

Second Conference on Heavy-Ion Collisions in the LHC era and beyond
ICISE, Quy Nhon, Vietnam, July 26-31, 2015

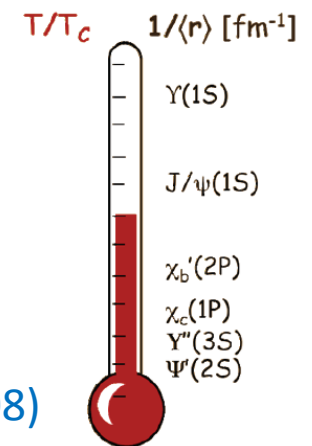
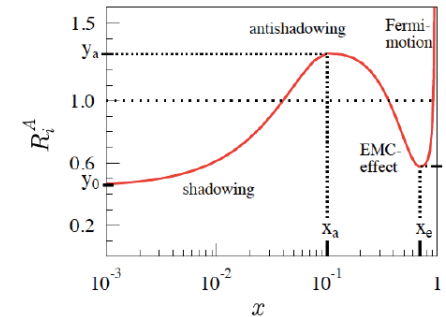
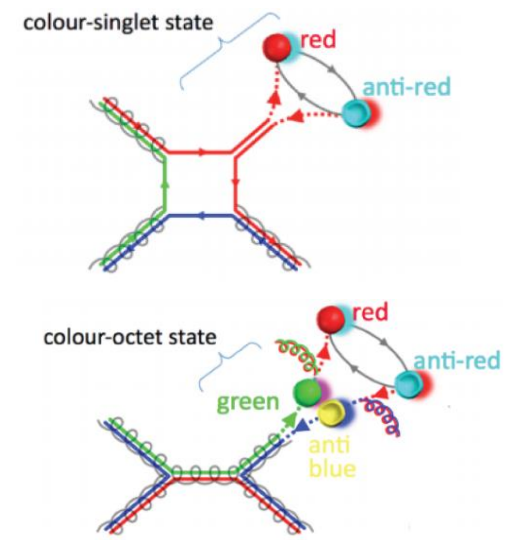
Quarkonium Production in Heavy-Ion Collisions at RHIC and LHC

Review of Recent Experimental Data

Byungsik Hong
(Korea University)

Introduction

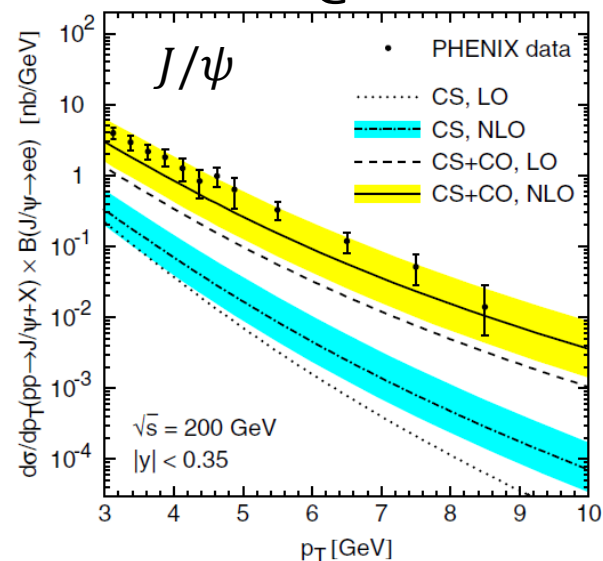
- pp
 - Reference to understand pA and AA data
 - Production mechanism: Color Octet vs. Singlet
 - Polarization for interactions with surroundings not affected by initial-state effect
- pA
 - Nuclear modification of gluon PDF (nPDF): shadowing, saturation, CGC, etc.
 - Medium-induced coherent gluon radiation
 - Co-mover absorption
- AA
 - Color-charge screening effect: λ_D vs. r
 - Sequential suppression: Different states dissociate at different temperatures
 - Regeneration from independently produced q and \bar{q} : larger for J/ψ than Υ



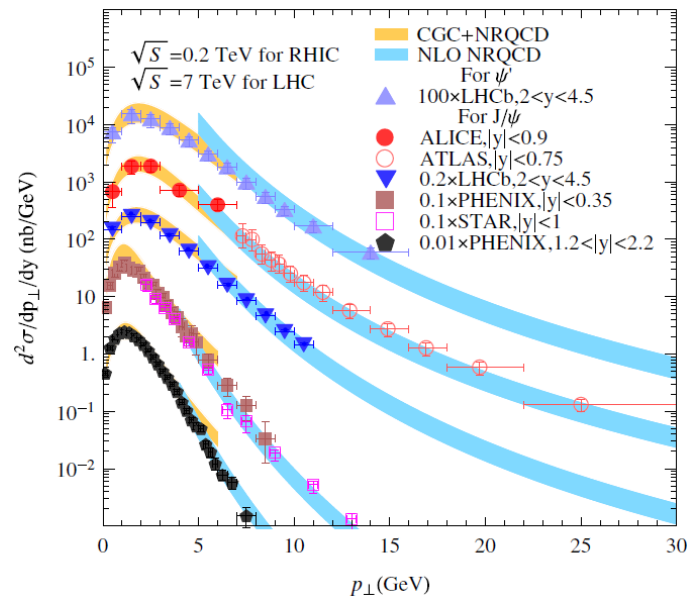
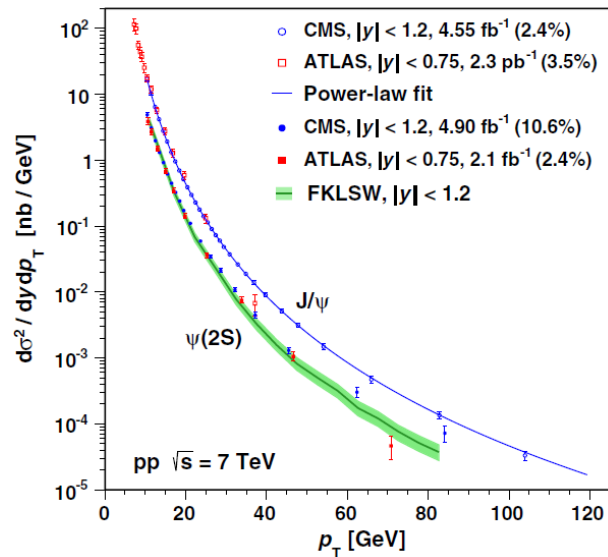
A. Mocsy et al., PRD 77, 014501 (2008)

J/ψ in pp

PHENIX @ 200 GeV



LHC @ 7 TeV



Butenschoen & Kniehl,
PRD 84, 051501 (2011)

NLO NRQCD fits well
in $p_T > 3$ GeV/c

CMS,
PRL 114, 191802 (2015)

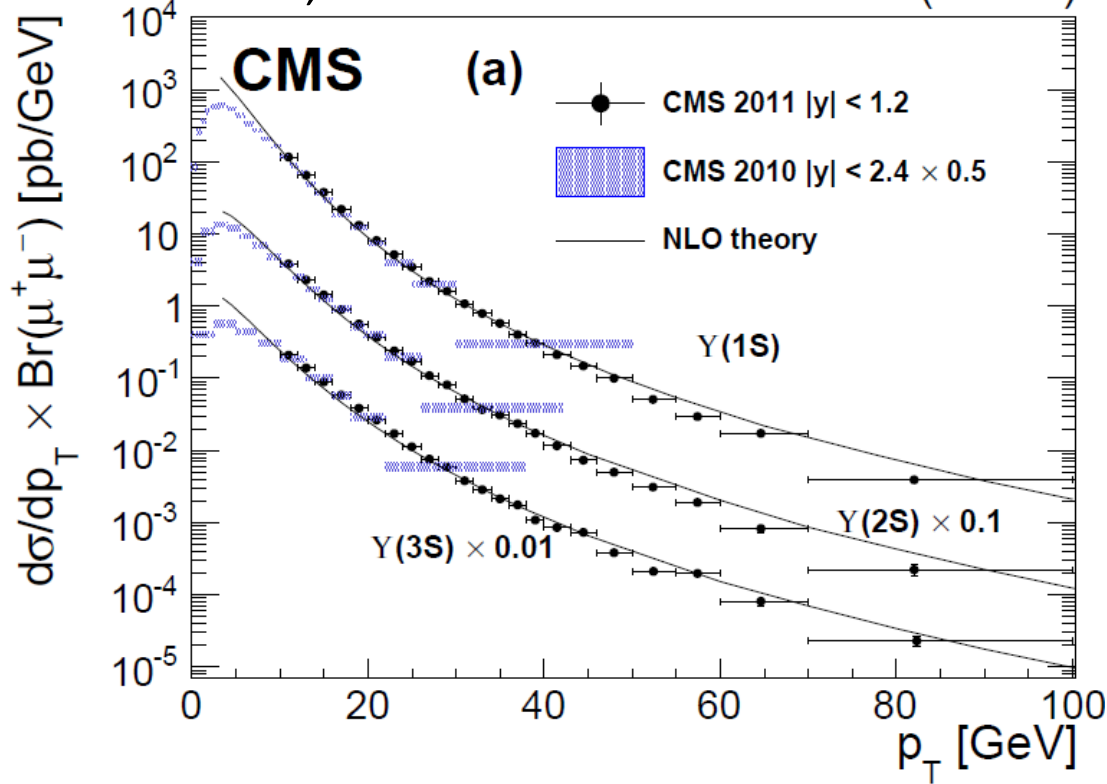
Ma & Venugopalan,
PRL 113, 192301 (2014)

Color Glass Condensate
effective theory at low p_T

Reasonable agreement between data and
NRQCD models for $0 < p_T < 30$ GeV/c

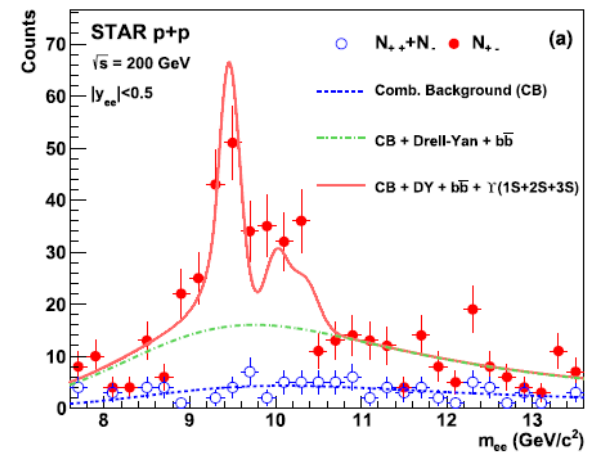
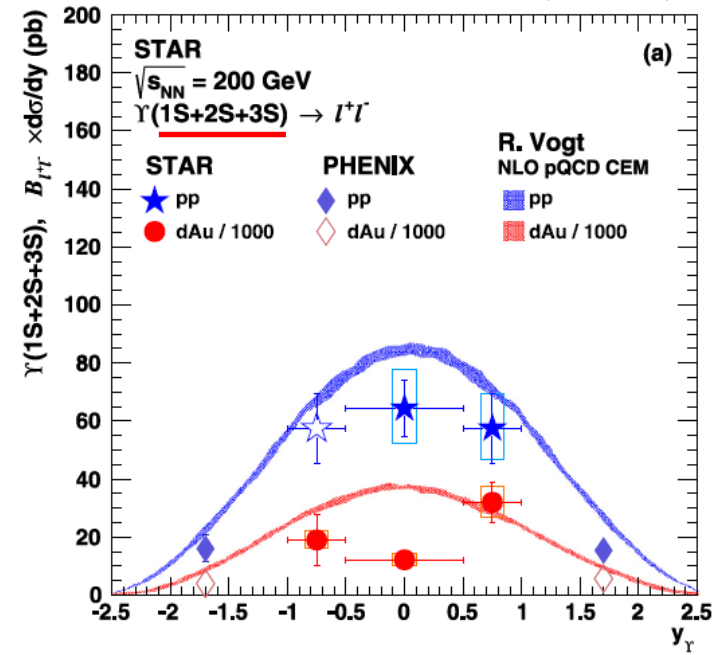
Υ in pp

CMS, arXiv: 1501.07750 4.9 fb⁻¹ (7 TeV)



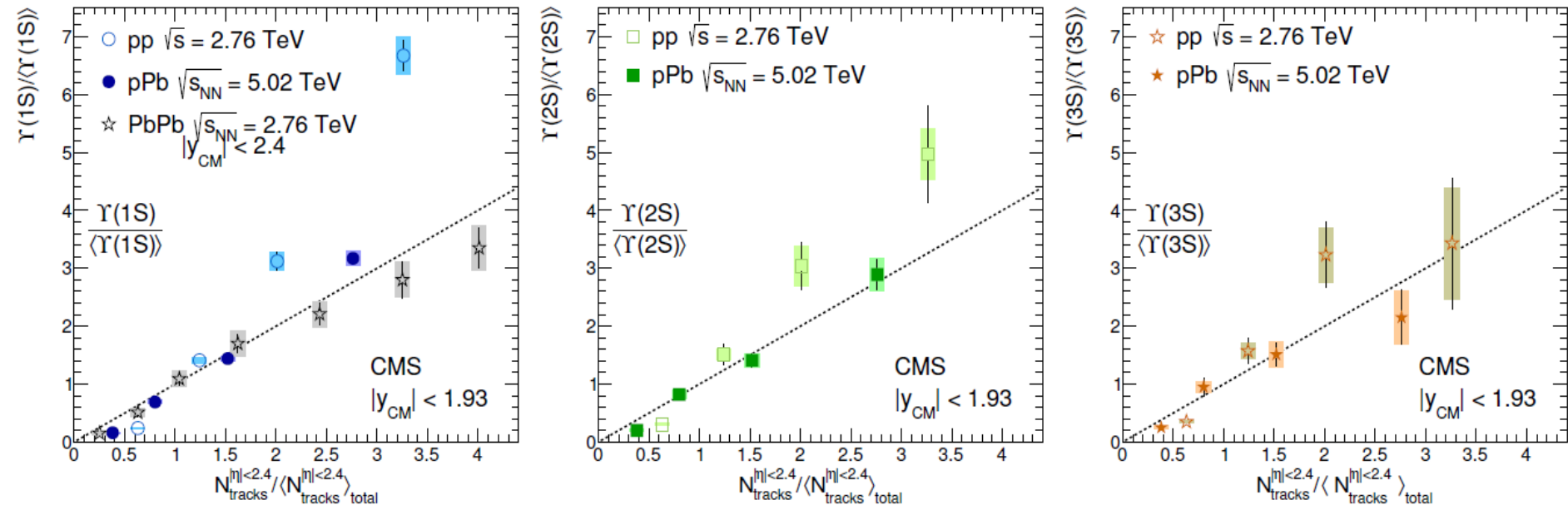
- New data significantly extends the p_T reach up to 100 GeV/c at LHC.
- QCD models can describe the Υ data well in pp especially at LHC.

STAR, PLB 735, 127 (2014)



Non-Linear Heavy-Quark Yields in pp

CMS, JHEP 04, 103 (2014)

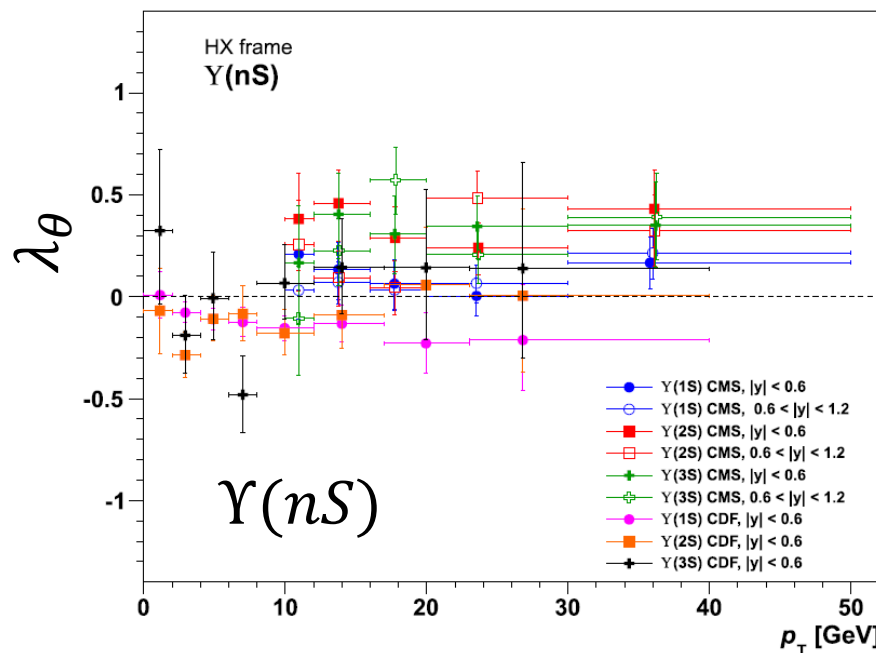
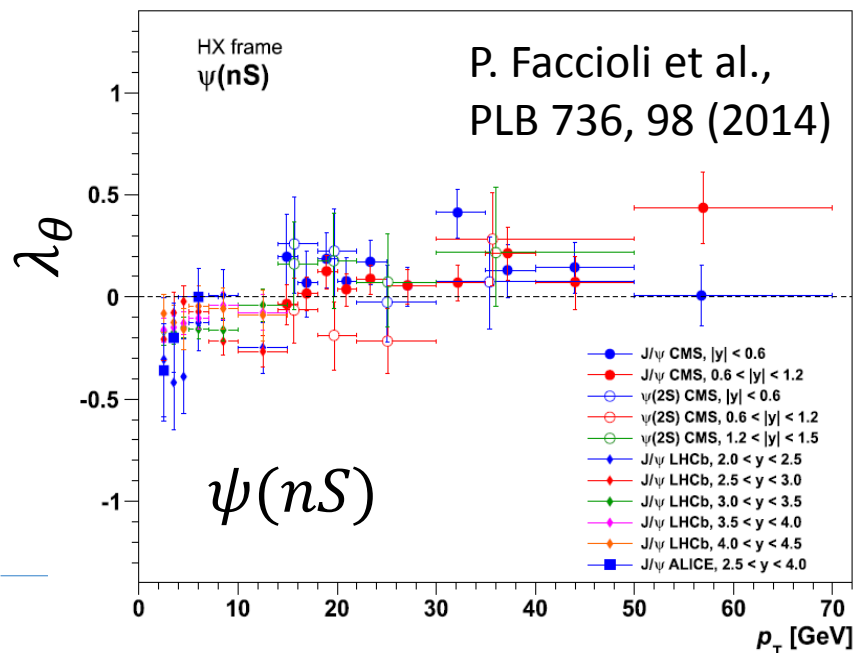
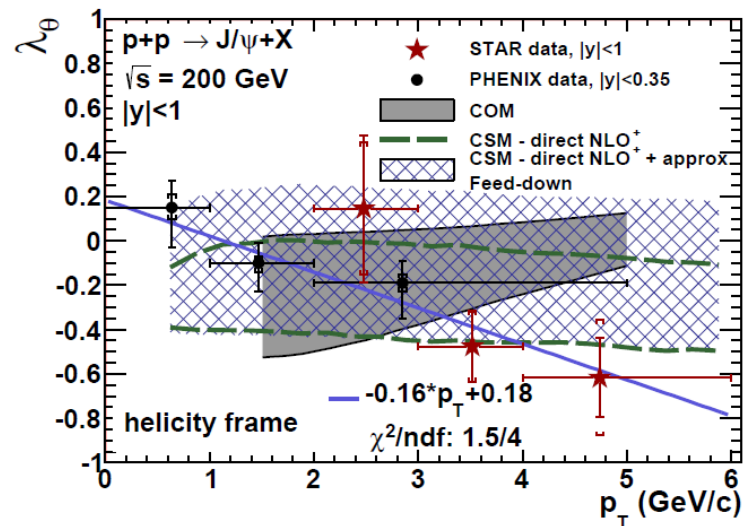


- Stronger rises of the Υ yields vs. event activity
 - Common to both open and closed beauty at RHIC and LHC
 - Similar trend observed for D and J/ψ at RHIC and LHC
 - $\frac{\Upsilon(1S)}{\langle \Upsilon(1S) \rangle} > \frac{\Upsilon(2S)}{\langle \Upsilon(2S) \rangle} > \frac{\Upsilon(3S)}{\langle \Upsilon(3S) \rangle}$: Why?
- Proposed ideas
 - Multi-parton interaction/Percolation model with string screening ...

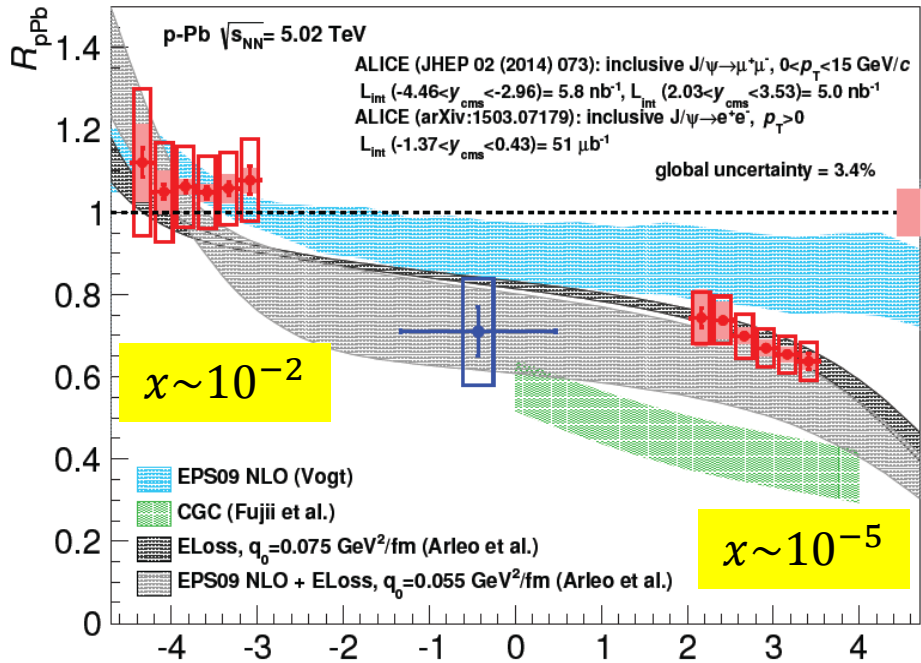
Polarization in pp

- Different polarization at RHIC and LHC
 - Decreasing with p_T for J/ψ at RHIC
 - No significant dependences on p_T , y , flavor at LHC
- Pre-resonant $Q\bar{Q}$ pairs dominantly produced in color octet state, $^1S_0^{[8]}$
 - $Q\bar{Q}$ pair radiates or absorbs soft gluons to form color-neutral quarkonium: Interaction with surroundings

STAR, PLB 739, 180 (2014)
 PHENIX, PRD 82. 012001 (2010)

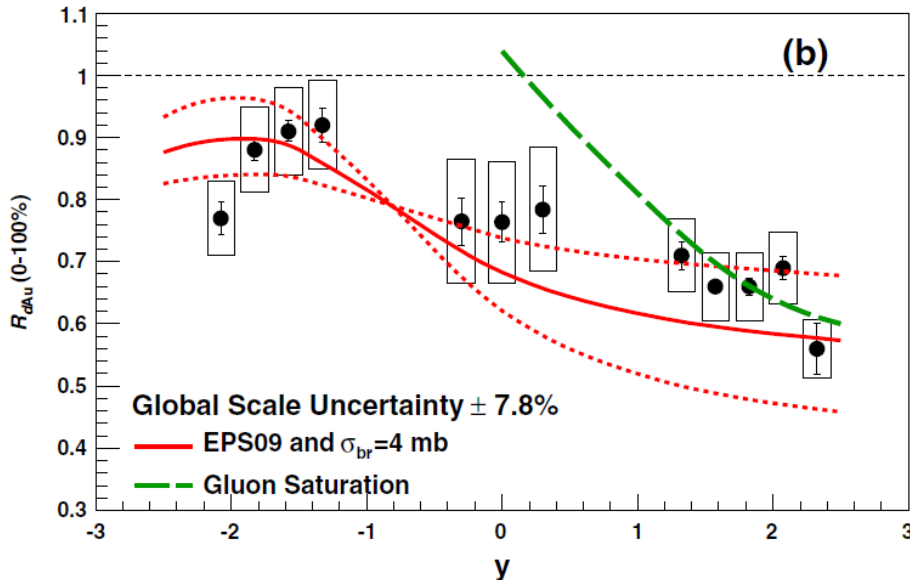


Inclusive J/ψ in pA



pPb @ $\sqrt{s_{NN}} = 5.02$ TeV, 0-100%
 ALICE, JHEP 02, 073 (2014)

- ⇐ Backward data agree with nPDF and/or energy loss models.
- ⇐ Forward data: energy loss essential, but CGC overestimates suppression.

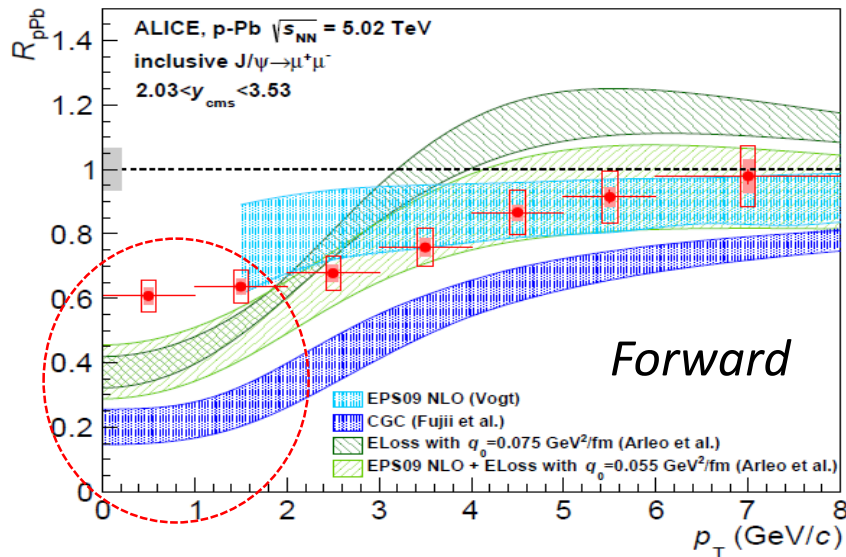
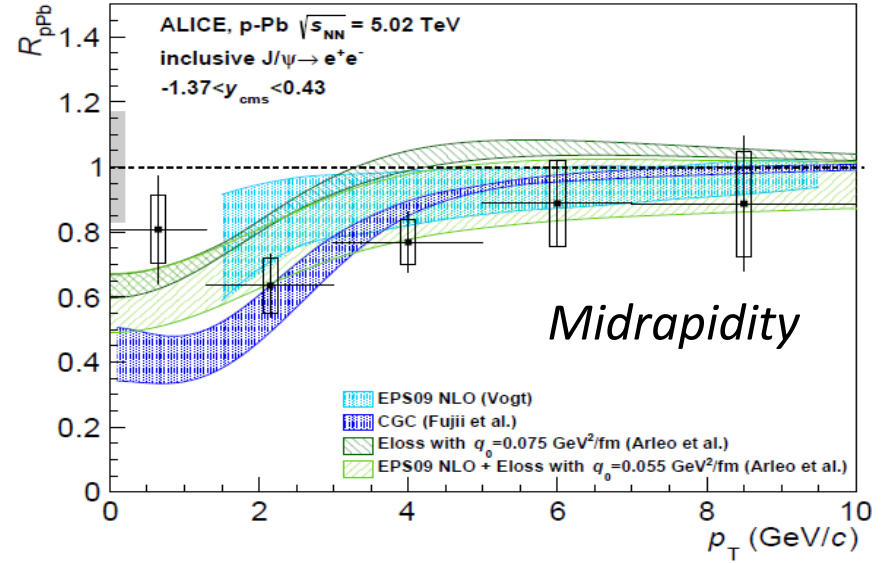
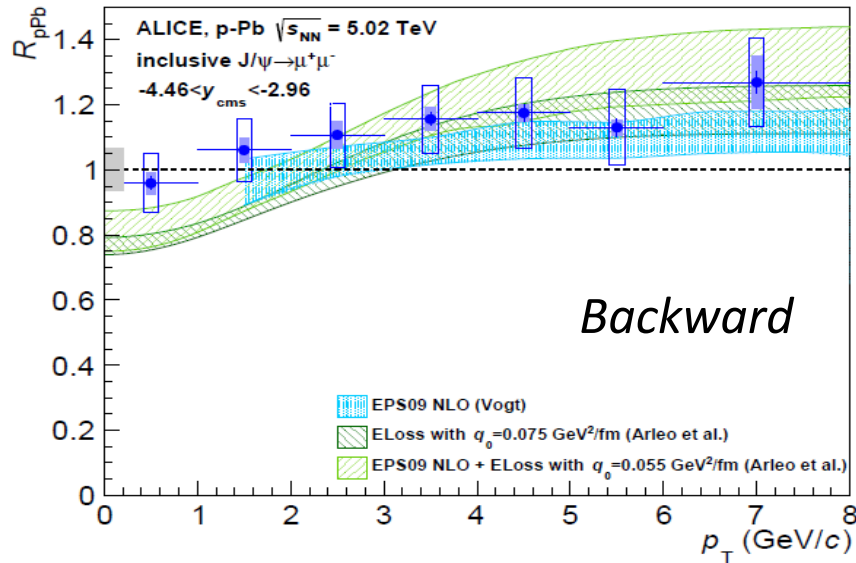


dAu @ $\sqrt{s_{NN}} = 200$ GeV, 0-100%
 PHENIX, PRL 107, 142301 (2011)

- ⇐ Agree with nPDF and $\sigma_{br} = 4$ mb [Eskola et al., JHEP 04, 065 (2009)]
- ⇐ Cf., the same model fails to reproduce R_{CP} .

Inclusive J/ψ in pA

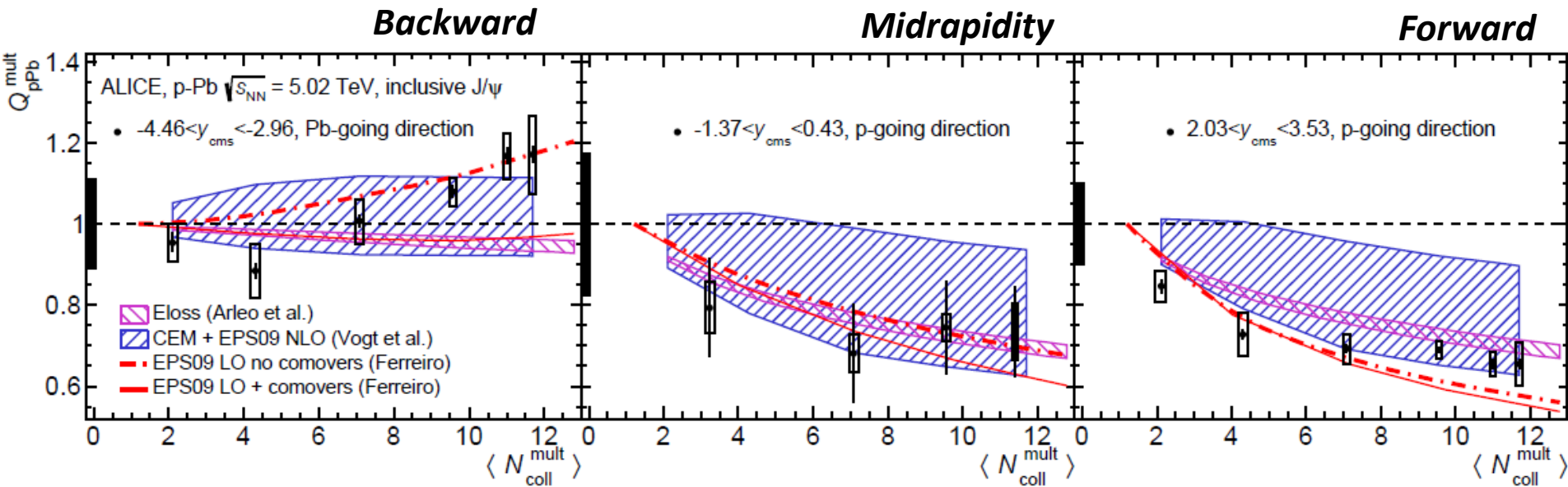
ALICE, JHEP 02, 073 (2014)
JHEP 06, 055 (2015)



- R_{pPb} increases with p_T for whole rapidity region.
- nPDF and energy loss effects fail to reproduce the forward data at low p_T .

Inclusive J/ψ in pA

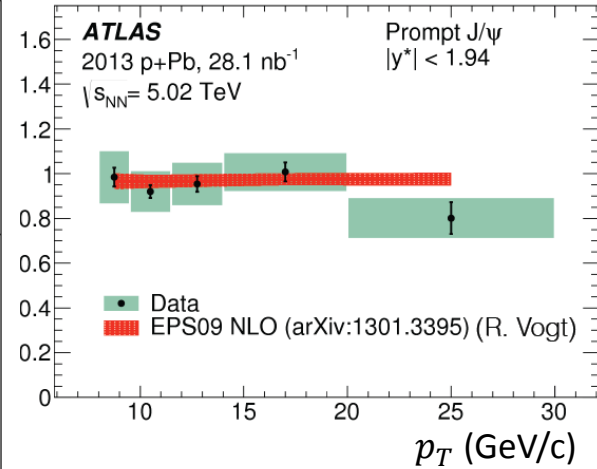
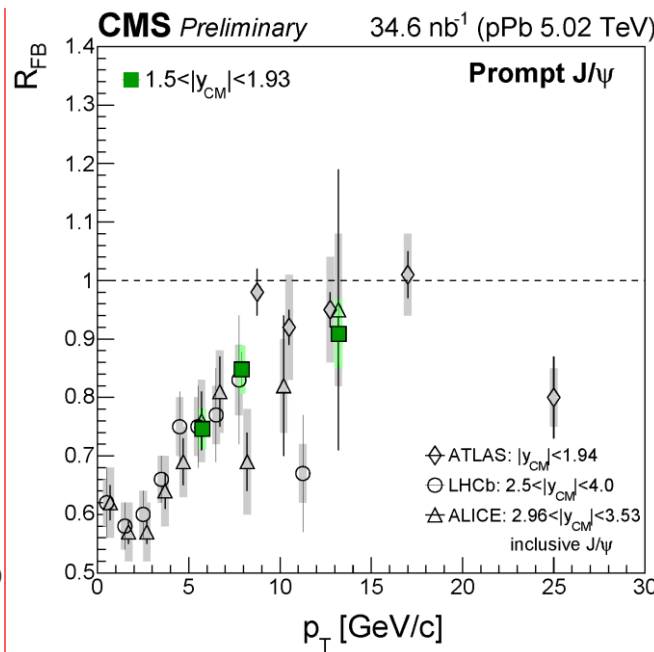
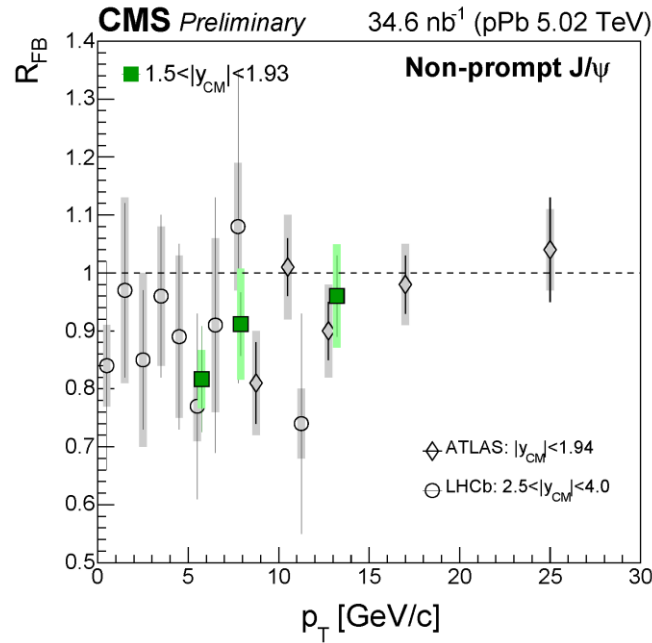
ALICE, arXiv:1506.08808



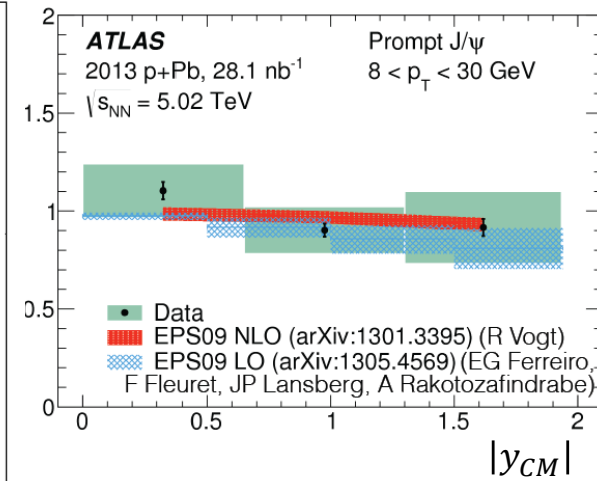
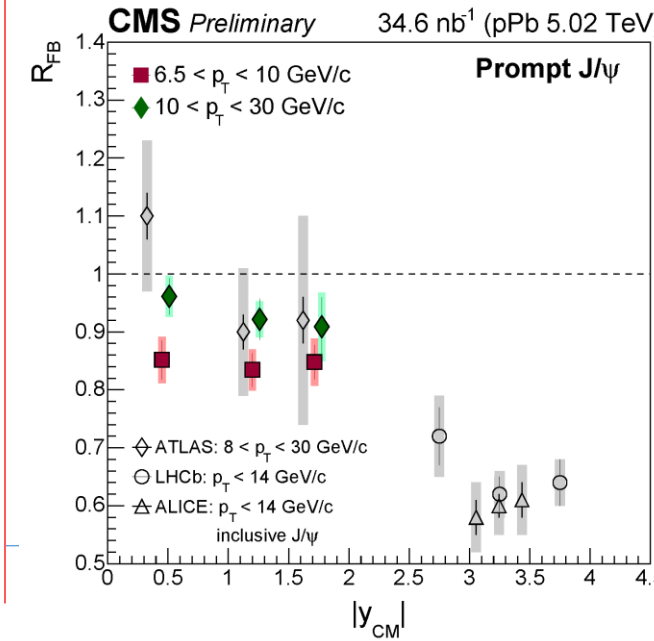
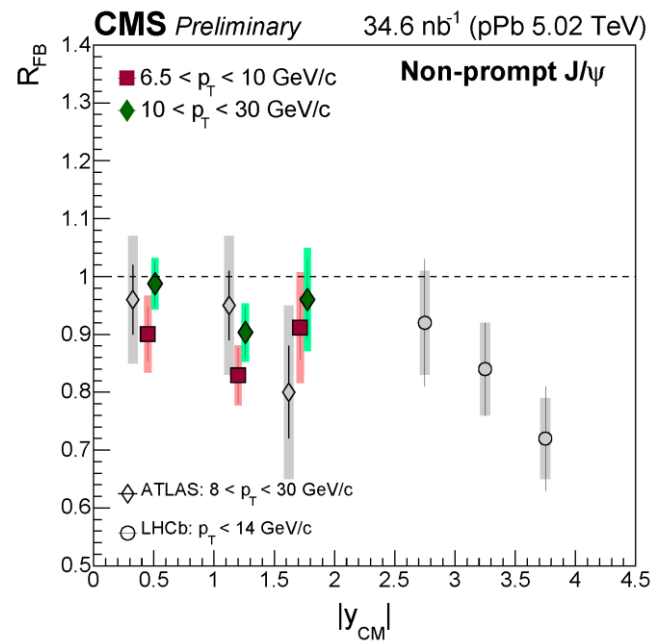
$$Q_{pPb}^{J/\psi,i} = \frac{N_{pPb}^i}{\langle T_{pPb}^i \rangle \sigma_{pp}^{J/\psi \rightarrow \mu^+ \mu^-}} \text{ with } i \text{ the event class determined by ZN energy}$$

- Backward data: $Q_{pPb} \sim 1$ in peripheral events, and increases with centrality.
- Midrapidity and forward data: Suppression of Q_{pPb} increases with centrality.
- Coherent energy loss and shadowing models with comovers underestimate Q_{pPb} at backward region in central collisions.

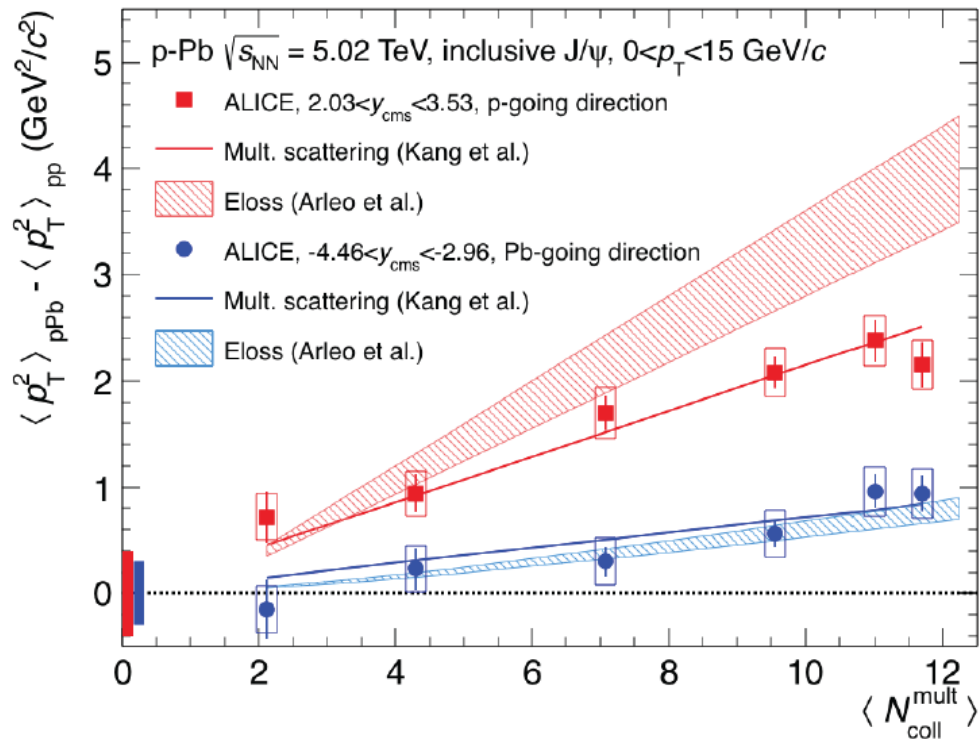
Prompt & Non-Prompt J/ψ in pA



CMS, PAS HIN-14-009
ATLAS, arXiv:1505.08141



p_T Broadening of J/ψ in pA



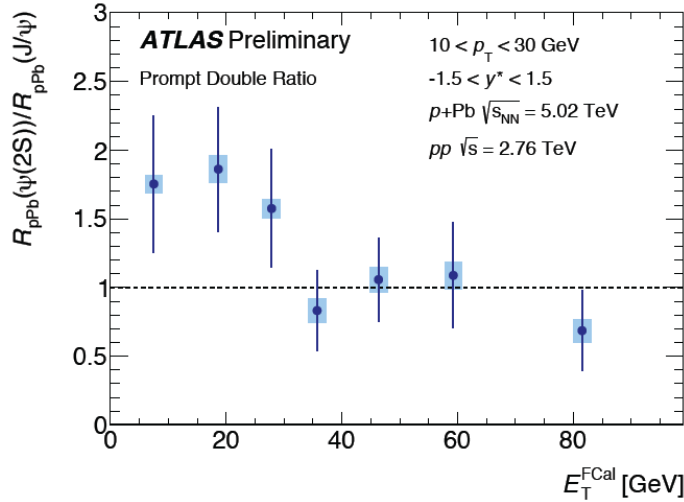
ALICE, arXiv:1506.08808

- Multiple scattering model: Kang et al., PRD 77, 114027 (2008), PLB 721, 277 (2013)
- Eloss model: Arleo et al., JHEP 1305, 155 (2013)

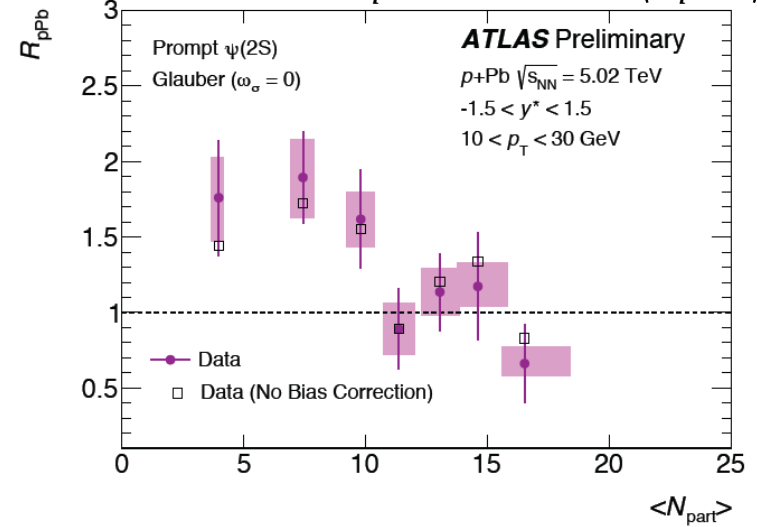
- The p_T distribution is harder
 - in pPb than that in pp in forward as well as backward rapidities.
 - in forward than that in backward in all centralities.
- Multiple scattering model reproduces the forward and backward data.
- Coherent energy loss model overestimates $\Delta\langle p_T^2 \rangle$ at forward region.

R_{pA} of J/ψ and $\psi(2S)$

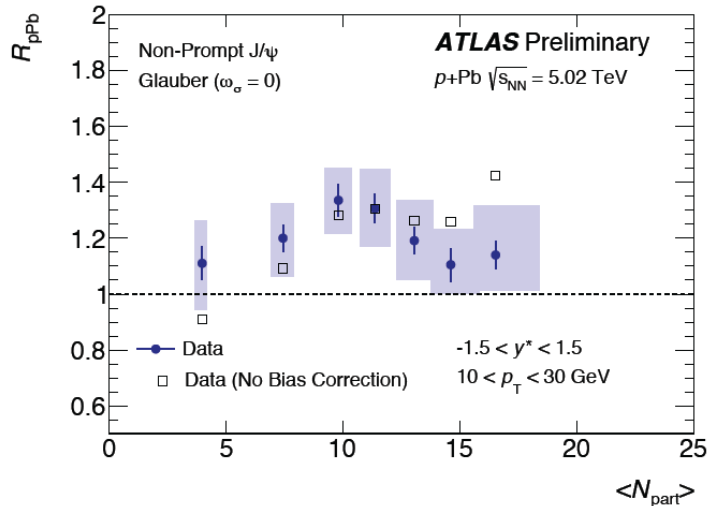
W. Brooks, HP2015 (ATLAS-CONF-2015-023)



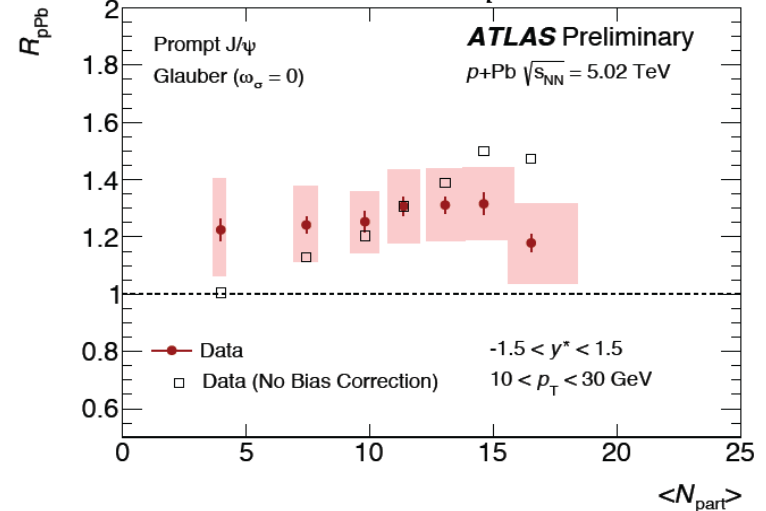
Prompt $\psi(2S)$: $R_{pA} > 1$ for low $\langle N_{part} \rangle$



Non-prompt J/ψ : $R_{pA} > 1$ for mid- $\langle N_{part} \rangle$



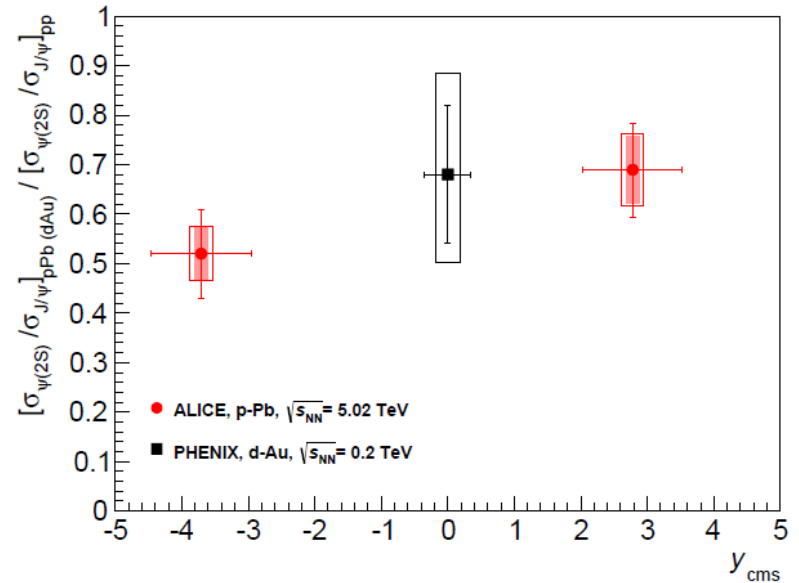
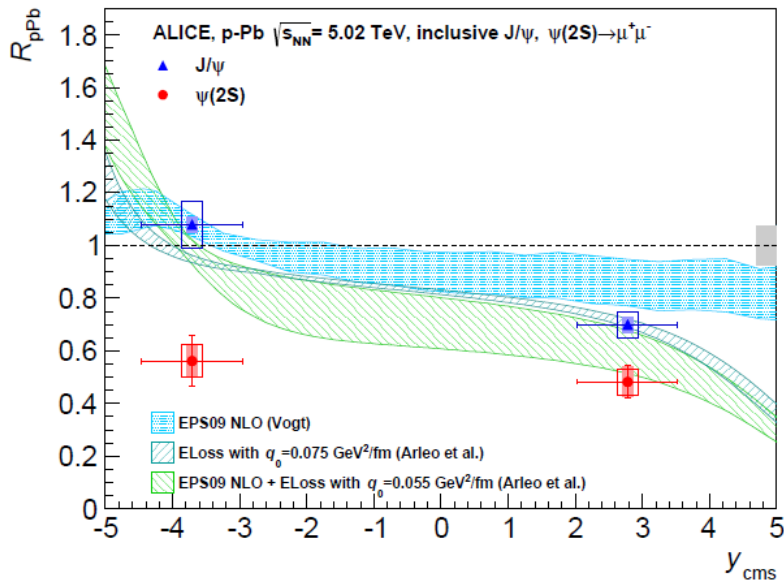
Prompt J/ψ : $R_{pA} > 1$



$\psi(2S)$ in pA

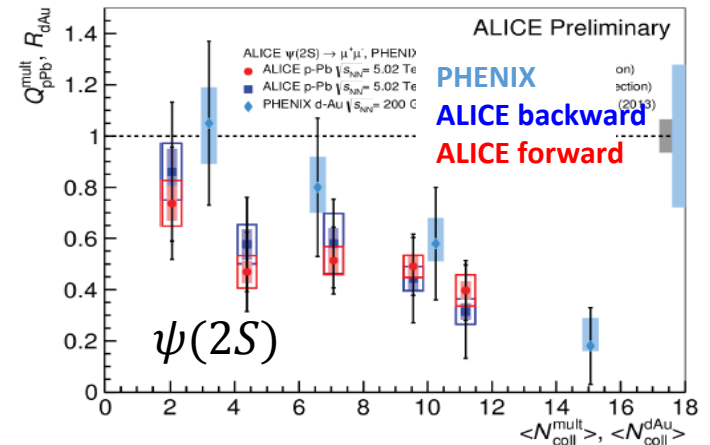
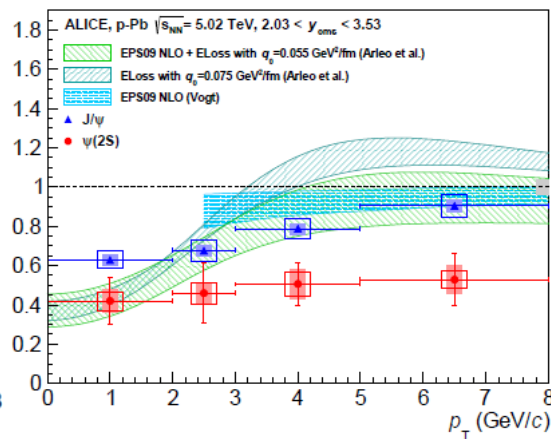
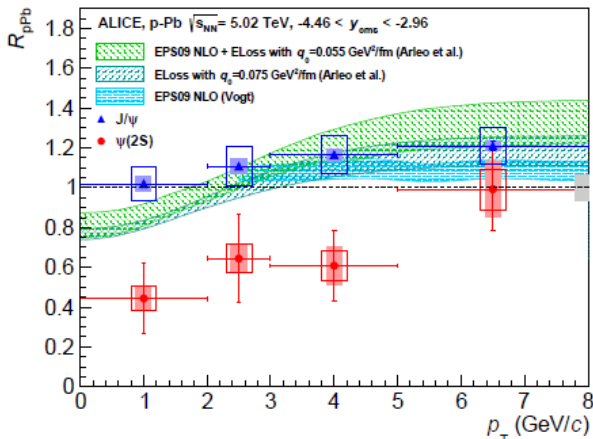
ALICE, arXiv:1405.3796

PHENIX, dAu, PRL 111, 202301 (2013)



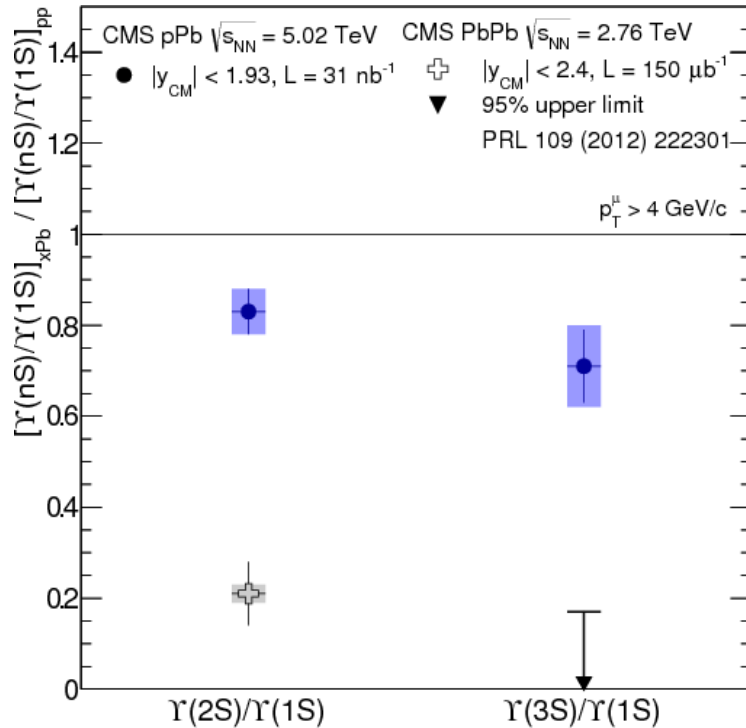
Backward

Forward

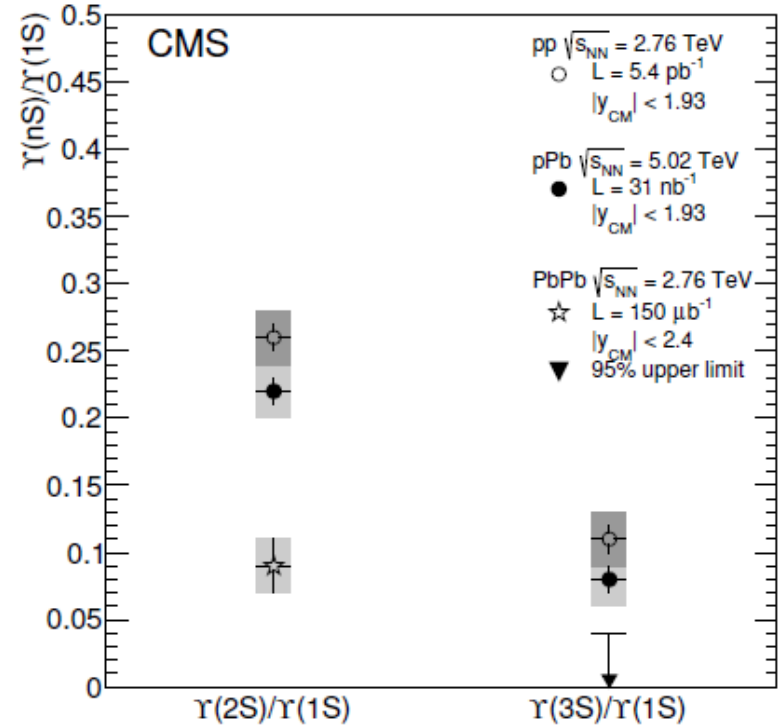


Υ in pPb

$$\frac{[\Upsilon(nS)]_{pPb}}{[\Upsilon(1S)]_{pPb}} = \frac{R_{pPb}(\Upsilon(nS))}{R_{pPb}(\Upsilon(1S))}$$

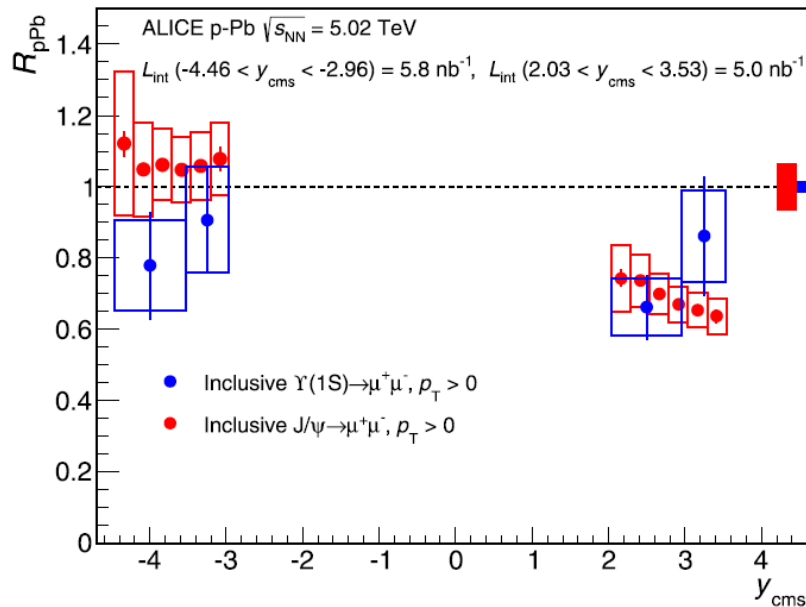


CMS, JHEP 04, 103 (2014)



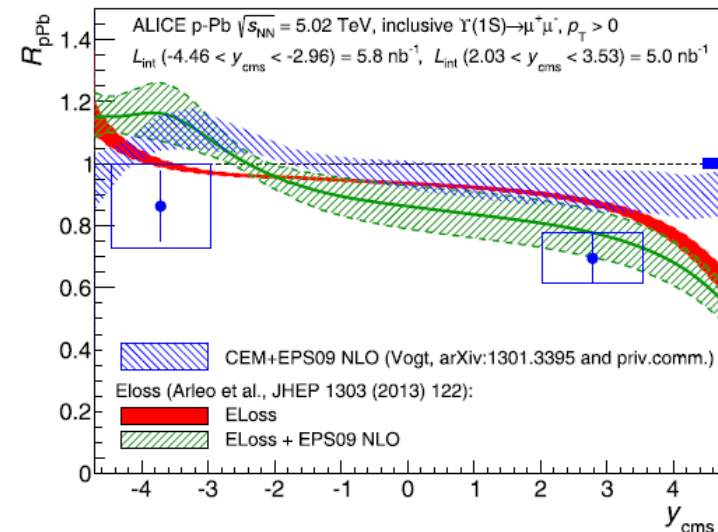
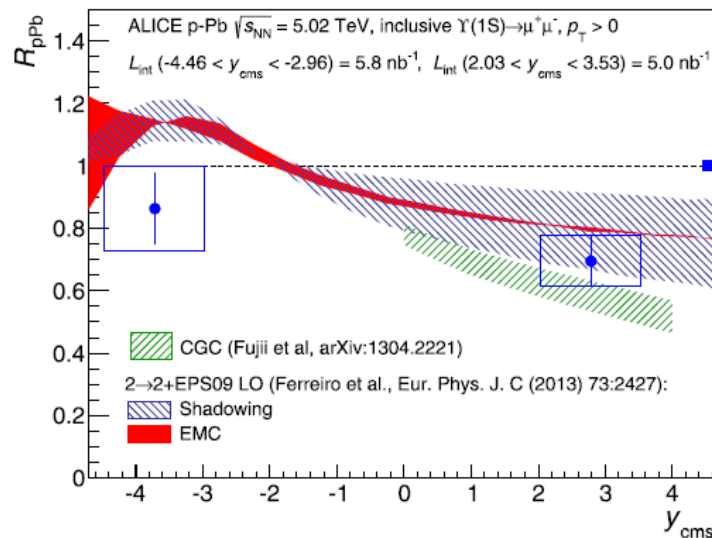
- Suppression is significantly larger for PbPb than for pPb
- Suppression of $\Upsilon(3S)$ is larger than that of $\Upsilon(2S)$ in pPb

$\Upsilon(1S)$ in pPb

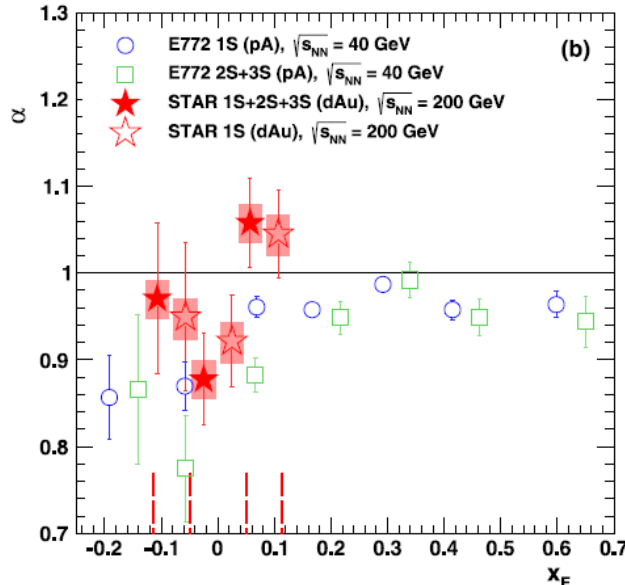
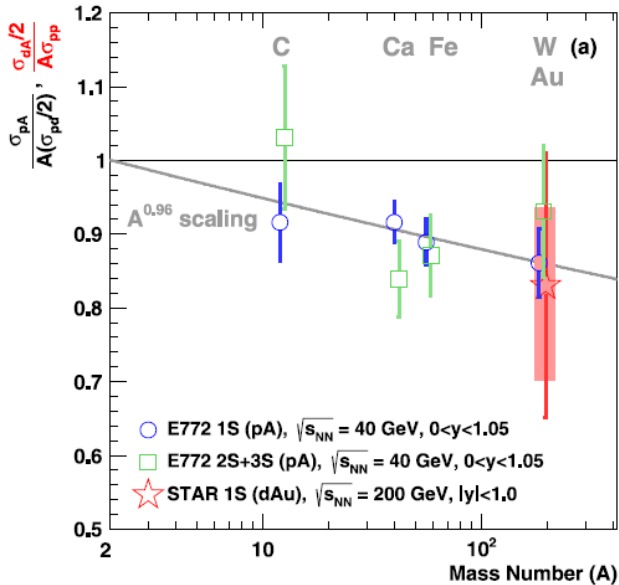
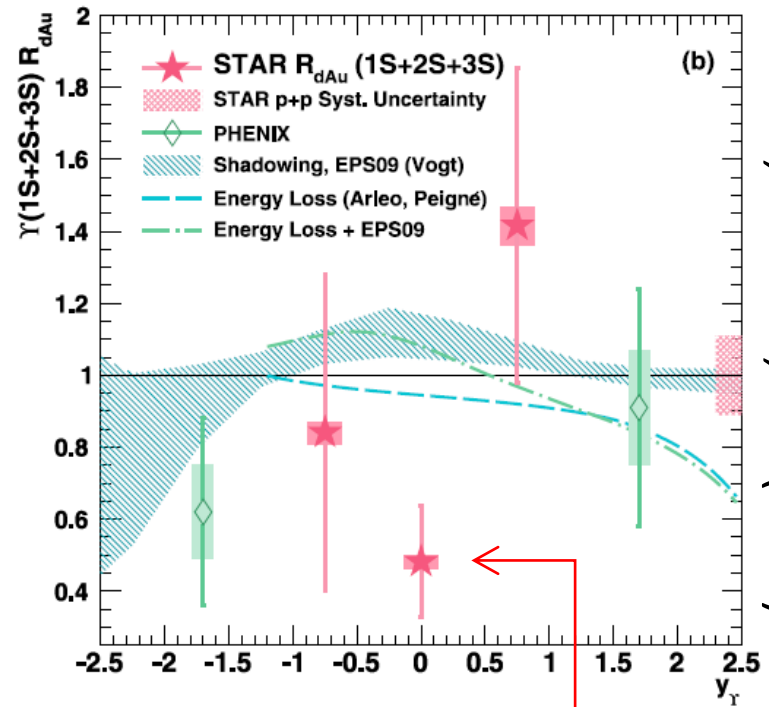
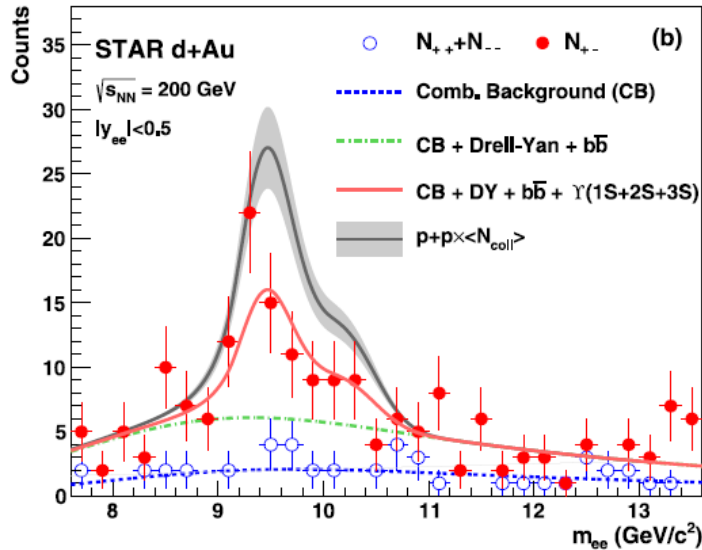


ALICE, PLB 740, 105 (2015)

- Smaller R_{pPb} (more suppression) for $\Upsilon(1S)$ than for J/ψ at backward rapidities
- Fair agreement between the data and the various model calculations
- Need differential analysis with more statistics in the future



Υ in dAu @ RHIC



Indication of suppression at mid- y

$$\sigma_{pA} = A^\alpha \sigma_{pp}$$

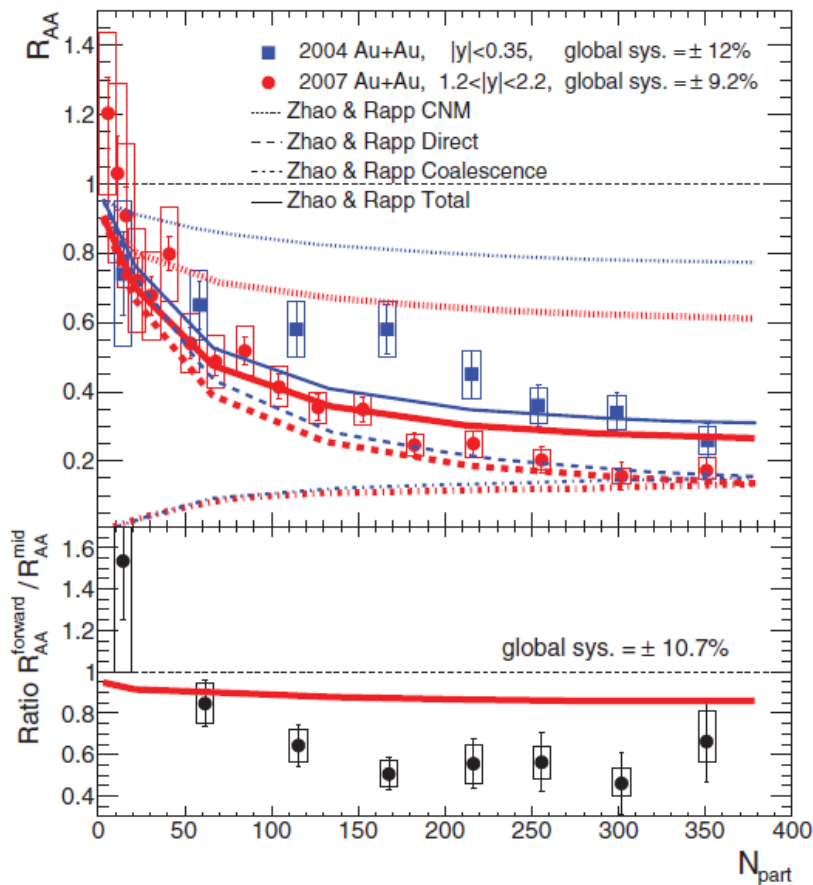
($\alpha = 0.962 \pm 0.006$)

J/ψ in AuAu @ RHIC

Midrapidity vs. forward rapidity

PHENIX, PRC 84, 054912 (2011)

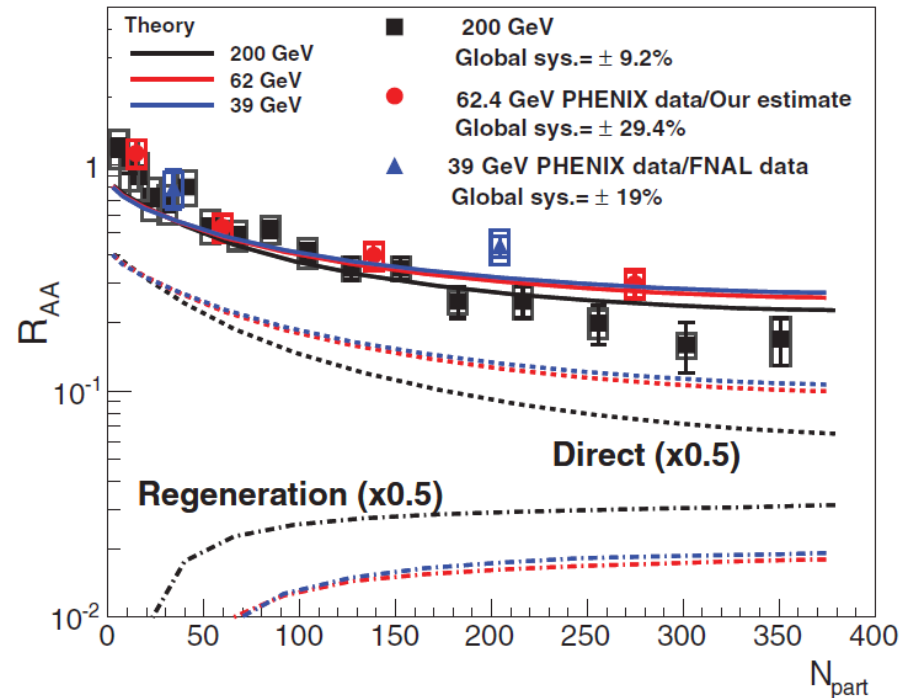
Model: Zhao & Rapp, EPJC 62, 109 (2009)



Energy dependence

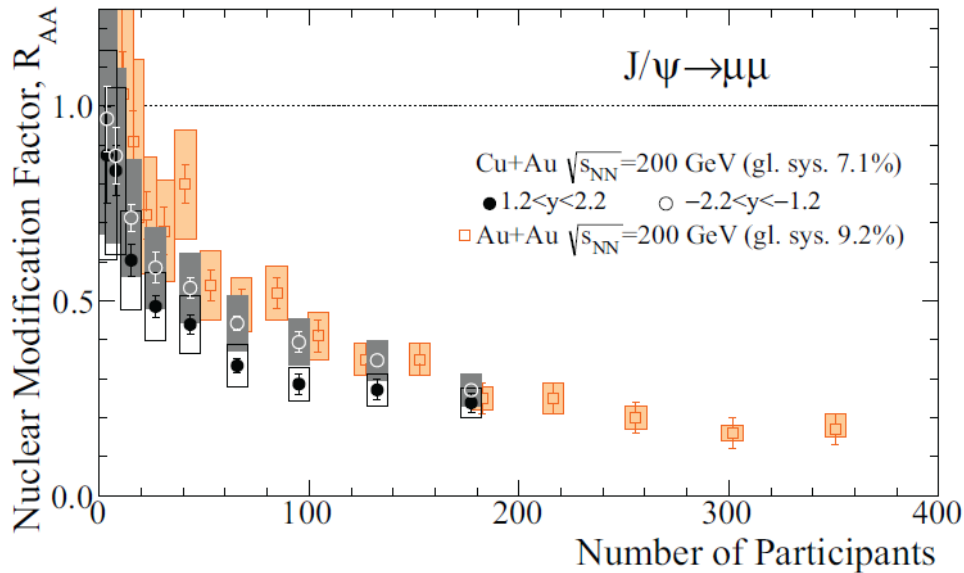
PHENIX, PRC 86, 064901 (2012)

Model: Zhao & Rapp, PRC 82, 064905 (2010)



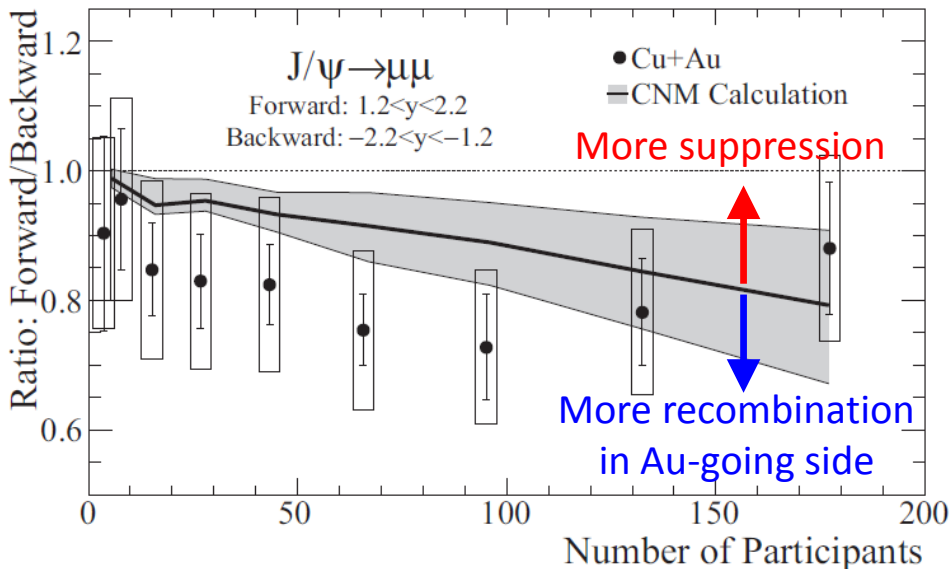
↑ Very little, if any, energy dependence
 ⇐ Stronger suppression at forward rapidity than that at midrapidity

J/ψ in AA @ RHIC



PHENIX, PRC 90, 064908 (2014)

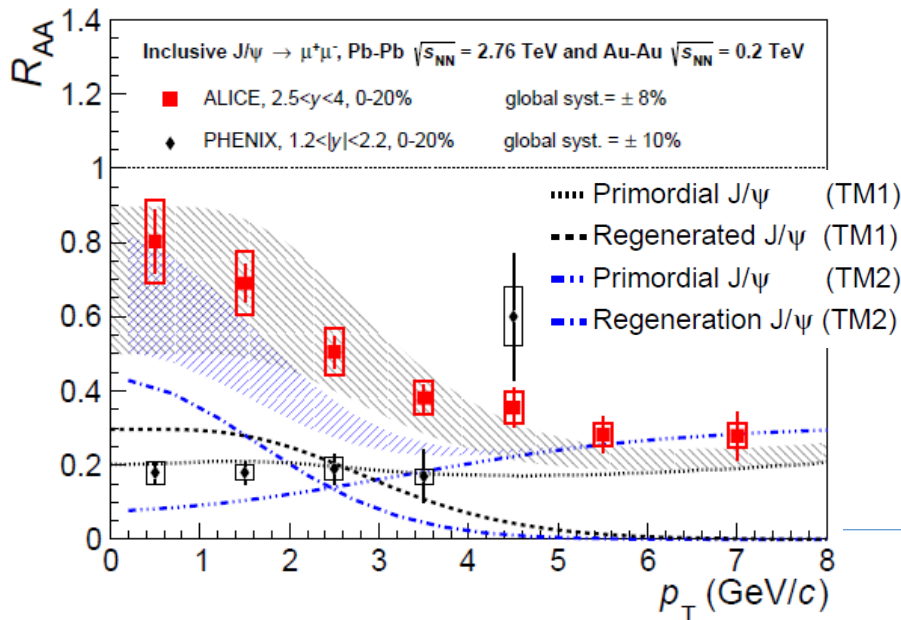
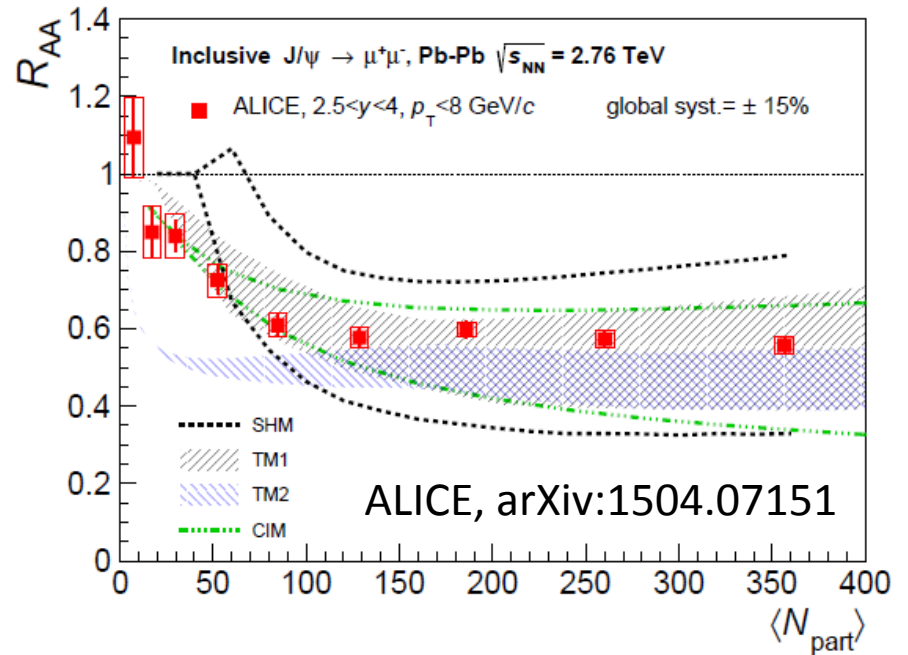
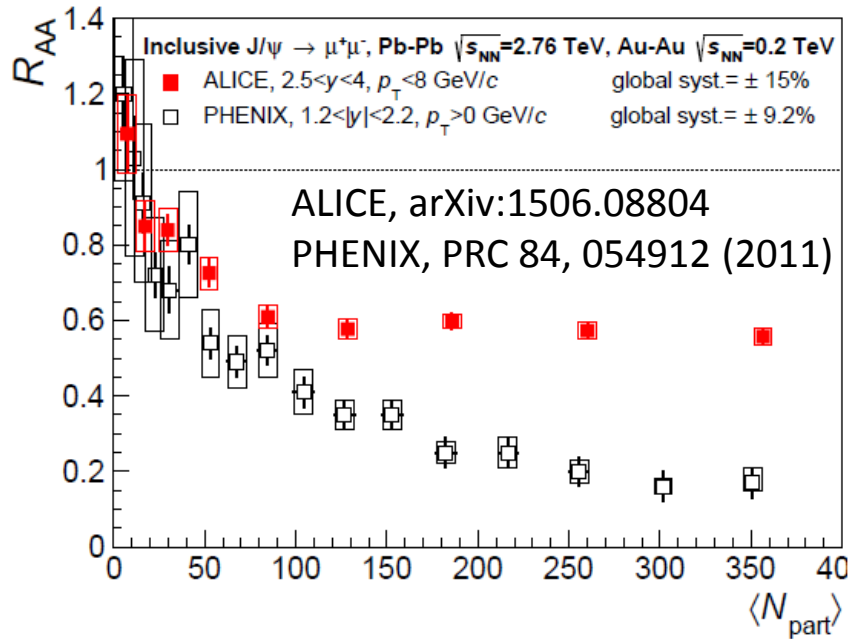
- PHENIX strategy: Changing the relative contribution of cold and hot nuclear matter effects by varying the system size.
- Au-going direction \approx AuAu
- Cu-going side more suppressed



- CNM model with EPS09 & 4 mb effective cross section for all rapidities gives right F/B ratio. [Nagle et al., PRC 84, 044911 (2011)]
- Hot matter effect is greater in Au-going side as the particle multiplicity is $\sim 20\%$ higher.

Inclusive J/ψ in PbPb

TM1: Zhao et al., NPA 859, 114 (2011)
 TM2: Zhou et al., PRC 89, 054911 (2014)

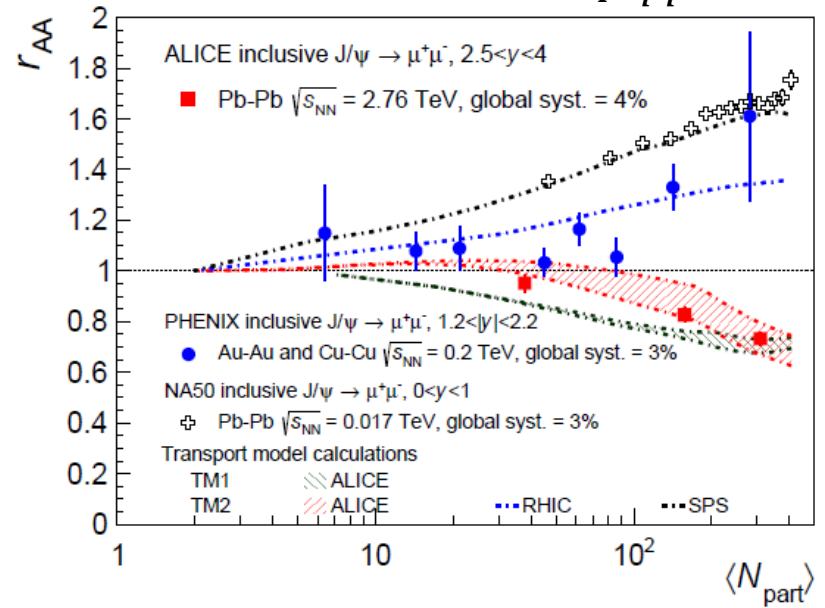
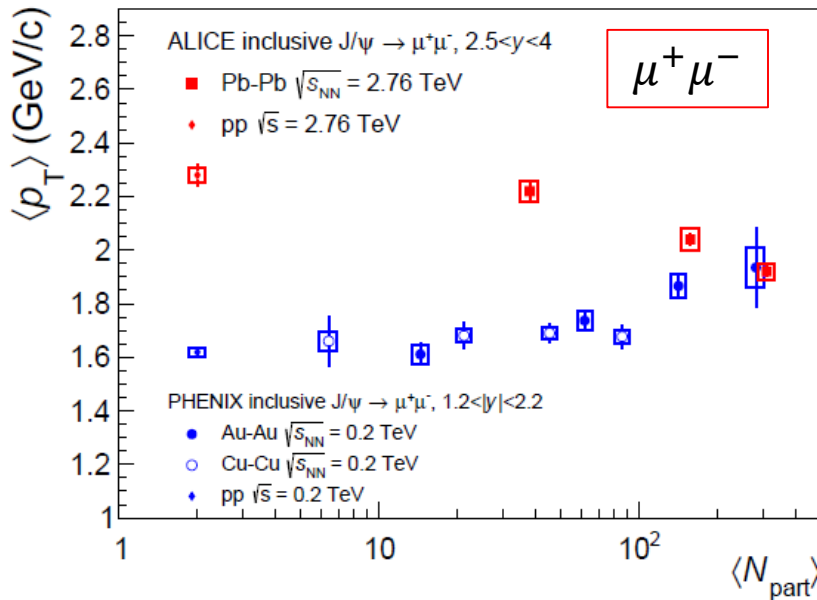


↖ ALICE R_{AA} constant for $\langle N_{part} \rangle > 70$
 ↑ Models with shadowing and regeneration can reasonably describe the data.

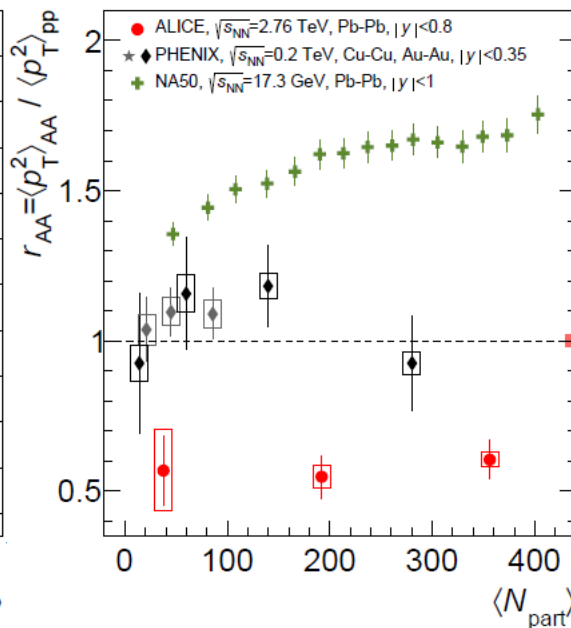
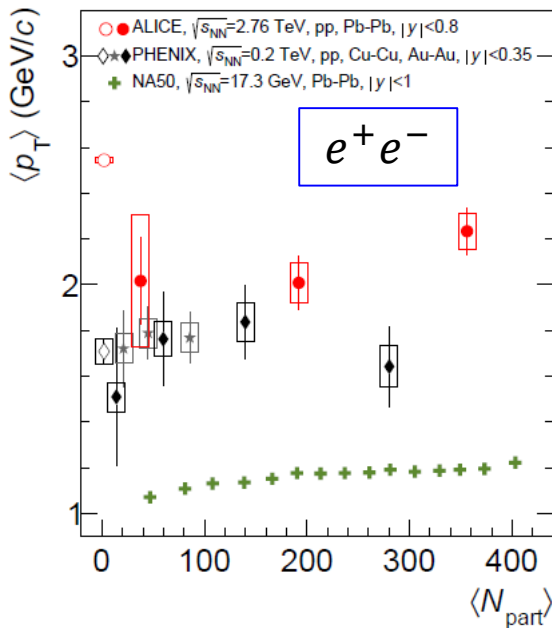
⇐ The rise towards $p_T = 0$ is due to the dominant regeneration component.

Inclusive J/ψ in PbPb

$$r_{AA} = \frac{\langle p_T^2 \rangle_{AA}}{\langle p_T^2 \rangle_{pp}}$$



ALICE, arXiv:1506.08804

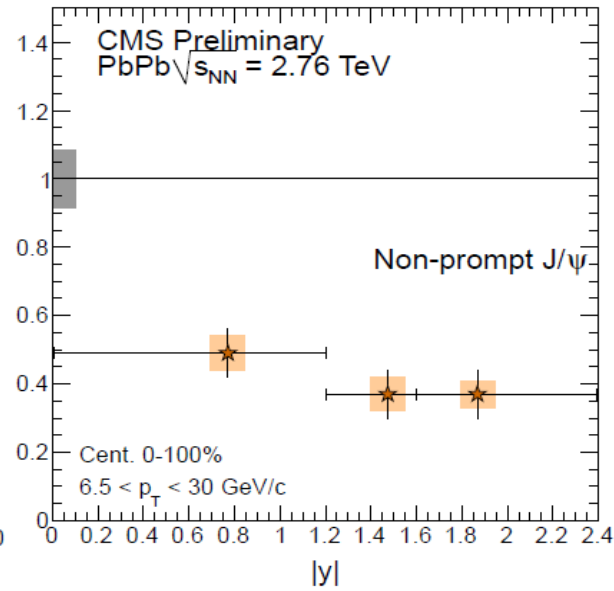
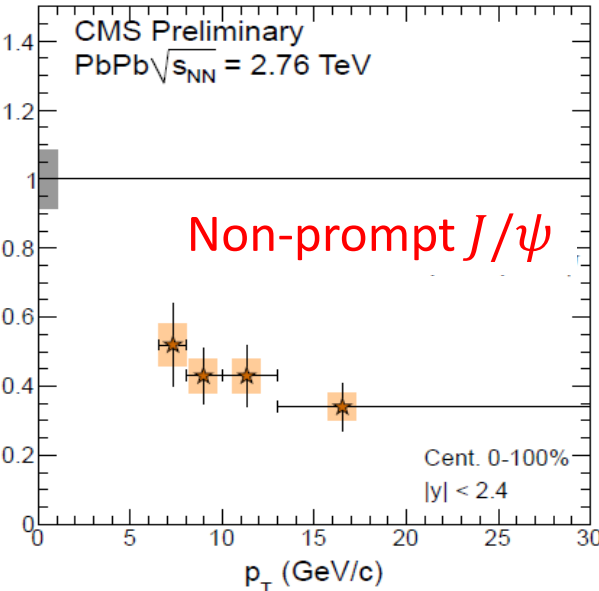
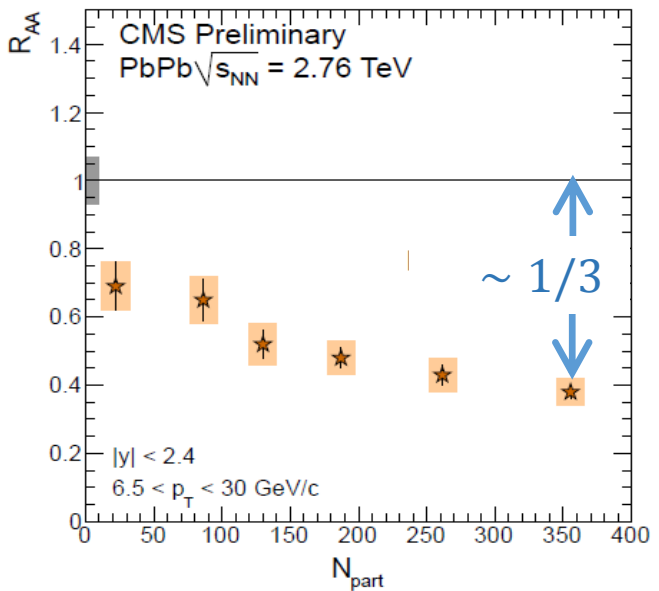
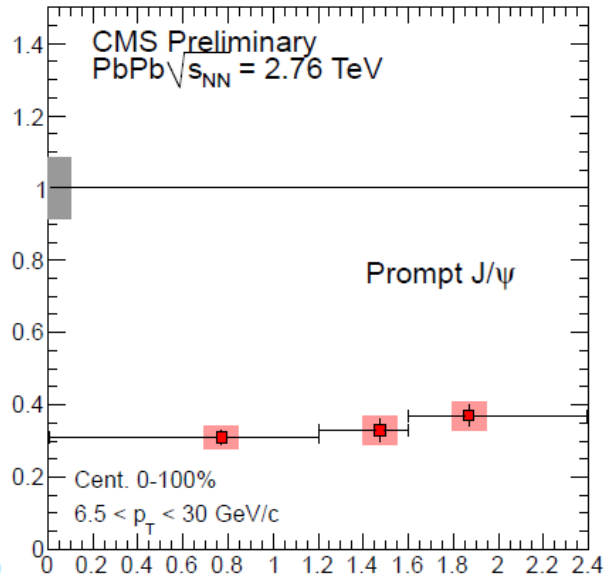
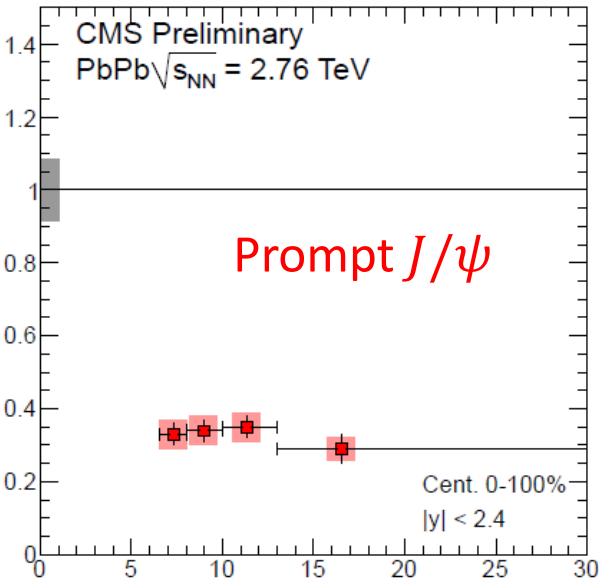
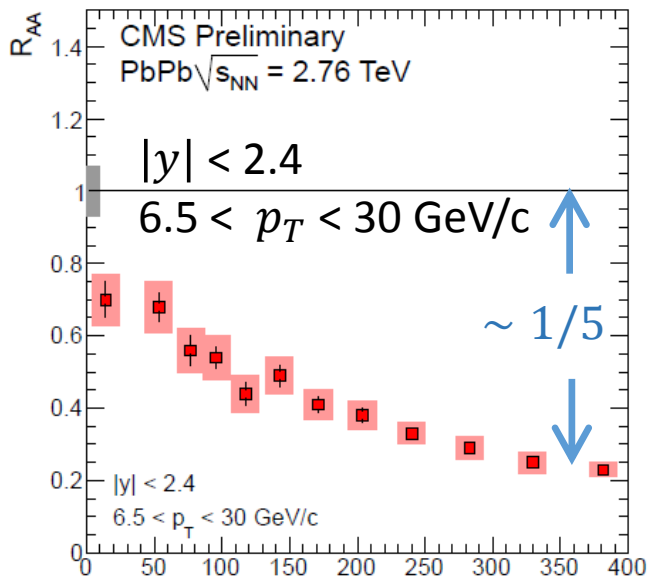


ALICE, arXiv:1504.07151

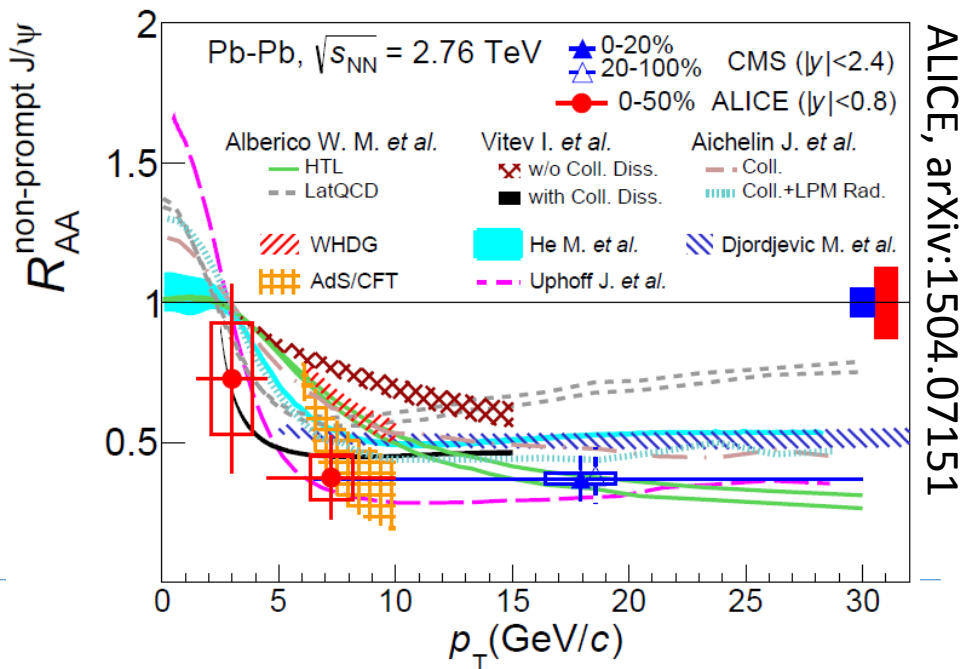
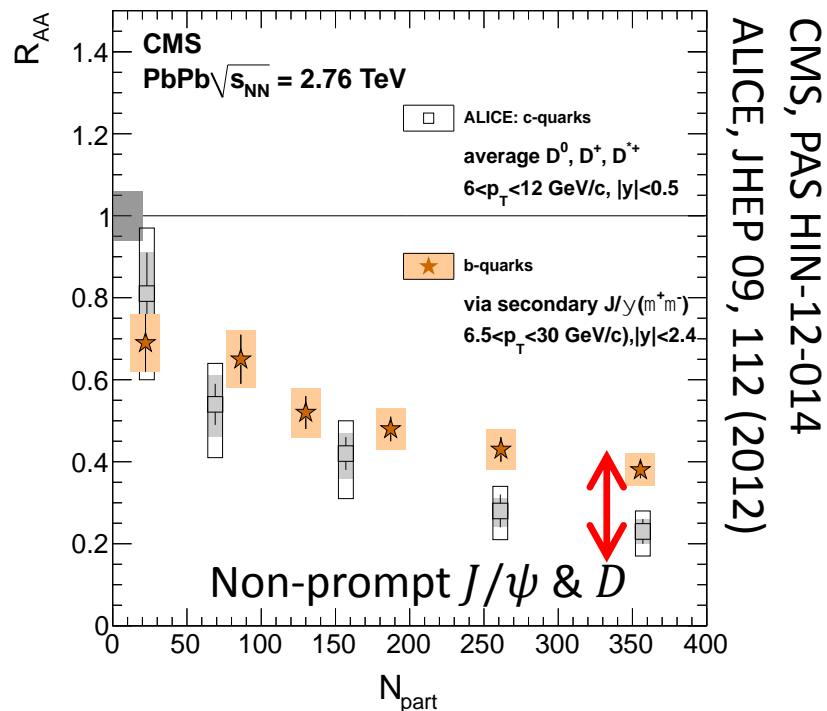
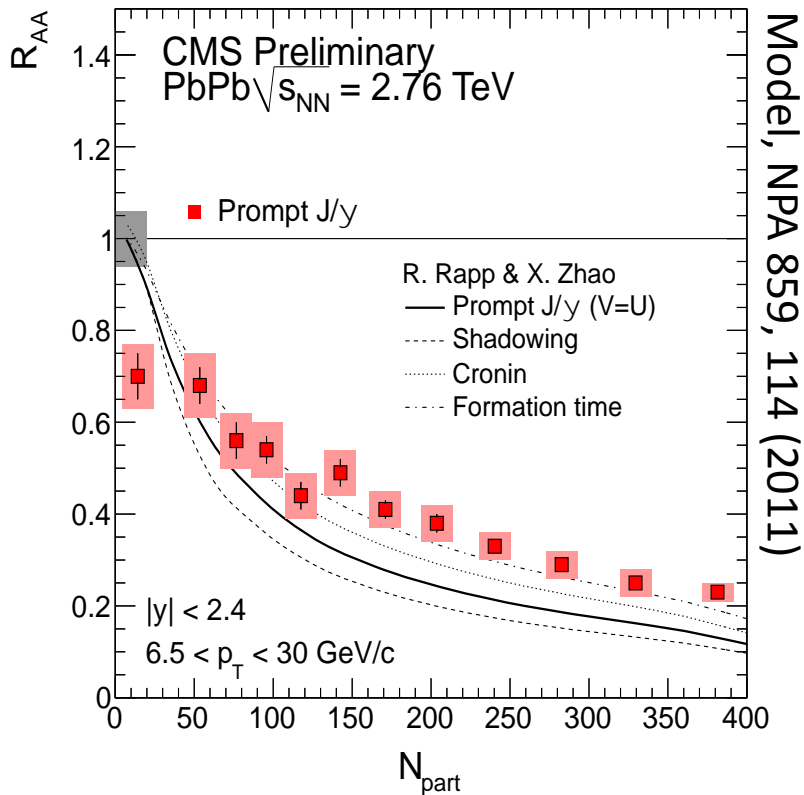
- $\langle N_{part} \rangle$ dependence of r_{AA}
 - Increases with centrality at SPS: Cronin effect
 - Decreases with centrality at LHC: Onset of regeneration and thermalization of the charm quarks?

J/ψ in PbPb

CMS, PAS HIN-12-014

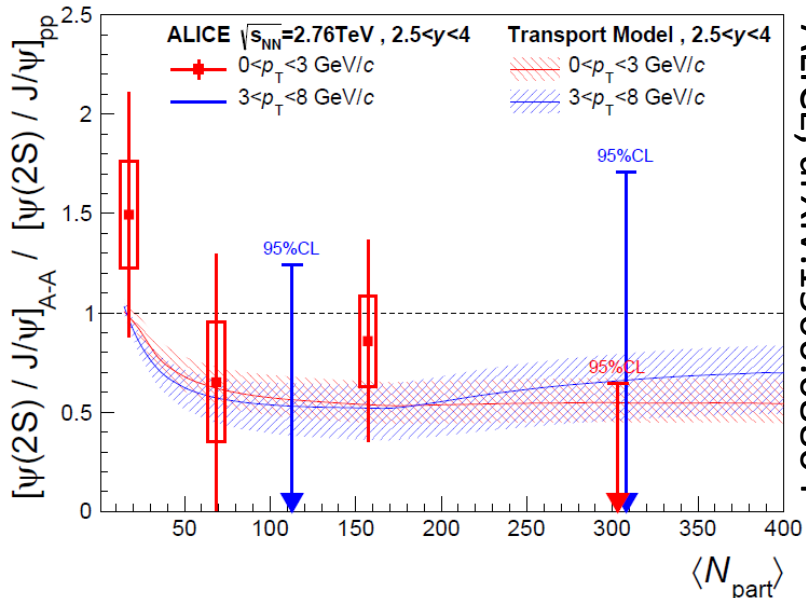
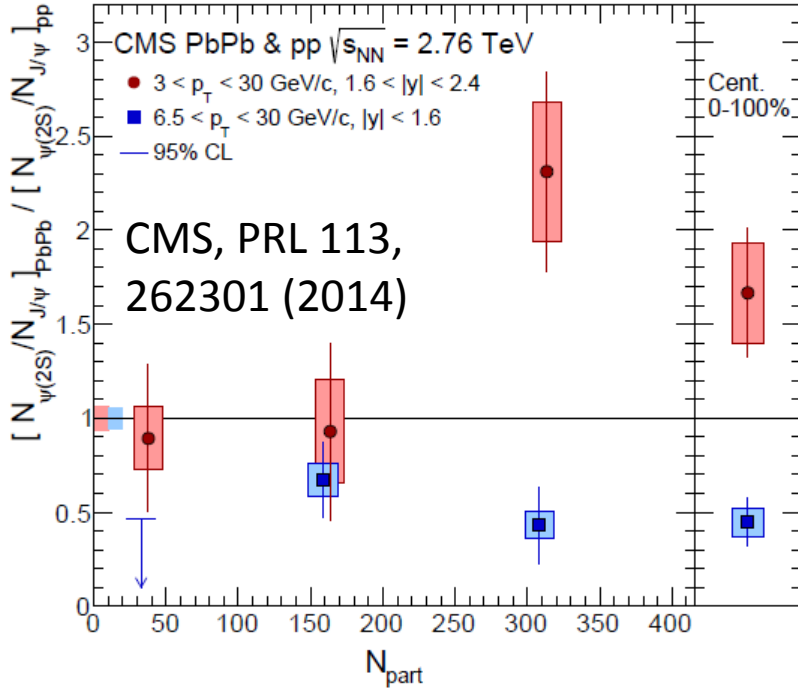


J/ψ in PbPb

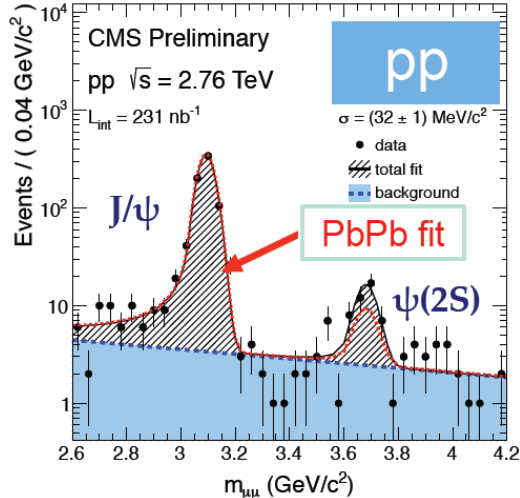
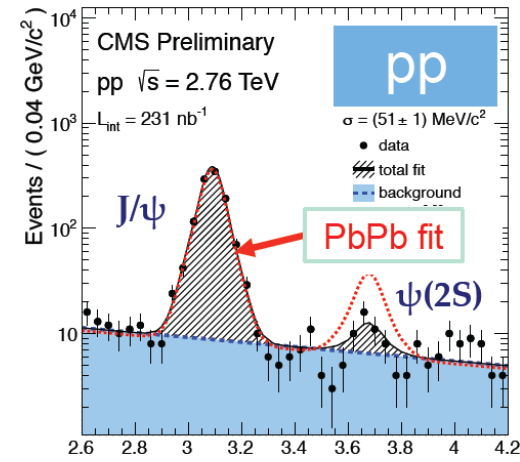


- ↑ No need for regenerations at high p_T
- ↗ $R_{AA}(B) > R_{AA}(D)$: Mass ordering predicted by dead cone effect
- ⇒ Collisional dissociation and gluon radiation

$\psi(2S)$ in PbPb



ALICE, arXiv:1506.08804



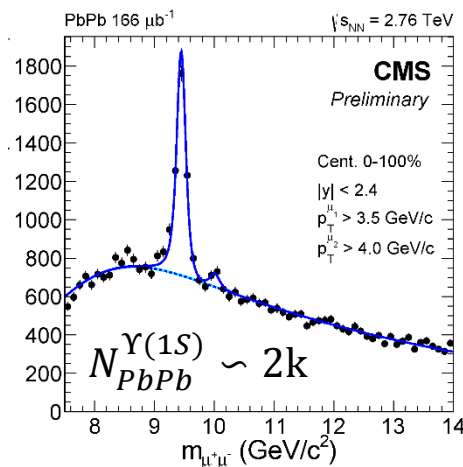
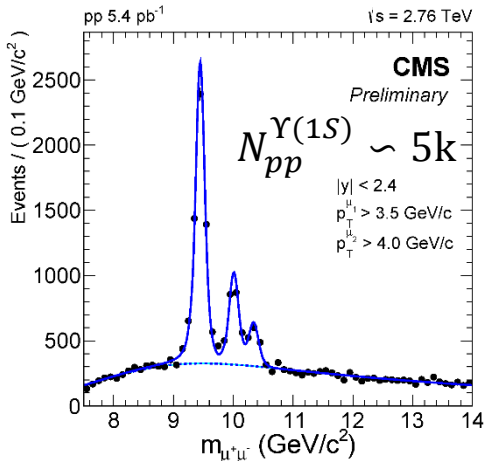
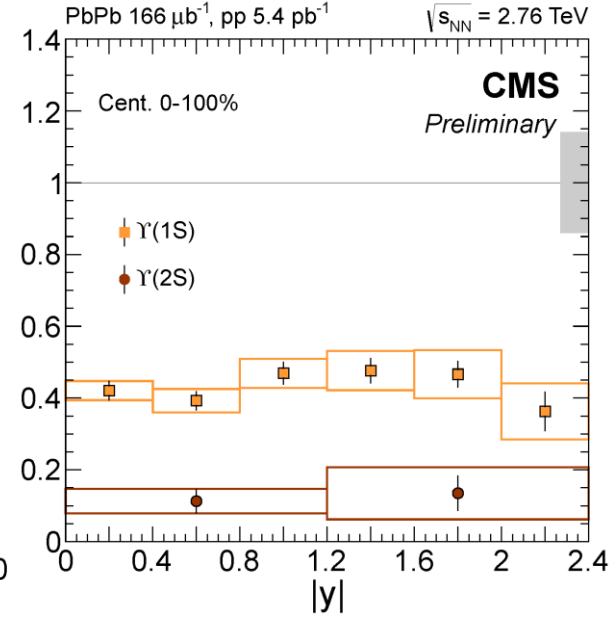
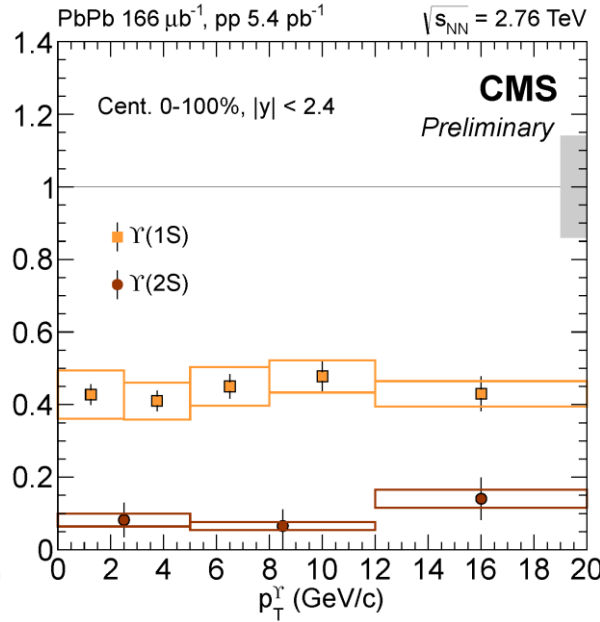
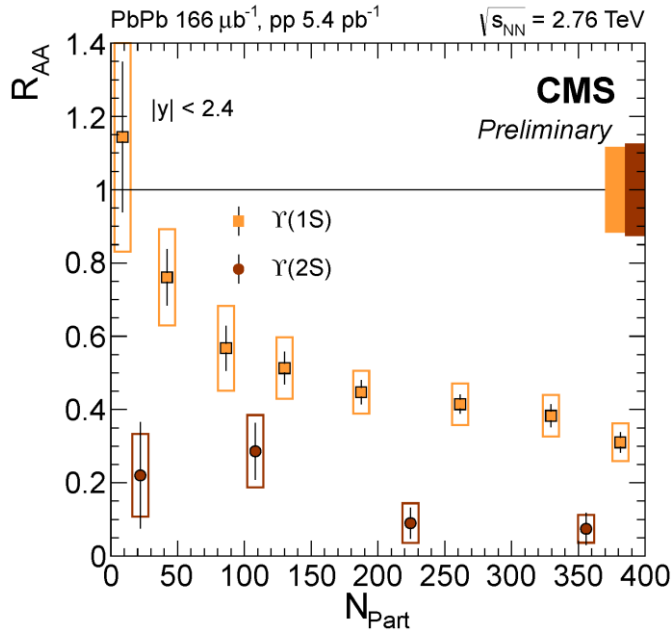
For $3 < p_T < 30$ GeV/c in $1.6 < |y| < 2.4$, $R_{\psi(2S)}$ in central (20%) PbPb is ~ 5 times larger than that in pp with larger systematic error.

For $6.5 < p_T < 30$ GeV/c in $|y| < 1.6$, $R_{\psi(2S)}$ in central (20%) PbPb is ~ 2 times smaller than that in pp.

- Indication of $\psi(2S)$ being less suppressed than J/ψ ($< 2\sigma$ effect) at low p_T in the most central events: ALICE needs more J/ψ statistics during LHC Run-2.

$\Upsilon(nS)$ in PbPb

CMS, HIN-15-001 (X20 more pp sample, etc.)
Old data: PRL 109, 222301 (2012)



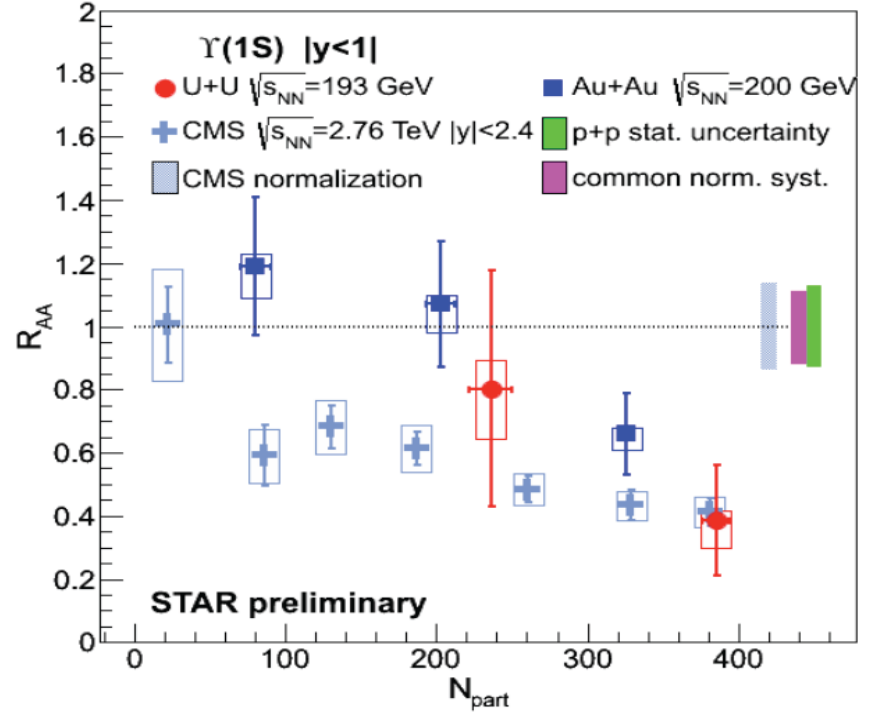
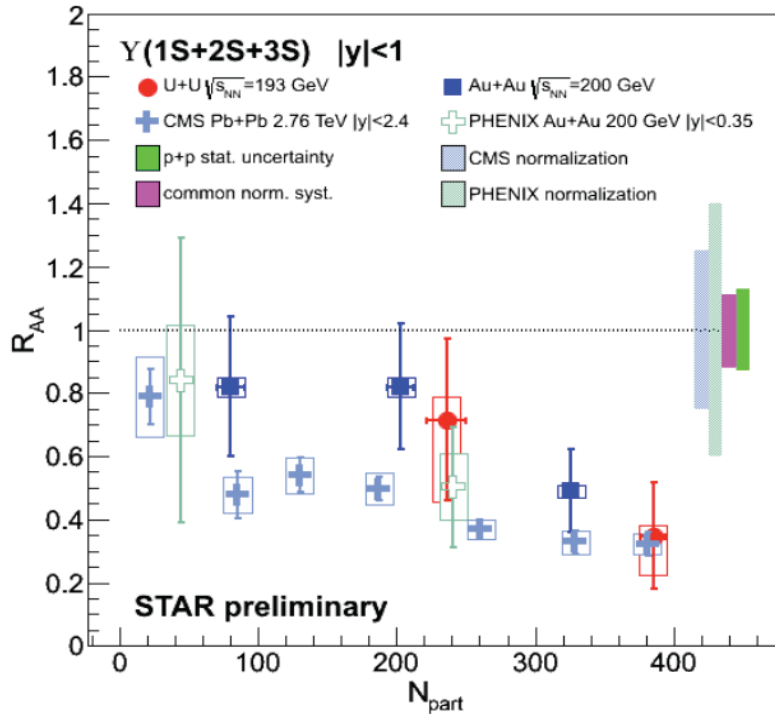
- Centrality integrated results
 - $R_{AA}[\Upsilon(1S)] = 0.425 \pm 0.029 \pm 0.070$
 - $R_{AA}[\Upsilon(2S)] = 0.116 \pm 0.028 \pm 0.022$
 - $R_{AA}[\Upsilon(3S)] < 0.14$ at 95% CL
- Υ states are suppressed sequentially
 - $R_{AA}[\Upsilon(3S)] < R_{AA}[\Upsilon(2S)] < R_{AA}[\Upsilon(1S)]$

Comparison of $\Upsilon(nS)$ in AA

STAR (Au+Au), PLB 735, 127 (2014)

STAR (U+U), R. Vertesi, HP2015

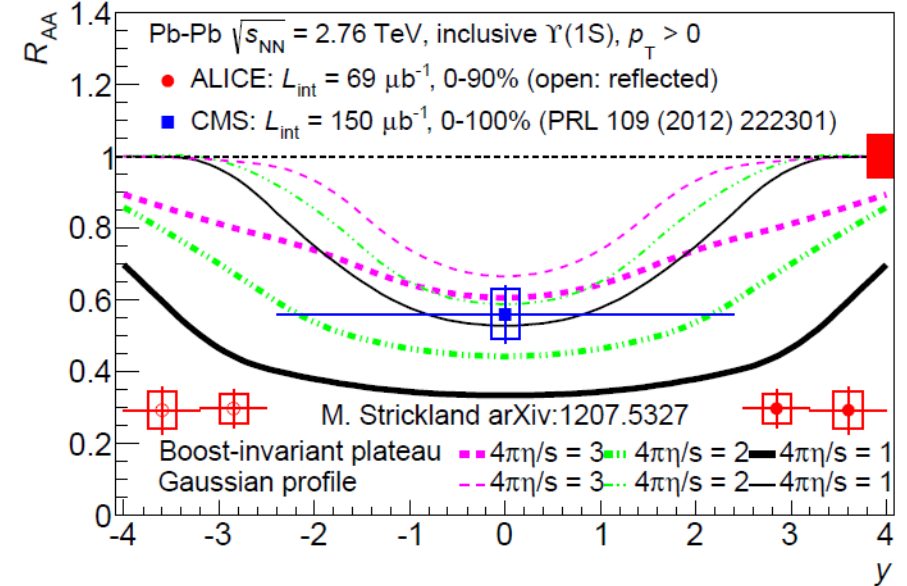
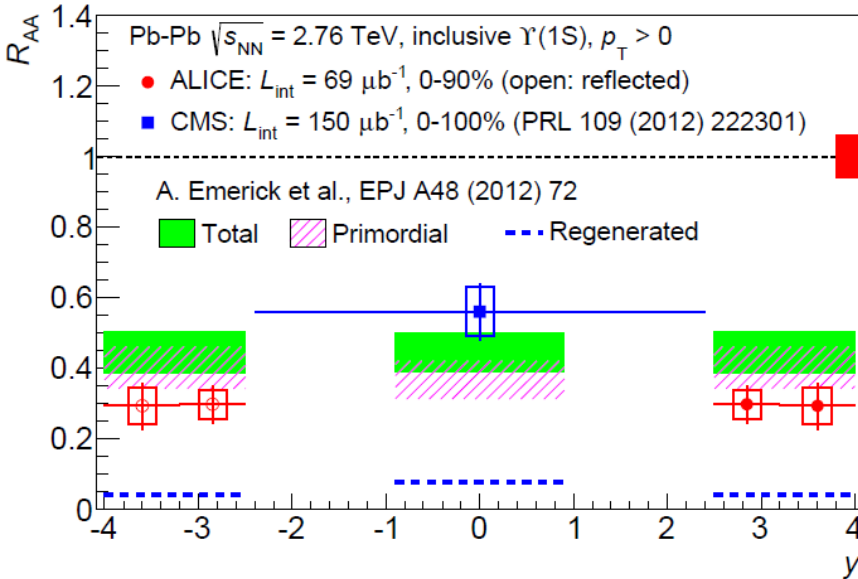
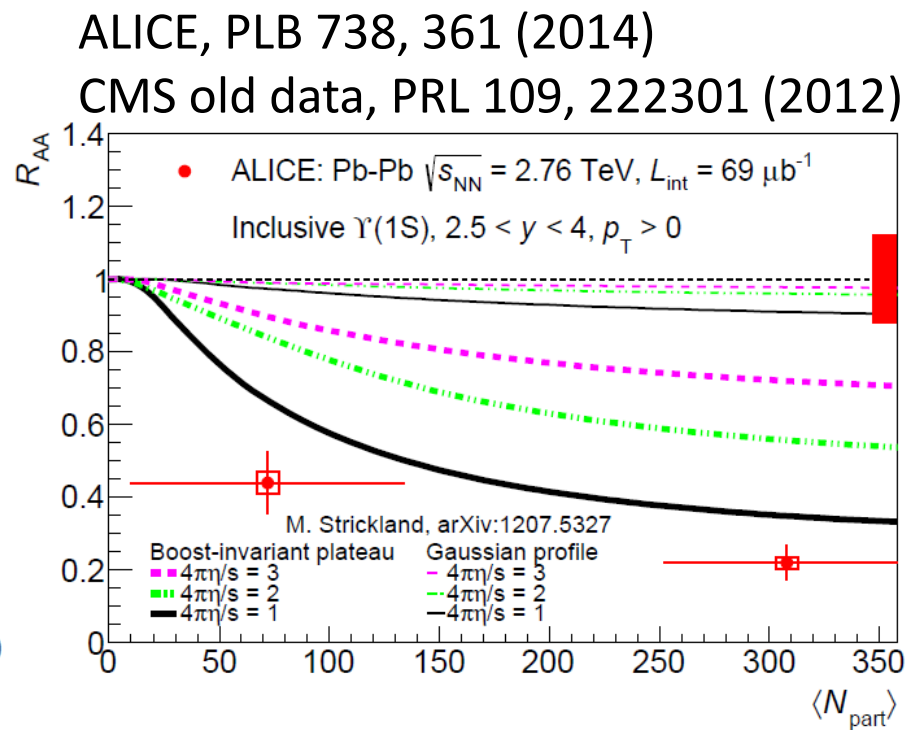
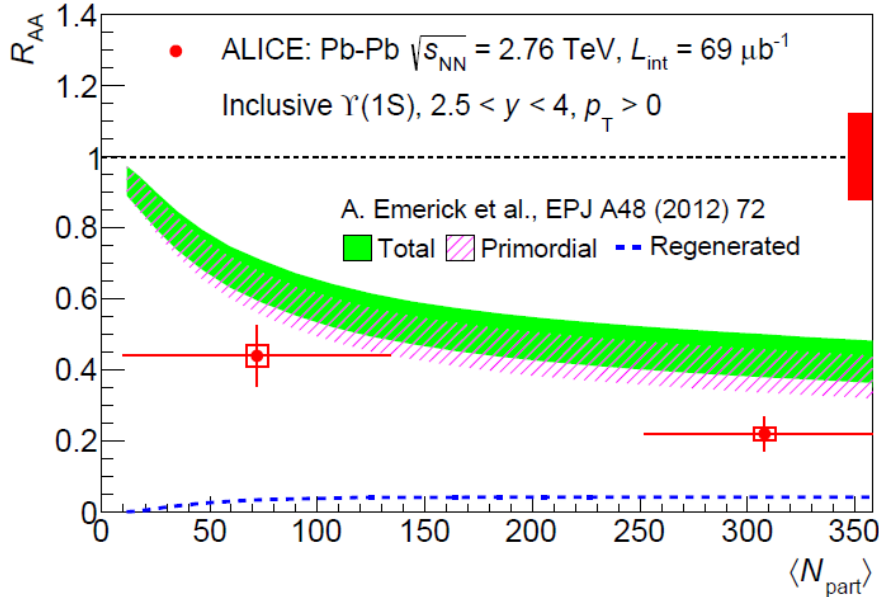
CMS, PRL 109, 222301 (2012)



- Suppressions are compatible between RHIC and LHC at the most central collisions.
- Centrality dependence is weaker at LHC

R. Vertesi for STAR @ HP2015

$\Upsilon(1S)$ in PbPb



Summary

1. pp

- Currently, J/ψ and Υ data are available from $p_T=0$ GeV/c at RHIC and LHC, which provide good references to understand pA and AA data.
- Non-linear increasing trend of quarkonium yields for highly active events and polarization are yet need to be understood.

2. pA

- Quarkonium yields of prompt & non-prompt J/ψ and $\Upsilon(1S)$ are suppressed at forward (small x) region with an exception of Υ at RHIC.
- R_{pPb} s for prompt $\psi(2S)$ and non-prompt J/ψ are enhanced in some specific centrality ranges.
- p_T broadening of J/ψ is larger at forward rapidities.

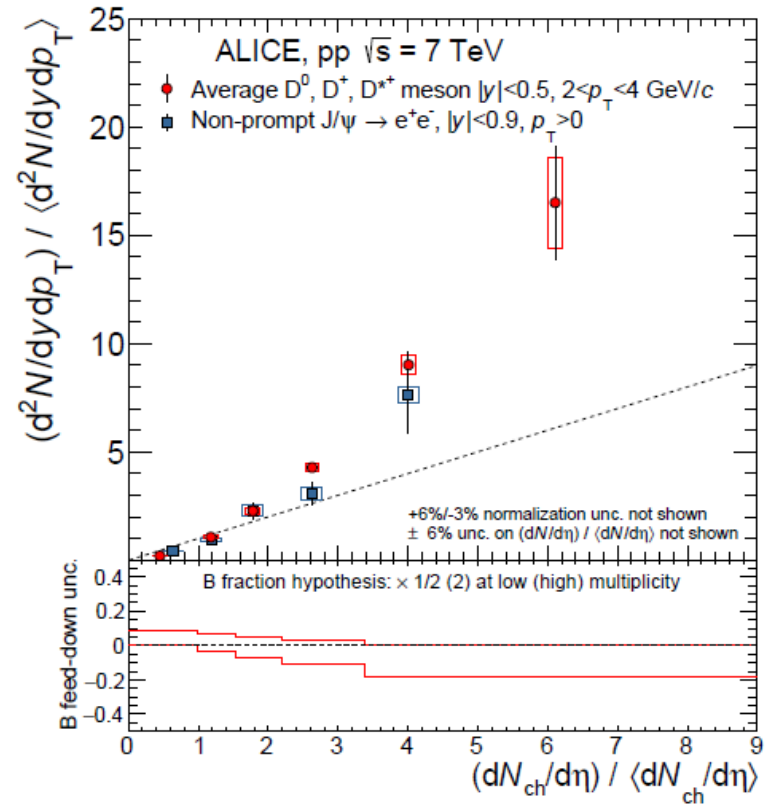
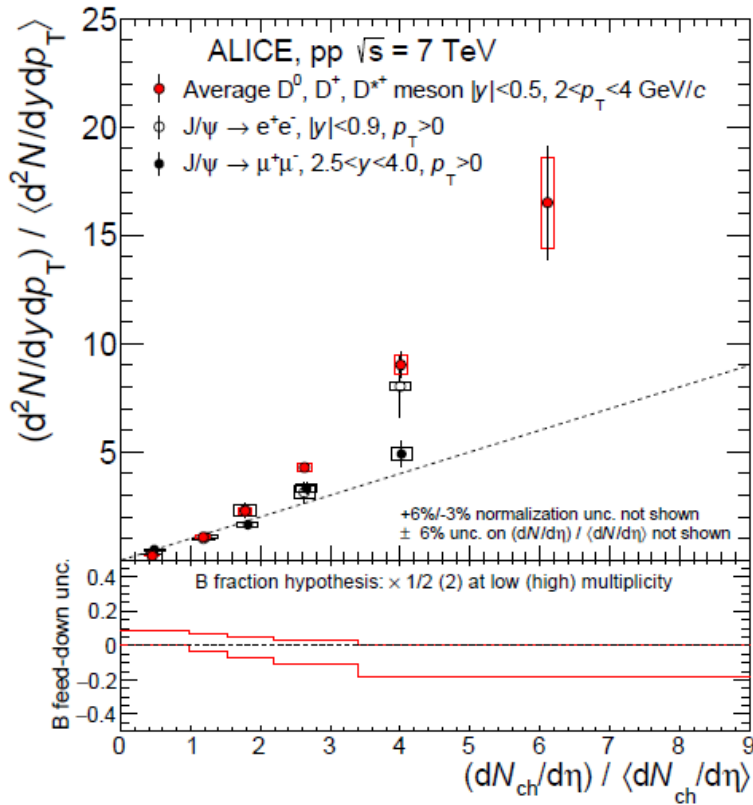
3. AA

- Systematic study of CNM and HNM effects using asymmetric AA collision systems has been started by PHENIX.
- Regeneration component is necessary to describe the low- p_T data.
- Less suppression of $\psi(2S)$ relative to J/ψ for the most central events was observed by CMS: ALICE can give only upper limit at the moment.
- Sequential suppression of Υ family was observed.
- Υ suppressions are compatible between RHIC and LHC at the most central collisions.
- Centrality dependence of Υ suppression is weaker at LHC.

Backups

Non-Linear Charm-Quark Yields in pp

ALICE: arXiv: 1505.00664



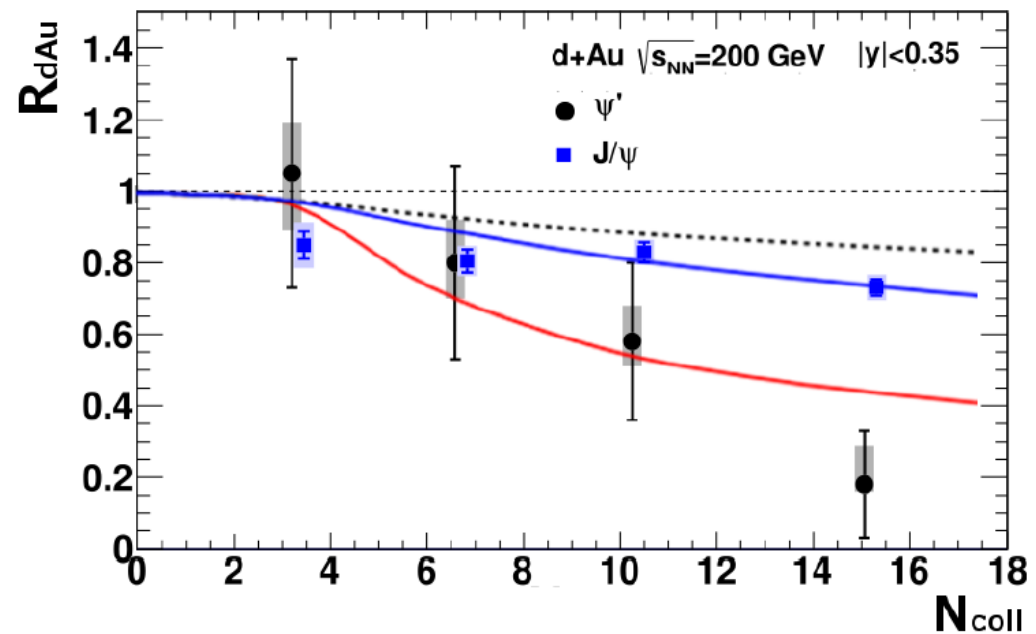
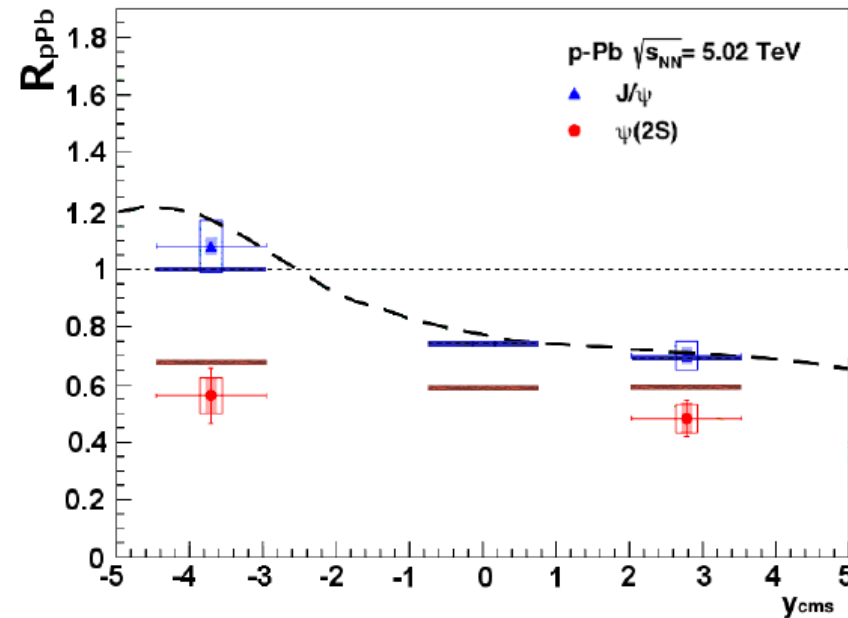
- J/ψ and D show similar non-linear behavior at LHC.
- STAR shows similar rising trend at RHIC (R. Ma @ HP2015)
- Universal behavior?

$\psi(2S)$ in pA

ALICE, arXiv:1405.3796

PHENIX, dAu, PRL 111, 202301 (2013)

Ferreiro, arXiv:1411.0549



- Shadowing and coherent energy loss cannot explain the difference between J/ψ and $\psi(2S)$.
- Final state effect due to scattering of $c\bar{c}$ with comovers?
 - Effect should be larger for more loosely bound $\psi(2S)$
 - Effect should be larger in backward direction with higher comover density
- Comover interaction with EPS09 agrees with the ALICE and RHIC data.