Charmonium production in pp, p-Pb and Pb-Pb collisions at forward rapidity with the ALICE detector at the LHC

Arianna Batista Camejo
on behalf of the ALICE Collaboration

DUBNA 2015

Outline

- Motivation
- Experimental apparatus
- General remarks on analysis procedure
- Selection of results from Run 1

  J/ψ and ψ(2S) differential cross section in pp collisions at $\sqrt{s}$ = 7 TeV

  J/ψ and ψ(2S) nuclear modification factor in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

  J/ψ nuclear modification factor in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

  Comparison to models

- Conclusions

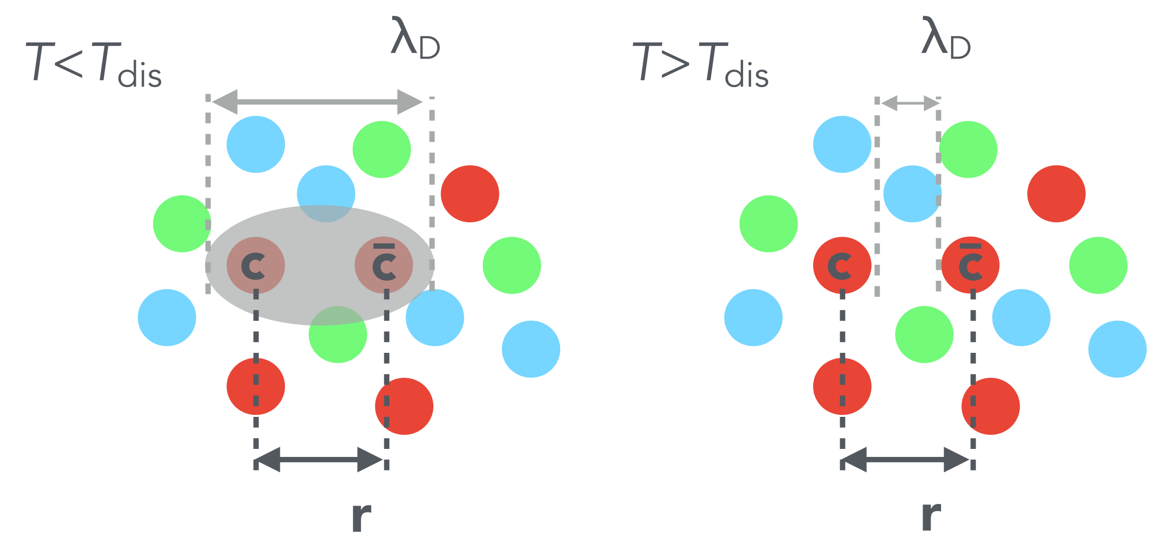
Motivation I

ALICE

In the QGP medium, due to high density of color charges one might expect:

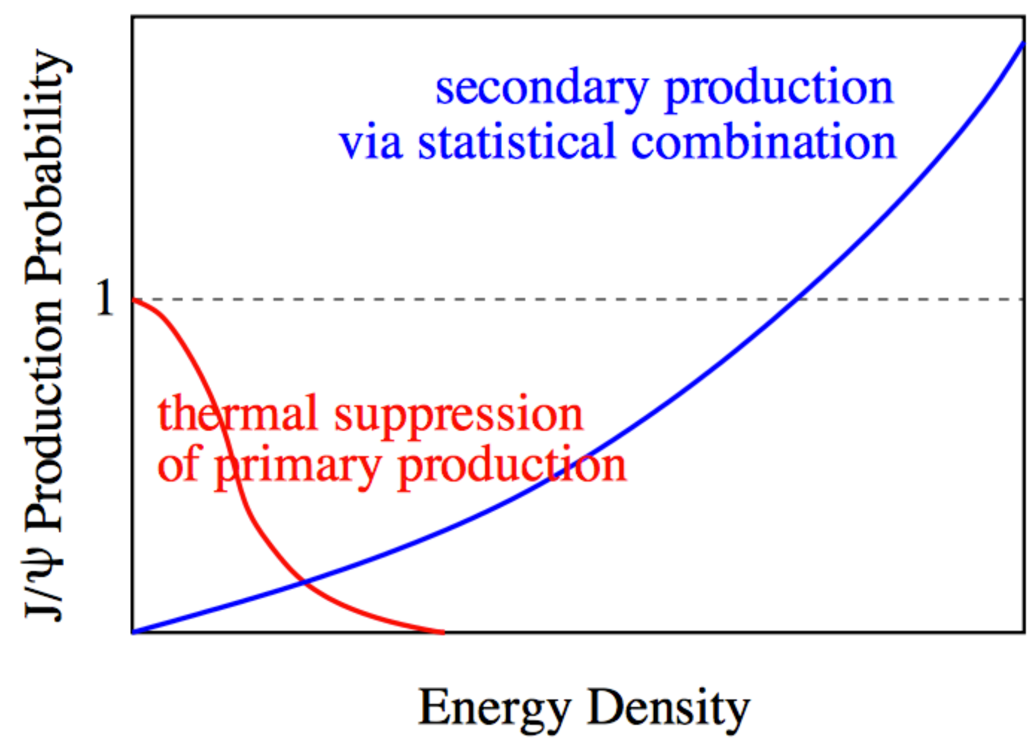
- charmonium **suppression** as a result of color screening effects [1]

- **regeneration** of charmonia due to the abundance of c and c̄ quarks that might (re)combine through the QGP or at the hadronization stage [2,3]



To quantify the effect of the medium: nuclear modification factor R_{AA}.

$$R_{\mathrm{AA}} = \frac{N_{\mathrm{AA}}}{\langle T_{\mathrm{AA}} \rangle \times \sigma_{\mathrm{pp}}}$$



N_{AA} : production yield in AA collisions

$<T_{AA}>$: average value of the nuclear overlap function

σ_{pp} : production cross section in pp collisions

[1] Phys. Lett. B 178 (1986) 416
[2] Phys. Rev. C 65 (2001) 054905
[3] Phys. Lett. B 490 (2000) 196

Motivation II

Quarkonium production measurements in pp collisions constitute a test of QCD.

production of the heavy-quark pair (**perturbative** treatment)	x	evolution into the physical quarkonium state (**non-perturbative**)

Different theoretical models (CEM [1], CSM [2], COM [3]) are not able to simultaneously describe quarkonium production and polarization [4].

Charmonium yields might be also affected by **cold nuclear matter effects** (CNM); proton-nucleus collisions are essential to calibrate and disentangle these effects.

- difference between nPDF and PDF [5]
- parton saturation [6]
- energy loss [7]
- nuclear absorption [8]
- interaction with comovers [9]

To quantify CNM effects: nuclear modification factor R_{pA}

[1] Phys. Lett. B 67 (1977) 217
[2] Phys. Rev. D. 12 (1975) 2007
[3] Phys. Rev. D 51 (1995) 1125
[4] Eur. Phys. J. C 61 (2009) 693
[5] Phys. Rev. C 88 (2013) 047901
[6] Nucl. Phys. 1924 (2014) 47-64
[7] Phys. Rev. Lett. 109 (2012) 122301
[8] Nucl. Phys. A700 (2002) 539
[9] Phys. Rev. Lett 78 (1197) 1006

Charmonium detection at forward rapidity with ALICE

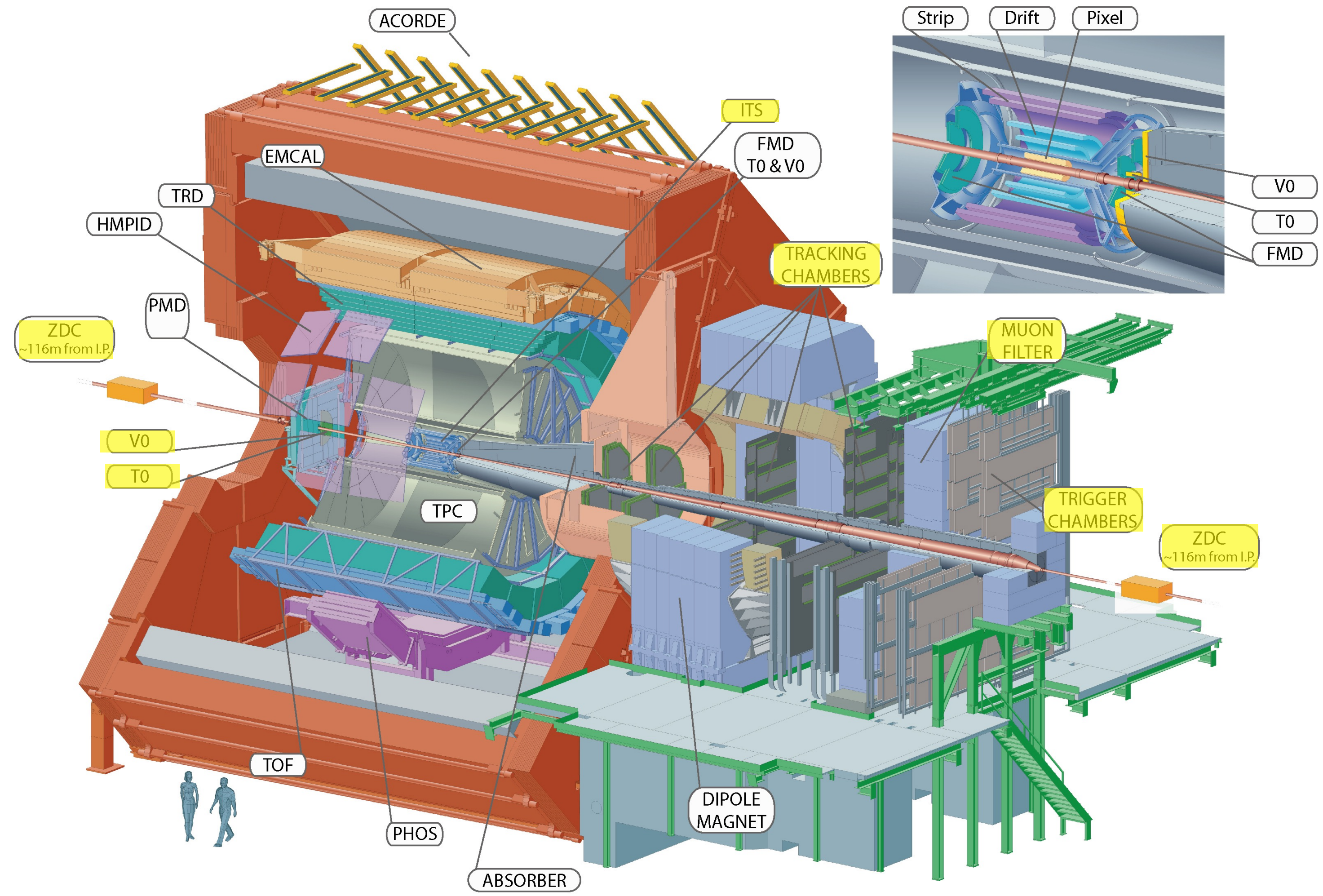
$\mu^+\mu^-$ decay channel

Forward Muon Spectrometer reconstruction of charmonia in the rapidity range **2.5 < *y* < 4** and down to $\boldsymbol{p_T = 0}$.

The **Silicon Pixel Detector** is used for primary vertex reconstruction.

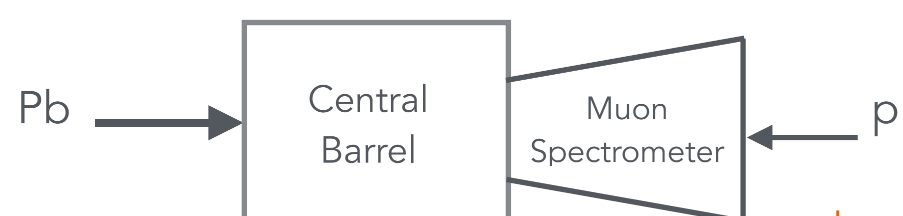
V0, **T0** and **Muon Trigger** are used for triggering purposes.

V0 and **Zero Degree Calorimeter** for centrality estimation.



JINST 3 (2008) S08002

In p-Pb collisions the rapidity in the center-of-mass system is shifted with respect to the laboratory. Two rapidity ranges covered by the Muon Spectrometer:



forward rapidity

$2.03 < y_{cms} < 3.53$

backward rapidity

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

Analysis procedure

Selection

- Muon tracks in the pseudo rapidity acceptance of the muon spectrometer: $-4 < \eta < -2.5$

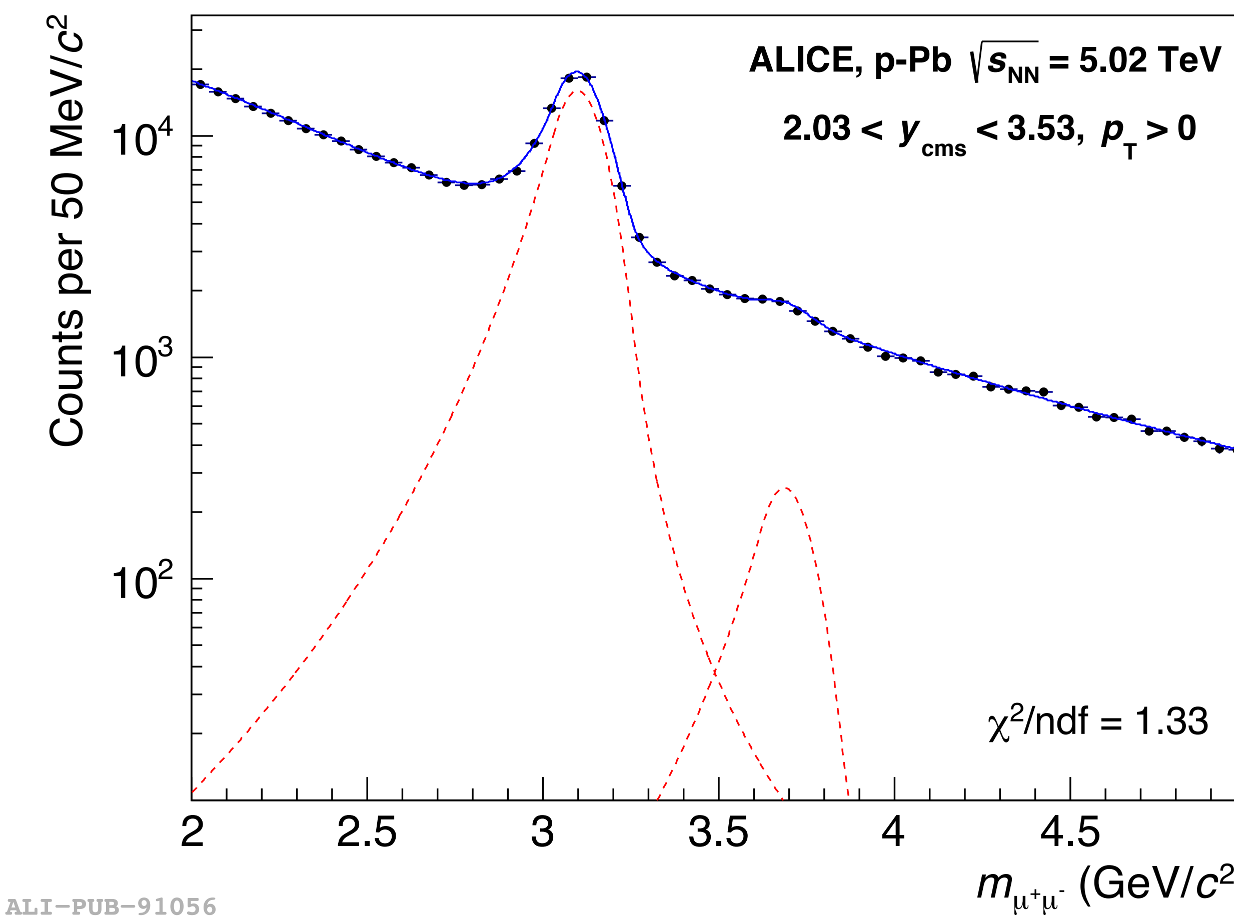
- Transverse radius of the track at the end of the front absorber: $17.6 < R_{abs} < 89.5$ cm

- Muon tracks in the tracking chambers must match a track reconstructed in the trigger system.

Signal extraction

- Two extended Crystal Ball or two pseudo-Gaussian functions for J/ψ and ψ(2S) signals.

- Variable Width Gaussian or 4th order polynomial multiplied by an exponential function for background.



JHEP12 (2014) 073

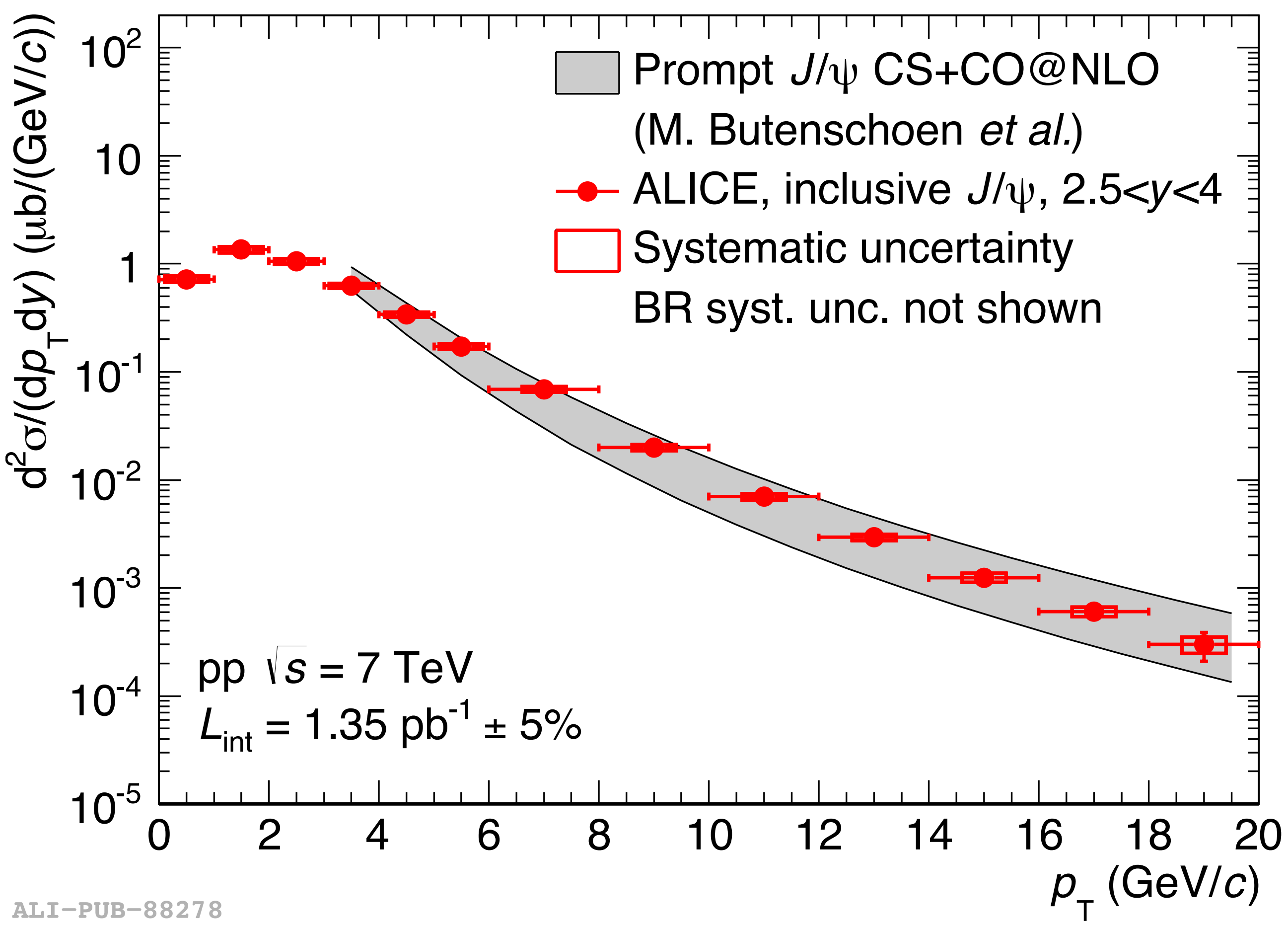
Inclusive measurements

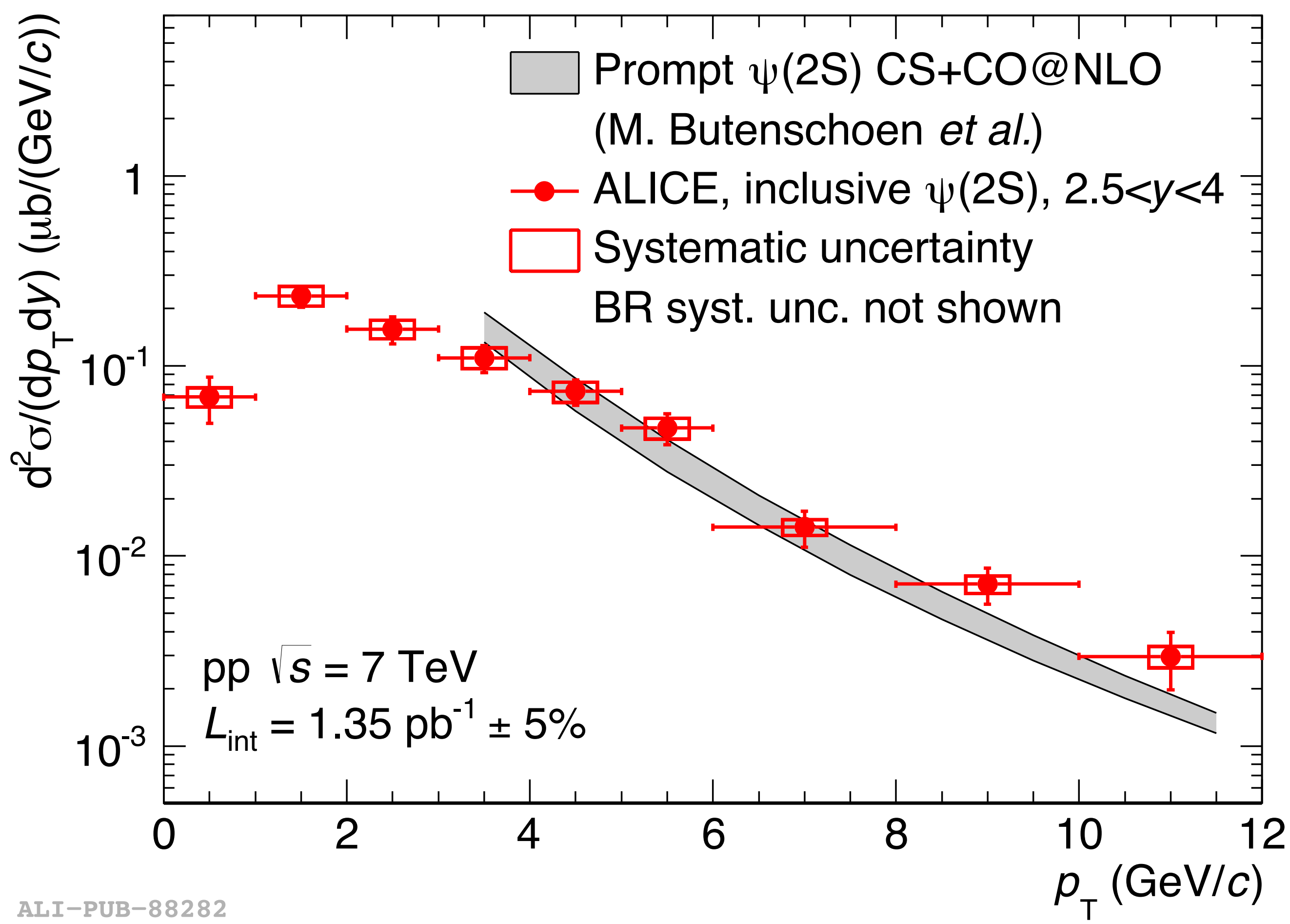
direct **J/ψ**
+ feed down (from ψ(2S) and χ_C states)
+ non-prompt (b-decays)

direct **ψ(2S)**
+ non-prompt (b-decays)

J/ψ and ψ(2S) differential production cross sections

pp@7TeV ALICE





Eur. Phys. J. C 74 (2014) 2974

NLO NRQCD calculations for prompt J/ψ and ψ(2S).

CS contributions + CO from fits to data by means of Long Distance Matrix Elements (LDME).

Reasonable agreement with data for both observables.

pp collisions - Conclusions

ALICE

Differential J/ψ and ψ(2S) production cross sections at $\sqrt{s}$ = 7 TeV have been measured and are in agreement with model predictions.

Other results from Run 1:

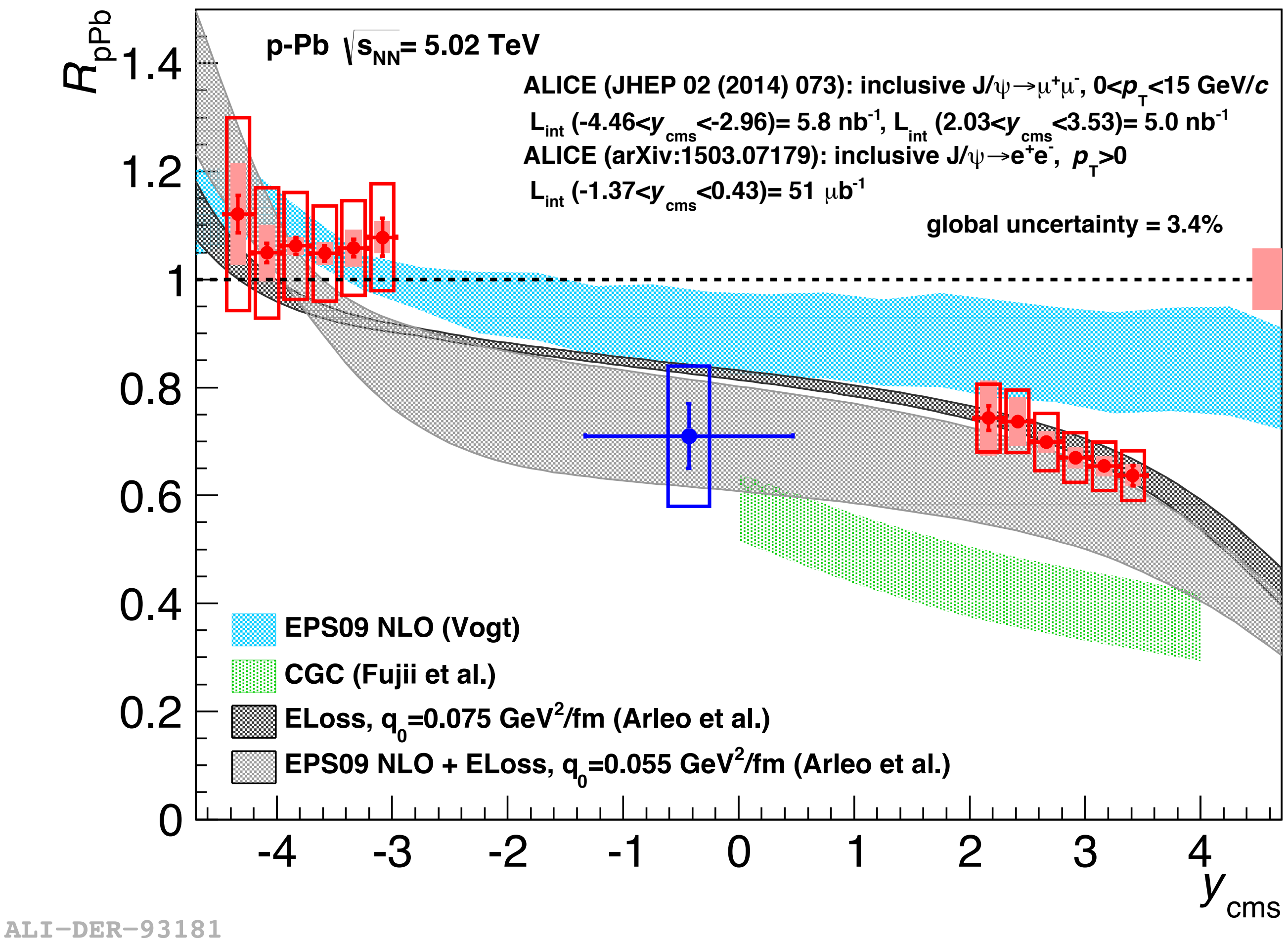
Inclusive J/ψ production in pp collisions at $\sqrt{s}$ = 2.76 TeV
Phys. Lett. B 718 (2012) 295

J/ψ production as a function of charge particle multiplicity in pp collisions at $\sqrt{s}$ = 7 TeV
Phys. Lett. B 712 (2012) 165

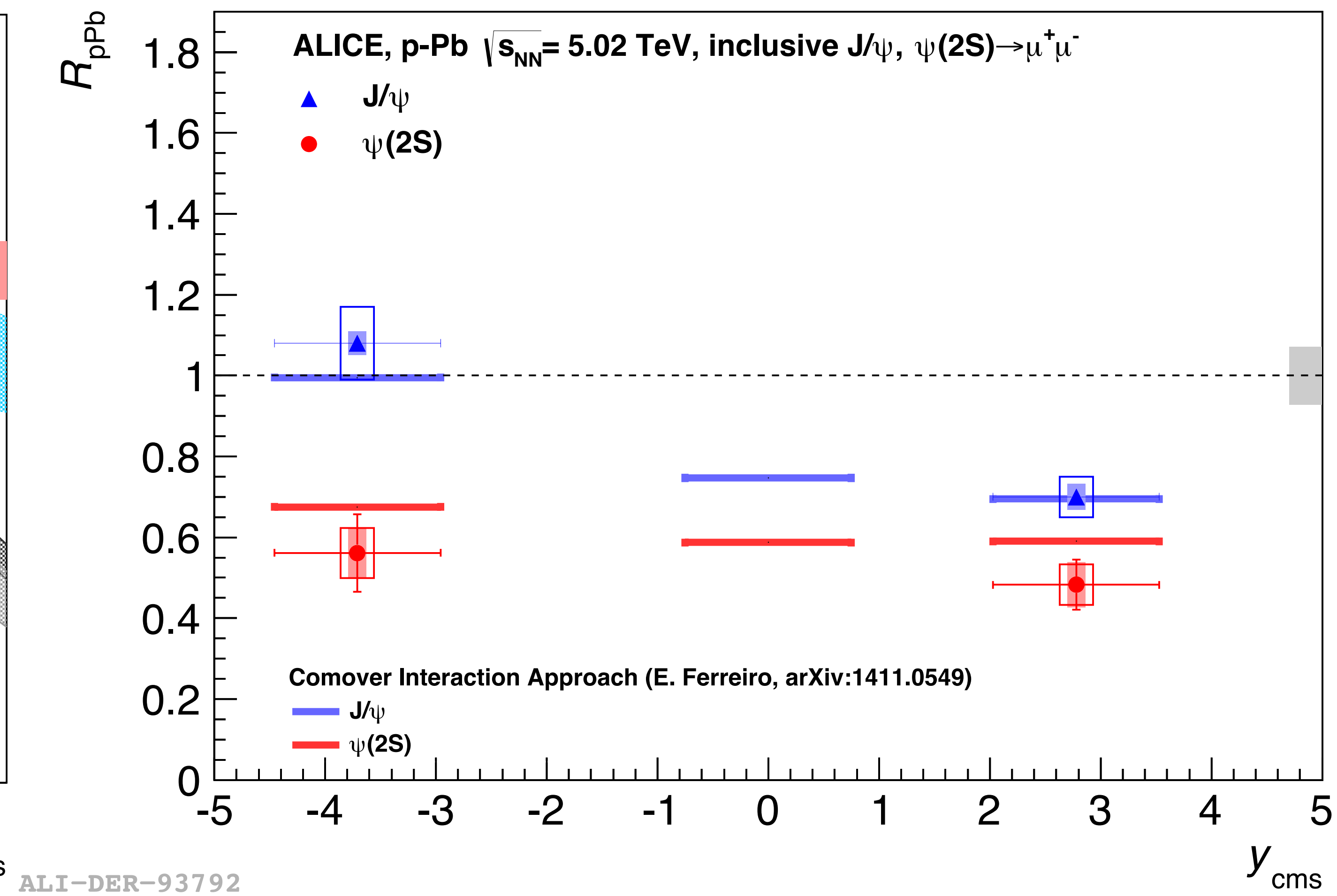
J/ψ polarization in pp collisions at $\sqrt{s}$ = 7 TeV
Phys. Rev. Lett. B 108 (2012) 082001

J/ψ and ψ(2S) R_{pPb} as a function of rapidity

p-Pb@5.02TeV



JHEP02 (2014) 073



arXiv: 1411.0549v1

J/ψ: Backward rapidity data does not favor strong anti-shadowing behaviour.

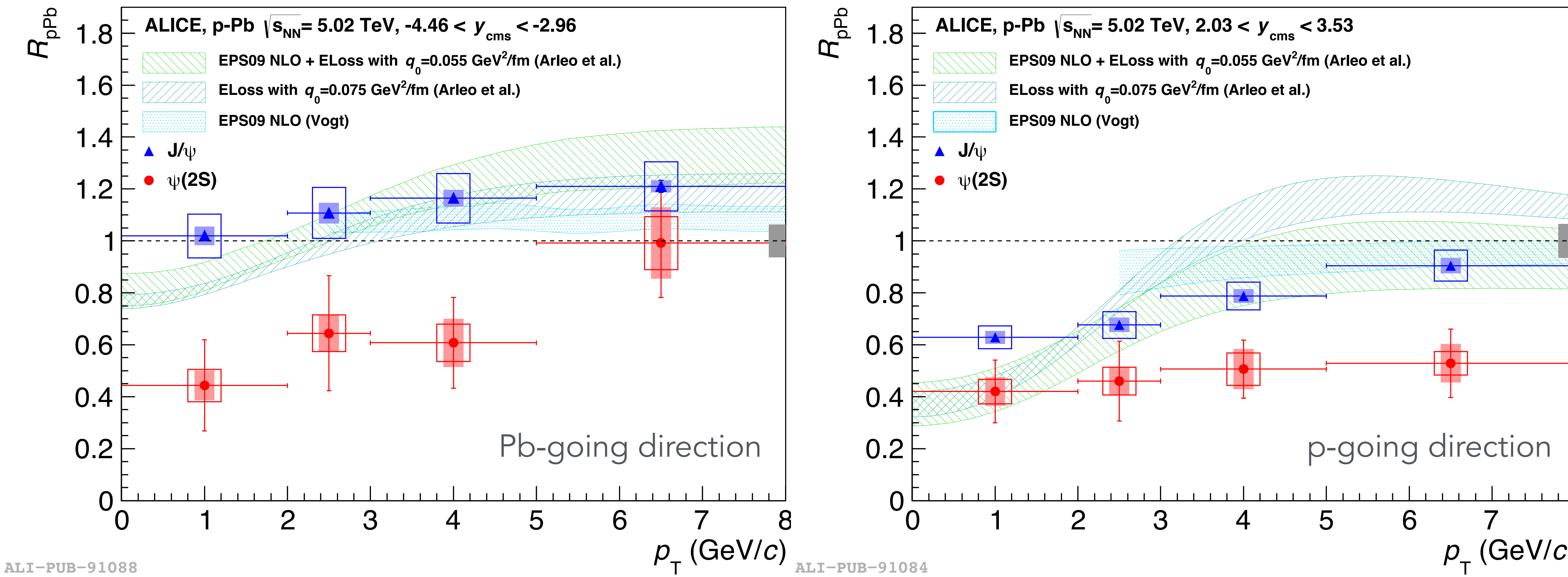
Coherent parton energy loss processes are able to describe the experimental data at forward rapidities. Backward and mid rapidities are better described with the inclusion of nPDF.

ψ(2S): Stronger suppression than for J/ψ.

Interaction with comovers could explain the suppression (shadowing and energy loss effects are not sensitive to the final quantum state of the charmonium state).

J/ψ and ψ(2S) R_{pPb} as a function of p_T

p-Pb@5.02TeV ALICE



JHEP12 (2014) 073

J/ψ: Pure shadowing effects reproduce the data for $p_T > 2.5$ GeV/*c*.

Pure energy loss scenario predicts a steeper p_T dependence at forward rapidity.

Models including coherent parton energy loss processes + shadowing effects are able to describe the experimental data for $p_T > 2$ GeV/*c*. A steeper behaviour is predicted for low-p_T values.

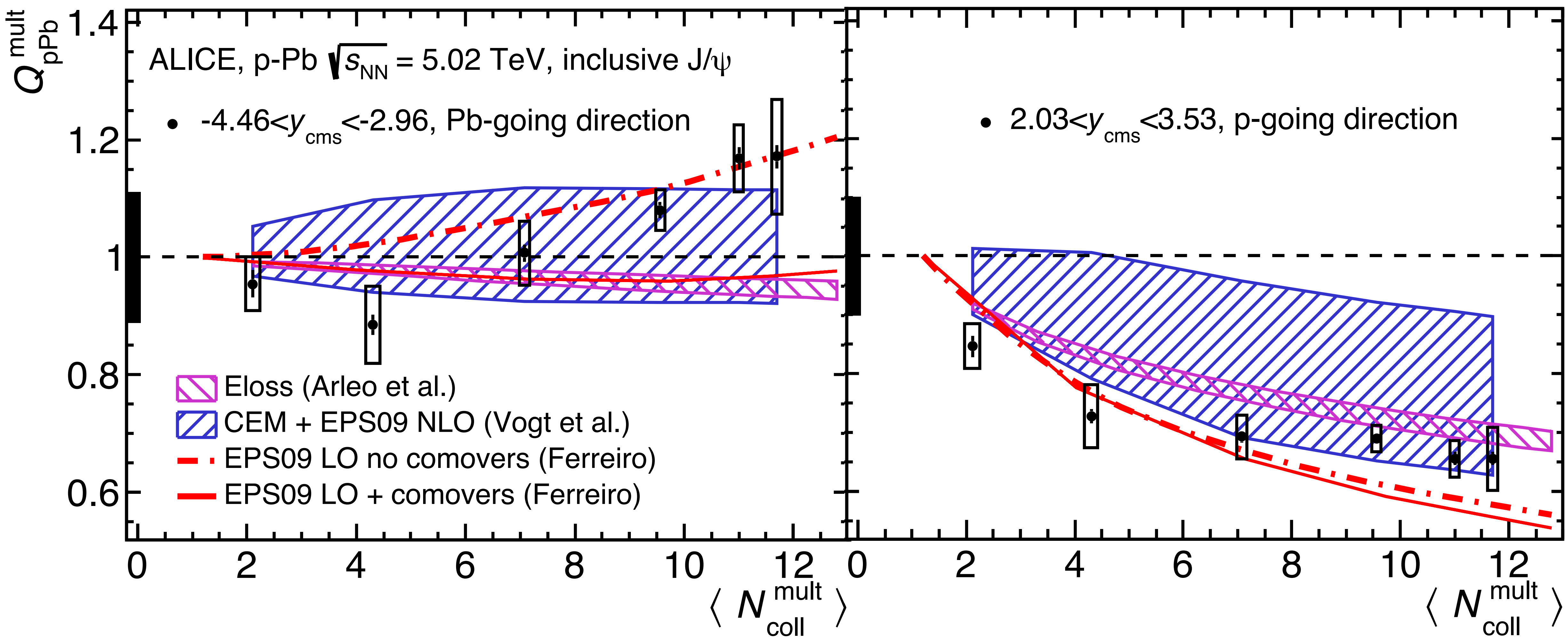
Models including only shadowing and coherent energy loss effects underestimate ψ(2S) suppression.

J/ψ Q_{pPb}* as a function of centrality

p-Pb@5.02TeV ALICE

*Q_{pPb} is used instead of R_{pPb} due to possible bias in centrality estimation.

$$Q_{\rm pPb}^{\rm mult} = \frac{N_{\rm pPb}^{\rm cent}}{\langle T_{\rm pPb}^{\rm mult} \rangle \times \sigma_{\rm pp}}$$



arXiv: 1506.08808v1

Models including shadowing effects reproduce the data at forward and backward rapidity.

Pure energy loss scenario shows better agreement with data at forward rapidity.

The effect of comovers has little impact at forward rapidity contrary to the case of backward rapidity, however data are better described by models not taking into account this effect.

p-Pb collisions - Conclusions

- Cold Nuclear Matter effects are not negligible and must be taken into account for proper interpretation of Pb-Pb collisions.

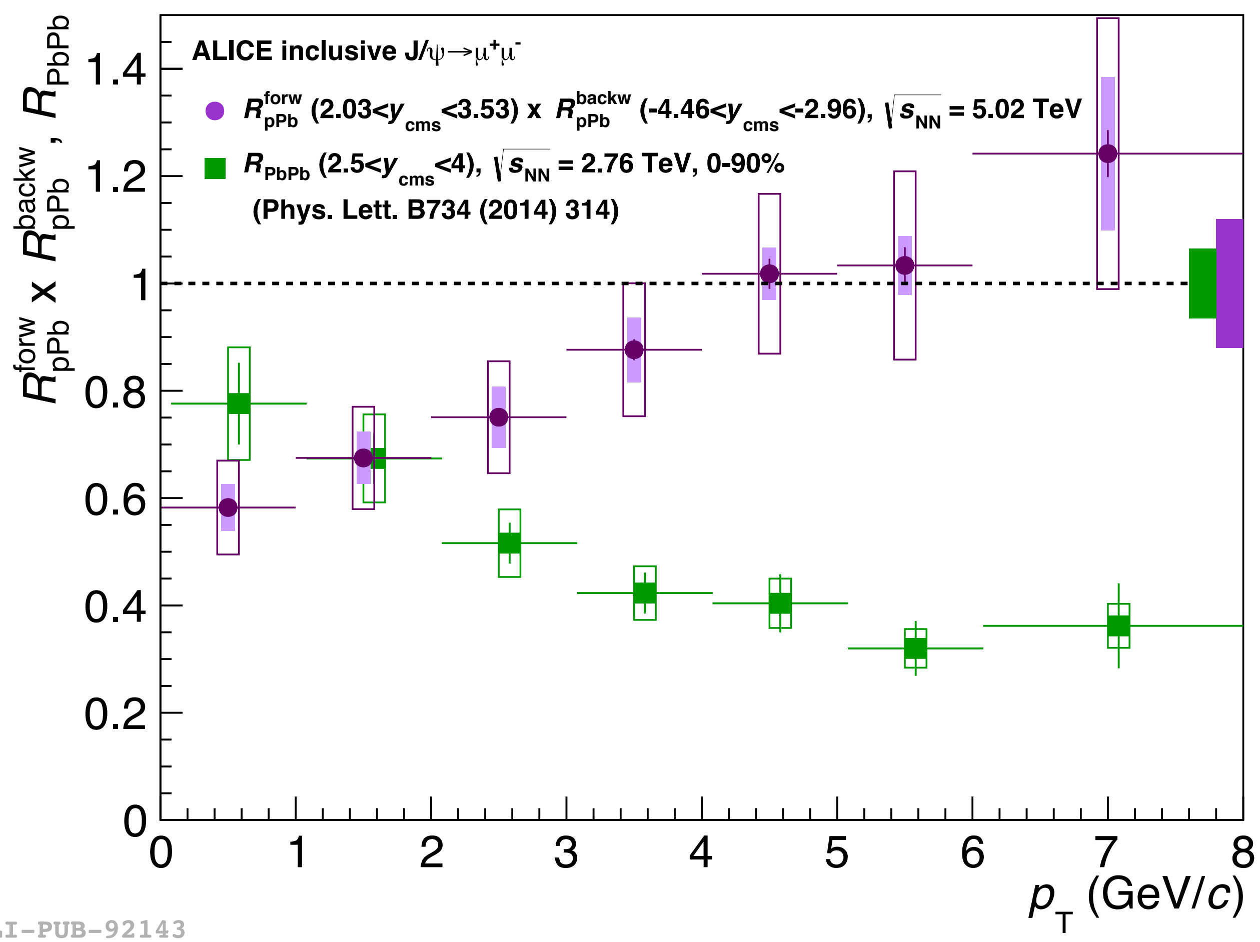
- Coherent energy loss and shadowing can explain the main characteristics of J/ψ production in CNM.

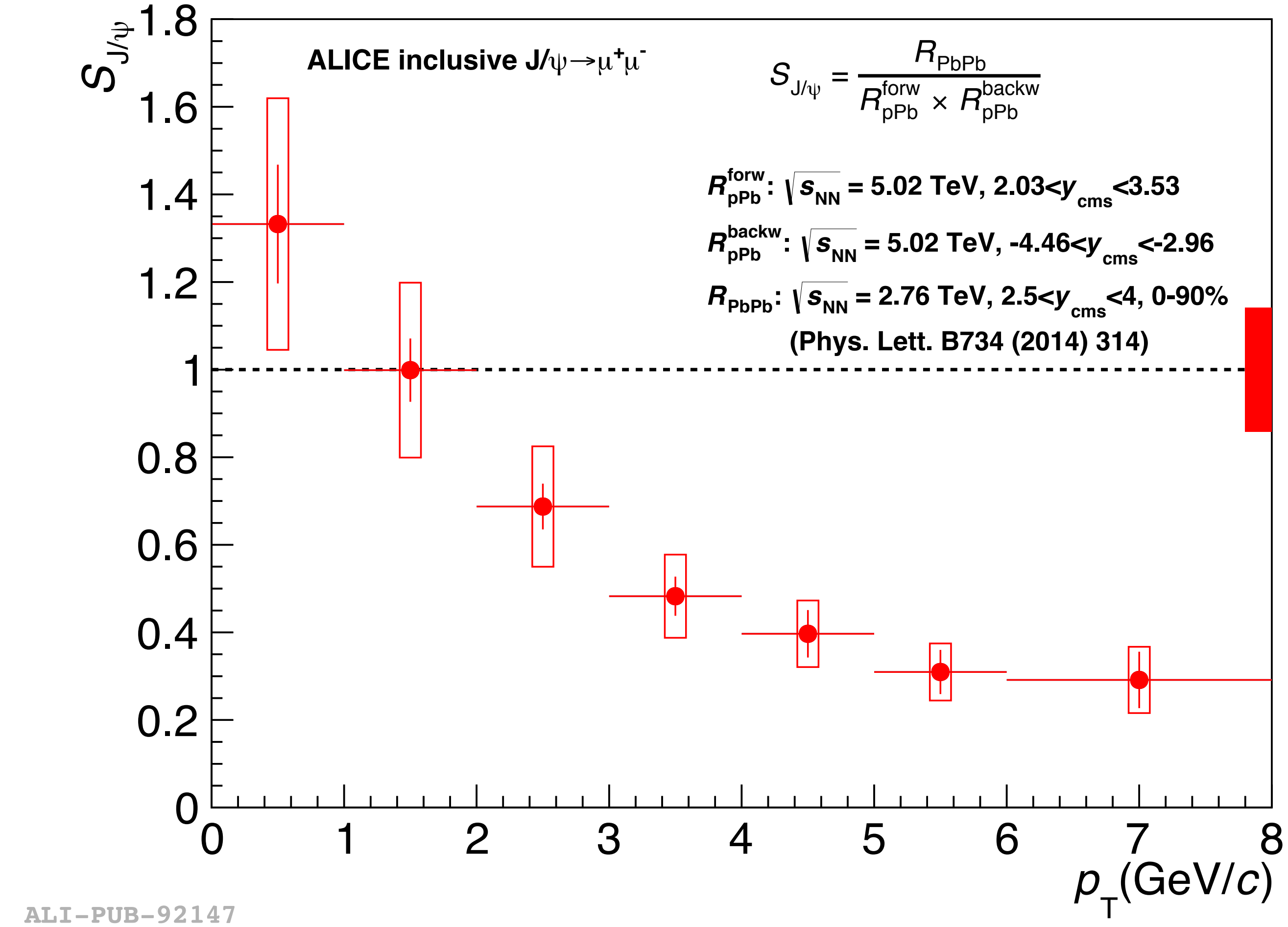
- Interaction with comovers could explain the stronger suppression observed for ψ(2S).

Comparison between p-Pb and Pb-Pb

Pb-Pb@2.76TeV ALICE

CNM effects in Pb-Pb collisions (assuming shadowing as the main CNM mechanism) can be estimated by the product: $R^{\rm forw}_{\rm pPb} \times R^{\rm backw}_{\rm pPb}$





CNM effects induce a strong suppression at low $p_{\rm T}$.

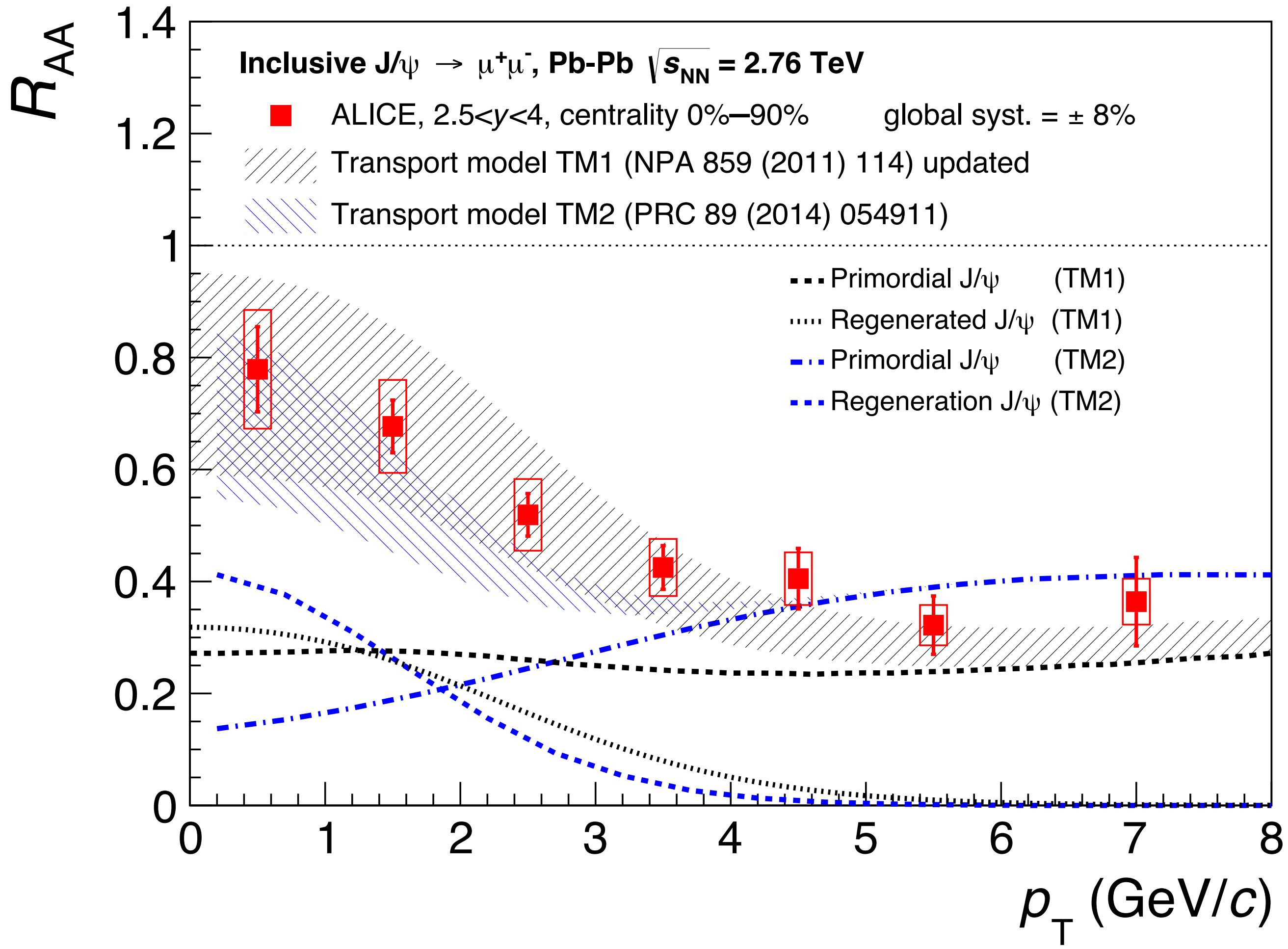
At high $p_{\rm T}$ values the suppression observed in Pb-Pb is much larger than expected from the extrapolation of CNM effects.

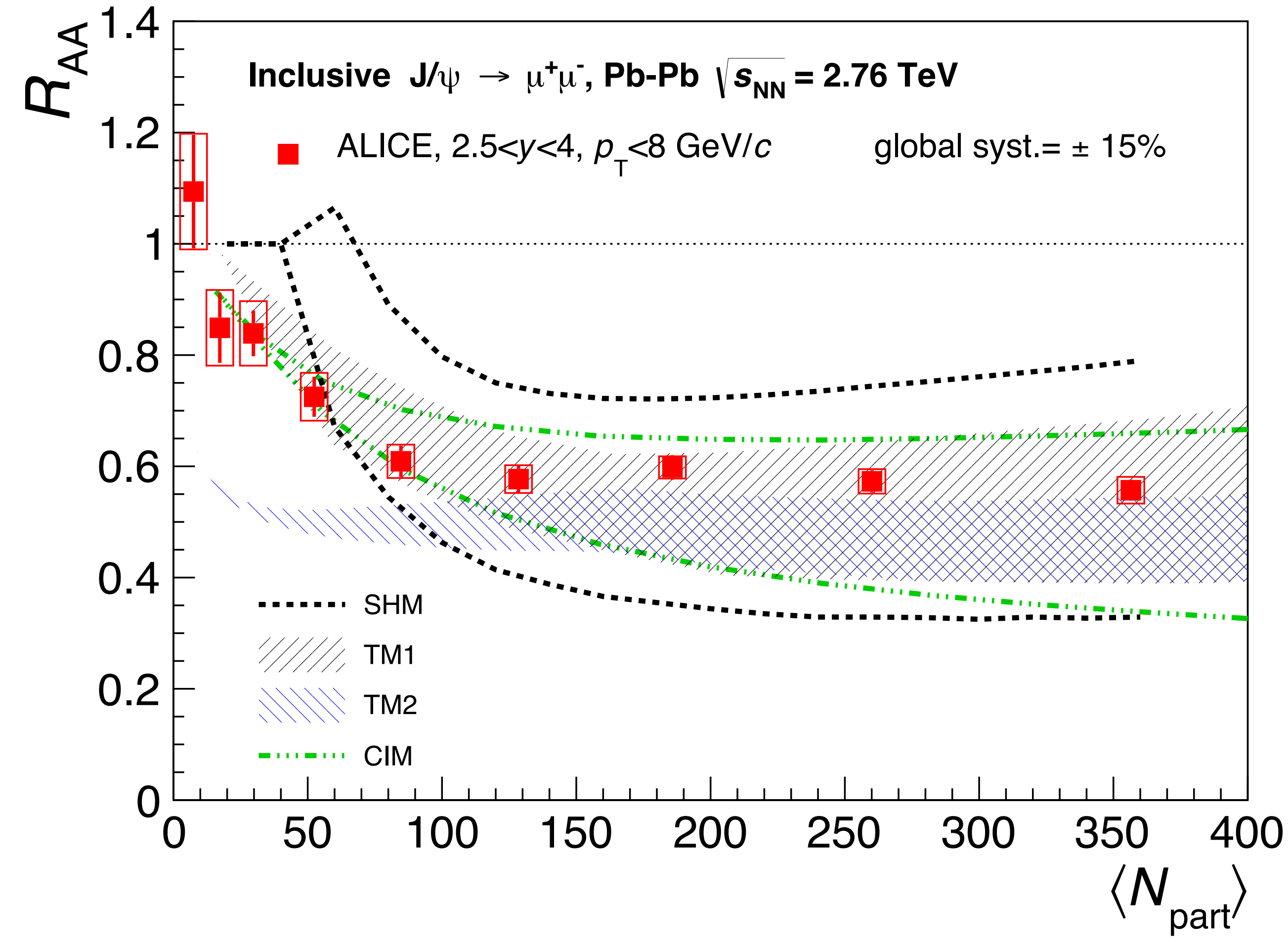
Hint of an enhancement at low $p_{\rm T}$.

arXiv:1503.07179v1

J/ψ R_{AA} as a function of p_T and centrality

Pb-Pb@2.76TeV ALICE





arXiv: 1506.08804v1

Models including full (SHM) or partial (TM1, TM2, CIM) J/ψ regeneration can describe the R_{AA} dependence on centrality. Models uncertainties reflect mostly the uncertainties on the cc cross section and CNM effects.

p_T dependence is in agreement with transport models including primordial J/ψ suppression and regeneration.

A suppression of inclusive J/ψ is observed for central collisions. No dependence with centrality for $\langle N_{part} \rangle > 70$.

Pb-Pb collisions - Conclusions

- J/ψ suppression has been observed in Pb-Pb collisions at forward rapidity.
- Strong dependence of R_{AA} on the J/ψ transverse momentum. Cold nuclear matter effects do not explain the suppression at high p_T.
- Transport models including a regeneration component are able to describe the data.

Overall remarks

J/ψ data suggests that a mixing of suppression by the hot medium and regeneration effects is at work in Pb-Pb collisions.

Coherent energy loss and shadowing effects can explain the main characteristics of J/ψ production in cold nuclear matter. Stronger ψ(2S) suppression in p-Pb collisions could be explained by the interaction with the final state hadronic system.

Charmonium production cross sections in pp collisions are in agreement with NRQCD calculations. Measurements help to constrain theoretical models.

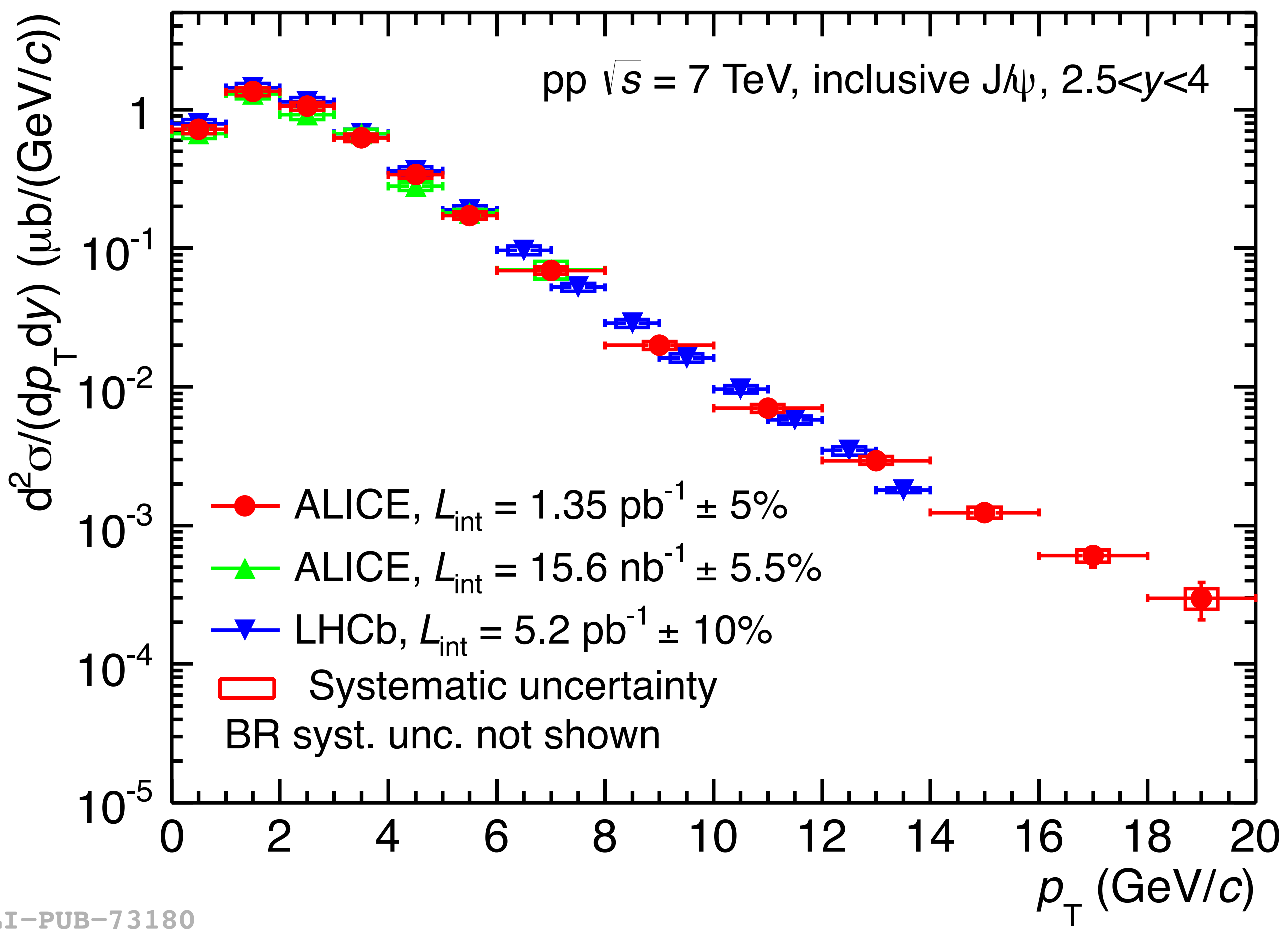
New data from recently started LHC Run 2 will allow to study charmonium production at higher collision energies and help to sharpen our conclusions.

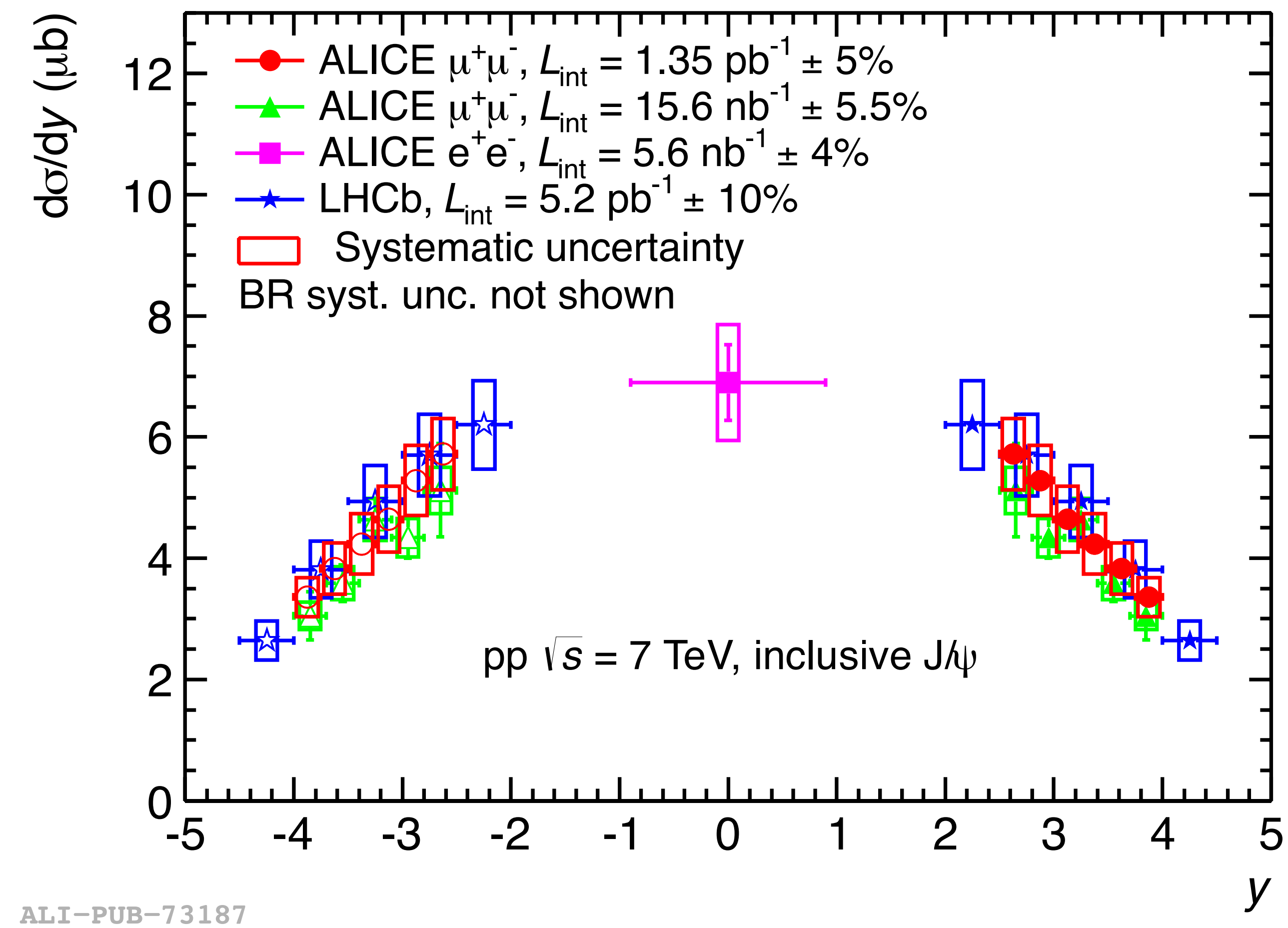
Backups

J/ψ differential production cross section

pp@7TeV ALICE

***p_T* and *y* dependence**





ALICE results are compatible with LHCb (LHCb includes prompt J/ψ and b-meson decays contributions)

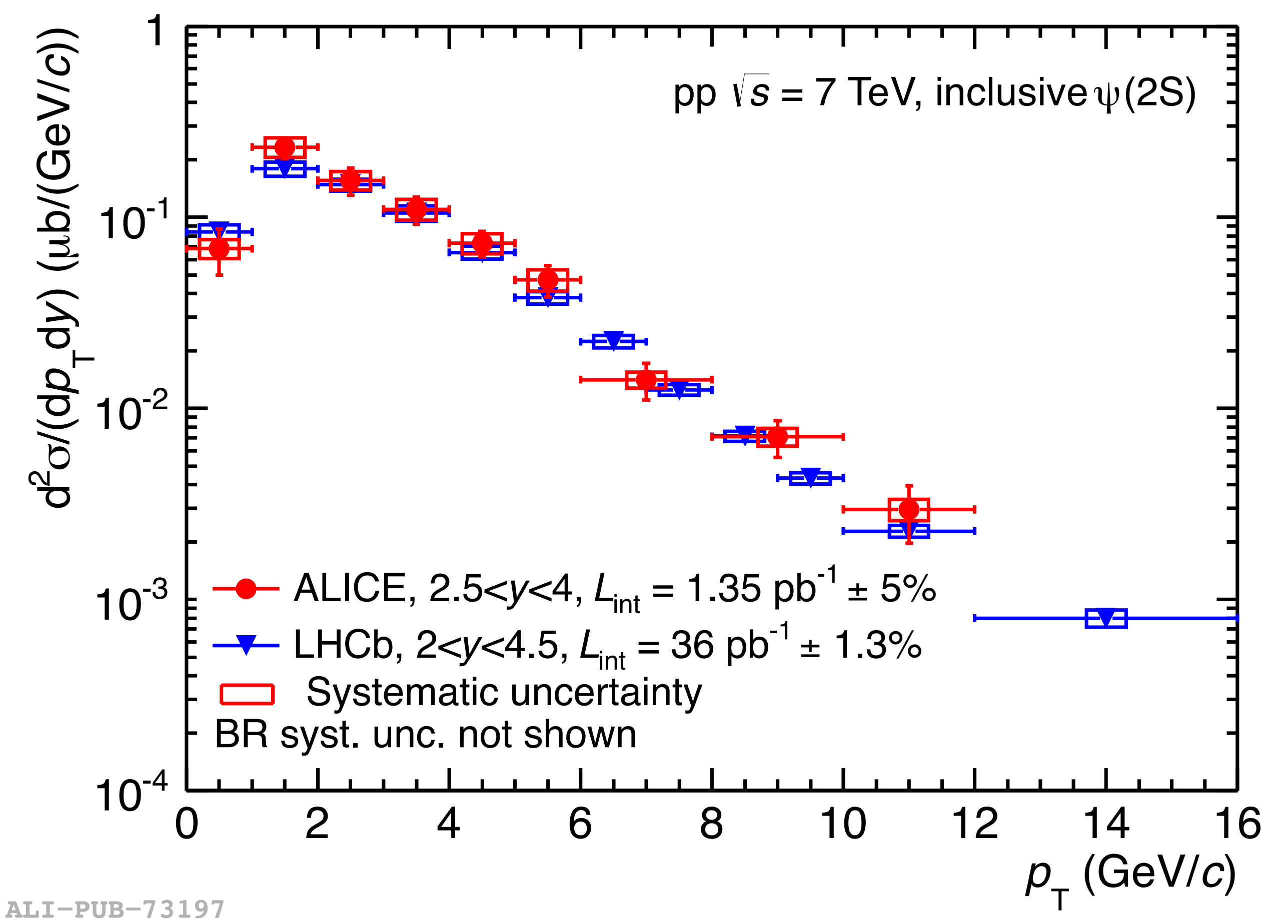
Wide rapidity range. J/ψ measurement at mid-rapidity in the di-electron channel complements the forward rapidity measurement.

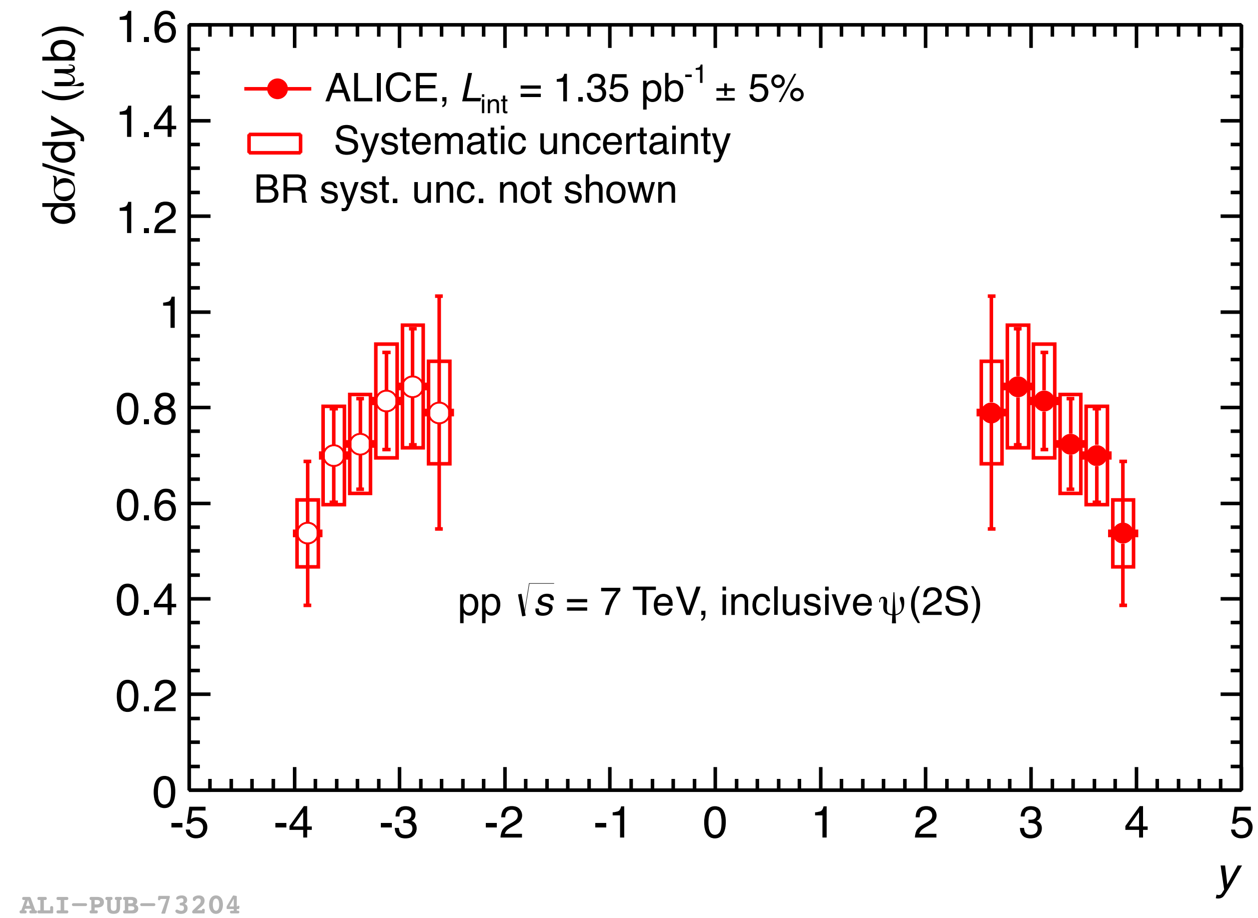
Eur. Phys. J. C 74 (2014) 2974

ψ(2S) differential production cross section

pp@7TeV ALICE

***p_T* and *y* dependence**





ALICE and LHCb results compatible within uncertainties.

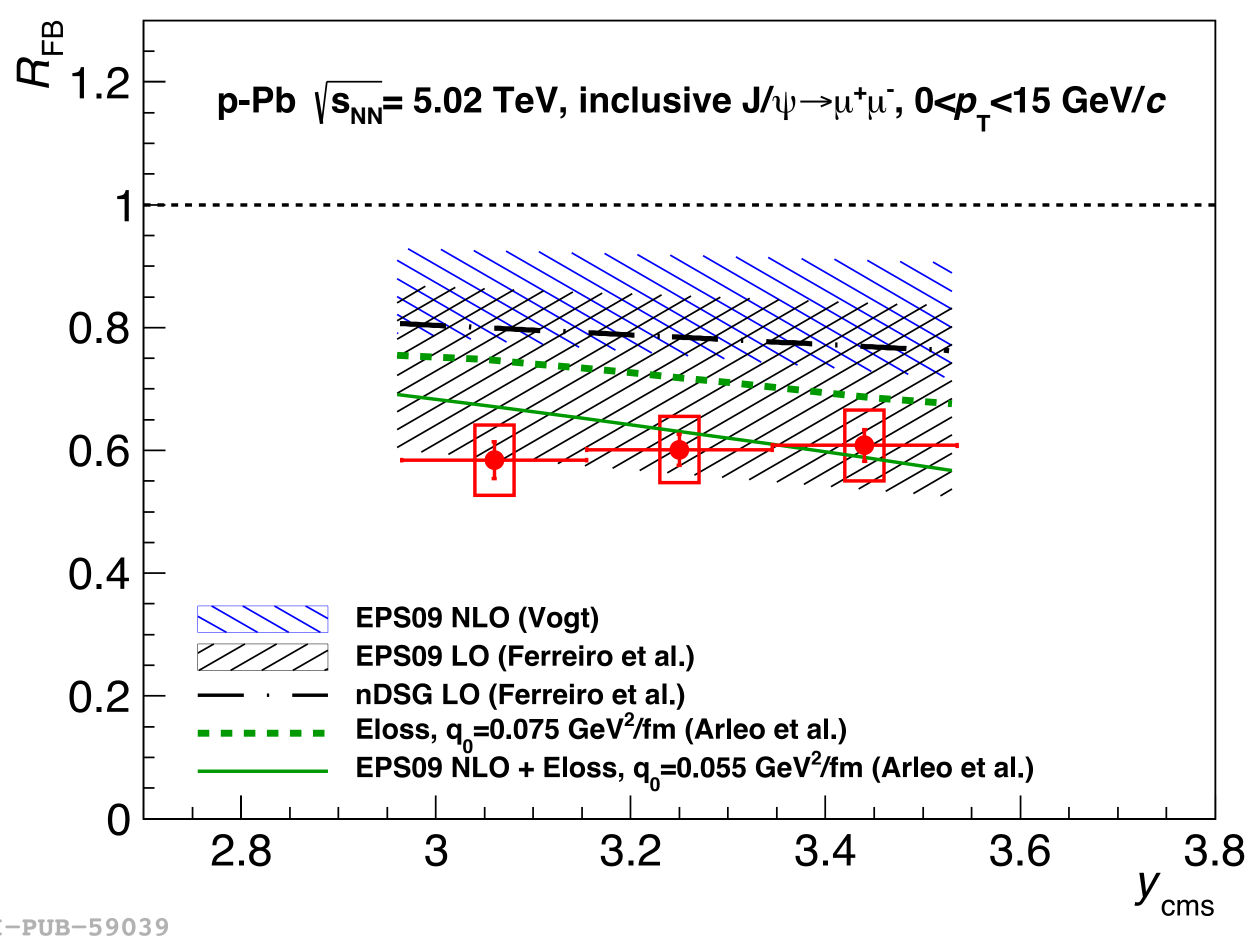
LHCb measurements cover a wider rapidity range.

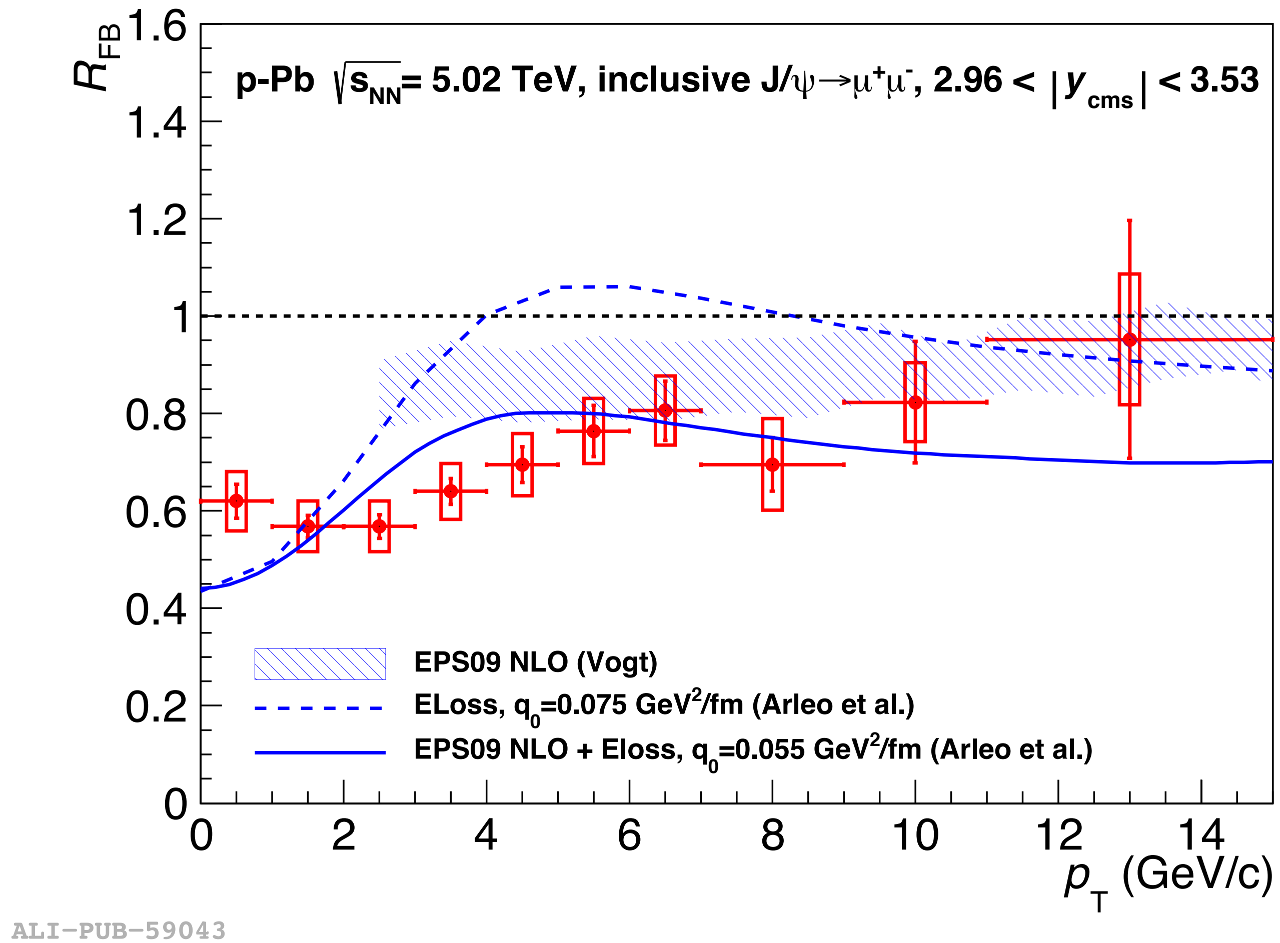
Eur. Phys. J. C 74 (2014) 2974

J/ψ R_{FB} (*) as a function of rapidity and p_T

p-Pb@5.02TeV ALICE

* R_{FB} forward to backward ratio (R_{pPb}/R_{Pbp})





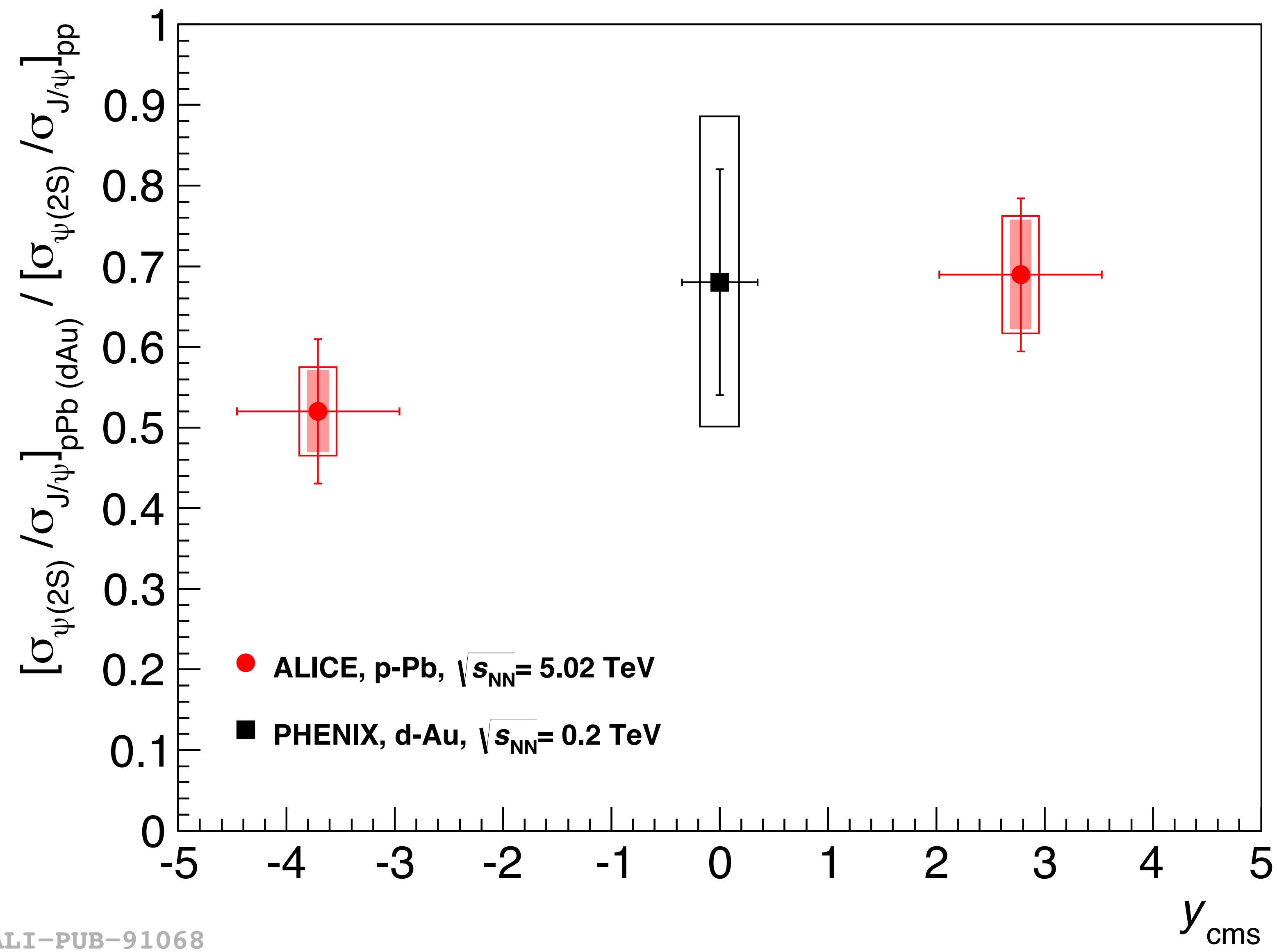
JHEP02 (2014) 073

No variation as a function of rapidity.

Energy loss with the inclusion of shadowing models is able to qualitatively describe the data.

Double ratio $[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pA} / [\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pp}$

p-Pb@5.02TeV ALICE



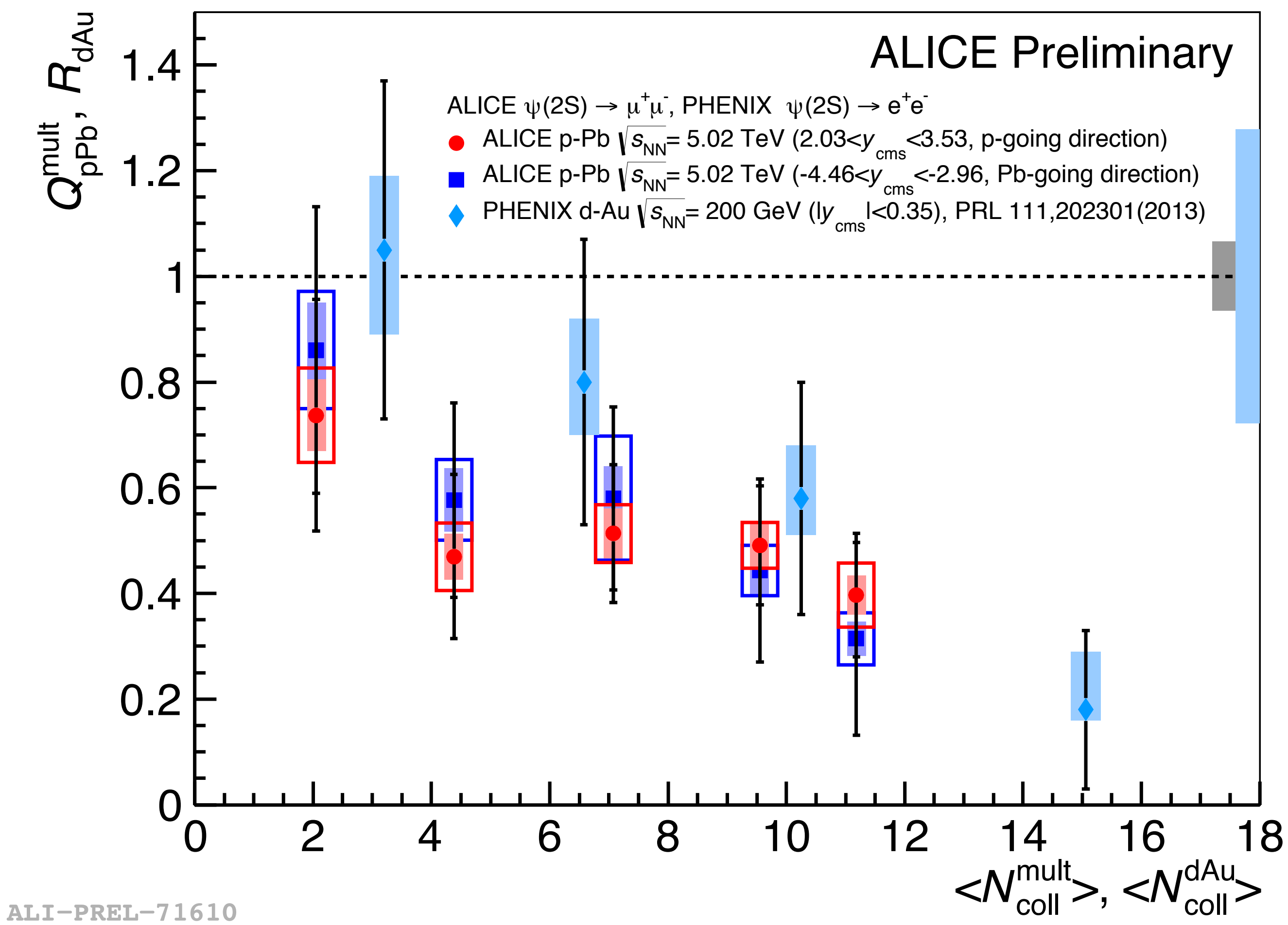
JHEP12 (2014) 073

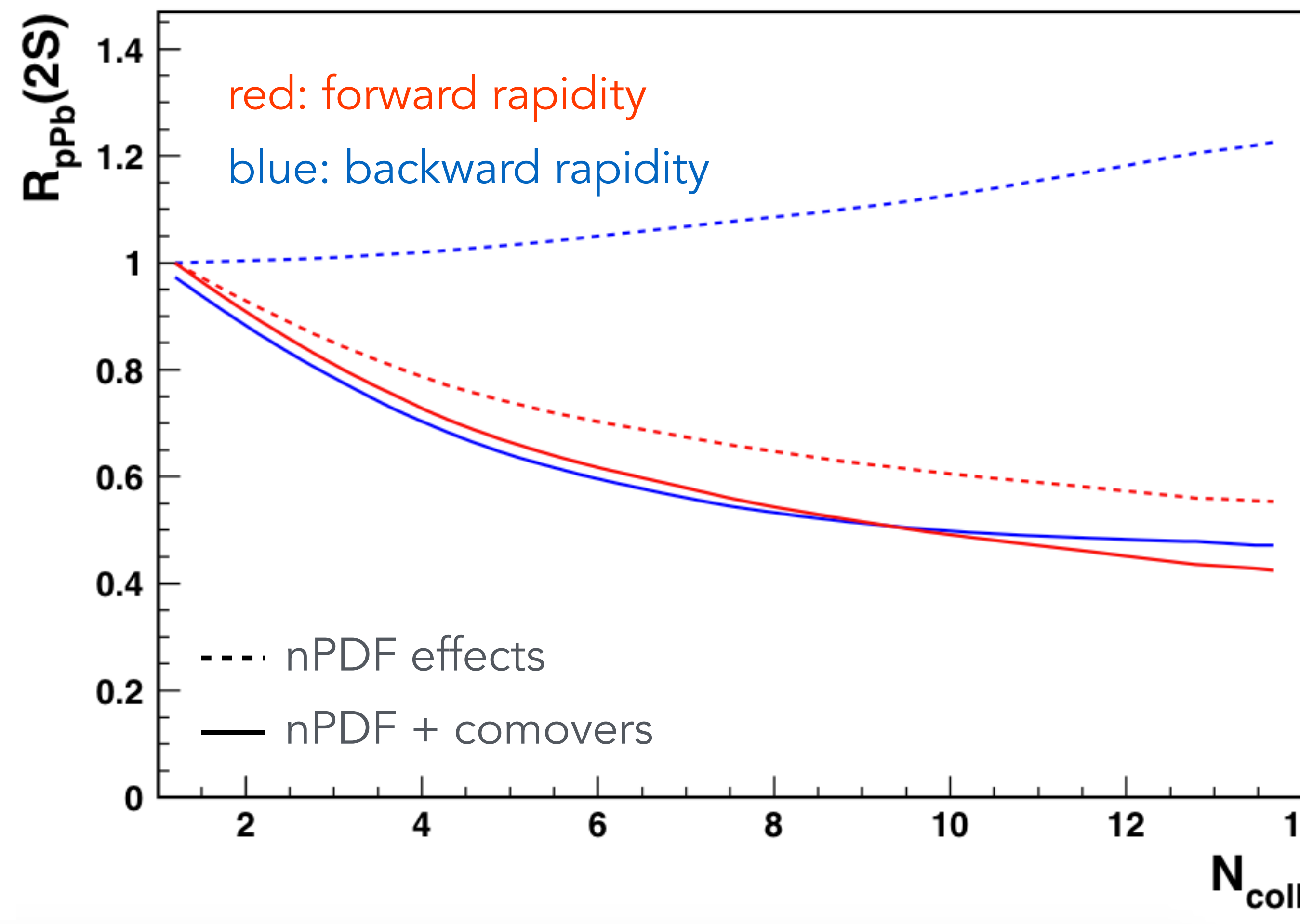
Stronger suppression for ψ(2S) than for J/ψ.

ψ(2S) Q_{pPb}* as a function of centrality

p-Pb@5.02TeV ALICE

*Q_{pPb} is used instead of R_{pPb} due to possible bias in centrality estimation.



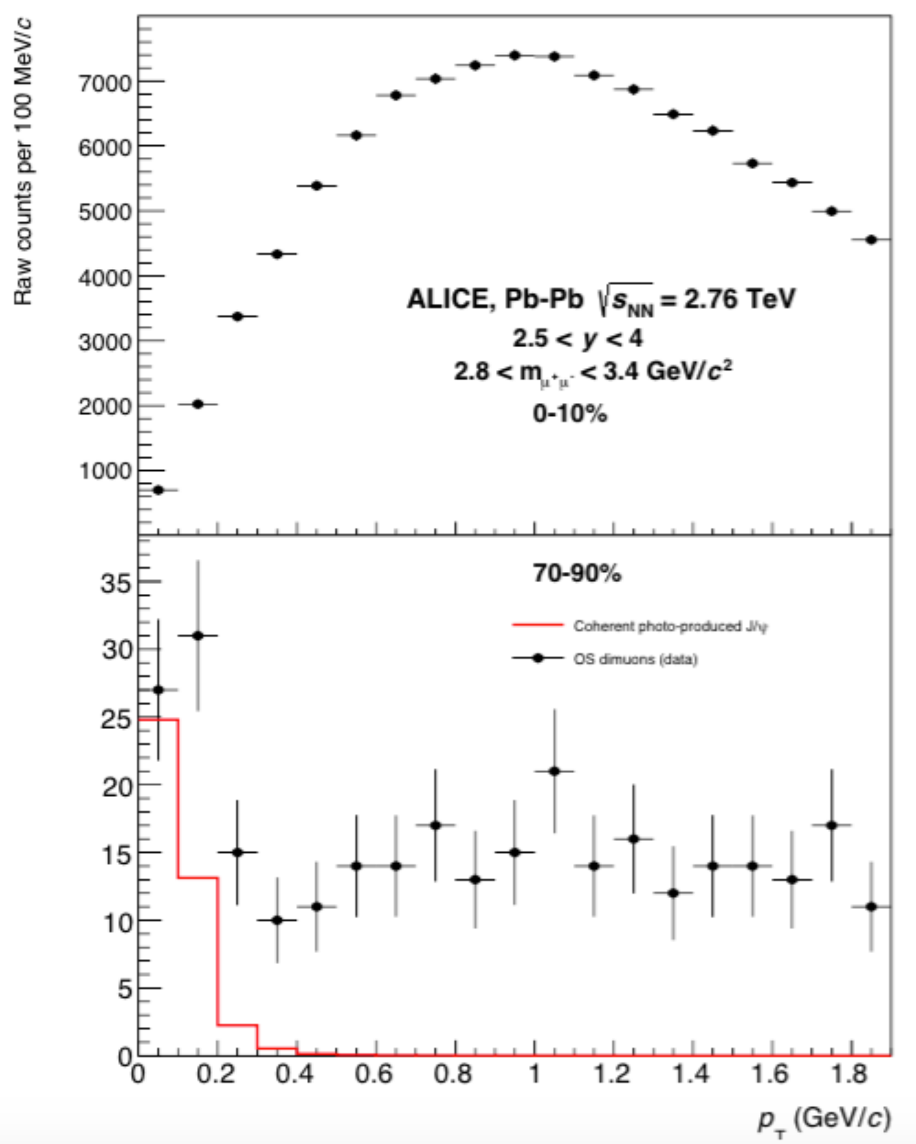


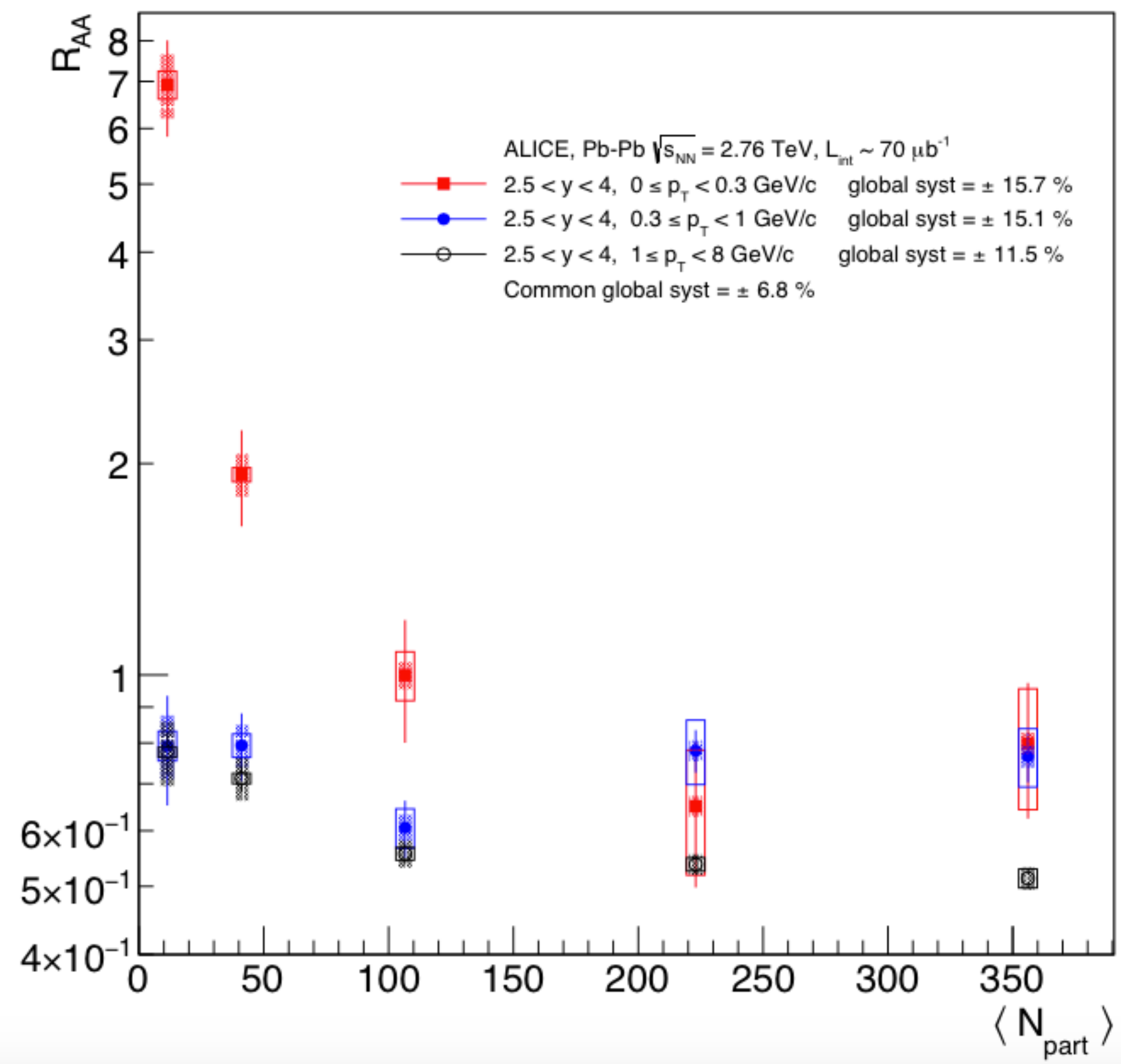
arXiv: 1411.0549v1

ψ(2S) suppression is similar at forward and backward rapidity. It could be explained by models that take into account interaction with comovers (as a dominant effect at backward rapidity) and shadowing effects (at forward rapidity).

J/ψ yield excess at low p_T

Pb-Pb@2.76TeV ALICE





Excess of opposite sign dimuon pairs at very low p_T.

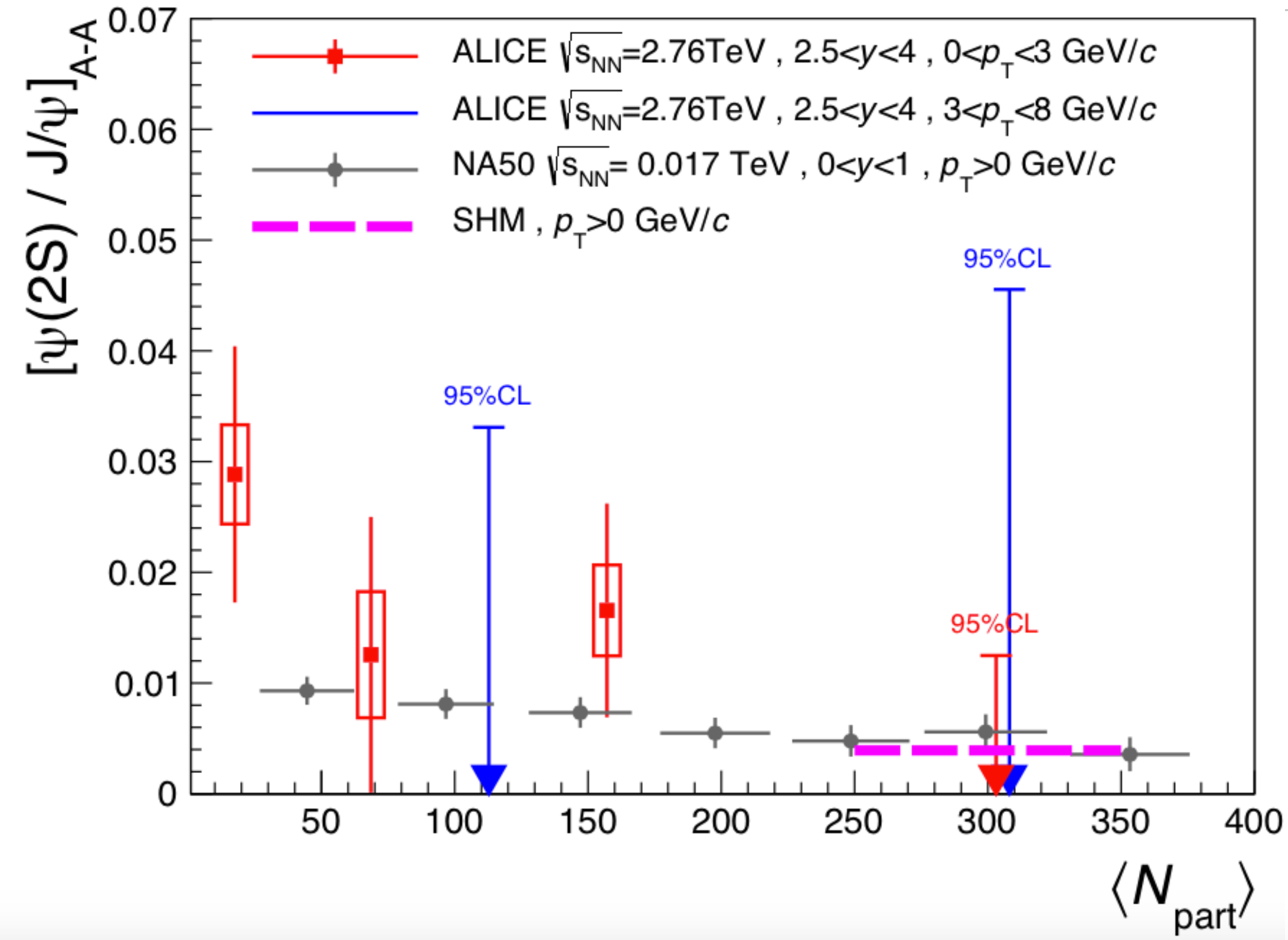
R_{AA} increase at low p_T for most peripheral collisions is not predicted by the previously considered transport models [?].

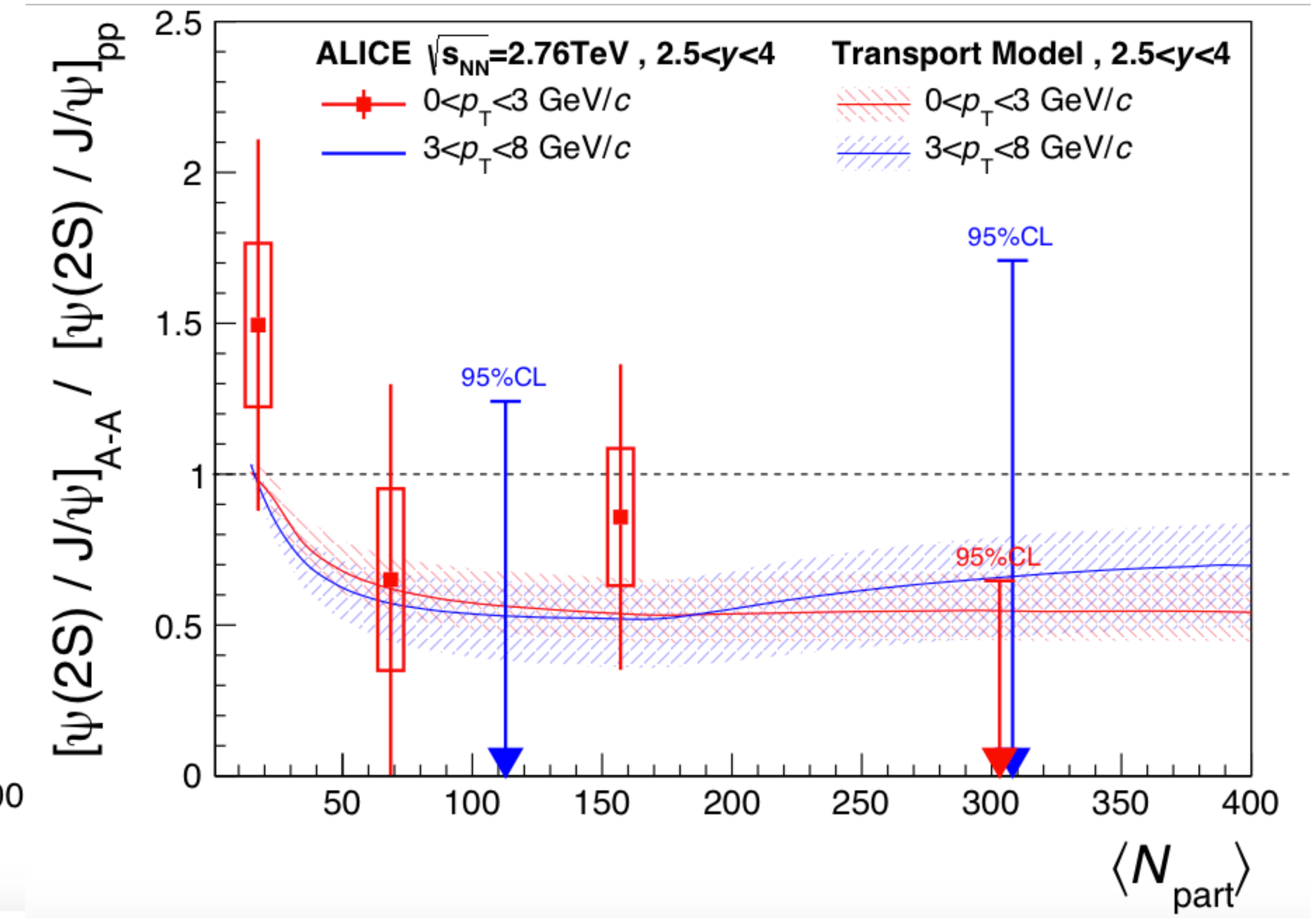
Possible explanation: J/ψ photo-production.

arXiv…

ψ(2S)/J/ψ ratio

Pb-Pb@2.76TeV ALICE





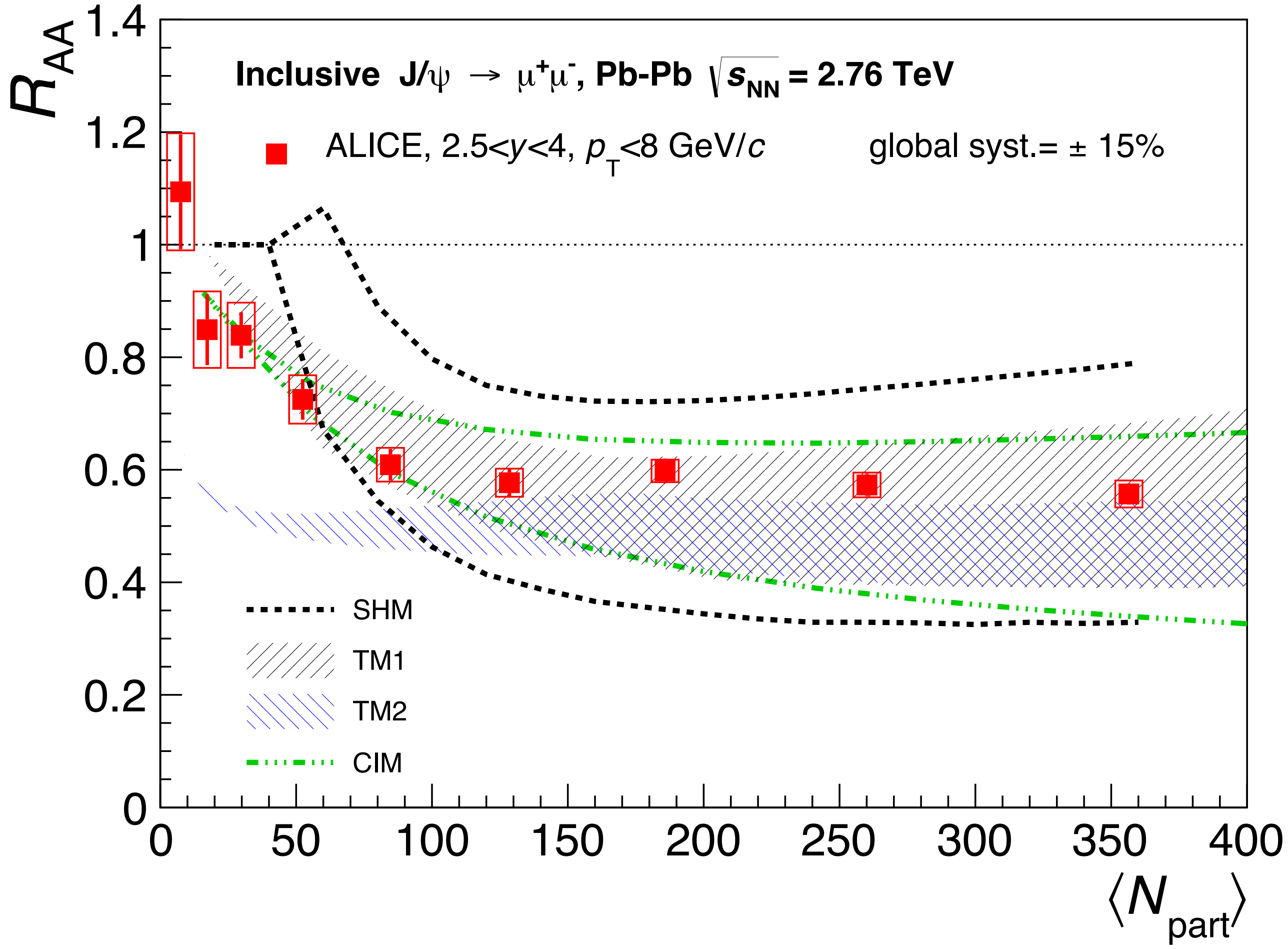
No clear conclusions due to the high statistical uncertainties: suppression pattern of ψ(2S) could be, either compatible to those of J/ψ (except for the low p_T range in most central collisions), or compatible with stronger suppression.

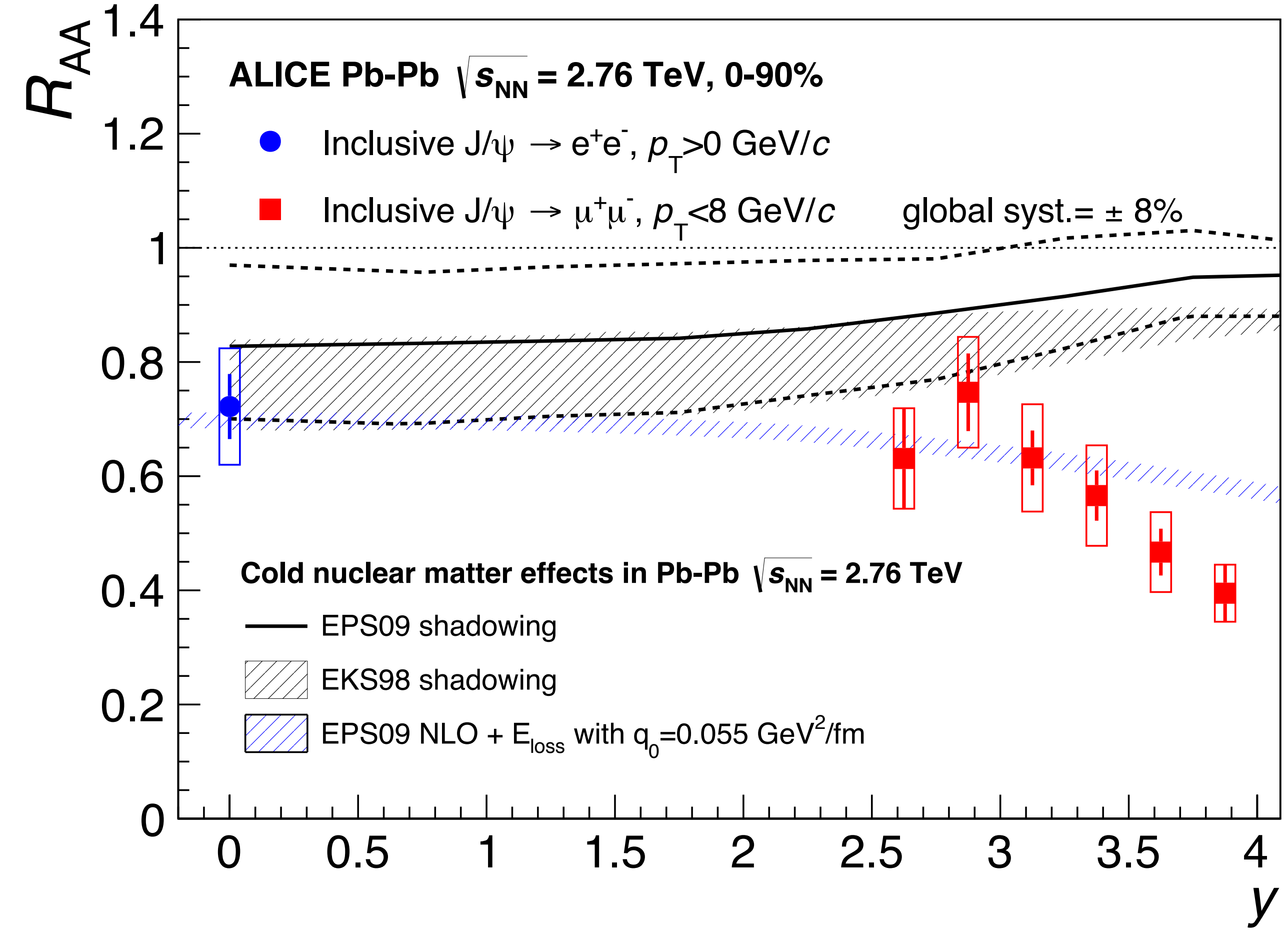
Limit set to the double ψ(2S)/J/ψ ratio for most central collisions in the lower p_T range indicates a stronger suppression of ψ(2S), as expected according to transport models calculations.

arXiv…

J/ψ R_{AA} as a function of centrality and rapidity

Pb-Pb@2.76TeV ALICE





A suppression of inclusive J/ψ is observed for central collisions. No dependence with centrality for $\langle N_{part} \rangle > 70$.

Regeneration models can describe the R_{AA} behaviour as a function of centrality.

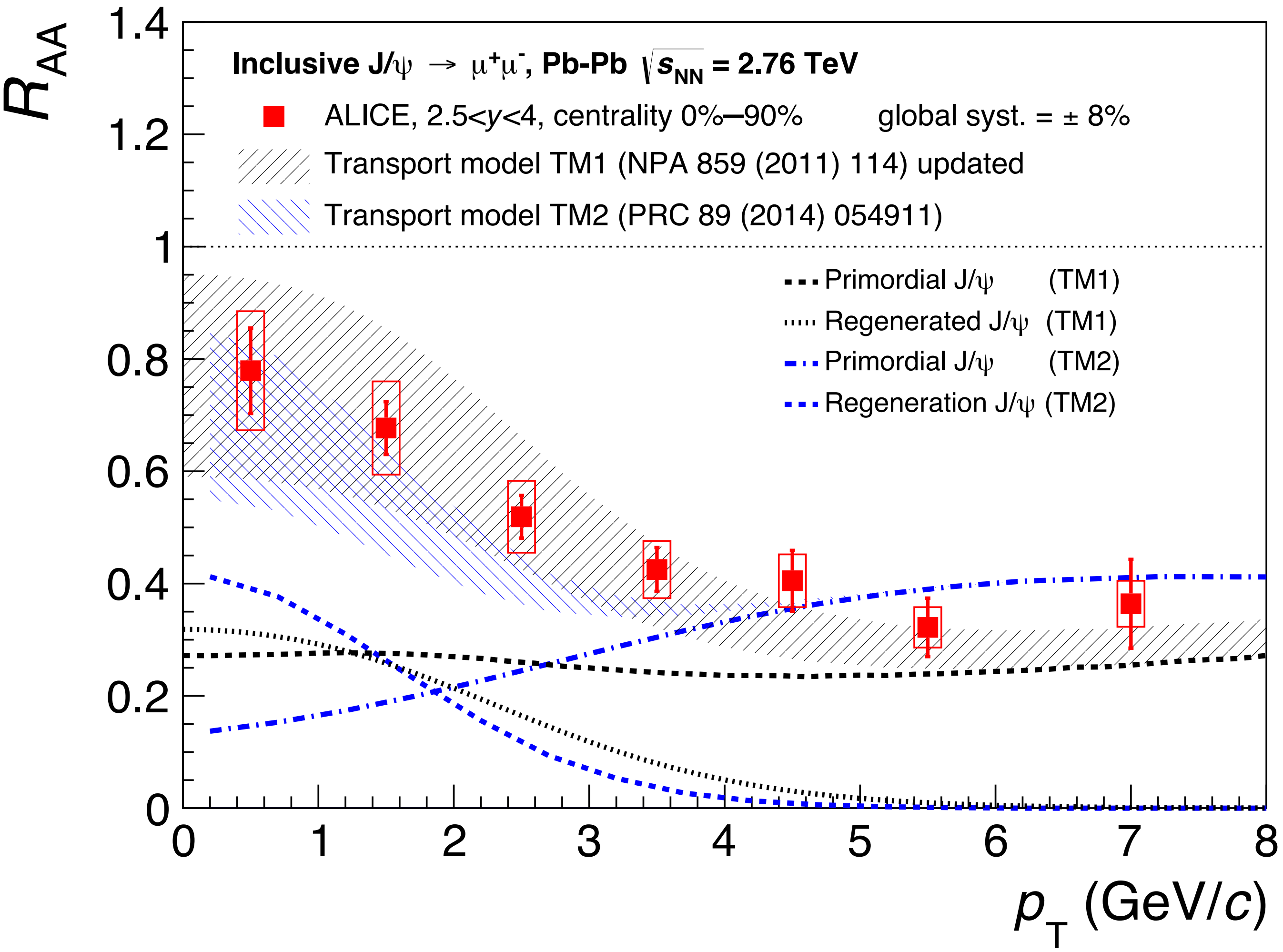
Calculations including CNM effects + recombination show a good agreement with data.

Rapidity dependence suggests the influence of hot medium effects.

arXiv: 1506.08804v1

J/ψ R_{AA} and elliptic flow as a function of p_T

Pb-Pb@2.76TeV ALICE



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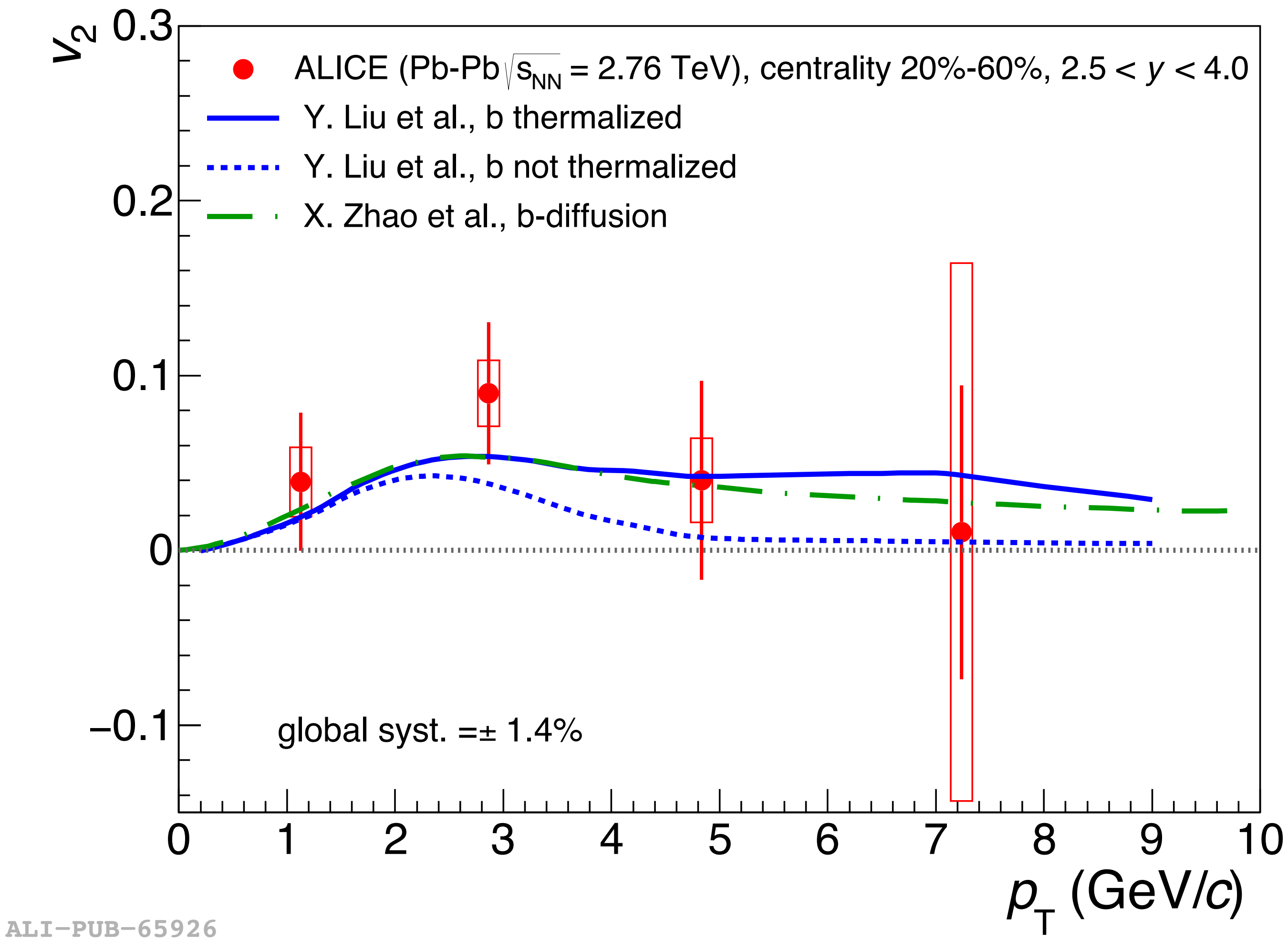
Phys. Lett. B 734 (2014) 314



Phys. Rev. Lett. 111 (2013) 162301

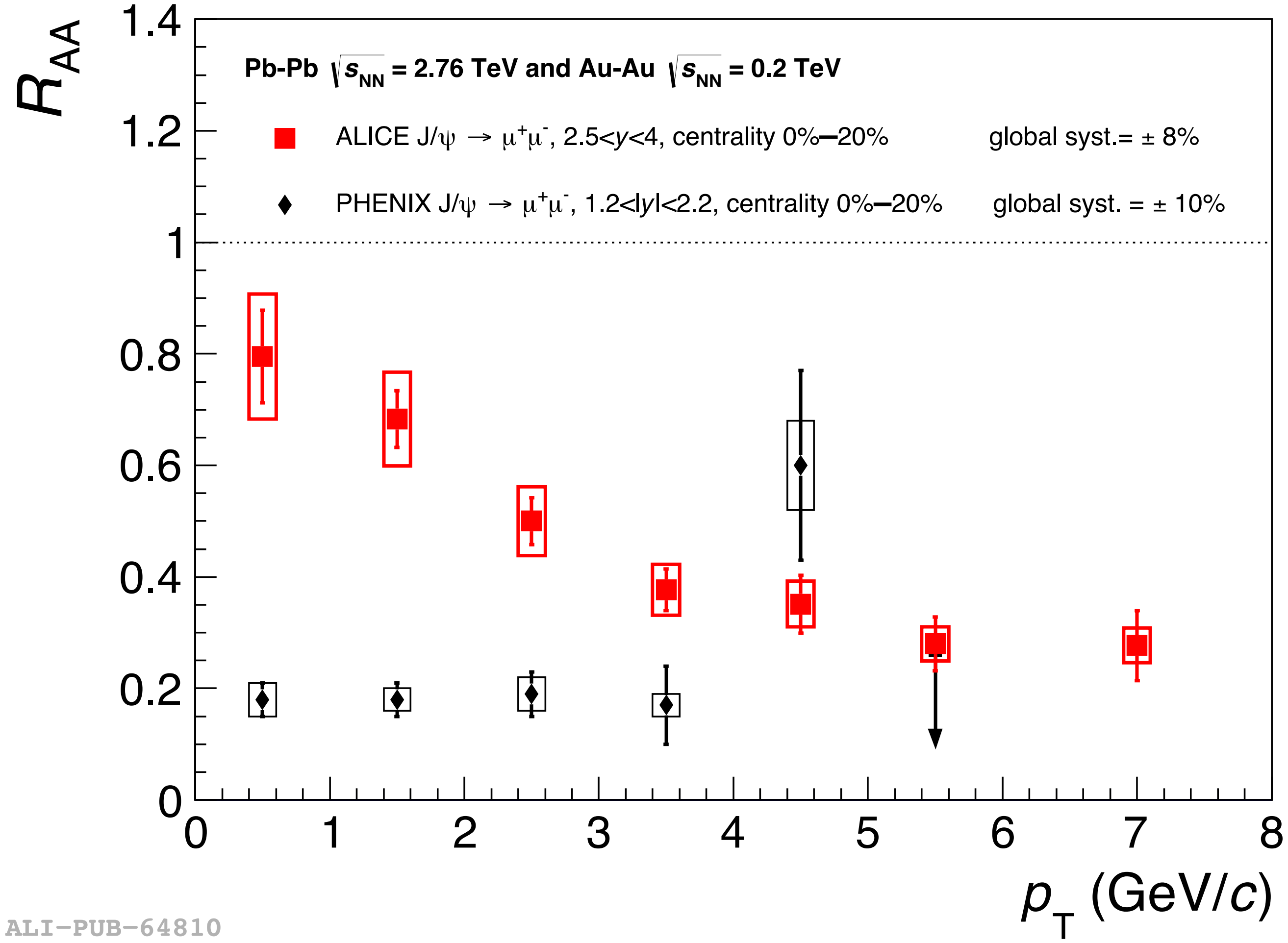
p_T dependence is in agreement with transport models including primordial J/ψ suppression and regeneration.

Anisotropy (nonzero v_2) in the intermediate p_T range is compatible with predictions for regeneration scenarios.

Transport models including a J/ψ regeneration component can describe the v_2 p_T dependence.

J/ψ R_{AA} as a function of p_T

Pb-Pb@2.76TeV ALICE



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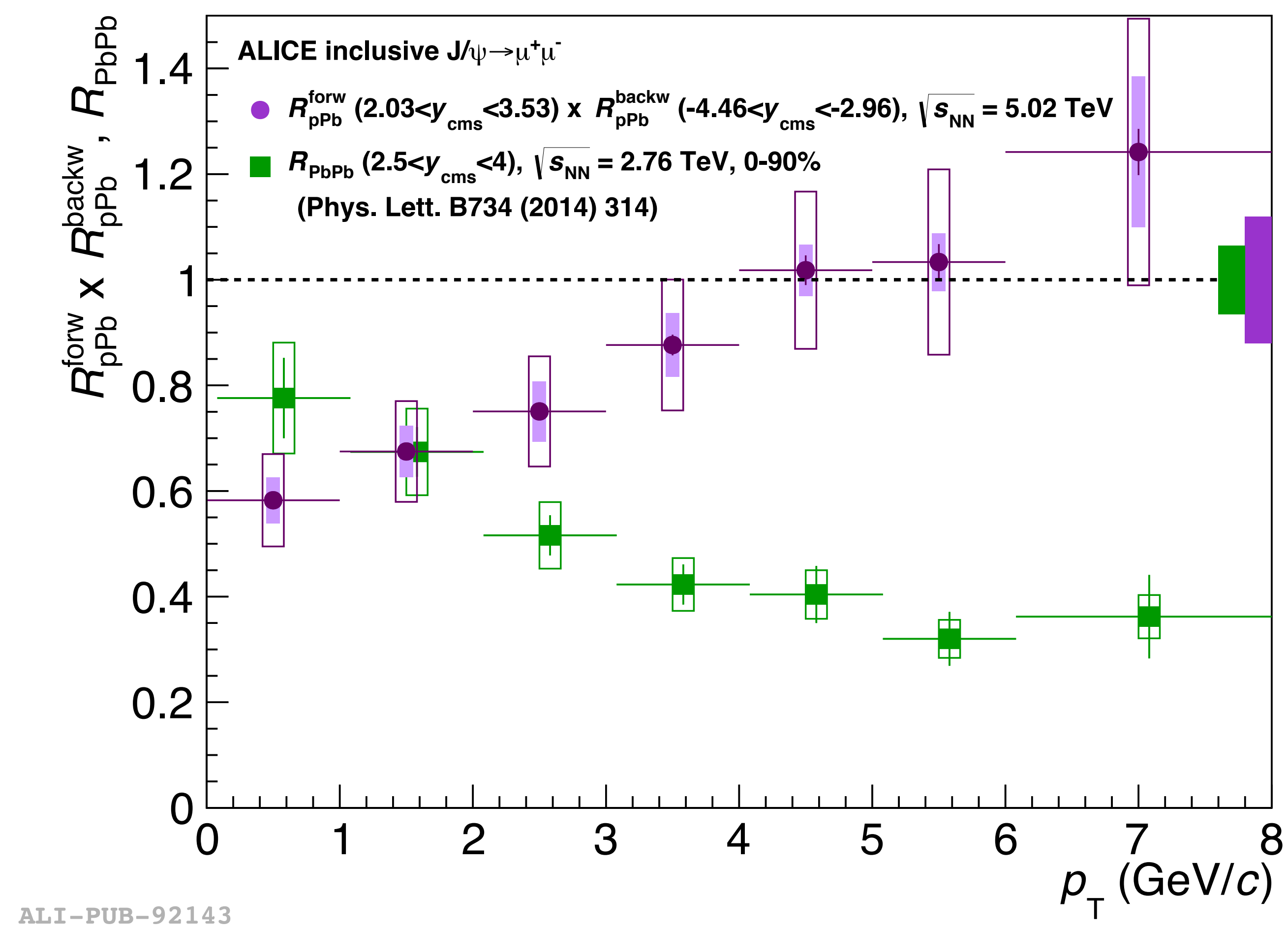

JHEP06 (2015) 055

Comparison with PHENIX suggests the influence of (re)combination mechanisms in the low p_T region.

Hint of an enhancement at low p_T.

At high p_T values the suppression observed in Pb-Pb is much larger than expected from the extrapolation of CNM effects.

$\mathbf{R_{pPb}^{forw} \times R_{Pbp}^{backw}}$ extrapolation of **CNM effects** in Pb-Pb collisions (assuming shadowing as the main CNM mechanism)