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Recent results on charmonium production in Pb-Pb collisions with nuclear overlap in ALICE

R. Caron

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Recent results on charmonium production in Pb-Pb collisions with nuclear overlap in ALICE

Robin Caron, on behalf of the ALICE collaboration

Institut de Physique des Deux Infinis (CNRS-IN2P3)



March 30, 2023

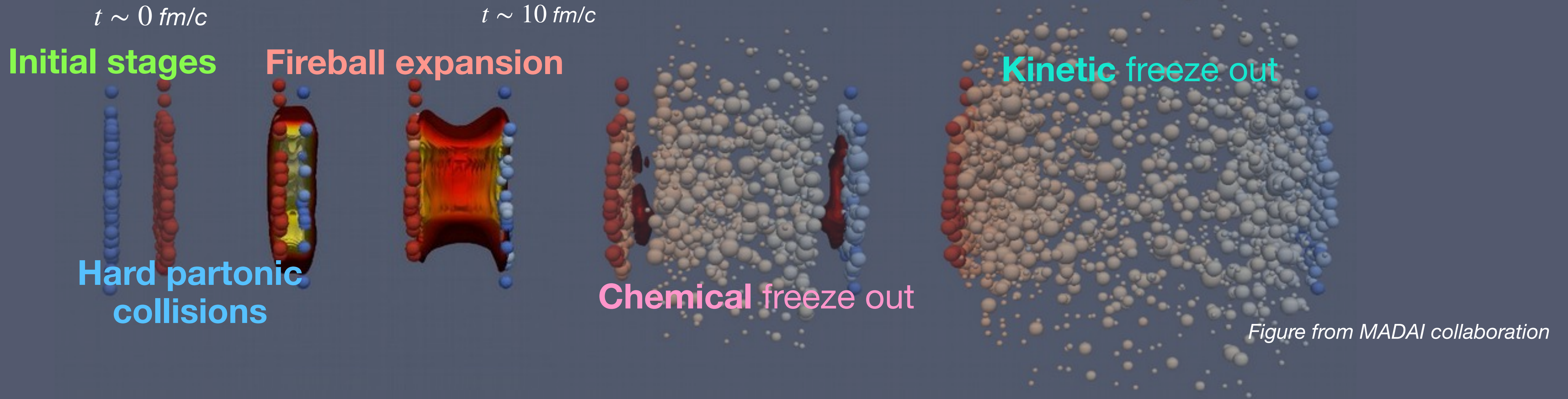


Outline

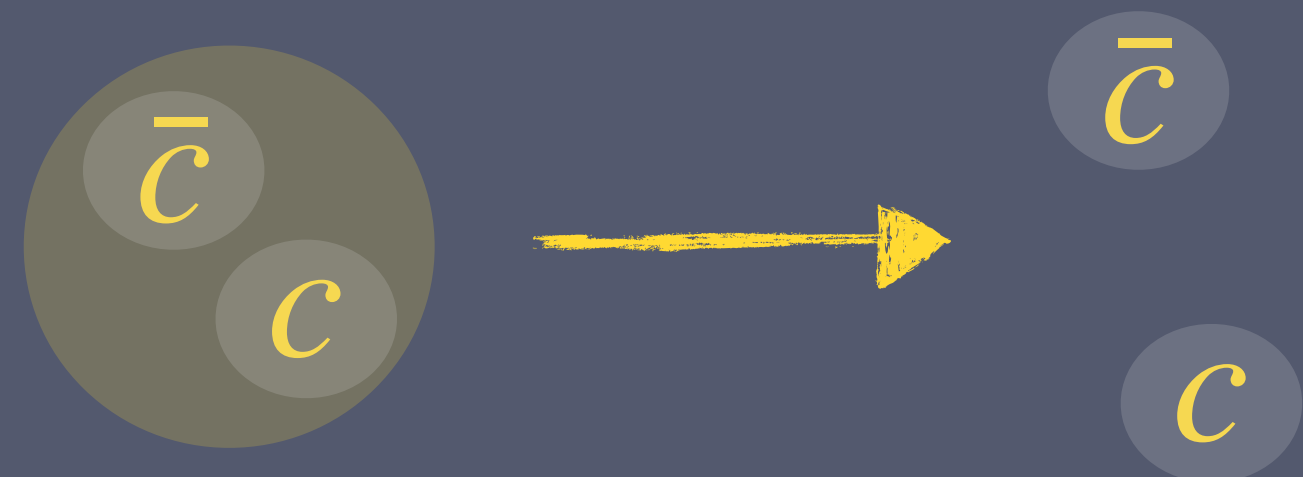


- **Introduction**
- **Charmonium production in Pb-Pb collisions**
 - **Inclusive J/ψ and $\psi(2S)$ production**
 - **Prompt and non-prompt J/ψ production**
 - **Coherent J/ψ photoproduction in collisions with nuclear overlap**
- **Summary**

Evolution of a heavy-ion collision



Charmonium: a powerful tool to study medium properties and initial conditions



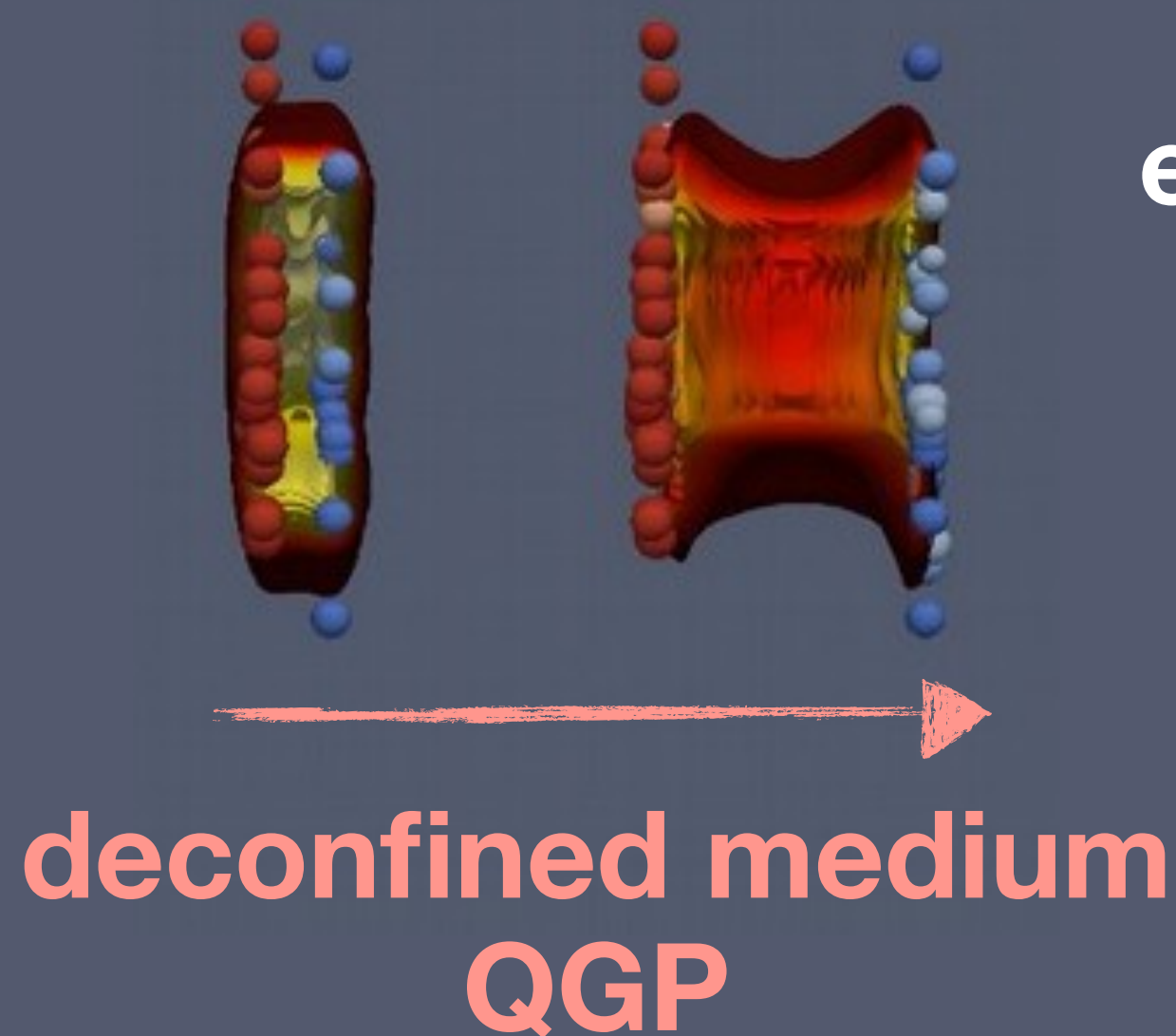
Signature of deconfinement:

suppression of charmonia inside the quark-gluon plasma (QGP), originally proposed in [1]

Why charmonium?

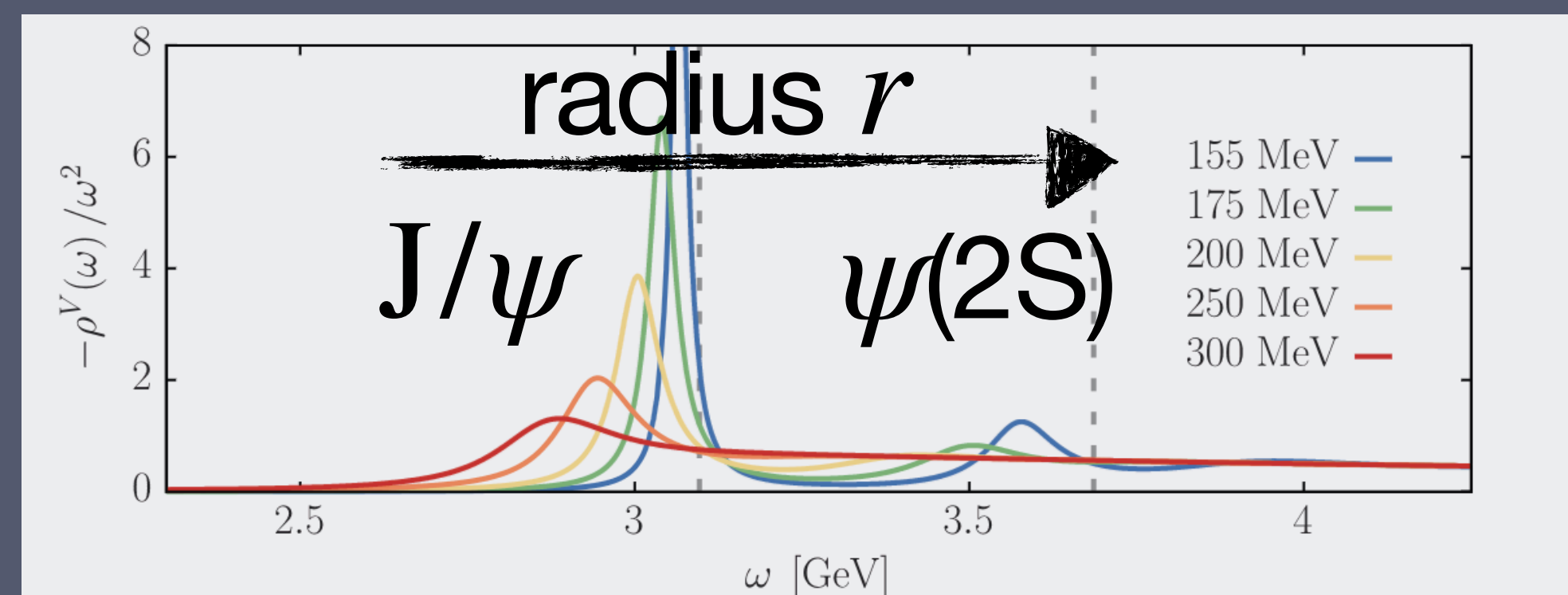
color screening and medium-induced dissociation
(with static vs dynamic dissociation)

$$\tau_0 \sim 1 \text{ fm}/c$$



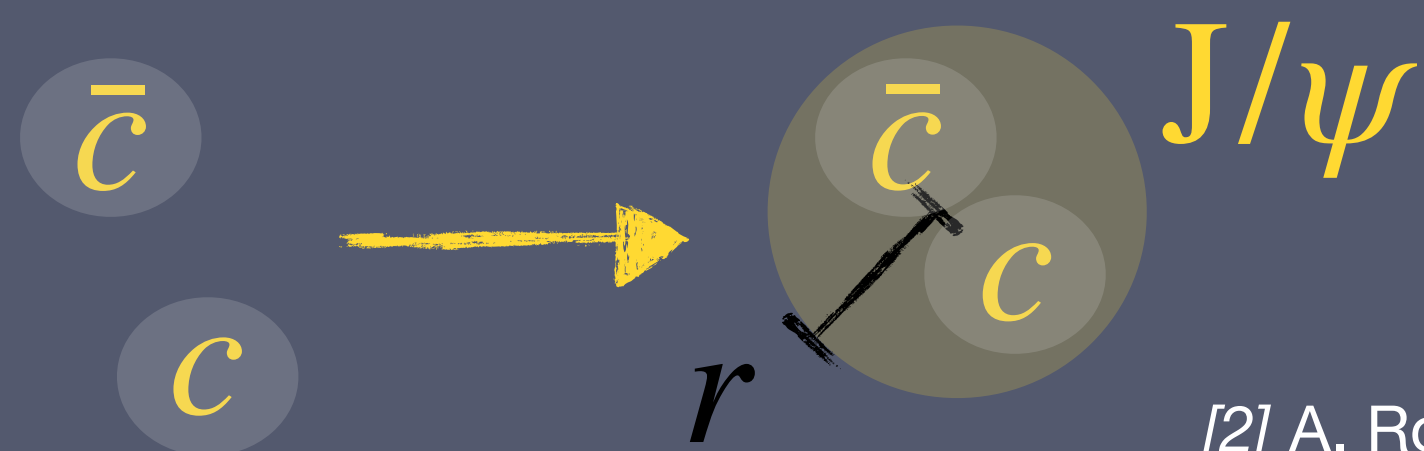
excited states more suppressed w.r.t. ground state

sensitive to medium temperature



[2]

In central Pb-Pb collision at LHC: $O(100)$ $c\bar{c}$ pairs produced close to $\tau \sim 0.1 \text{ fm}/c$ (and few $b\bar{b}$)



Regeneration: strongly supported scenario at LHC due to large $N_{c\bar{c}}$ created - affecting differently J/ψ and $\psi(2S)$

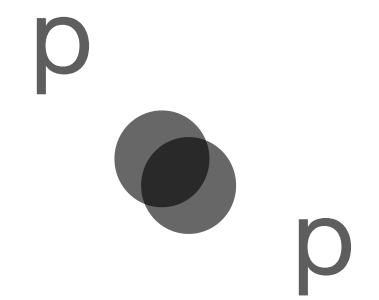
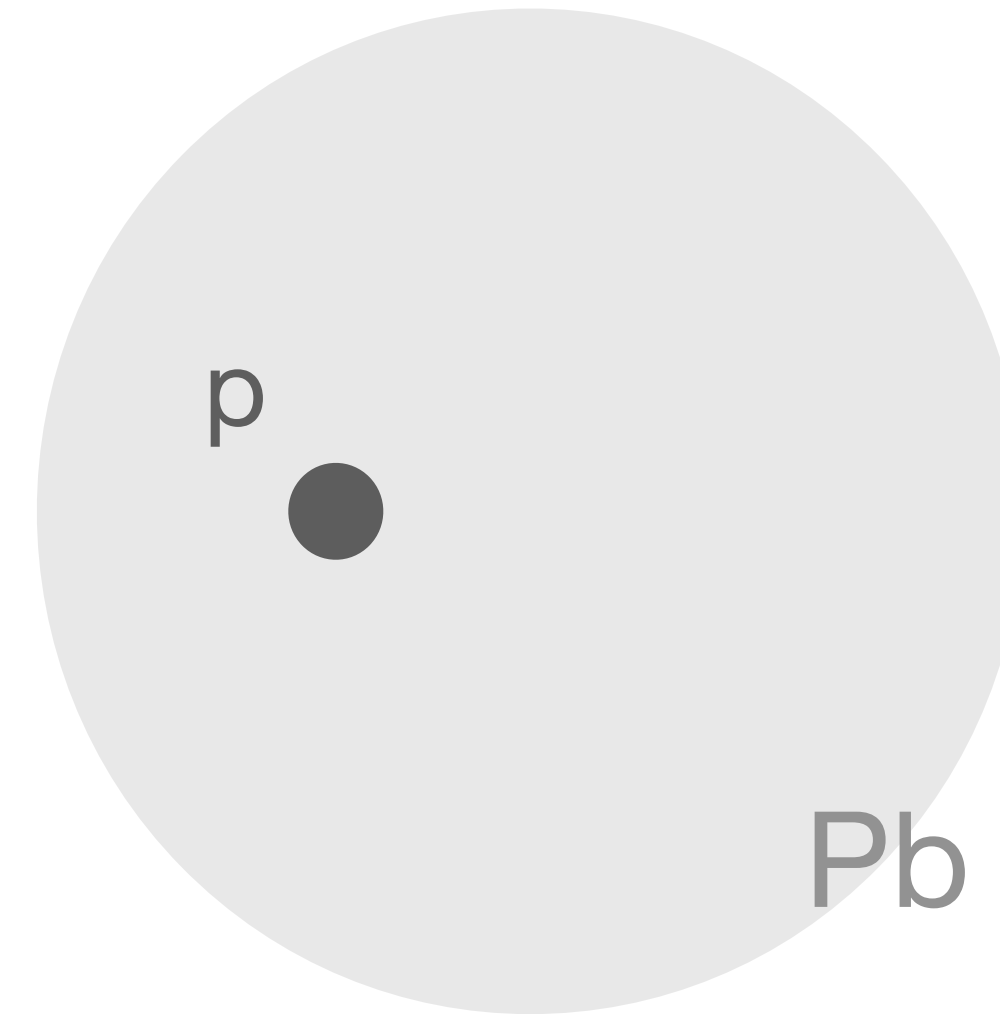
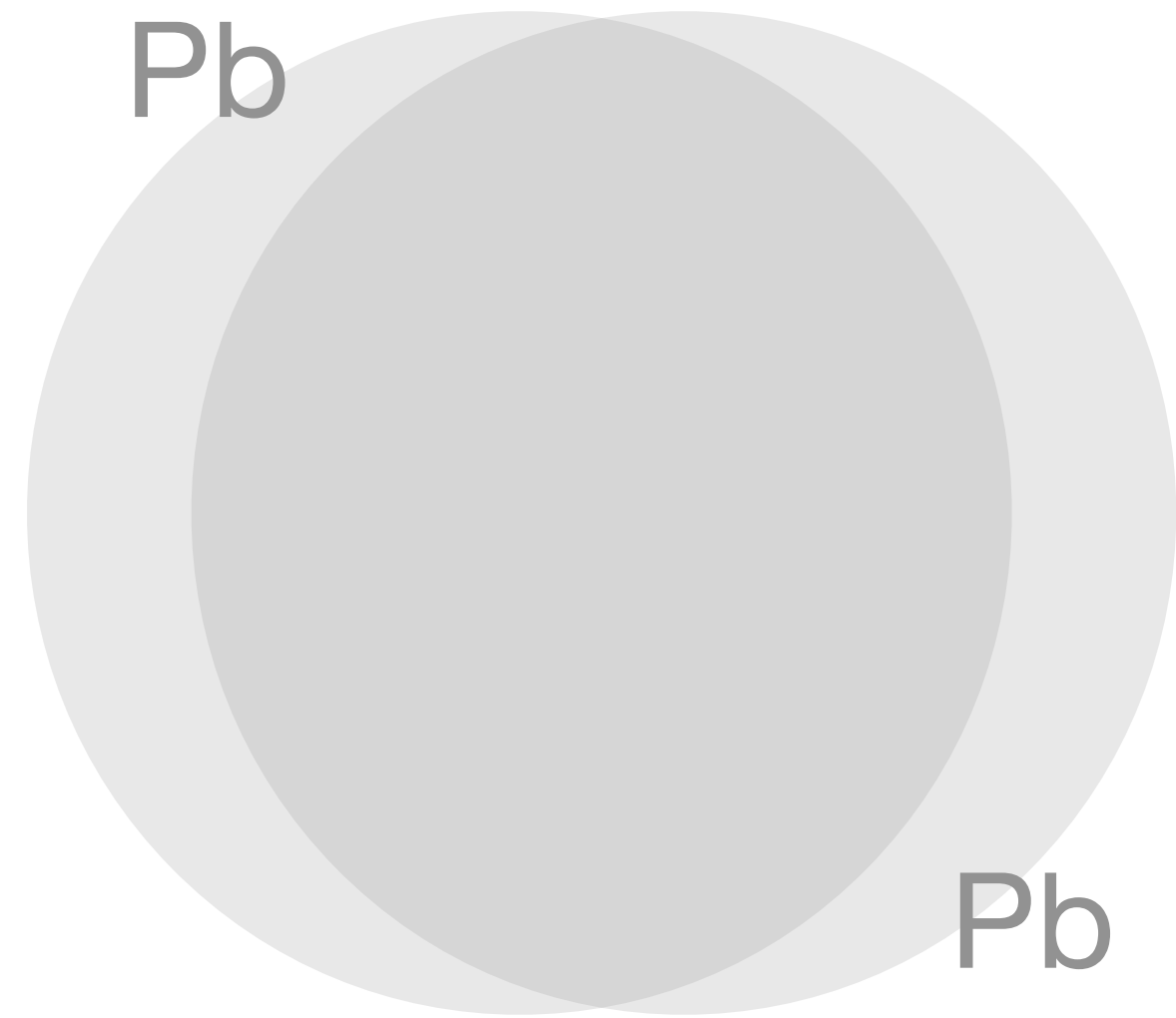
[3,4]

[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

Charmonium production across systems size

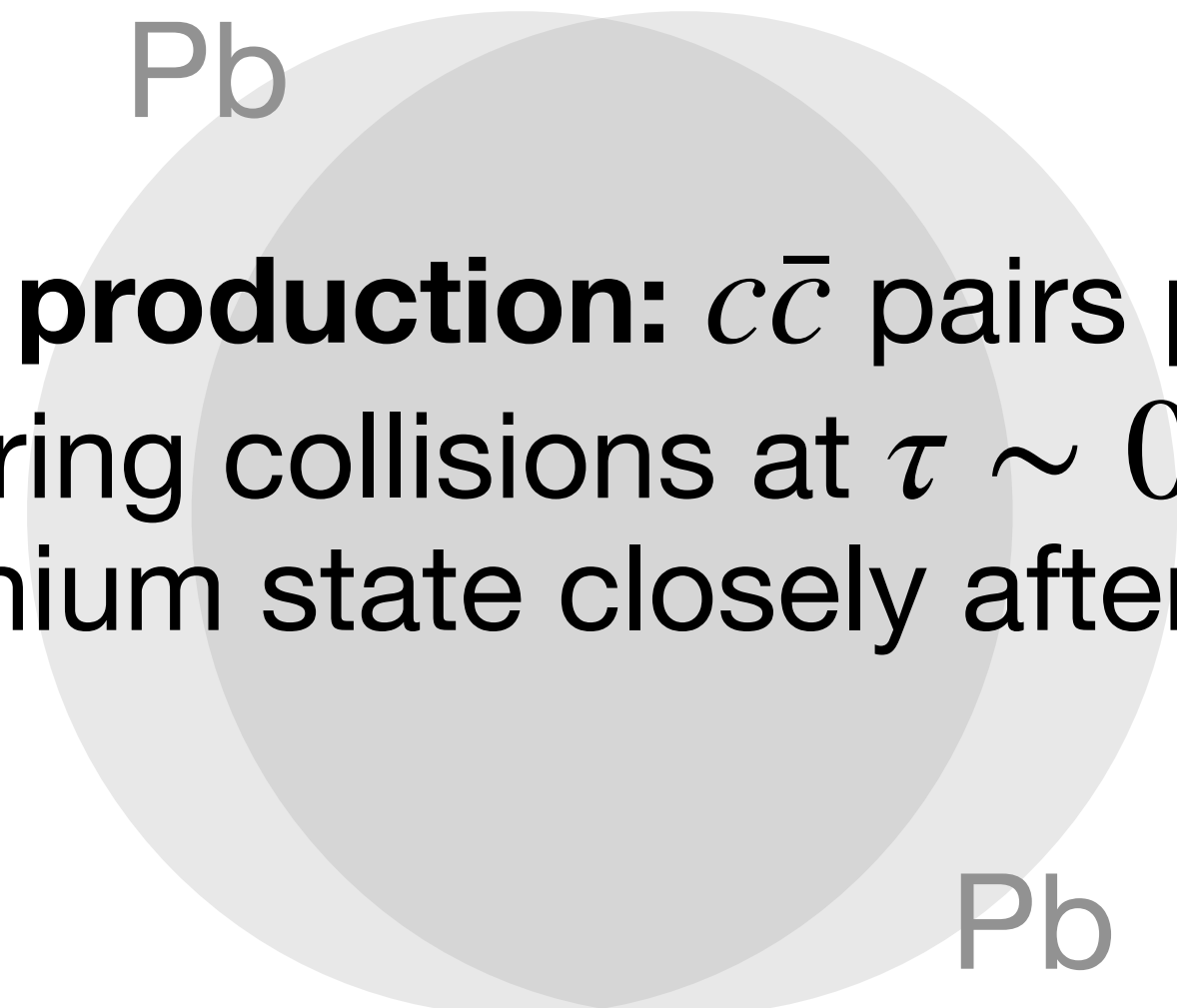


cold nuclear matter effects

reference system
test of QCD

high multiplicity p-Pb or pp: study of **multiparton interactions** and **collectivity in small system**

Charmonium production across systems size



Hadronic production: $c\bar{c}$ pairs produced by hard scattering collisions at $\tau \sim 0.1$ and bound charmonium state closely after (< 1 fm/c)

Hot medium effect: $c\bar{c}$ dissociation vs recombination, collectivity, heavy quark energy loss

Photoproduction: first studied in Ultra Peripheral Collisions (UPCs), now also observed in Pb-Pb with nuclear overlap, probe the initial stages of the collision and possibly new QGP probe

$$gg \rightarrow c\bar{c}$$

Mainly **gluon initiated process at LHC**
(might be also $q\bar{q}$ annihilation)

$$J/\psi + g \rightarrow c + \bar{c} + g \quad \text{if } T > T_{\text{diss}}$$

$$c + \bar{c} \rightarrow J/\psi + g \quad \text{if } T < T_{\text{diss}}$$

LO:

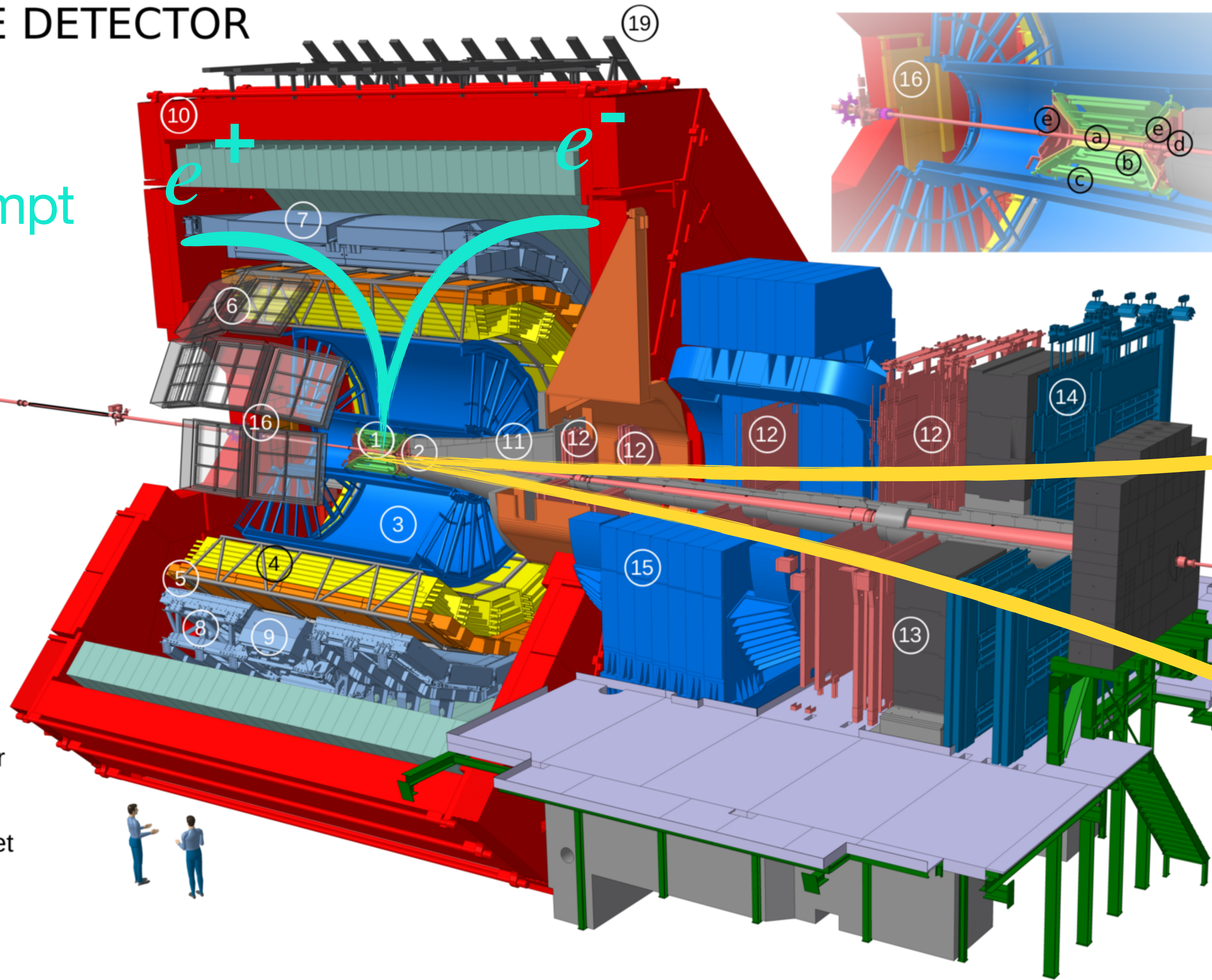
THE ALICE DETECTOR

$J/\psi \rightarrow ee$
 $|y| < 0.9$

Prompt/Non-prompt
 separation

Run 2 configuration

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCal
8. DCal
9. PHOS, CPV
10. L3 Magnet
11. Absorber
12. Muon Tracker
13. Muon Wall
14. Muon Trigger
15. Dipole Magnet
16. PMD
17. AD
18. ZDC
19. ACORDE



- a. ITS SPD (Pixel)
- b. ITS SDD (Drift)
- c. ITS SSD (Strip)
- d. V0 and T0
- e. FMD



$2.5 < y < 4$

μ^+

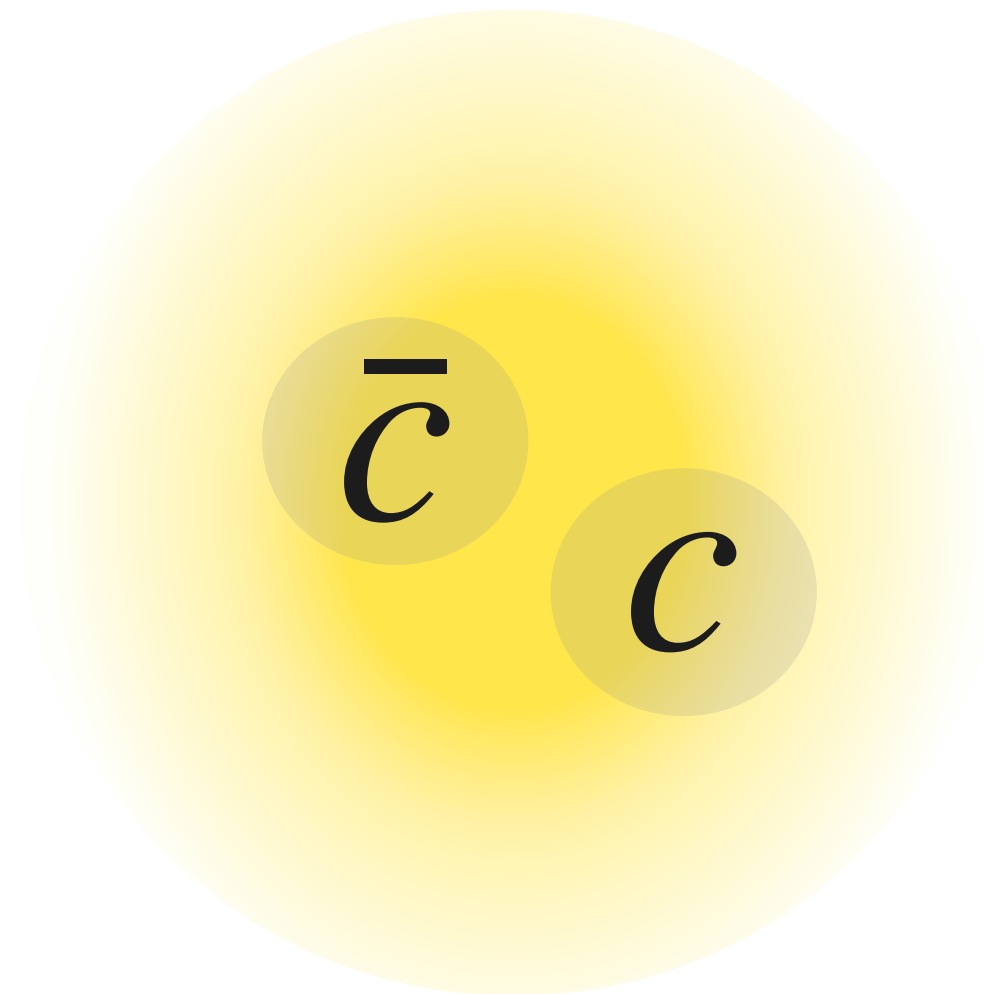
μ^-

$J/\psi \rightarrow \mu\mu$

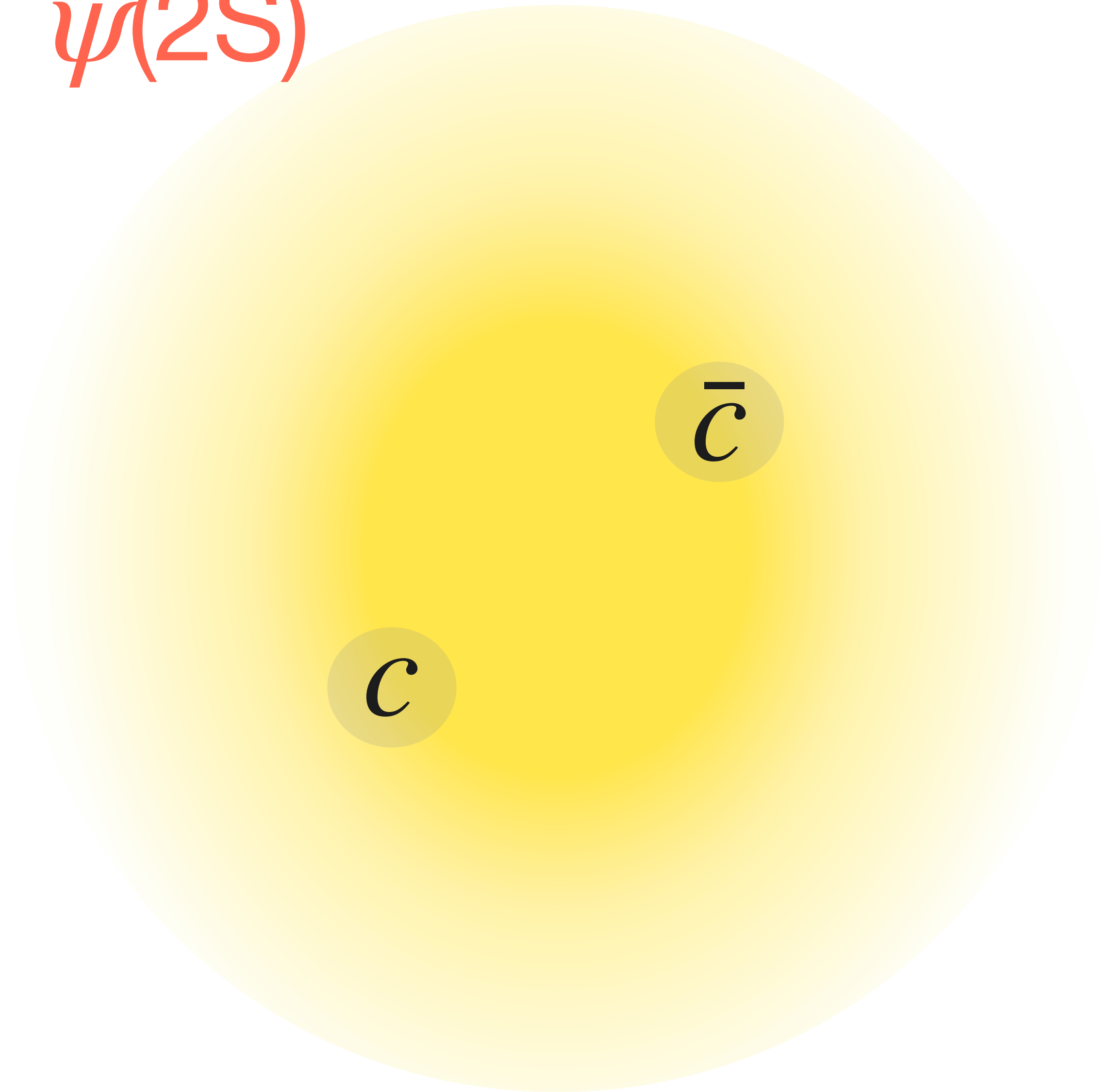
$\psi(2S) \rightarrow \mu\mu$

Inclusive measurement down to $p_T = 0$ GeV/c for both y

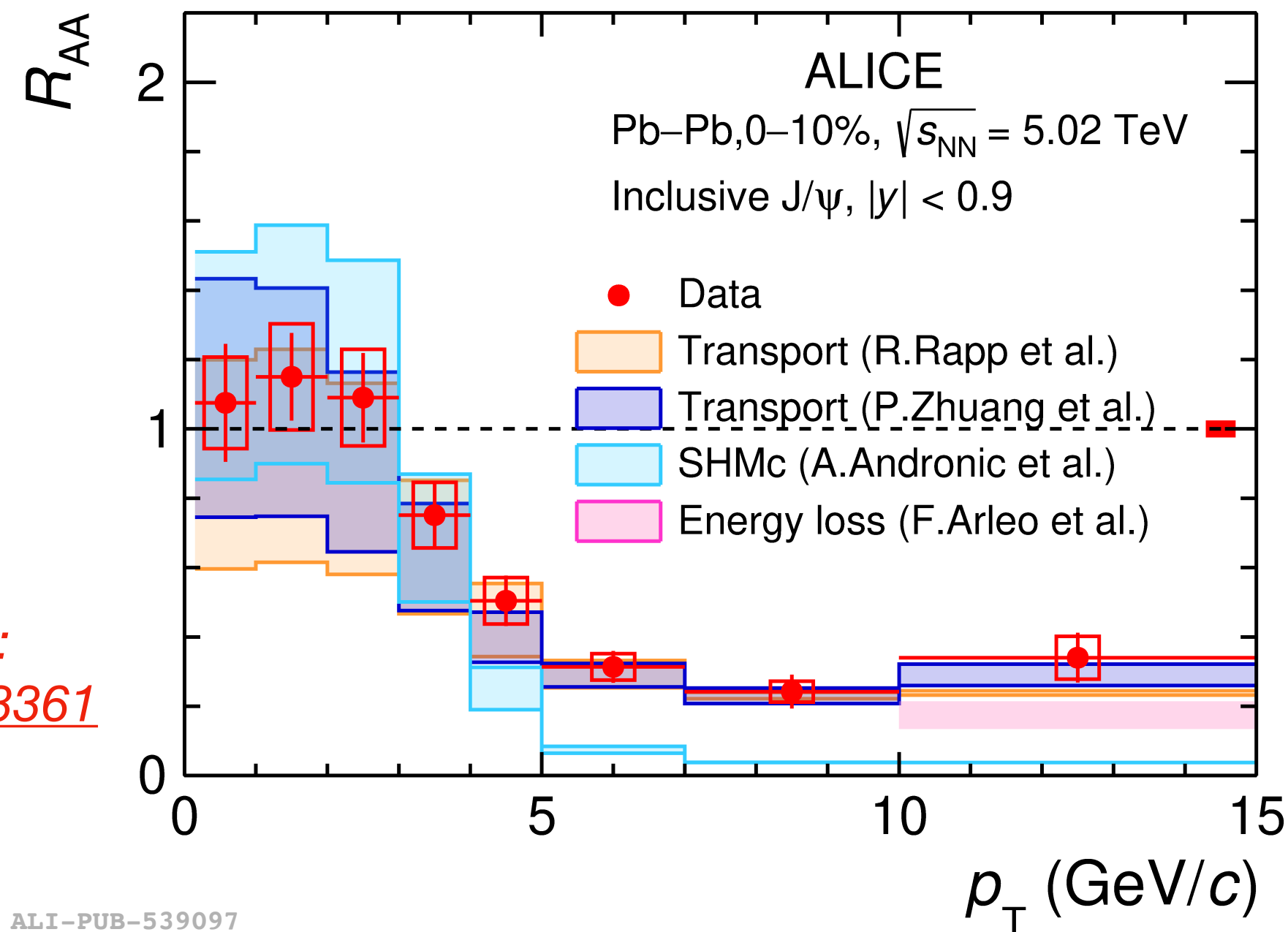
J/ψ



$\psi(2S)$



J/ψ nuclear modification factor (R_{AA})



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

○ > 1 : Enhancement

○ < 1 : Suppression

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{d^2 N_{AA} / dp_T dy}{d^2 \sigma_{pp} / dp_T dy}$$

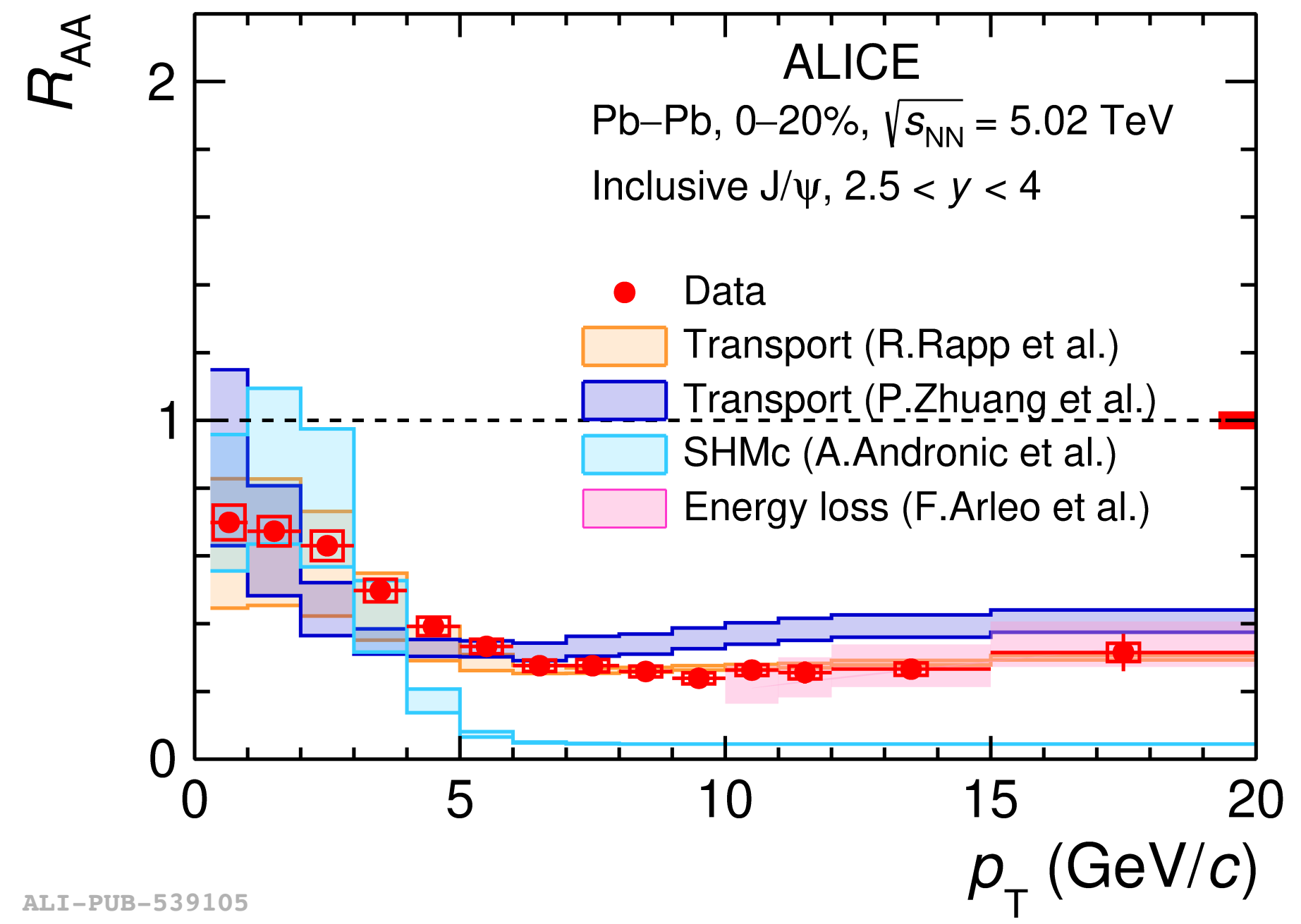
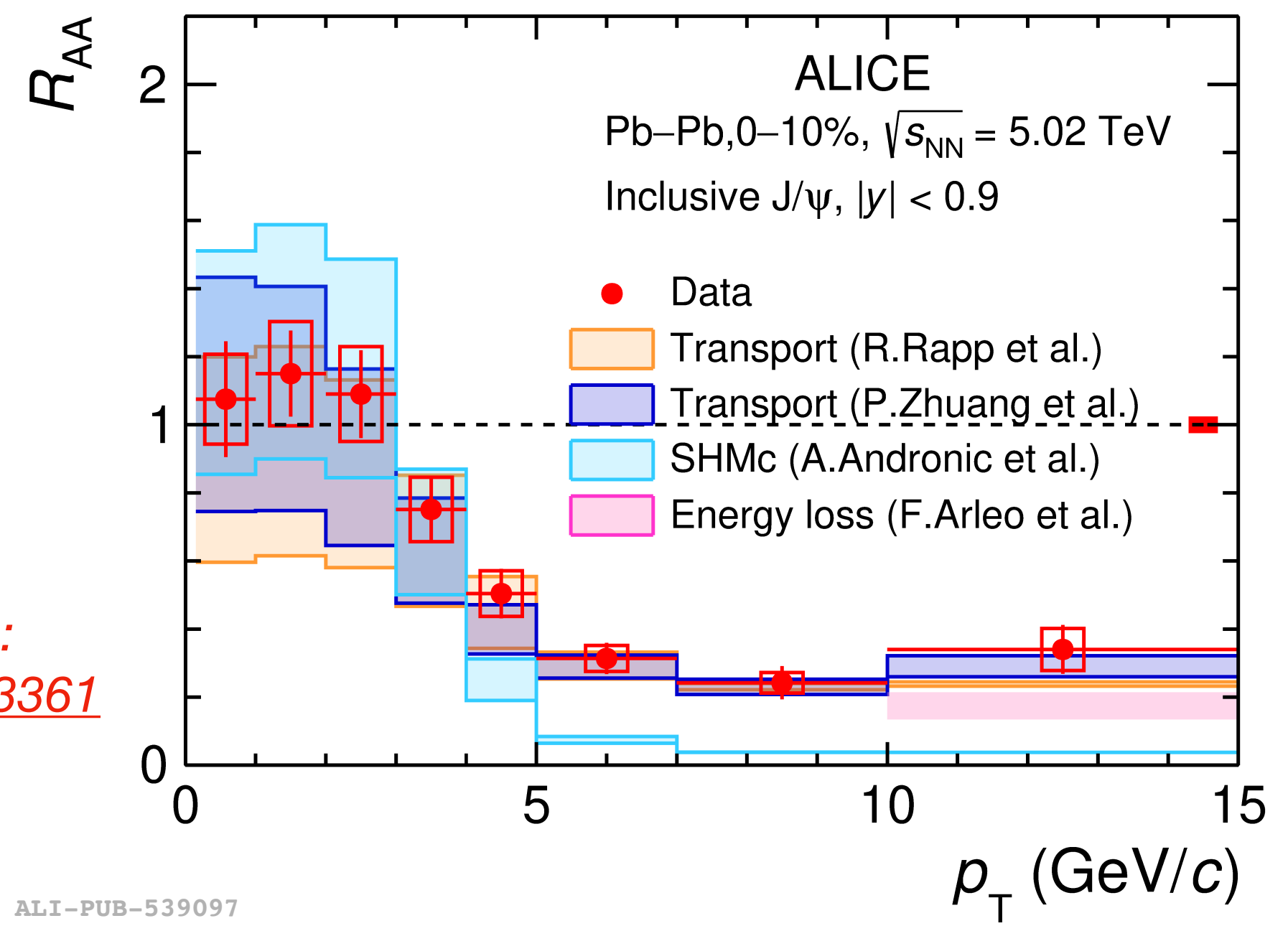
* $\langle T_{AA} \rangle$: average nuclear overlap function

NEW PAPER:
[arXiv:2303.13361](https://arxiv.org/abs/2303.13361)

ALI-PUB-539097

- Models implementing **regeneration**, either at the freeze-out (**SHMc**) or during the medium evolution (**TAMU**), are in agreement with data at low p_T
- **J/ψ R_{AA}** : more suppressed at high p_T and showing a rising trend towards lower p_T

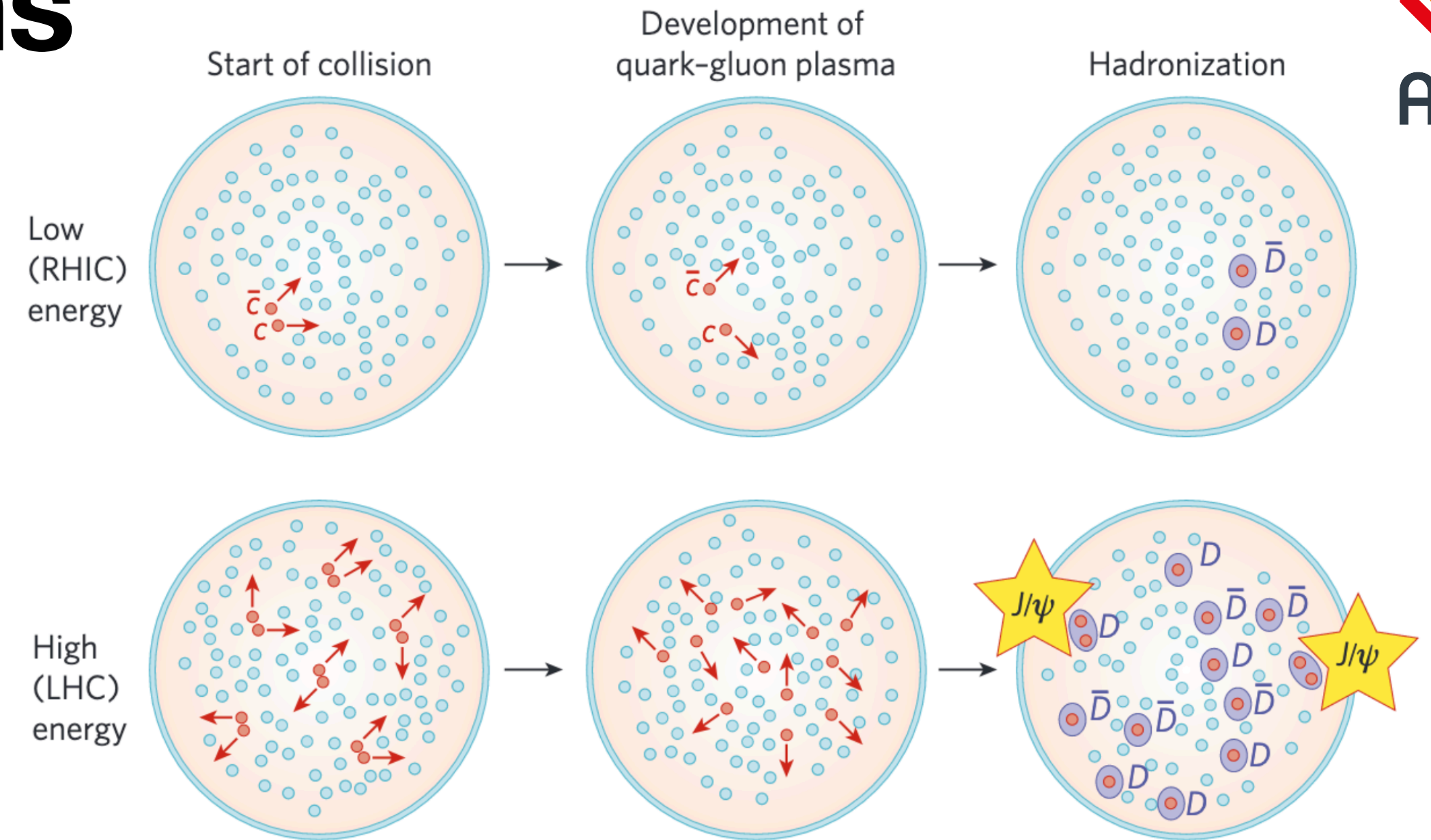
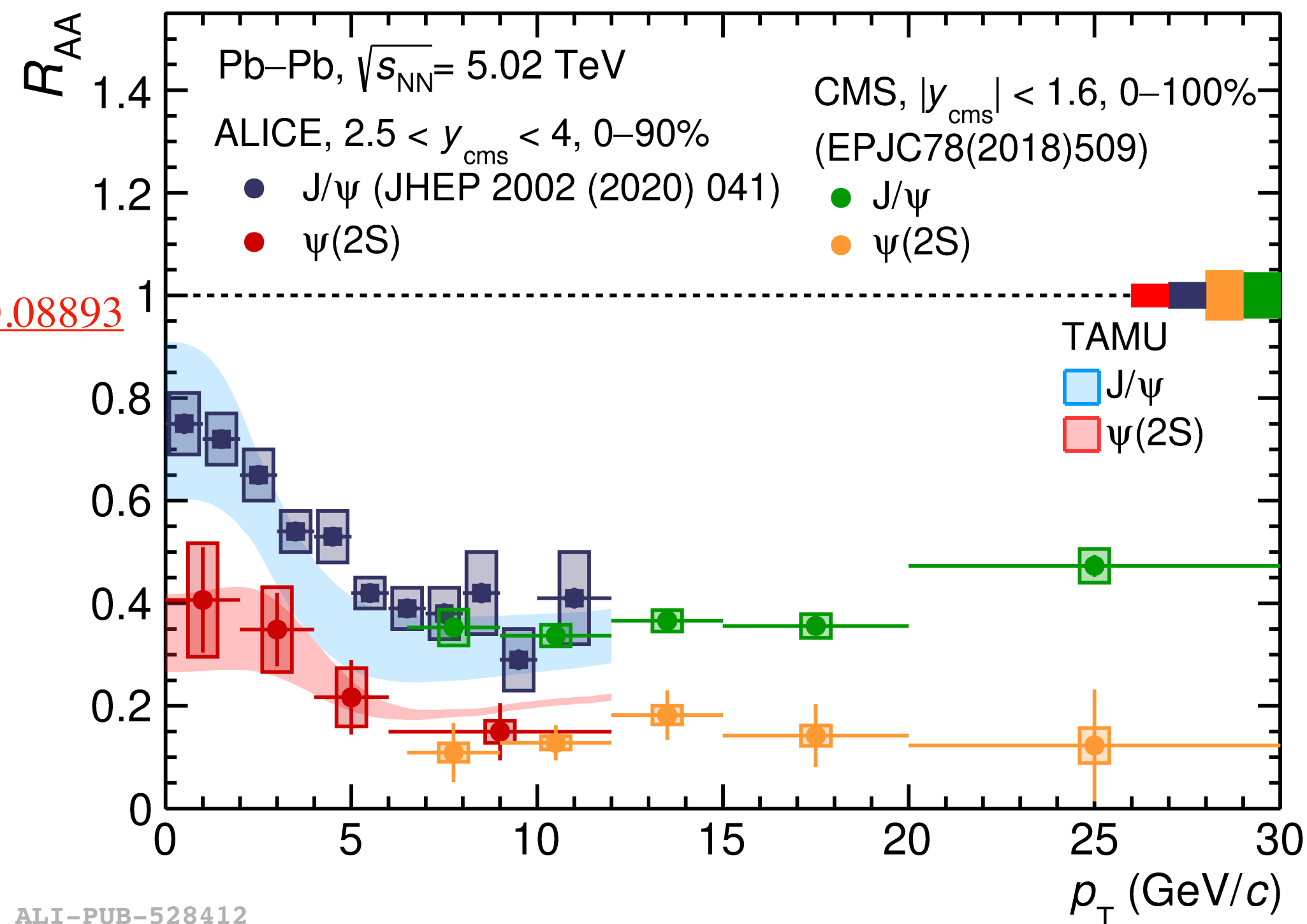
J/ψ nuclear modification factor (R_{AA})



NEW PAPER:
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- 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 and showing a rising trend towards lower p_T
- $R_{AA}^{mid-y} > R_{AA}^{fwd-y}$ (low p_T) as expected by recombination scenario ($N_{c\bar{c}}^{mid-y} > N_{c\bar{c}}^{fwd-y}$)

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

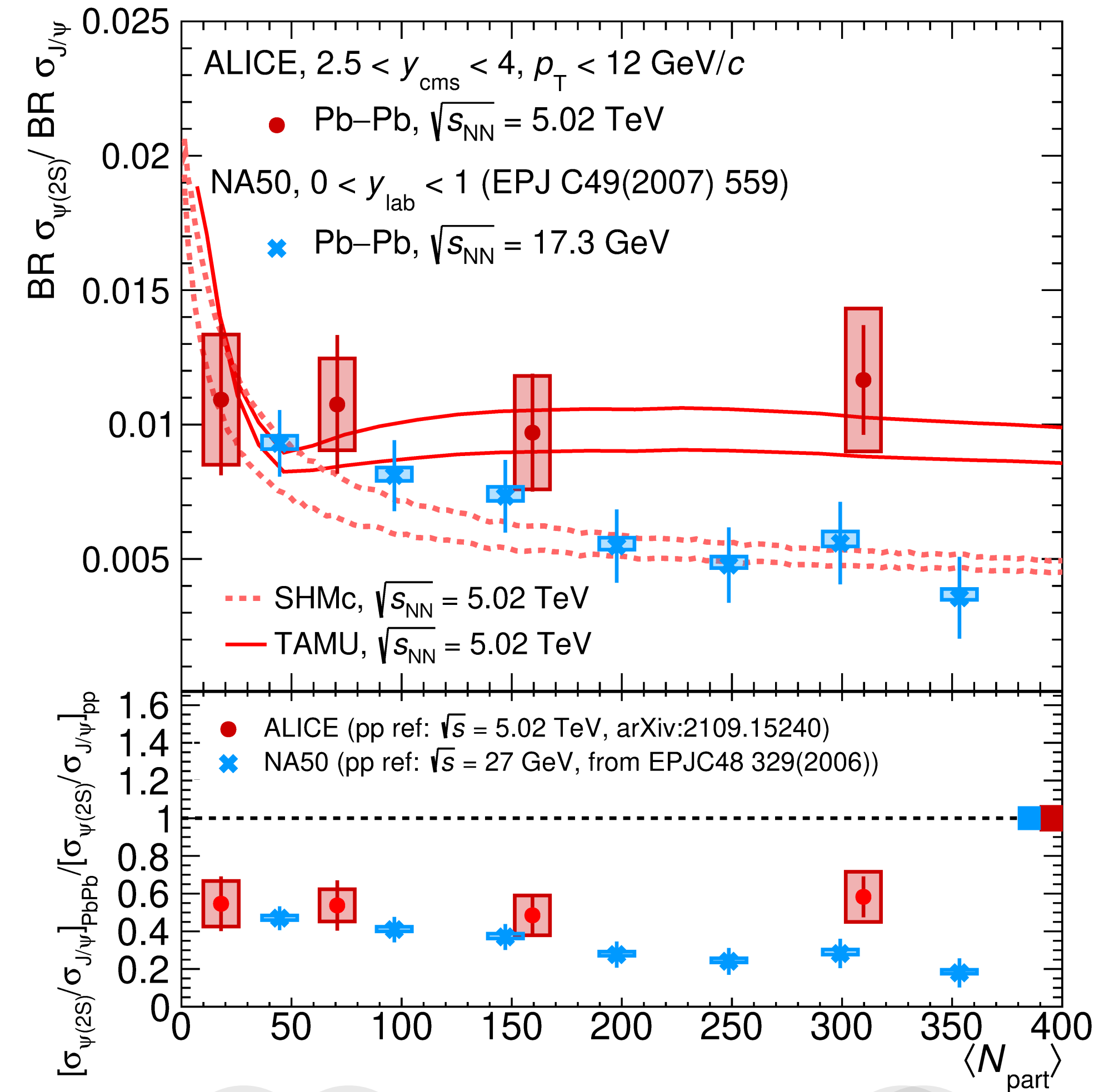


- At low- p_T : **recombination** expected to play an important role for both J/ψ and $\psi(2S)$
- J/ψ and $\psi(2S)$ **suppression hierarchy** over the full p_T range and for centrality integrated
- At high p_T : agreement with CMS data ($|y_{cms}| < 1.6$) where **energy loss** calculations provide a good description here for the J/ψ (see figures in previous slides)

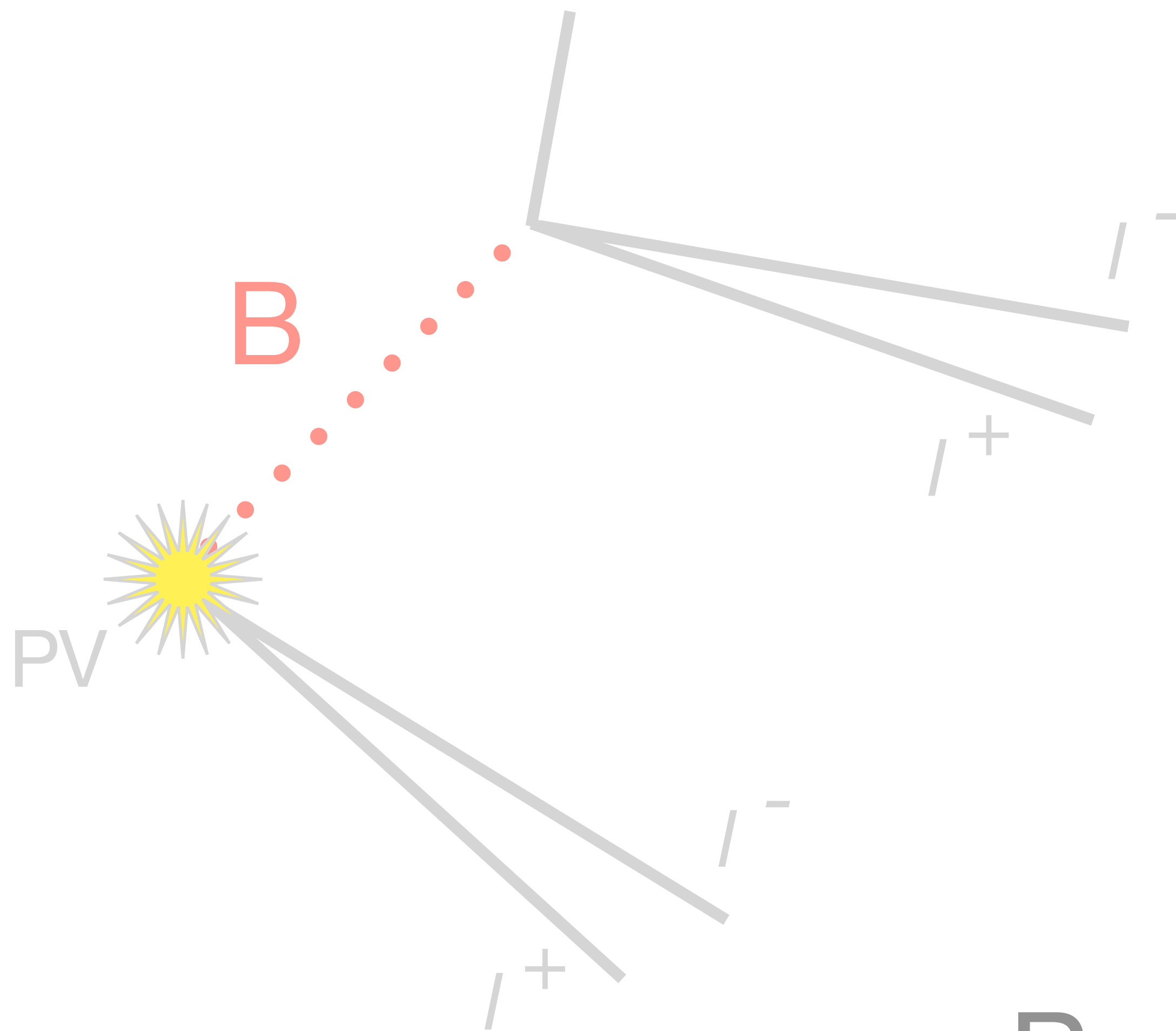
$\psi(2S) / J/\psi$ ratio in Pb-Pb collisions

[arXiv:2210.08893](https://arxiv.org/abs/2210.08893)

- 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)
- No evidence of centrality dependence
- Strong suppression of the $\psi(2S) / J/\psi$ ratio in PbPb w.r.t pp



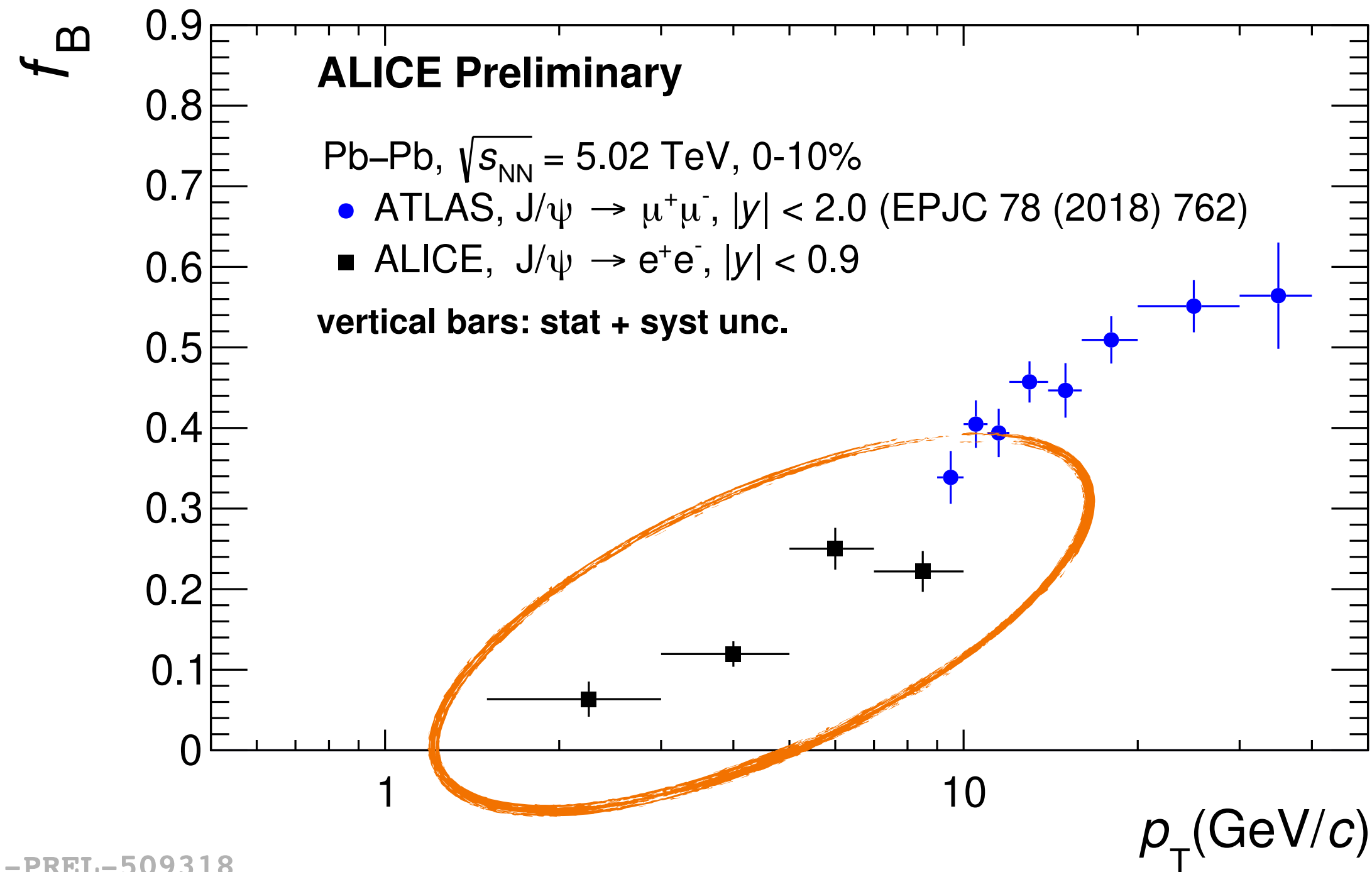
ALI-PUB-528400



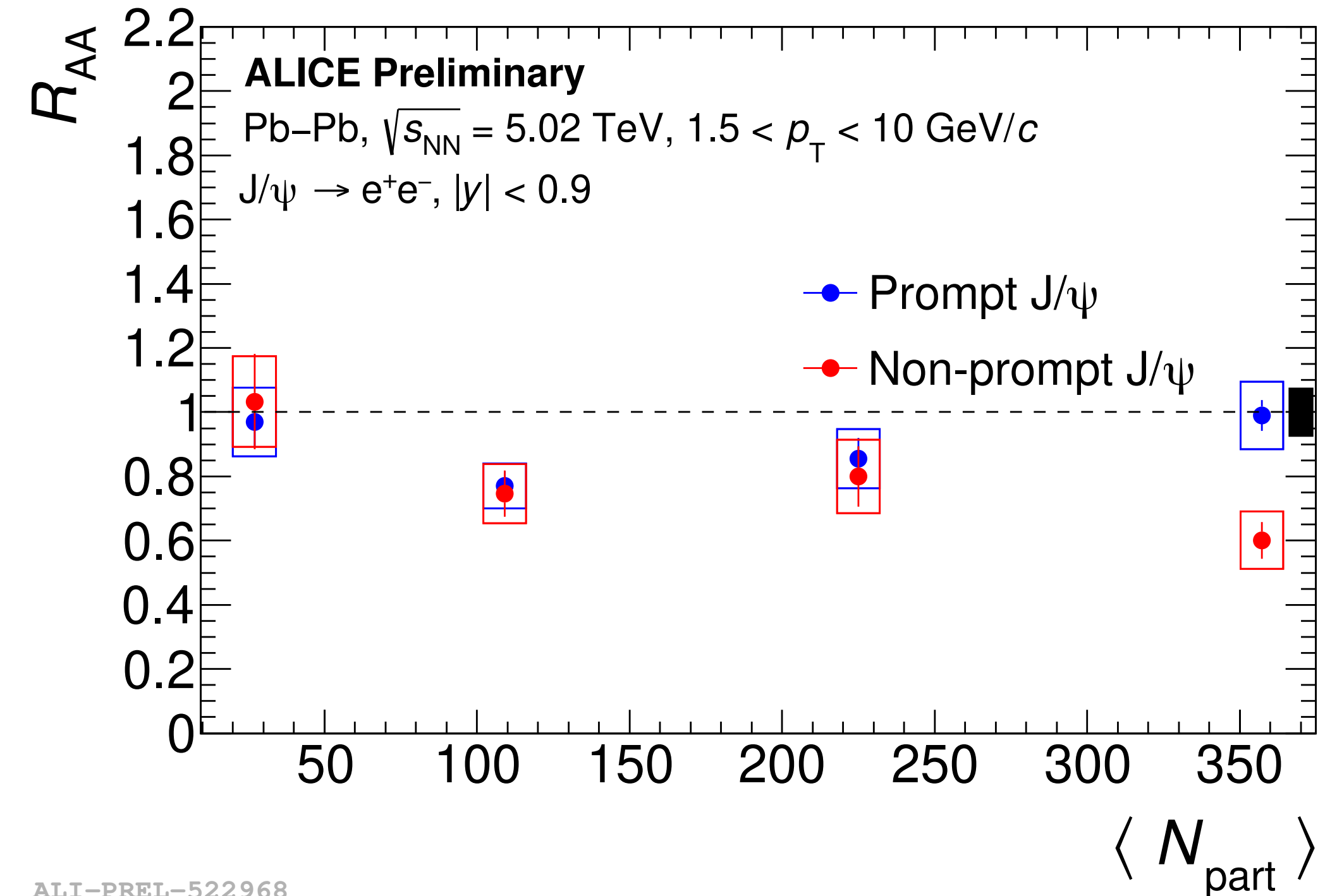
Non-prompt J/ψ

Prompt J/ψ

Prompt/non-prompt J/ψ production in Pb-Pb collisions



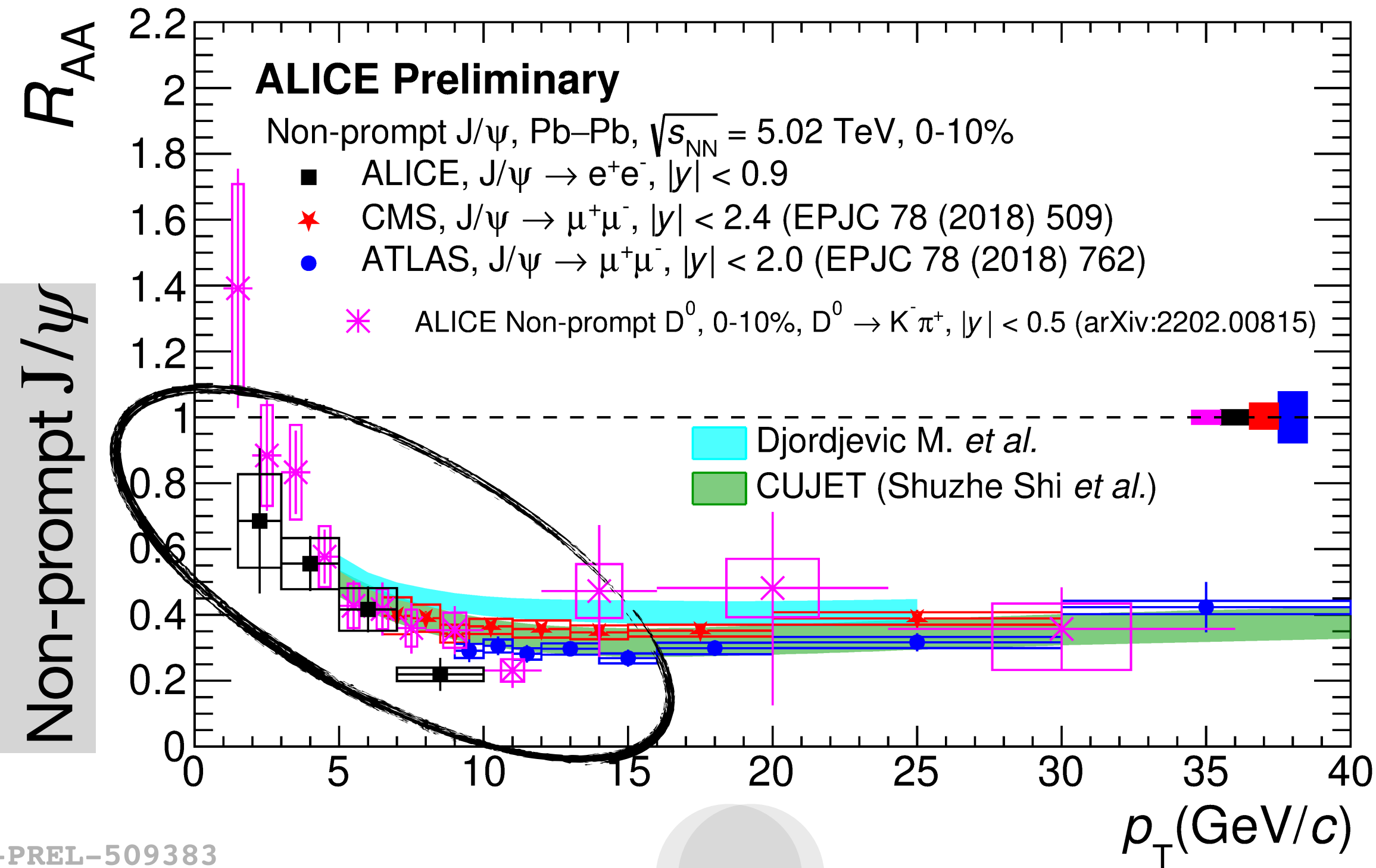
ALI-PREL-509318



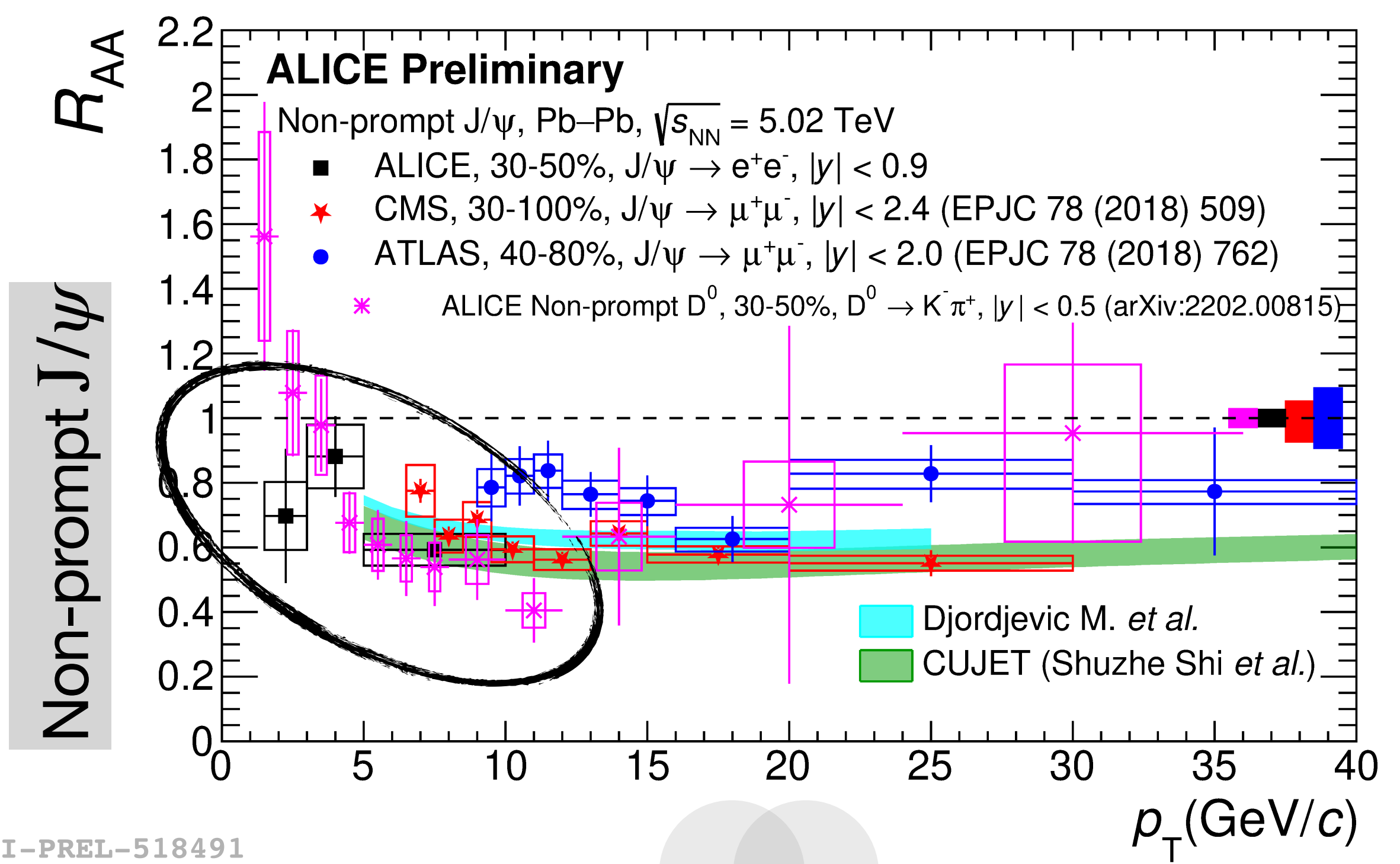
ALI-PREL-522968

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

Measuring beauty from non-prompt J/ψ in Pb-Pb



ALI-PREL-509383



ALI-PREL-518491

- Measurements of non-prompt J/ψ and non prompt D^0 mesons give access to b -hadron suppression at low p_T
- Models including **collisional and radiative energy loss** consistent with data (high p_T)

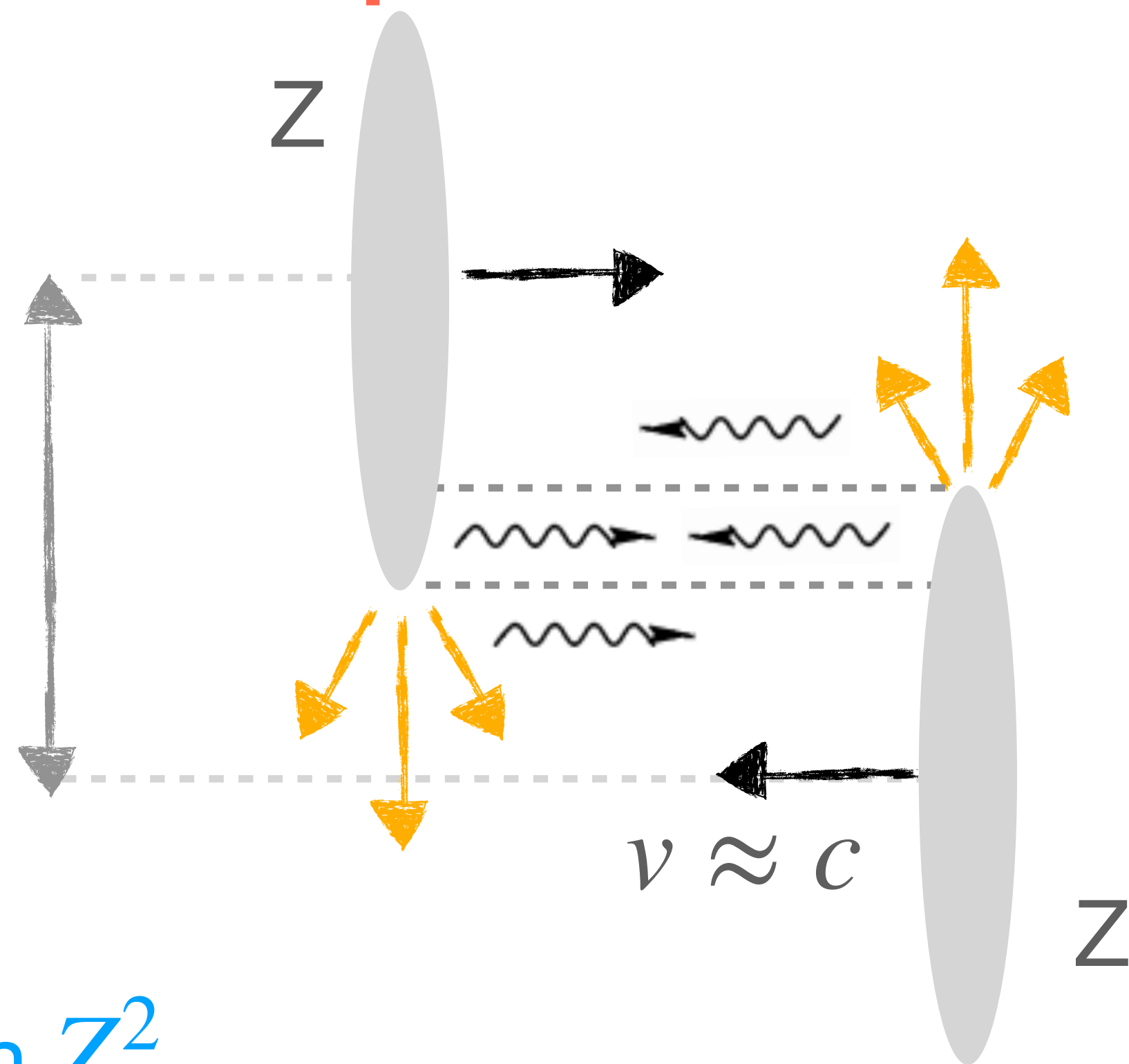
Photo-produced J/ψ



UPC:

$$b > R_1 + R_2$$

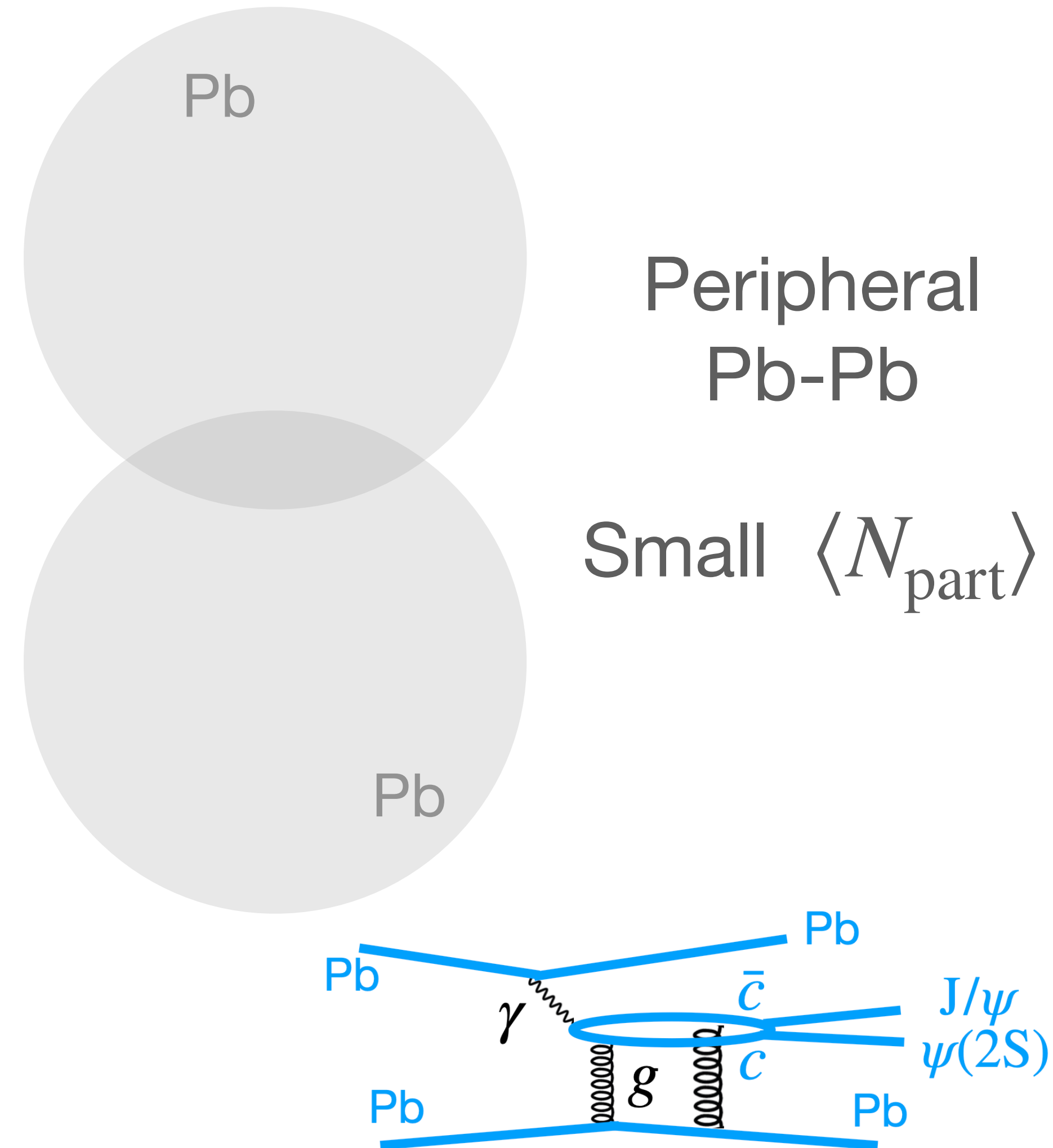
$$b < R_1 + R_2$$



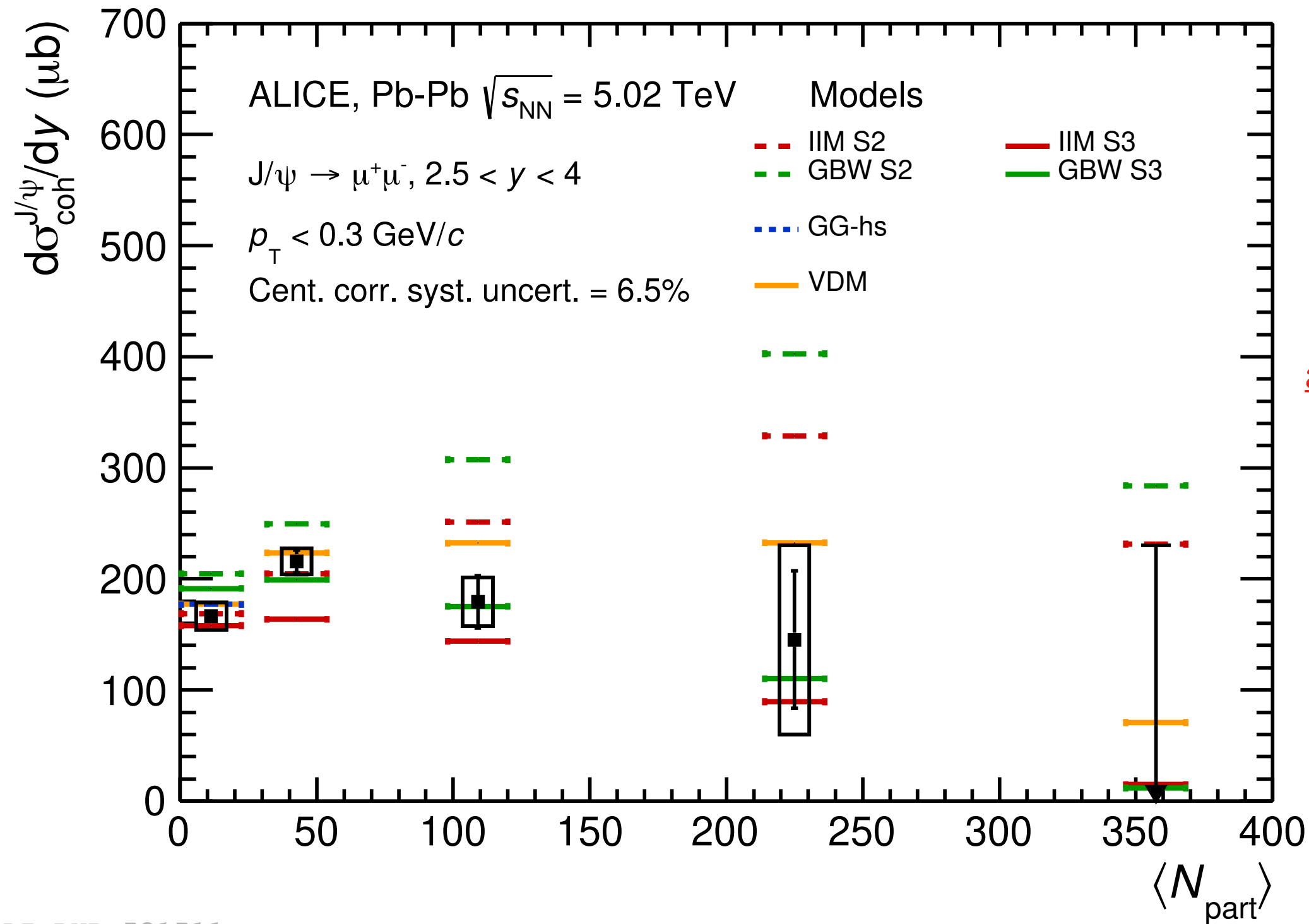
γ flux grows with Z^2

EM field carried by ultrarelativistic Pb nuclei

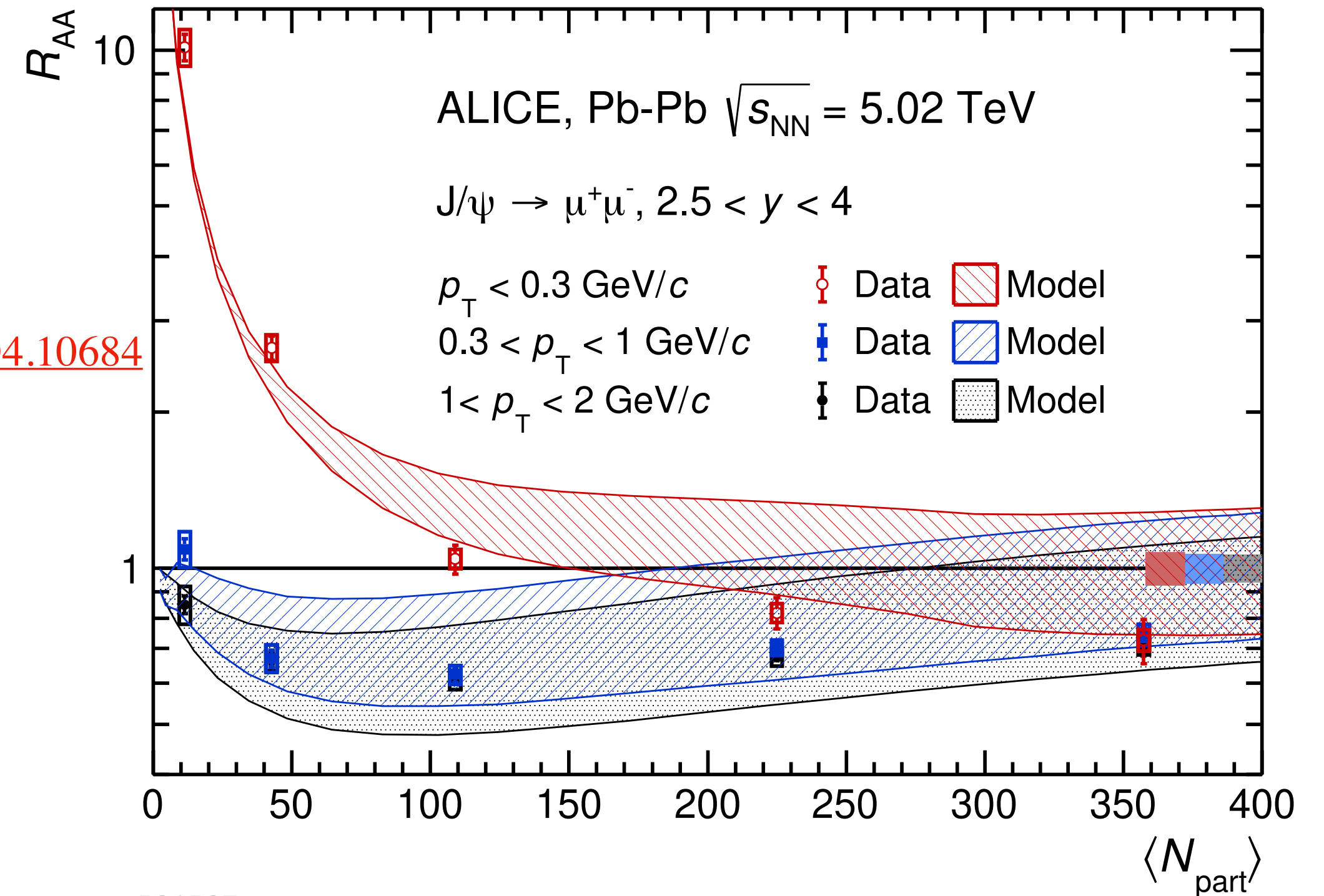
(Coherently) photo-produced J/ψ present in Pb-Pb collisions with nuclear overlap, with characteristic production peak at $p_T \sim 60 \text{ MeV}/c$



J/ψ photoproduction in Pb-Pb at forward rapidity



[arXiv:2204.10684](https://arxiv.org/abs/2204.10684)

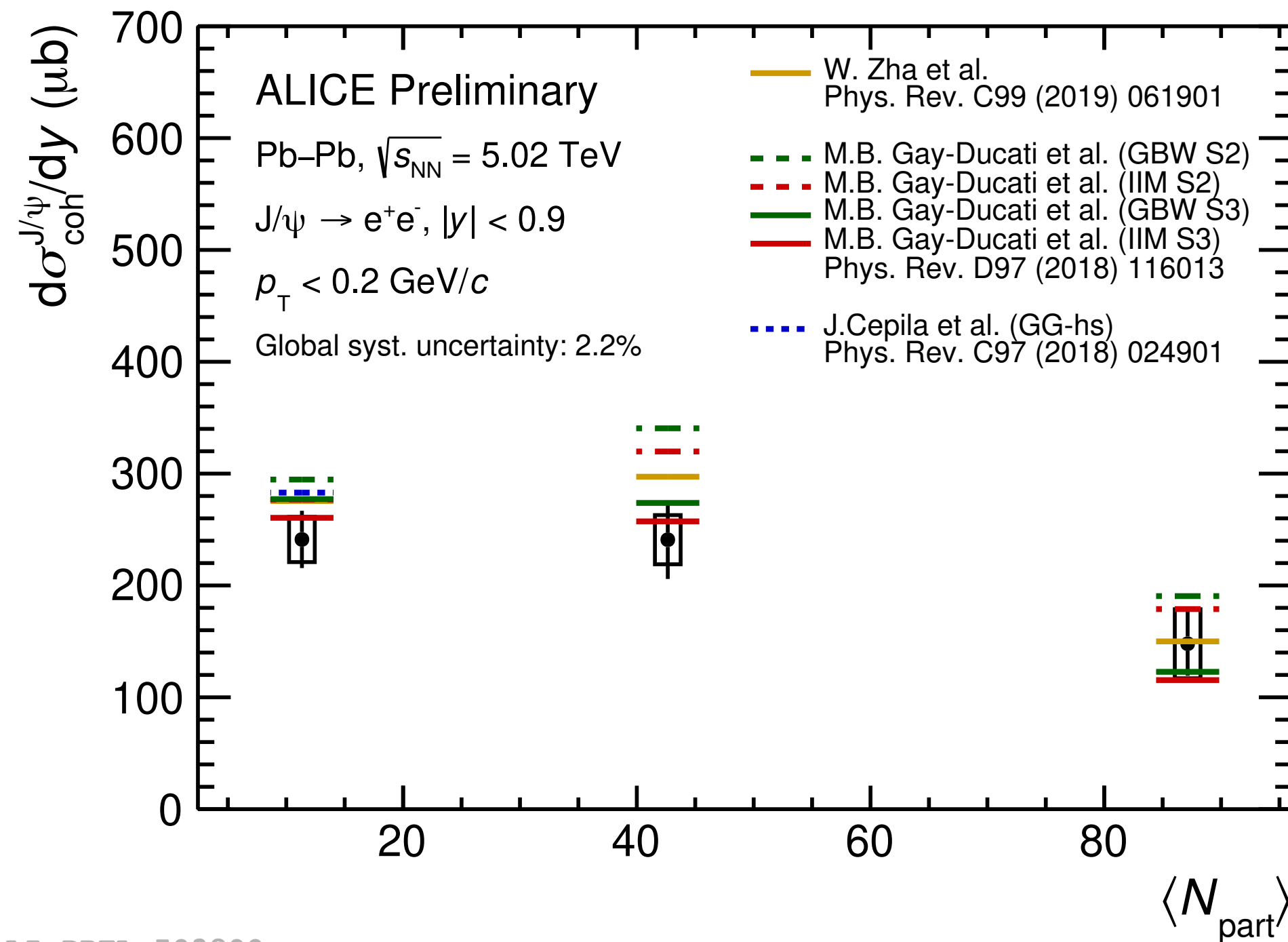


ALI-PUB-521511

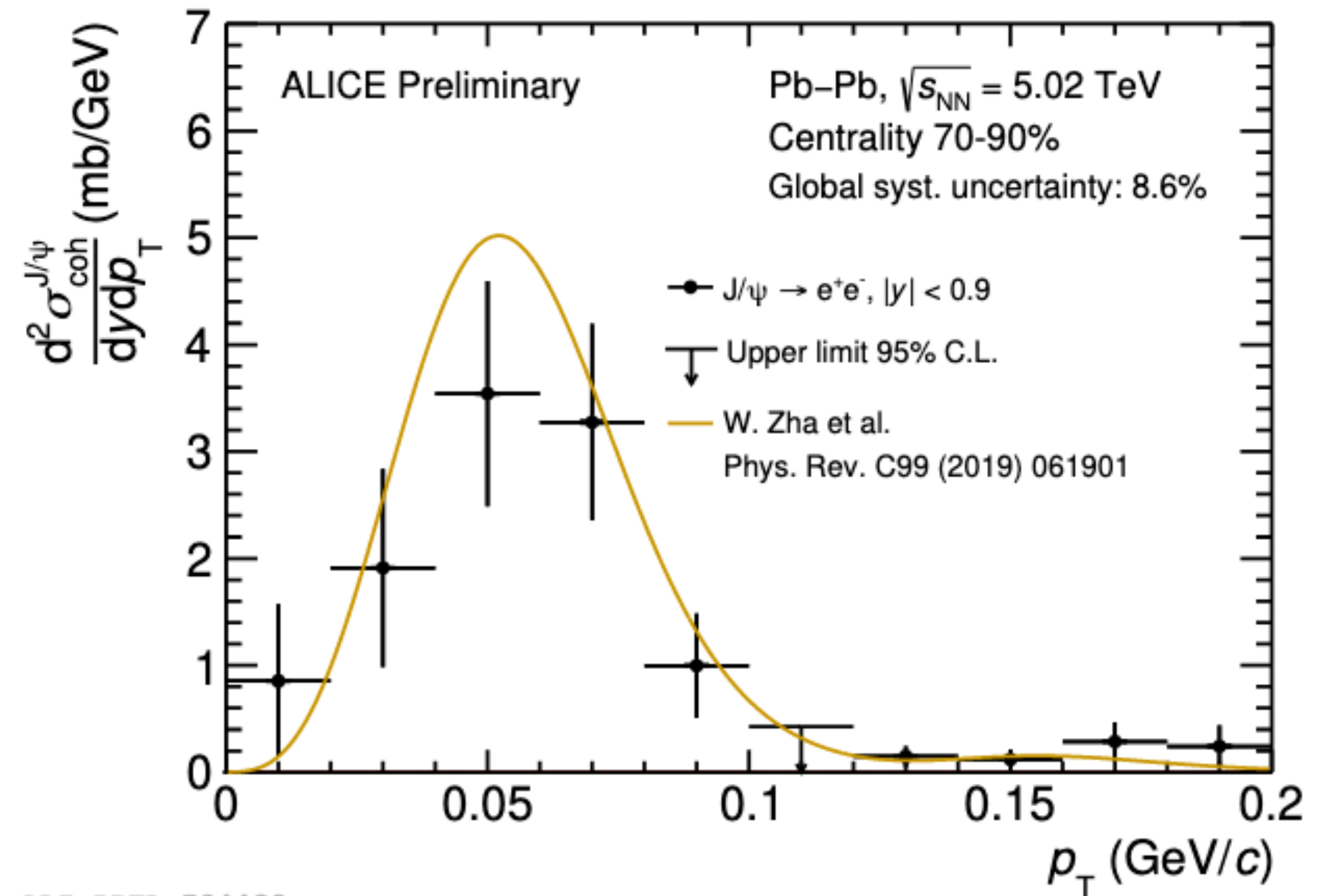
ALI-PUB-521507

- Clear **observation** of J/ψ excess at very low p_T , **photoproduction not only in UPCs**
- EM fields are producing abundantly J/ψ for $p_T < 0.3$ GeV/c. Data are compatible with the “S3” scenario **I** (where the overlap region is assumed to not contribute to σ_{coh}) and with **VDM** (modification of the photon γ flux only)

J/ψ photoproduction in Pb-Pb at midrapidity



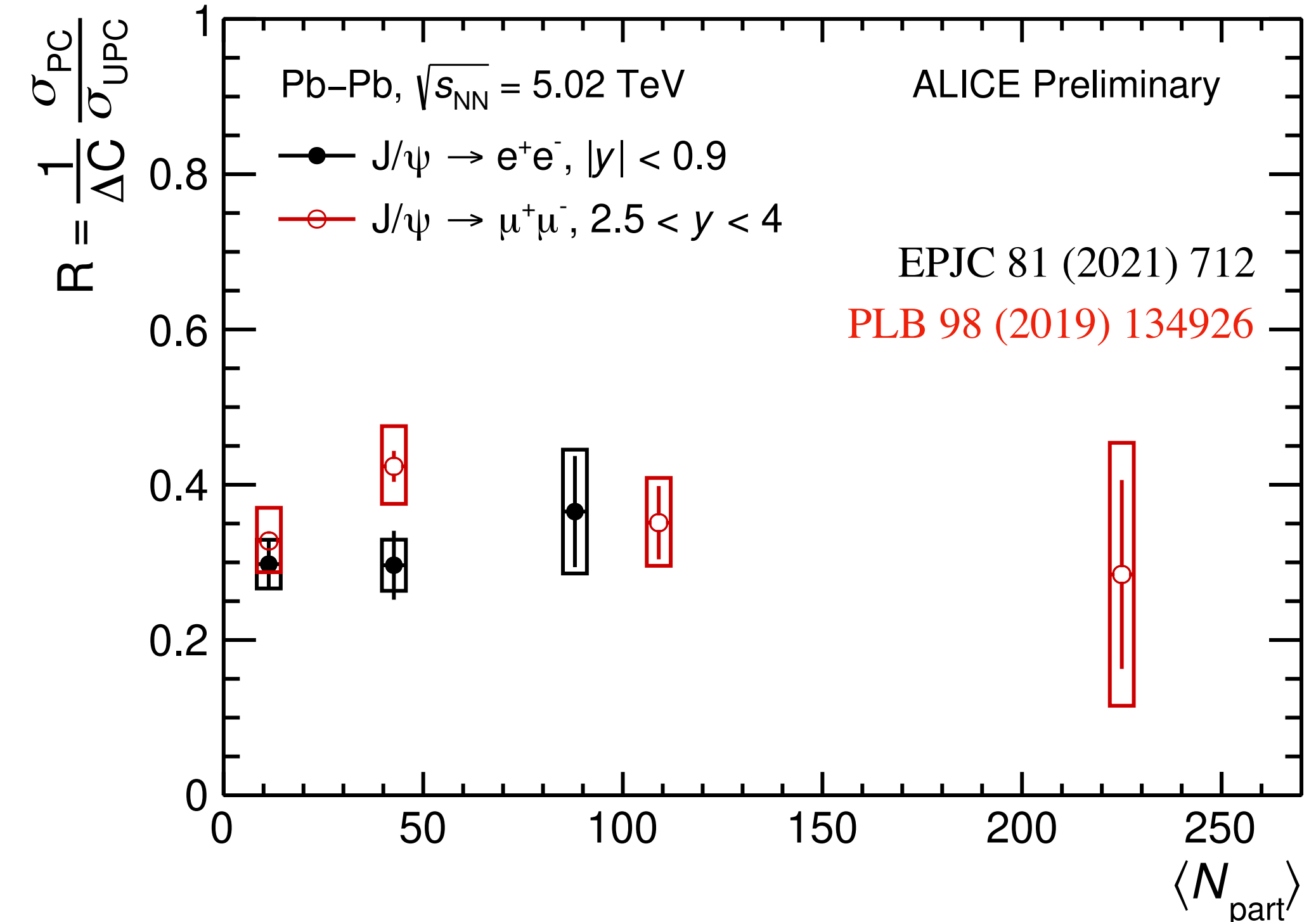
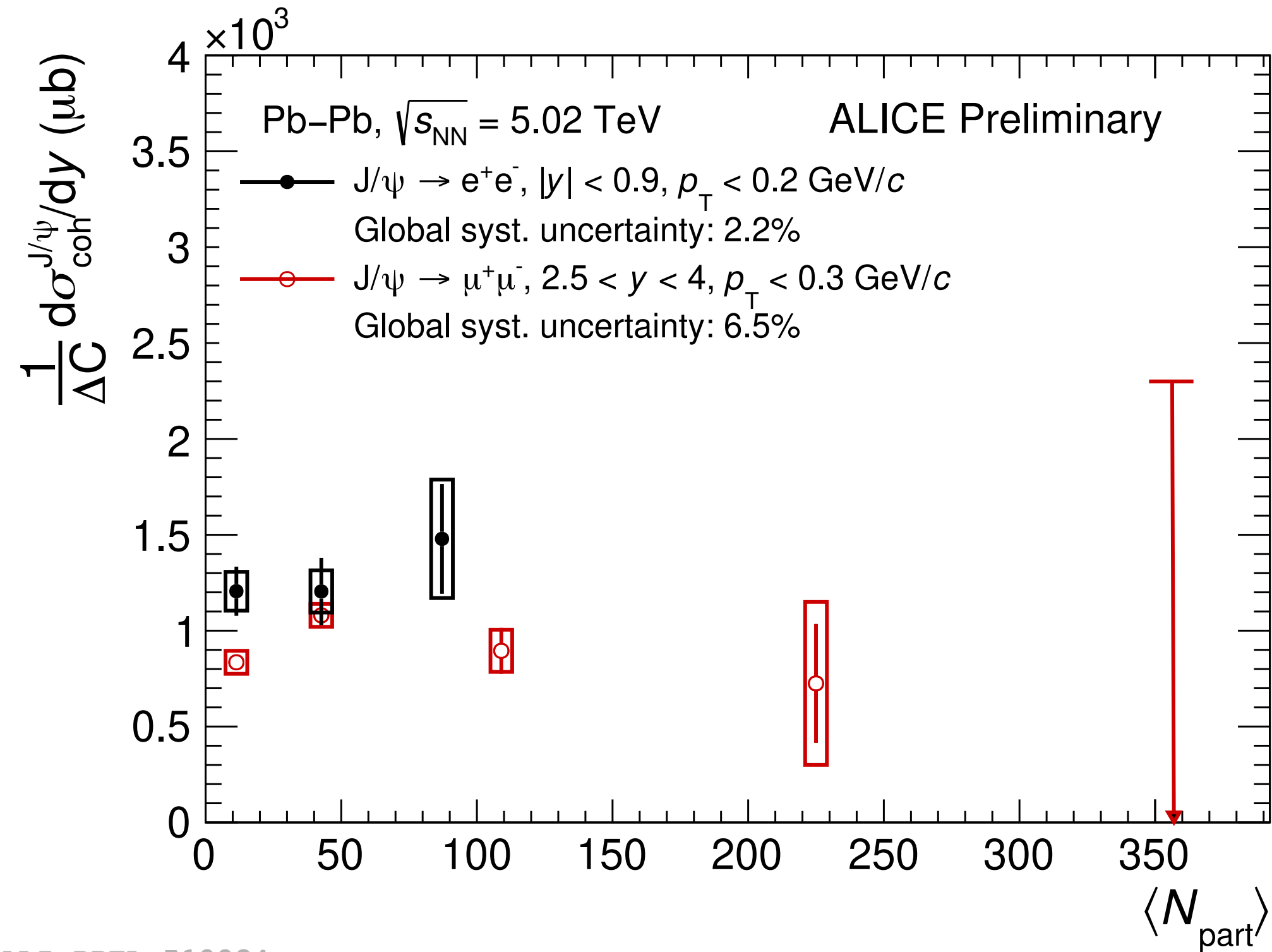
ALI-PREL-503800



ALI-PREL-504480

- Clear **excess** observed in the J/ψ production in peripheral Pb-Pb at mid-y ($p_T < 0.2$ GeV/c)
- Models including at least γ flux (+ possibly $\sigma_{\gamma\text{Pb}}$) modification can explain the data for both y
- In addition model (W. Zha et al.) adding **destructive interferences** can describe the p_T dependence of $d^2\sigma/dp_T dy$

Coherent J/ψ production with nuclear overlap, normalized to UPC



ALI-PREL-519984

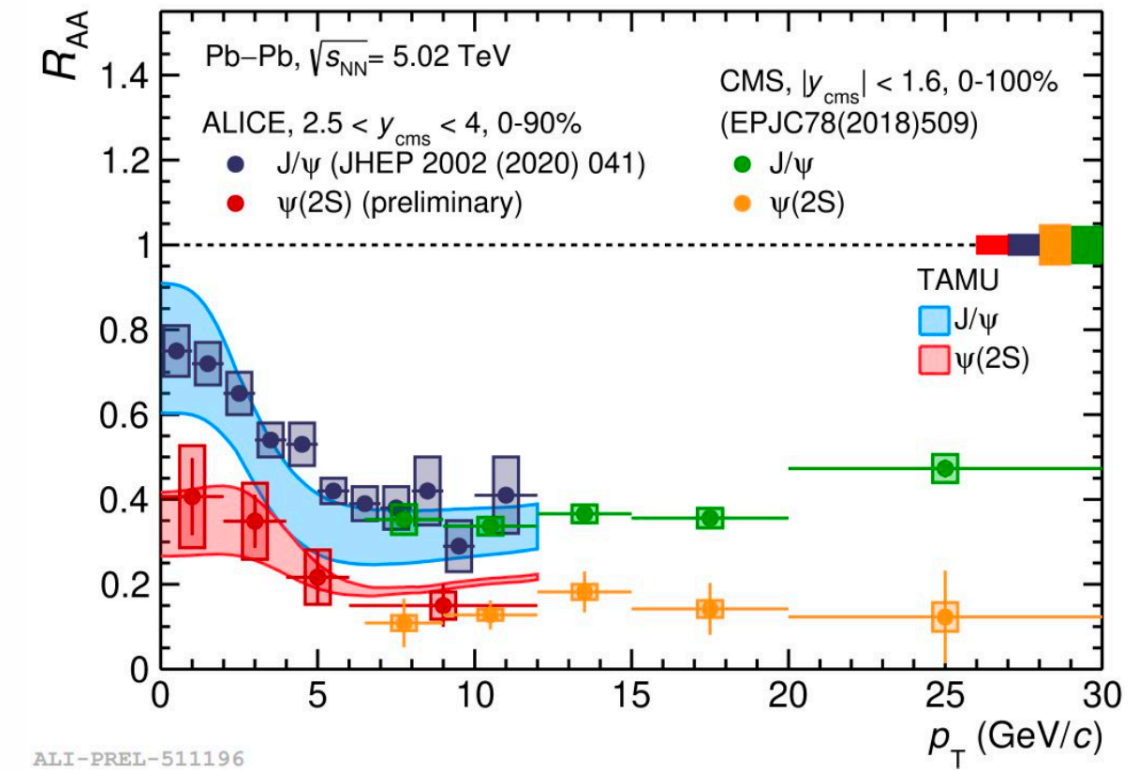
ALI-PREL-519979

- No clear evidence of centrality dependence of the coherent J/ψ cross-section at mid and forward rapidity, also the case for the ratio: $R = \frac{1}{\Delta C} \frac{\sigma_{PC}}{\sigma_{UPC}}$

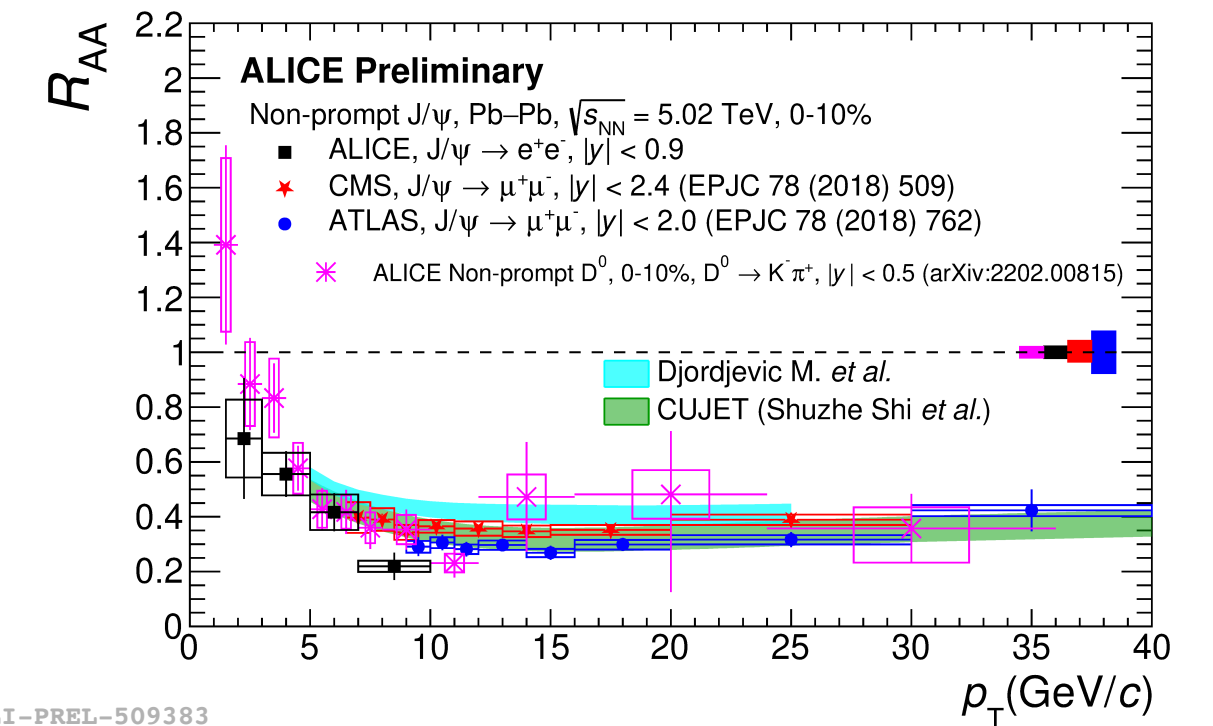
Summary



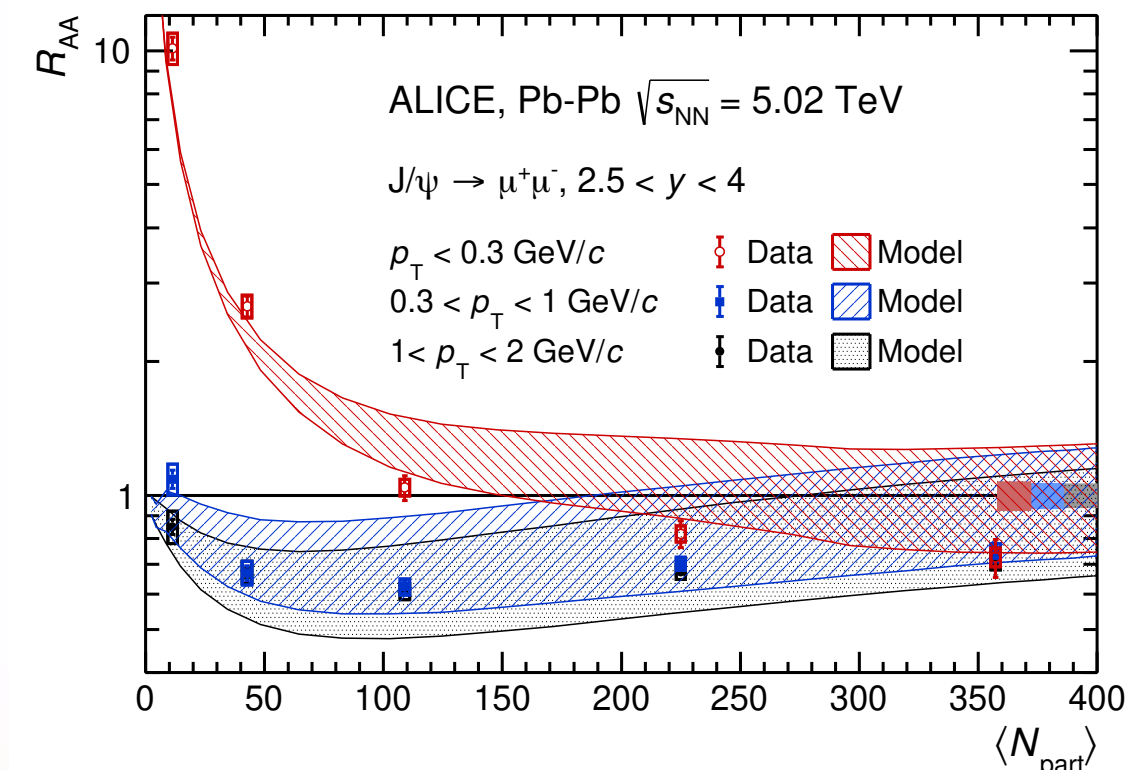
- **Sequential suppression** well studied for bottomonia but now also observed for charmonia, hint of low- p_T $\psi(2S)$ recombination
- Prompt J/ψ less suppressed towards more central collisions (charm quark recombination)
- Non-prompt J/ψ high p_T data could be explained by models including **collisional and radiative energy loss**
- **Observation** of coherent J/ψ photoproduction in different y regions not only in UPC but also in peripheral Pb-Pb collisions, where EM fields are competing with the strong interactions



ALI-PREL-511196



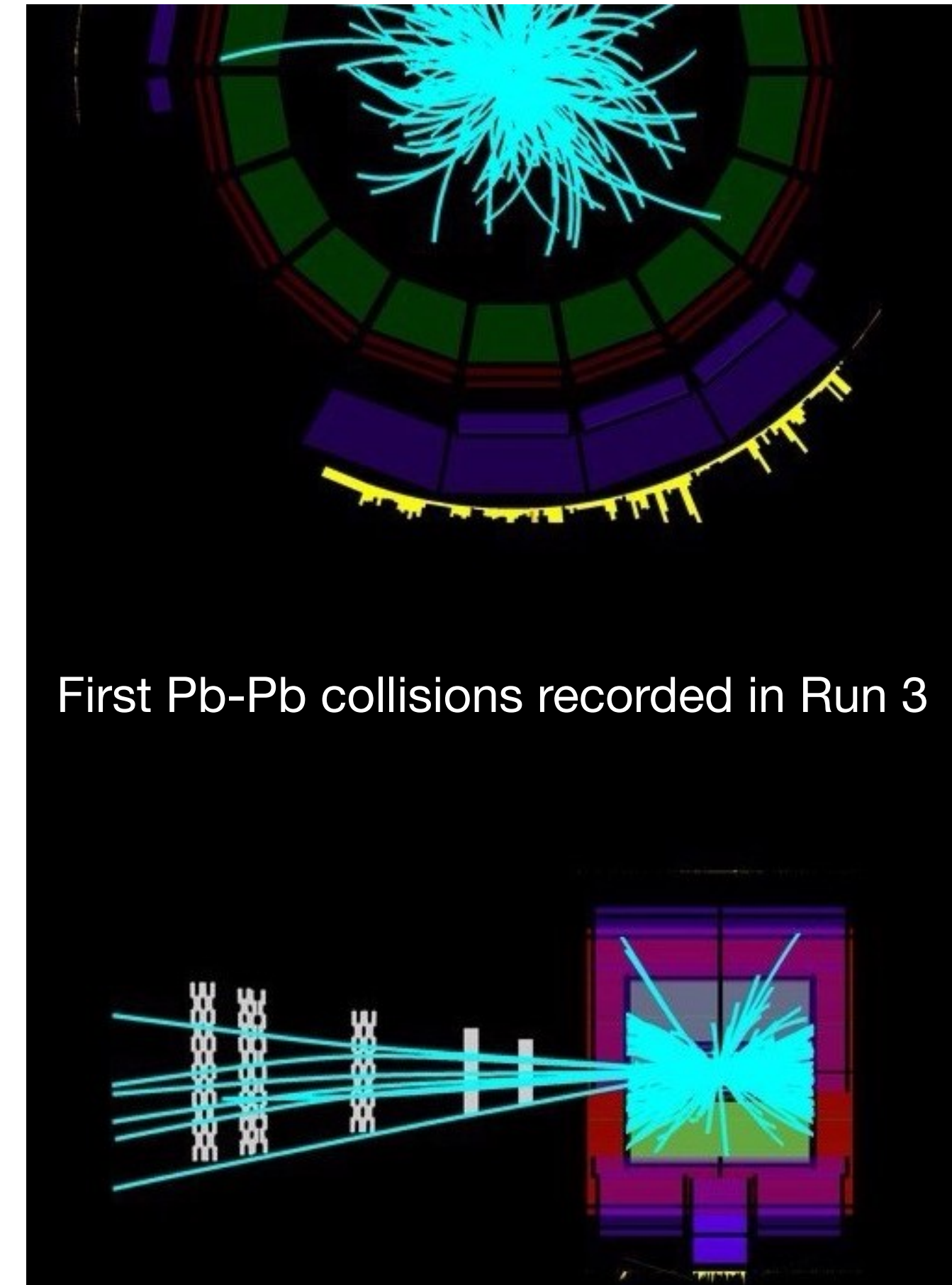
ALI-PREL-509383



ALI-PUB-521507

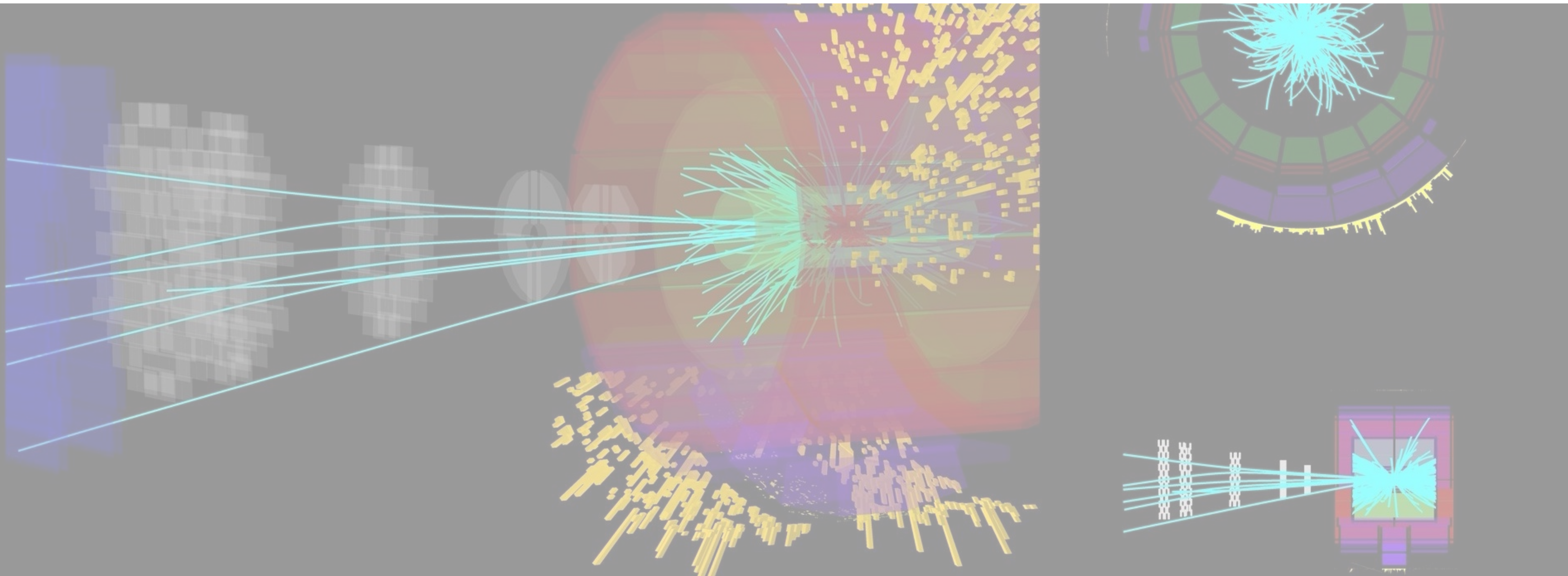
Prospect for Run 3

- Larger data sample → will benefit for both mid & forward y
- New muon forward silicon tracker (MFT) will allow prompt vs non-prompt separation for both J/ψ , $\psi(2S)$
- First $\psi(2S)$ azimuthal anisotropy (v_2) down to low- p_T , azimuthal distributions & polarisation of photoproduced J/ψ
- Excellent momentum resolution will allow p_T -differential charmonium σ_{coh} measurements (with the study of full nucleus vs spectators for the coherence condition)
- Study of possible interaction of photoproduced $J/\psi \leftrightarrow$ QGP
- Photoproduced J/ψ could be a completely new probe of the charmonium dissociation in the QGP



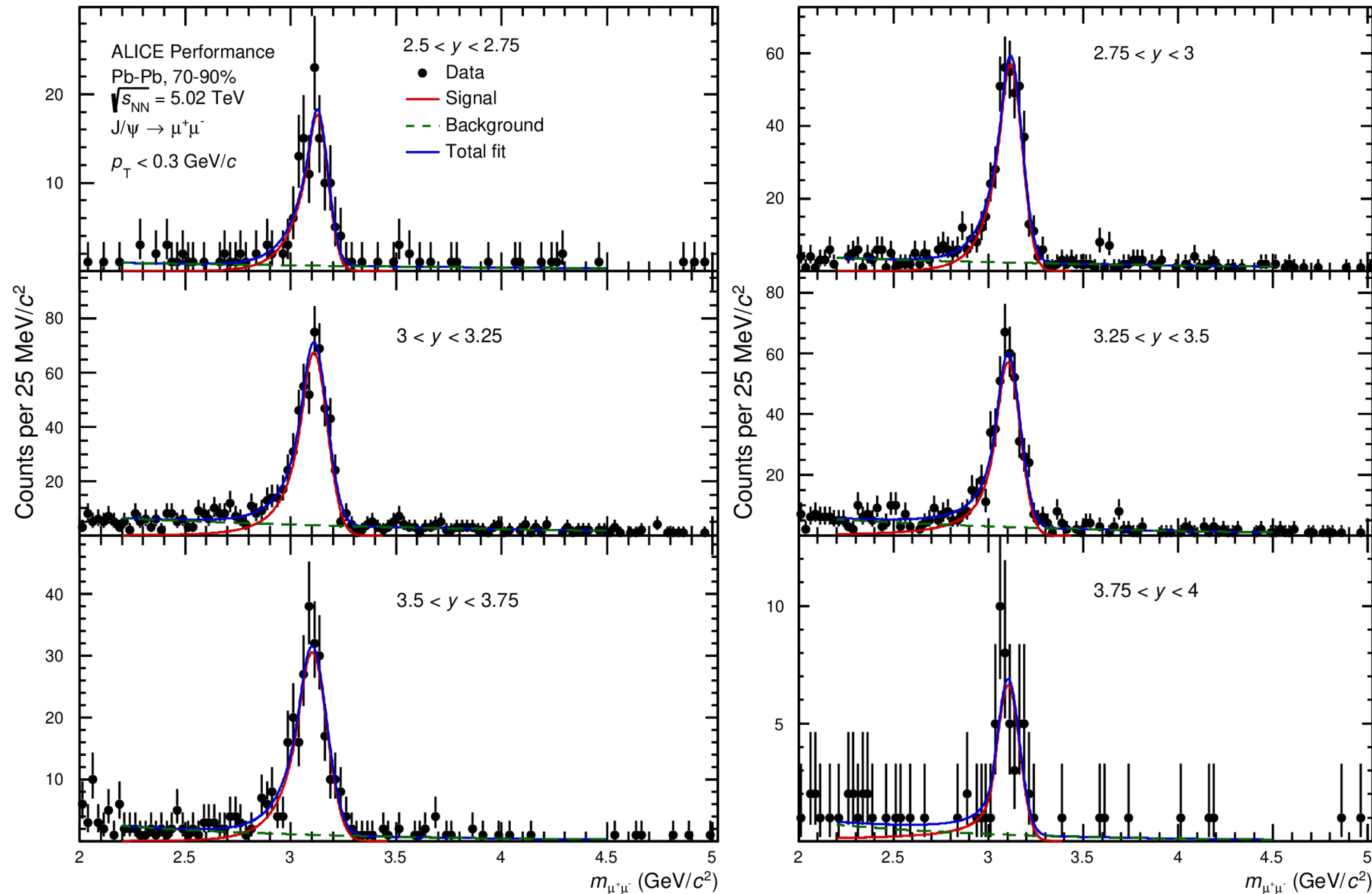
First Pb-Pb collisions recorded in Run 3

Thank you for your attention!



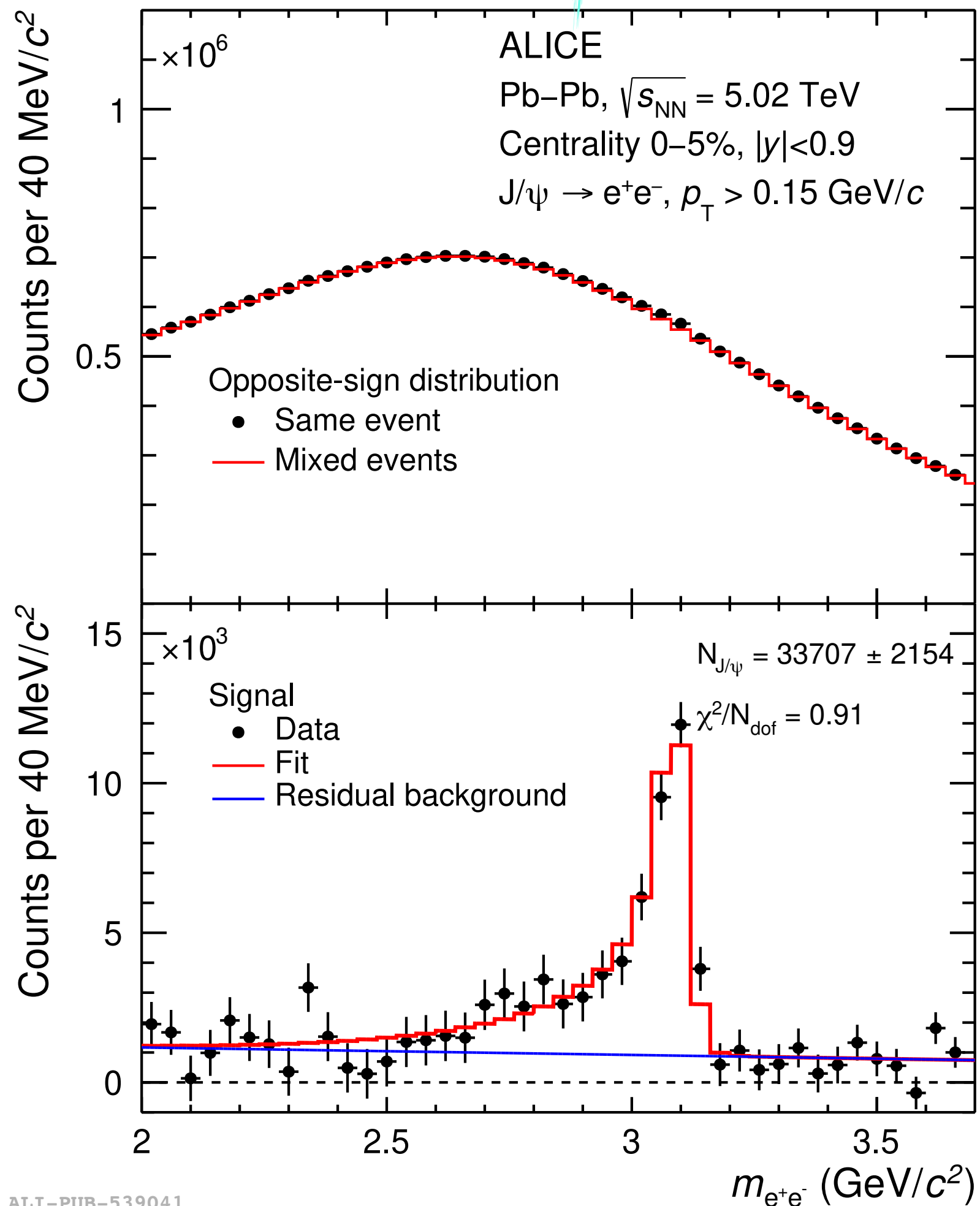
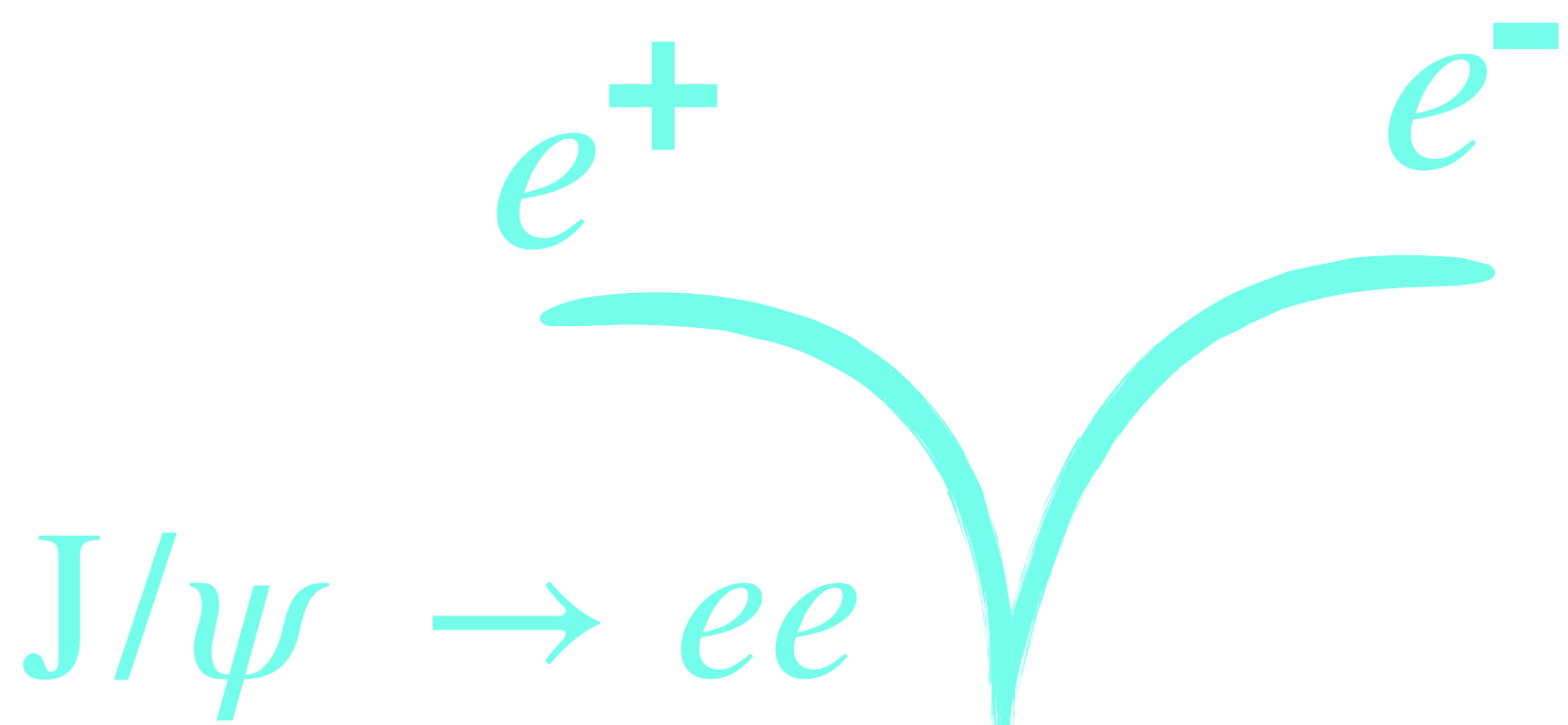
Run 3 started: new measurements are coming soon

Ongoing y -differential J/ψ photoproduced measurement in Pb-Pb

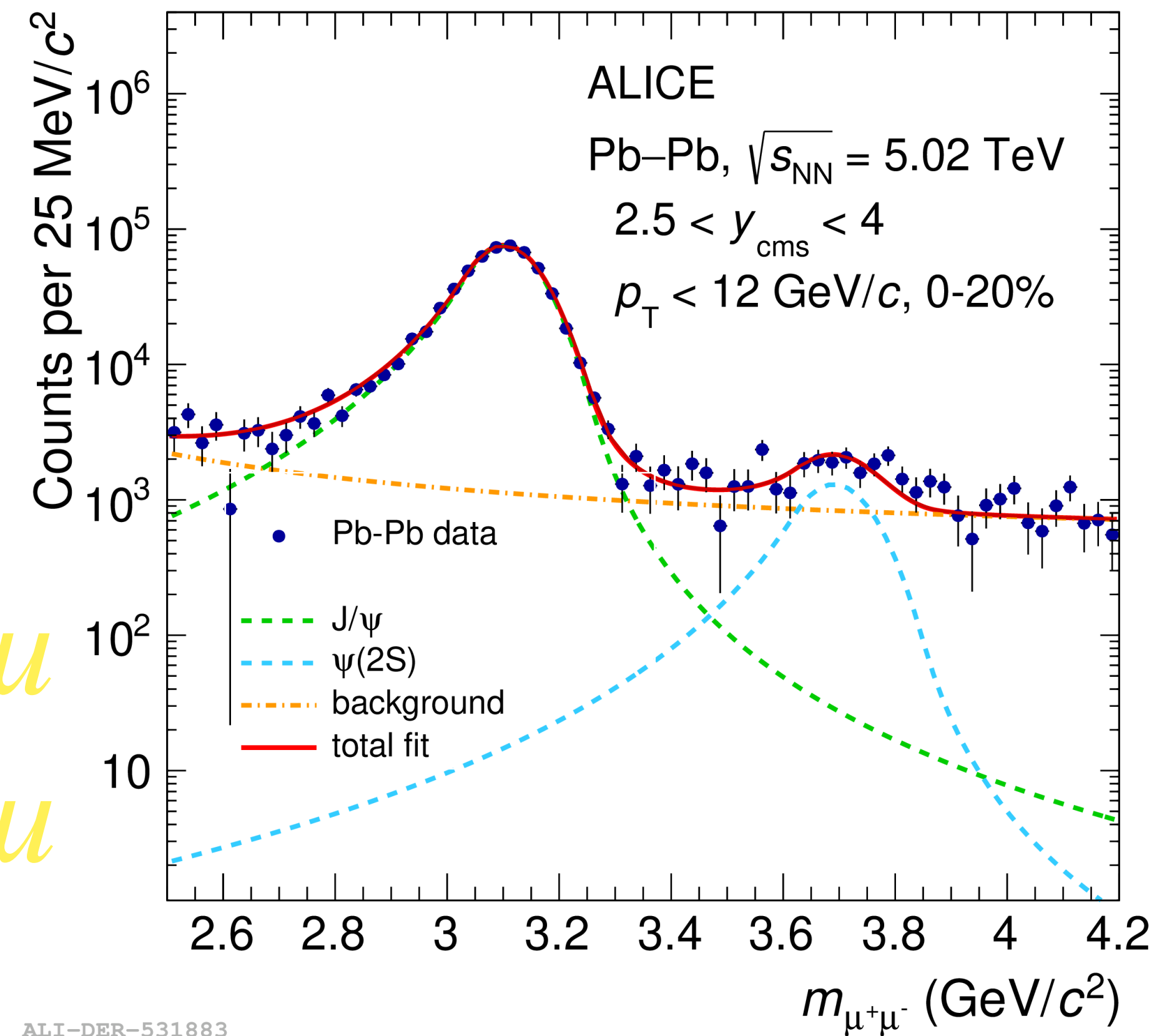
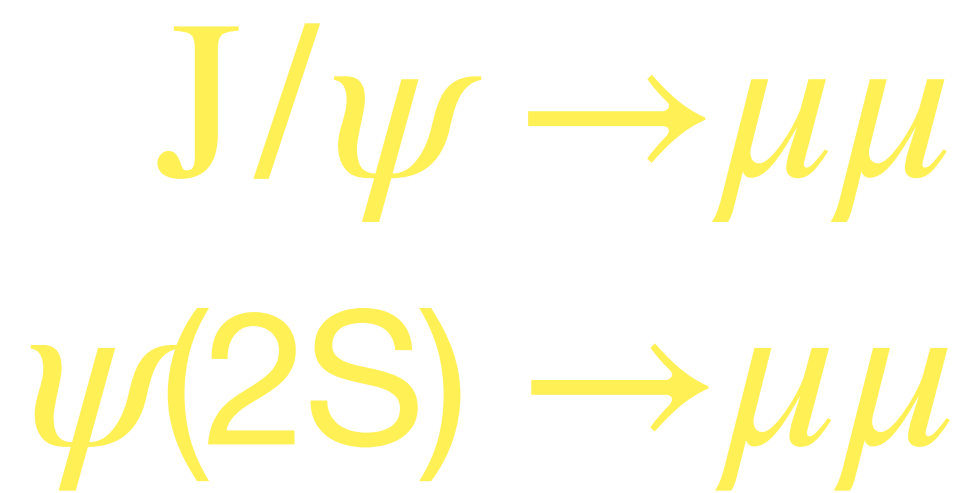
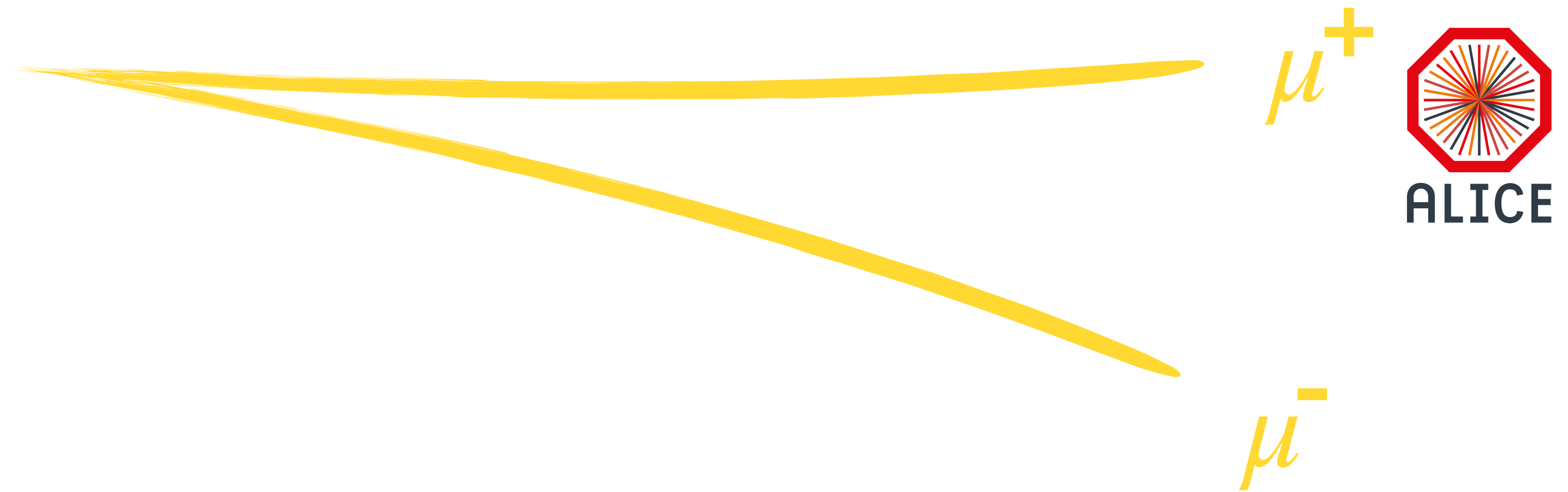


**NEW RESULT SOON:
ONGOING ANALYSIS**

- Large dimuon candidates collected at forward rapidity allow to perform y -differential extraction
- Important to add more constrains on $d^2\sigma/dp_T dy$

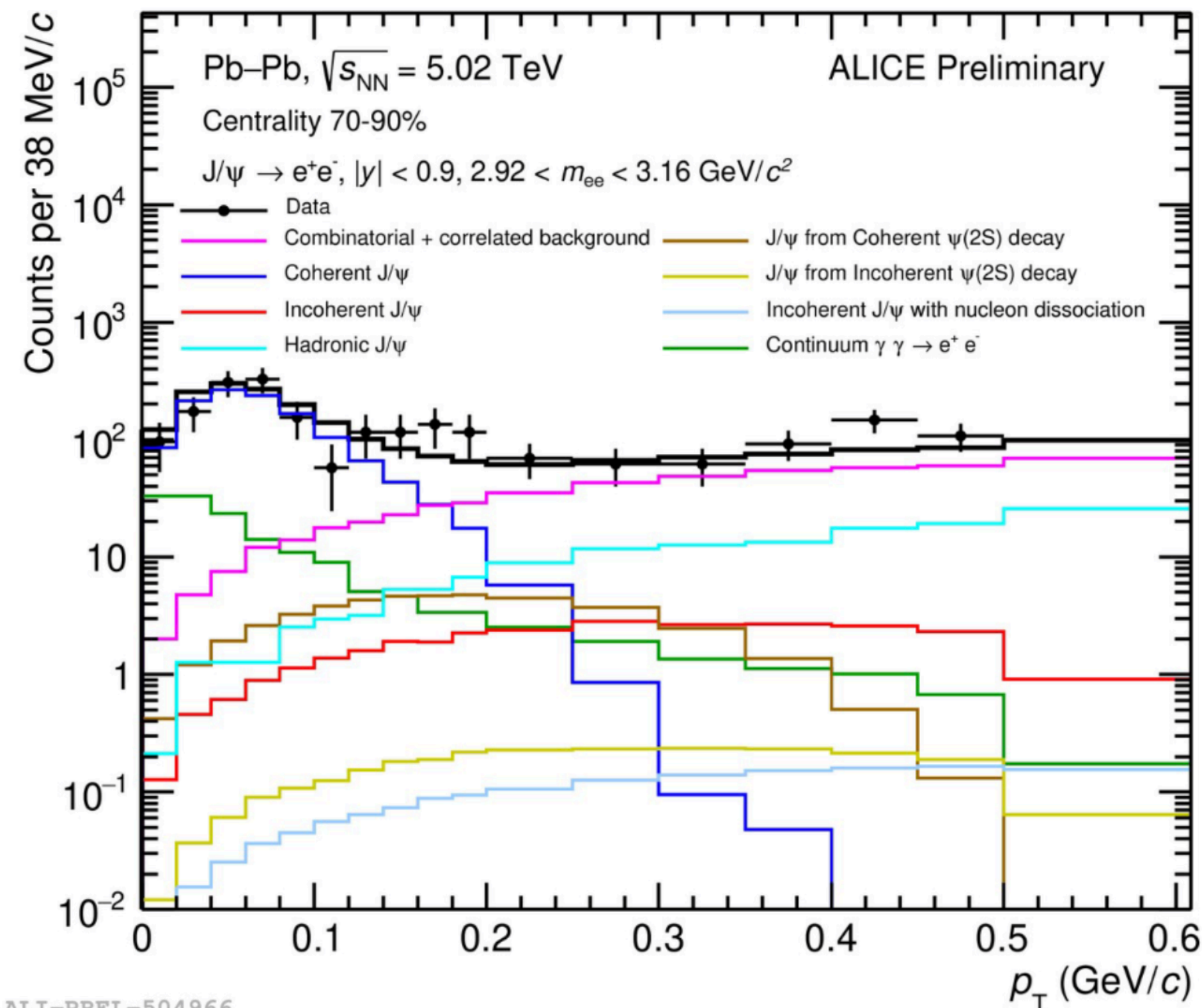


ALI-PUB-539041



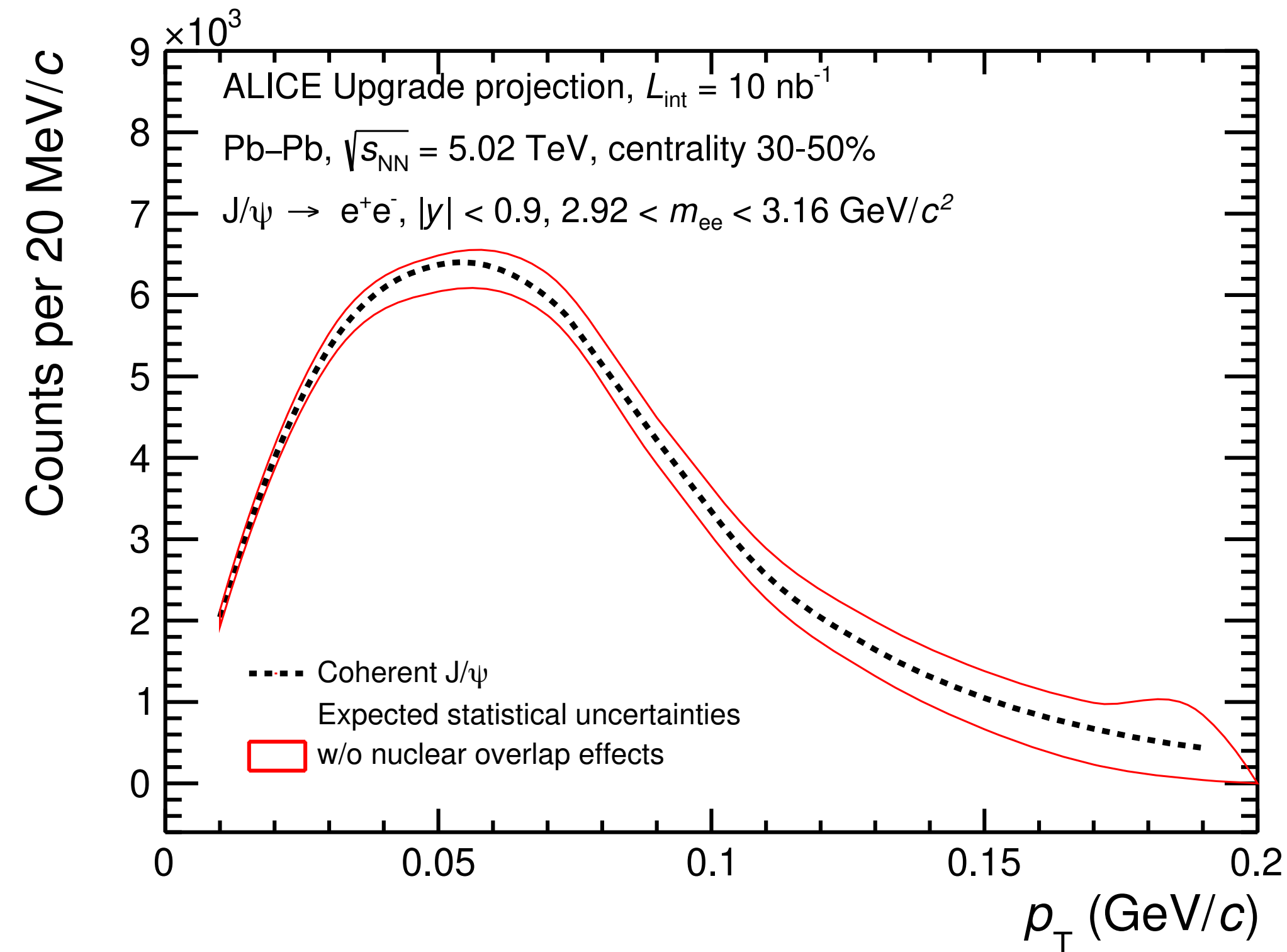
ALI-DER-531883

Extraction of photoproduced J/ψ

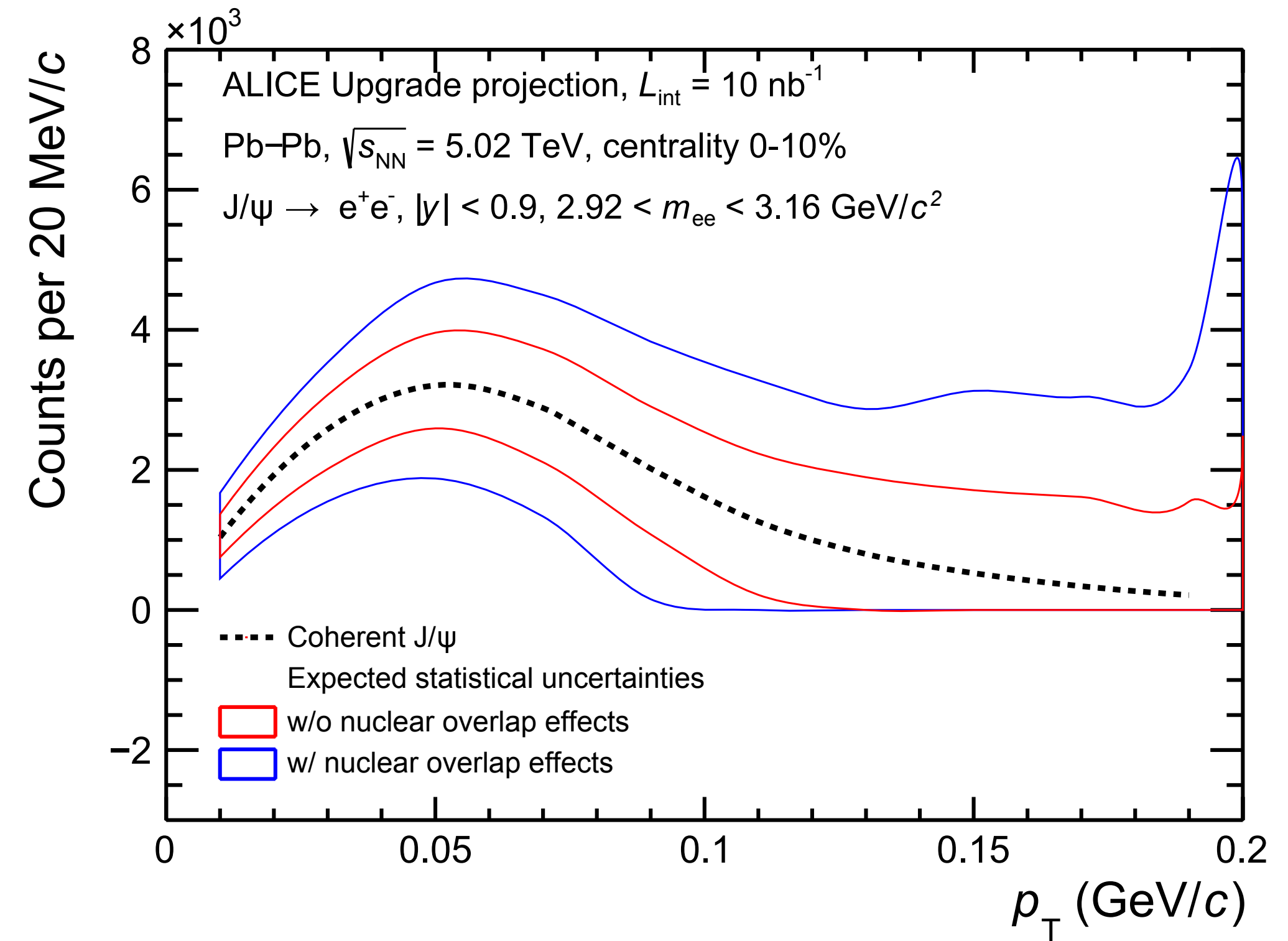


- Coherent production extracted using a template fit:
- Photoproduction components, hadronic J/ψ production, combinatorial and correlated background
- Photoproduction templates based on STARLIGHT simulations:
- coherent J/ψ , incoherent J/ψ (and with nucleon dissociation), feed-down from coh. and incoh. $\psi(2S)$, gamma-gamma continuum

Projection of J/ψ photoproduction in Pb-Pb at midrapidity



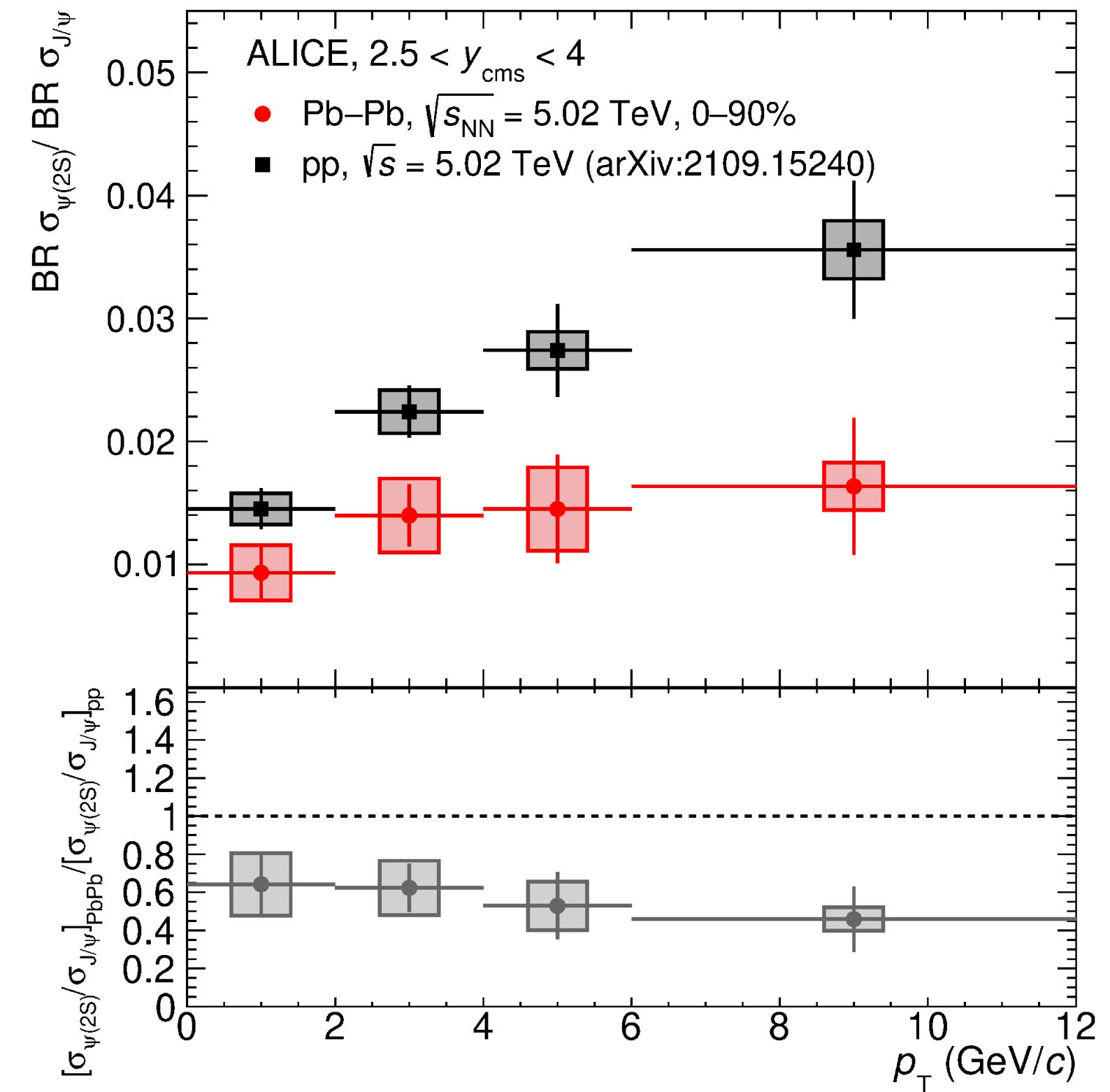
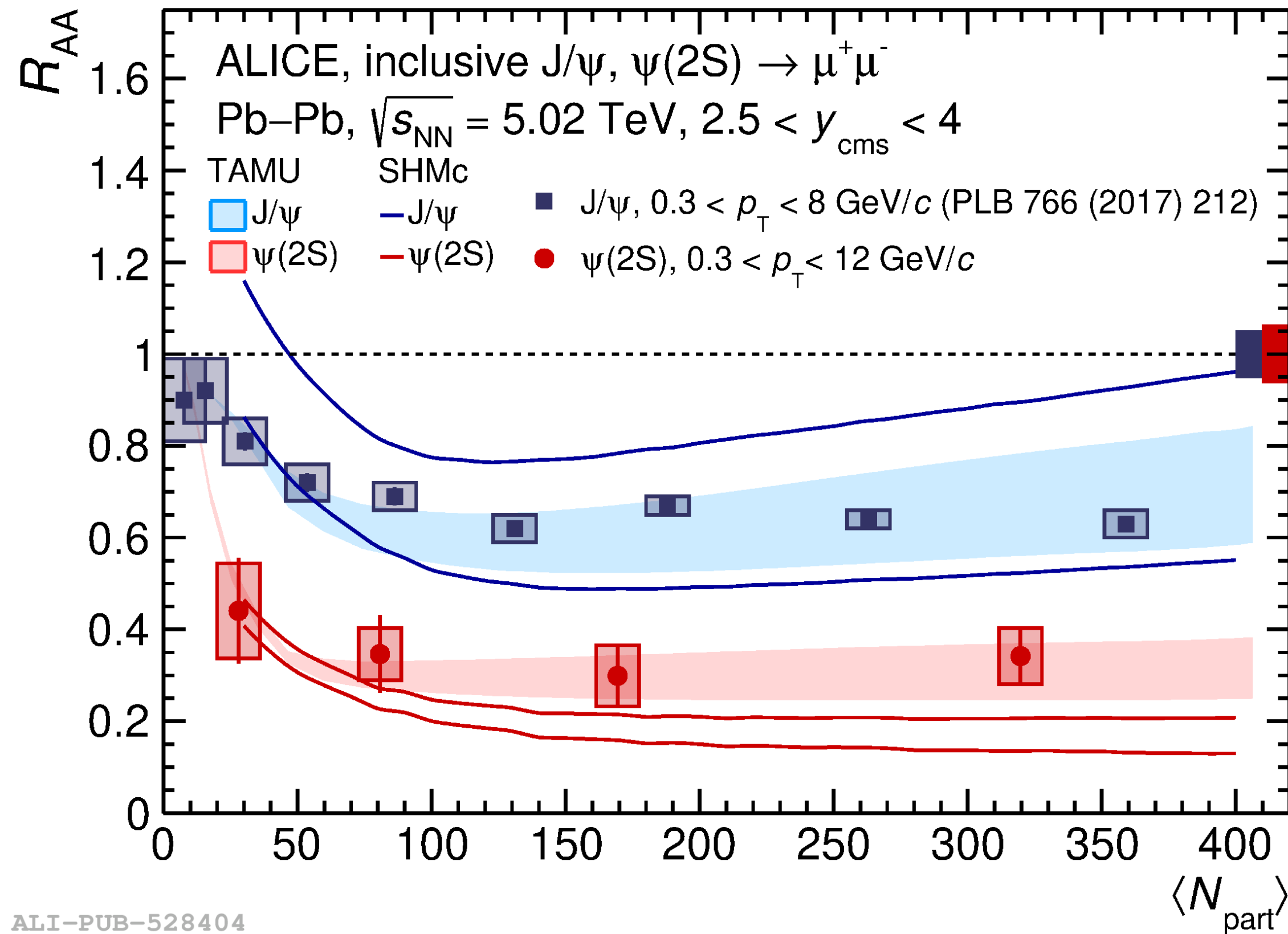
ALI-SIMUL-513942



ALI-SIMUL-514006

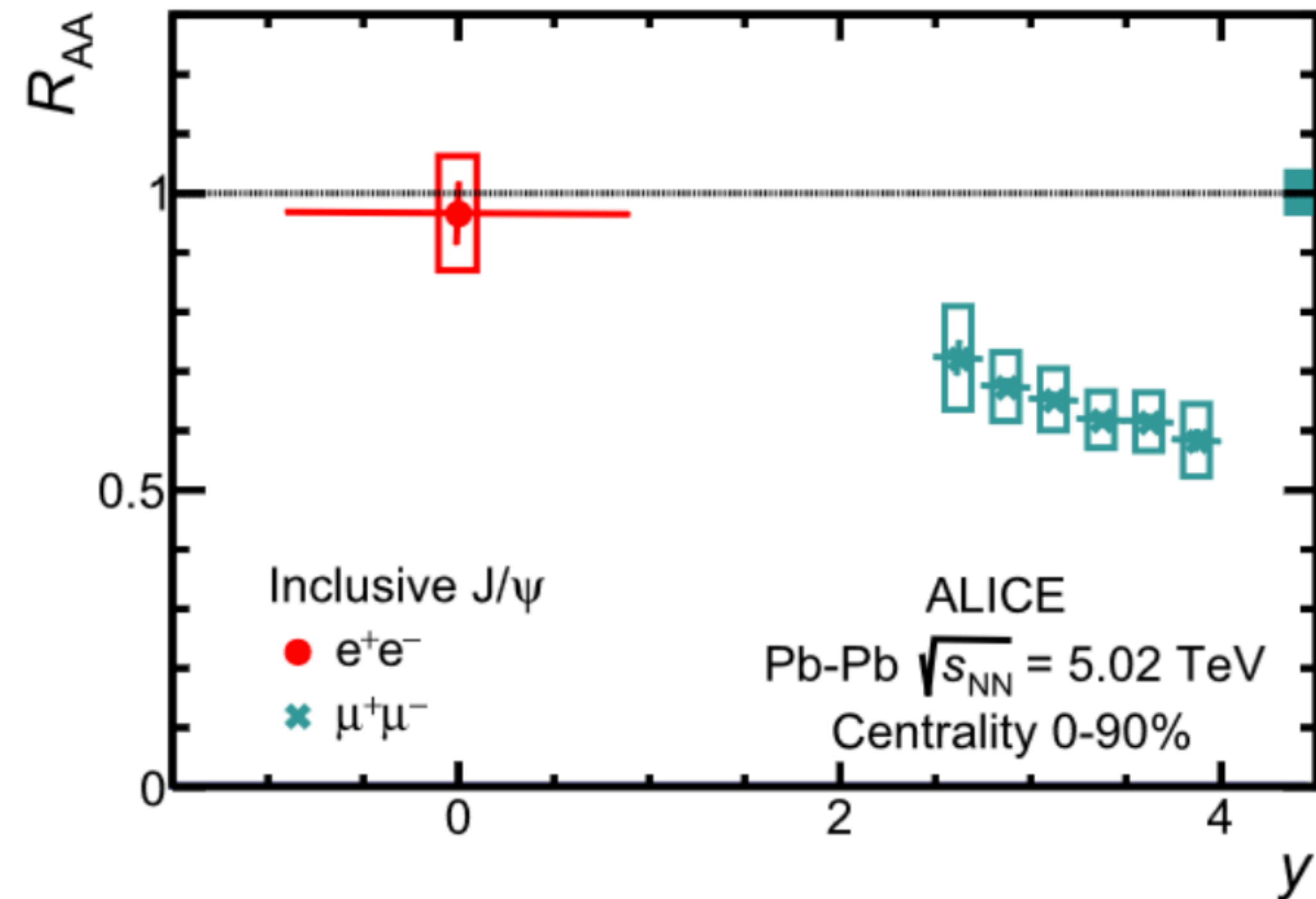
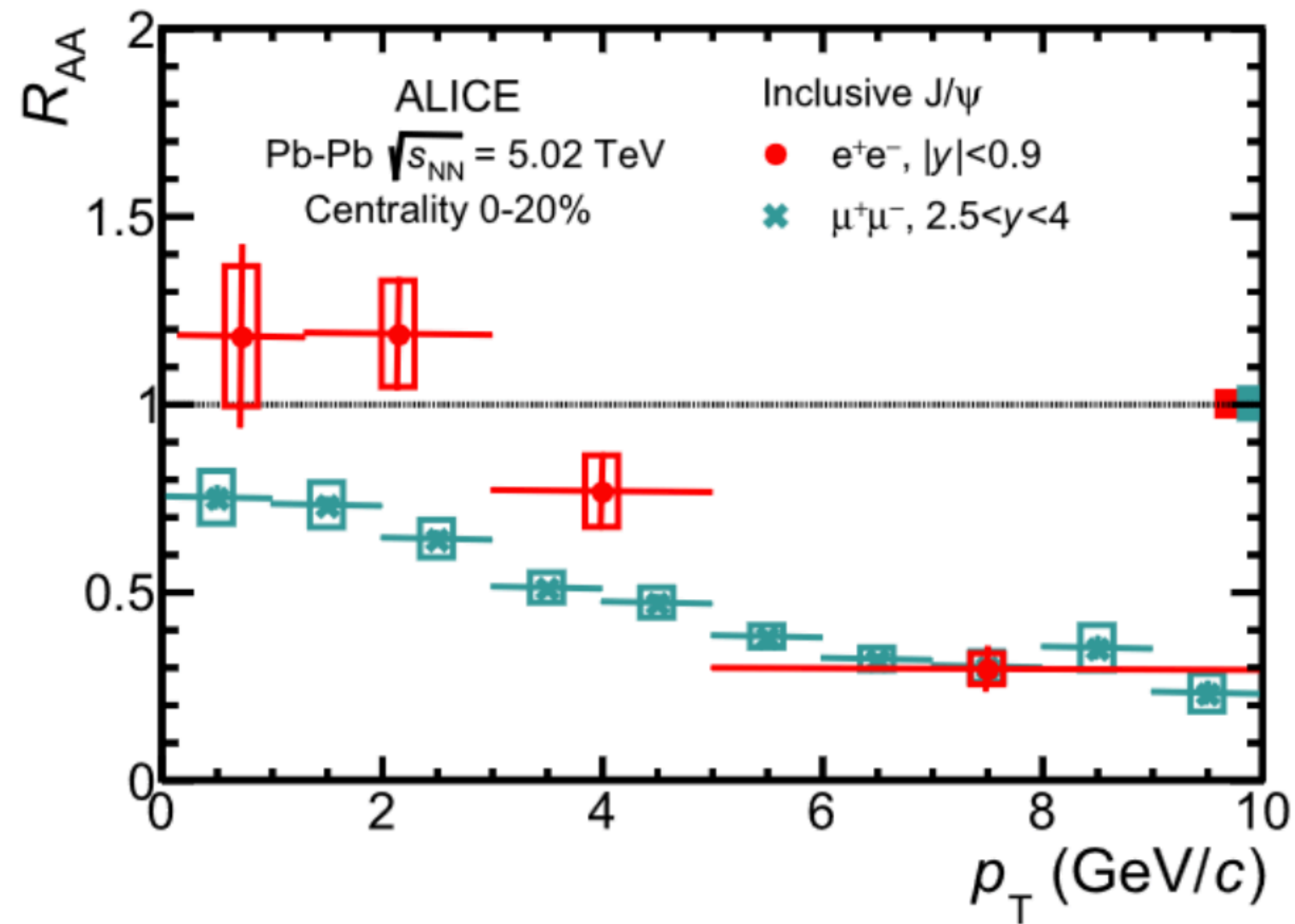
- J/ψ photoproduction in peripheral Pb-Pb will be much precise with $L_{\text{int}} \sim 10 \text{ nb}^{-1}$
- Central collisions for 0-10% will be available to constrain more theoretical models

J/ψ and ψ(2S) production in Pb-Pb collisions



- Double ratio values indicate the relative suppression of the ψ(2S) w.r.t. J/ψ which is decreasing slightly with p_T up to ~ 0.5

J/ψ production over p_T and rapidities



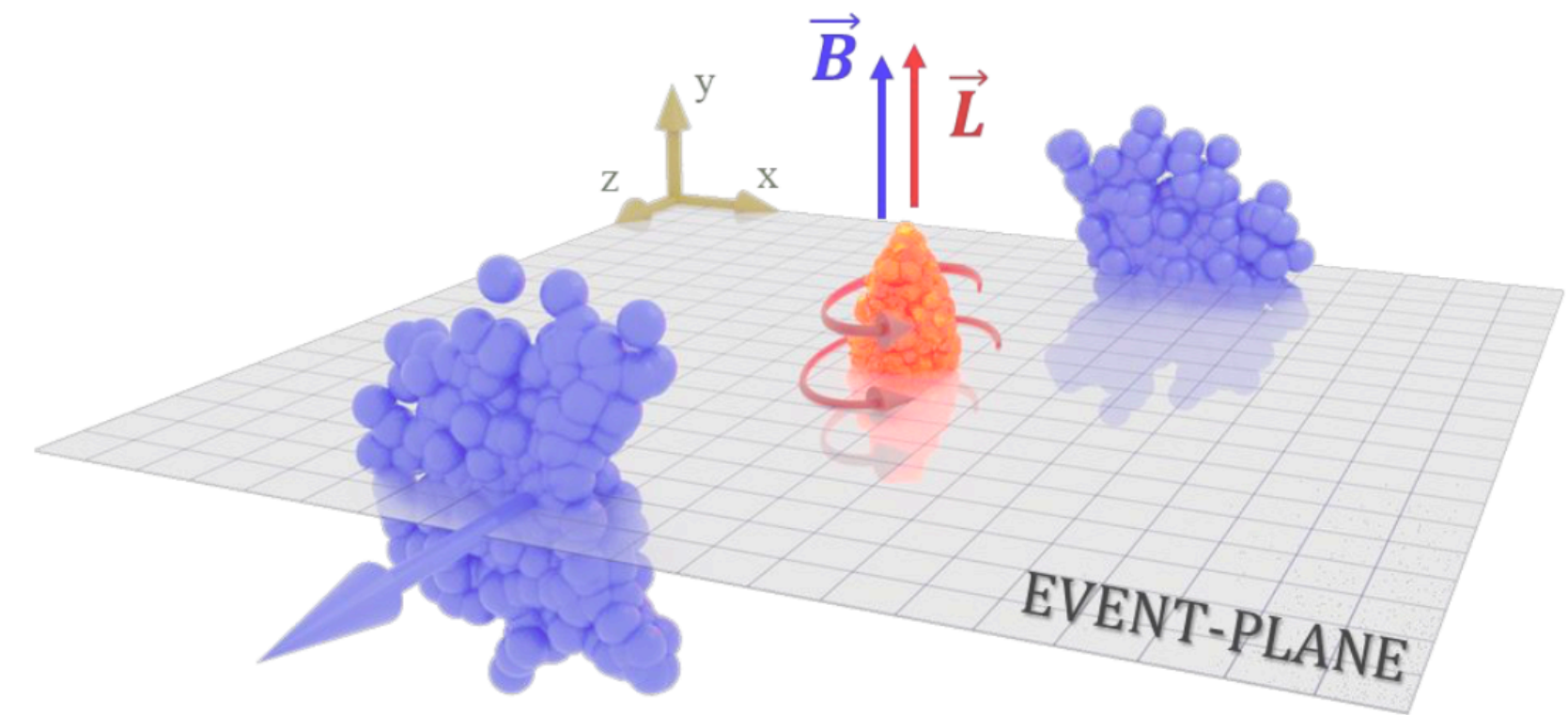
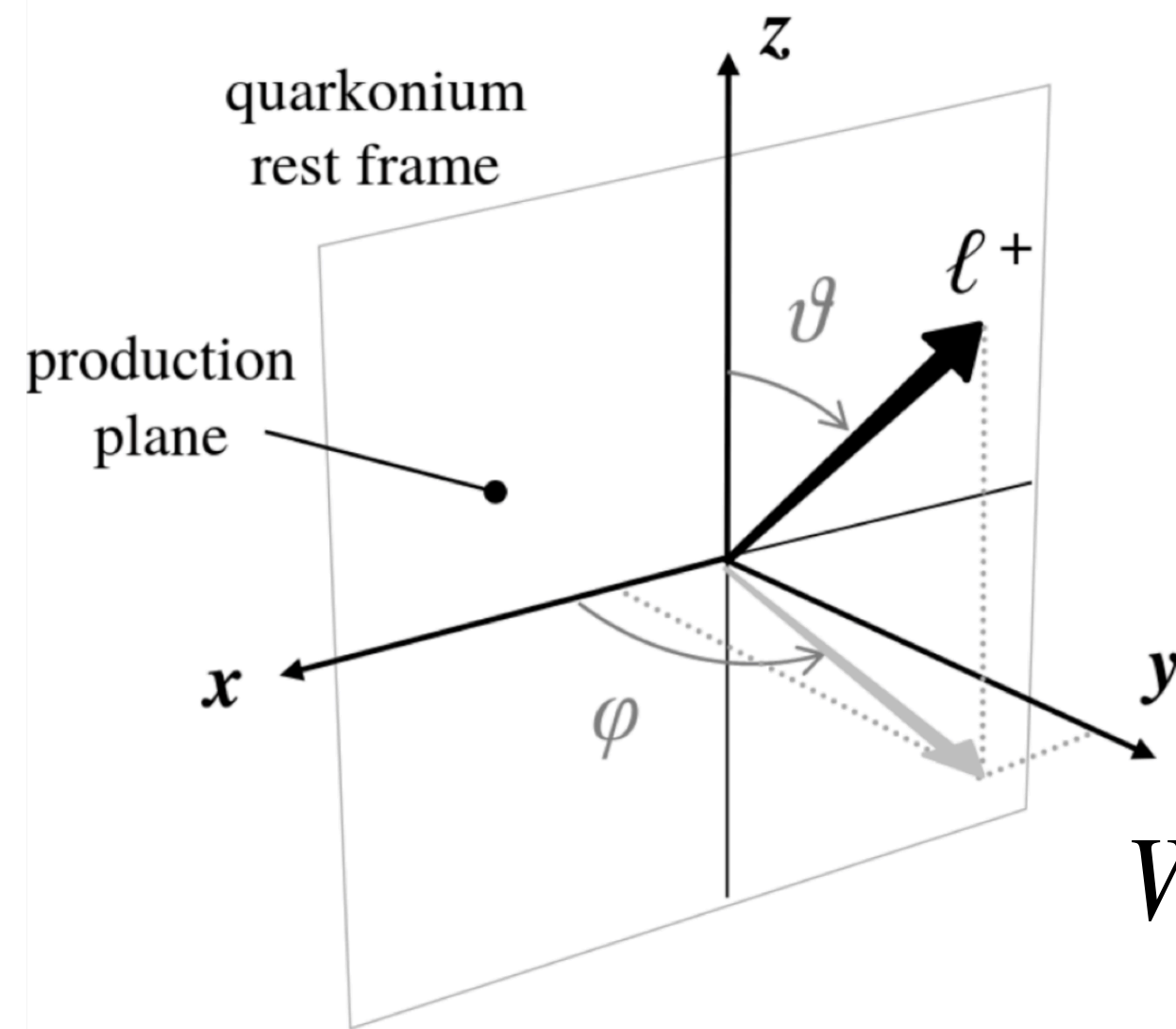
From Physics Letter B, Vol 805, 10 June 2020, 135434

- Larger recombination effects are expected for mid-rapidity compared to the forward rapidity region

J/ψ 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:

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



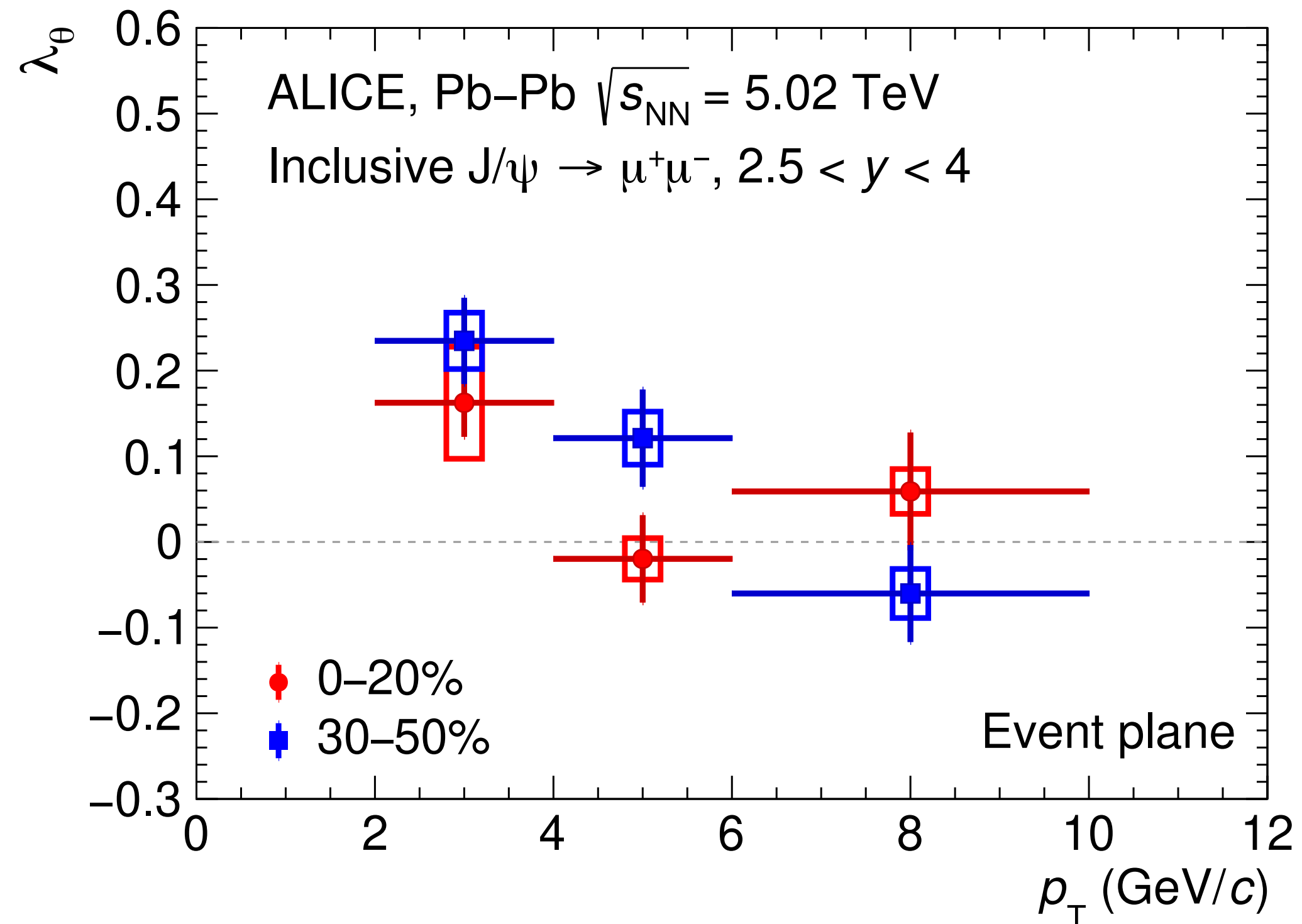
$$W(\cos \theta, \varphi) \propto \frac{1}{3 + \lambda_\theta} \cdot (1 + \lambda_\theta \cos^2 \theta + \lambda_\varphi \sin^2 \theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos 2\varphi)$$

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

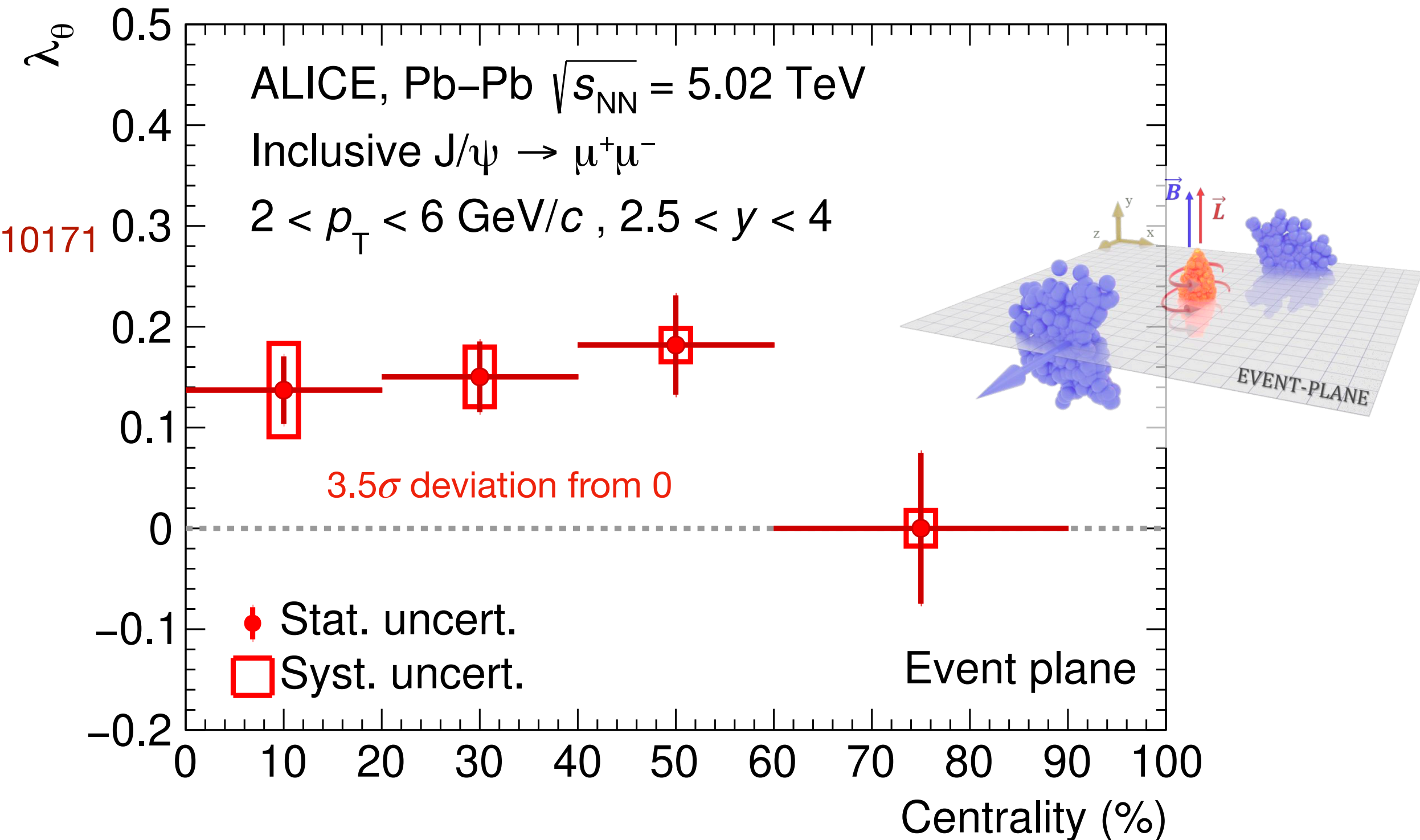
$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0, 0, 0)$ No polarisation

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

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



arXiv:2204.10171

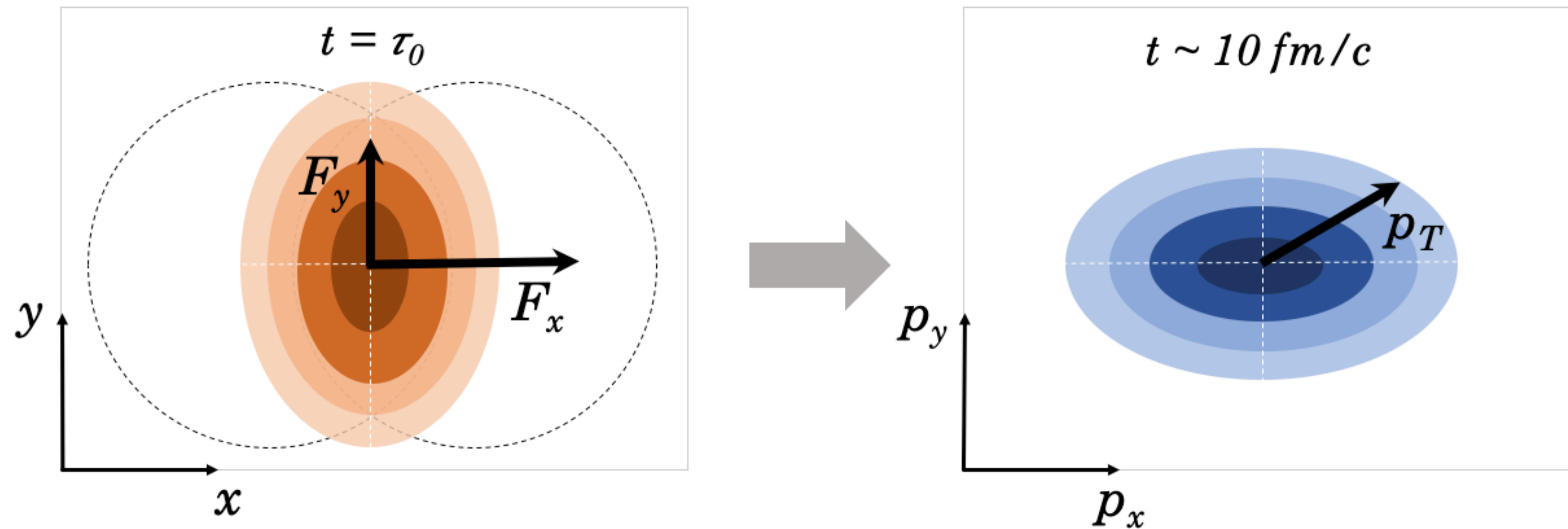


ALI-PUB-521057

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?**

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**

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



$n = 2$



$n = 3$

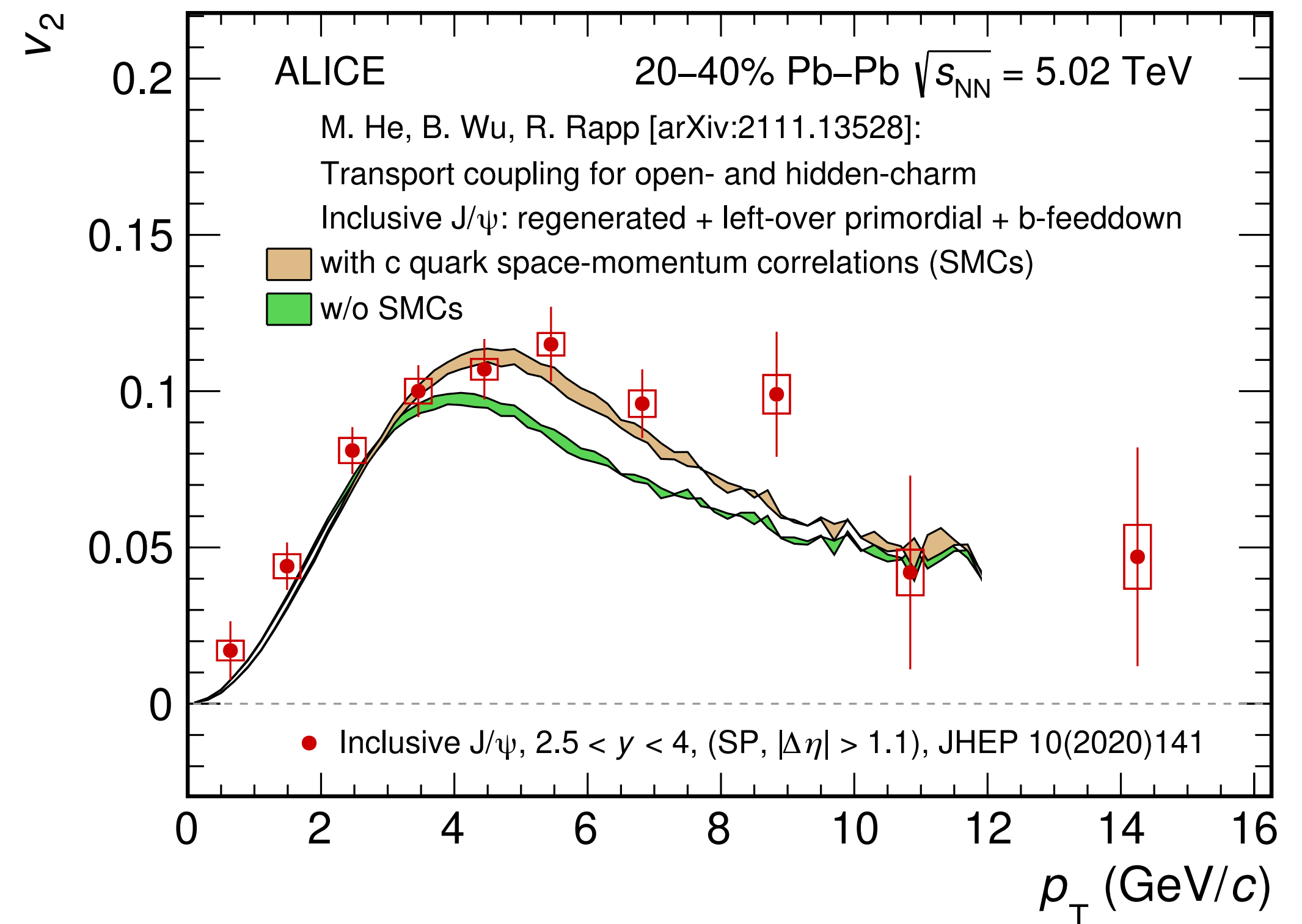
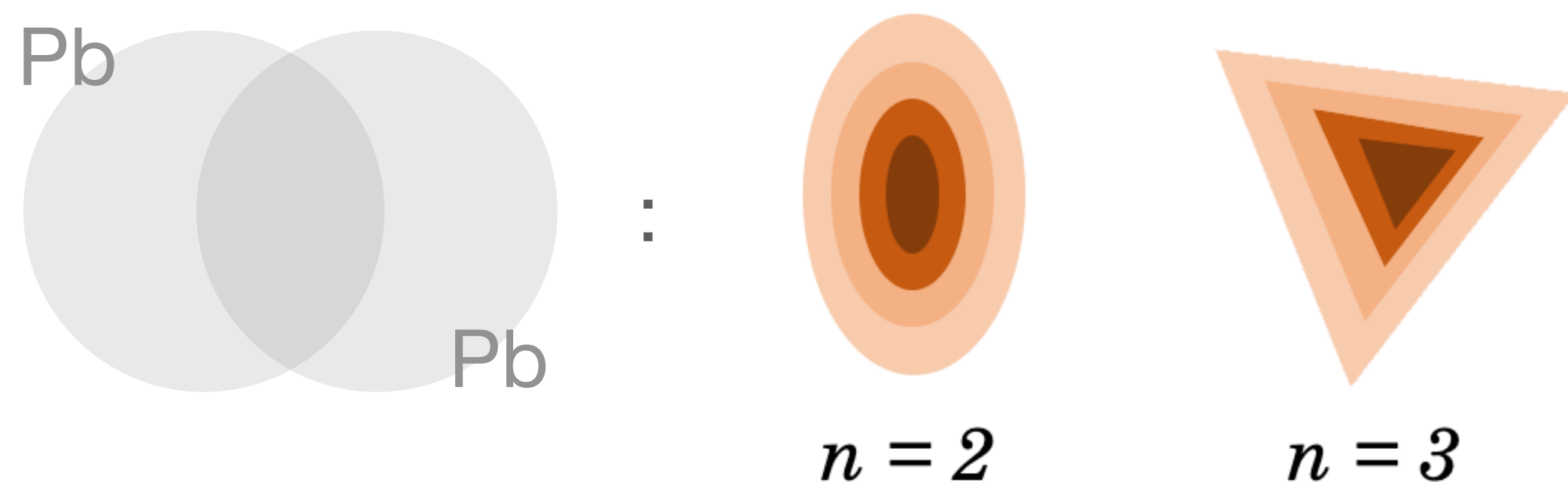
ϵ_n

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

Elliptic flow v_2

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

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

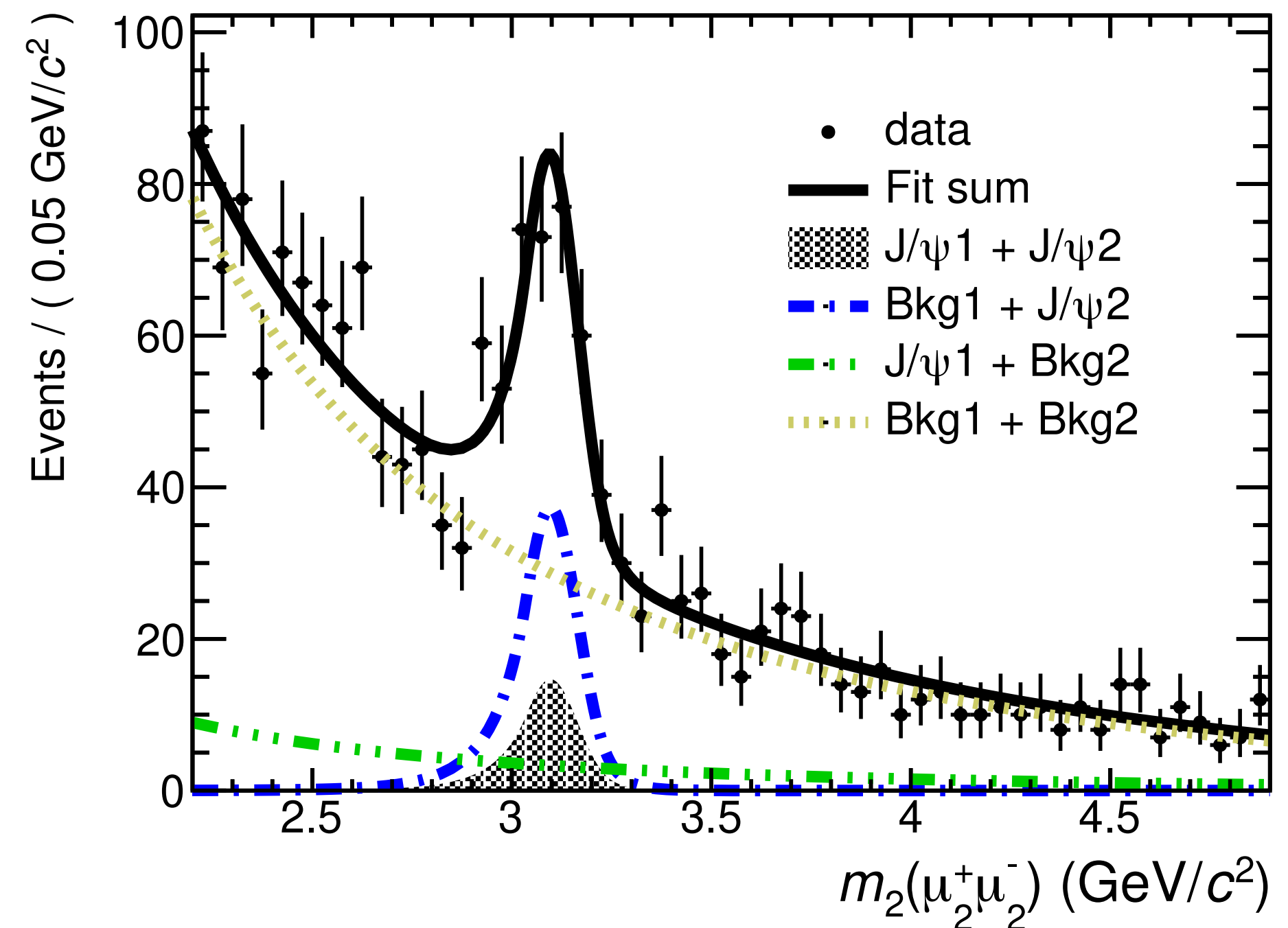
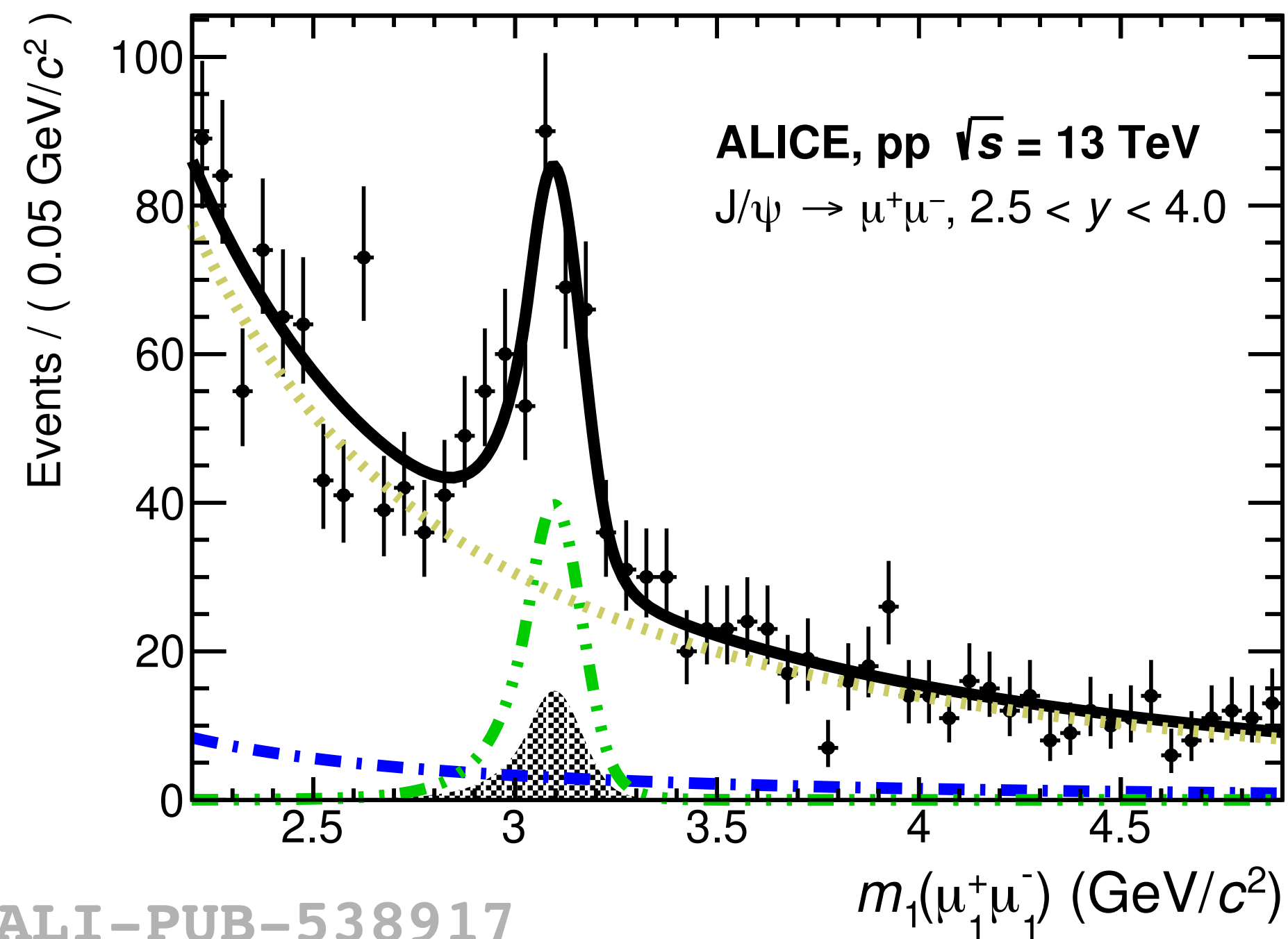


ALI-PUB-500427

- Low p_T (< 5 GeV/c): transport model implementing **regeneration** can describe measured J/ψ 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

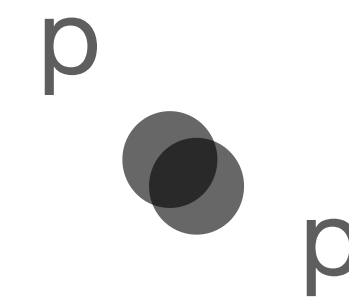
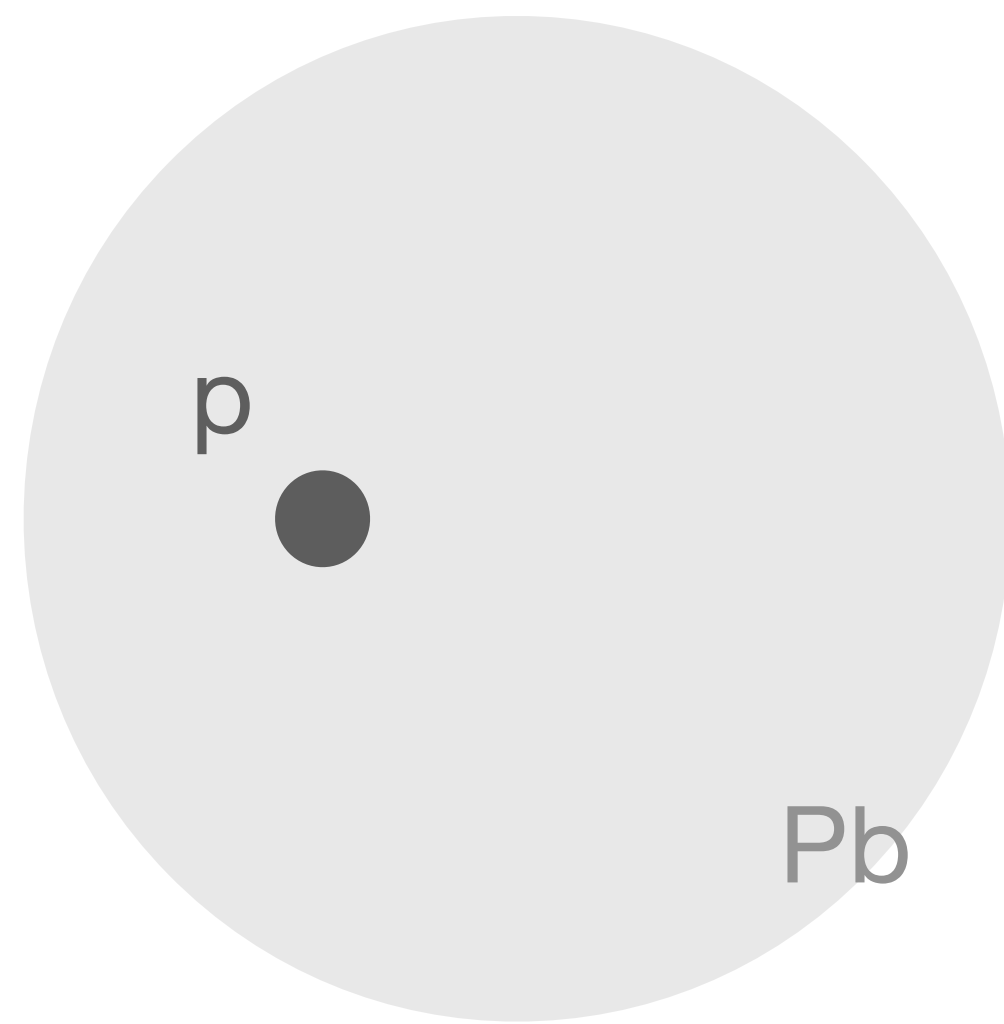
J/ψ pair production in pp collisions

[arXiv:2303.13431](https://arxiv.org/abs/2303.13431)

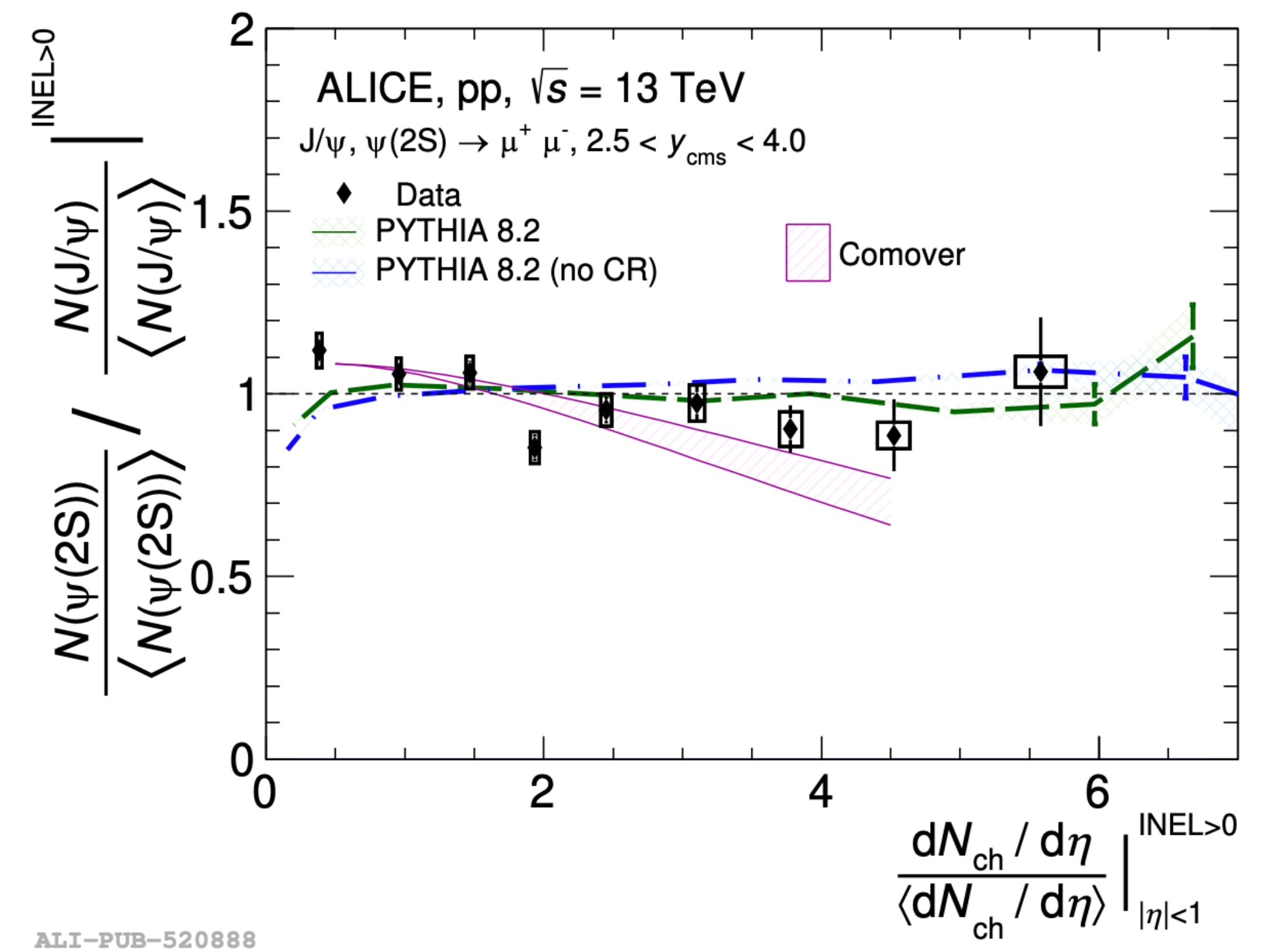
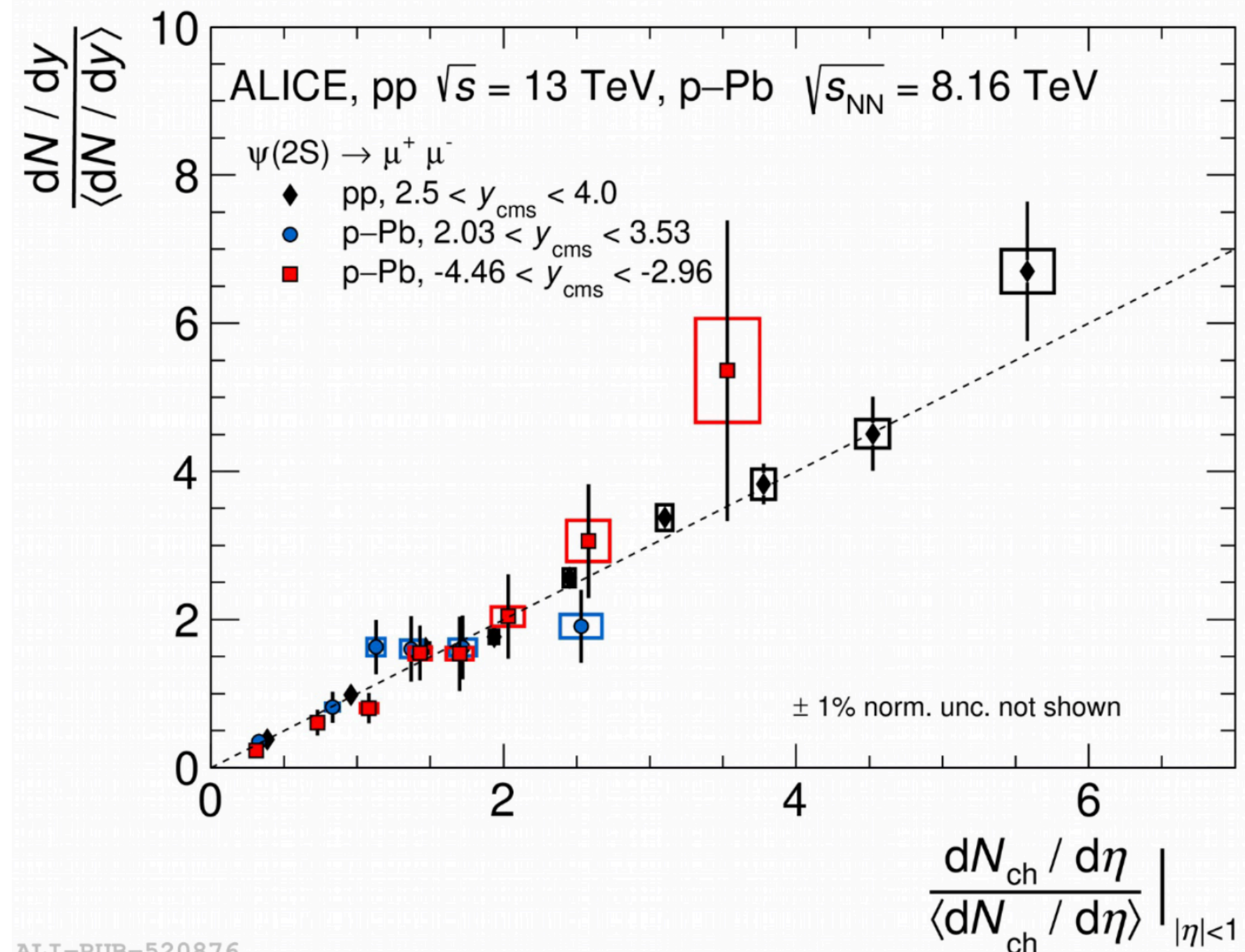


- Constrains on J/ψ production (NRQCD) and double parton scattering
- Despite different acceptance and inclusive or prompt: good agreement w LHCb result

Going towards small collision systems

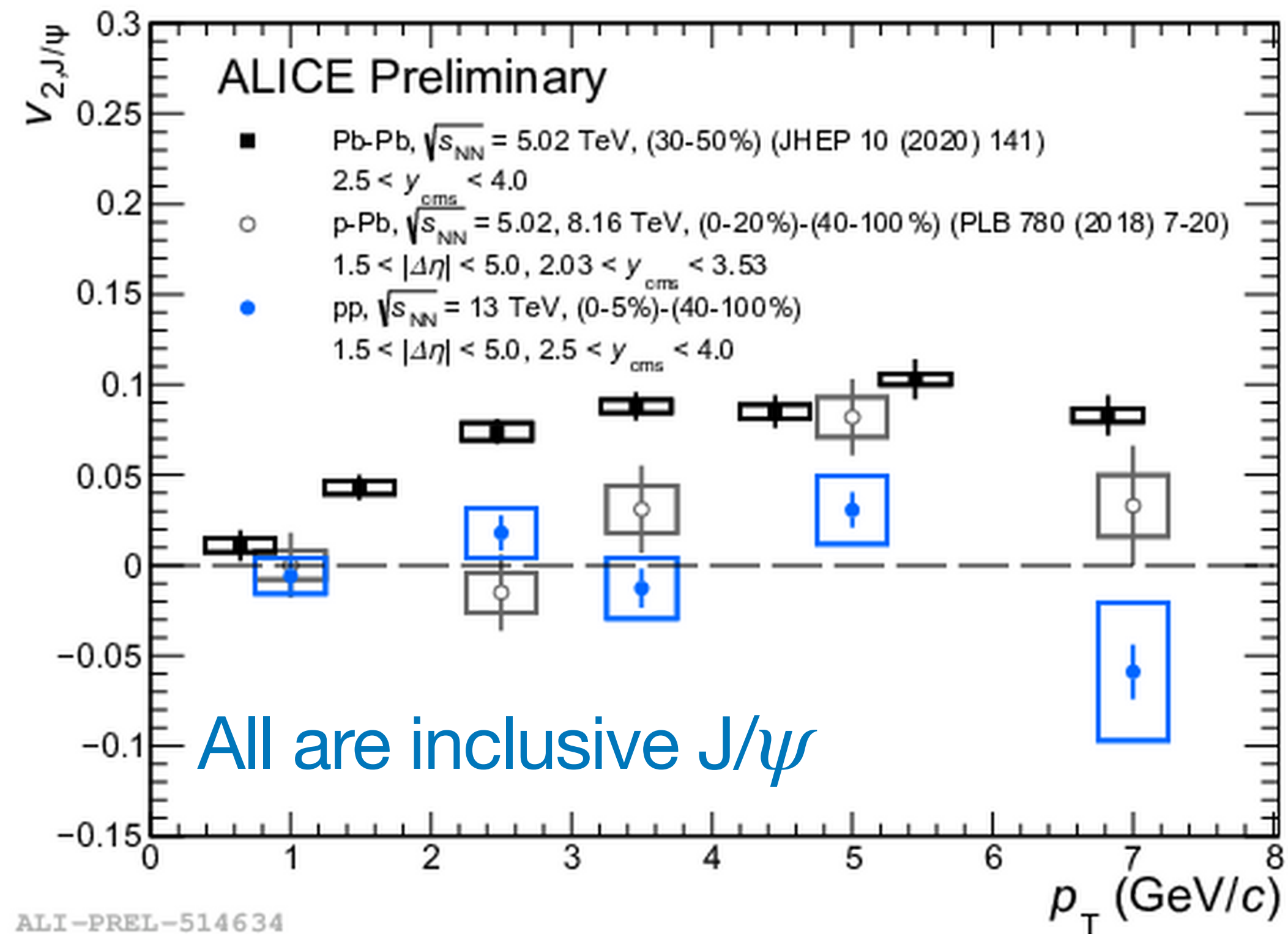
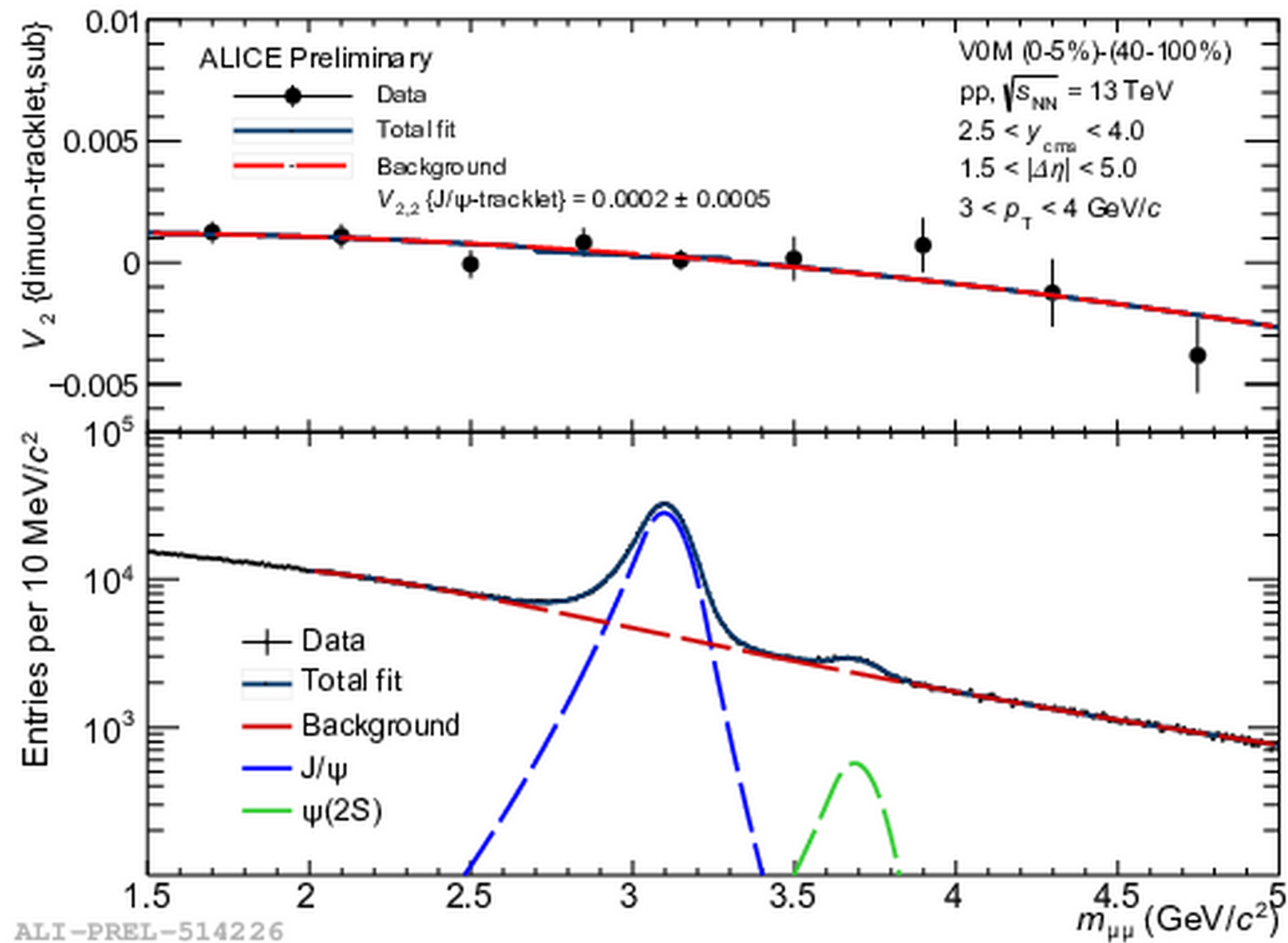


$\psi(2S)$ production in pp and p-Pb collisions



- 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

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

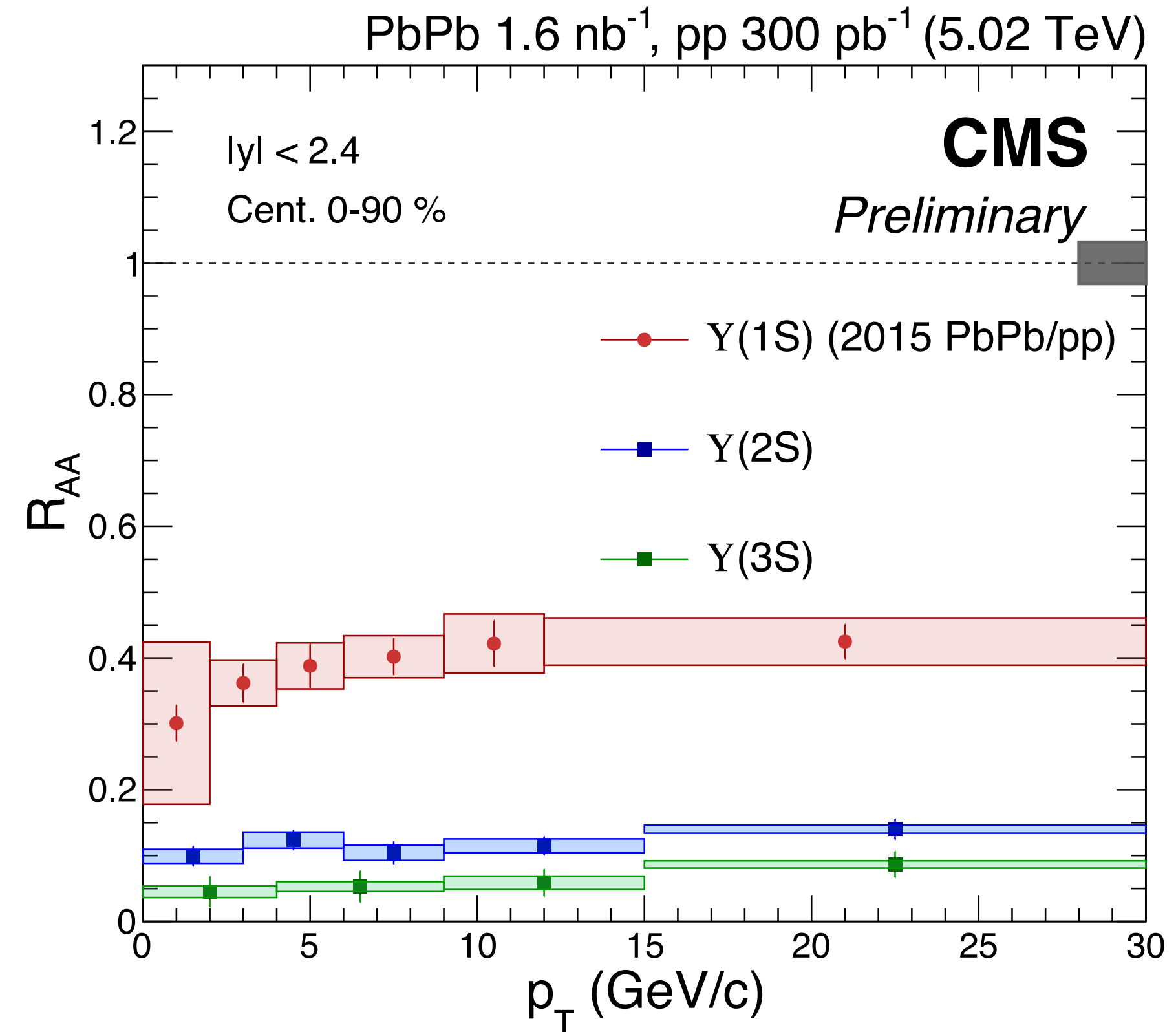
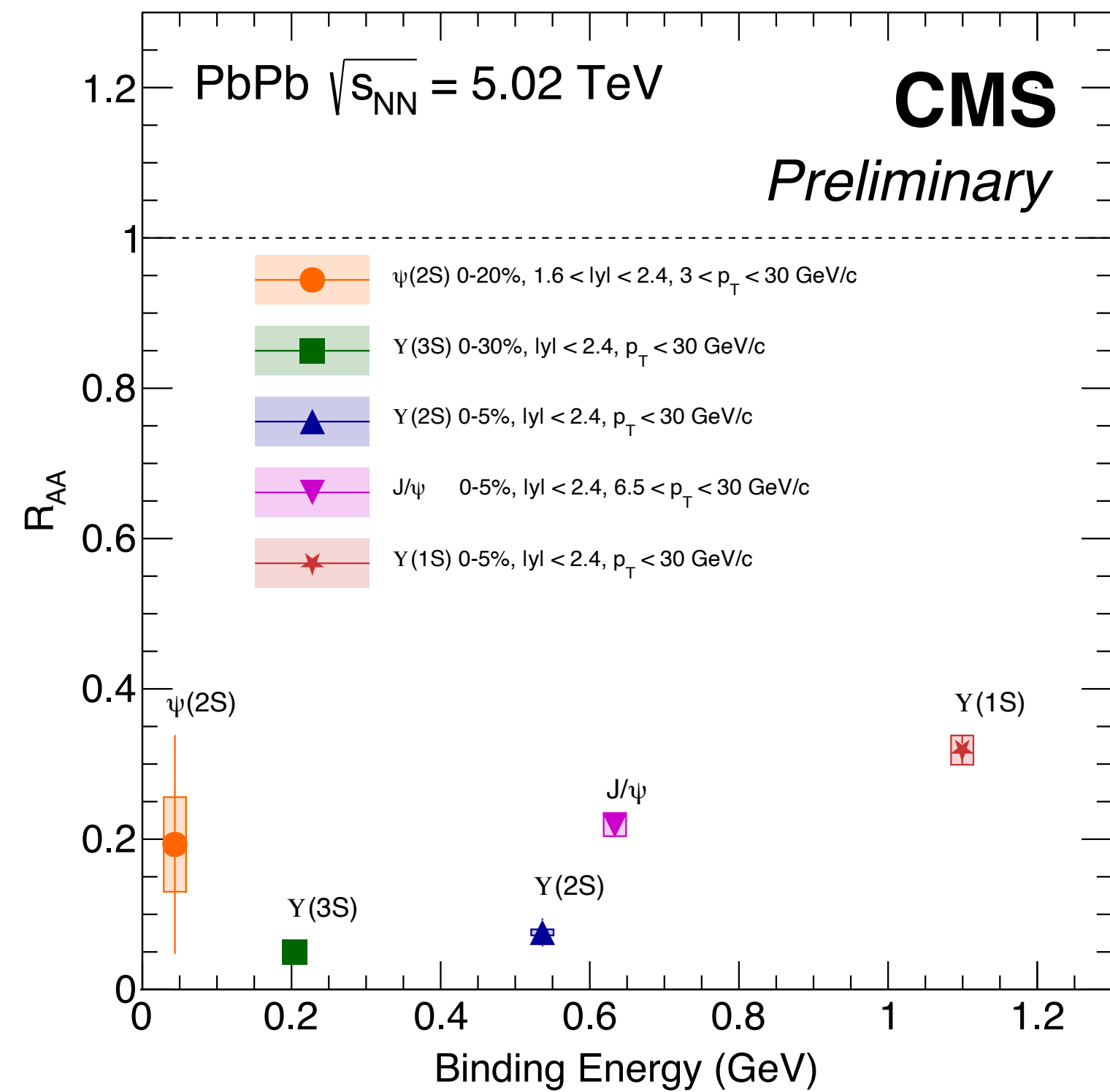


PbPb
 pPb
 pp

- 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** ($v_2^{pp} < v_2^{pPb} < v_2^{PbPb}$)

Other LHC experiment results

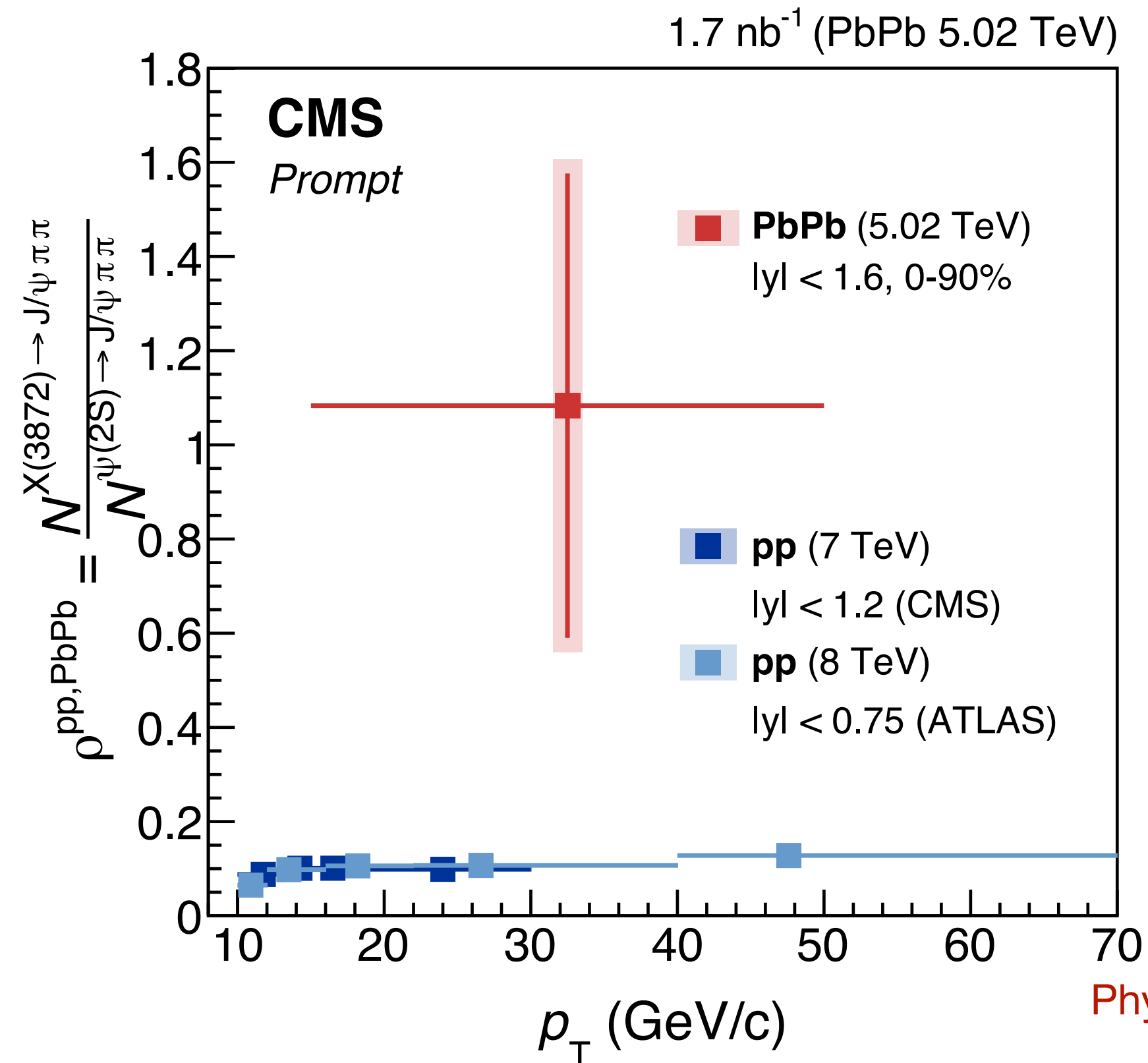
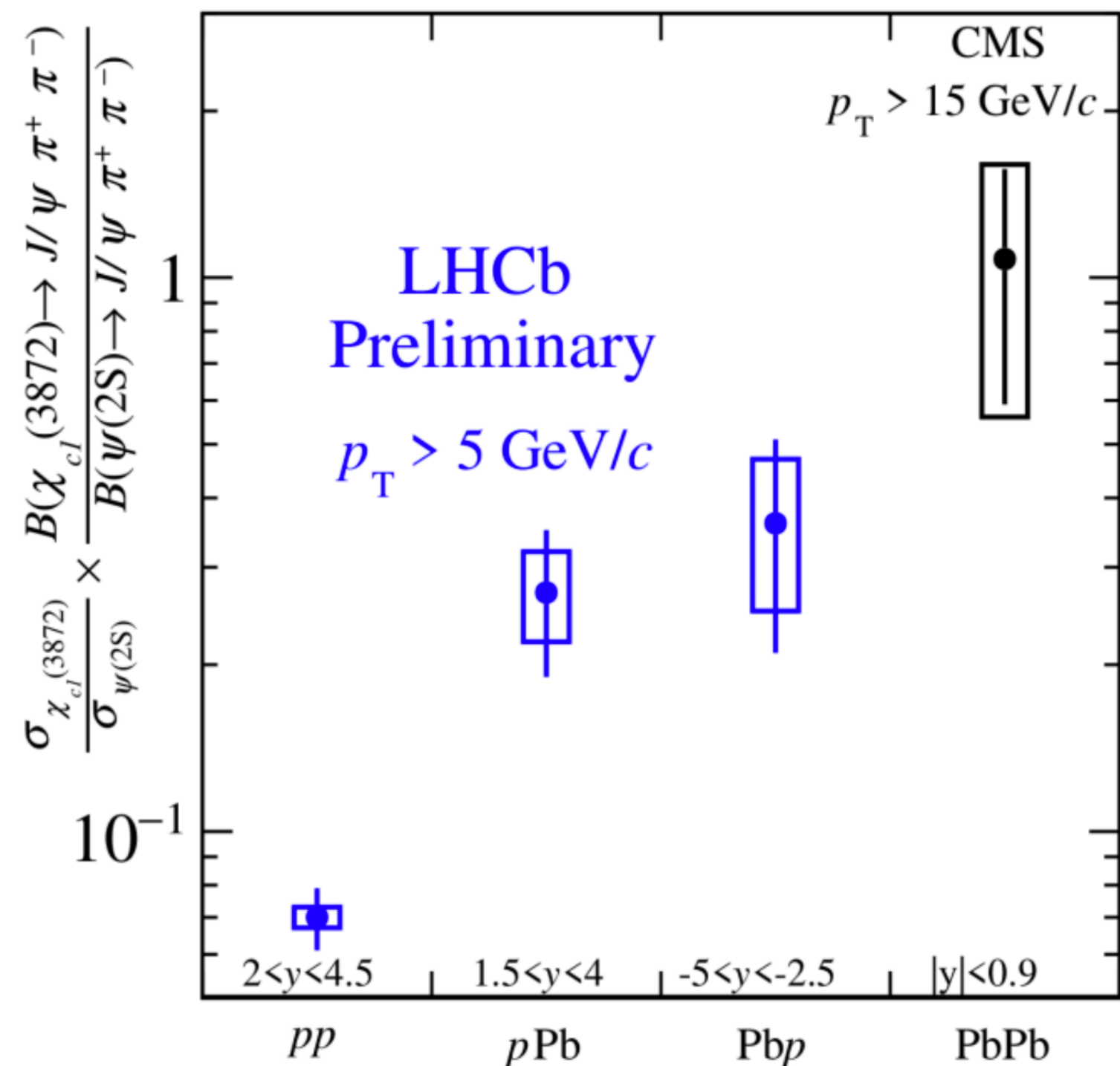
Integrated and p_T -differential R_{AA}



- 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

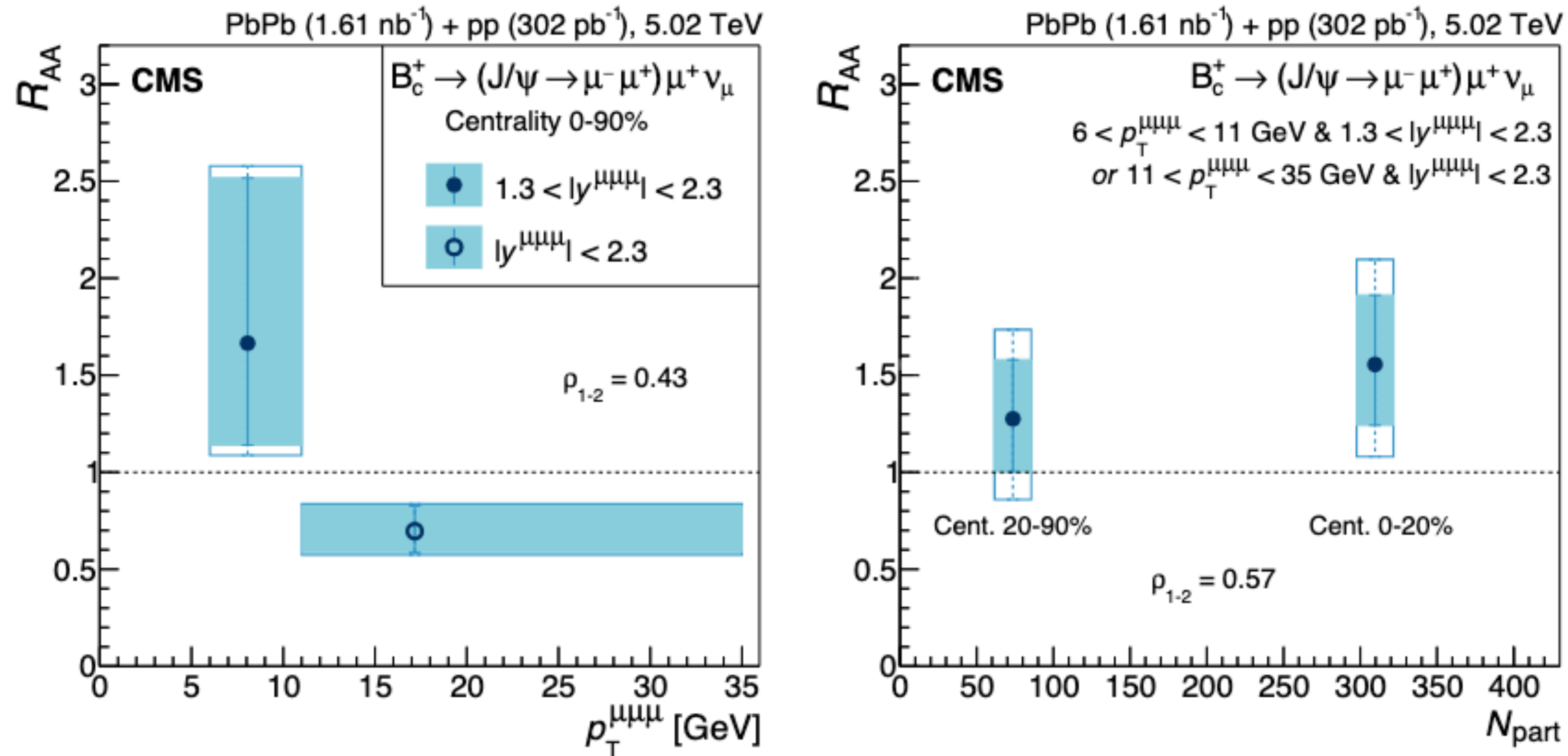
hadron molecule

?

Phys. Rev. Lett. 128, 032001

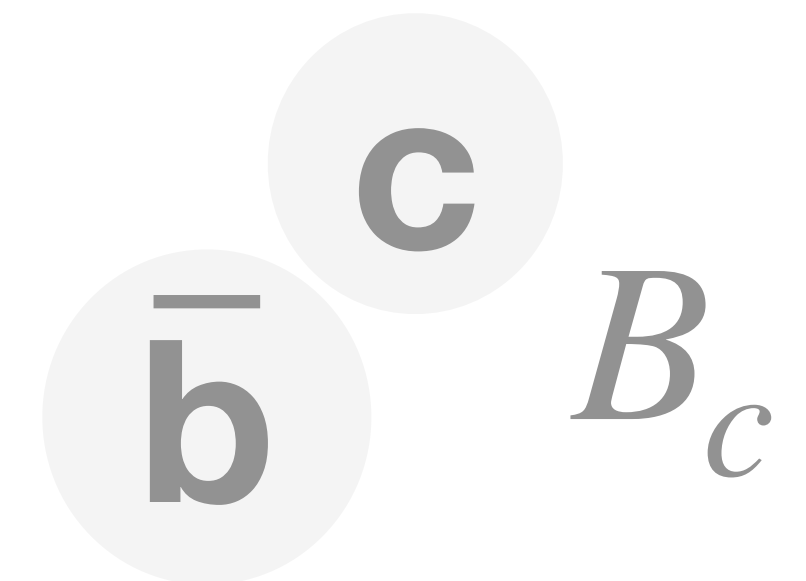
- First evidence of X(3872) in Pb-Pb is reported: 4.2σ standard deviation
- Prompt X(3872) to $\psi(2S)$ yield ratio: **unique experimental** input for theory
- Indication for **medium-induced coalescence**

B_c measurement in Pb-Pb collisions

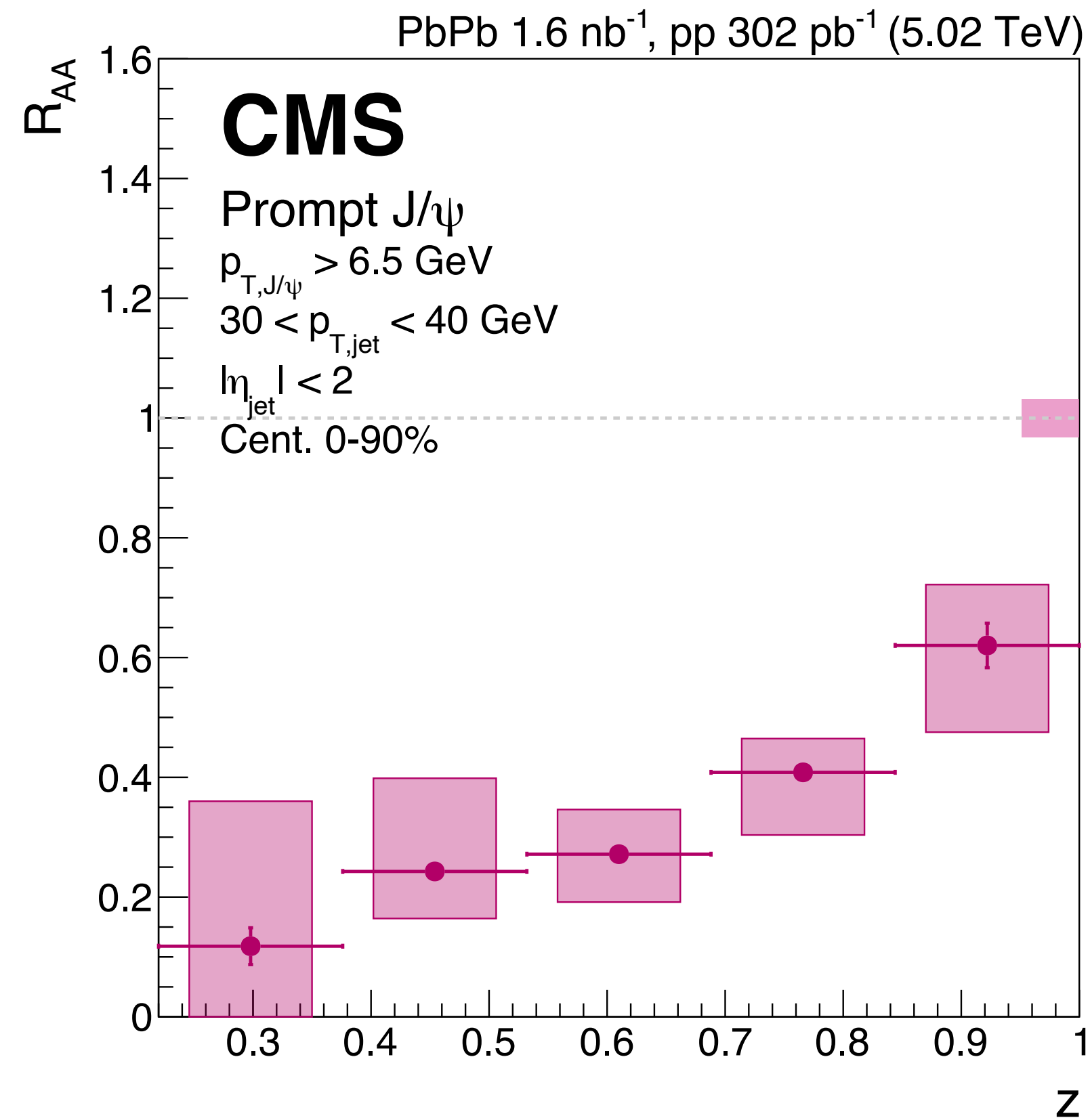
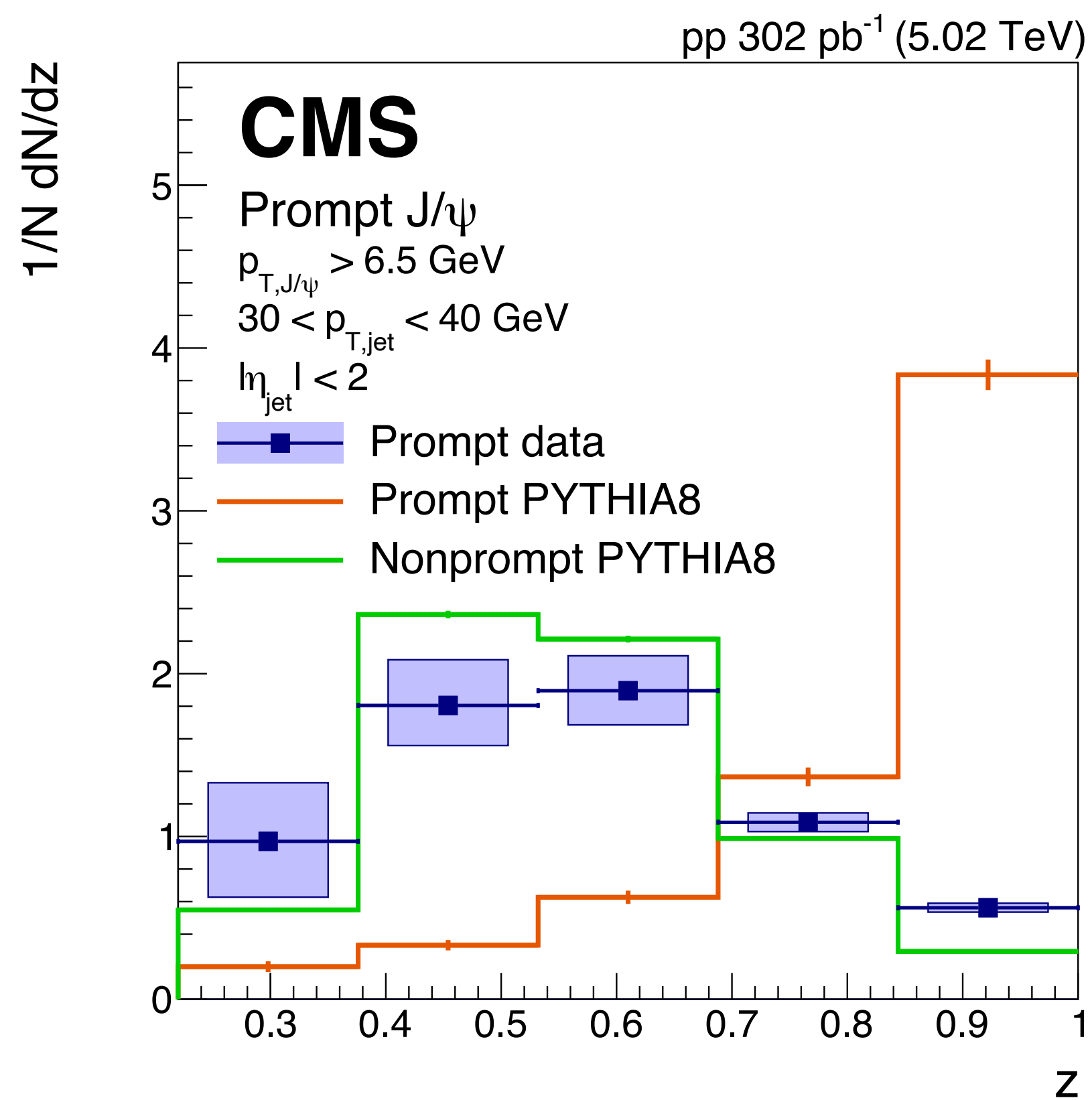


arXiv:2201.02659

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

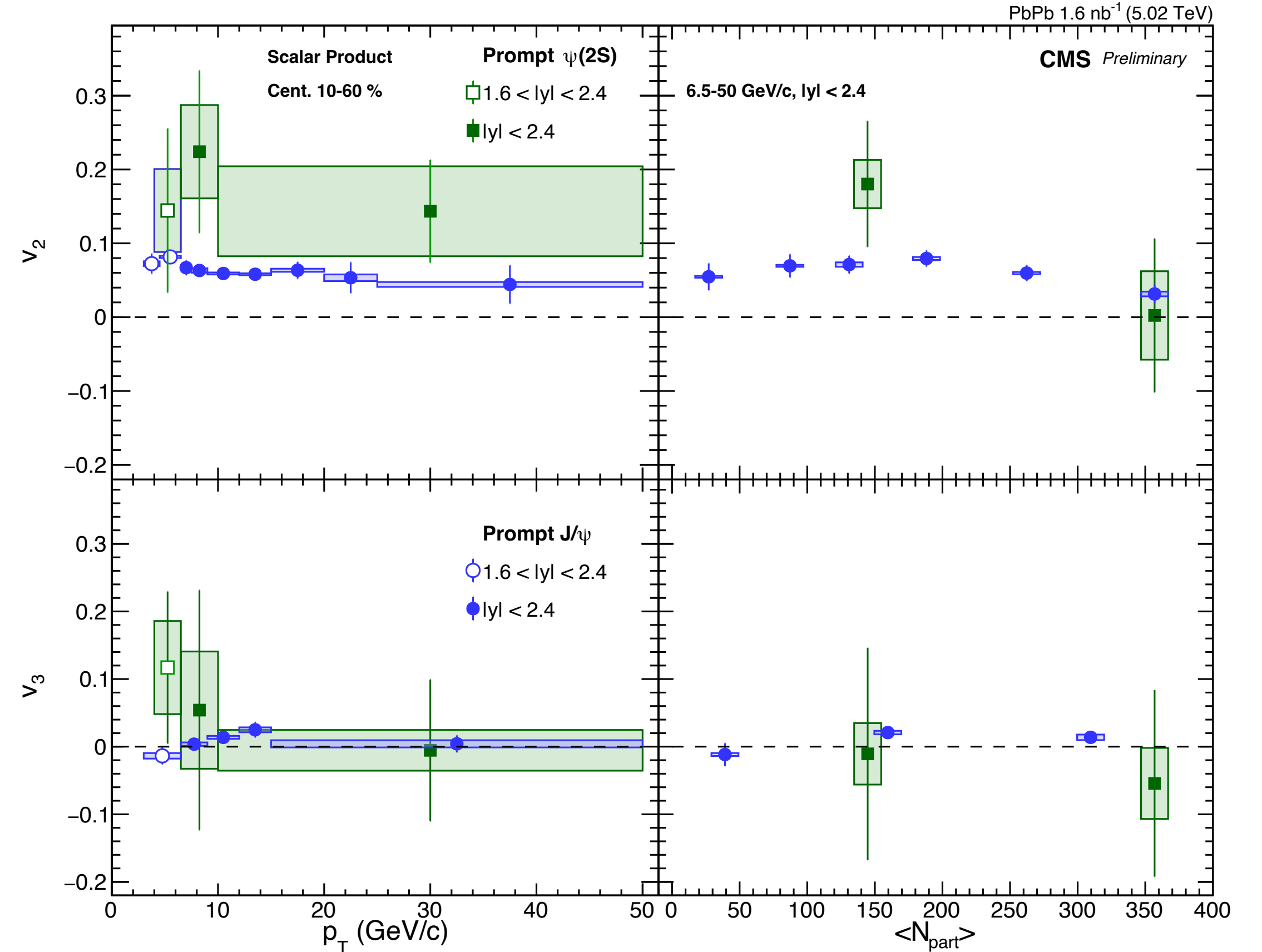
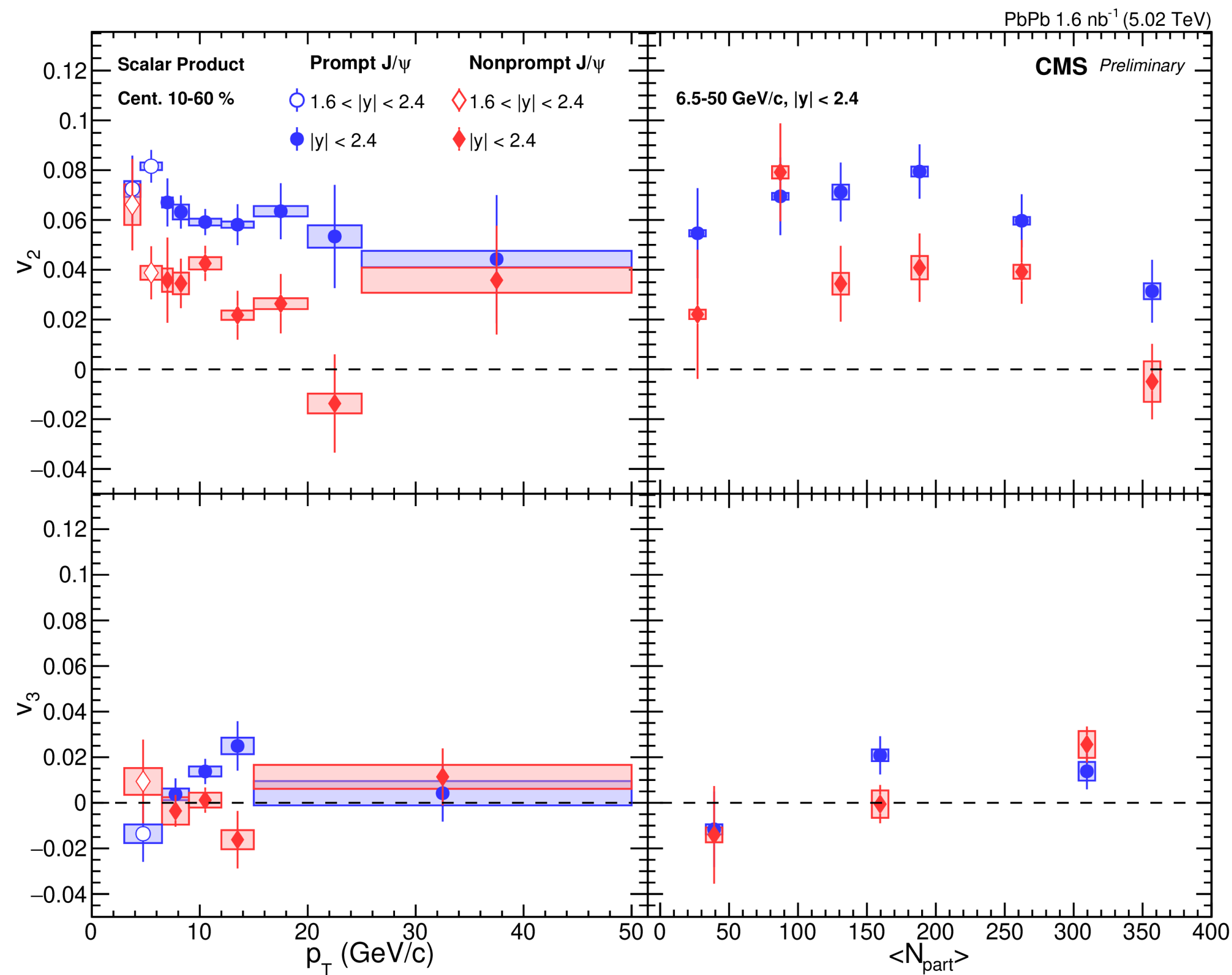


Fragmentation of jets with prompt J/ψ in Pb-Pb and pp



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

J/ψ and prompt ψ(2S) v_n in Pb-Pb collisions



○ Larger v_2 is observed for prompt J/ψ w.r.t. non-prompt while all ~ 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