ALICE

Quarkonium measurements at forward rapidity with ALICE at LHC

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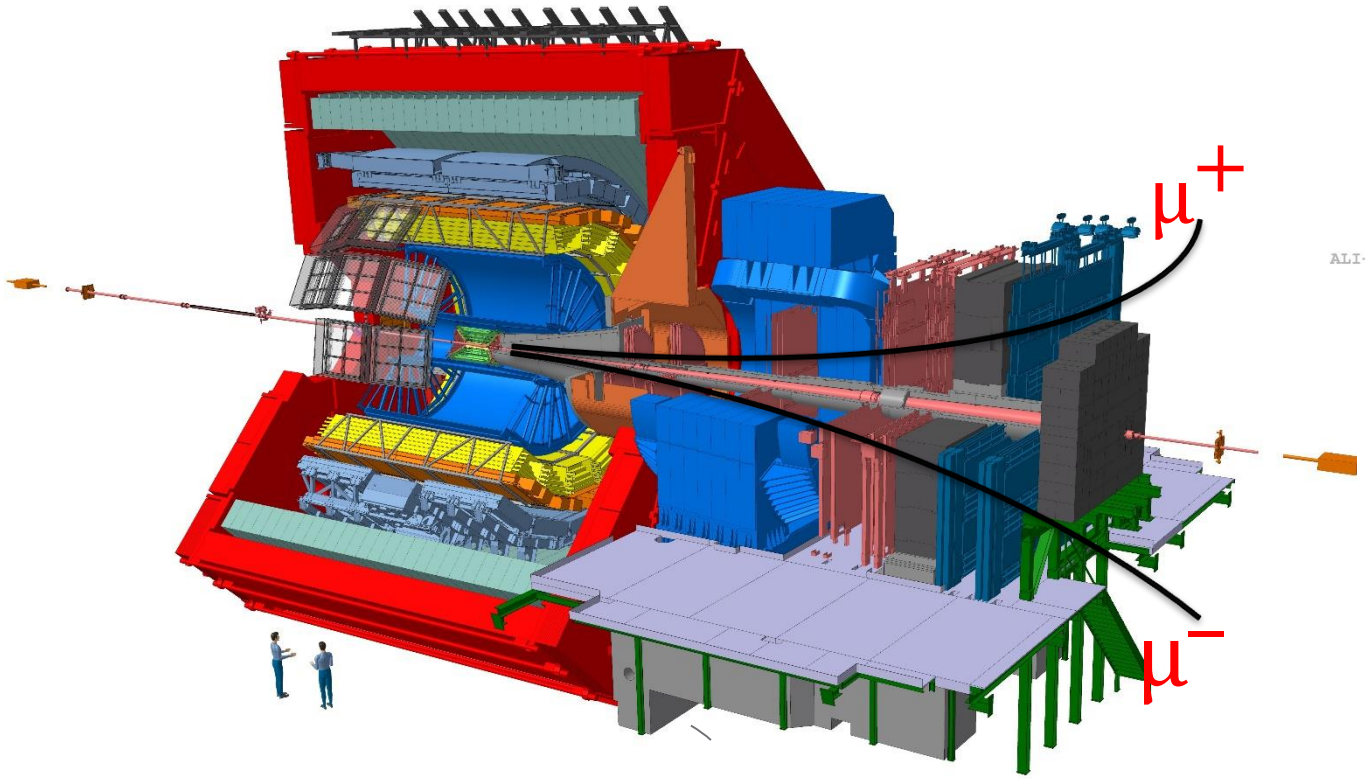
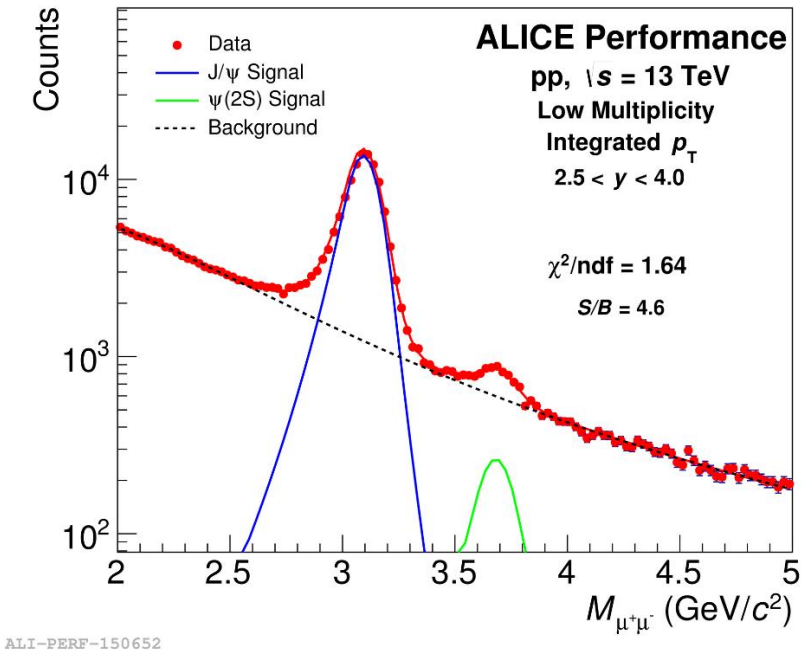
A Large Ion Collider Experiment

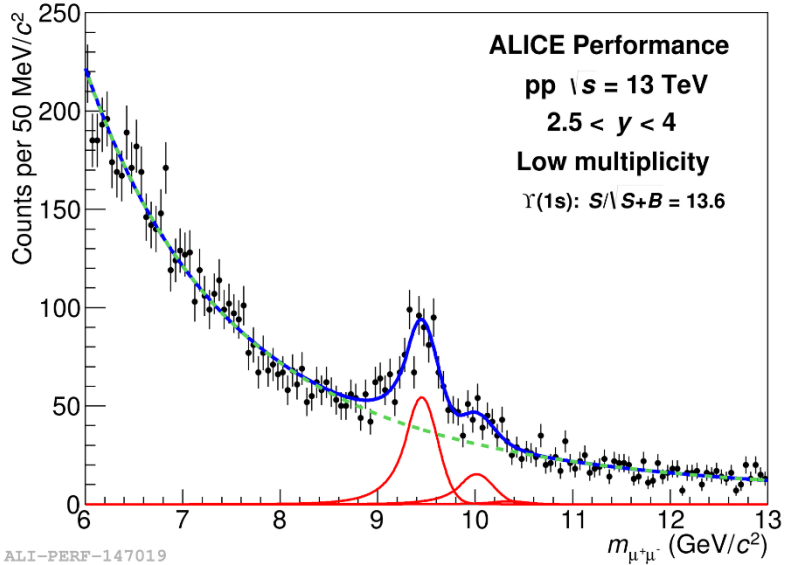
ALICE measures quarkonia at forward rapidity ($2.5<y<4$) in the di-muon decay channel



charmonia



bottomonia

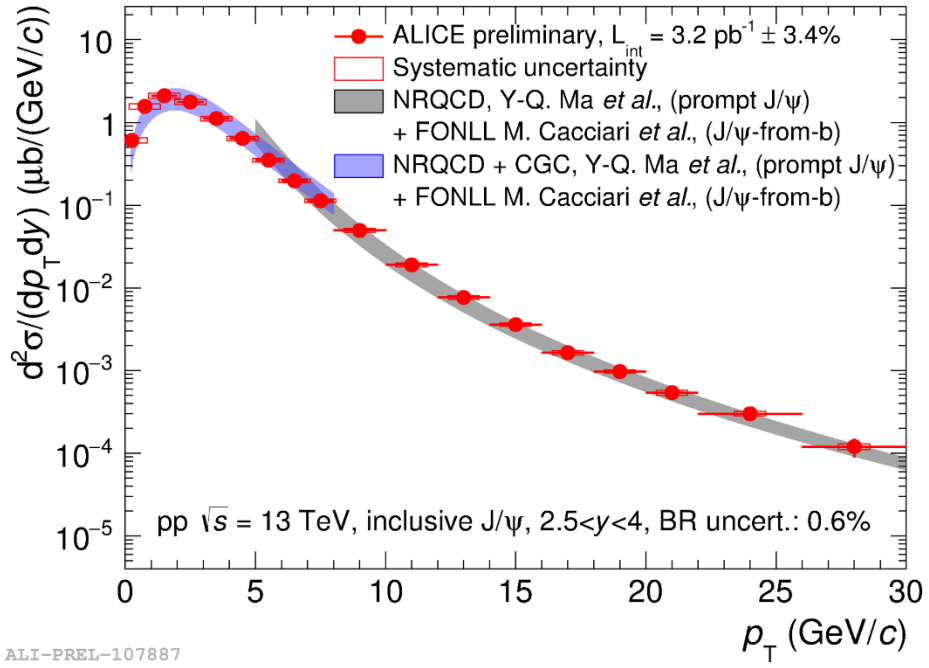


Quarkonium production in pp collisions

- Two distinct steps for quarkonium production process:
  - $Q\bar{Q}$ pairs evolve into the colorless bound state (non-perturbative)
  - Heavy-quark pair ($Q\bar{Q}$) produced in initial hard-scattering process (perturbative)

1. Color Evaporation Model [Phys. Rev. D 12 (1975) 2007]
2. **C**olor **S**inglet **M**ode [Phys. Lett., 102B:364–370, 1981]
3. **N**on **R**elativistic **QCD** (NRQCD) [Phys. Rev., D51:1125–1171, 1995]

Recent theoretical developments, e.g. combining NRQCD with **C**olor **G**lass **C**ondensate (GCG+NRQCD) reproduce the J/ψ p_T shape. [Phys. Rev. Lett. 113 (2014) 192301]



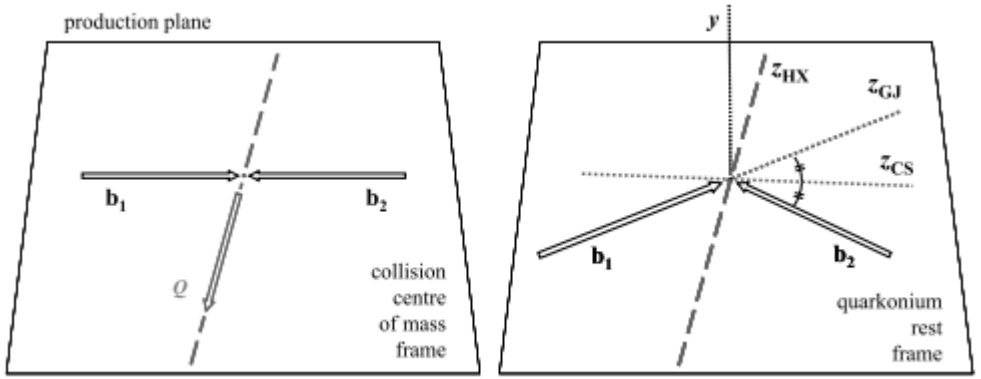
EPJC 77 (2017) 392

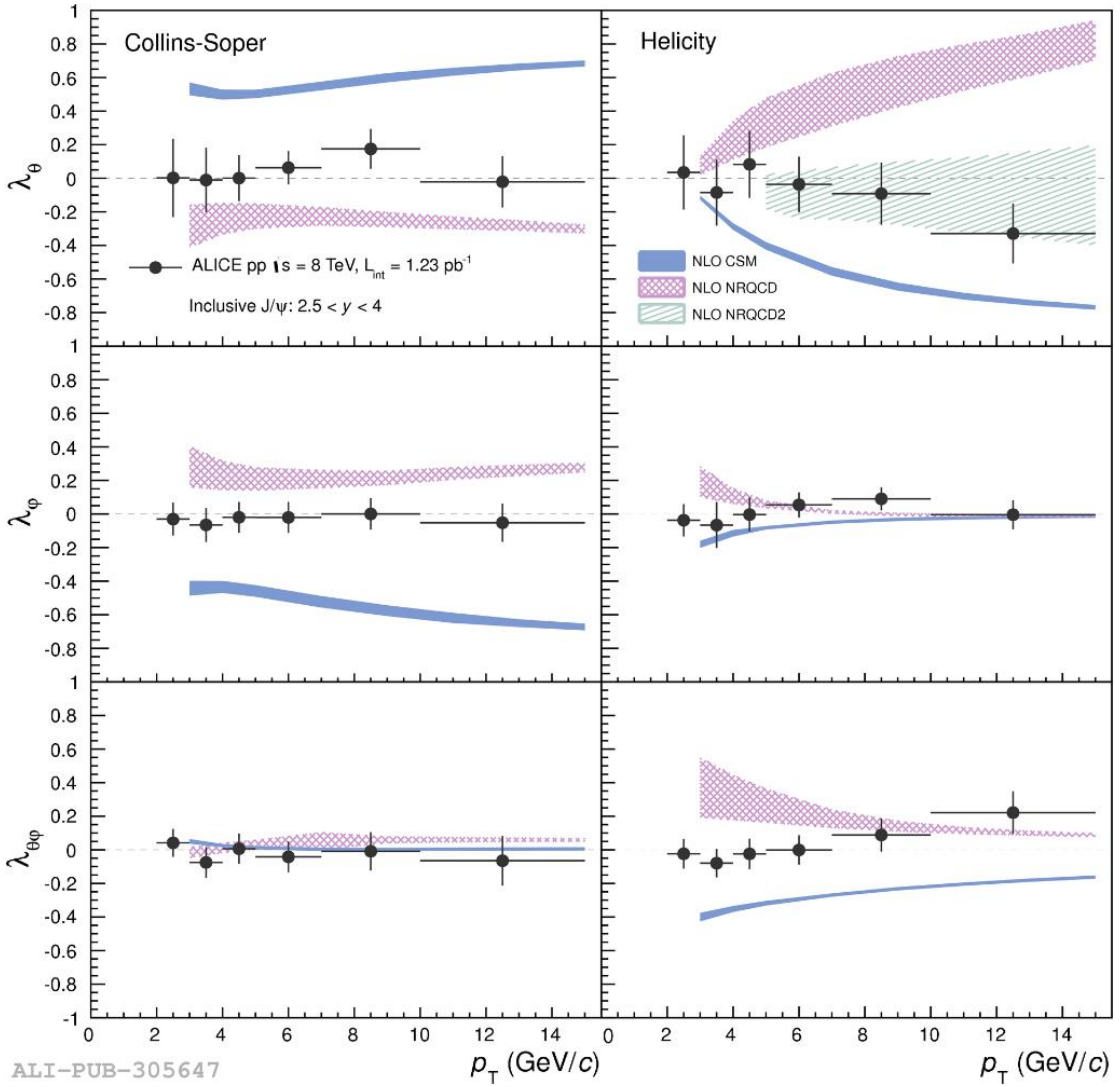
J/ψ polarisation in pp collisions at 8 TeV

EPJC 78 (2018) 562

J/ψ decay products expressed as:

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

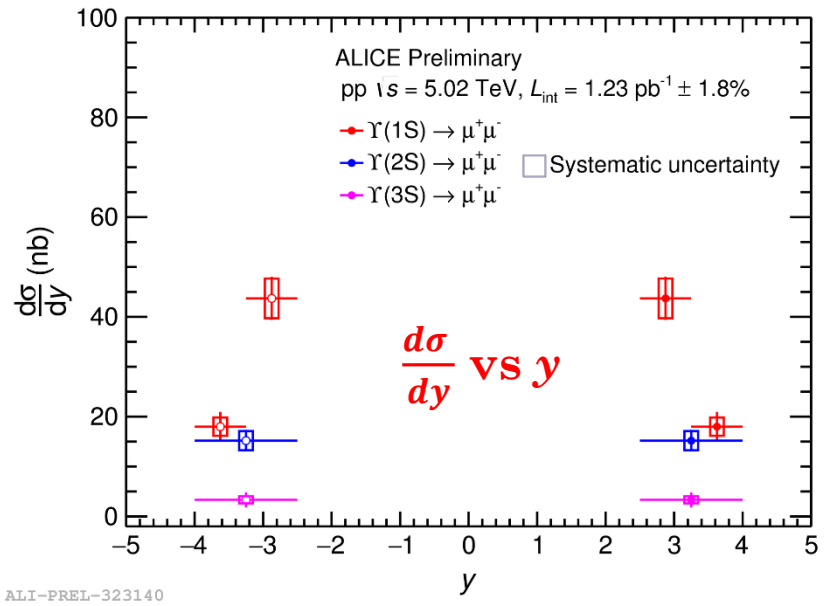




- ALICE measurements show little to no p_T dependence and are compatible with zero
- CSM and NLO NRQCD predictions do not describe the polarisation parameters

Upsilon cross section in pp collisions at 5.02 TeV

- First measurements at forward rapidity with 2017 data set. Luminosity increased by a factor of 10 w.r.t 2015 data set
- R_{AA} analysis in Pb-Pb collision will benefit from 5.02 TeV pp measurements



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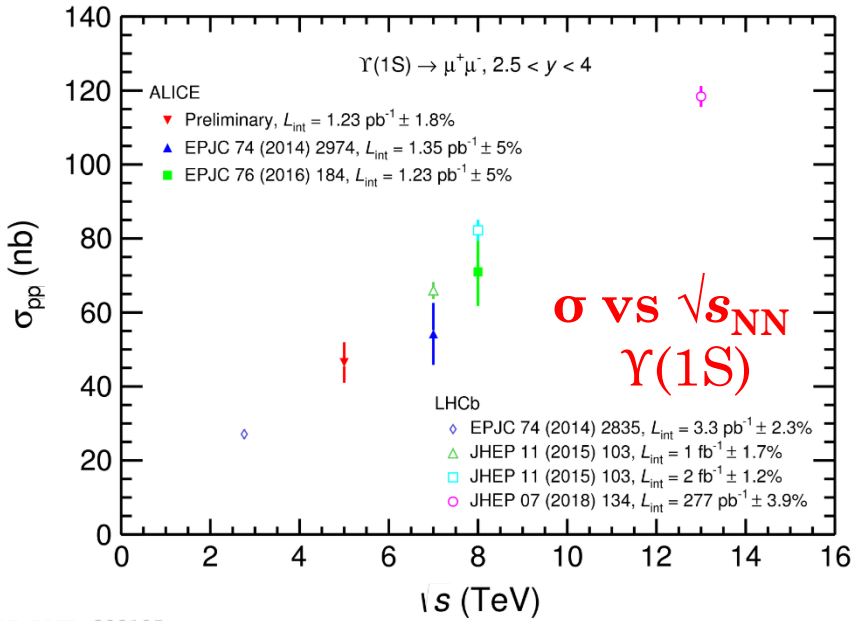
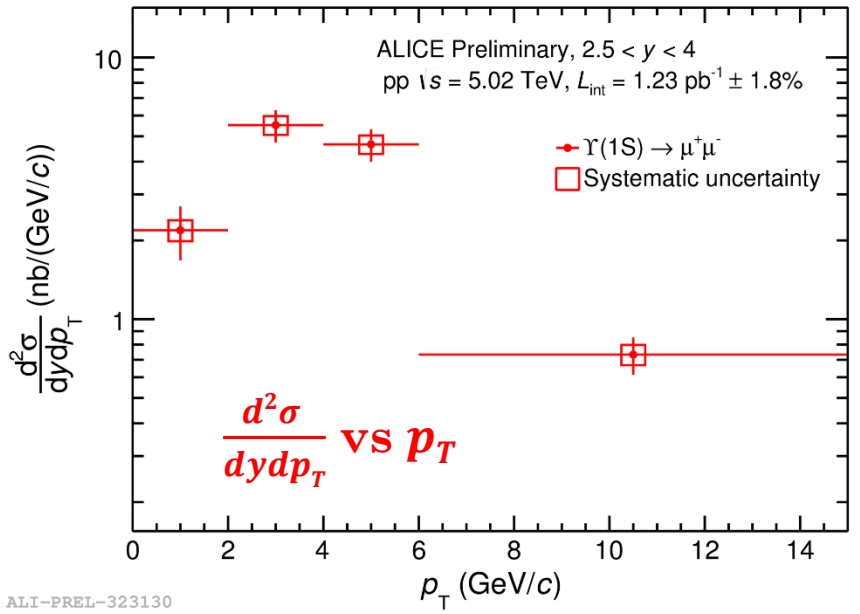
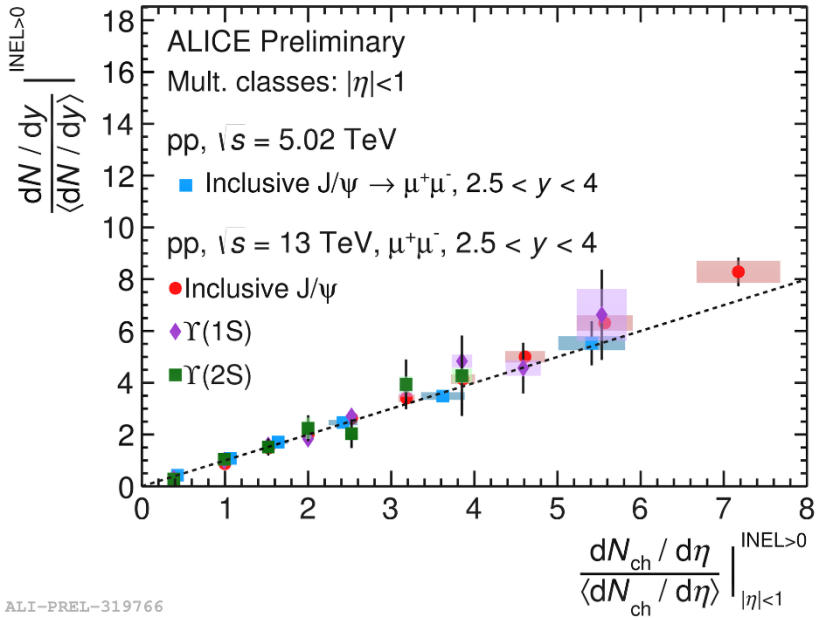
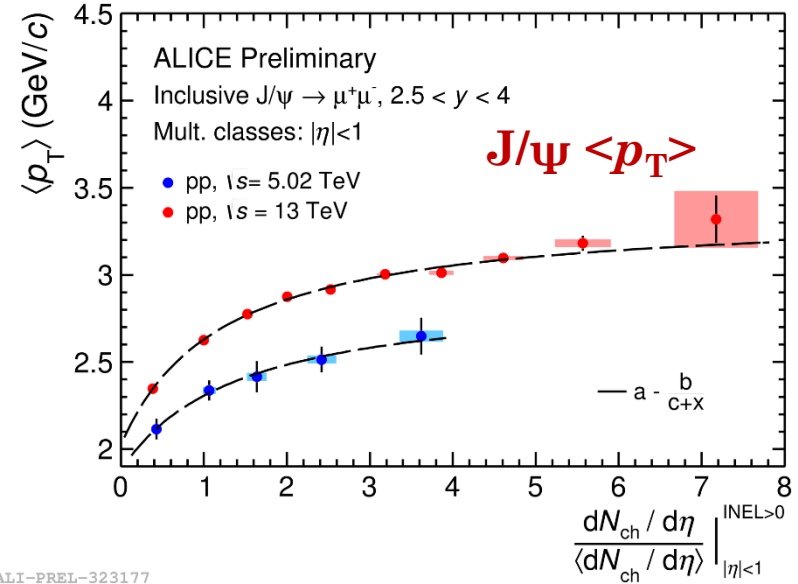




Multiplicity dependence of quarkonium production in pp

Charged-particle multiplicity dependence is an important observable to study the production mechanism, multi parton interactions and interplay between soft and hard processes





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- Linear increase with multiplicity for different quarkonium states
- 5.02 and 13 TeV results show similar trends, no strong energy dependence is observed.
- J/ψ <p_T> increases with increasing multiplicity with a little saturation towards higher multiplicity

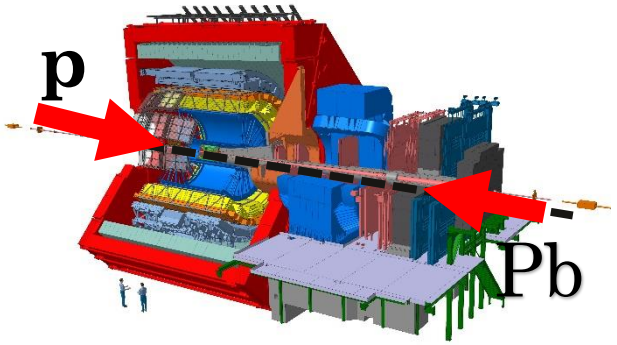
p-Pb collisions in ALICE

p-Pb collisions : study Cold Nuclear Matter effects (**CNM**)

Initial state effects: before creation of $\mathbf{Q\bar{Q}}$

- **Shadowing and anti-shadowing**
  modification of the PDF
- **Parton energy loss**
  gluon radiation by scattering

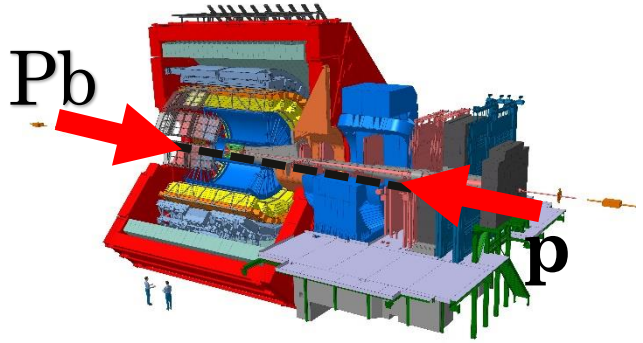
$$R_{\mathrm{pA}} = \frac{\sigma_{\mathrm{pA}}}{\mathrm{A}\times\sigma_{\mathrm{pp}}}$$



$2.03<y_{cms}<3.53$

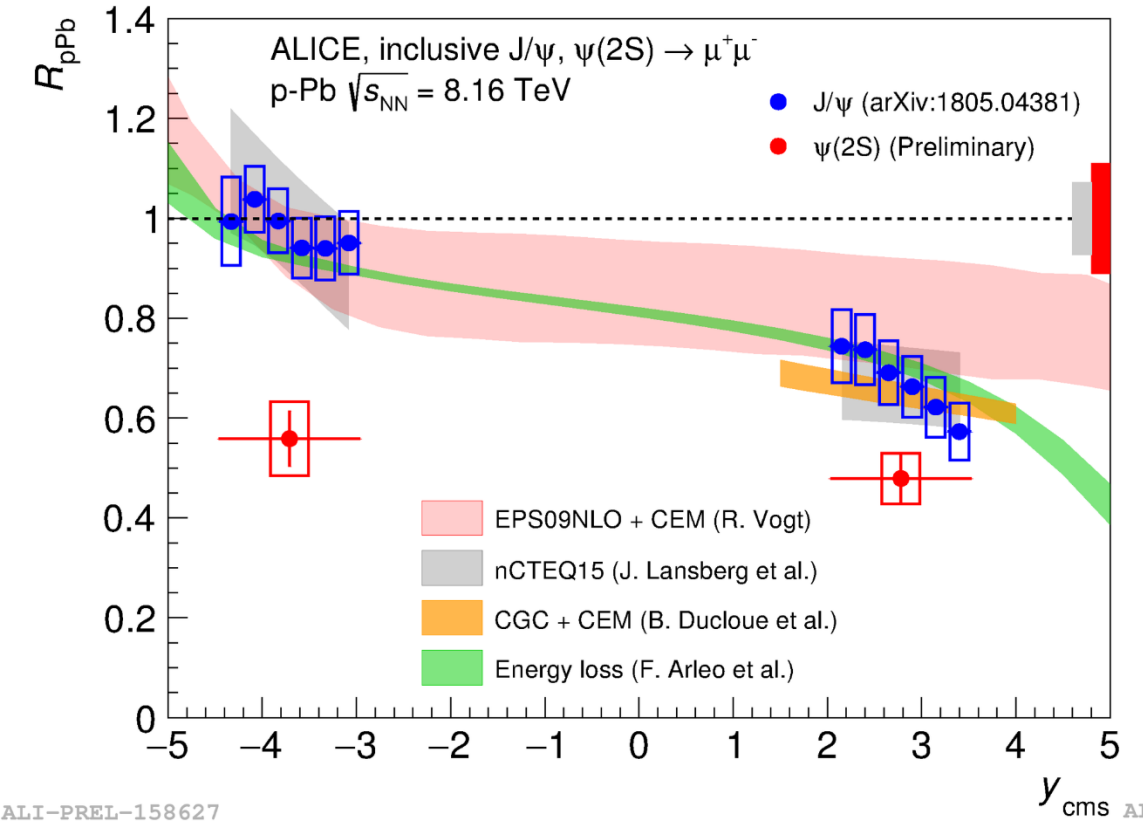
Final state effects: After the $\mathbf{Q\bar{Q}}$ pairs creation

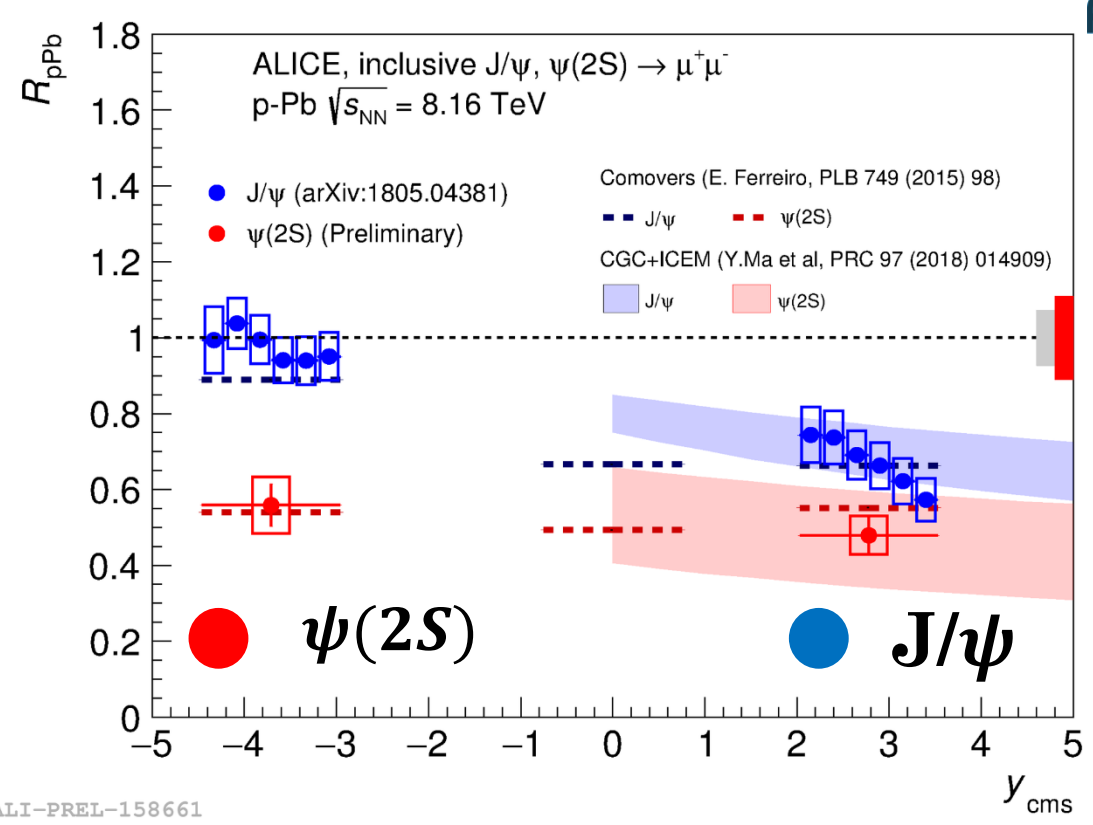
- Interaction with hadronic medium
  - Breakup by comovers
  - Nuclear absorption



$-4.46<y_{cms}<-2.96$

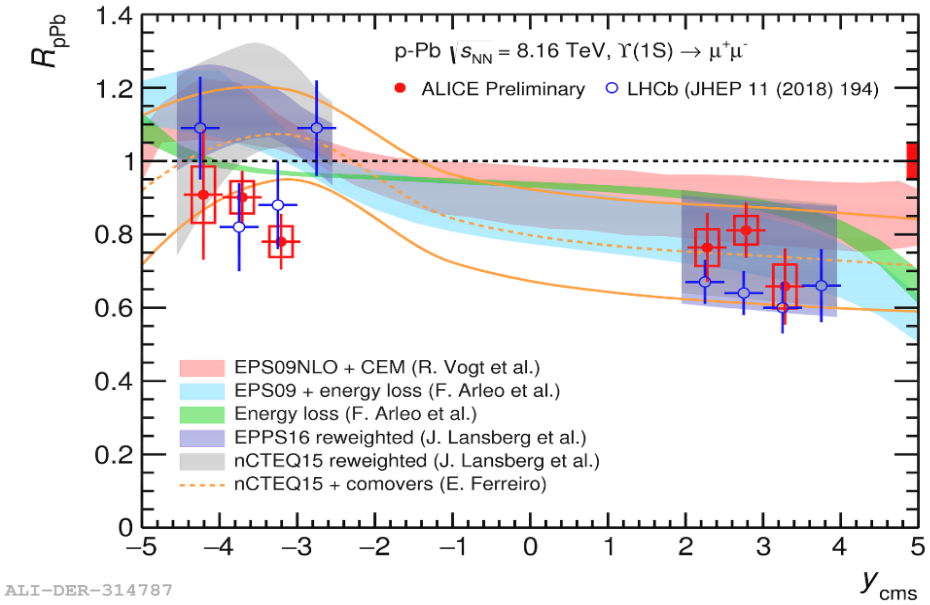
J/ψ and ψ(2S) R_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV

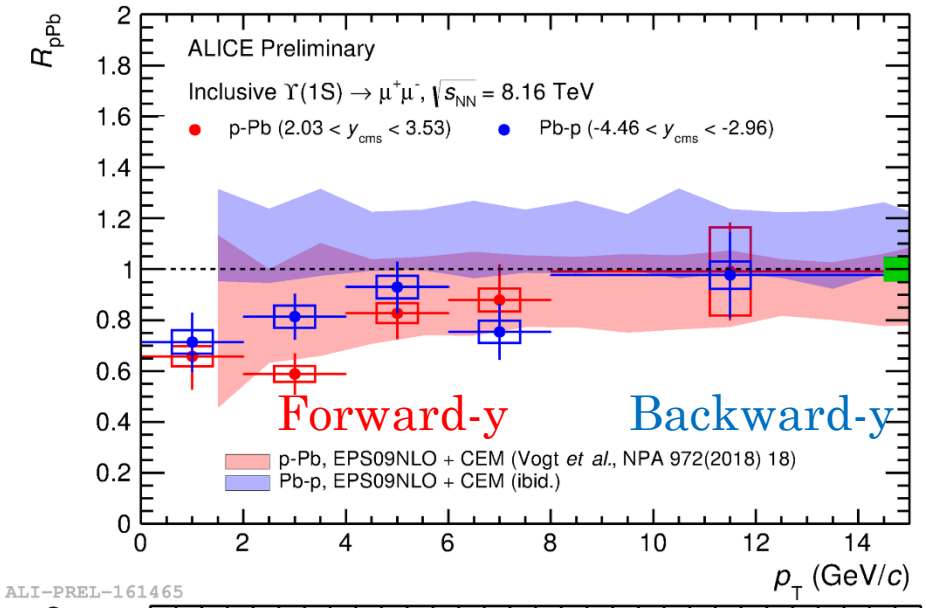


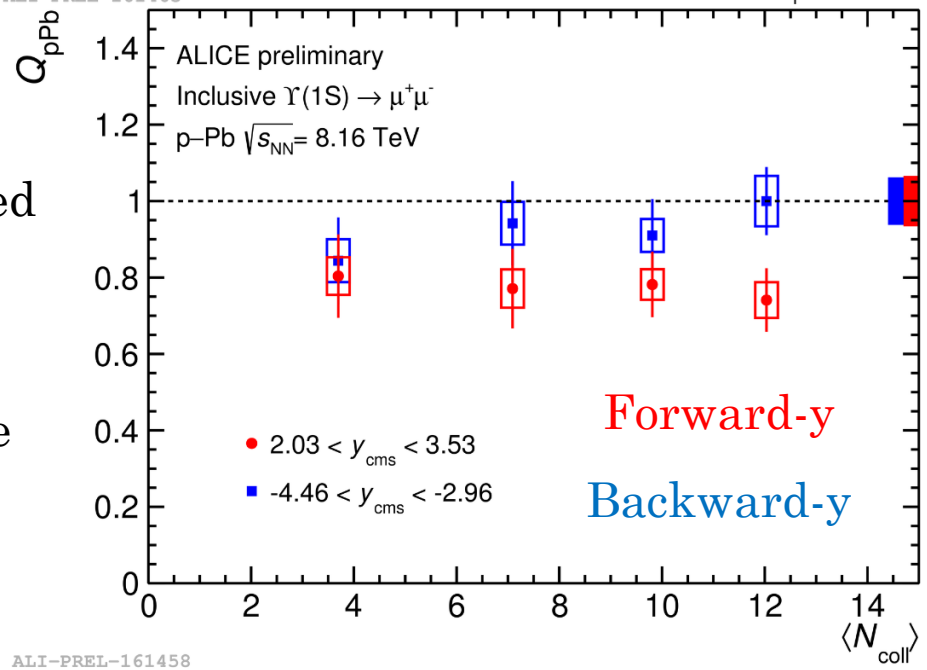


- J/ψ suppression consistent with initial state effects
- ψ(2S) shows a strong suppression compared to J/ψ especially at backward rapidity
- Initial state effects models can not explain the ψ(2S) data
- Models including final-state effects reproduce ψ(2S) behavior at both forward and backward rapidity

$\Upsilon(1S)$ R_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV



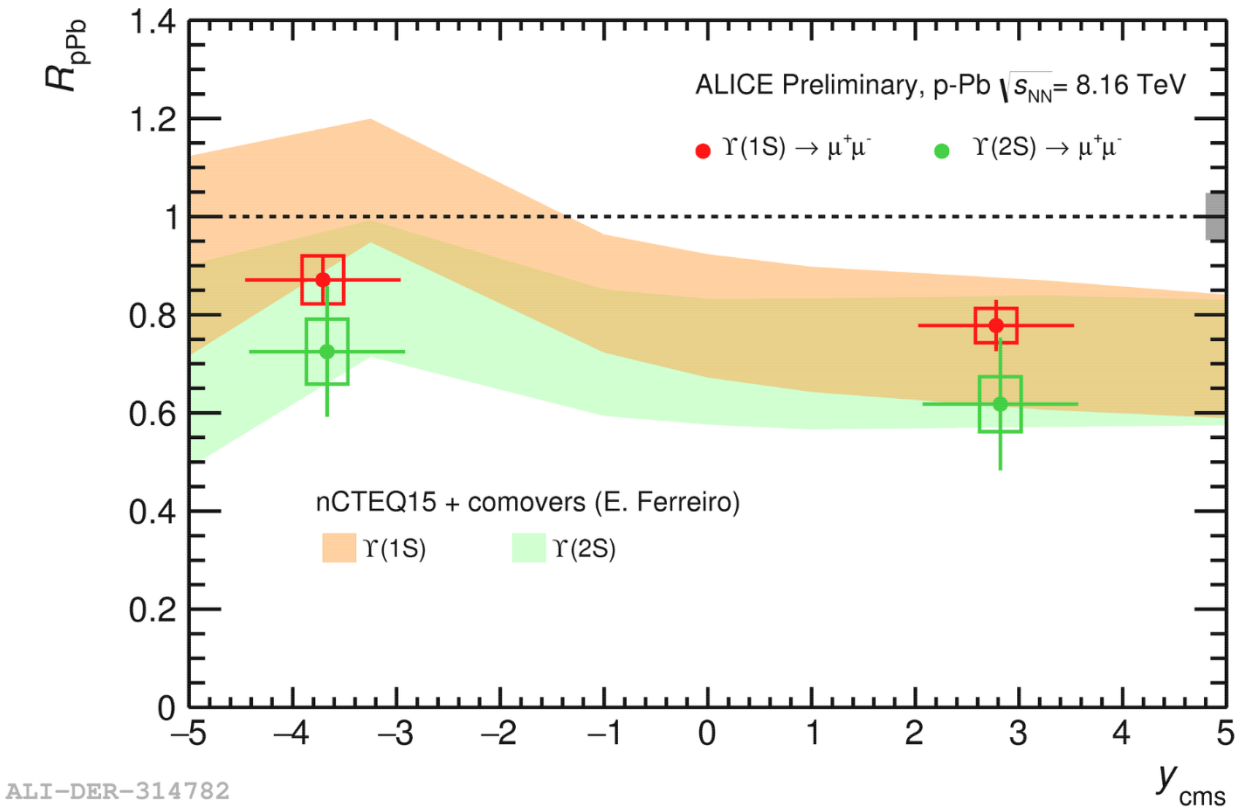




- Indication of $\Upsilon(1S)$ suppression both at forward and backward rapidity. Stronger $\Upsilon(1S)$ suppression observed at low p_T.
- Models including shadowing and energy loss describe the data at forward rapidity within uncertainties while they overestimate the data at backward rapidity
- No evidence for centrality dependence

ALICE-PUBLIC-2018-008

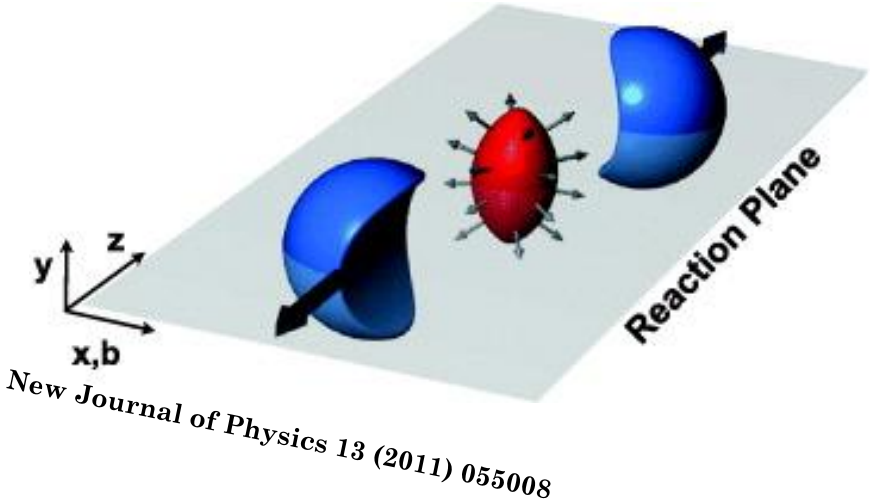
Υ(1S) and Υ(2S) R_{pPb} at $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV



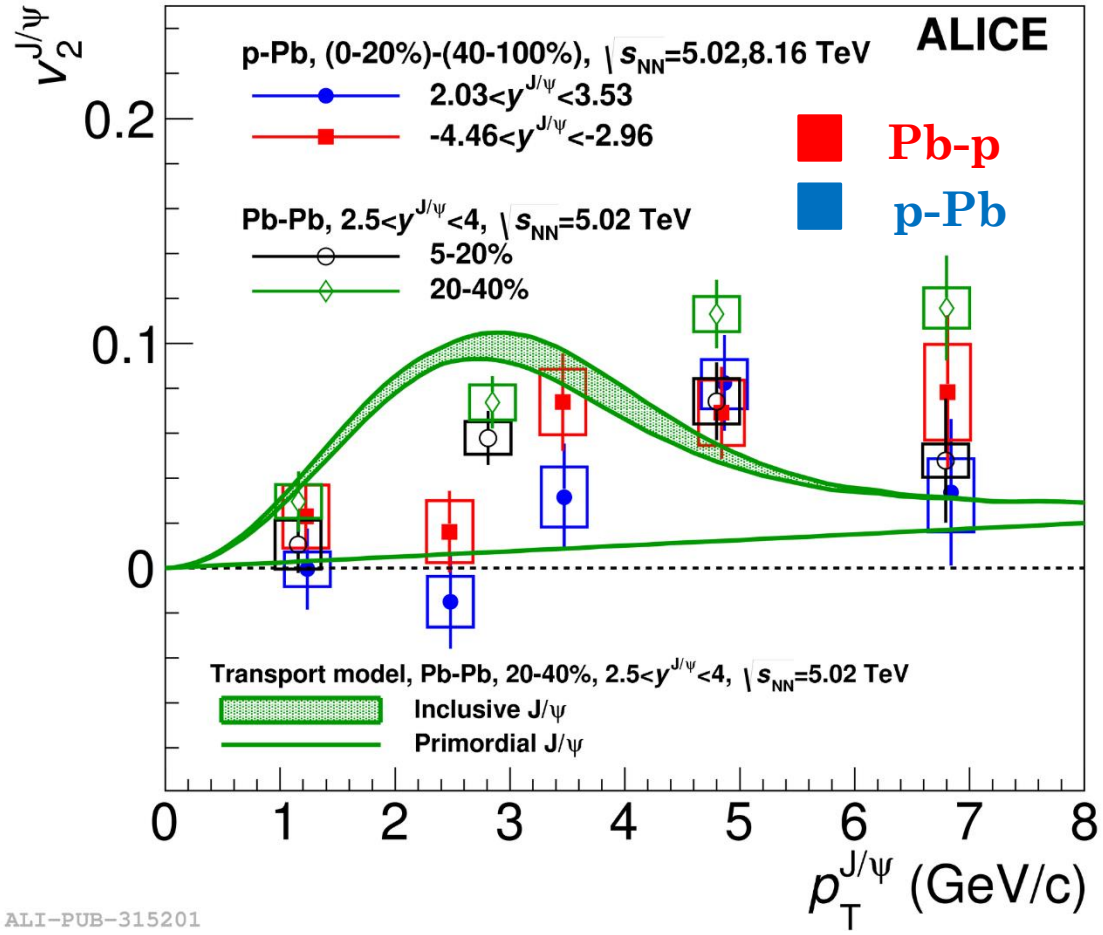
ALICE-PUBLIC-2018-008

- The two resonances show similar suppression, slightly larger for Υ(2S).
- A Model which includes shadowing + interaction with comoving particles describes the data.

J/ψ elliptic flow v_2 in p-Pb collisions at 8.16 TeV



New Journal of Physics 13 (2011) 055008



PLB 780(2018)7-20

- Elliptic flow is defined as the 2nd order coefficient v_2 of the Fourier expansion of the azimuthal distribution

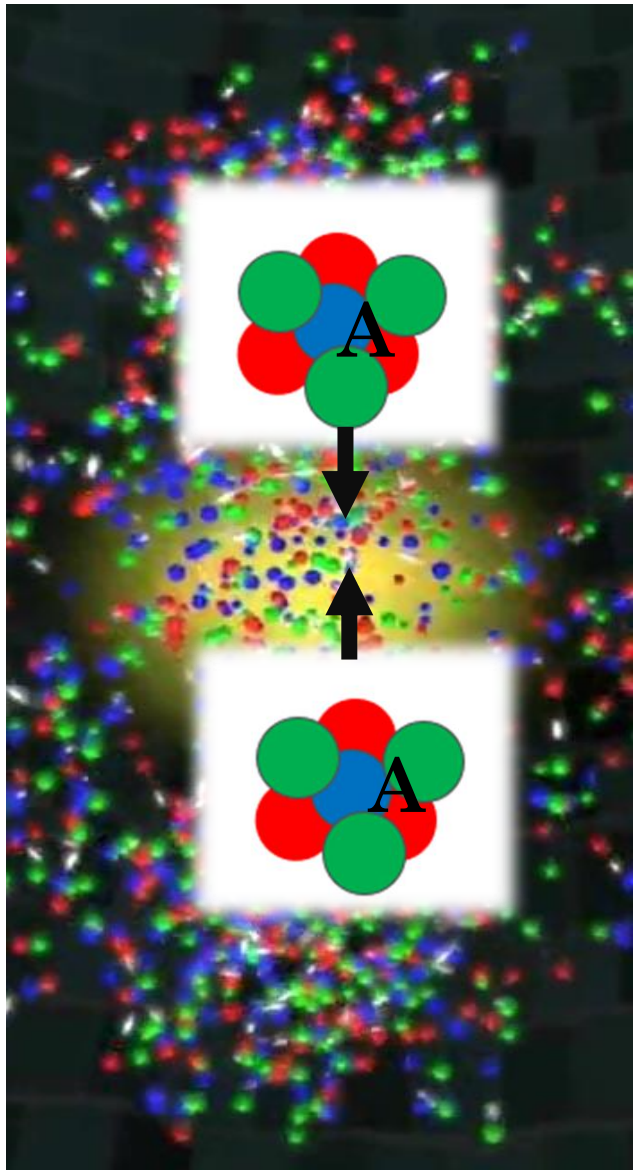
- At low p_T (<3GeV/c) v_2 compatible with zero in both rapidity intervals
- At high p_T (>3 GeV/c) positive v_2 of the same order as that measured in Pb-Pb
- Transport model does not describe the data in Pb-Pb and p-Pb (p-Pb prediction not shown)

Quarkonium production in Pb-Pb (Xe-Xe) collisions

Quarkonium as a probe of the deconfined medium (QGP) created in the heavy-ion collisions.

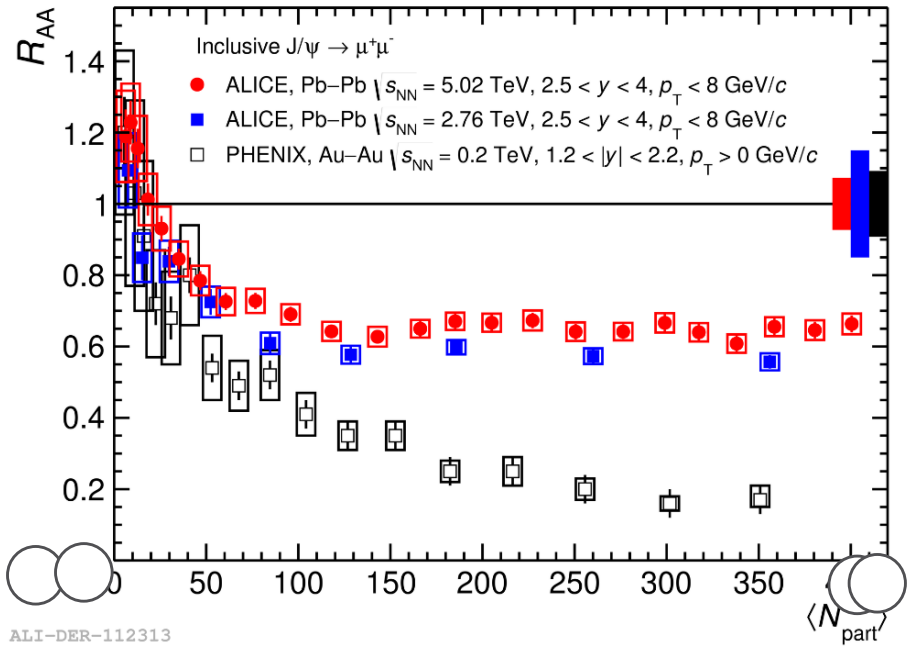
Suppression : dissociation via color screening [PLB 178 (1986) 178]

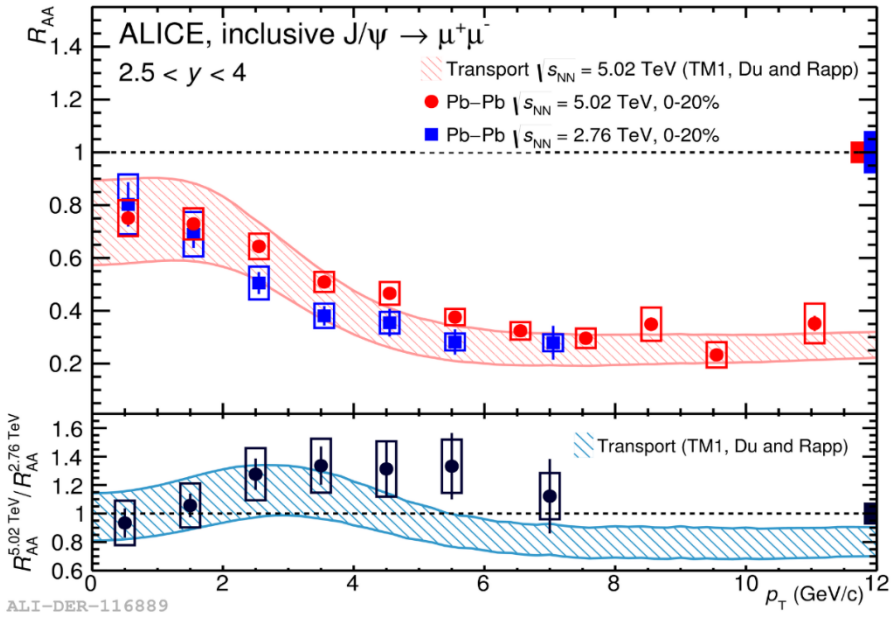
Enhancement : recombination of $Q\bar{Q}$ [PLB 490 (2000) 196, PRC 65 (2001) 054905]



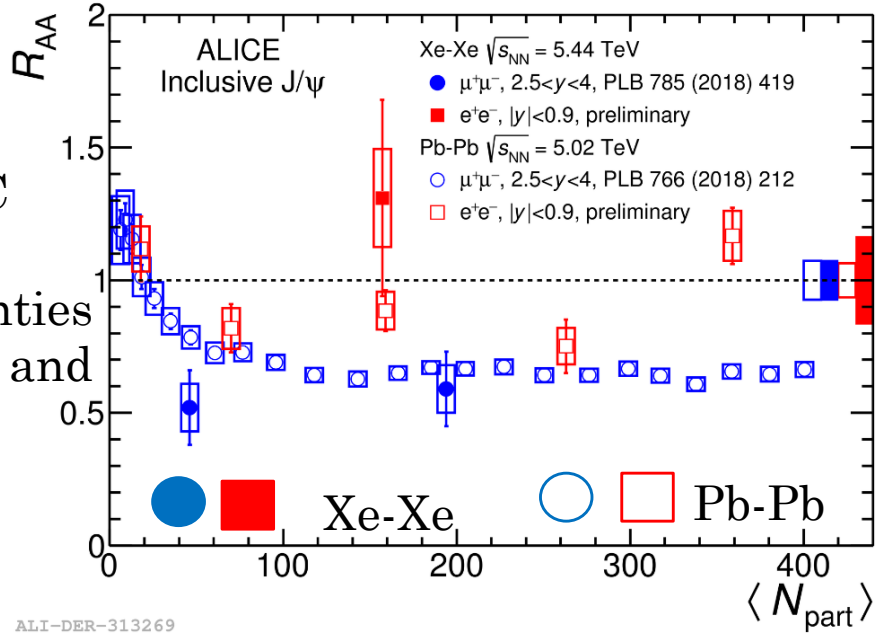
Charmonium in Pb-Pb and Xe-Xe

PLB 766 (2017) 212





- Strong J/ψ suppression is observed at RHIC whereas LHC shows an interplay of suppression and (re)generation
- Transport Models (TM) describe the data within uncertainties
- The J/ψ R_{AA} is found to be of similar magnitude in Pb-Pb and Xe-Xe collisions.



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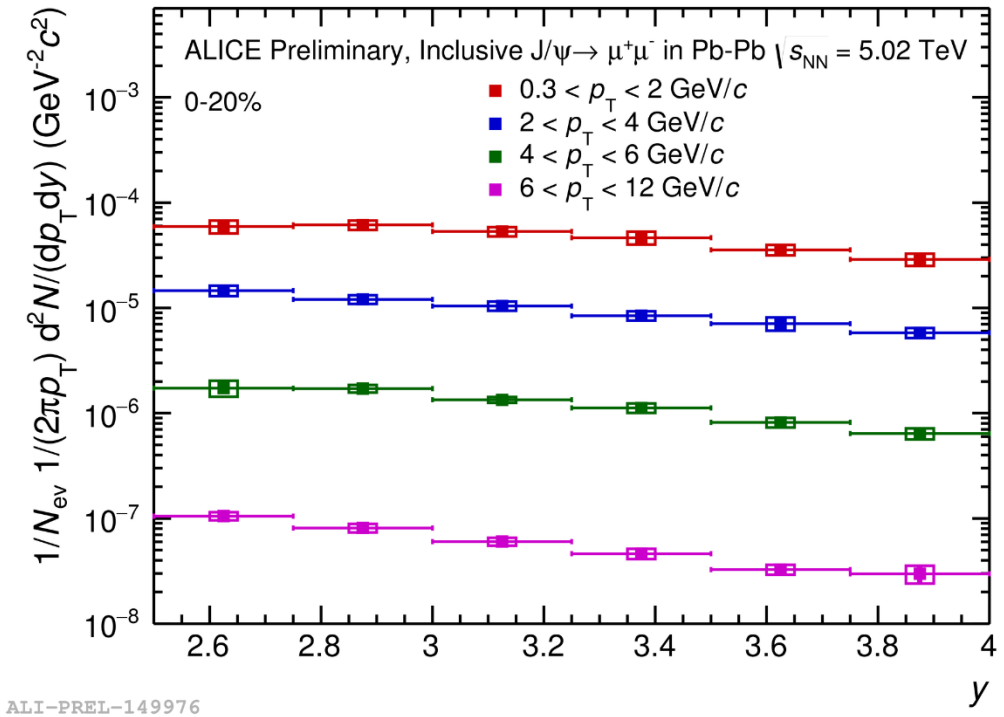
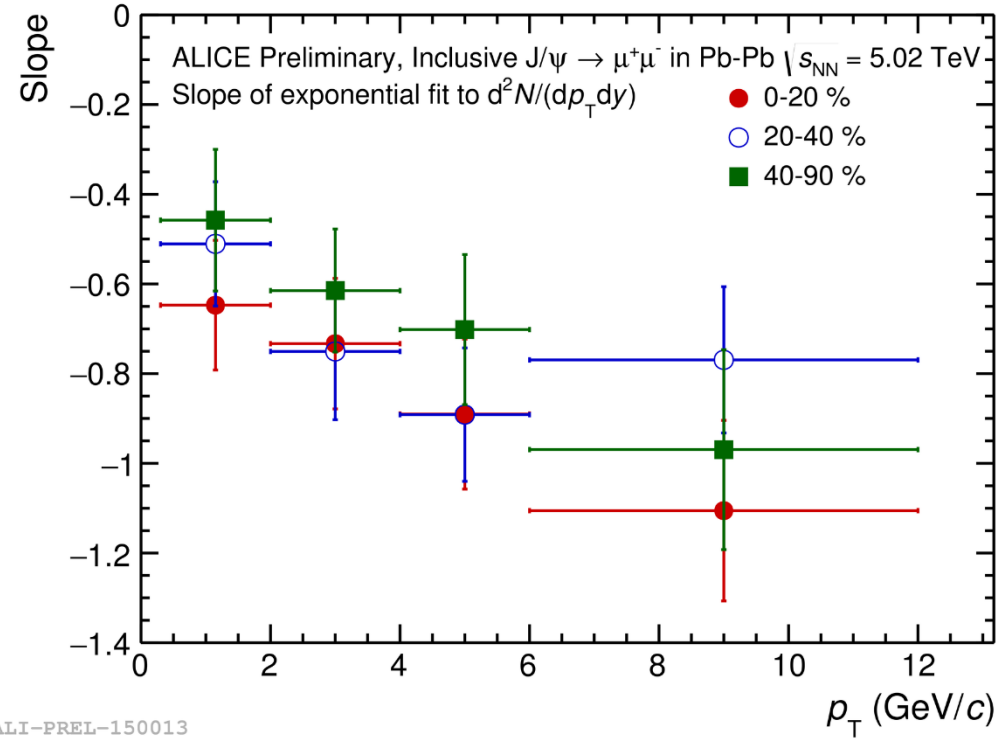
Triple-differential J/ψ yields in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

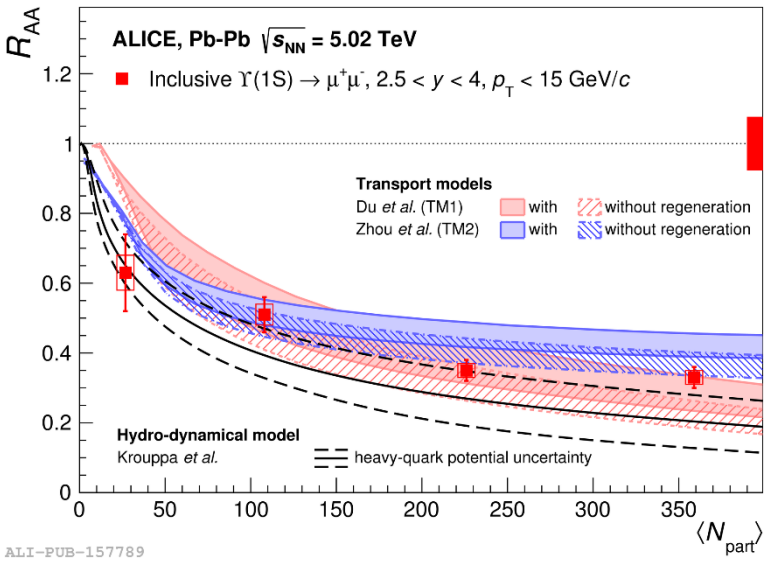




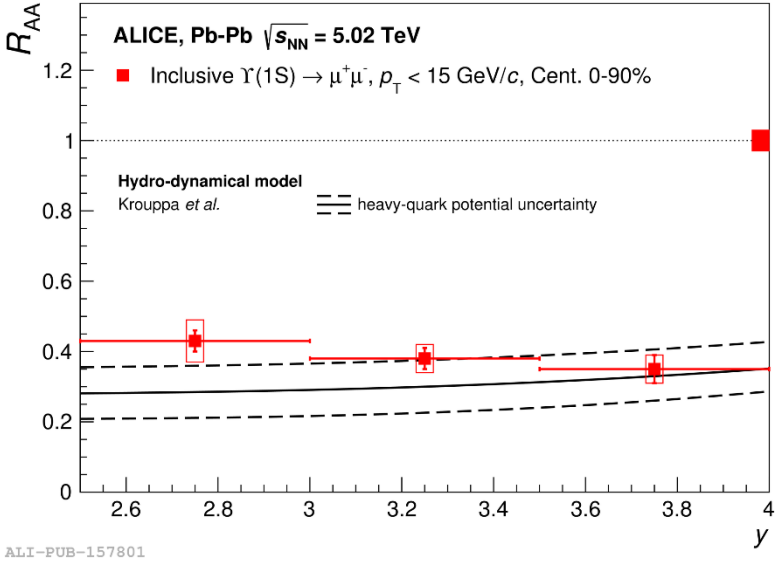
- Fit rapidity spectra in bins of p_T and centrality with exponential function
- Rapidity spectra soften towards higher p_T
- pp reference for triple-differential R_{AA} underway, **stay tuned!!!**

Υ(1S) in Pb-Pb

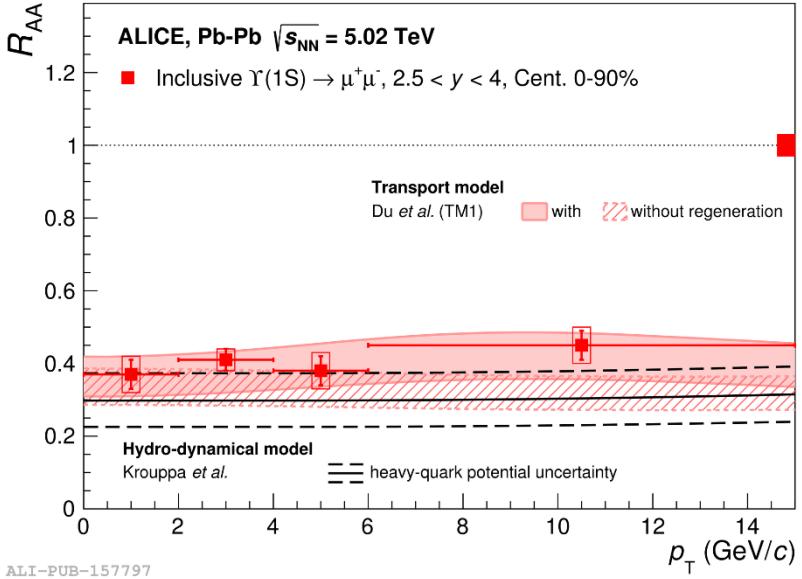
PLB 790 (2019) 89



Centrality



Rapidity



p_T

- Stronger suppression is observed in central collisions than in peripheral events
- No variation of R_{AA} is observed as function of p_T and rapidity
- Transport models (TM) with and without (re)generation describe the data within uncertainties.

Adding the 2018 and 2015 data allows to increase the statistics by a factor 3, will give more precise measurements

J/ψ polarisation in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

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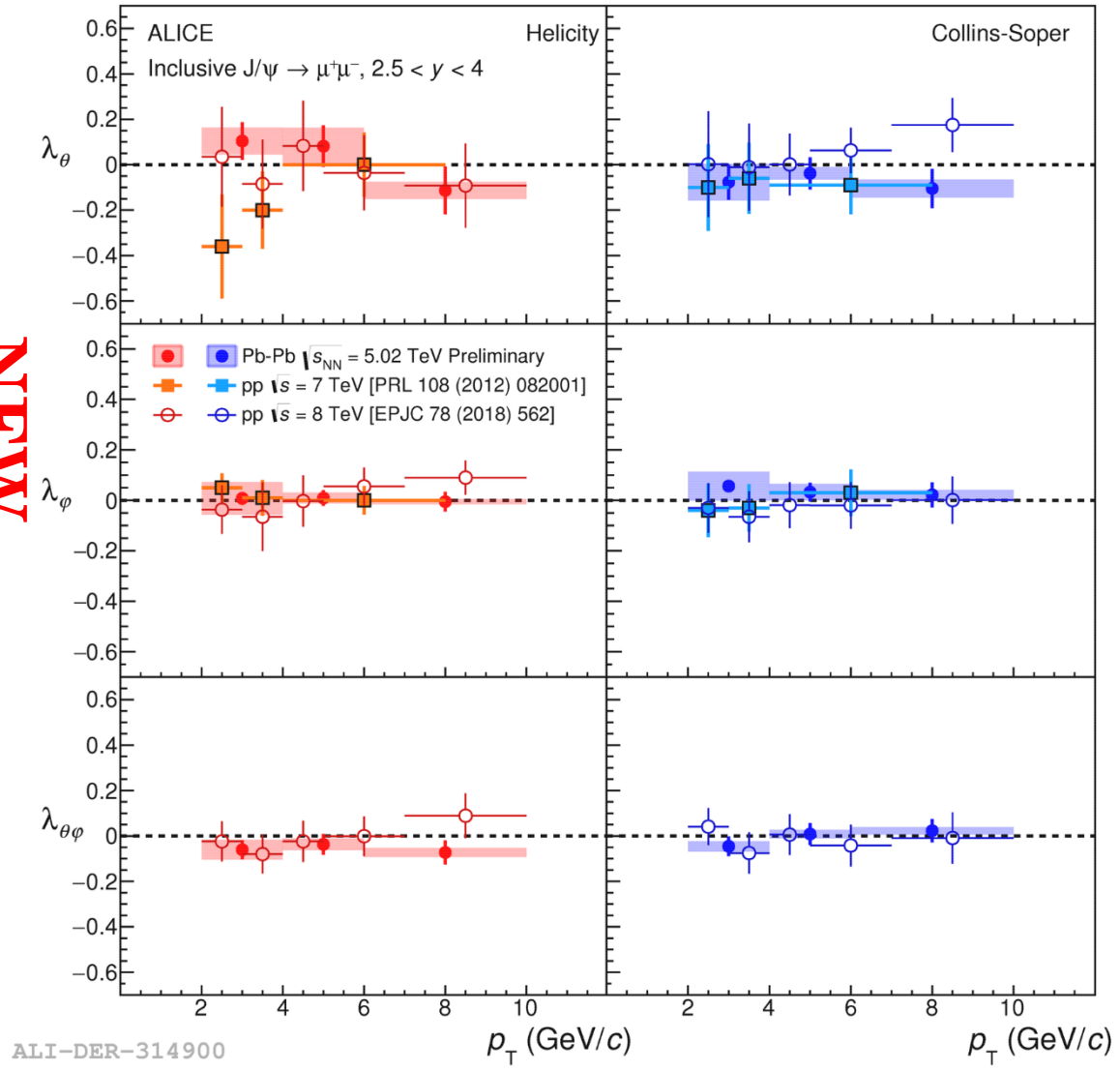

- First LHC measurements
- No significant J/ψ polarization observed in Pb-Pb collisions

Υ(1S) elliptic flow v_2 in Pb-Pb collisions at 5.02 TeV

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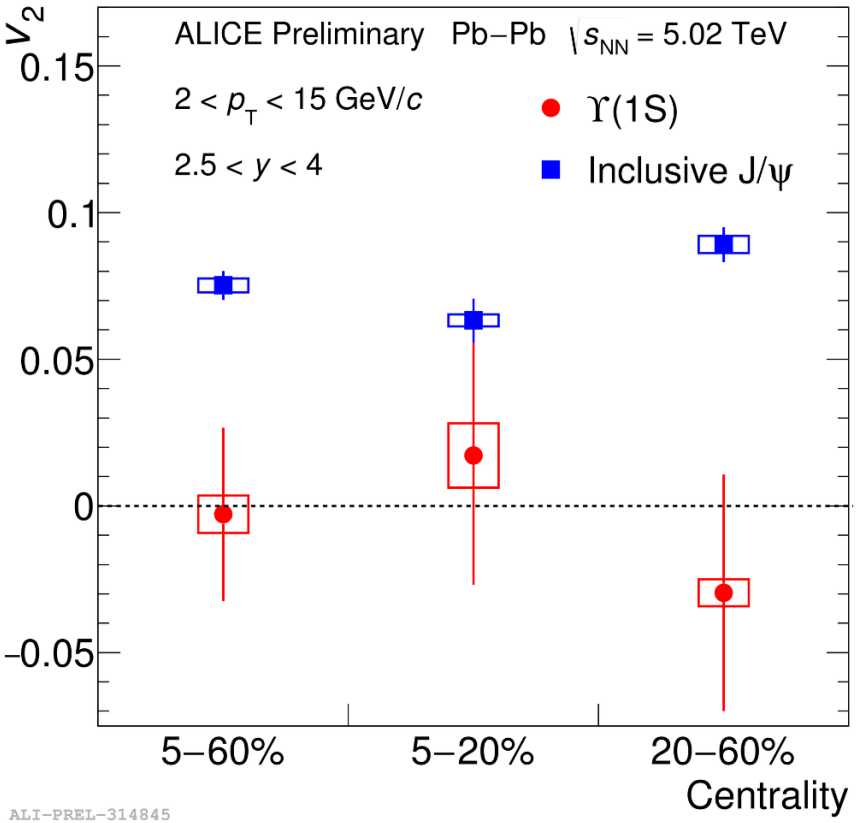
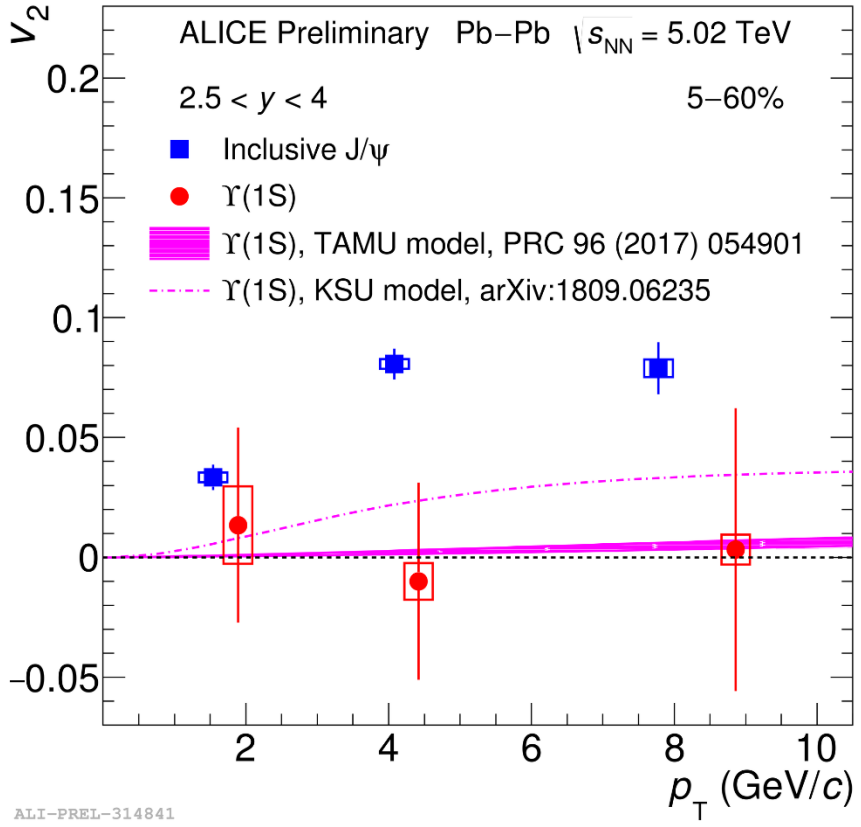




- Measurement includes both 2015 and 2018 Pb-Pb data sets.
- Υ(1S) v_2 is compatible with zero (all other hadrons exhibit non-zero flow)
- Compatibility with zero consistent with no recombination expectations
- Available theoretical model predictions describe the data within uncertainties
- Excluding low p_T, Υ(1S) v_2 is 2.6σ lower with respect to that of inclusive J/ψ.

HF-2019 (Tuesday,11/6) : Erin Gauger

Summary

- **pp collisions**
  - ALICE results are consistent with the other LHC experiments. New 5.02 TeV results will serve as reference for heavy ion collisions
  - Theoretical predictions describe the cross section data over all p_T but polarisation is still a puzzle.
  - The quarkonium production increases linearly as a function of charged-particle multiplicity in different rapidity region
    - ❖ Exhibits no strong $\sqrt{s}$ dependence and also found to be similar for charmonium and bottomonium.

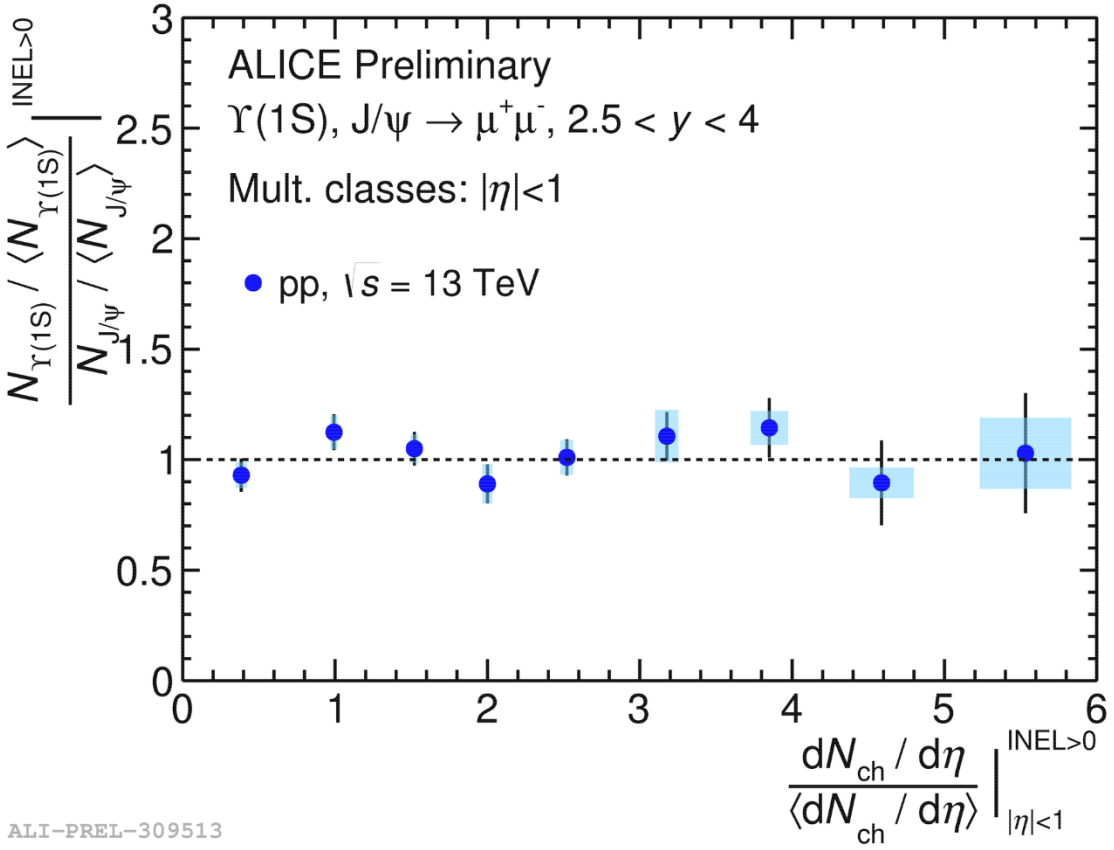
- **p-Pb collisions**
  - The nuclear modification factor can be explained by Cold Nuclear Matter effects.
  - Final state effects required to explain the $\psi(2S)$ R_{pPb}
  - J/ψ v_2 is non zero at high p_T in central p-Pb collisions.

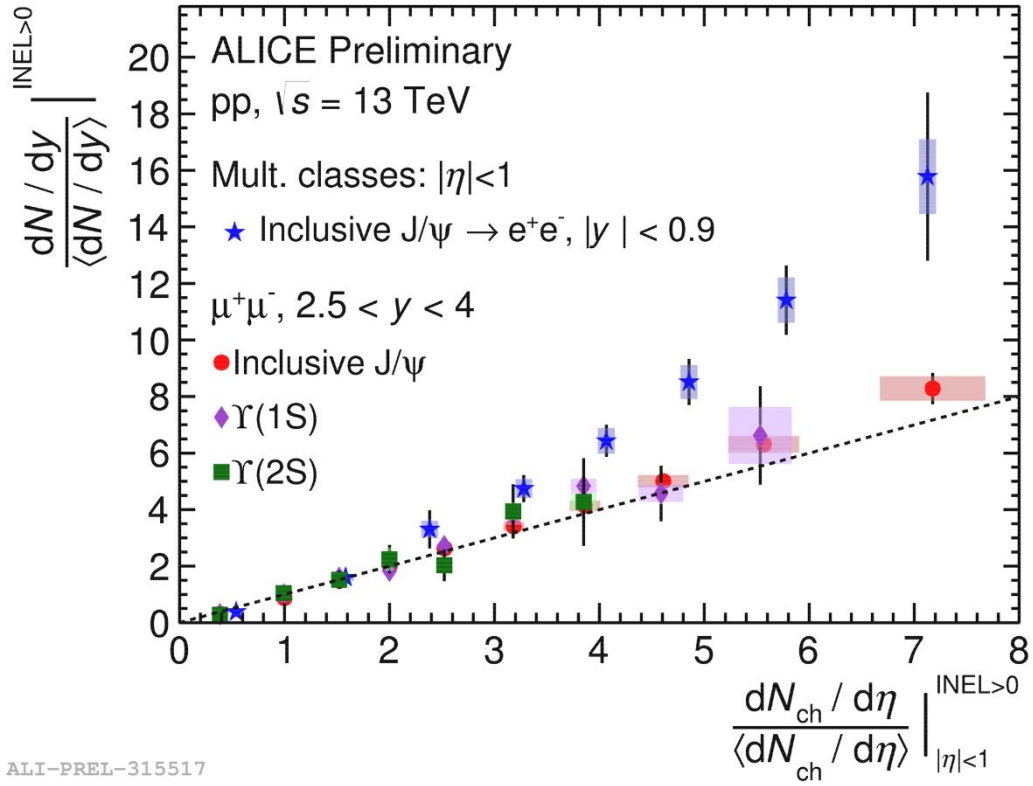
- **Heavy-ion collisions**
  - J/ψ R_{AA} results at LHC form an interplay of two main mechanisms : suppression and (re)generation whereas for $\Upsilon(1S)$ suppression plays a dominant role with negligible (re)generation.
  - Weak or no J/ψ polarization is found.
  - The measured zero elliptic flow of $\Upsilon(1S)$ points to negligible (re)generation.

Thank You

Backup Slide

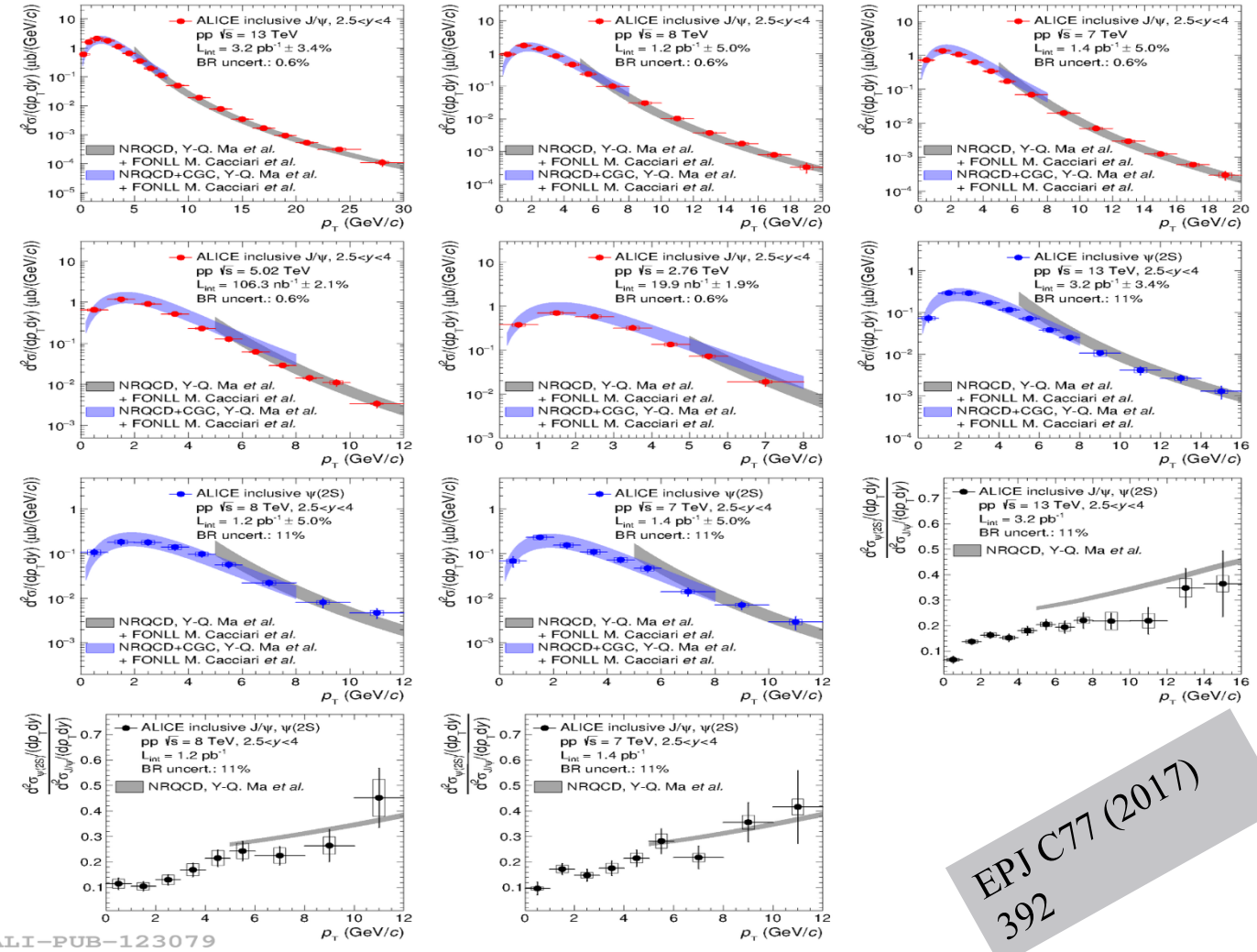
Relative yields of quarkonium vs multiplicity in pp

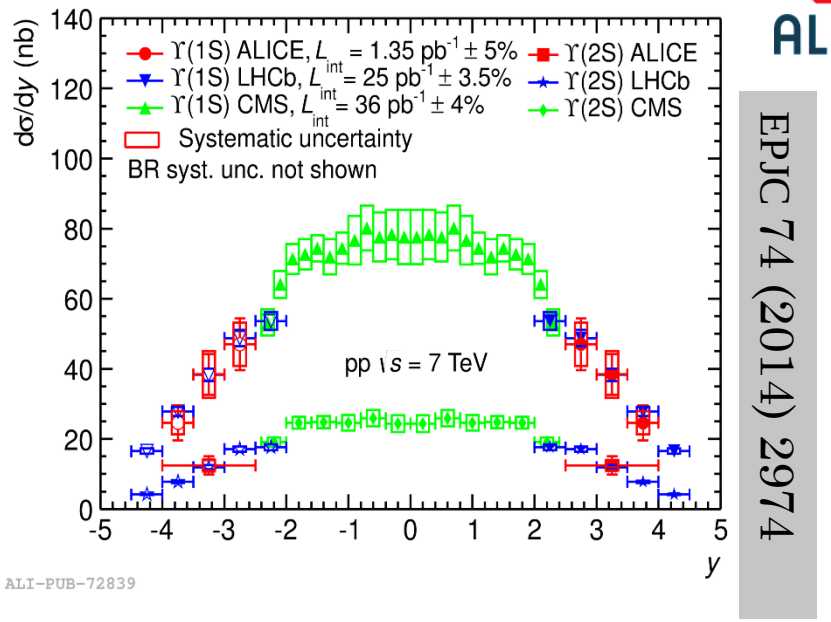




- Liner increase of J/ψ, Υ(1S), Υ(2S) at forward rapidity. However deviation from linear increase for J/ψ at mid rapidity.

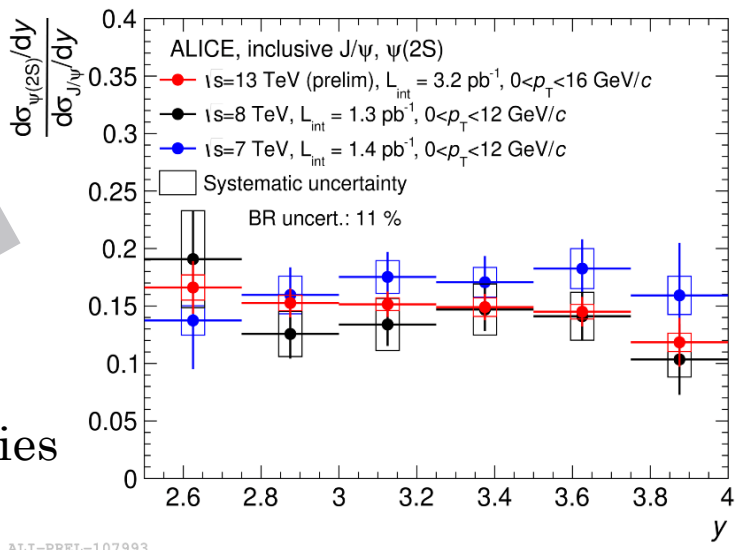
J/ψ, ψ(2S),Υ(nS) production cross section





EPJC 74 (2014) 2974

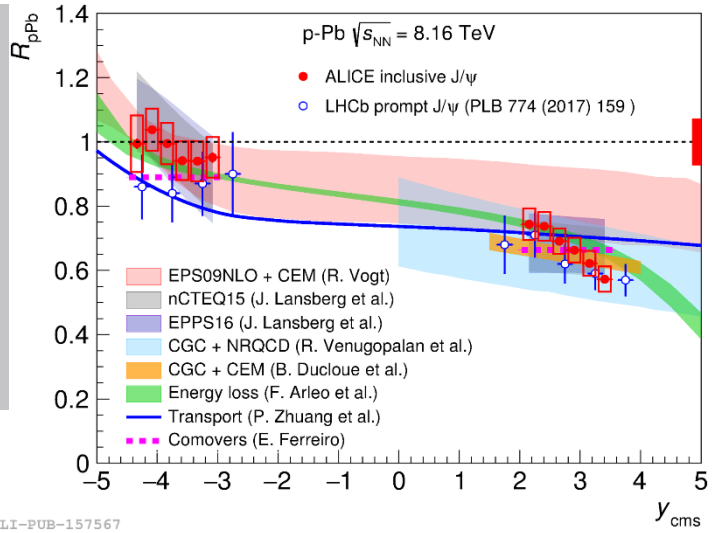
EPJ C77 (2017) 392

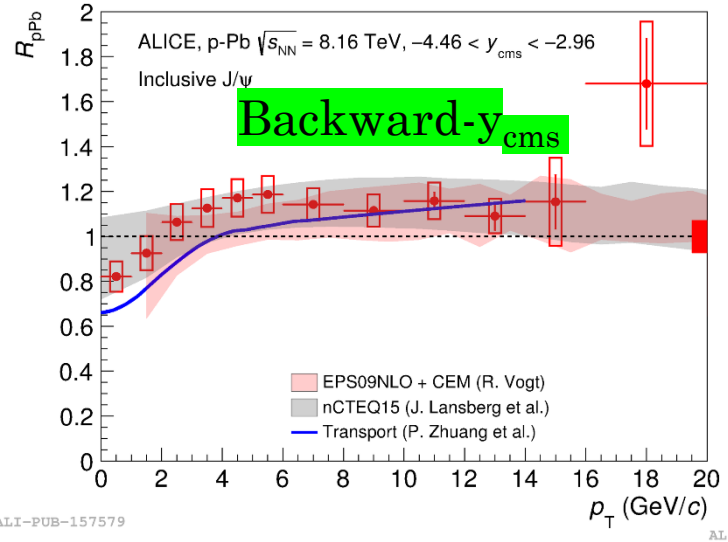


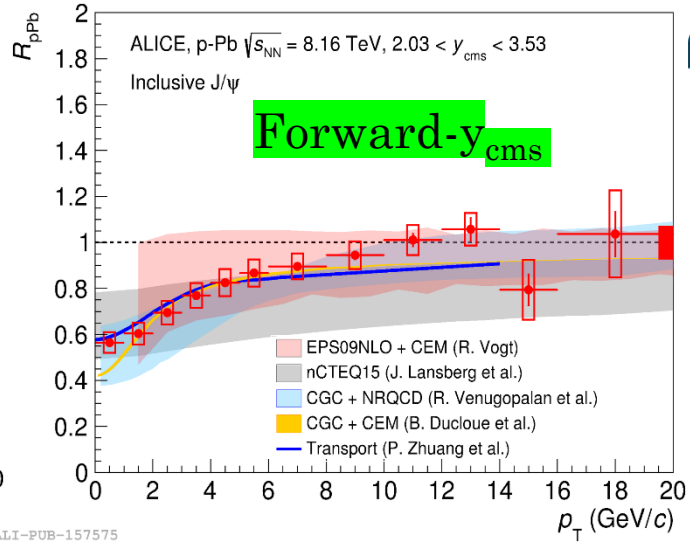
- Cross section has been measured at all available LHC energies
- CGC+NRQCD model describes the pT dependent results
- ψ(2S)/J/ψ increases with p_T and flat as function of rapidity

J/ψ R_{pA} as function of y_{cms} p_T centrality at $\sqrt{s_{NN}}$ 8.16 TeV

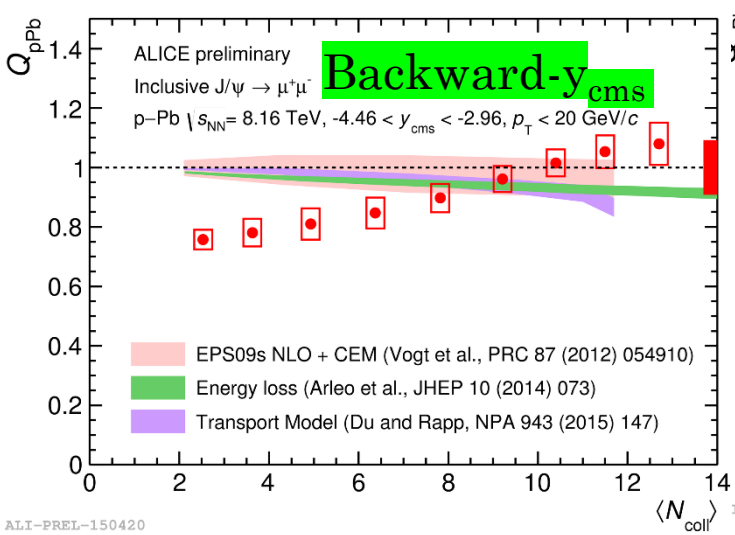
JHEP 07 (2018) 160

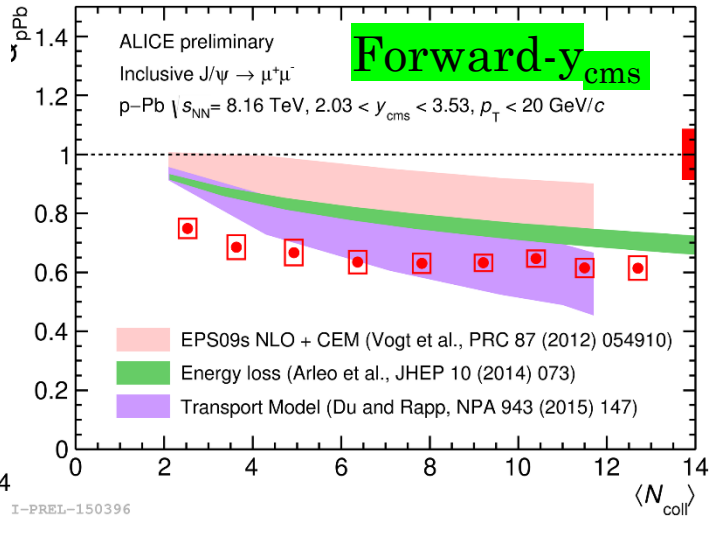






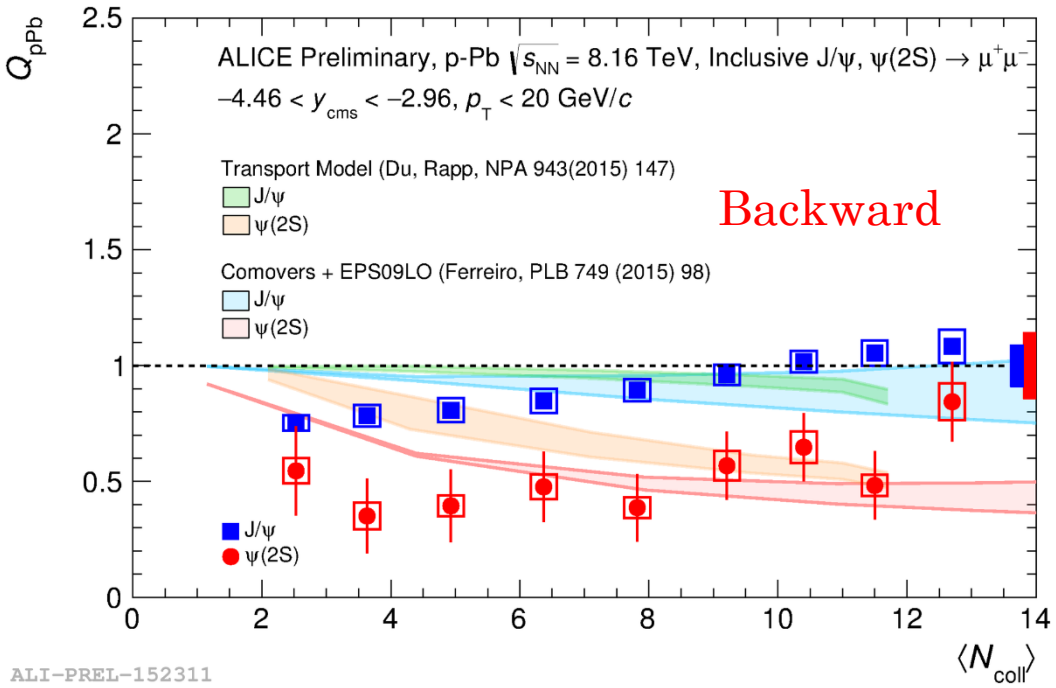
- J/ψ stronger suppression is observed at forward rapidity, while R_{pPb} is compatible with unity at backward rapidity.
- The p_T dependence result of R_{pPb} shows an increase from low to high p_T at both forward and backward rapidity.
- Models based on different shadowing calculation, CGC, energy loss, transport models and comovers describe the data.

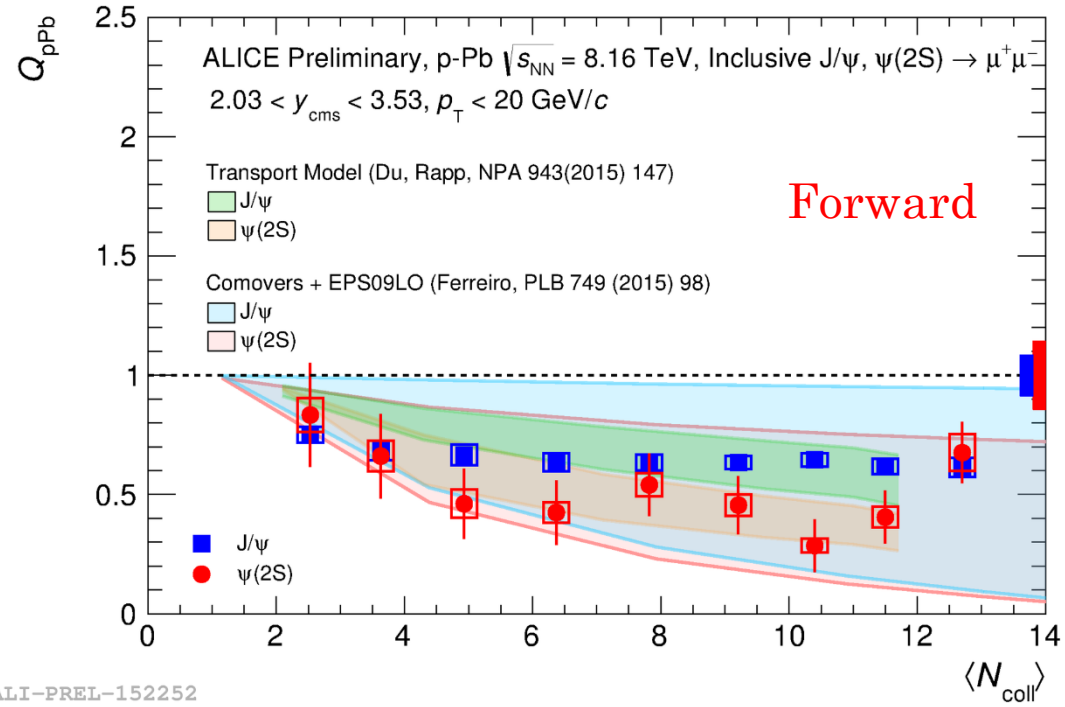




- Centrality estimates using Zero Degree Calorimeters (ZDC)
- Q_{pA} increases peripheral to central collision at backward rapidity while opposite trends is observed at forward rapidity.

$\Psi(2S)$ Q_{pA} vs centrality in p-Pb 8.16 TeV

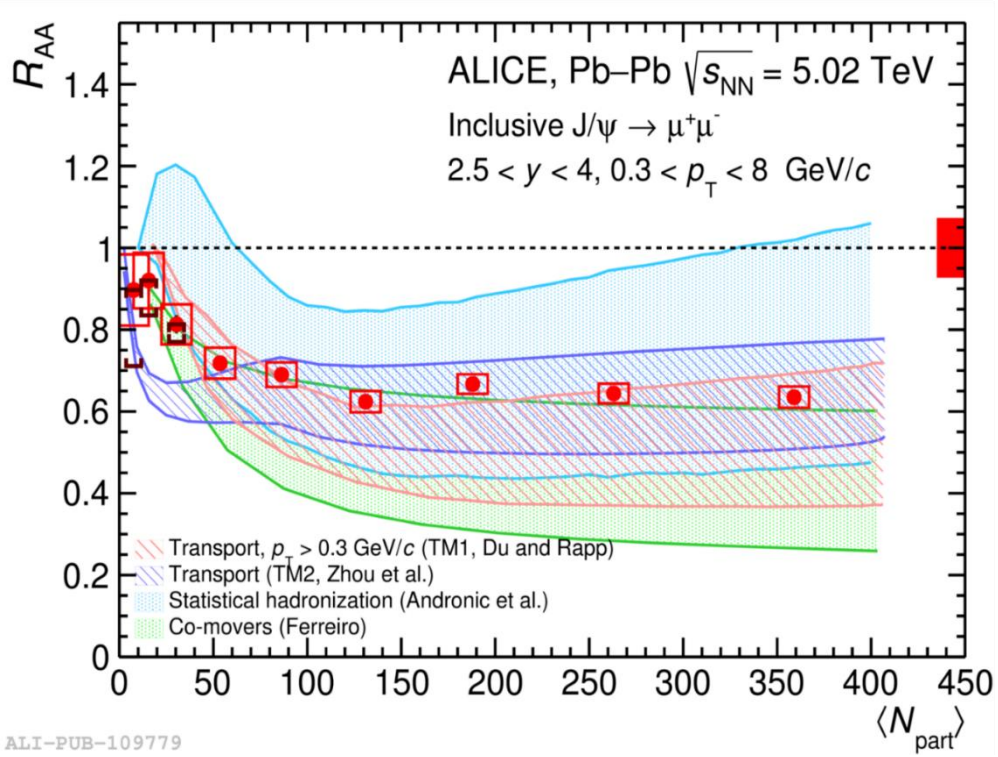




- In centrality classes $\Psi(2S)$ **suppression observed** both at forward and backward rapidity
- Final state effects fairly described the $\Psi(2S)$ Q_{pA} at forward rapidity
- Some tension in data and model at backward rapidity.

Charmonium predictions in Pb-Pb

PLB 766 (2017) 212

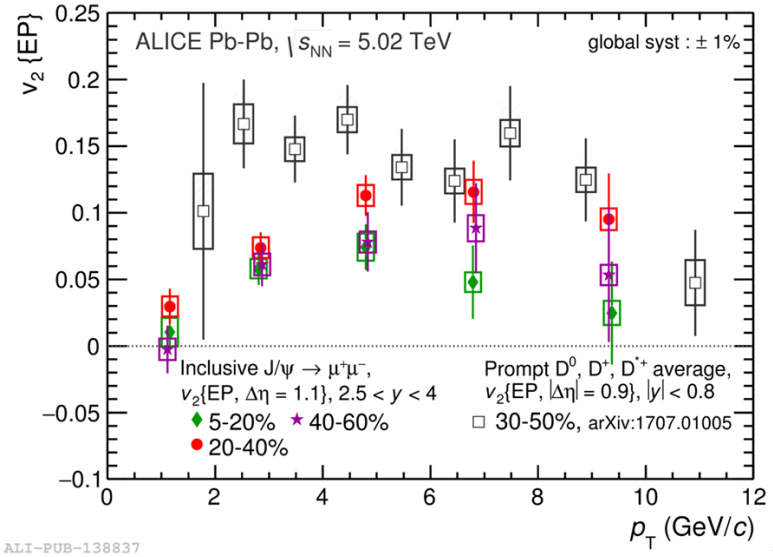


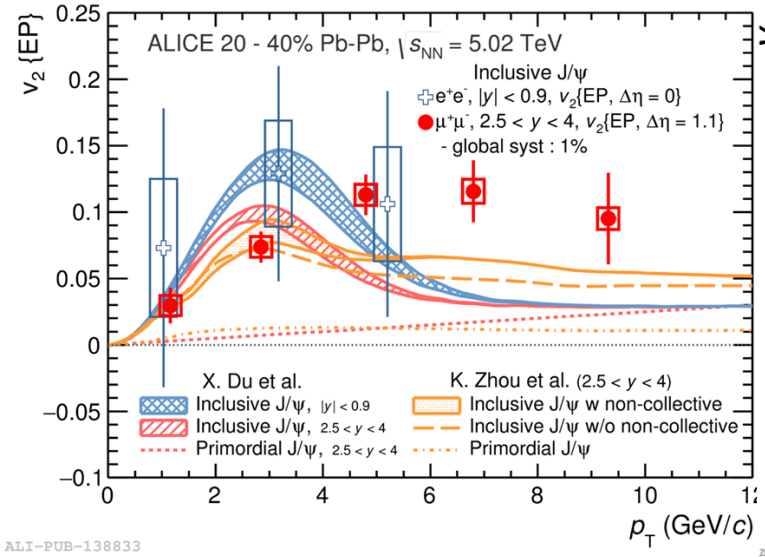
TM1: Nucl. Phys. A859 (2011) 114–125
TM2: Phys. Rev. C89 no. 5, 459 (2014) 054911
Stat. hadronization: NPA 904-905 (2013) 535c
Co-movers: Phys. Lett. B731 (2014) 57–63

- All models describe the data with its larger uncertainties.
- large uncertainties associated to charm cross section and shadowing
- Precise charm cross section measurement and more differential analyses needed

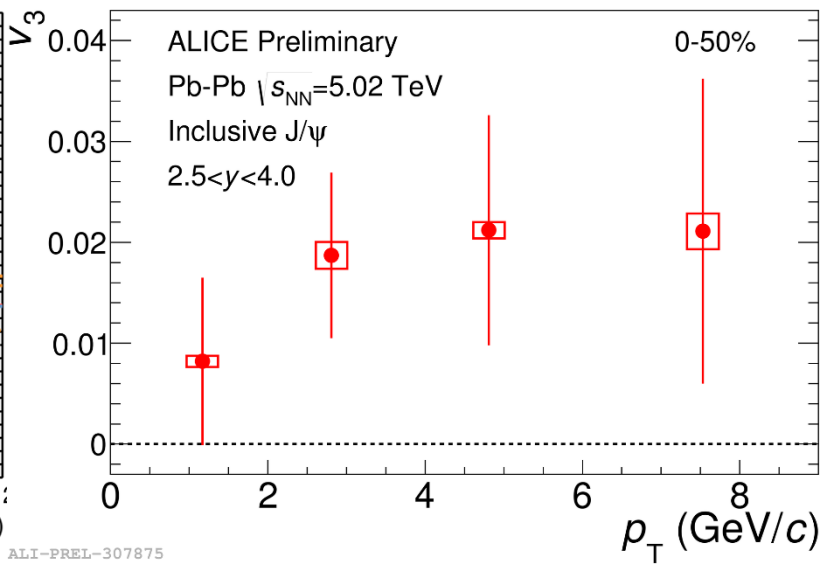
J/ψ flow in Pb-Pb

PRL 119(2017) 242301





arXiv : 1811.12727



- J/ψ and prompt open-charm mesons show non-zero elliptic flow.
- The transport model predictions unable to describe the data in the high p_T region.
- A non-zero v_3 of J/ψ (3.7σ significance) has been measured for the first time.