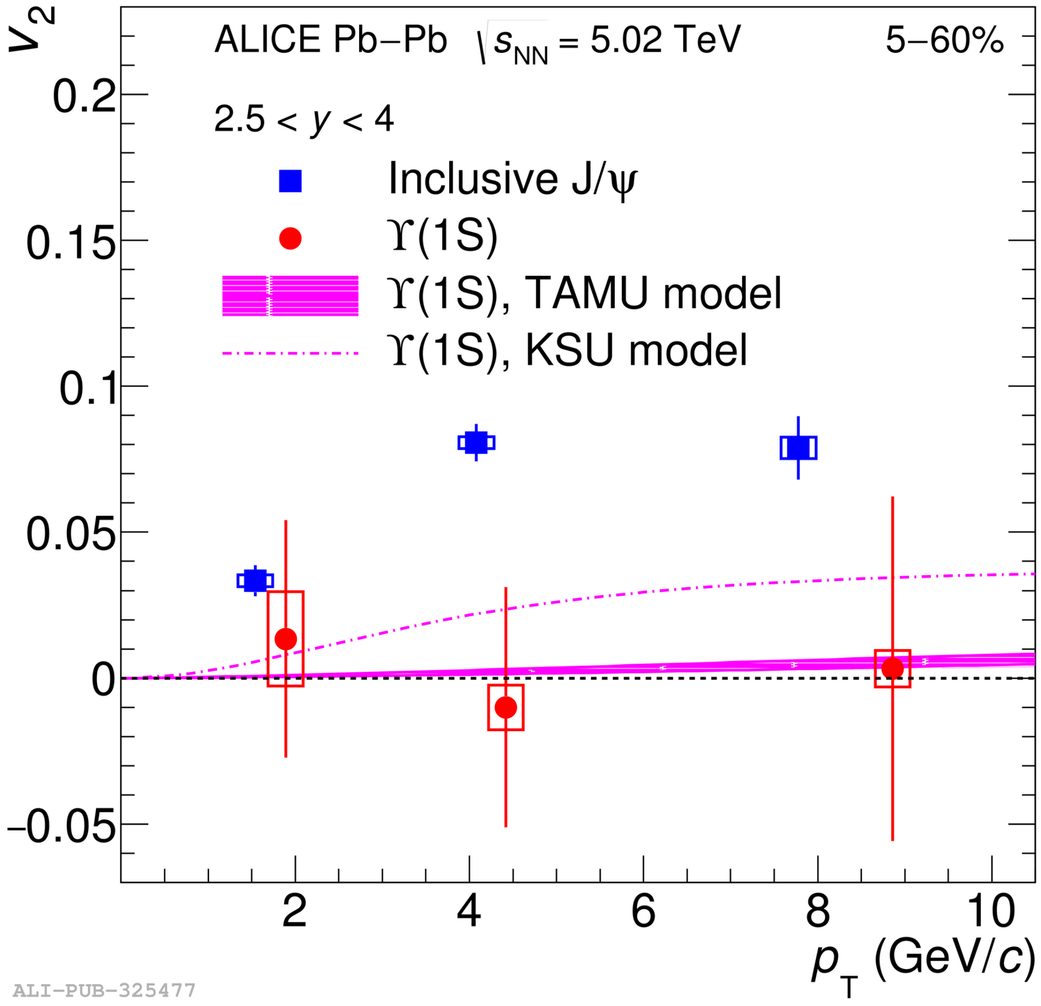
- **v_2 compatible with zero** (a non-zero flow is measured for all other hadrons !)
- 2.6σ lower than J/ψ v_2 in $2 < p_T < 15$ GeV/c
- v_2 compatible with the small values predicted by the available theoretical models including **regeneration** (TAMU) **or not** (KSU)

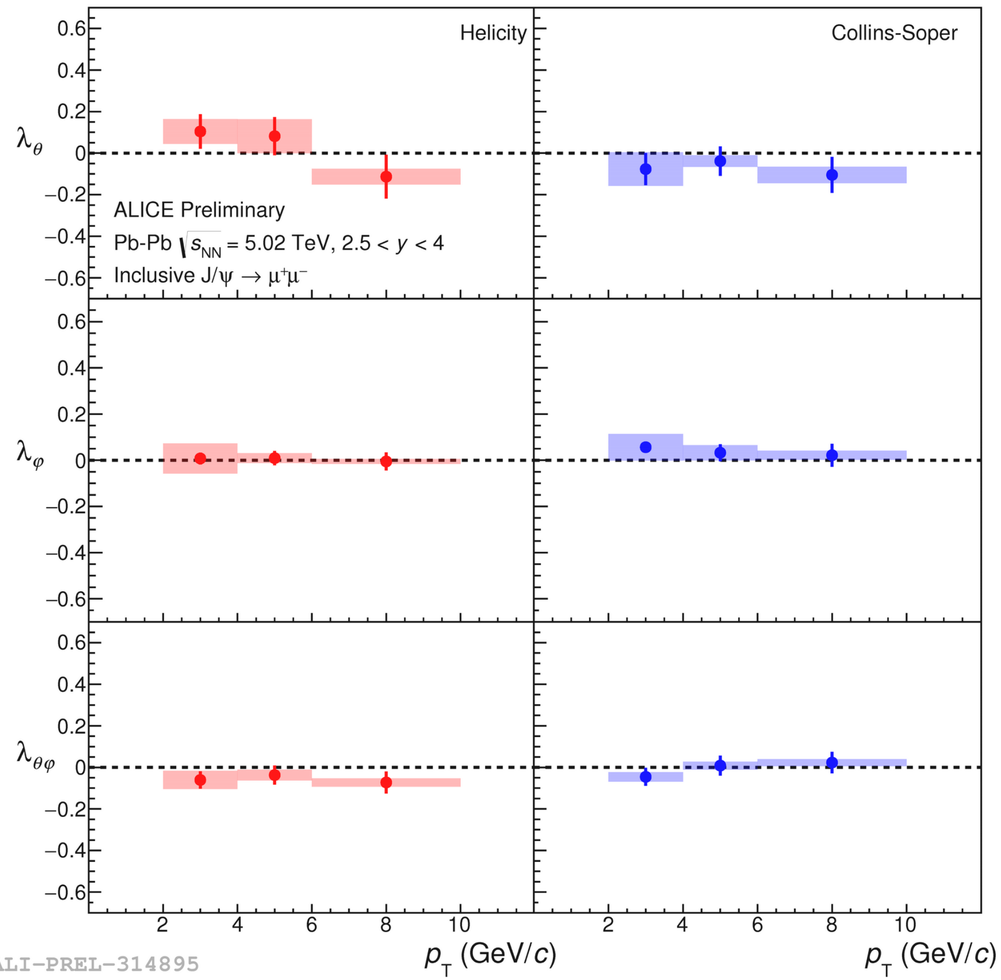


J/ψ polarisation

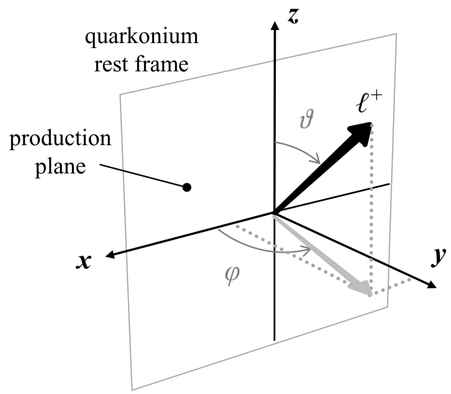
NEW !

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

from EPJC (2010) 69: 657-673



Polarisation parameters evaluated from the angular distribution of decay muons in the quarkonium rest frame.



First measurement in Pb-Pb collisions (2015 only)

- **compatible with zero**

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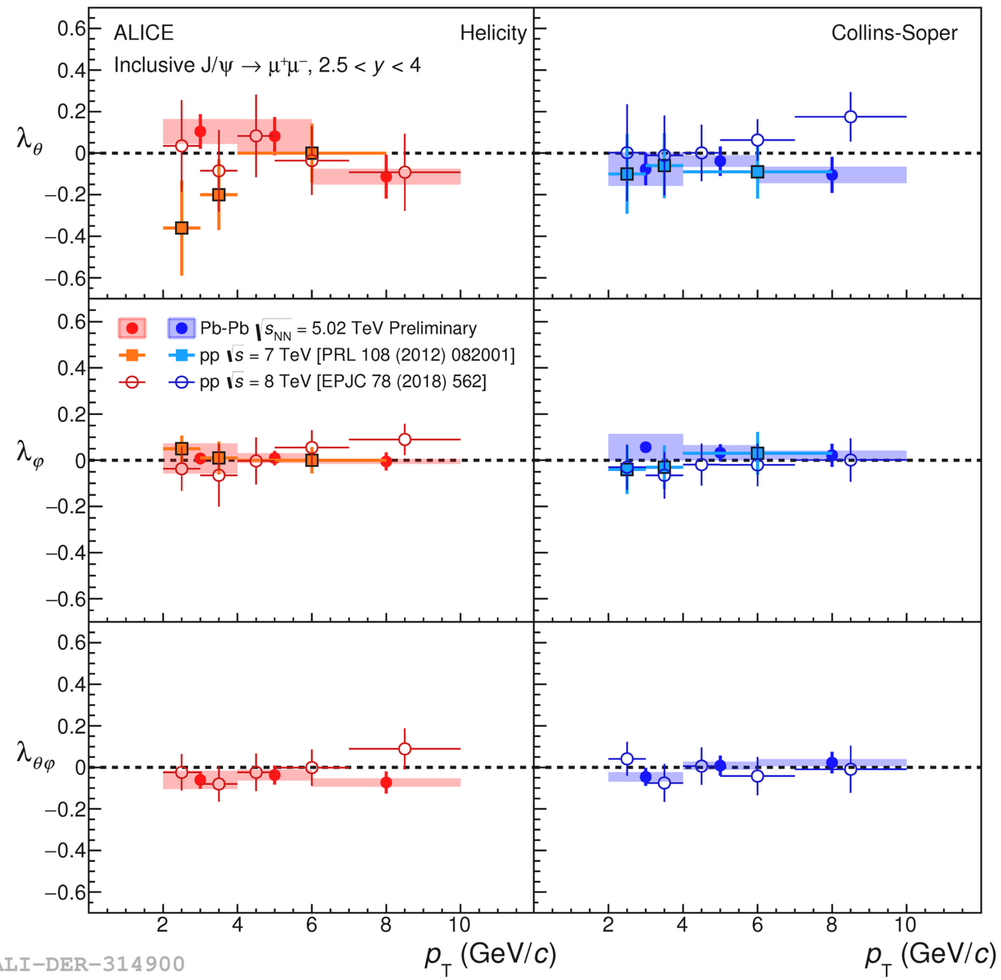

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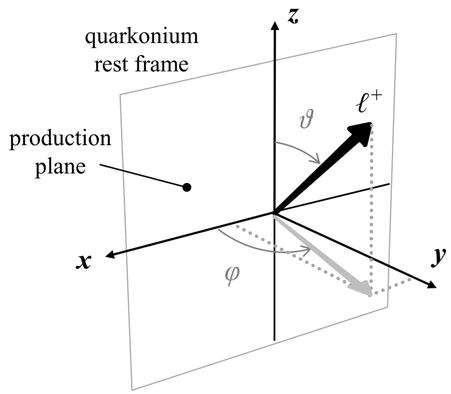

First measurement in Pb-Pb collisions (2015 only)

- **compatible with zero and with pp results** in both reference frames

J/ψ polarisation

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ALICE

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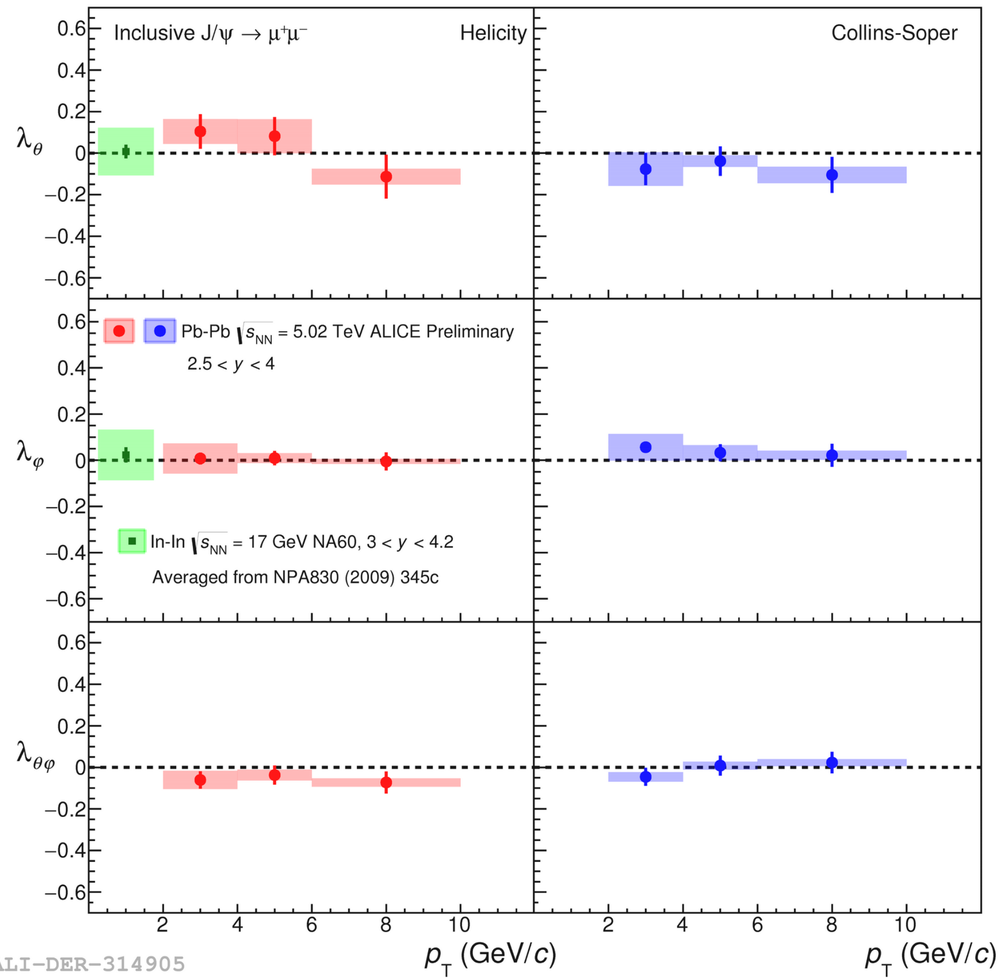

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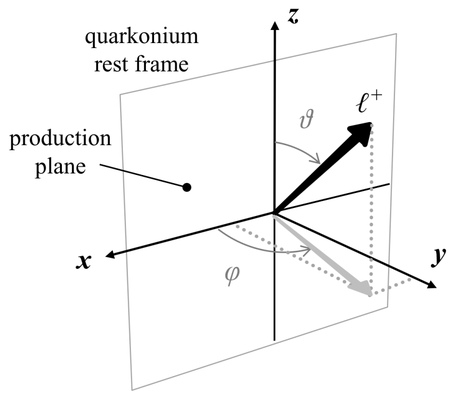


First measurement in Pb-Pb collisions (2015 only)

- **compatible with zero and with pp results** in both reference frames
- consistent with the first measurement at SPS
- study centrality dependence with 2018 dataset !

Summary

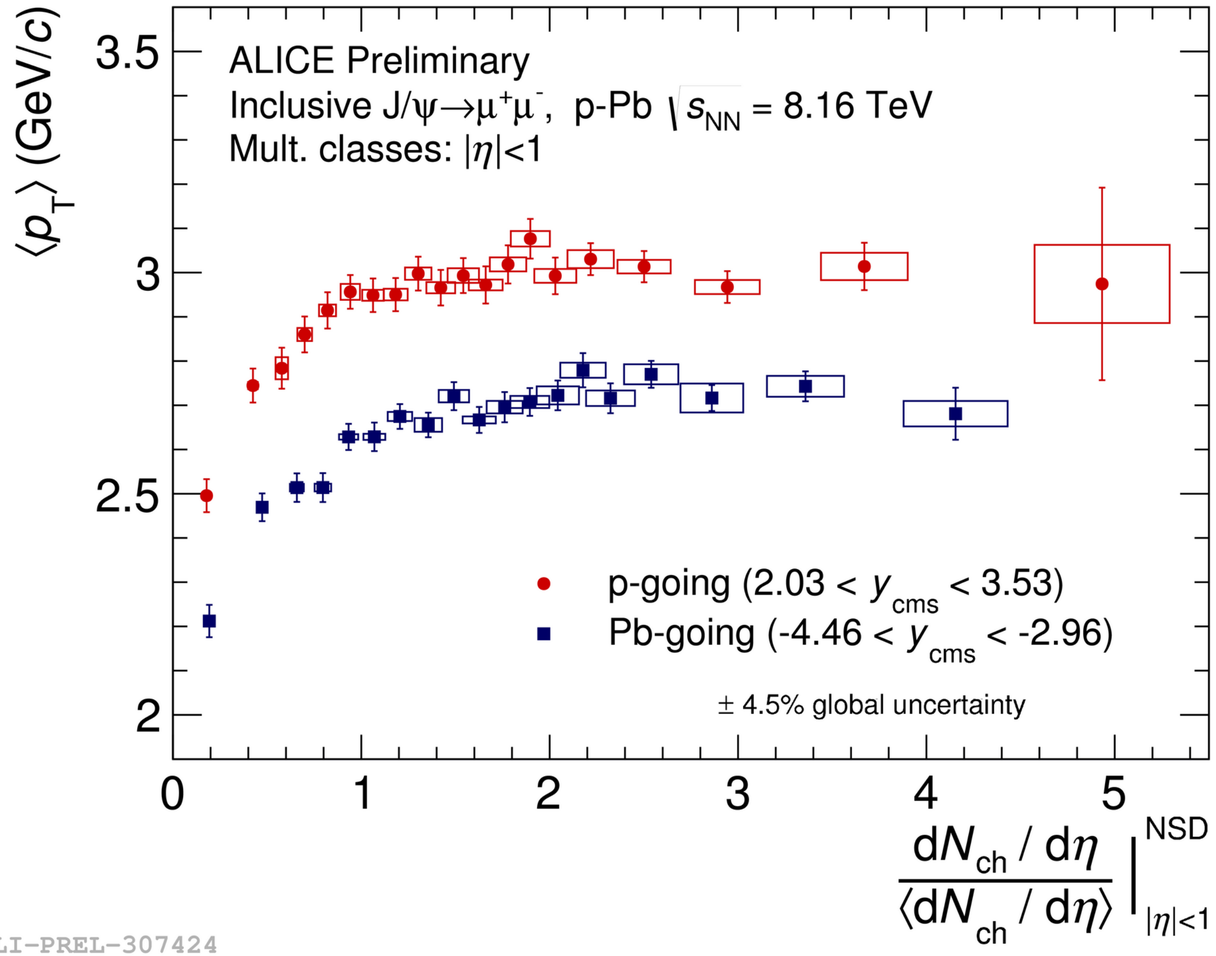
ALICE measurements of quarkonia at forward rapidity are of great interest to study heavy-ion physics at LHC

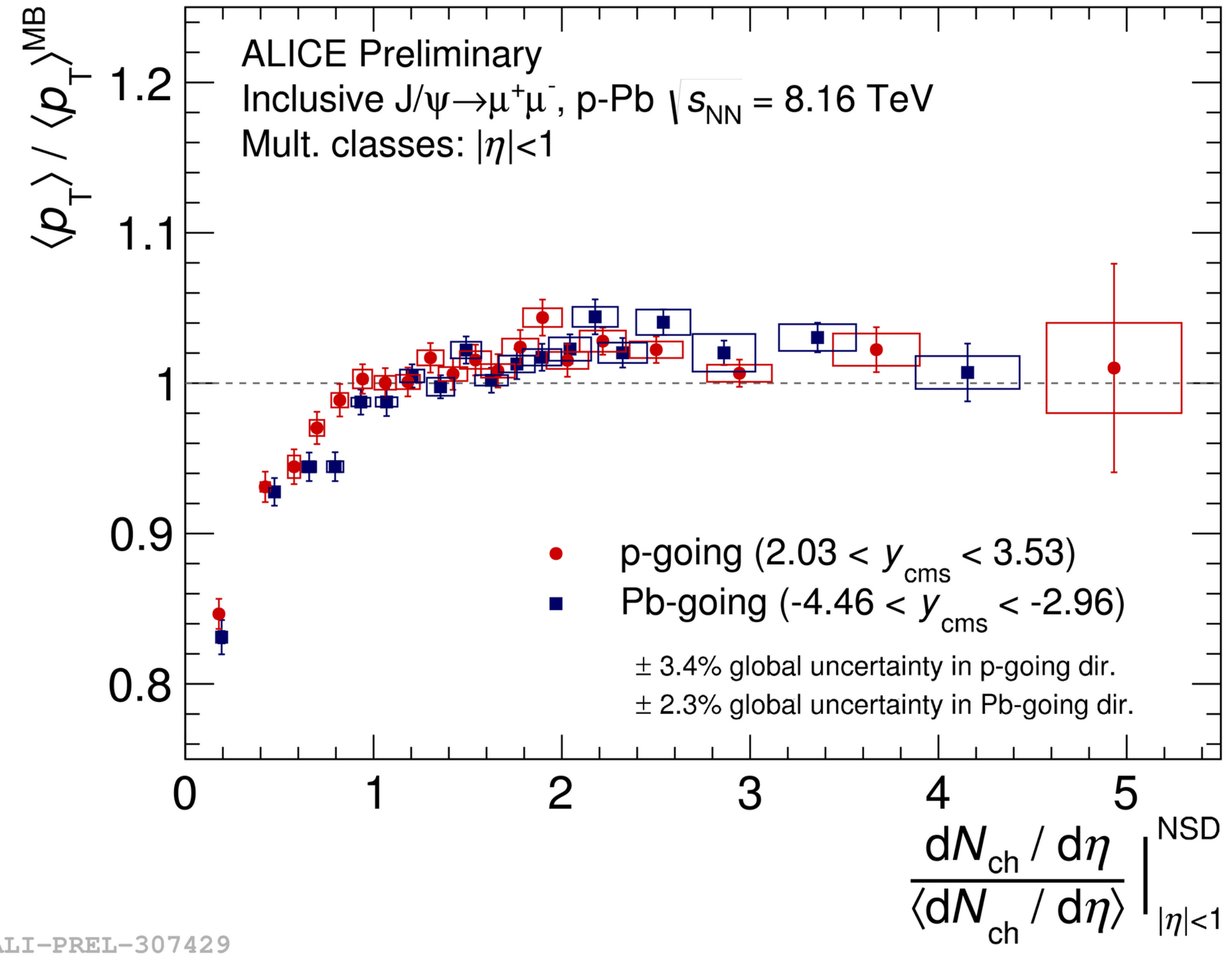
- multiplicity dependence in *small systems*
  - ☛ **increase** of production yield and $\langle p_T \rangle$ with charged-particle multiplicity
- suppression of quarkonium production
  - ☛ final-state effects needed to explain excited-state suppression in p-Pb
  - ☛ **regeneration of J/ψ** and **sequential suppression of bottomonia** in AA
- anisotropy in azimuthal particle distribution
  - ☛ transport model does not describe positive J/ψ v_2 at high p_T in p-Pb and Pb-Pb
  - ☛ **positive J/ψ v_3** (3.7σ) and **Υ(1S) v_2 compatible with zero**
- **first measurement of J/ψ polarisation parameters in Pb-Pb**

… and much more to come with full Run 2 data analysis !

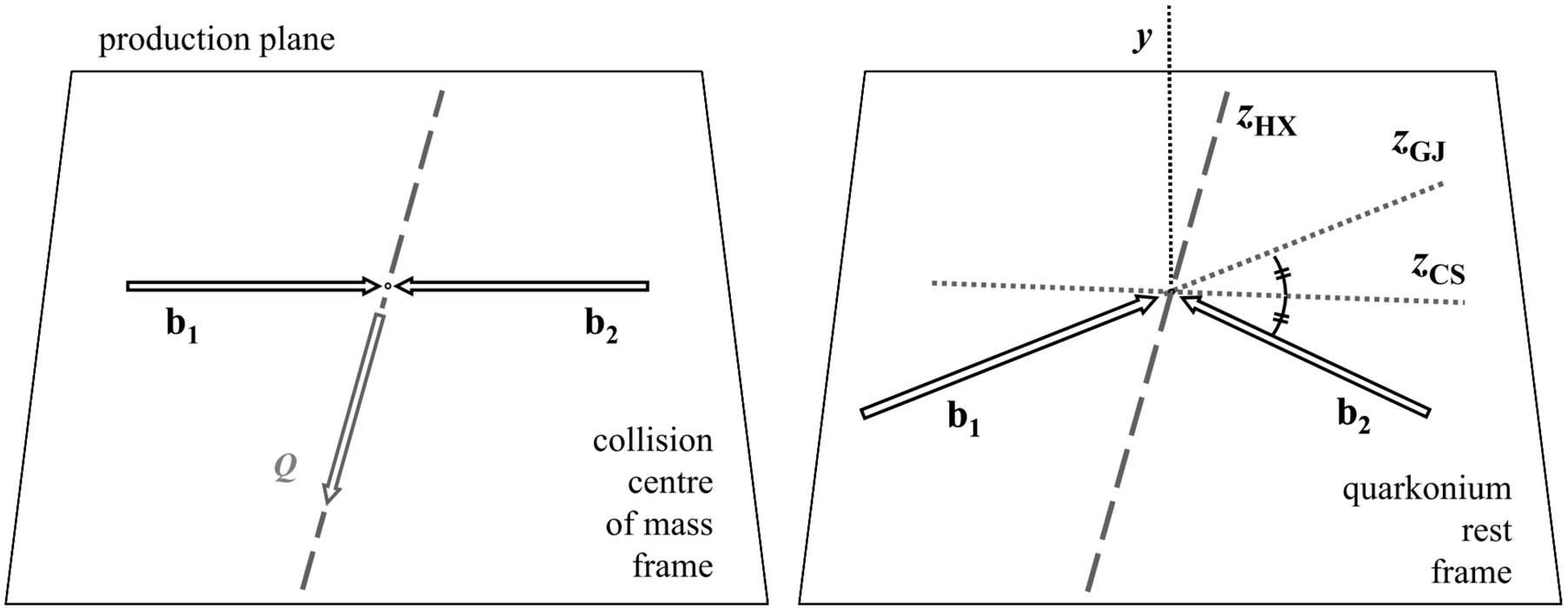
Backup

Mean p_T of inclusive J/ψ in p-Pb





J/ψ polarisation [EPJC (2010) 69: 657-673]

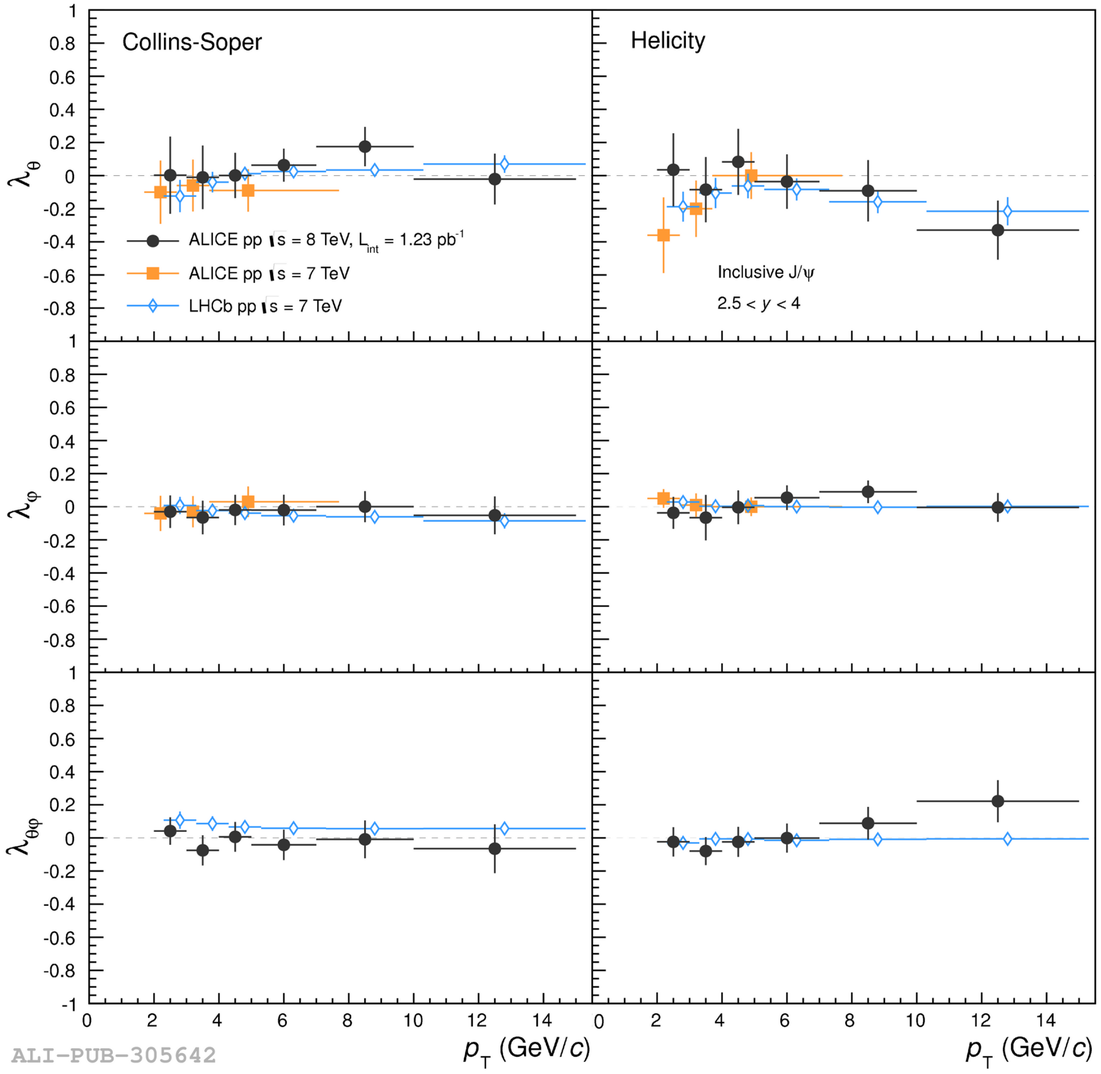


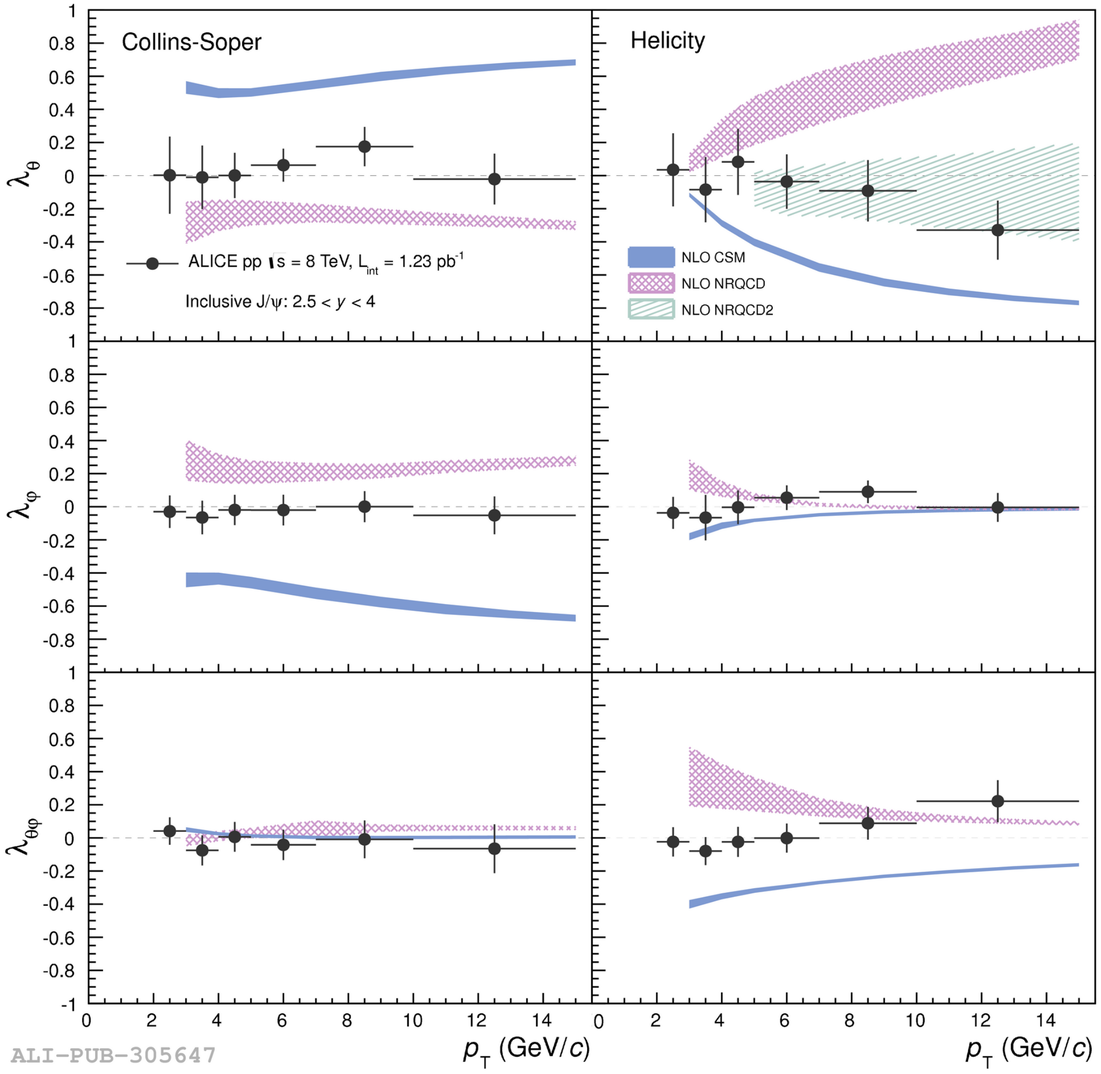
Conventions for the definition of the polarisation *z*-axis:

- Collins-Soper (CS) = bisector of the angle between one beam and the opposite of the other beam
- Helicity (HX) = flight direction of the quarkonium in the centre-of-mass of the beams

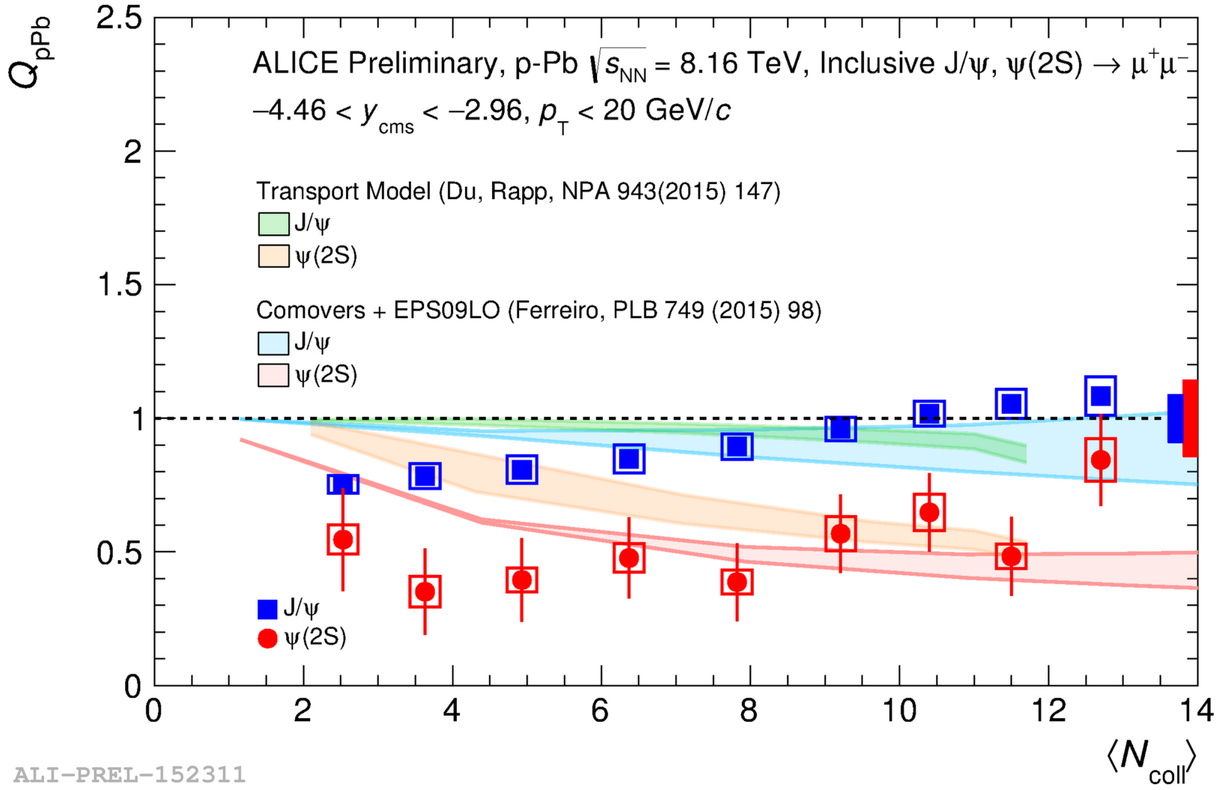
J/ψ polarisation in proton-proton

EPJC 78 (2018) 562

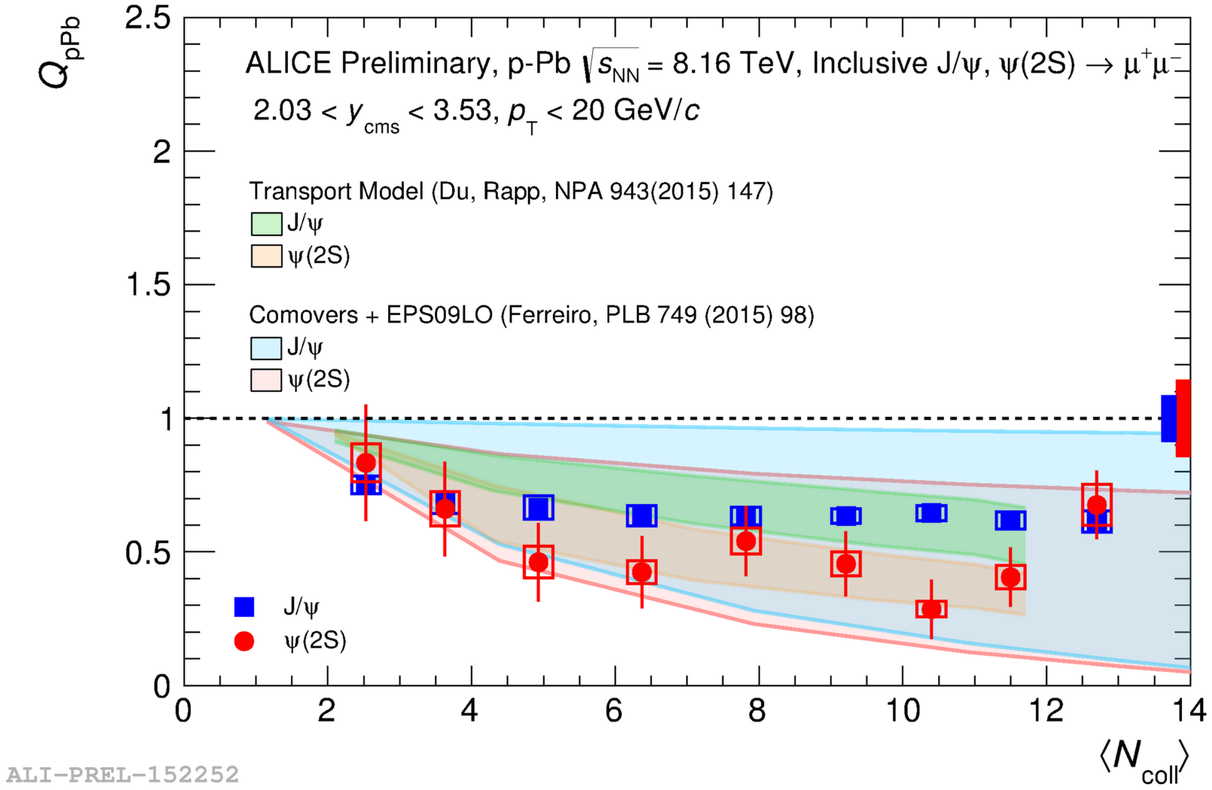




Charmonium Q_{pPb}



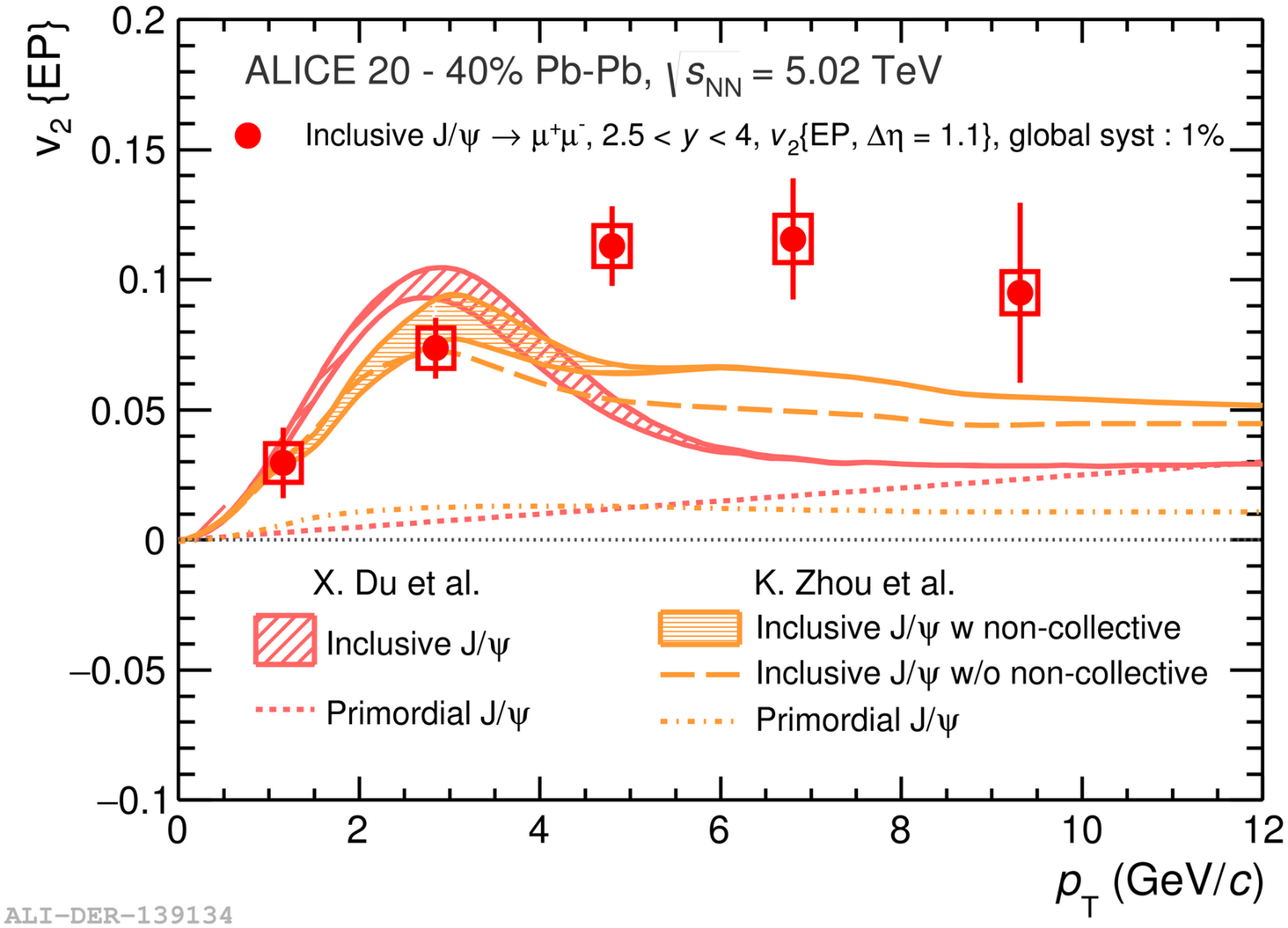
Backward rapidity



Forward rapidity

Inclusive J/ψ v_2 in Pb-Pb

PRL 119 (2017) 242301



Transport models are not able to describe the data trend at high p_T