Quarkonium production in p-A and A-A collisions

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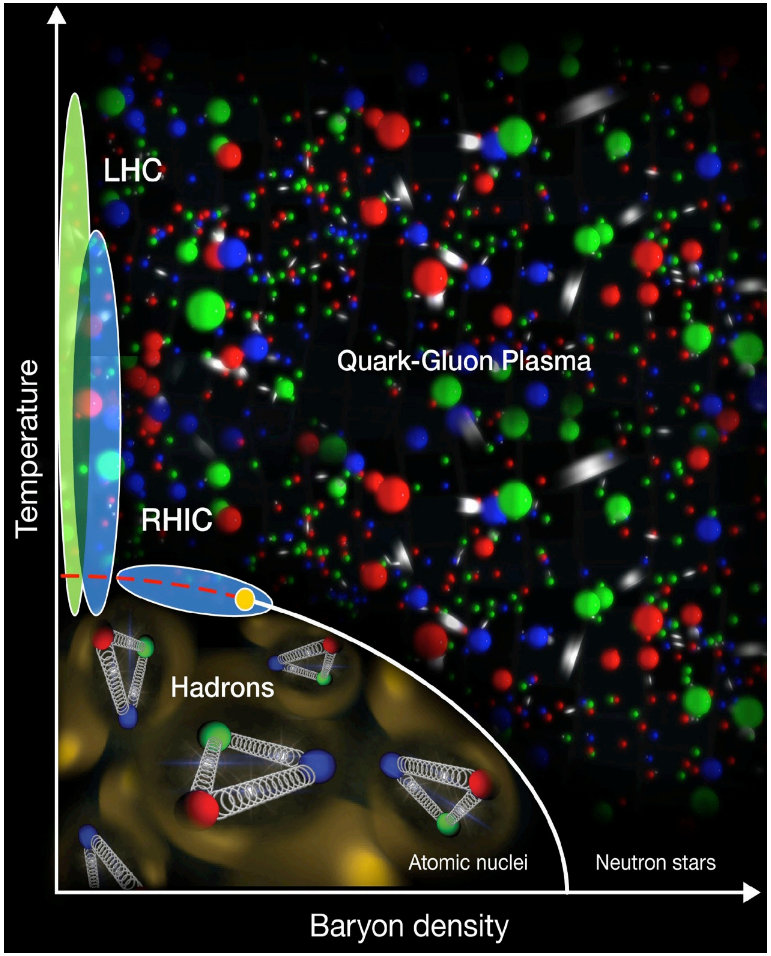
Outline

- ✧ Quark-Gluon Plasma vs Cold Nuclear Matter
- ✧ Pb-Pb results
- ✧ p-Pb results
- ✧ From p-Pb to Pb-Pb
- ✧ Summary and outlook

Quark-Gluon Plasma



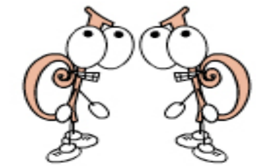
- QCD: strong force describes the interactions between quarks and gluons forming hadrons.
- Lattice QCD predicts a deconfined state of matter (QGP) at high temperature.
- QGP can be recreated in Heavy-Ion Collisions (HIC) at hadron colliders.
- QGP lifetime is small (~2-4 fm/*c* at RHIC, ~15-20 fm/*c* at the LHC)*, a direct observation of the QGP is not possible.
- Experimental probes of QGP: jet quenching, strangeness enhancement, quarkonia, etc.

* 1 fm/c ~ 10^{-24} sec

Quarkonia, a key tool for the QGP

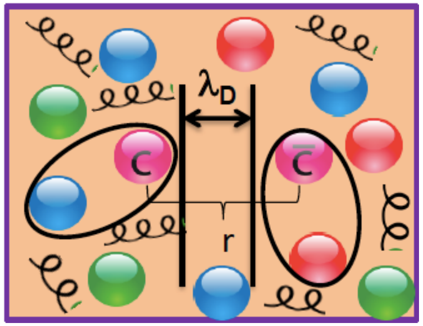
- ✧ Bound states of charm or beauty quark and its anti-quark
- ✧ Heavy and tightly bound

$c + \bar{c}$ = charmonia (J/ψ, ψ(2S), …)



$b + \bar{b}$ = bottomonia (ϒ(nS))

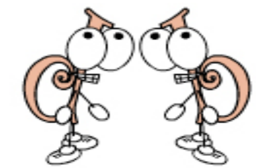
- ✧ Heavy quark pairs produced in the initial hard partonic collisions.
- ✧ **Suppressed** by Debye color screening:
  - ❖ Color charge of one quark masked by surrounding quarks.
  - ❖ Prevents $q\bar{q}$ binding in the QGP.
  - ❖ Debye screening radius (λ_D) vs quarkonium radius (r).
  - ❖ $\lambda_D < r \Rightarrow$ the quarks are effectively masked from each other.



Suppression vs enhancement

- ✧ Bound states of charm or beauty quark and its anti-quark
- ✧ Heavy and tightly bound

$c + \bar{c}$ = charmonia (J/ψ, $\psi(2S)$, …)



$b + \bar{b}$ = bottomonia ($\Upsilon(nS)$)

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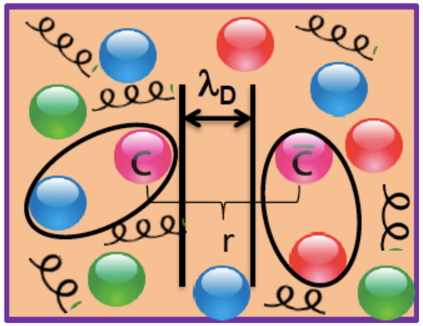
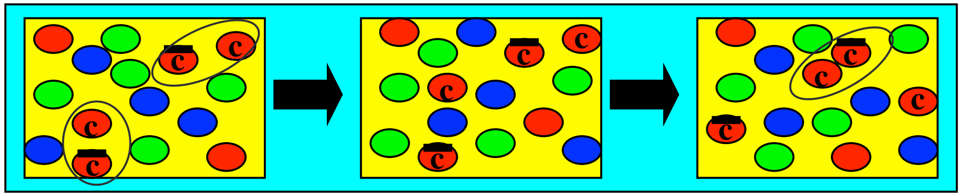
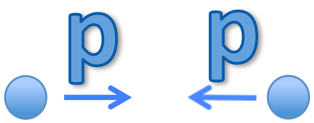


- ✧ **Recombination**
  - ✓ In central HIC, $N_{c\bar{c}} > 1$. (RHIC: ~10; LHC: ~100).
  - ✓ Regeneration of J/ψ pairs possible from independently produced c & $\bar{c}$

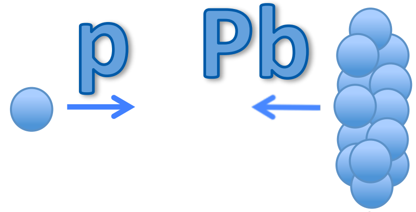


- ➢ Leads to an enhancement of J/ψ (or less dramatic suppression if 2 effects compete).
  - ❑ No/small regeneration is expected for bottomonia.

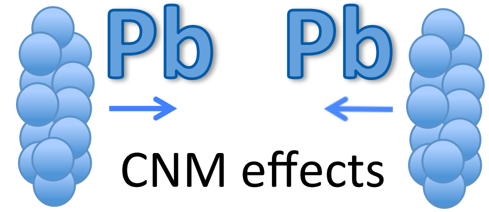
Nuclear matter effects



Elementary collision
No nuclear matter effects

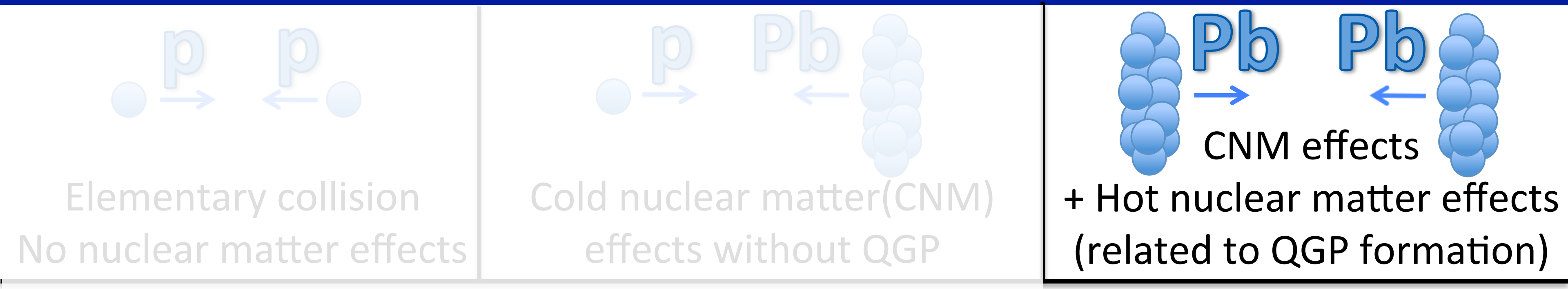


Cold nuclear matter(CNM)
effects without QGP



CNM effects
+ Hot nuclear matter effects
(related to QGP formation)

Nuclear matter effects



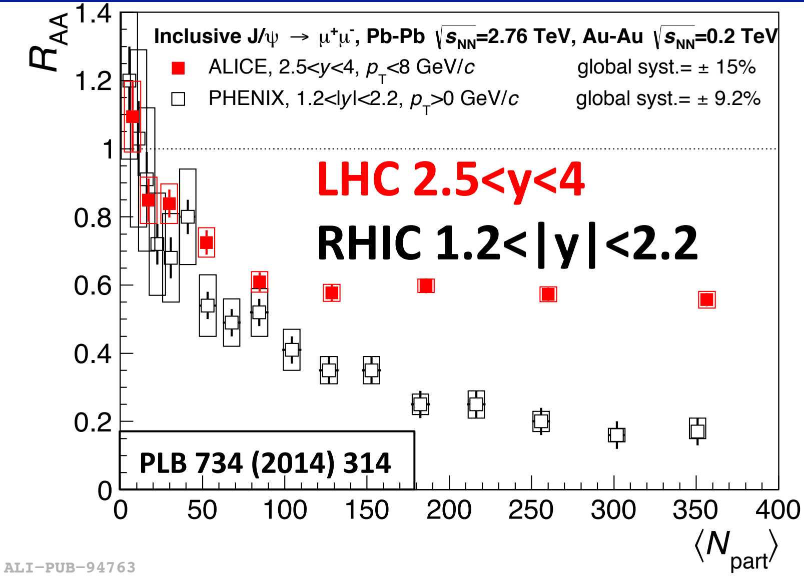
Main observable:

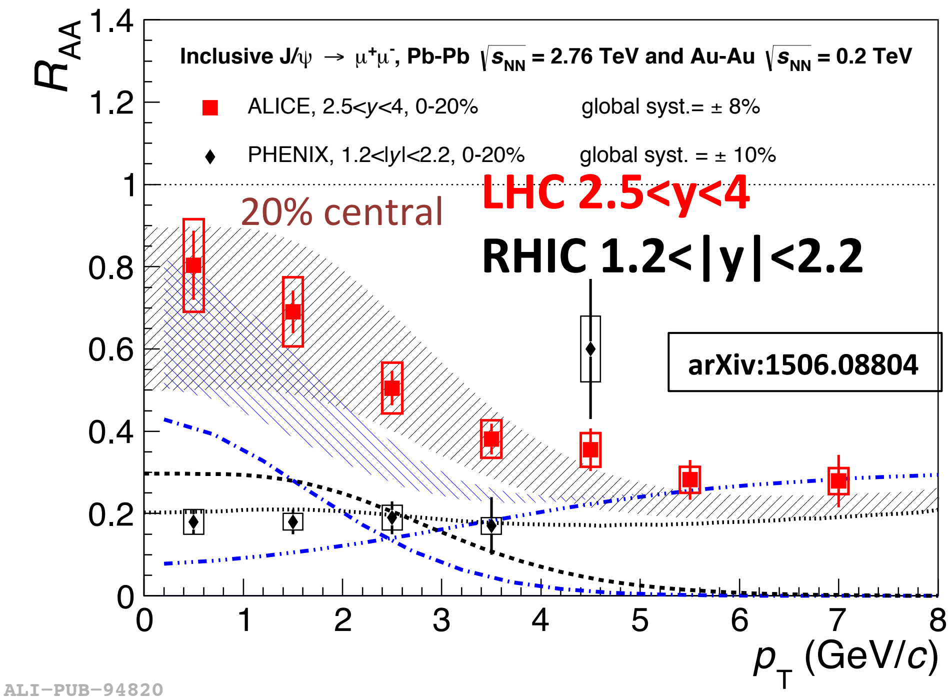
$$R_{AA} = \frac{Y_{AA}}{N_{coll} Y_{pp}}$$

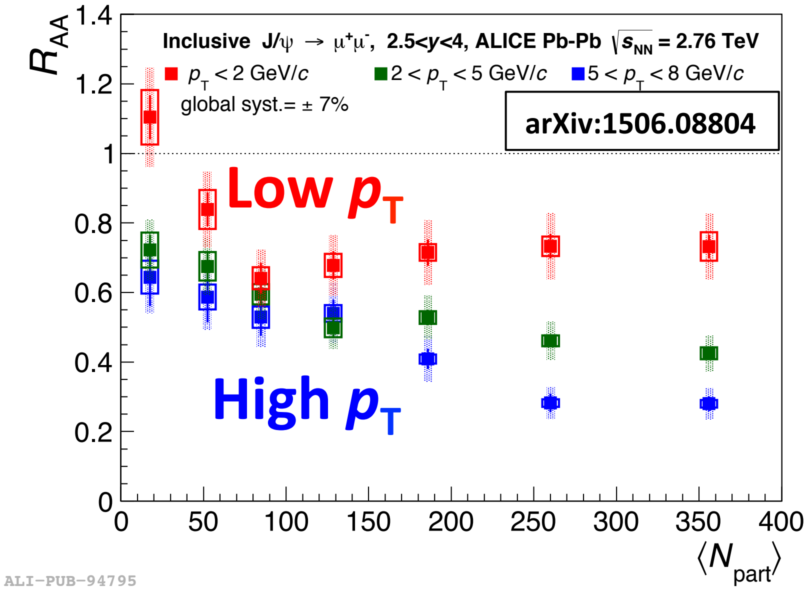
ratio of the production yield in AA to that in pp, scaled by the number of binary nucleon-nucleon collisions.

❖ If $R_{AA} \neq 1 \Rightarrow$ there are some nuclear matter effects.

J/ψ suppression in Pb-Pb

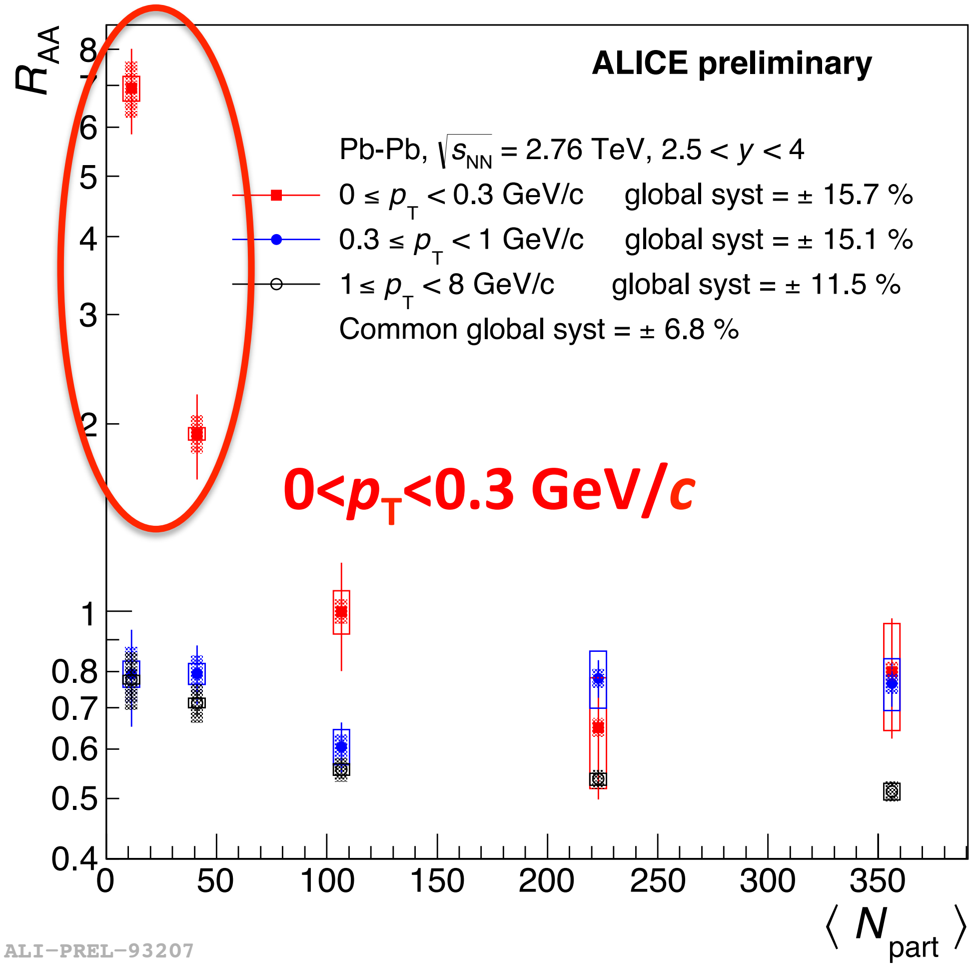


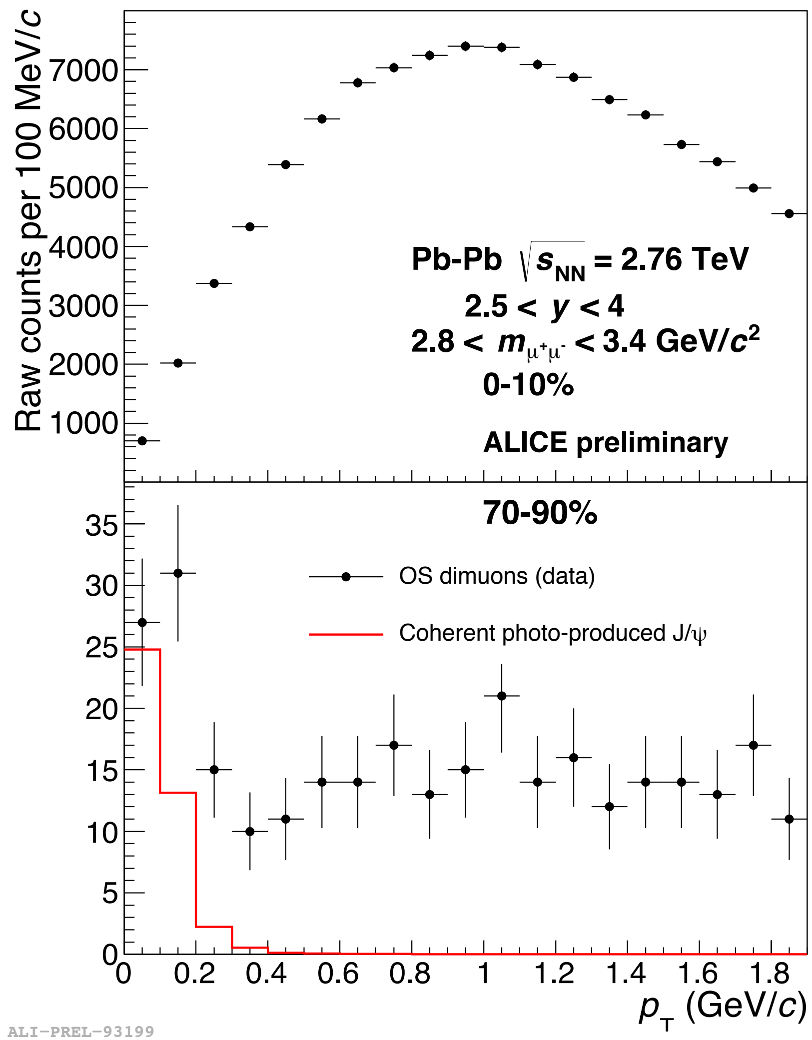




- Different R_{AA} at LHC vs RHIC: recombination.
- Regeneration is larger at low p_T.
- High-p_T J/ψ are suppressed.
- J/ψ suppression is less pronounced in central compared to peripheral collisions.

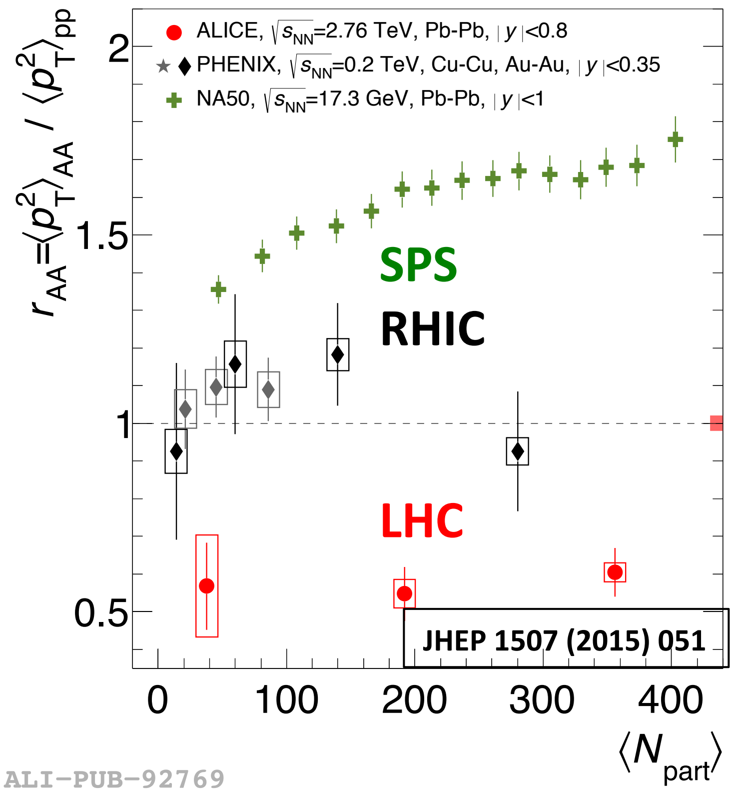
Low-p_T J/ψ in Pb-Pb

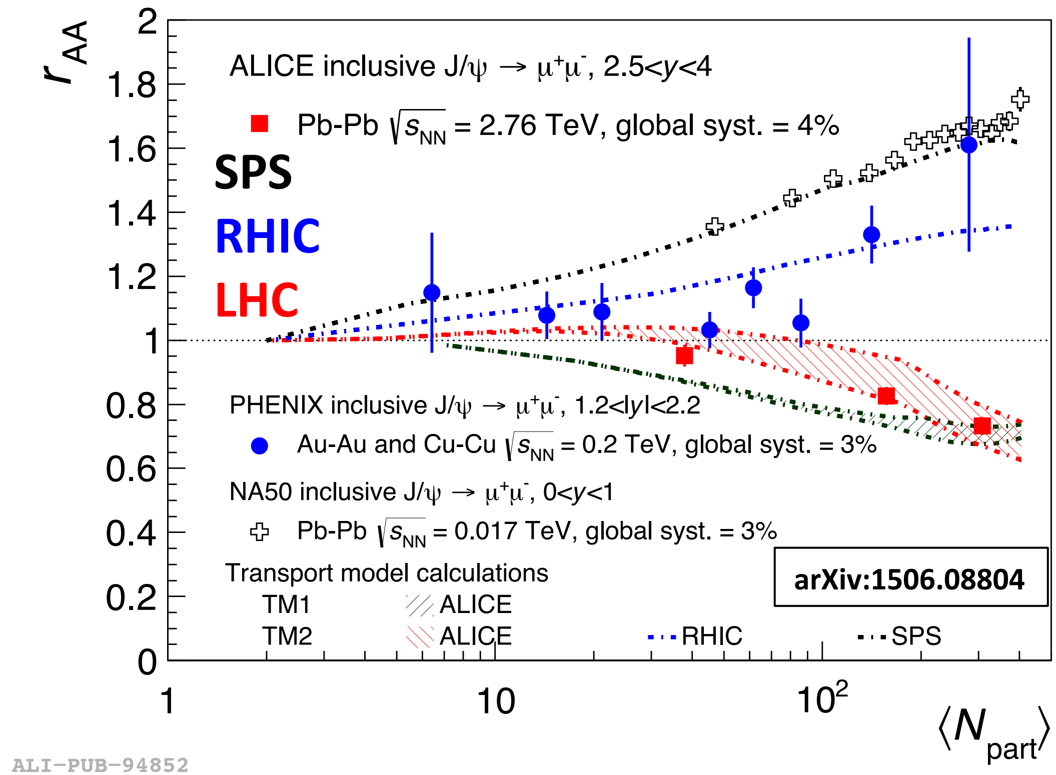




- Huge R_{AA} increase at low N_{part}.
- p_T spectrum is similar to the photo-production seen in UPC (b>2R).

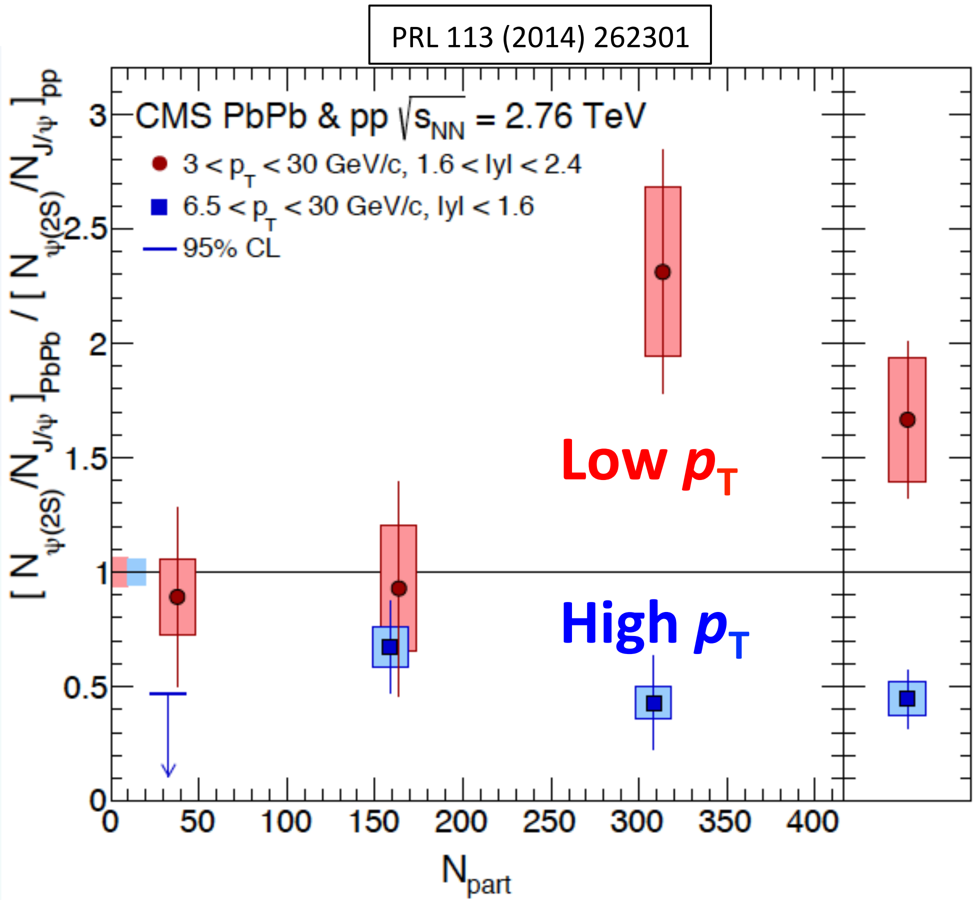
< p_T > of J/ψ in Pb-Pb





- Significant reduction of J/ψ < p_T^2 > in Pb-Pb as compared to pp collisions.
- Opposite trend at RHIC and SPS energies.
- Transport model with regeneration component reproduces data at different energies.

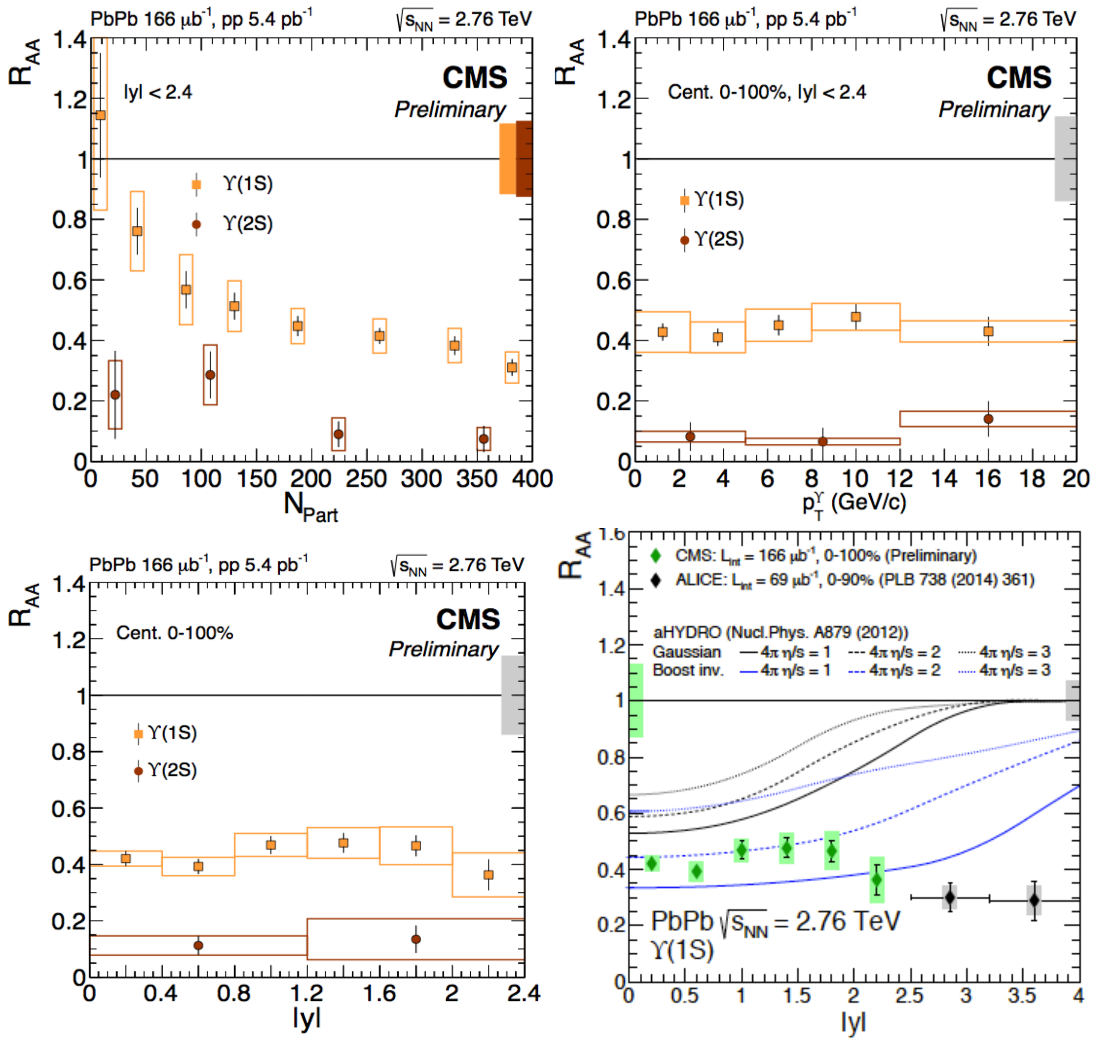
ψ(2S) vs J/ψ in Pb-Pb



- High-p_T J/ψ and ψ(2S) are suppressed, consistent with the sequential melting.
- At lower p_T, and forward y, less ψ(2S) suppression.
- At high p_T, enhanced suppression in central events.

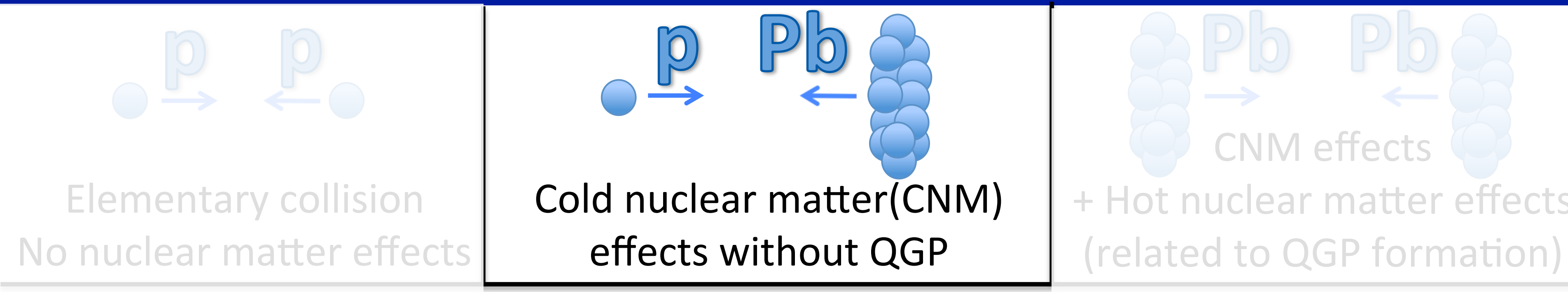
Bottomonia in Pb-Pb

PLB 738 (2014) 361	CMS-PAS-HIN-15-001

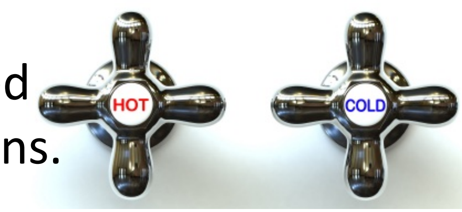


- Update of CMS results.
  - New reference at same energy.
  - Larger statistics.
- Υ(1S) R_{AA} decreases with centrality down to 0.3.
- $R_{AA}(p_T)$ ≈ constant in 0-100%.
- Flat $R_{AA}(y)$, closer to ALICE now.
- Zero or negligible statistical regeneration for Υ(1S).

Nuclear matter effects



➢ To disentangle hot and CNM effects, p-Pb collisions are needed as an intermediate step between Pb-Pb and benchmark pp collisions.



❖ In p-Pb collisions different kinds of CNM effects can be considered:

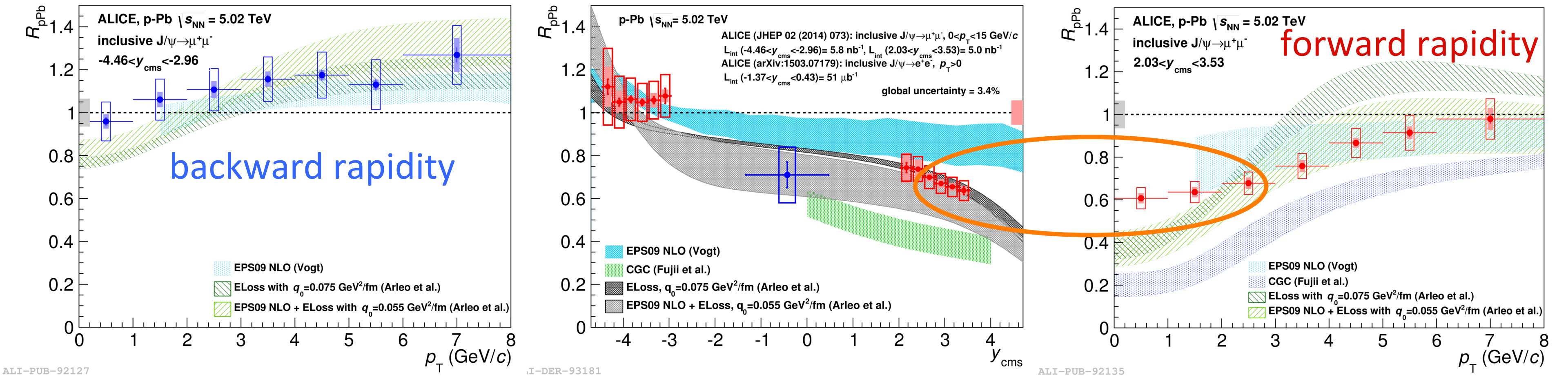
① **Initial-state:**
- ✓ gluon shadowing
- ✓ gluon saturation

② **Final-state:**
- ✓ nuclear absorption

③ **Coherent parton energy loss**

J/ψ vs p_T and y in p-Pb

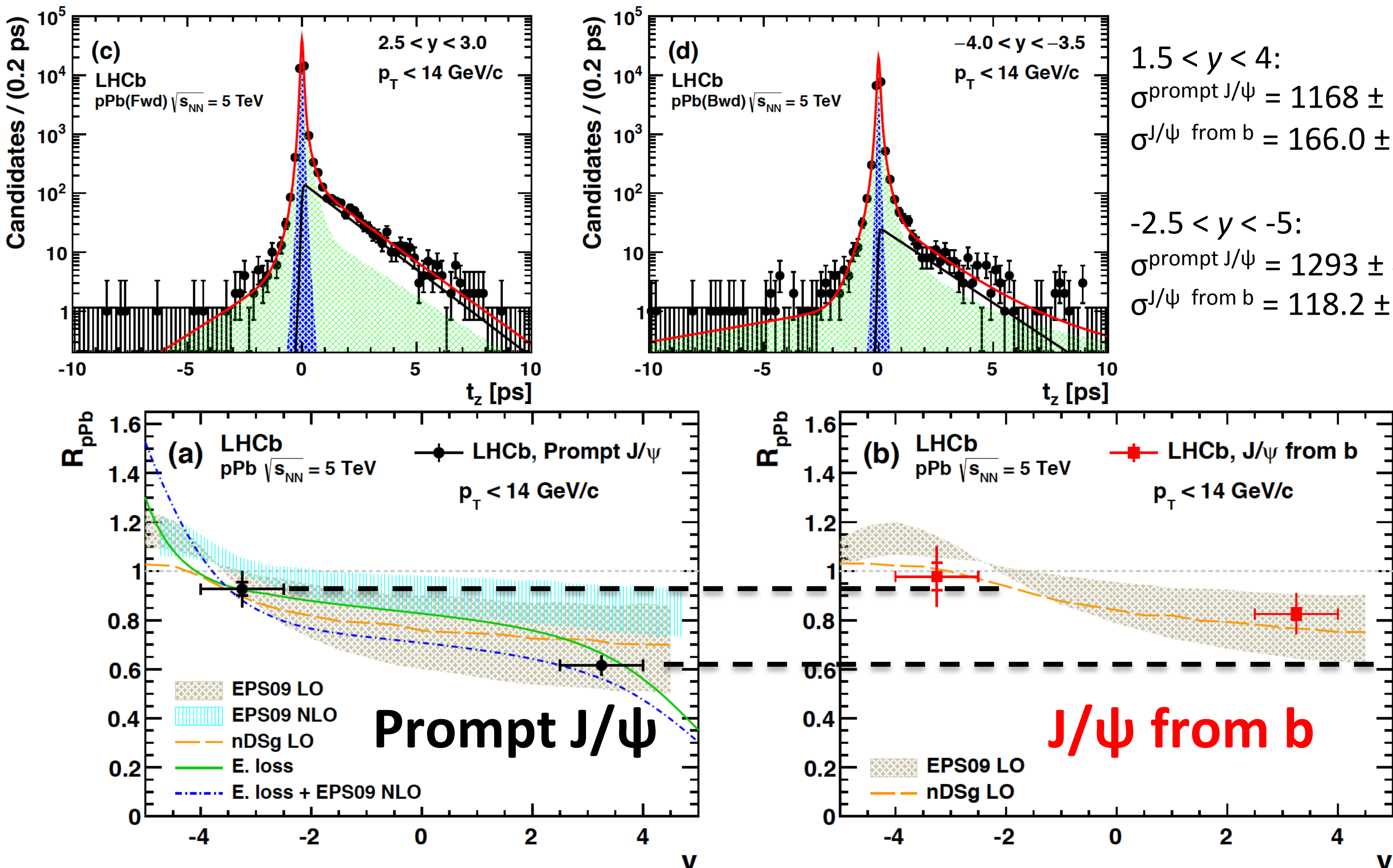
JHEP 1402 (2014) 073 | arXiv: 1503.07179



- $R_{pPb} \approx 1$ for all p_T at backward y, and for high p_T at forward y.
- At forward y, R_{pPb} increases with p_T.
- As a function of rapidity, R_{pPb} decreases from backward to forward y.
- ***Shadowing and coherent Eloss:*** fairly reproduce p_T and y dependence, except low p_T at forward y, where ***coherent Eloss*** underestimates the data.
- ***CGC:*** overestimates the suppression at forward-y over the full p_T range.

Prompt J/ψ in p-Pb

JHEP 02 (2014) 072



1.5 < *y* < 4:

$\sigma^{prompt\ J/\psi}$ = 1168 ± 15 ± 54 μb (88% inclusive)

$\sigma^{J/\psi\ from\ b}$ = 166.0 ± 4.1 ± 8.2 μb (12% incl.)

-2.5 < *y* < -5:

$\sigma^{prompt\ J/\psi}$ = 1293 ± 42 ± 75 μb (92% incl.)

$\sigma^{J/\psi\ from\ b}$ = 118.2 ± 6.8 ± 11.7 μb (8% incl.)

- No difference between prompt and non-prompt J/ψ R_{pPb} at backward *y*.
- At forward *y*, the difference <25%.
- Small non-prompt fraction + large uncertainties ⇒ safe to compare to inclusive.

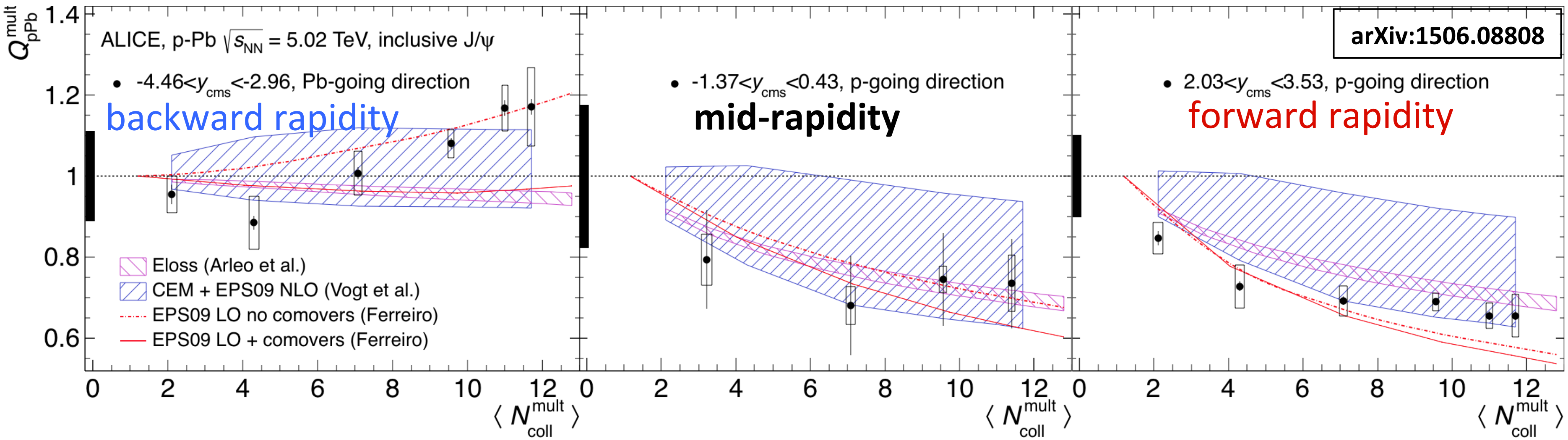
J/ψ Q_{pPb} vs centrality

$$Q_{pPb}^{J/\psi,i} = \frac{Y_{pPb}^{i}}{\left\langle T_{pPb}^{i} \right\rangle \sigma_{pp}^{J/\psi \rightarrow \mu^+\mu^-}}$$

T^i_{pPb} - nuclear thickness function in a given ZN energy event class* i.

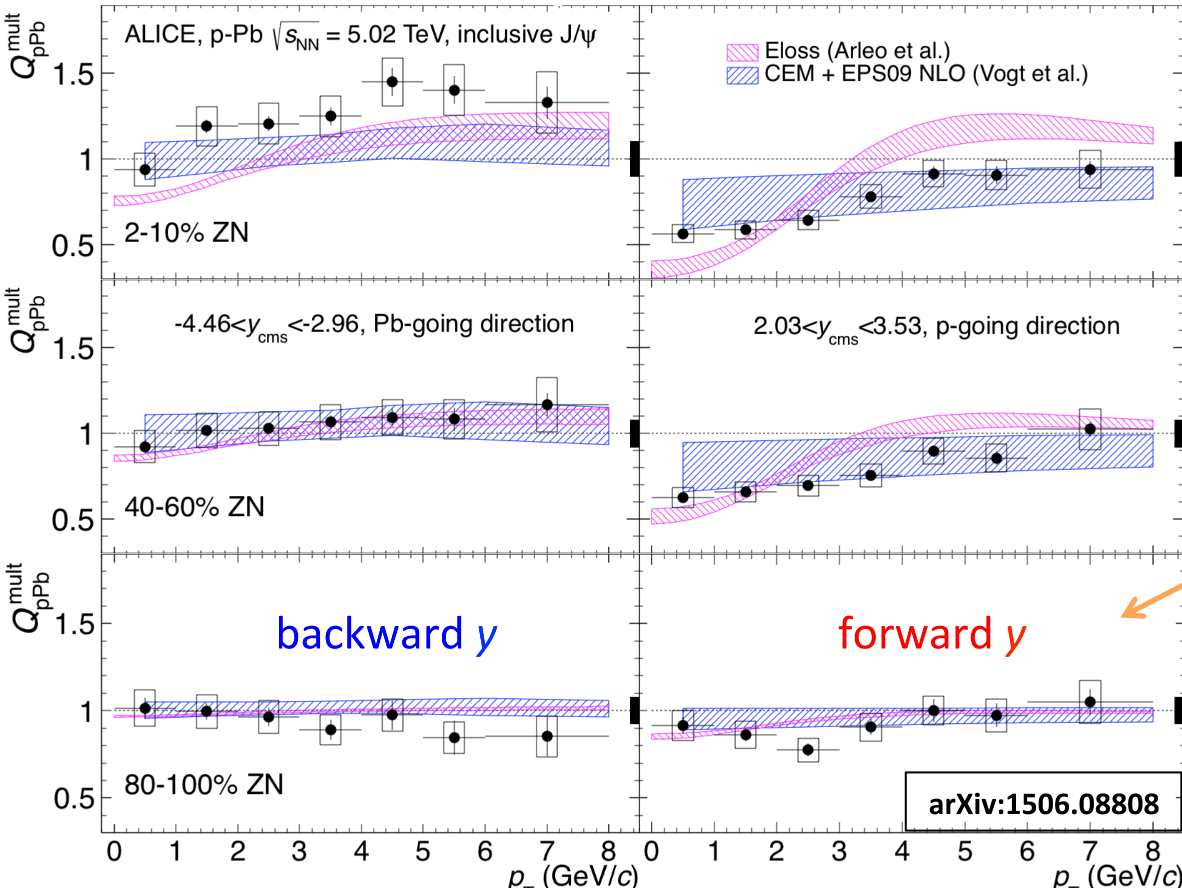
$\sigma_{pp}^{J/\psi \rightarrow \mu\mu}$ – interpolated pp cross-section at √s = 5.02 TeV.

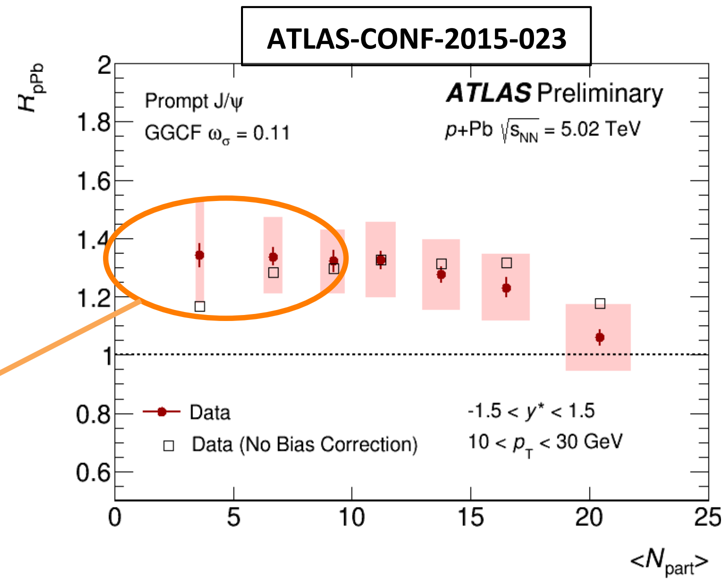
*ZN is the neutron part of the ZDC



- Large J/ψ suppression at forward *y*, increasing with N_{coll}.
- Consistent with no CNM effects at backward *y*.
- Large uncertainties at **mid-*y***.

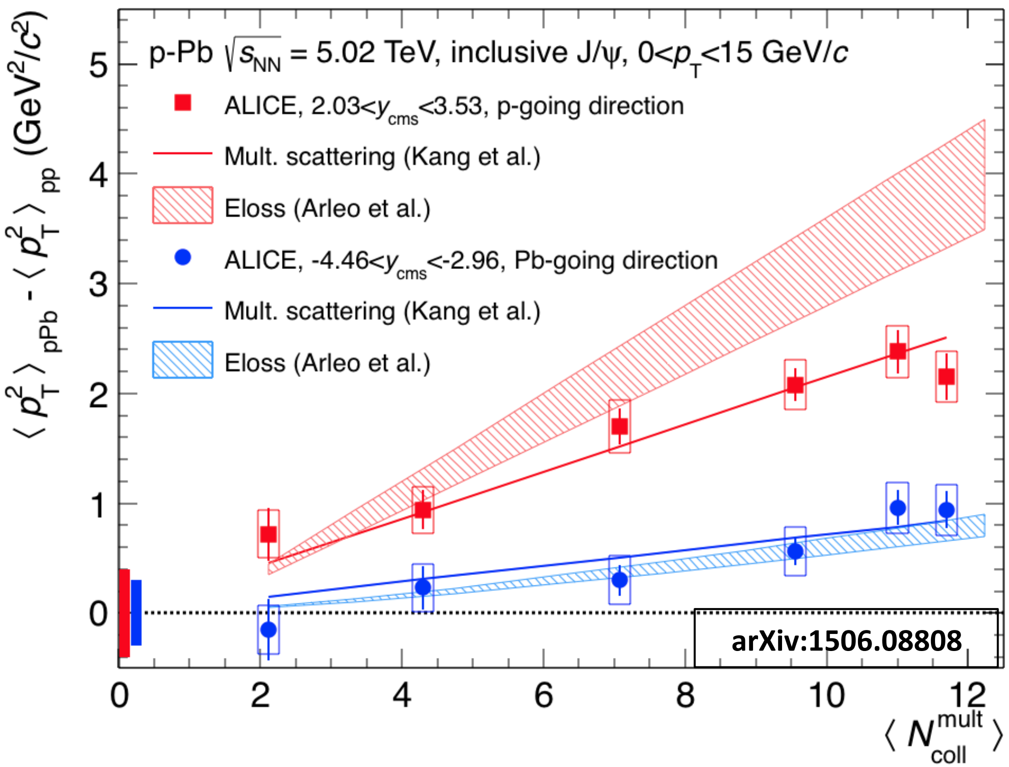
J/ψ Q_{pPb} vs p_T and centrality





- Large CNM effects in most central events: Q_{pPb} increases with p_T at both backward and forward *y*.
- At small centrality Q_{pPb} is consistent with unity for backward and forward *y*.
- Surprising trend in ATLAS at high p_T for the most peripheral collisions.

J/ψ p_T broadening



$\Delta\langle p_T^2\rangle = \langle p_T^2\rangle_{pPb} - \langle p_T^2\rangle_{pp}$,

$\langle p_T^2\rangle_{pp}$ is from interpolated pp distributions at √s = 5.02 TeV

*Boxes at $\Delta\langle p_T^2\rangle = 0$: uncertainty from $\langle p_T^2\rangle_{pp}$ at $\sqrt{s_{NN}}$=5.02 TeV

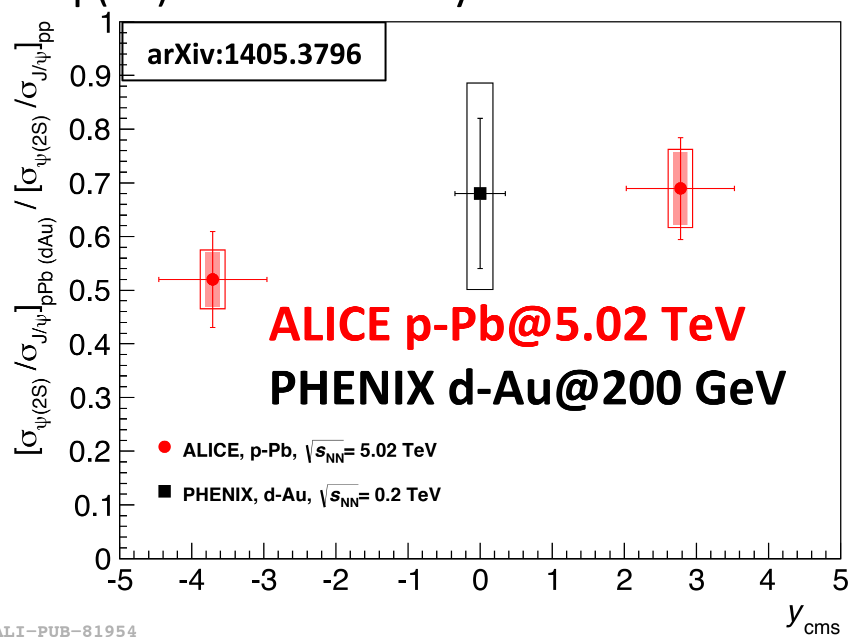
Models

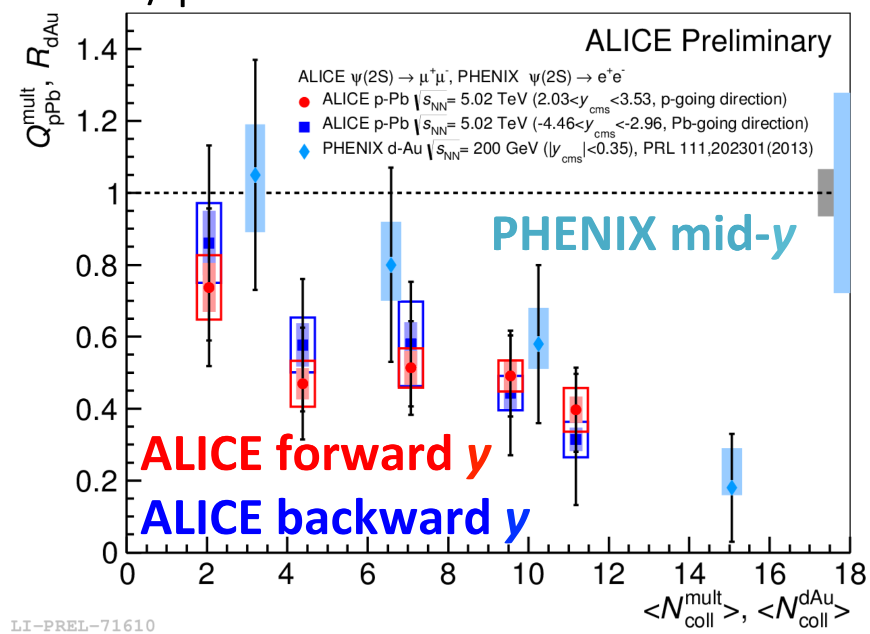
- **Multiple scattering** model (Kang et al. Phys.Rev. D77 (2008) 114027, Phys.Lett. B721 (2013) 277).
- **Coherent energy loss** (Arleo et al., JHEP1305(2013)155).

- Harder p_T distribution at forward y than at backward y.
- At backward y, the $\langle p_T^2\rangle_{pPb} \approx \langle p_T^2\rangle_{pp}$ in peripheral collisions.
- Such a strong p_T broadening indicates a presence of Multi-Parton Interactions in p-Pb collisions.

ψ(2S) vs J/ψ in p-Pb

✧ ψ(2S) is more weakly bound state with respect to J/ψ.





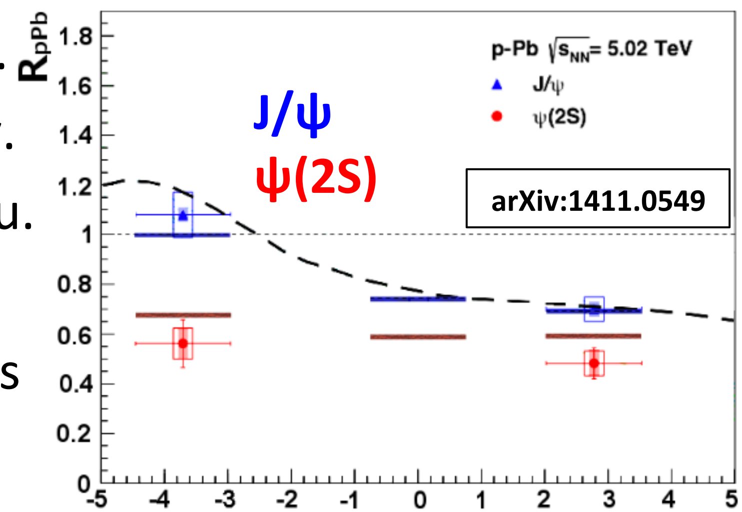
➢ $[\psi(2S)/J/\psi]_{pPb,dAu}$ is suppressed compared to pp.

➢ ψ(2S) suppression in p-Pb depends on centrality.

➢ Similar behaviour in ALICE p-Pb and PHENIX d-Au.

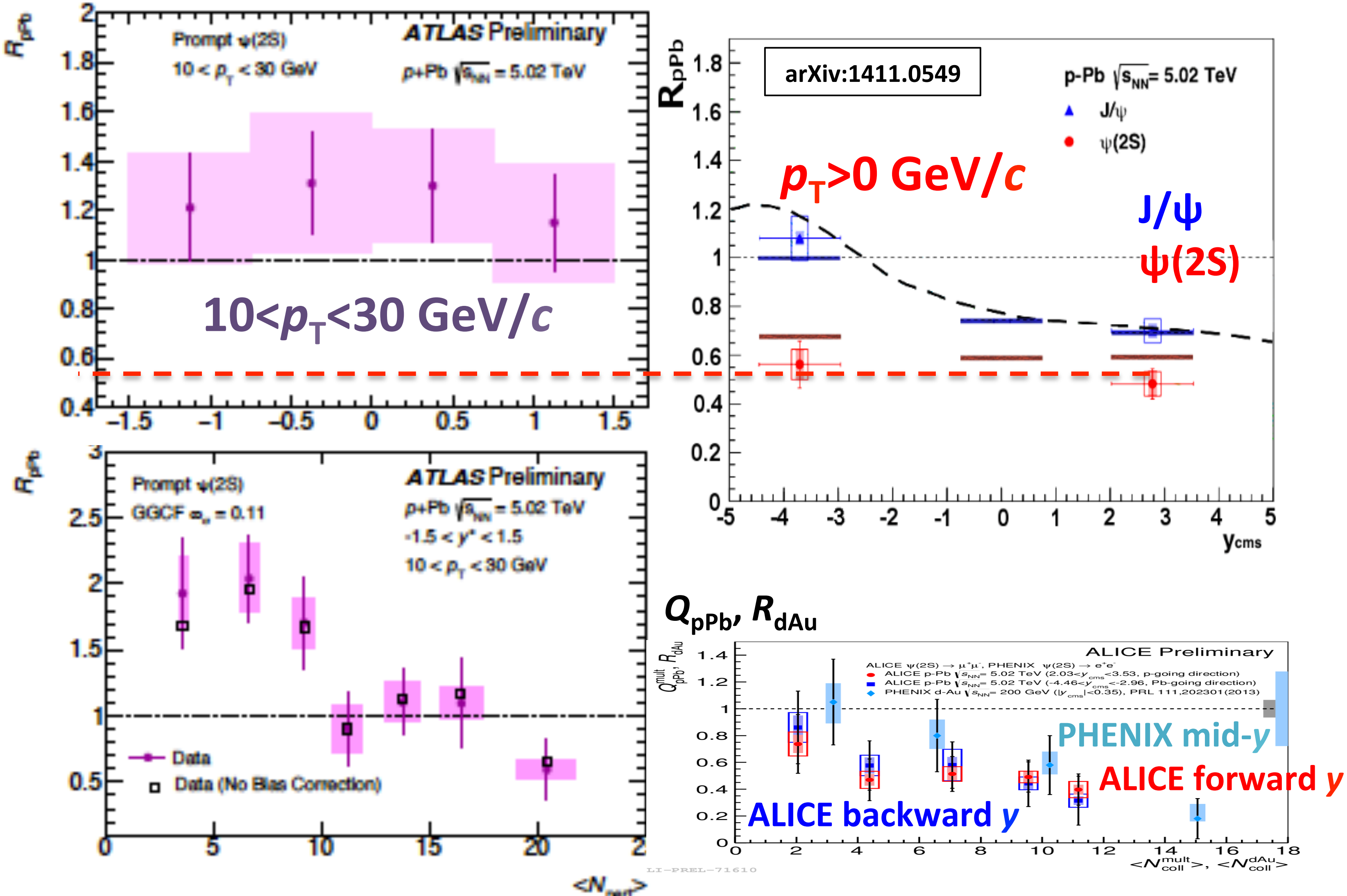
❑ Dependence on *y*? on energy?

❑ Model with comover interactions + EPS09 agrees with ALICE and PHENIX. **Final state effect?**



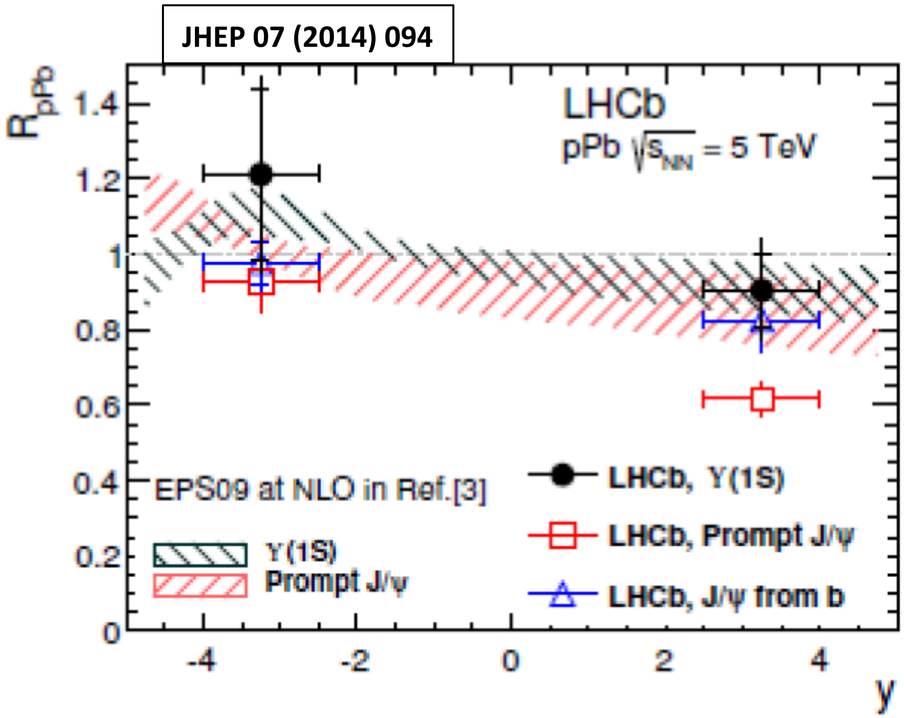
y_{cms}

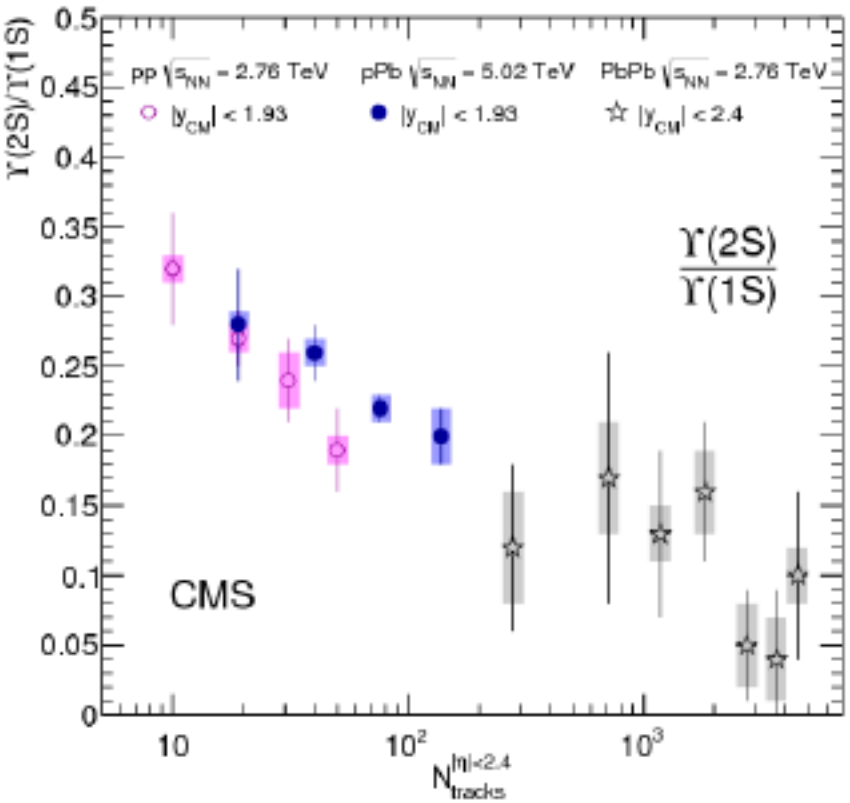
$\psi(2S)$ vs J/ψ in p-Pb



- p_T dependence? or reference issue?

Y(nS) in p-Pb





- Similar suppression of Y(1S) and (prompt) J/ψ.
- Y(2S)/Y(1S) decreases with increasing multiplicity.

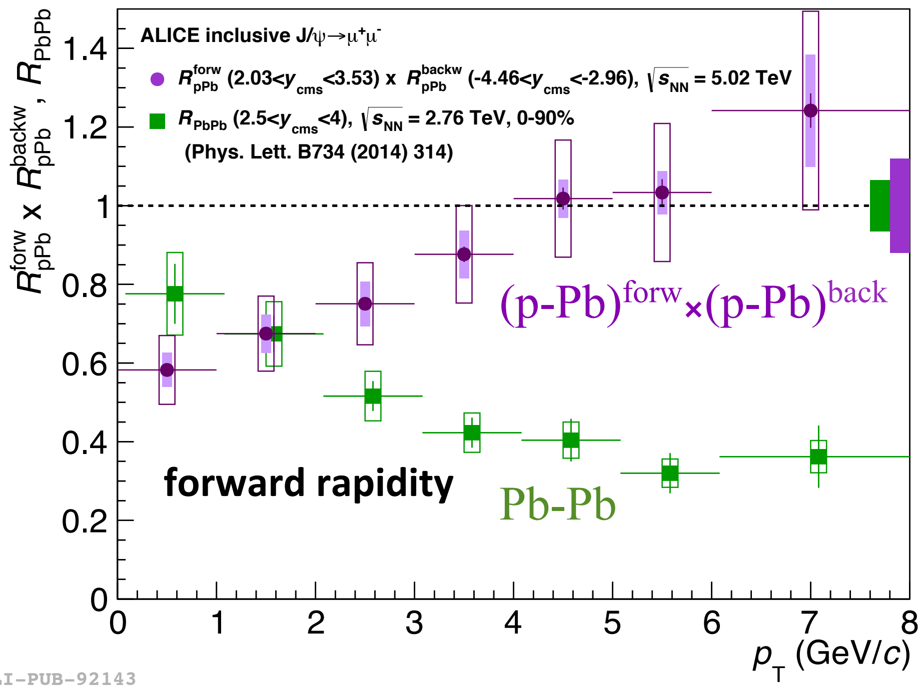
J/ψ: from p-Pb to Pb-Pb

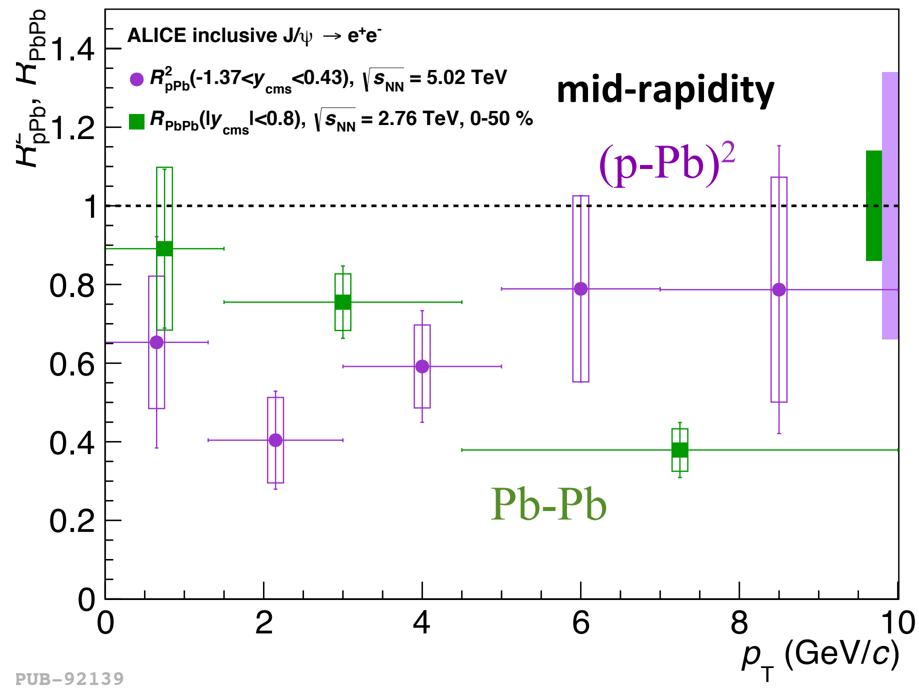
Hypothesis

JHEP 1506 (2015) 055

✓ Assume similar x in Pb for Pb-Pb@$\sqrt{s_{NN}}$=2.76 TeV and in p-Pb@$\sqrt{s_{NN}}$=5.02 TeV.

✓ Factorization of shadowing effects in p-Pb and Pb-Pb ⇒ $R^{Shad}_{PbPb} = R_{pPb}(y \geq 0) \times R_{pPb}(y \leq 0)$.





➢ High p_T: suppression in Pb-Pb due to hot nuclear matter effects (QGP).

➢ Low p_T: less or same suppression with $R_{Pb\text{-}Pb}$ compared to R^{Shad}_{PbPb}.

→ Hint for (re)combination in Pb-Pb?

Summary

- Quarkonium production in Pb-Pb is mainly dominated by the hot nuclear matter effects.
- In p-Pb: strong CNM effects in quarkonium production; depend on p_T, y and centrality.
- The CNM effects are higher in the most central collisions, decreasing towards peripheral.
- Strong p_T broadening is found at forward y.
- No model is able to reproduce precisely all observables, though shadowing and coherent energy loss work well.
- The ψ(2S) is suppressed more than J/ψ in p-Pb compared to pp collisions.
- Comover model can describe different behaviour of the 2 charmonium states in p-Pb.
- Some inconsistencies between ALICE and ATLAS: p_T dependence or reference issue?
- Data taking of pp@5.02TeV are appreciated.

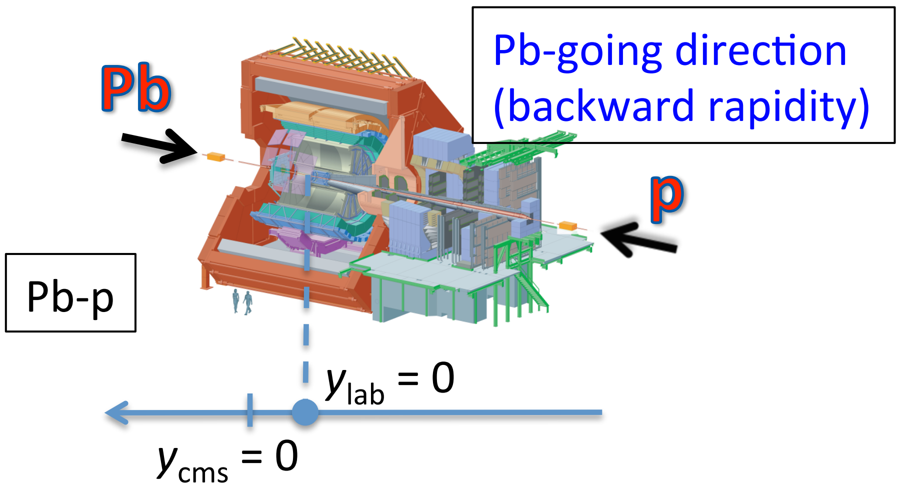
Thank you!

Backup slides

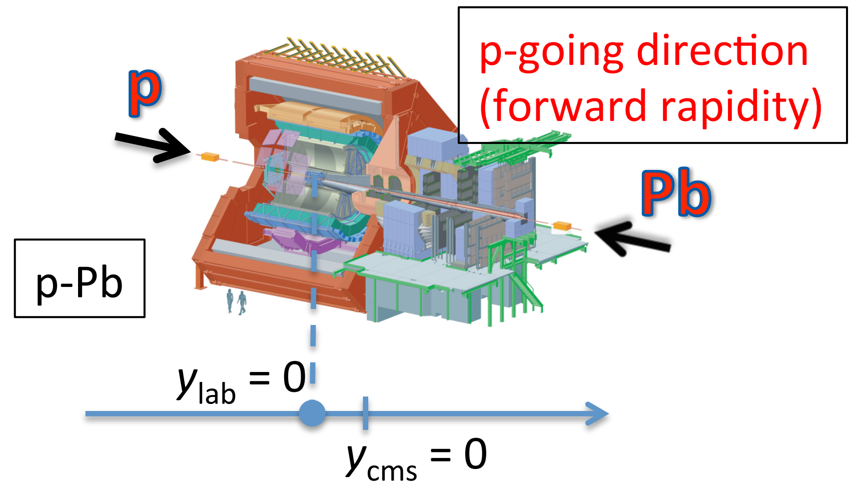
p-Pb detector setup

❖ Shift in y_{cms} in p-Pb collisions

LHC beam asymmetry (E_{Pb}=1.58•A TeV, E_p=4 TeV) ⇒ $|\Delta y|_{cms} = 0.5\ \mathrm{Log}(Z_{Pb}A_p/Z_pA_{Pb}) = 0.465$



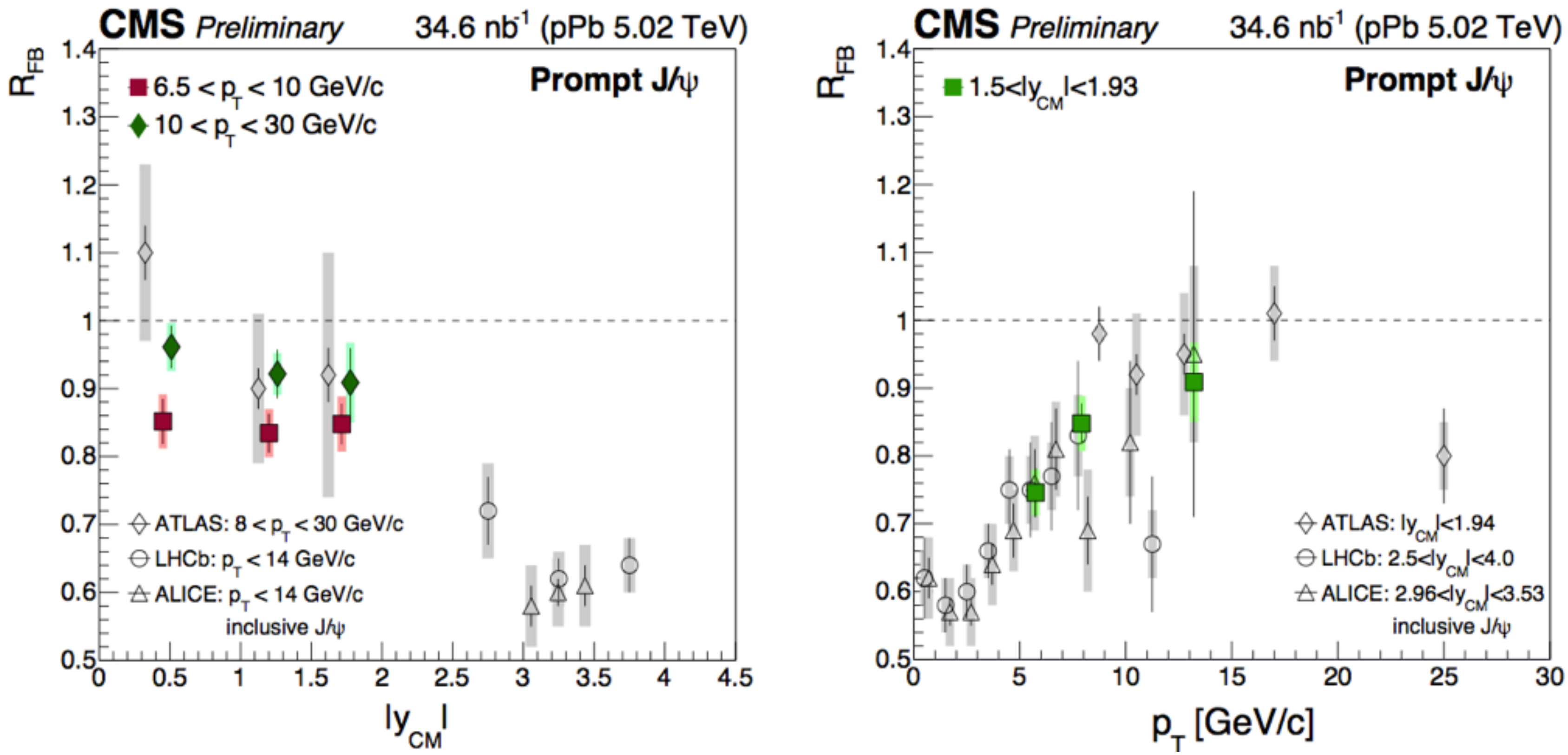
J/ψ, ψ(2S), ϒ(nS) → $\mu^+\mu^-$: $-4.46 < y_{cms} < -2.96$



J/ψ → e^+e^-: $-1.37 < y_{cms} < 0.43$

J/ψ, Ψ(2S), ϒ(nS) → $\mu^+\mu^-$: $2.03 < y_{cms} < 3.53$

Prompt J/ψ in p-Pb



Υ(1S) vs Υ(2S) cross-sections

PLB 740 (2015) 105

- Υ(1S) cross-sections in p-Pb@5.02 TeV (ALICE):

$-4.46 < y_{cms} < -2.96$: $5.57 \pm 0.72^{stat.} \pm 0.60^{syst.}$ μb
$2.03 < y_{cms} < 3.53$: $8.45 \pm 0.94^{stat.} \pm 0.77^{syst.}$ μb

- Υ(2S) cross-sections in p-Pb@5.02 TeV (ALICE):

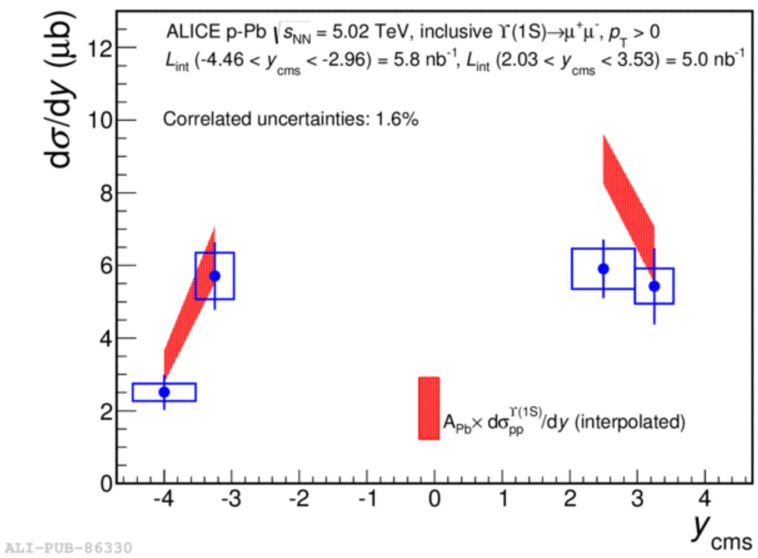
$-4.46 < y_{cms} < -2.96$: $1.85 \pm 0.61^{stat.} \pm 0.32^{syst.}$ μb
$2.03 < y_{cms} < 3.53$: $2.97 \pm 0.82^{stat.} \pm 0.50^{syst.}$ μb

❖ [Υ(2S)/Υ(1S)] in p-Pb@5.02 TeV (ALICE):

$-4.46 < y_{cms} < -2.96$): $0.26 \pm 0.09 \pm 0.04$
$2.03 < y_{cms} < 3.53$: $0.27 \pm 0.08 \pm 0.04$

❖ [Υ(2S)/Υ(1S)] in pp@7 TeV (ALICE):

$2.5 < y < 4.0$: 0.28 ± 0.08

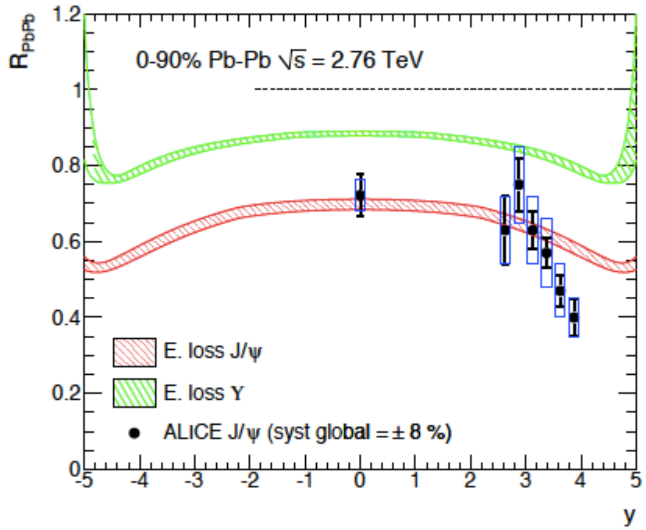


➢ For ALICE no evidence of different CNM effects on Υ(2S) compared to Υ(1S).

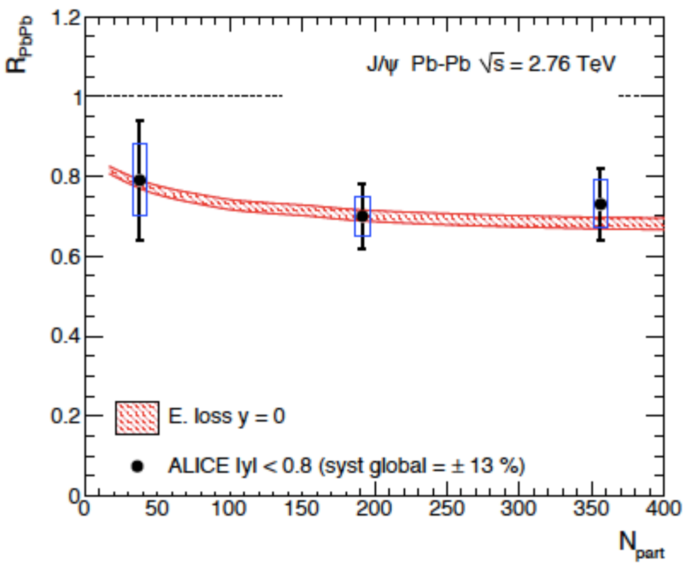
❑ CMS measured at mid-*y* $[\Upsilon(2S)/\Upsilon(1S)]_{pPb}/[\Upsilon(2S)/\Upsilon(1S)]_{pp} = 0.83 \pm 0.05^{stat.} \pm 0.05^{syst.}$

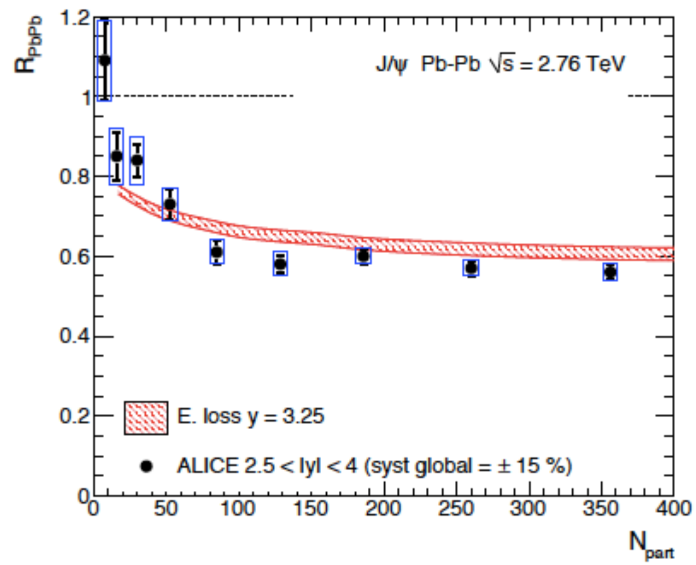
Coherent parton energy loss in Pb-Pb

F. Arleo et al.
arXiv:1407.5054



✧ Factorization of the effects in p-Pb and Pb-Pb is also assumed.





➢ Good job of the model (if the regeneration does indeed compensate the Debye screening).