XLV International Symposium on Multiparticle Dynamics (ISMD2015)
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# Overview of Quarkonium Production in Heavy-Ion Collisions at LHC

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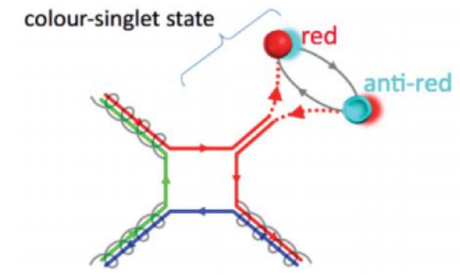
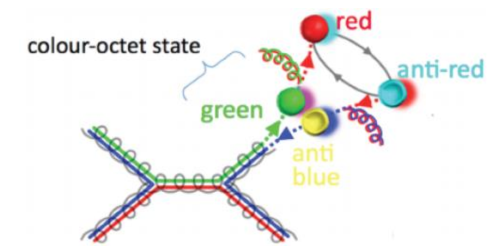
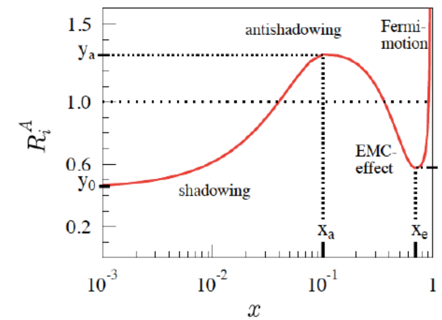
# Introduction

- pp
  - Reference to understand pA and AA data
  - Cross section for production mechanism
    - Color Octet vs. Color Singlet
  - Polarization for interactions with surroundings not affected by initial-state effect

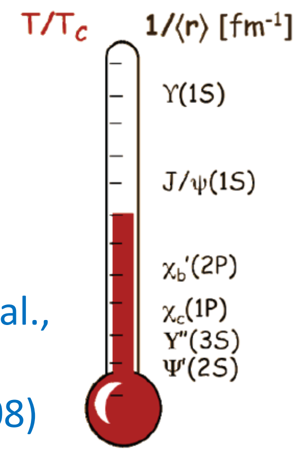



- pA
  - Nuclear modification of gluon PDF (nPDF): shadowing, saturation, CGC, etc.
  - Medium-induced coherent gluon radiation
  - Co-mover absorption



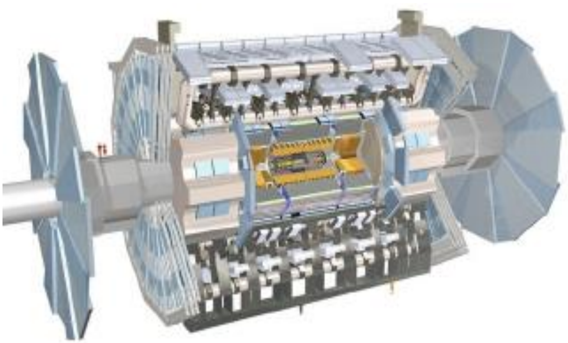

- AA
  - Color-charge screening effect: $\lambda_D$ vs. $r$
    - Sequential suppression: Different states dissociate at different temperatures
  - Regeneration of $q$ and $\bar{q}$
    - Expected to be larger for $J/\psi$ than for $\Upsilon$



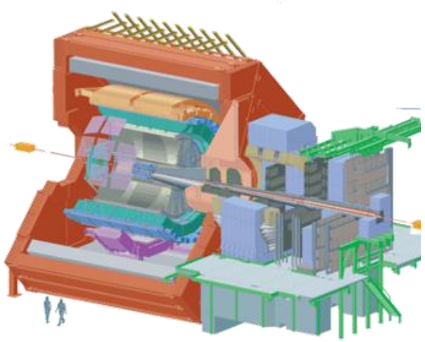

A. Mocsy et al., PRD 77, 014501 (2008)

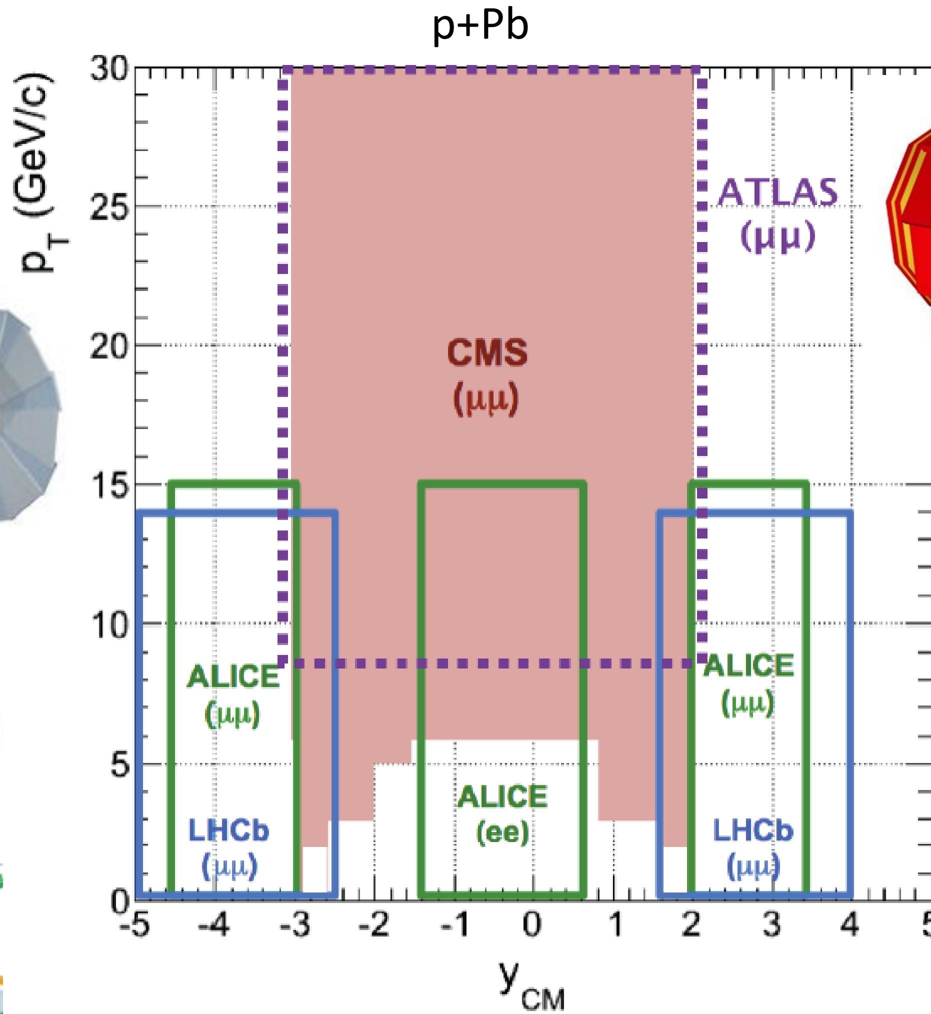
# Complimentary acceptance for LHC detectors

**ATLAS**

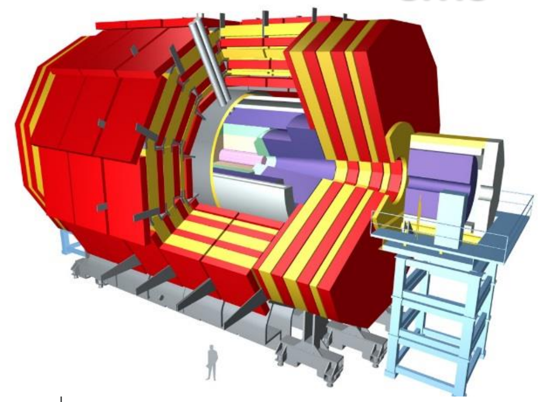


**ALICE**

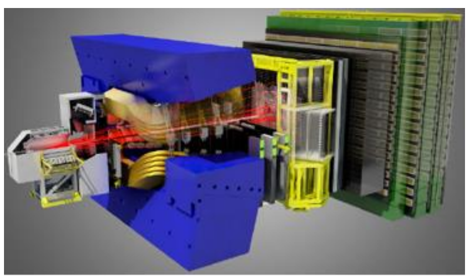





**CMS**

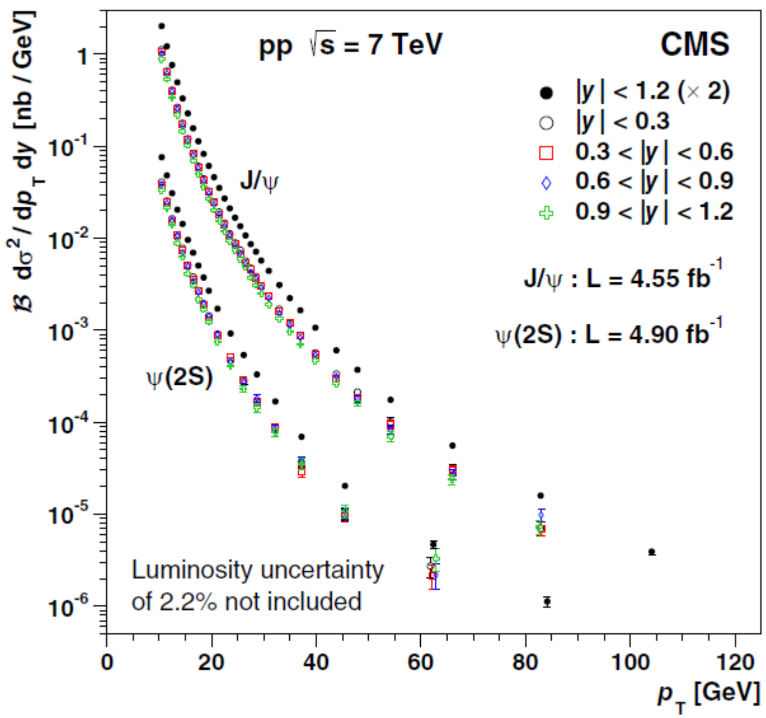


**LHCb**

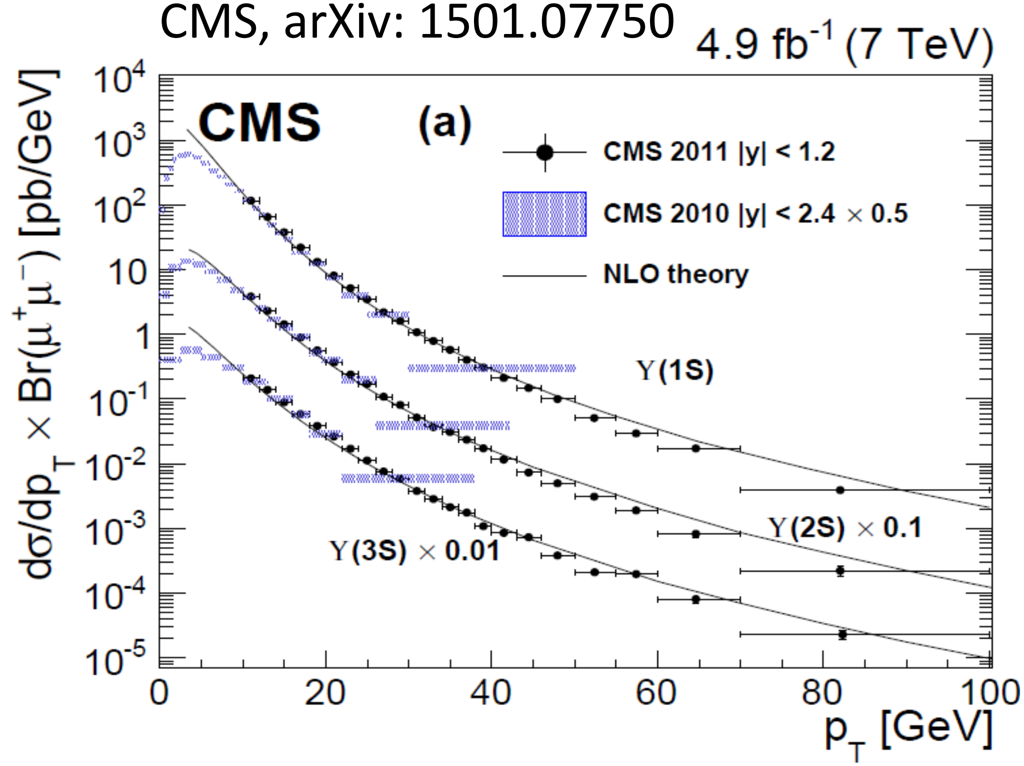


# Quarkonium cross section in pp

CMS, PRL 114, 191802 (2015)




CMS, arXiv: 1501.07750

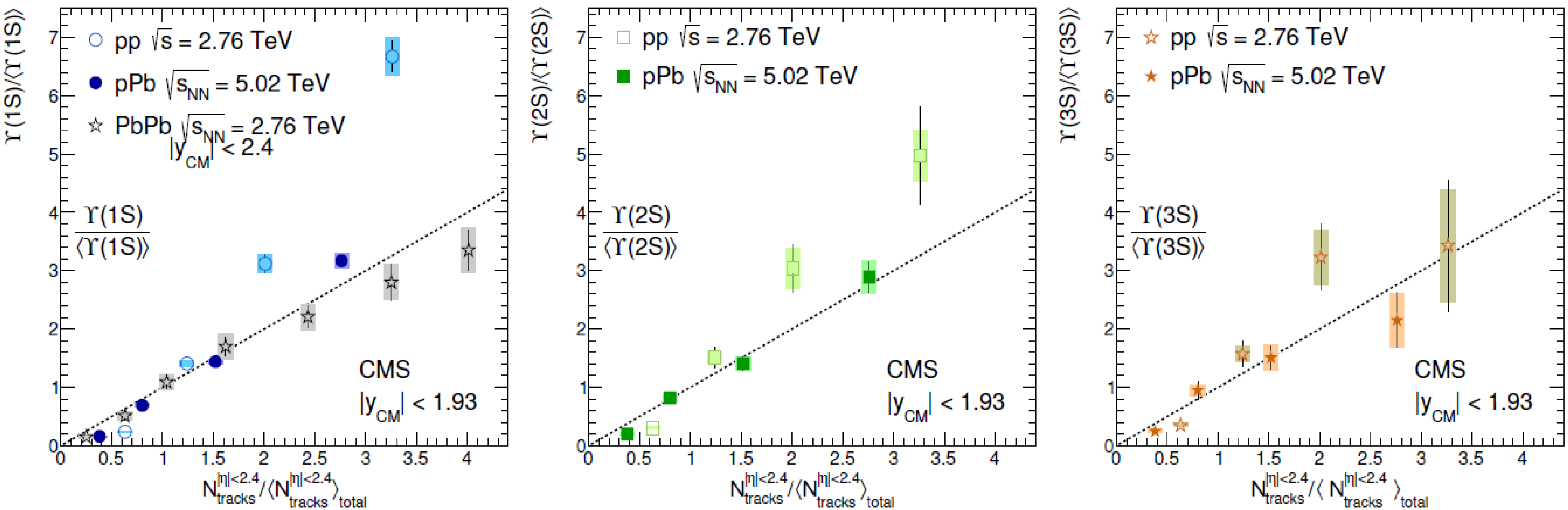



↑ New $J/\psi$, $\psi(2S)$ and $\Upsilon(nS)$ spectra extend $p_T$ beyond 100 GeV/c at LHC.

↑ Good agreement between data and NLO pQCD, especially, for high $p_T$

# Non-linear heavy-quark yields in pp

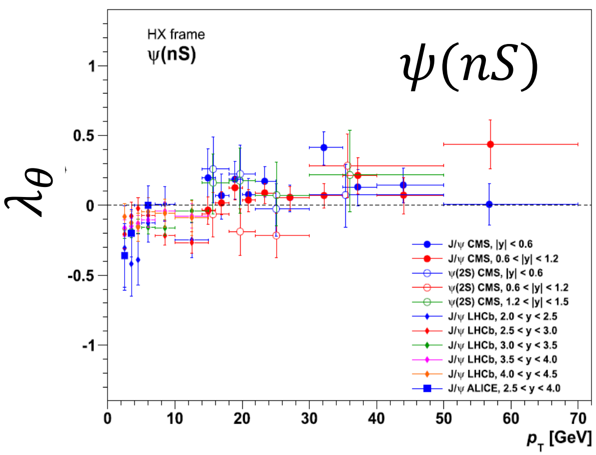
CMS, JHEP 04, 103 (2014)

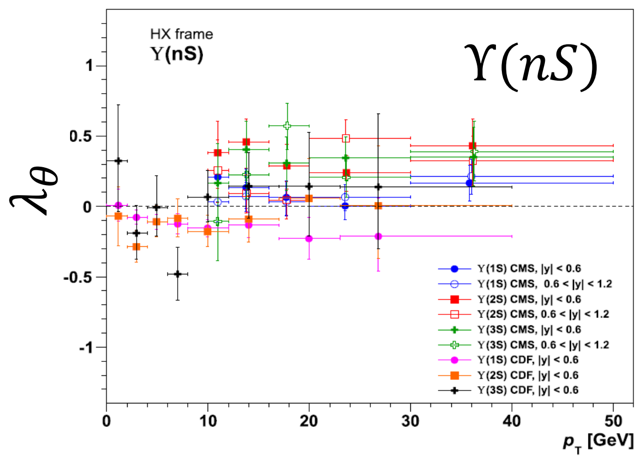



- Stronger rises of the $\Upsilon$ yields vs. event activity
  - Common to both closed and open bottom at RHIC and LHC
  - Similar trend for the charm sector at RHIC and LHC
  - $\frac{\Upsilon(1S)}{\langle\Upsilon(1S)\rangle} > \frac{\Upsilon(2S)}{\langle\Upsilon(2S)\rangle} > \frac{\Upsilon(3S)}{\langle\Upsilon(3S)\rangle}$: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

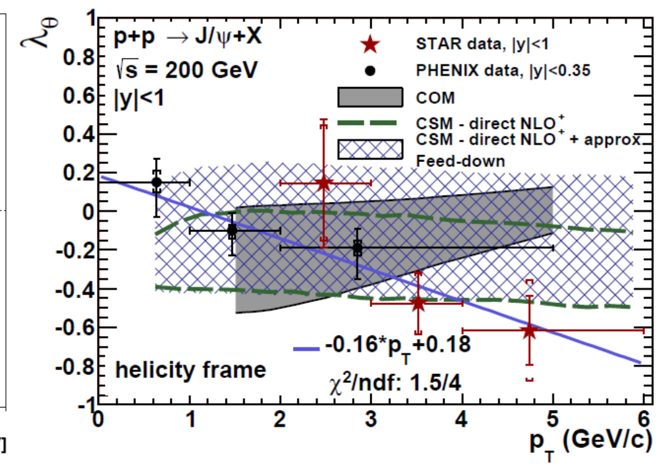
# Quarkonium polarization in pp

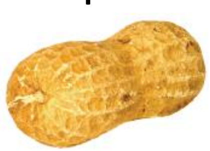
Compilation done by P. Faccioli et al. in PLB 736, 98 (2014)



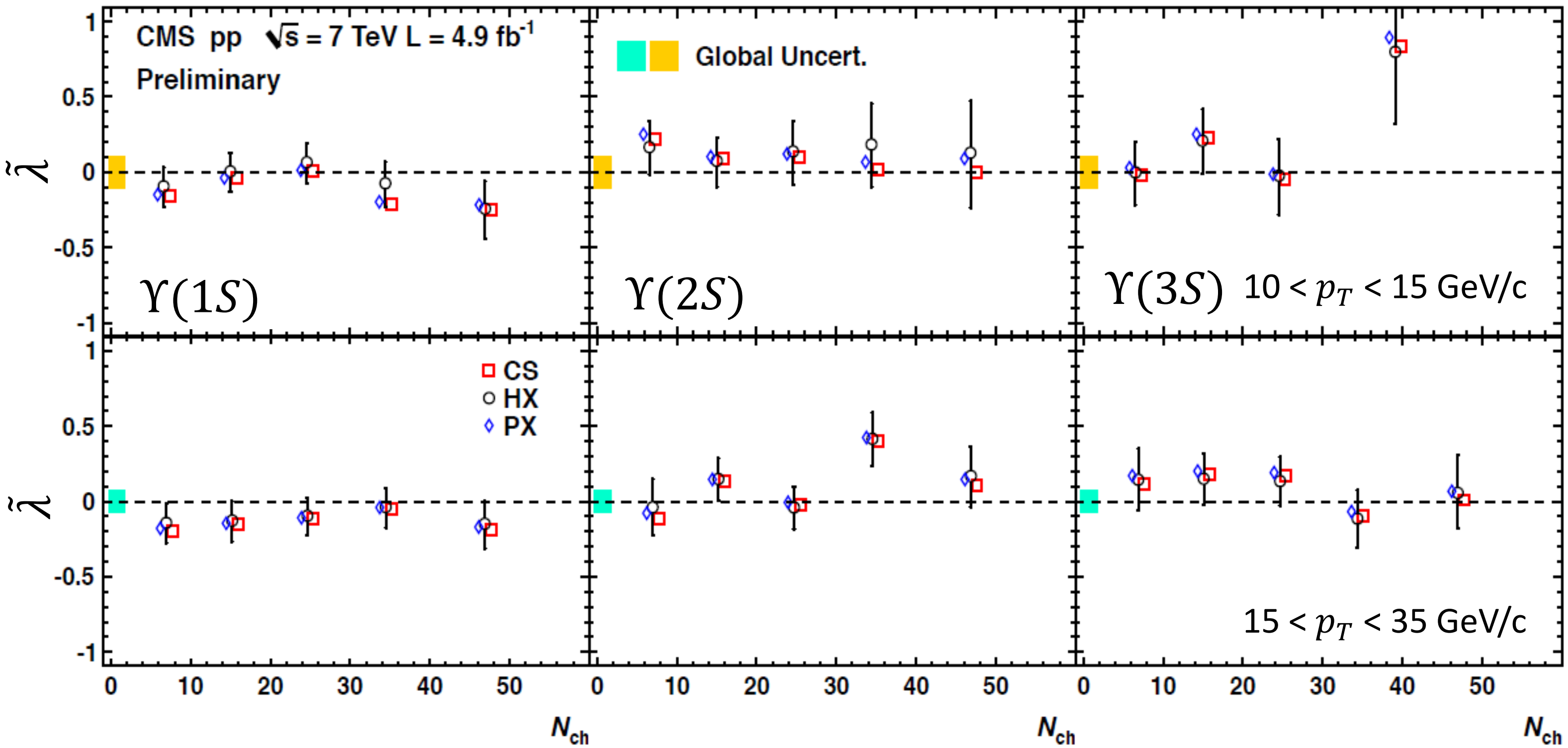

STAR, PLB 739, 180 (2014)
PHENIX, PRD 82. 012001 (2010)




- Data points are scattered around the unpolarized limit with no significant dependences on $p_T$, $y$, flavor and feed-down effect at LHC.
  - Quarkonia are produced via common production mechanism
  - Pre-resonant $Q\bar{Q}$ pairs are dominantly produced in color octet state, ${}^1S_0^{[8]}$
- Try a frame independent approach using $\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1-\lambda_\phi}$
  - $\tilde{\lambda}$=+1 for  and $\tilde{\lambda}$=-1 for 

# $\Upsilon$ polarization in pp

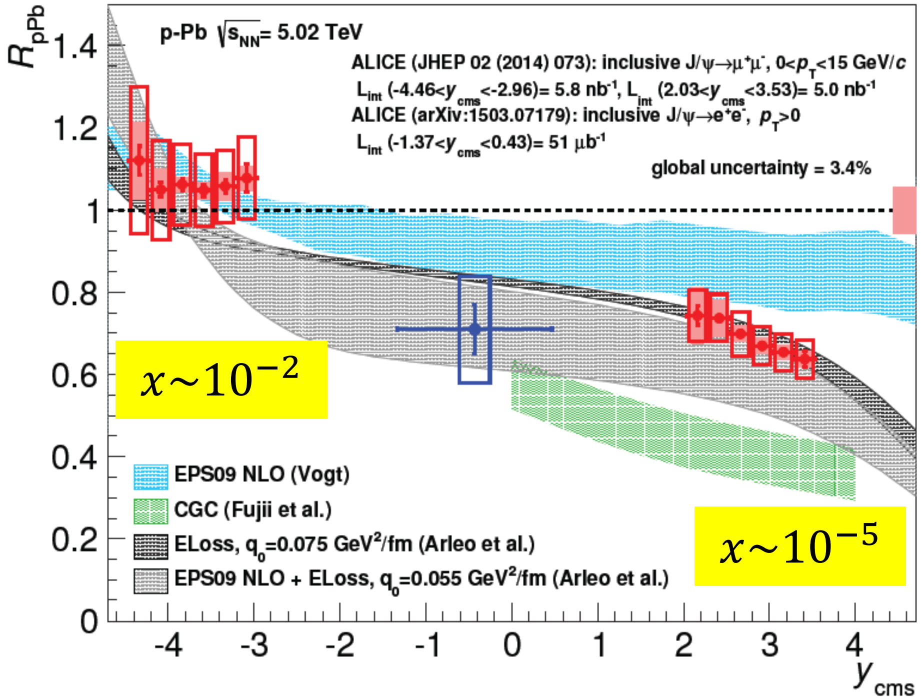
CMS-HIN-15-003




- Polarization results obtained in HX, CS, PX agree each other.
- No significant changes in $\Upsilon(nS)$ polarizations can be seen as a function of $N_{ch}$ in pp

HX (C.M. helicity frame): polar axis = $\Upsilon$ momentum
CS (Collins-Soper frame): polar axis = average of two beam directions in the $\Upsilon$ rest frame
PX (Perpendicular helicity frame): polar axis = orthogonal to the CS frame

# Inclusive $J/\psi$ 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 (Eloss) models.

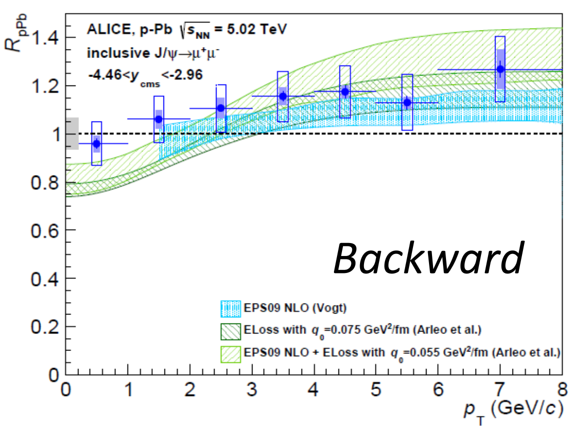
← Forward data: energy loss essential, but CGC overestimates suppression.

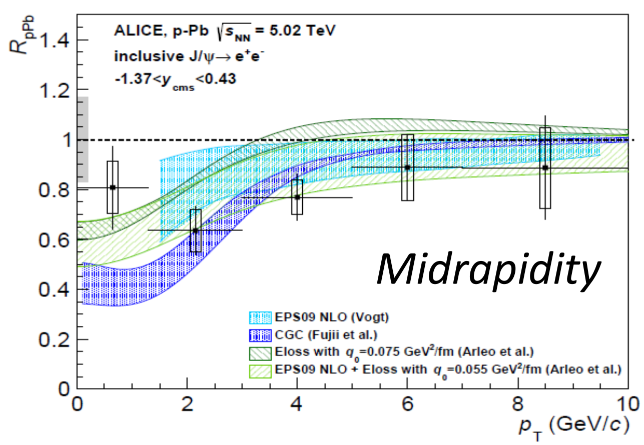
ALICE, JHEP 06, 055 (2015)

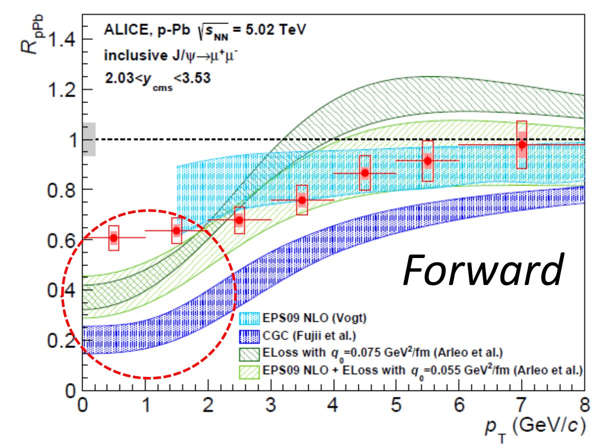
↓ No significant nuclear effects in backward region.

↓ Mid and forward rapidities: $J/\psi$ suppression at low $p_T$ (< 5 GeV/c)

↓ nPDF+Eloss fails to reproduce the data at low $p_T$ in forward region.

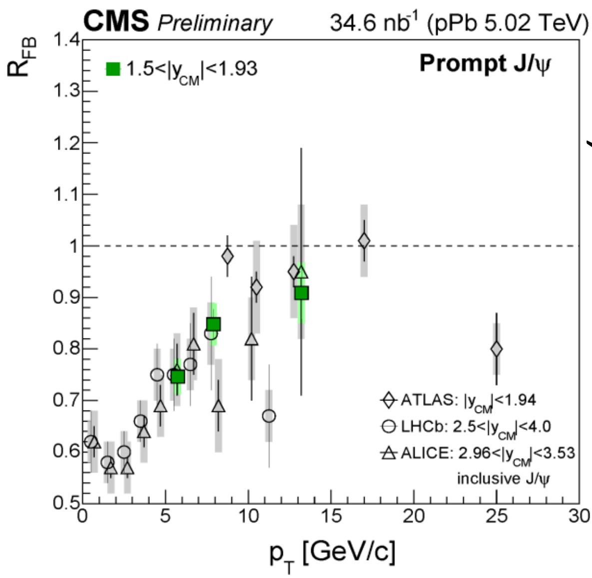


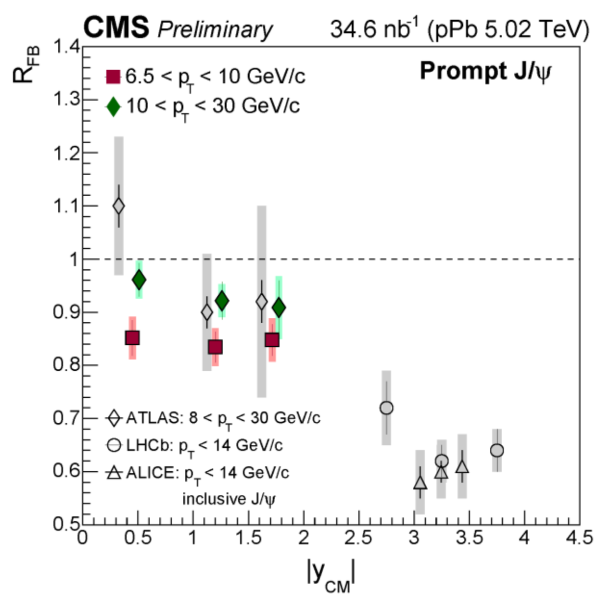



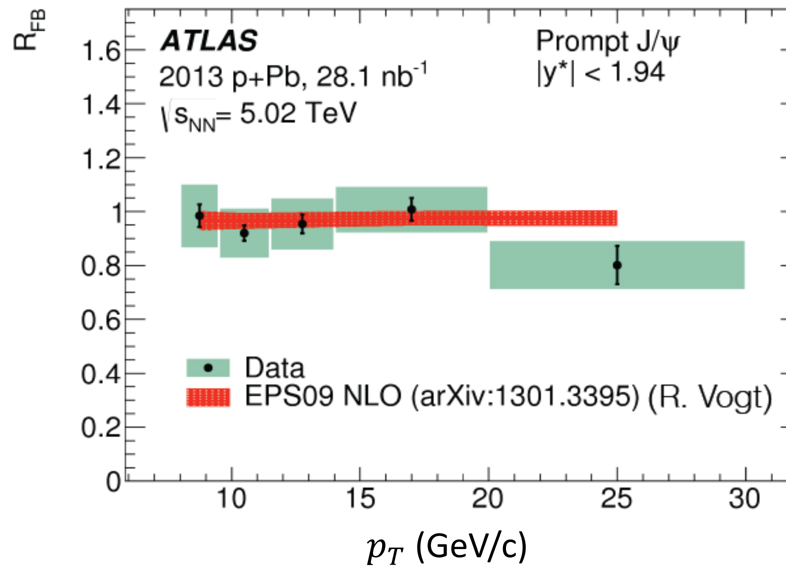
# Prompt $J/\psi$ in pA

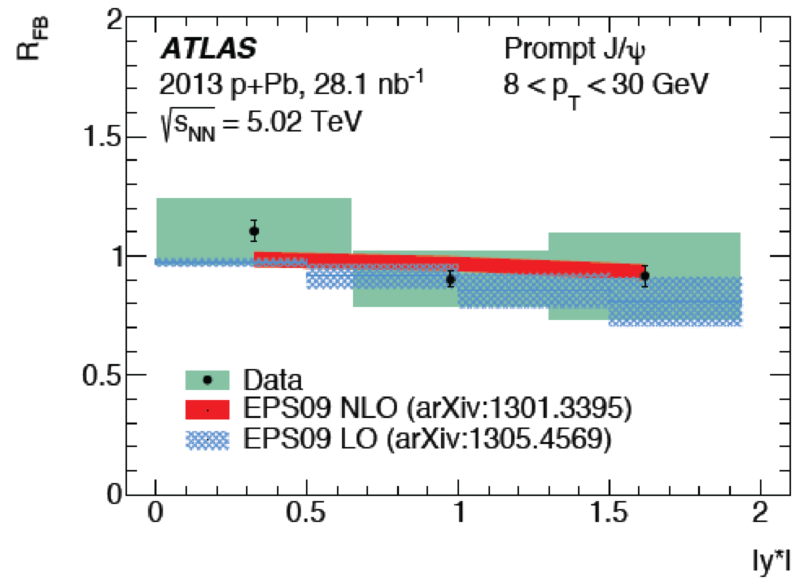
$$R_{FB}(p_T, y) = \frac{d^2\sigma(p_T, y > 0)/dp_T dy}{d^2\sigma(p_T, y < 0)/dp_T dy}$$




CMS, PAS HIN-14-009



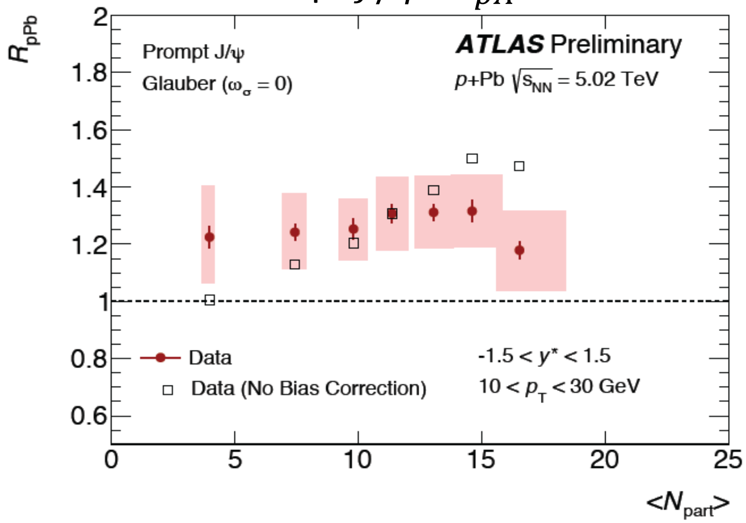




ATLAS, PRC 92, 034904 (2015)

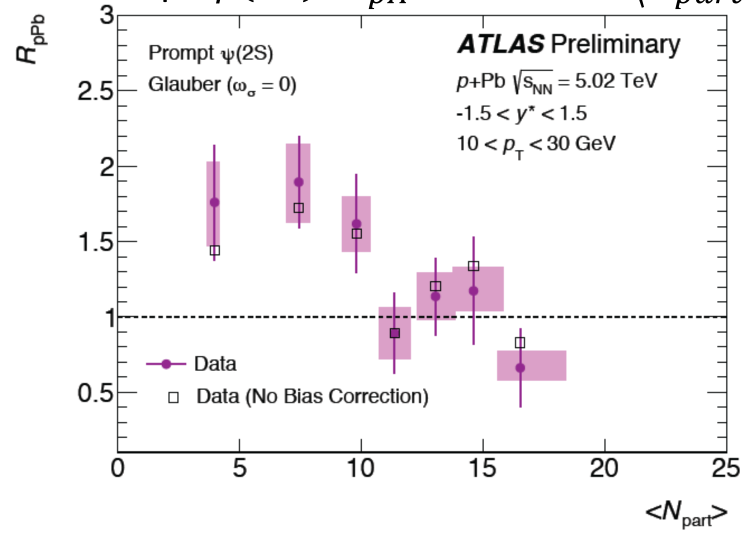
# $R_{pA}$ of $J/\psi$ and $\psi(2S)$

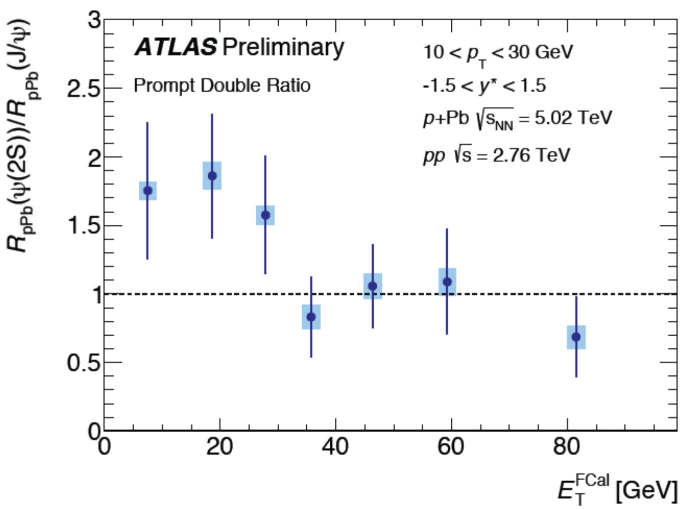
ATLAS-CONF-2015-023

Prompt $J/\psi$: $R_{pA} > 1$

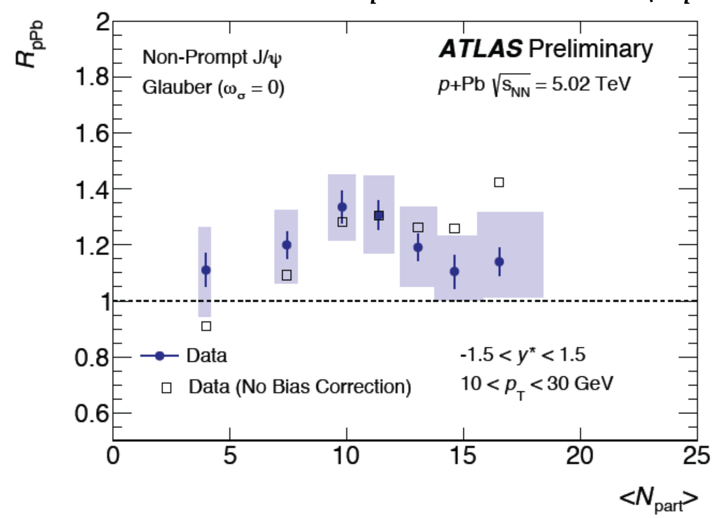



Prompt $\psi(2S)$: $R_{pA} > 1$ for low $\langle N_{part} \rangle$



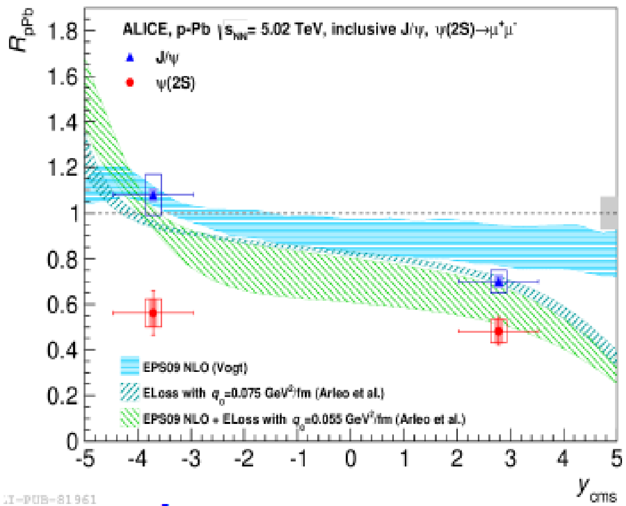



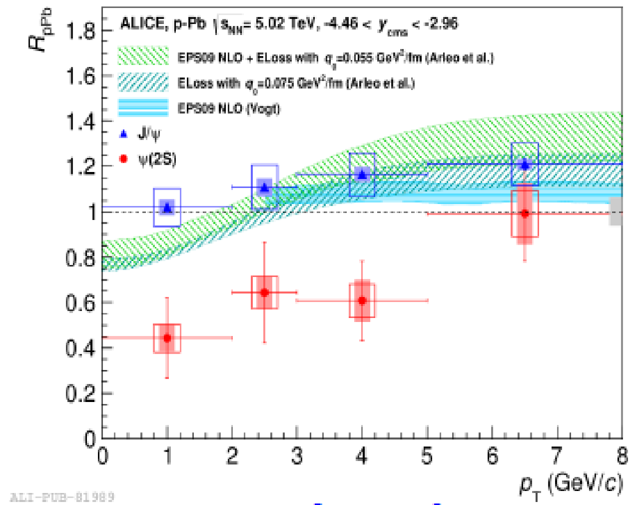

Non-prompt $J/\psi$: $R_{pA} > 1$ for mid-$\langle N_{part} \rangle$

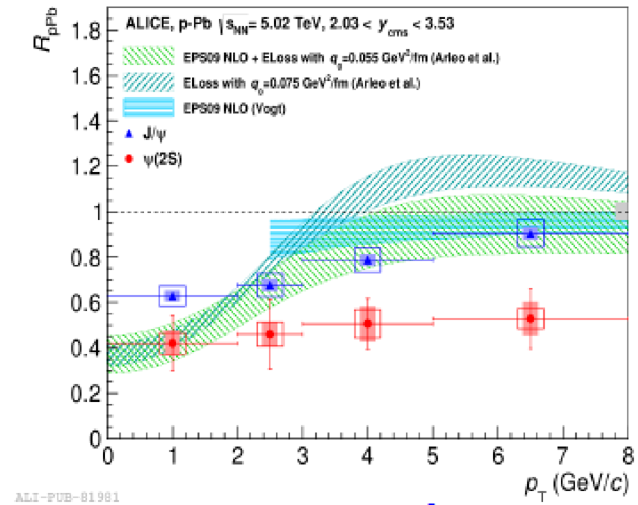


# $\psi(2S)$ in pA

ALICE, JHEP 12, 073 (2014)

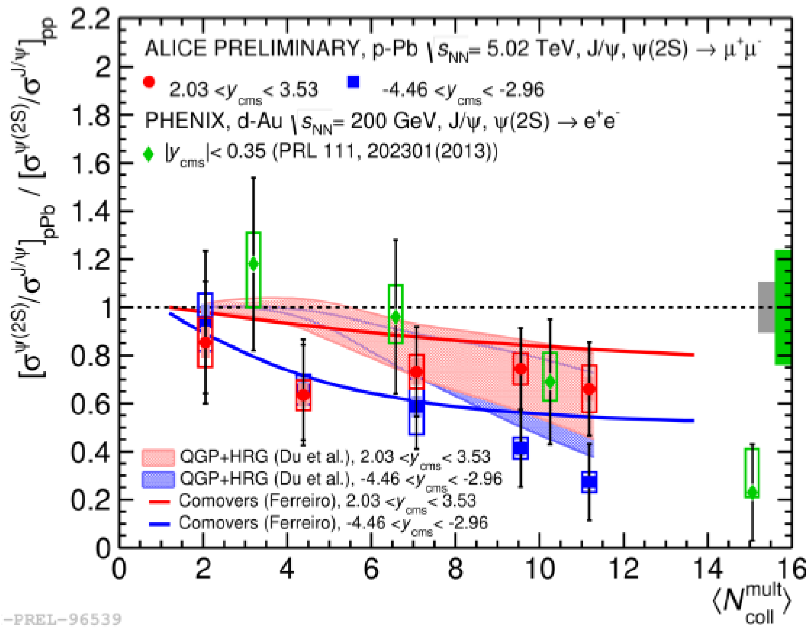


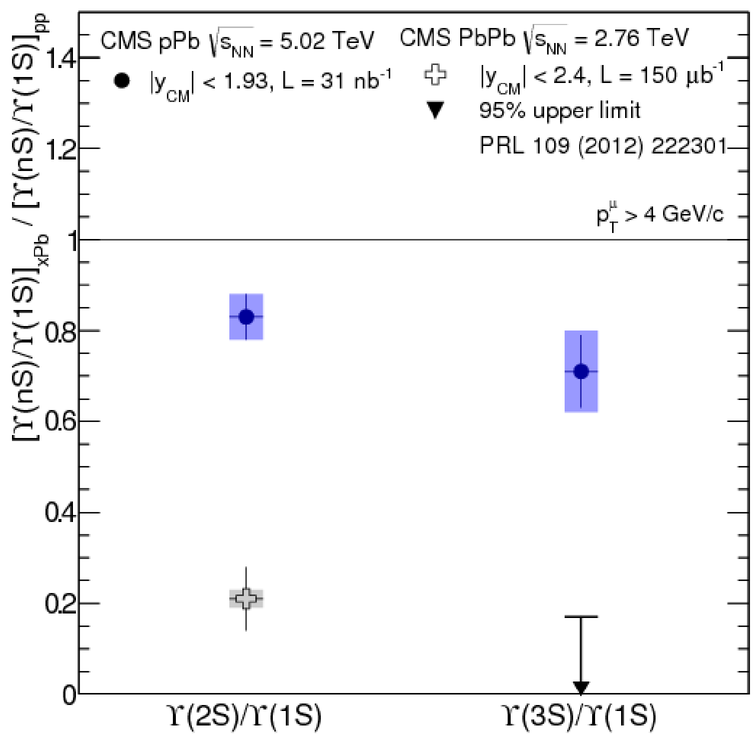

**Bck-y** ⟶ **Fwd-y** **Backward-y** **Forward-y**

- ↑ $\psi(2S)$ is more suppressed than $J/\psi$ at both backward and forward rapidities.
- ↑ nPDF and/or Eloss cannot describe the large suppression for $\psi(2S)$:
  - Shadowing and Eloss are expected to be identical for $J/\psi$ and $\psi(2S)$.
- → QGP+Hadronic Resonance Gas (Du and Rapp) and comover dissociation model (Ferreiro) can describe $\psi(2S)$ suppression.

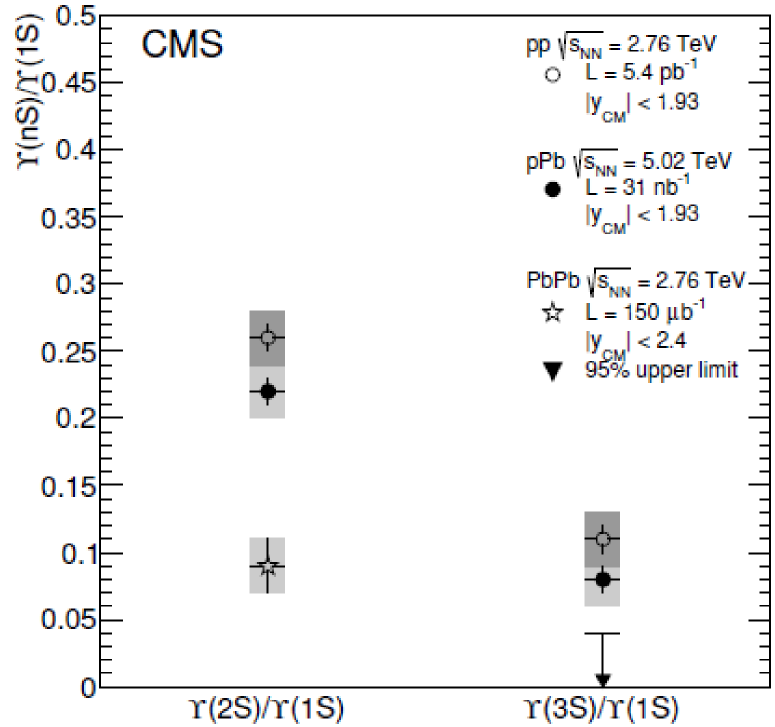


# $\Upsilon(nS)$ in pPb

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

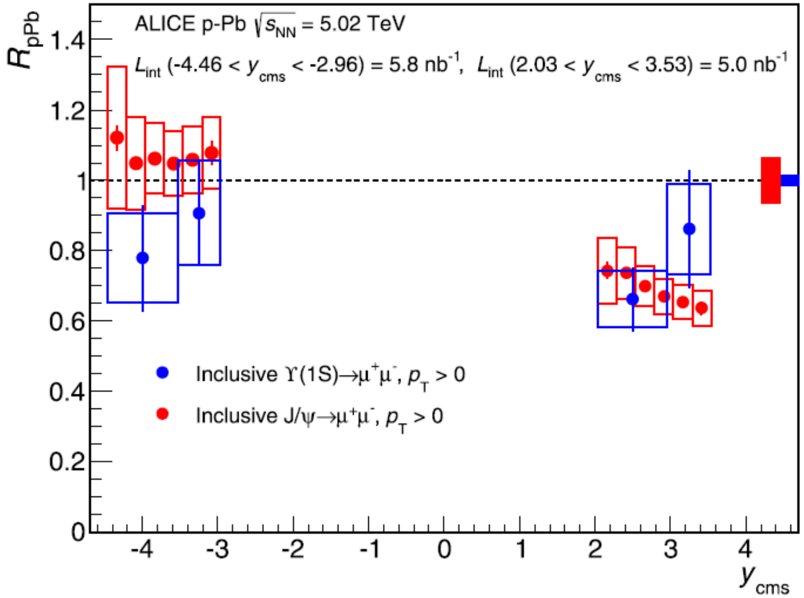



CMS, JHEP 04, 103 (2014)



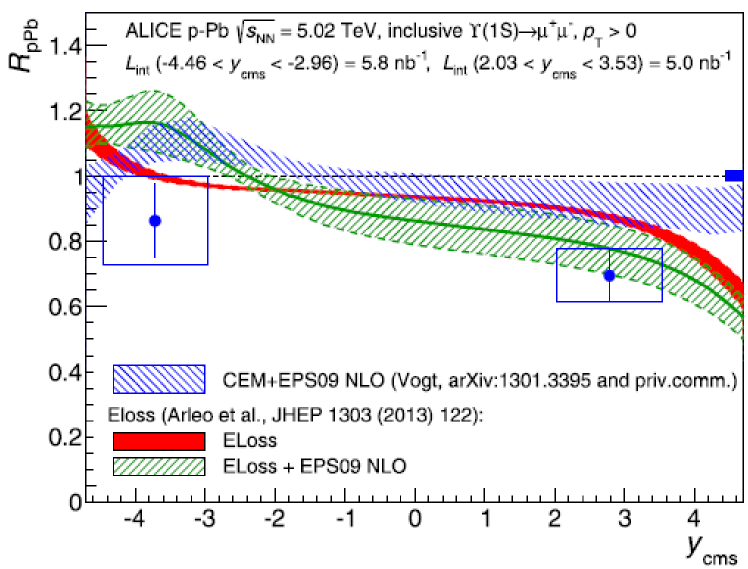

- Suppression is significantly larger for PbPb than for pPb
- Suppression of $\Upsilon(3S)$ is larger than that of $\Upsilon(2S)$ in pPb

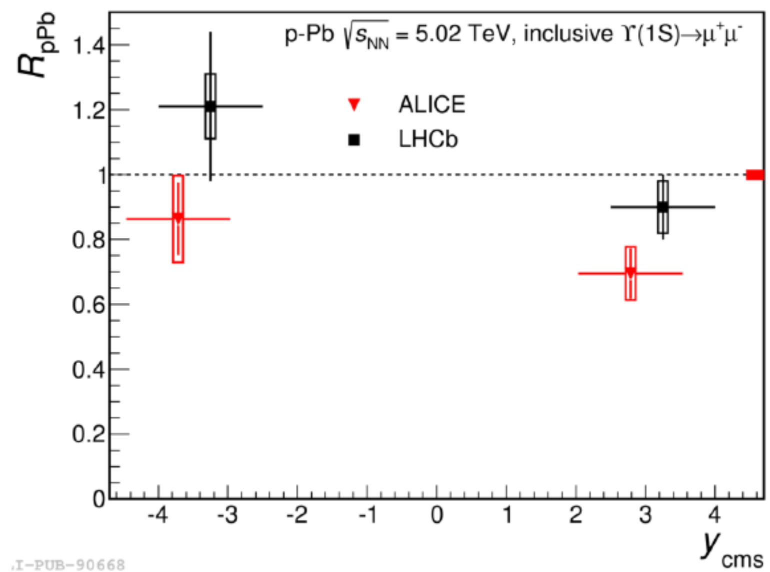
# $\Upsilon(1S)$ in pPb




ALICE, PLB 740, 105 (2015)

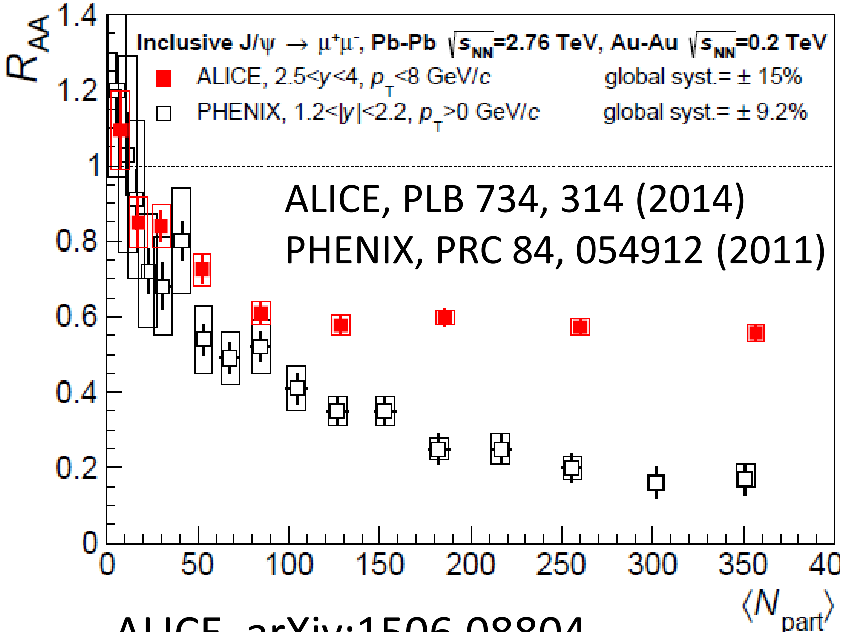
- ← Smaller $R_{pPb}$ (more suppression) for $\Upsilon(1S)$ than for $J/\psi$ at backward
- ↙ Fair agreement between the data and the various nPDF and/or Eloss model calculations
- ↓ LHCb data are systematically larger than ALICE data for forward and backward rapidities.

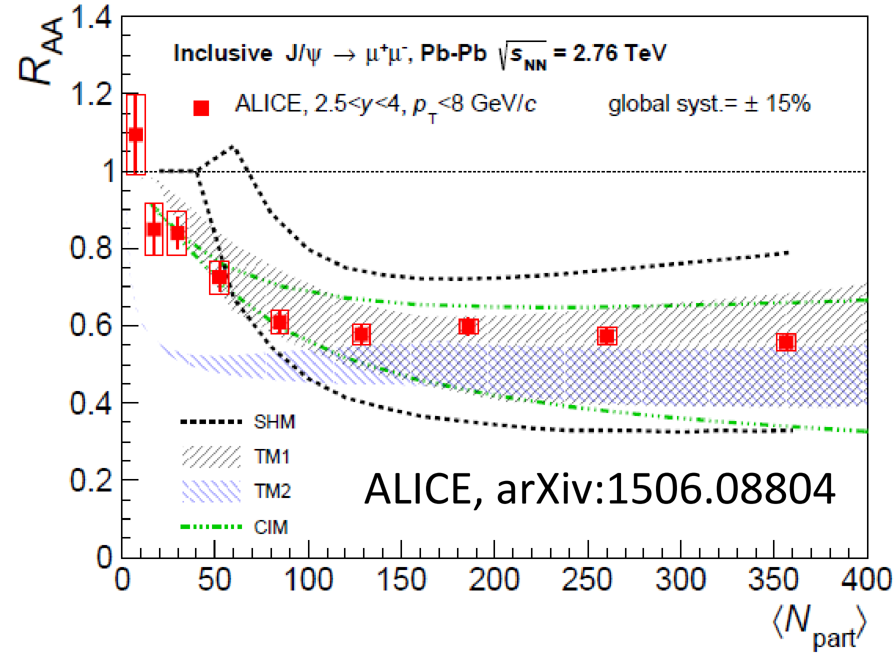


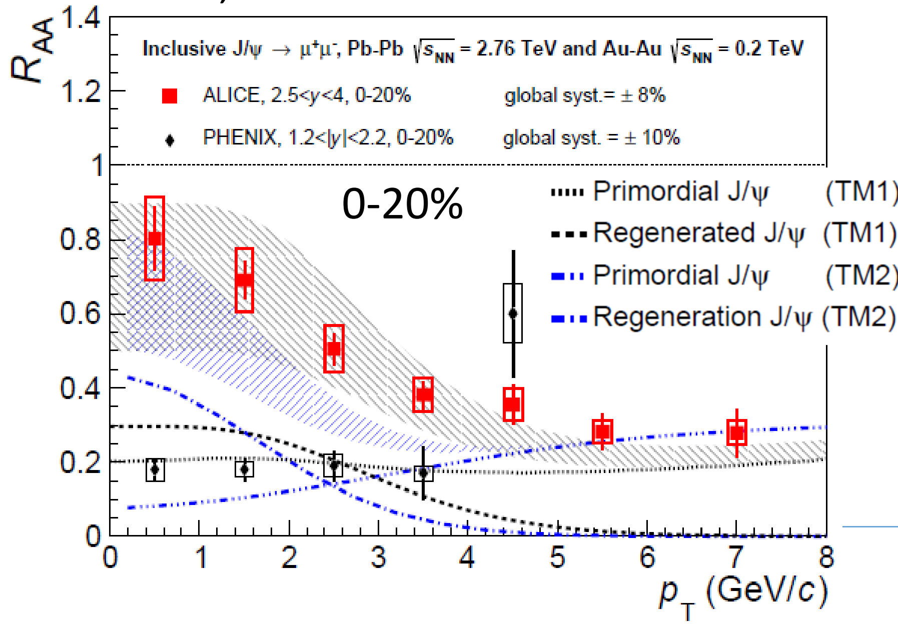
# Inclusive $J/\psi$ in PbPb

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




ALICE, arXiv:1506.08804




↖ ALICE $R_{AA}$ constant for $\langle N_{part} \rangle > 70$

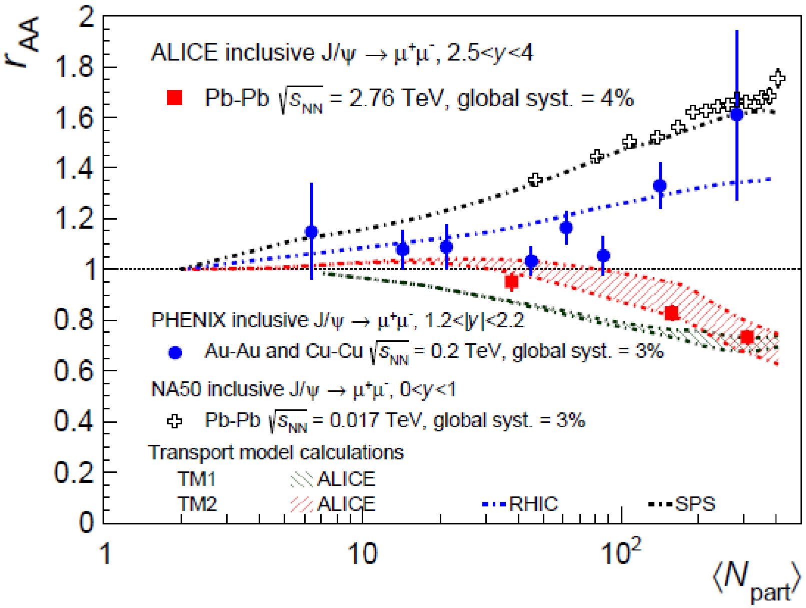
↑ Models with shadowing and regeneration can reasonably describe the data.

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

# Inclusive $J/\psi$ in PbPb

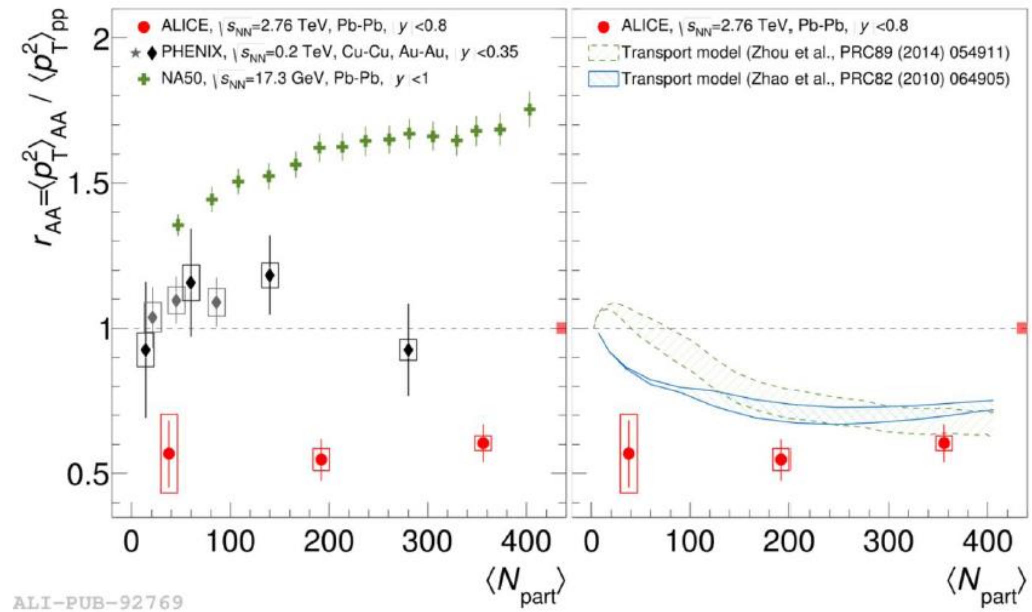
ALICE, arXiv:1506.08804

$\mu^+\mu^-$ in forward




ALICE, JHEP 07, 051 (2015)

$e^+e^-$ at midrapidity

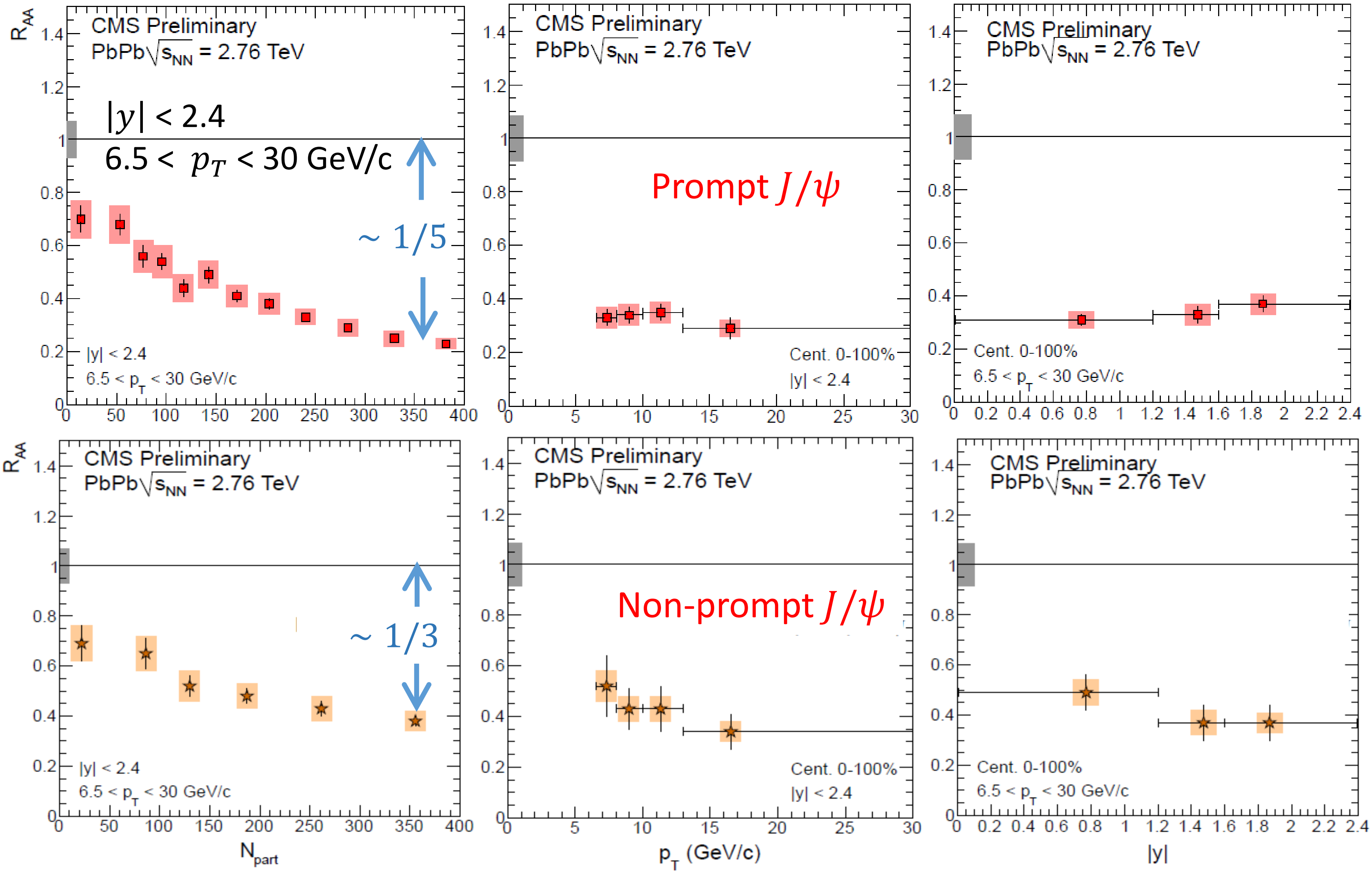



$$r_{AA} = \langle p_T^2\rangle_{AA} \Big/ \langle p_T^2\rangle_{pp}$$

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

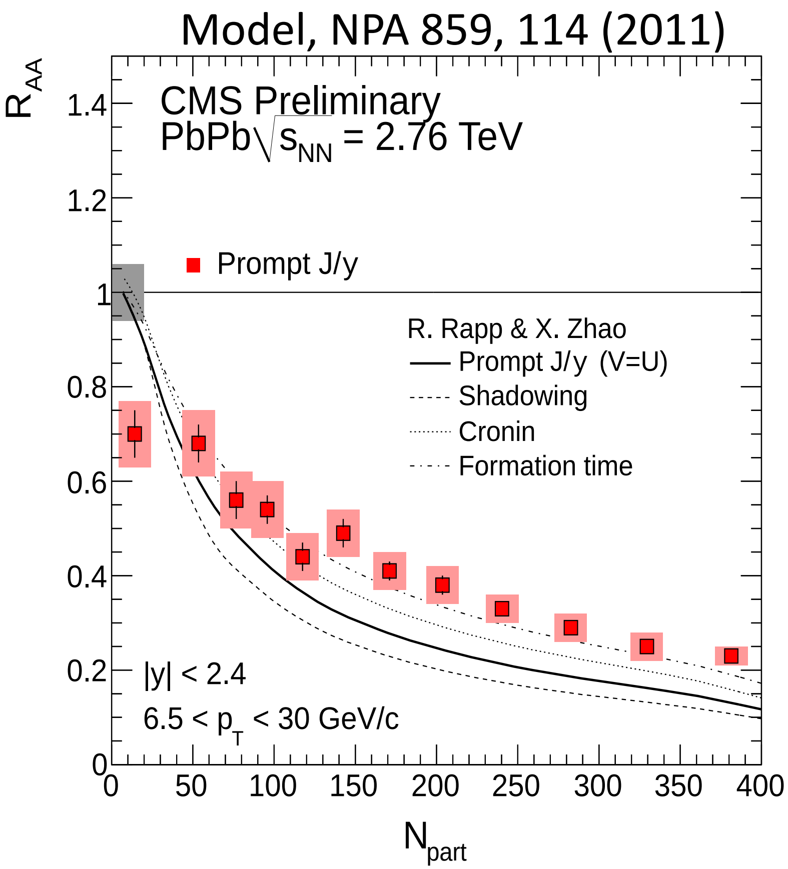
# $J/\psi$ in PbPb

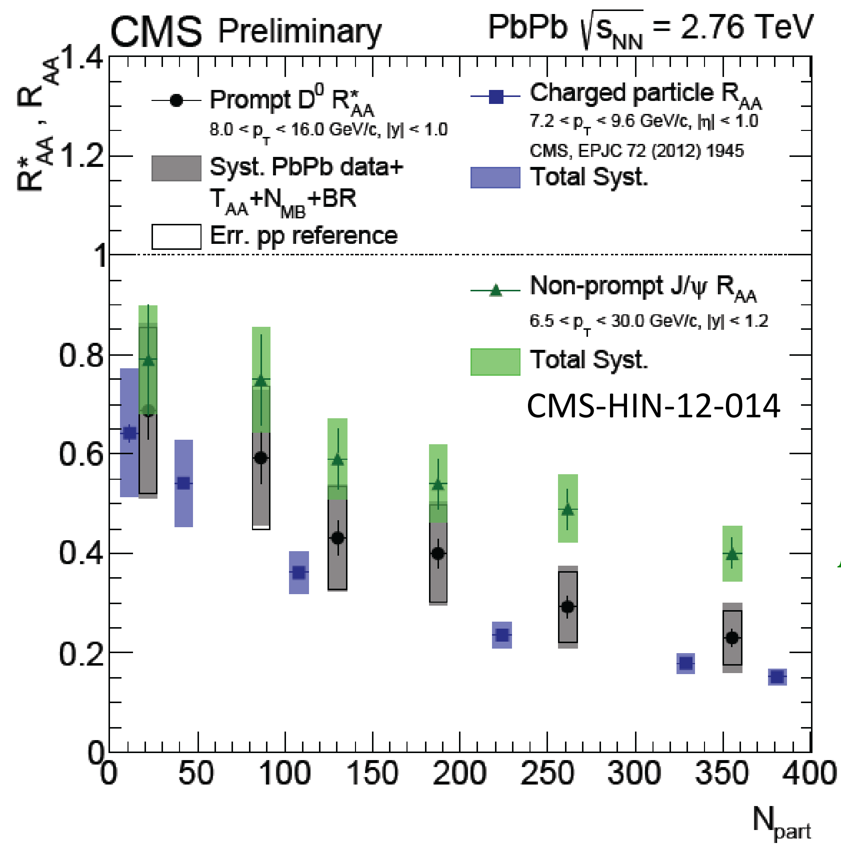
CMS, PAS HIN-12-014



# $J/\psi$ in PbPb

CMS-HIN-15-005



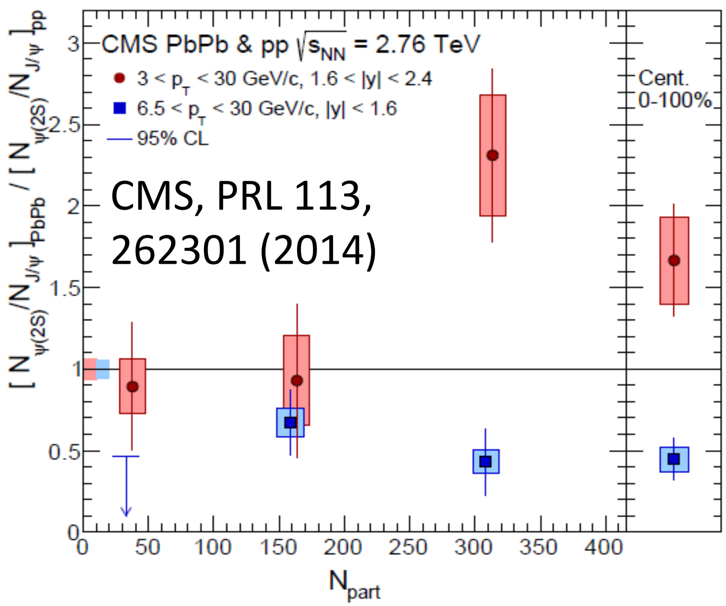

$B \to J/\psi$

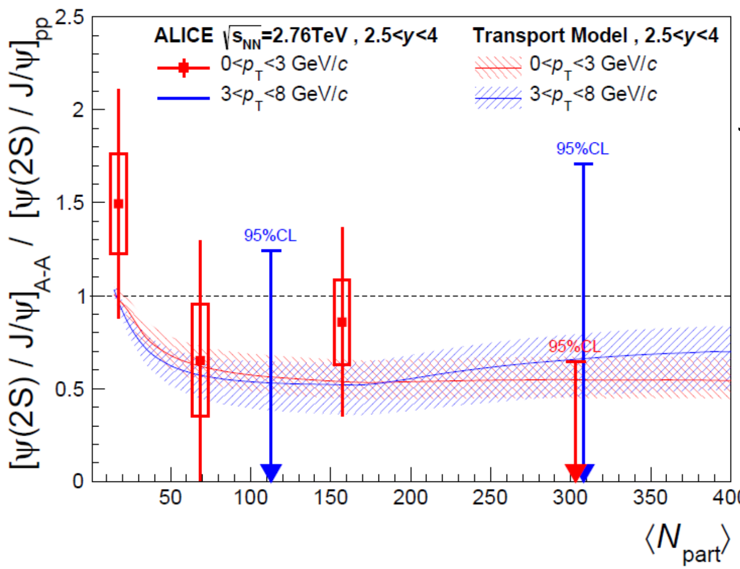
$D^0$

Charged hadrons

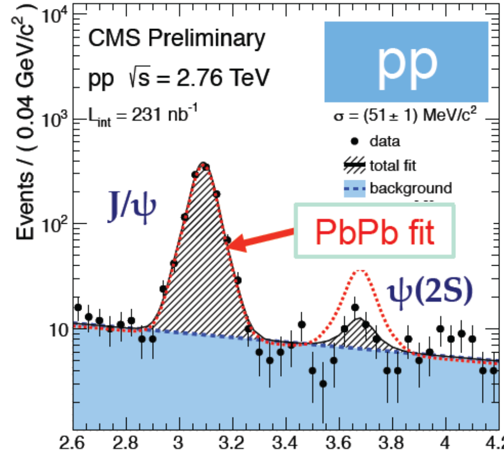
- No need for regenerations at high $p_T$
- $R_{AA}(B) > R_{AA}(D)$: Mass ordering predicted by dead cone effect

# $\psi(2S)$ in PbPb

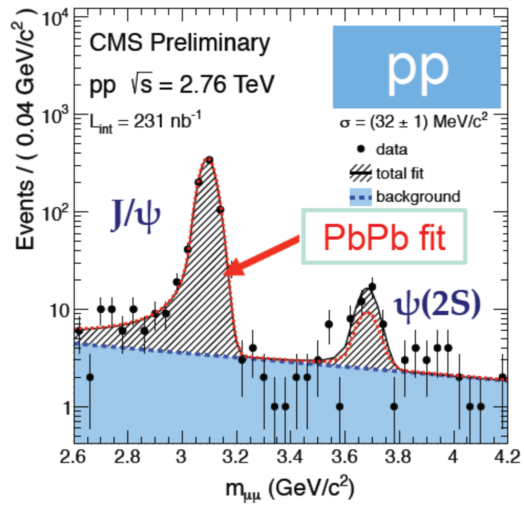



ALICE, arXiv:1506.08804




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.

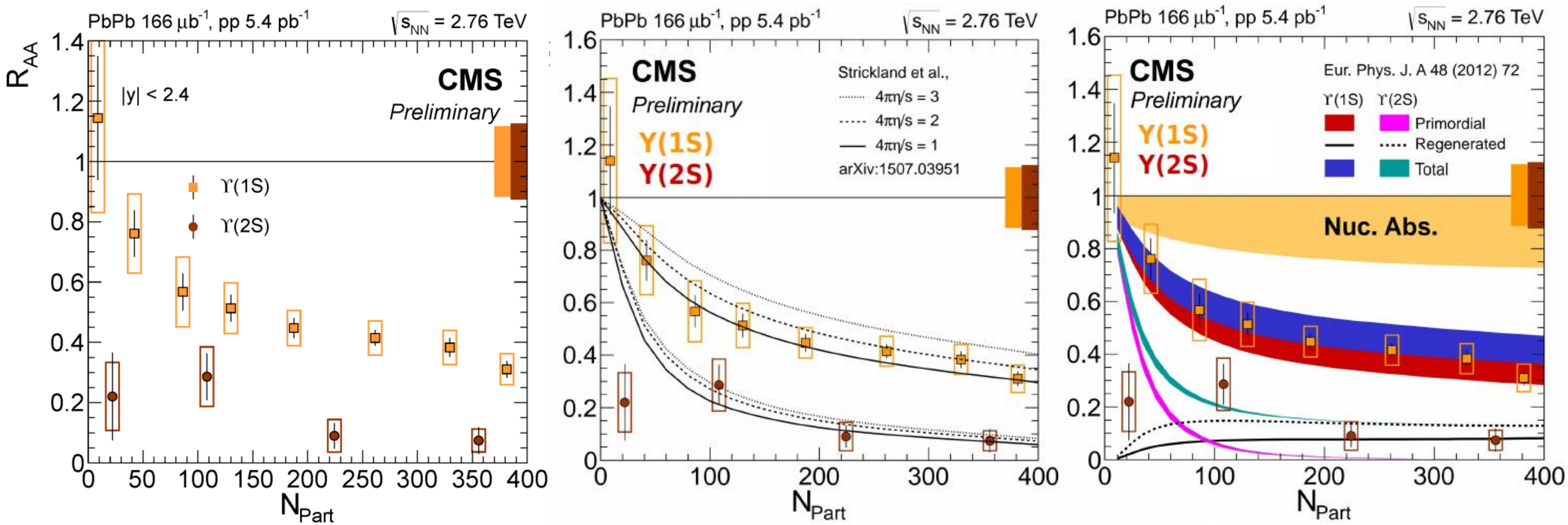



For 6.5<$p_T$<30 GeV/c in $|y|$ < 1.6, $R_{\psi(2S)}$ in central (20%) PbPb is ~2 times smaller than that in pp.

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

# $\Upsilon(nS)$ in PbPb

CMS, HIN-15-001




↑ Centrality integrated results: $\Upsilon$ states suppressed sequentially (0-100%)

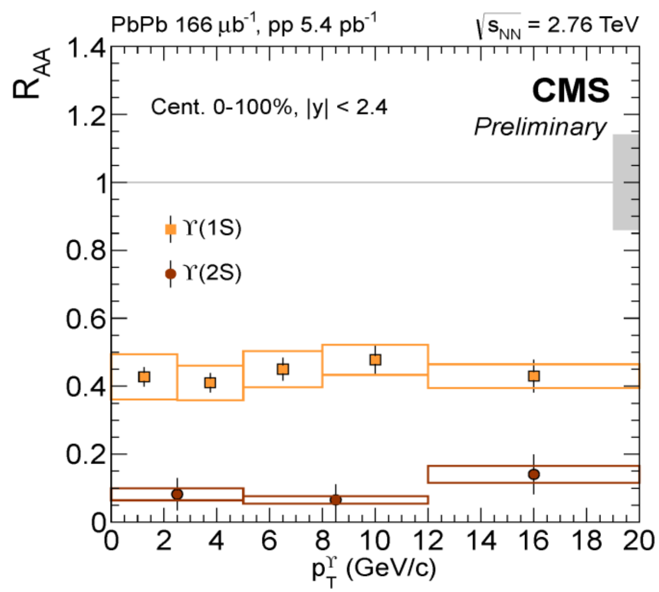
$$R_{AA}[\Upsilon(1S)] = 0.425 \pm 0.029 \pm 0.070$$
$$R_{AA}[\Upsilon(2S)] = 0.116 \pm 0.028 \pm 0.022$$
$$R_{AA}[\Upsilon(3S)] < 0.14 \text{ at } 95\% \text{ CL}$$

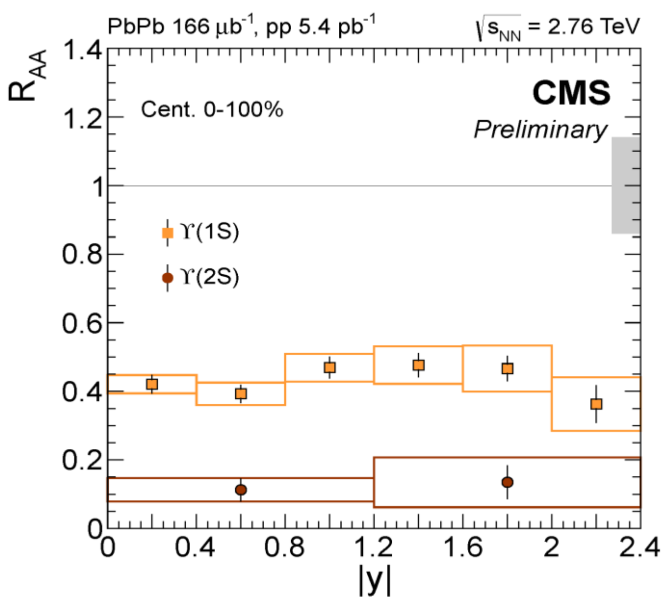
↗ Anisotropic hydrodynamic model for thermal suppression of bottomonia
- 2 temperatures along $y$, 3 shear viscosities, no CNM, no regeneration, …

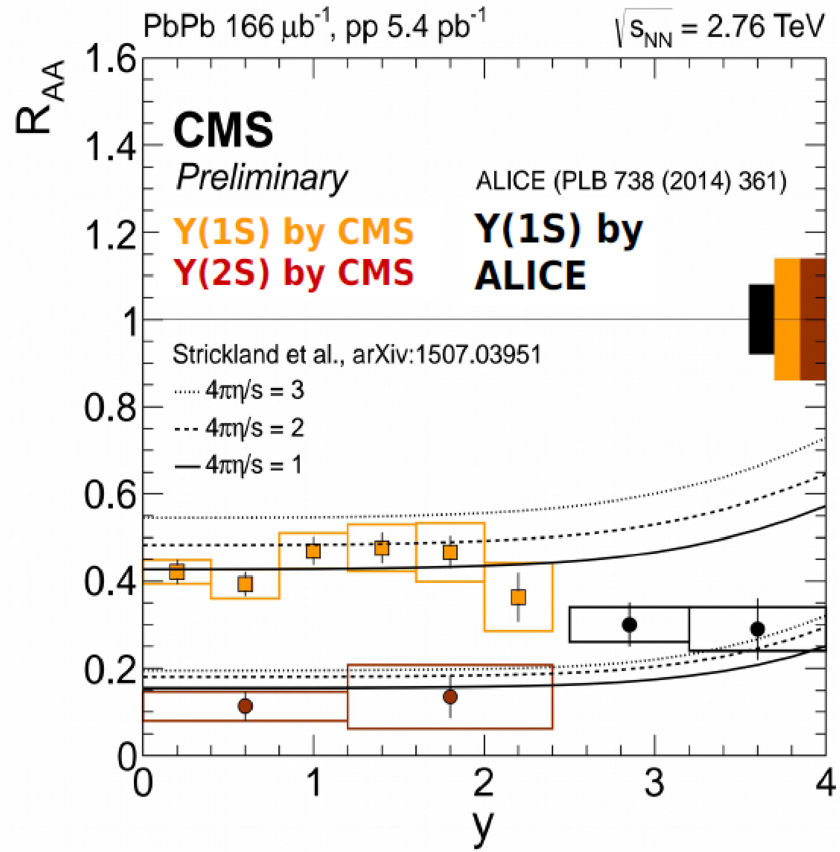
↗ Transport model taking into account CNM and regeneration

# $\Upsilon(nS)$ in PbPb

CMS, HIN-15-001



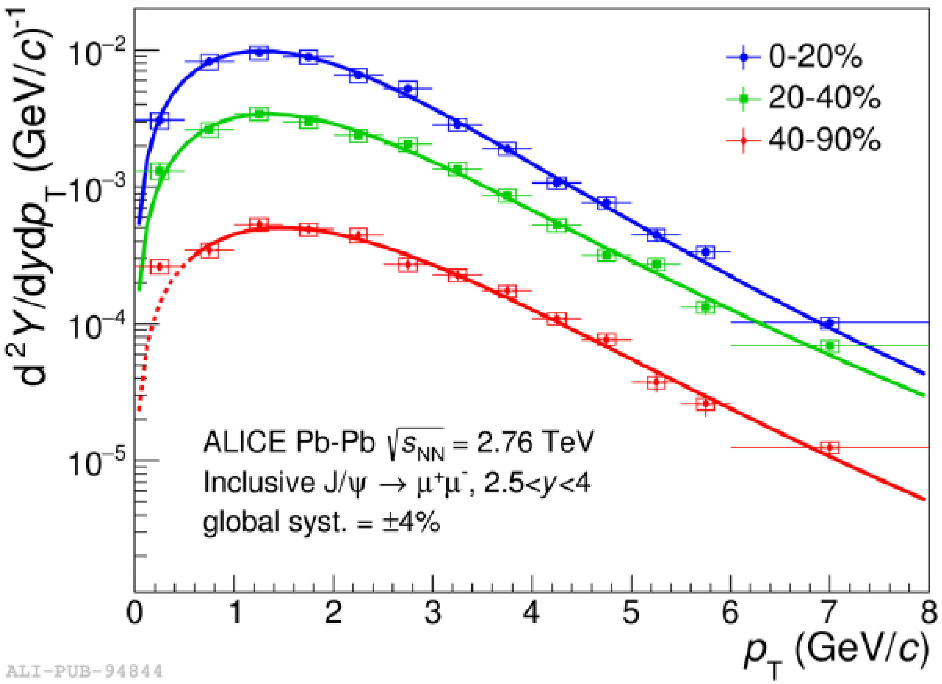



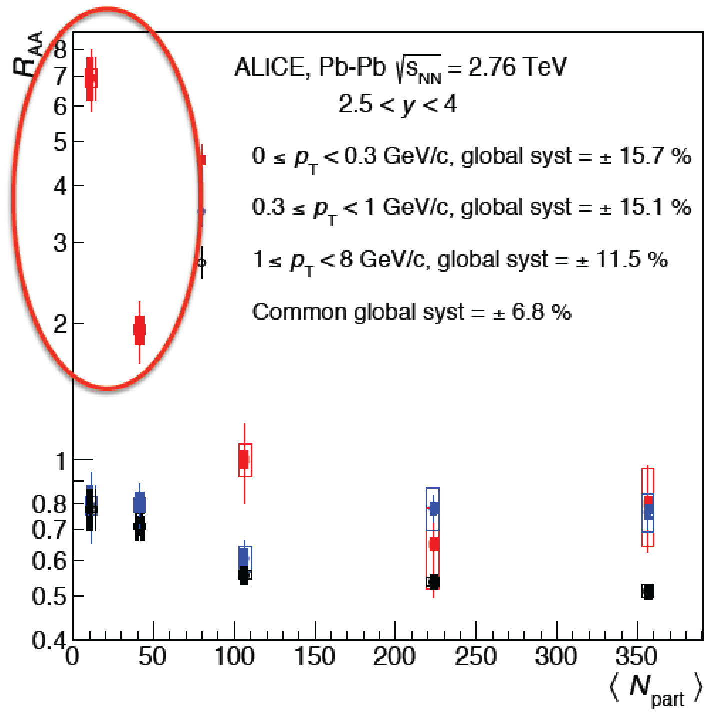

← $\Upsilon$ suppression does not strongly depend on kinematics.

↑ Anisotropic hydro model cannot reproduce the forward data: CNM may help?

# $J/\psi$ photo-production

ALICE, arXiv:1506.08804

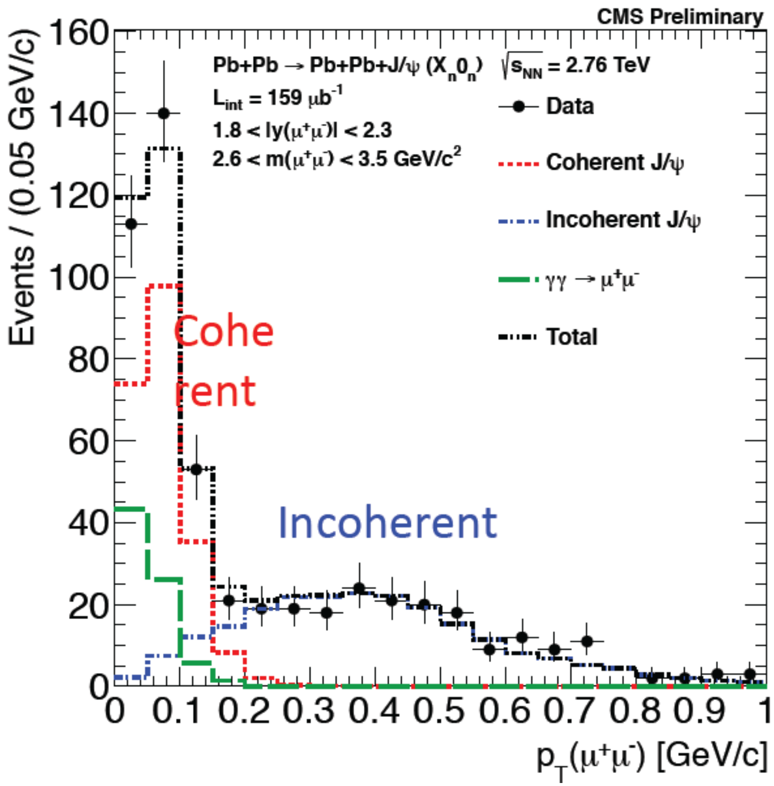


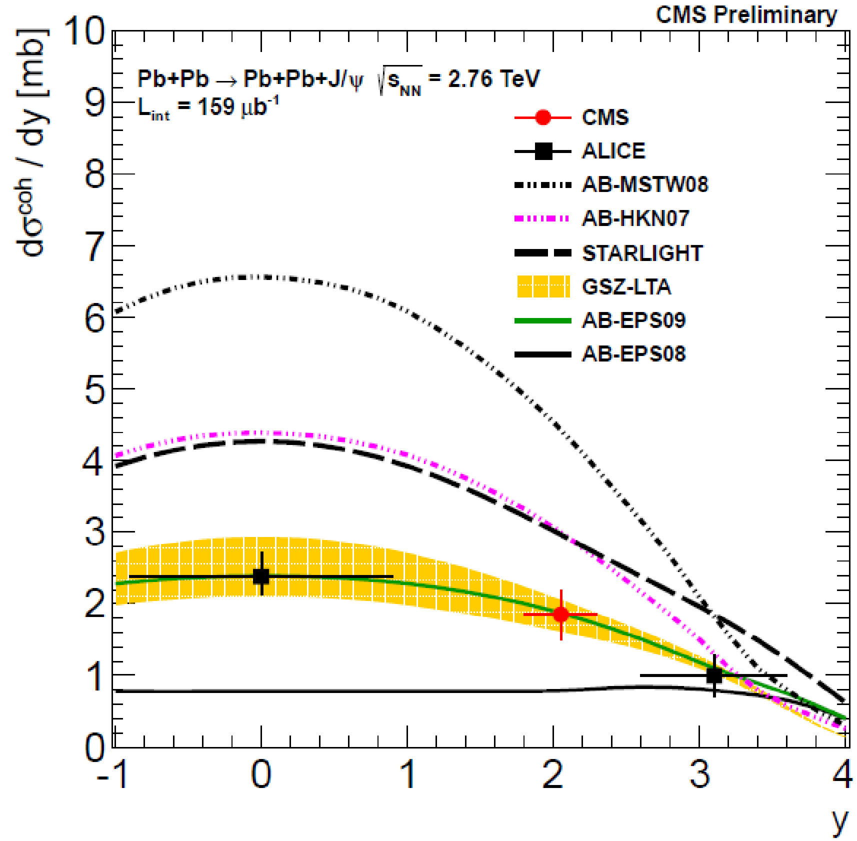



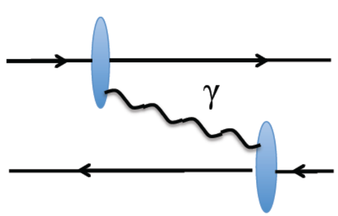

- An excess of $J/\psi$ observed at low $p_T < 300$ MeV/c in peripheral collisions
- Possible origin: coherent $J/\psi$ photo-production in ultra-peripheral collisions

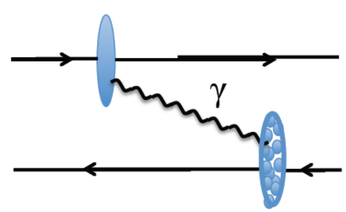
# $J/\psi$ photo-production

CMS, HIN-12-009




**Coherent** component for $p_T \lesssim 150$ MeV/c

**Incoherent** component

ALICE and CMS data favor moderate nuclear shadowing models such as **AB-EPS09** and **GSZ-LTA** for nPDF.

# Summary

1. pp
   - New $J/\psi$ and $\Upsilon$ data at LHC will help constraining production models.
   - Non-linear increasing yields and polarizations are yet to be understood.
2. pA
   - Interplay between shadowing and energy loss can describe $J/\psi$ data.
   - Co-mover effect is important to understand the $\psi(2S)$ production.
3. AA
   - Suppression and regeneration are necessary to describe the low-$p_T$ $J/\psi$ data on nuclear modification factor and $p_T$ broadening.
   - Less suppression of $\psi(2S)$ relative to $J/\psi$ for the most central collisions has been observed that needs to be confirmed by RUN II.
   - $\Upsilon$ suppression does not strongly depend on kinematic variables.
   - Photo-production of $J/\psi$ favors moderate nuclear shadowing.
4. LHC RUN II with large statistics will be crucial to understand many puzzles in the current heavy-ion results.