Heavy quarkonium production in Pb-Pb and p-Pb collisions with ALICE at the LHC

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on behalf of the ALICE Collaboration
University of Oslo

Strangeness in Quark Matter SQM2015, 6-11 July 2015, JINR Dubna, Russia

Why heavy quarkonia?

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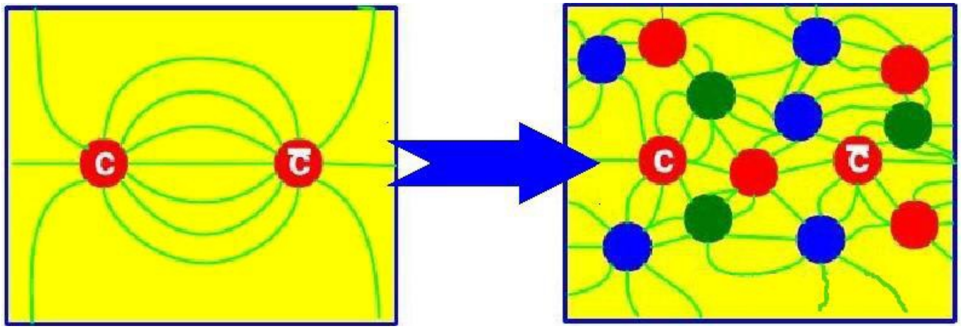
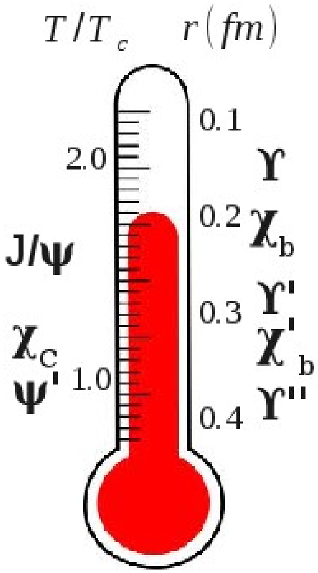
- Colour screening (Matsui and Satz, 1986)



Why heavy quarkonia?

- Sequential suppression (Digal, Petreczcy, Satz 2001)



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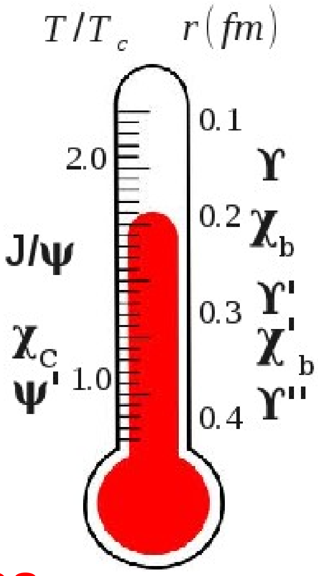

- Continuous melting and regeneration of quarkonium states (Thews et al. 2001)

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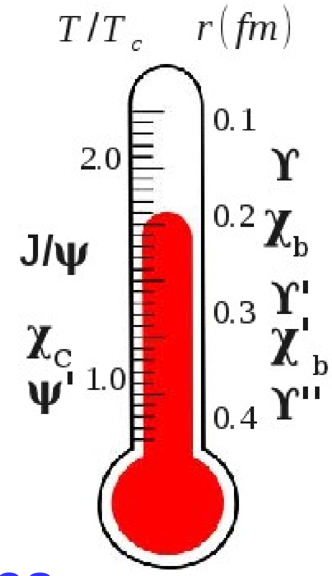
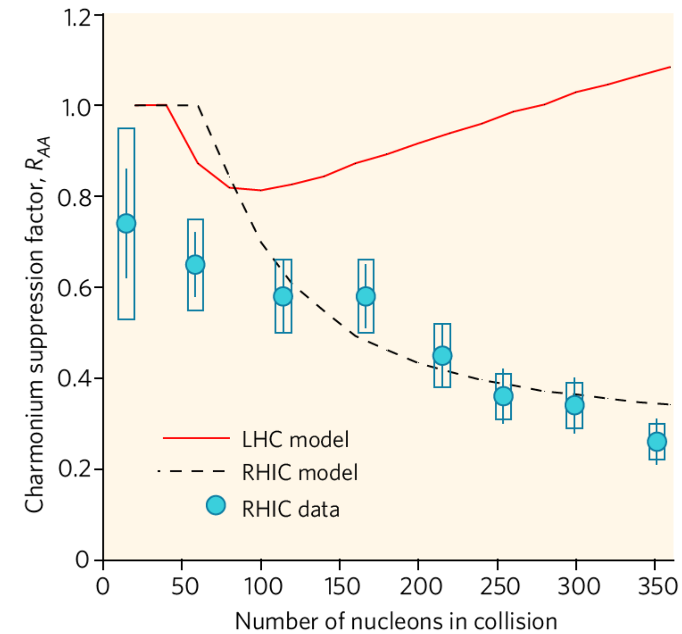


- Continuous melting and regeneration of quarkonium states (Thews et al. 2001)
- Charmonium creation at the phase boundary (Braun-Munzinger and Stachel 2000)



Why heavy quarkonia?

- Well calibrated probe
  - $c\bar{c}$ and $b\bar{b}$ pairs are produced early in the collision
  - Number of heavy quarks conserved during the system evolution

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- Well calibrated probe
  - $c\bar{c}$ and $b\bar{b}$ pairs are produced early in the collision
  - Number of heavy quarks conserved during the system evolution
- Copious production at the LHC
  - ~100 $c\bar{c}$ pairs in central Pb-Pb ($\sigma_{c\bar{c}}$(pp @ 7TeV) = 8.5mb; ALICE JHEP1207(2012) 191)
  - 5-6 $b\bar{b}$ pairs in central Pb-Pb ($\sigma_{b\bar{b}}$(pp @ 7TeV) = 0.28mb; ALICE JHEP 1211 (2012) 06)

Why heavy quarkonia?

- Cold Nuclear Matter (CNM) effects:
  - Nuclear absorption (negligible at the LHC)
  - Formation time
  - Shadowing / gluon saturation effects
  - Coherent parton energy loss

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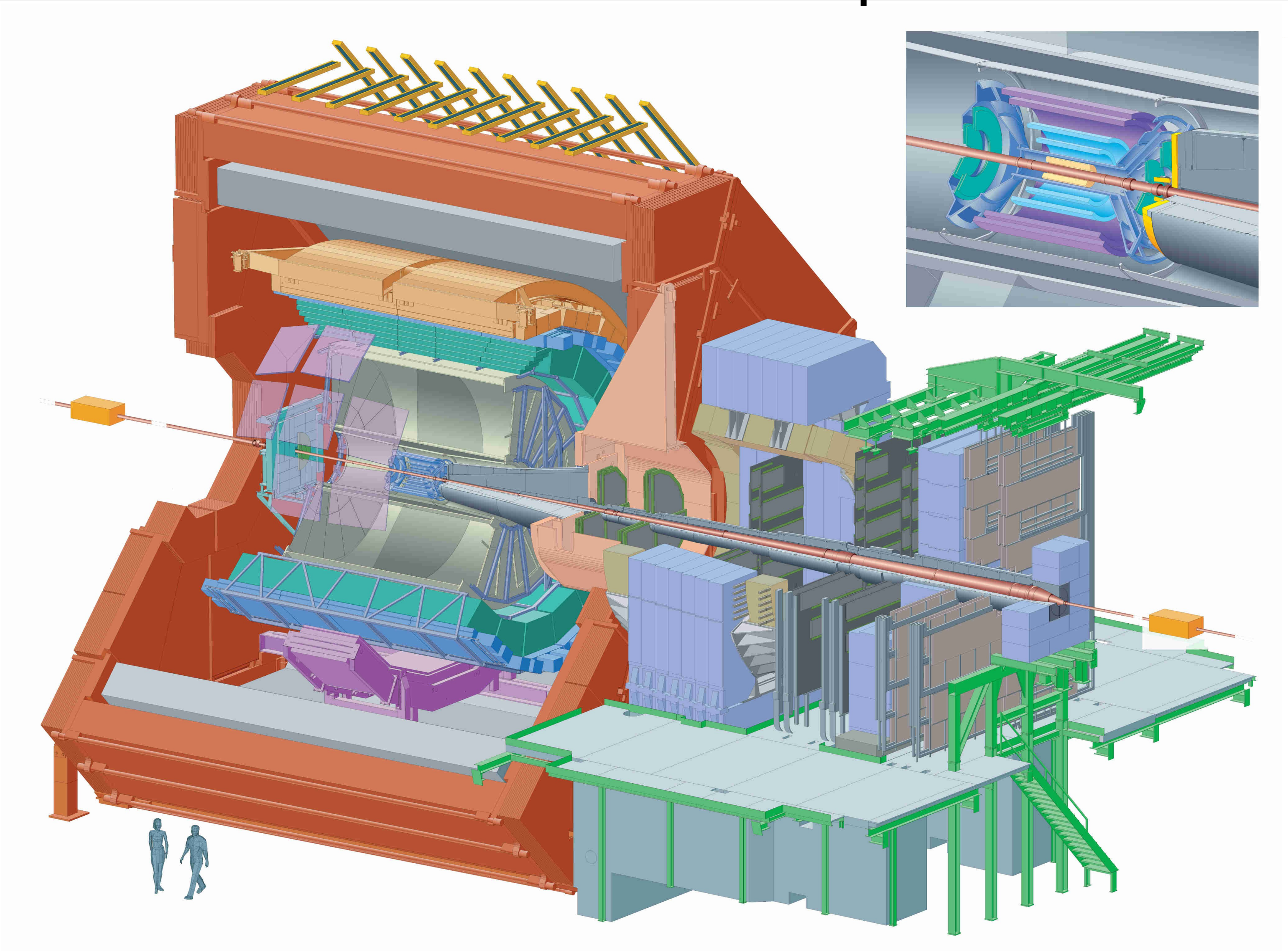
- Cold Nuclear Matter (CNM) effects:
  - Nuclear absorption (negligible at the LHC)
  - Formation time
  - Shadowing / gluon saturation effects
  - Coherent parton energy loss
- Use p-Pb collisions measurements to understand CNM effects and extrapolate to Pb-Pb

The ALICE setup



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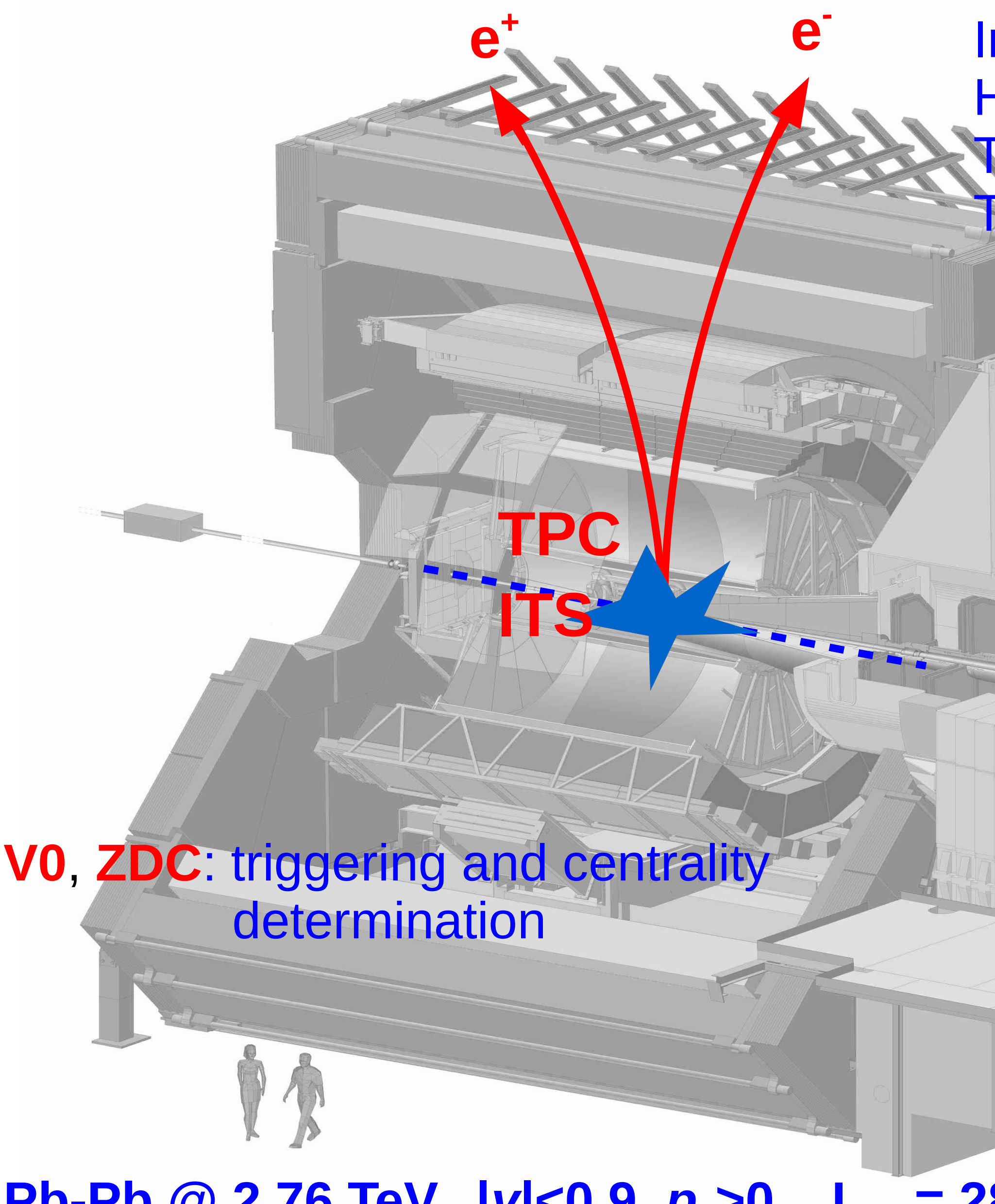
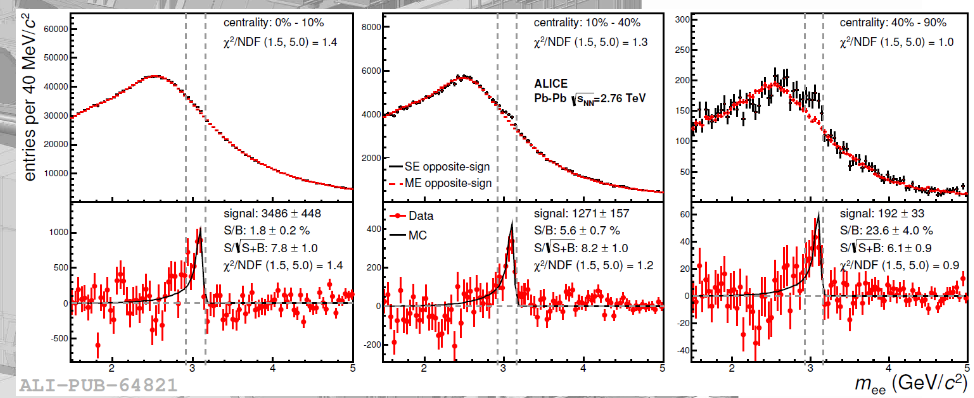


Inner Tracking System (**ITS**):
High resolution tracking
Time Projection Chamber (**TPC**):
Tracking and particle identification

PLB734 (2014) 314

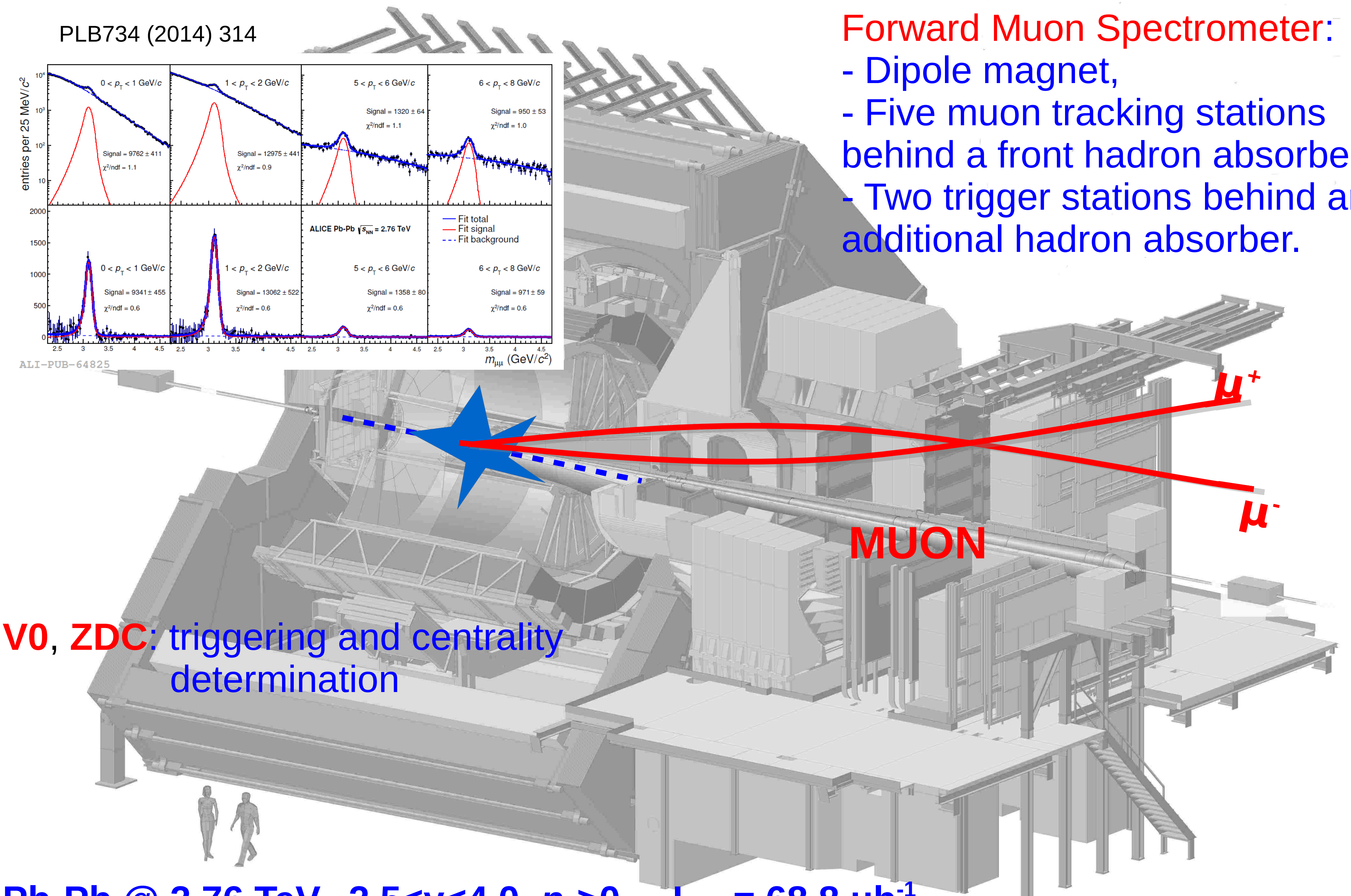


V0, **ZDC**: triggering and centrality determination

Pb-Pb @ 2.76 TeV, $|y|<0.9$, $p_T>0$, L_{int} = 28 μb^{-1}

The ALICE setup

PLB734 (2014) 314

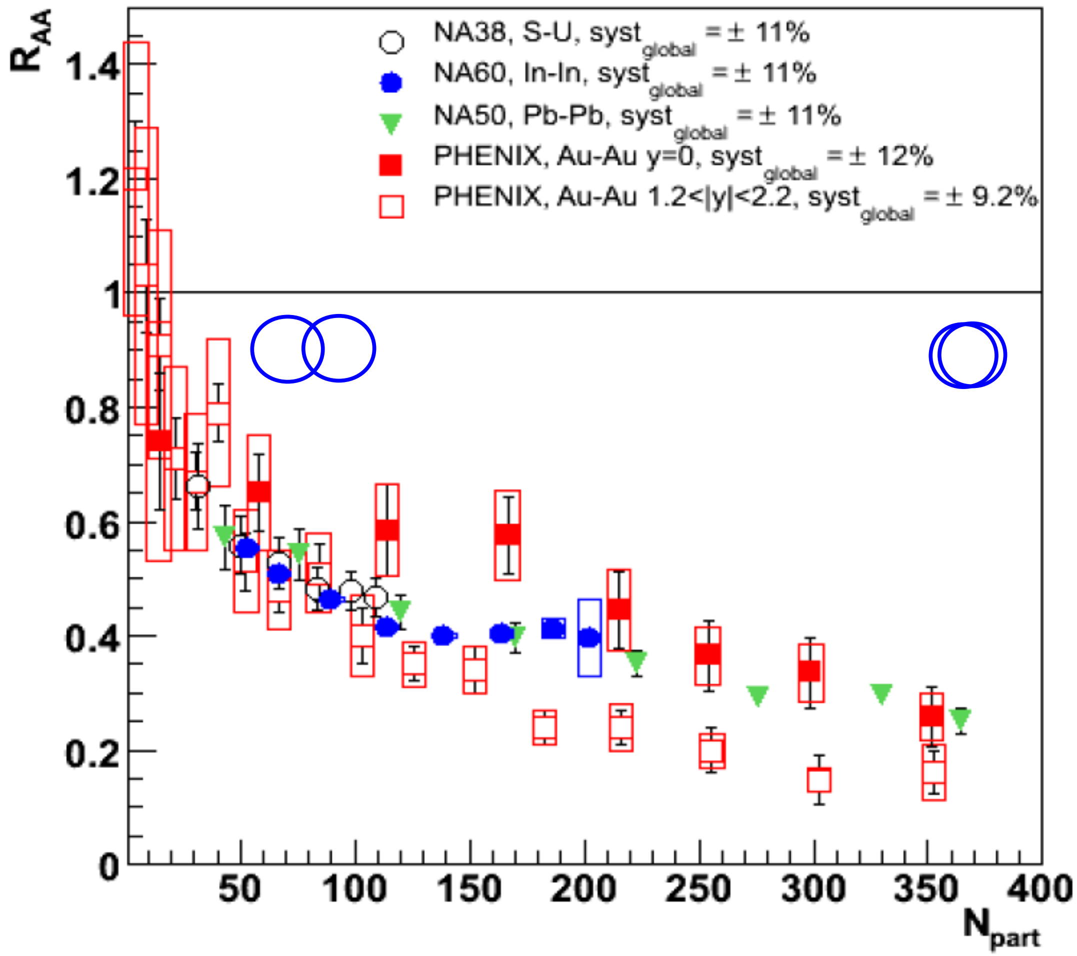


Forward Muon Spectrometer:
- Dipole magnet,
- Five muon tracking stations behind a front hadron absorber,
- Two trigger stations behind an additional hadron absorber.

V0, **ZDC**: triggering and centrality determination

Pb-Pb @ 2.76 TeV, 2.5<y<4.0, p_T>0, L_{int} = 68.8 μb^{-1}

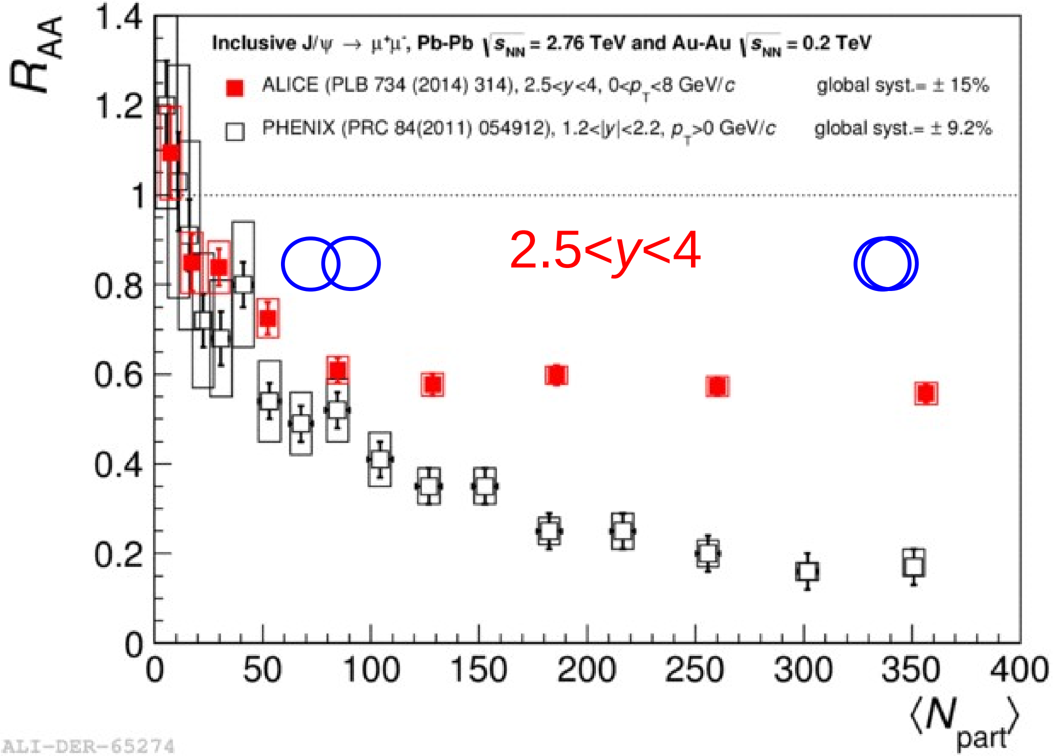
J/ψ at lower energy experiments

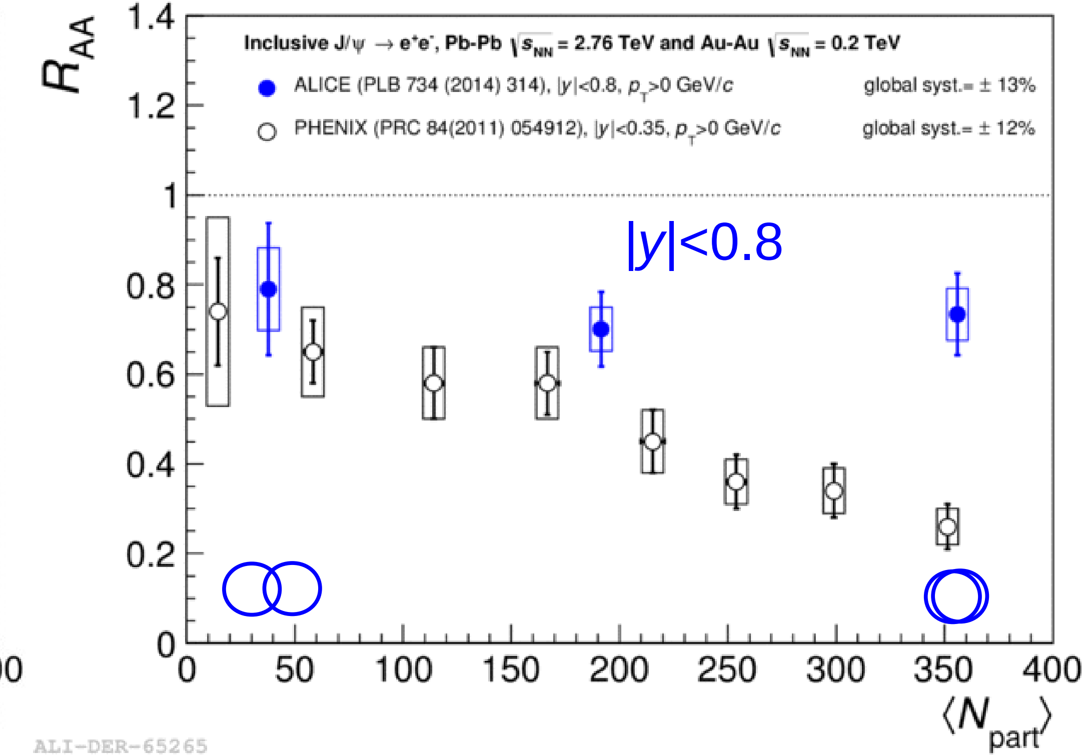


- J/ψ is strongly suppressed in central collisions at both SPS and RHIC energies, but:
  - Similar R_{AA} pattern despite very different collision energies
  - At RHIC, $R_{AA}(y=0) > R_{AA}(1.2<|y|<2.2)$

Inclusive J/ψ at RHIC and LHC

Parralel talk by Arianna Camejo, thursday
Parralel talk by Steffen Weber, thursday

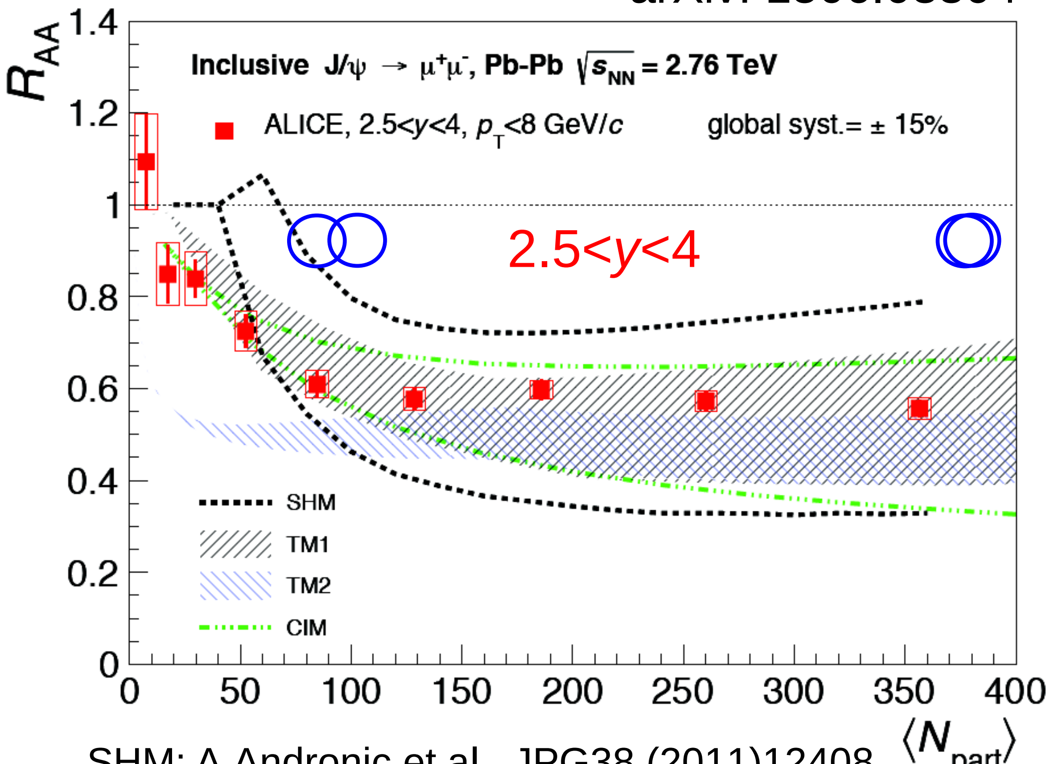


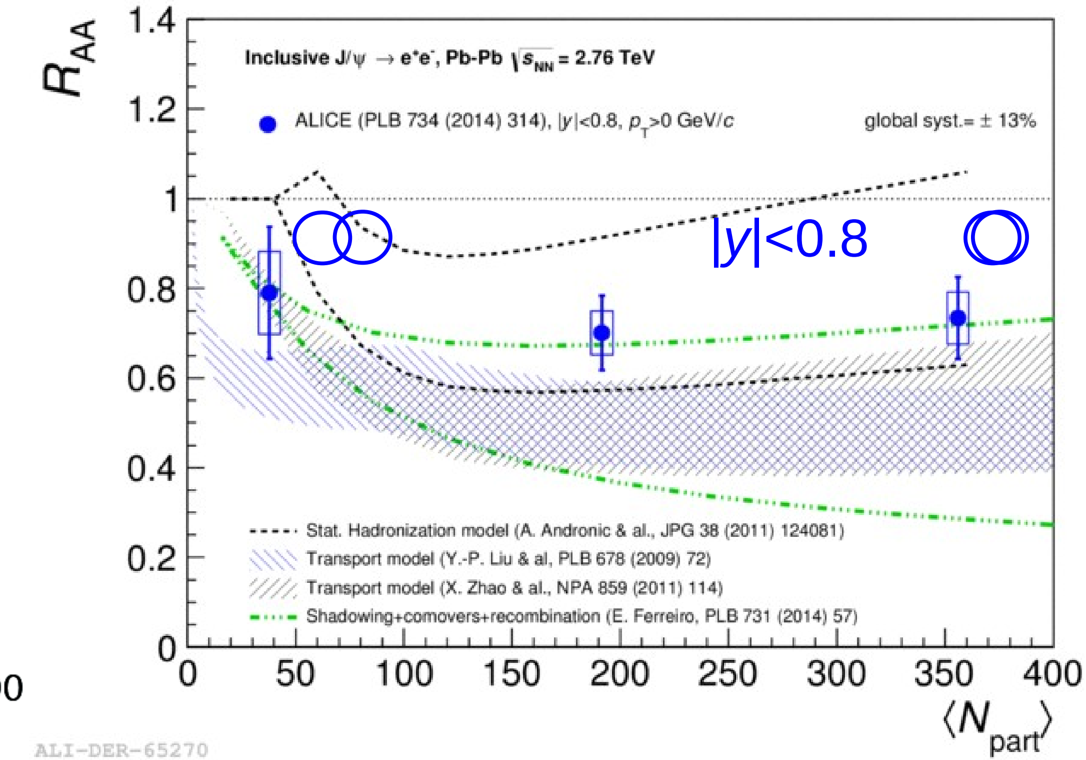


- Much less suppression compared to lower energy (PHENIX) in central collisions
- Hint of less suppression at mid- than at forward rapidity

Inclusive J/ψ at the LHC

arXiv: 1506.08804



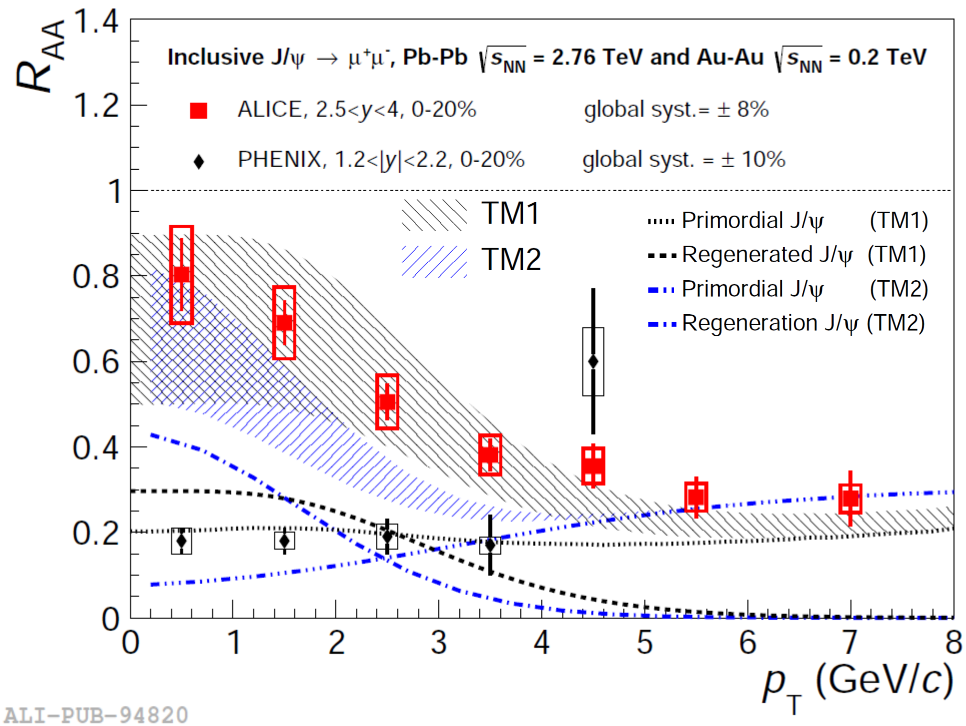


SHM: A.Andronic et al., JPG38 (2011)12408
TM1: X.Zhao et al.,NPA859 (2011) 114
TM2: Y.-P.Liu et al., PLB578 (2009) 72
CIM: E.Ferreiro, PLB731 (2014) 57

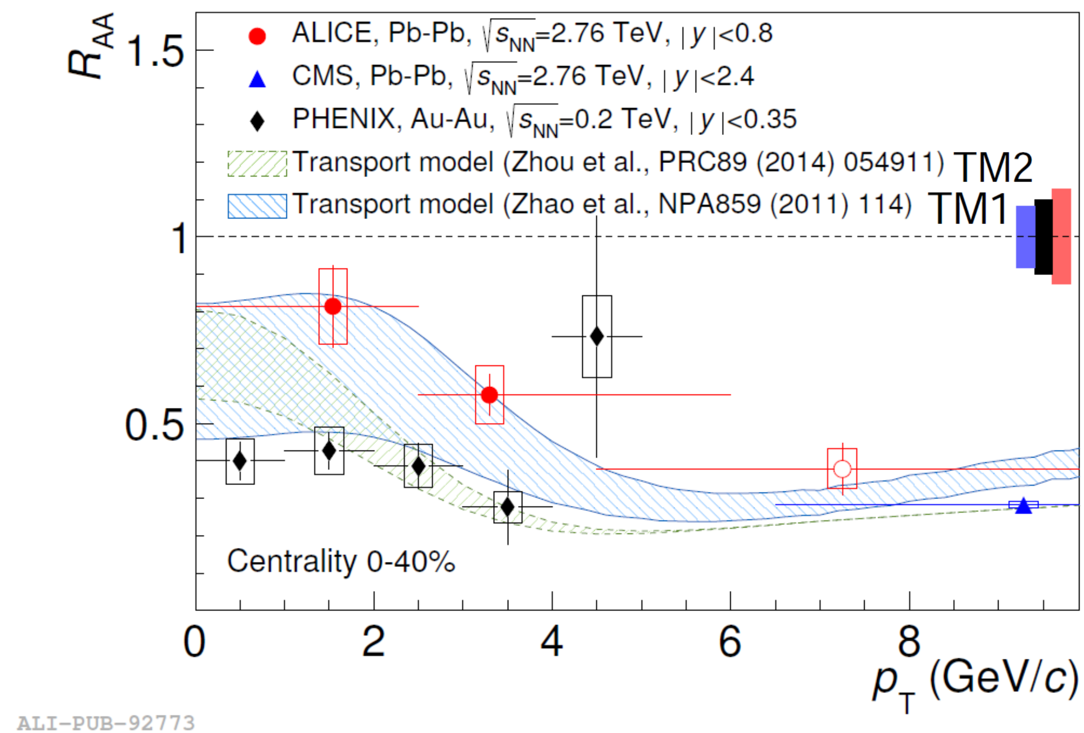
- Models which include (re)combination agree with the data.
- Model uncertainties are dominated by the poor knowledge of the total $c\bar{c}$ cross-section / CNM effects

Inclusive J/ψ as a function of p_T

arXiv: 1506.08804

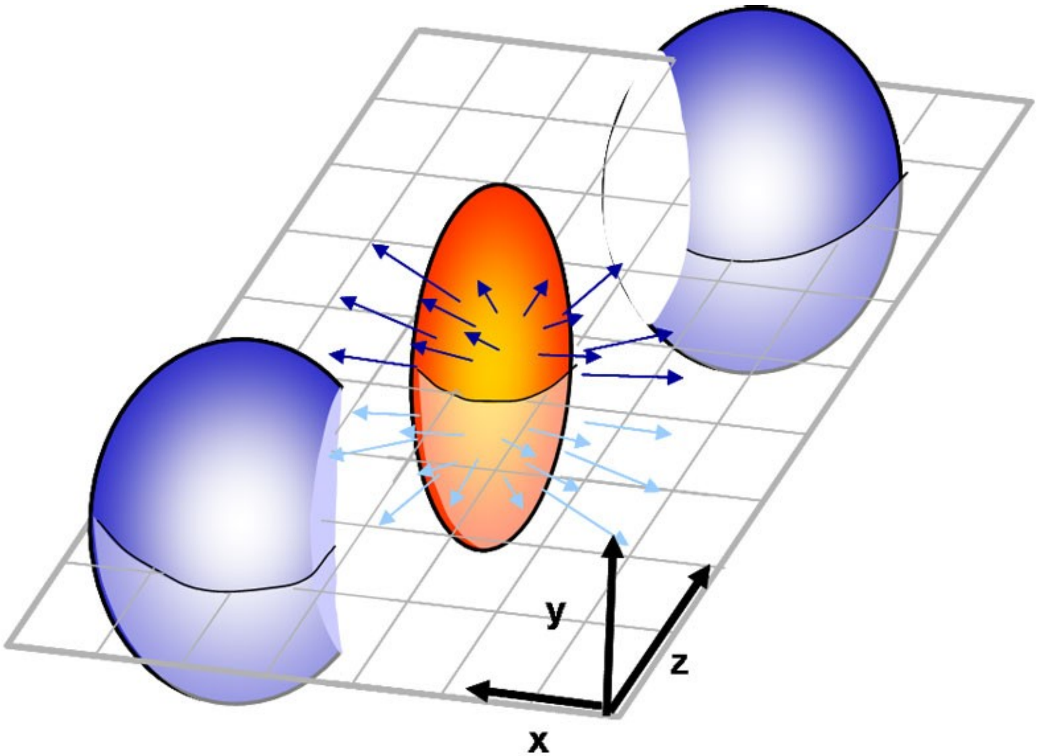


arXiv: 1504.07151

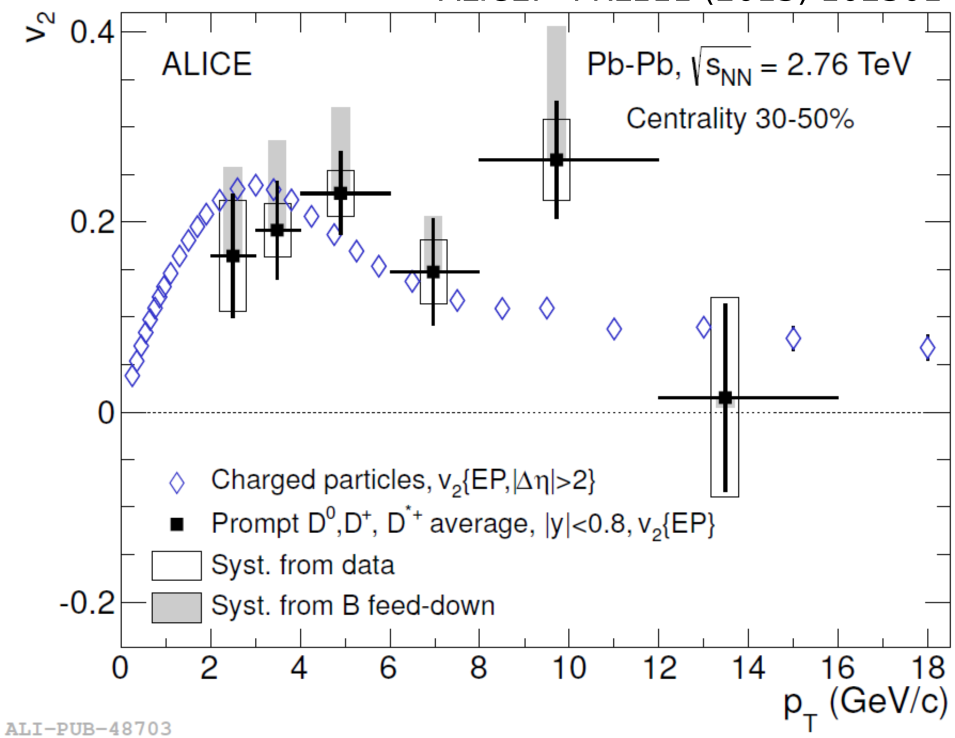


- Striking difference between LHC and RHIC at low p_T
- A strong enhancement at low p_T w.r.t. lower energies is described by transport models in terms of J/ψ regeneration

Elliptic flow



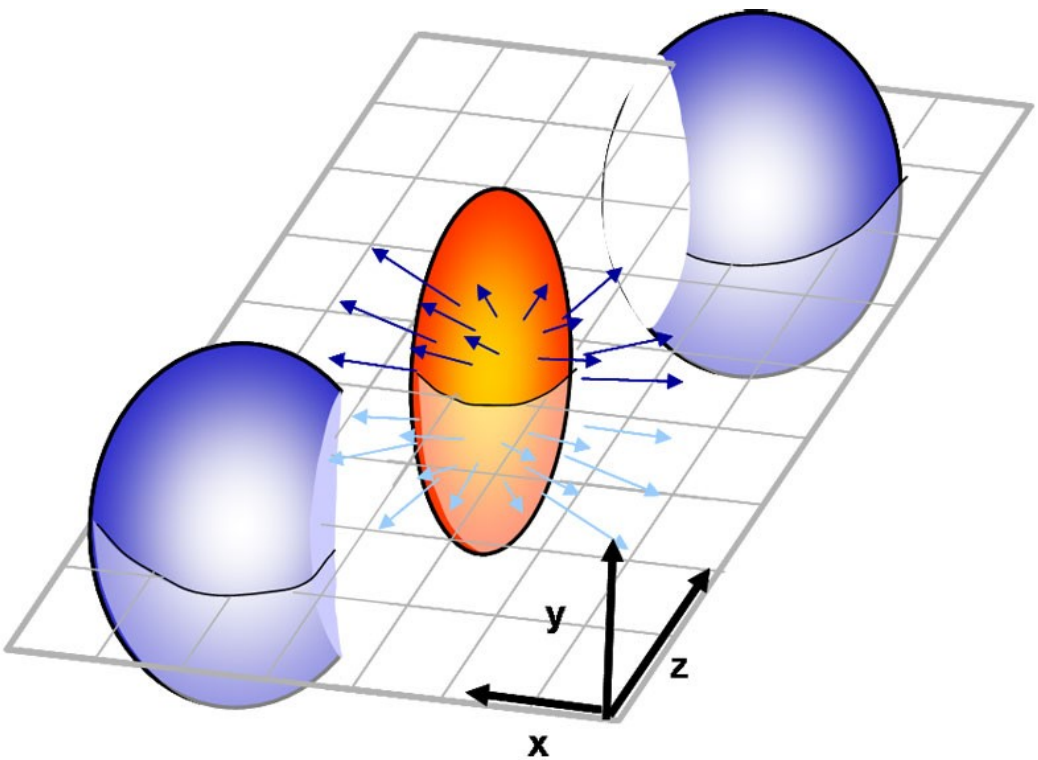
ALICE: PRL111 (2013) 102301



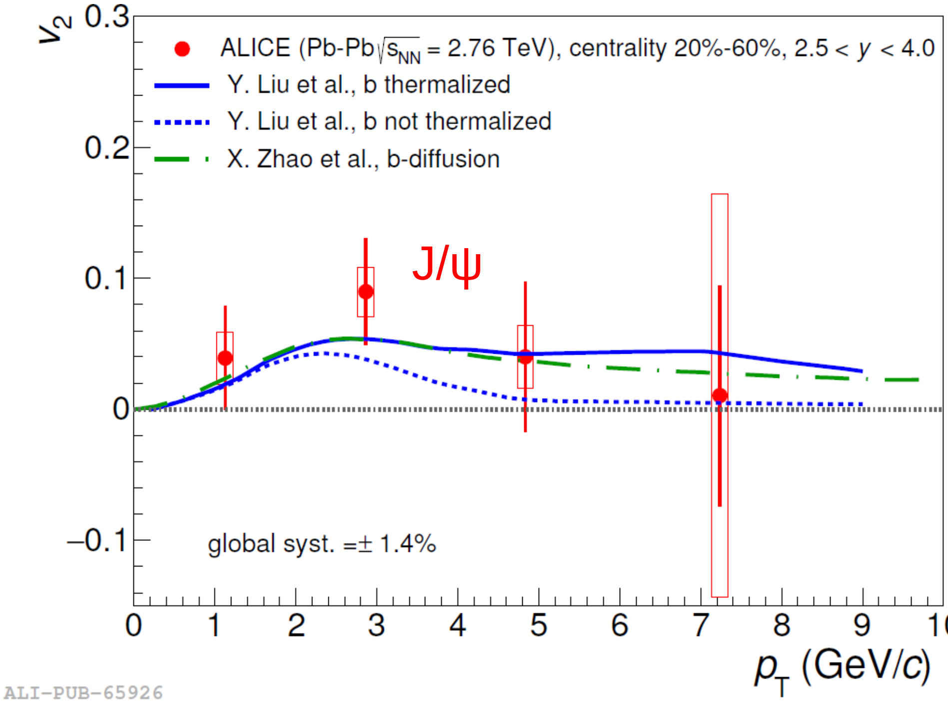
$$\frac{dN}{d\phi} \simeq 1+2v_1\cos(\phi-\Psi_r)+2v_2\cos(2(\phi-\Psi_r))+\ldots$$

- Strong elliptic flow observed for light particles and D mesons
- Is J/ψ inheriting any of the fireball collective flow ?

J/ψ elliptic flow



ALICE: PRL111 (2013) 162301

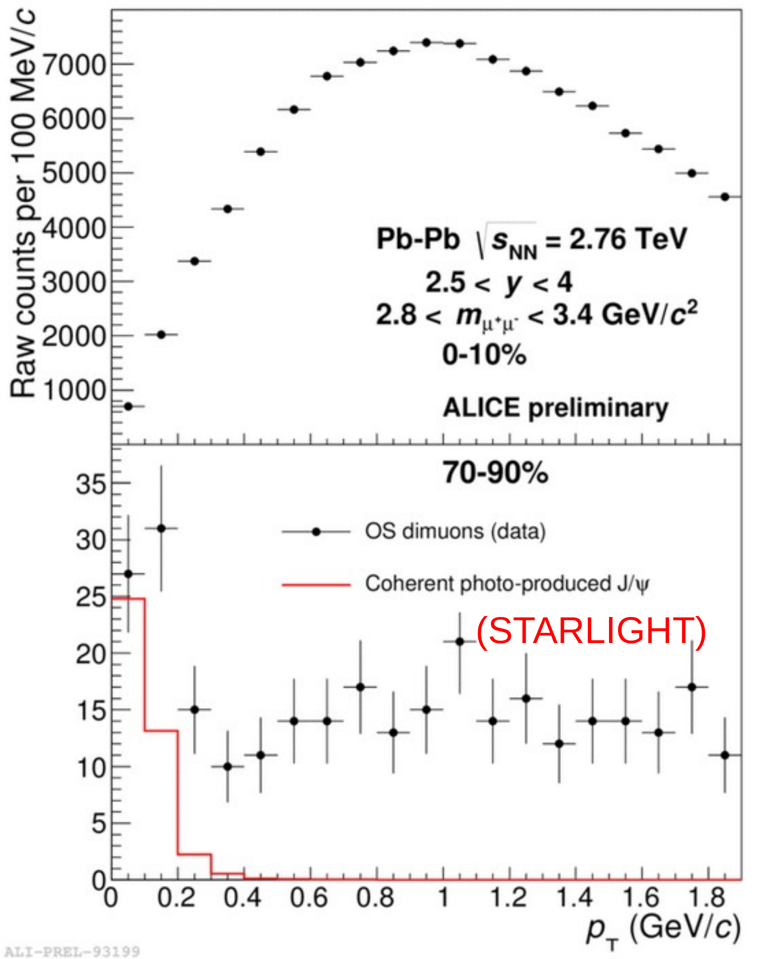


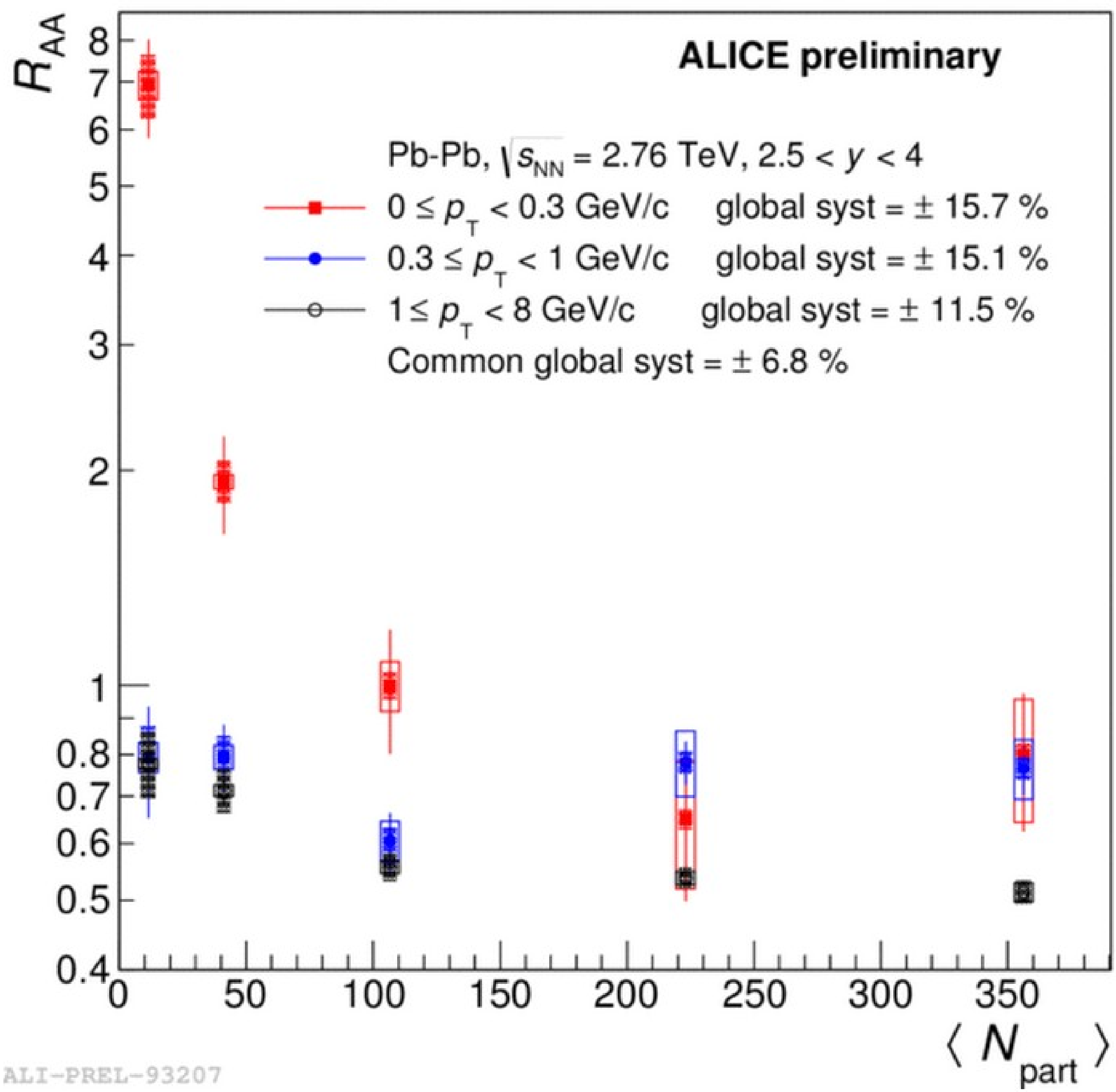
$$\frac{dN}{d\phi} \simeq 1 + 2v_1 \cos(\phi - \Psi_r) + 2v_2 \cos(2(\phi - \Psi_r)) + \ldots$$

- The intermediate-p_T J/ψ hints towards a non-zero v_2 in semi-central collisions
- Key measurement for the next run and ALICE upgrade

Plenary talk by Andrea Dainese, saturday

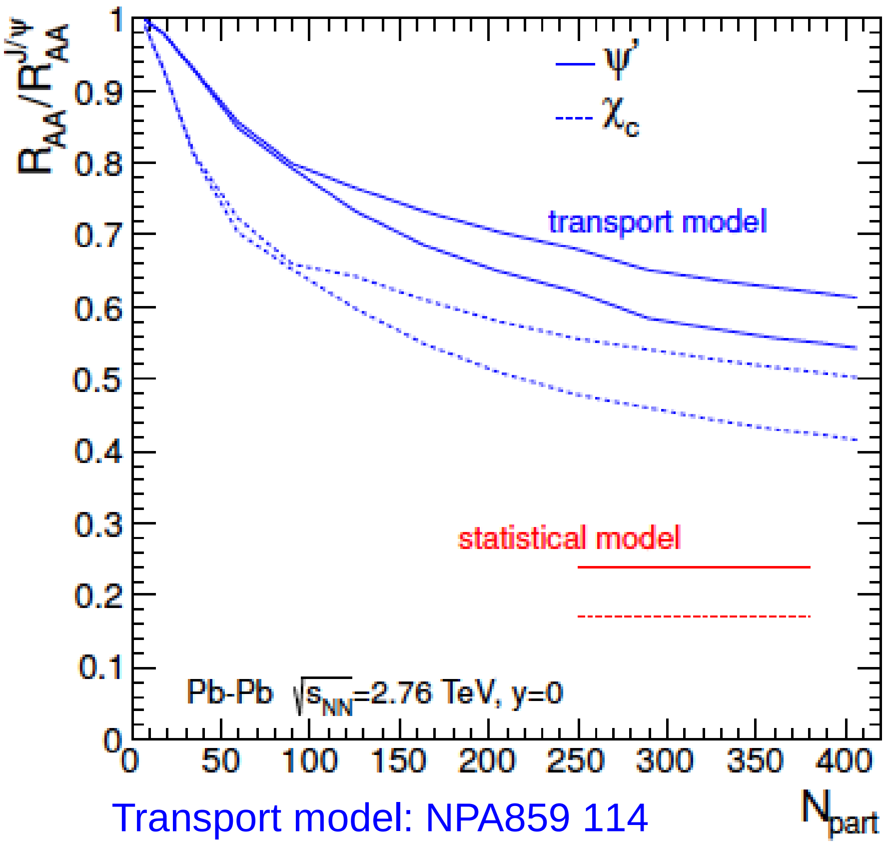
Digression: "very" low-p_T J/ψ R_{AA}





- J/ψ p_T spectrum at low p_T similar to the one from photo-production in $b>2R$ collisions
- J/ψ R_{AA} for p_T<300 MeV/c ~ 7 for the most peripheral collisions !!!

ψ(2S) production in Pb-Pb collisions at the LHC

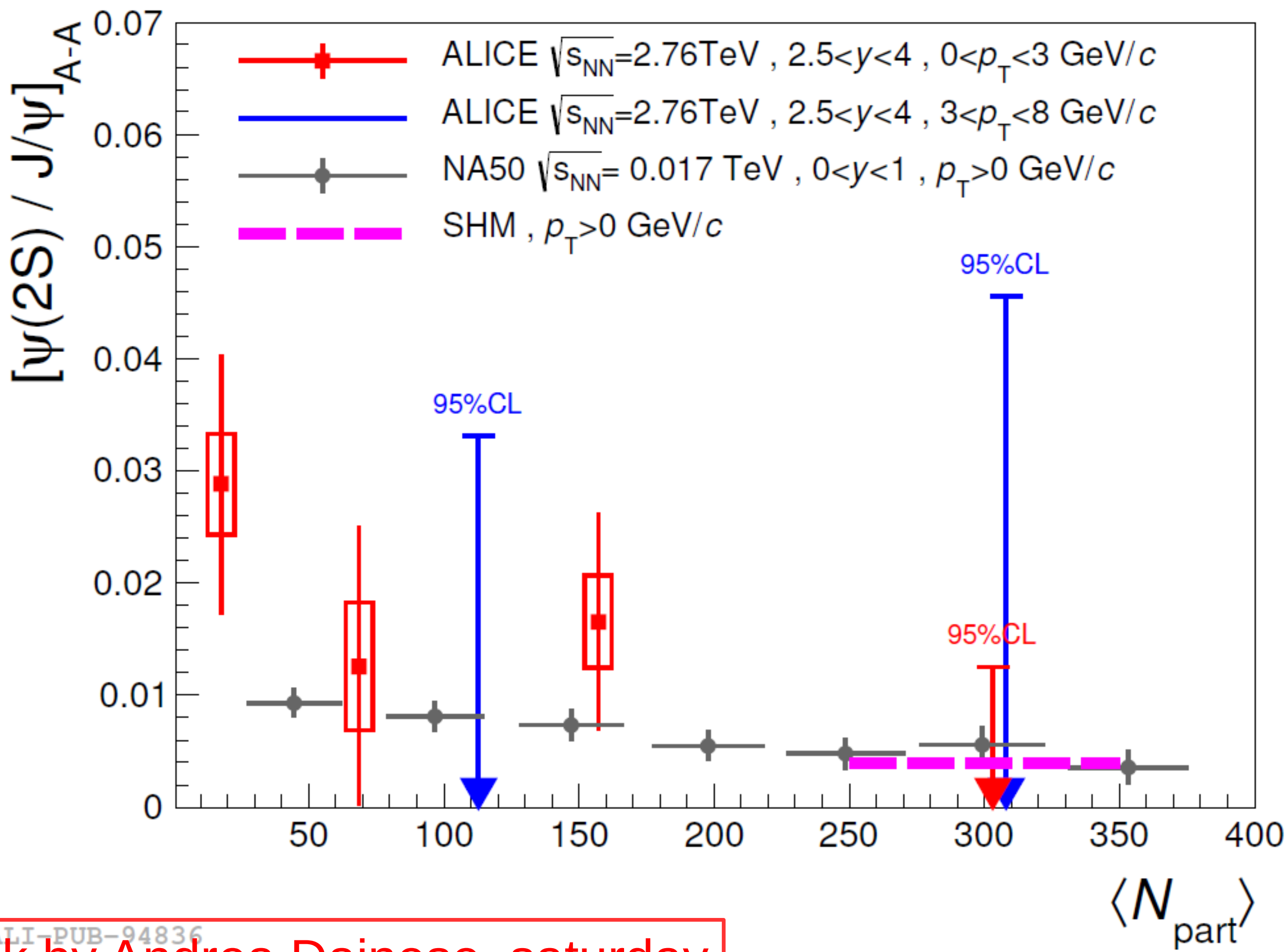


Transport model: NPA859 114
Statistical model: PLB490 196

- ψ(2S) is much less bound than J/ψ
- Ratio of R_{AA} for different charmonia is less dependent on the charm cross-section
- Transport and statistical hadronization models can be disentangled !

ψ(2S) production in Pb-Pb collisions at the LHC

arXiv: 1506.08804



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- No strong conclusion can be drawn with the present data
- Both SHM and transport models are consistent with the present results
- Key measurement for the ALICE upgrade

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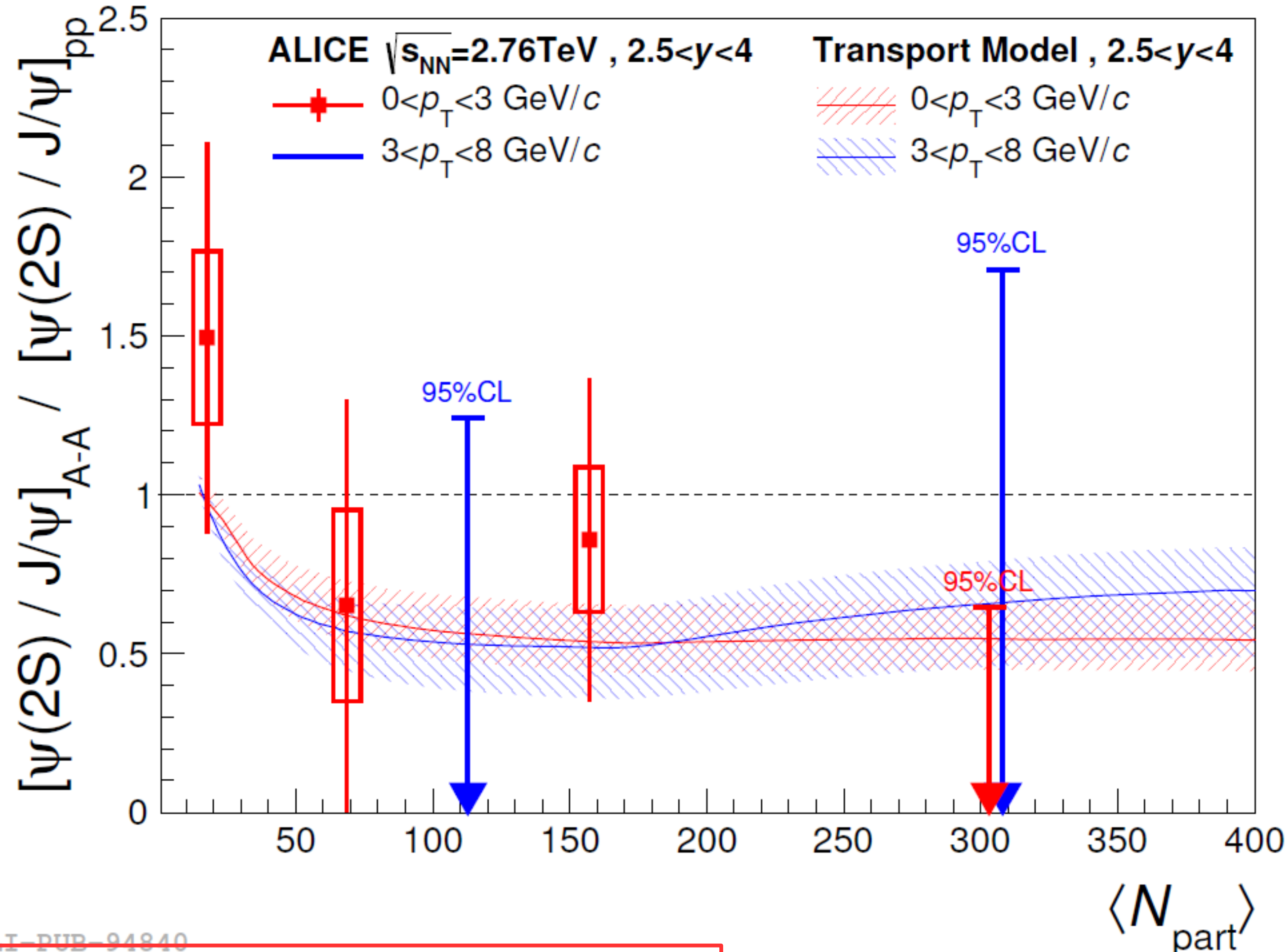

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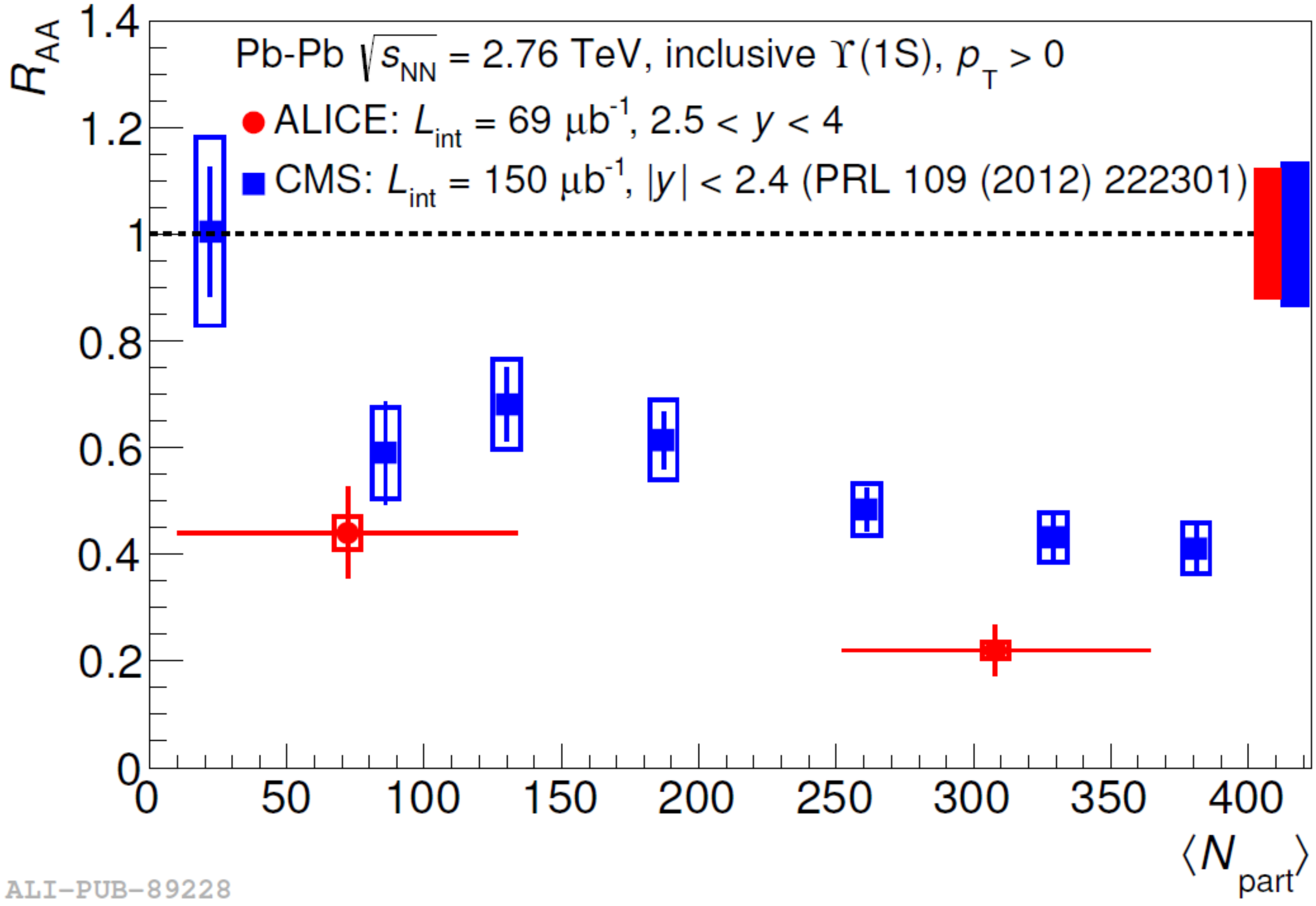
Y(1S) production vs centrality at the LHC

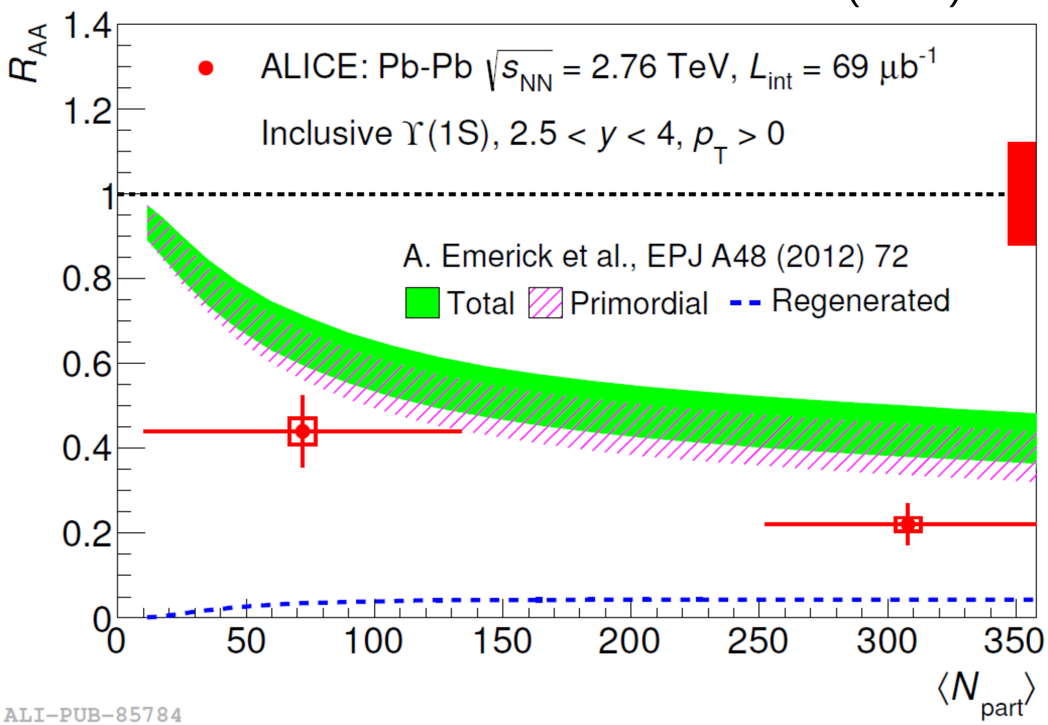
ALICE: PLB 738 (2014) 361
CMS: PRL 109 (2012) 222301

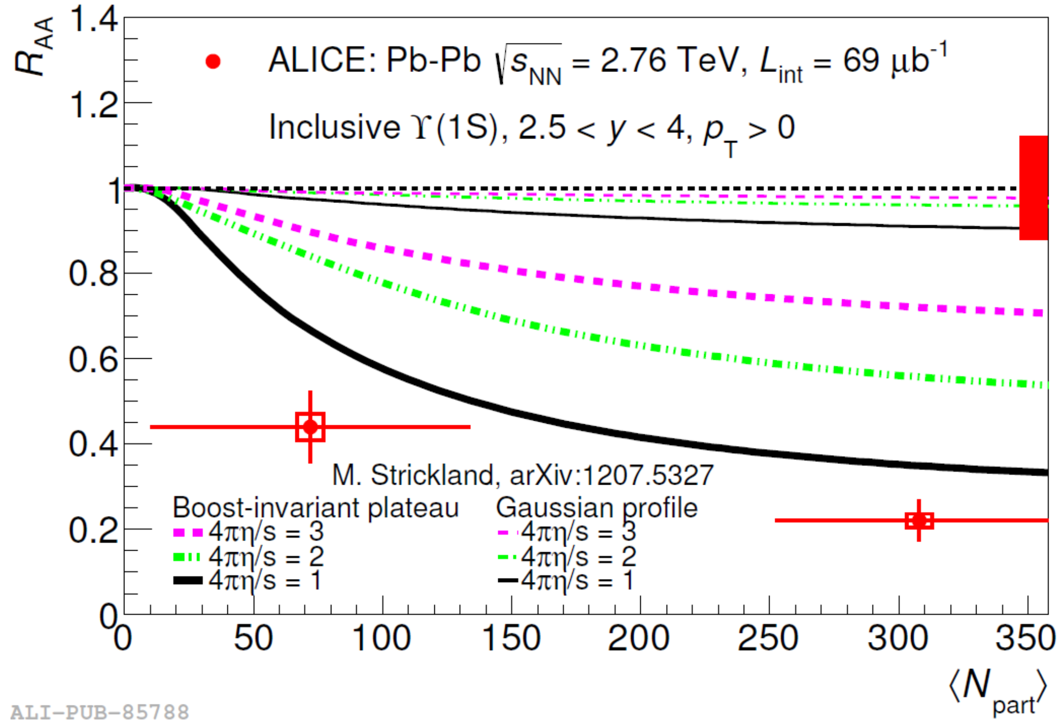


➔ Strong suppression observed for Y(1S) in central collisions

Υ(1S) production vs centrality at the LHC

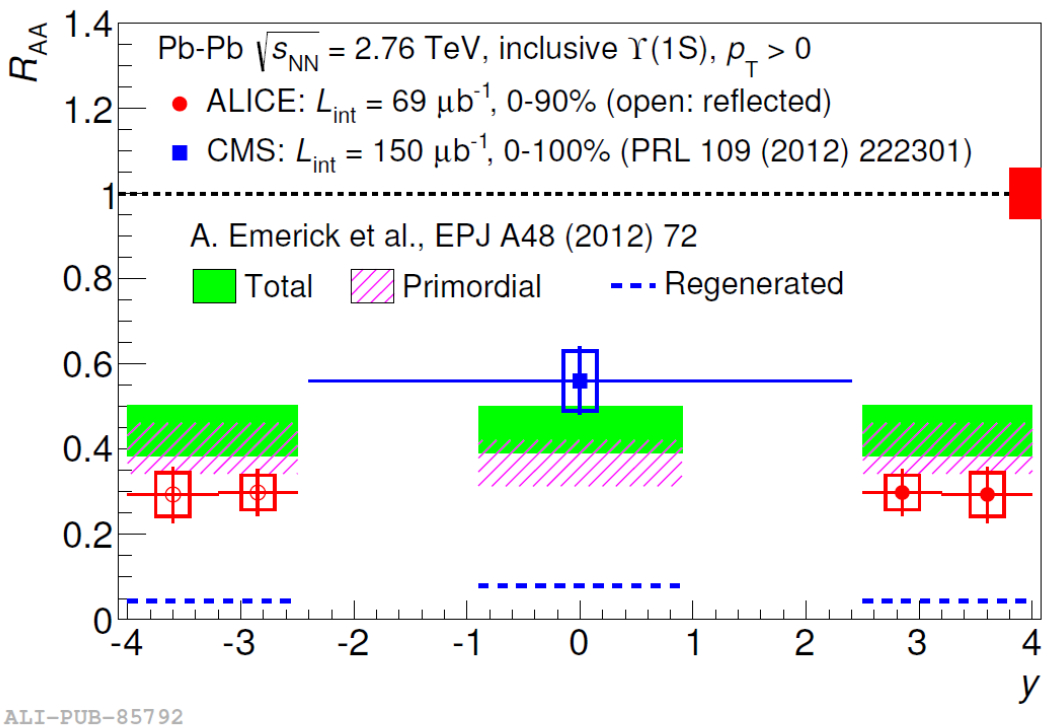
PLB 738 (2014) 361

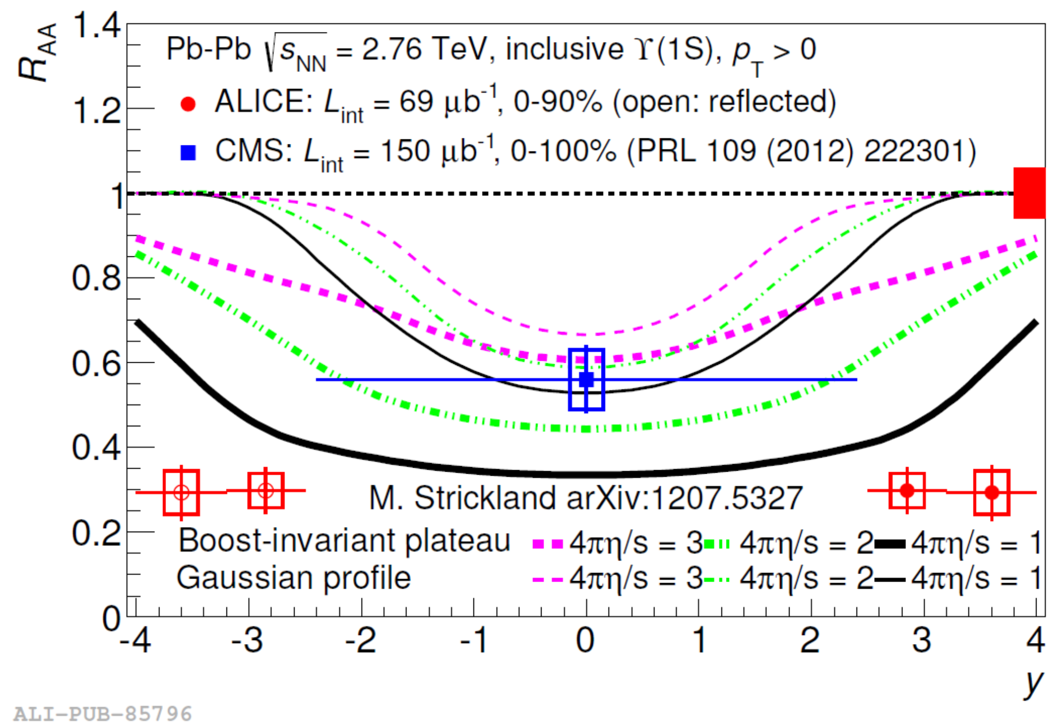




- Strong suppression observed for Υ(1S) in central collisions
- Very small contribution from recombination effects expected for bottomonia (Emerick et al.)
- Thermal suppression in a hydrodynamical model with shear viscosity (Strickland et al.) requires the lowest *η/s* to fit the data

Υ(1S) production vs rapidity at the LHC





ALICE: PLB 738 (2014) 361
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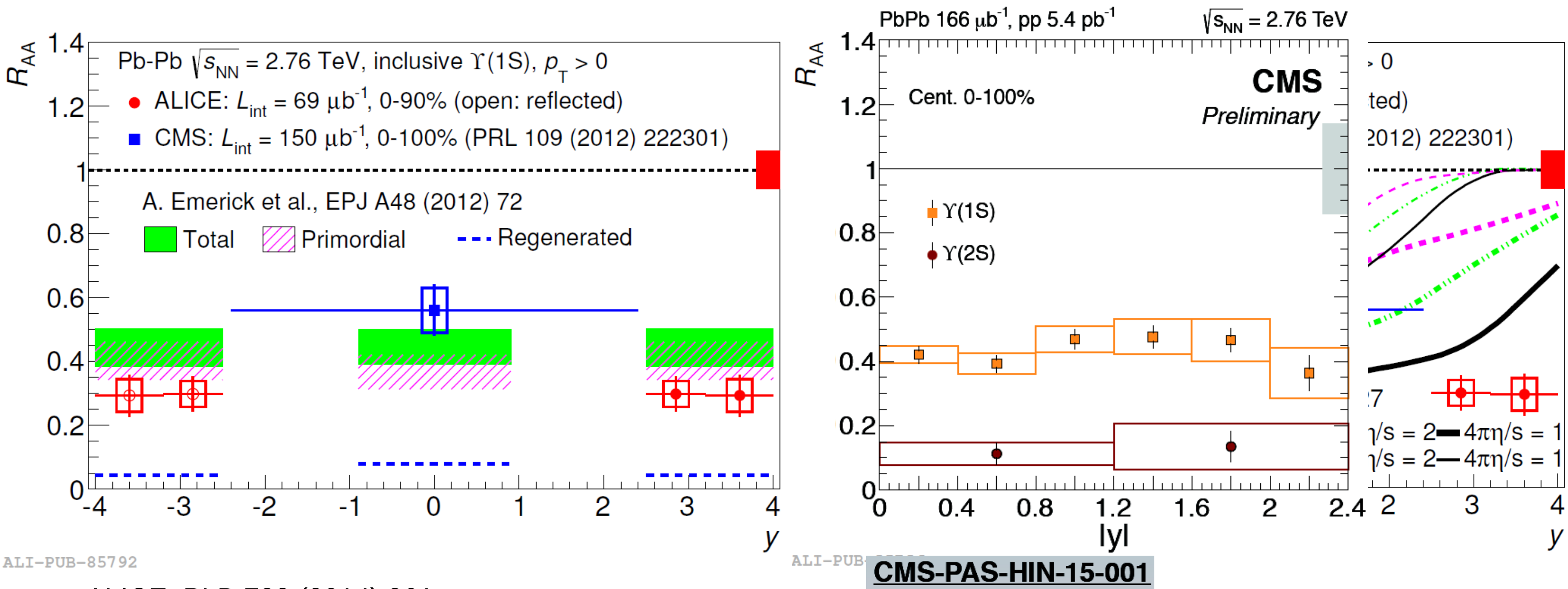
- Comparisons to early CMS mid-rapidity results suggest a rapidity dependence of the Υ(1S) suppression
- The hydrodynamical model underestimates the Υ(1S) suppression at forward rapidity

Y(1S) production vs rapidity at the LHC



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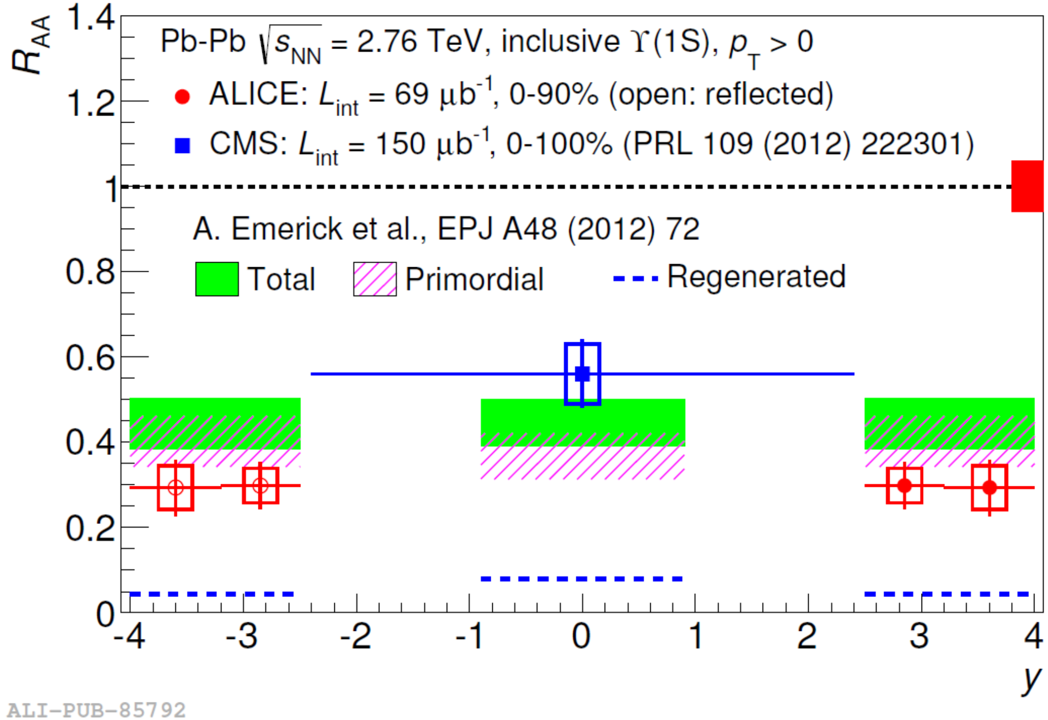
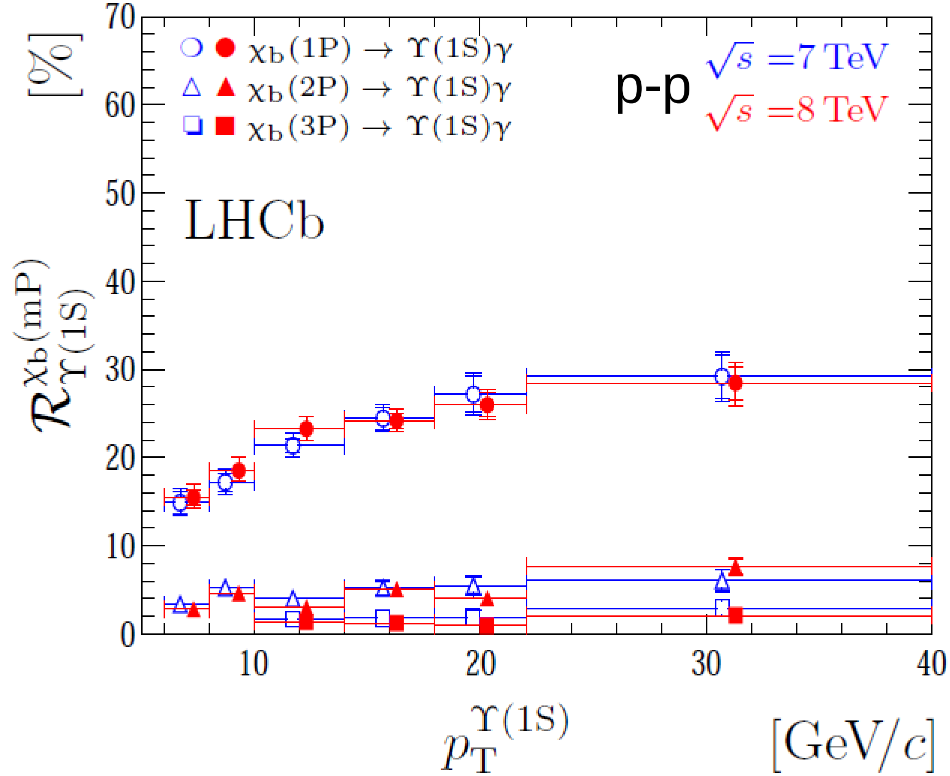
CMS: PRL 109 (2012) 222301

- Comparisons to early CMS mid-rapidity results suggest a rapidity dependence of the Y(1S) suppression
- The hydrodynamical model underestimates the Y(1S) suppression at forward rapidity
- The newest CMS results hint towards a smoother rapidity dependence

Y(1S) production vs rapidity at the LHC

arXiv: 1407.7734





ALICE: PLB 738 (2014) 361
CMS: PRL 109 (2012) 222301

- Is the direct Y(1S) suppressed?
- LHCb data in pp collisions suggest that feed-down corrections cannot compensate for the whole observed suppression
- Crucial for the sequential melting model

Pb-Pb summary

- Strong support for the (re)combination mechanism of charmonium production at low p_T in Pb-Pb collisions:
  - Integrated J/ψ R_{AA} in central collisions much higher w.r.t. RHIC results
  - The effect is concentrated at low p_T
  - Indications of non-zero elliptic flow at forward rapidity
- ψ(2S) results are inconclusive with the present data
- ϒ(1S) suppressed at forward rapidity, in agreement with transport model calculation
  - Is the direct ϒ(1S) suppressed?

p - Pb @ 5.02 TeV

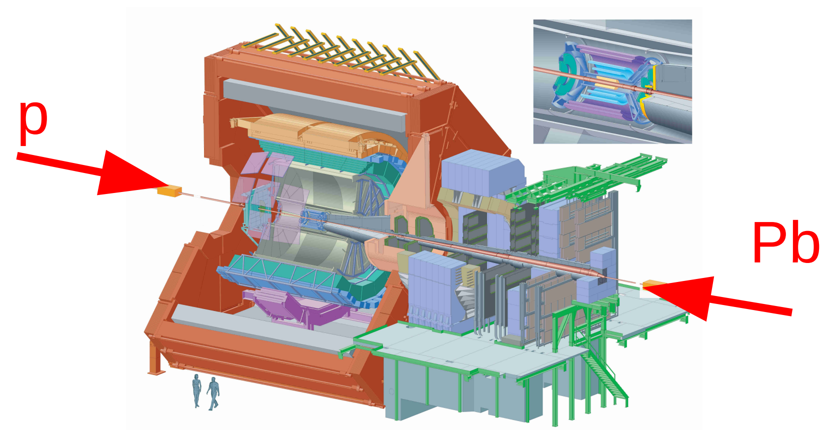
E_{Pb}=1.58 A TeV, E_p=4 TeV

The center-of-mass of the collision is shifted by Δy=0.465 towards the proton fragmention direction

p → ← Pb (p-going)

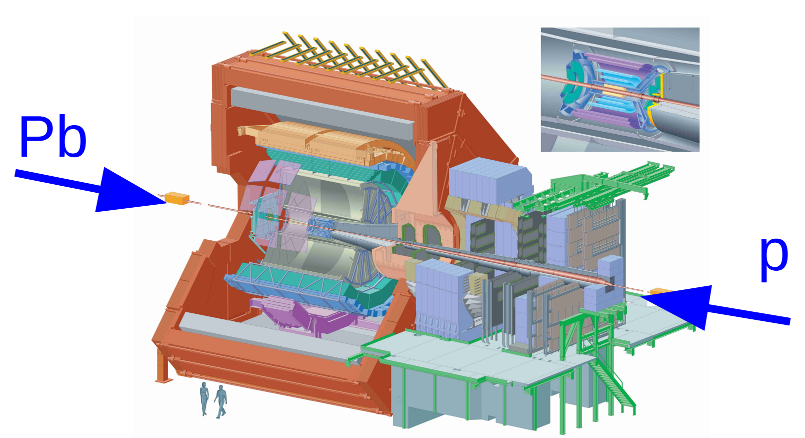
p-Pb, $-1.37<y<0.43$, L_{int} = 52 μb^{-1}

$2.03<y<3.53$, L_{int} = 5.0 nb^{-1}



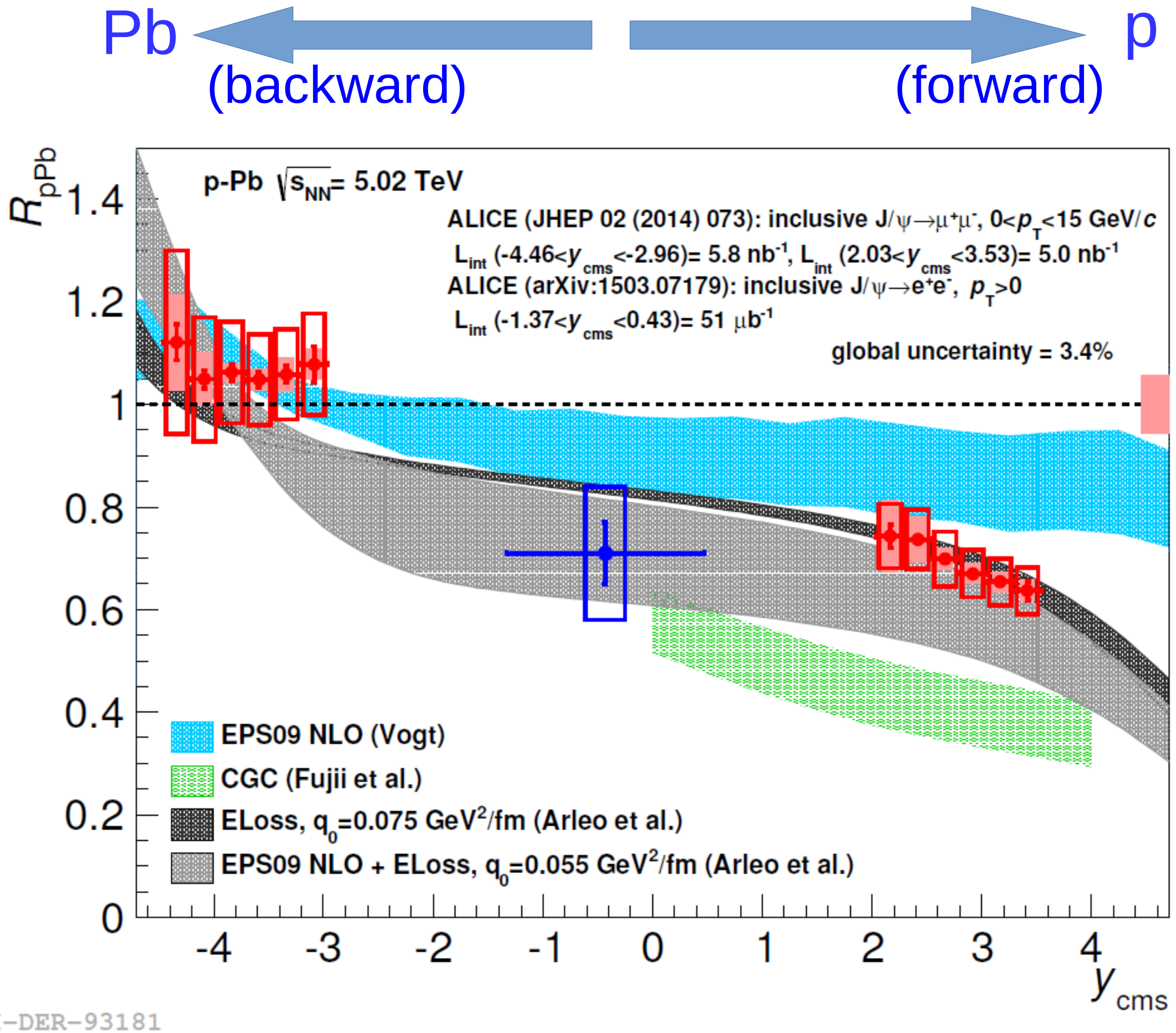
Pb → ← p (Pb-going)

Pb-p, $-4.46<y<-2.96$, L_{int} = 5.8 nb^{-1}



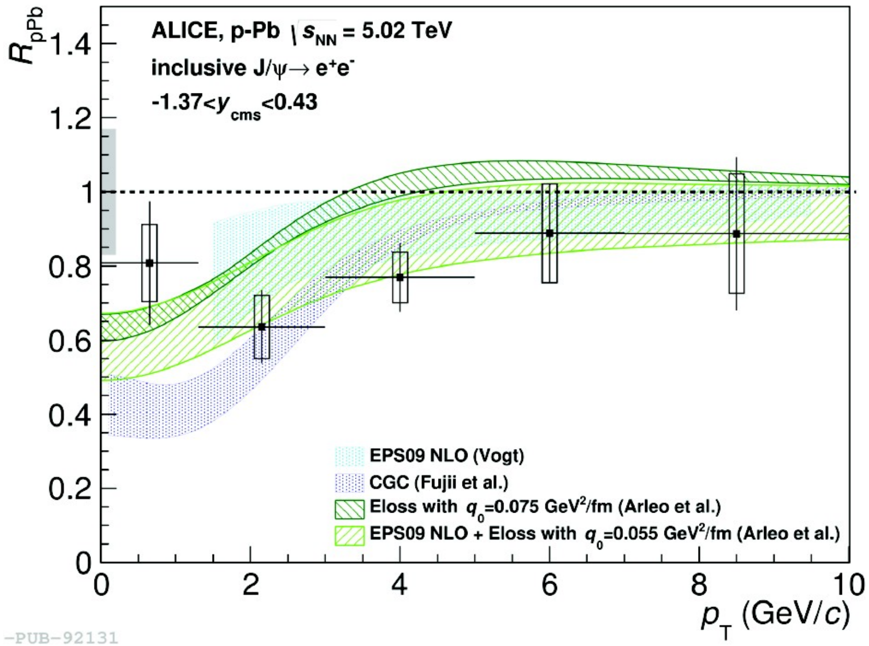
Inclusive J/ψ vs rapidity

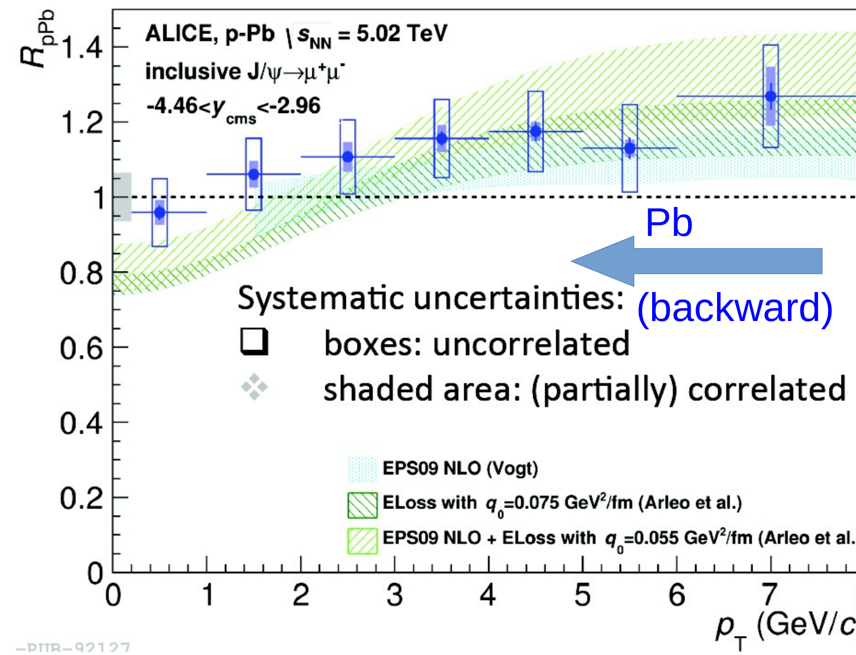
Parralel talk by Arianna Camejo, thursday
Parralel talk by Steffen Weber, thursday

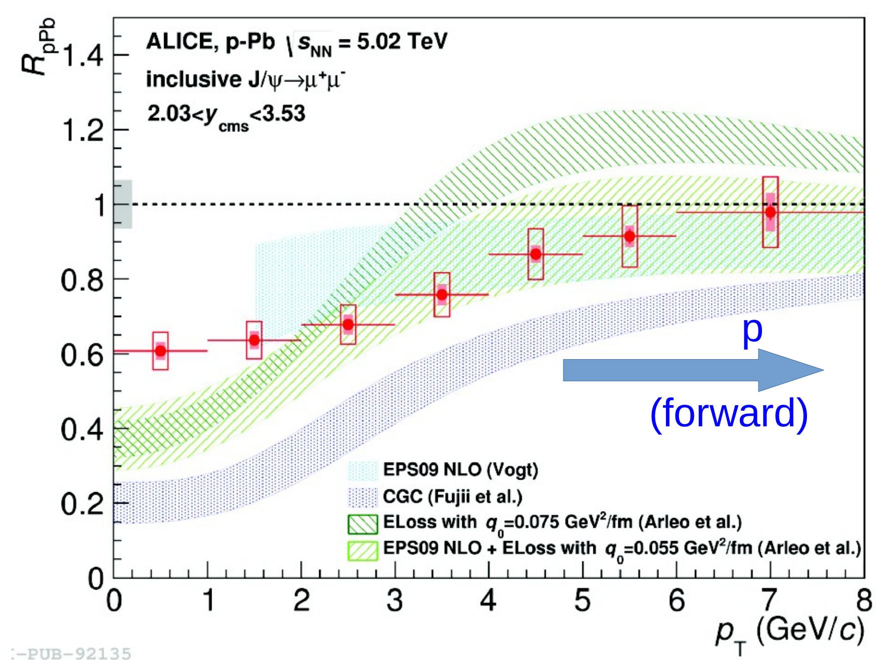


- J/ψ is suppressed at mid-rapidity and in the forward direction, compatible with energy loss (+shadowing) models
- No suppression observed in the backward direction

Inclusive J/ψ vs p_T

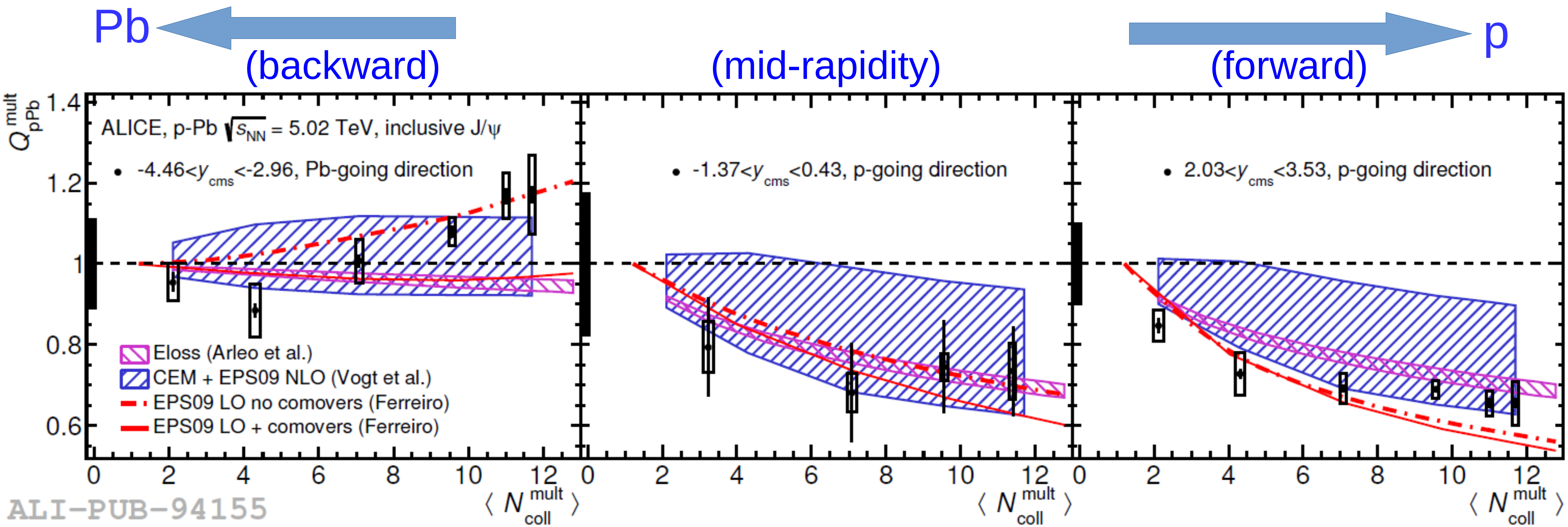






- J/ψ is suppressed at mid- and forward rapidity, except for the highest-p_T region
- R_{pPb} grows with p_T, consistent with expectations from shadowing and energy loss calculations
- Early CGC calculations overestimate the suppression at forward rapidity

Inclusive J/ψ vs event activity



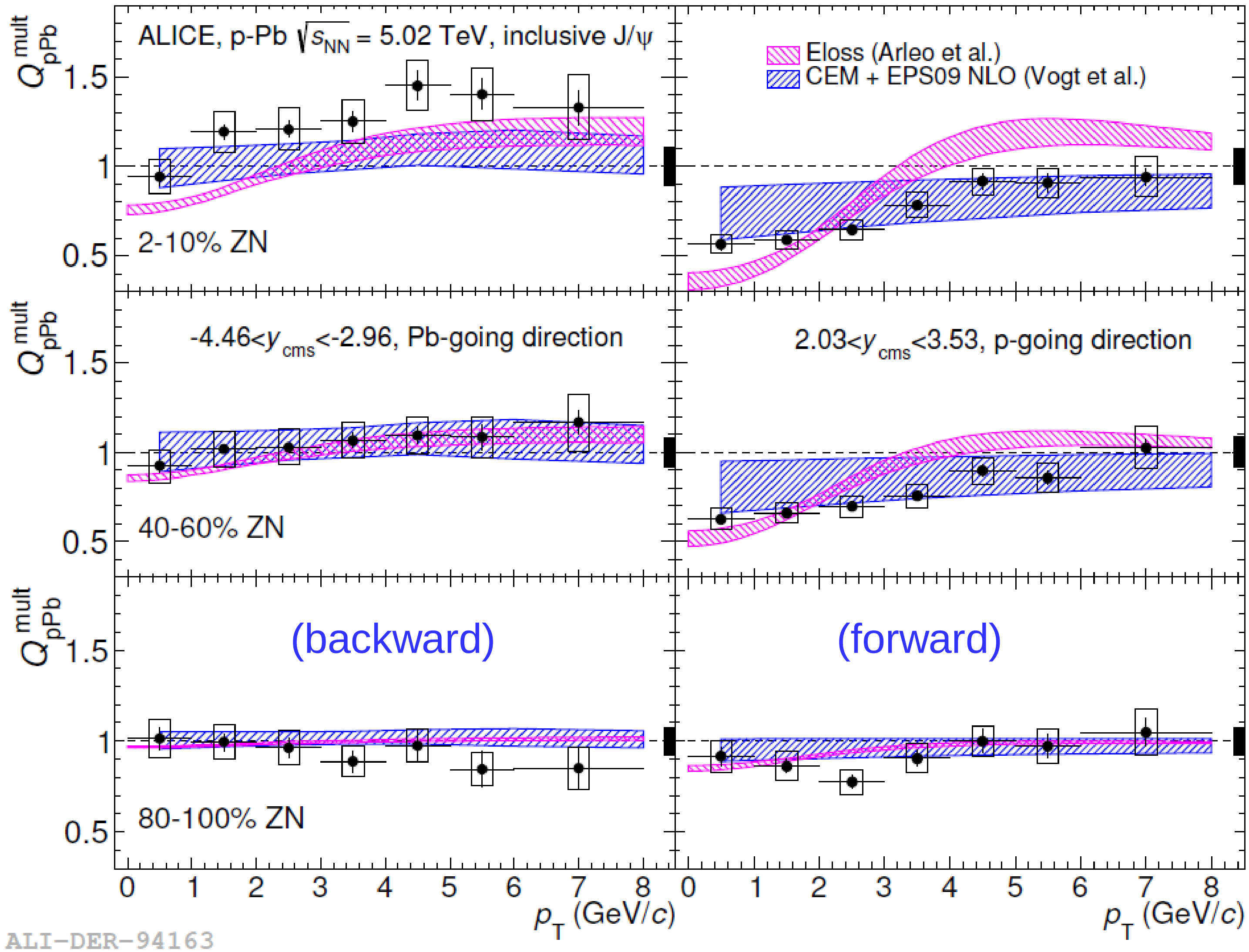
Talk by Alberica Toia, thursday
Talk by Arianna Camejo, thursday

arXiv:1506.08808

- At backward, Q_{pPb} grows with increasing centrality
- At mid- and forward-rapidity the J/ψ is suppressed, with a significant centrality dependence at forward
- At backward rapidity, the comover and energy loss calculations seem to be disfavoured by the data
- At mid- and forward rapidity, models provide a fair description of the data

Inclusive J/ψ vs event activity and p_T

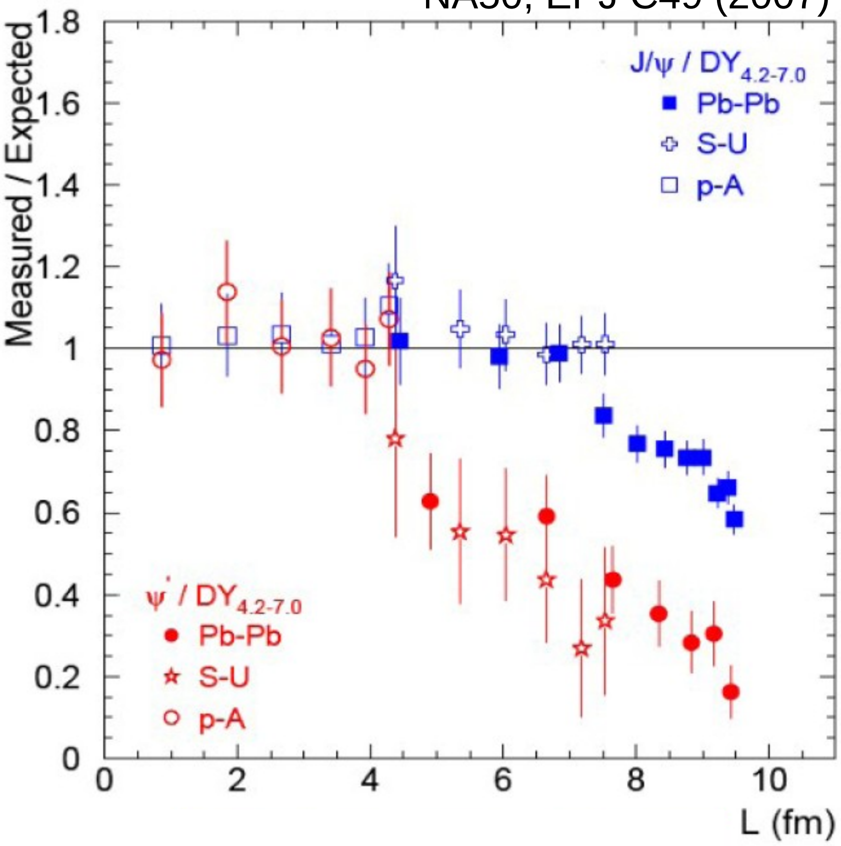
arXiv:1506.08808



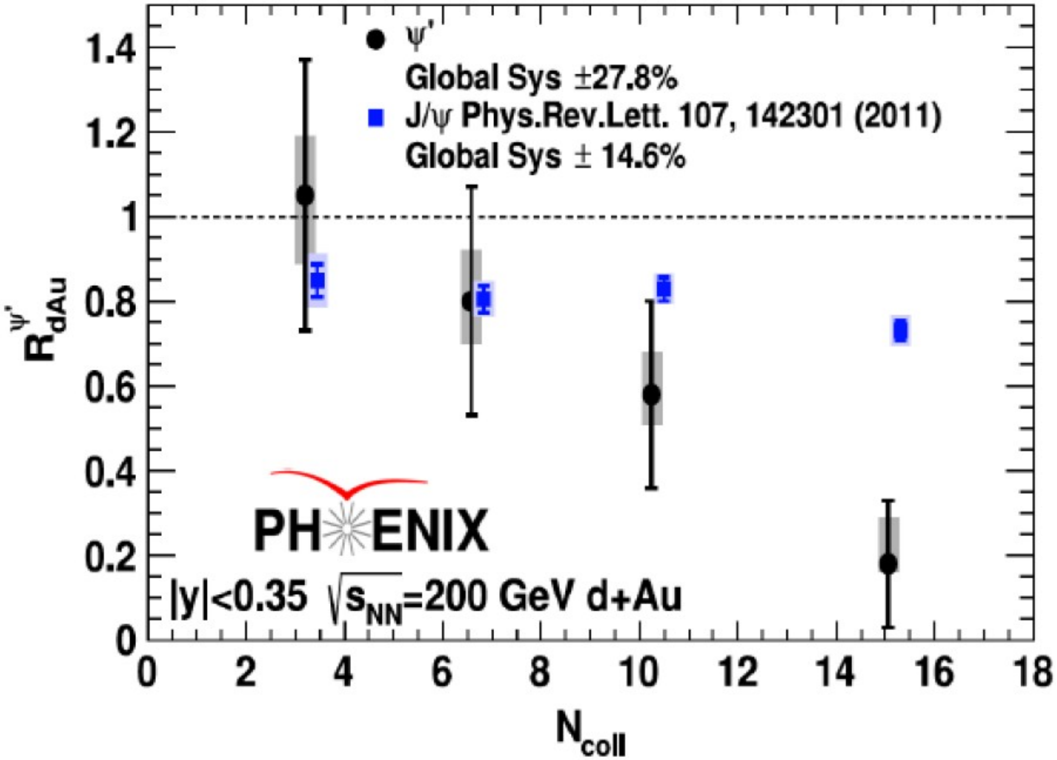
- Strongest nuclear effects observed at low p_T and large event activity
- No nuclear effects observed for the events with the smallest event activity

ψ(2S) at SPS and RHIC

NA50, EPJ C49 (2007)



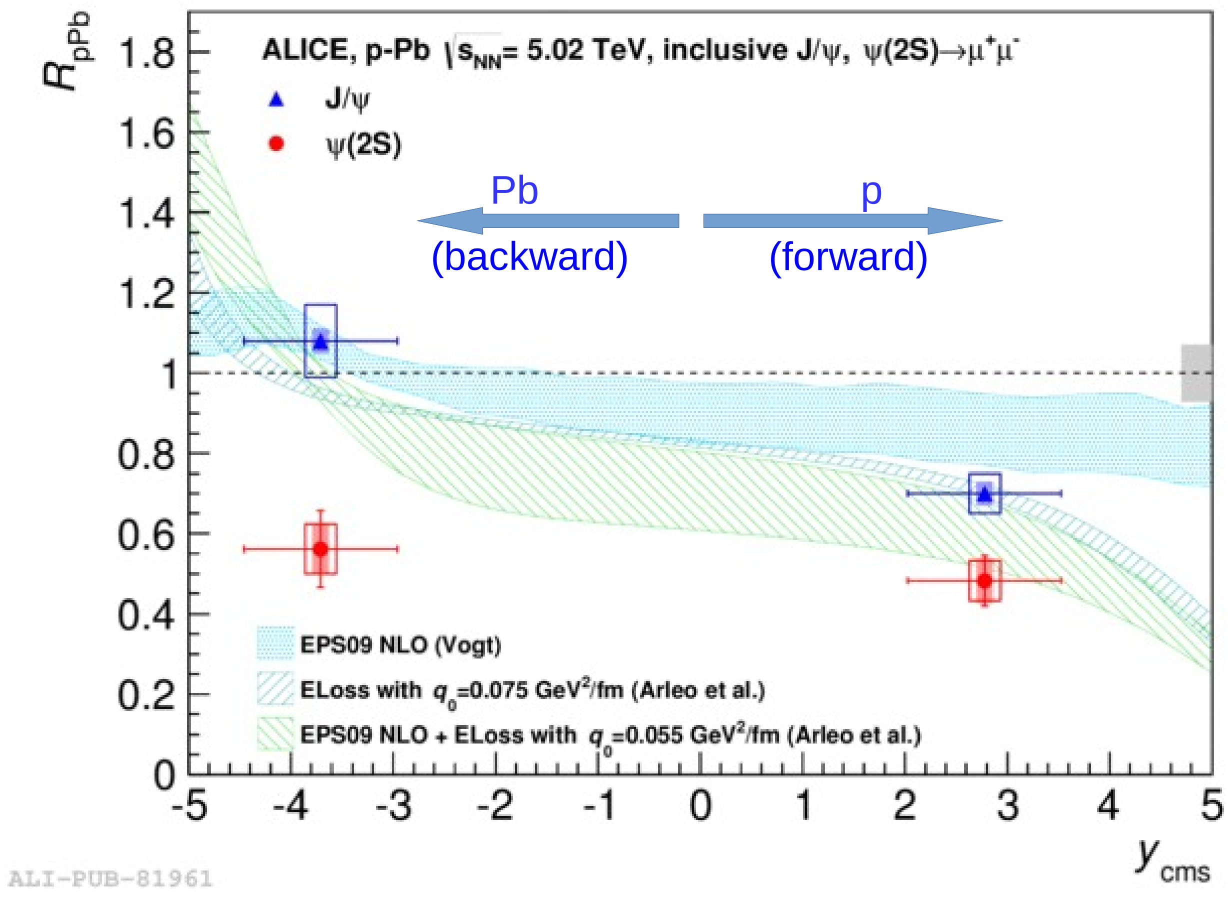
PRL 111 (2013) 202301



- At SPS, no ψ' suppression w.r.t. CNM expectations in p-A collisions
  - Final state interactions of the formed resonance in the cold nuclear medium
- Puzzle? ψ' suppressed more than J/ψ in d-Au at RHIC
  - No significant differences between J/ψ and ψ' expected at RHIC and LHC from shadowing or formation time effects

ψ(2S) vs rapidity at the LHC

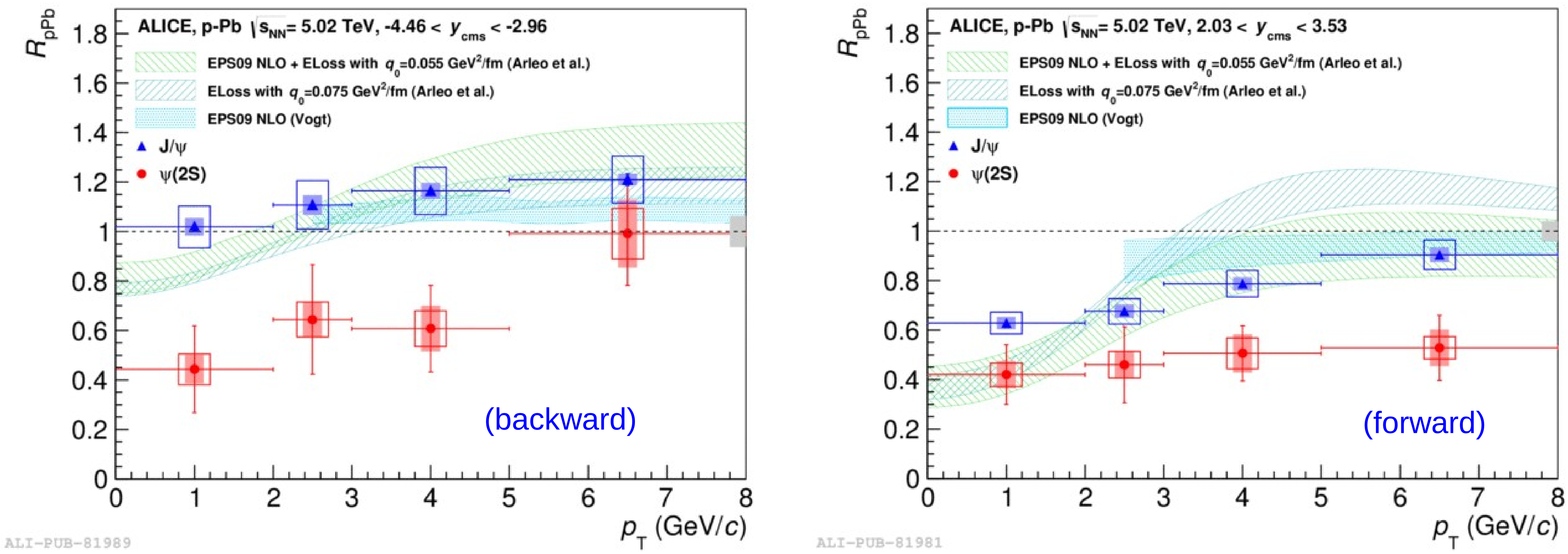
arXiv:1405.3796



- Strong ψ' suppression observed in p-Pb at both forward and backward rapidities
- Not expected from either shadowing or energy loss models

ψ(2S) vs p_T at the LHC

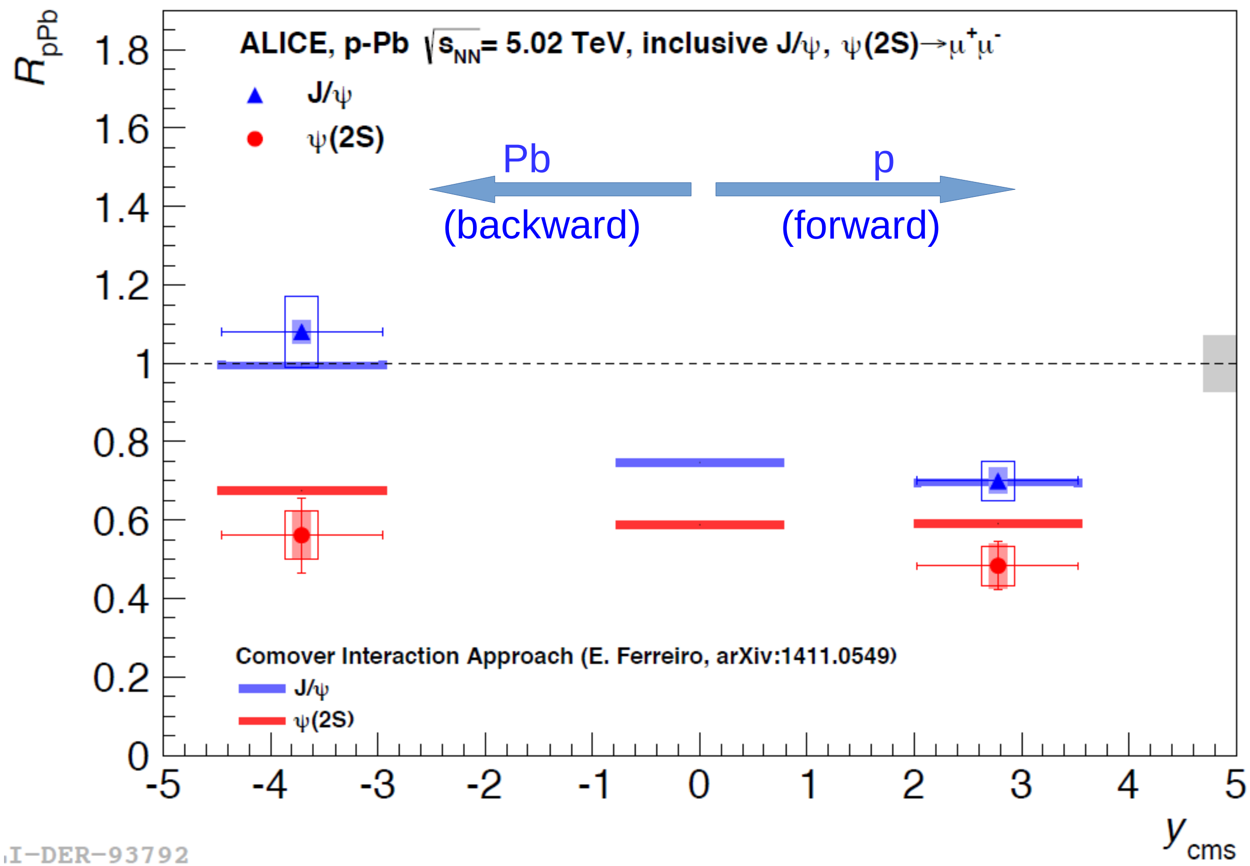
arXiv:1405.3796



- Hint that the suppression is larger at low p_T

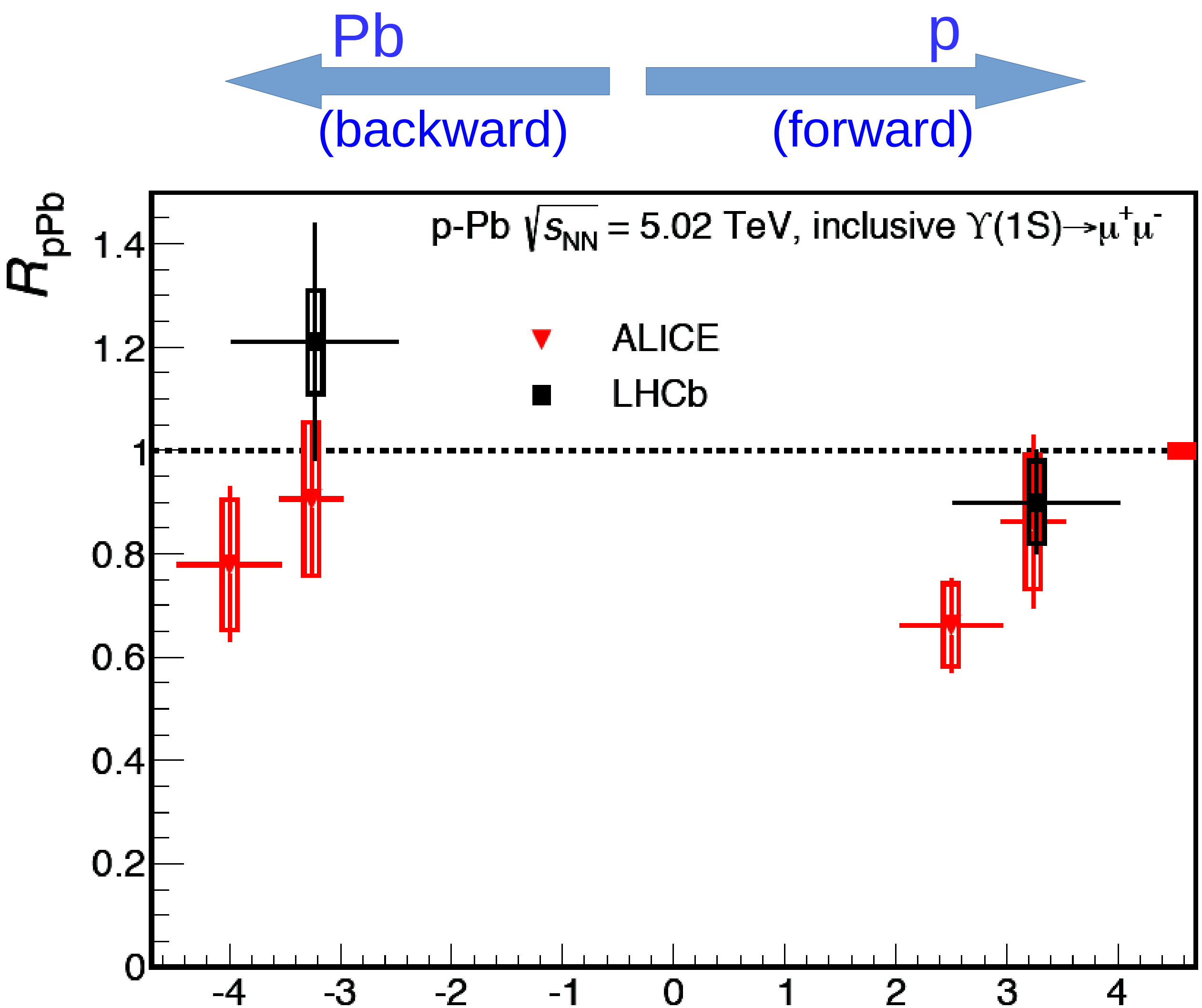
ψ(2S) vs rapidity

arXiv:1405.3796



- A qualitative description of the data is given in the comover interaction approach

Inclusive Υ(1S)

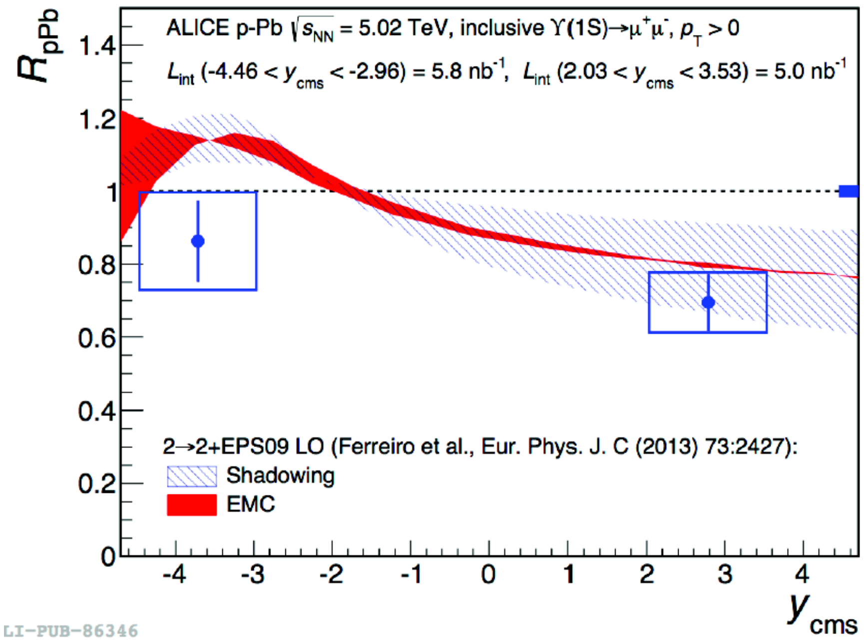


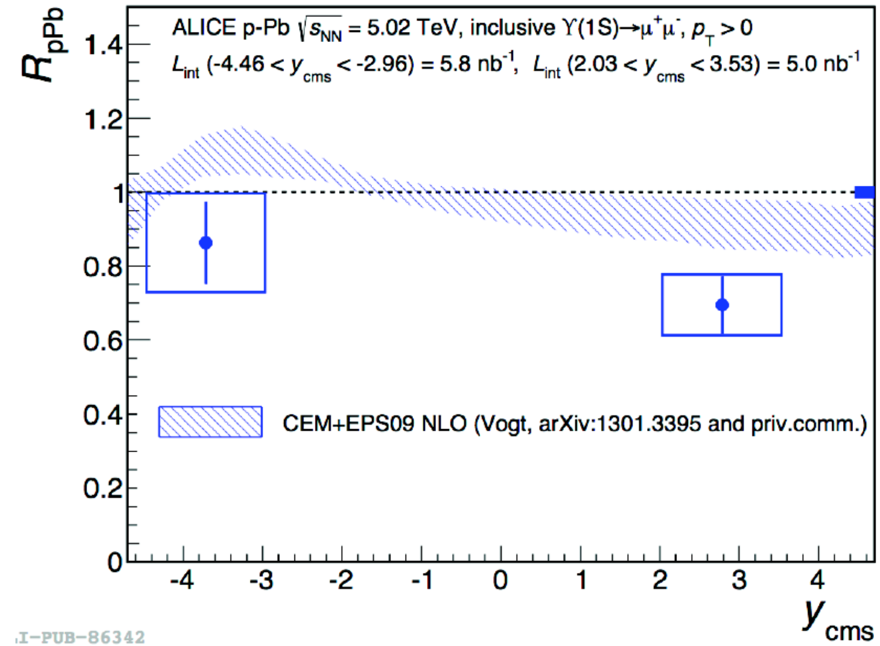
ALICE: PLB740 (2015) 105
LHCb-CONF-2014-003

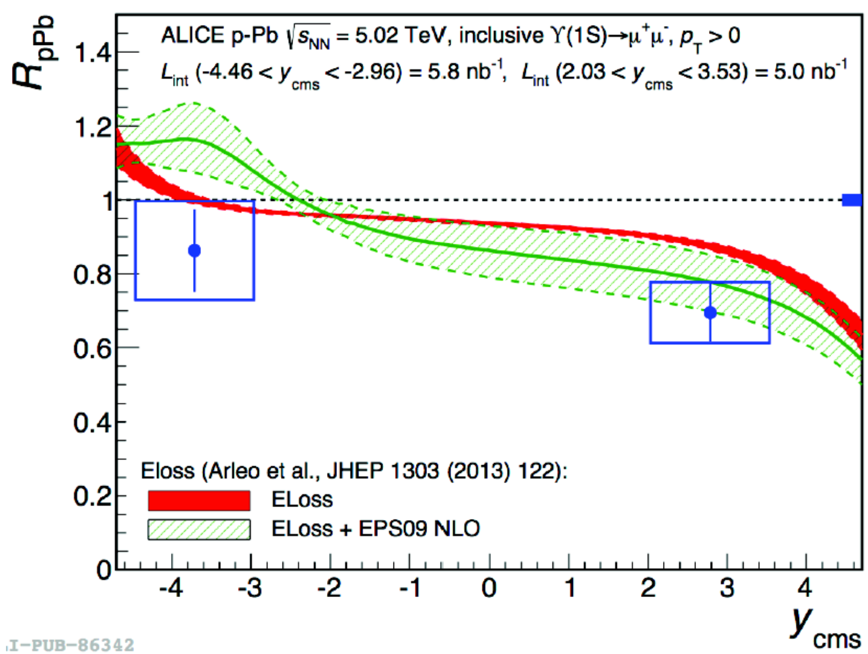
- Indication of a suppression at forward rapidity
- Consistent with no suppression at backward rapidity

Inclusive Υ(1S)

PLB740(2015)105







- Fair agreement with various calculations including:
  - 2->2 production model at LO (Ferreiro et al.)
  - CEM at NLO (Vogt)
  - Coherent parton energy loss (Arleo et al.)

p-Pb summary

- The J/ψ production at forward rapidity is suppressed towards low p_T and high event activity
- Model calculations including shadowing and parton energy loss fairly describe the data
- The large ψ(2S) suppression beyond the one seen for J/ψ cannot be explained within shadowing and energy loss scenarios.
- Model calculations assuming final-state interactions of the charmonium (pre-)resonance with comovers seem to describe the data.
- ϒ(1S) measurements indicate a small degree of suppression at forward rapidity and are consistent with no nuclear effects at backward rapidity

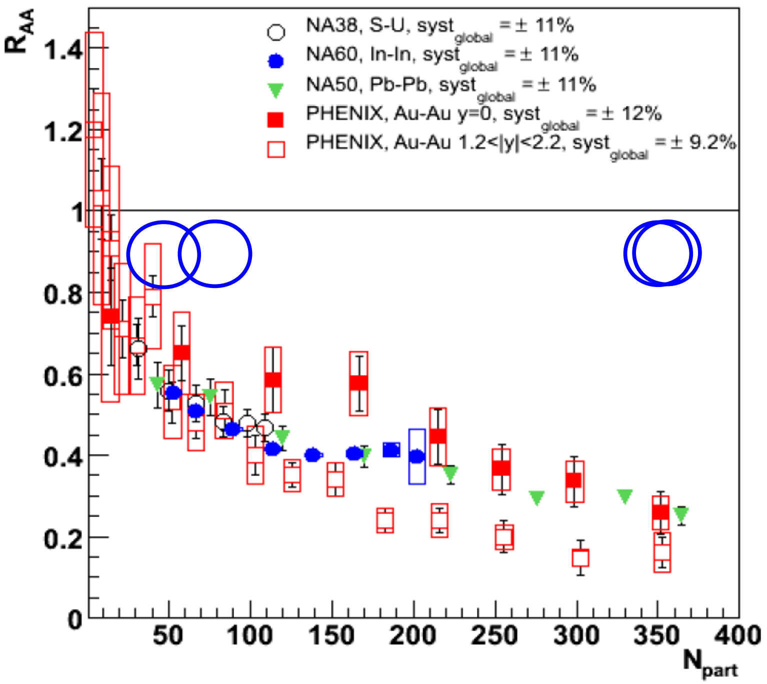
Summary & Outlook

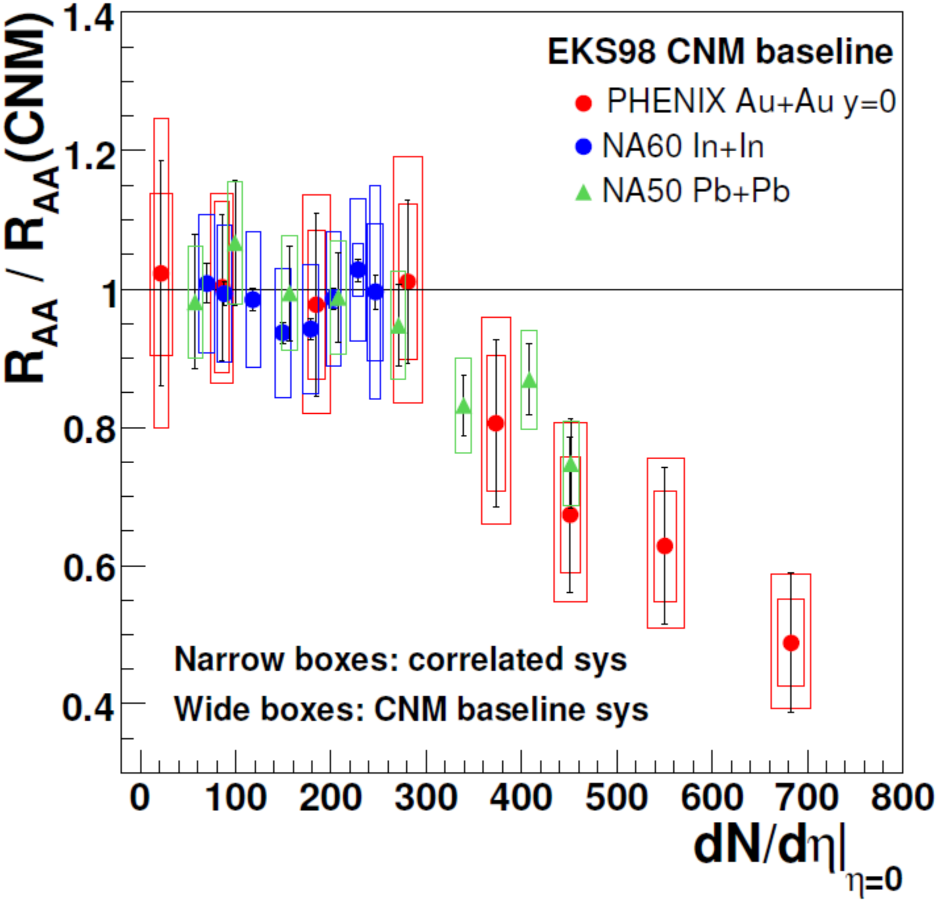
- A lot of progress has been made in understanding the nuclear modification of heavy quarkonium production in p-Pb and Pb-Pb collisions
- Charmonia:
  - The results on the J/ψ R_{AA} at low momentum give a strong support for the recombination mechanism
    - The non-null v_2 is consistent with this interpretation
  - Charmonium measurements become less of a QGP thermometer and more of a tool to study deconfinement
  - Extrapolating the CNM effects from p-Pb to Pb-Pb collisions will improve the quantitative understanding of the hot medium effects and constrain models. Not an easy task!
- Bottomonia:
  - Seems to be a clearer case due to smaller recombination and CNM effects
  - The Υ(1S) measurements constrain the sequential suppression models. A careful assessment of the feed-down contributions and CNM effects is needed

Backup

J/ψ at lower energy experiments

Brambilla et al., 2011

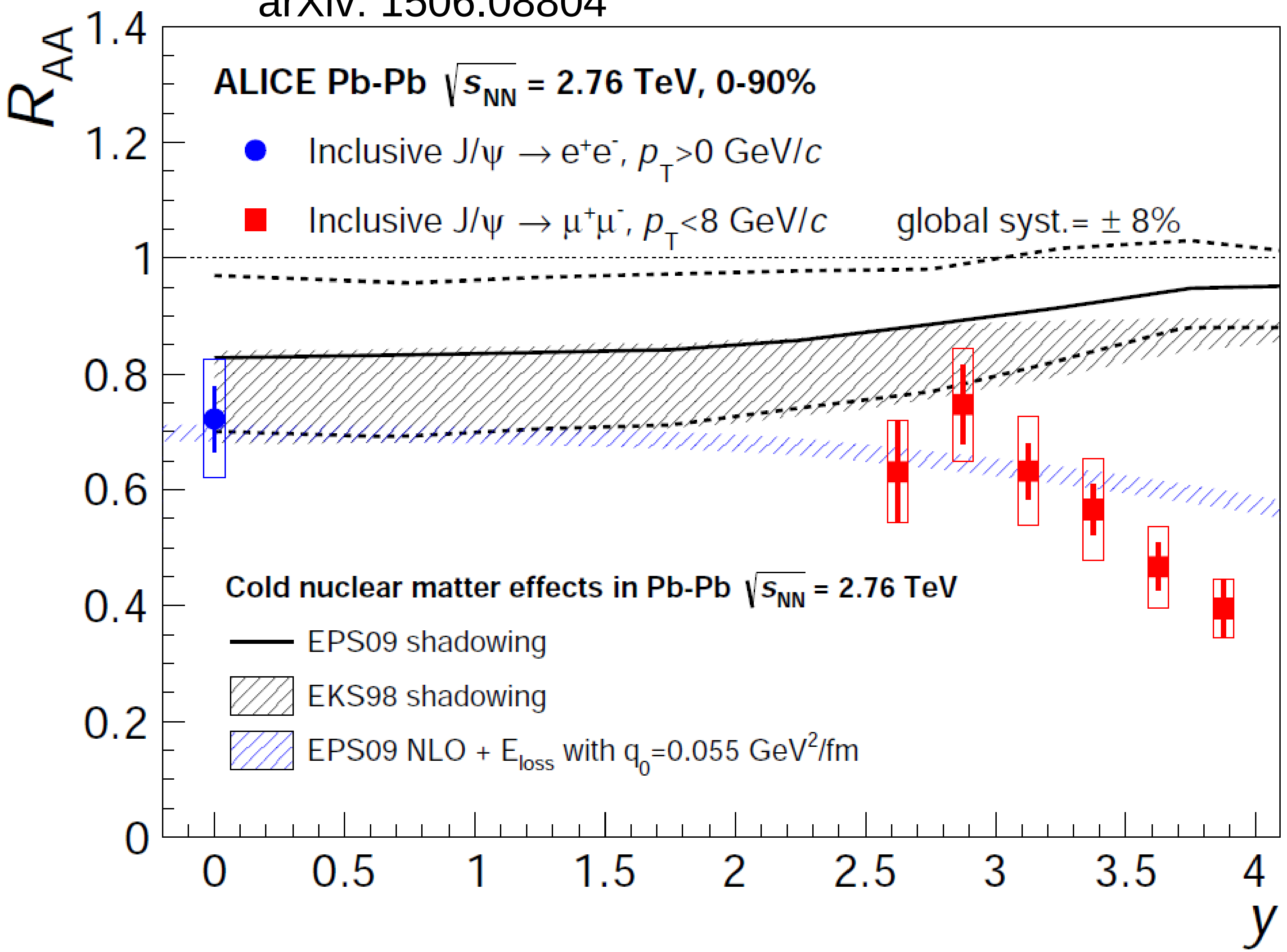




- J/ψ is suppressed in the most central AA collisions beyond CNM effects

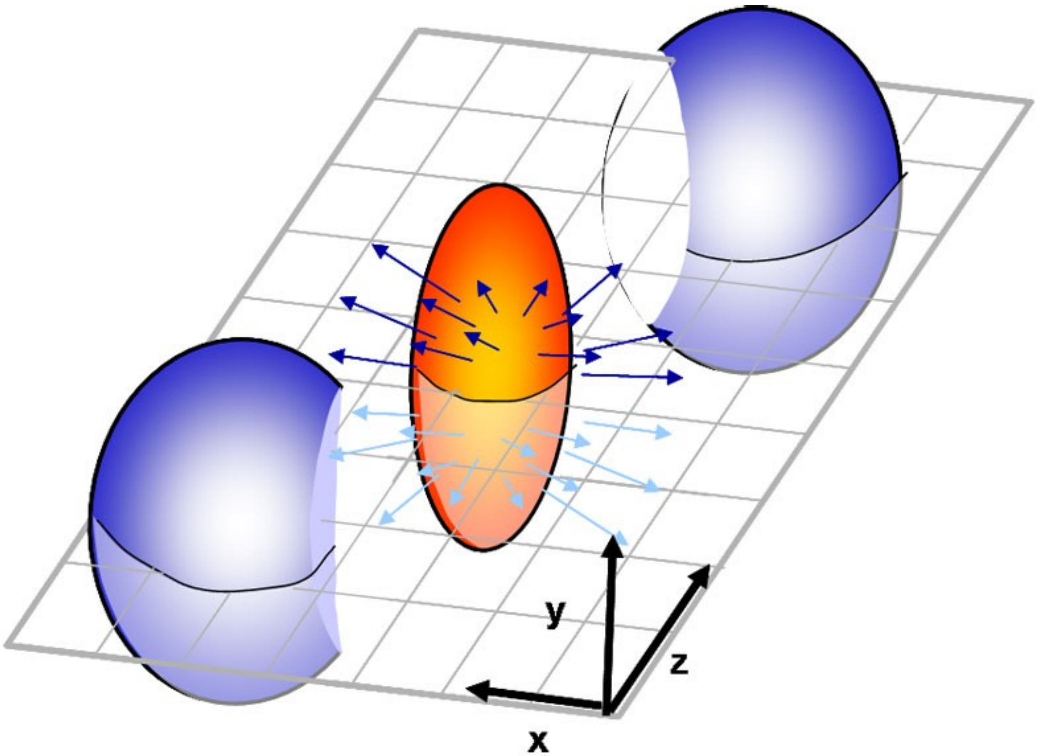
Inclusive J/ψ as a function of rapidity

arXiv: 1506.08804

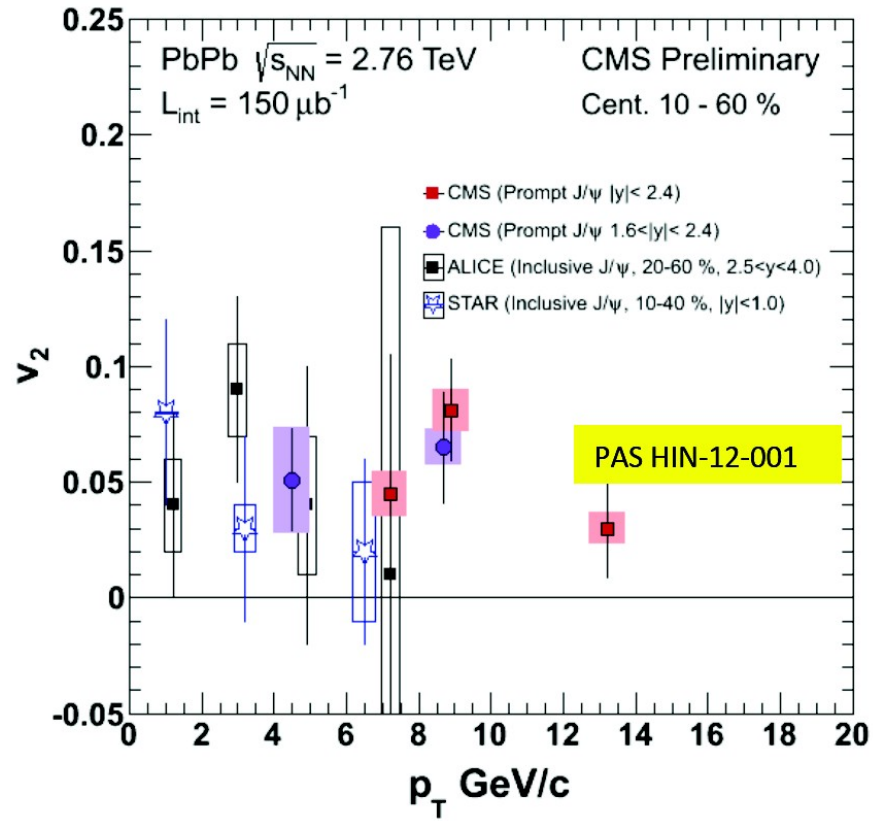


- Strong rapidity dependence for low-p_T at y>3 (ALICE) partially described in a coherent energy loss model (Arleo et al.)

Elliptic flow



$$\frac{dN}{d\phi} \simeq 1 + 2v_1\cos(\phi - \Psi_r) + 2v_2\cos(2(\phi - \Psi_r)) + \ldots$$

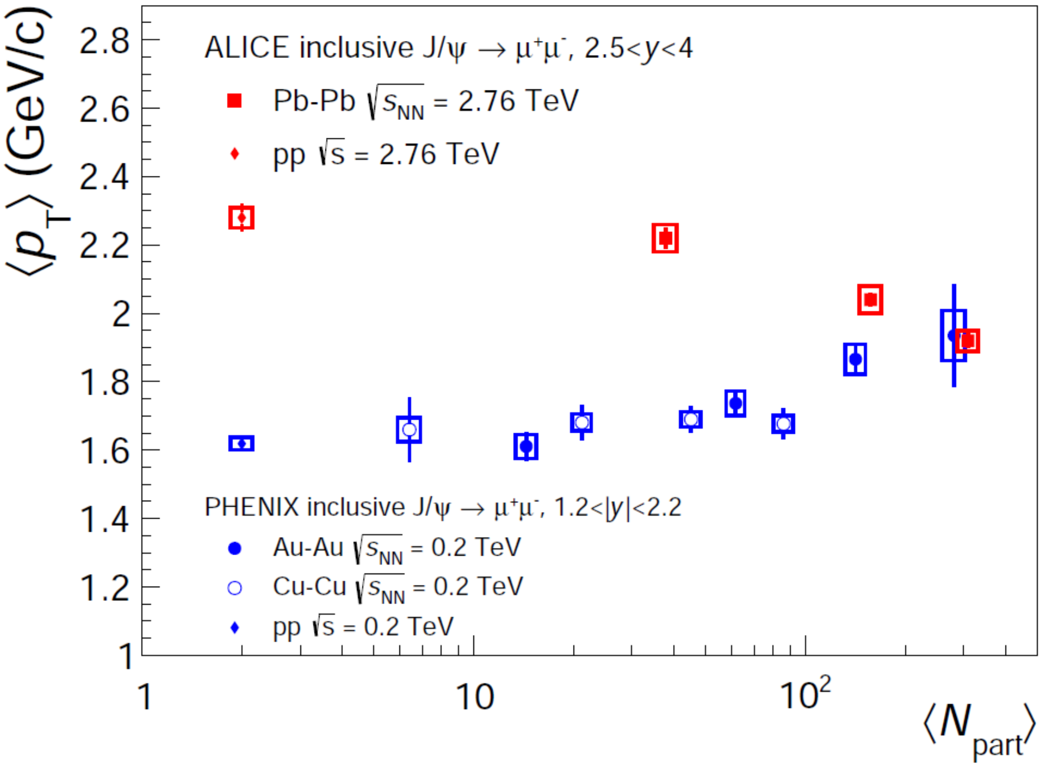


ALICE: PRL111(2013)162301
STAR: arXiv: 1212.3304

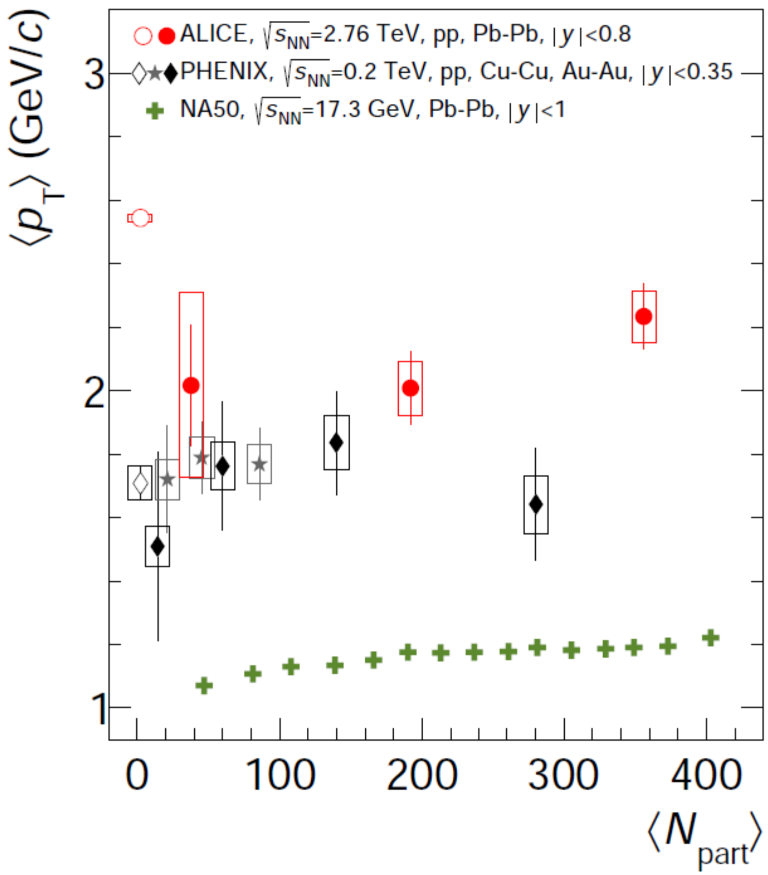
- The intermediate-p_T J/ψ hints toward a non-zero v_2 in semi-central collisions

Inclusive J/ψ as a function of p_T

arXiv: 1506.08804

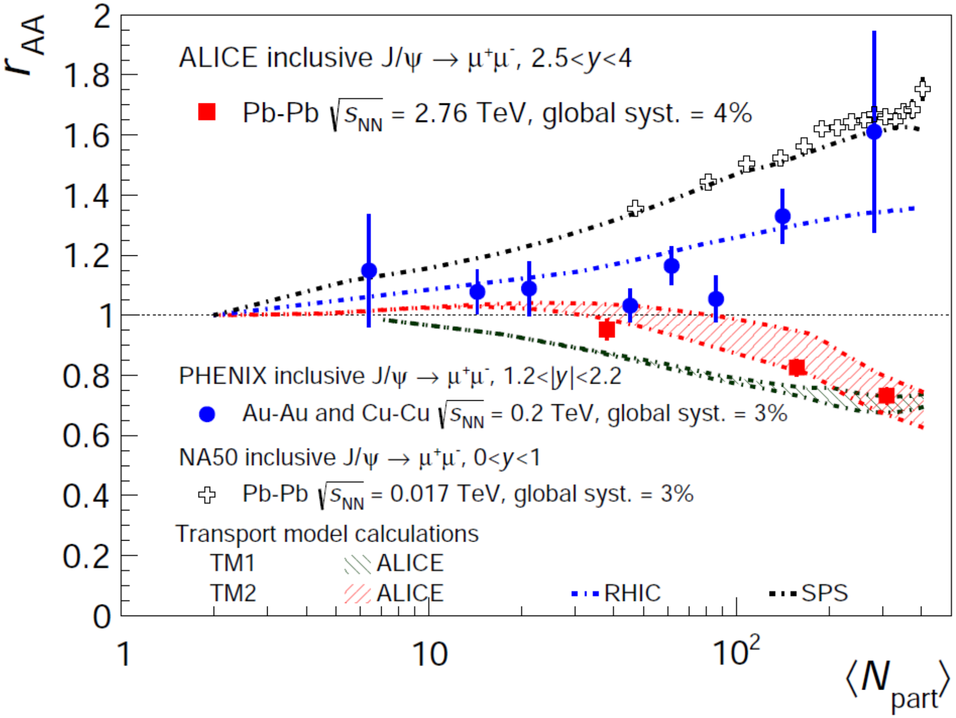


arXiv: 1504.07151



Inclusive J/ψ as a function of p_T

arXiv: 1506.08804



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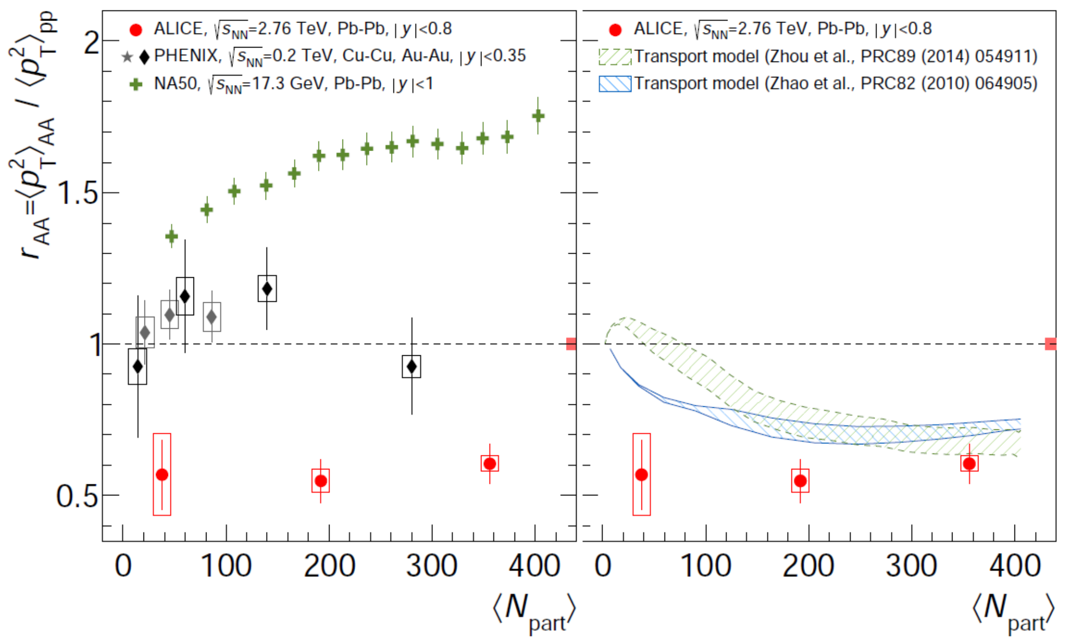
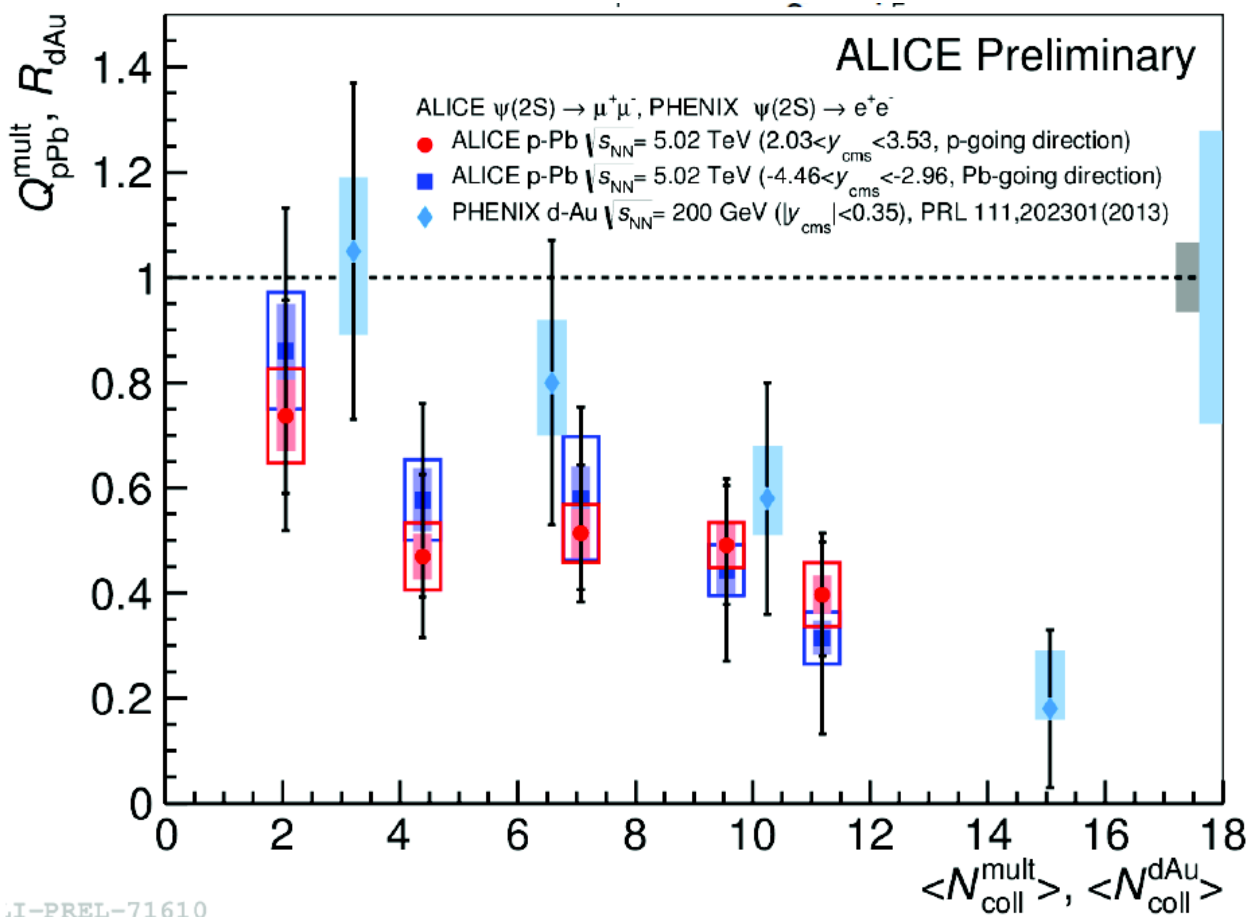


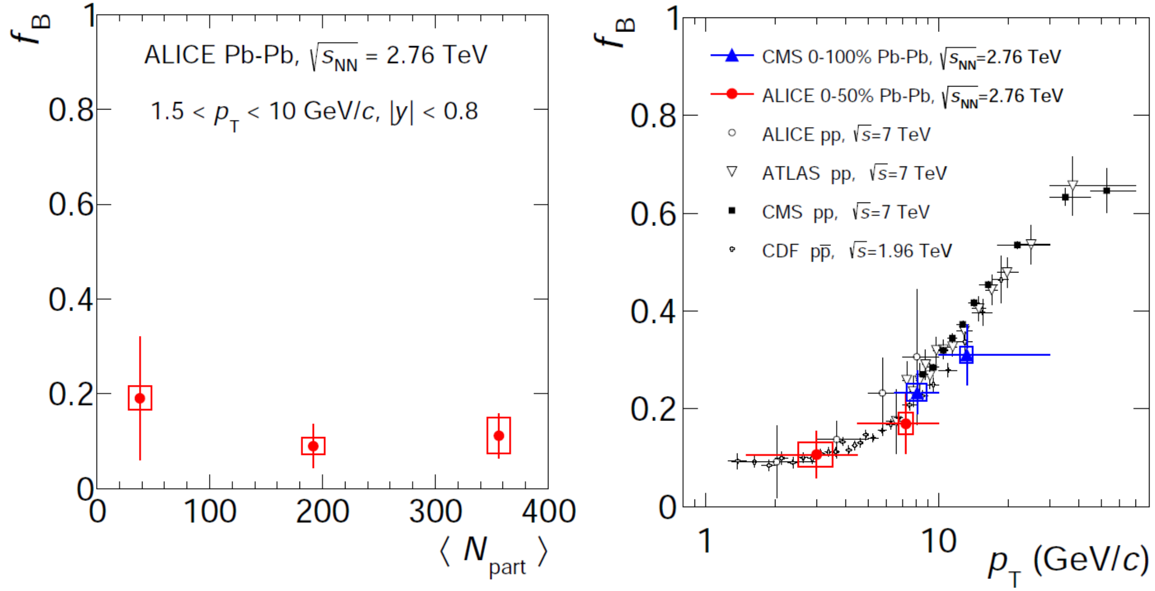
Charmonia vs event activity

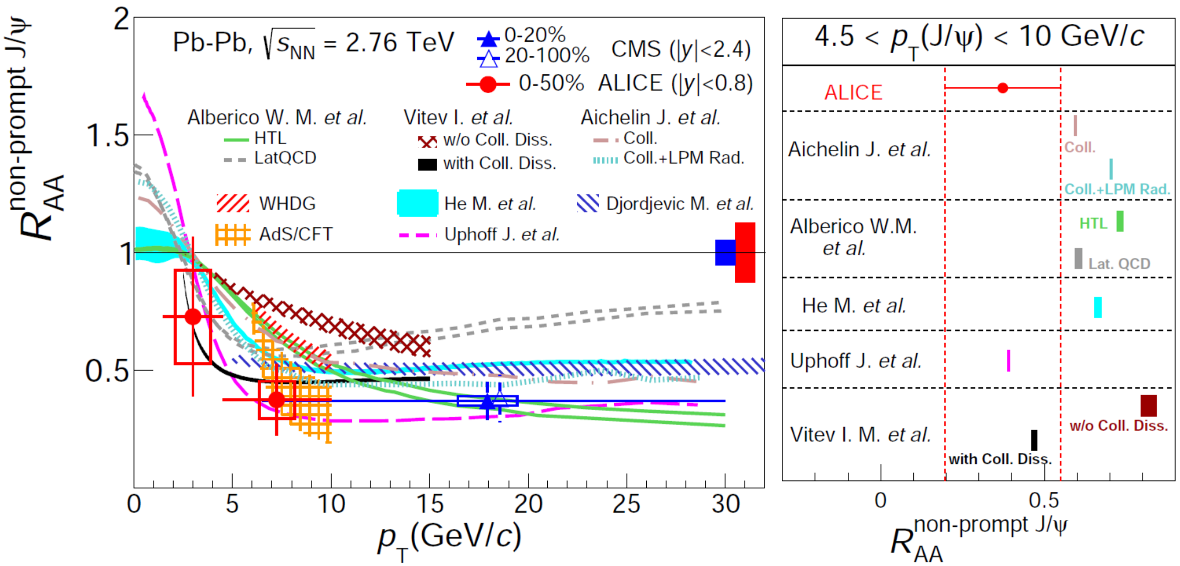


- ψ(2S) strongly suppressed in events with large activity in the ZDC
  - The trend suggests a final state effect
  - e.g. the pre-resonant state interaction with the comover cloud?
    Ferreiro et al. arXiv: 1411.0549
- The J/ψ suppression is also dependent on event activity.

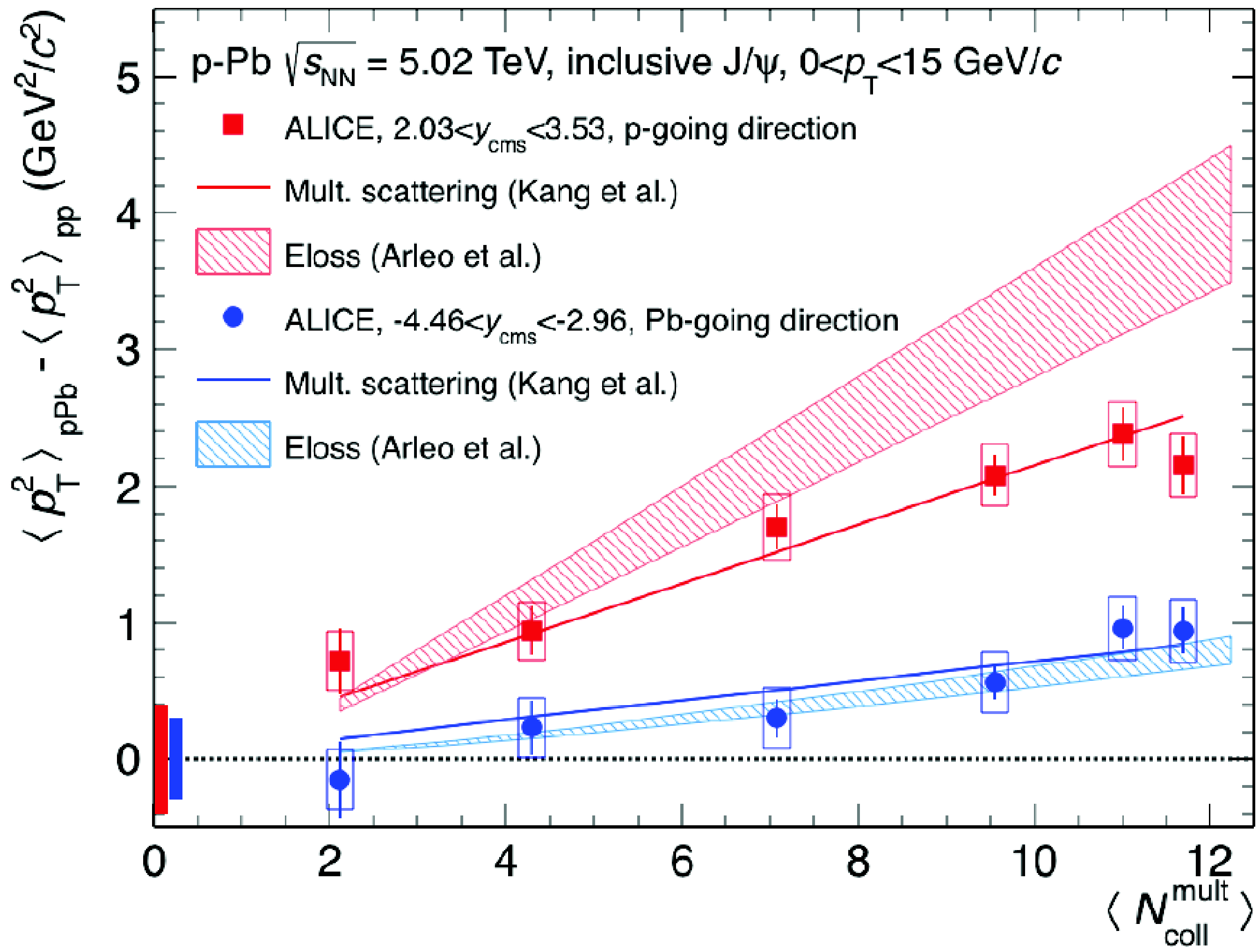
Non-prompt J/ψ

arXiv: 1504.07151





J/ψ p_T broadening



- J/ψ p_T broadening observed at forward-y, growing with increasing centrality
- Model calculations in agreement with data