Heavy quarkonium in Pb-Pb and p-Pb collisions at the LHC

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University of Oslo

Ab initio approaches in many-body QCD confront heavy-ion experiments, Heidelberg 15-17 december 2014

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
- Copious production at the LHC
  - ~100 $c\bar{c}$ pairs (central Pb-Pb)
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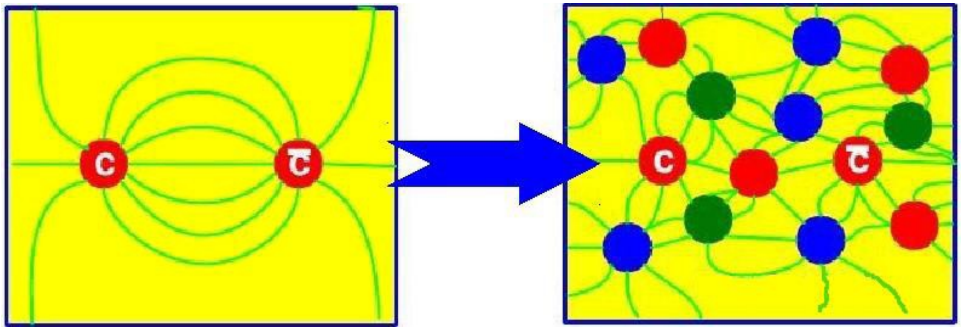

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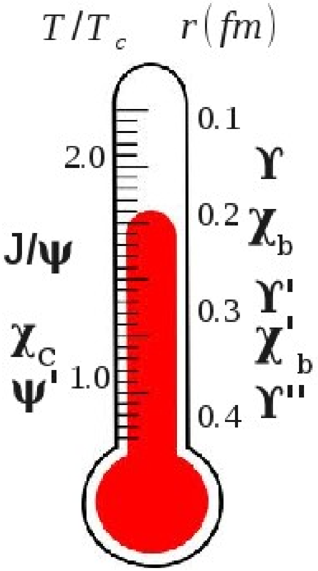

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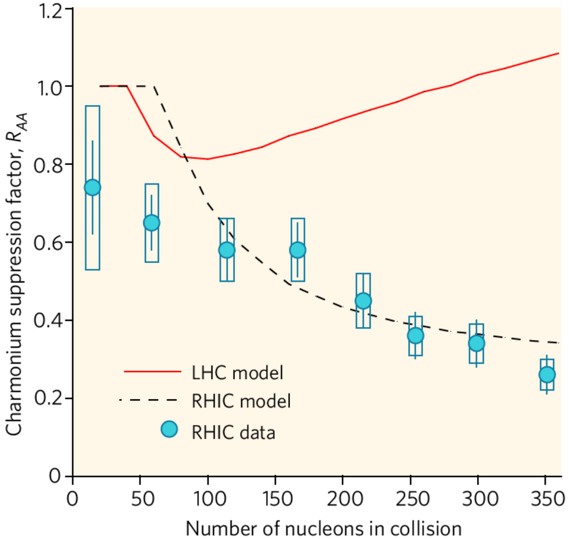
- Melting <-> formation of quarkonium states (Thews et al. 2001)
- Charmonium creation at the phase boundary (Braun-Munzinger and Stachel 2000)



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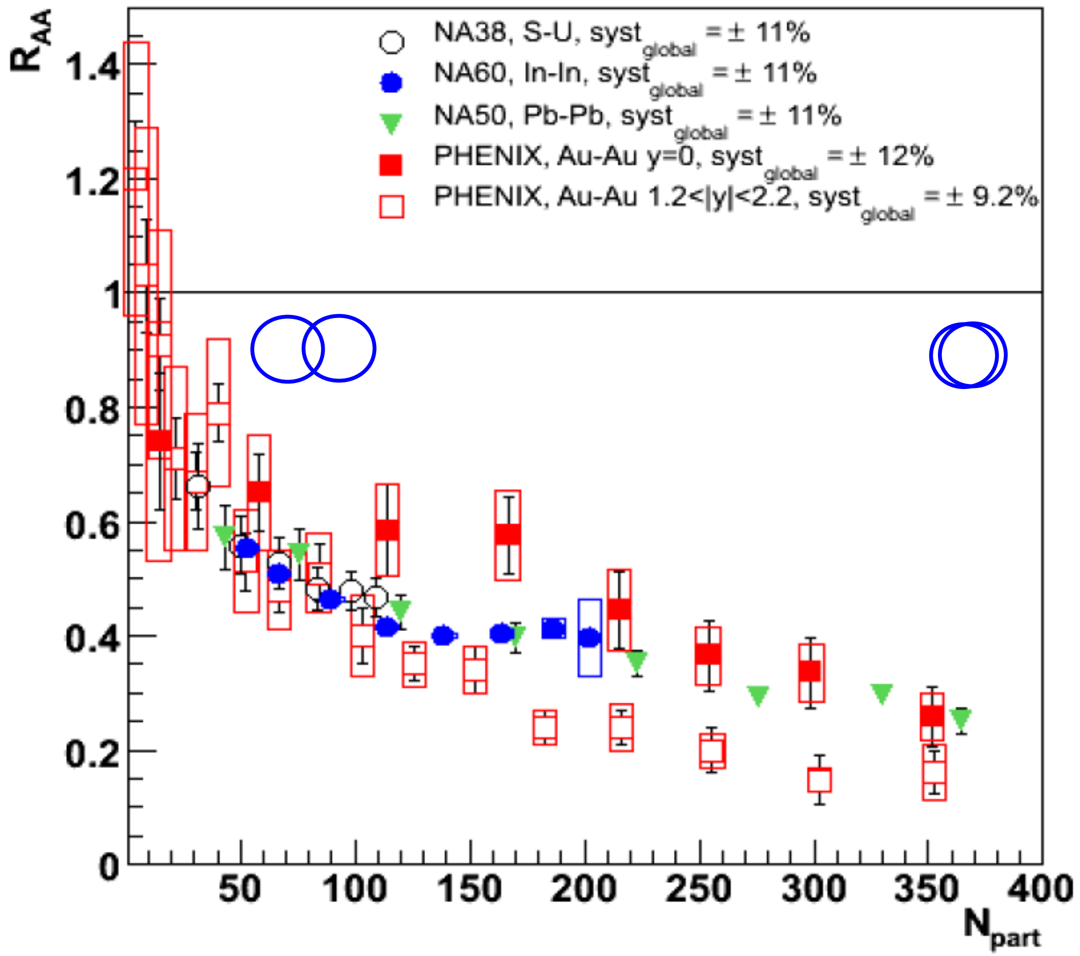
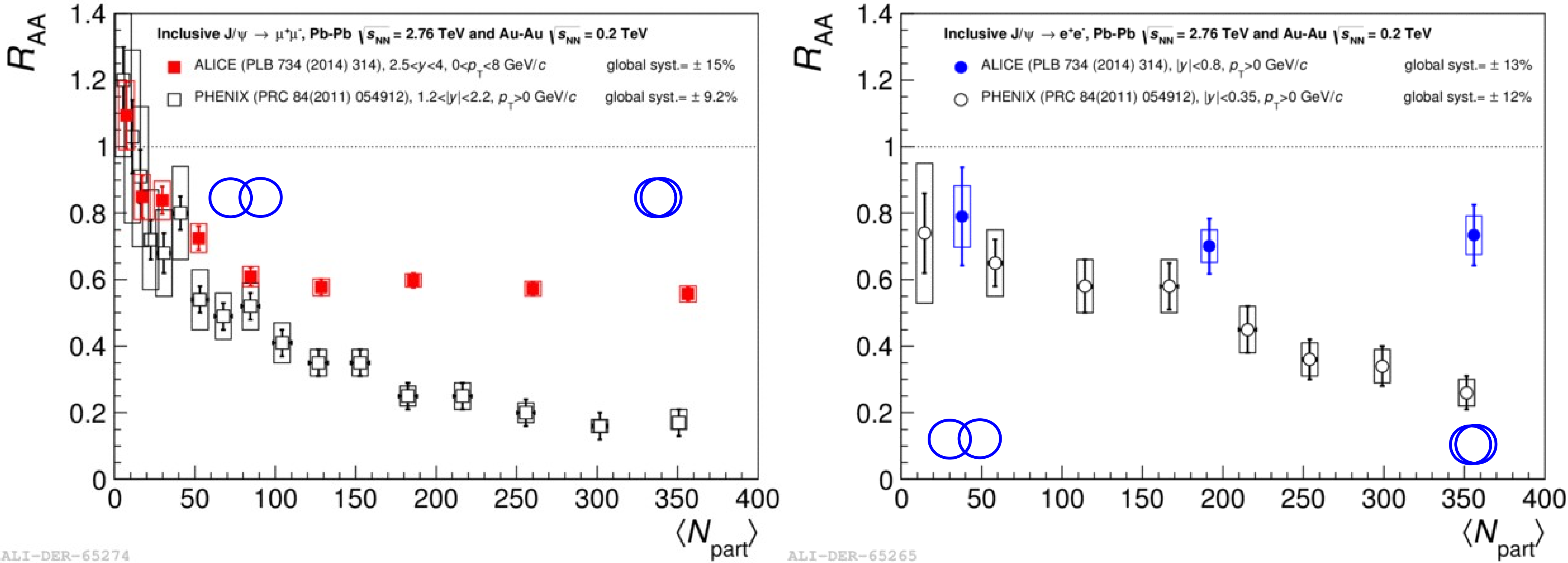
- Cold Nuclear Matter (CNM) effects:
  - Shadowing / gluon saturation effects
  - Nuclear absorbtion (negligible at LHC)
  - Coherent parton energy loss

J/ψ at lower energy experiments



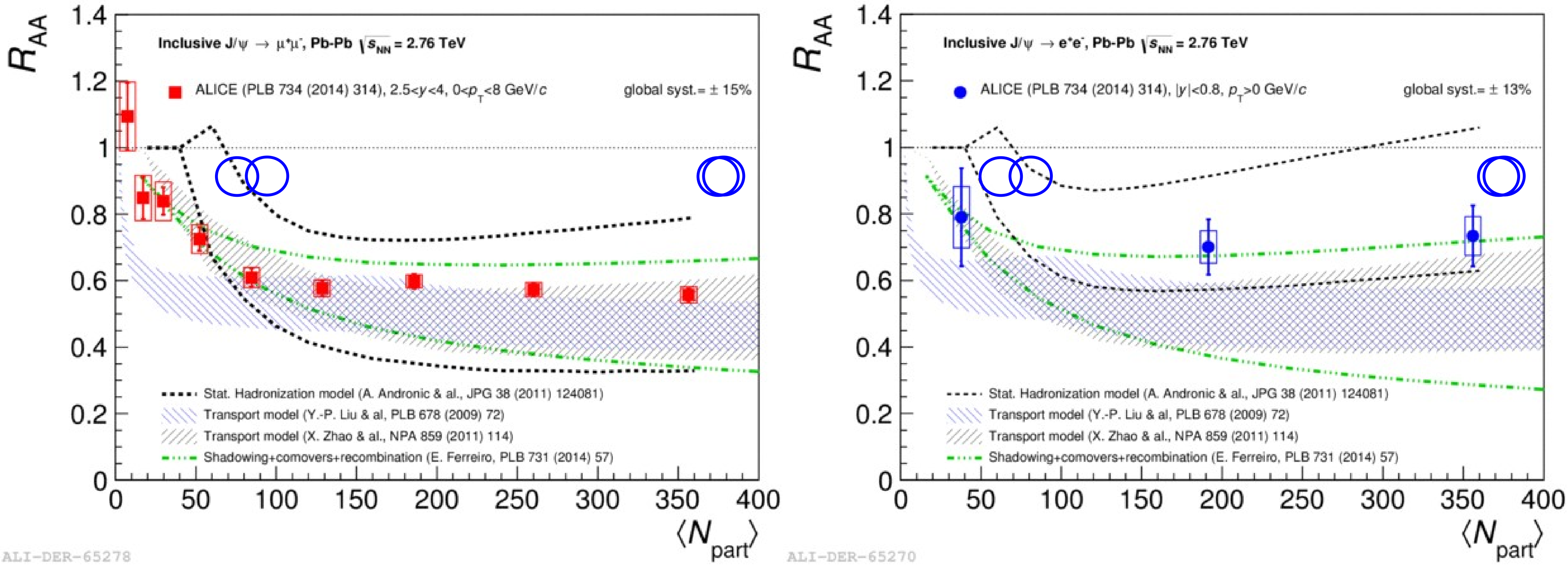
- J/ψ is strongly suppressed in central collisions at both SPS and RHIC energies, but:
  - Similar R_{AA} pattern despite very different collision energies
  - At RHIC, $R_{AA}(y=0) > R_{AA}(1.2<|y|<2.2)$

Inclusive J/ψ at the LHC



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

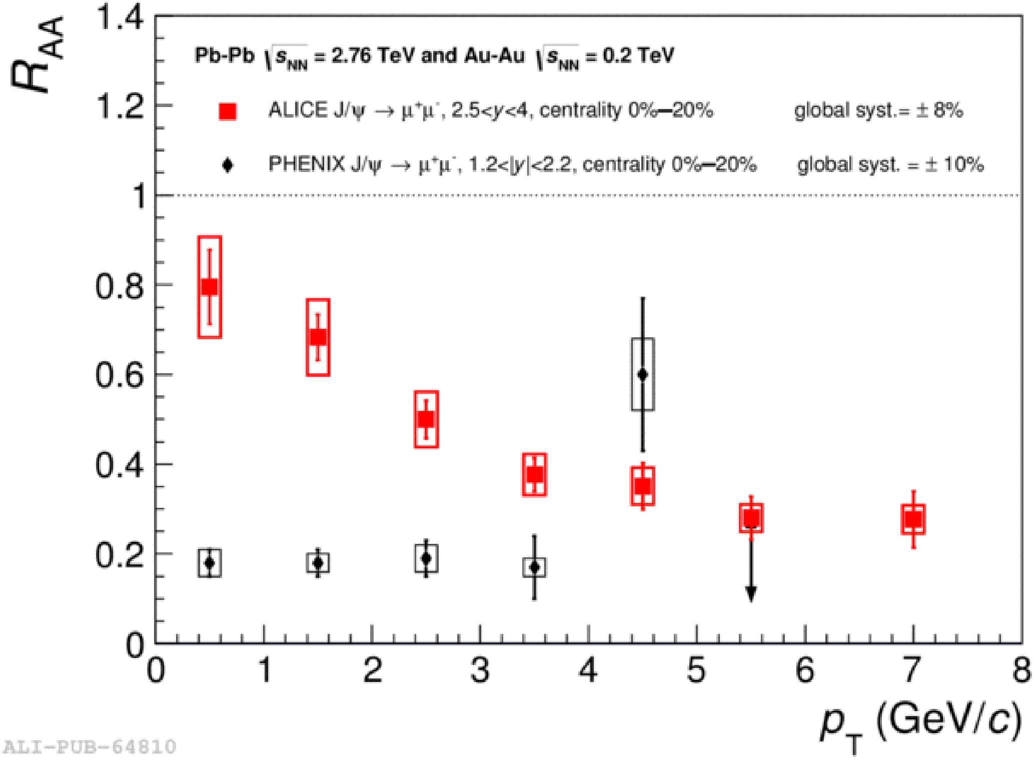
Inclusive J/ψ at the LHC



- 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

PLB734 (2014) 314



- Striking difference between LHC and RHIC at low-p_T
  - Evidence for (re)combination ?

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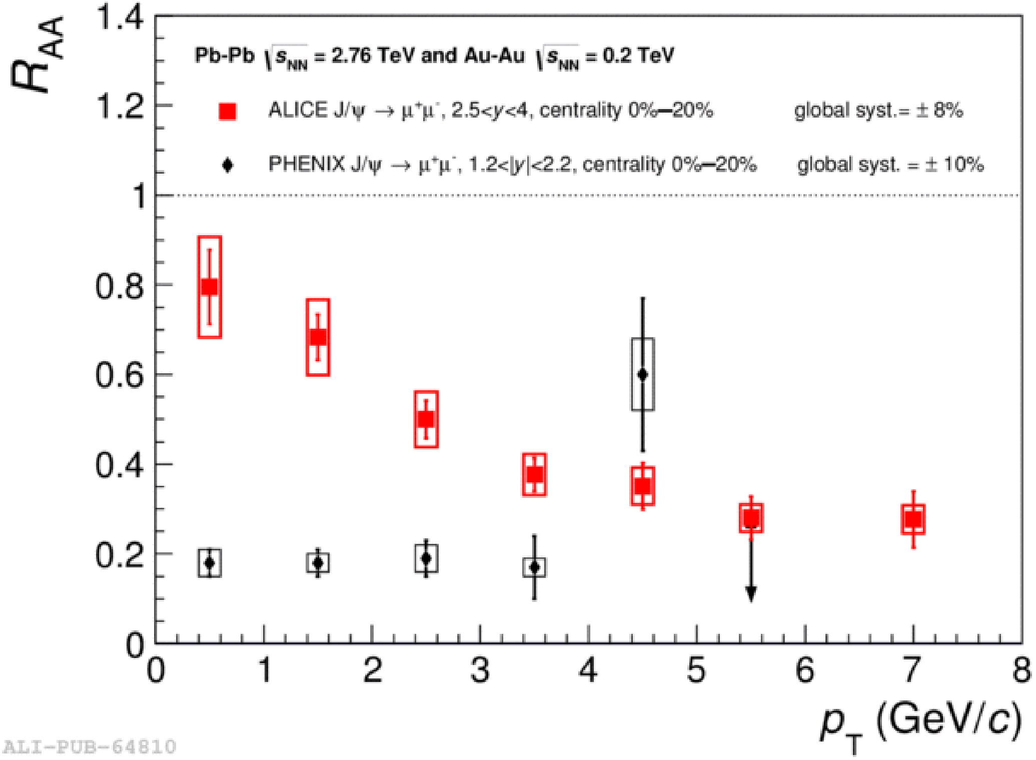
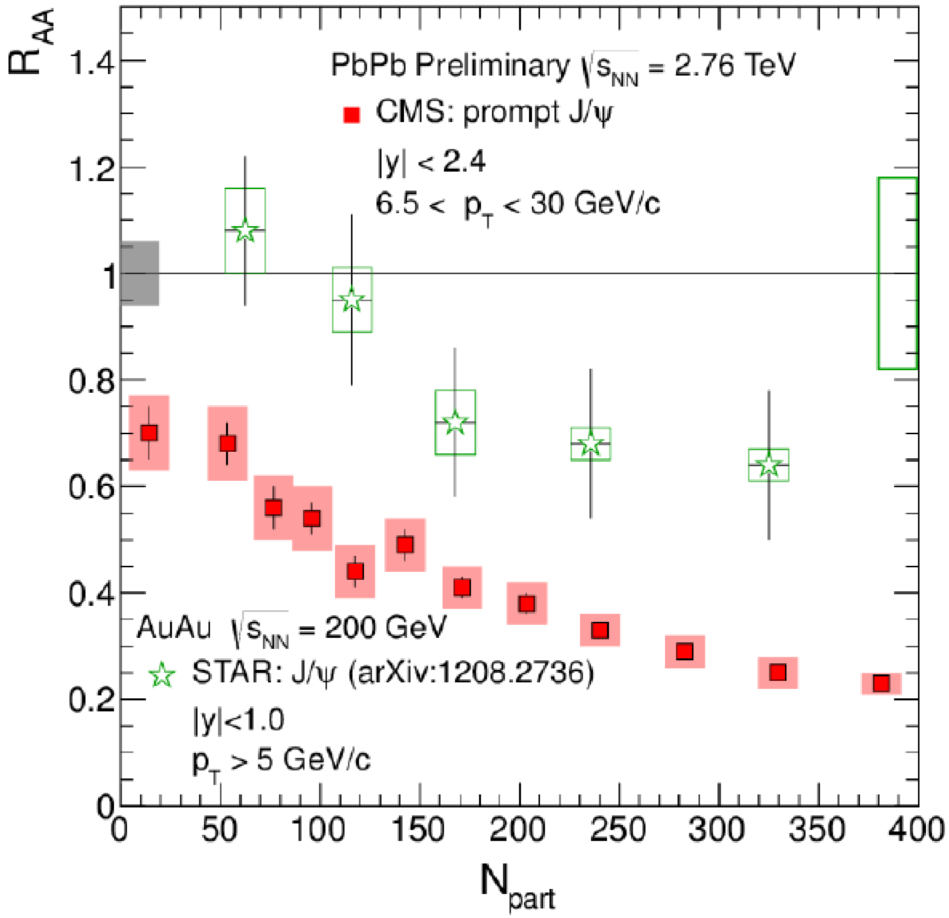
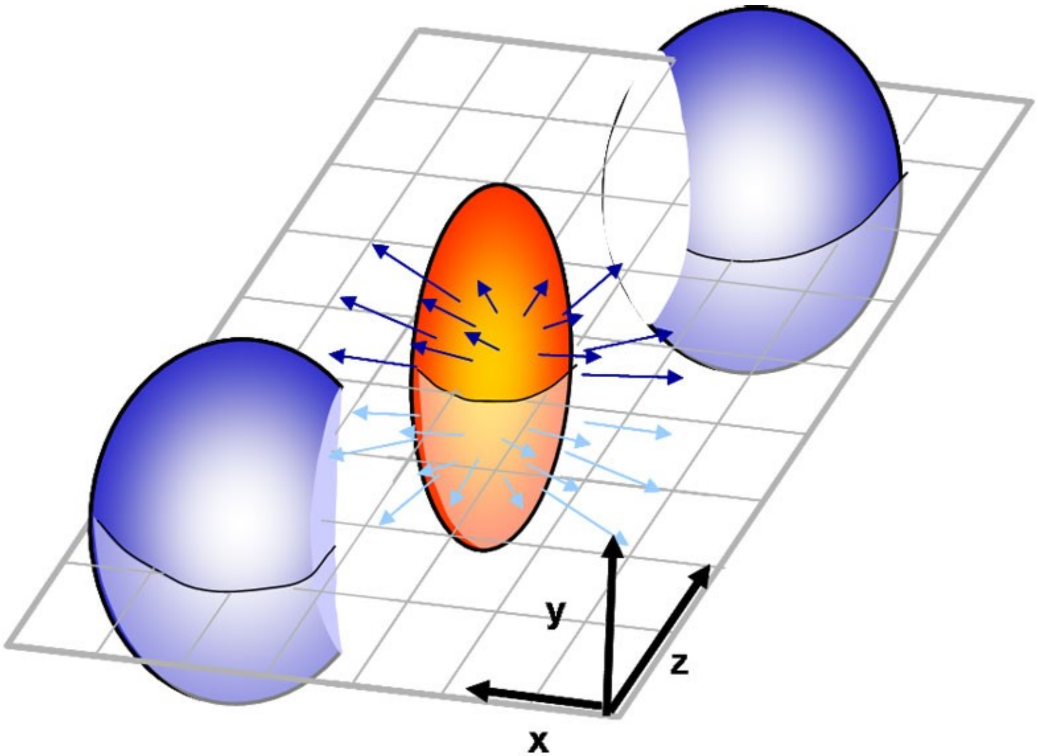
PLB734 (2014) 314

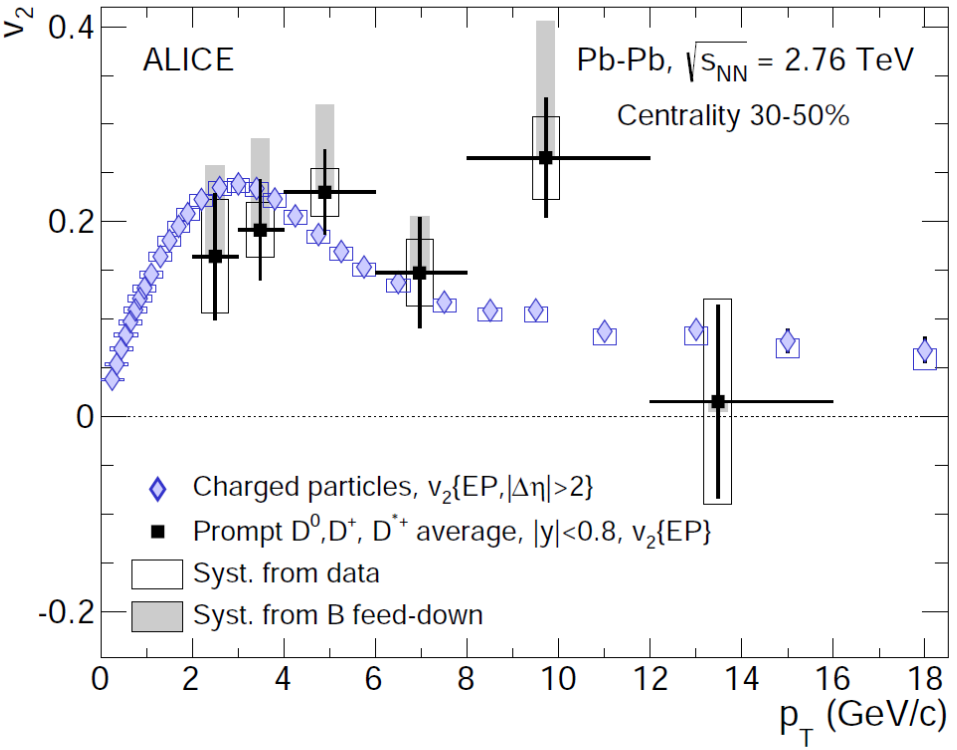




- Striking difference between LHC and RHIC at low-p_T
  - Evidence for (re)combination ?
- Stronger suppression seen at LHC for the high p_T J/ψ

Elliptic flow

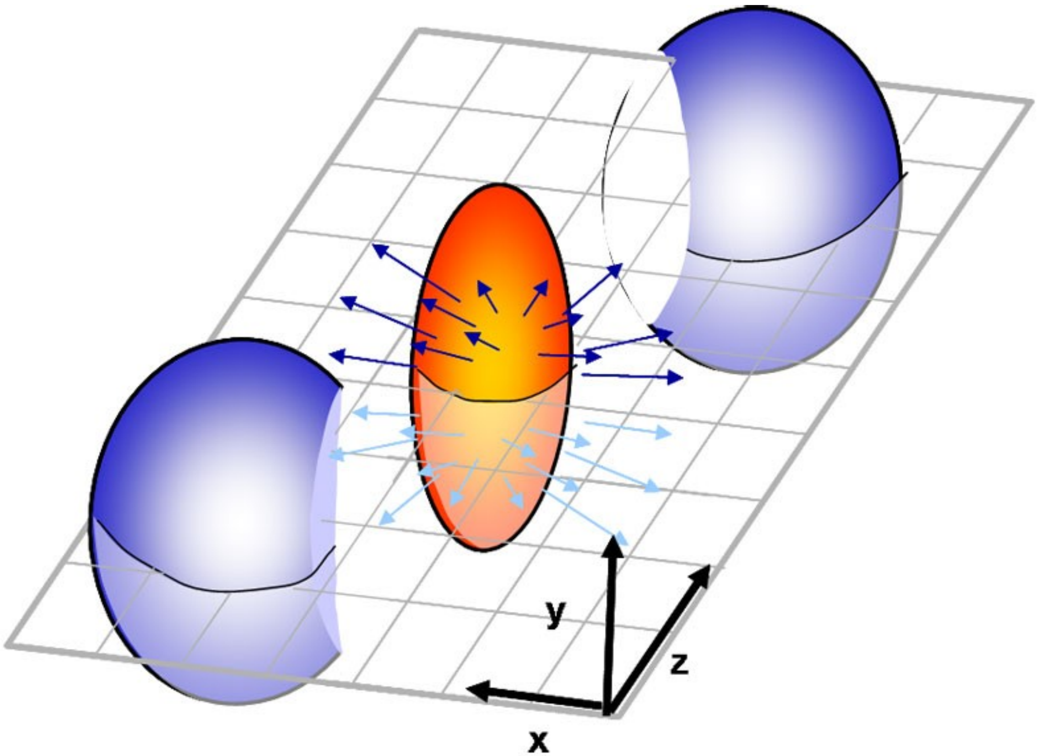




$$\frac{dN}{d\phi} \simeq 1 + 2v_1 \cos(\phi - \Psi_r) + 2v_2 \cos(2(\phi - \Psi_r)) + \ldots$$

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

Elliptic flow



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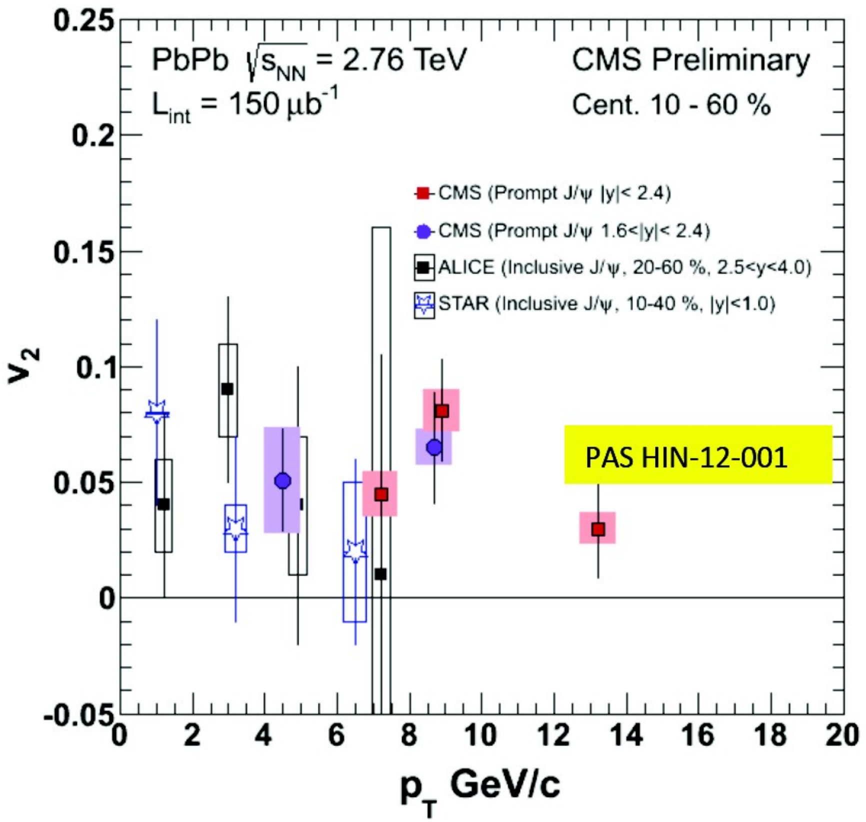
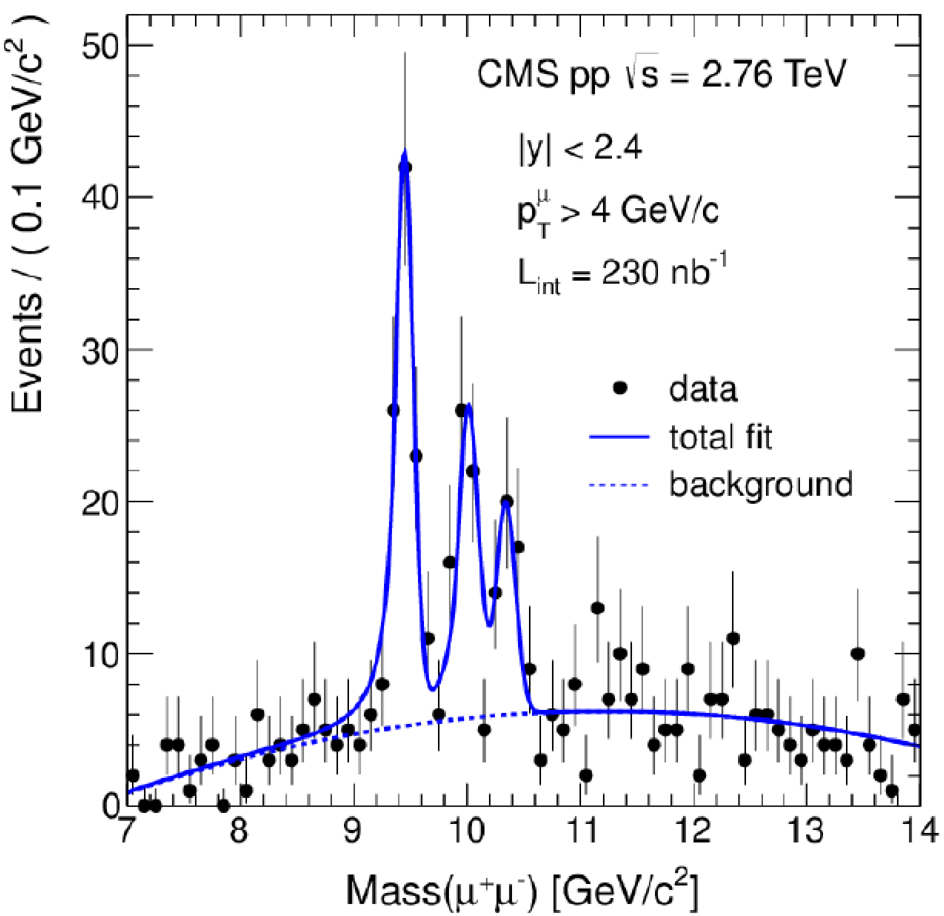


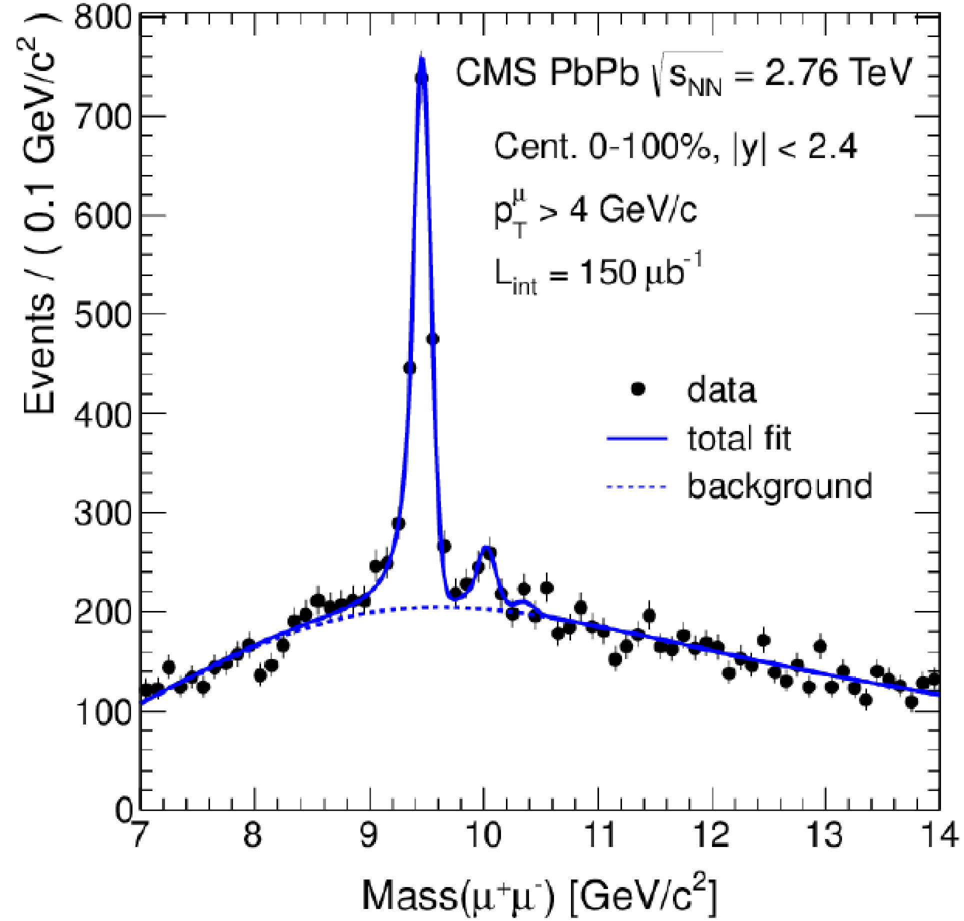
ALICE: PRL111(2013)162301
STAR: arXiv: 1212.3304

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

Bottomonium

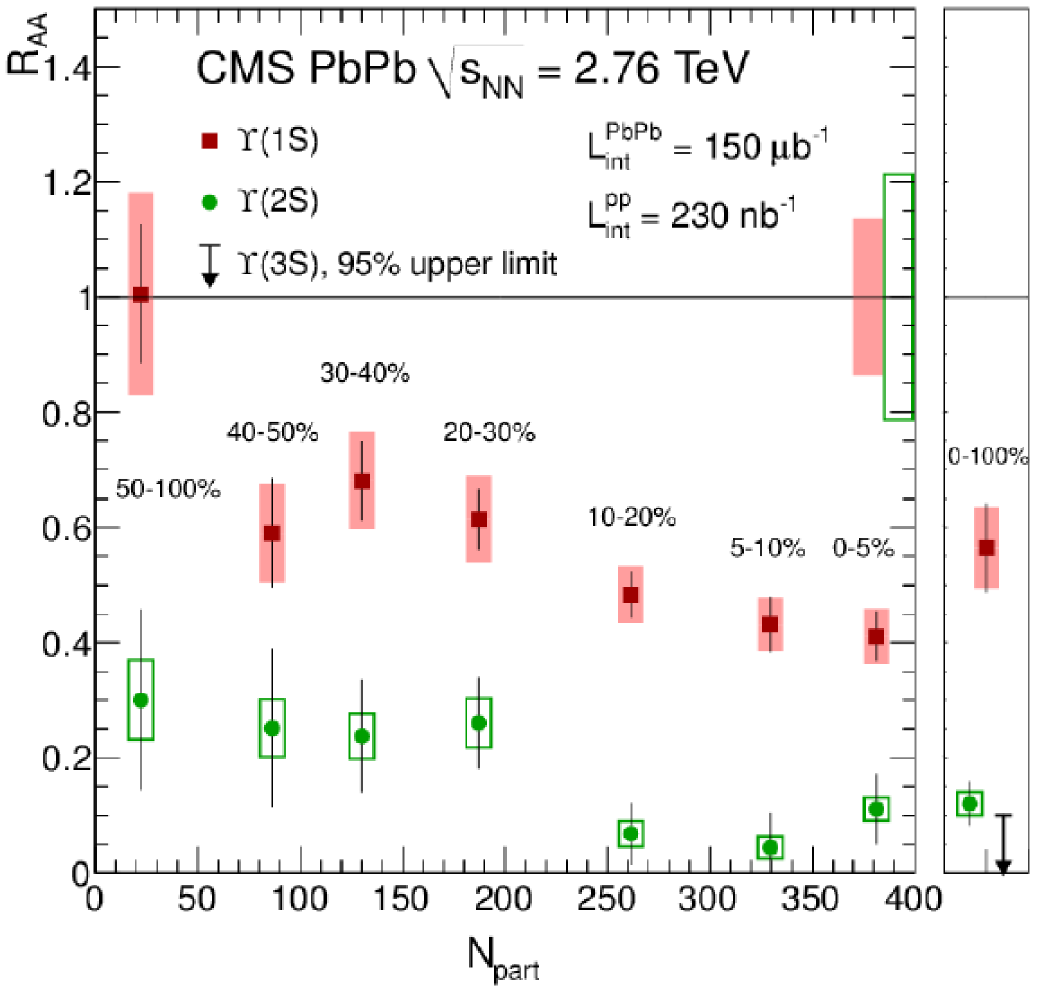
PRL109 (2012) 222301





Inclusive Υ production vs centrality

PRL109 (2012) 222301



- Strong suppression observed for the Υ(2S) and Υ(3S) states

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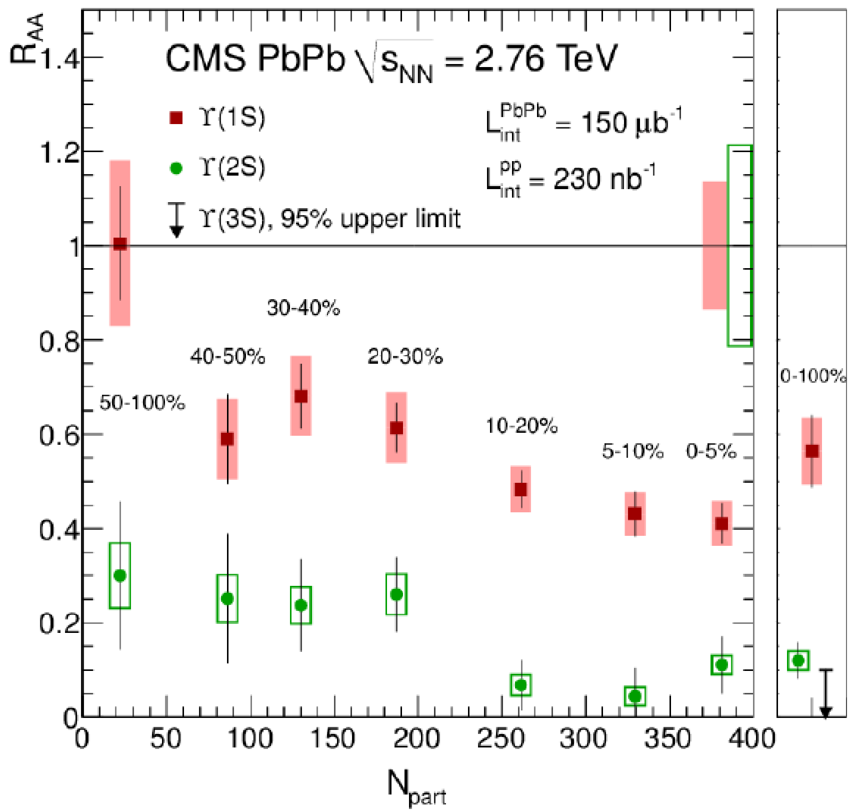
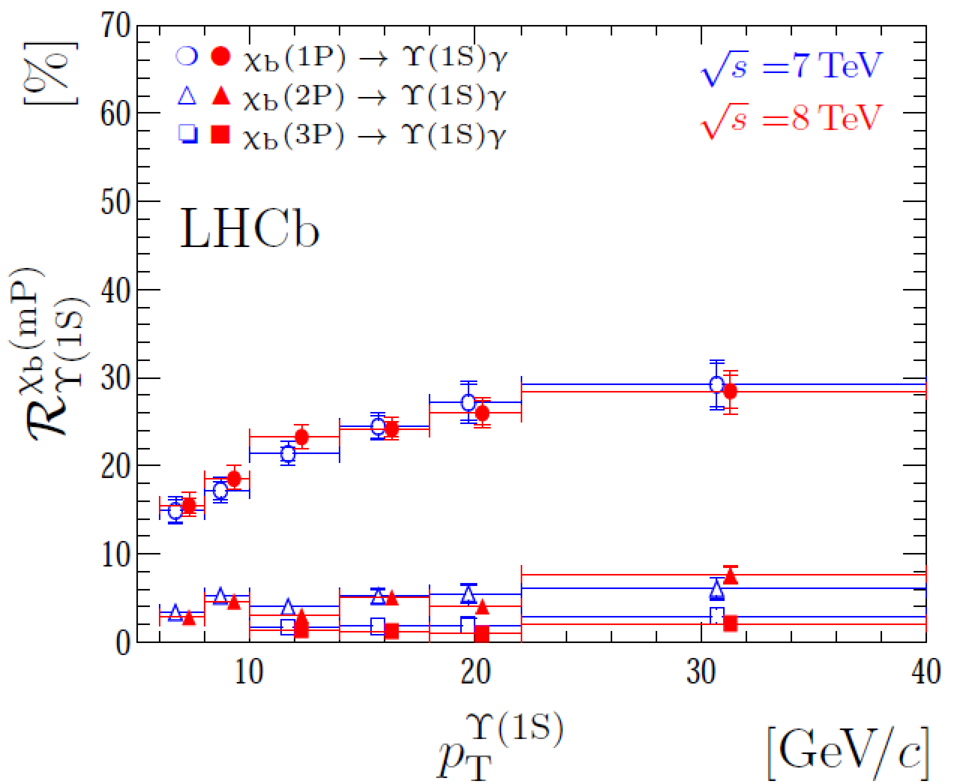
PRL109 (2012) 222301

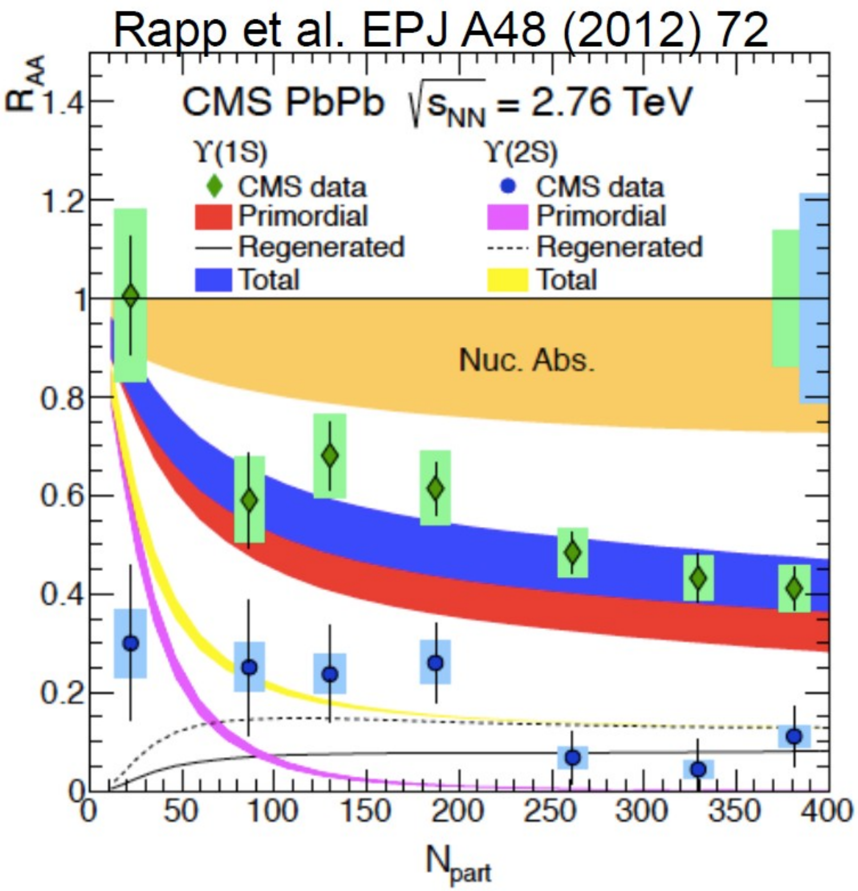


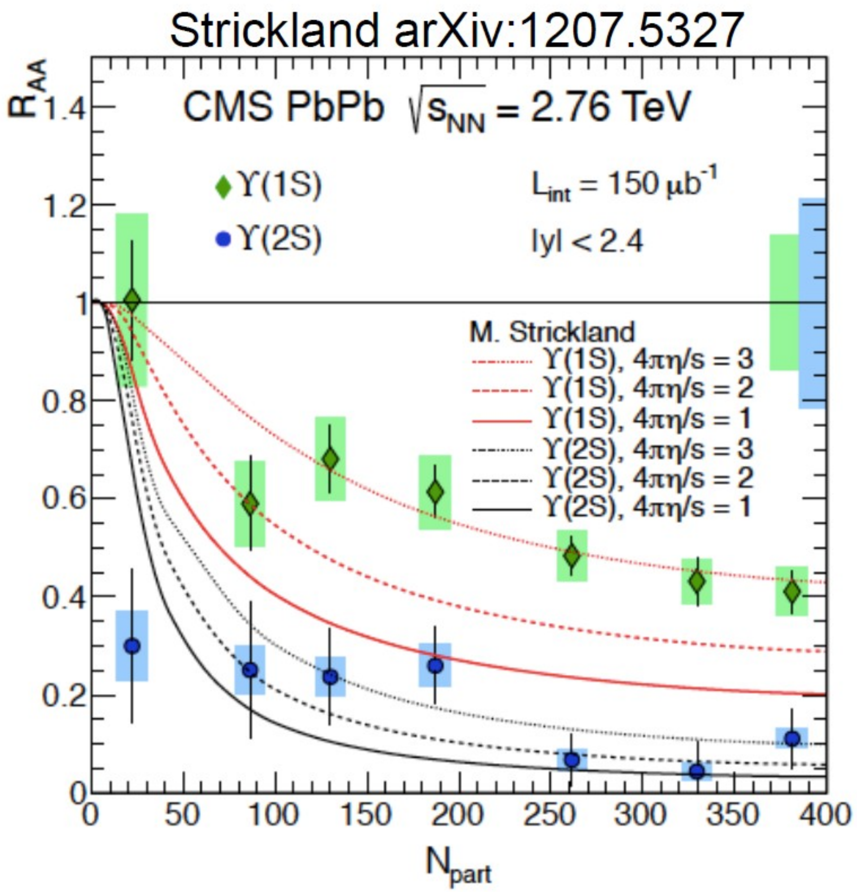
arXiv: 1407.7734



- Strong suppression observed for the Υ(2S) and Υ(3S) states
- Inclusive Υ(1S) is also strongly suppressed in central collisions, BUT
  - There is a large (up to 50%) feed down from higher mass S-wave and P-wave states

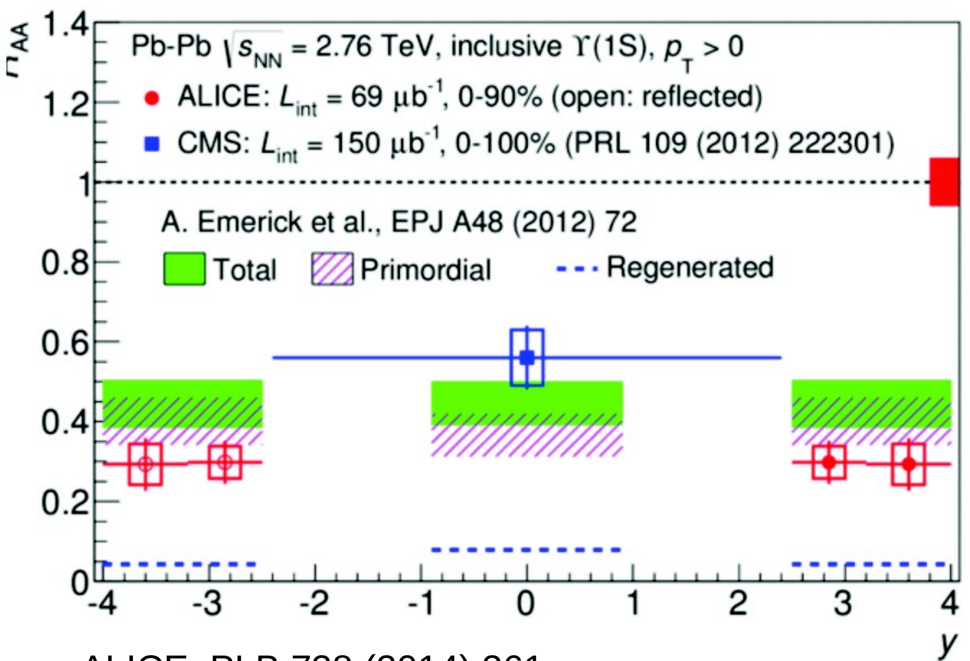
Υ production vs centrality

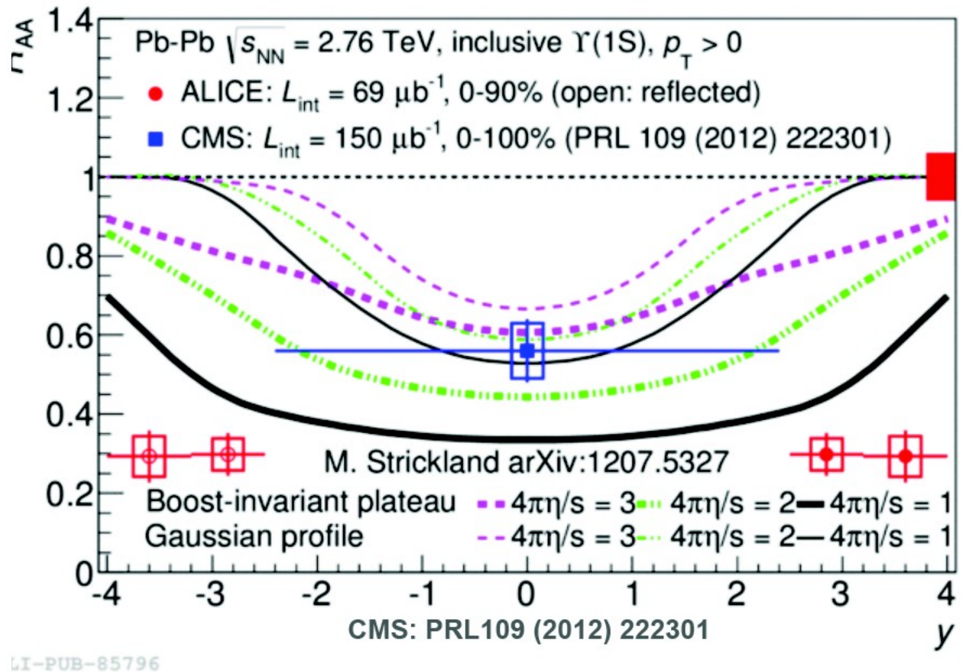




- Small contributions expected from (re)combination
- Thermal suppression of bottomonium states (Strickland) in a hydro model with shear viscosity

Y(1S) production vs rapidity





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

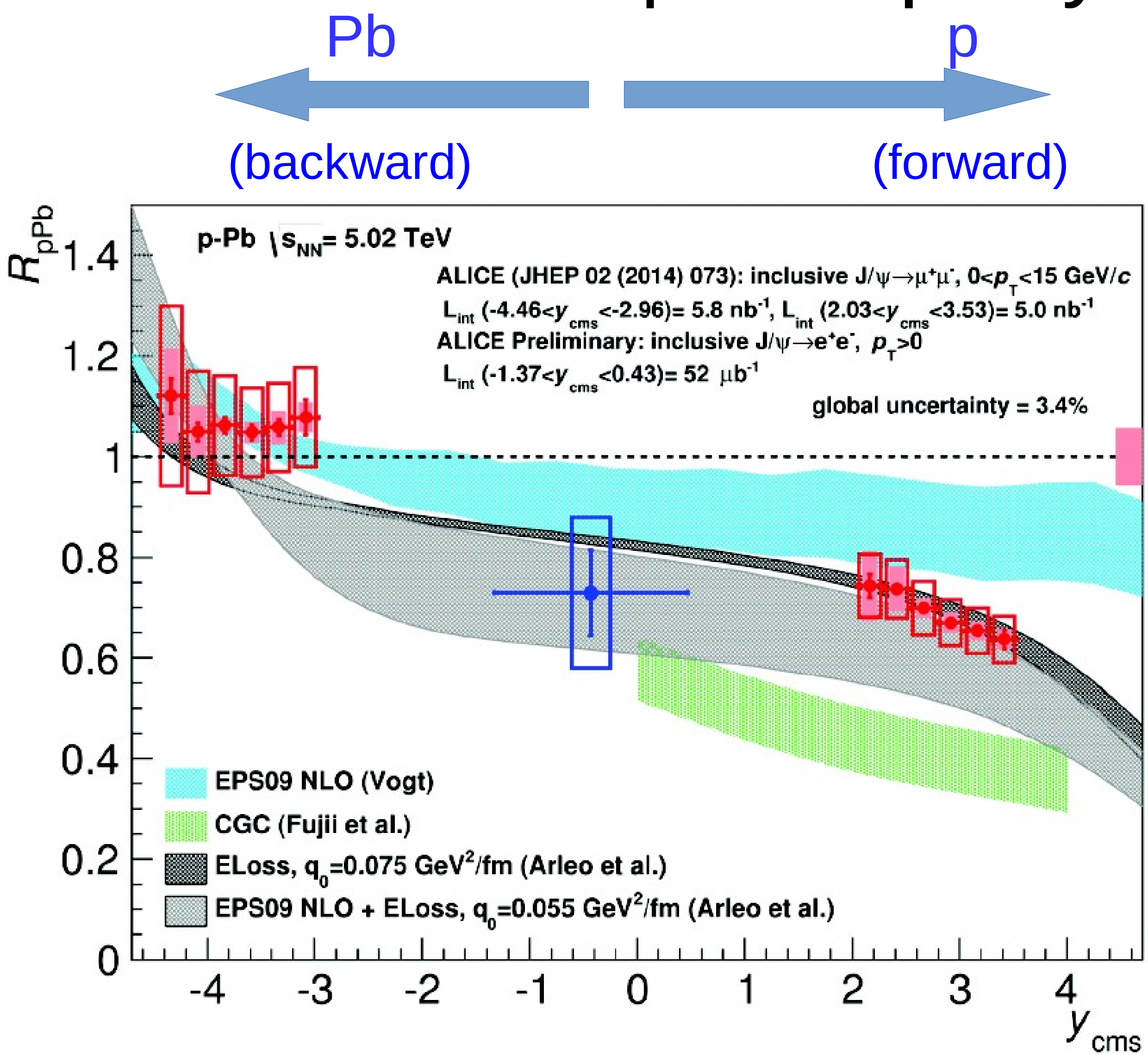
- Stronger suppression for Y(1S) at forward rapidity compared to mid-rapidity
- The models underestimate the Y(1S) suppression at forward rapidity

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
- Can we still use charmonia as a QGP probe at the LHC?
- Υ(2S) and Υ(3S) states are strongly suppressed in Pb-Pb collisions at all centralities
- The inclusive Υ(1S) is also suppressed BUT feed-down effects must be taken into account precisely
  - Is the direct Υ(1S) still suppressed after the feed-down corrections?

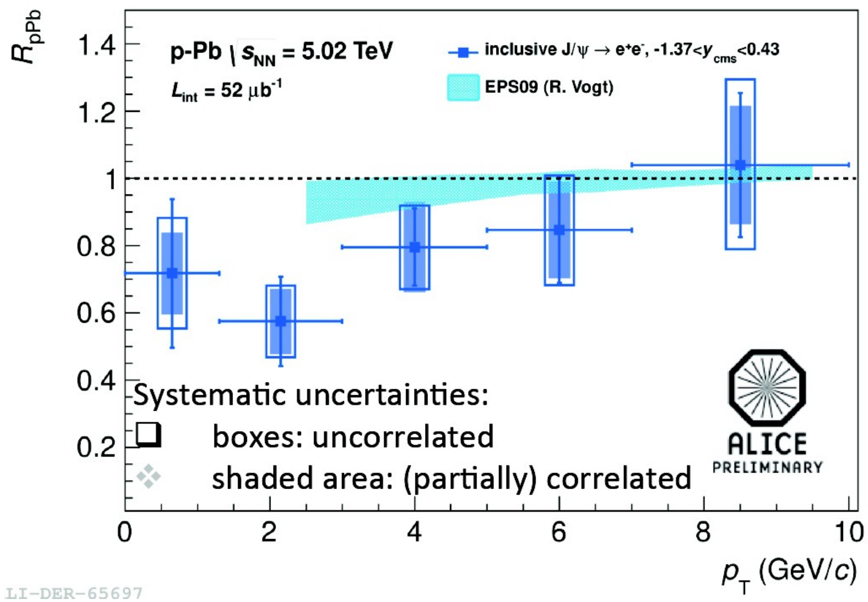
p-Pb @ 5 TeV

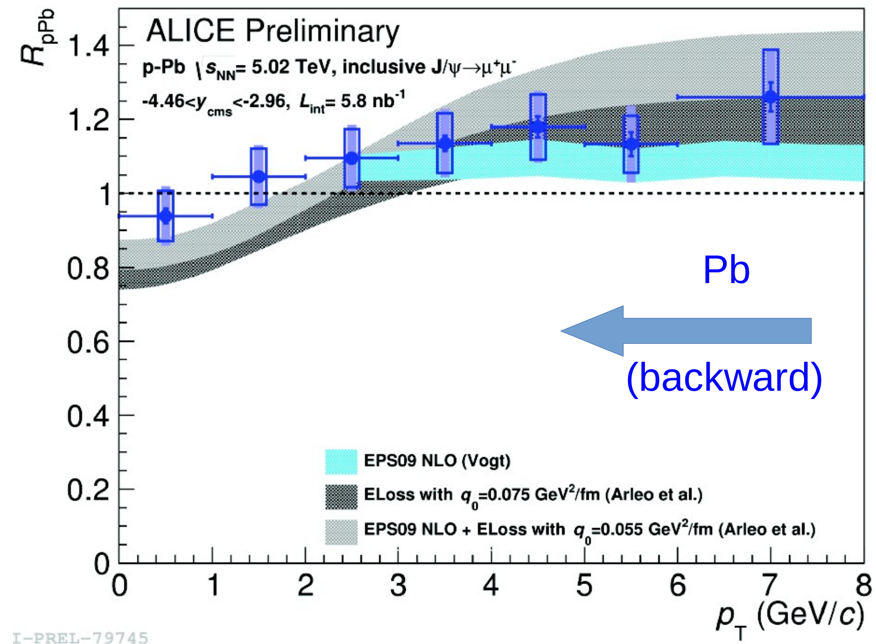
Inclusive J/ψ vs rapidity

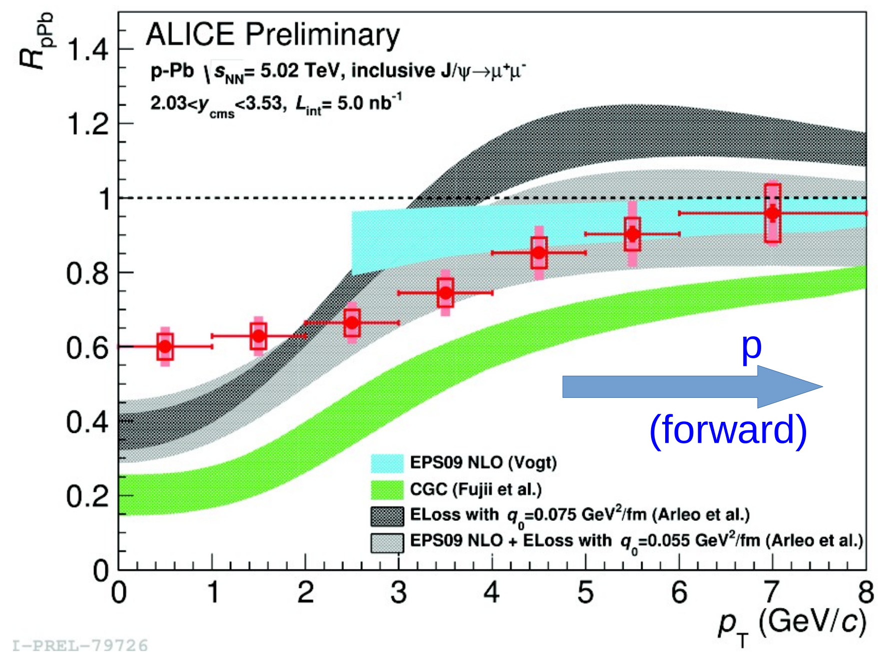


- J/ψ is suppressed at mid-rapidity and in the forward direction, compatible with energy loss (+shadowing) models
- No suppression observed in the backward direction

Inclusive J/ψ vs p_T



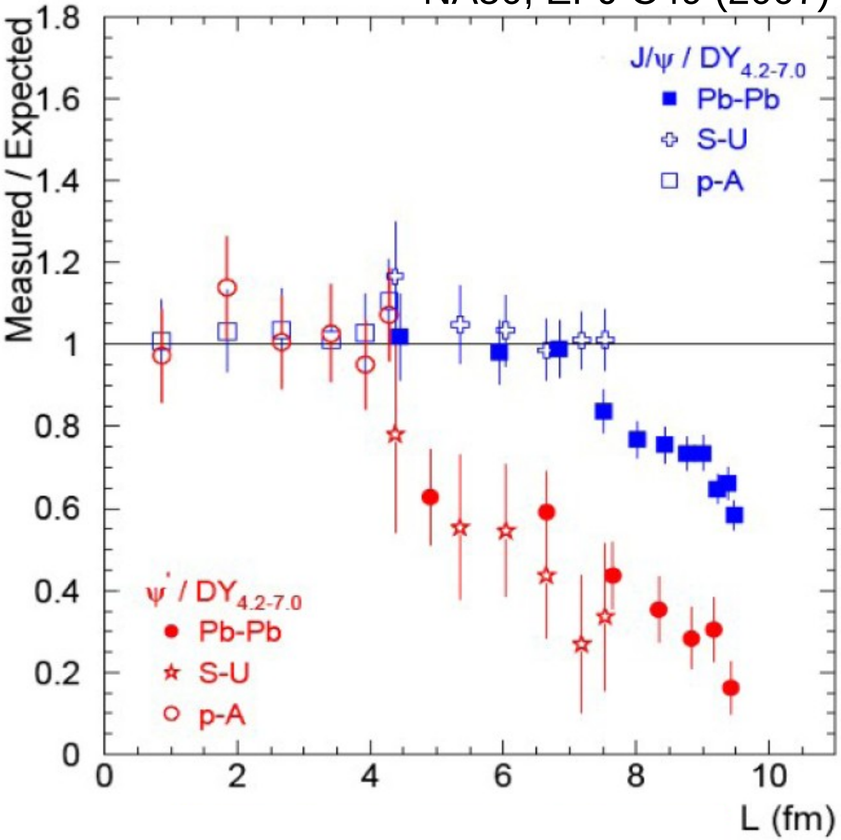




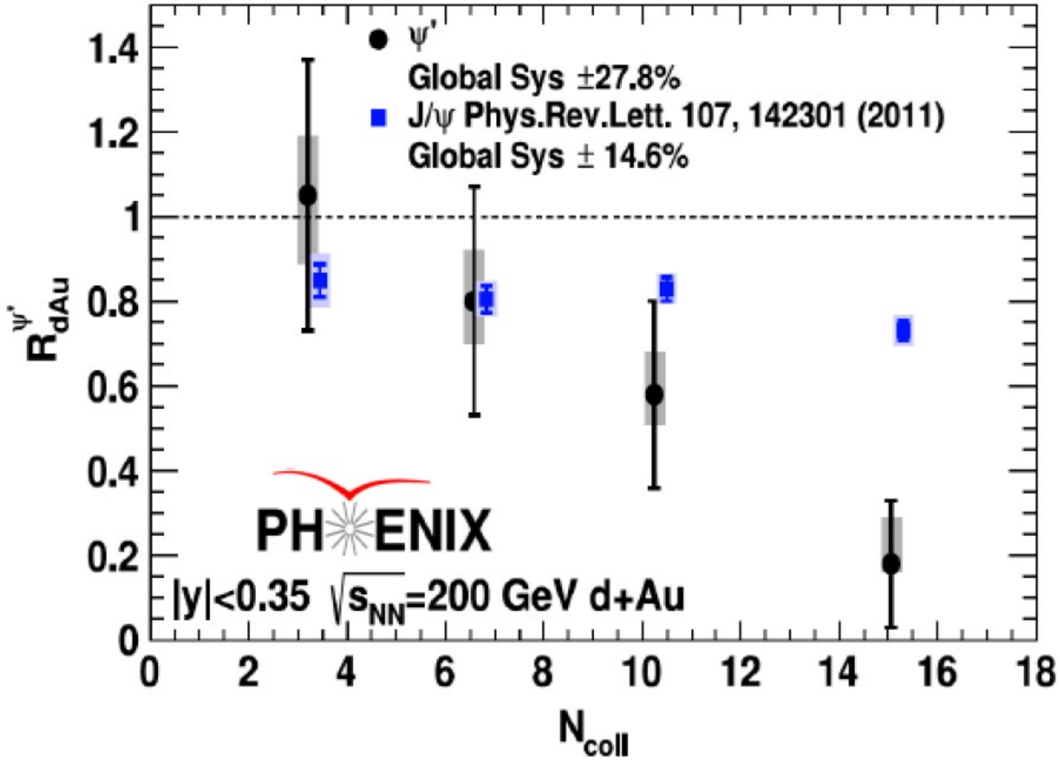
- J/ψ is suppressed at mid and forward rapidity, except for the highest p_T region
- R_{pPb} grows with p_T, consistent with expectations from shadowing and energy loss calculations
- Early CGC calculation overestimate the suppression at forward rapidity

ψ' at SPS and RHIC

NA50, EPJ C49 (2007)



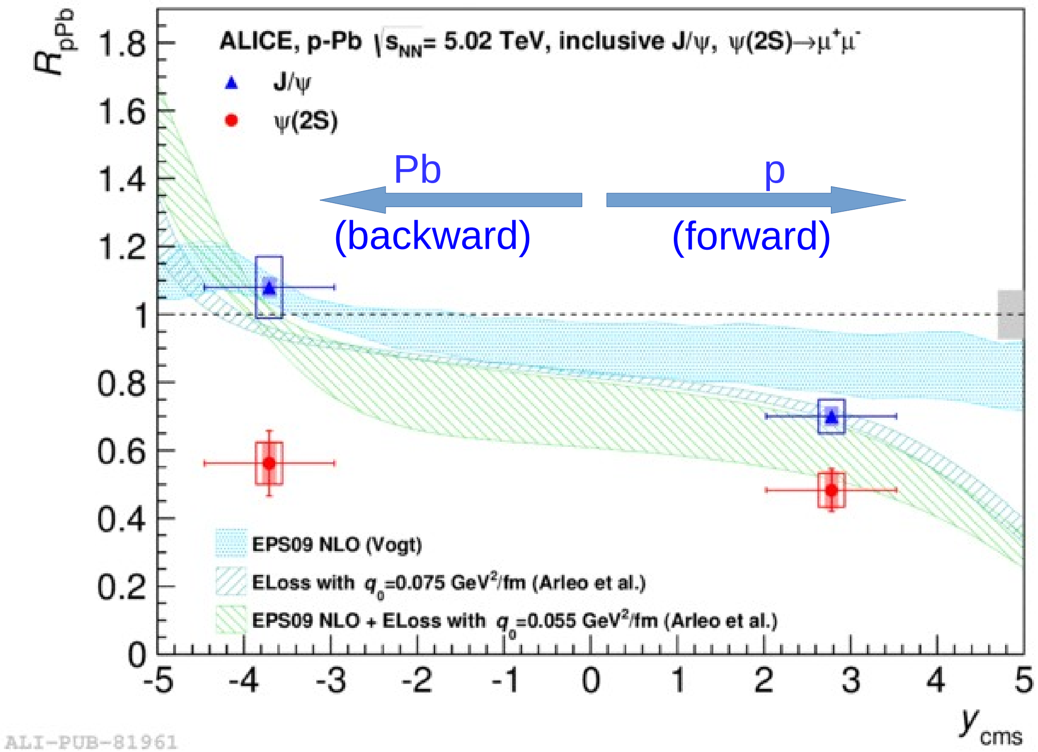
PRL 111 (2013) 202301



- ψ' suppressed at SPS in relatively small systems (like S-U), not in p-A
  - 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 CNM effects or formation time

ψ' at the LHC

arXiv:1405.3796



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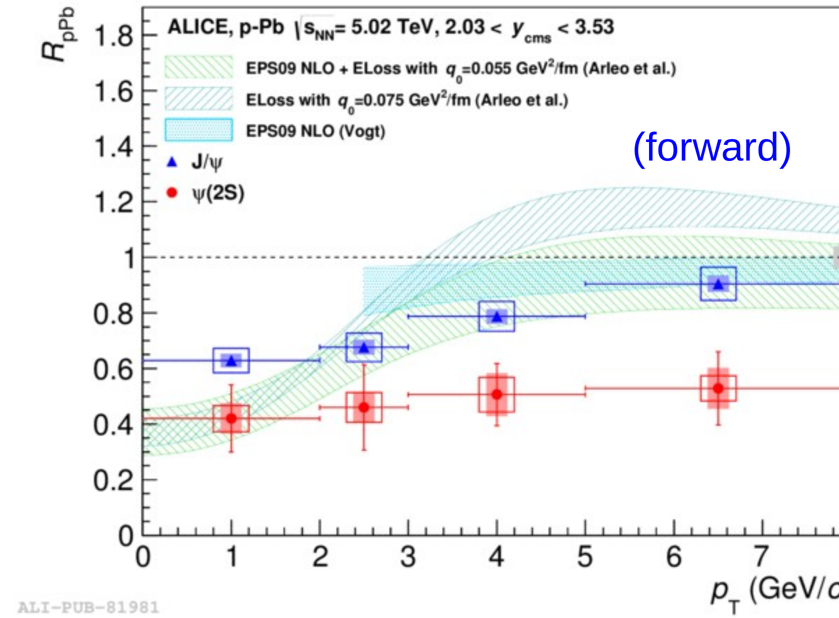
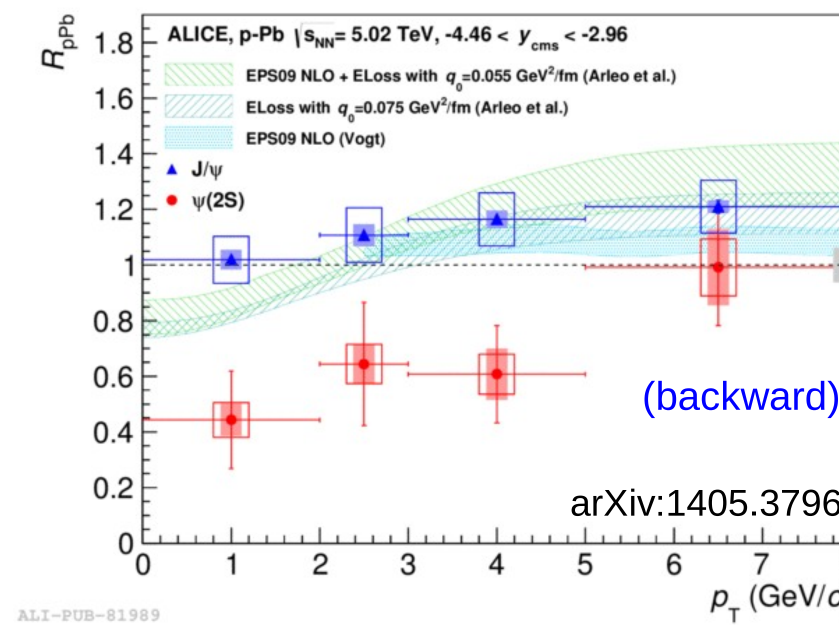
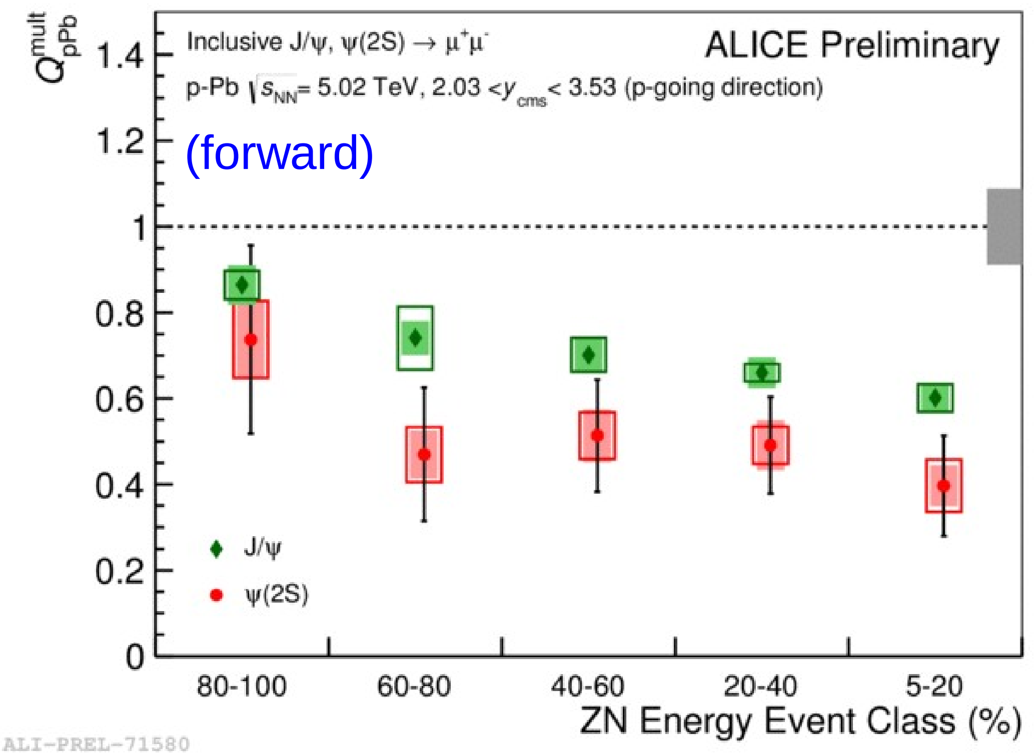
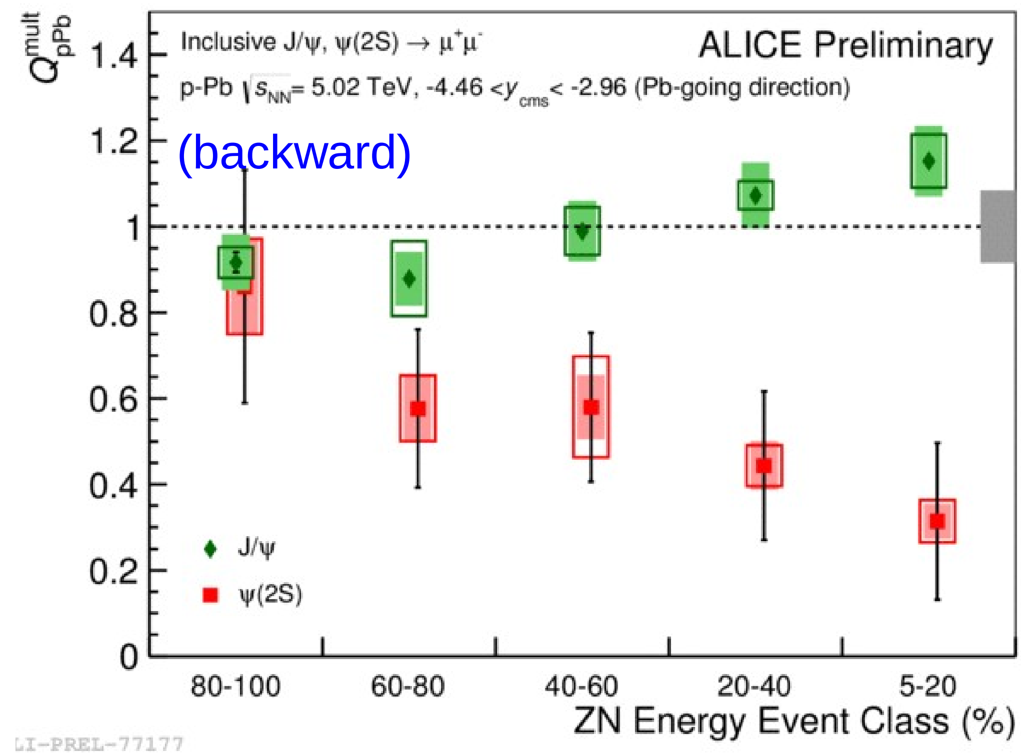




- Strong ψ' suppression observed in p-Pb at both forward and backward rapidities
- Not expected from either shadowing or energy loss models

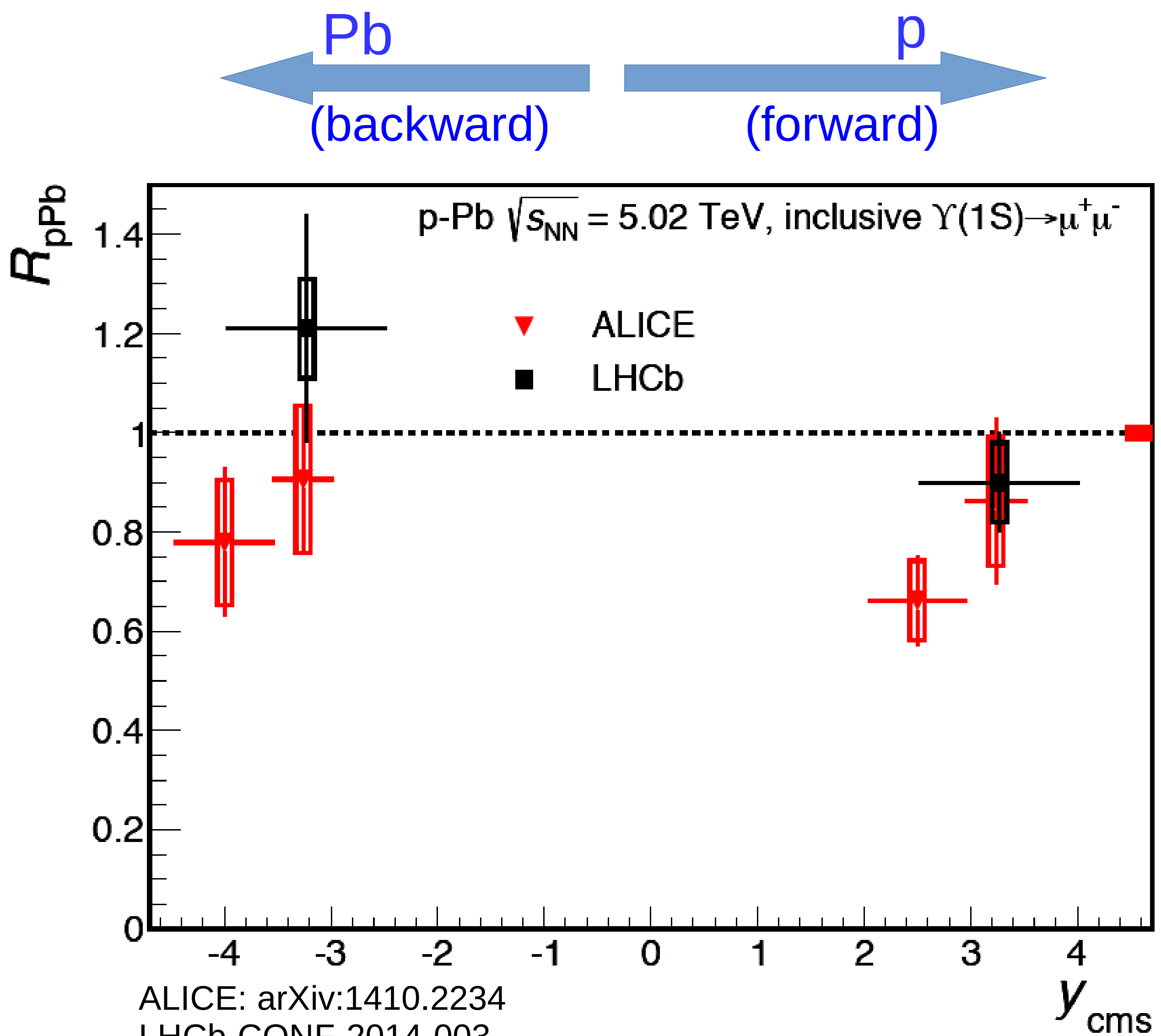
Charmonia vs event activity





- ψ' 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.

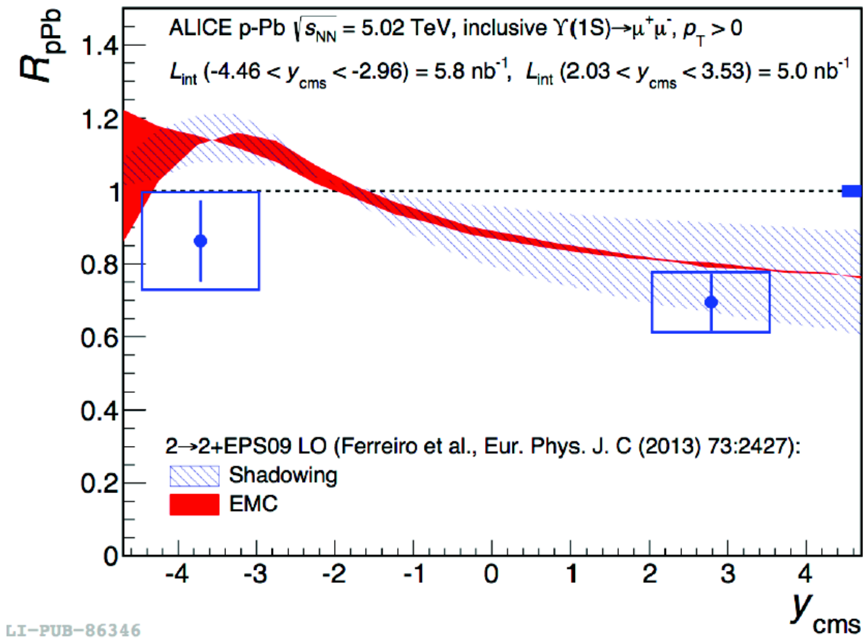
Inclusive Υ(1S)

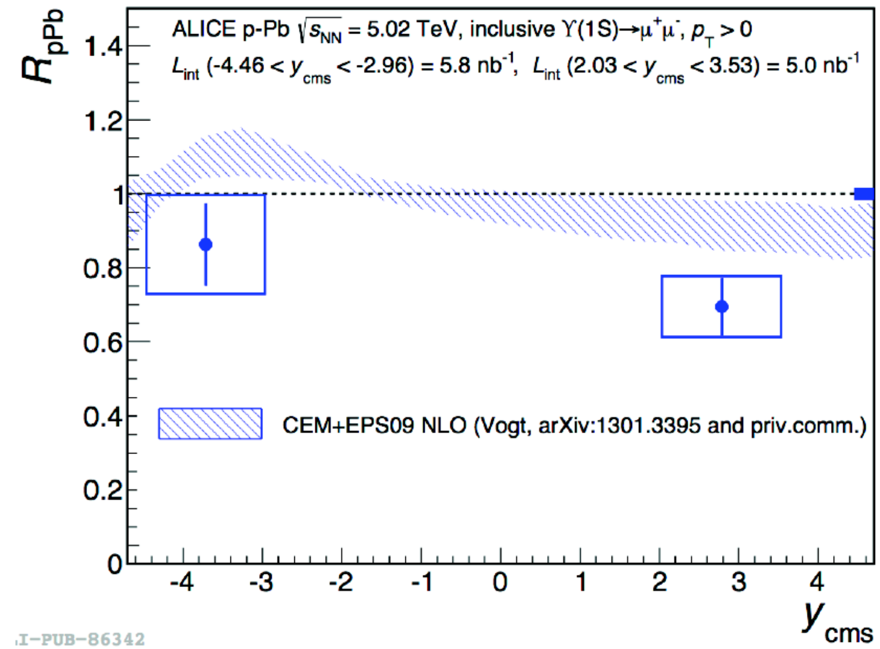


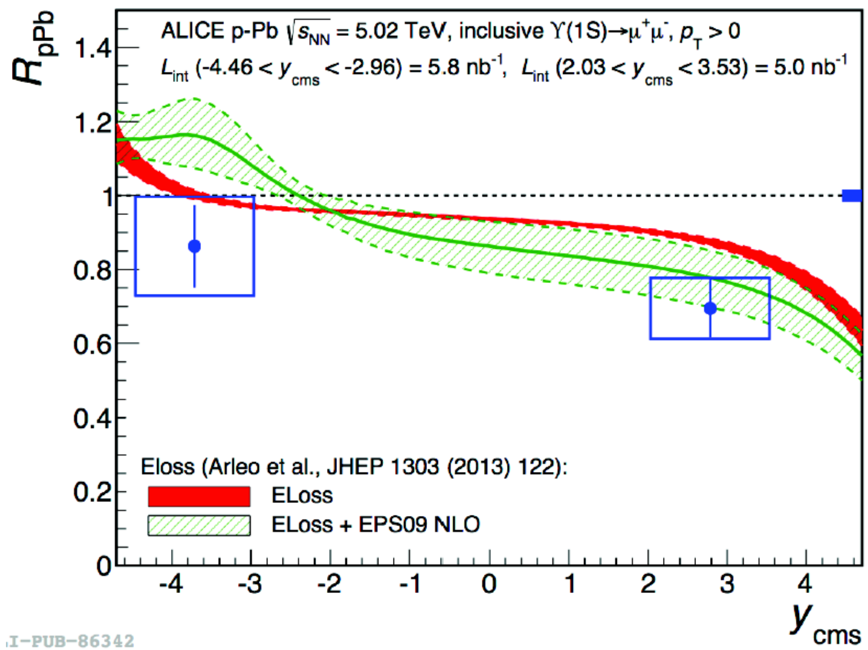
ALICE: arXiv:1410.2234
LHCb-CONF-2014-003

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

Inclusive Υ(1S)



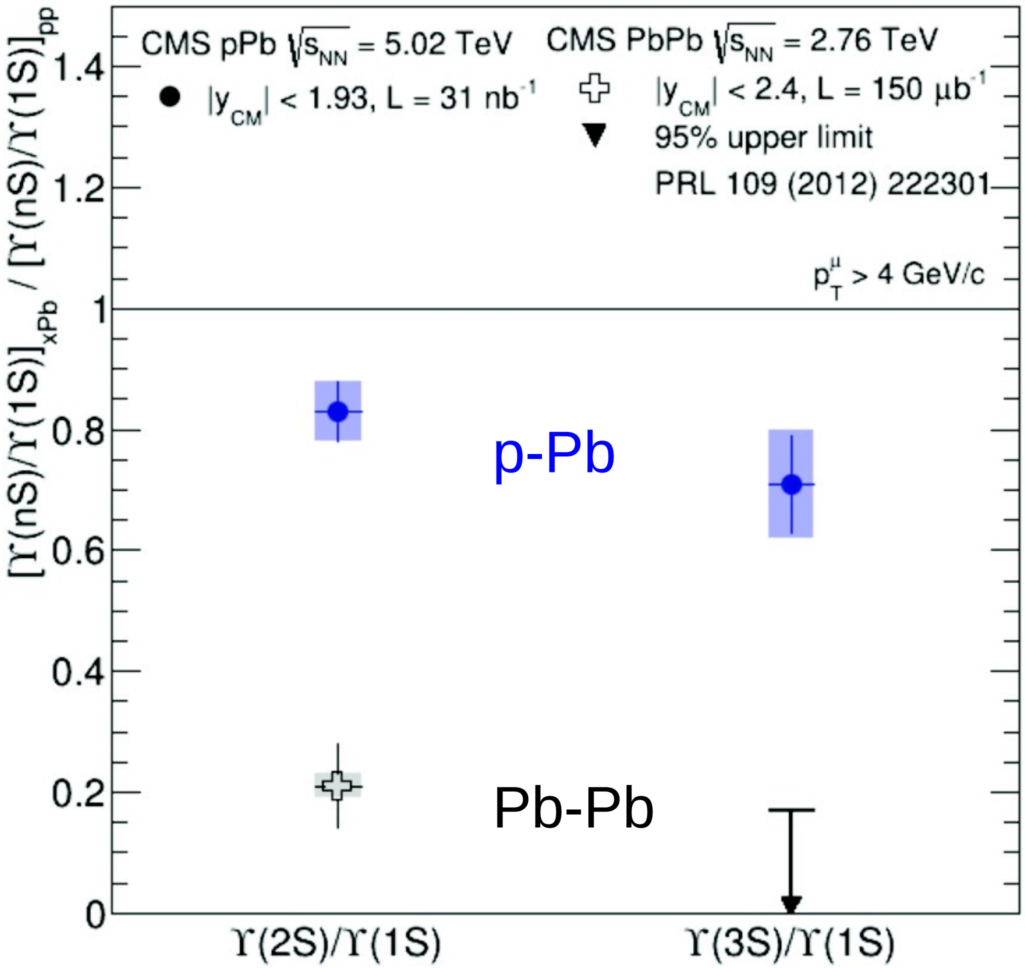




- Fair agreement with various calculations including:
  - 2->2 production model at LO (Ferreiro et al.)
  - CEM at NLO (Vogt)
  - Coherent parton energy loss (Arleo et al.)

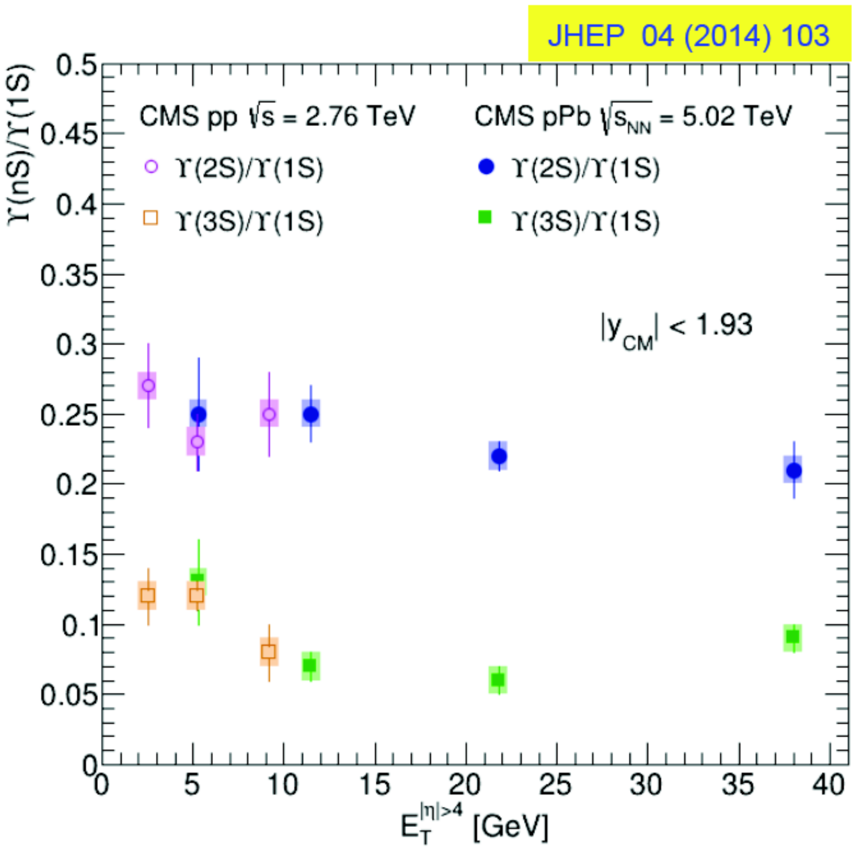
Inclusive Υ(2S) and Υ(3S)

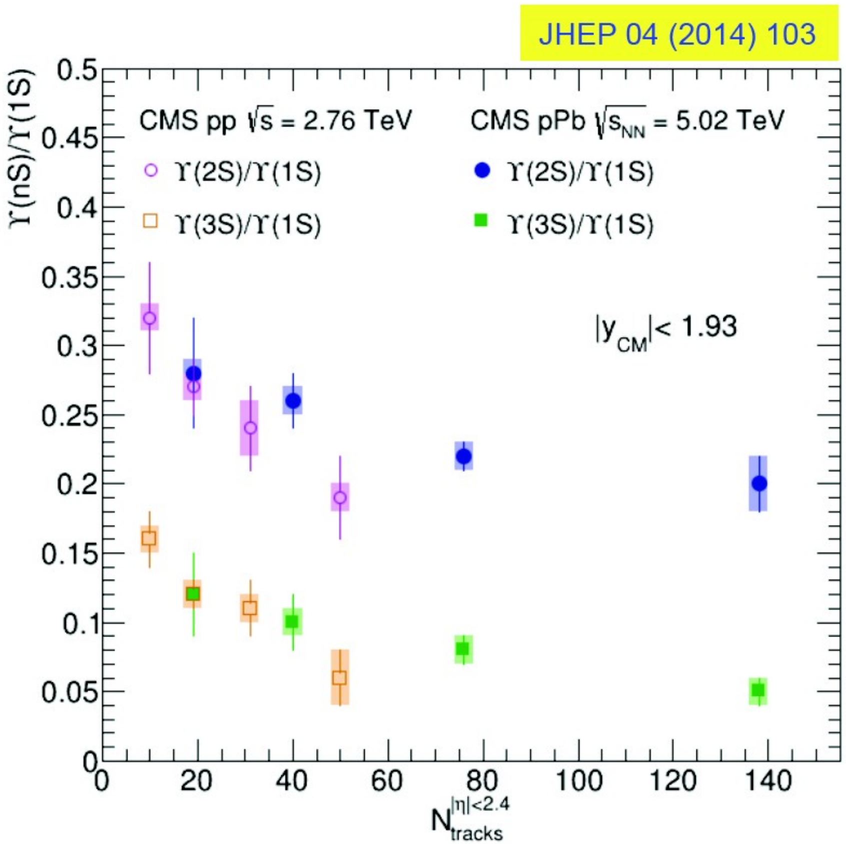
p-Pb data: JHEP 04 (2014) 103



- Excited states suppressed more w.r.t. to the ground state in p-Pb
- Similar effect seen for ψ'

Y(2S) and Y(3S)





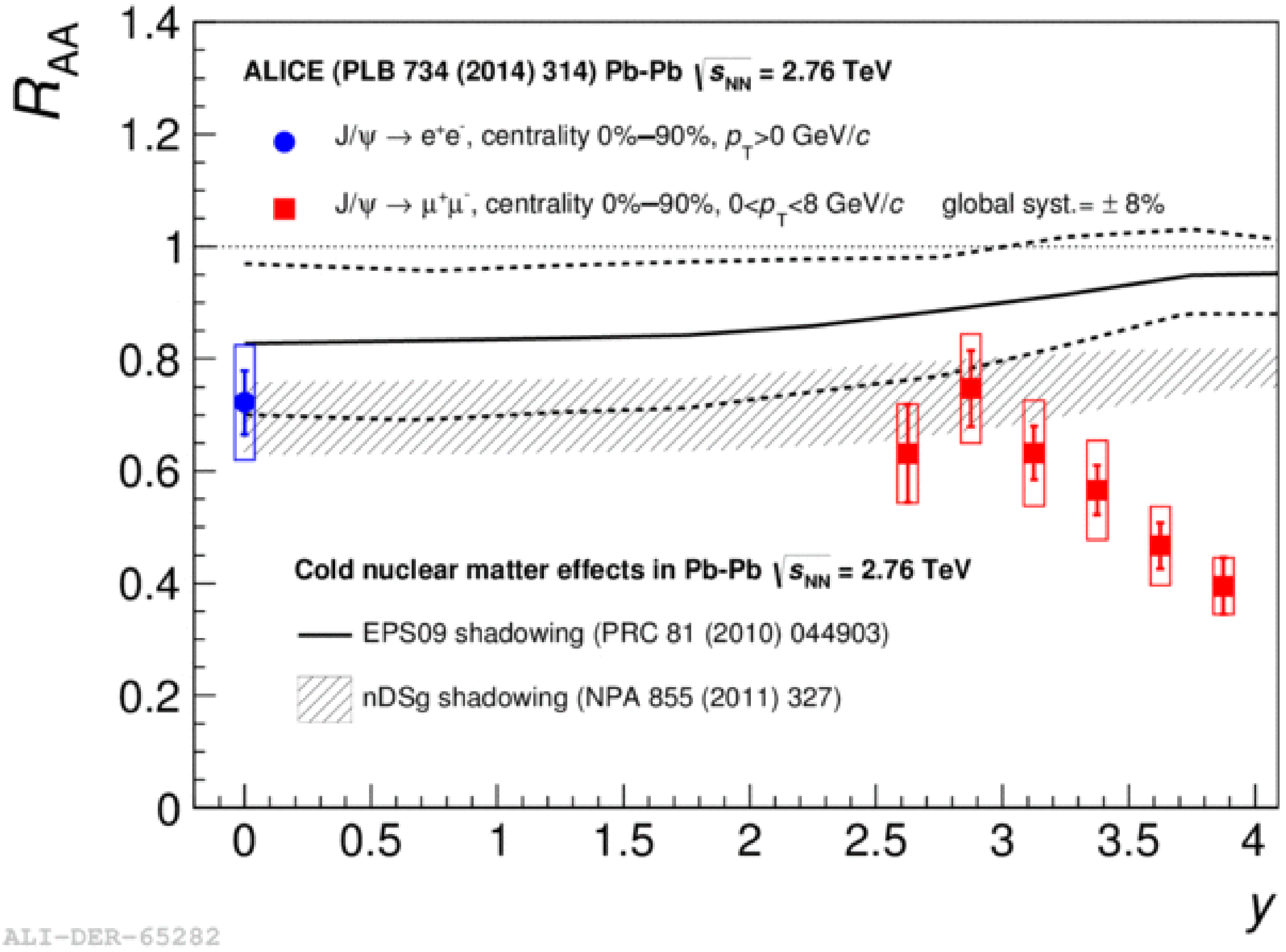
- Y(nS)/Y(1S) ratios decrease with the increasing forward transverse energy and mid-rapidity charged particle multiplicity
- Large local particle density (i.e. comovers) breaks the Y states?
- Possible bias on the event multiplicity depending on the Y state?

p-Pb summary

- The J/ψ and Υ(1S) measurements in p-Pb are compatible with shadowing and parton energy loss expectations
- The large ψ(2S) suppression beyond the one seen for J/ψ in p-Pb cannot be explained within the current models.
- The Υ(2S) and Υ(3S) states are also suppressed w.r.t. the ground state.
- The dependence of the ψ(2S), Υ(2S) and Υ(3S) suppression on event activity seem to indicate a comover-like final state effect in p-Pb collisions, not understood yet quantitatively

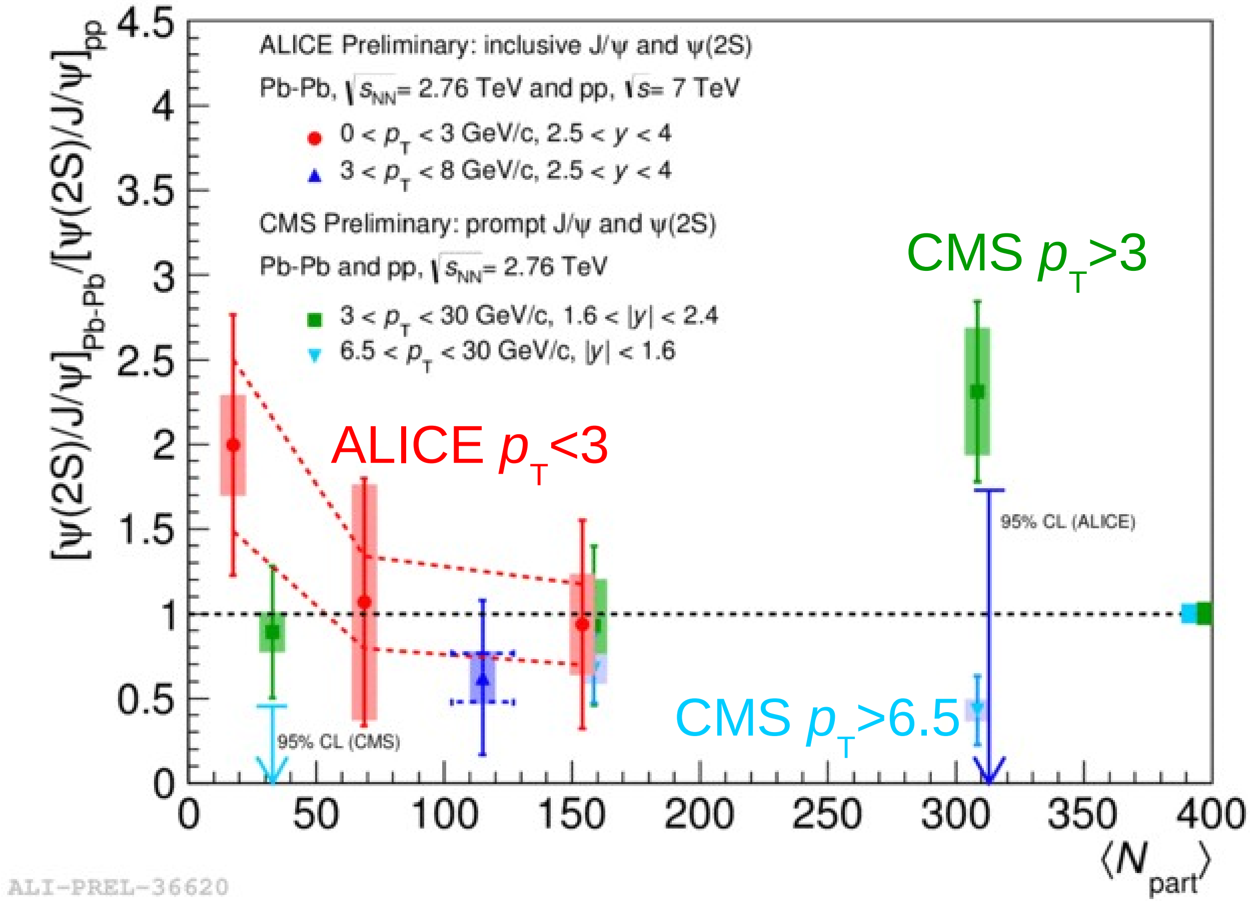
Backup

Inclusive J/ψ as a function of rapidity



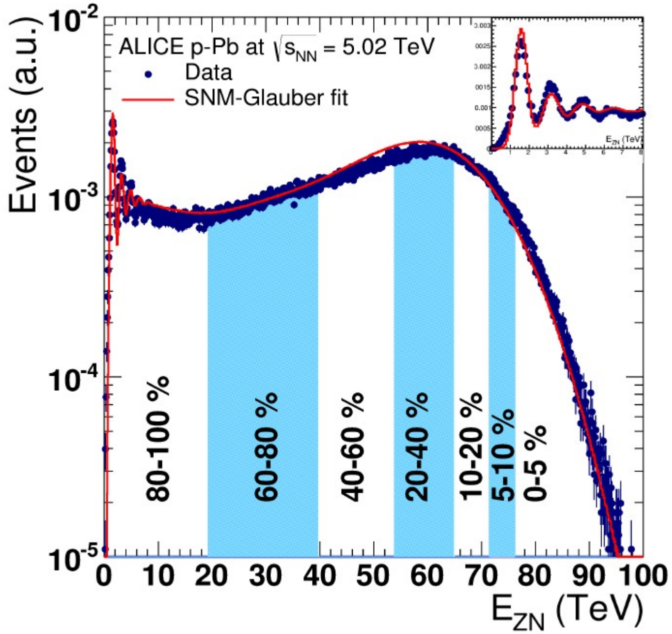
- Strong rapidity dependence for low-p_T at y>3 (ALICE)
  - CNM effects, (re)combination ?

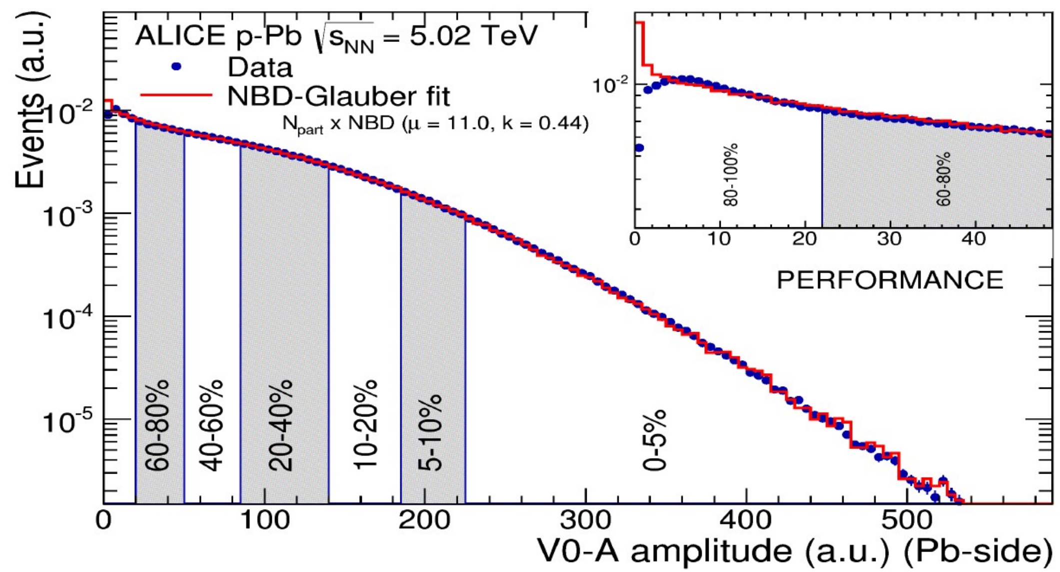
ψ' production

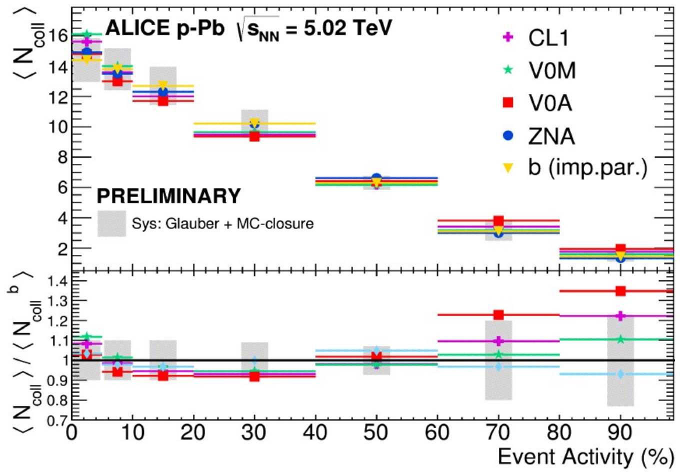


➢ No strong conclusion possible yet due to large uncertainties

p-Pb event activity



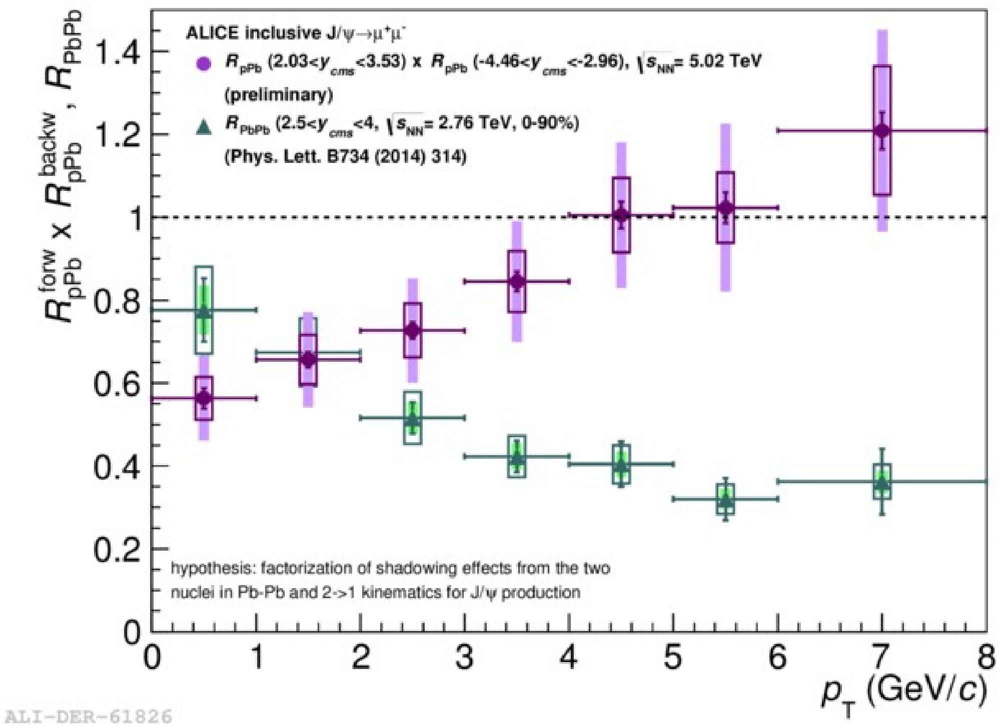


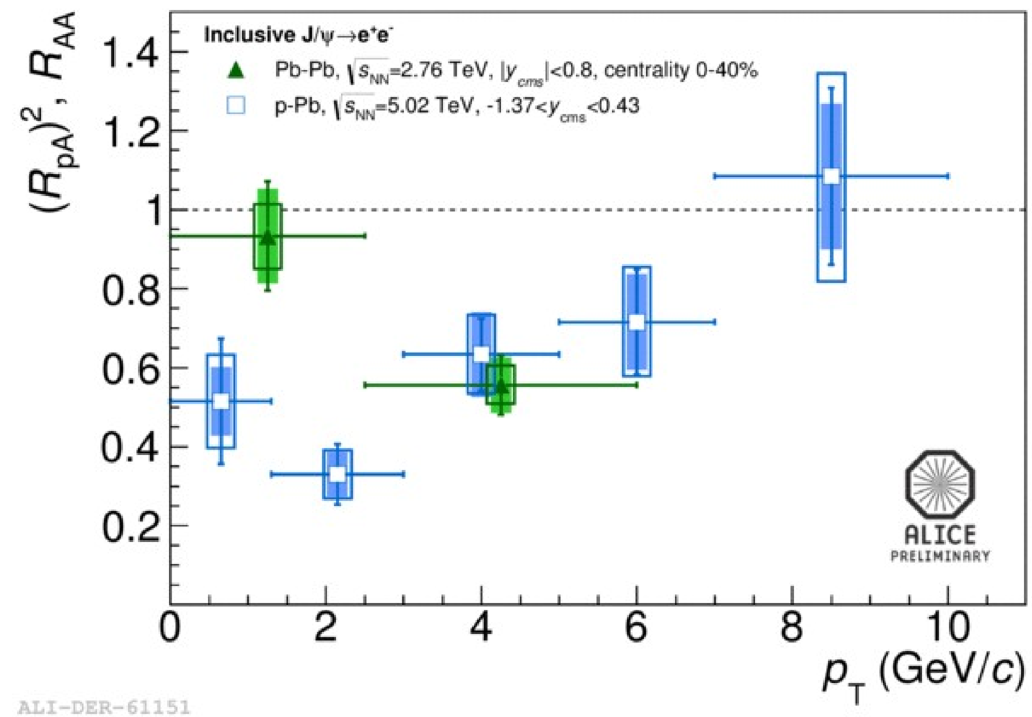


- Categorize events based on the multiplicity/energy measured with various detectors -> proxy to centrality
- Caveat: Correlation between multiplicity estimators and collision centrality much weaker compared to AA collisions -> posible biases!
- Assume p-Pb is a superposition of binary NN collisions and perform a Glauber fit, as for Pb-Pb
- Use the Glauber <N_{coll}> to define the nuclear modification factor in p-Pb event activity classes

$$R_{pPb} \to Q_{pPb} = \frac{Y^{i}_{pPb}}{\langle T^{i}_{pPb} \rangle \sigma^{J/\psi}_{pp}}$$

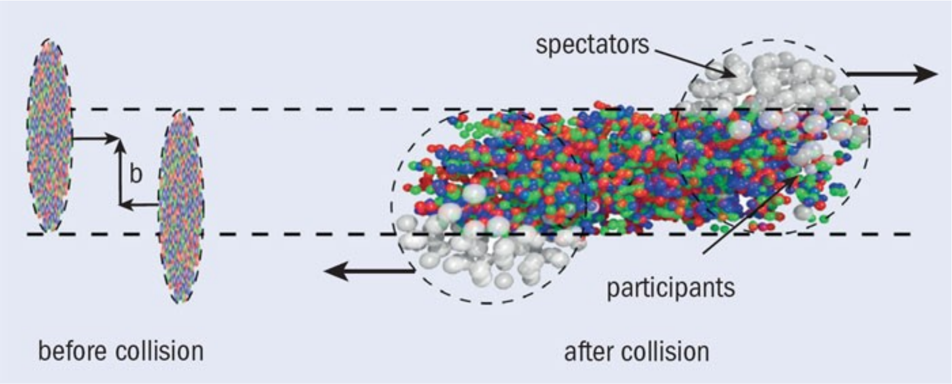
Quantifying CNM effects



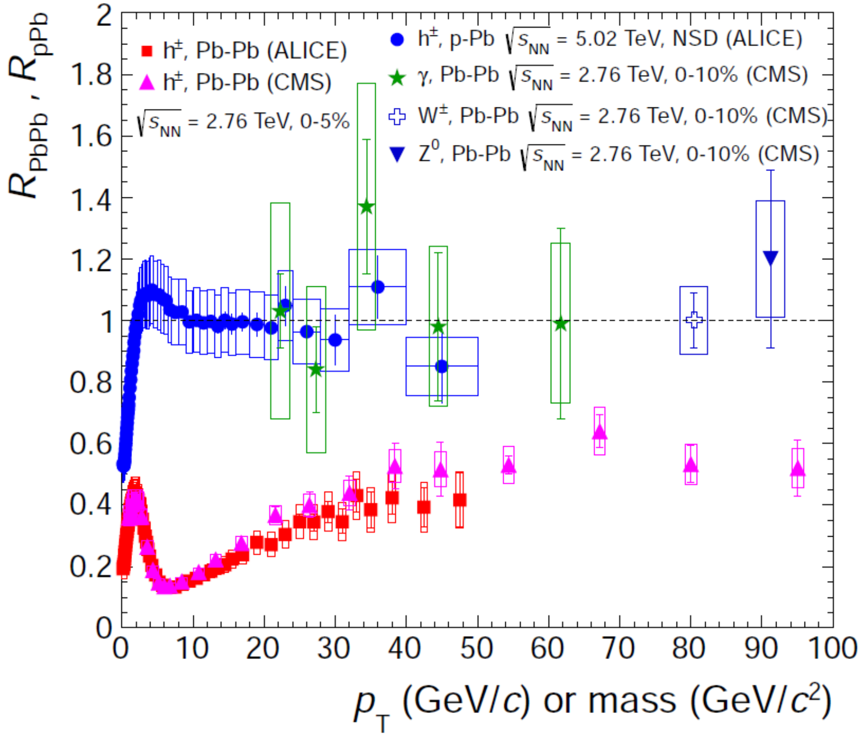


- Similar Bjorken-*x* ranges probed for Pb-Pb @ 2.76 TeV and p-Pb @ 5.02 TeV
- Assume 2->1 kinematics for the J/ψ production mechanism:
  - Factorization of shadowing effects: CNM(Pb-Pb) = $R_{pPb}(y>0) \times R_{pPb}(y<0)$
- At low p_T, (re)combination effects are equal or even larger than the suppression effects, when CNM effects are taken into account
- A large suppression is observed at forward rapidity and high p_T, where the CNM effects are negligible.

Quantifying medium effects -nuclear modification factor-



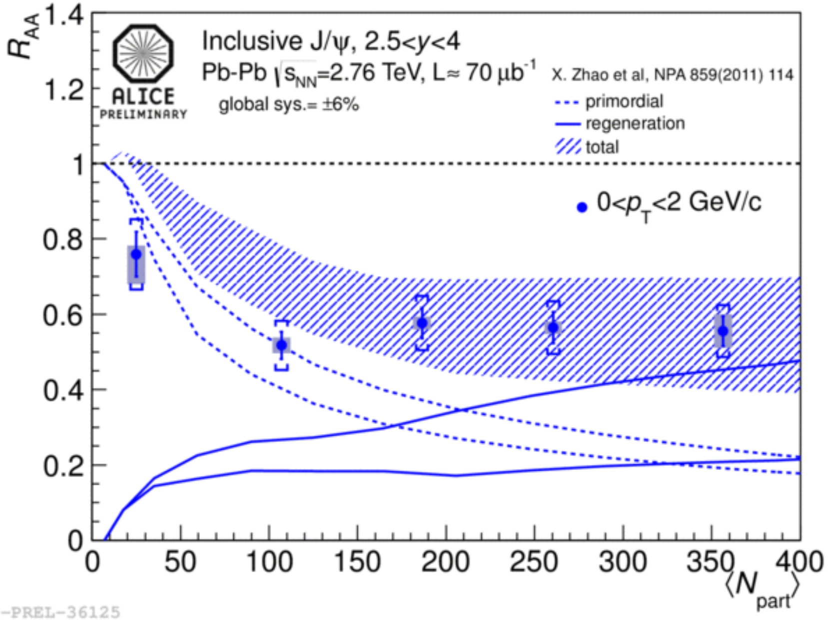
$$R_{AA} = \frac{d^2 N_{AA} / dp_T dy}{N_{coll} \times d^2 N_{pp} / dp_T dy}$$

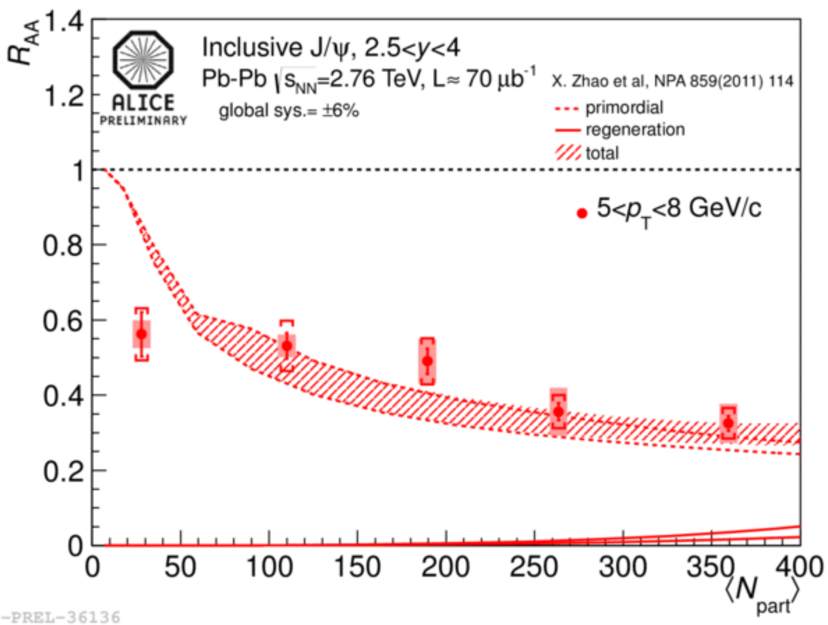


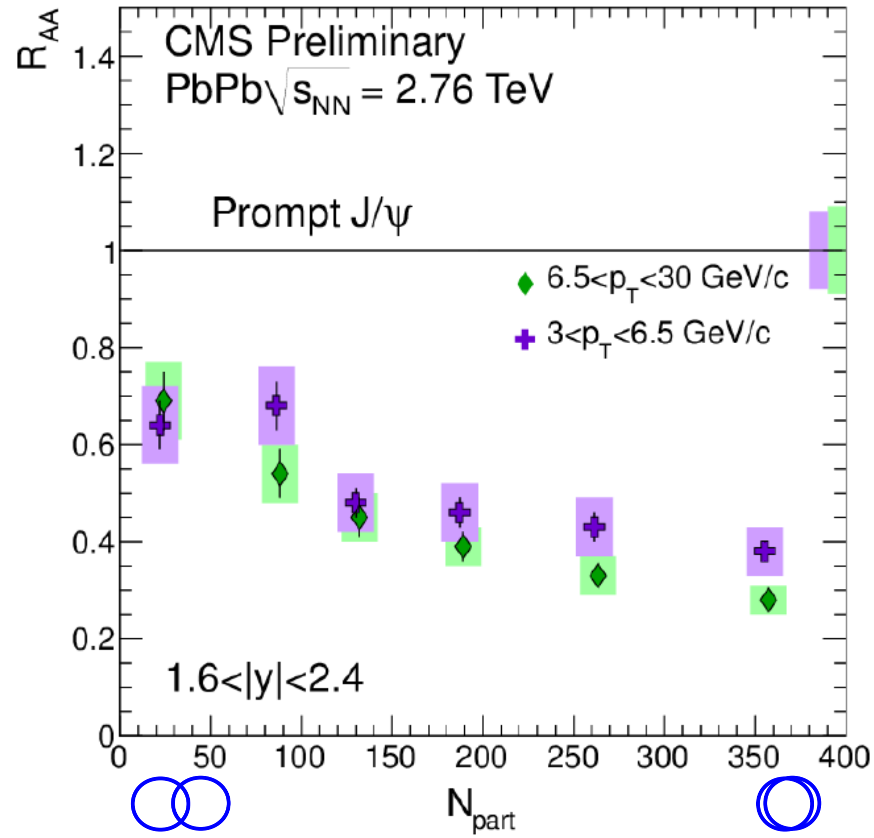
- Superposition of NN collisions → R_{AA}=1
- Strong suppression for light hadrons observed at LHC in Pb-Pb collisions
- Weakly interacting particles are not affected by the QGP
  - Photons, $W^{\pm}$ and Z^0 R_{AA} is compatible with unity.

p-Pb, ALICE EPJ C74 (2014) 9, 3054
Pb-Pb, ALICE, Phys.Lett.B720 (2013)52
Pb-Pb, CMS, EPJC (2012) 72
γ, CMS, PLB 710 (2012) 256
$W^{\pm}$, CMS, PLB715 (2012) 66
Z^0, CMS, PRL106 (2011) 212301

J/ψ as a function of p_T







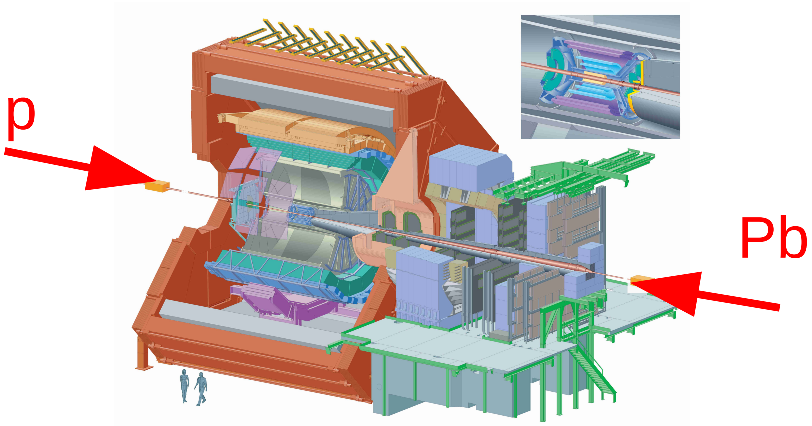
- Less suppression observed at low p_T (ALICE)
  - 50% of the J/ψ yield produced via (re)combination in transport models
- Stronger suppression and centrality dependence at high p_T (CMS, ALICE)

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

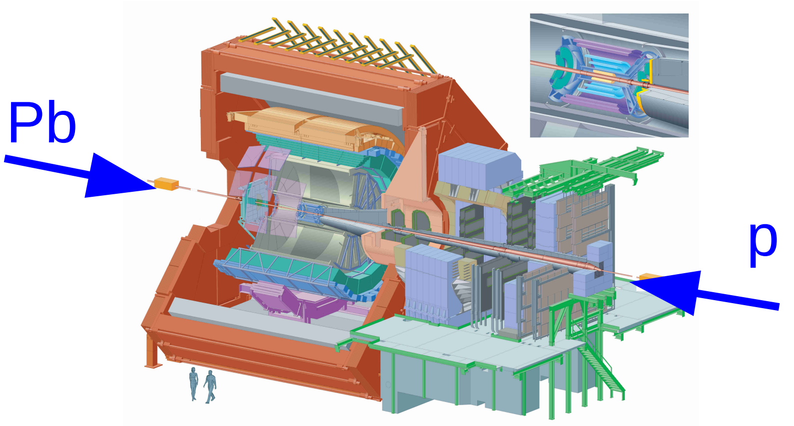
p Pb (p-going)

p-Pb, $-1.37<y<0.43$, L_{int} = 52 μb^{-1}
$2.03<y<3.53$, L_{int} = 5.0 nb^{-1}

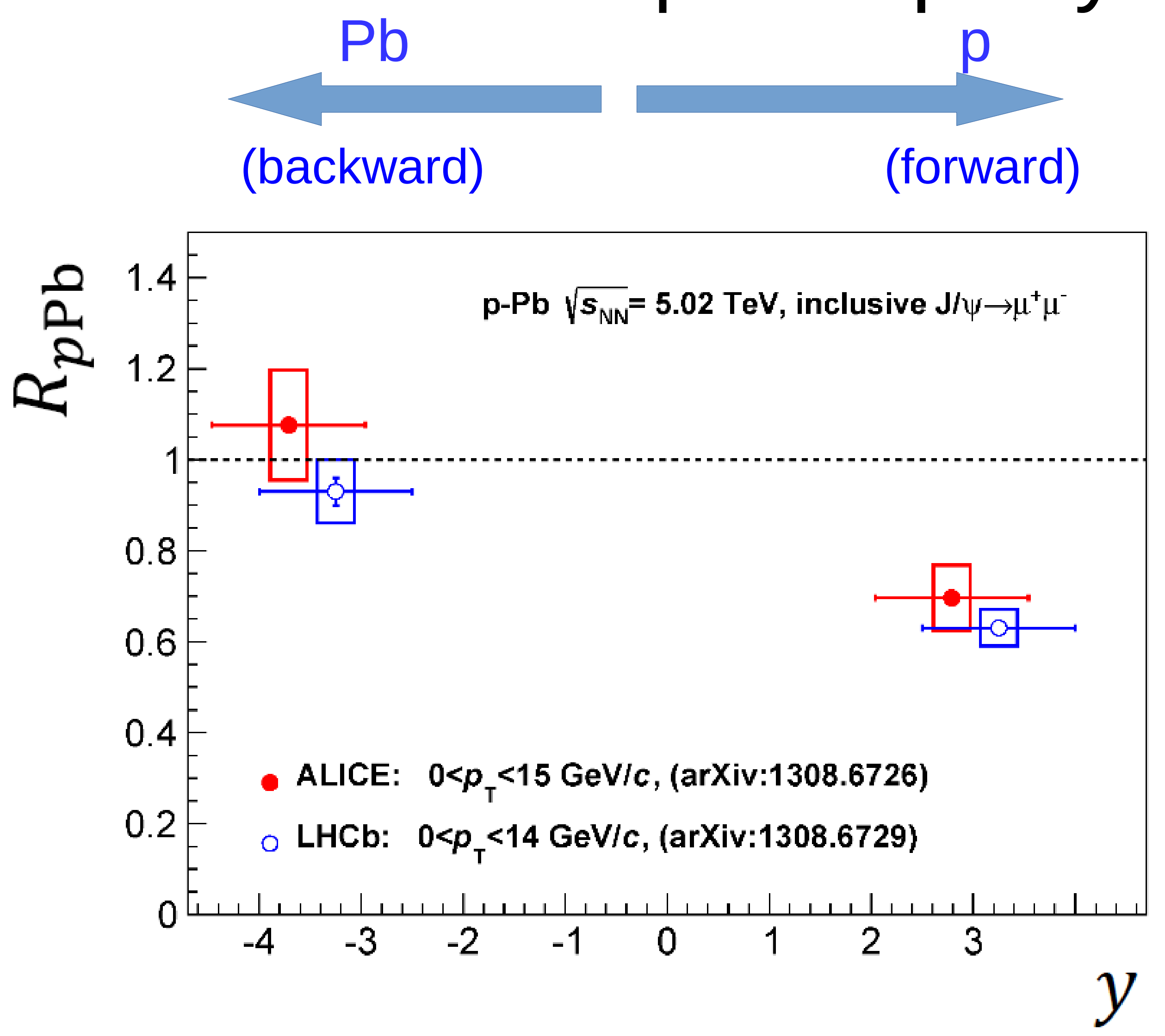


Pb p (Pb-going)

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



Inclusive J/ψ vs rapidity



- 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

J/psi vs pt in event activity categories