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## Heavy ions: Quarkonia

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# Heavy ions: Quarkonia

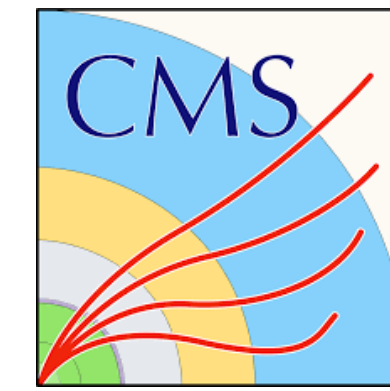
Highlights from ALICE, ATLAS, CMS, LHCb

Robin Caron, Institut de Physique des Deux Infinis (CNRS-IN2P3)

The 10th Annual  
Large Hadron Collider Physics Conference  
May 16-21, 2022 Taipei, Taiwan

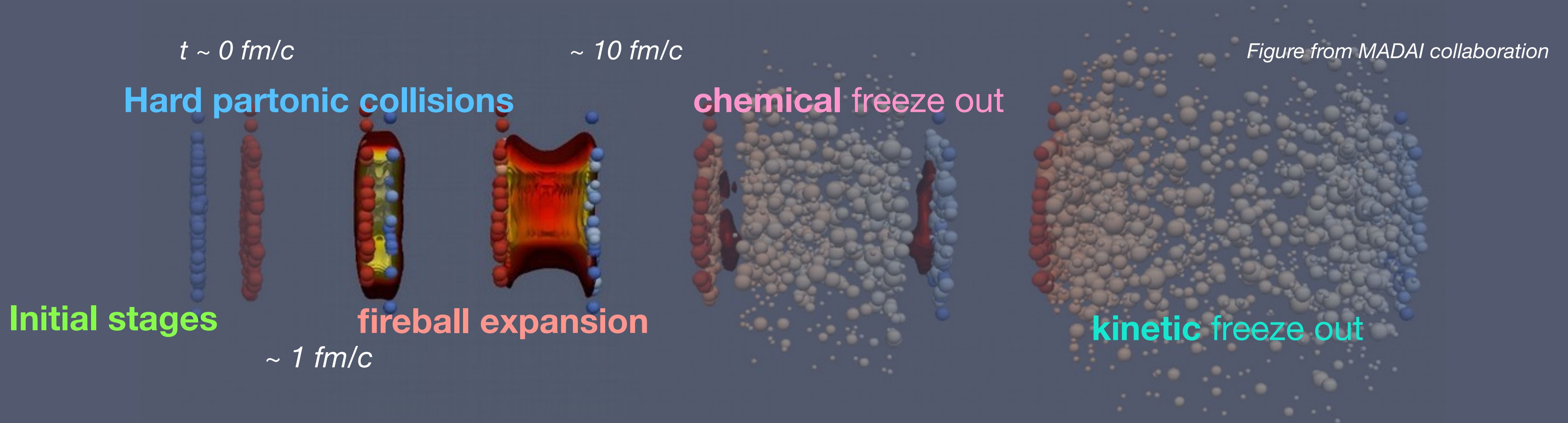


# Outline



- **Introduction**
- **Quarkonia from Pb-Pb to pp collisions**
  - **Charmonia**
  - **Bottomonia**
- **Summary**

# Evolution of a heavy ion collision



**Quarkonia: a powerful tool to study medium properties and initial conditions**



**Signature of deconfinement:**  
suppression of quarkonia inside  
the quark-gluon plasma (QGP) [1]

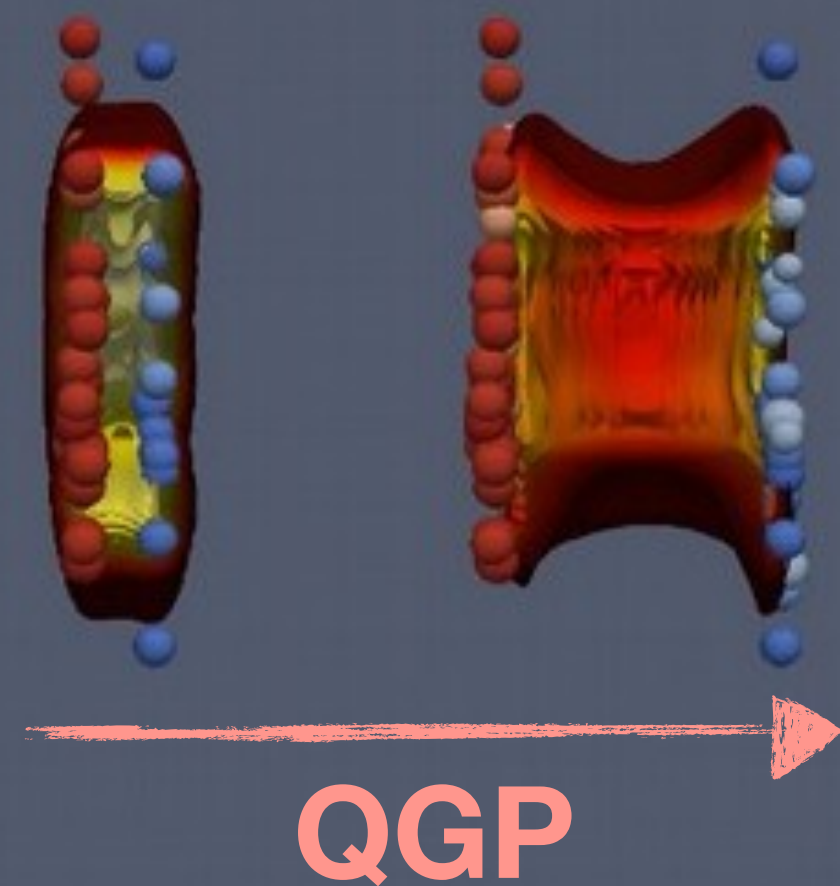
[1] T. Matsui, H. Satz, *Phys.Lett.B* 178 (1986) 416-422

# Why quarkonia?

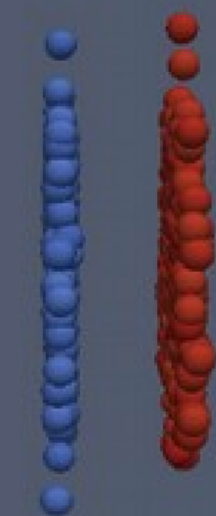


## Sequential suppression:

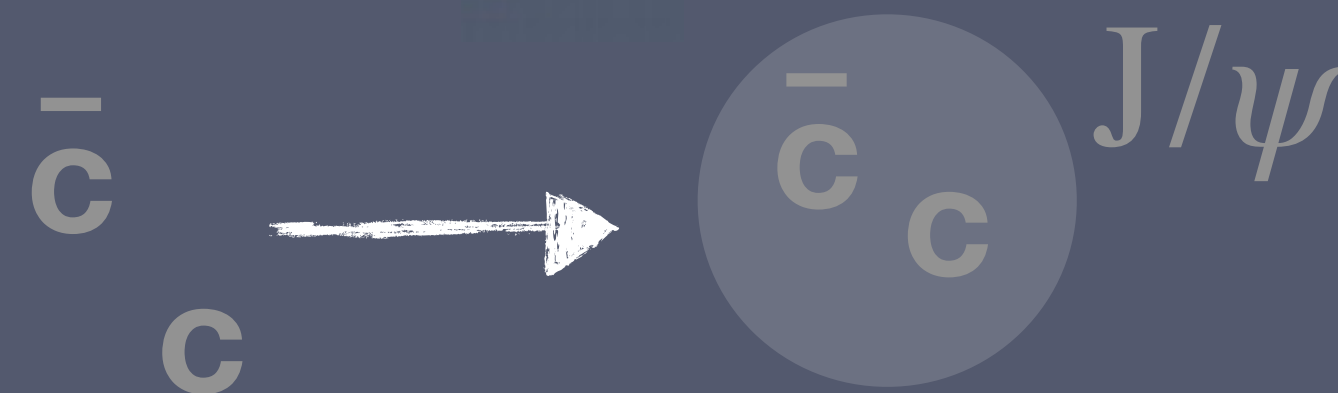
- **color screening** and medium-induced dissociation
- sensitive to **medium temperature**
- excited states more suppressed w.r.t. ground states
- static vs dynamic dissociation [2]



central Pb–Pb collisions at the LHC



$c\bar{c}$ : O(100) and few  $b\bar{b}$  pairs produced close to  $t \sim 0$  fm/c



**Regeneration:** strongly supported scenario at the LHC because of large number of  $c\bar{c}$  pairs [3,4]

[2] A. Rothkopf, Phys. Rep. 858(2020) 1-117

[3] Braun-Munzinger, Stachel, Nature 448 (2007) 302

[4] R.L. Thews et al., Phys. Rev. C 63 (Apr. 2001) 054905

# Why quarkonia?... Across systems size

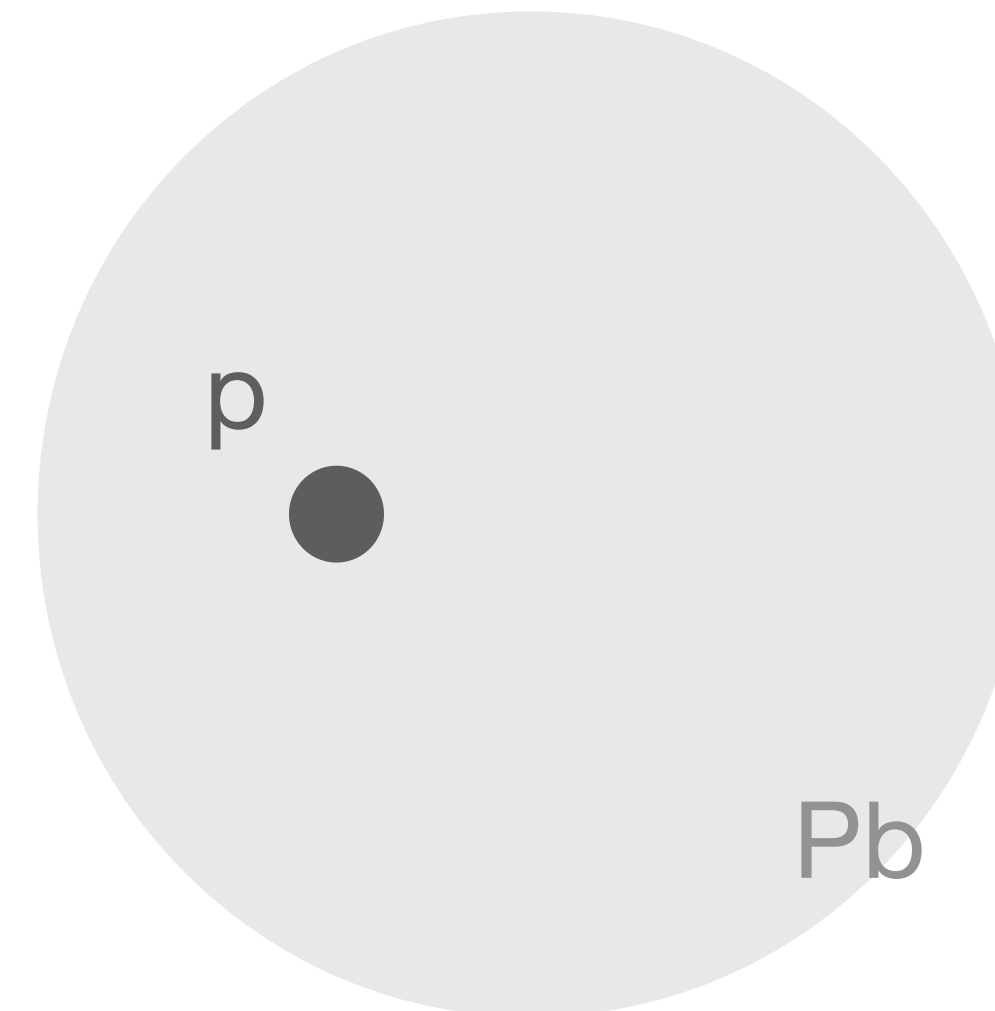
probe the **initial stages** of the collisions (**photoproduction + polarization vs. EP measurements**)



heavy quark **energy loss** in the medium  
(e.g. **non-prompt  $J/\psi$  measurement**,  
**prompt  $J/\psi$  at high  $p_T$** )

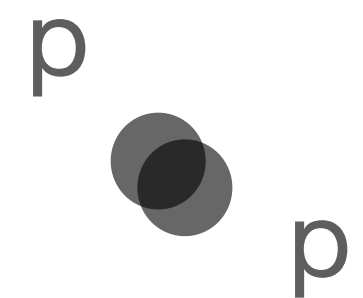
cold nuclear matter effects

$$(R_{pPb}, v_2)$$

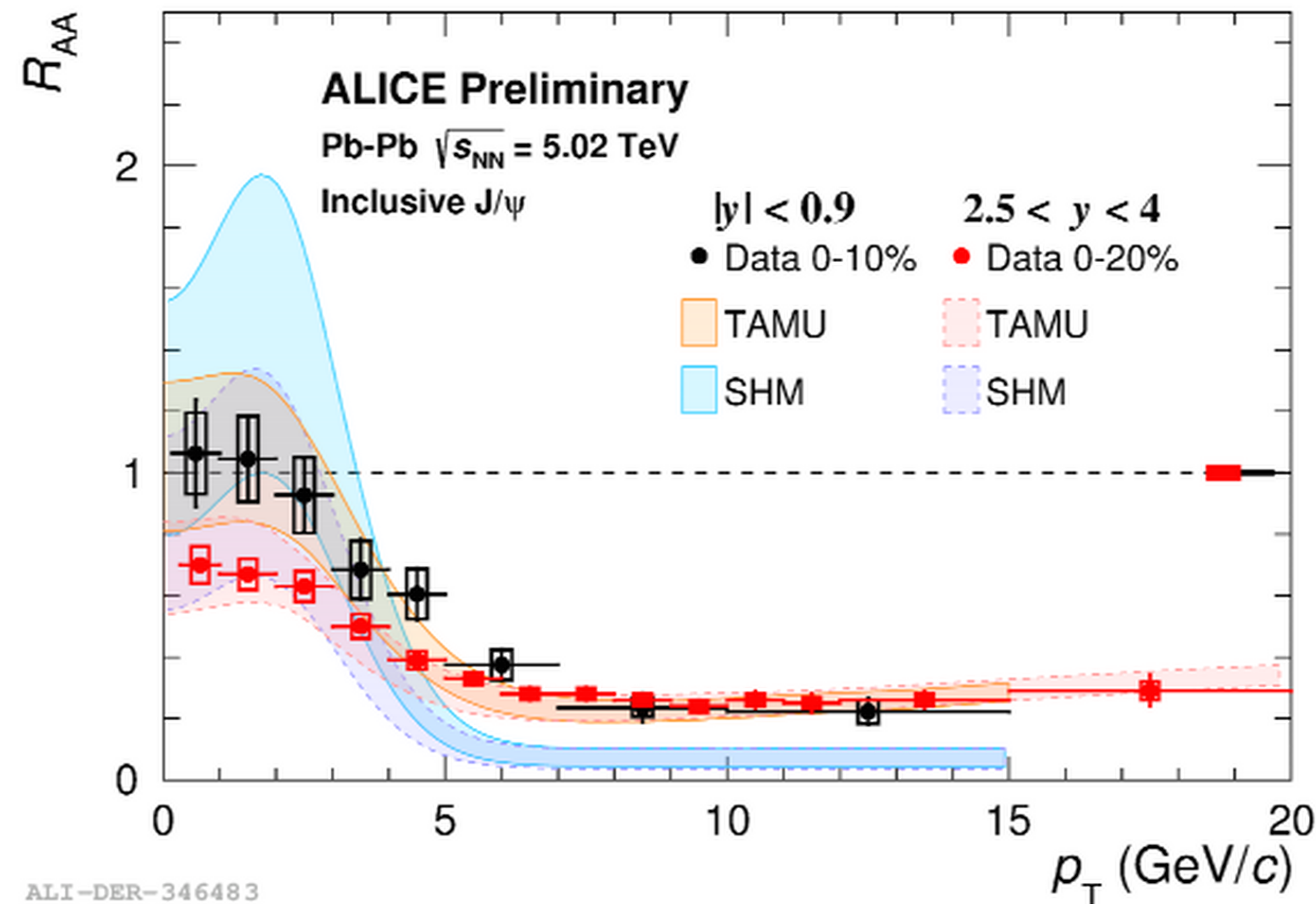


Shed light on multiparton interactions (**via multiplicity dependent studies**)  
+ **collectivity in small system** ( $v_2$ )

reference system  
test of QCD



# Observable: nuclear modification factor $R_{AA}$



- Measuring production in AA relative to production in pp collisions:

- $> 1$ : Enhancement

- $< 1$ : Suppression

$$R_{AA} = \frac{1}{\langle N_{\text{coll}} \rangle} \frac{(dN/dy)_{AA}}{(dN/dy)_{pp}}$$

- Models implementing **regeneration**, either at the freeze-out (SHM) or during the medium evolution (TAMU), are in agreement with data at low  $p_T$

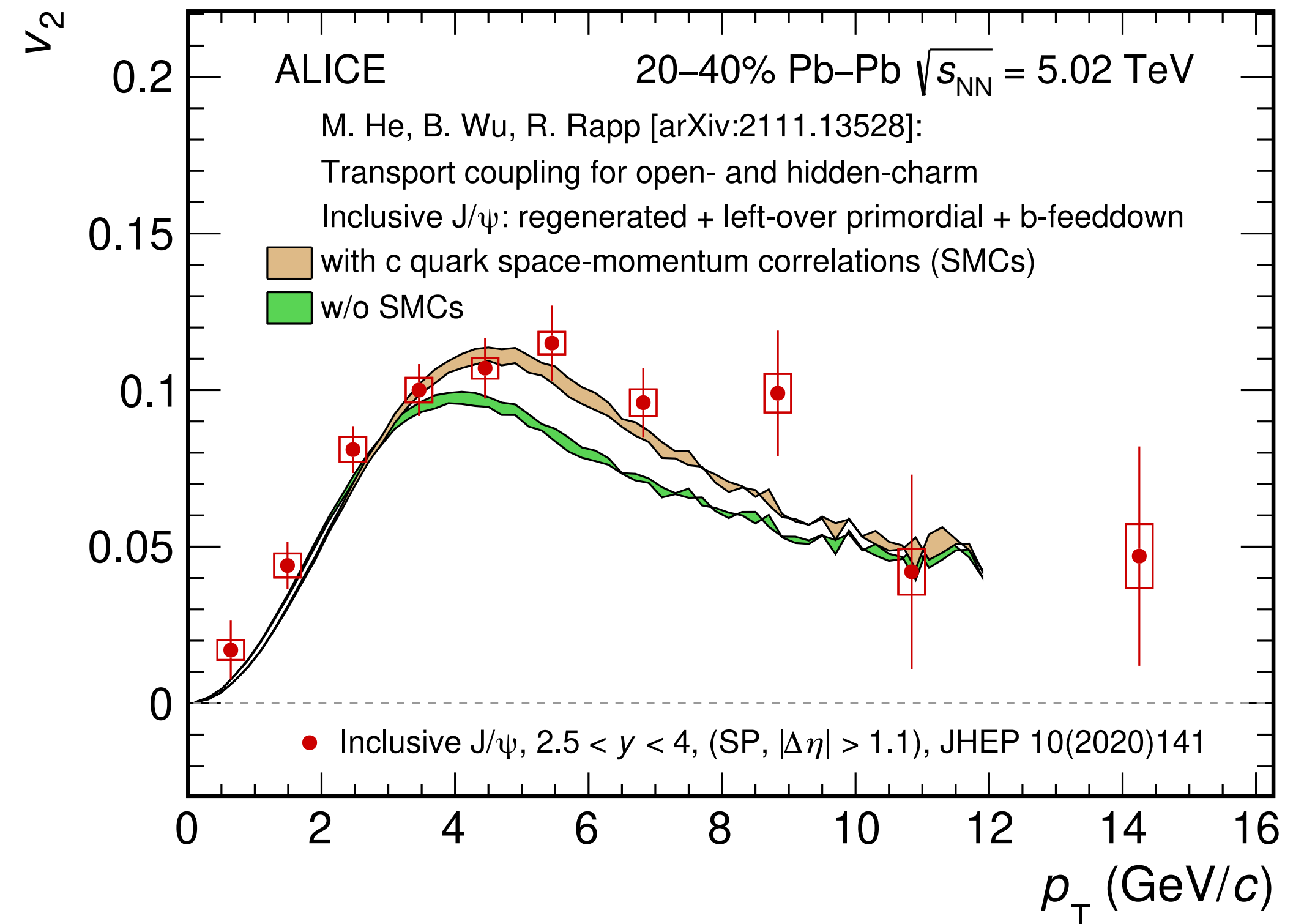
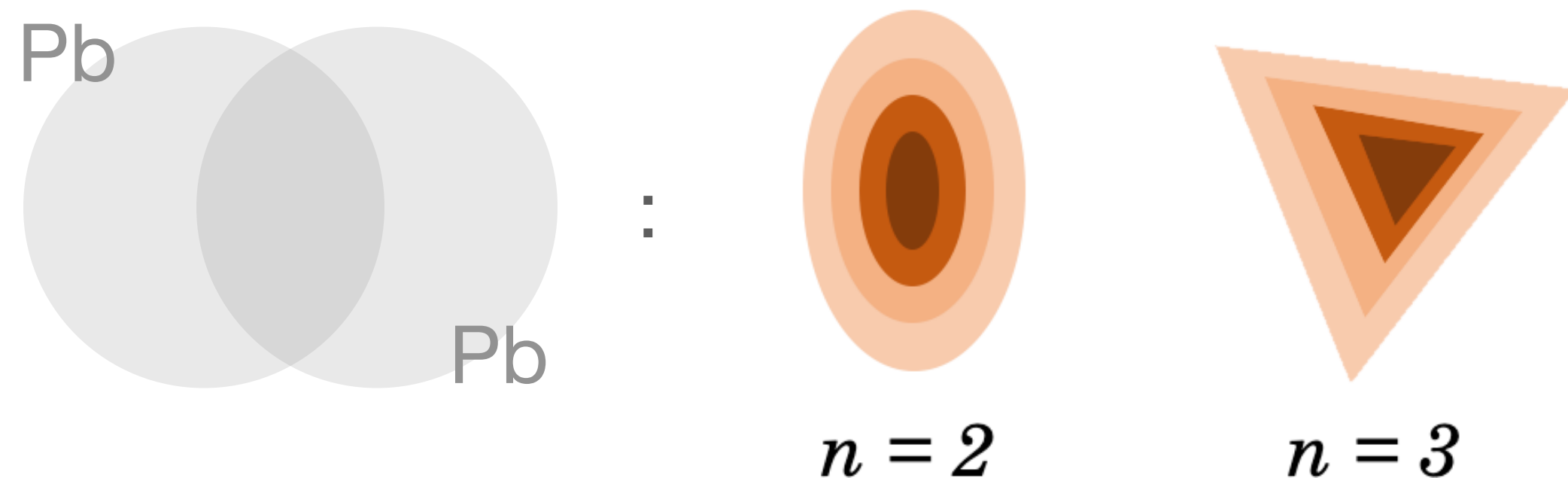
- $J/\psi R_{AA}$ : more suppressed at high  $p_T$ , showing a rising trend towards lower  $p_T$

- $R_{AA}^{\text{mid-}y} > R_{AA}^{\text{fwd-}y}$  (low  $p_T$ ) as expected by recombination scenario ( $N_{c\bar{c}}^{\text{mid-}y} > N_{c\bar{c}}^{\text{fwd-}y}$ )

# Observable: elliptic flow $v_2$

- Initial spatial anisotropy is converted into a **momentum space anisotropy**

$$\frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1} v_n \cos n(\varphi - \Psi_n)$$

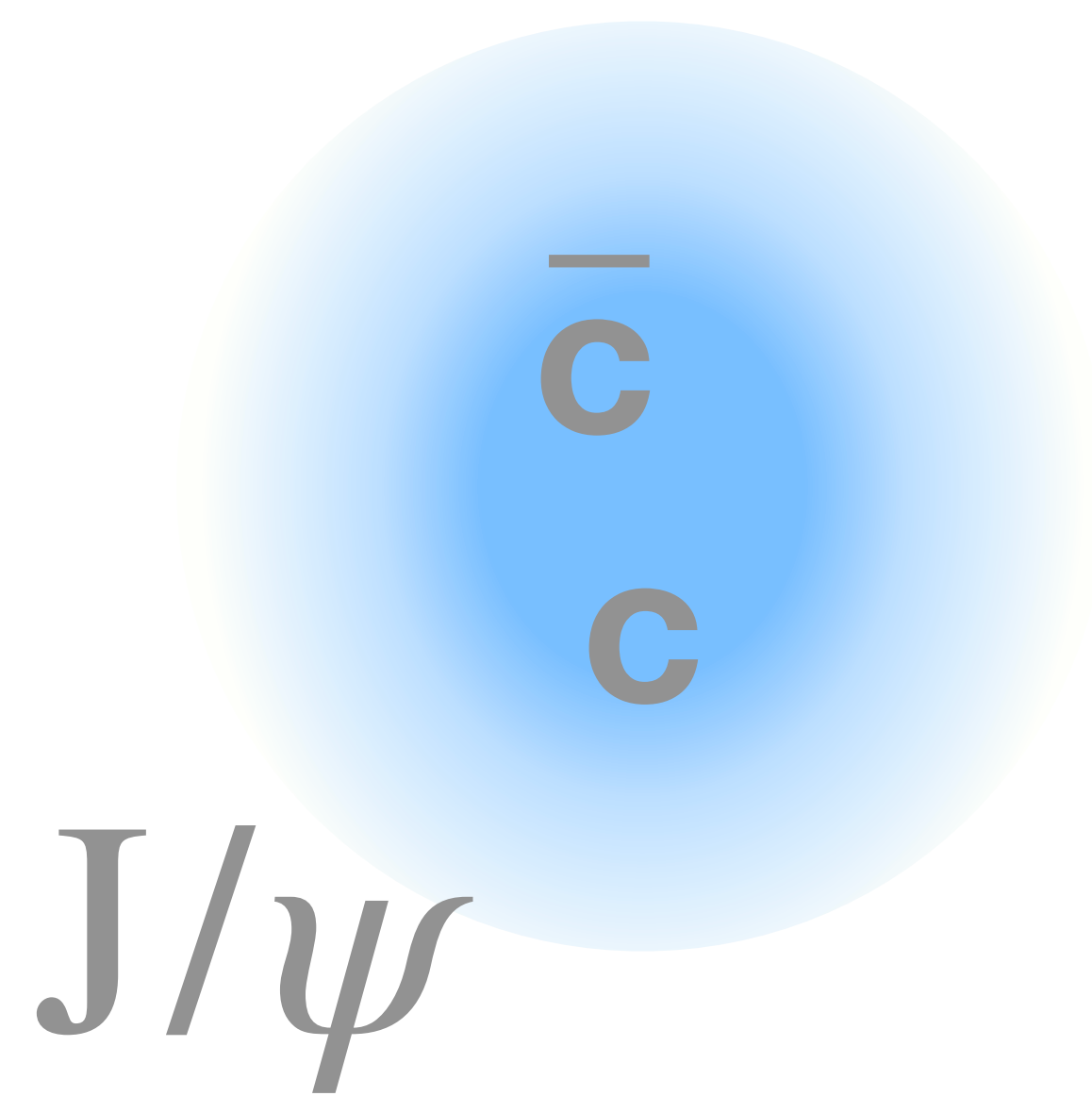


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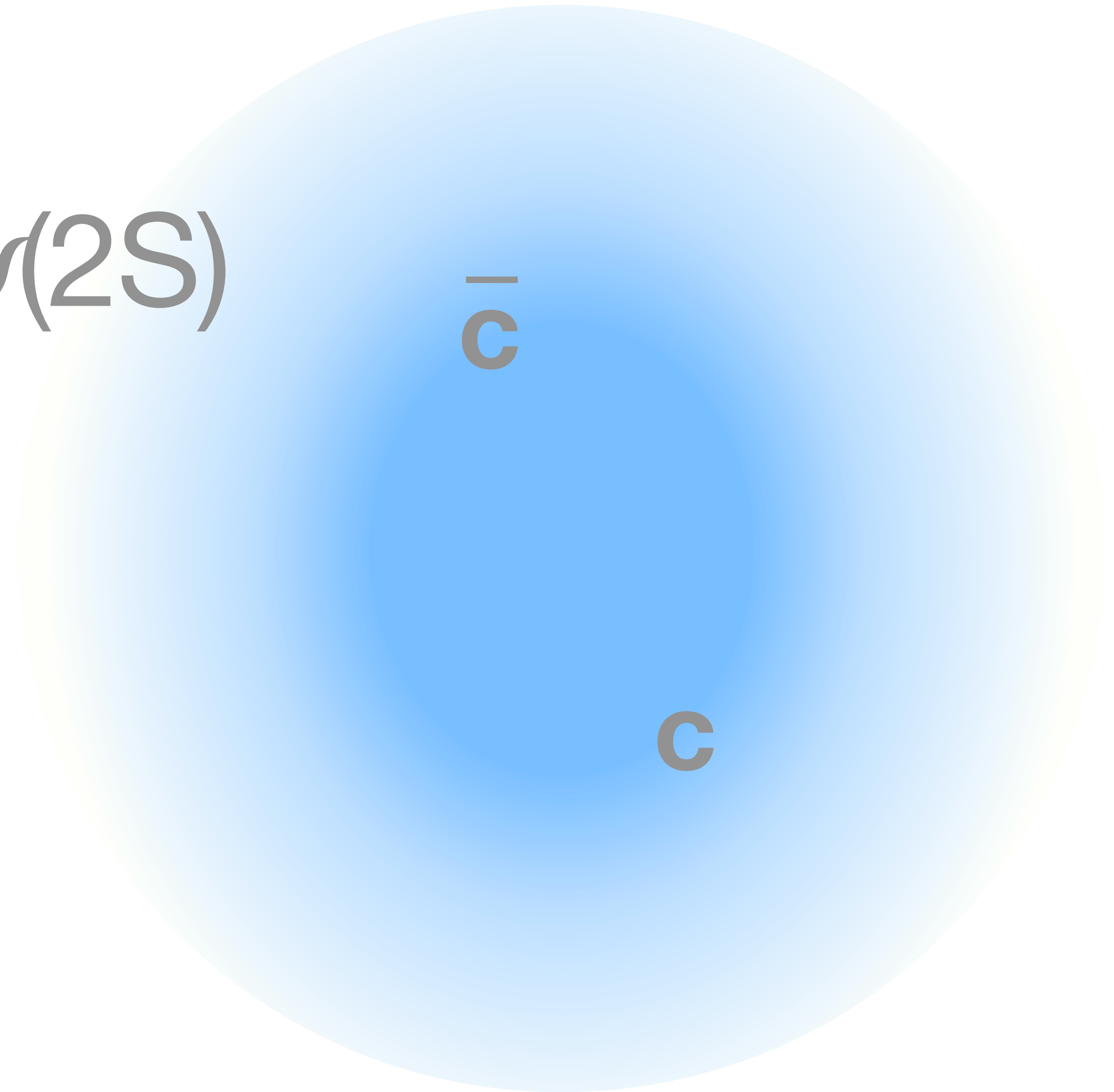
- Low  $p_T$  ( $< 5$  GeV/c): transport model implementing **regeneration** can describe measured  $J/\psi$   $v_2$ , the latter inherited from collective flow of c quarks during recombination
- High  $p_T$   $v_2$ : path-length dependence mechanism + c quark space-momentum correlations



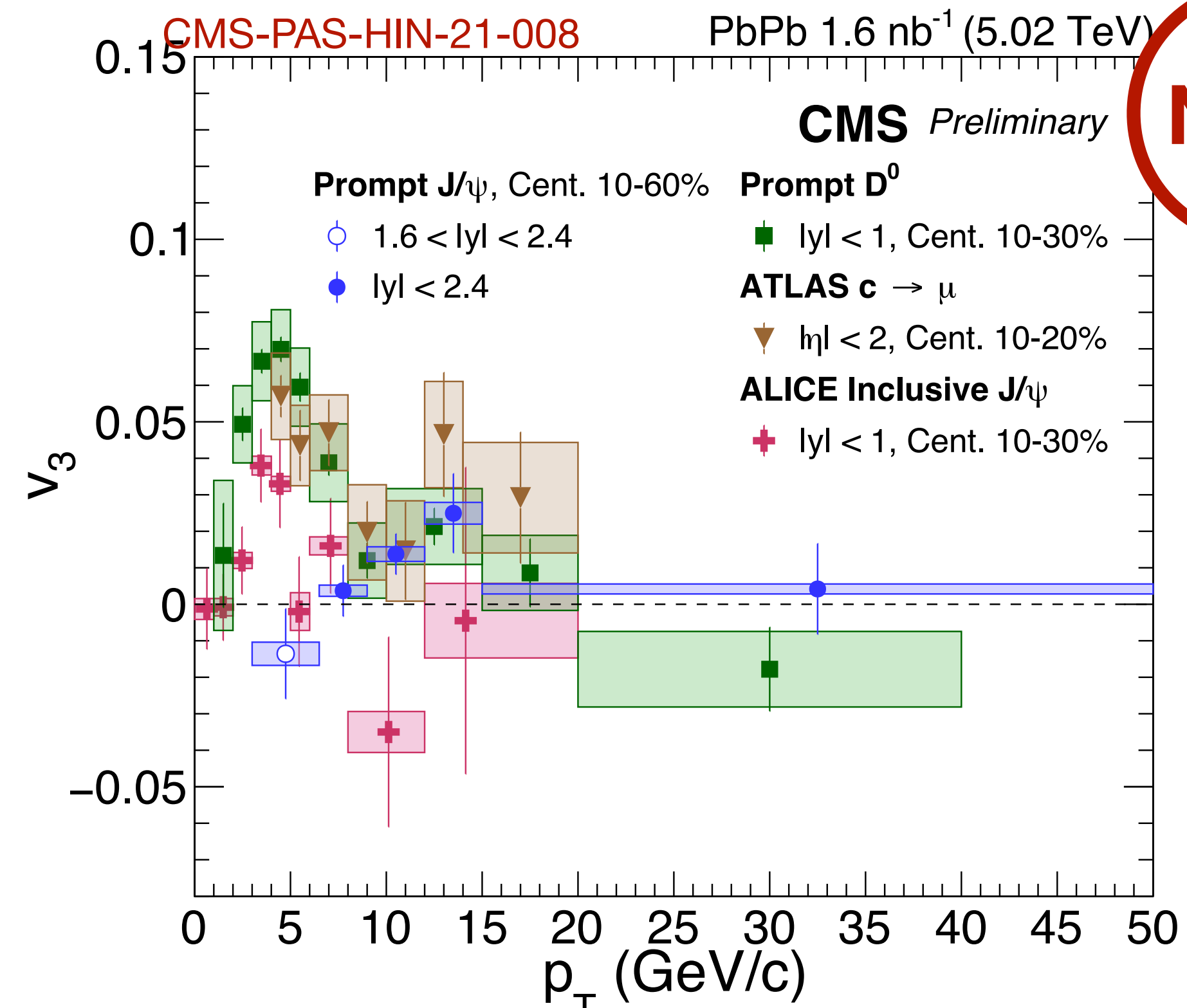
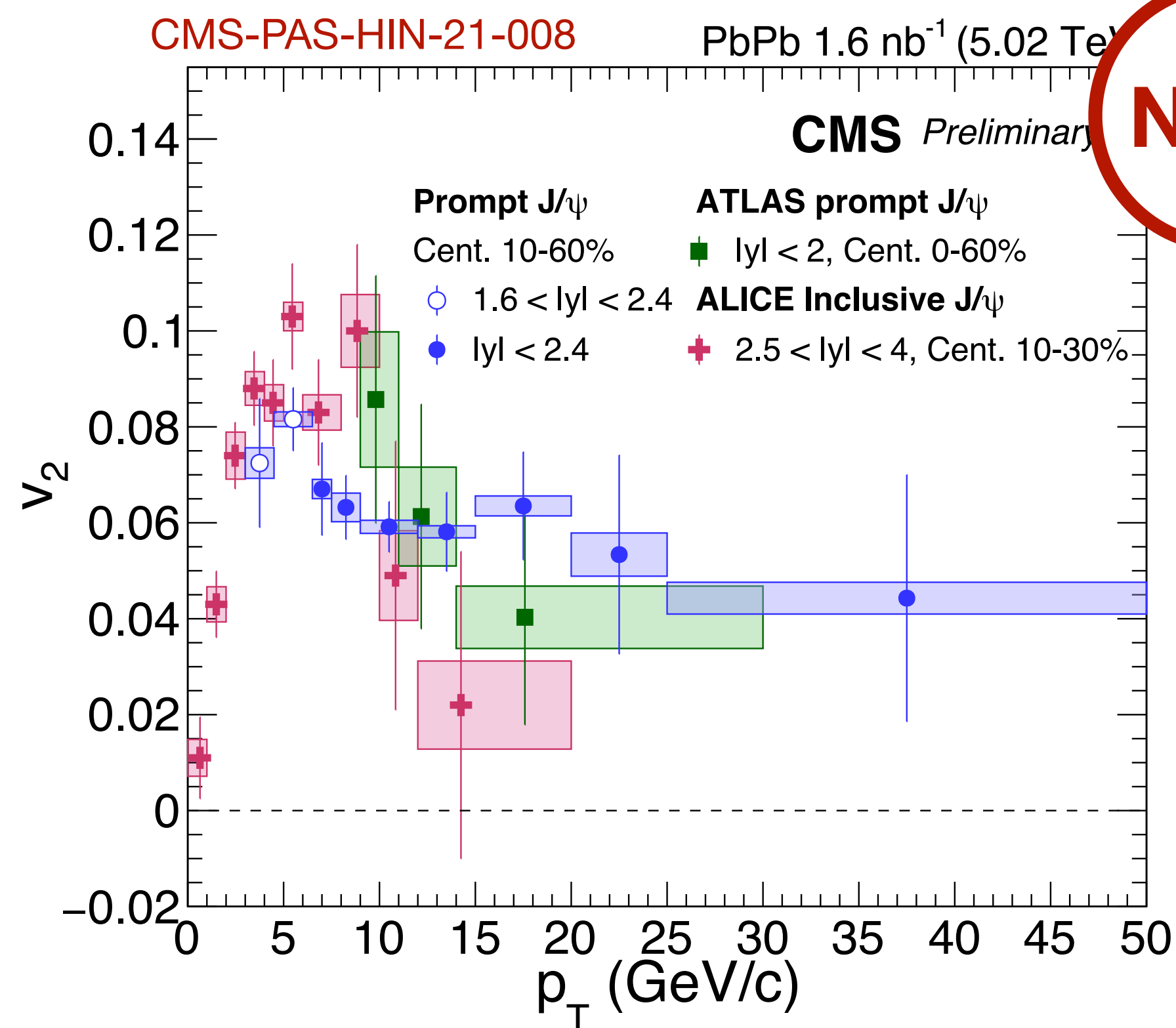
# New results on charmonia



$\psi(2S)$



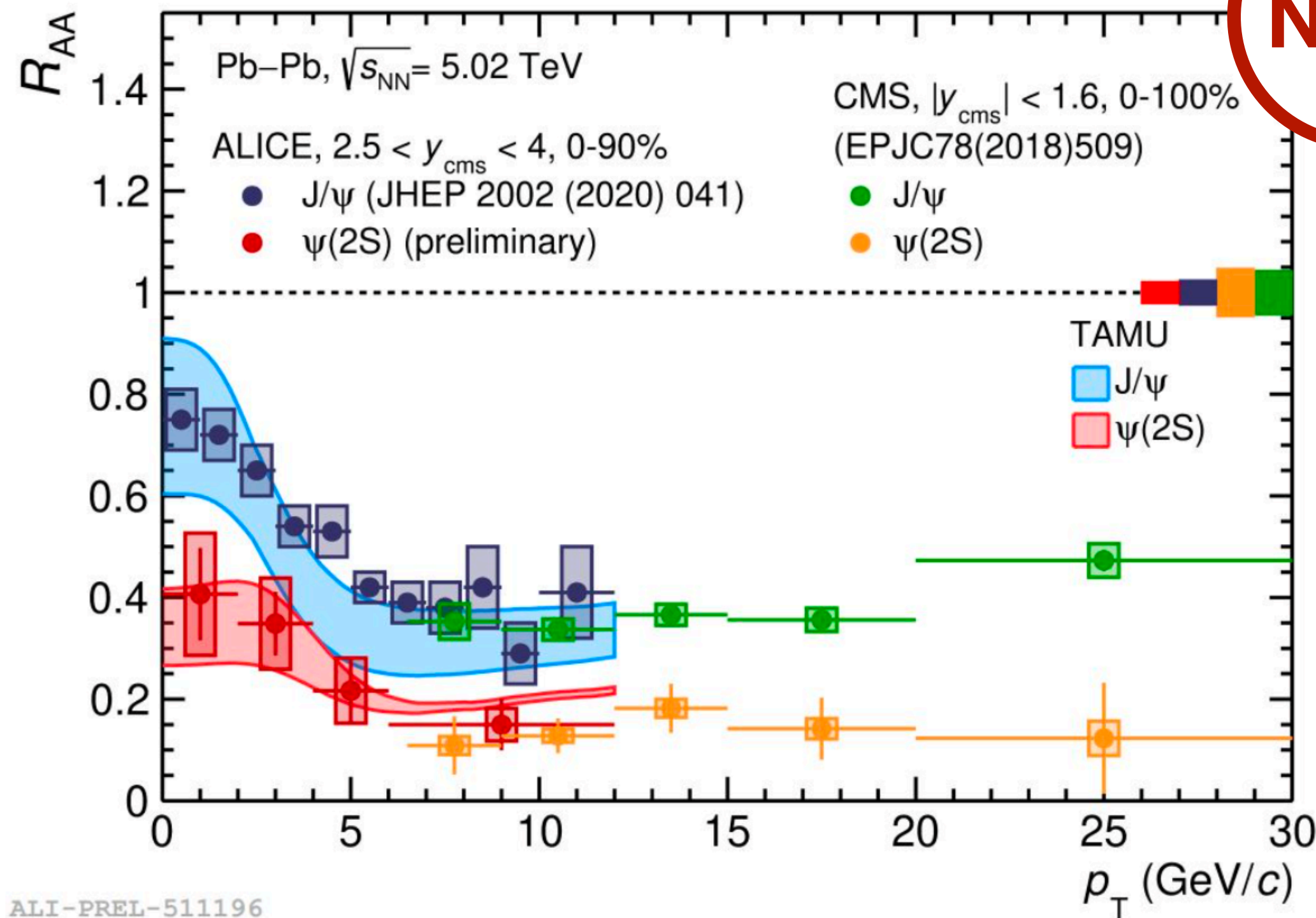
# Prompt $v_n^{J/\psi}$ measurements in Pb-Pb collisions



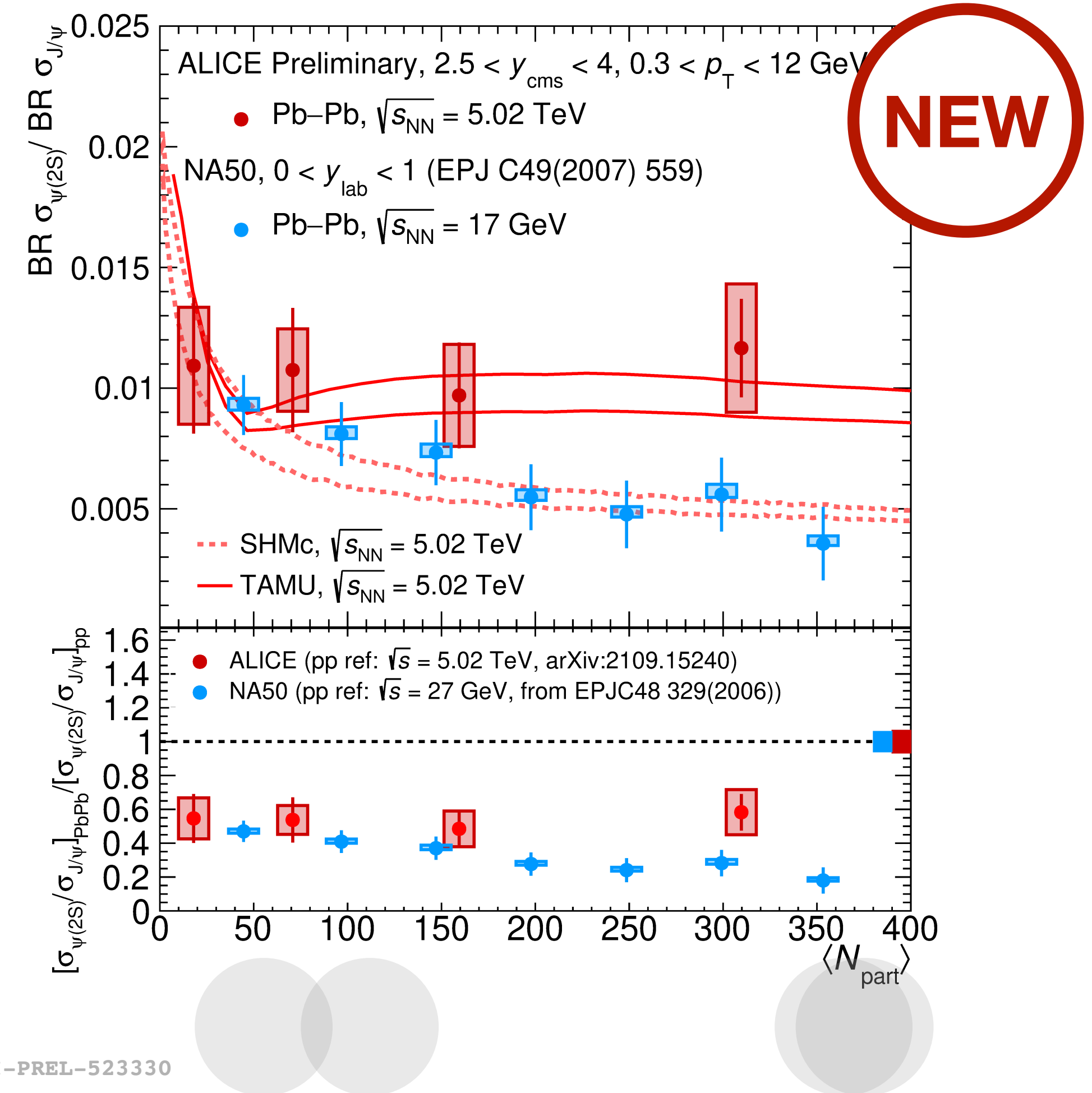
- Prompt J/ψ : significant  $v_2$  up to high  $p_T$  (~30 GeV/c), while  $v_3$  is smaller
- Largest  $v_2^{J/\psi}$  at low  $p_T$  (~5 GeV/c, expected from recombination) and also hint for  $v_3$
- High  $p_T$   $v_2$ : path-length dependence effect at play for all particles

# $\psi(2S)$ $R_{AA}$ in Pb-Pb collisions

**NEW**



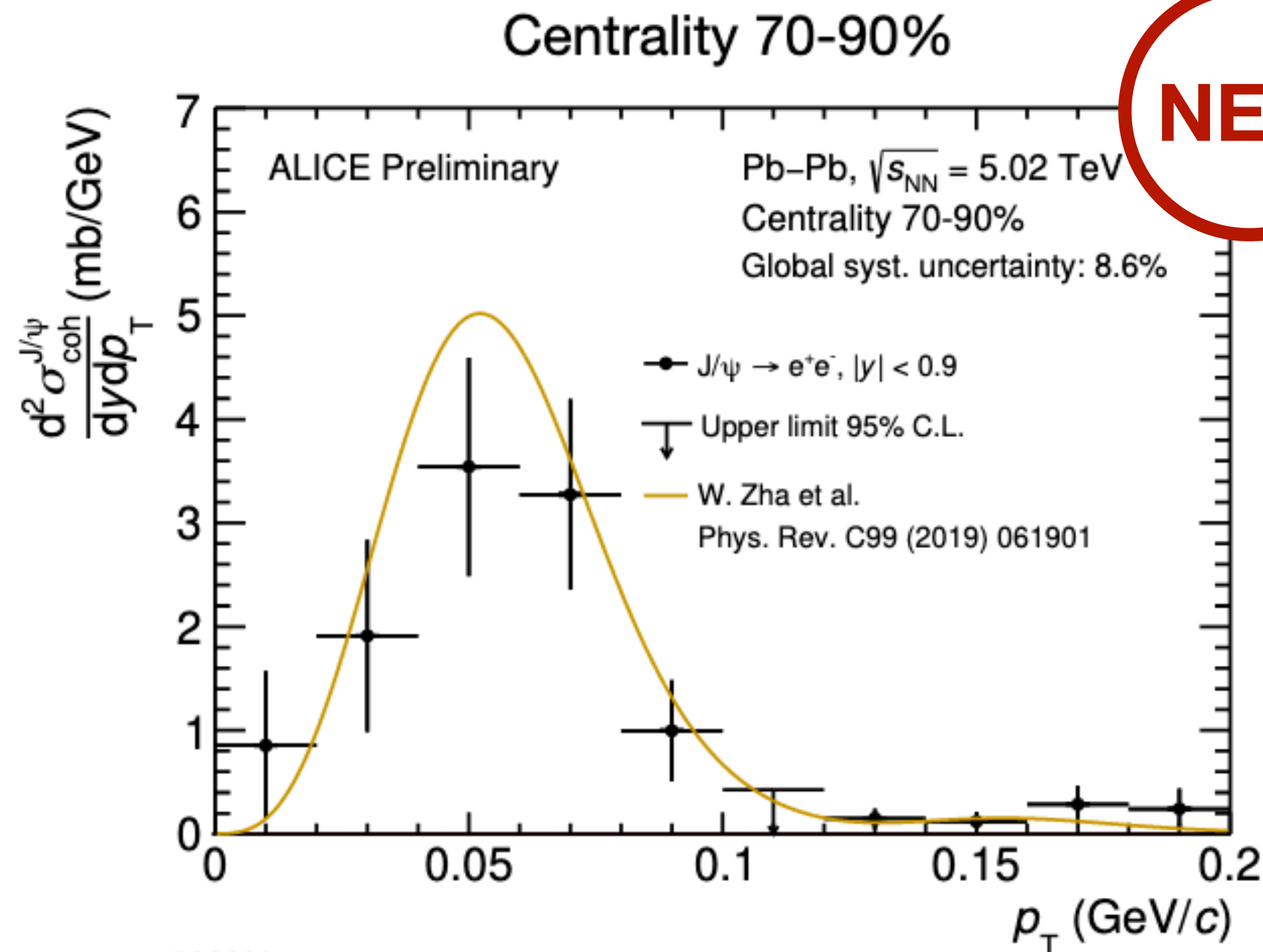
ALI-PREL-511196



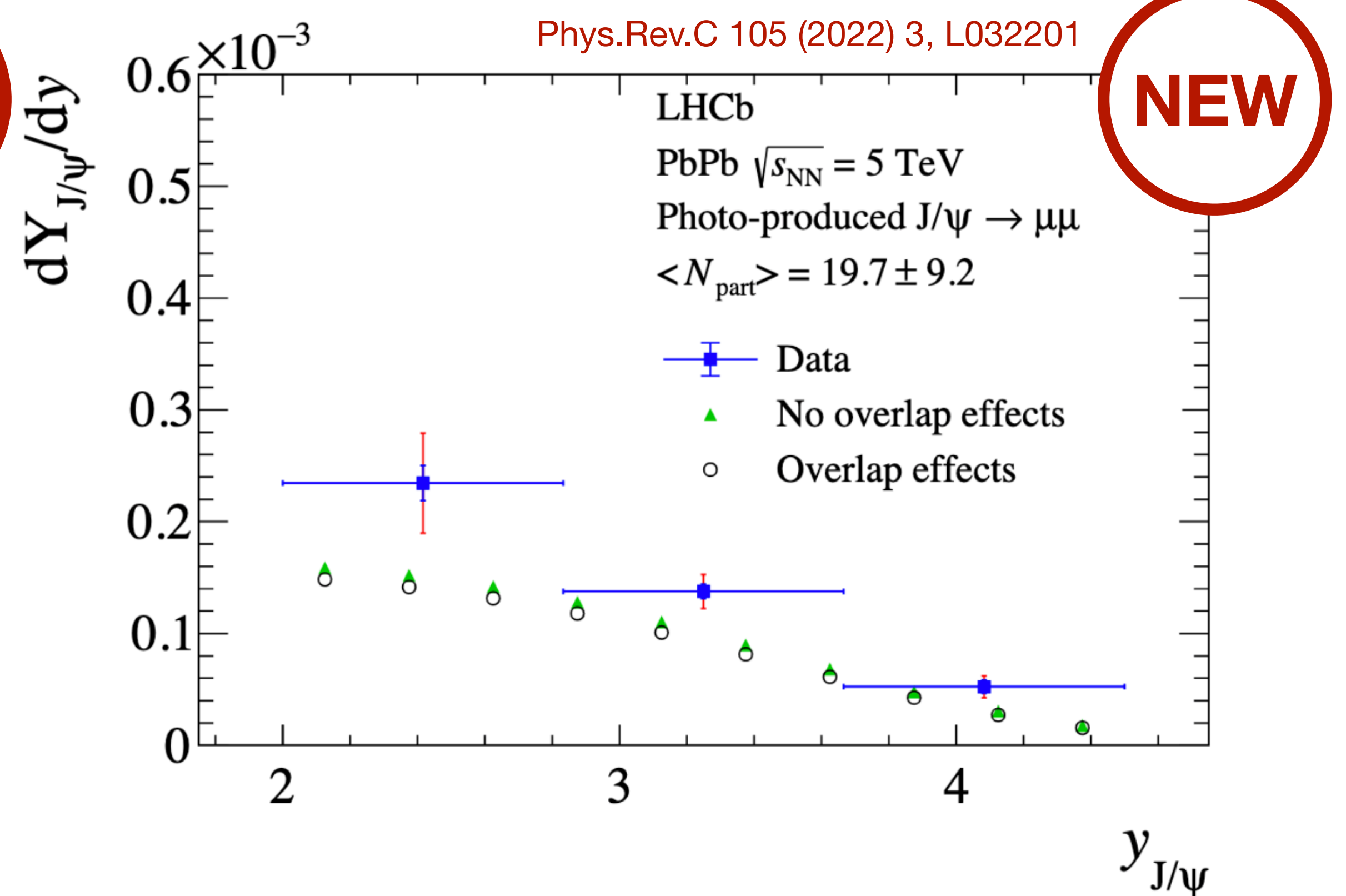
ALI-PREL-523330

- **Suppression hierarchy** between J/ $\psi$  and  $\psi(2S)$  over  $p_T$  and for all centralities
- **Hint of a larger  $\psi(2S) / J/\psi$  ratio** in central collisions at the LHC w.r.t SPS (ratio described by TAMU model, while it is underestimated by SHMc in central events)

# J/ψ photoproduction in peripheral Pb-Pb

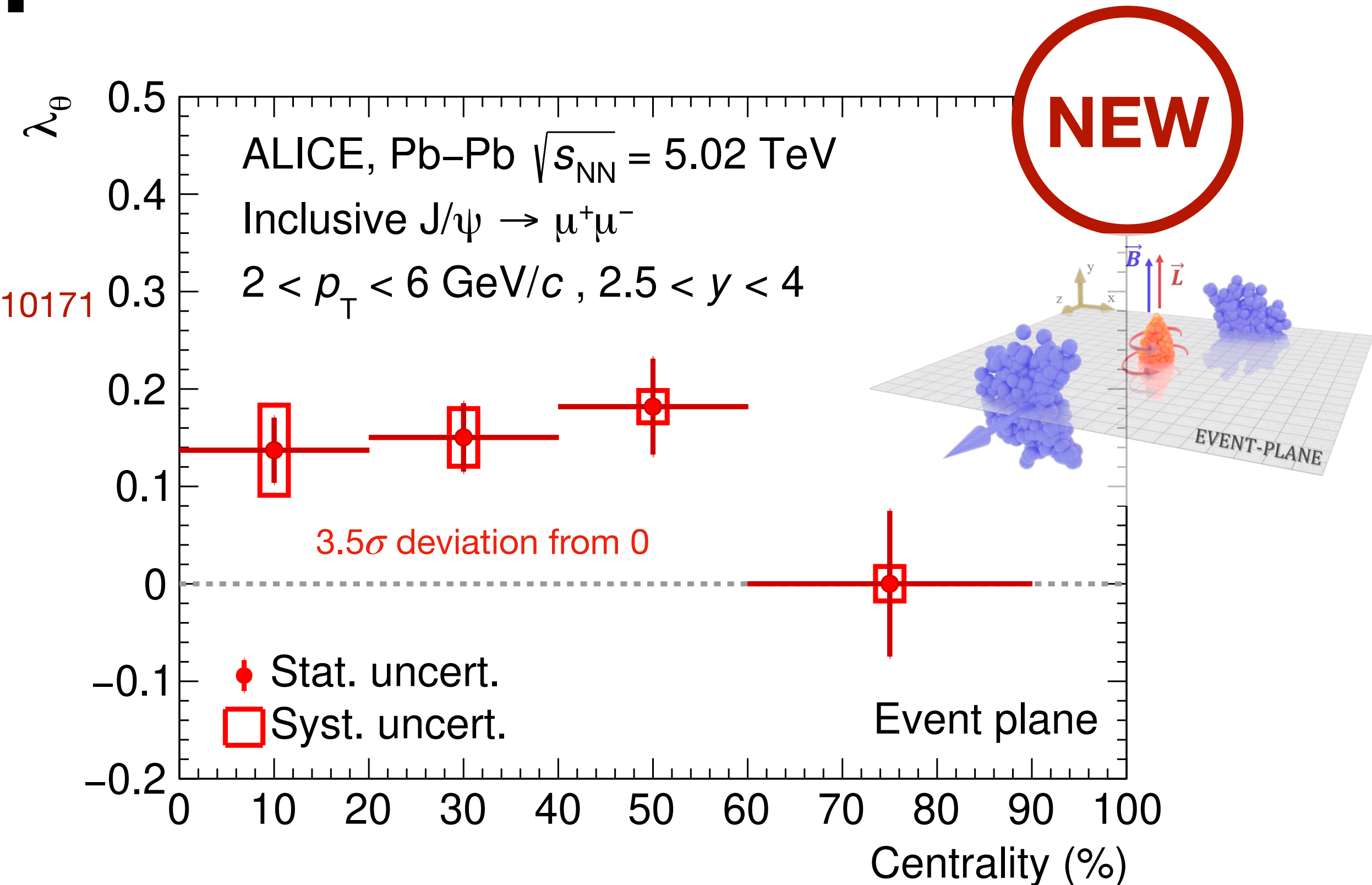
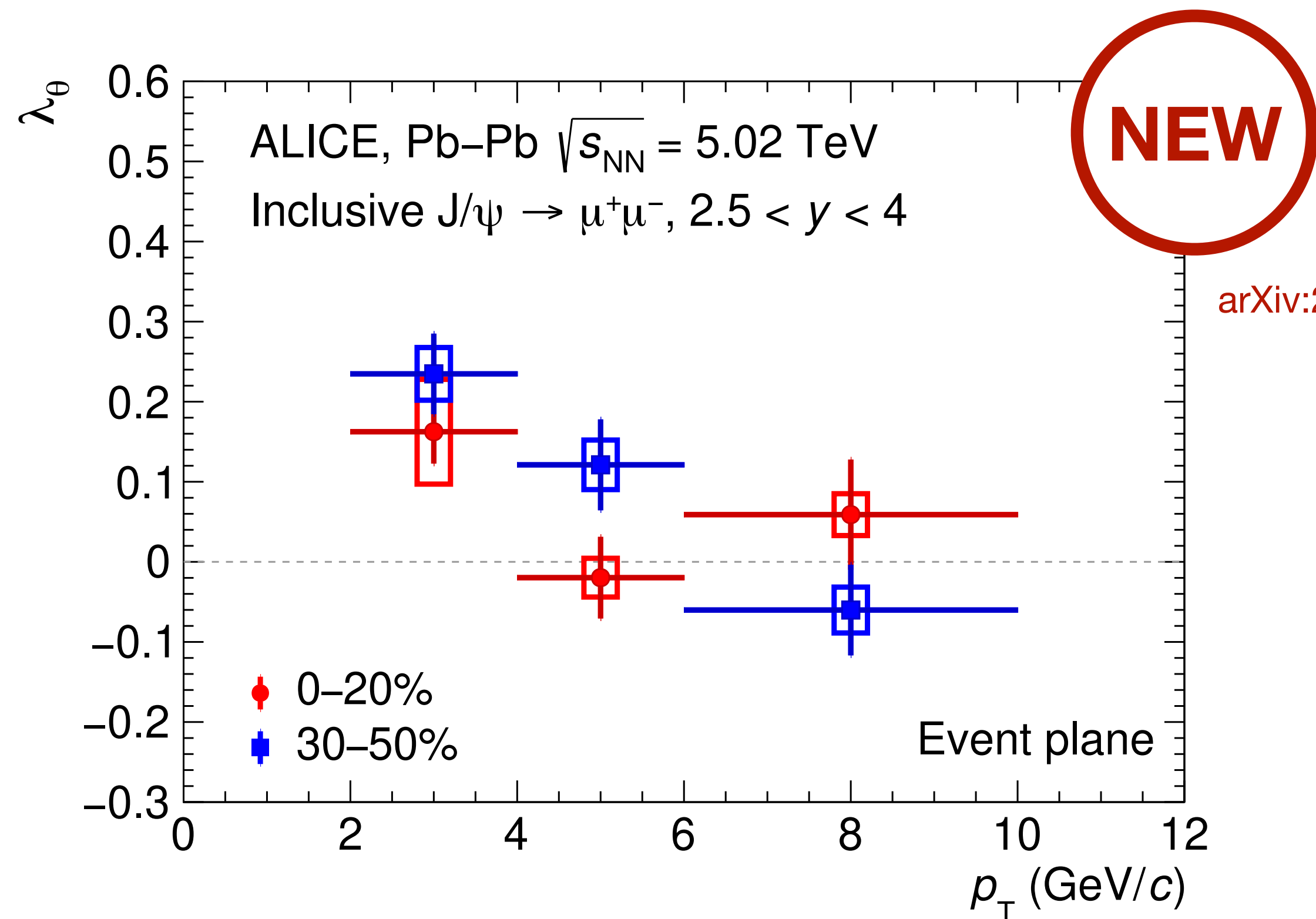


ALI-PREL-504480



- J/ψ photoproduction observed in peripheral Pb-Pb and not only in UPC
- Theoretical models (for UPC) including modification of the photon flux and sometimes also the effect of the overlap between the nuclei (small impact) describe the data

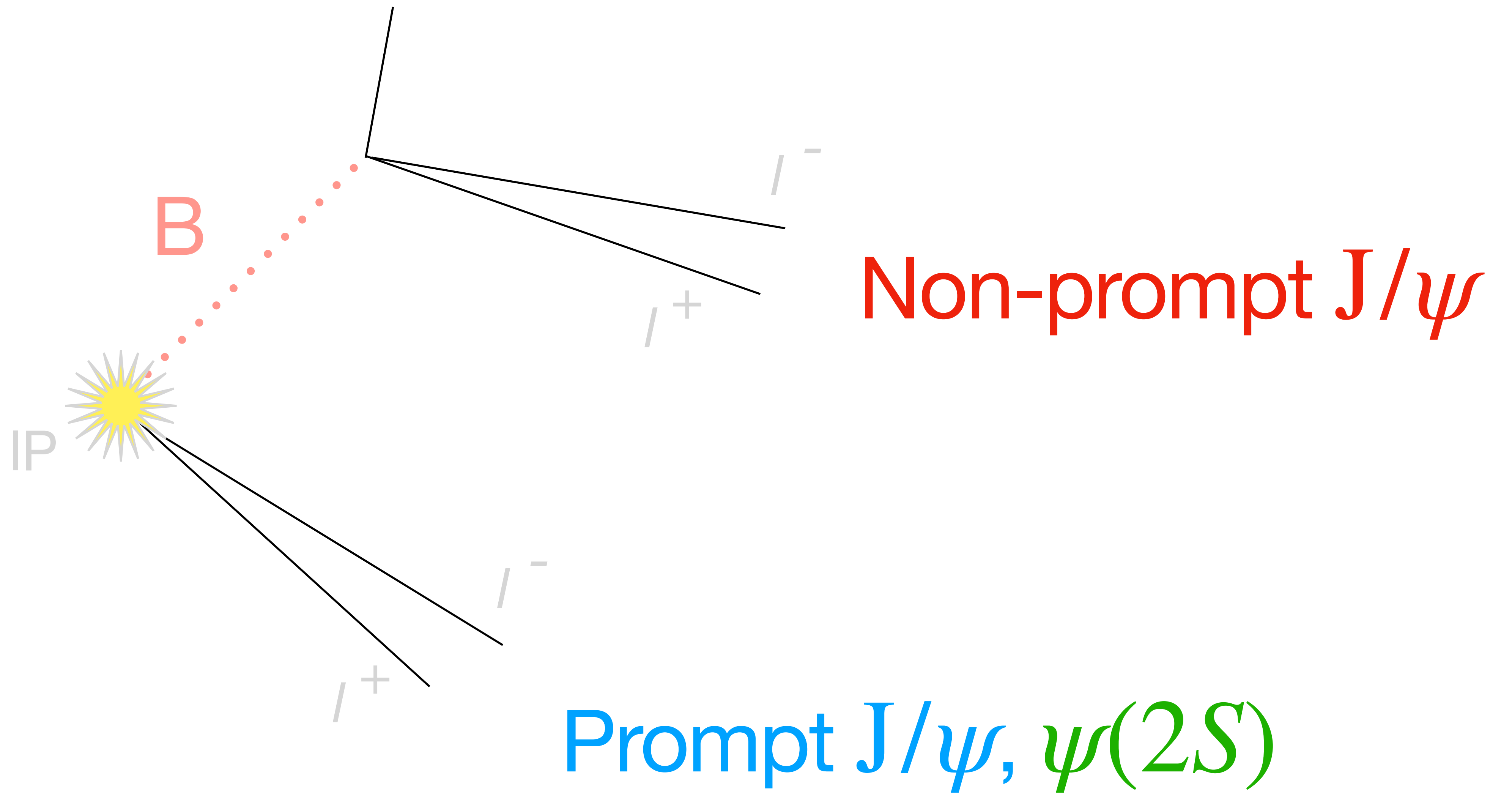
# J/ψ polarisation vs event plane in Pb-Pb collisions



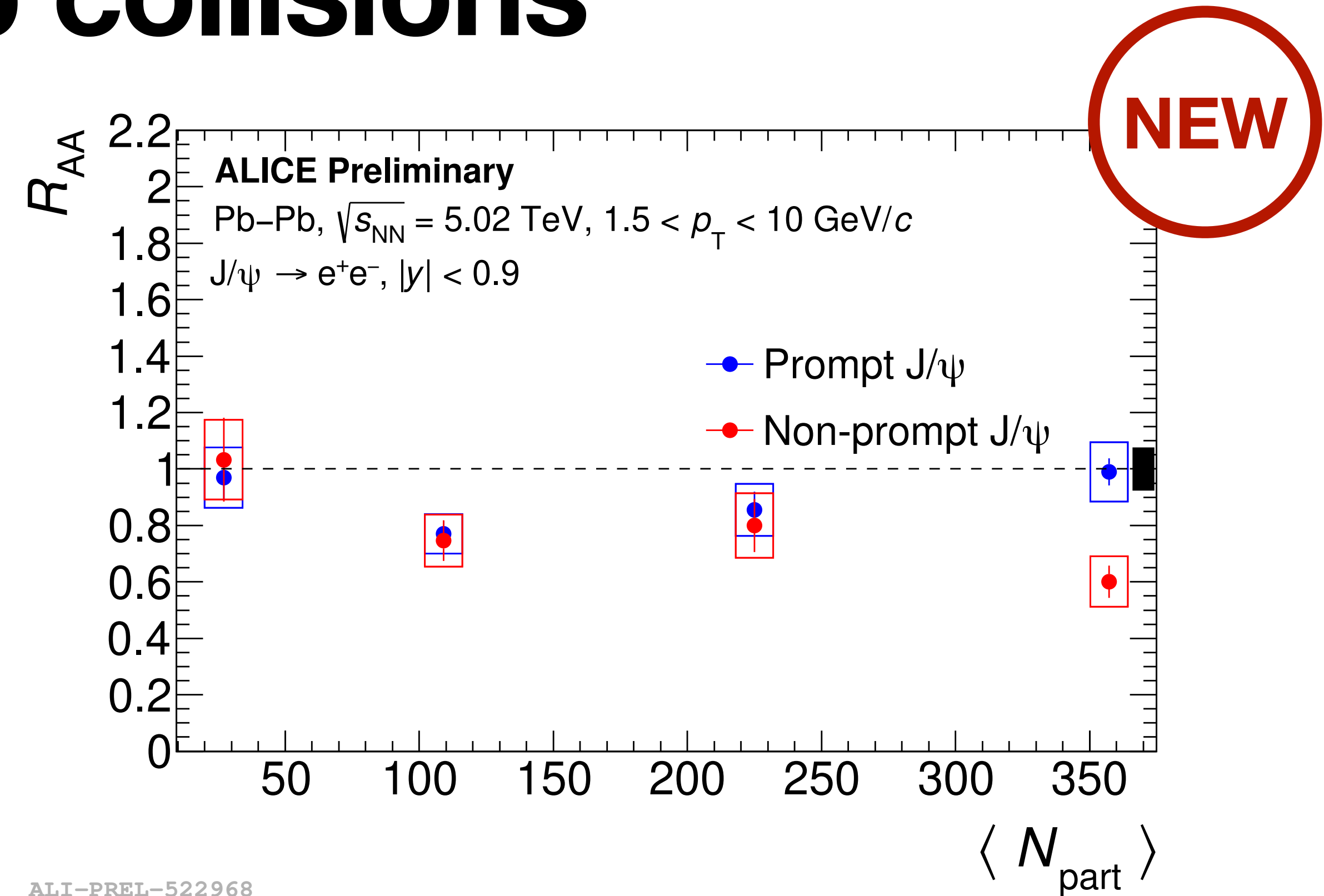
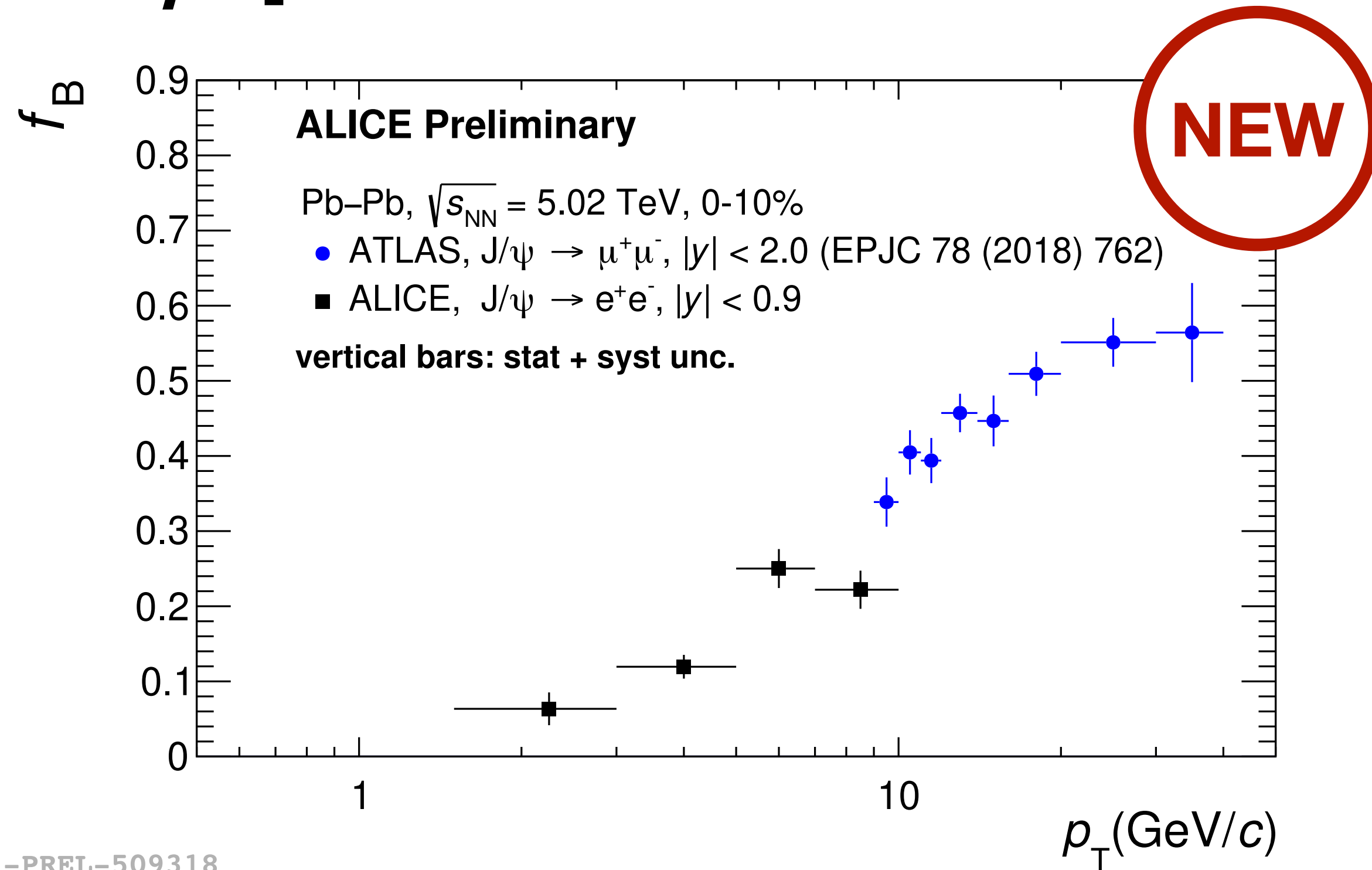
ALI-PUB-521057

ALI-PUB-521052

- Vanishing polarisation at larger momenta
- **First evidence** of J/ψ polarisation w.r.t. EP at low  $p_T$  (possibly larger in semi-central events)
- Sensitivity to **vorticity and B field?**



# J/ψ production in Pb-Pb collisions

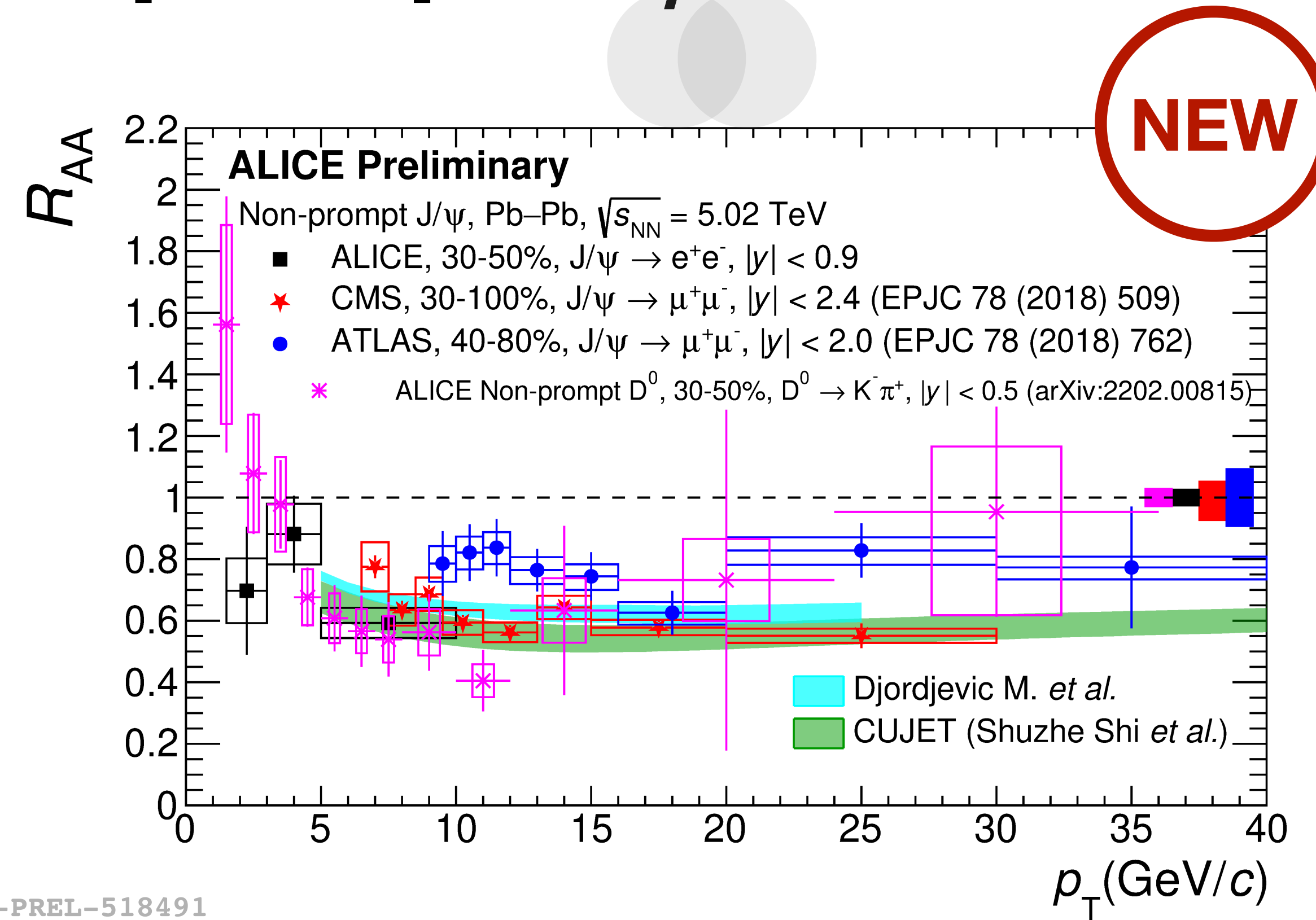
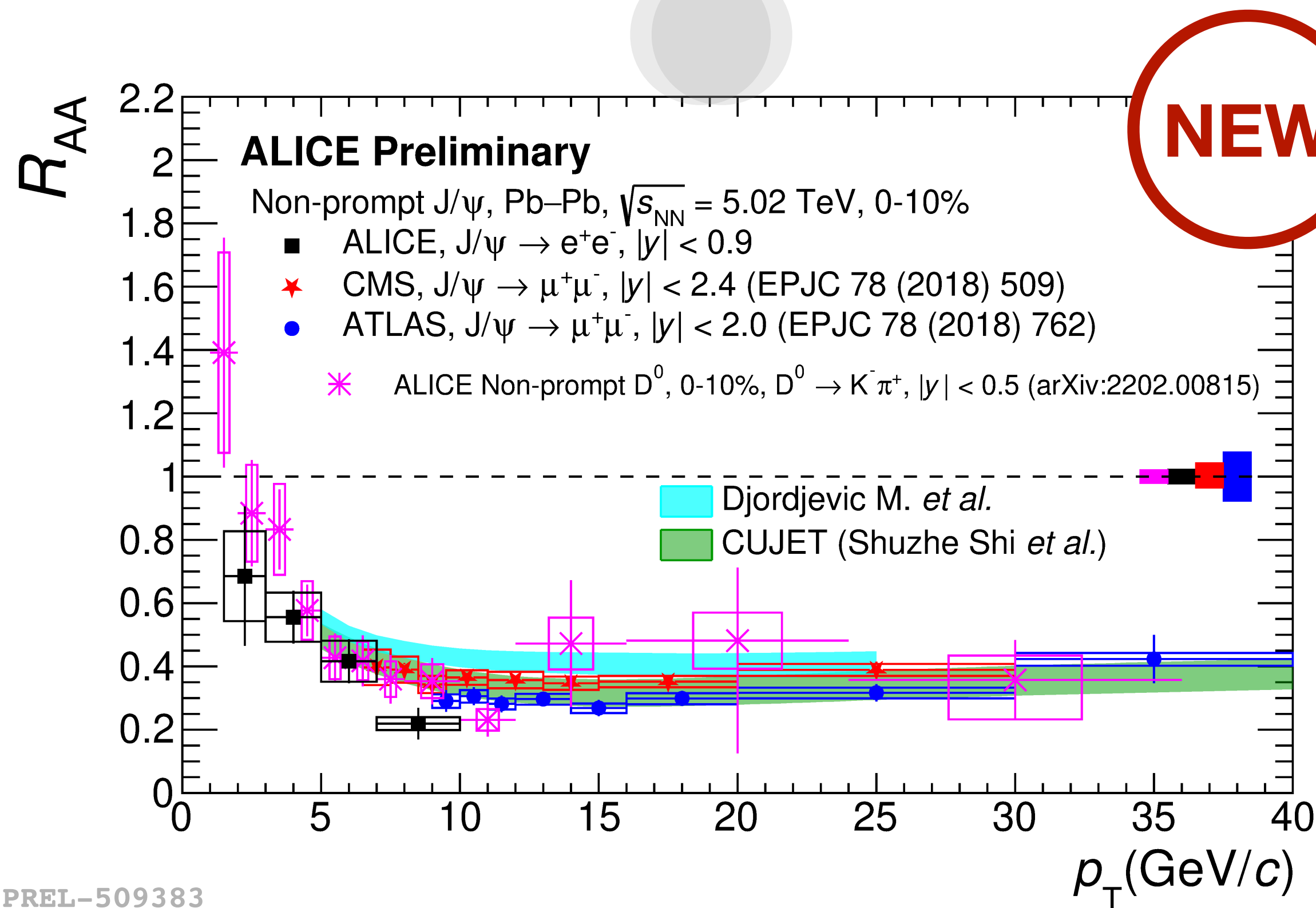


ALI-PREL-509318

ALI-PREL-522968

- ALICE extends non-prompt J/ψ fraction ( $f_B$ ) measurements down to very low  $p_T$
- Non-prompt J/ψ  $R_{AA}$  more suppressed towards more central collisions
- Recombination can explain the raising trend of  $R_{AA}^{\text{prompt } J/\psi}$  towards more central collisions

# Measuring beauty from non-prompt $J/\psi$ in Pb-Pb

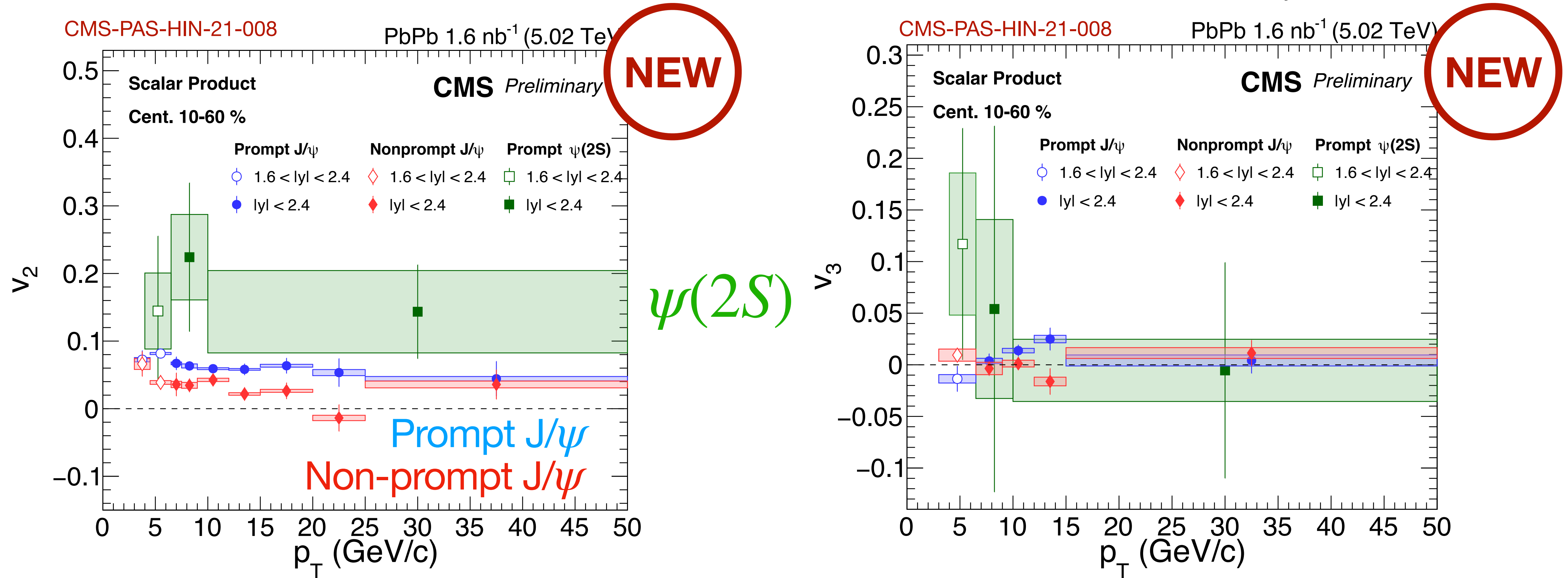


○ Unprecedented access to the low  $p_T$  region for beauty hadron  $R_{AA}$  through the measurements of non-prompt  $J/\psi$  and non prompt  $D^0$  meson

○ Models including **collisional and radiative energy loss** consistent with data (high  $p_T$ )

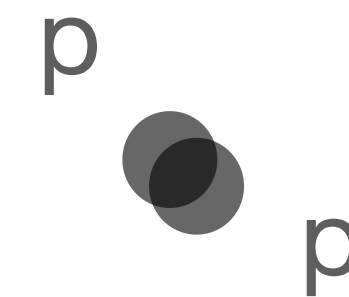
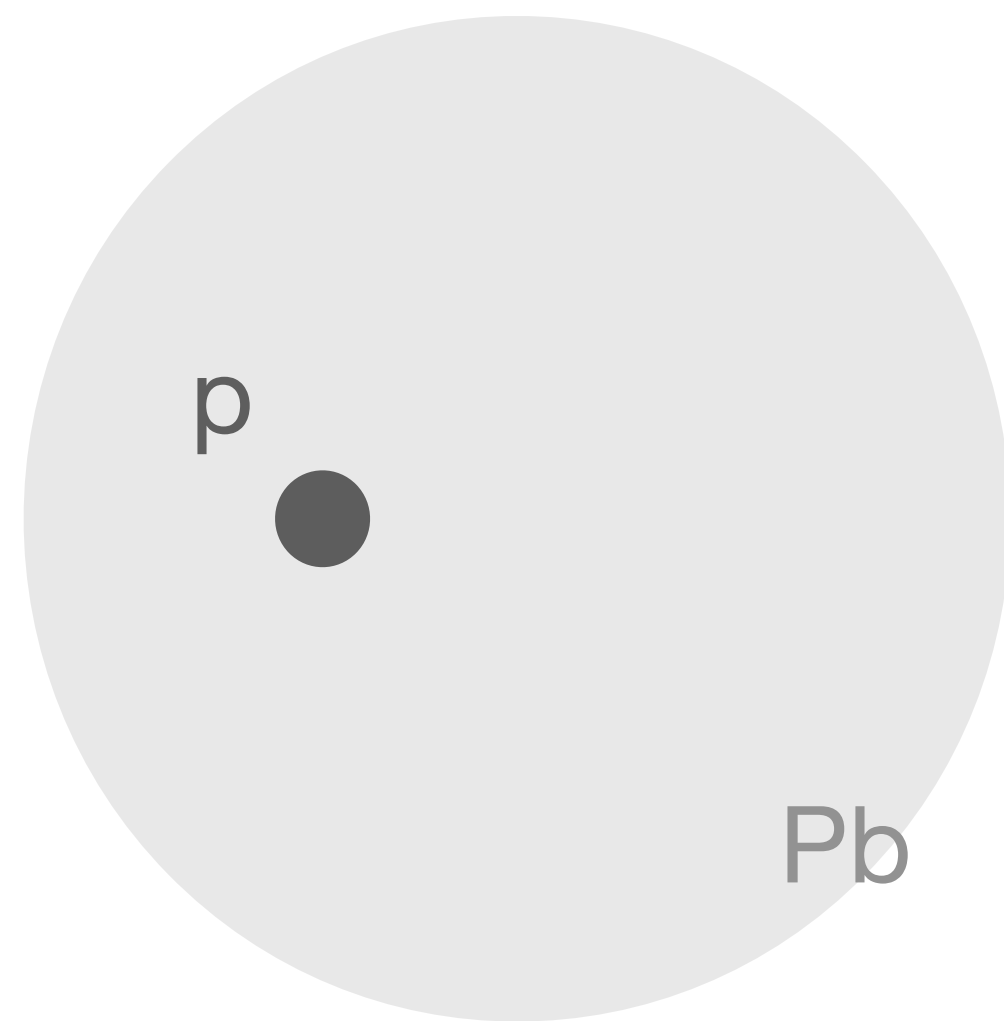


# Prompt $\psi(2S)$ , prompt and non-prompt $J/\psi$ $v_n$ in Pb-Pb

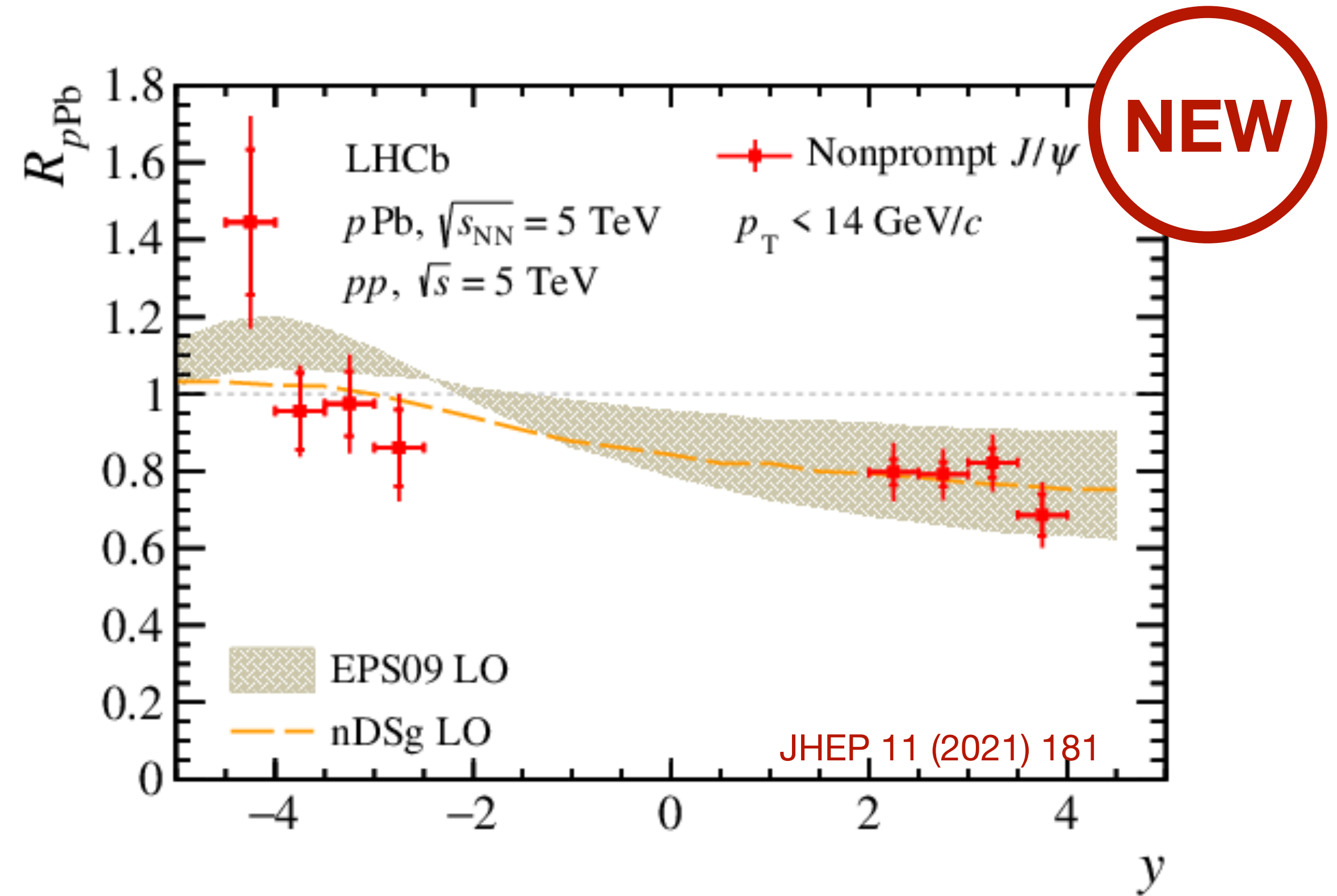
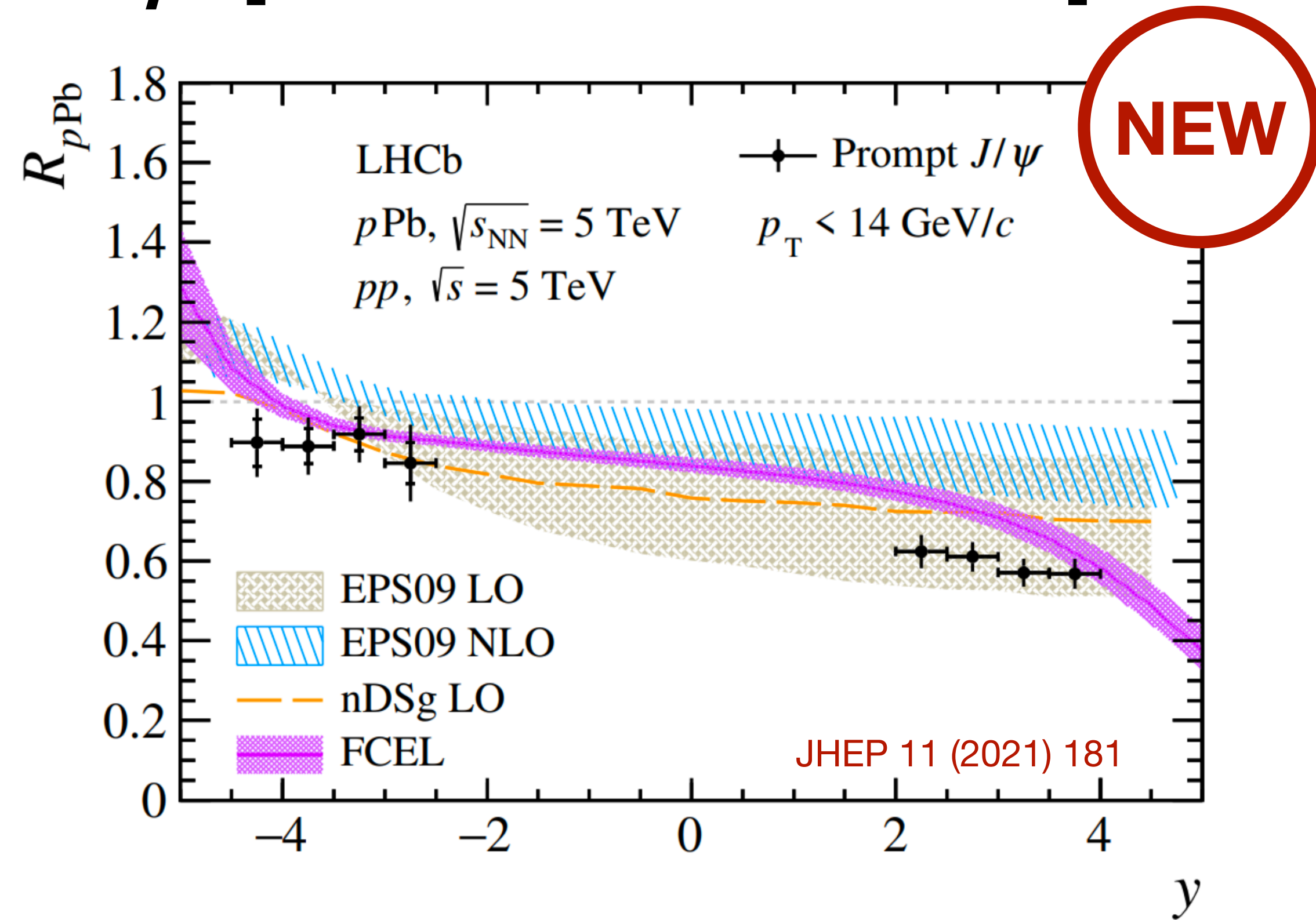


- **Hint of prompt  $v_2^{\psi(2S)} > 0$  ( $p_T > 5$  GeV/c):** larger than  $v_2$  of prompt and non-prompt  $J/\psi$
- Prompt  $\psi(2S)$   $v_3$  found **compatible with 0** and with  $J/\psi$   $v_3$

# Going towards small collision systems

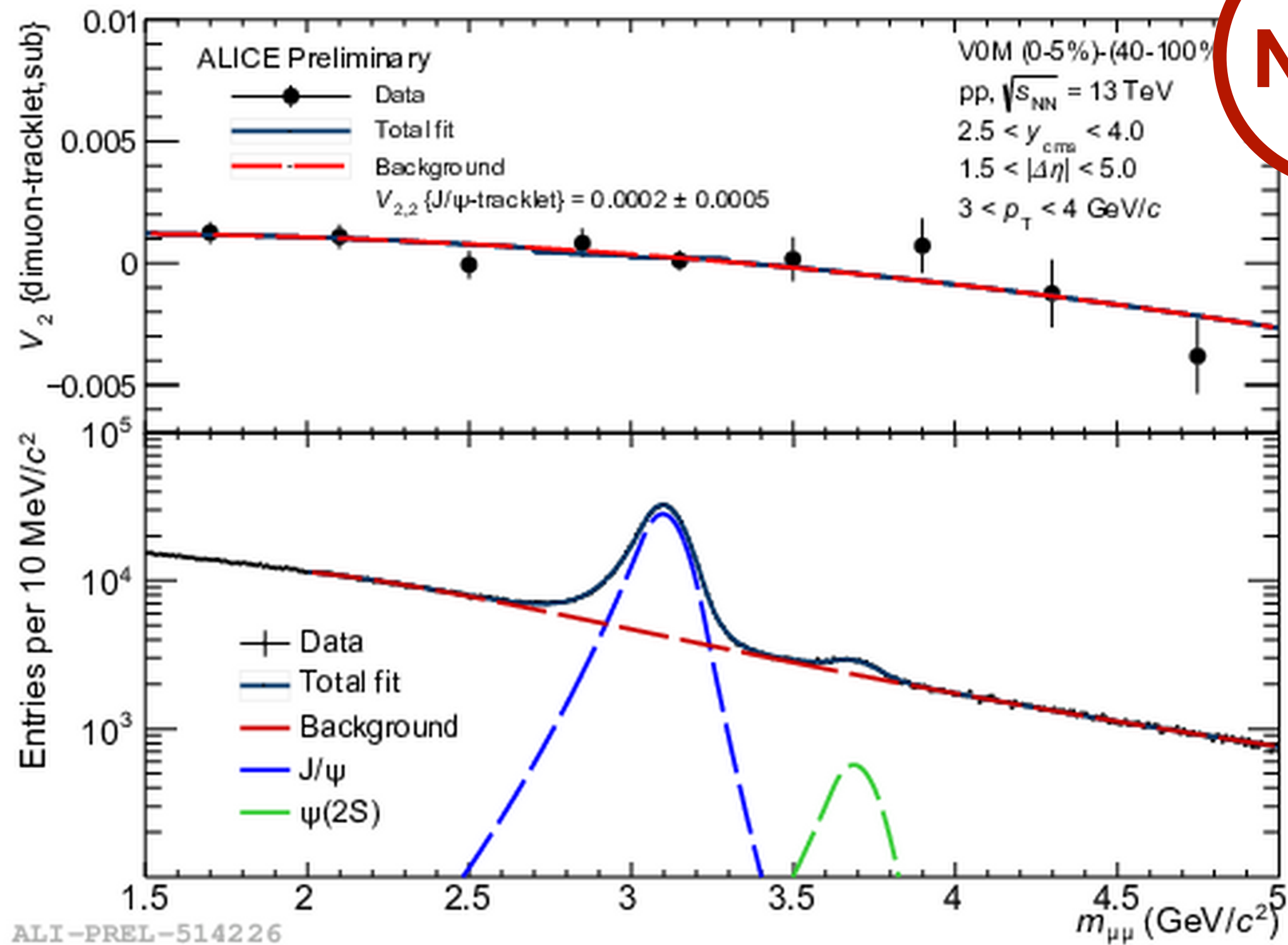


# J/ψ production in p-Pb collisions

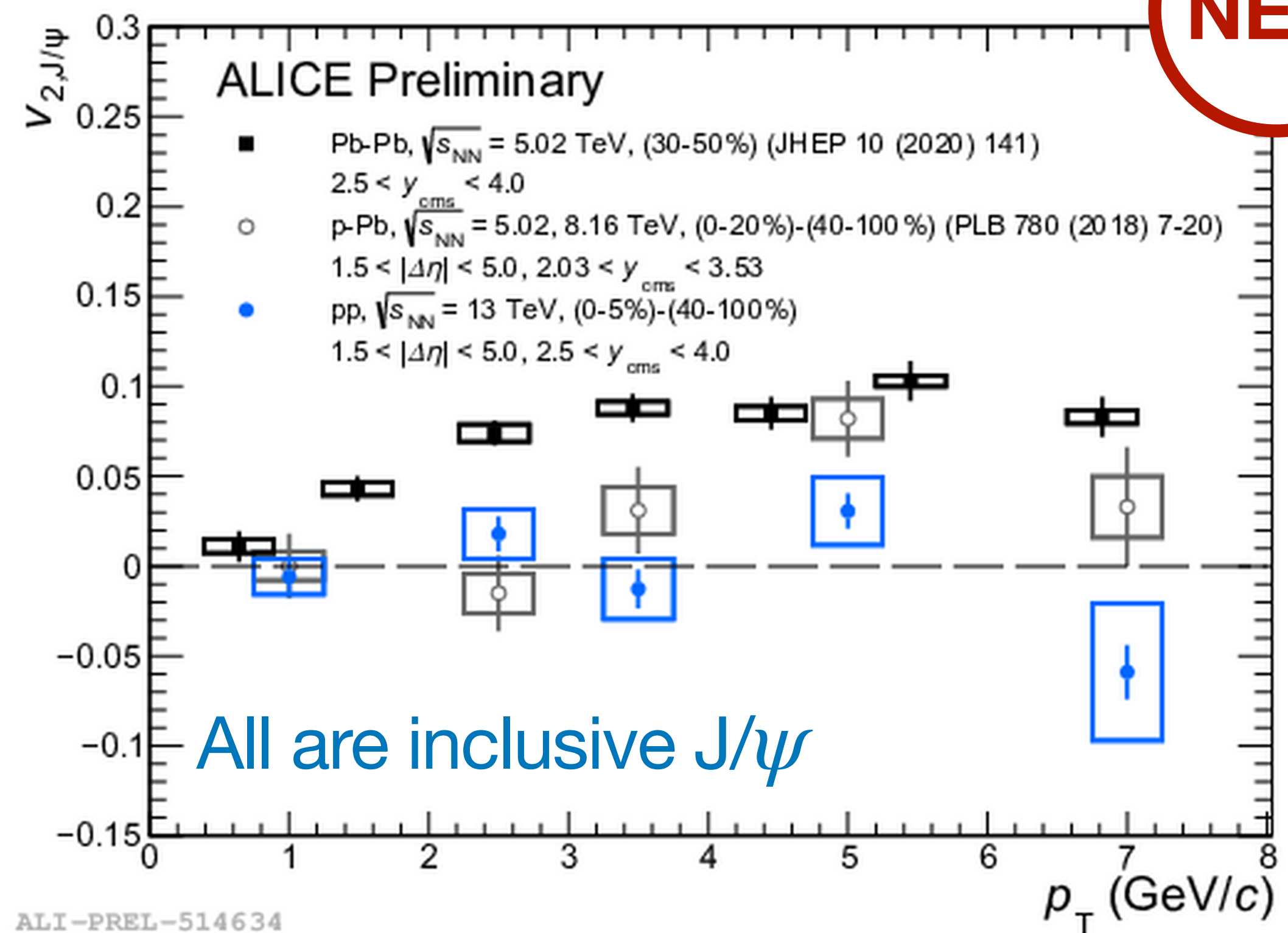


- Updated  $R_{pPb}$  for (non-)prompt  $J/\psi$  thanks to new differential cross sections in pp
- Stronger suppression at forward- $y$  w.r.t. backward- $y$  for (non-)prompt  $J/\psi$
- Prompt  $J/\psi$ : tension between data and EPS09 NLO nPDF parametrisation

# $v_2^{J/\psi}$ measurement in pp collisions



NEW

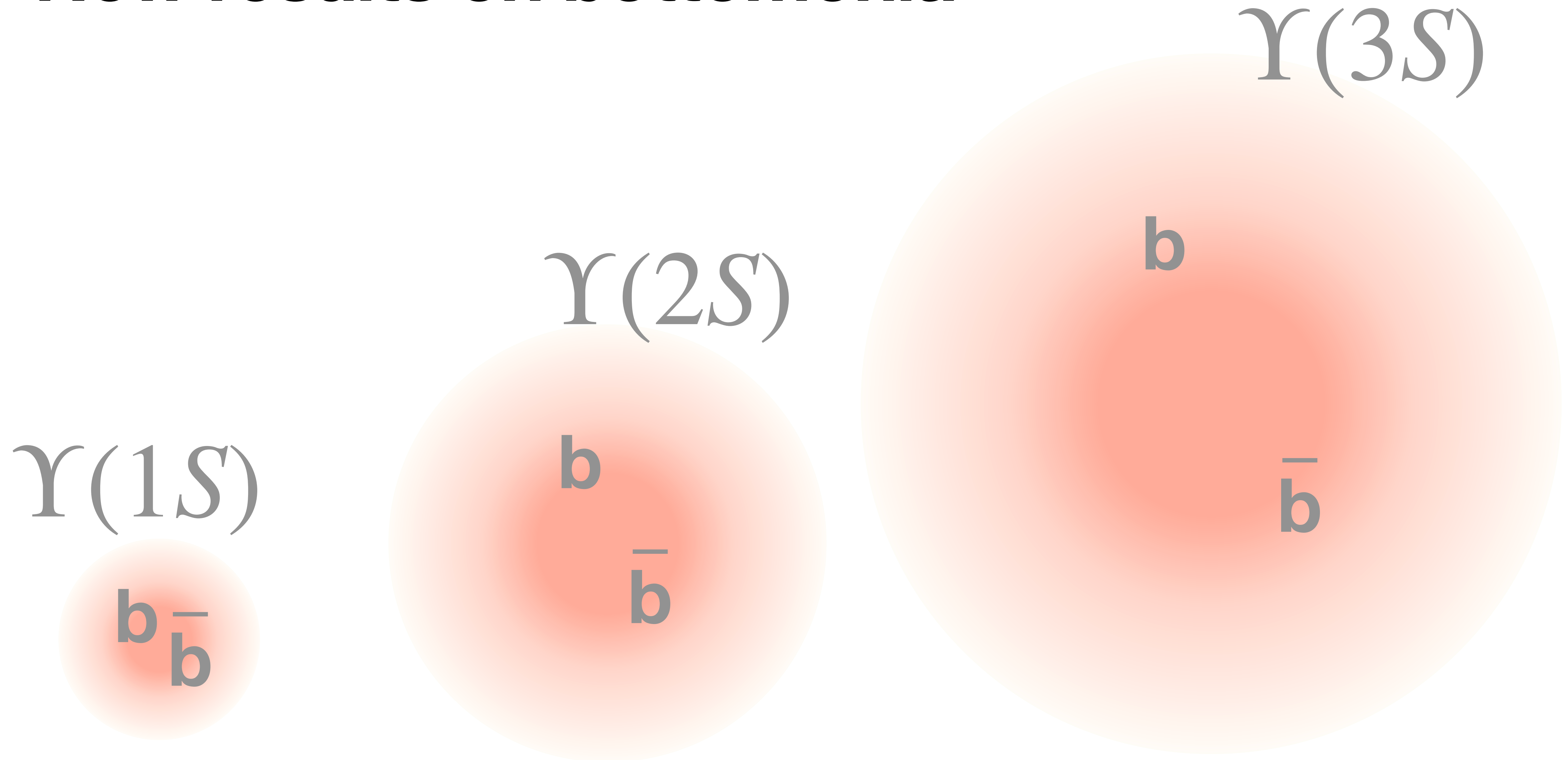


NEW

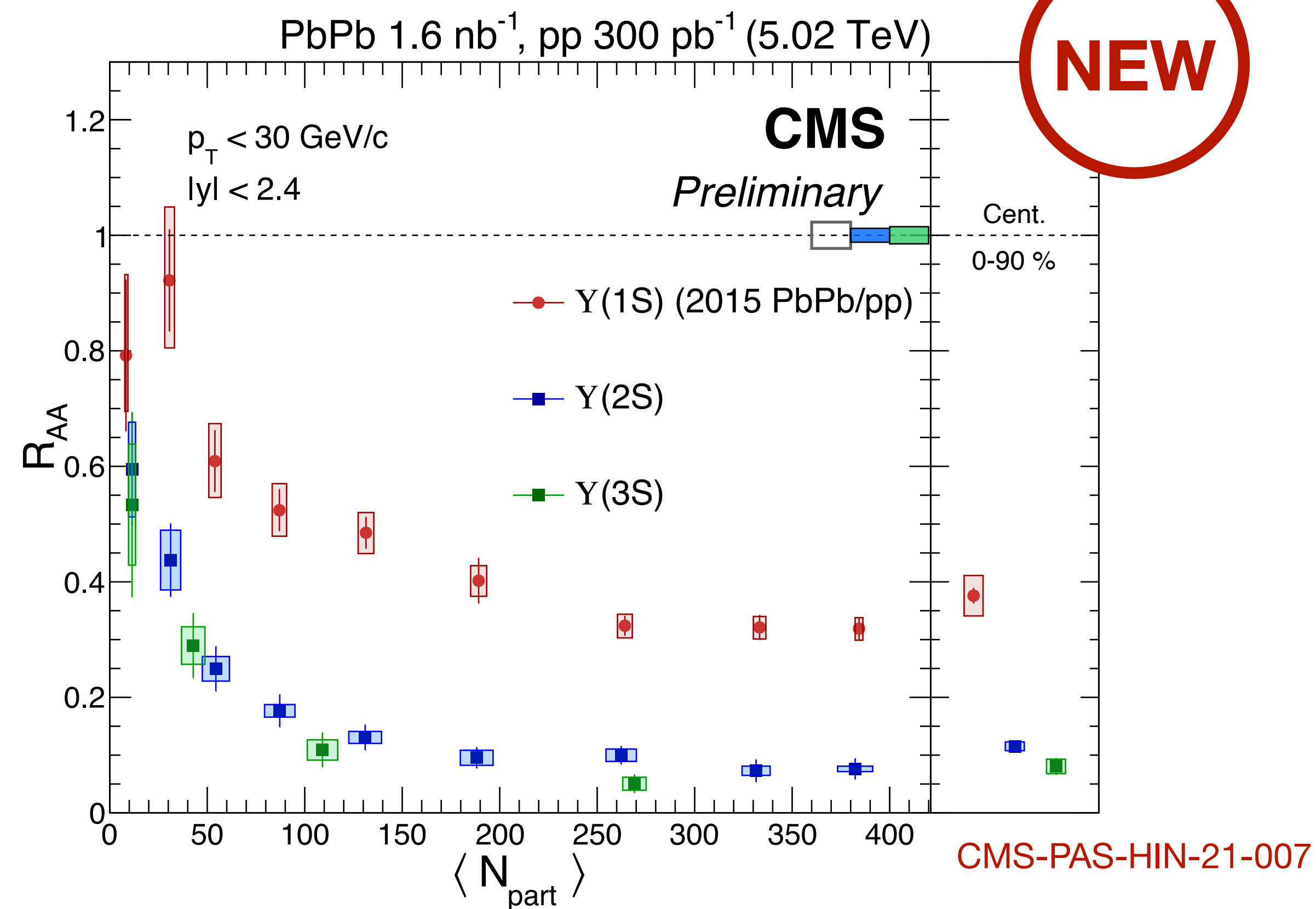
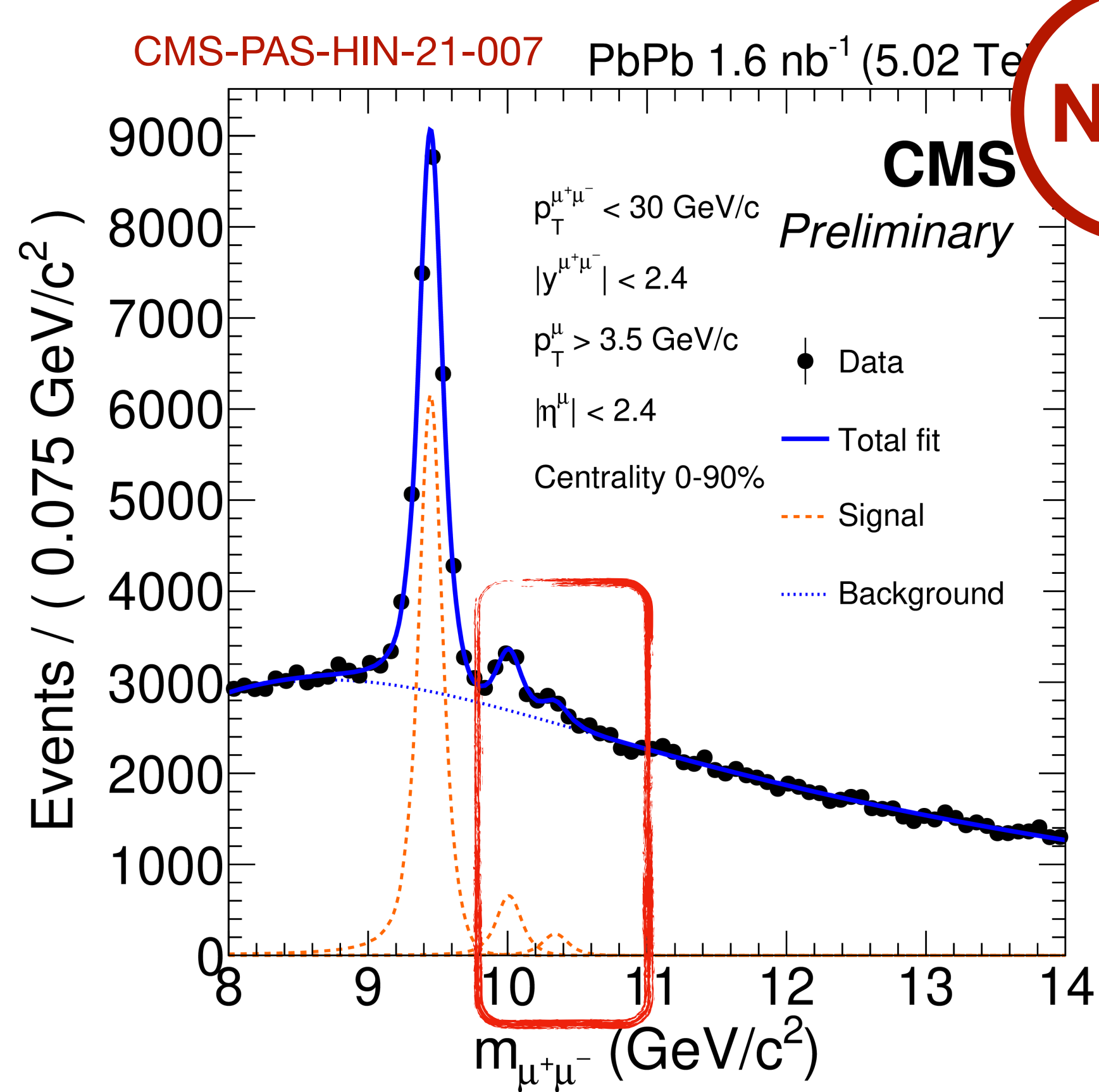
PbPb  
pPb  
pp

- Collective effects observed for light flavours... open question for heavy flavours
- No significant  $p_T$  dependence and  $v_2^{J/\psi}$  in pp **compatible with 0** ( $v_2^{pp} < v_2^{pPb} < v_2^{PbPb}$ )

# New results on bottomonia



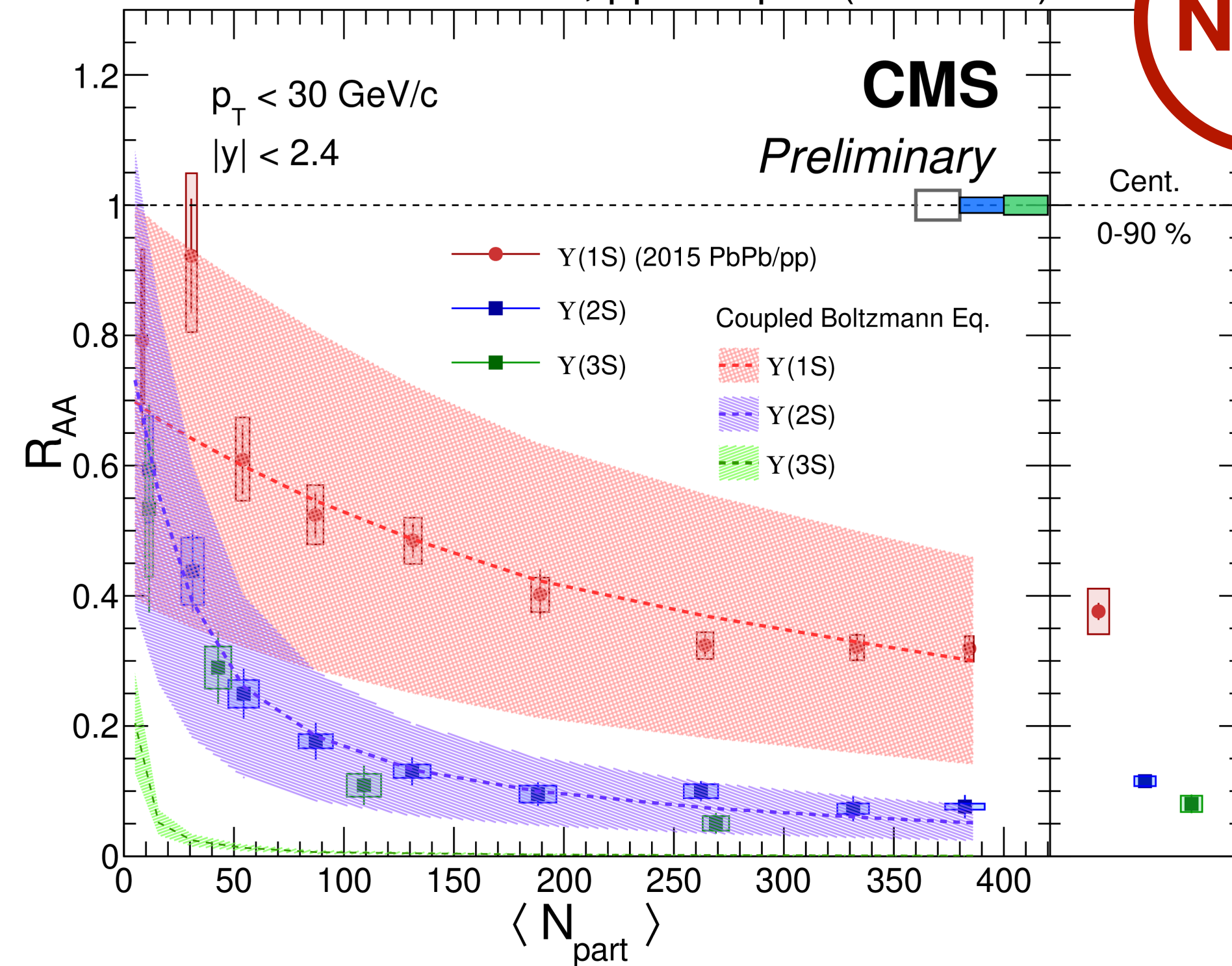
# $\Upsilon(3S)$ observation and $R_{AA}$ in Pb-Pb collisions



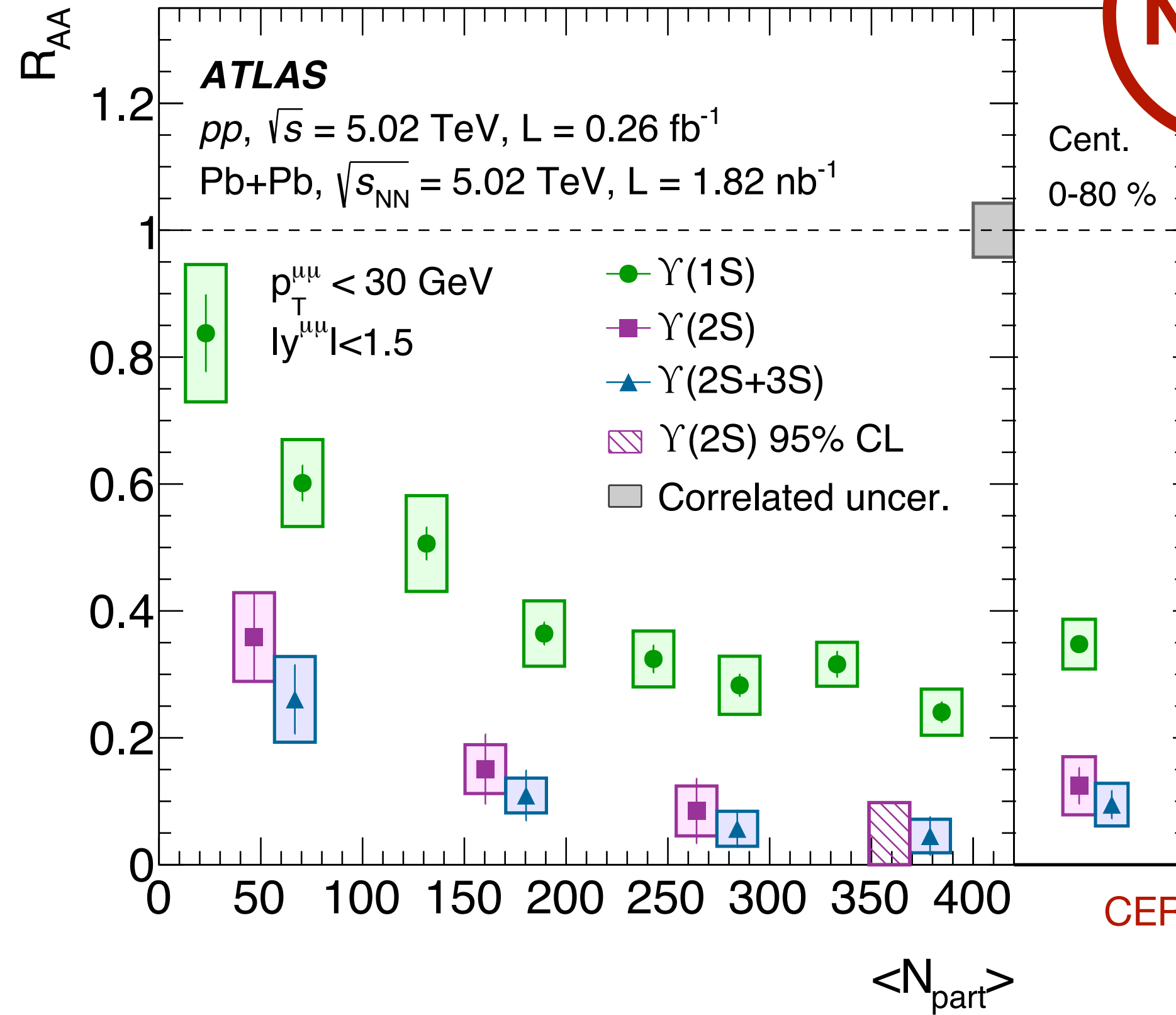
- **Observation** of  $\Upsilon(3S)$  in Pb-Pb collisions (using BDT based on decay topology)
- **Sequential suppression**: excited states suppressed in all centralities much more than  $\Upsilon(1S)$

# $\Upsilon(nS) R_{AA}$ in Pb-Pb collisions

CMS-PAS-HIN-21-007 PbPb 1.6 nb<sup>-1</sup>, pp 300 pb<sup>-1</sup> (5.02 TeV)



**NEW**

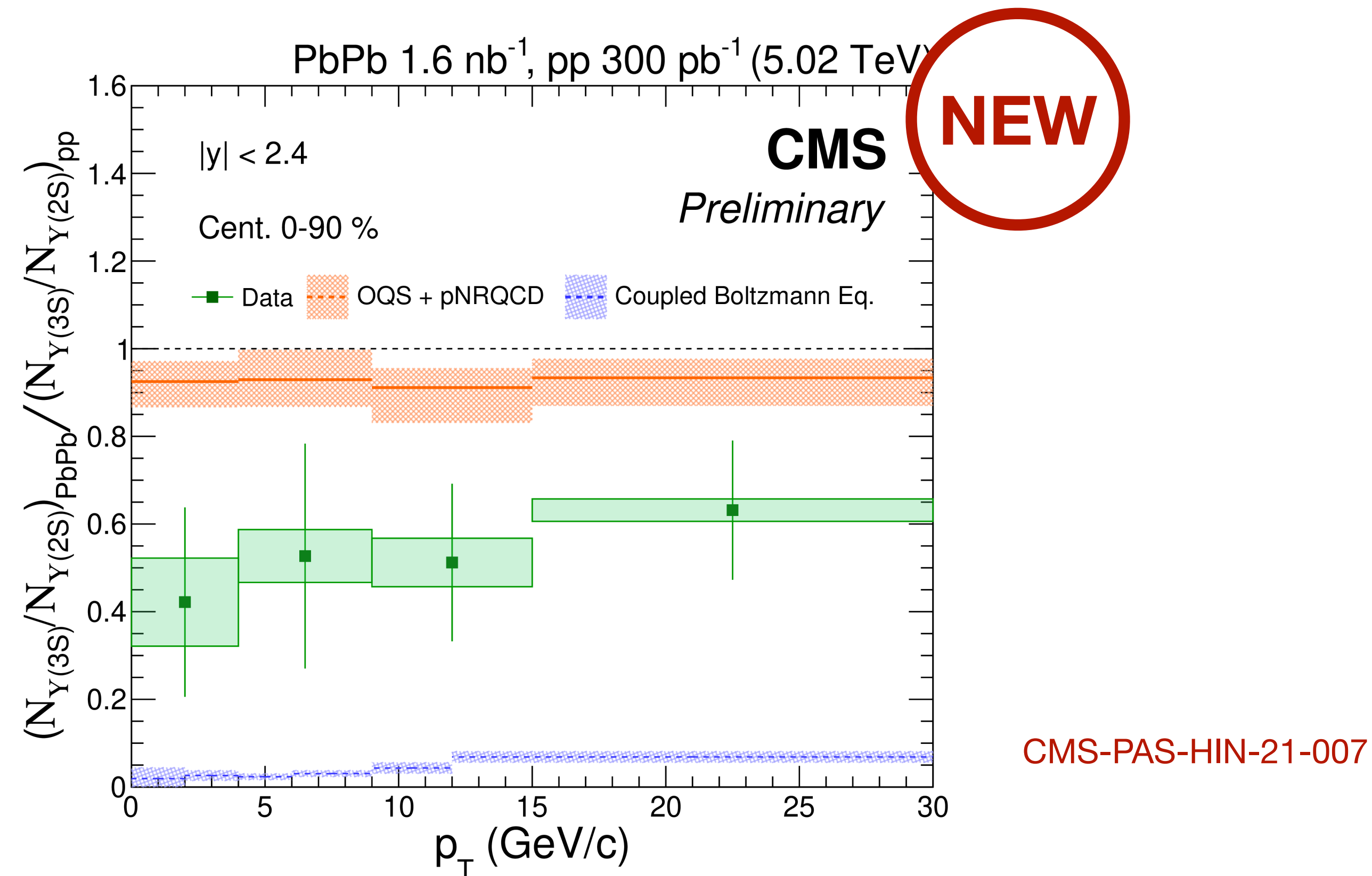


**NEW**

CERN-EP-2022-045

- Stronger suppression of  $\Upsilon(3S)$  w.r.t.  $\Upsilon(2S)$  as a function of centrality expected from theory and not observed in the data
- $R_{AA}^{\Upsilon(nS)}$  measurements from ALICE (not shown), ATLAS and CMS show similar trend

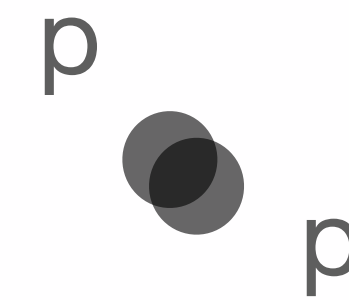
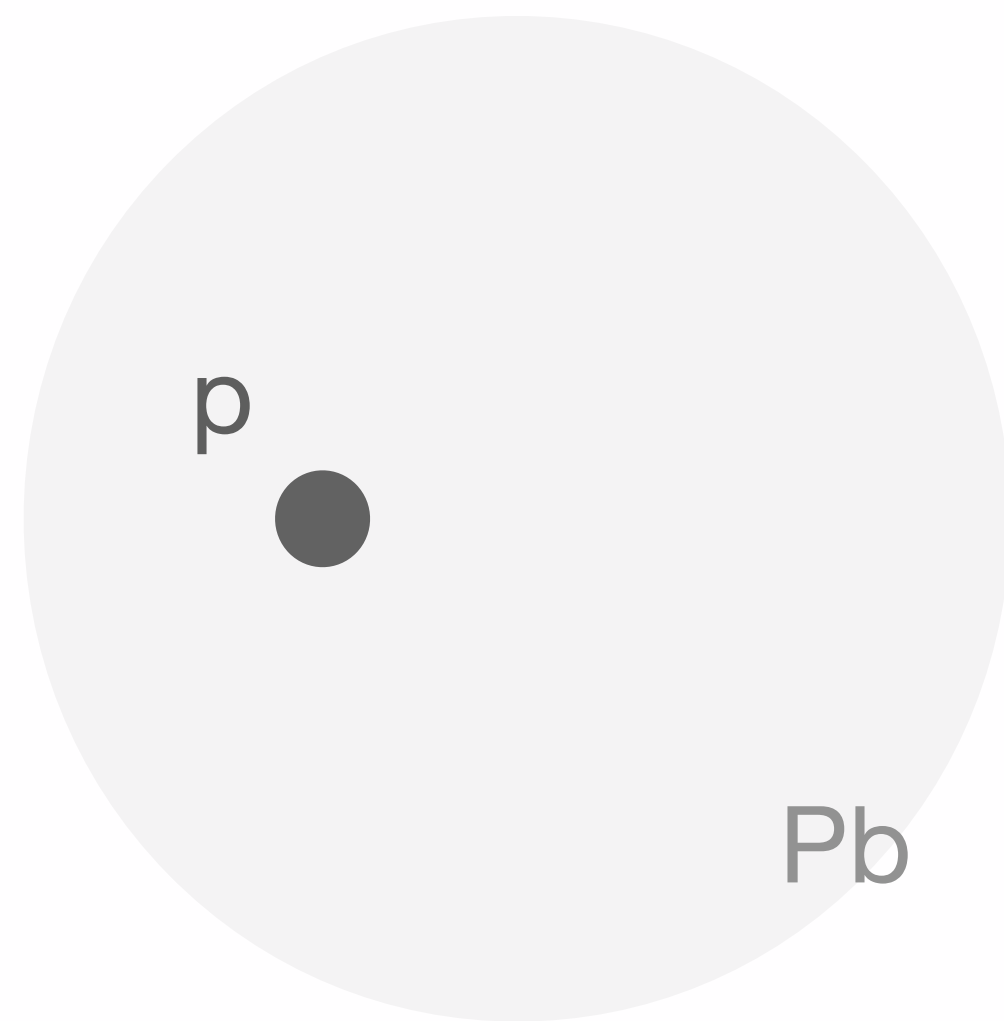
# $\Upsilon(3S)/\Upsilon(2S)$ ratio in Pb-Pb over pp collisions



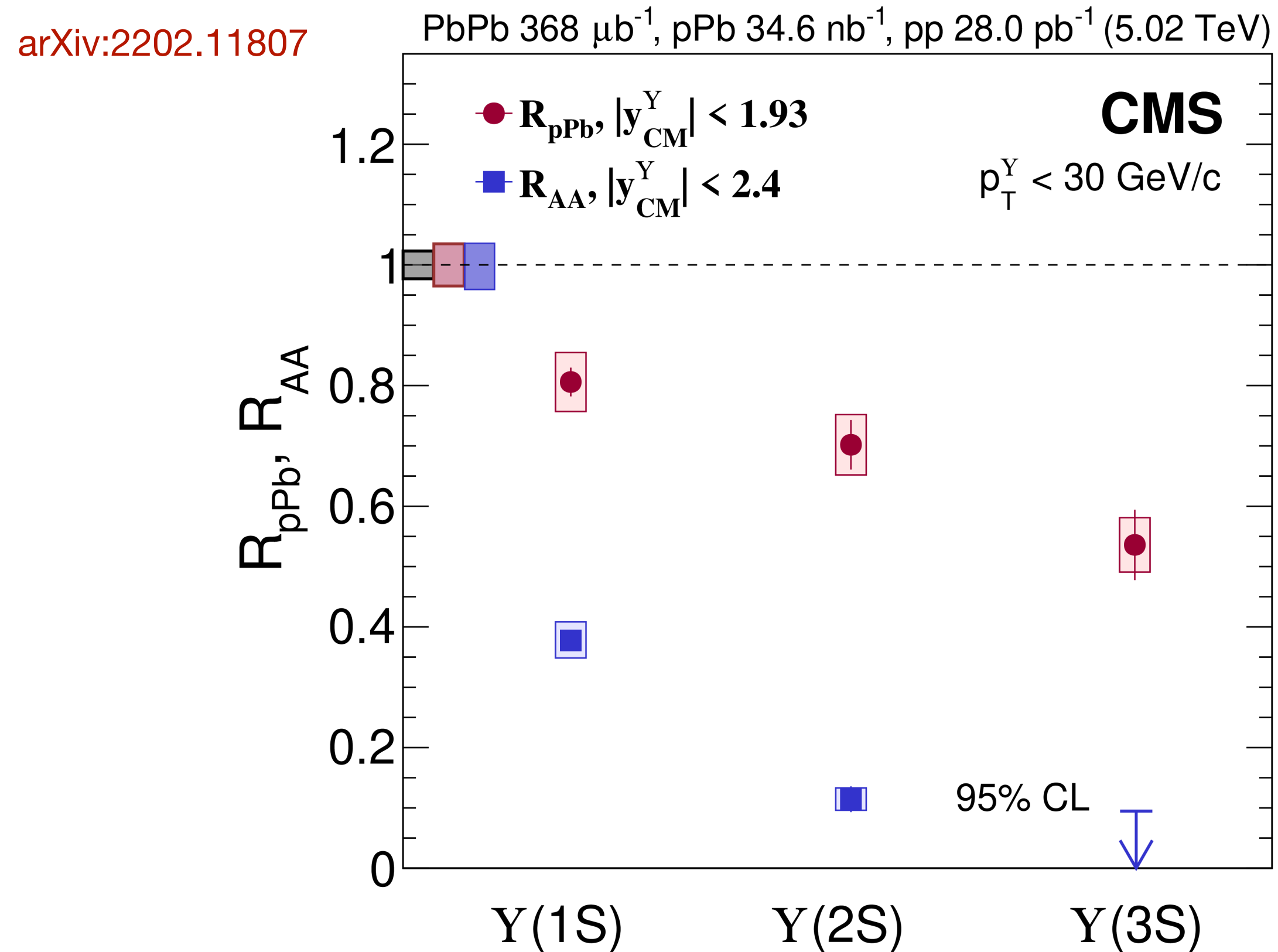
- $\Upsilon(3S)$  more suppressed than  $\Upsilon(2S)$  over all  $p_T$  intervals (double yield ratio)
- Models are not able to explain the data



# Going towards small collision systems

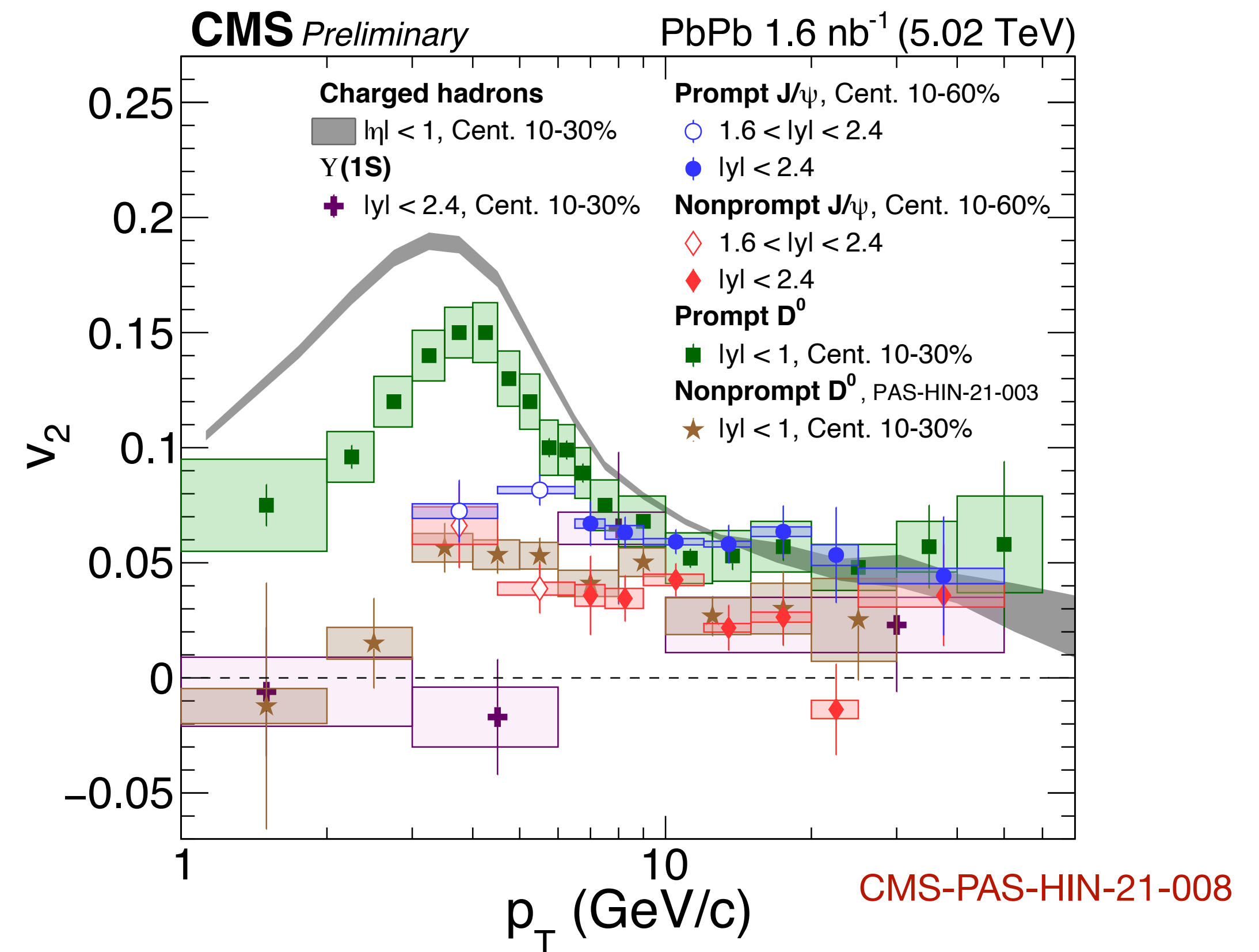
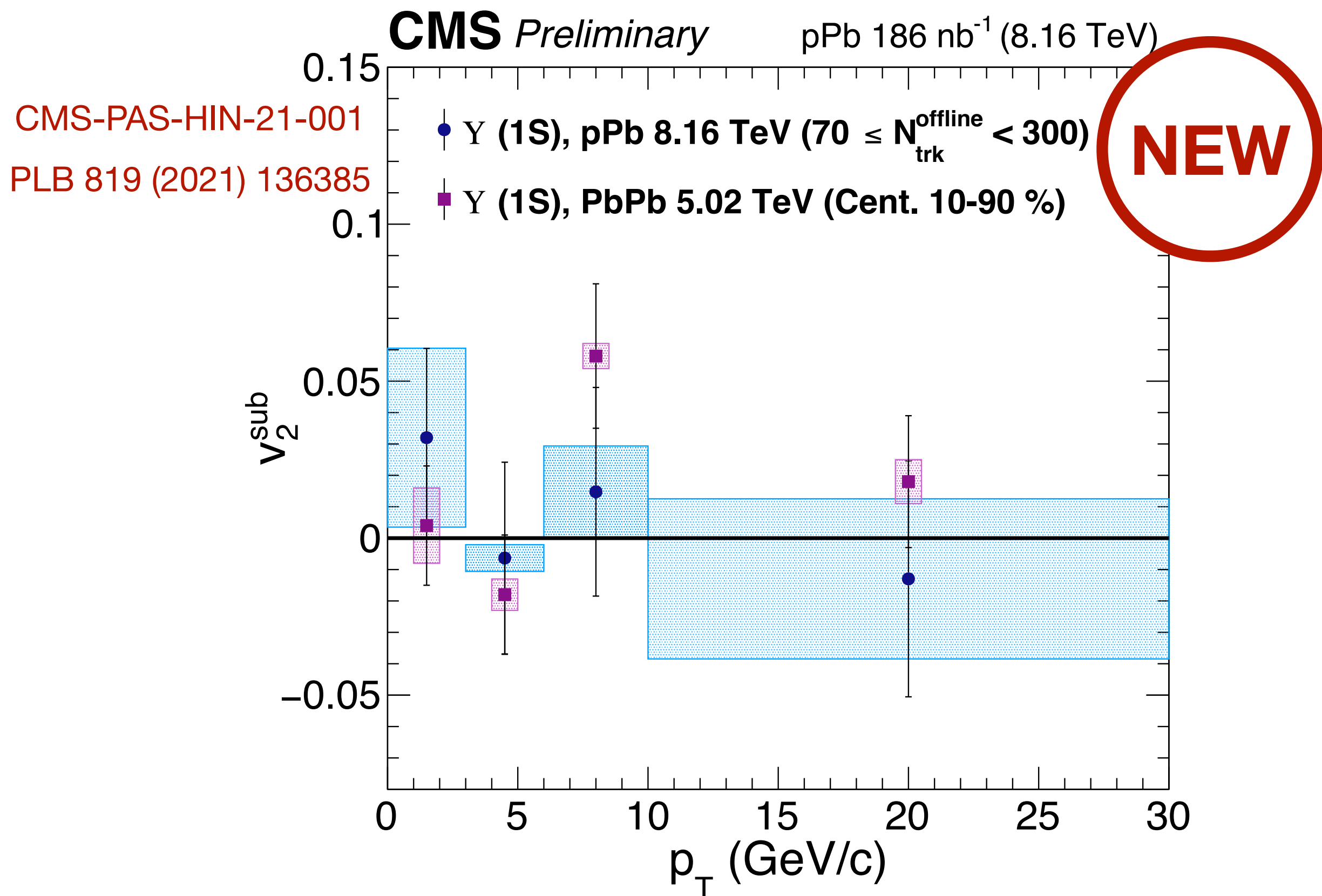


# $R_{pPb}$ of $\Upsilon(nS)$ states



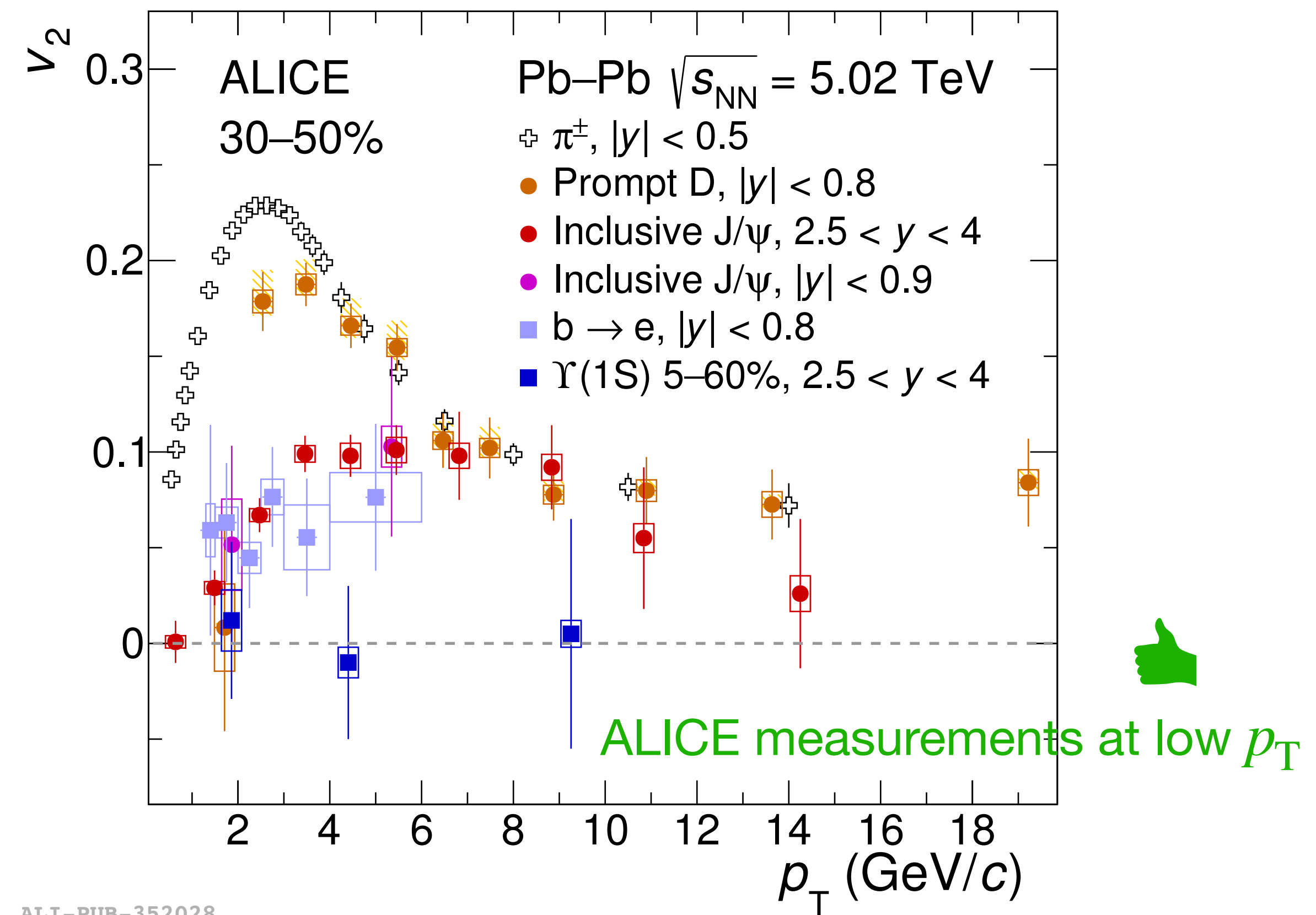
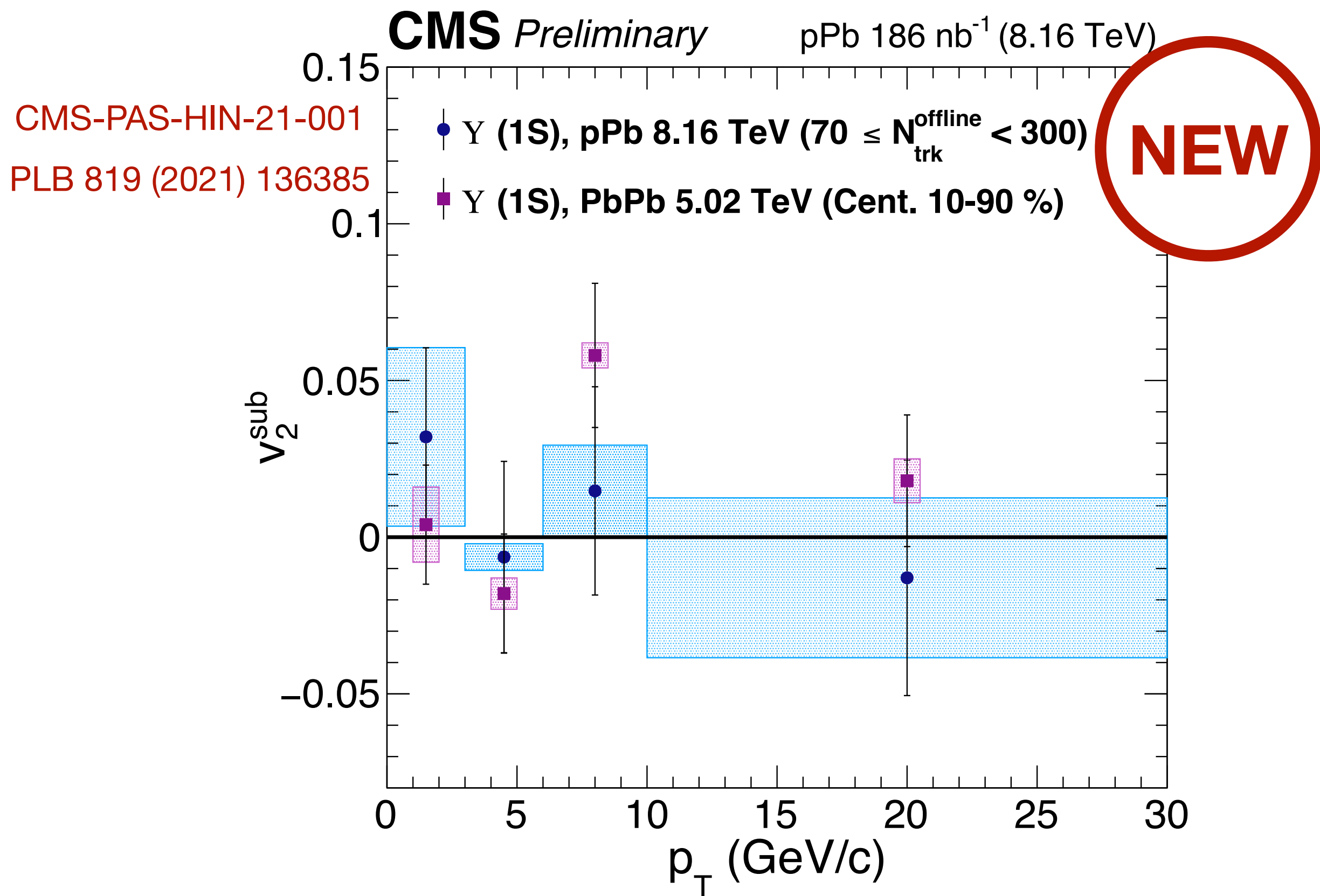
- $\Upsilon(nS)$  states in p-Pb are found to be less suppressed than in Pb-Pb collisions

# $\Upsilon(1S)$ $v_2$ in p-Pb and comparison to Pb-Pb collisions



- First  $v_2^{\Upsilon(1S)}$  in p-Pb collisions, **compatible with 0** (as observed for Pb-Pb)
- Low  $p_T$  :  $v_2^{\Upsilon} < v_2^{J/\psi} < v_2^D < v_2^{h^\pm}$ , while at high  $p_T$ : **common mechanism?**

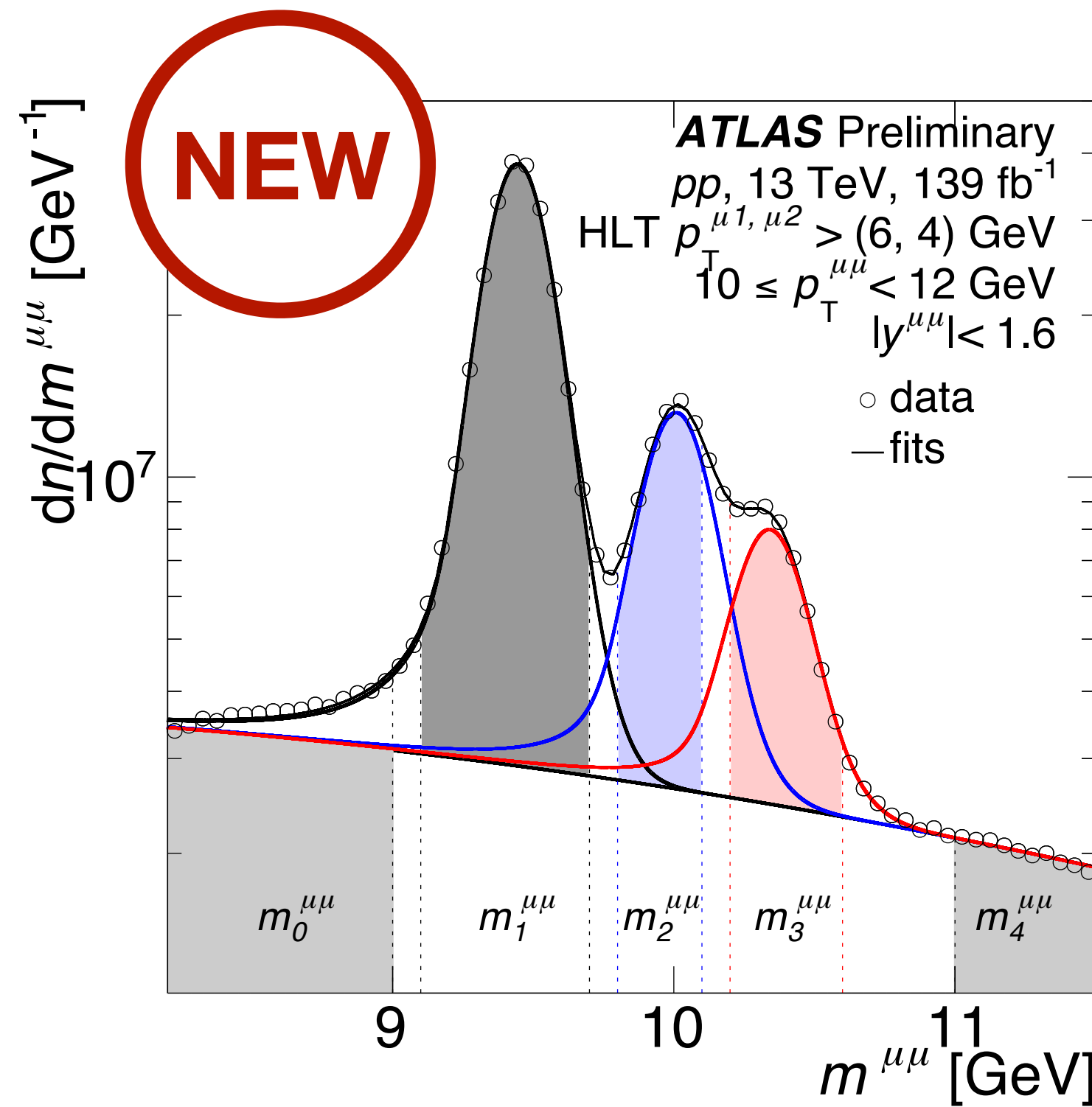
# $\Upsilon(1S)$ $v_2$ in p-Pb and comparison to Pb-Pb collisions



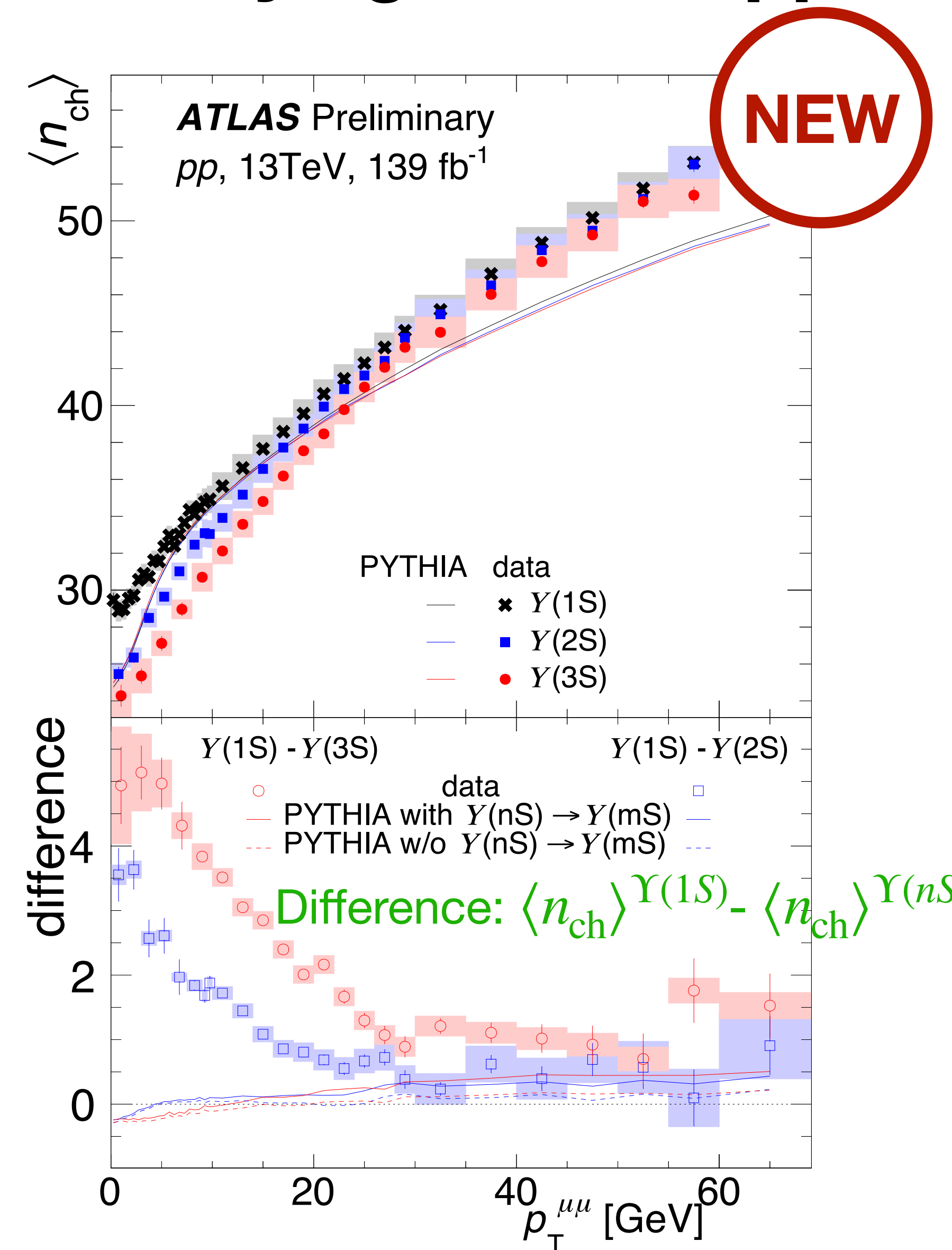
○ First  $v_2^{\Upsilon(1S)}$  in p-Pb collisions, **compatible with 0** (as observed for Pb-Pb)

○ Low  $p_T$  :  $v_2^{\Upsilon} < v_2^{J/\psi} < v_2^D < v_2^{h^\pm}$ , while at high  $p_T$ : **common mechanism?**

# Correlations of $\Upsilon(nS)$ production with the underlying event in pp





ATLAS-CONF-2022-023

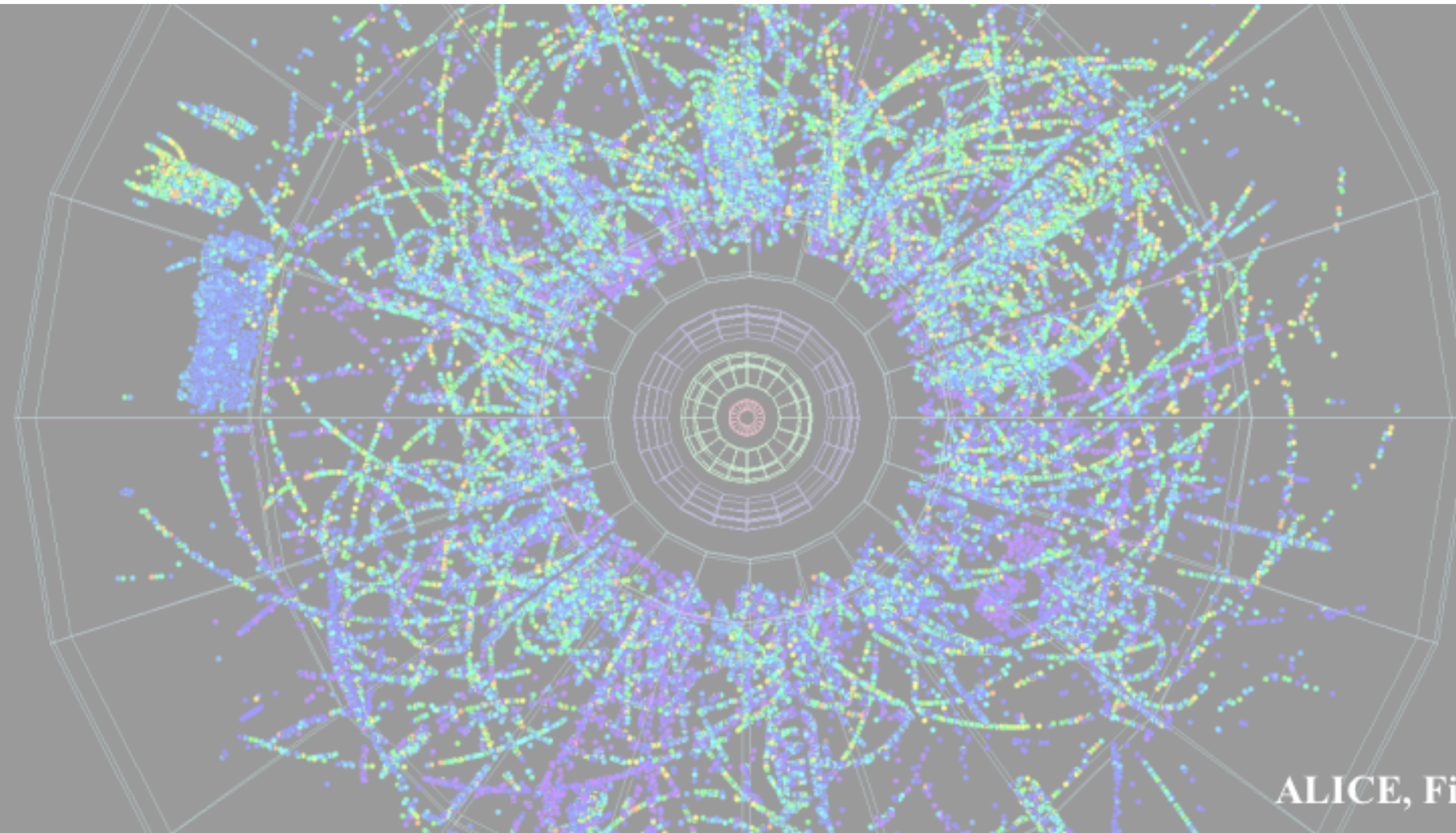


- **Significant difference** is observed in the particle multiplicity  $\langle n_{\text{ch}} \rangle$  for events containing  $\Upsilon(nS)$
- PYTHIA 8 can not reproduce the data for  $p_T < 30$  GeV/c (even including color reconnection)

# Summary

- Plenty of new LHC results on quarkonia: 
- **Sequential suppression:** clearly observed for bottomonia
- **Regeneration:** most consistent scenario for the production of charmonia at low- $p_T$ ... negligible effect for bottomonia (while  $B_c$ : very large  $R_{AA}$  at low  $p_T$  and larger than quarkonia, hint of coalescence; X(3872) results; see backup)
- Significant **J/ $\psi$  polarisation** in Pb-Pb w.r.t. EP: looking forward to theory calculations
- **Collective flow:** non zero  $v_2^{J/\psi}$  for Pb-Pb and p-Pb but  $v_2^{J/\psi} \sim 0$  for pp collisions... Hint of non zero  $v_2$  for prompt  $\psi(2S)$  in Pb-Pb...  $\Upsilon(1S)$  not affected
- **Very challenging** for theorists to describe both  $R_{AA}$  and  $v_2$  ... in general, models can reproduce the data qualitatively well; tensions are visible in some cases 

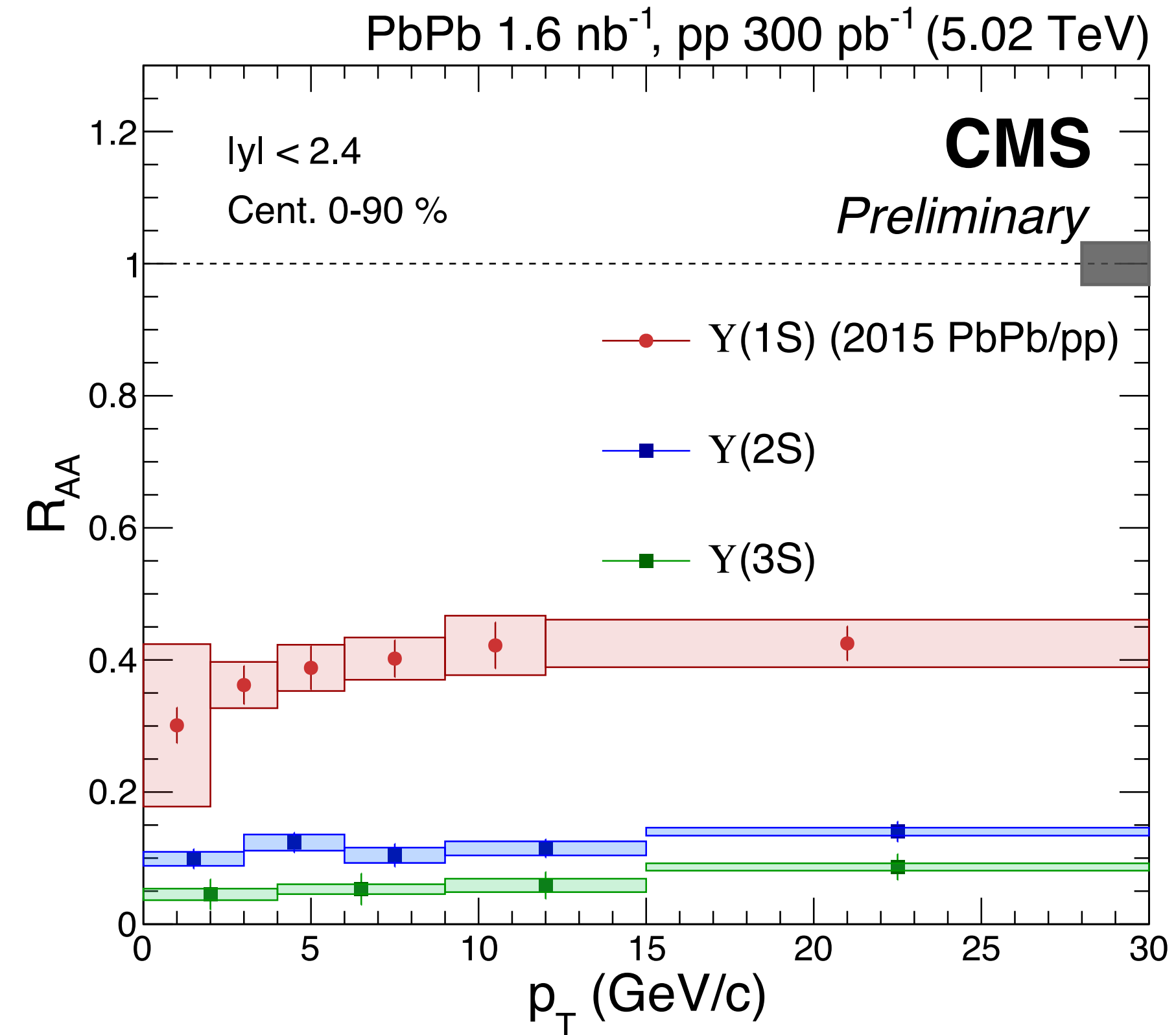
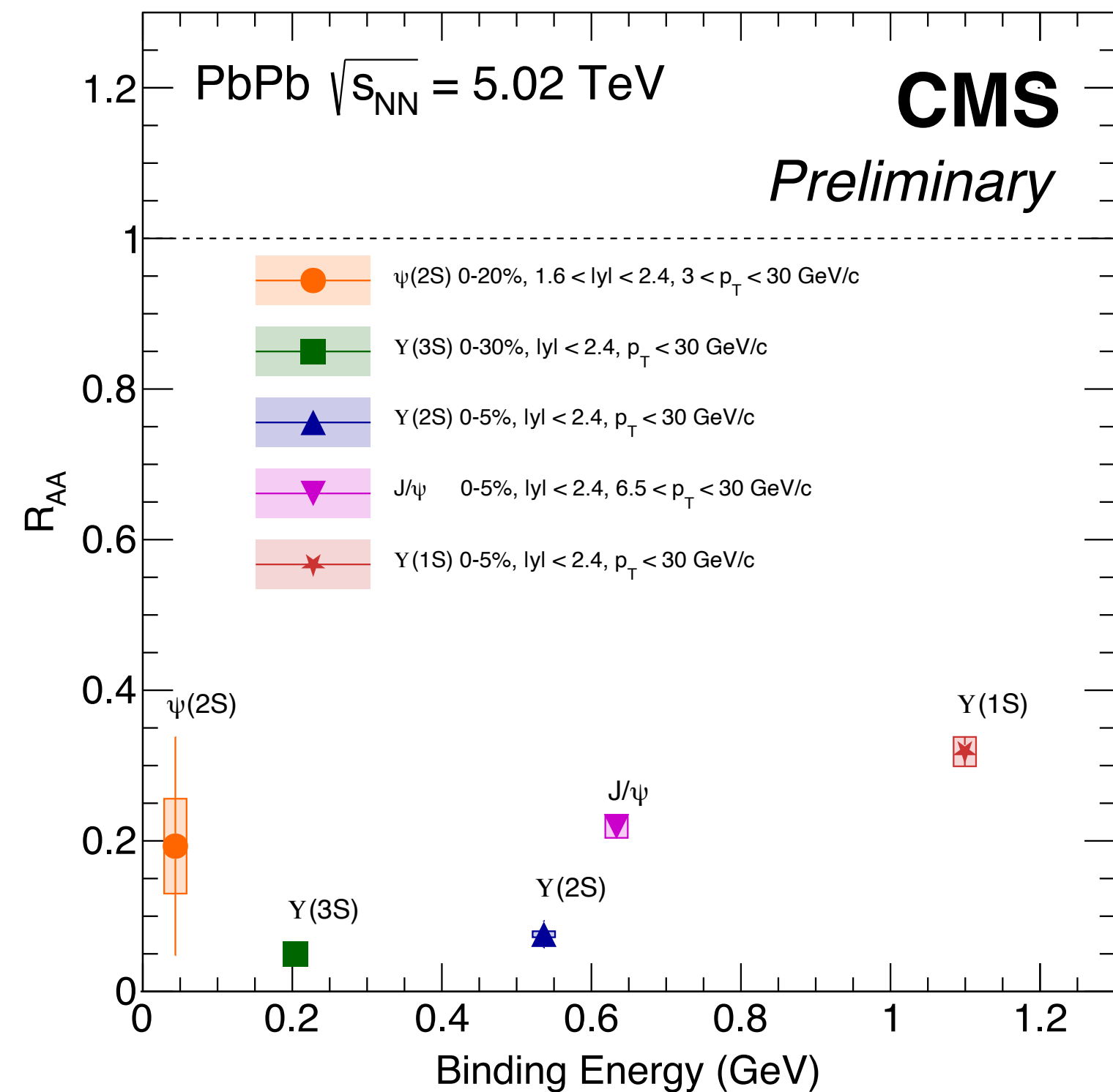
# Thank you for your attention!



ALICE, Figure: <https://cds.cern.ch/record/1477949>

## Run 3 is coming: new available measurements with unprecedented precision

# Integrated and $p_T$ -differential $R_{AA}$

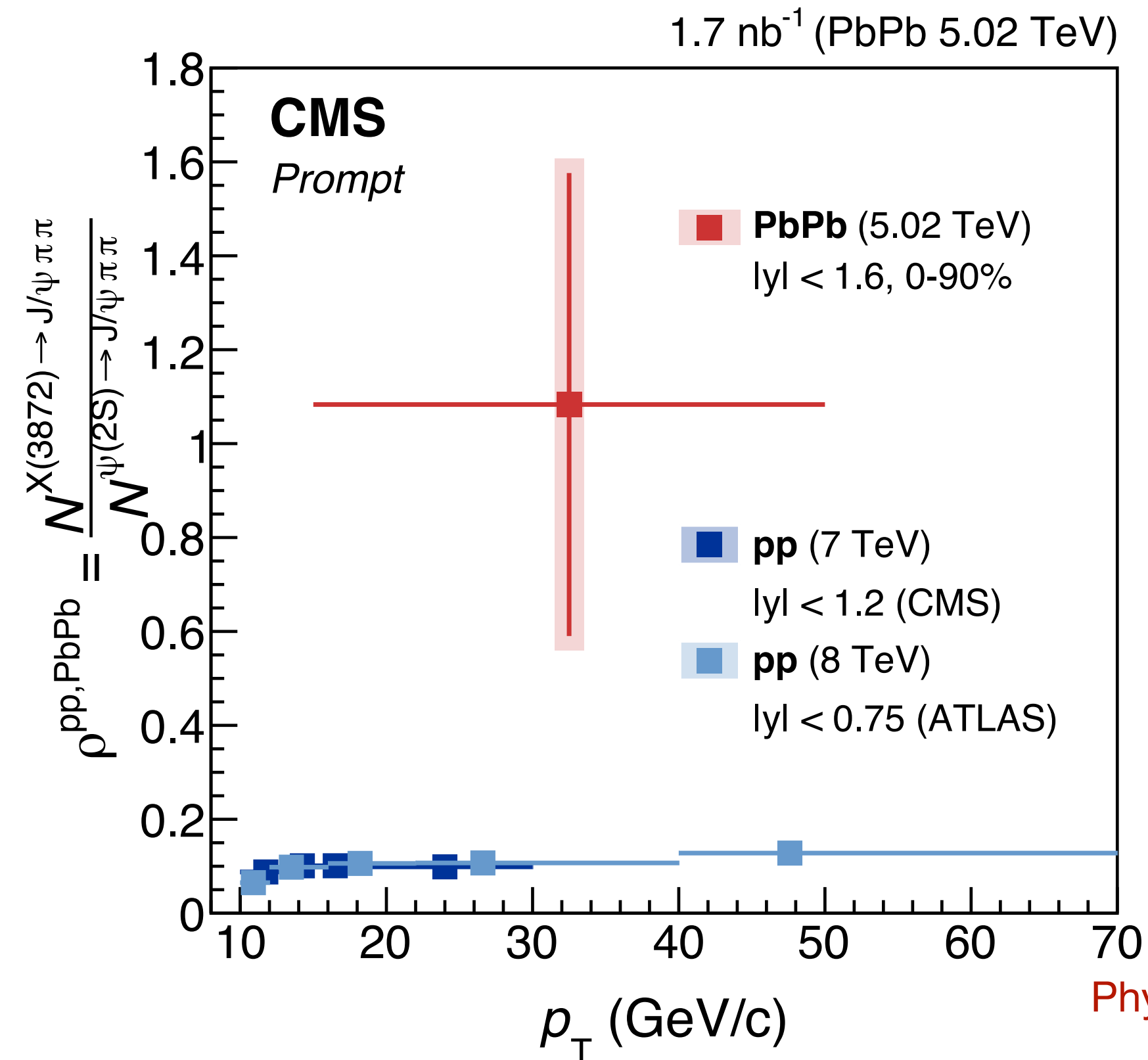
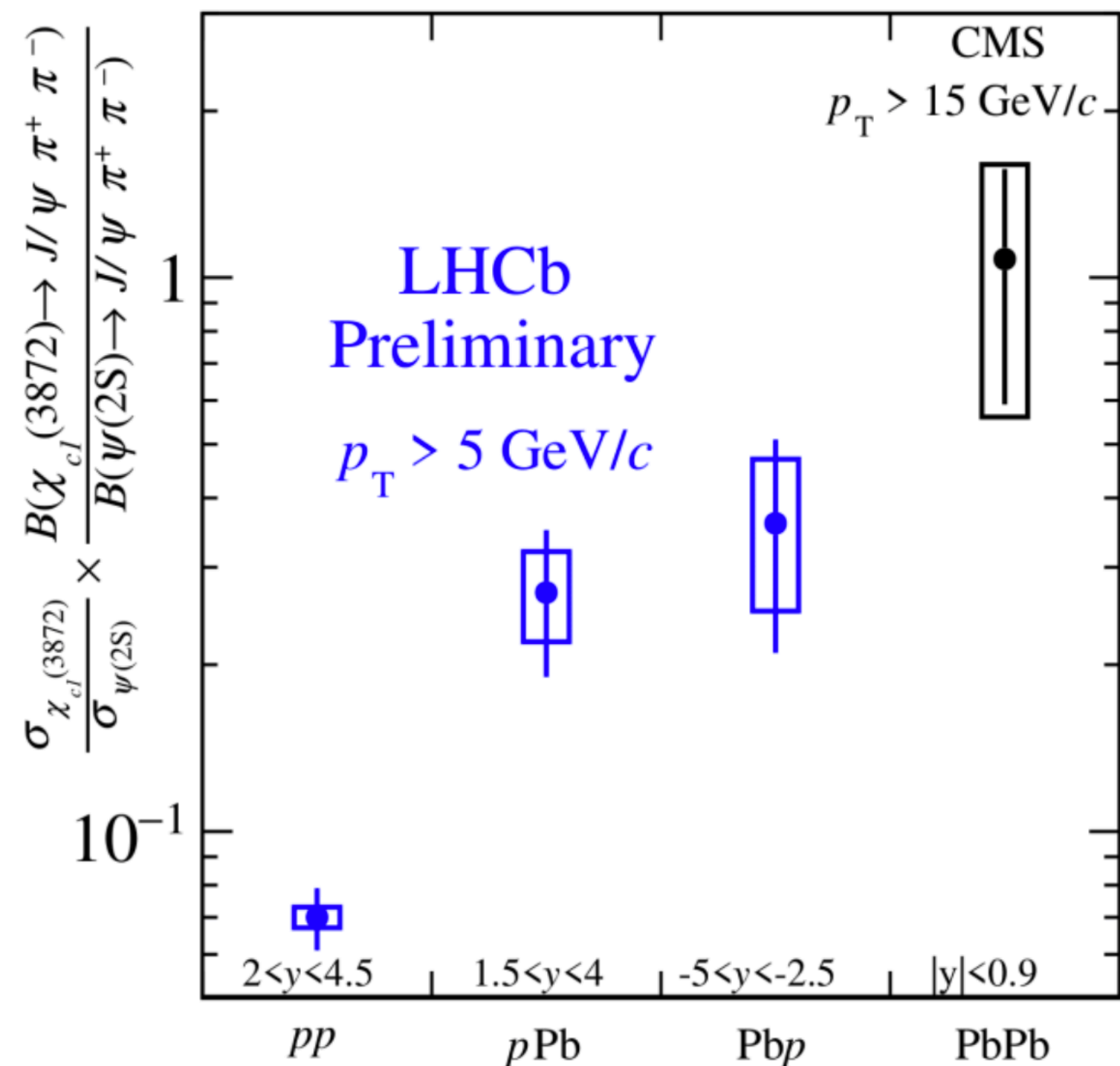


- Sequential suppression for conventional charmonia and bottomonia states
- Larger  $R_{AA}$  when the binding energy is increasing



# X(3872) measurement in Pb-Pb collisions

[LHCb-CONF-2022-001]



$uc\bar{u}\bar{c}$

Tetraquark

or

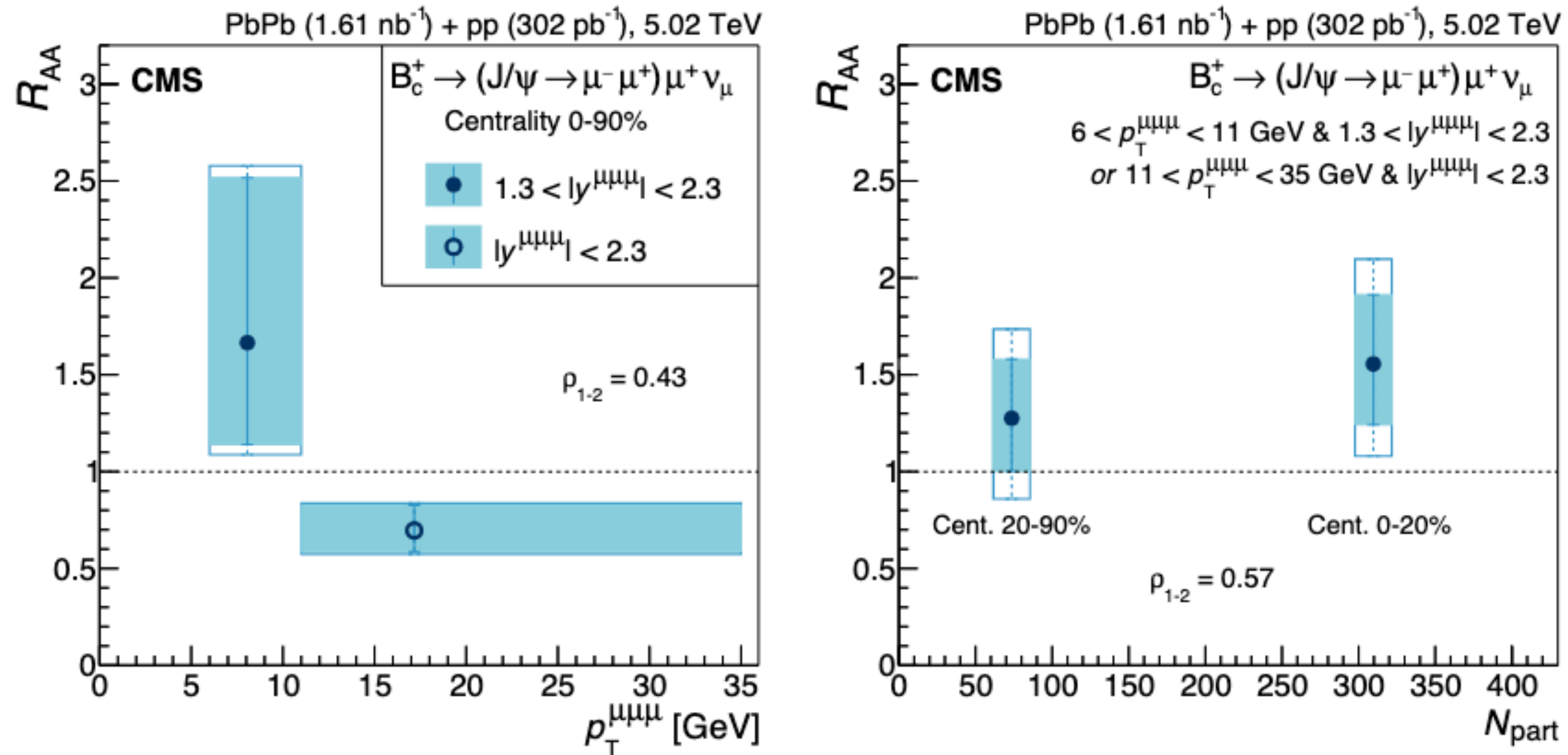
hadron molecule

?

Phys. Rev. Lett. 128, 032001

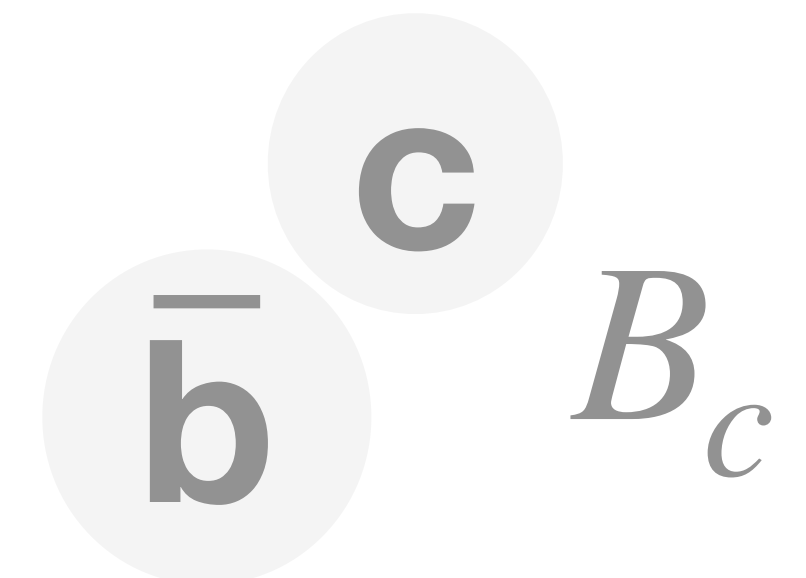
- First evidence of X(3872) in Pb-Pb is reported:  $4.2\sigma$  standard deviation
- Prompt X(3872) to  $\psi(2S)$  yield ratio: **unique experimental** input for theory
- Indication for **medium-induced coalescence**

# $B_c$ measurement in Pb-Pb collisions

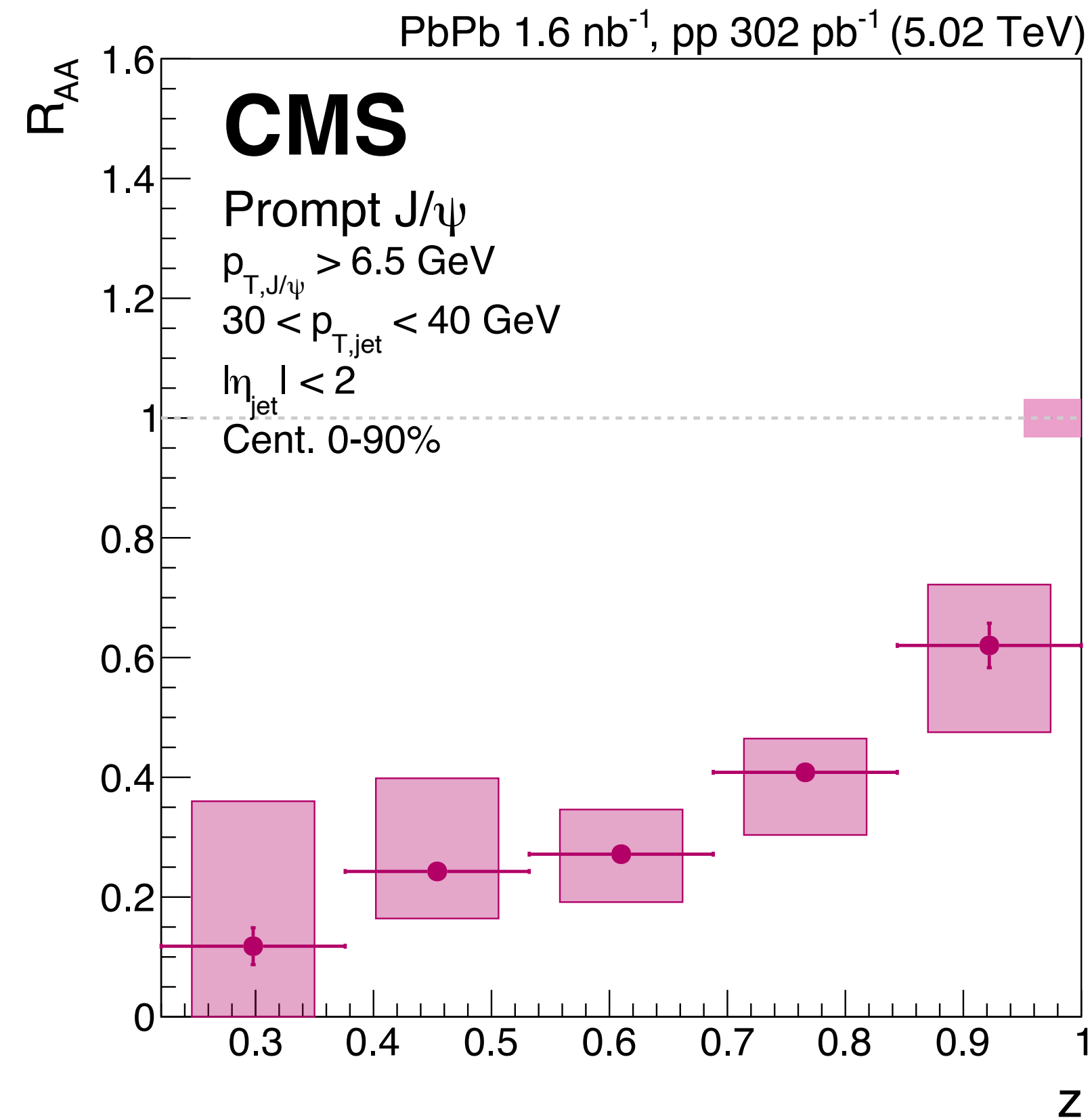
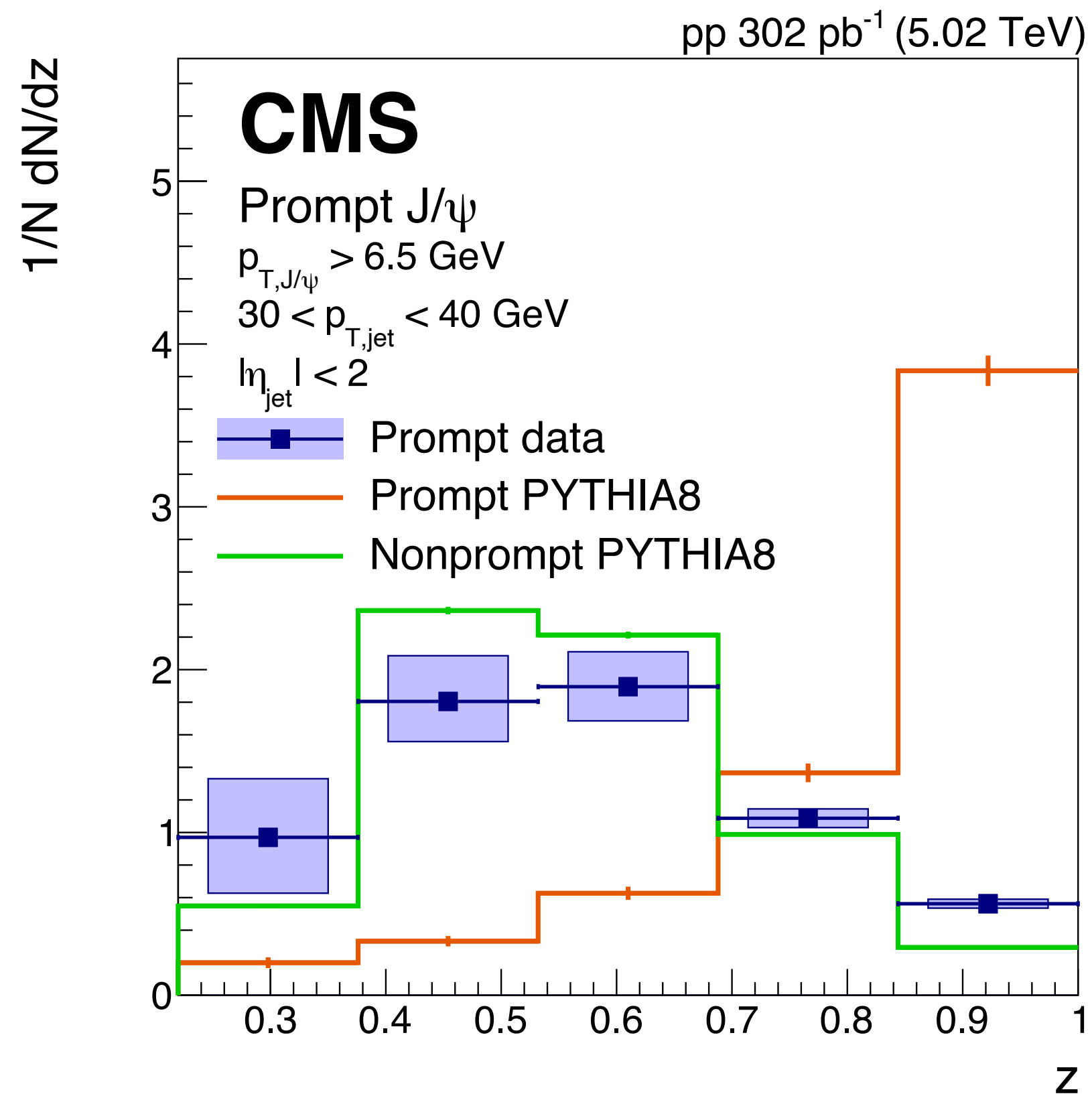


arXiv:2201.02659

- Evidence of very large  $R_{AA}$  in Pb-Pb is measured w.r.t. quarkonia
- Further indication for **coalescence** mechanism

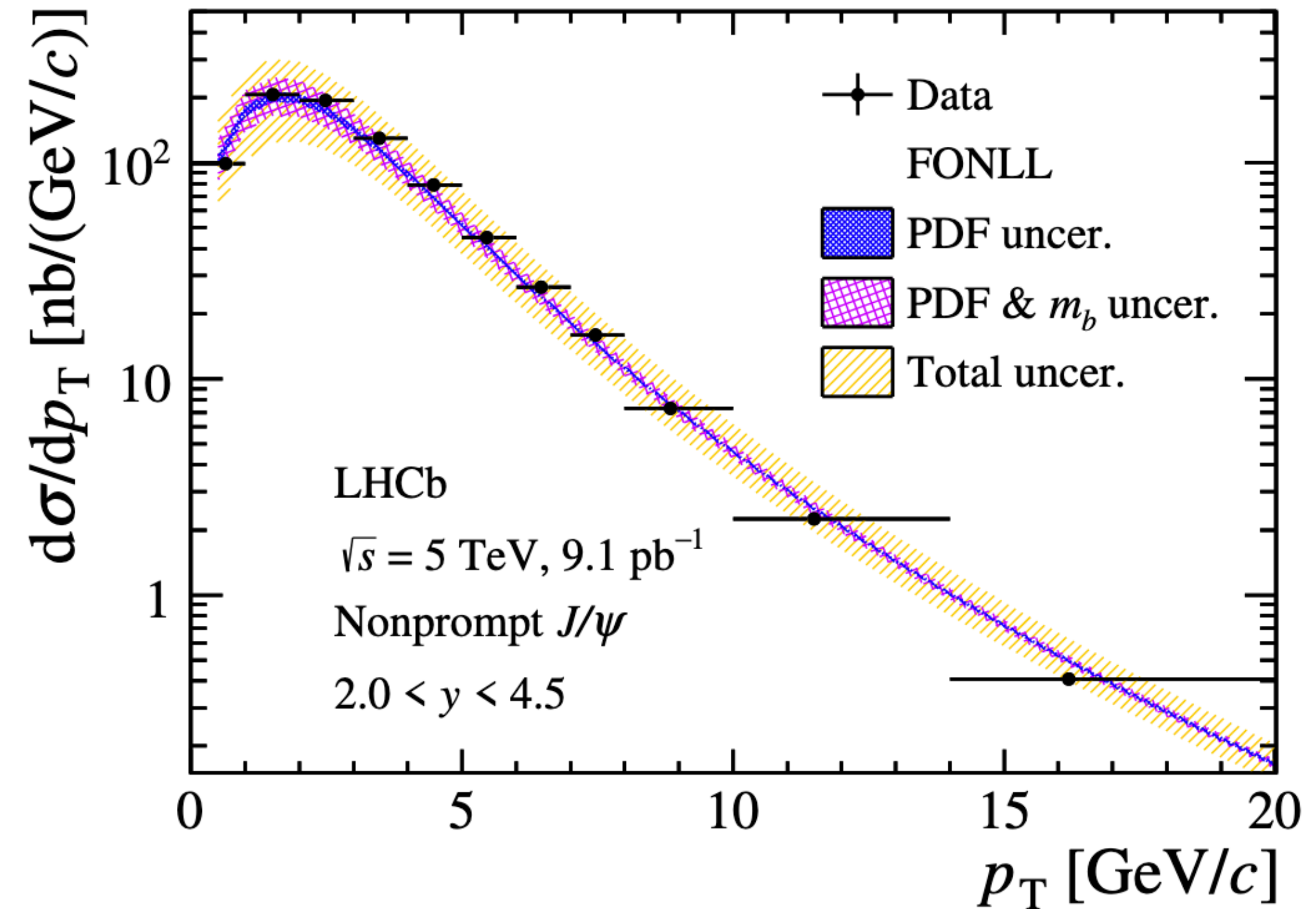
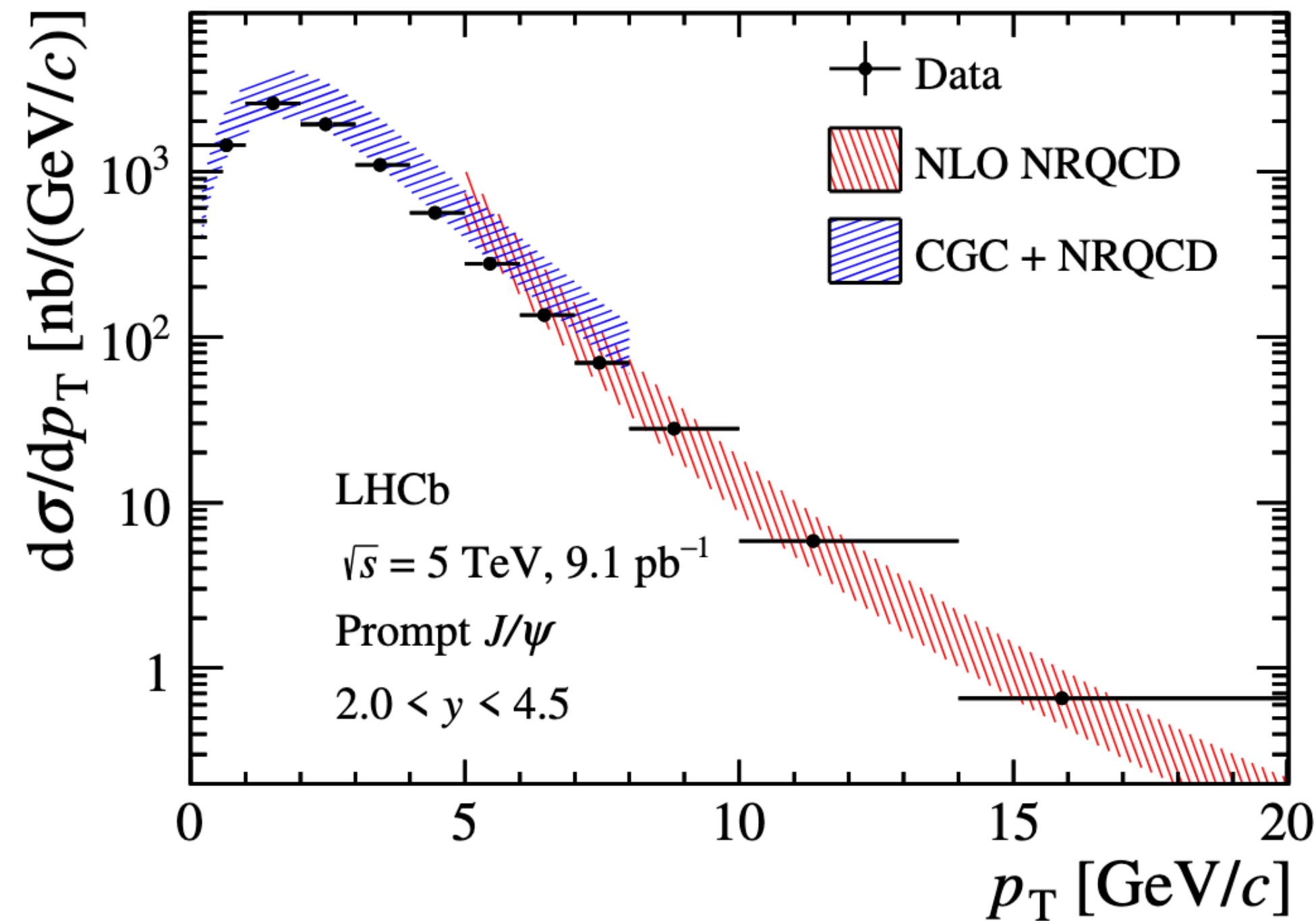


# Fragmentation of jets with prompt $J/\psi$ in Pb-Pb and pp



- Hint of a  $z$ -dependence of the  $J/\psi$  suppression ( $z = p_{T,J/\psi}/p_{T,jet}$ )
- Indication that the  $J/\psi$  - medium interaction depends on the fragmentation

# $J/\psi$ production in pp collisions



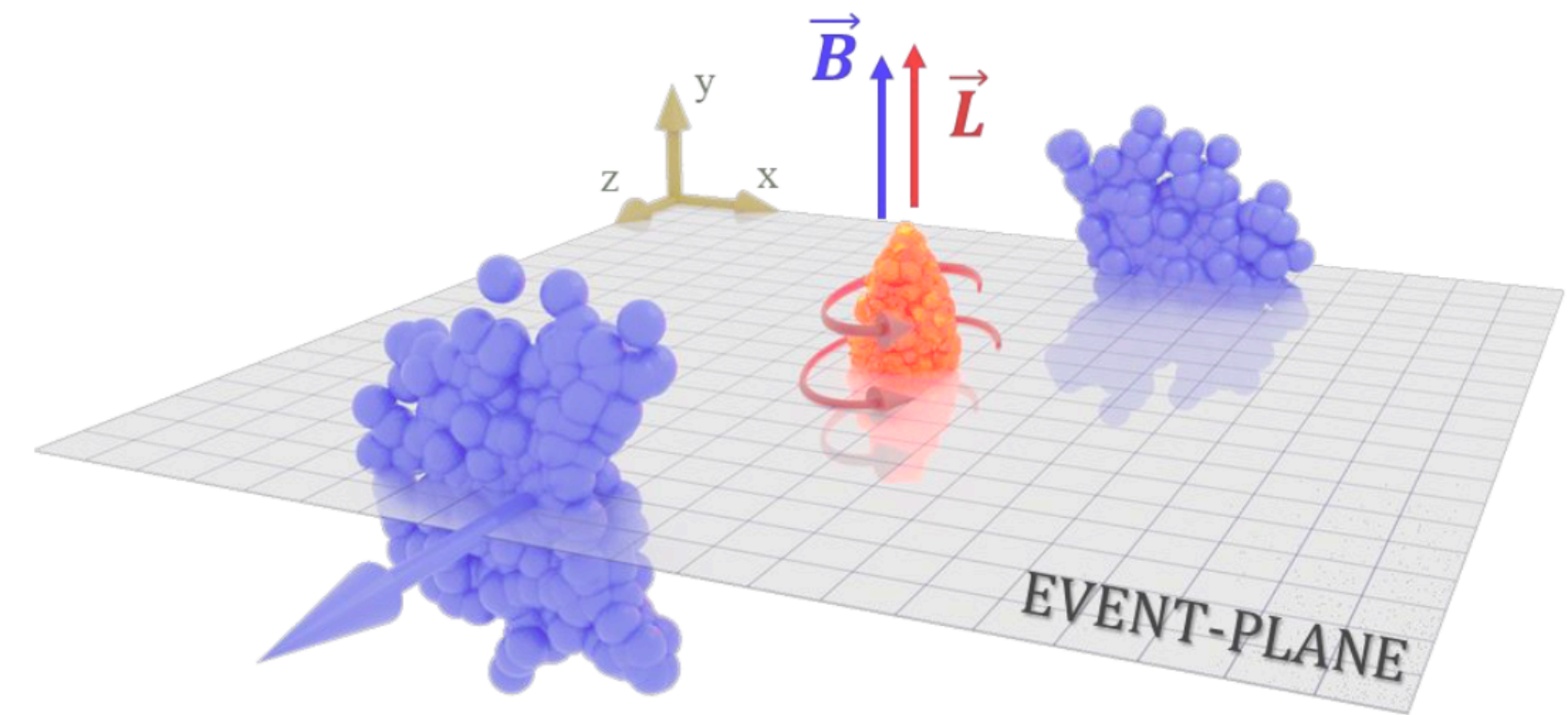
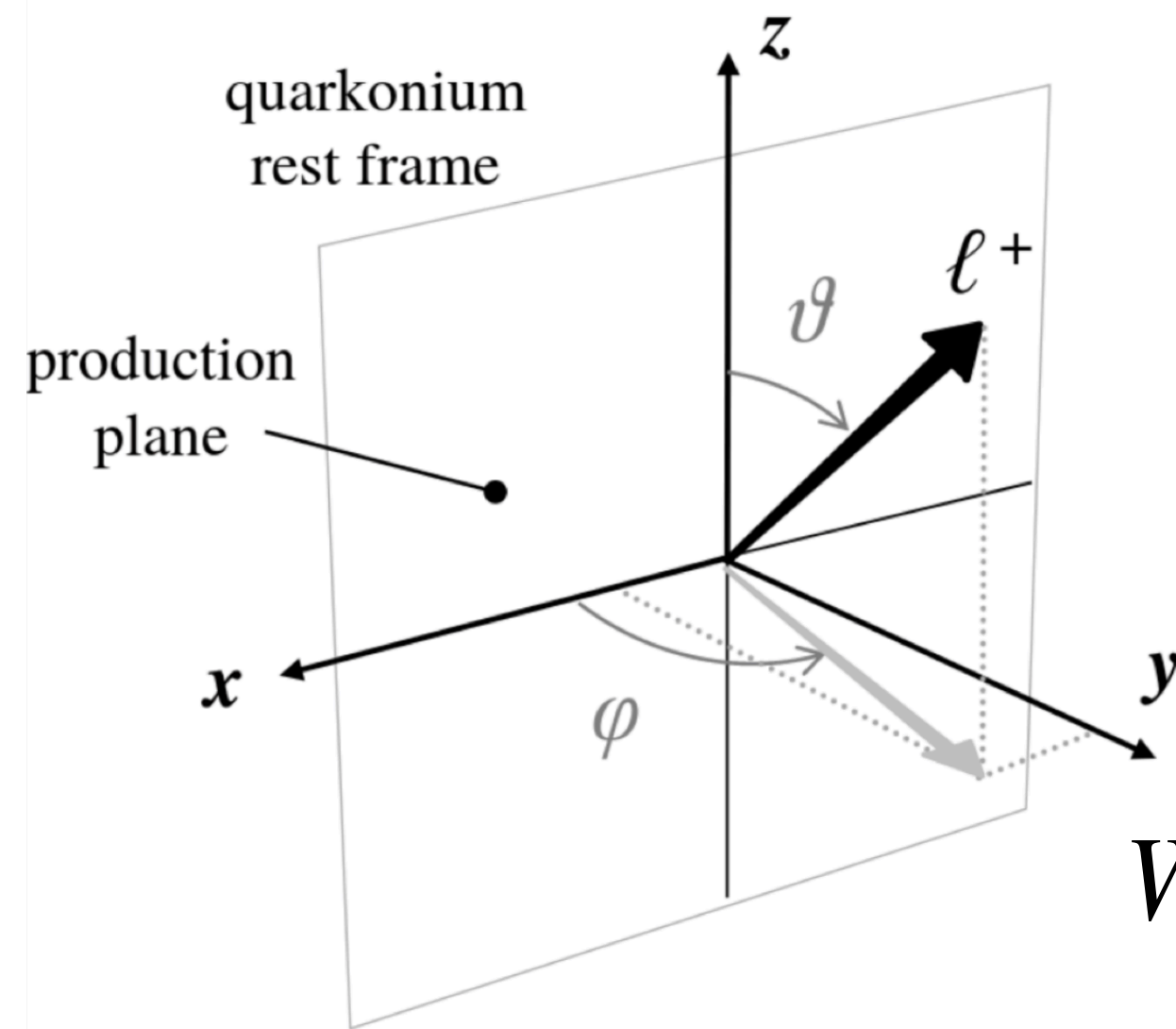
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- New measurements for prompt and non-prompt  $J/\psi$  : updated  $R_{pPb}$  results
- $p_T$ -differential cross sections well described by models

# $J/\psi$ polarisation in Pb-Pb collisions

- Related to **spin alignment of a particle w.r.t a given axis**
- For a vector meson ( $\mathbf{v}$ ), the total angular momentum ( $\mathbf{J}, J_z$ ) is:

$$|v; \mathbf{J}, J_z\rangle = b_{+1} |1, +1\rangle + b_0 |1, 0\rangle + b_{-1} |1, -1\rangle$$



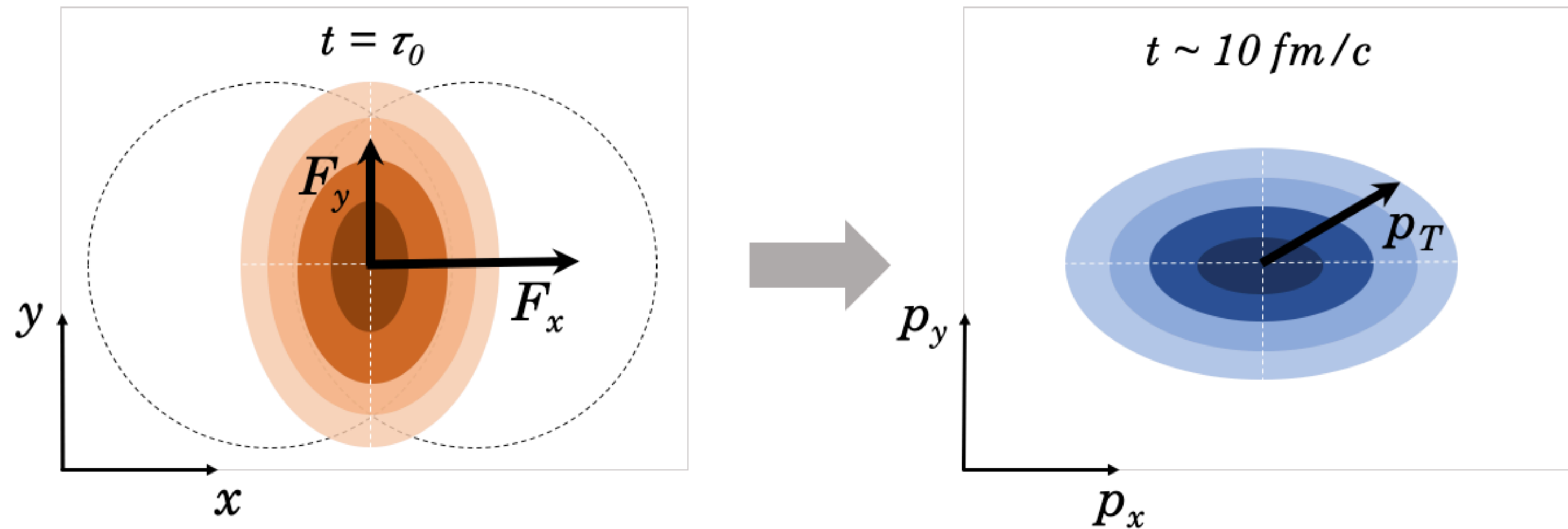
$$W(\cos \theta, \varphi) \propto \frac{1}{3 + \lambda_\theta} \cdot (1 + \lambda_\theta \cos^2 \theta + \lambda_\varphi \sin^2 \theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos 2\varphi)$$

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (+1, 0, 0)$   $\longrightarrow$  Pure longitudinal

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0, 0, 0)$  No polarisation


$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1, 0, 0)$   $\longrightarrow$  Pure transverse

# $v_n$ coefficients in Pb-Pb collisions




- Related to **initial geometry** of the overlap region and **high pressure gradients**
- Spatial anisotropy is transferred into a **momentum space anisotropy**

$$\frac{dN}{d\varphi} \propto 1 + 2 \sum_{n=1} v_n \cos n(\varphi - \Psi_n)$$



$n = 2$

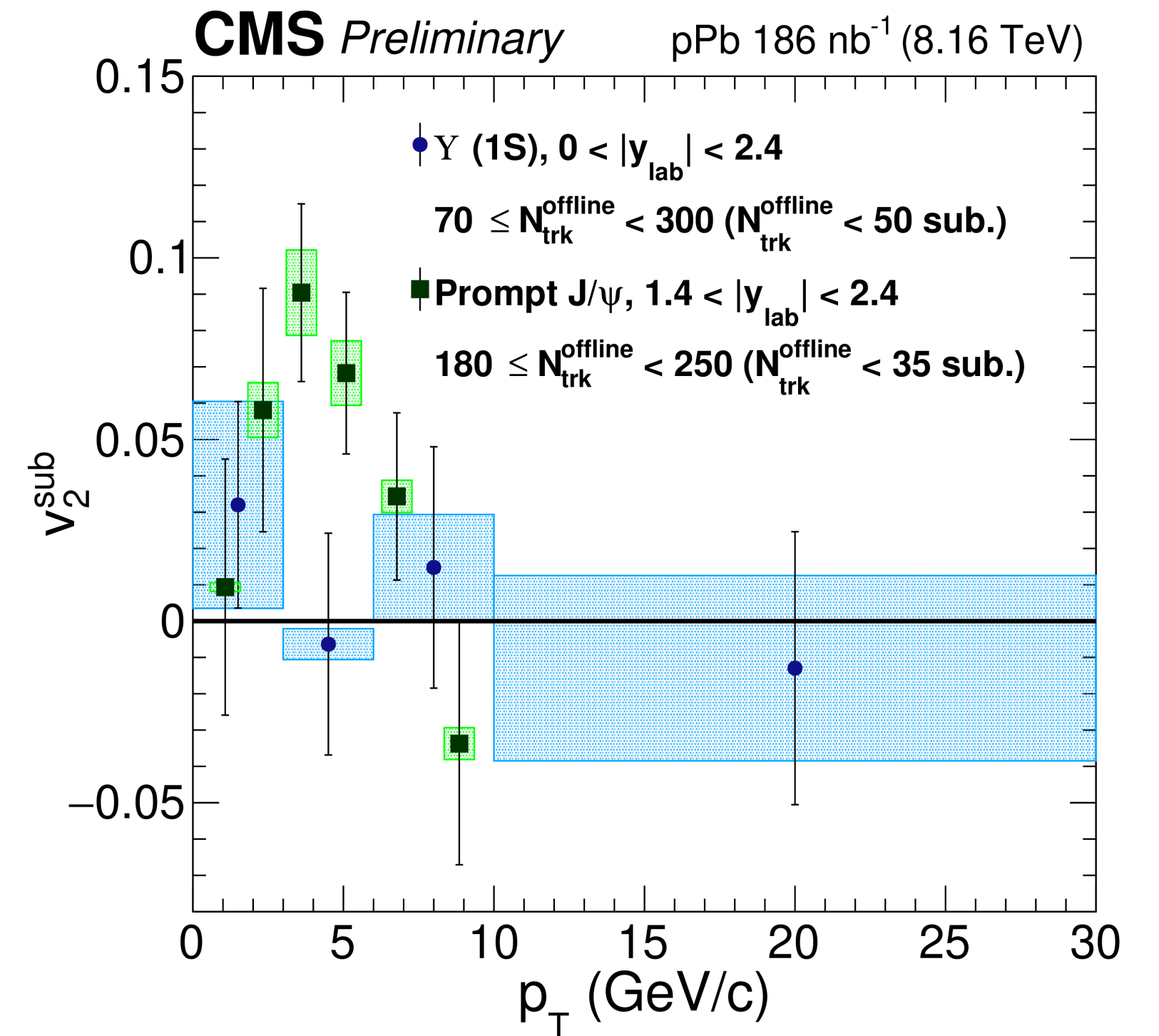
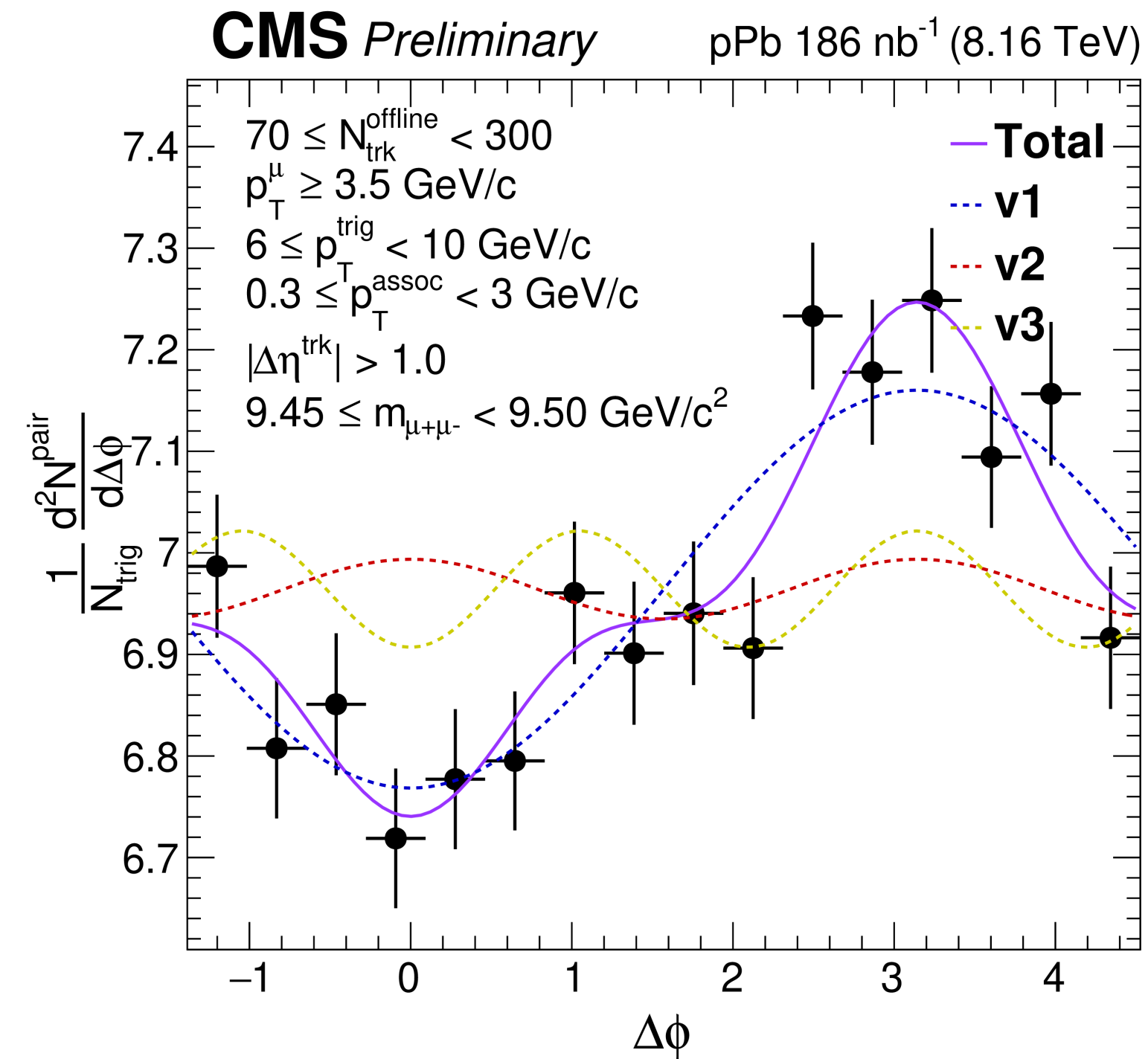
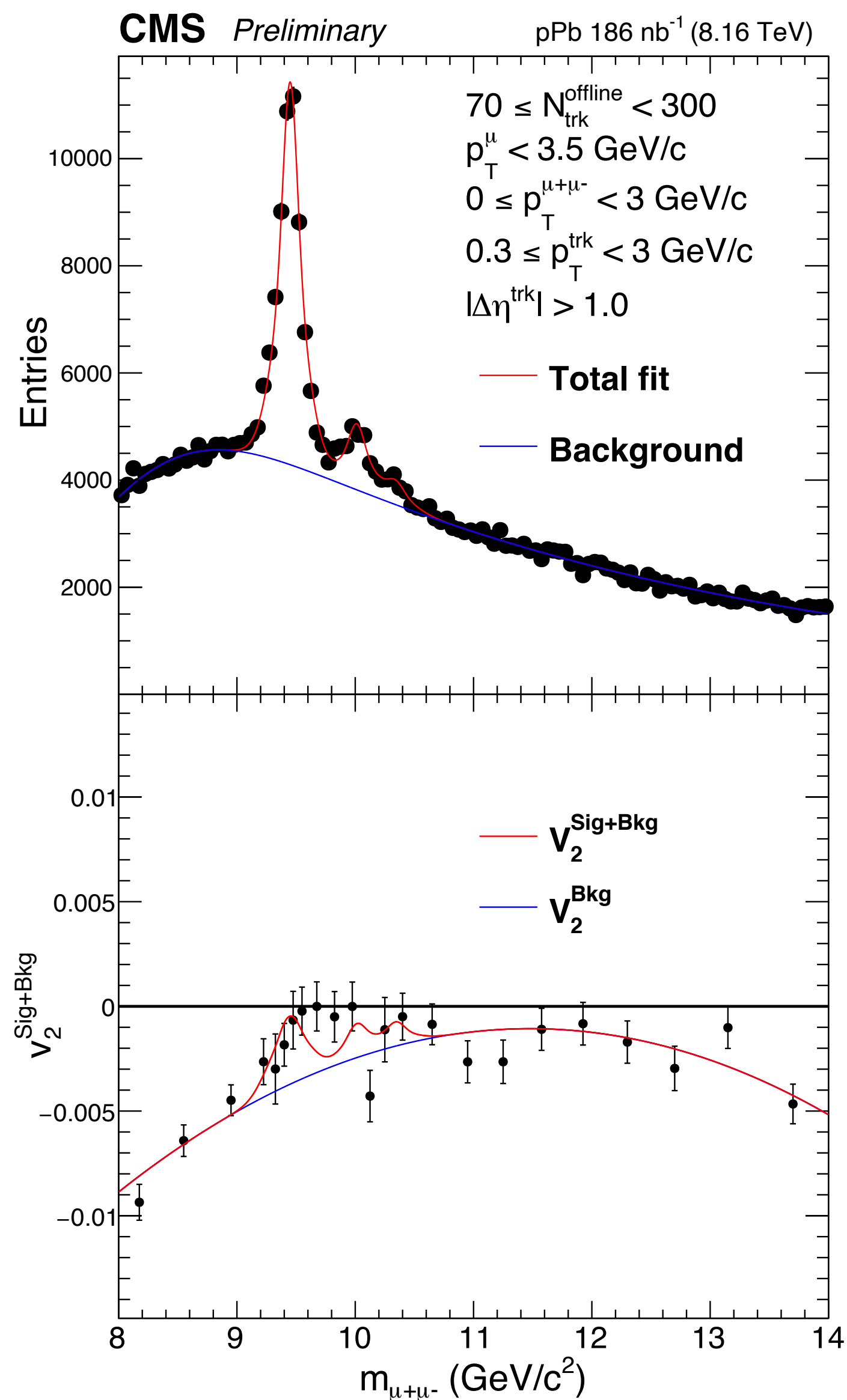


$n = 3$

$\epsilon_n$

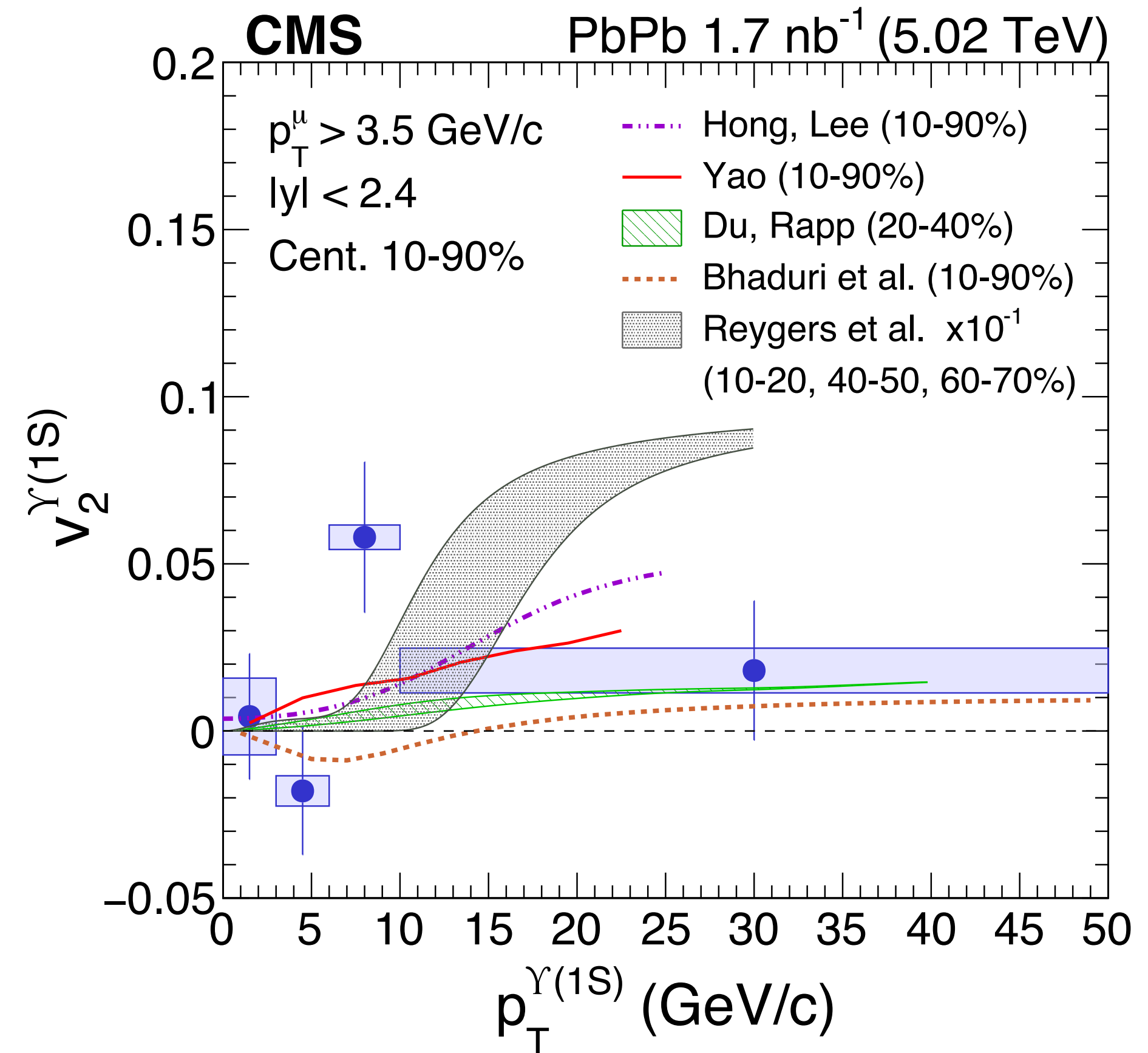
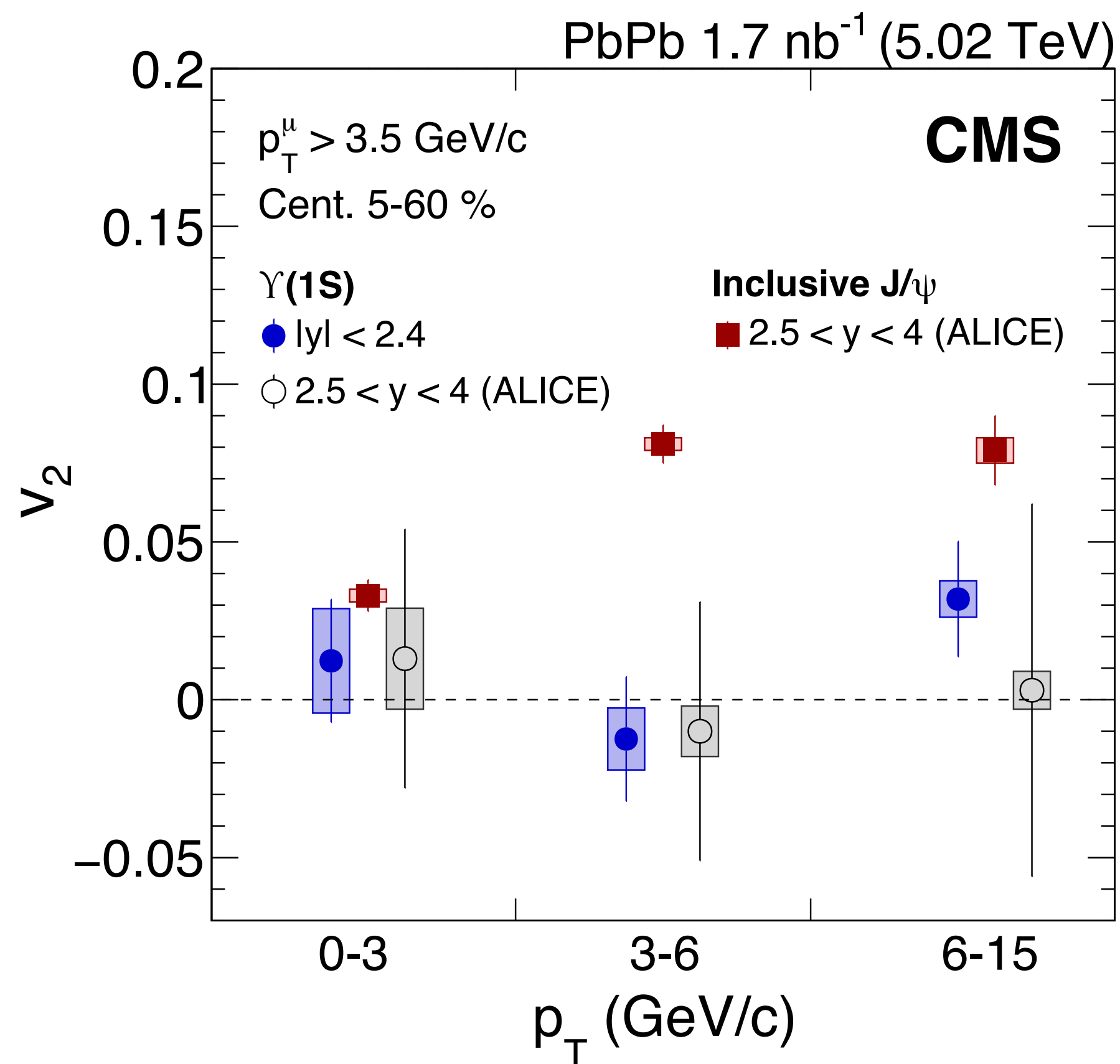
$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$

# $\Upsilon(1S)$ $v_2$ extraction in p-Pb collisions



- Fourier decomposition of azimuthal distribution using  $v_n$
- Simultaneous fit on dimuon invariant mass
- High multiplicity p-Pb collisions:  $v_2^\Upsilon < v_2^{J/\psi}$

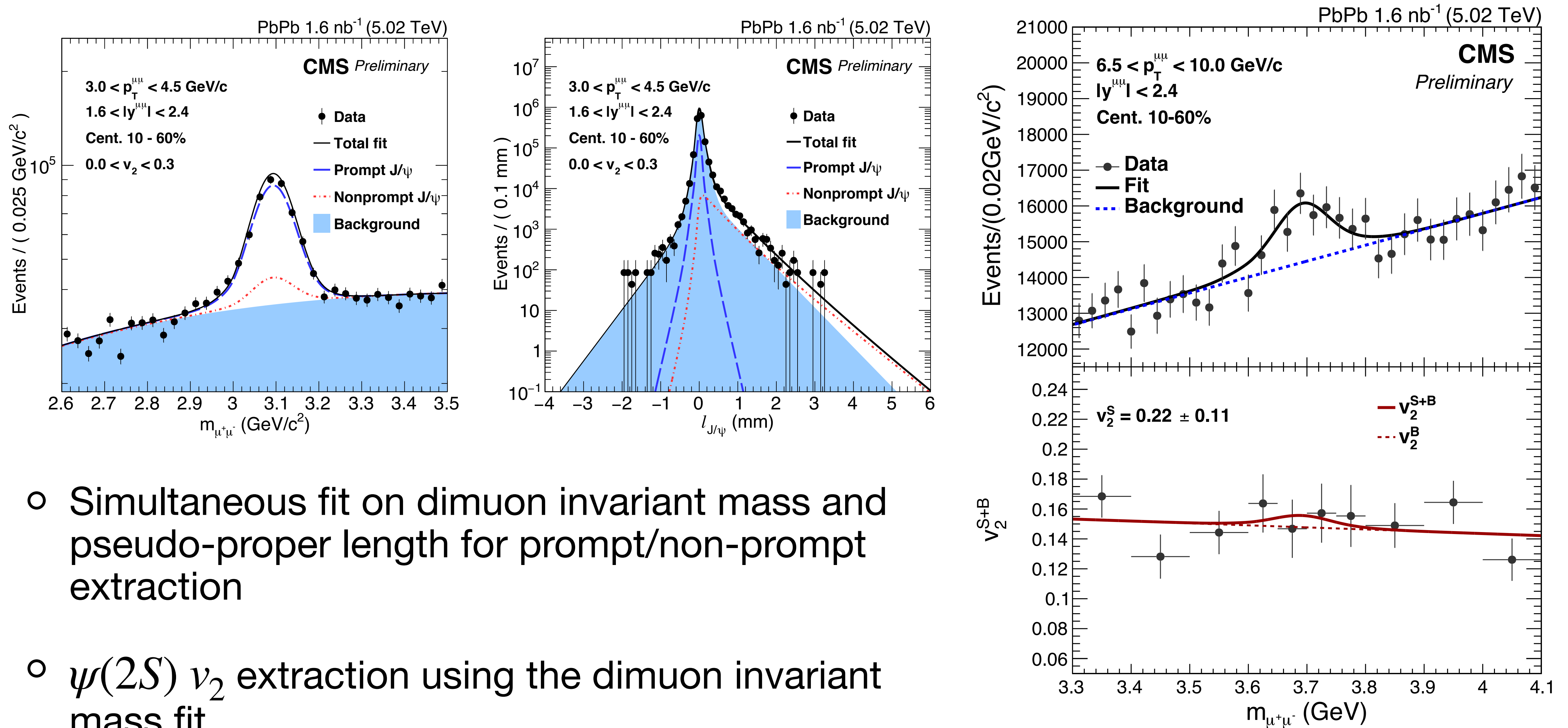
# $\Upsilon(1S)$ $v_2$ in Pb-Pb collisions



- $\Upsilon(1S)$   $v_2$  measurements in PbPb collisions compatible with 0 and lower than J/ψ
- All current theoretical models (including regeneration or not) can describe data

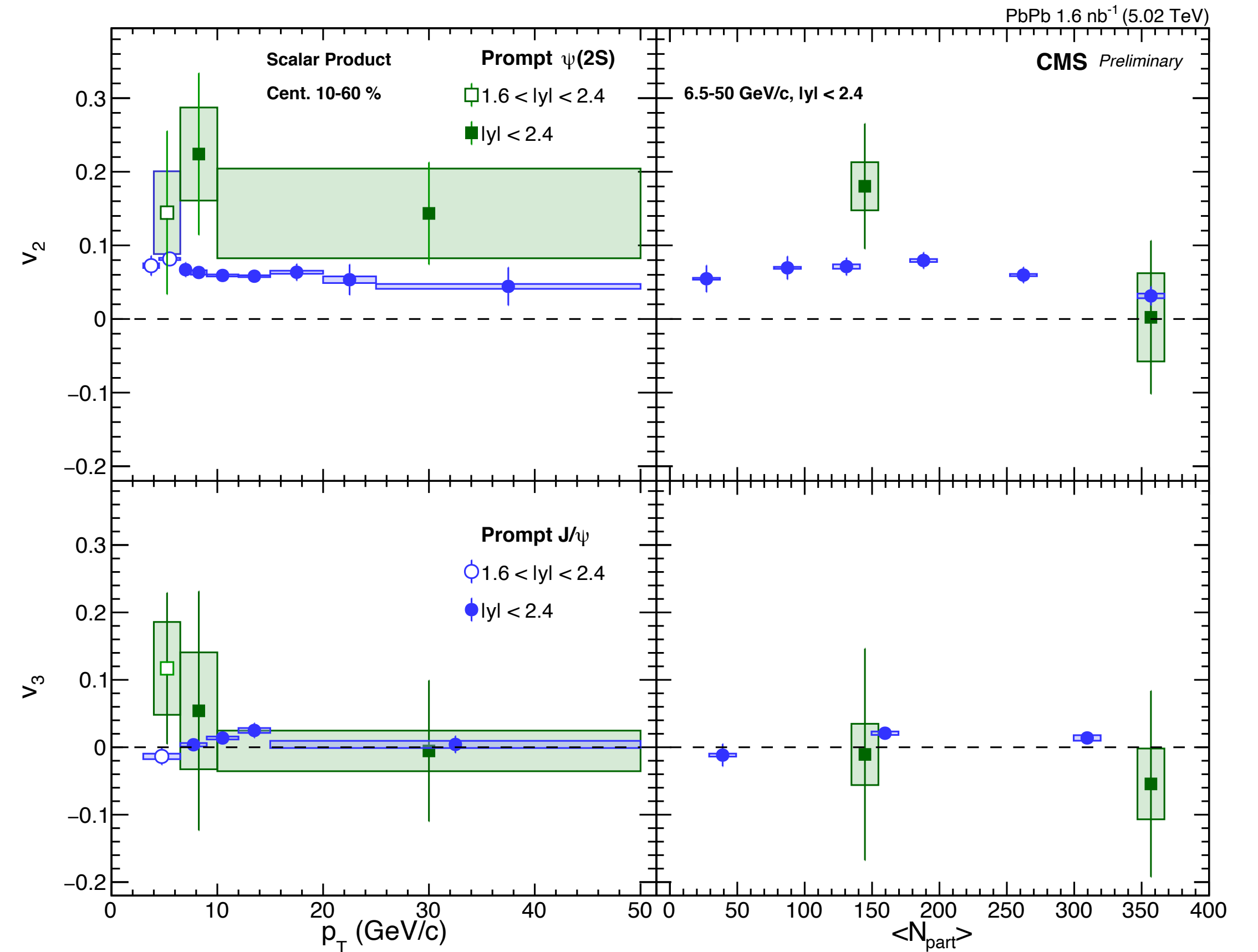
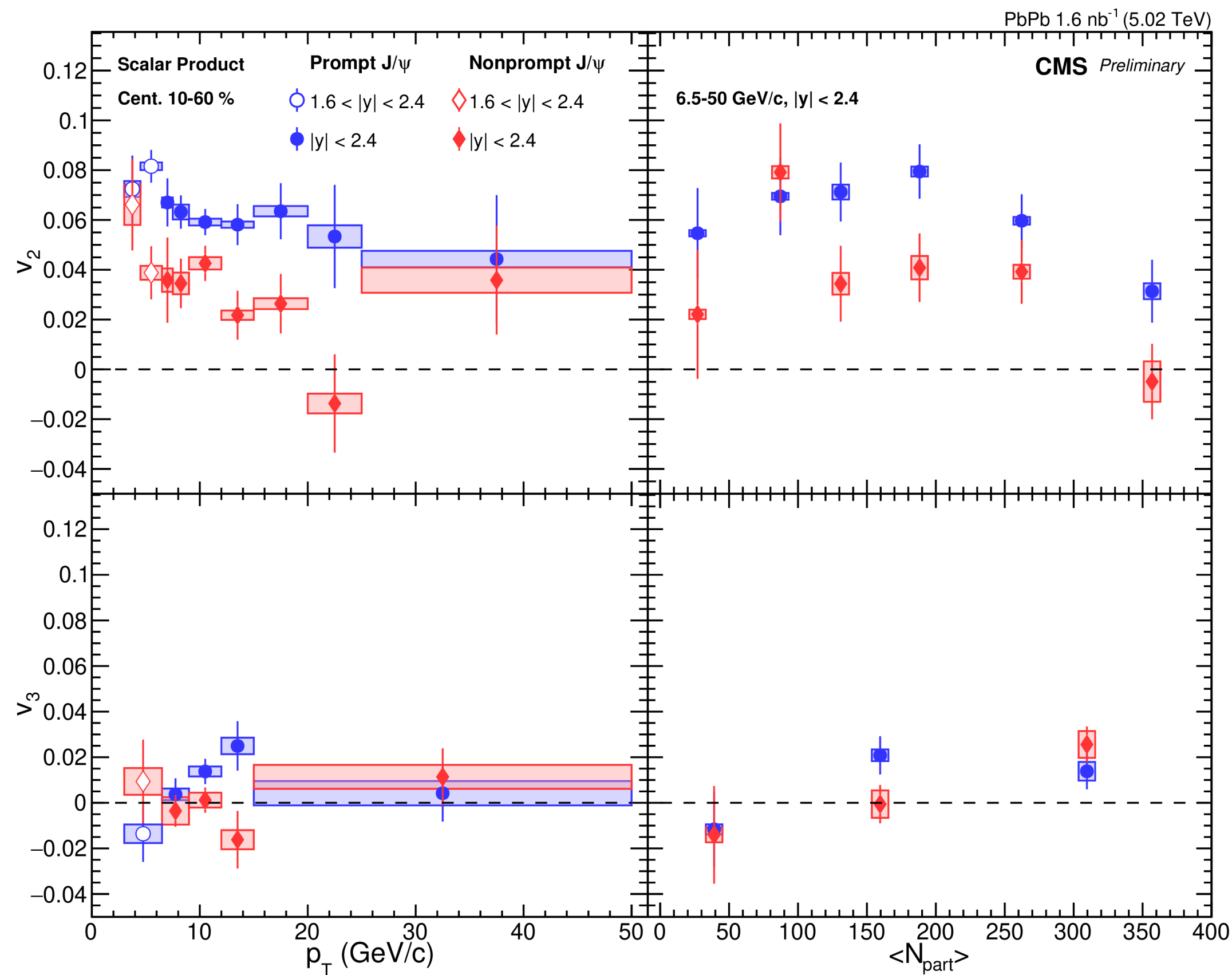


# Non-prompt $J/\psi$ and $\psi(2S)$ $v_2$ extraction in Pb-Pb



- Simultaneous fit on dimuon invariant mass and pseudo-proper length for prompt/non-prompt extraction
- $\psi(2S)$   $v_2$  extraction using the dimuon invariant mass fit

# J/ψ and prompt ψ(2S) v<sub>n</sub> in Pb-Pb collisions

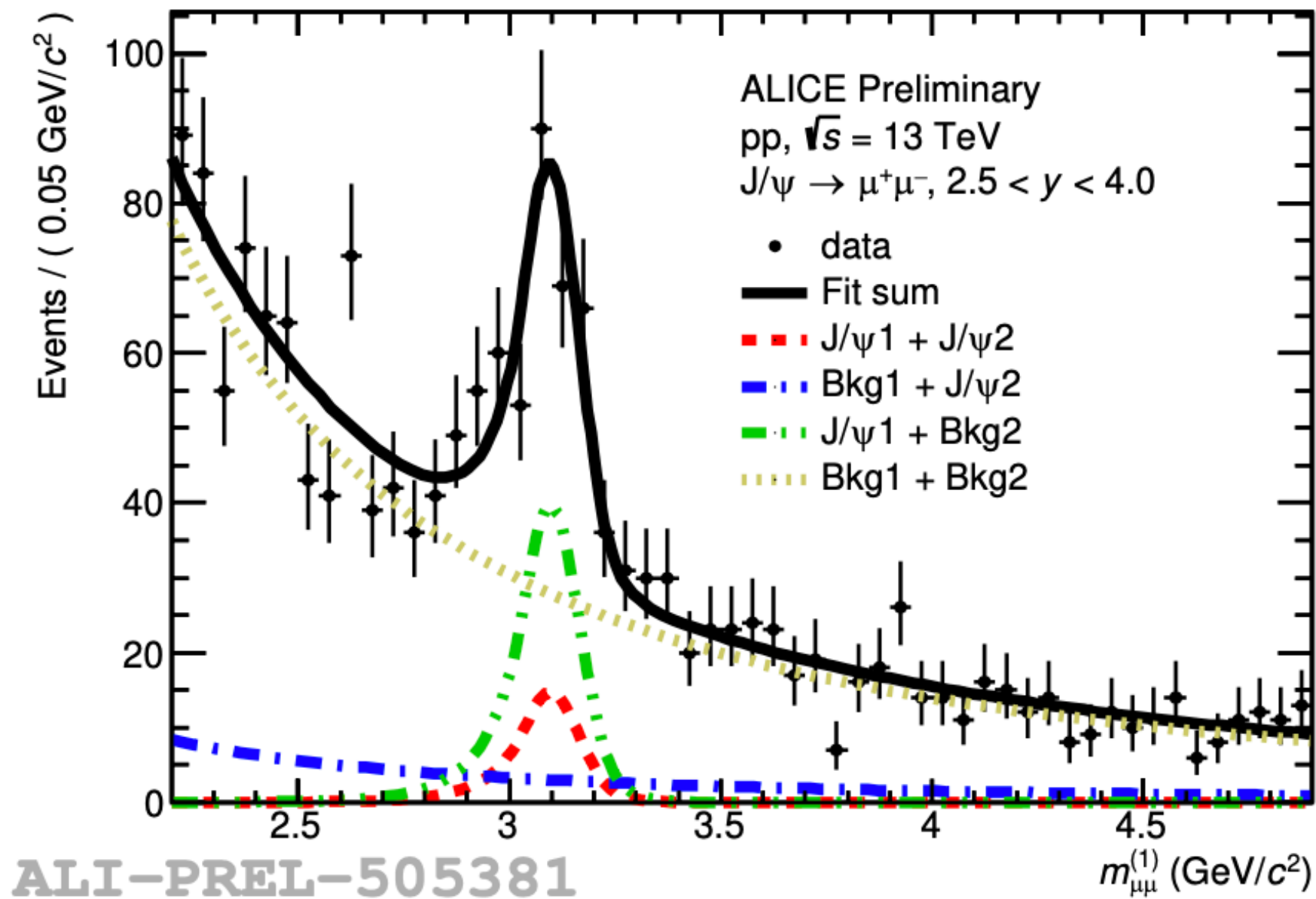


○ Larger  $v_2$  is observed for prompt J/ψ w.r.t. non-prompt while all  $\sim 0$  for  $v_3$

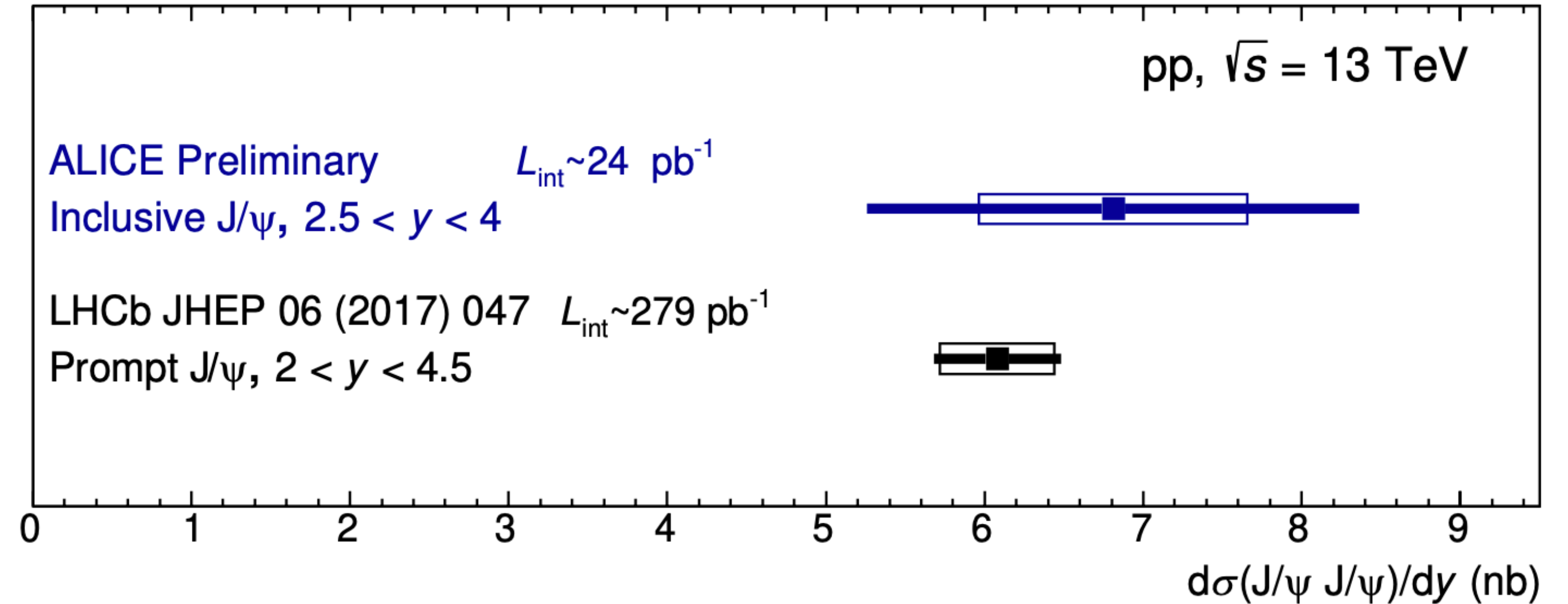
○ Hierarchy is observed:  $v_2^{b \rightarrow J/\psi} < v_2^{J/\psi} < v_2^{\psi(2S)}$  however not clear w.r.t. centrality

# J/ψ pair production in Pb-Pb collisions

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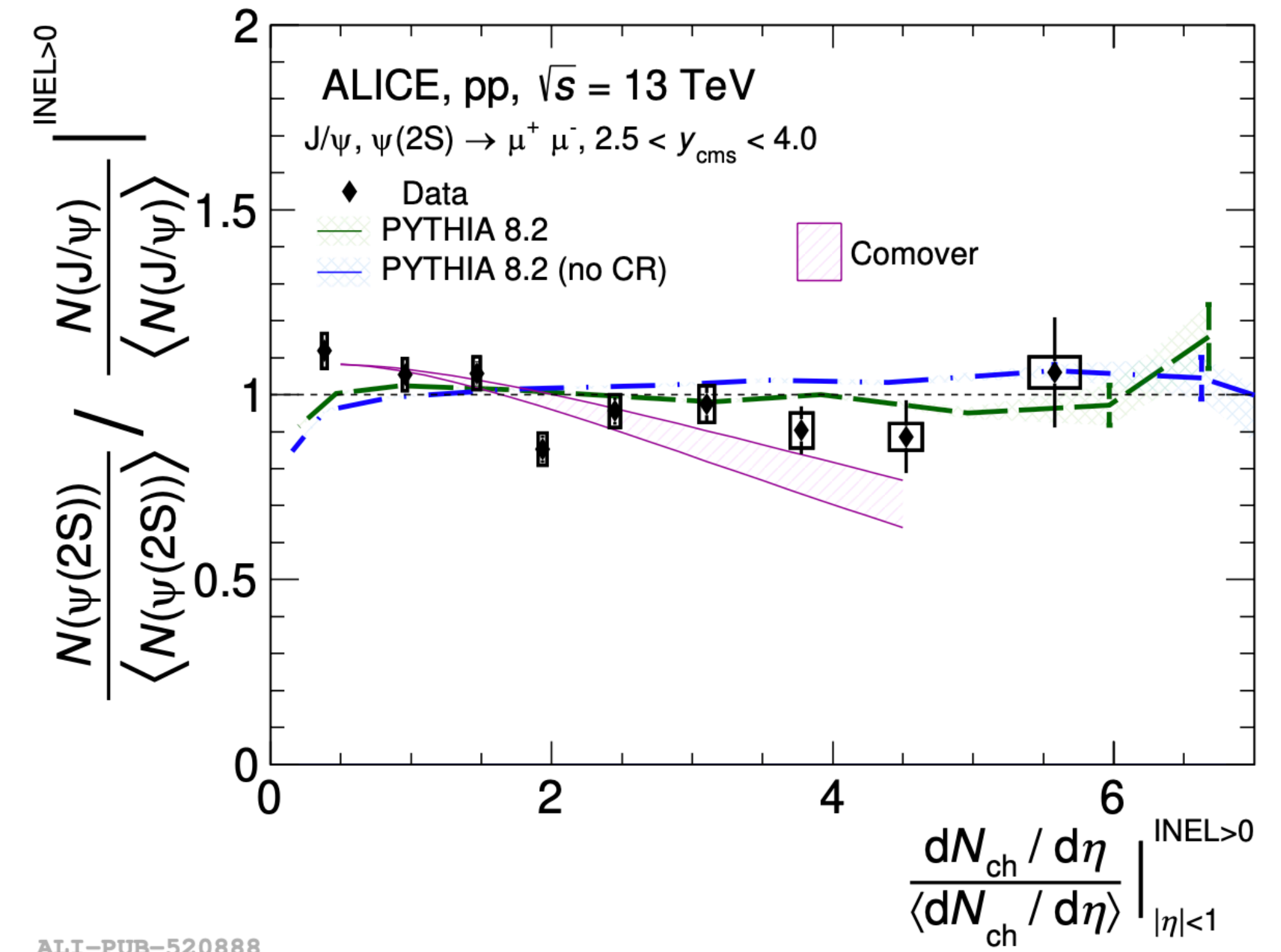
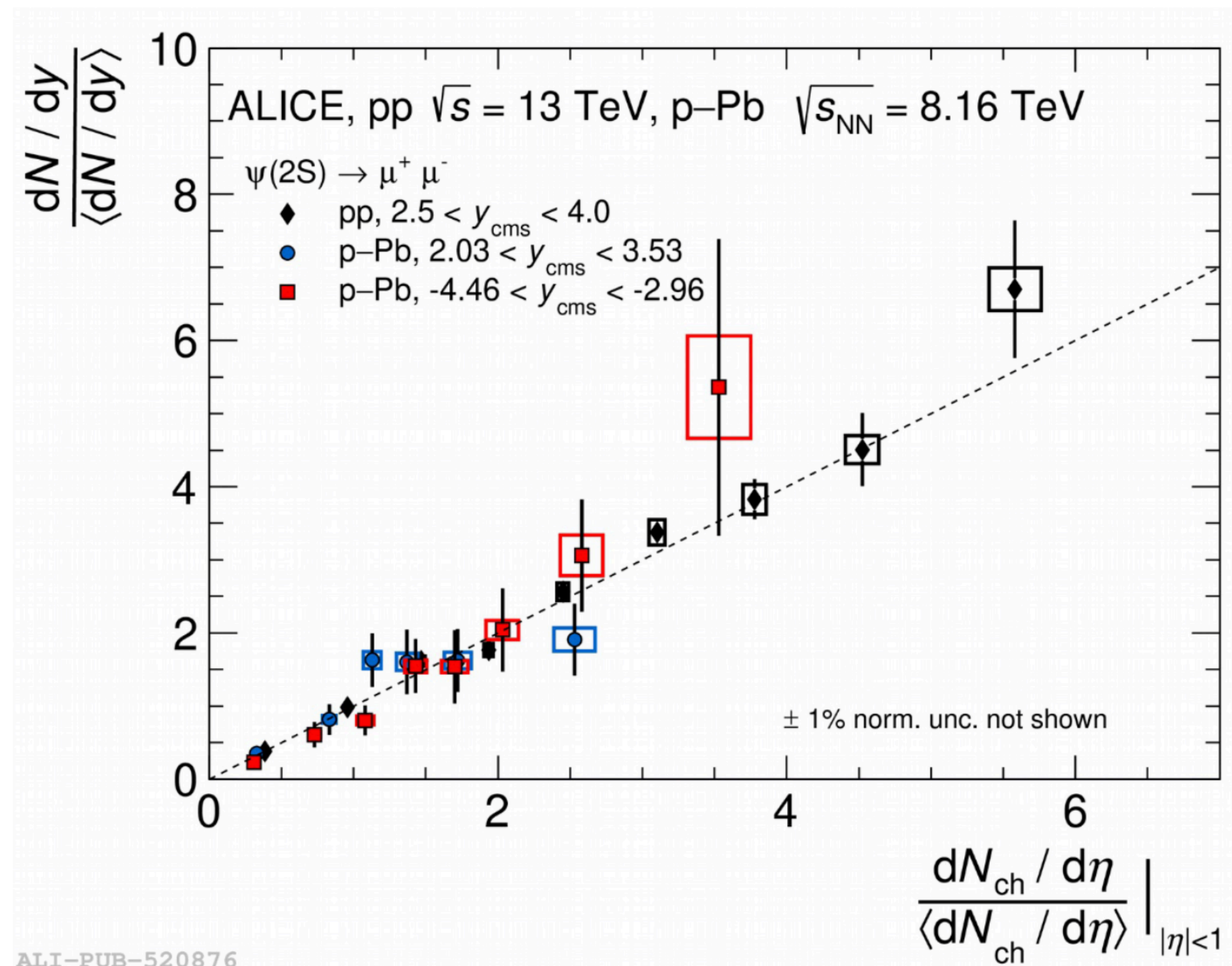


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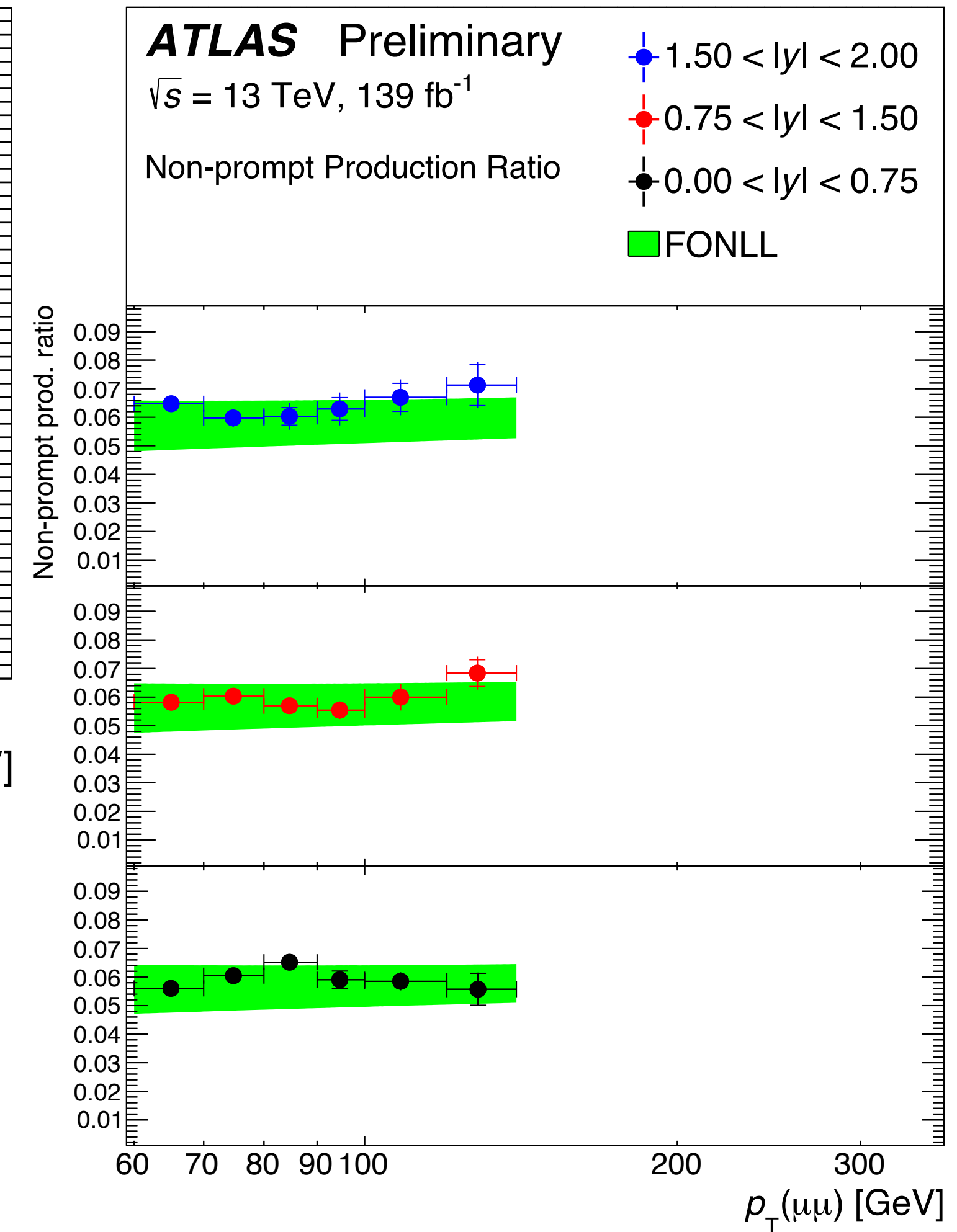
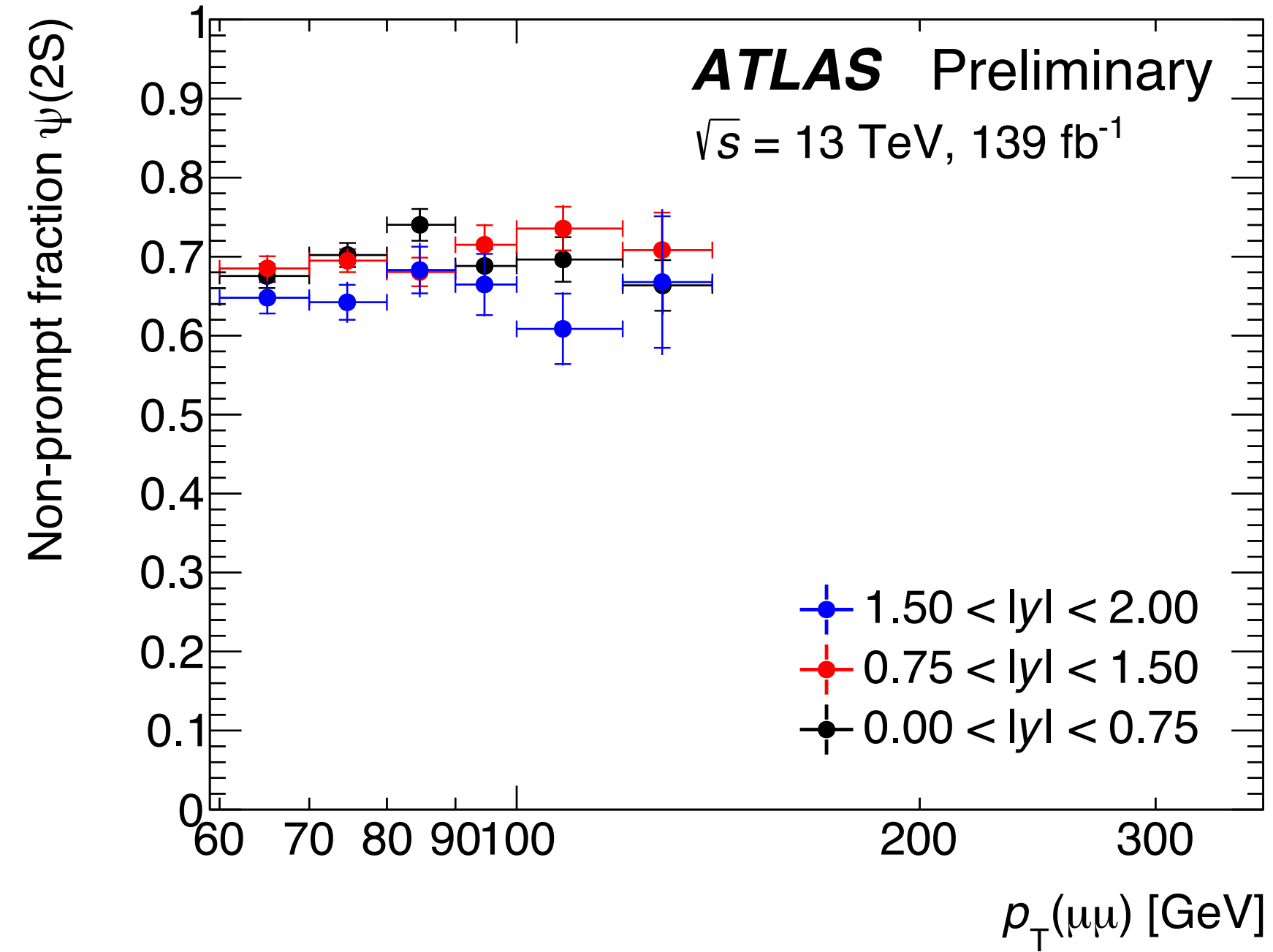
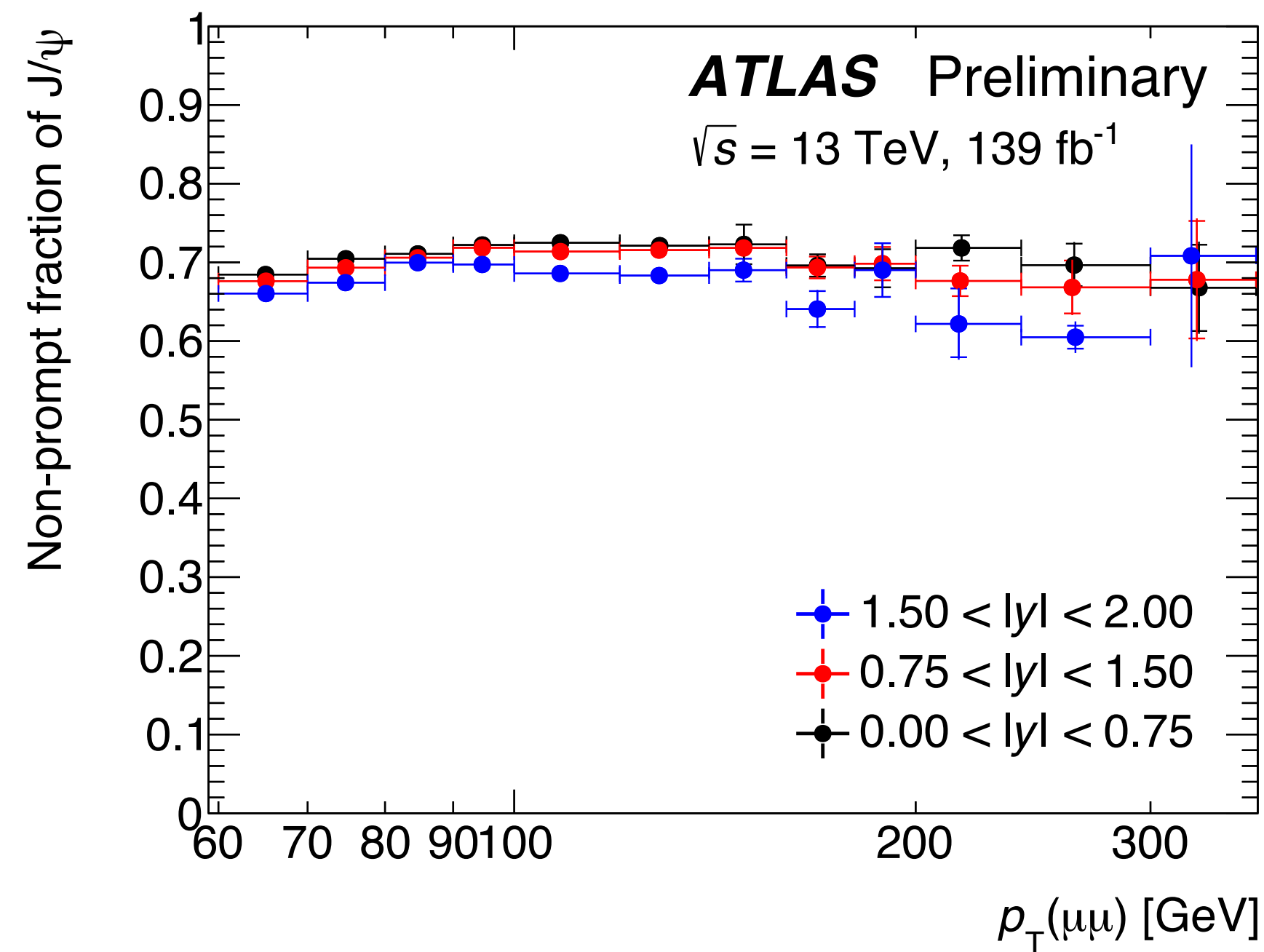
- Constrains on J/ψ production (NRQCD) and double parton scattering
- Despite different acceptance and inclusive or prompt: **good agreement w LHCb**

# $\psi(2S)$ production in pp and p-Pb collisions



- Linear increase of  $\psi(2S)$  normalized yield vs. multiplicity while  $\psi(2S)/J/\psi$  is flat
- Agreement with models at low  $p_T$
- pp and p-Pb data are compatible within the uncertainties

# High- $p_T$ $J/\psi$ and $\psi(2S)$ production pp collisions



- Non-prompt fractions of  $\psi(2S)$  and  $J/\psi$ : hint of a small rapidity dependence
- Good agreement between FONLL calculations and non-prompt production  $\psi(2S)/J/\psi$  ratio data