Heavy ions: Quarkonia

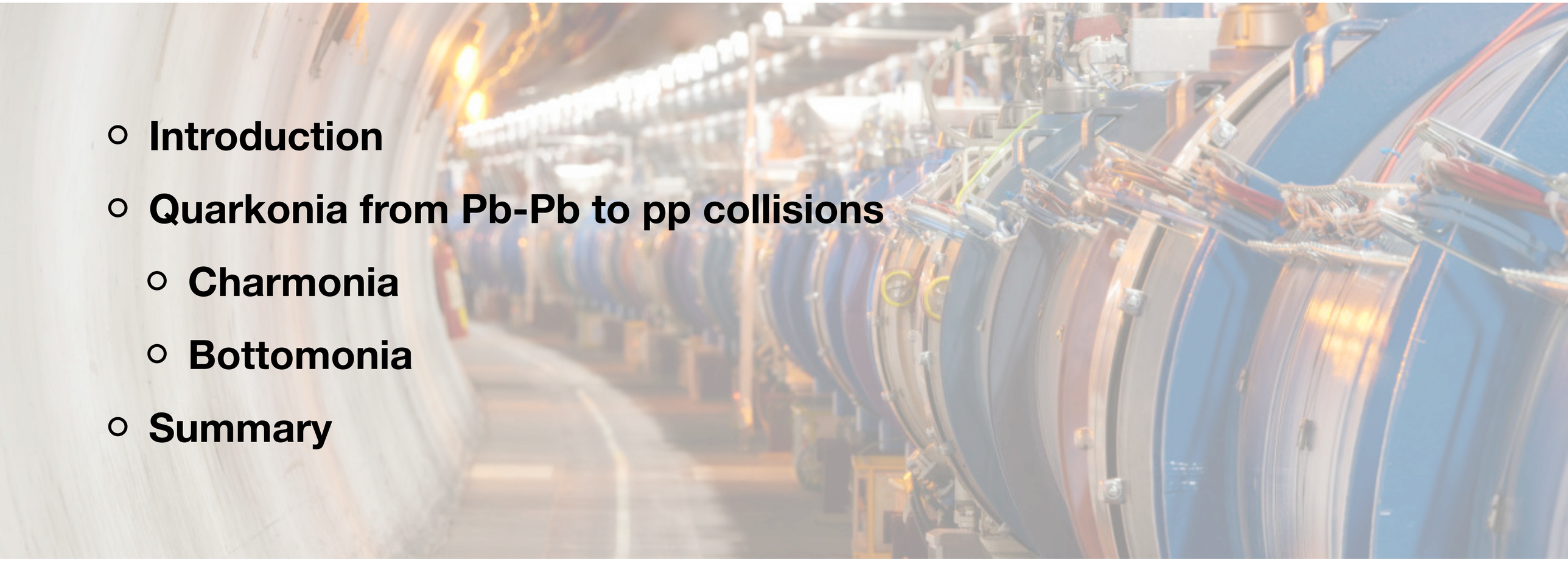
Highlights from ALICE, ATLAS, CMS, LHCb

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

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

2022 LHCP TAIPEI

Outline



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

Evolution of a heavy ion collision

t ~ 0 fm/c

Hard partonic collisions

Initial stages

~ 1 fm/c

fireball expansion

~ 10 fm/c

chemical freeze out

kinetic freeze out

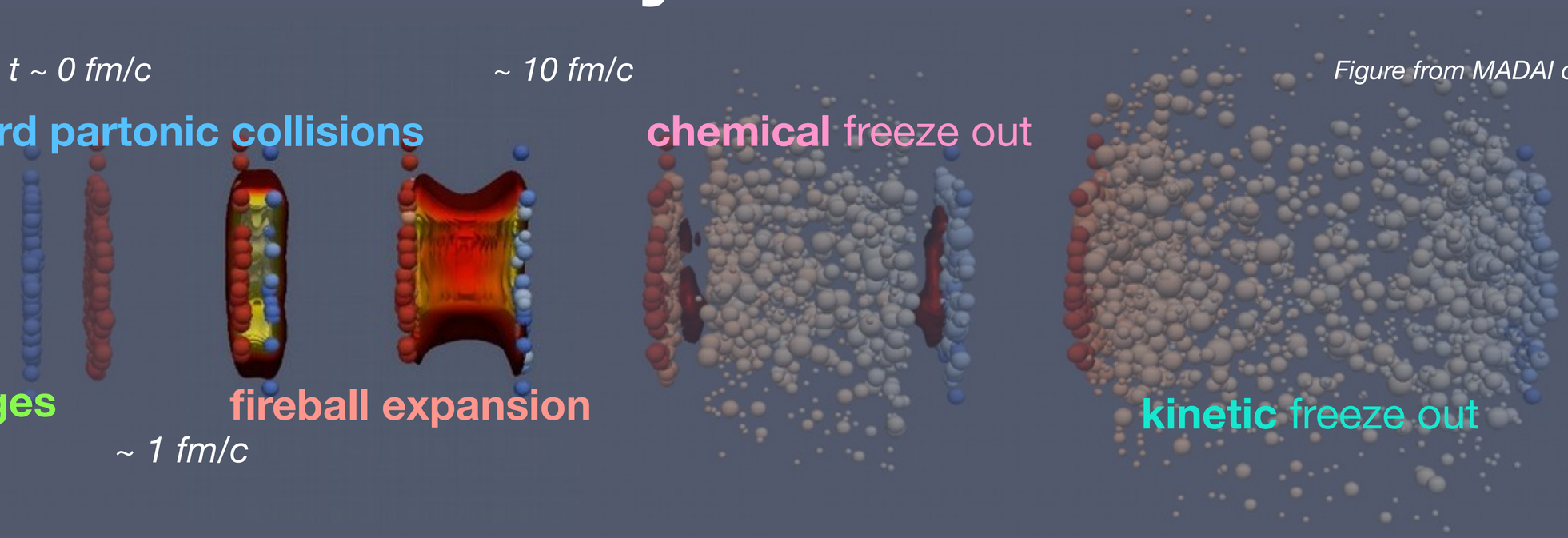
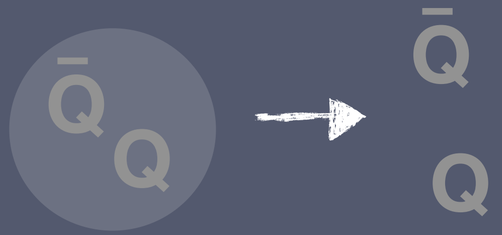


Figure from MADAI collaboration

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

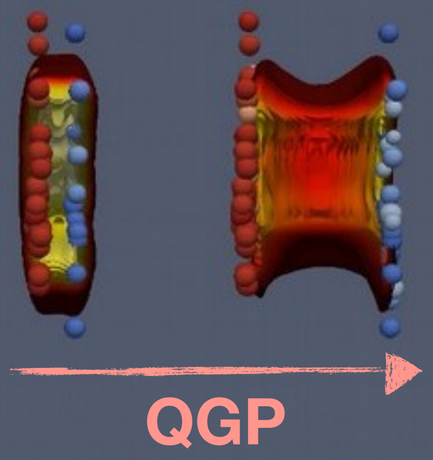


Signature of deconfinement:

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

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

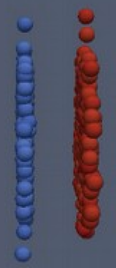
Why quarkonia?



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



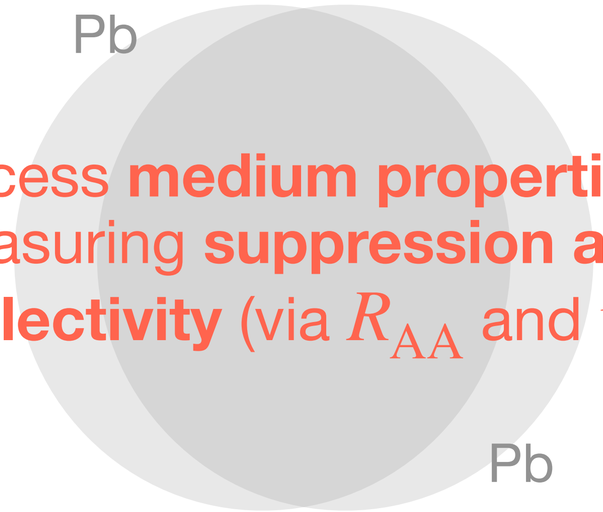
$c\bar{c}$: O(100) and few $b\bar{b}$ pairs produced close to t ~ 0 fm/c

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)



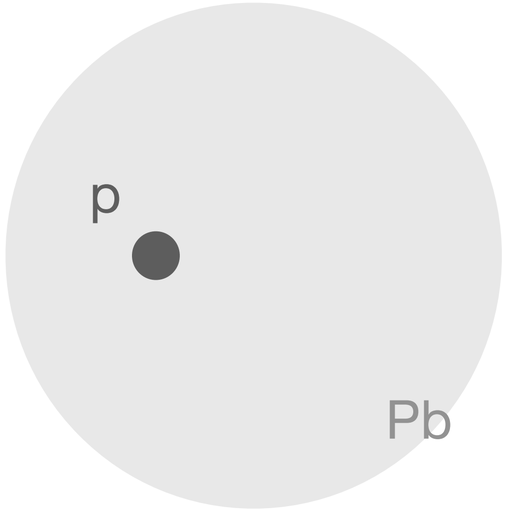
Access **medium properties** measuring **suppression and collectivity** (via R_{AA} and v_n)

heavy quark **energy loss** in the medium

(e.g. non-prompt J/ψ measurement, prompt J/ψ at high p_{T})

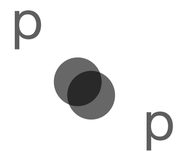
cold nuclear matter effects

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



reference system

test of QCD

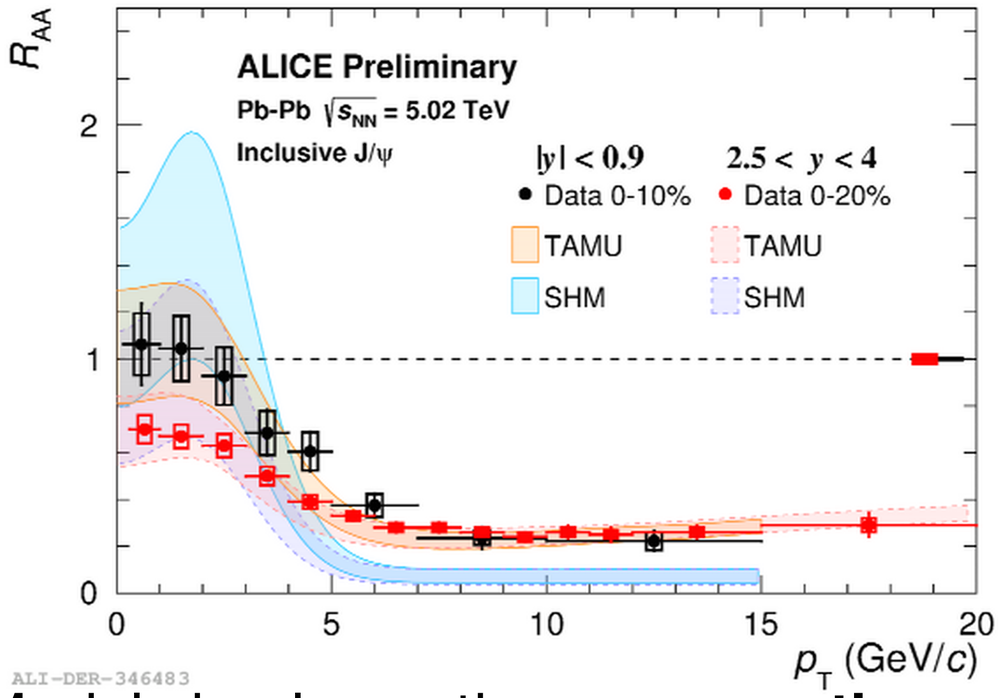


Shed light on

multiparton interactions (via multiplicity dependent studies)

+ **collectivity in small system** (v_2)

Observable: nuclear modification factor R_{AA}



- Measuring production in AA relative to production in pp collisions:
  - >1: Enhancement
  - <1: Suppression

$$R_{\mathrm{AA}} = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{(\mathrm{d}N/\mathrm{d}y)_{\mathrm{AA}}}{(\mathrm{d}N/\mathrm{d}y)_{\mathrm{pp}}}$$

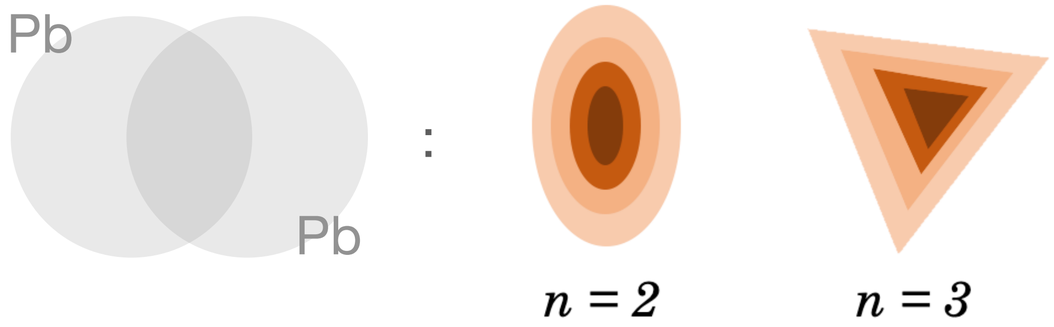
- Models implementing **regeneration**, either at the freeze-out (SHM) or during the medium evolution (TAMU), are in agreement with data at low p_{T}
- $\mathrm{J}/\psi\, R_{\mathrm{AA}}$: more suppressed at high p_{T}, showing a rising trend towards lower p_{T}
- $R_{\mathrm{AA}}^{\mathrm{mid-y}} > R_{\mathrm{AA}}^{\mathrm{fwd-y}}$ (low p_{T}) as expected by recombination scenario ($N_{\mathrm{c\bar{c}}}^{\mathrm{mid-y}} > N_{\mathrm{c\bar{c}}}^{\mathrm{fwd-y}}$)

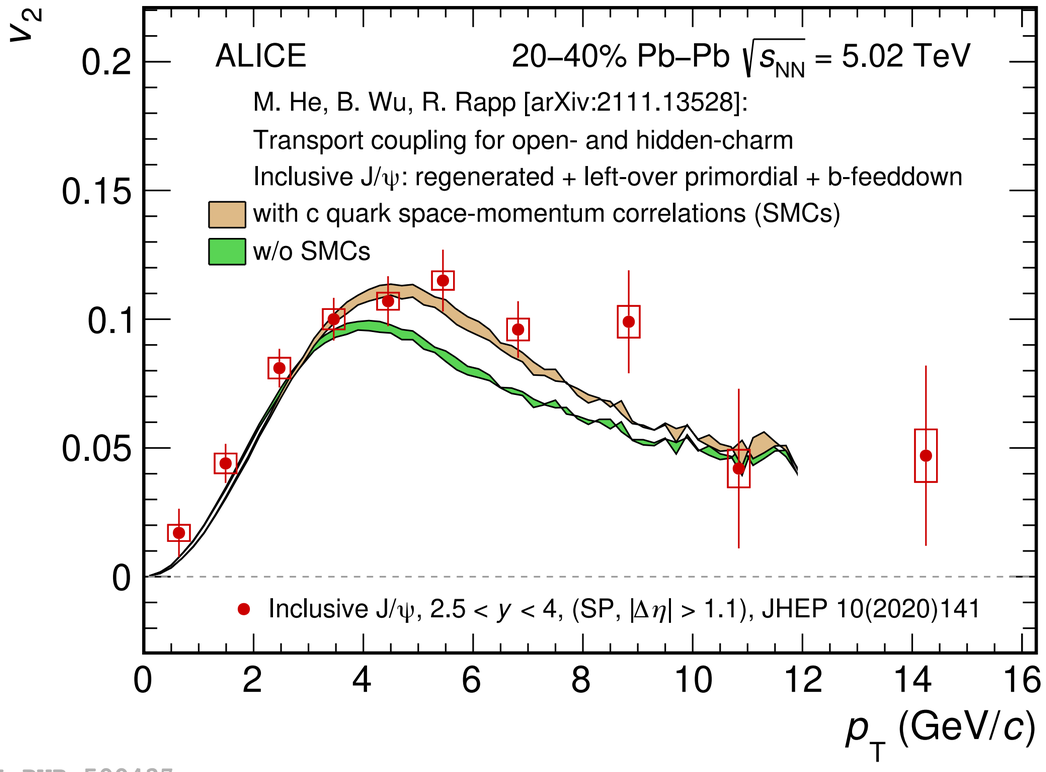
SHM: Andronic A. et al., Phys. Lett. B797 (2019) 134836,
TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158

Observable: elliptic flow v_2

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

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



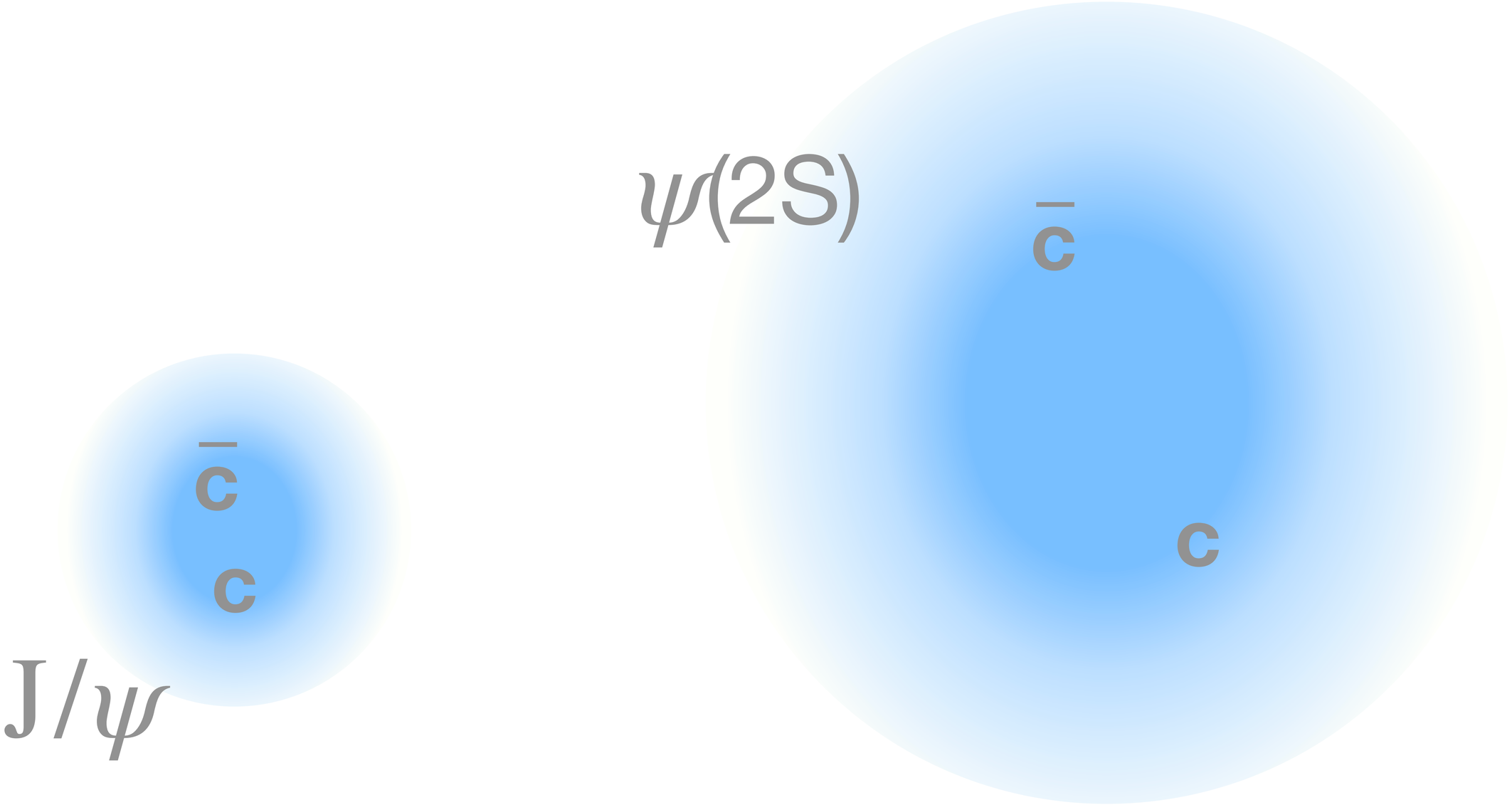


ALI-PUB-500427

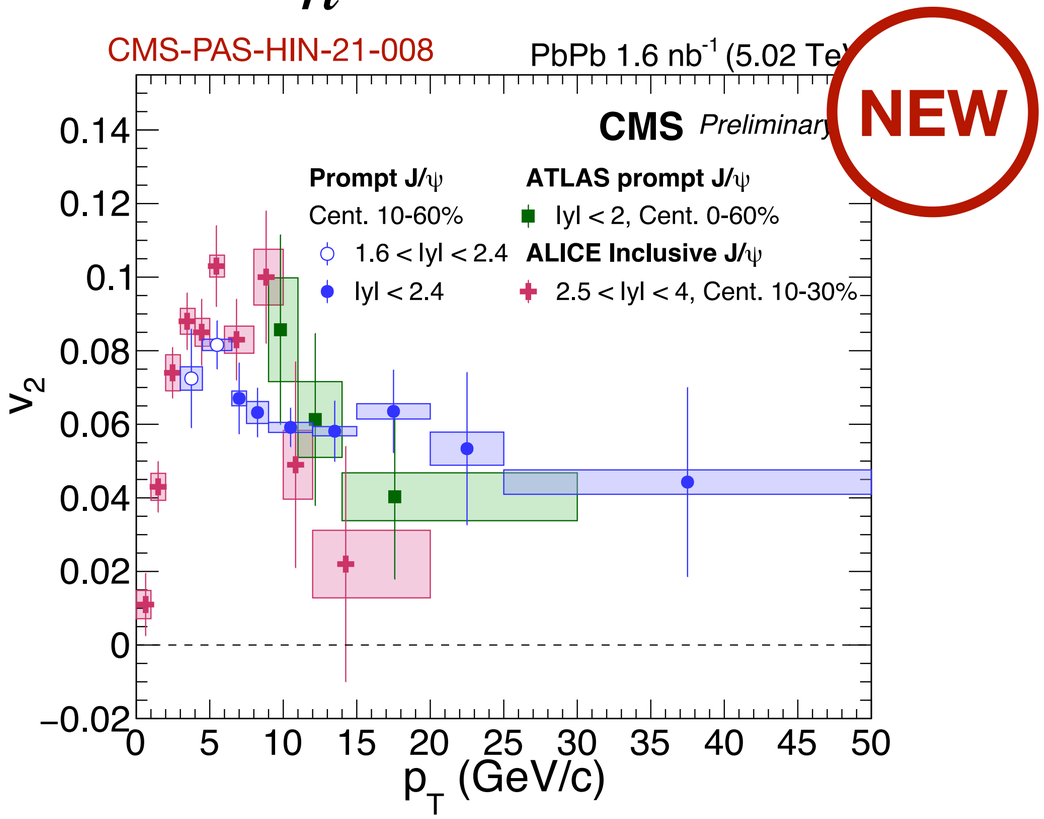
- Low p_T (< 5 GeV/c): transport model implementing **regeneration** can describe measured J/ψ v_2, the latter inherited from collective flow of c quarks during recombination

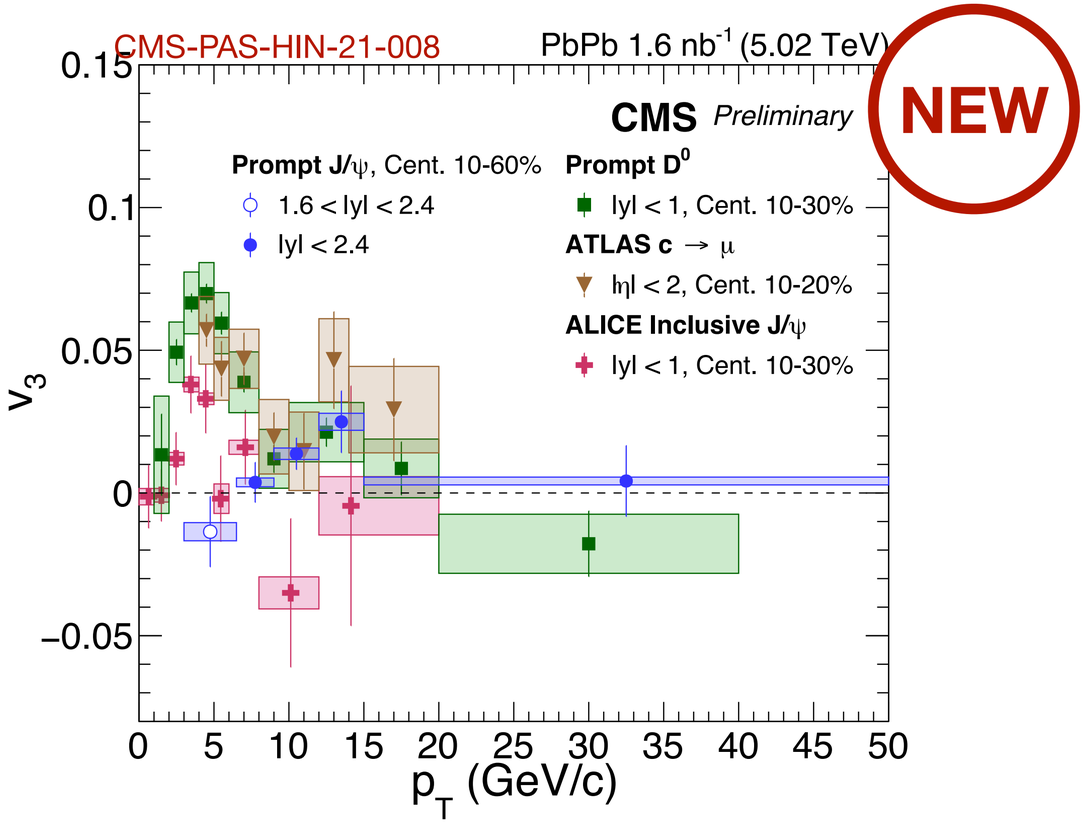
- High p_T v_2: path-length dependence mechanism + c quark space-momentum correlations

New results on charmonia



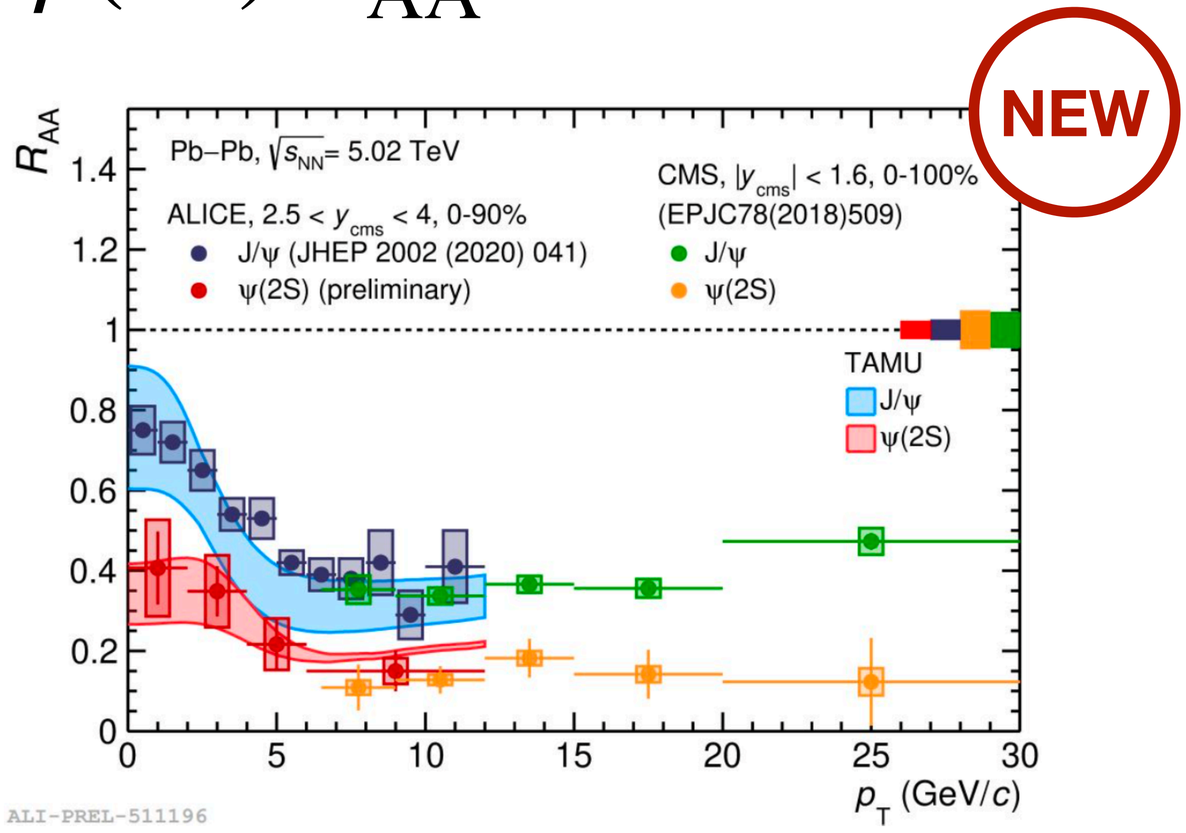
Prompt $v_n^{J/\psi}$ measurements in Pb-Pb collisions

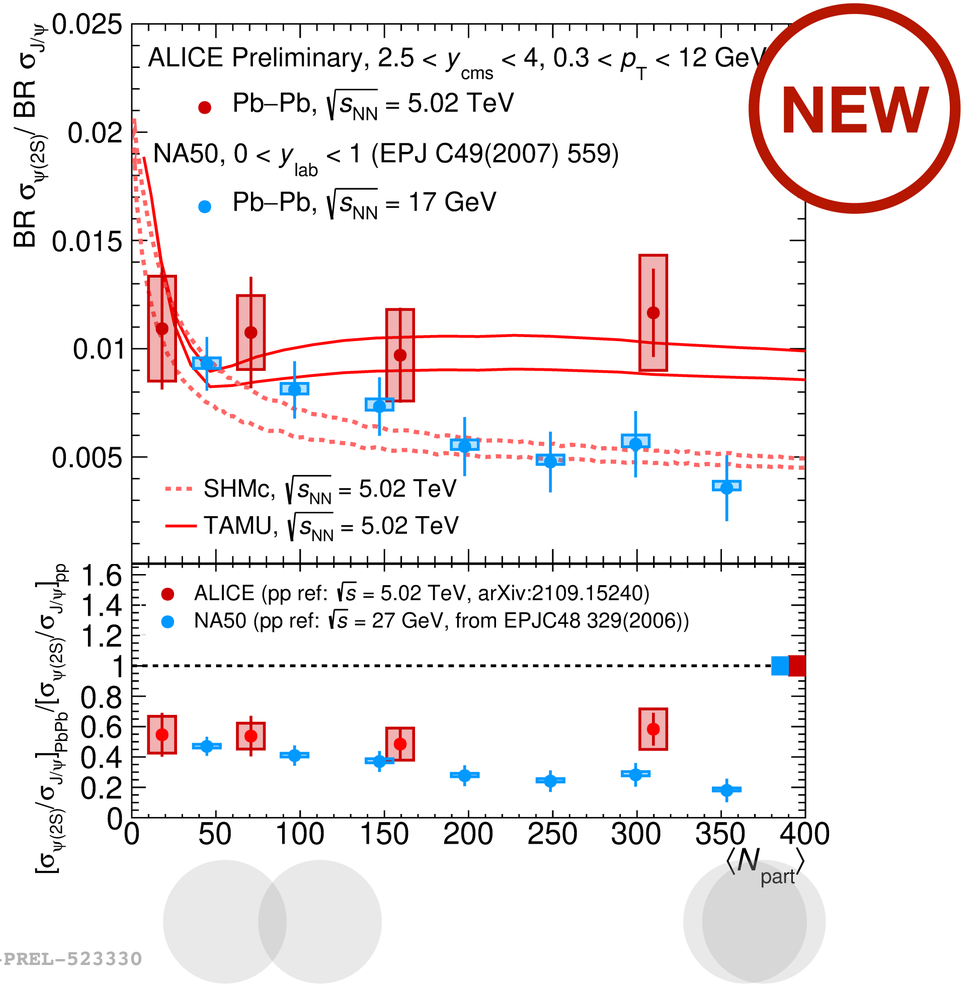




- Prompt J/ψ : significant v_2 up to high p_T (~30 GeV/c), while v_3 is smaller
- Largest $v_2^{J/\psi}$ at low p_T (~5 GeV/c, expected from recombination) and also hint for v_3
- High p_T v_2: path-length dependence effect at play for all particles

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

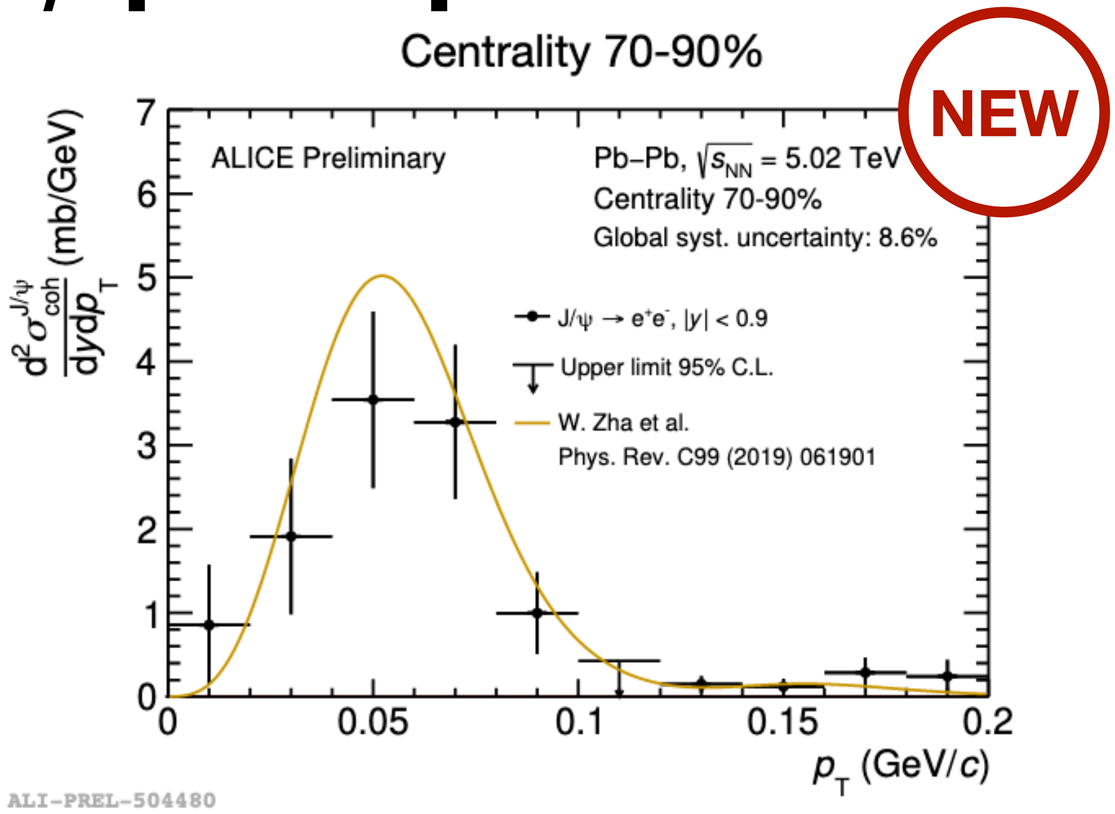


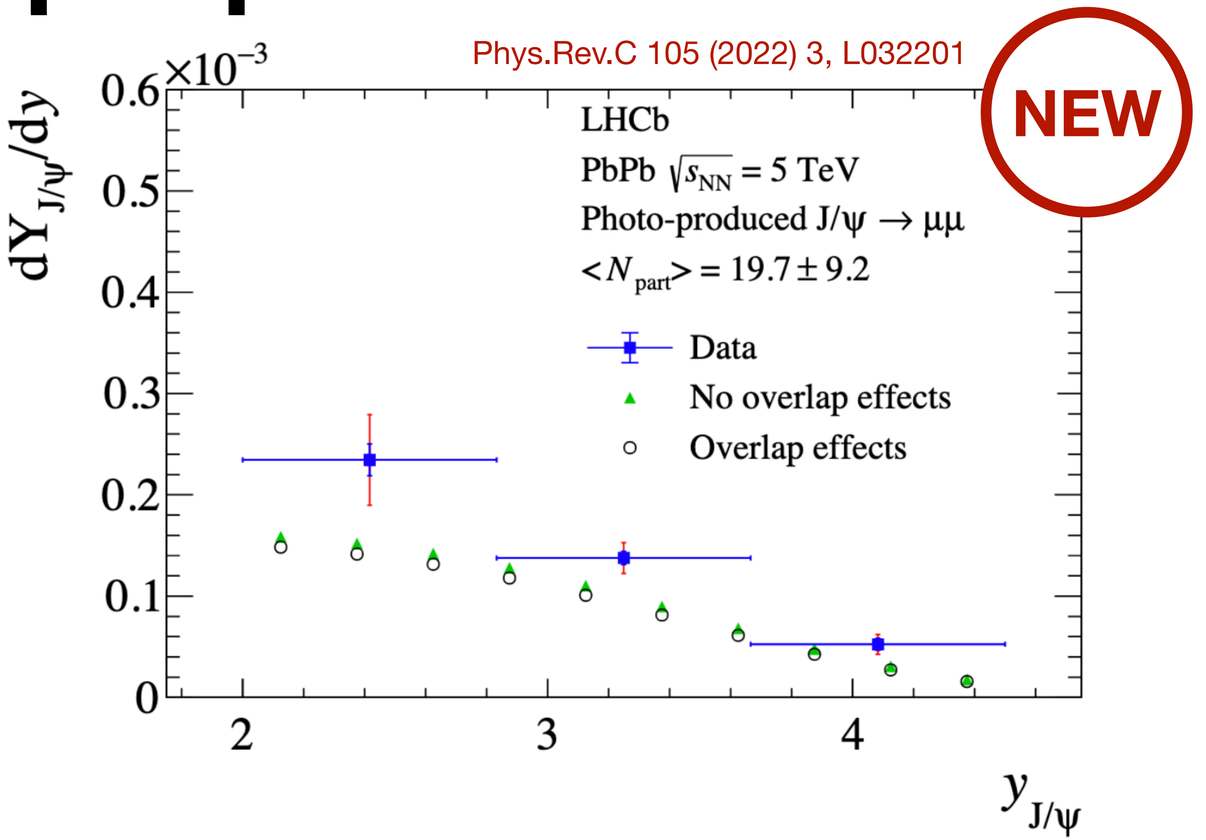


- **Suppression hierarchy** between J/ψ and $\psi(2S)$ over p_{T} and for all centralities
- **Hint of a larger** $\psi(2S)$ / J/ψ ratio in central collisions at the LHC w.r.t SPS (ratio described by TAMU model, while it is underestimated by SHMc in central events)

TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158
SHMc: Andronic A. et al., Nature 561, 321–330 (2018)

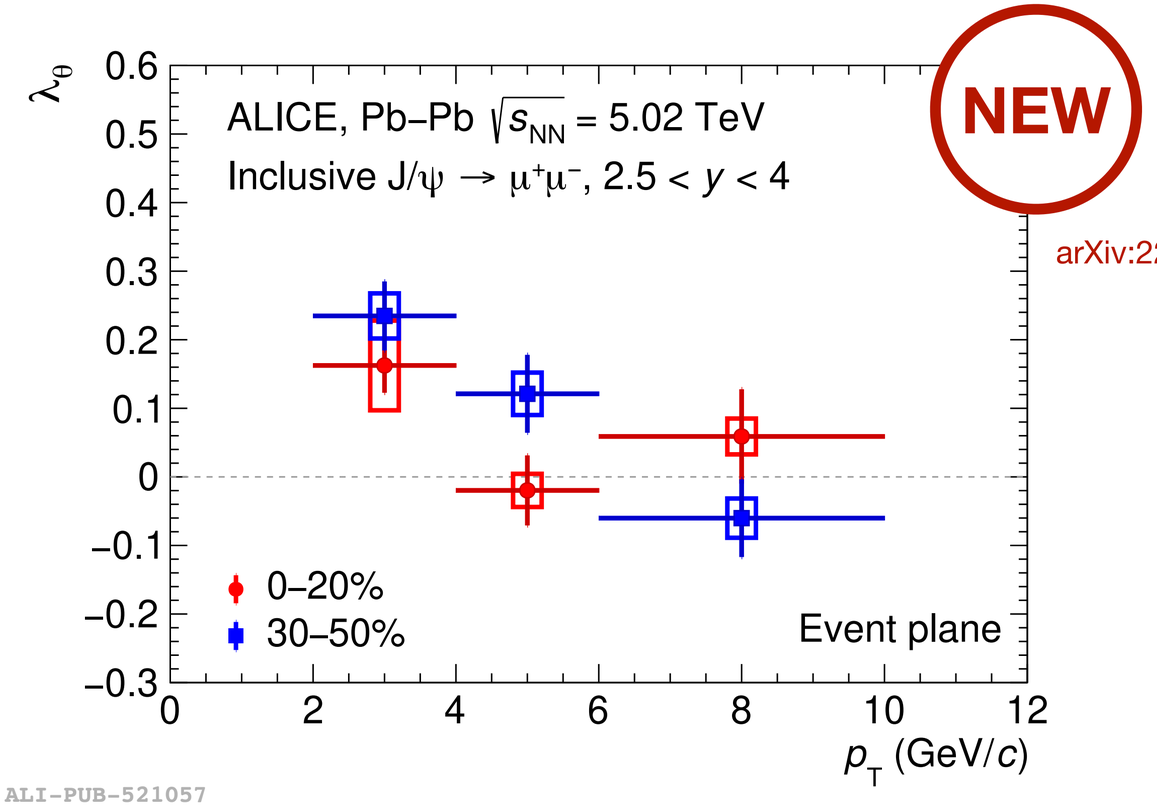
J/ψ photoproduction in peripheral Pb-Pb





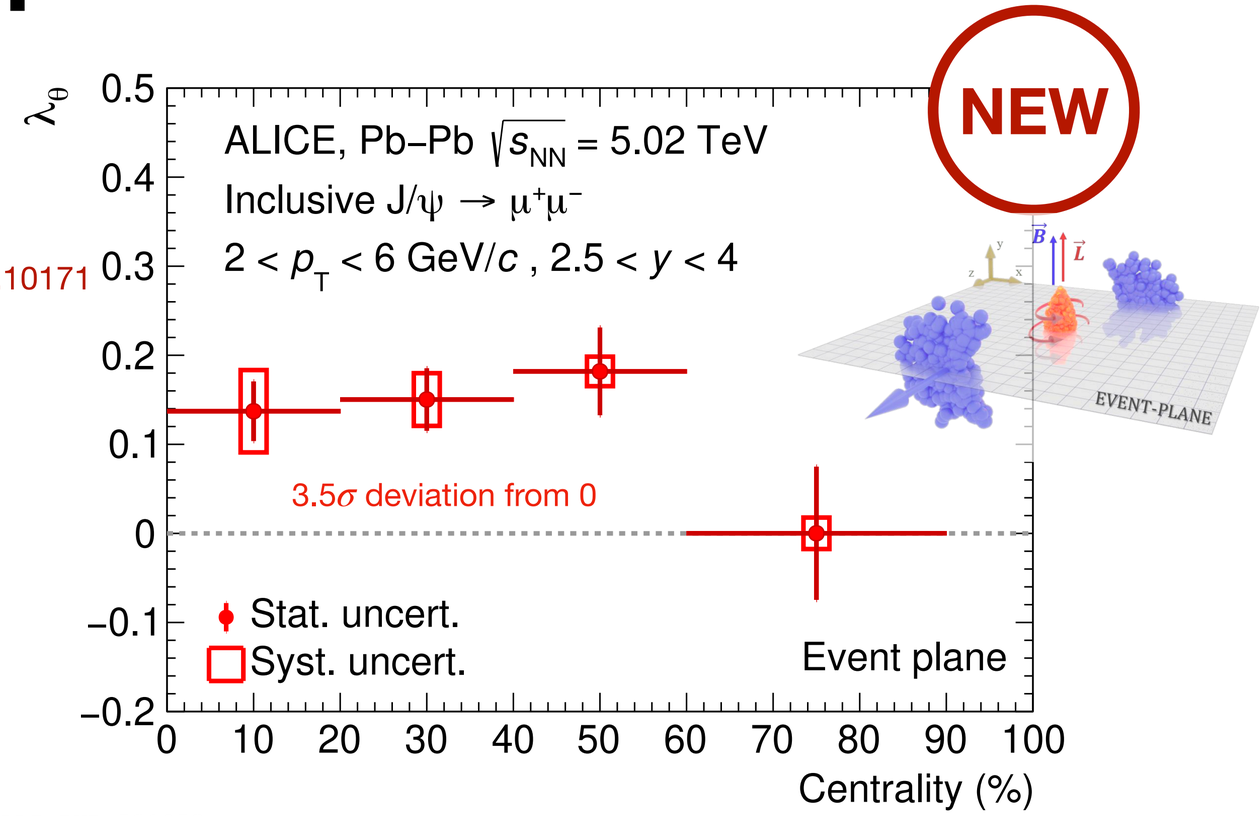
- J/ψ photoproduction observed in peripheral Pb-Pb and not only in UPC
- Theoretical models (for UPC) including modification of the photon flux and sometimes also the effect of the overlap between the nuclei (small impact) describe the data

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



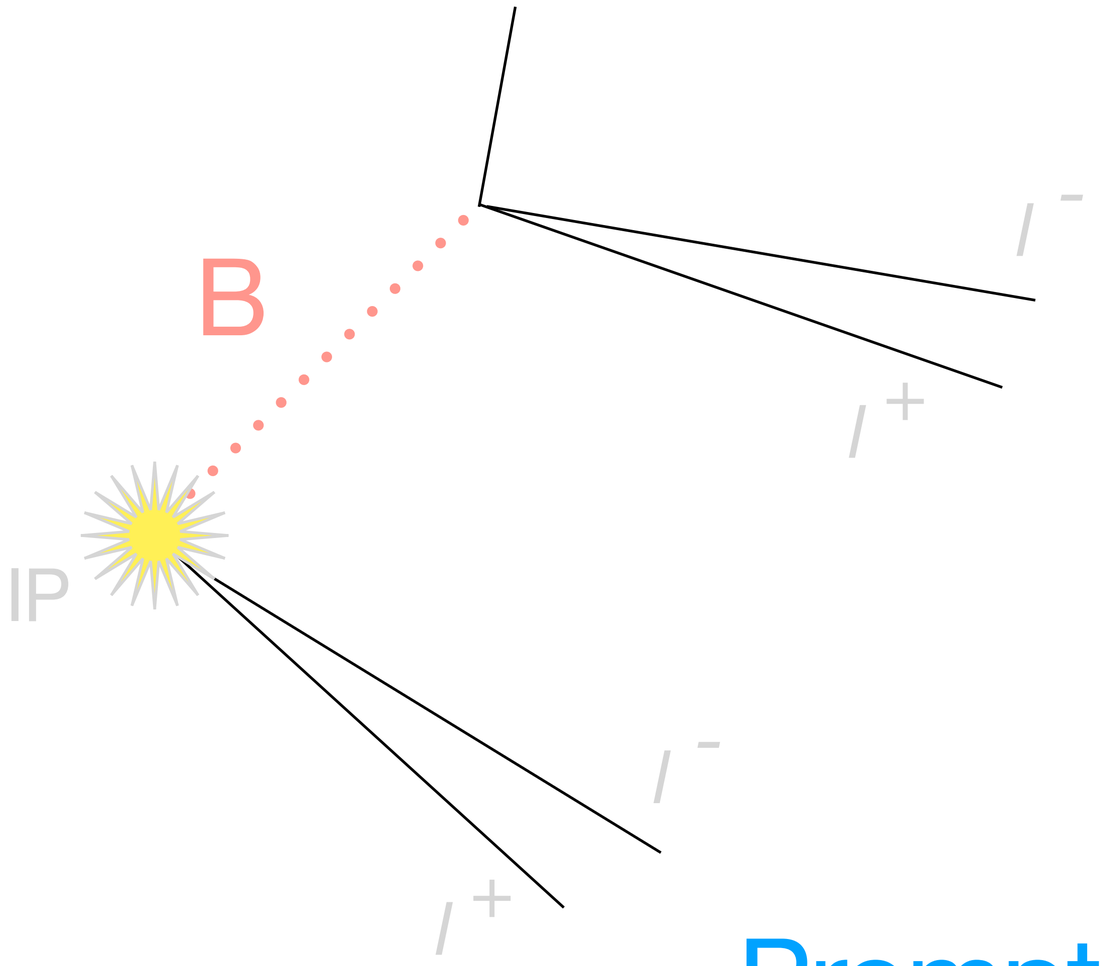
ALI-PUB-521057

arXiv:2204.10171



ALI-PUB-521052

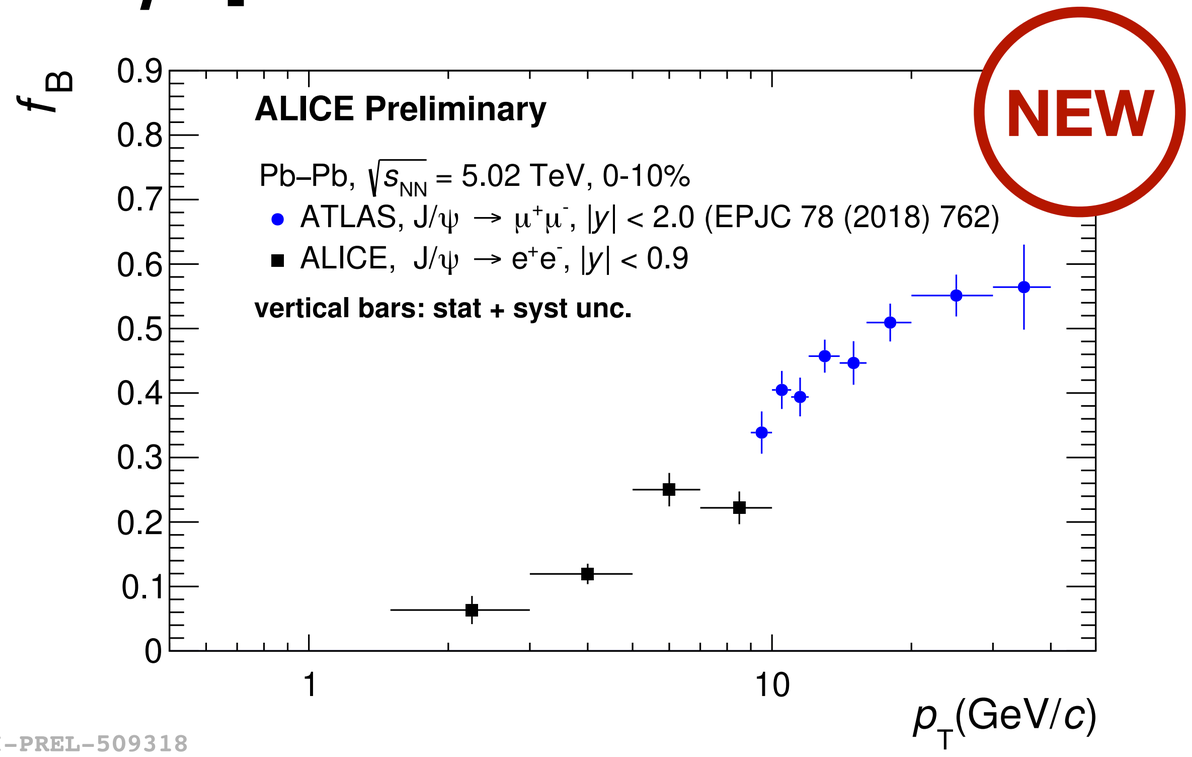
- Vanishing polarisation at larger momenta
- **First evidence** of J/ψ polarisation w.r.t. EP at low p_T (possibly larger in semi-central events)
- Sensitivity to **vorticity and B field**?

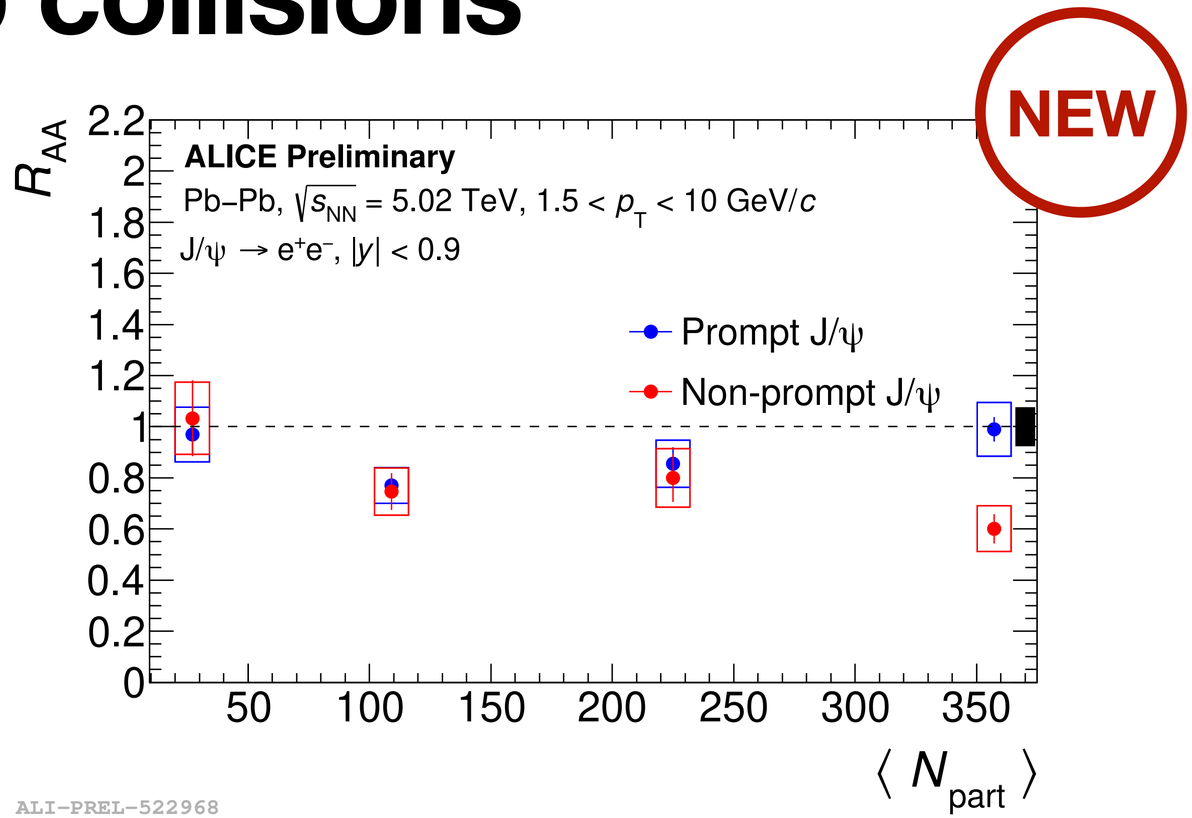


Non-prompt J/ψ

Prompt J/ψ, $\psi(2S)$

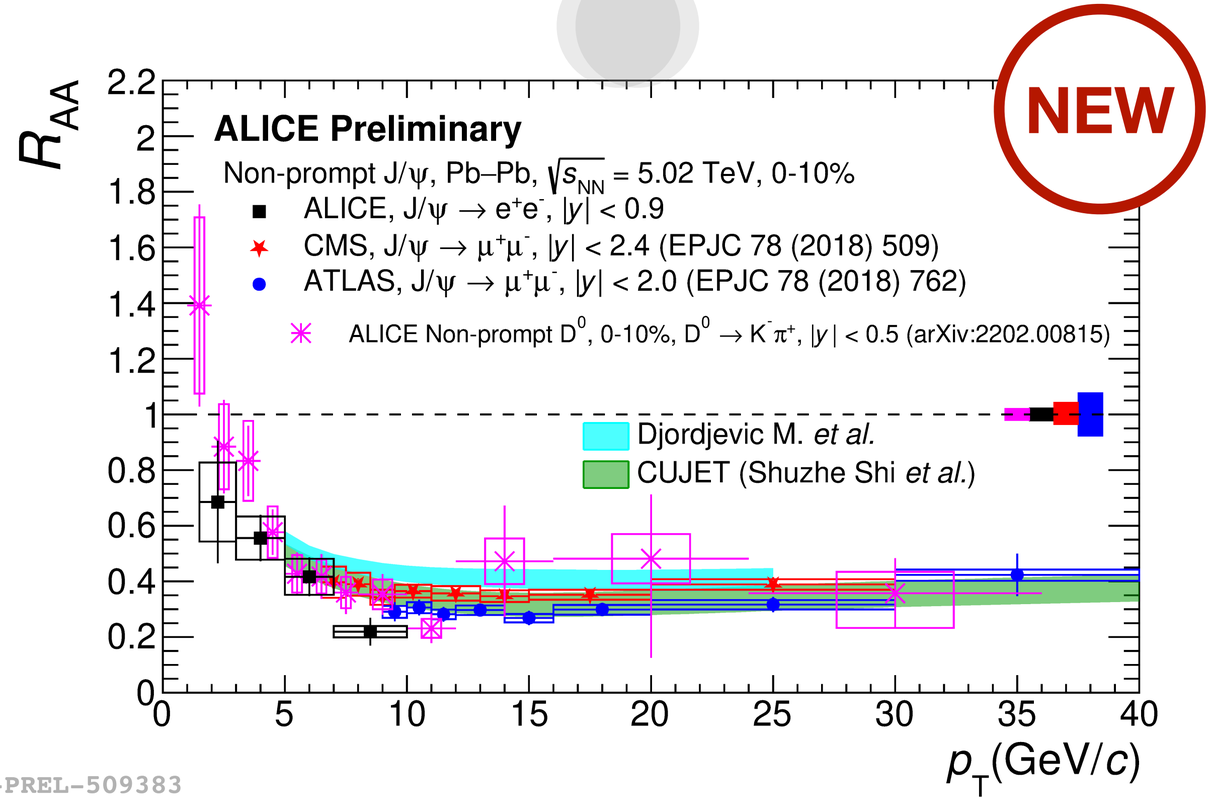
J/ψ production in Pb-Pb collisions

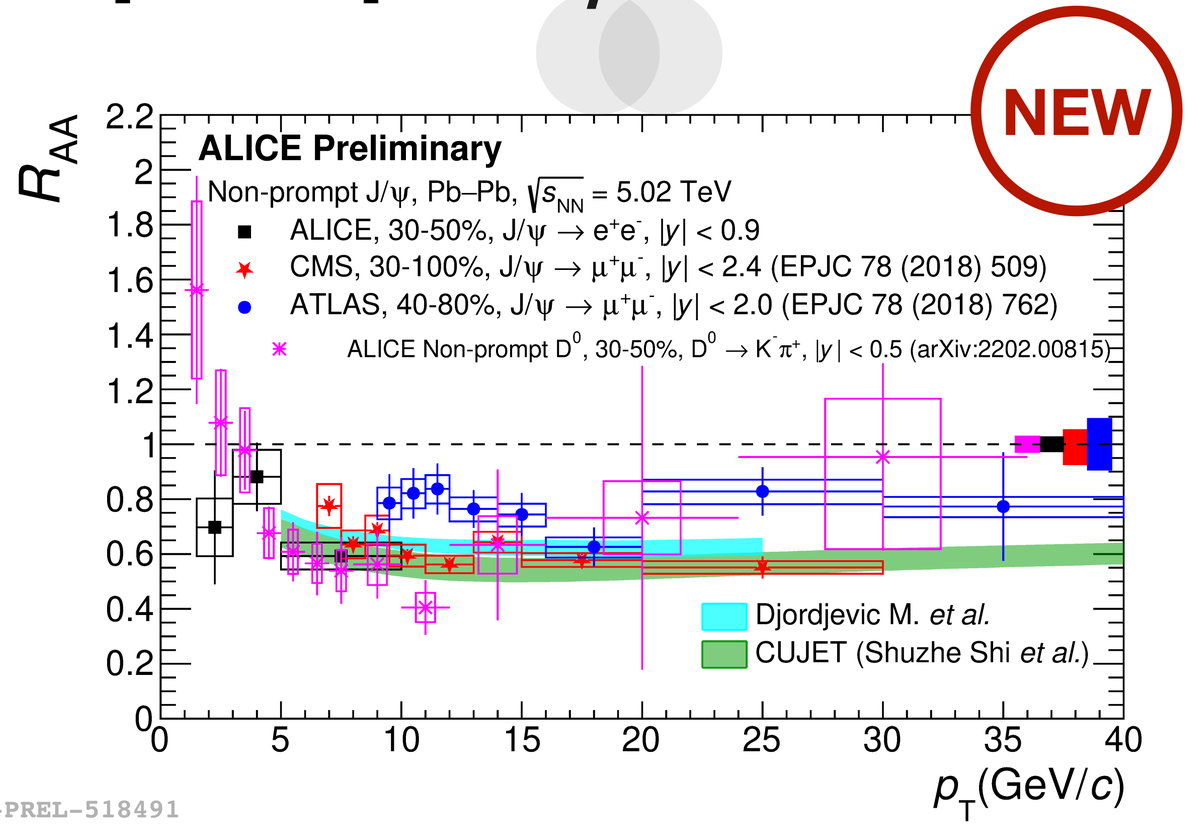




- ALICE extends non-prompt J/ψ fraction (f_{B}) measurements down to very low p_{T}
- Non-prompt J/ψ R_{AA} **more suppressed towards more central collisions**
- Recombination can explain the raising trend of $R_{\mathrm{AA}}^{\text{prompt J}/\psi}$ towards more central collisions

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



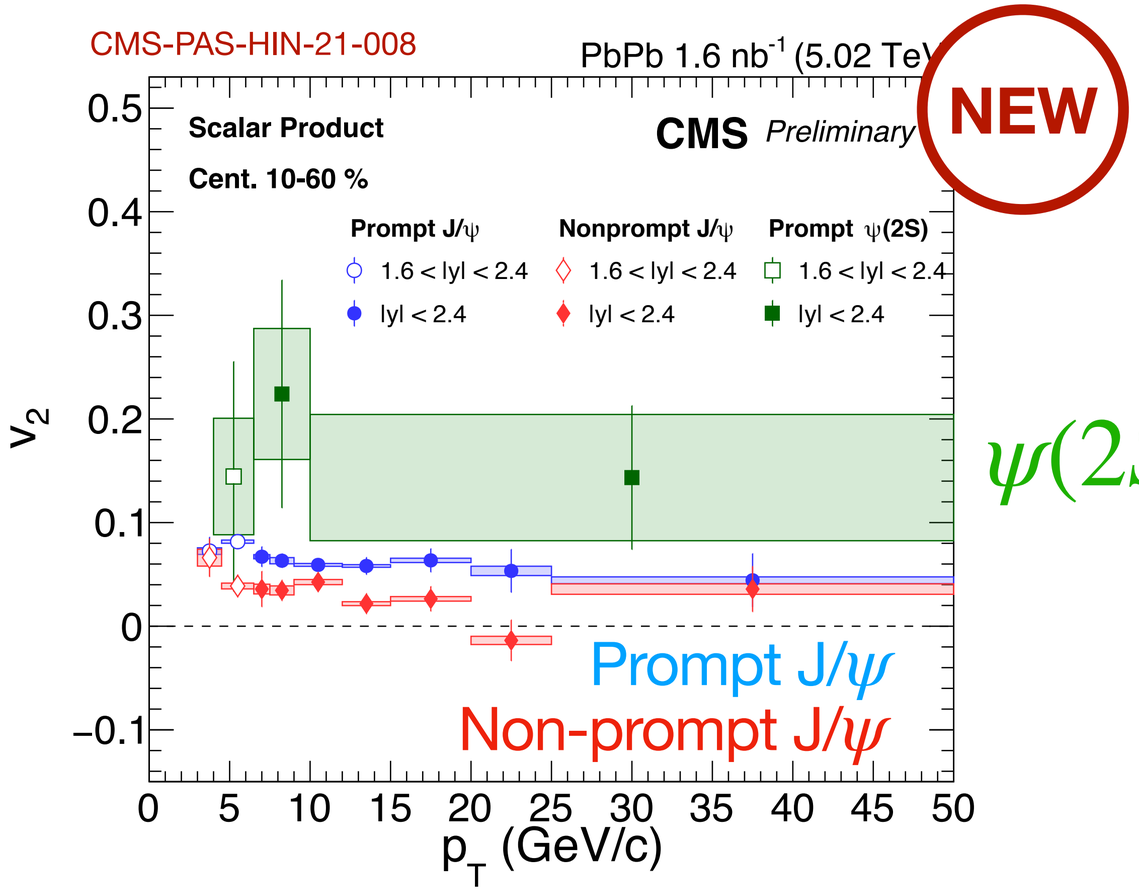


- Unprecedented access to the low p_{T} region for beauty hadron R_{AA} through the measurements of non-prompt J/ψ and non prompt D^0 meson

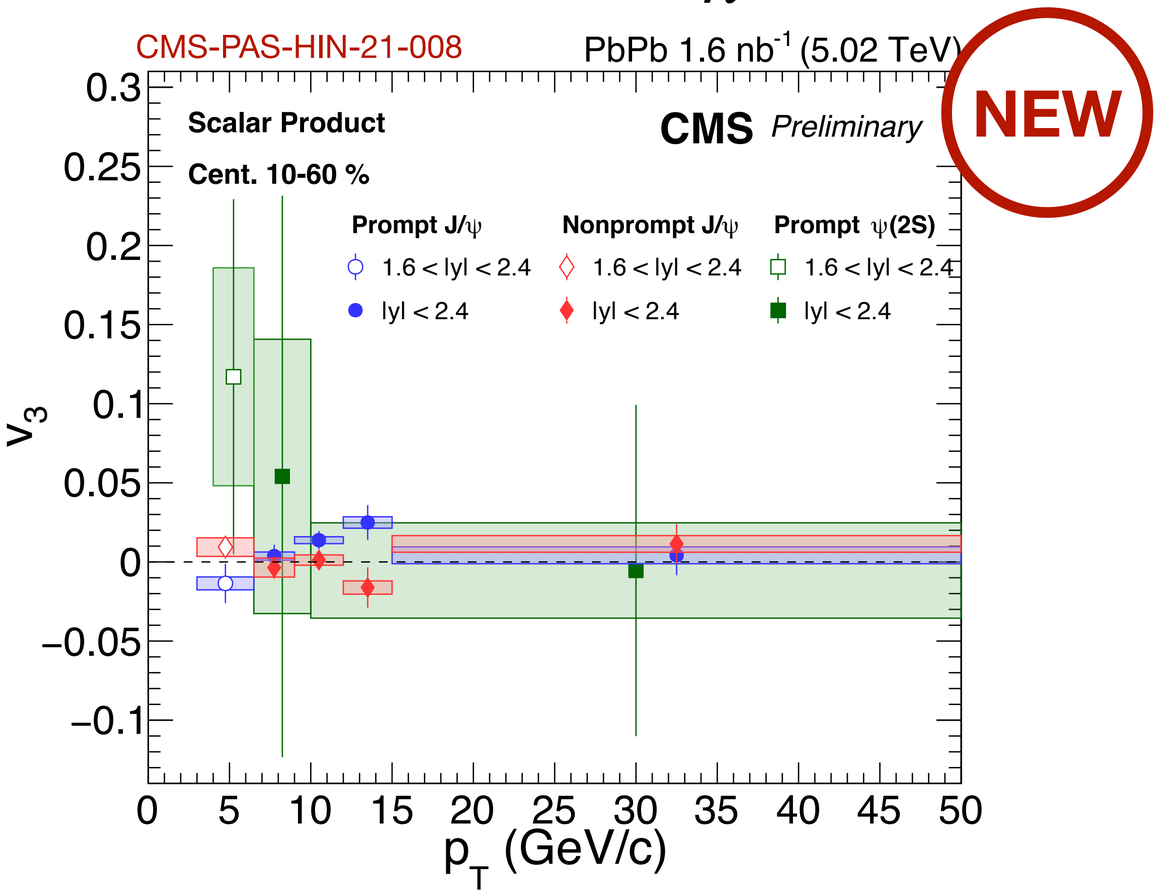
- Models including **collisional and radiative energy loss** consistent with data (high p_{T})

CUJET: Shuzhe S. et al. Chin.Phys.C 43 (2019) 4, 044101, Chin.Phys.C 42 (2018) 10, 104104
Djordjevic M. et al. arXiv:2110.01544

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

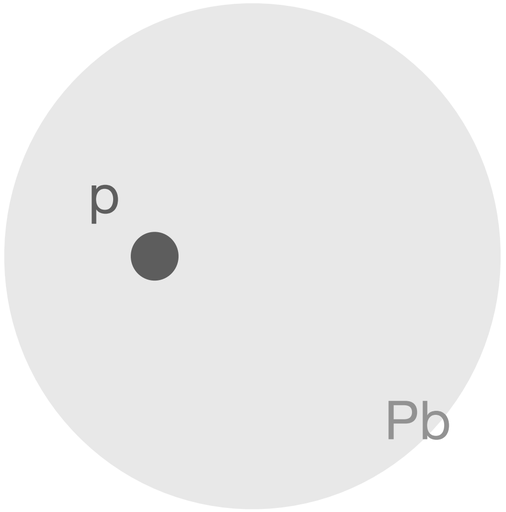


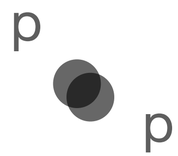
$\psi(2S)$



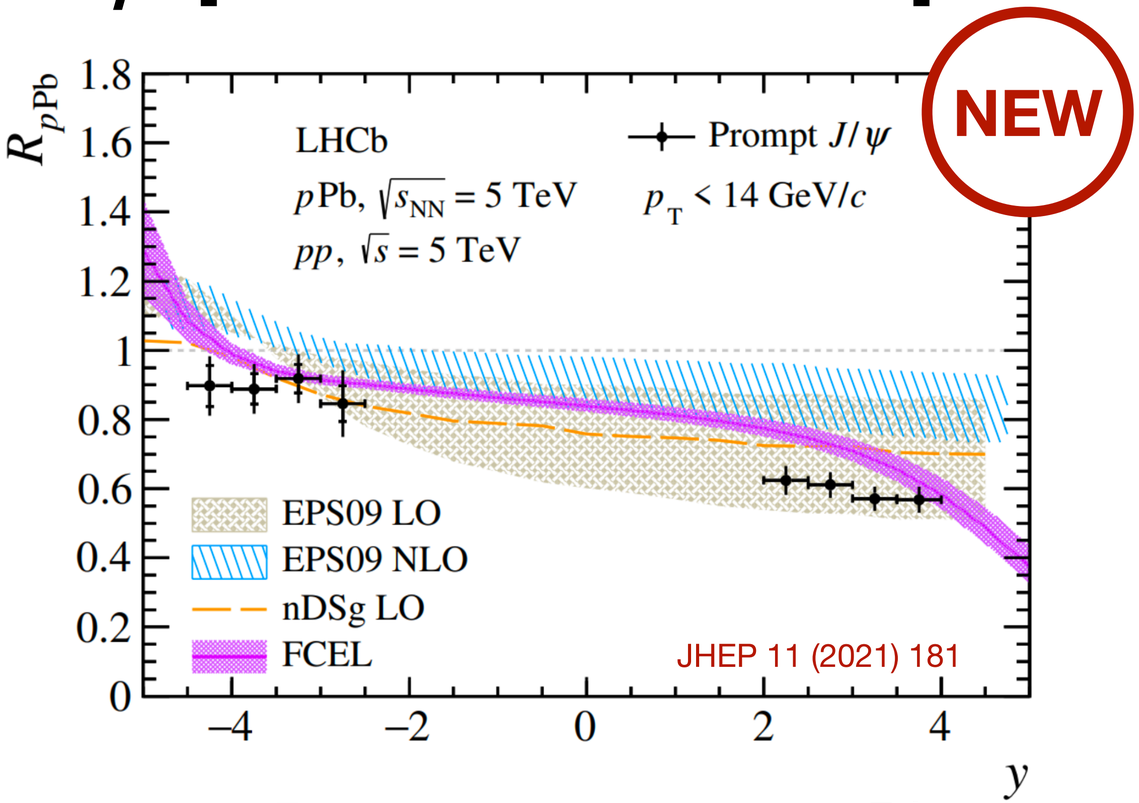
- **Hint of** prompt $v_2^{\psi(2S)} > 0$ (p_{T} >5 GeV/c): larger than v_2 of prompt and non-prompt J/ψ
- Prompt $\psi(2S)$ v_3 found **compatible with 0** and with J/ψ v_3

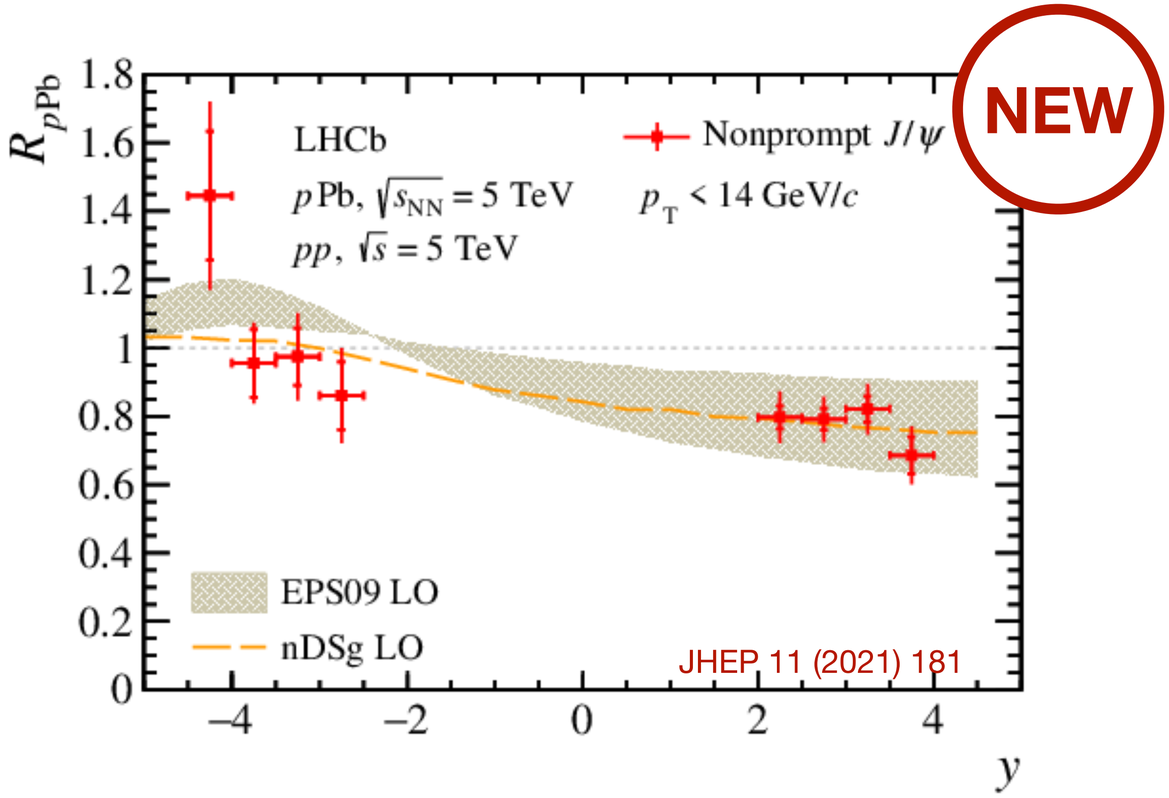
Going towards small collision systems





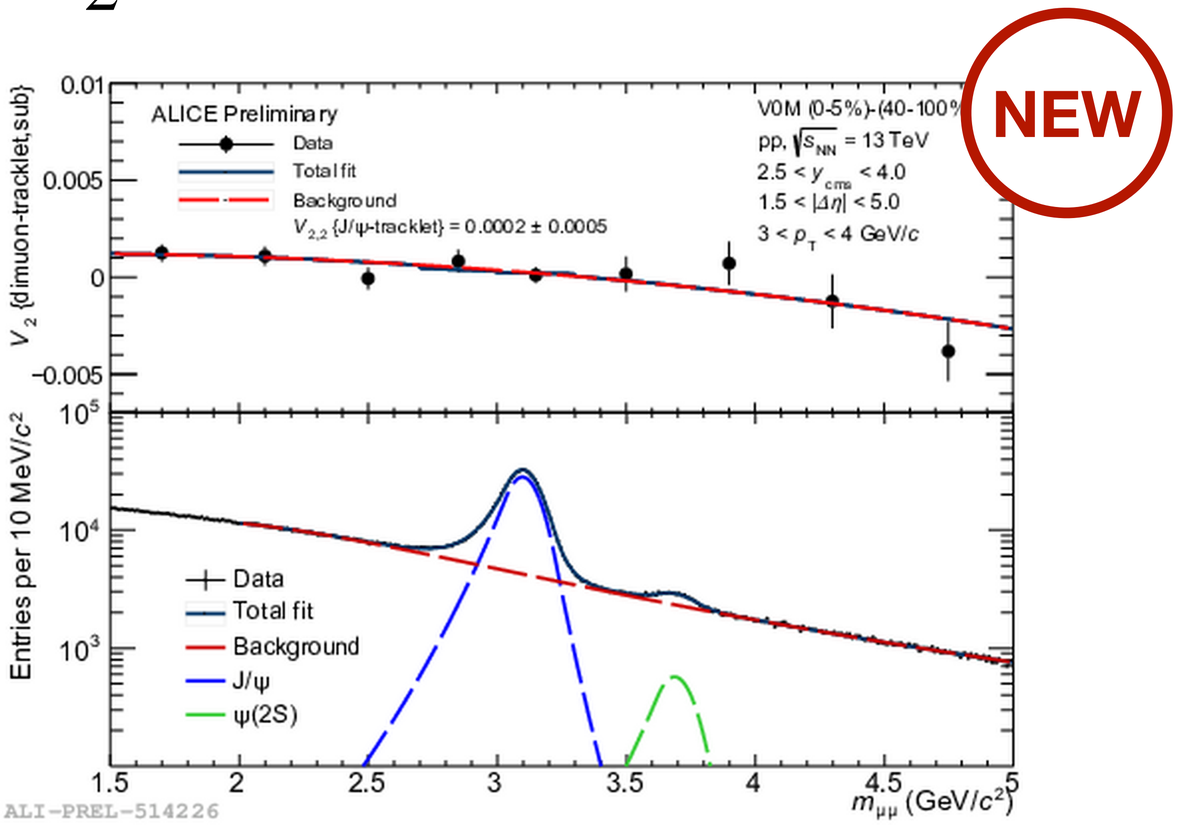
J/ψ production in p-Pb collisions



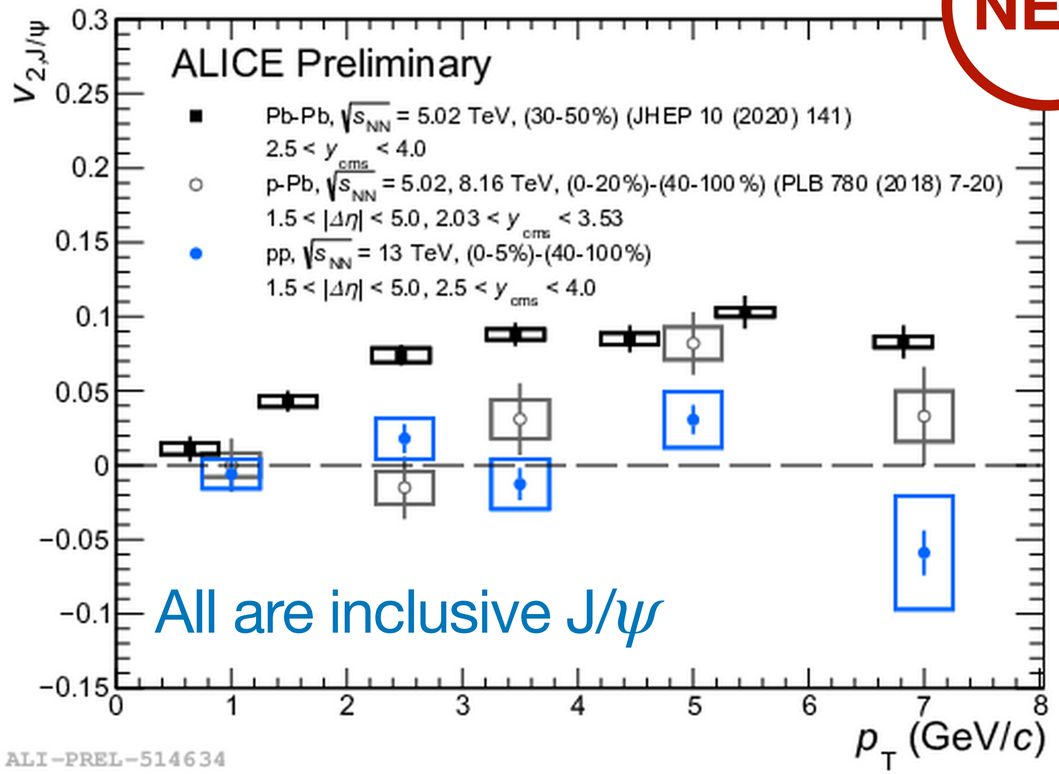


- Updated R_{pPb} for (non-)prompt J/ψ thanks to new differential cross sections in pp
- Stronger suppression at forward-y w.r.t. backward-y for (non-)prompt J/ψ
- Prompt J/ψ: tension between data and EPS09 NLO nPDF parametrisation

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



NEW

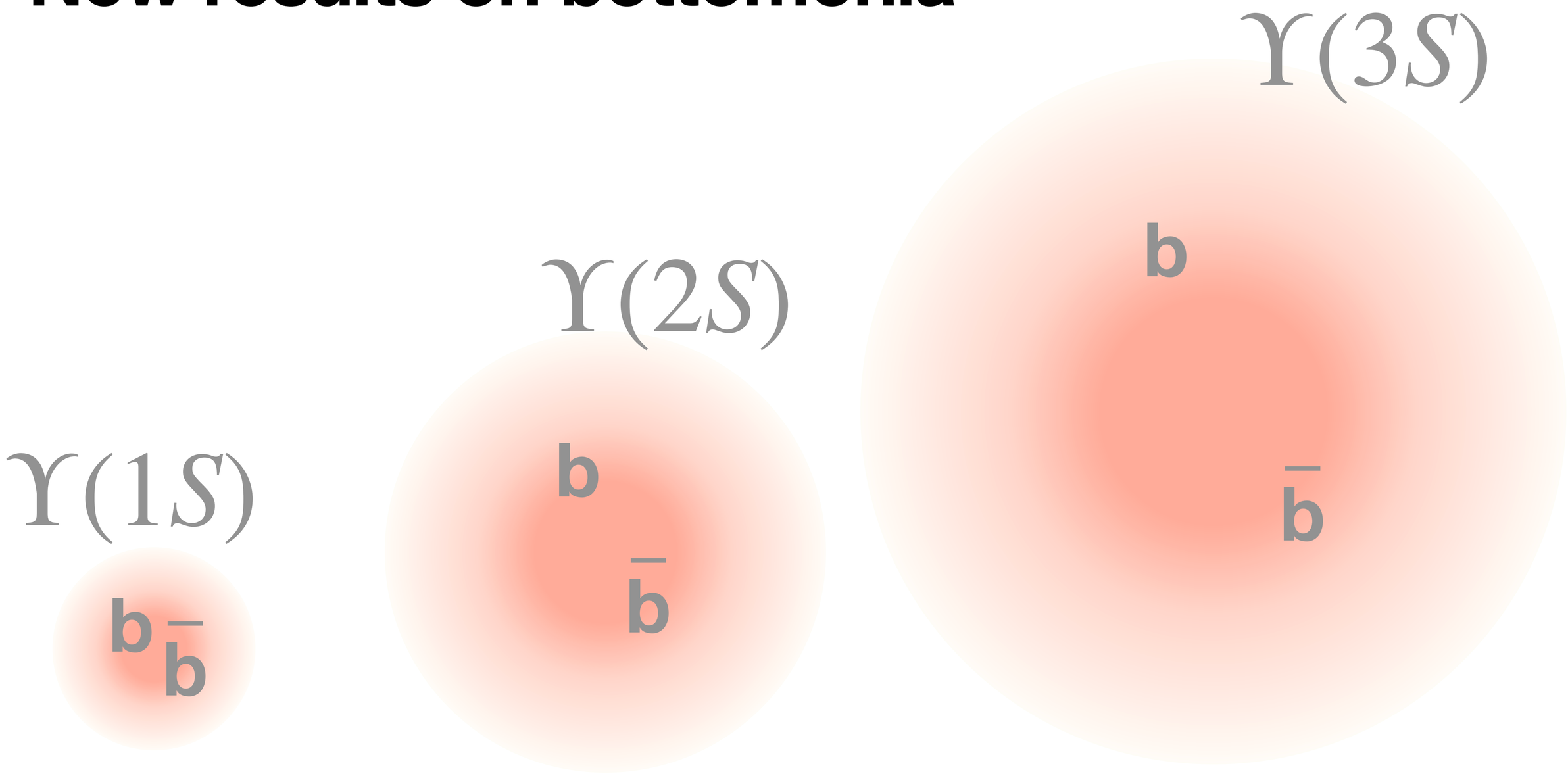


NEW

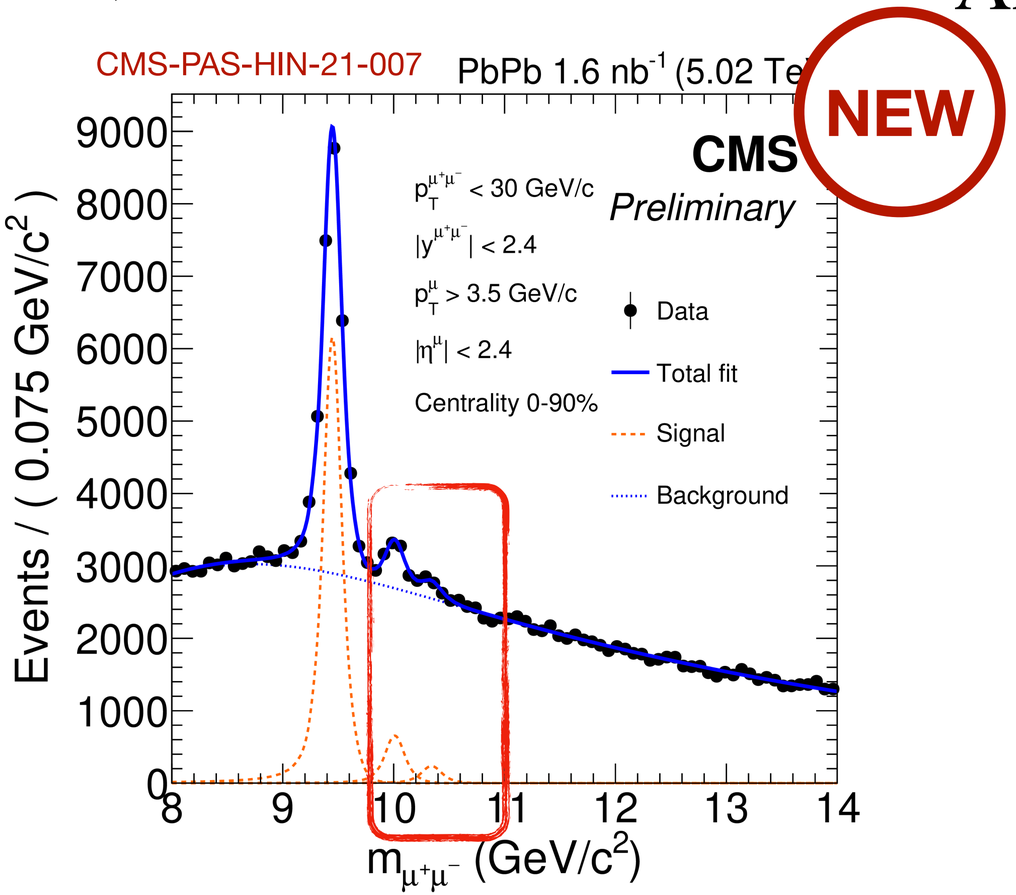
PbPb
pPb
pp

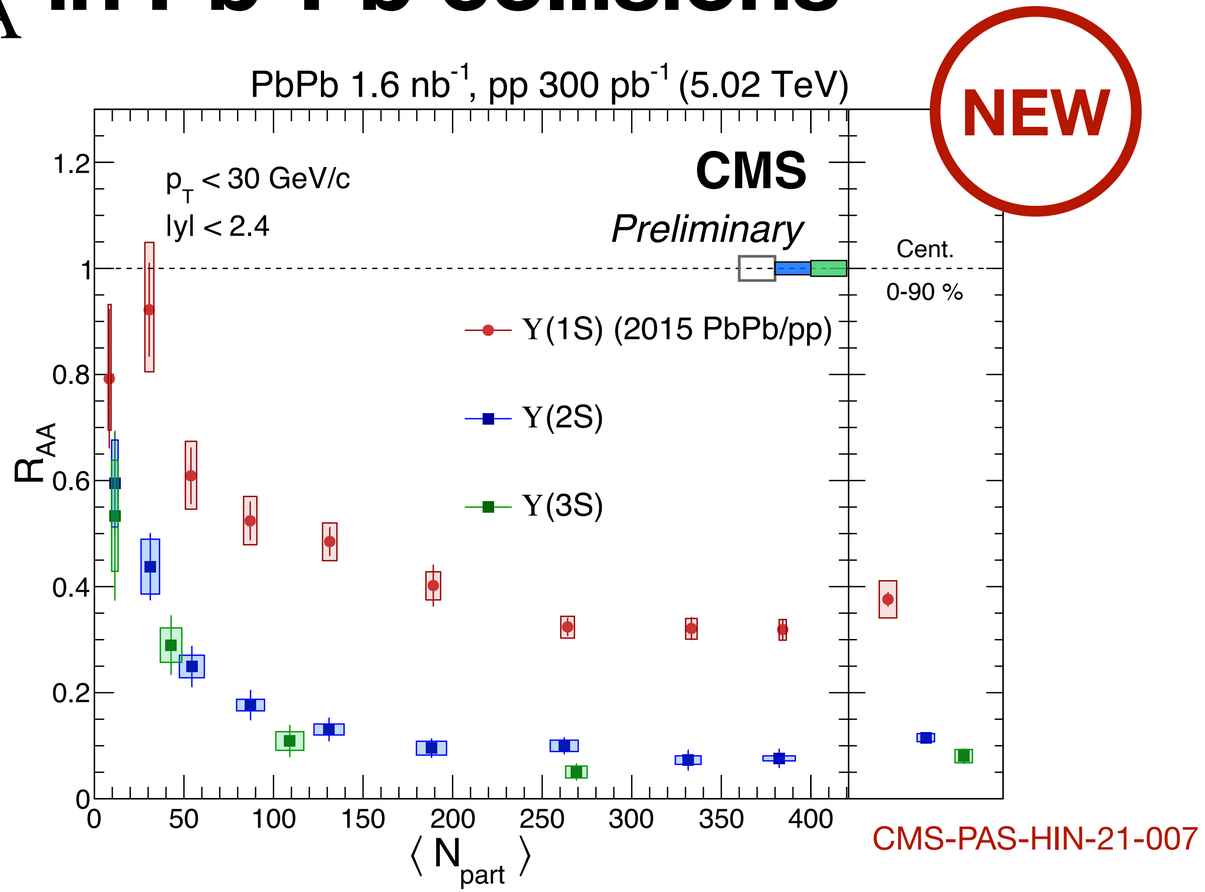
- Collective effects observed for light flavours… open question for heavy flavours
- No significant p_T dependence and $v_2^{J/\psi}$ in pp **compatible with 0** ($v_2^{pp} < v_2^{pPb} < v_2^{PbPb}$)

New results on bottomonia



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

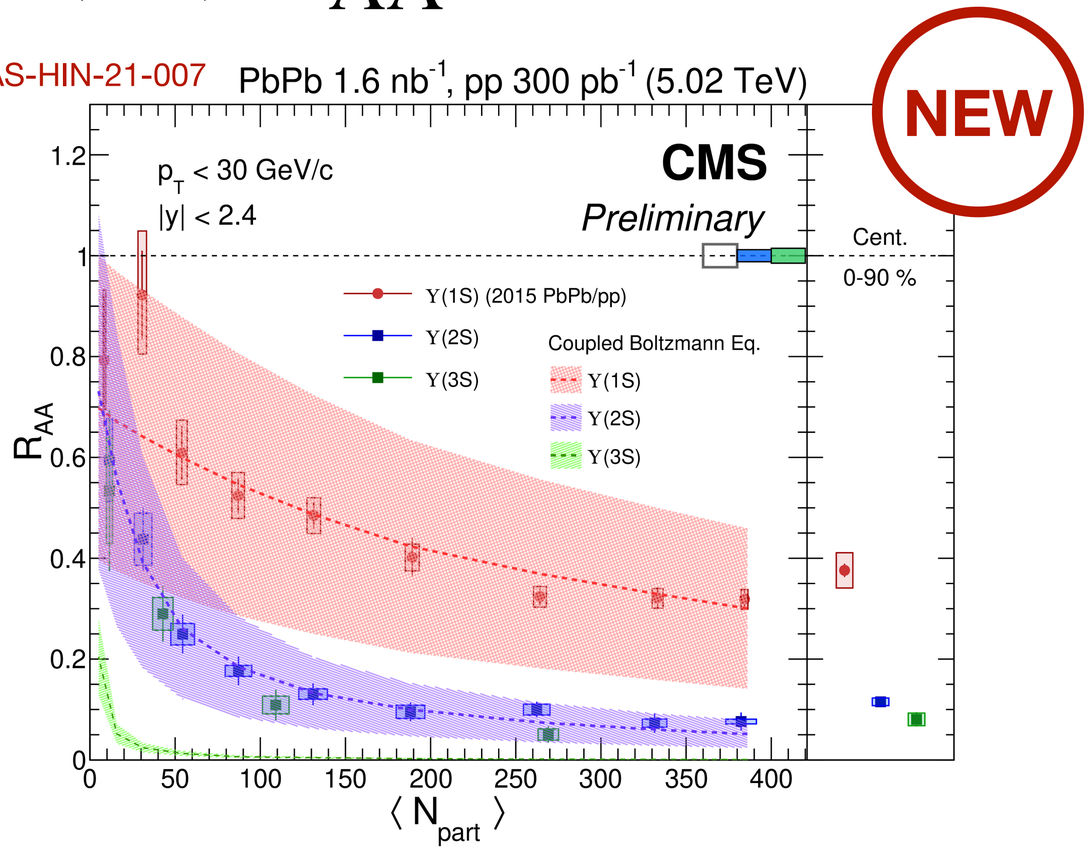


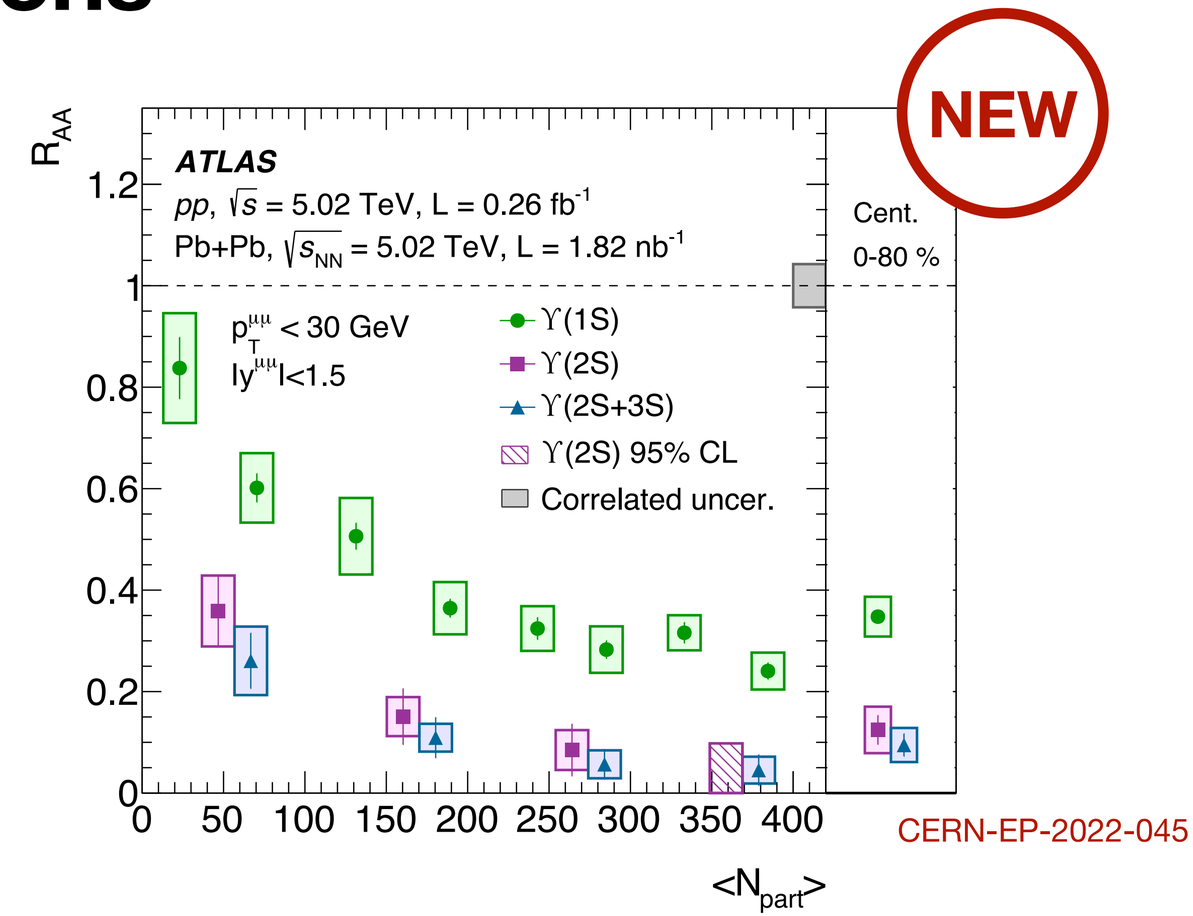


- **Observation** of $\Upsilon(3S)$ in Pb-Pb collisions (using BDT based on decay topology)
- **Sequential suppression**: excited states suppressed in all centralities much more than $\Upsilon(1S)$

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

CMS-PAS-HIN-21-007

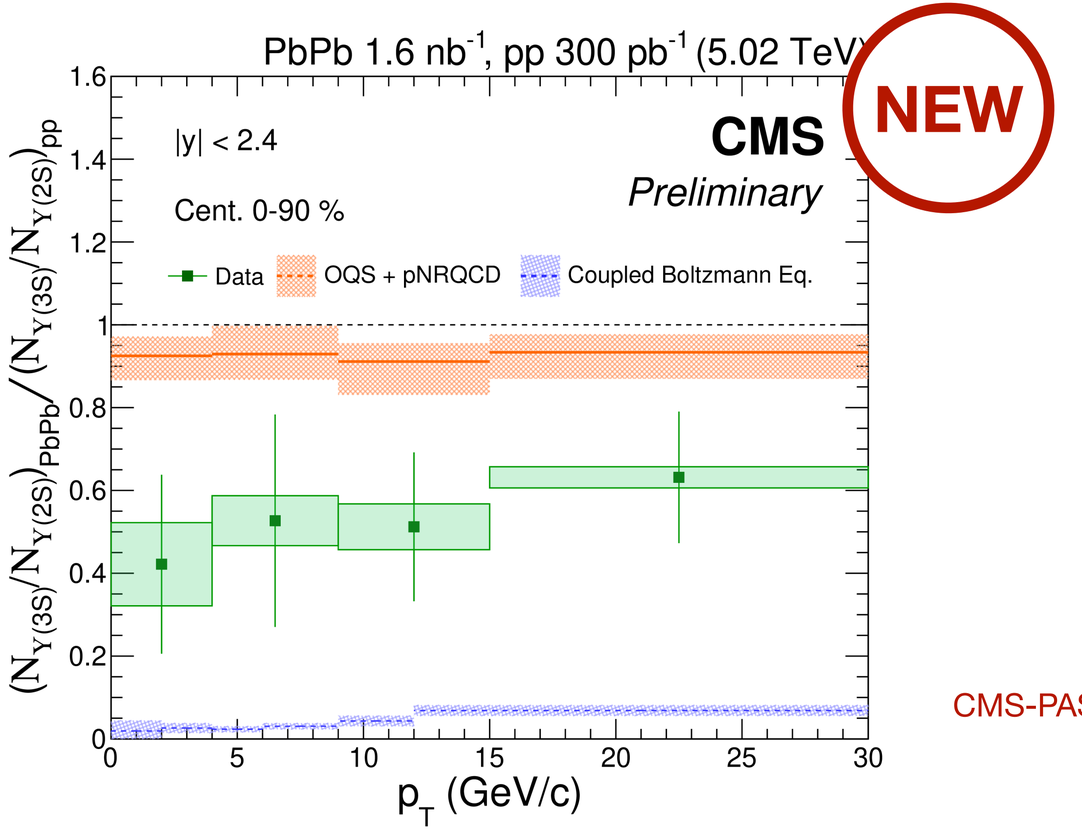




- Stronger suppression of $\Upsilon(3S)$ w.r.t. $\Upsilon(2S)$ as a function of centrality expected from theory and not observed in the data
- $R_{AA}^{\Upsilon(nS)}$ measurements from ALICE (not shown), ATLAS and CMS show similar trend

Coupled Boltzmann equations [JHEP 01 (2021) 046]

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

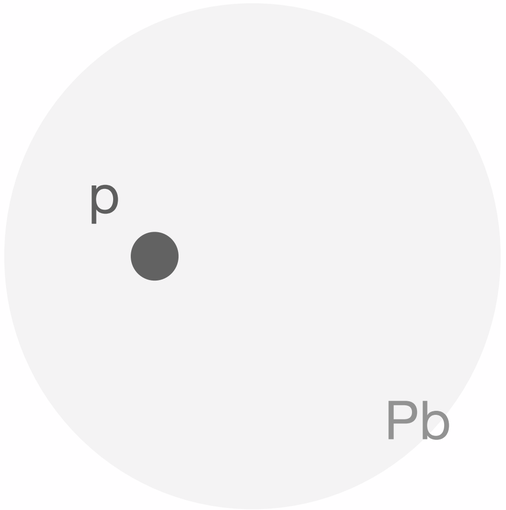


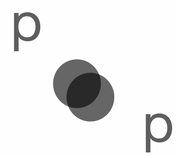
CMS-PAS-HIN-21-007

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

Coupled Boltzmann equations [JHEP 01 (2021) 046],
Open-quantum system [PRD 104 (2021) 094049]

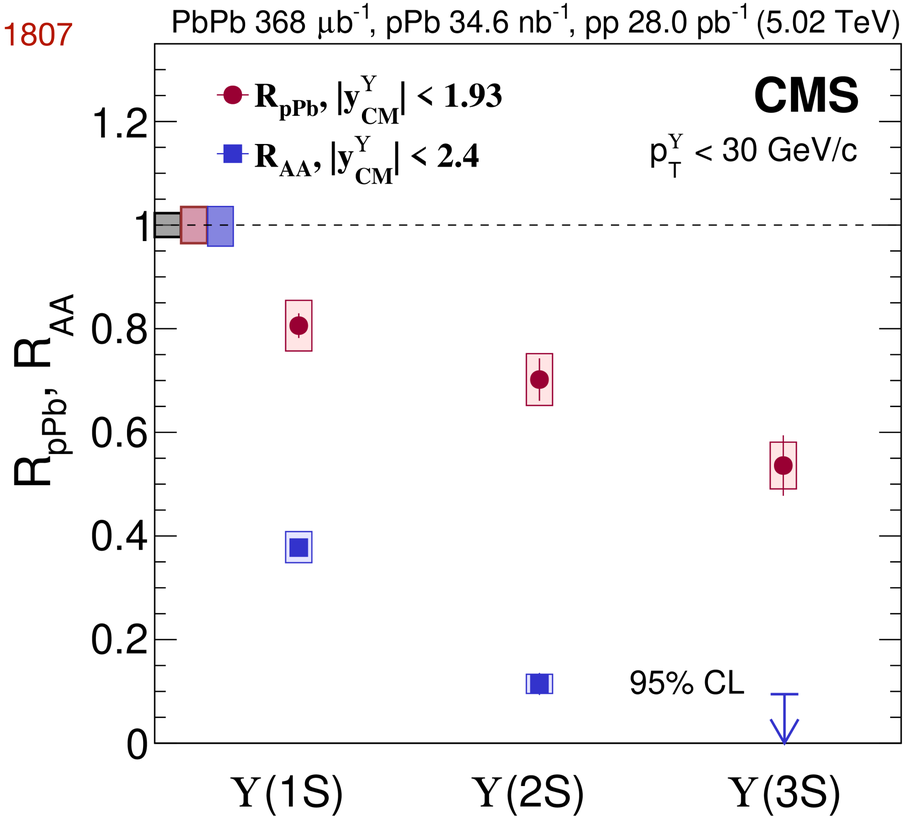
Going towards small collision systems





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

arXiv:2202.11807

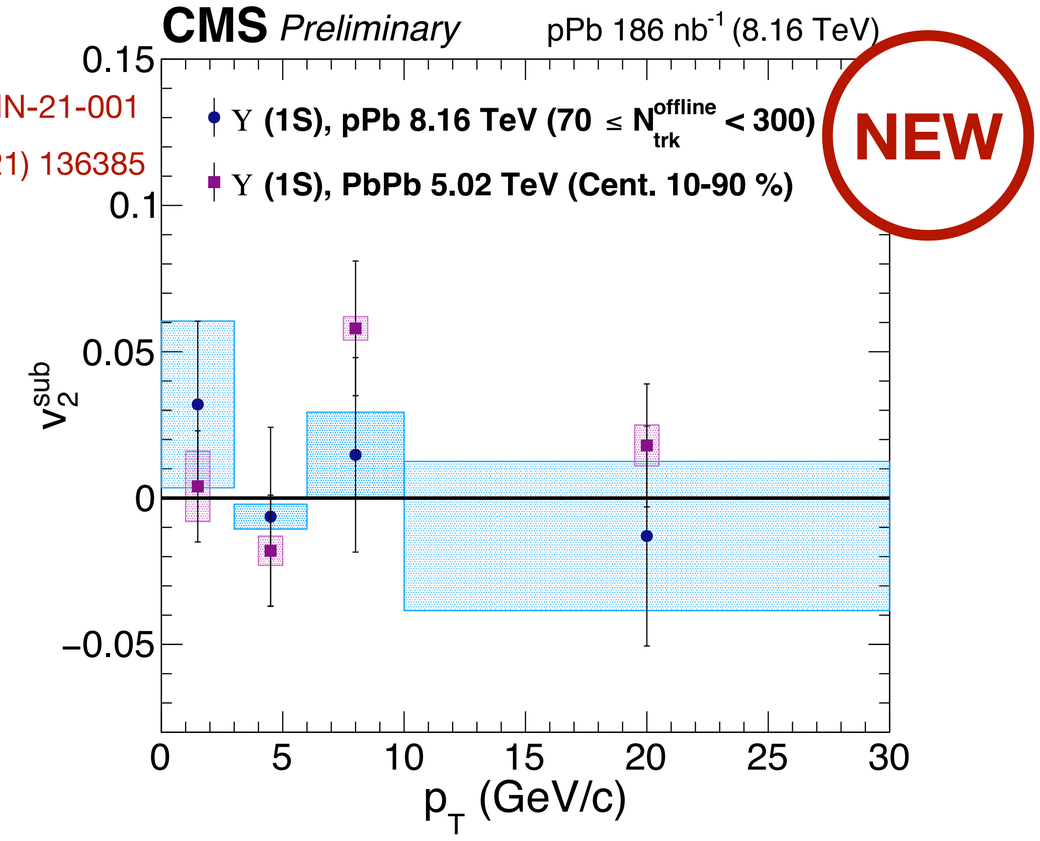


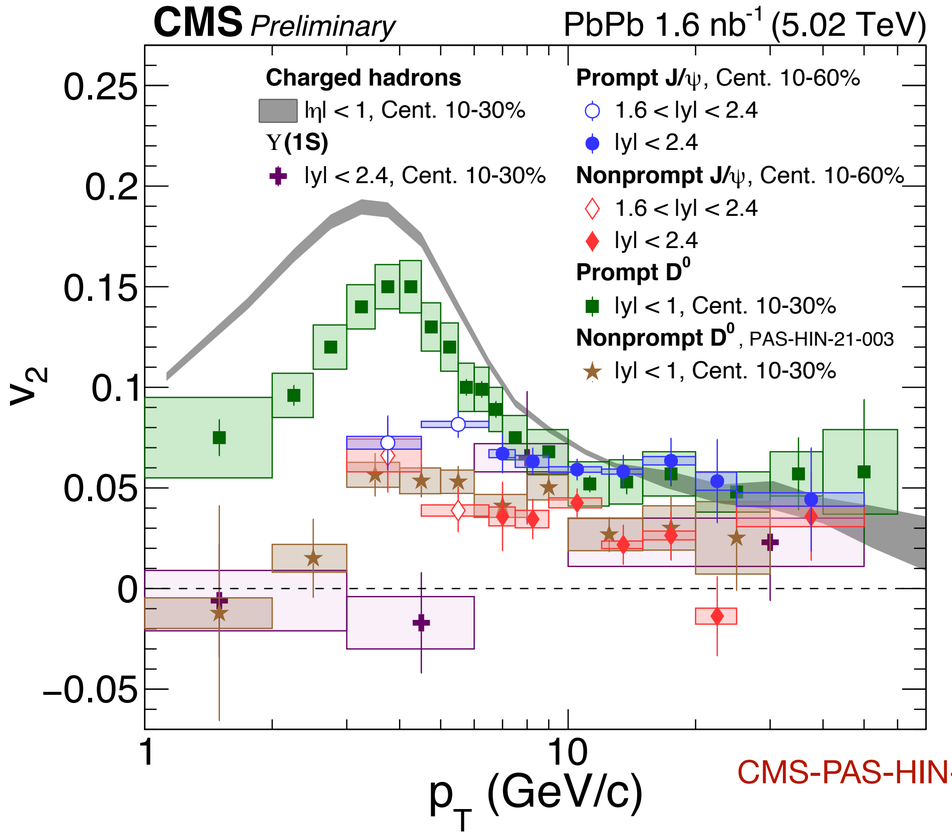
- $\Upsilon(nS)$ states in p-Pb are found to be less suppressed than in Pb-Pb collisions

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

CMS-PAS-HIN-21-001

PLB 819 (2021) 136385





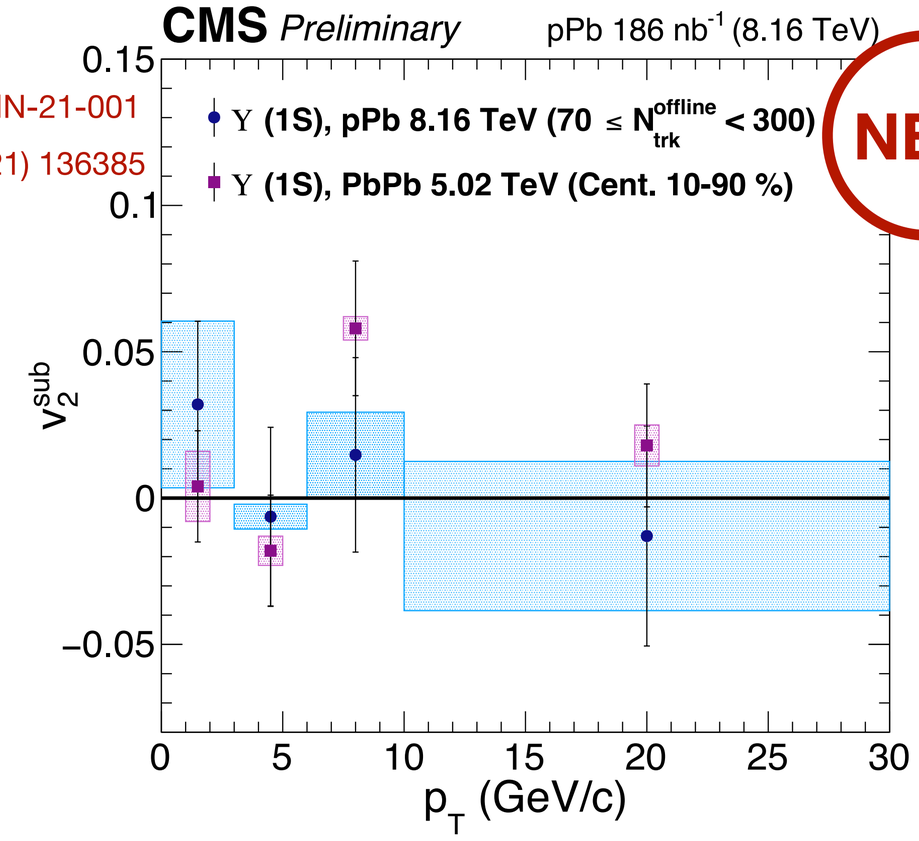
CMS-PAS-HIN-21-008

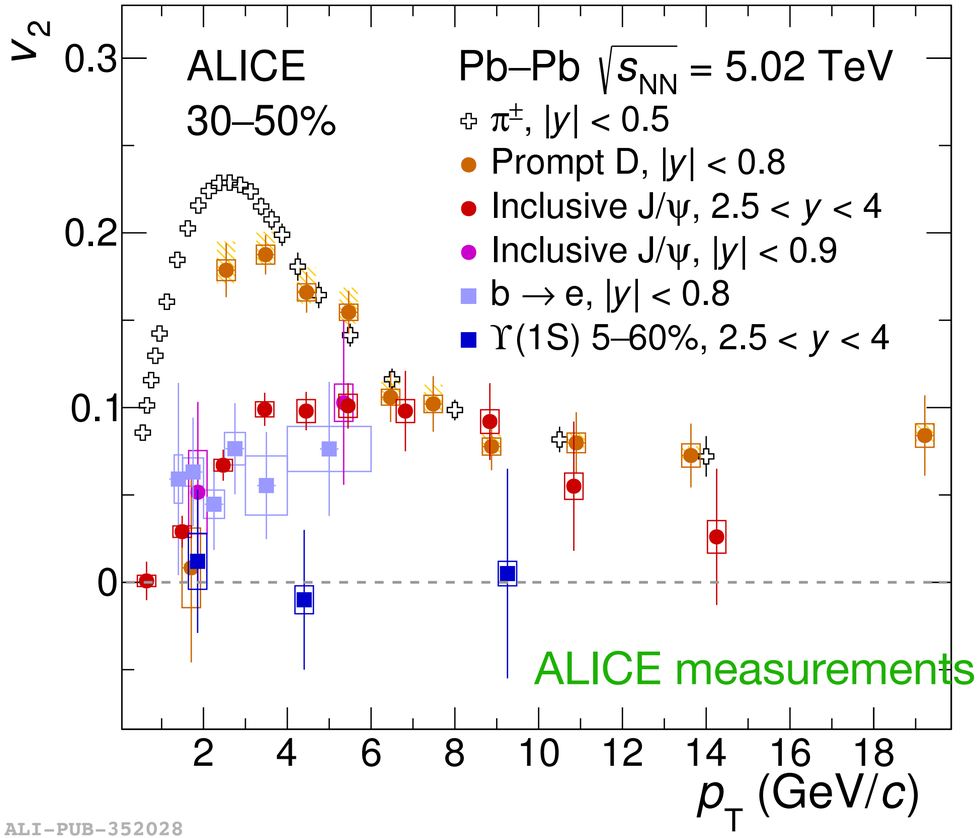
- First $v_2^{\Upsilon(1S)}$ in p-Pb collisions, **compatible with 0** (as observed for Pb-Pb)
- Low p_T : $v_2^{\Upsilon} < v_2^{J/\psi} < v_2^{D} < v_2^{h^{\pm}}$, while at high p_T: **common mechanism?**

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

CMS-PAS-HIN-21-001

PLB 819 (2021) 136385

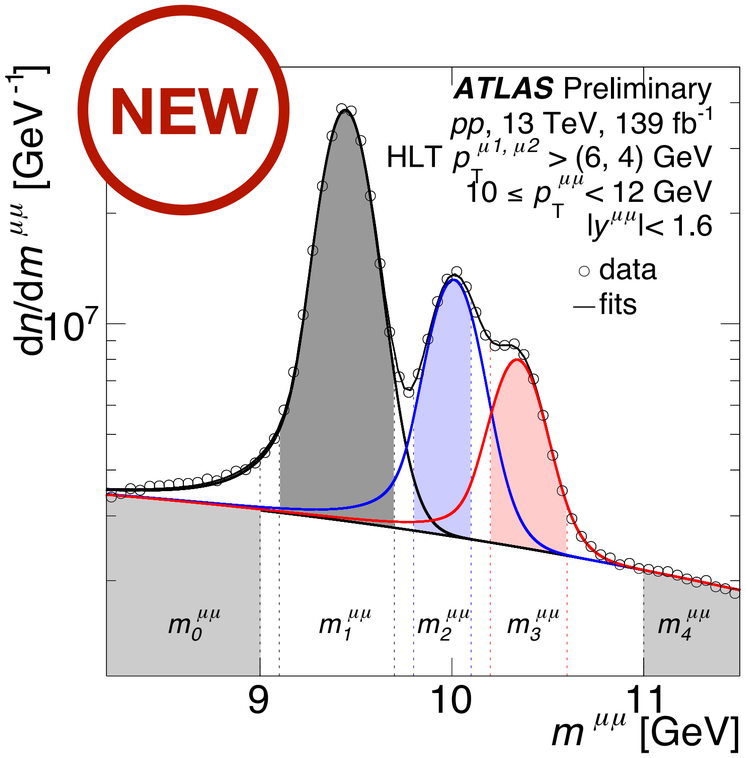




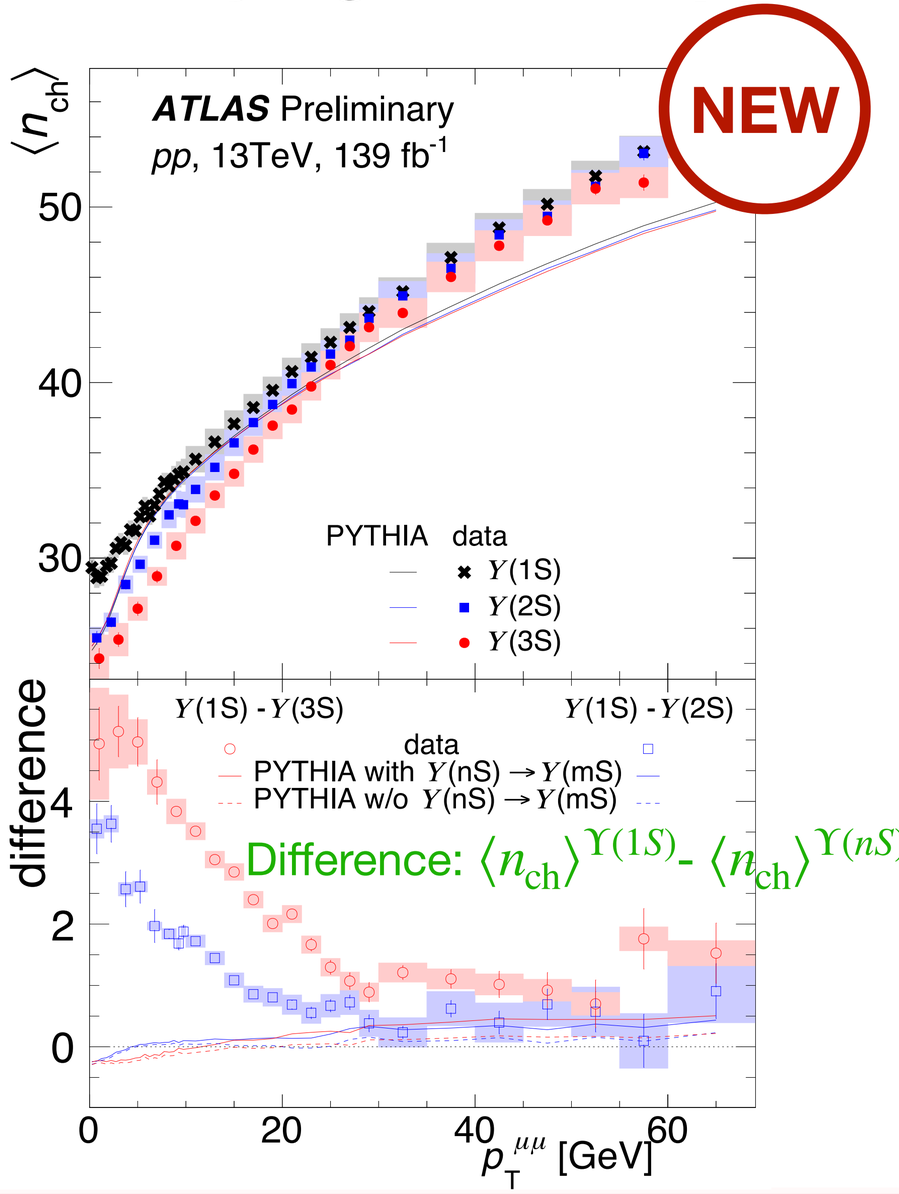
ALICE measurements at low p_{T}

- 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

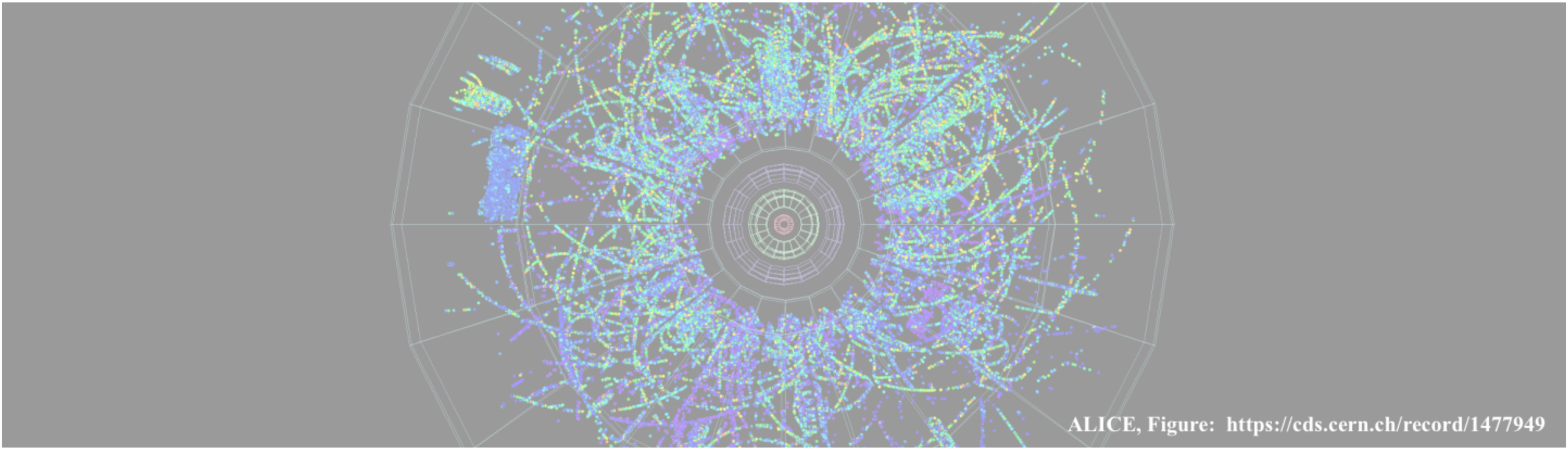


- **Significant difference** is observed in the particle multiplicity $\langle n_{\mathrm{ch}} \rangle$ for events containing $\Upsilon(nS)$
- PYTHIA 8 can not reproduce the data for $p_{\mathrm{T}} < 30$ GeV/c (even including color reconnection)

Summary

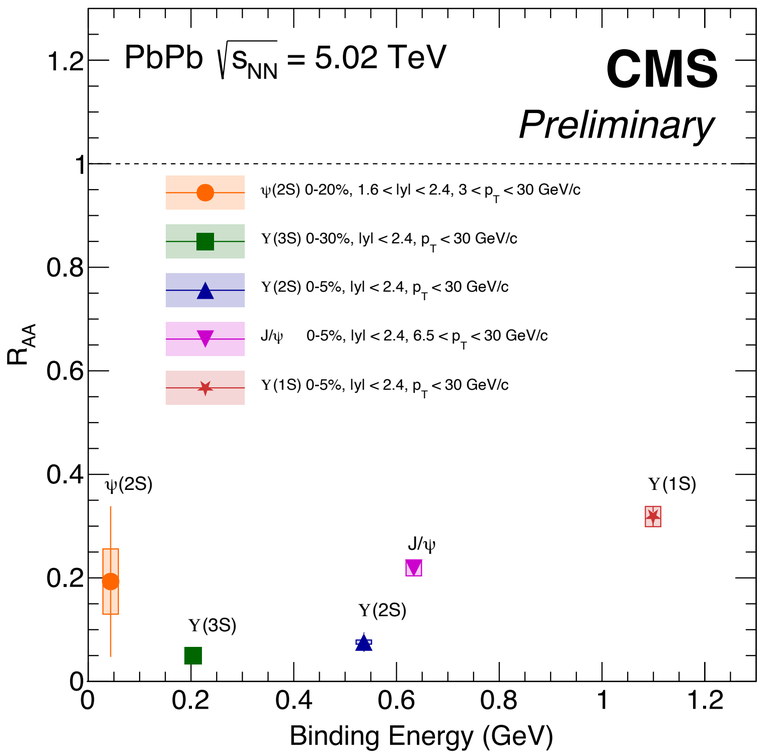
- Plenty of new LHC results on quarkonia:
  - **Sequential suppression:** clearly observed for bottomonia
  - **Regeneration:** most consistent scenario for the production of charmonia at low-p_{T}… negligible effect for bottomonia (while B_{c}: very large R_{AA} at low p_{T} and larger than quarkonia, hint of coalescence; X(3872) results; see backup)
  - Significant J/ψ **polarisation** in Pb-Pb w.r.t. EP: looking forward to theory calculations
  - **Collective flow:** non zero $v_2^{\mathrm{J}/\psi}$ for Pb-Pb and p-Pb but $v_2^{\mathrm{J}/\psi}$~ 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

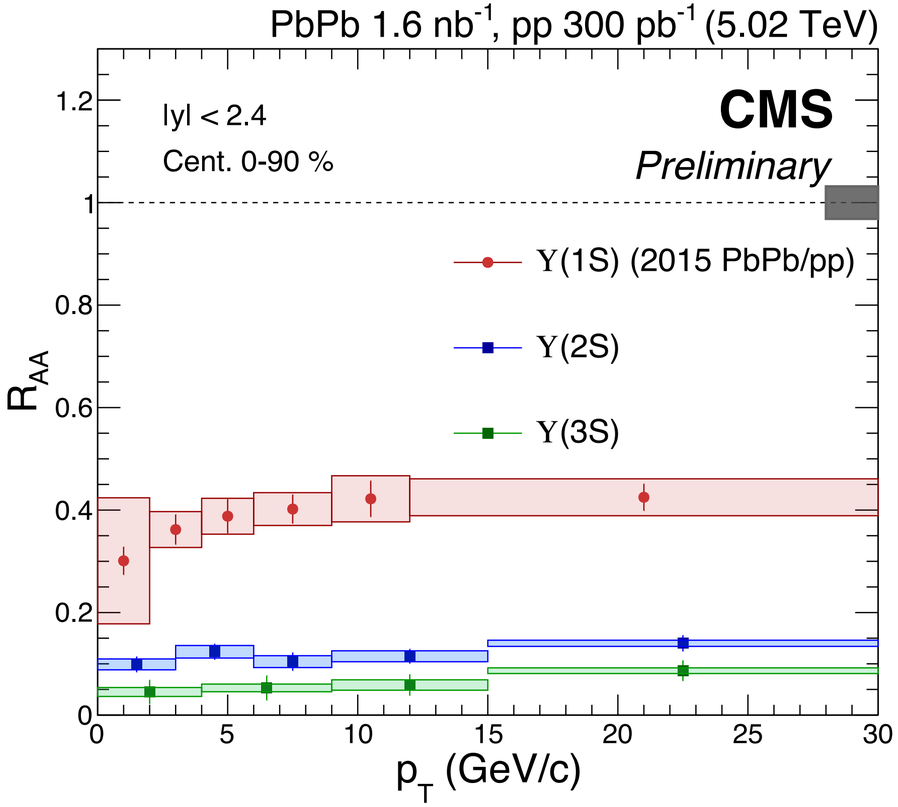
Thank you for your attention!



Run 3 is coming: new available measurements with unprecedented precision

Integrated and p_{T}-differential R_{AA}

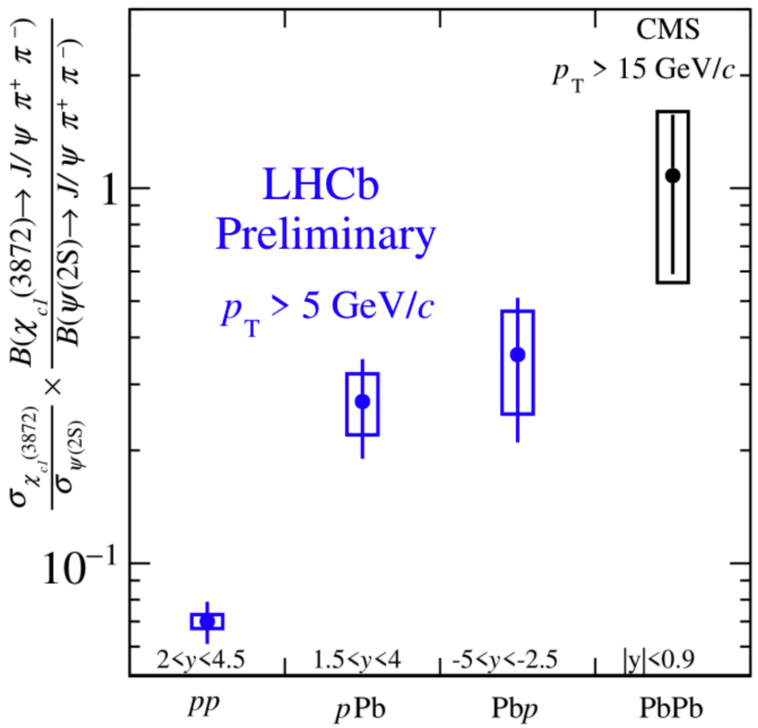


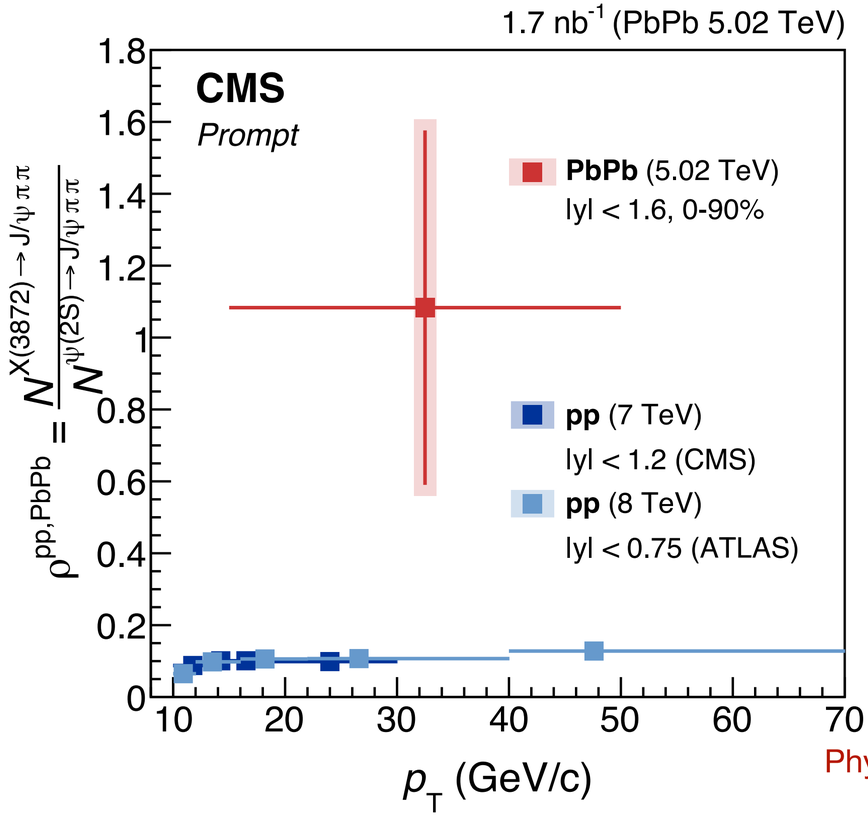


- Sequential suppression for conventional charmonia and bottomonia states
- Larger R_{AA} when the binding energy is increasing

X(3872) measurement in Pb-Pb collisions

[LHCb-CONF-2022-001]





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

Tetraquark

or

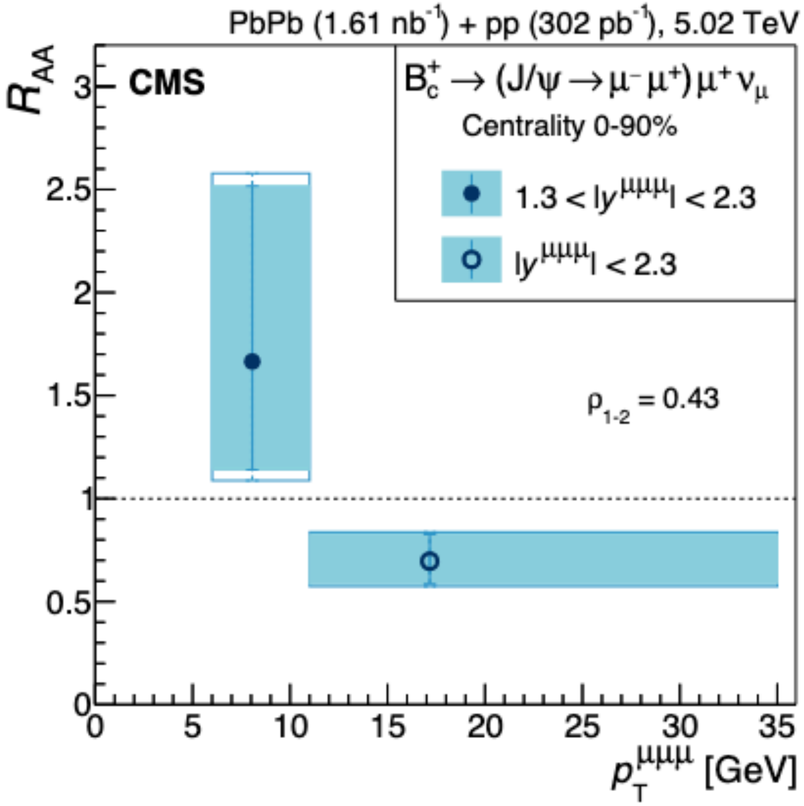
hadron molecule

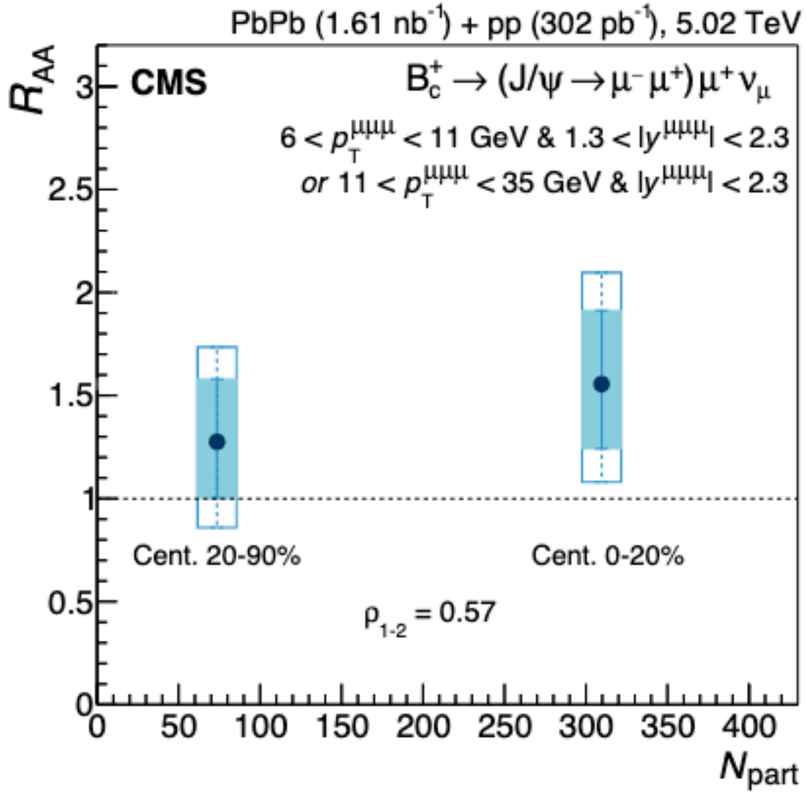
?

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**

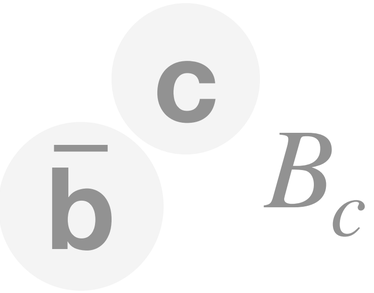
B_c measurement in Pb-Pb collisions



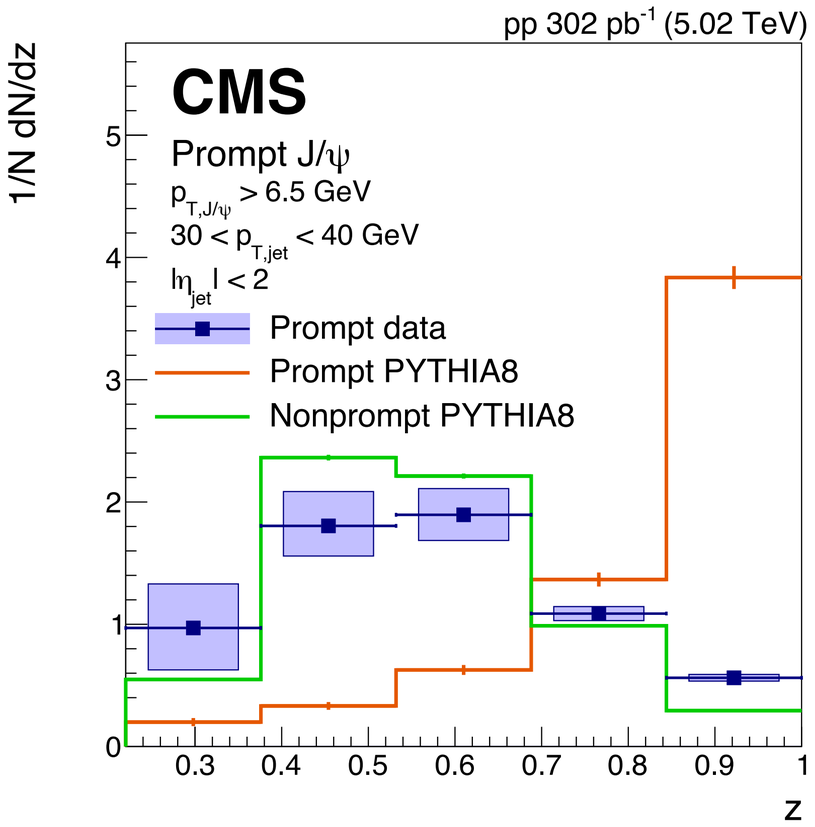


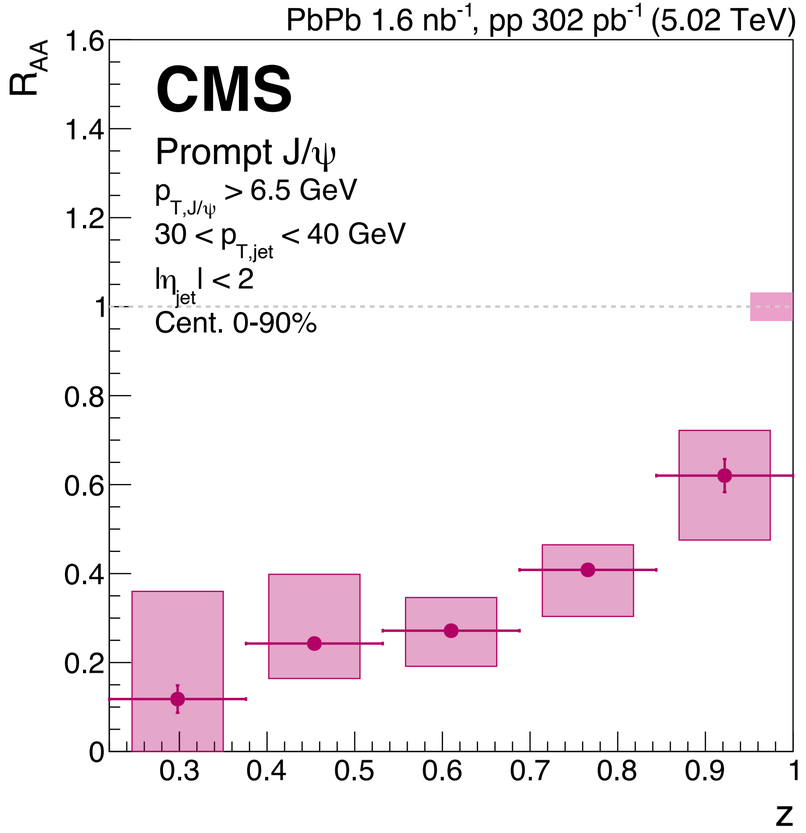
arXiv:2201.02659

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



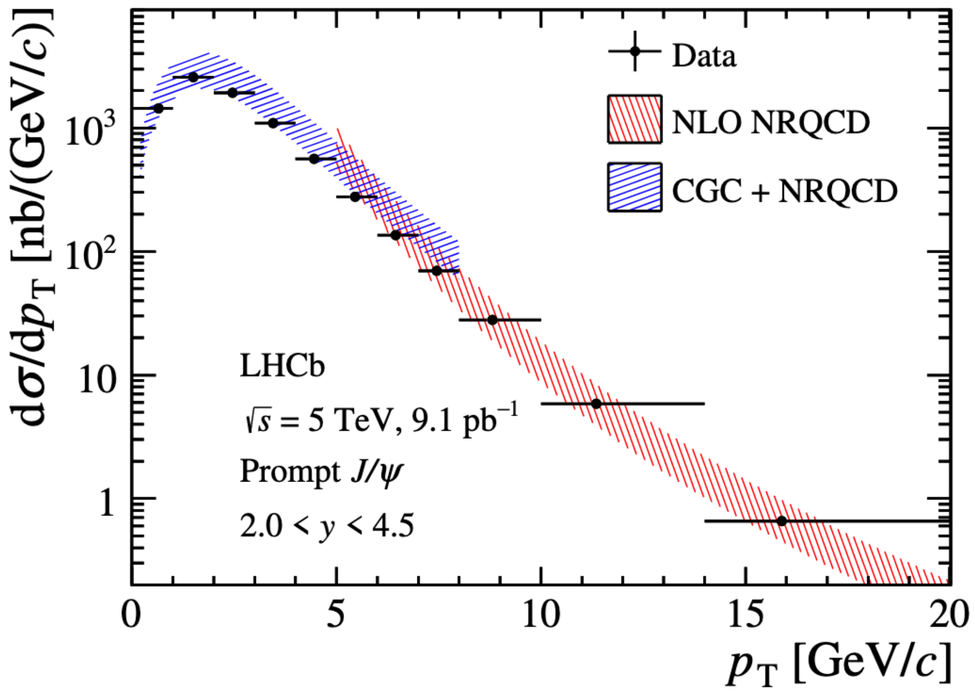
Fragmentation of jets with prompt J/ψ in Pb-Pb and pp

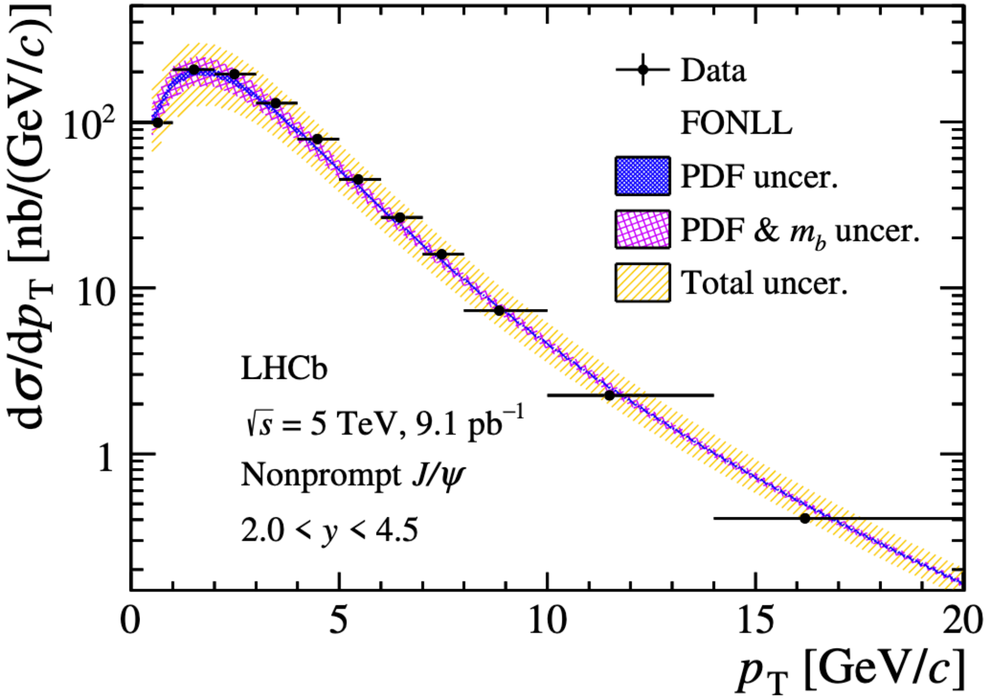




- Hint of a z-dependence of the J/ψ suppression ($z = p_{\mathrm{T,J}/\psi}/p_{\mathrm{T,jet}}$)
- Indication that the J/ψ - medium interaction depends on the fragmentation

J/ψ production in pp collisions





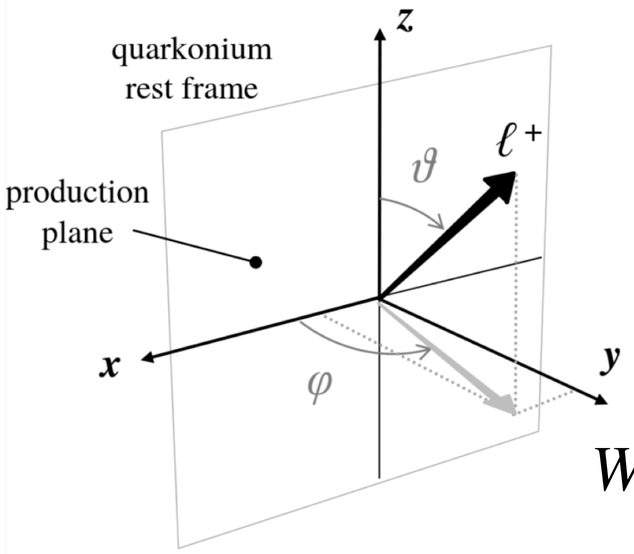
JHEP 11 (2021) 181

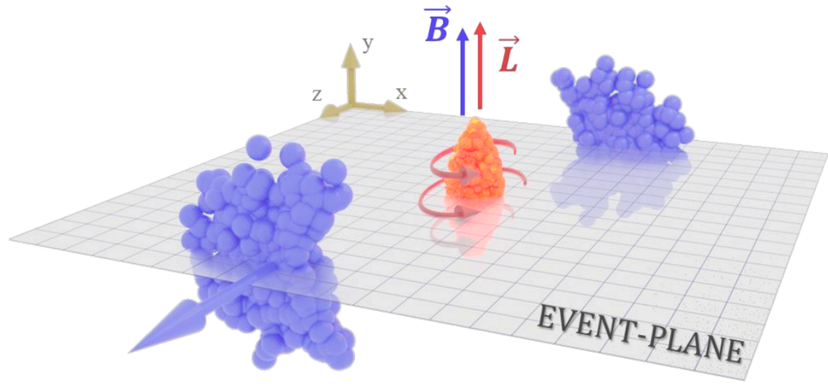
- New measurements for prompt and non-prompt J/ψ : updated R_{pPb} results
- p_T-differential cross sections well described by models

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 $(\mathbf{J}, \mathbf{J}_z)$ is:

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





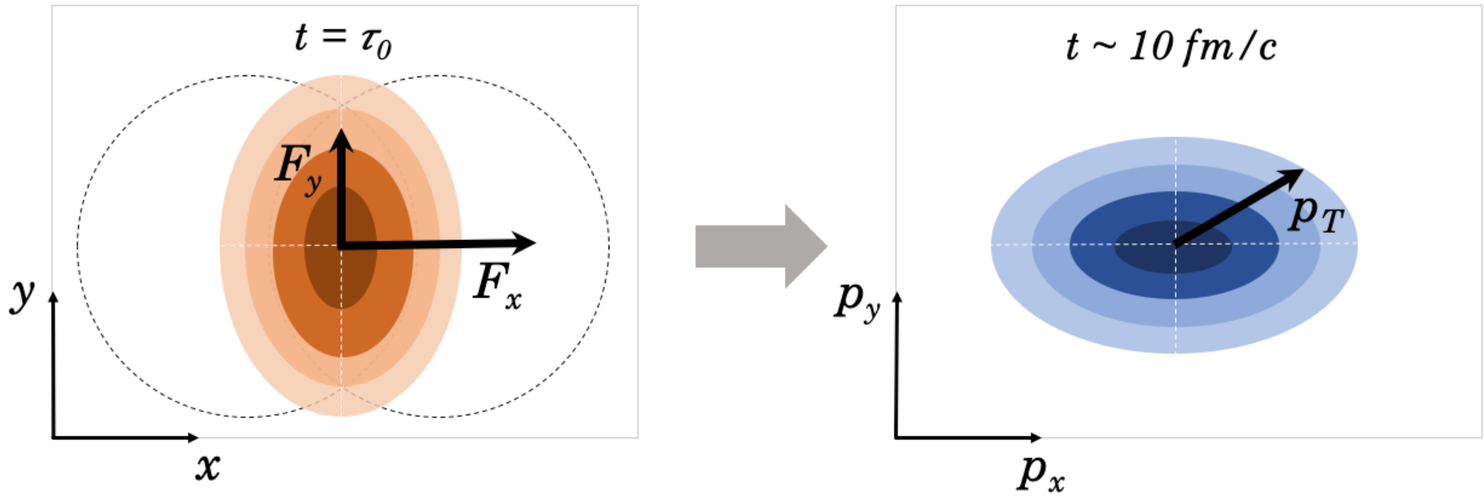
$$W(\cos\theta, \varphi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta \cos 2\varphi + \lambda_{\theta\varphi} \sin 2\theta \cos 2\varphi)$$

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

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

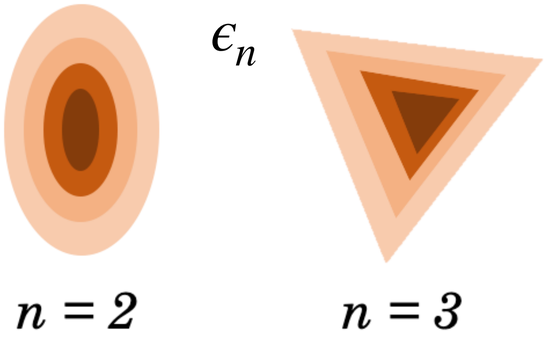
$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1,0,0)$ ⟶ Pure transverse

v_n coefficients in Pb-Pb collisions



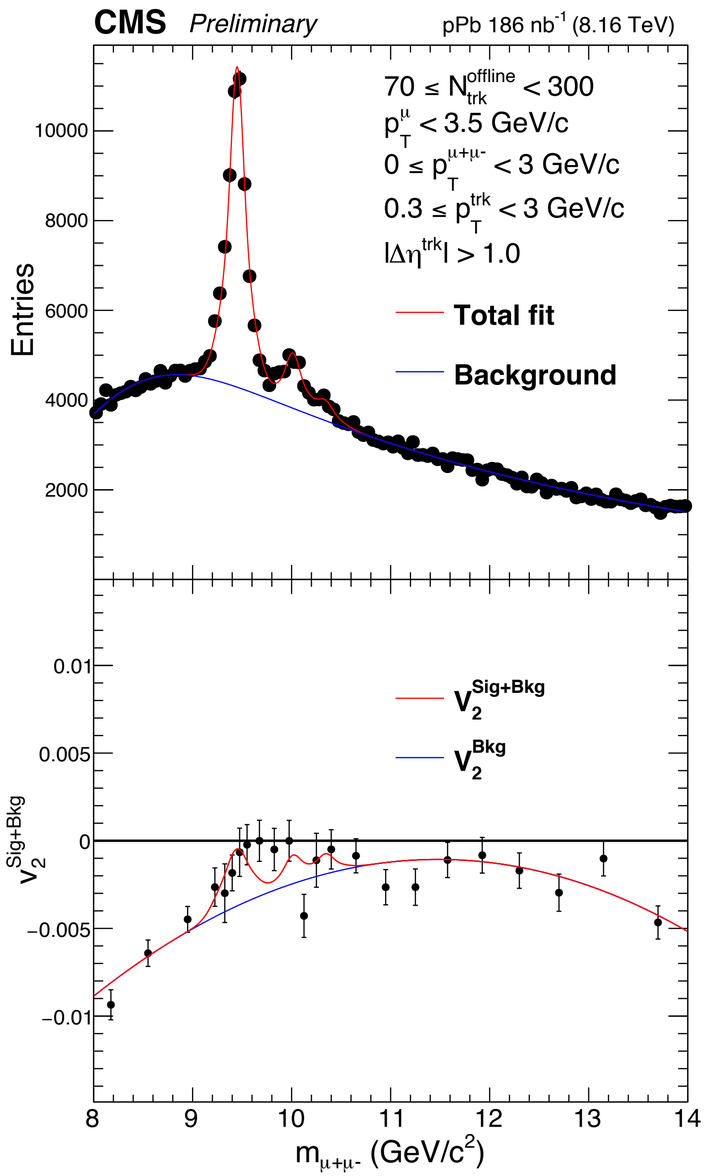
- Related to **initial geometry** of the overlap region and **high pressure gradients**
- Spatial anisotropy is transferred into a **momentum space anisotropy**

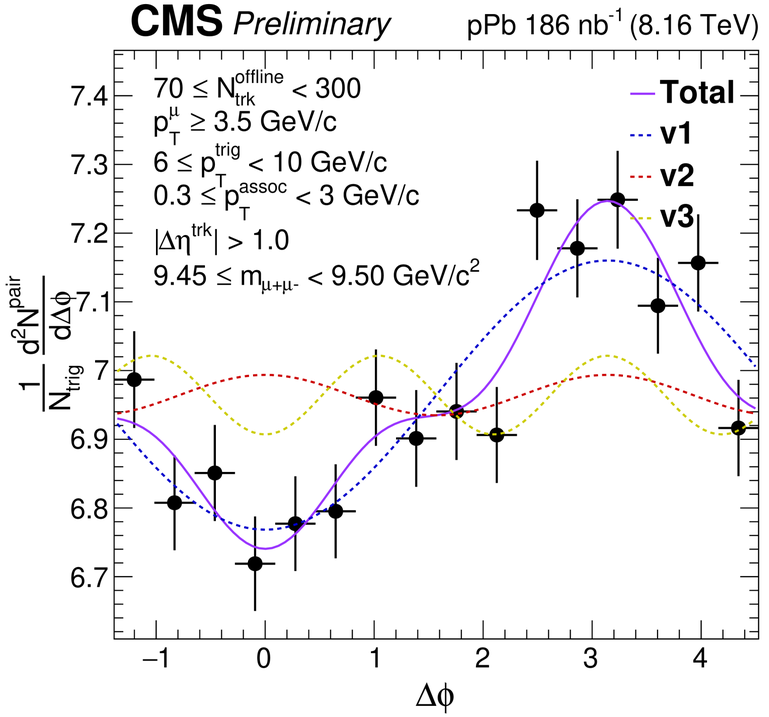
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1} v_n \cos n(\varphi - \Psi_n)$$

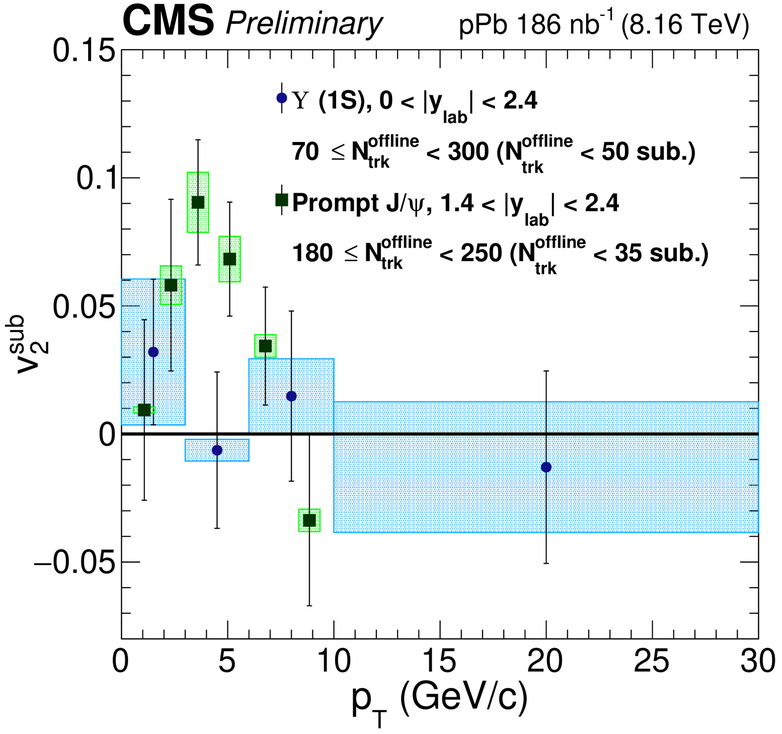


$$v_n = < \cos n(\varphi - \Psi_n) >$$

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

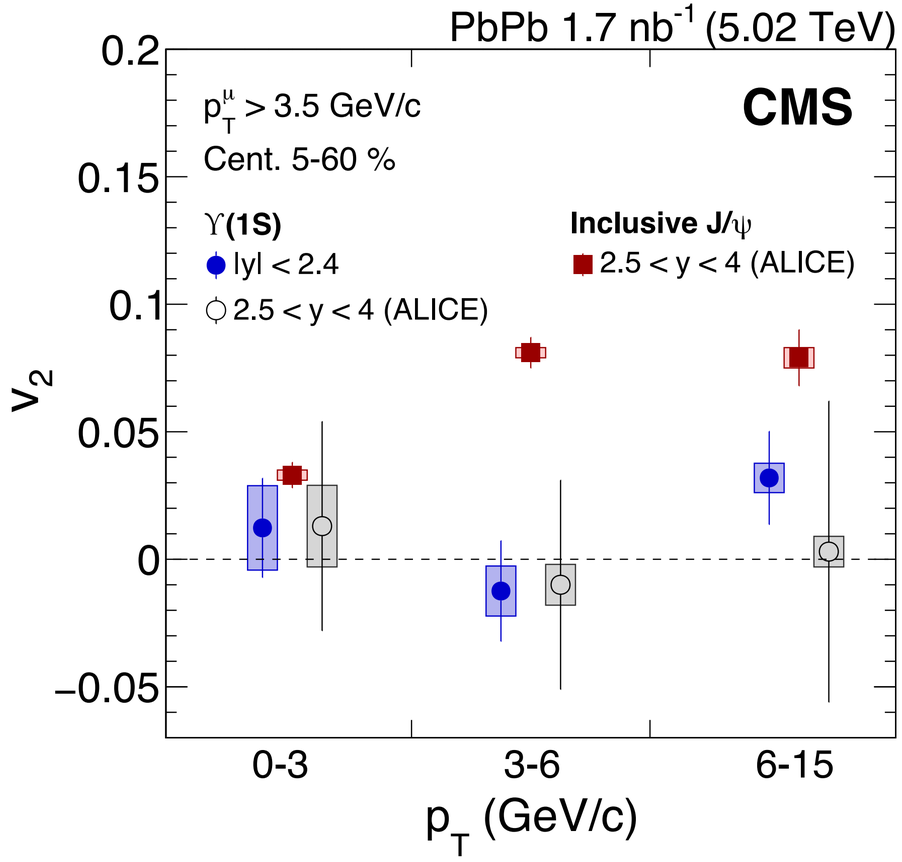


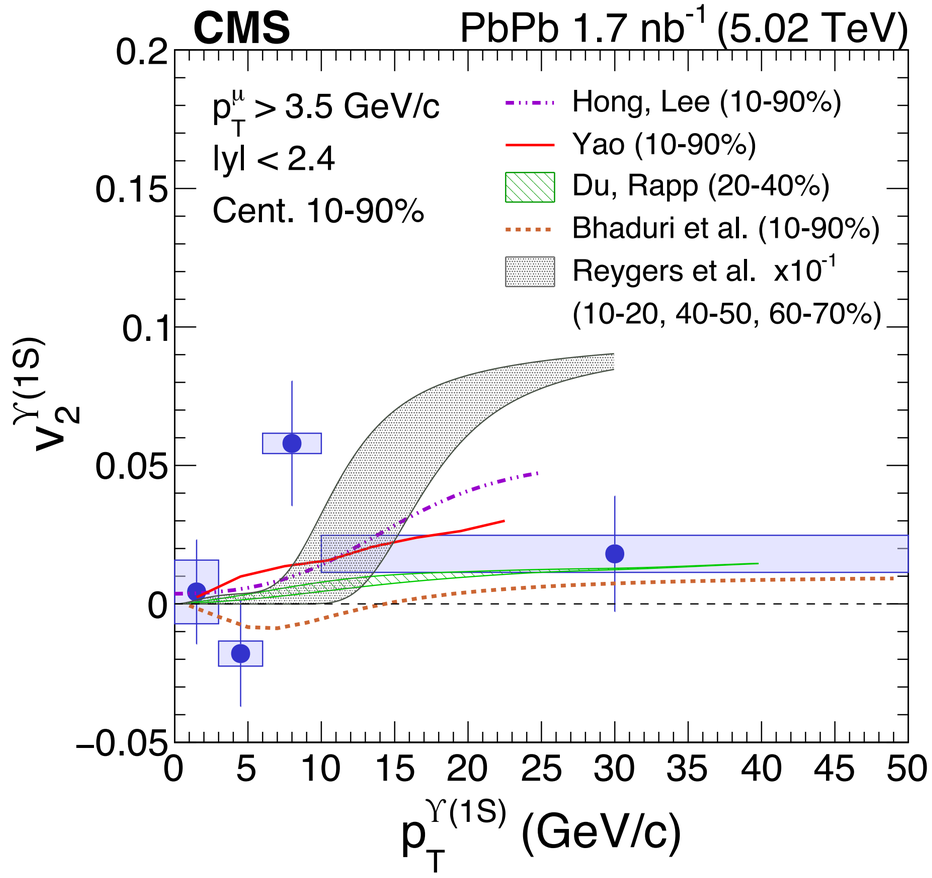




- Fourier decomposition of azimuthal distribution using v_n
- Simultaneous fit on dimuon invariant mass
- High multiplicity p-Pb collisions: $v_2^{\Upsilon} < v_2^{\mathrm{J}/\psi}$

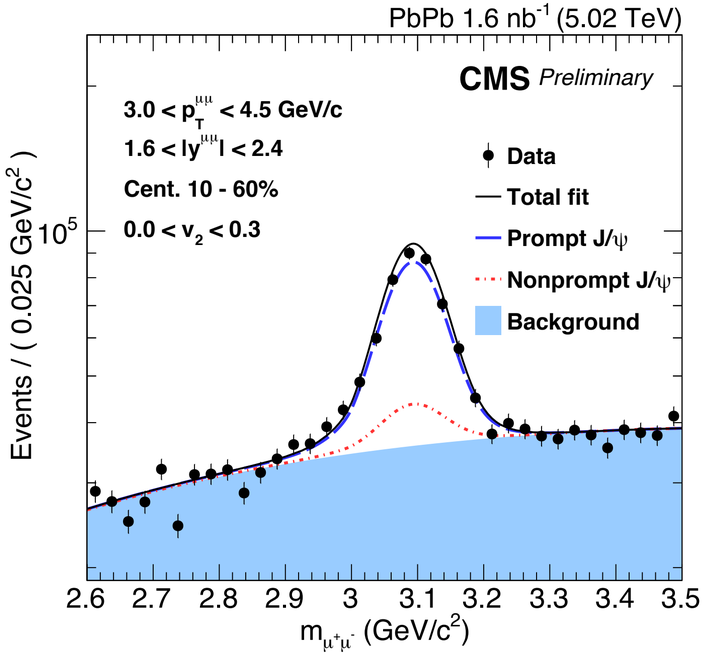
$\Upsilon(1S)$ v_2 in Pb-Pb collisions

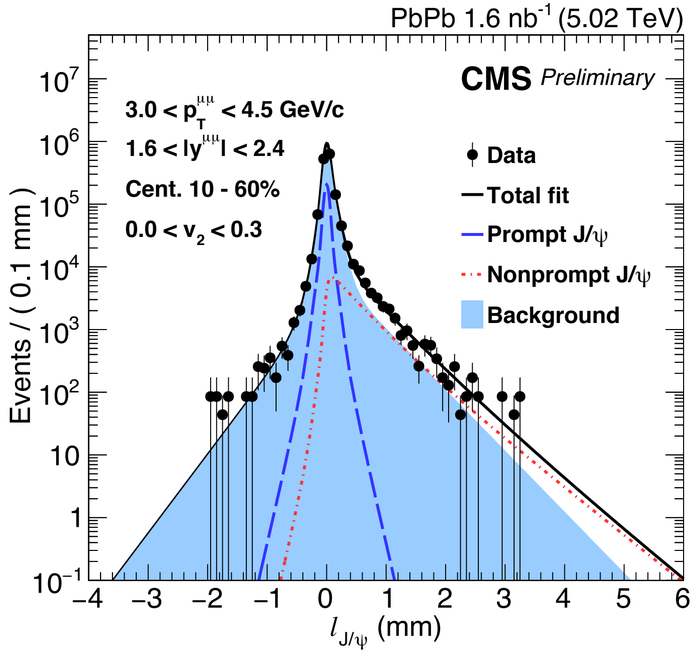


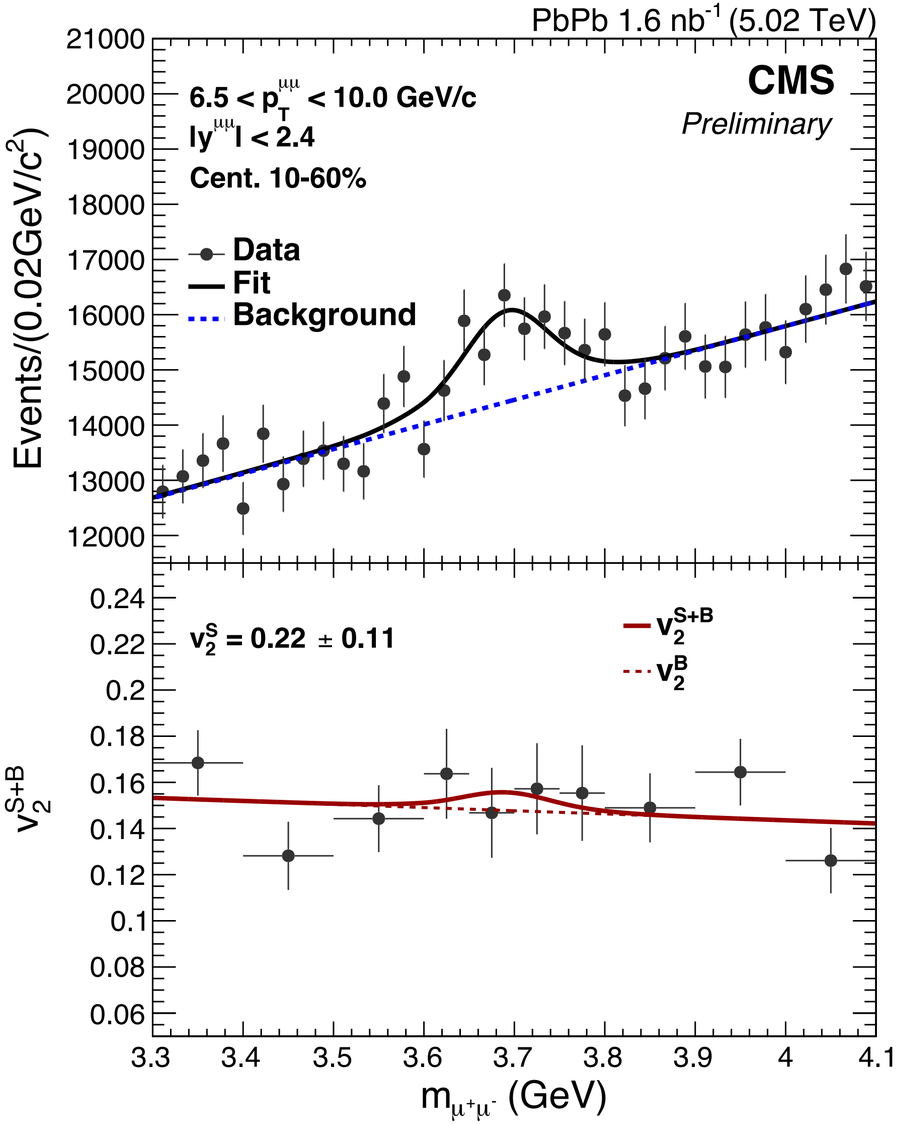


- $\Upsilon(1S)$ v_2 measurements in PbPb collisions compatible with 0 and lower than J/ψ
- All current theoretical models (including regeneration or not) can describe data

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

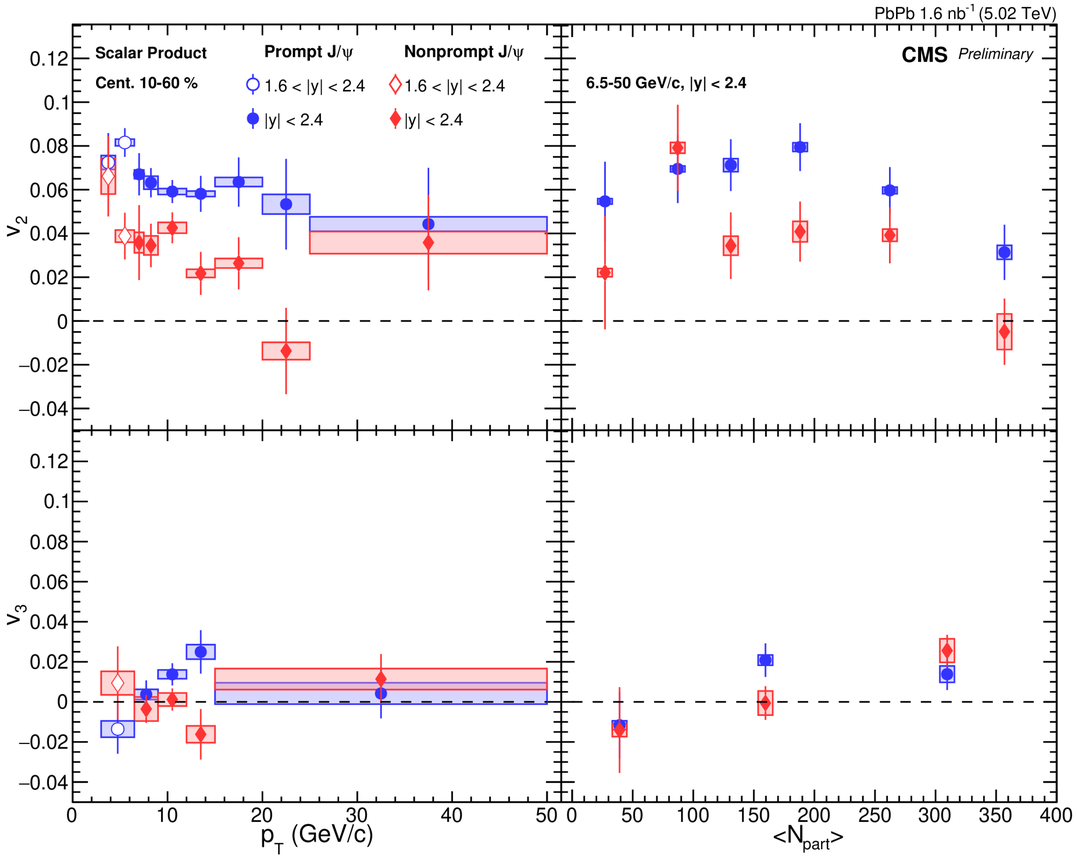


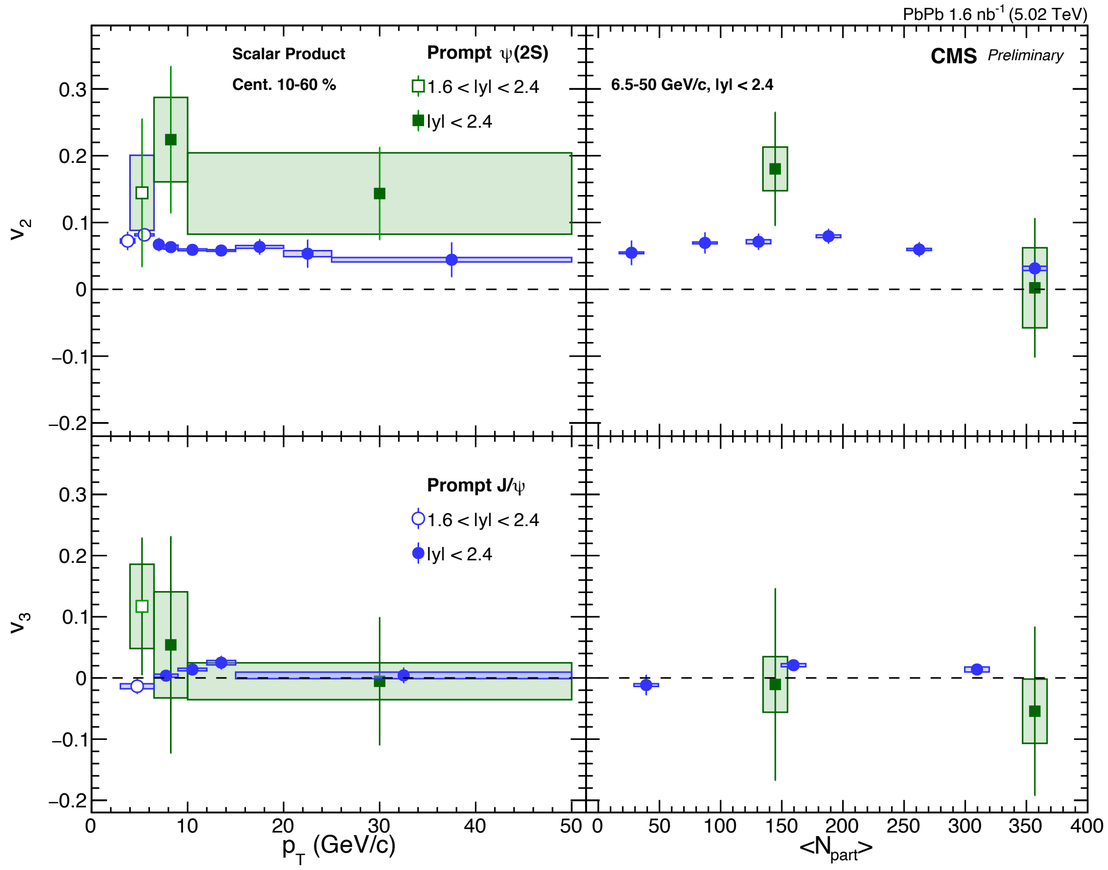




- Simultaneous fit on dimuon invariant mass and pseudo-proper length for prompt/non-prompt extraction
- $\psi(2S)$ v_2 extraction using the dimuon invariant mass fit

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

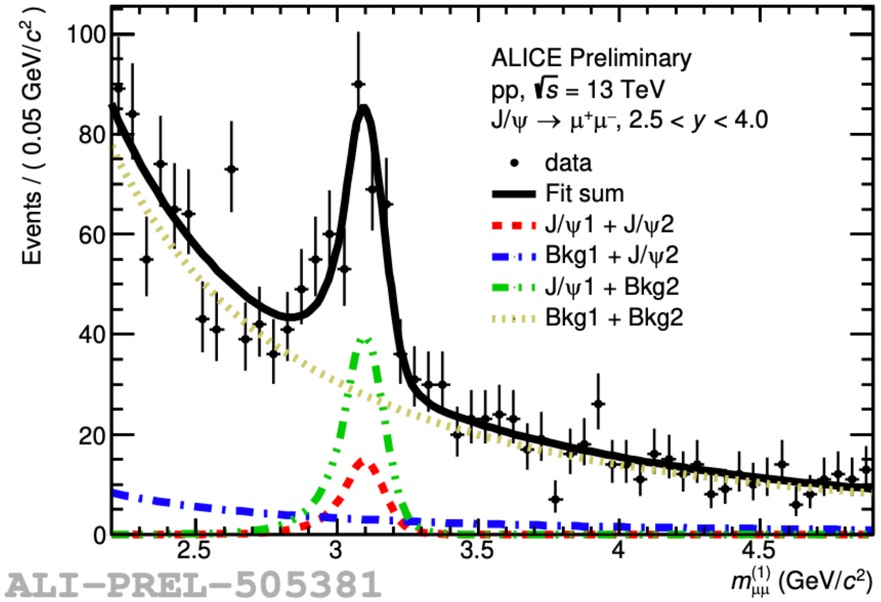


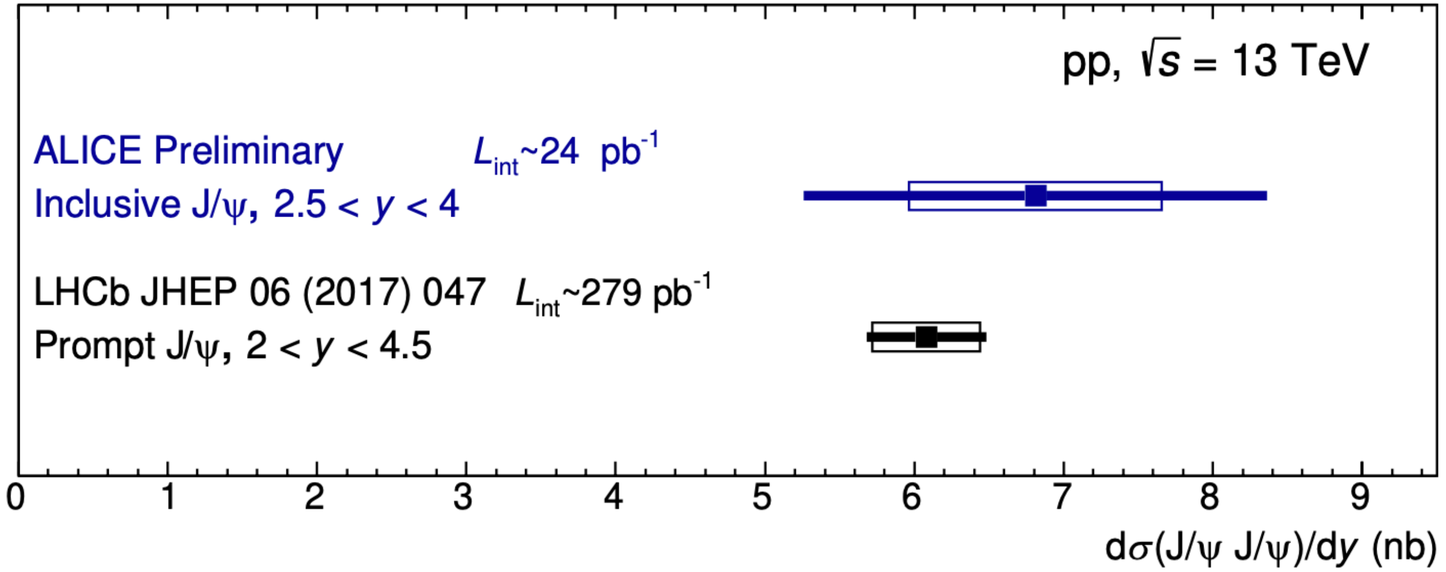


- Larger v_2 is observed for prompt J/ψ w.r.t. non-prompt while all ~0 for v_3
- Hierarchy is observed: $v_2^{b\to J/\psi} < v_2^{J/\psi} < v_2^{\psi(2S)}$ however not clear w.r.t. centrality

J/ψ pair production in Pb-Pb collisions

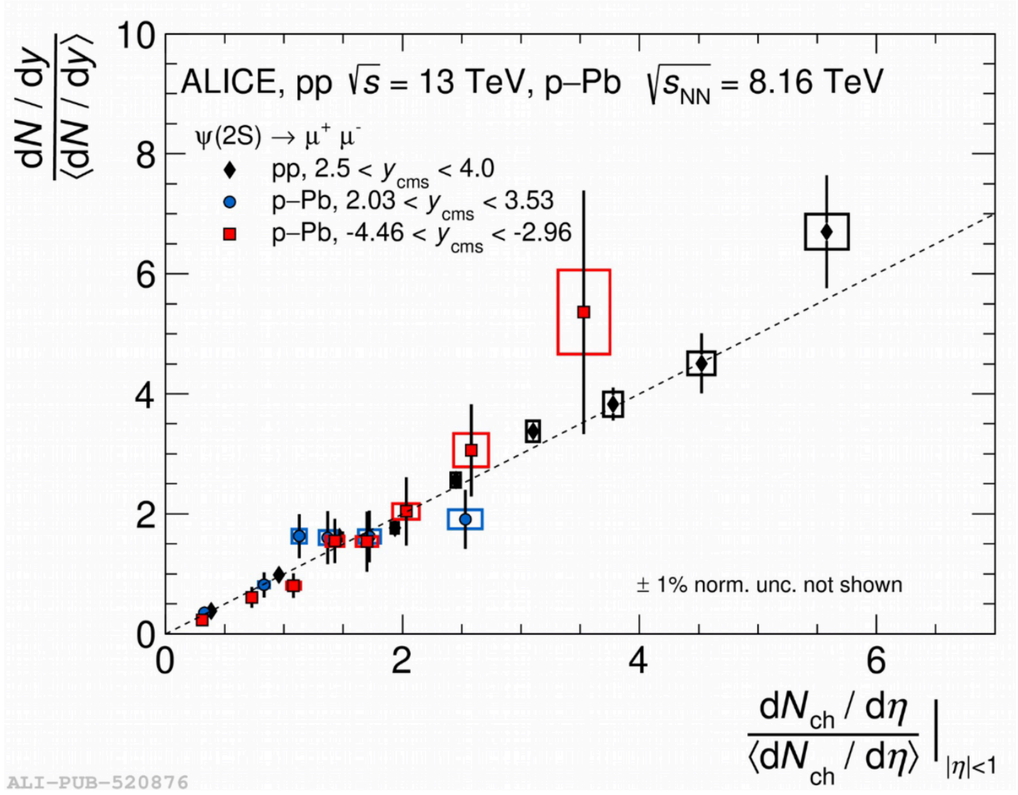
AIP, 1523 (2013) 1

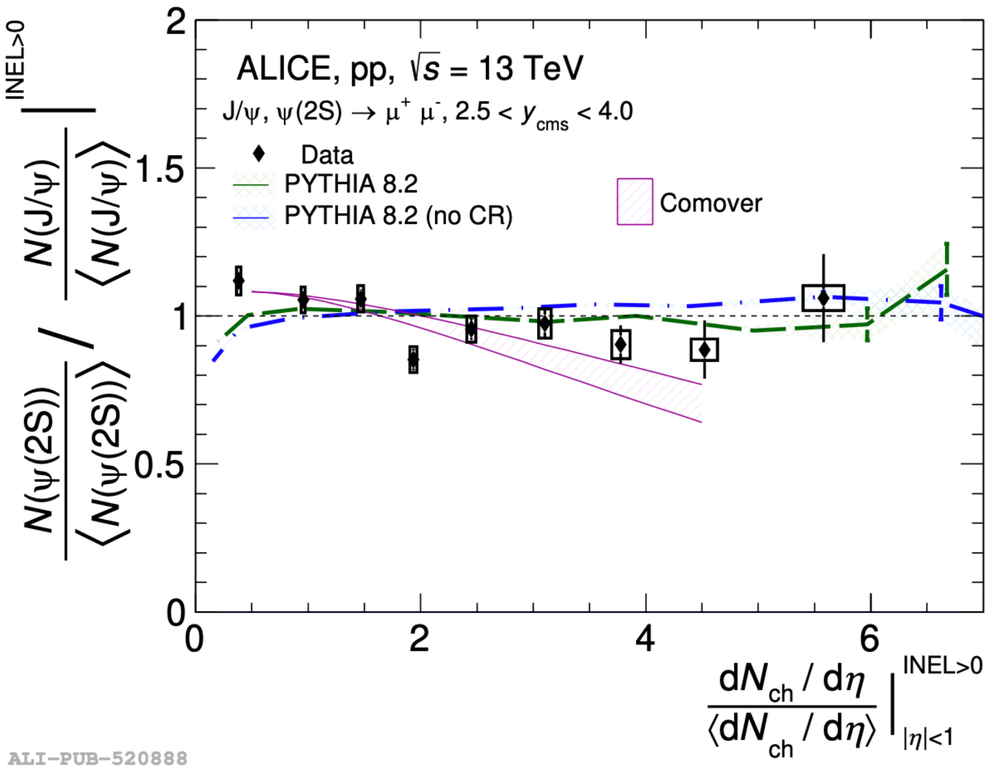




- Constrains on J/ψ production (NRQCD) and double parton scattering
- Despite different acceptance and inclusive or prompt: **good agreement w LHCb**

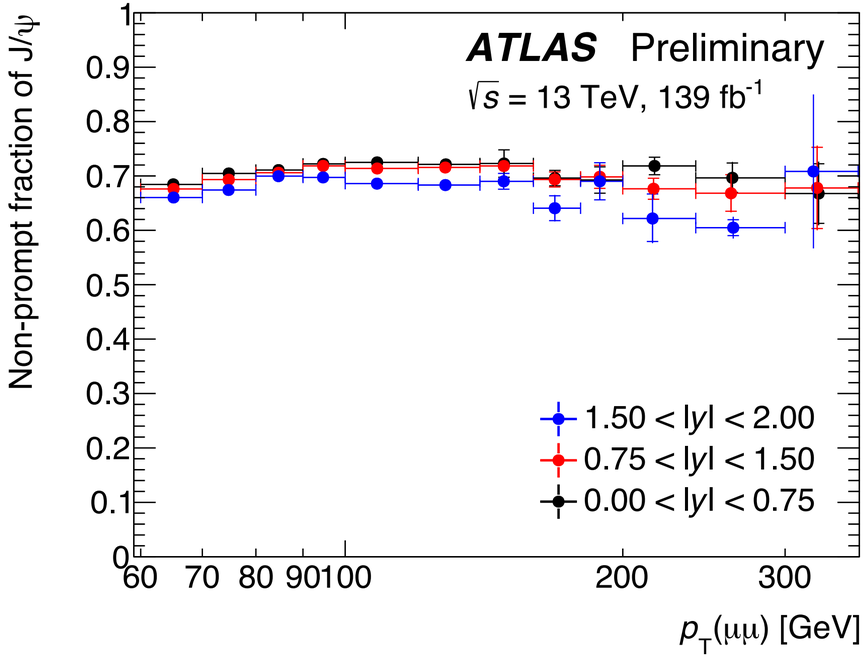
$\psi(2S)$ production in pp and p-Pb collisions

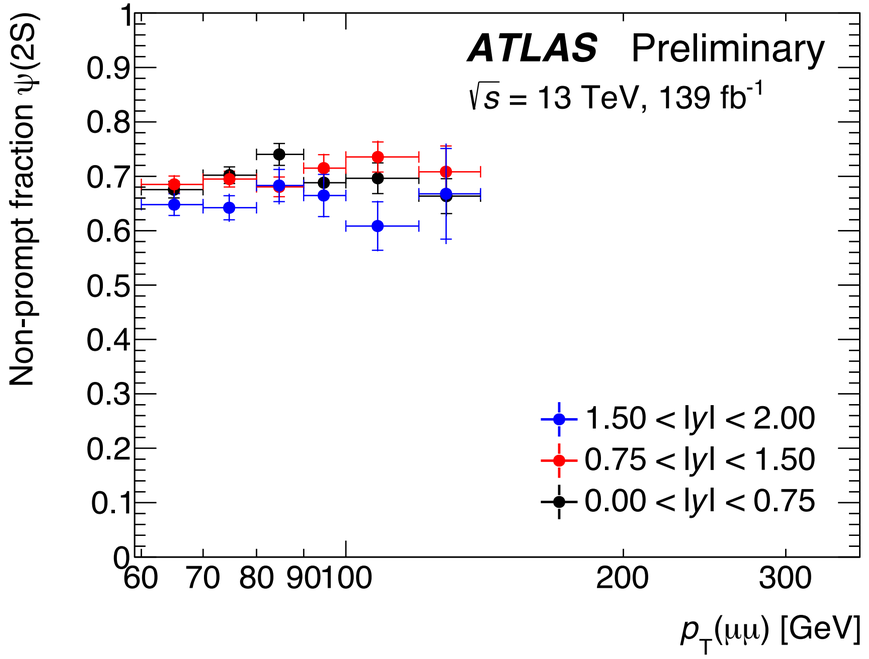


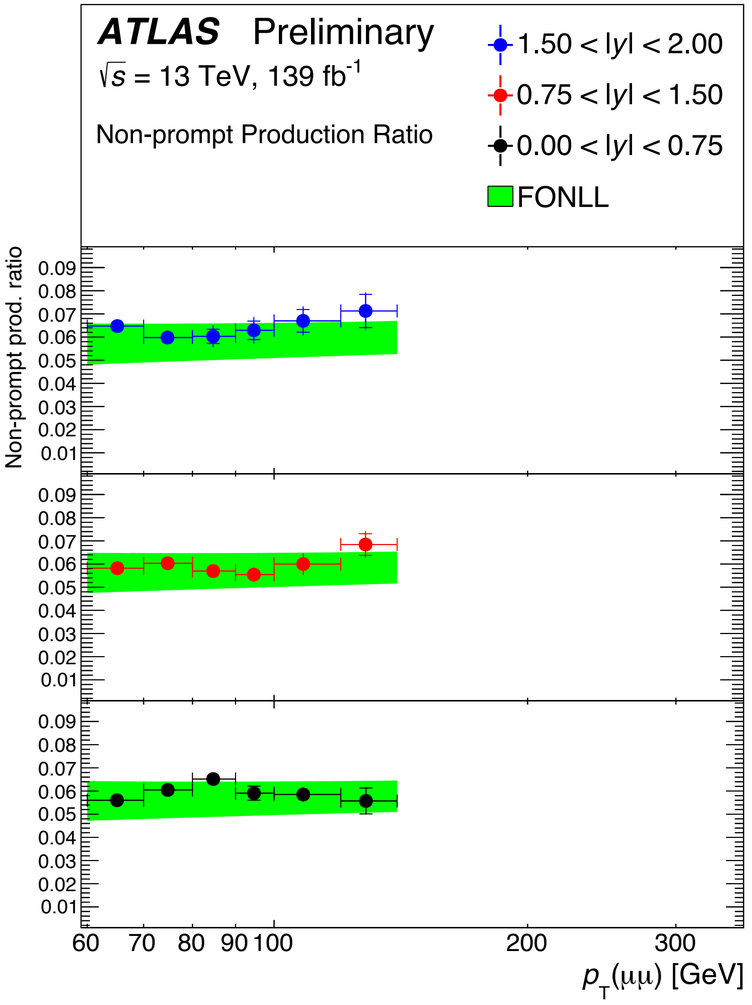


- Linear increase of $\psi(2S)$ normalized yield vs. multiplicity while $\psi(2S)/\mathrm{J}/\psi$ is flat
- Agreement with models at low p_{T}
- pp and p-Pb data are compatible within the uncertainties

High-p_{T} J/ψ and $\psi(2S)$ production pp collisions







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