Recent results on Quarkonia at forward rapidity with ALICE at the LHC

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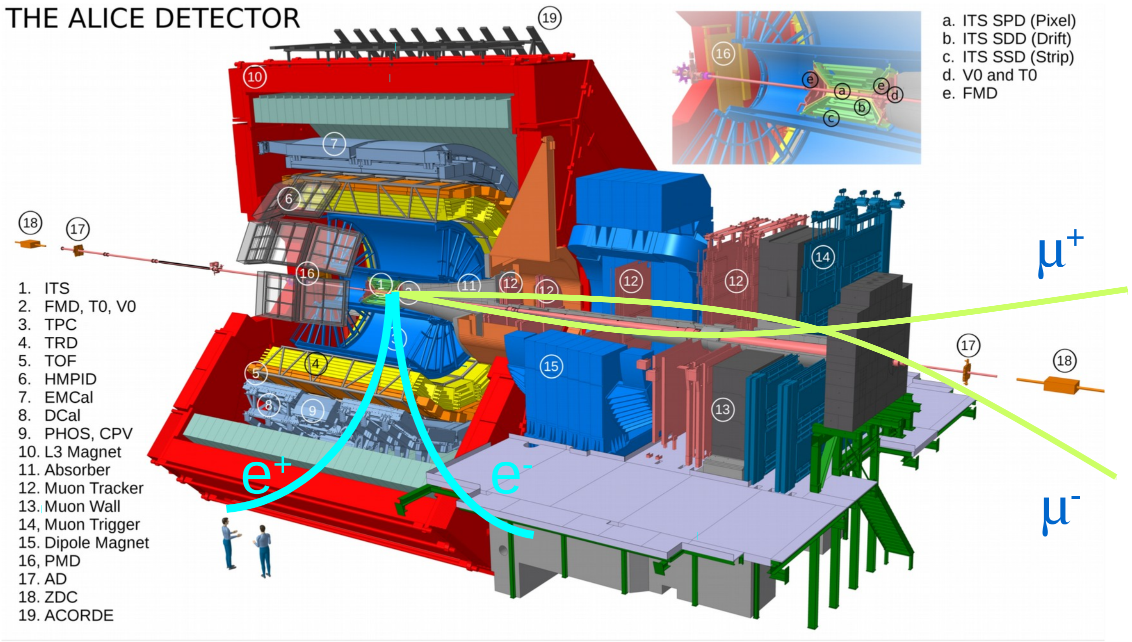
Istituto Nazionale di Fisica Nucleare

Outline

- ALICE detector
- pp results:
  - Quarkonium production cross section
  - Multiplicity dependence of quarkonium production
- p-Pb results:
  - Rapidity, p_{T} and centrality dependence of quarkonium production
  - Multi-differential study of J/ψ
  - Multiplicity dependence of quarkonium production
  - Elliptic flow of J/ψ
- Pb-Pb results:
  - Multi-differential study of J/ψ
  - Polarization of J/ψ
  - Azimuthal anisotropy of J/ψ
  - Elliptic flow of ϒ(1S)

A Large Ion Collider Experiment

→ Quarkonia in ALICE are measured in two rapidity ranges:



Central barrel:
$J/\psi \to e^+e^-$ ($|y| < 0.9$)

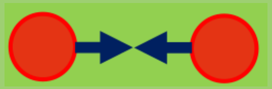
Electrons tracked using ITS and TPC
Particle identification: TPC (+TOF)

Forward muon arm:
$J/\psi \to \mu^+\mu^-$ ($2.5 < y < 4$)

Muons triggered and tracked in the muon spectrometer

→ Acceptance coverage in both y regions is down to zero p_T
→ The ALICE results presented in this talk refer to inclusive quarkonium at forward rapidity

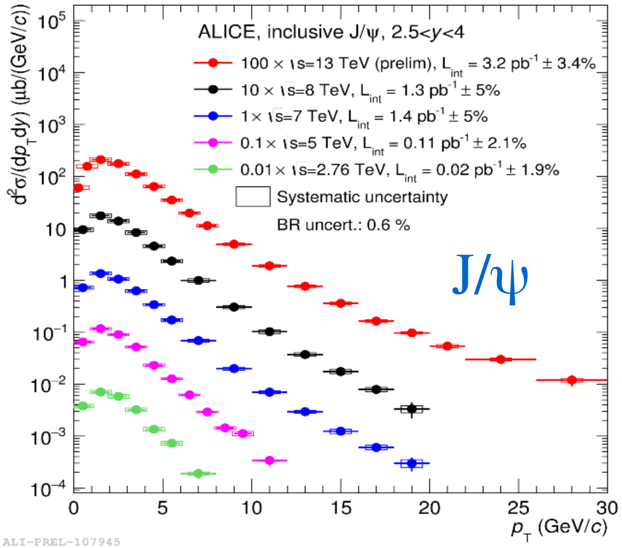
pp collisions

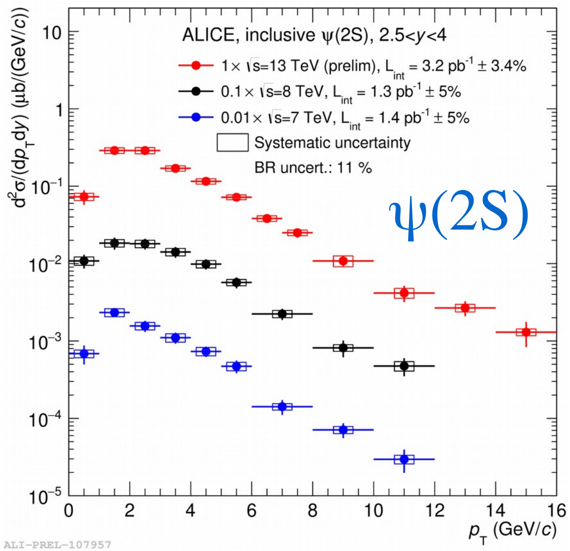


baseline for pA, AA collisions

study production mechanisms

Quarkonium production in pp collisions





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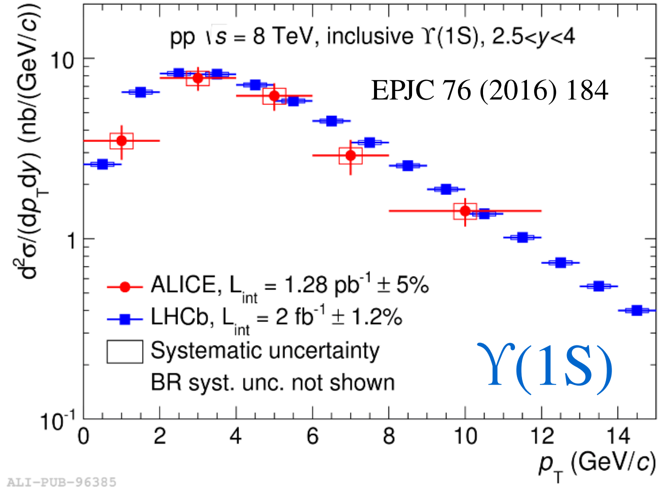
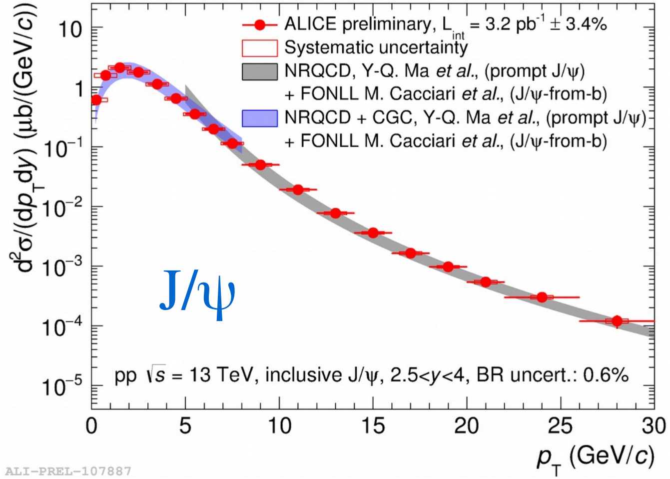
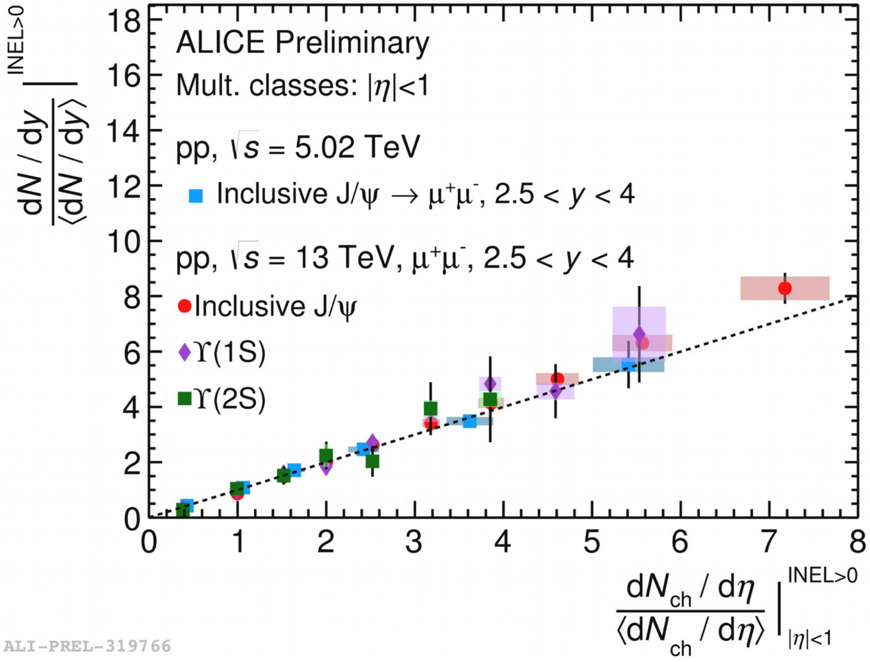
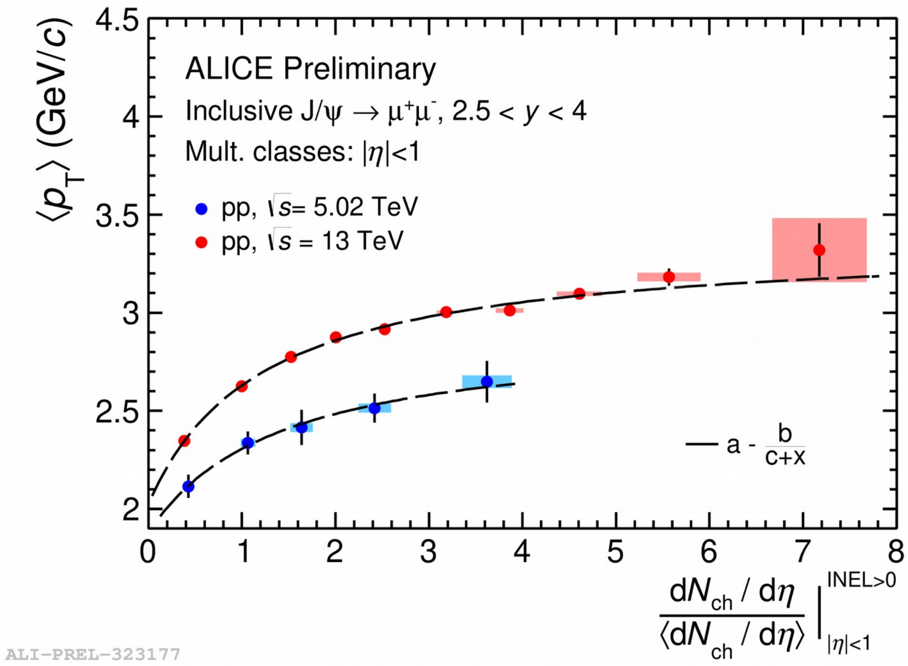




- Recent theoretical developments, e.g. combining Non Relativistic QCD (NRQCD) with Color Glass Condensate (CGC) reproduce the J/ψ p_T shape.
  [Phys. Rev. Lett. 113 (2014) 192301]

Multiplicity dependence of quarkonium production in pp

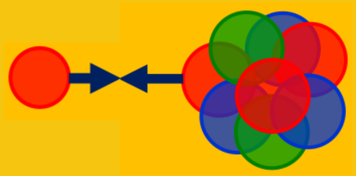




- To study the production mechanism, multi parton interactions and interplay between soft and hard processes

- Multiplicity is measured in a different rapidity interval from that of the J/ψ and ϒ
- Linear increase with multiplicity for different quarkonium states
- No strong dependence on $\sqrt{s}$ and quarkonium type
- J/ψ $\langle p_T \rangle$ increases with increasing multiplicity with a little saturation towards higher multiplicity

p-Pb



cold nuclear matter effects:
shadowing/CGC, energy loss...

p-Pb collisions in ALICE

→ To understand Cold Nuclear Matter (CNM) effects such as nuclear parton shadowing/color glass condensate, energy loss and comovers absorption

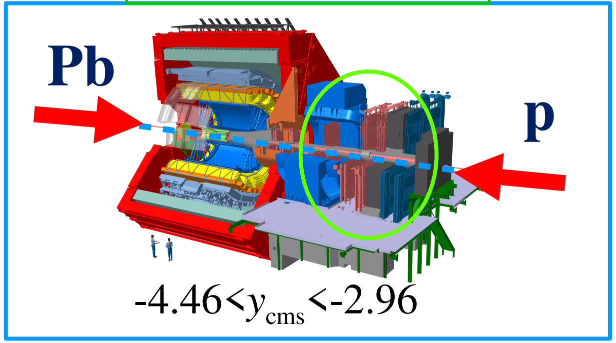
→ No Quark-Gluon Plasma (QGP) is expected in pA collisions.

→ The measurement of CNM effects in pA collisions is important to quantify the QGP effects in AA collisions

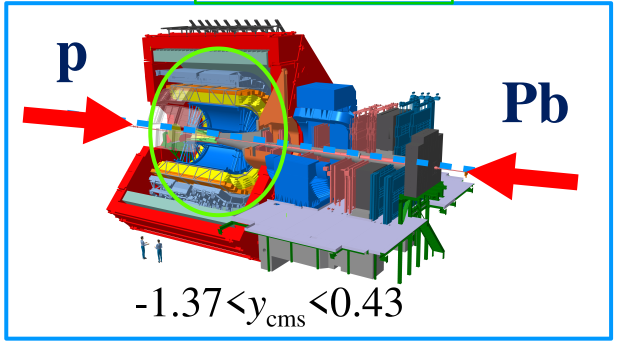
→ ALICE has collected p-Pb data at $\sqrt{s_{NN}}$ = 5.02 and 8.16 TeV

→ ALICE data are collected with two beam configurations: p-Pb and Pb-p, with Δy= +/- 0.465

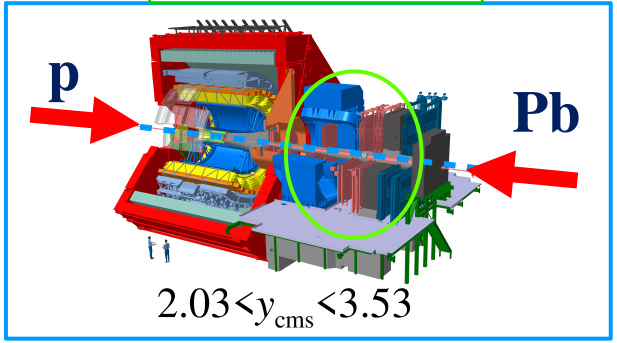
Backward rapidity



Mid rapidity

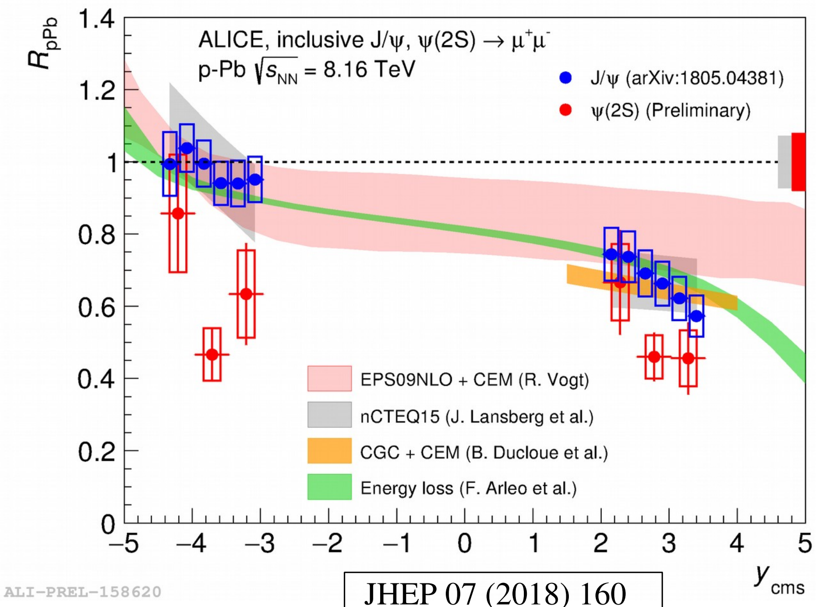


Forward rapidity



- Nuclear modification factor:

$$R^{J/\psi}_{pPb} = \frac{Y^{J/\psi}_{pPb}}{\langle T_{pPb} \rangle \, \sigma^{J/\psi}_{pp}}$$



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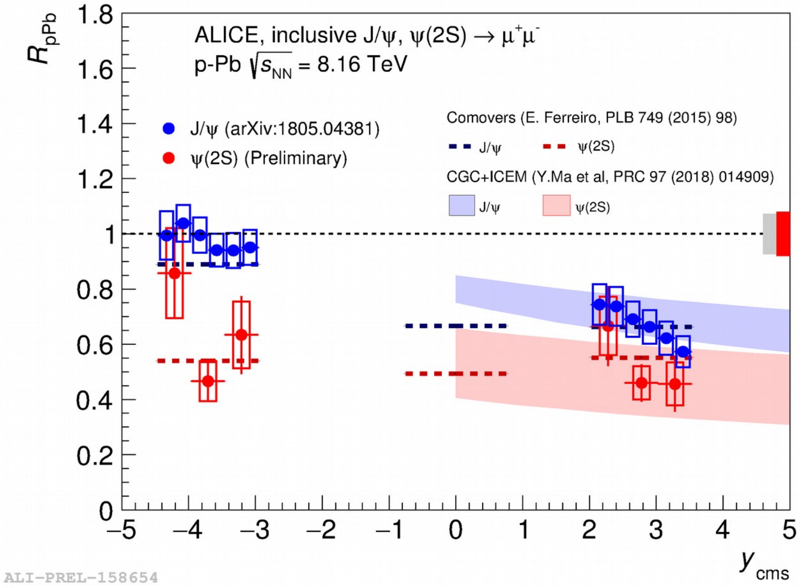
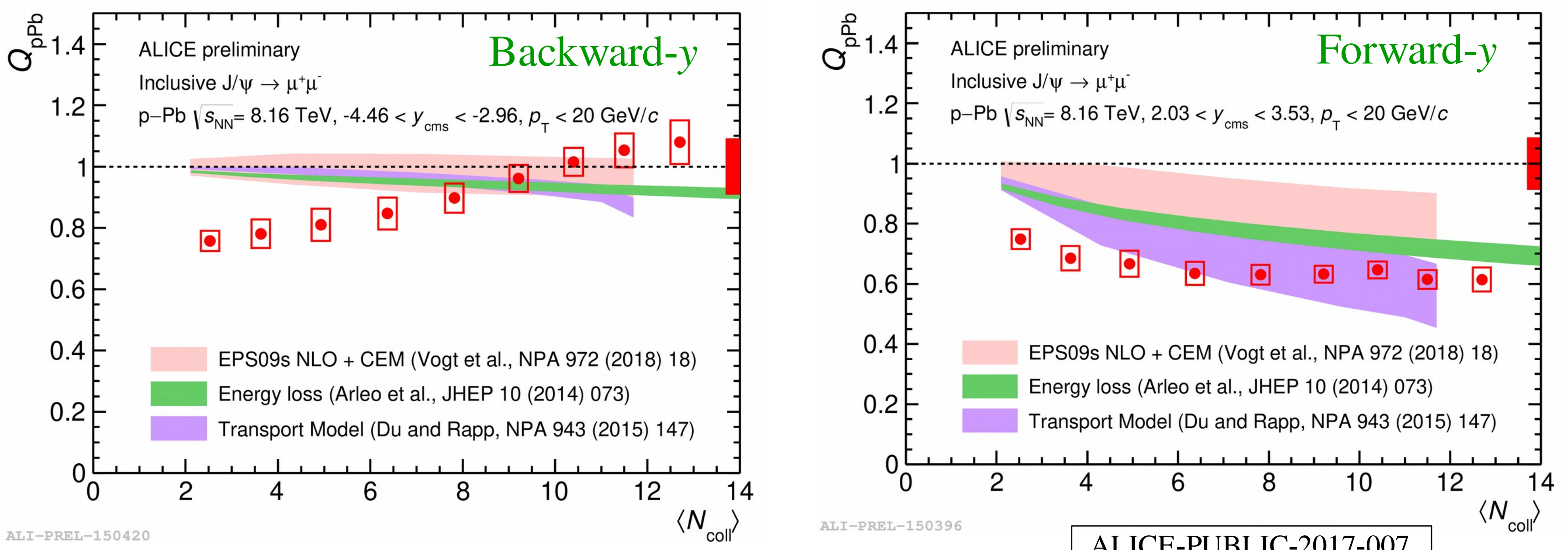


- ψ(2S) suppression is stronger than the J/ψ one, especially at backward rapidity
- Theoretical predictions based on shadowing and energy loss can not describe the stronger ψ(2S) suppression
- Models including final-state effects reproduce ψ(2S) behaviour at both forward and backward rapidity

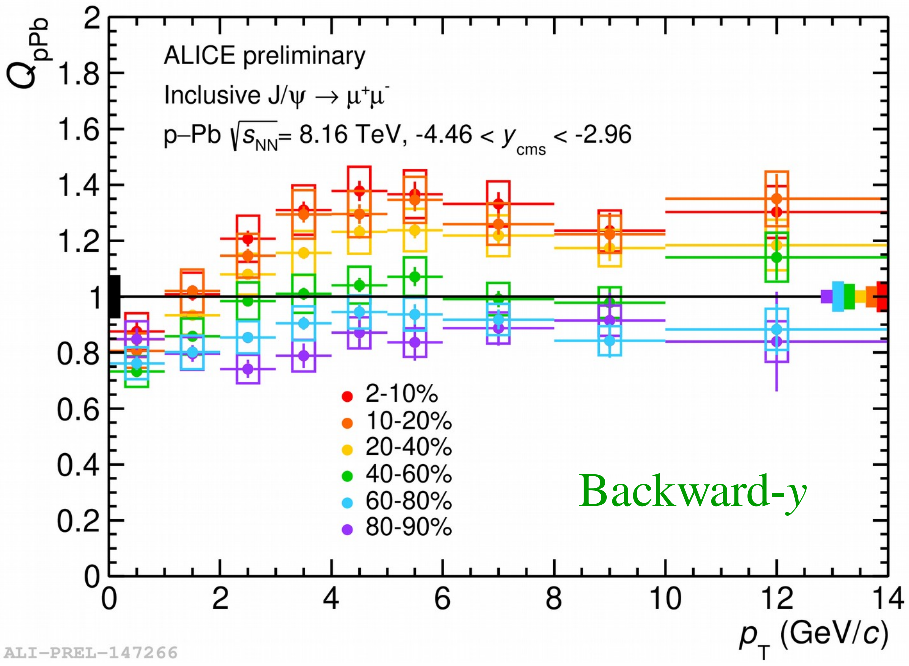
J/ψ Q_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV

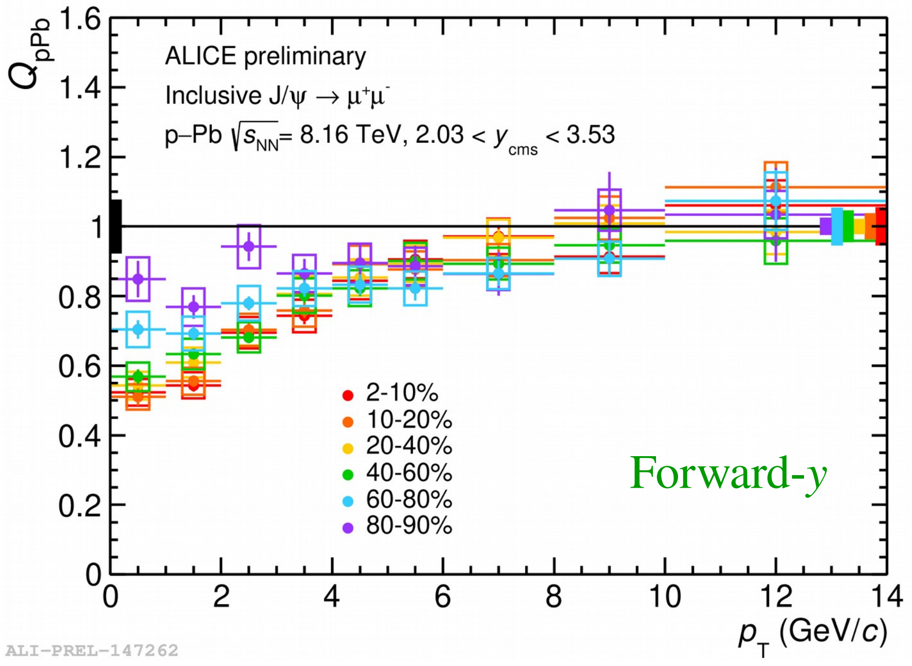


ALICE-PUBLIC-2017-007

- We use the symbol Q_{pPb} instead of R_{pPb} for nuclear modification factor due to potential bias from the centrality estimator
- The two Zero Degree Calorimeters (ZDC) have been used for the centrality estimation
- Q_{pPb} decreases slightly from peripheral to central collisions at forward rapidity, while trend is opposite at backward-*y* and these trends are not well captured by the models

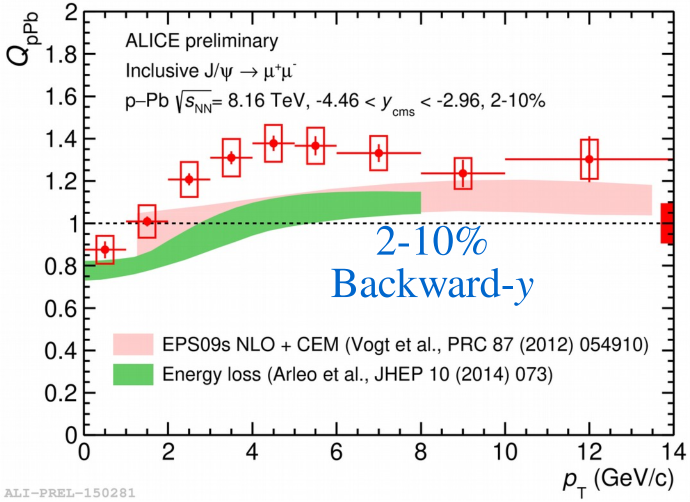
Multi-differential study of J/ψ Q_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV

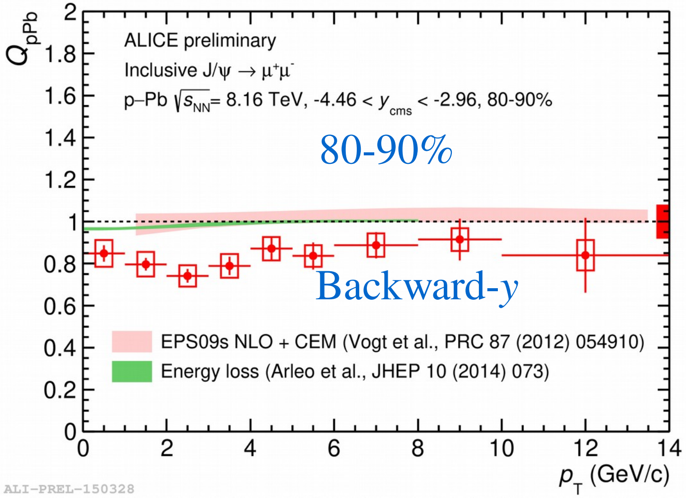


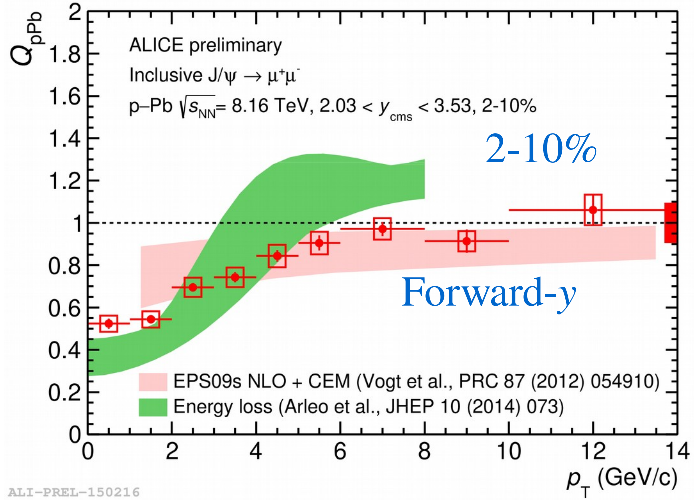


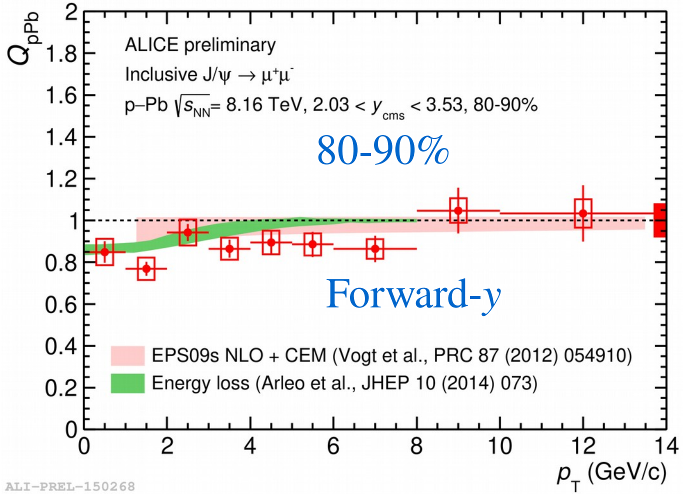
- Clear evolution of Q_{pPb} vs p_T in different centrality classes
- At backward rapidity, enhancement in most central collisions for p_T > 3 GeV/c
- At forward rapidity, stronger suppression at low p_T in most central collisions and Q_{pPb} is compatible with unity for p_T > 7 GeV/c within uncertainties for all centrality intervals

Multi-differential J/ψ Q_{pPb} compared to theoretical models



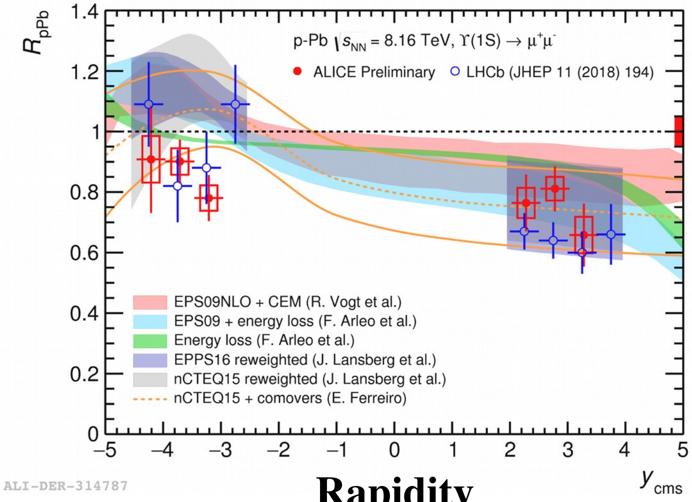




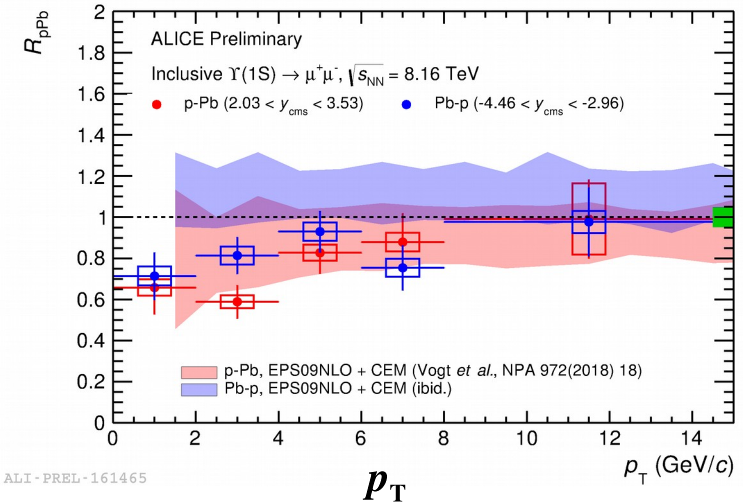


- In central collisions:
  - shadowing predicts a weaker p_T dependence w.r.t. the one observed in data
  - energy loss predicts an increase of Q_{pPb} with a different steepness than the measured one
- In peripheral collisions:
  both theory models show no p_T dependence, consistent with the Q_{pPb} measurement, within uncertainties
- The models can not describe simultaneously all aspects of J/ψ suppression (rapidity, p_T and centrality)

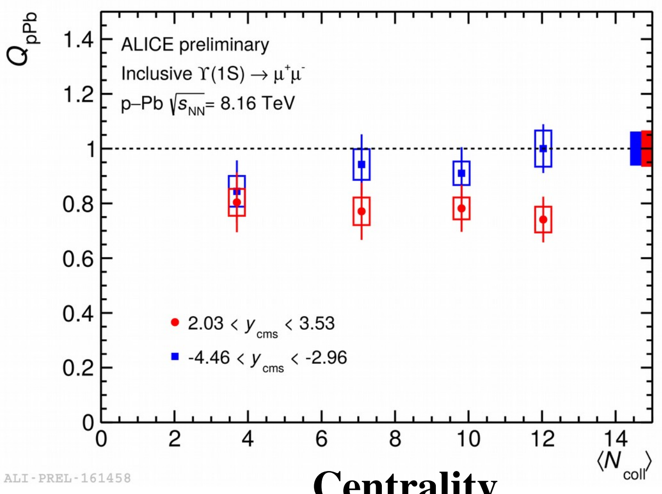
$\Upsilon(1S)$ R_{pPb} at $\sqrt{s_{NN}} = 8.16$ TeV



Rapidity



p_T

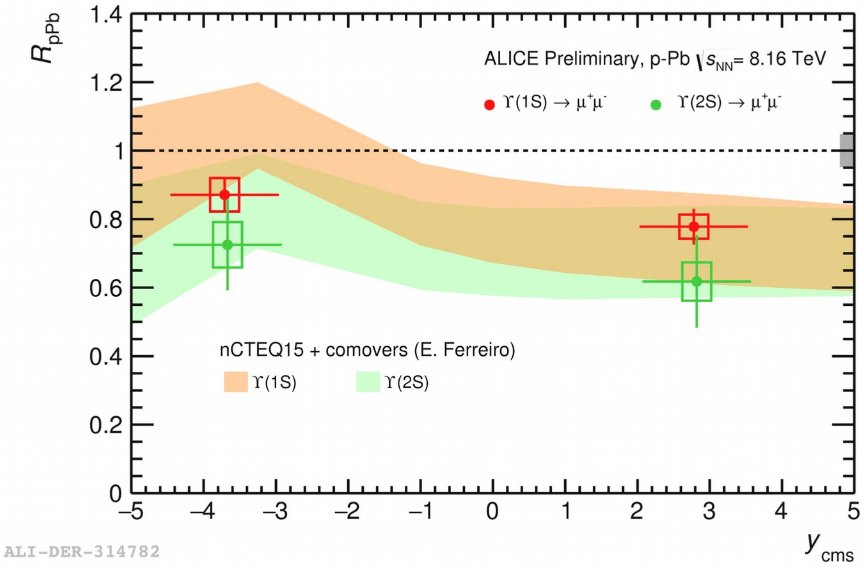


Centrality

ALICE-PUBLIC-2018-008

- $\Upsilon(1S)$ suppression is similar both at forward and backward rapidity
- Similar behaviour at both forward and backward rapidity with a hint of a stronger suppression at low p_T
- No evidence for centrality dependence
- Theoretical predictions based on shadowing and energy loss describe the forward rapidity results but slightly overestimate the backward rapidity results

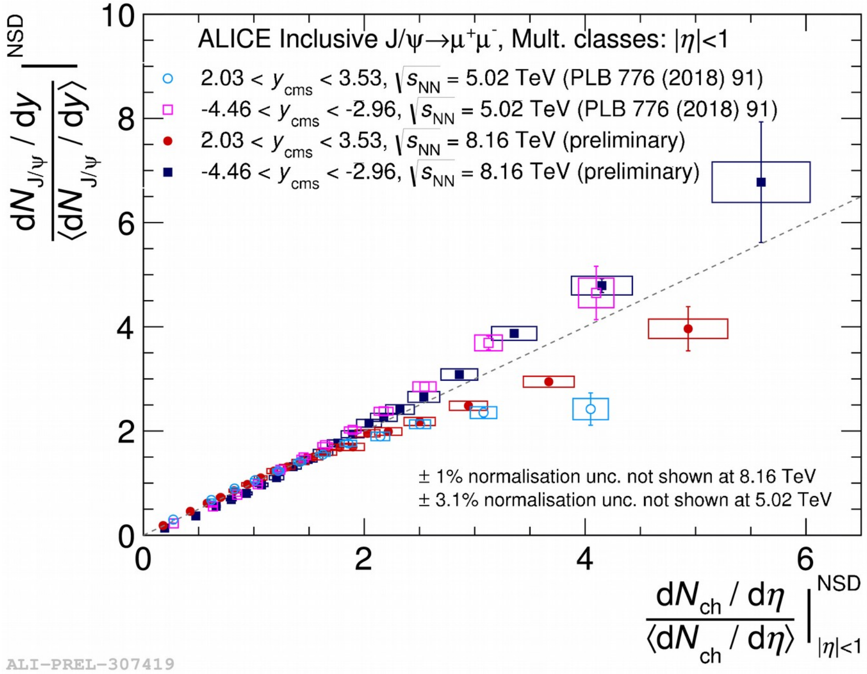
$\Upsilon(2S)$ R_{pPb} at $\sqrt{s_{NN}}$ = 8.16 TeV

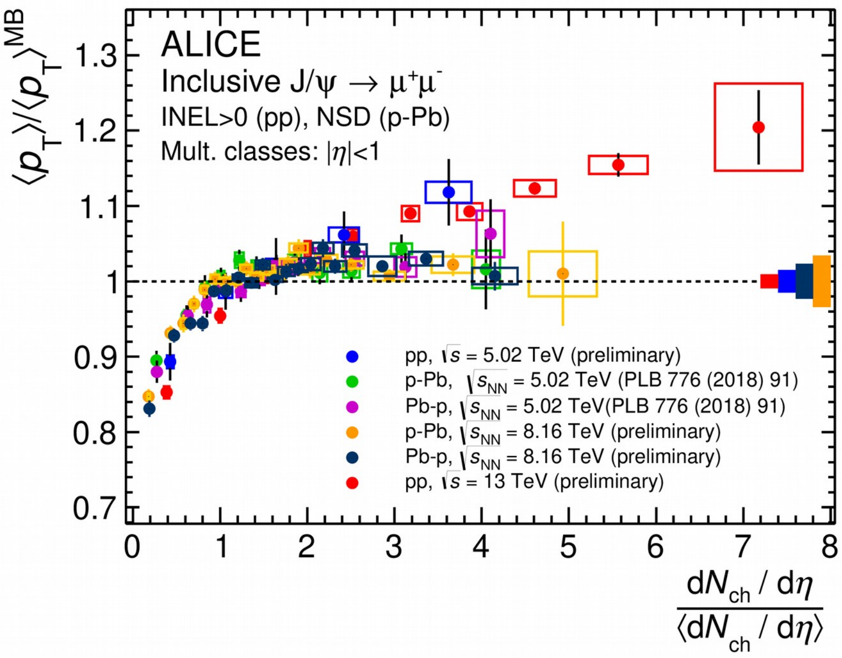


ALICE-PUBLIC-2018-008

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

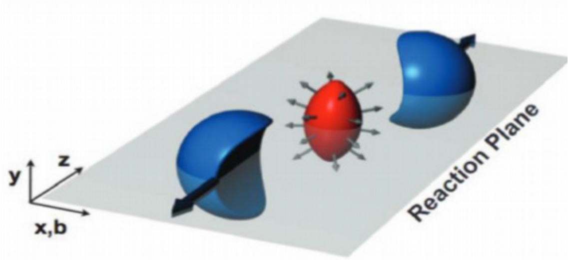
Multiplicity dependence of J/ψ in p-Pb





- Similar behaviour at low multiplicities (0-1.5)
- The yields at backward rapidity grow faster than the forward rapidity one, reaching values above those of the linear approach at large multiplicity, whereas the values at forward rapidity show a slower-than-linear increase
- The $\langle p_T \rangle$ is smaller at backward than at forward rapidity

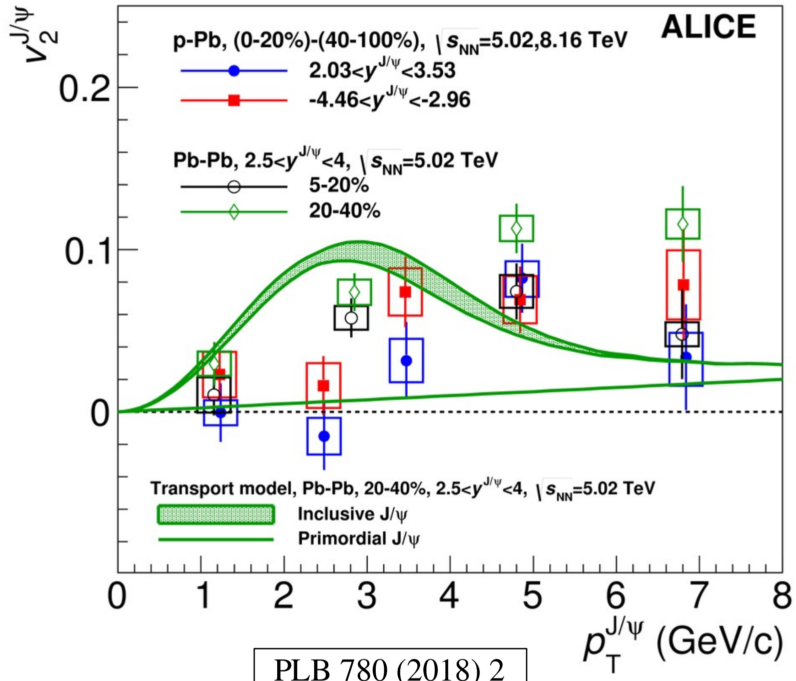
Elliptic flow (v_2) of J/ψ



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

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_n\right)\right)\right)$$

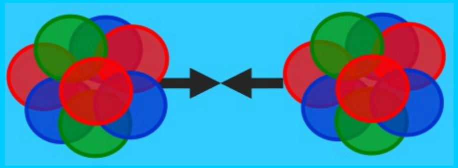
$$v_n = \langle \cos\left(n(\varphi - \Psi_n)\right)\rangle$$



PLB 780 (2018) 2

- Observation of non-zero v_2 in p-Pb for p_T > 3 GeV/c!
- Total significance (forward + backward, 5.02+8.16 TeV, 3 < p_T < 6 GeV/c) ~ 5σ
- Values are similar to the ones obtained in Pb-Pb for p_T > 3 GeV/c
- In Pb-Pb collisions, non-zero J/ψ v_2 suggests charm quark participation to the collective expansion of the system
- Common mechanism in p-Pb and Pb-Pb?

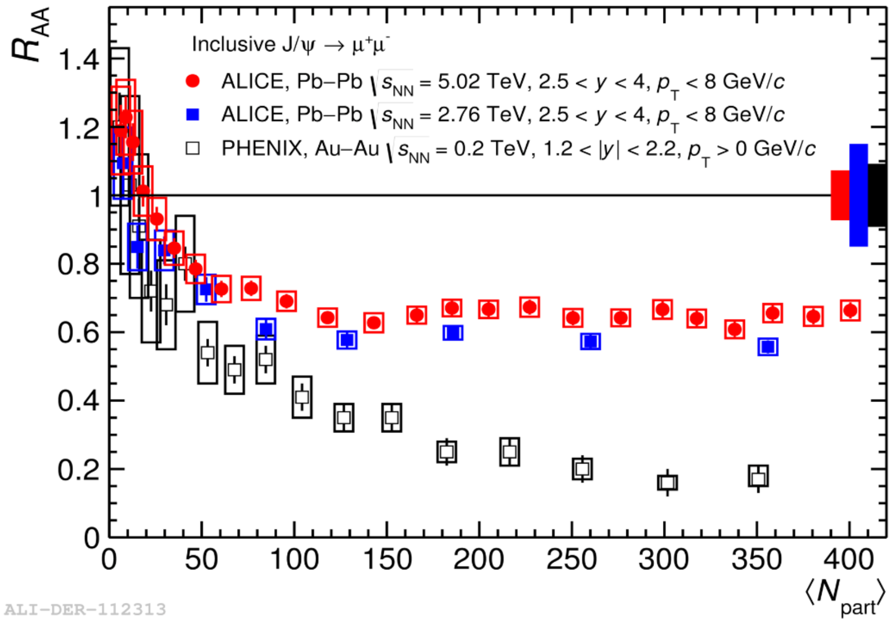
Pb-Pb

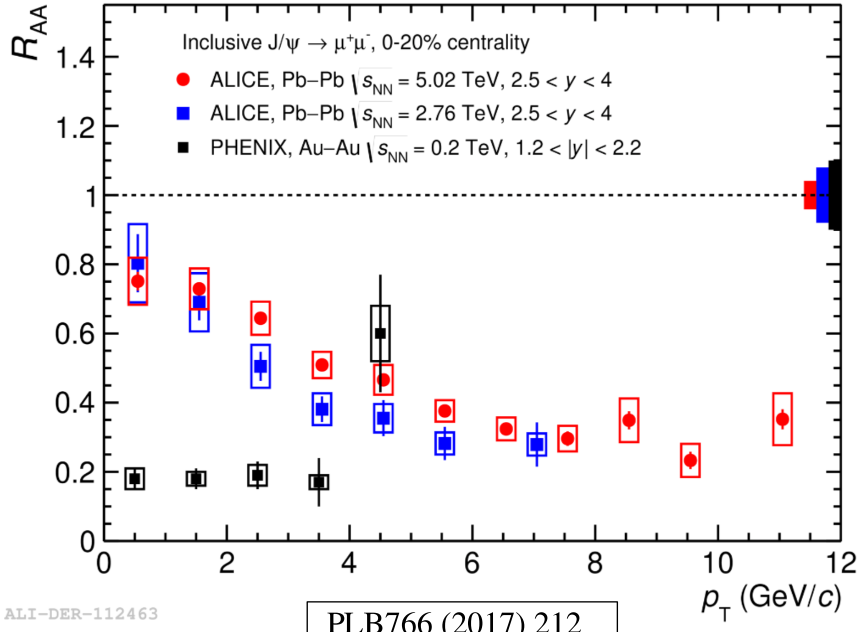


hot matter effects:

suppression vs regeneration

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



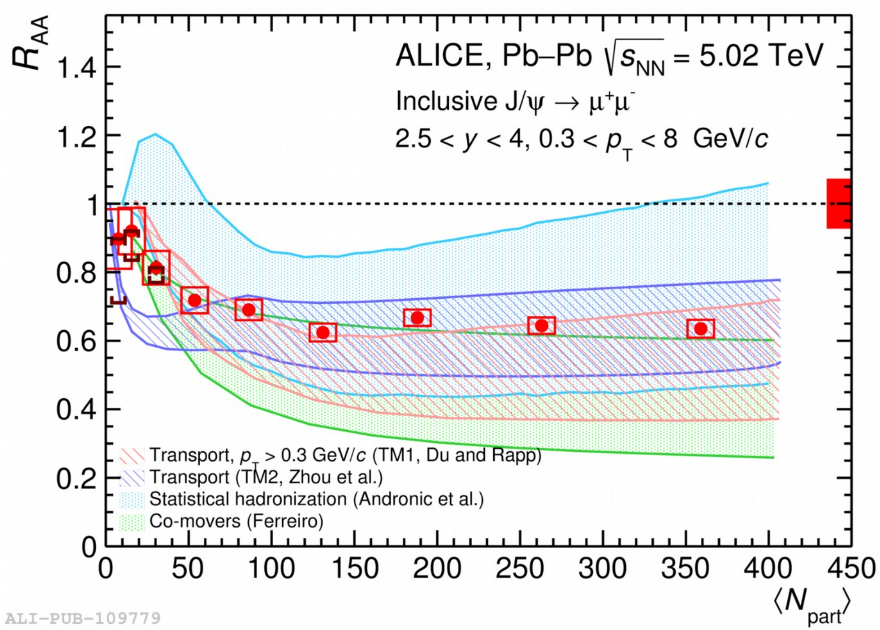


PLB766 (2017) 212

$$R_{AA}^{J/\psi} = \frac{Y_{AA}^{J/\psi}}{\langle T_{AA} \rangle \, \sigma_{pp}^{J/\psi}}$$

- Forward-*y* J/ψ suppression measured precisely in fine bins of centrality
- Clear J/ψ suppression with almost no centrality dependence for $N_{part} > 100$
- Weaker low-p_T suppression measured by ALICE compared to PHENIX
- Different behaviour for RHIC and LHC R_{AA} is related to the interplay of suppression and regeneration mechanisms

Comparison with theoretical models



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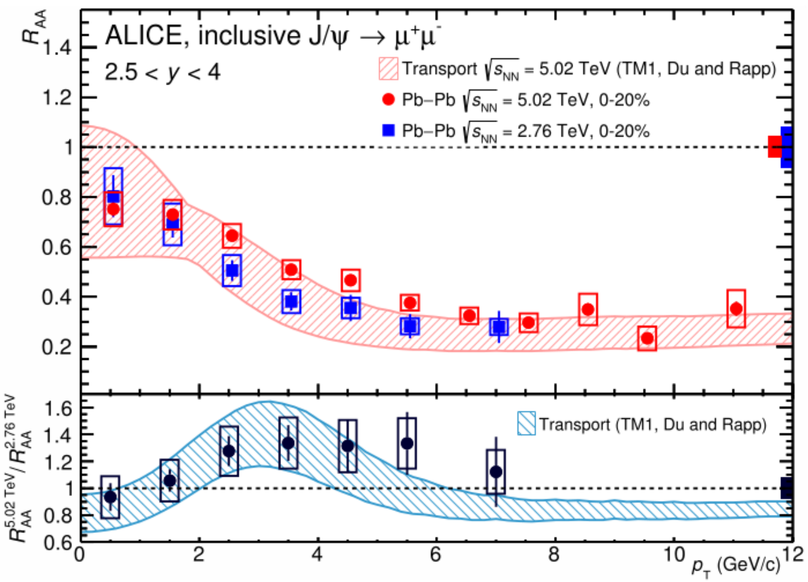
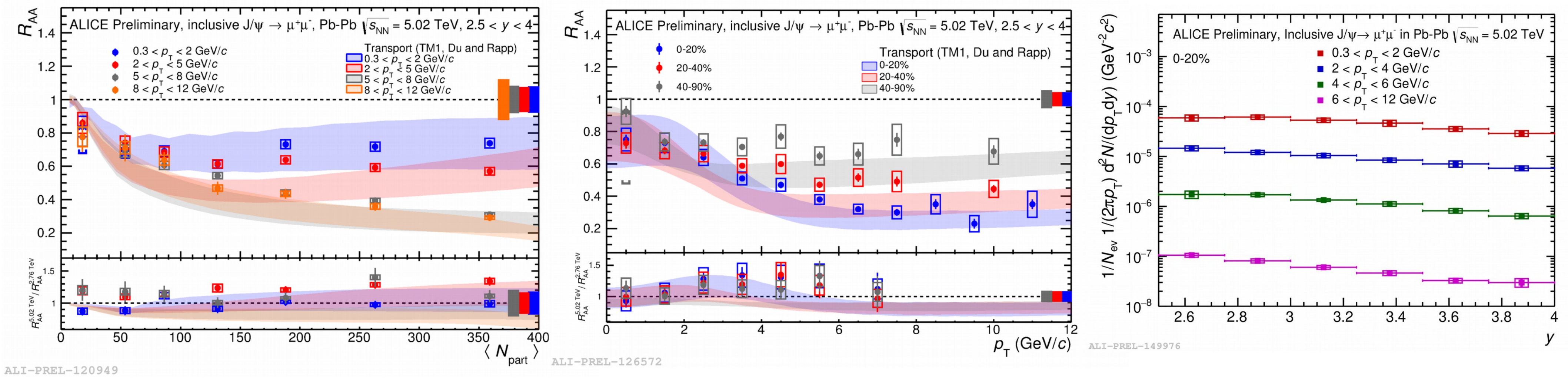


TM1: Nucl. Phys. A859 (2011) 114–125
TM2: Phys. Rev. C89 no. 5, 459 (2014) 054911
Stat. hadronization: NPA 904-905 (2013) 535c
Co-movers: Phys. Lett. B731 (2014) 57–63

- All models fairly describe the data but large uncertainties associated to charm cross section and shadowing
- Precise charm cross section measurement and more differential analyses needed

Multi-differential J/ψ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

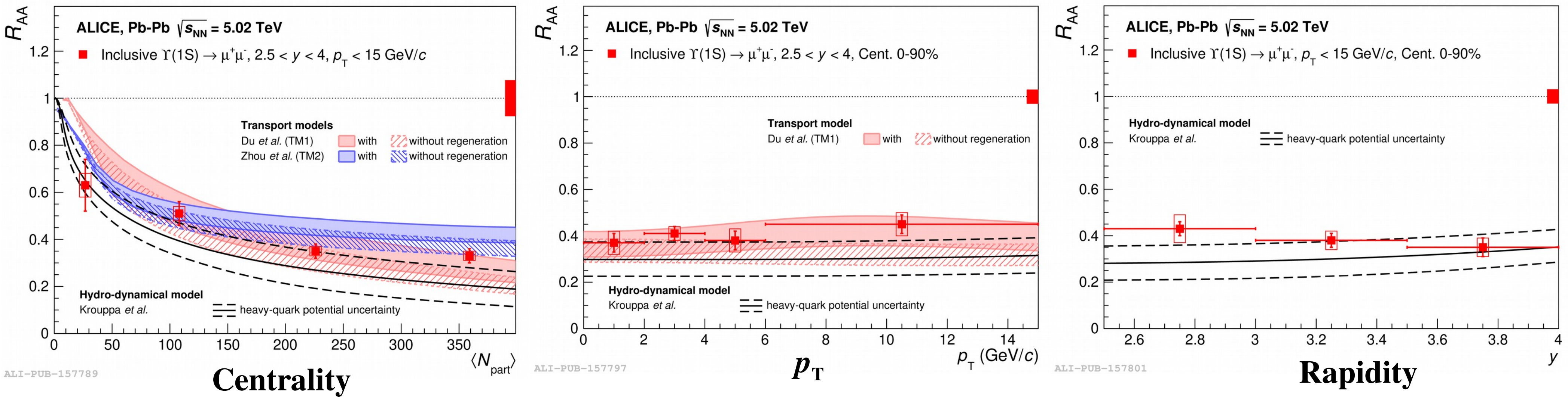


- Constraints to the theoretical models can be imposed by more differential R_{AA} studies

- The suppression is stronger at high p_T and for central collisions
- R_{AA} decreases by 60-80% at large p_T and for most central collisions
- TM1 prediction agrees with data within uncertainties

- Rapidity spectra soften towards higher p_T
- pp reference for triple-differential R_{AA} underway, stay tuned!!!

$\Upsilon(1S)$ R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV



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- The suppression is stronger in central collisions than in peripheral events
- R_{AA} does not show a significant dependence on p_T and y
- Amount of direct $\Upsilon(1S)$ suppression is an open question since feed-down fraction to $\Upsilon(1S)$ is not precisely known
- Transport models describe the results with and without a regeneration component within uncertainties
- Only upper edge of hydro-dynamical model agrees with data

NEW!!

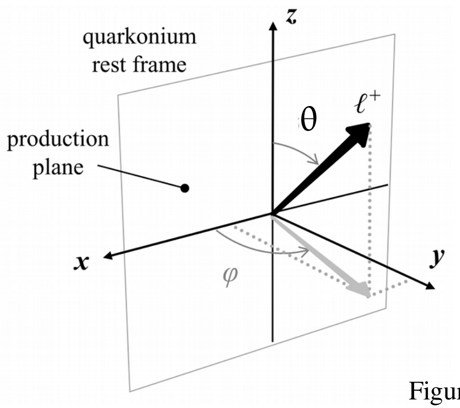
J/ψ polarization in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV

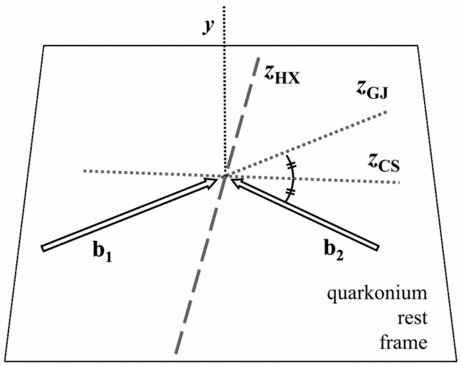
ALICE

- In two-body decays the angular distribution of the two decay products reflects the polarization of the quarkonium state
- Angular distribution:

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

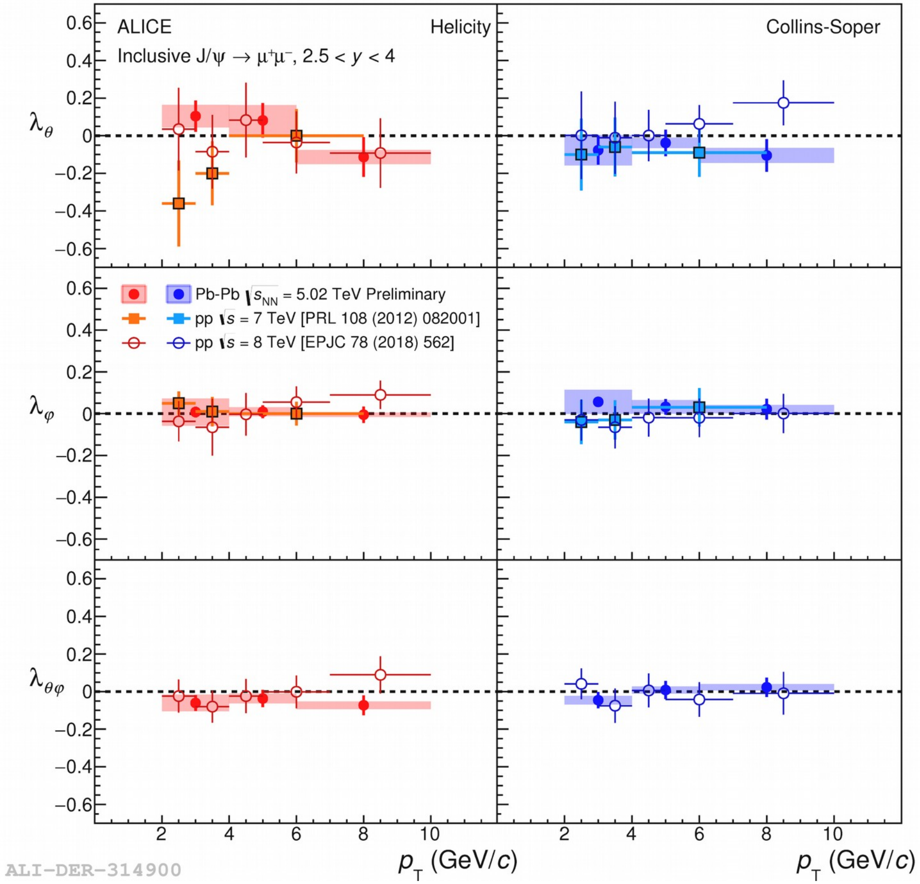
- Polarization axis:
  Helicity (HX): direction of J/ψ in the collision center of mass frame
  Collins-Soper (CS): the bisector of the angle between the beam and the opposite of the other beam, in the J/ψ rest frame



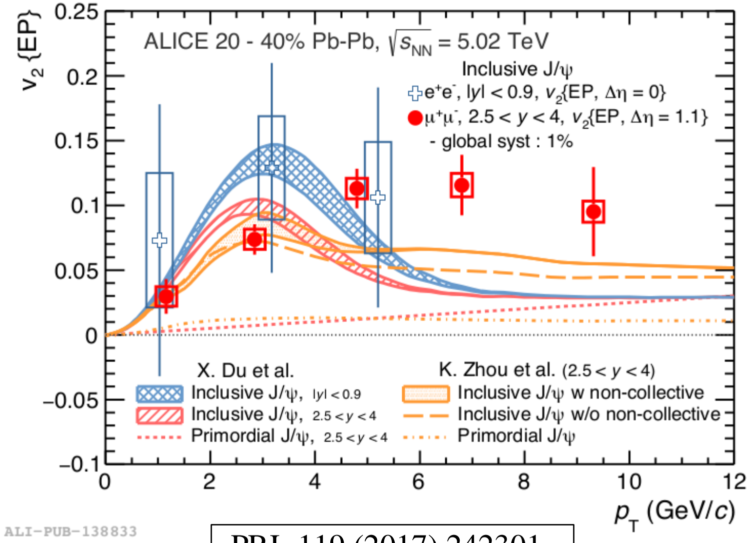


Figures from P. Faccioli et al. EPJC 69 (2010) 657-673

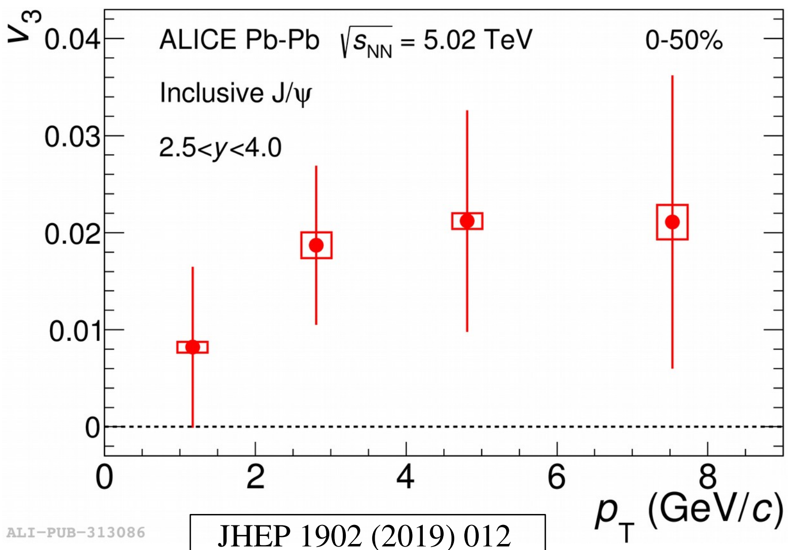
First LHC measurements in Pb-Pb



Elliptic (v_2) and triangular (v_3) flow of J/ψ in Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV



PRL 119 (2017) 242301

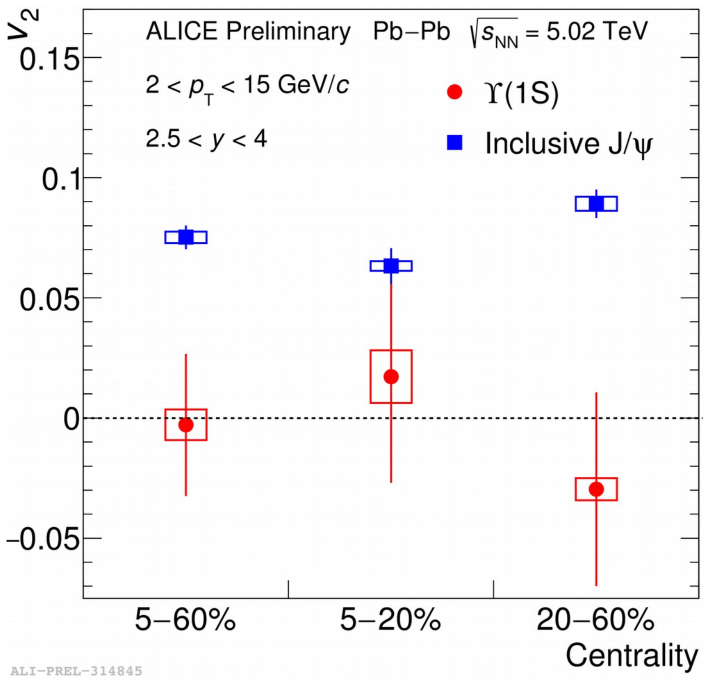


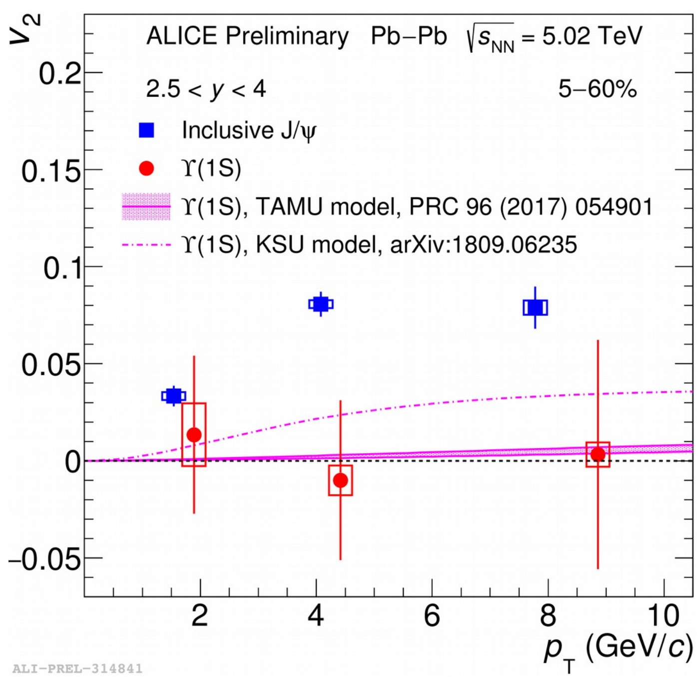
JHEP 1902 (2019) 012

- J/ψ v_2 at mid-y shows agreement with forward-y result within uncertainties
- Non-zero J/ψ v_2 is consistent with that of open-charm mesons
- The transport model predictions are not able to describe the data in higher p_T region
- A significant fraction of the observed J/ψ comes from charm quarks thermalized in the QGP

- First observation of positive J/ψ v_3 in Pb-Pb collisions (3.7 σ significance)

Elliptic flow (v_2) of Υ(1S) in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV





- The Kent State University (KSU) model calculations consider only the path-length dissociation of initially-created bottomonia inside the QGP medium
- The Texas A&M University (TAMU) model incorporates in addition a regeneration component originating from the recombination of thermalized bottom quarks

- Υ(1S) v_2 is compatible with zero and with the small values predicted by the available theoretical models within uncertainties
- Excluding low p_T, Υ(1S) v_2 is 2.6 σ lower with respect to that of inclusive J/ψ
- This Υ(1S) result includes both 2015 and 2018 Pb-Pb data sets

Conclusions

→ We have shown quarkonium production results measured in pp, p-Pb and Pb-Pb collisions
→ Models face difficulties in describing consistently all results

pp collisions:

→ Theoretical predictions describe the cross section results but not polarization
→ The quarkonium production increases linearly as a function of charged-particle multiplicity in different rapidity region

p-Pb collisions:

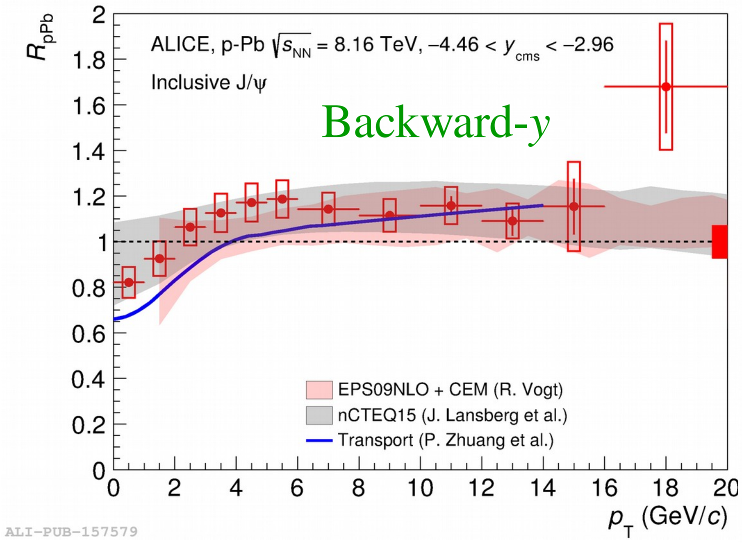
→ Theoretical models based on CNM effects qualitatively describe quarkonium results
→ Final-state effects needed to explain the ψ(2S) behaviour
→ Shadowing and energy loss models describe ϒ(1S) behaviour at forward-y results while they overestimate backward-y results

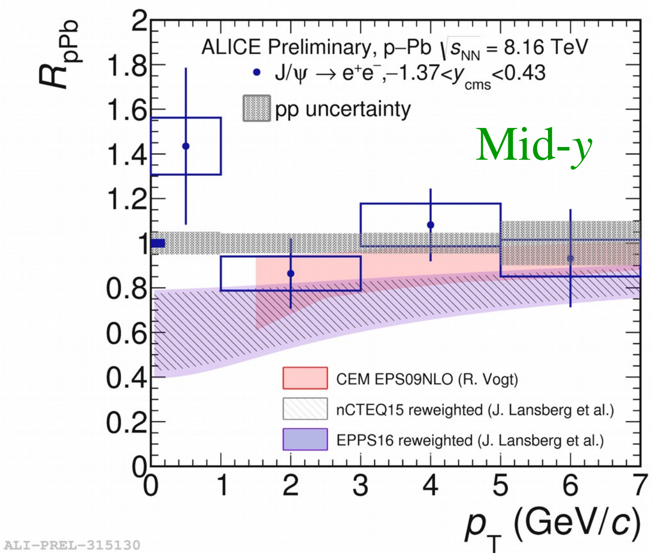
Pb-Pb collisions:

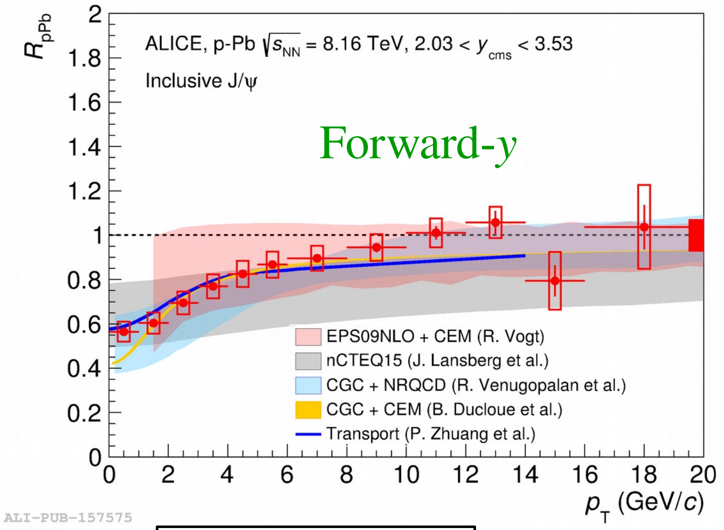
→ J/ψ R_{AA} at LHC shows an interplay of suppression and (re)generation
→ Non zero J/ψ elliptic flow agrees with regeneration picture
→ ϒ(1S) v_2 is compatible with zero and with the current model predictions within uncertainties

Thank you

J/ψ R_{pPb} vs p_T at $\sqrt{s_{NN}}$ = 8.16 TeV







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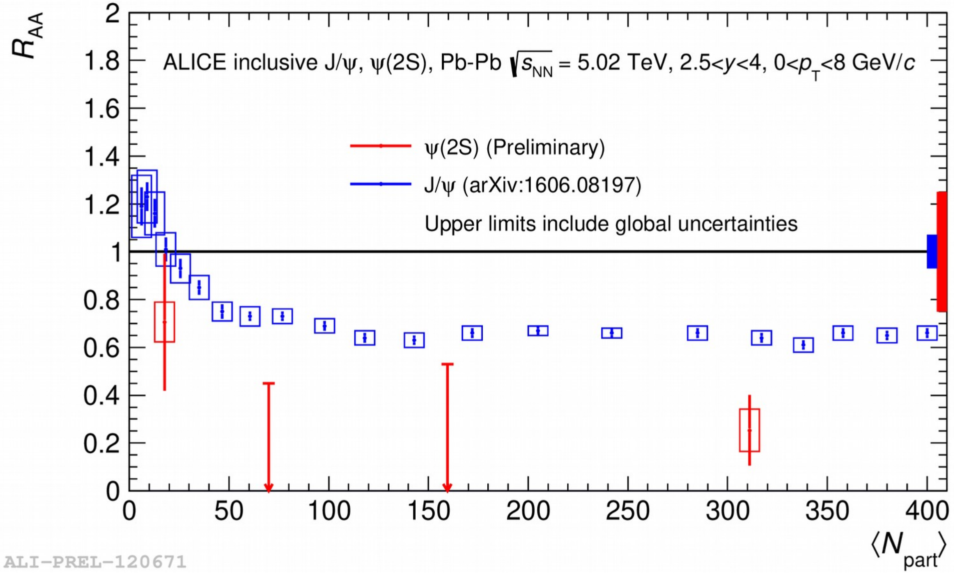
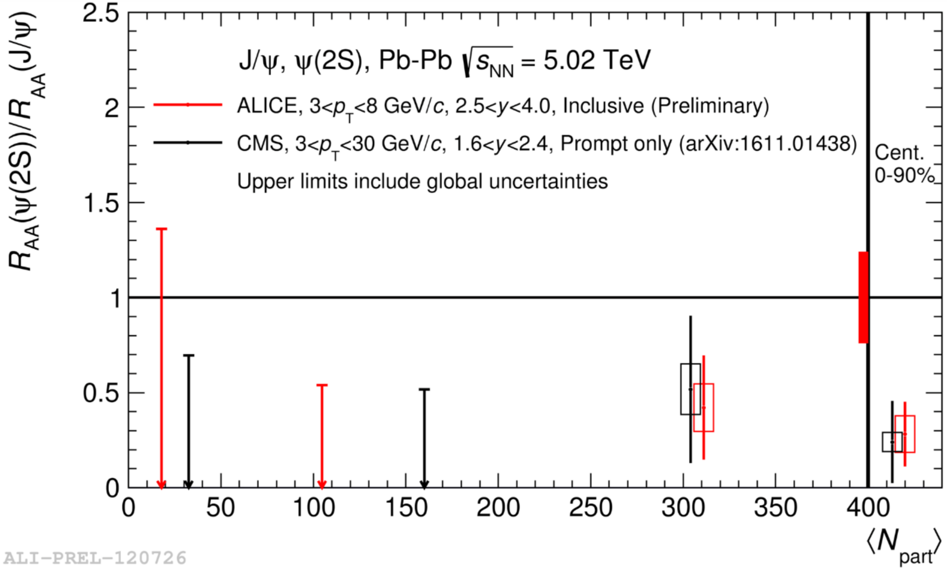
- R_{pPb} shows a p_T dependence, with an increase from low to high p_T at both forward and backward rapidity
- At mid rapidity R_{pPb} is compatible with unity with almost no p_T dependence
- Run2 results are more precise than the Run1 measurements at $\sqrt{s_{NN}}$ = 5.02 TeV [JHEP 06 (2015) 55]
- Uncertainties on the theoretical predictions are large compared to data

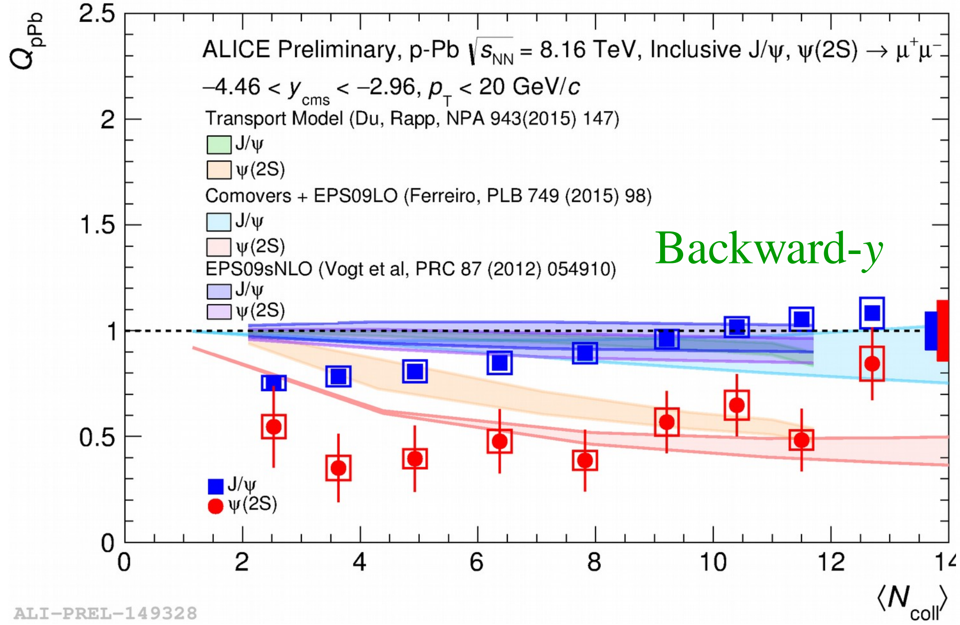
ψ(2S) R_{AA} in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

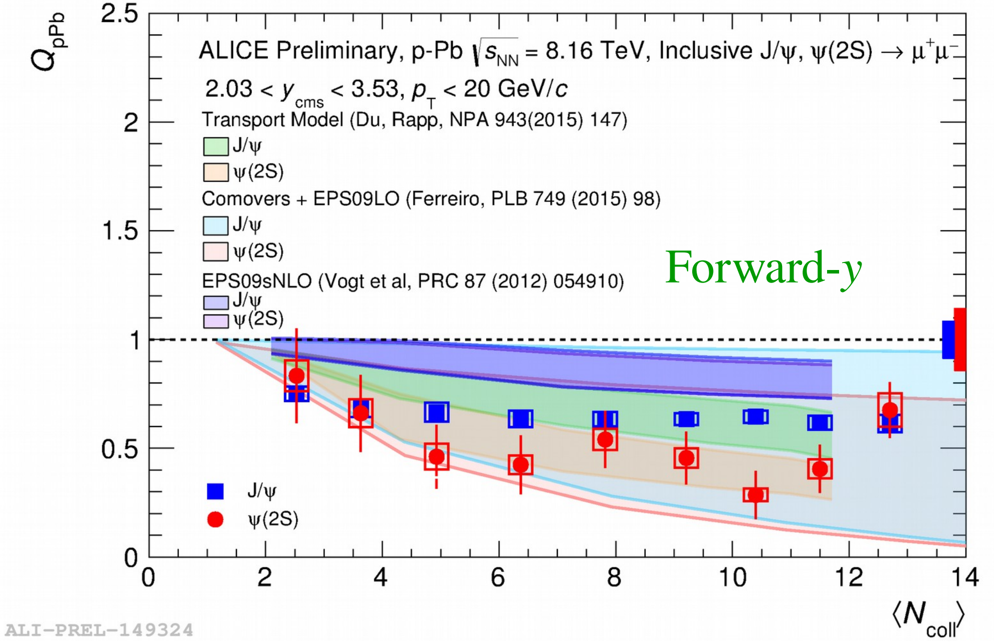




- ψ(2S) shows a stronger suppression, in semi-central and central collisions, than the J/ψ one
- However, the low significance limits the precision of the measurements
  [95% CL is provided for bins with too low significance]
- Results are compatible with CMS
- The 2018 data sample with ~ 3 times increase in statistics will give more precise measurement, stay tuned!

$\psi(2S)$ Q_{pPb} vs centrality at $\sqrt{s_{NN}}$ = 8.16 TeV





- The ψ(2S) suppression is stronger than J/ψ one, especially at backward rapidity
- At forward rapidity the Q_{pPb} of ψ(2S) follows the same trend as J/ψ while at backward rapidity trend is different
- At backward rapidity, final-state effects needed to explain the ψ(2S) behaviour. Some discrepancies between the data and the model in the peripheral region

Azimuthal anisotropy (v_2) of J/ψ in p-Pb collisions

Low multiplicity

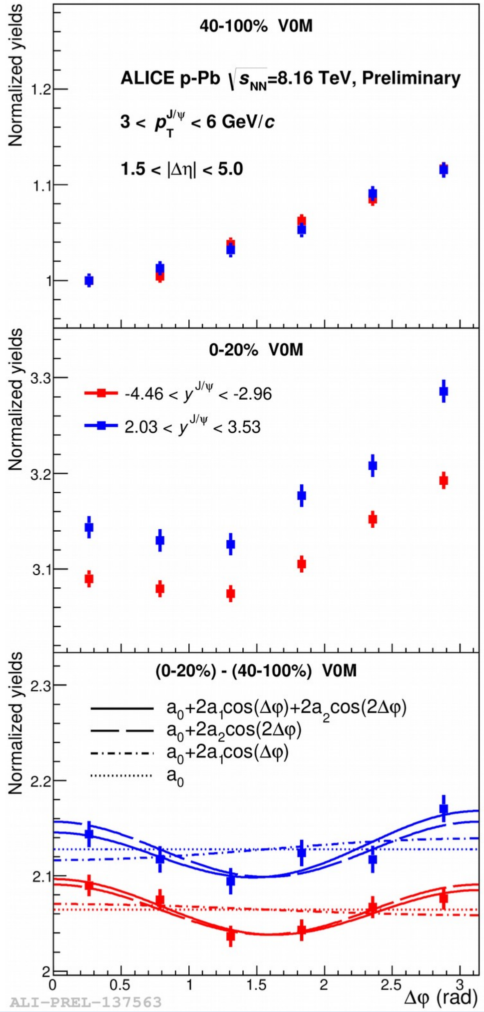
Clear away-side correlation presumably due to recoil jet

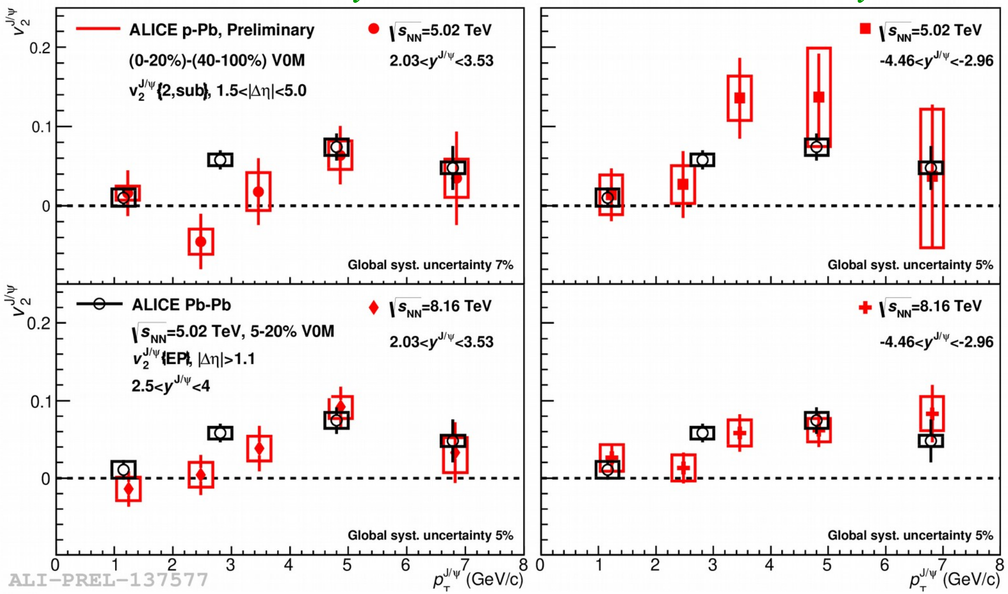
High multiplicity

Additional enhancement at both near and away sides

Low multiplicity
–
High multiplicity

Jet correlations eliminated via subtraction





- p_T < 3 GeV/c → v_2 compatible with 0
  In line with expectation of no recombination
- 3 < p_T < 6 GeV/c → v_2 > 0
  Total (forward+backward,5.02+8.16 TeV) significance about 5σ
  Values comparable to the measurements in central Pb-Pb collisions