# Experimental overview on quarkonia at the LHC

XVth Quark Confinement and the Hadron Spectrum Conference

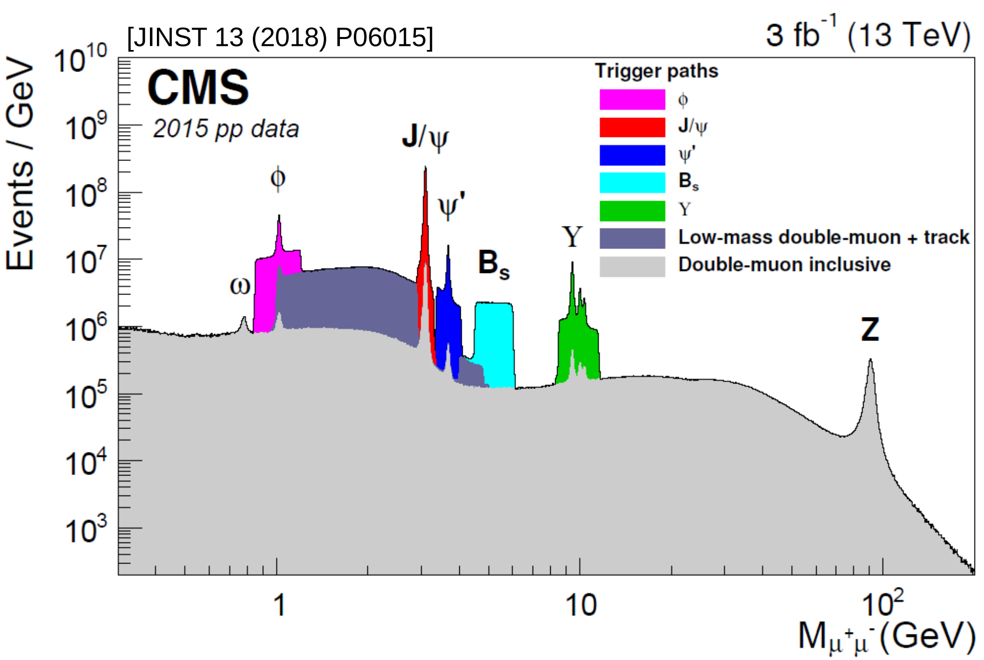
2022 - University of Stavanger

**F. Fionda**
University & INFN, Cagliari

**The XV$^{th}$ Quark confinement and the Hadron spectrum conference**
Aug. 1$^{th}$-6$^{th}$, 2022 – Stavanger (Norway)

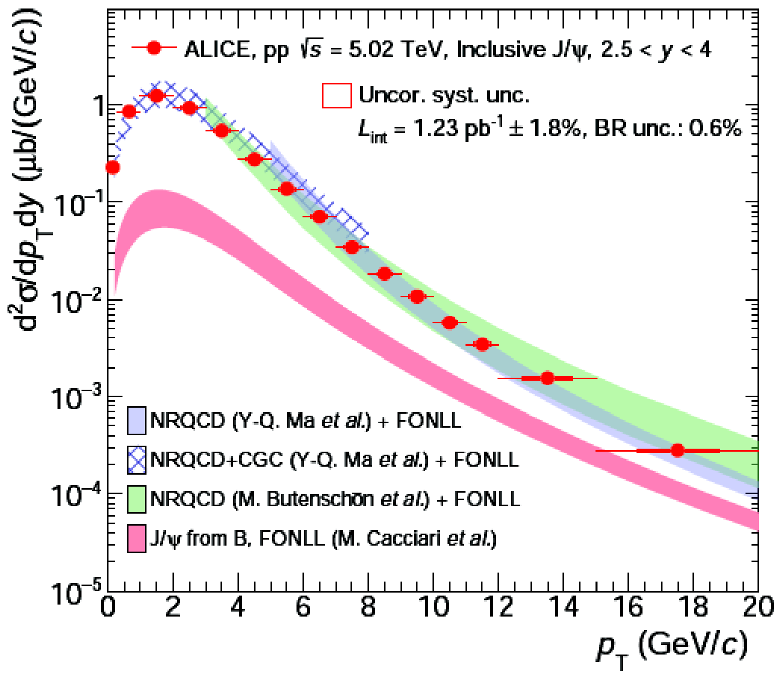
# Quarkonia

- **Bound states of $c\bar{c}$ and $b\bar{b}$ quarks:**
  - pQCD ($m_c$,$m_b$ >> $\Lambda_{QCD}$) applicable for computing the qq production cross section
  - Hadronization into a “colourless” bound state → non-perturbative process. Three main production models **(+ new recent updates)**:
    - Color Evaporation Model (CEM)
      - **Improved CEM (ICEM)**
    - Color Singlet Model (CSM)
    - Non-Relativistic QCD (NRQCD)
      - **NRQCD + Color Glass Condensate (CGC)**

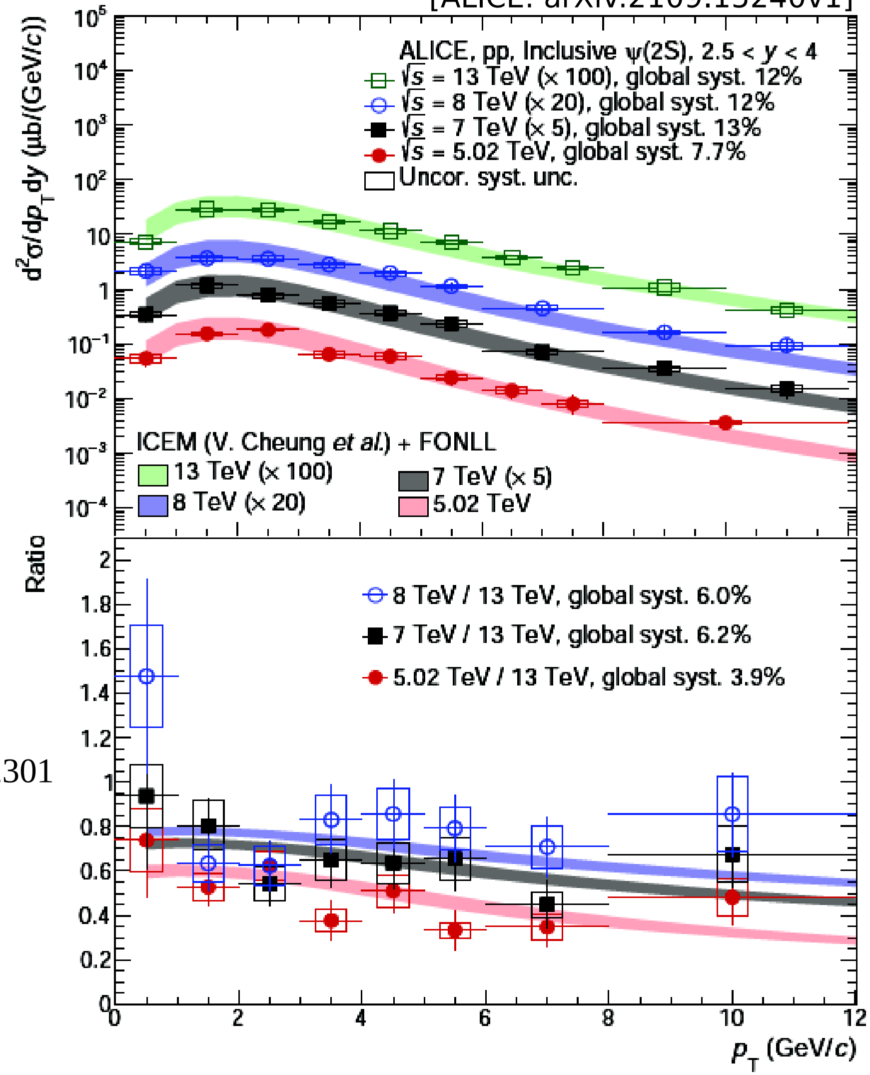



- Existing in a **variety of states** characterized by different masses and binding energies

# Quarkonia in pp collisions




[ALICE: arXiv:2109.15240v1]

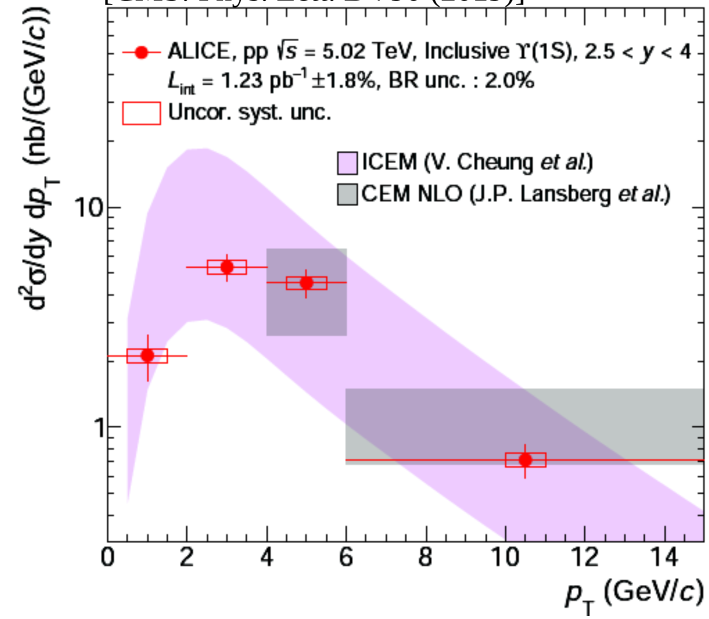


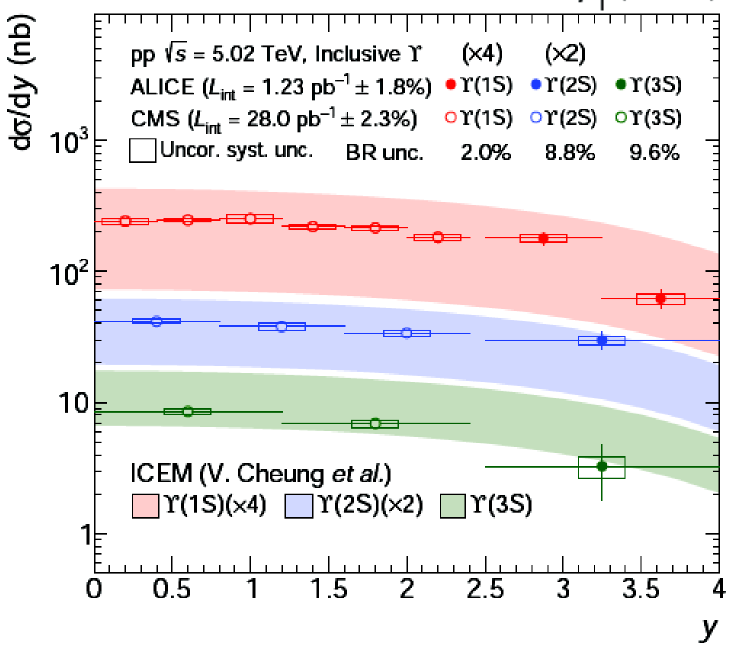

NRQCD (Ma et al): Phys. Rev. Lett. 106 (2011) 042002
NRQCD+CGC (Ma et al): Phys. Rev. Lett. 113 no. 19, (2014) 192301
NRQCD (Butenshon et al): Phys. Rev. Lett. 106 (2011) 022003
ICEM (Cheung, Vogt): Phys. Rev. D 98 no. 11, (2018) 114029
NLO CEM (Lansberg et al): Phys. Lett. B 807 (2020) 135559

– Charmonium cross sections described rather well by NRQCD based models and an improved version of CEM

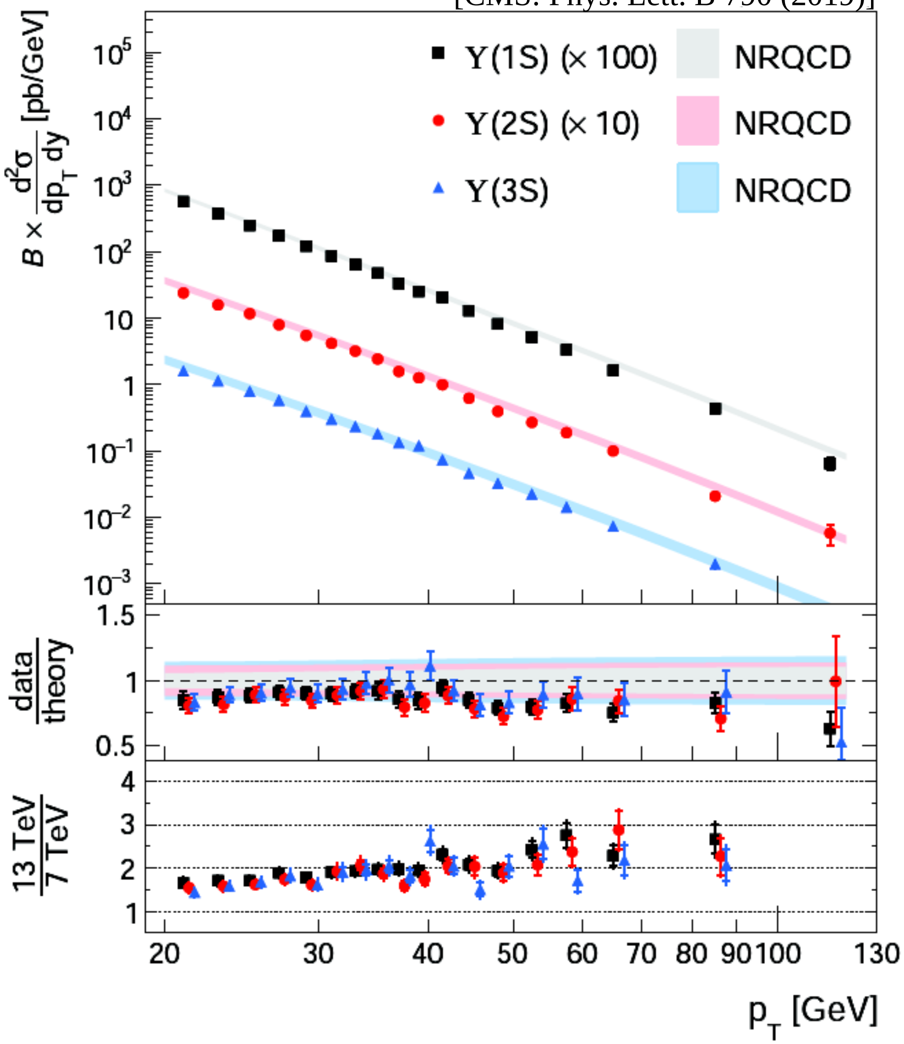
# Quarkonia in pp collisions

[ALICE: arXiv:2109.15240v1]
[CMS: Phys. Lett. B 790 (2019)]




[CMS: Phys. Lett. B 790 (2019)]

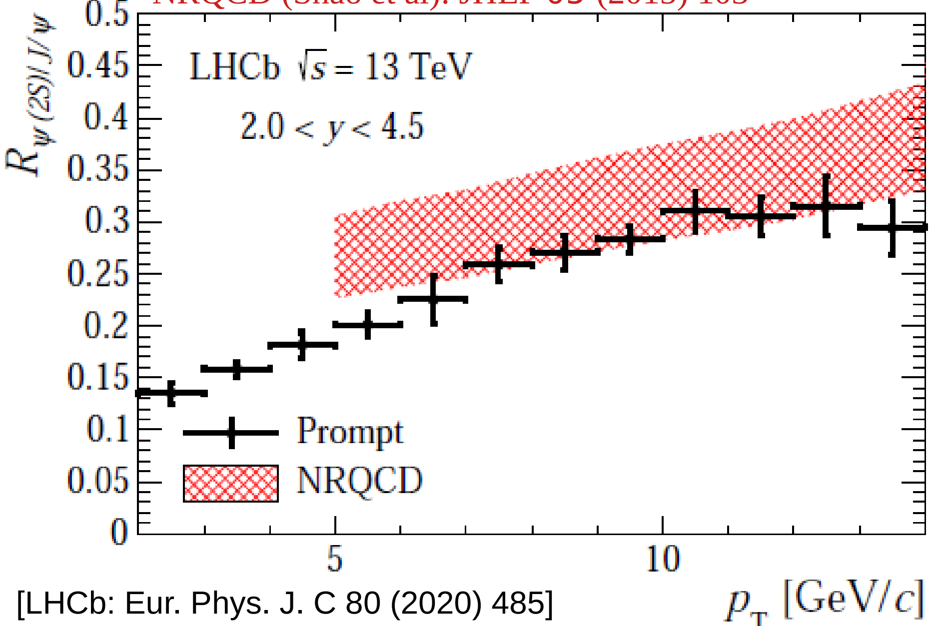



– Similar comments hold for bottonomia, but uncertainties are large

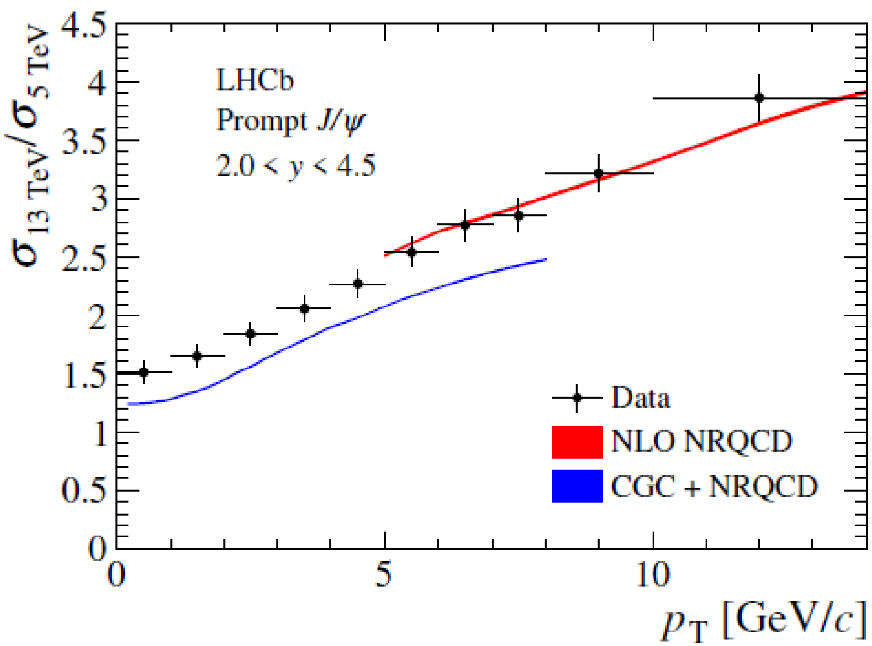
NLO NRQCD (H. Han et al): Phys. Rev. D 94 (2016) 014028
ICEM (Cheung, Vogt): Phys. Rev. D 98 no. 11, (2018) 114029
NLO CEM (Lansberg et al): Phys. Lett. B 807 (2020) 135559

# Quarkonia in pp collisions

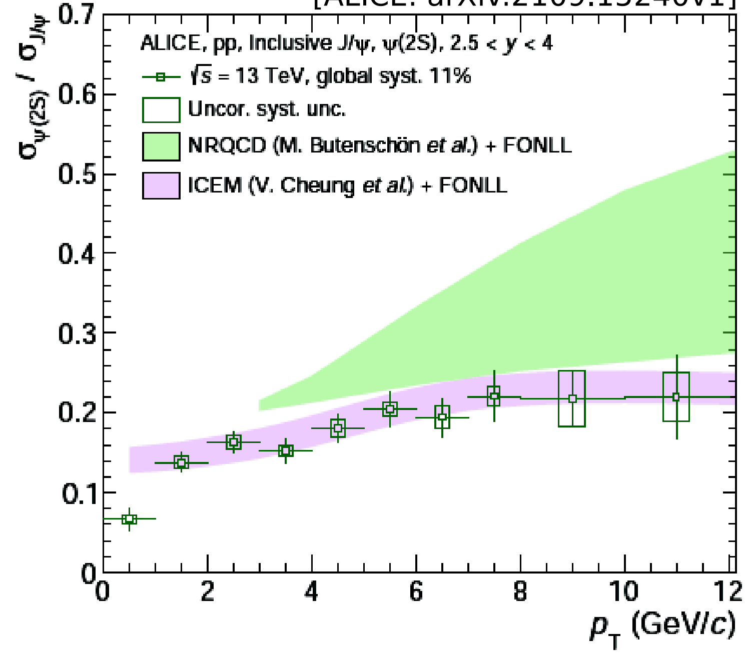
NRQCD (Shao et al): JHEP 05 (2015) 103




[LHCb: Eur. Phys. J. C 80 (2020) 485]
[LHCb: arXiv:2109.00220]




[ALICE: arXiv:2109.15240v1]

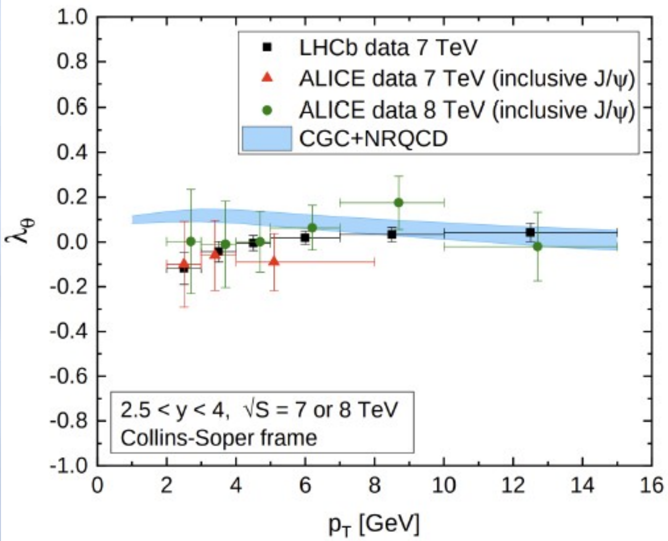


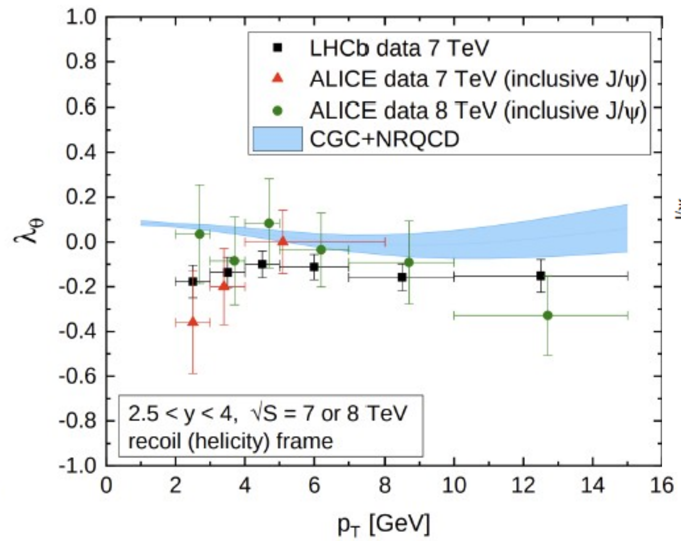

NRQCD (Butenshon et al): Phys. Rev. Lett. 106 (2011) 022003
ICEM (Cheung, Vogt): Phys. Rev. D 98 no. 11, (2018) 114029

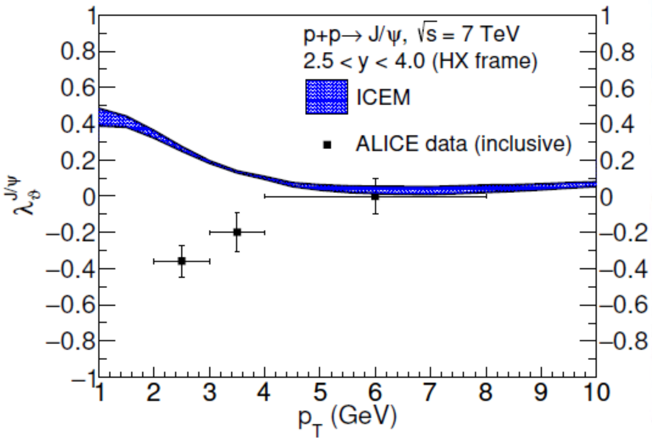
**However tensions still present, more visible when studying cross section ratios...**

NRQCD+CGC (Ma et al): Phys. Rev. Lett. 113 no. 19, (2014) 192301
NLO NRQCD (Ma et al): Phys. Rev. Lett. 106 (2011) 042002

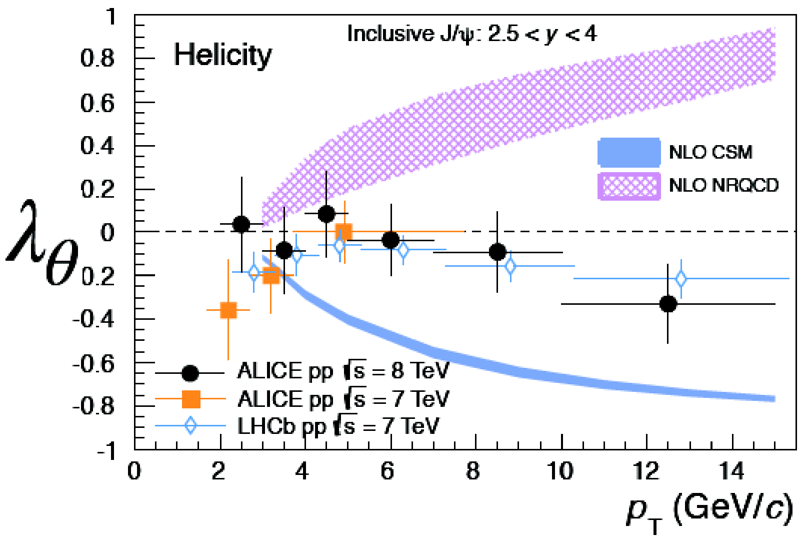
# Polarisation in pp collisions




[ALICE: Eur. Phys. J. C (2018) 78]
[ALICE: Phys. Rev. Lett. 108, 082001]
[LHCb: Eur. Phys. J. C 73(11), 2631, (2013)]

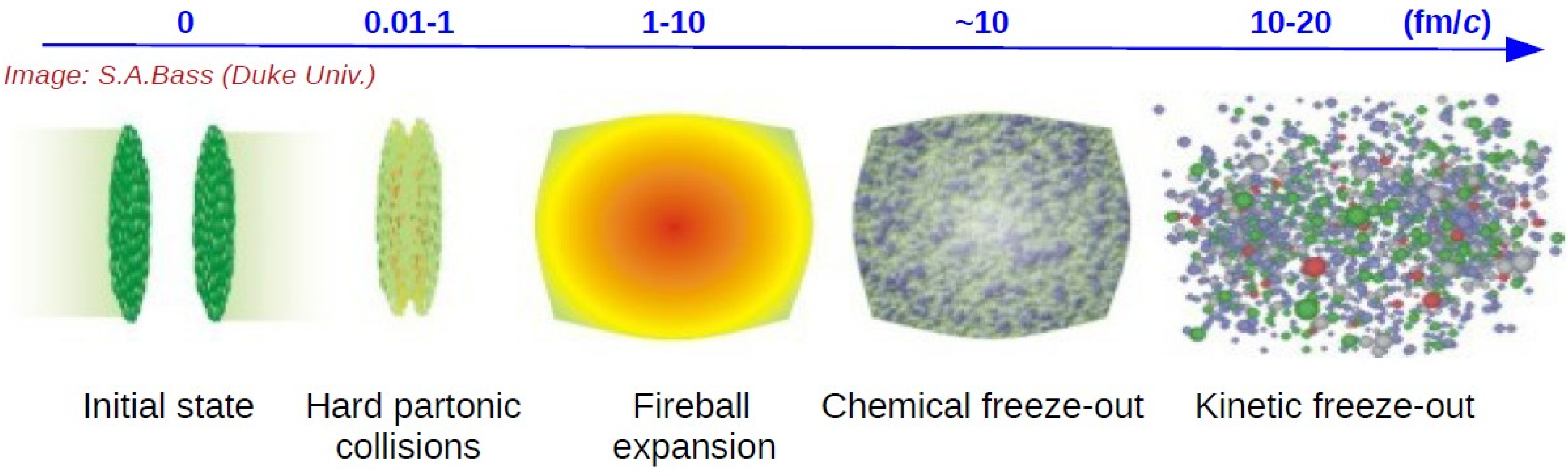



**However tensions still present, more visible when studying cross section ratios…**

**...and polarisation**

CSM, NLO NRQCD (M. Butenschoen and B. A. Knieh): Phys.Rev.Lett. 108 (2012) 172002
ICEM (Cheung, Vogt): Phys. Rev. D 98 no. 11, (2018) 114029
NRQCD+CGC: Y.-Q. Ma, T. Stebel and R. Venugopala, JHEP 1812 (2018) 057

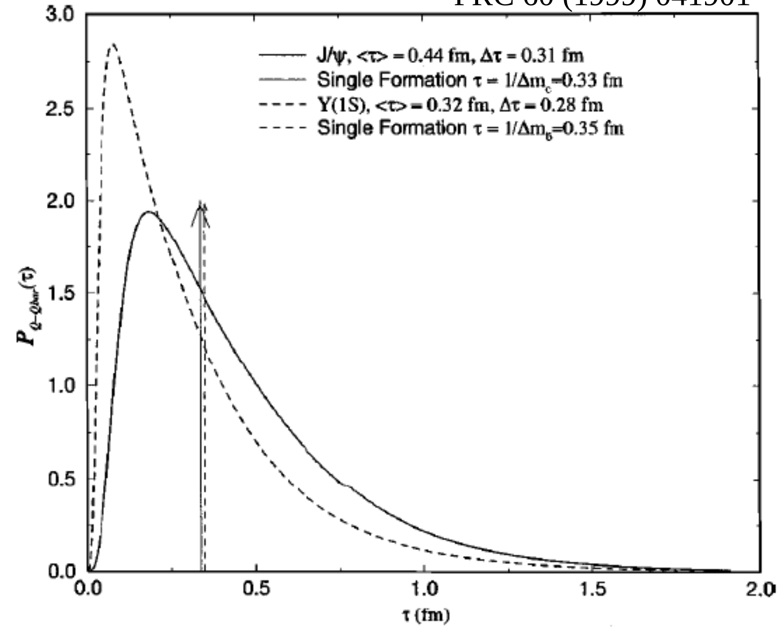
# Quarkonia in (UR) Heavy Ion collisions




Quarkonia as **probe of QGP**:

- Heavy-quark pair produced in initial hard partonic scatterings → **experience the entire collision hystory**
- Formation time of quarkonium state of the order of **0.2 - 2 fm/c** → states may form inside the plasma

PRC 60 (1999) 041901



# Quarkonia in (UR) Heavy Ion collisions

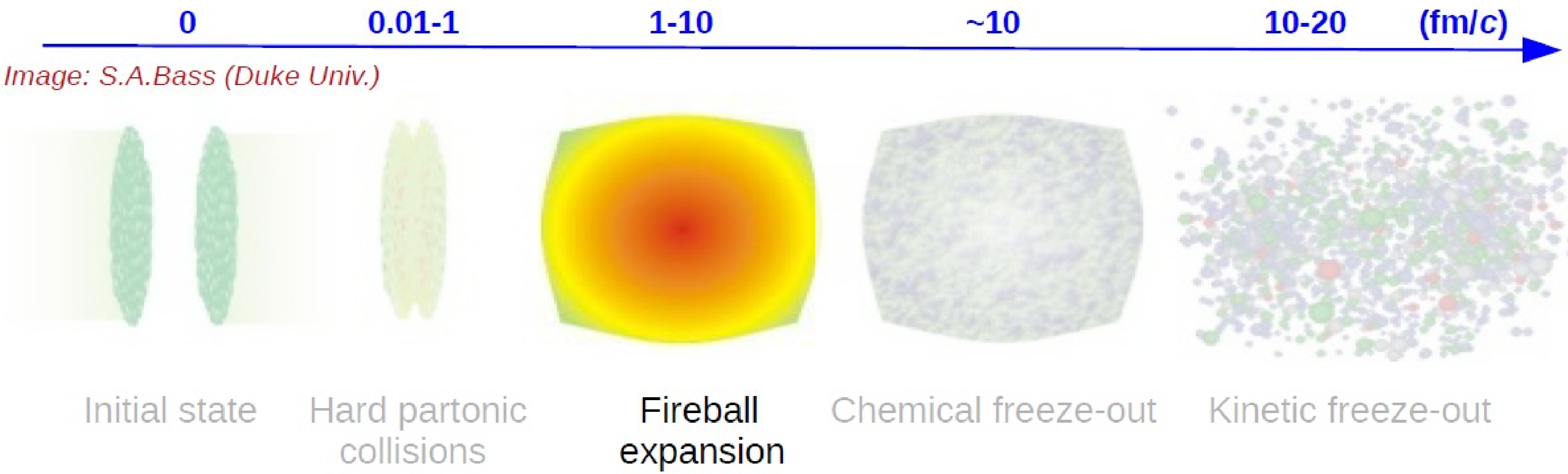
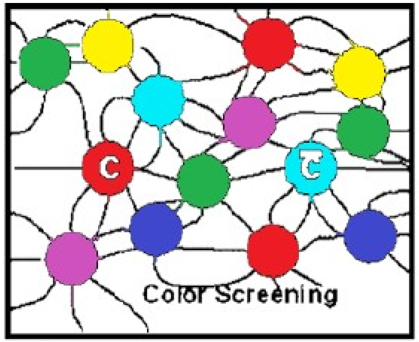



*Image: S.A.Bass (Duke Univ.)*

## In-medium dissociation (color Debye screening)

Matui & Satz, Phys.Lett. B178 (1986) 416-422

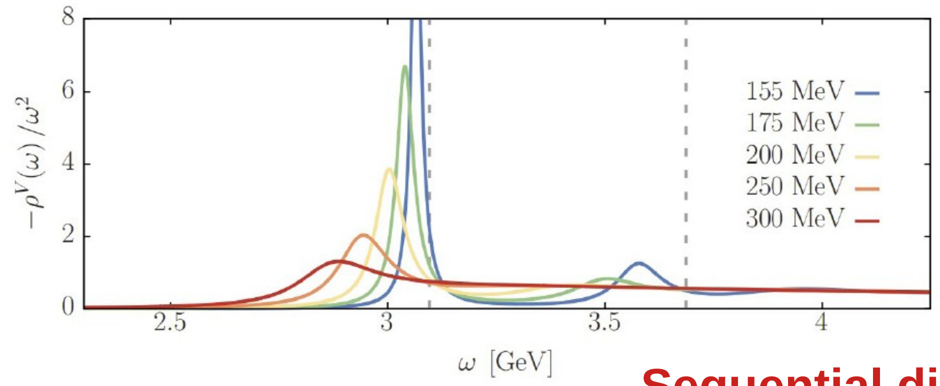


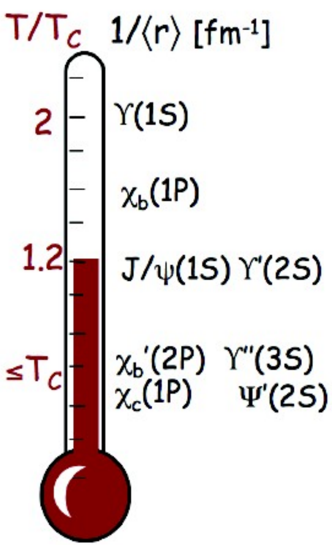

→ **Open-quantum system approach:**

Quarkonia described in terms of spectral functions modified in a deconfined medium

- Debye screening - real part of the potential
- "Decoherence" - imaginary part of the potential

→ **Spectral functions via lattice QCD calculations:**



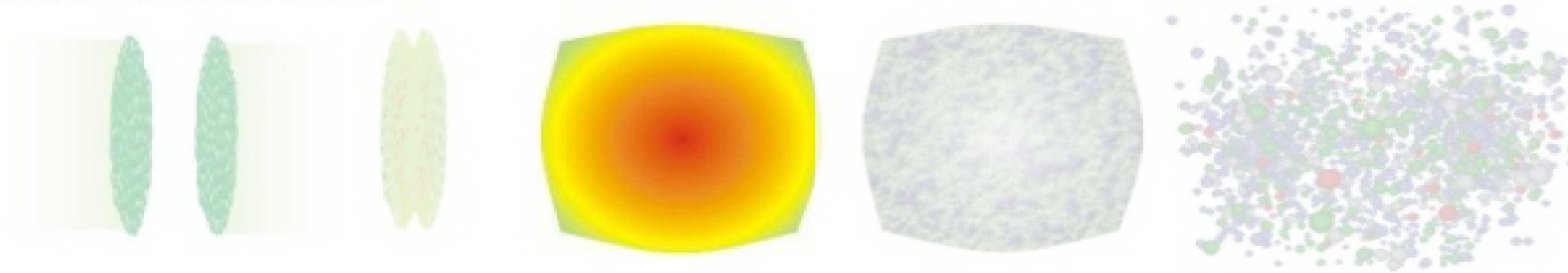

[EPJC 61 (2009) 705]

→ **Sequential dissociation**

# Quarkonia in (UR) Heavy Ion collisions

0 | 0.01-1 | 1-10 | ~10 | 10-20 | (fm/c)

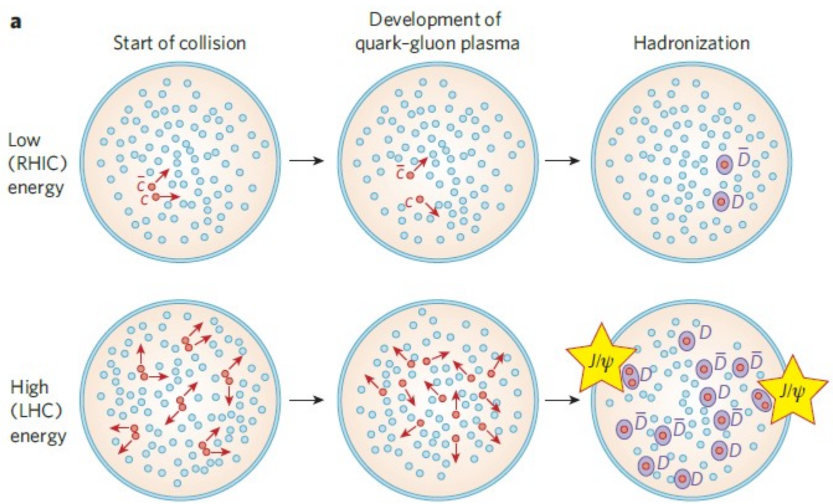
*Image: S.A.Bass (Duke Univ.)*



Initial state | Hard partonic collisions | Fireball expansion | Chemical freeze-out | Kinetic freeze-out

## Regeneration of quarkonia

Braun-Munzinger and Stachel, PLB 490 (2000) 196
Thews et al., PRC 63 (2001) 054905

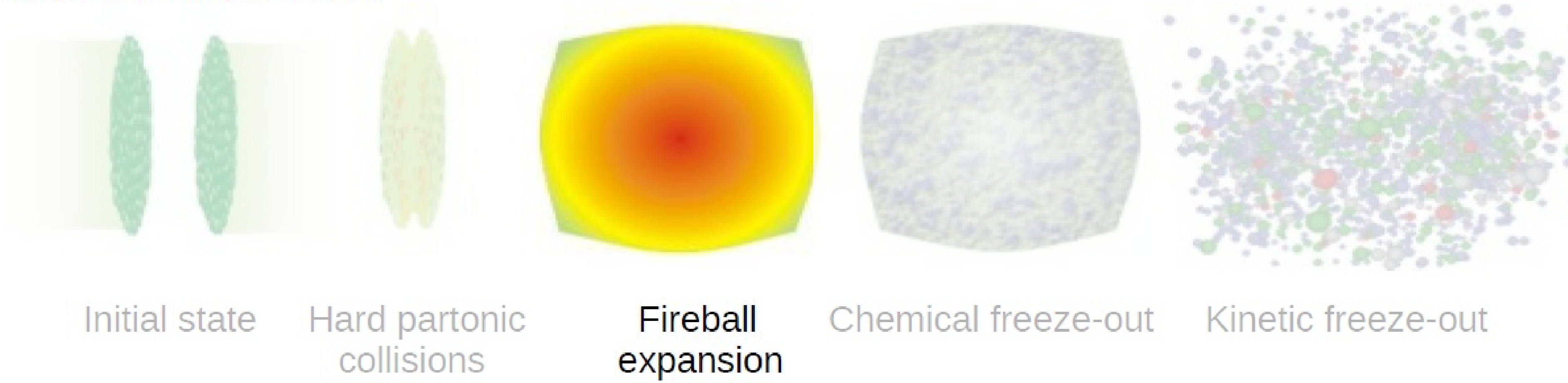



Nature 448 (2007) 302-309

# Quarkonia in (UR) Heavy Ion collisions

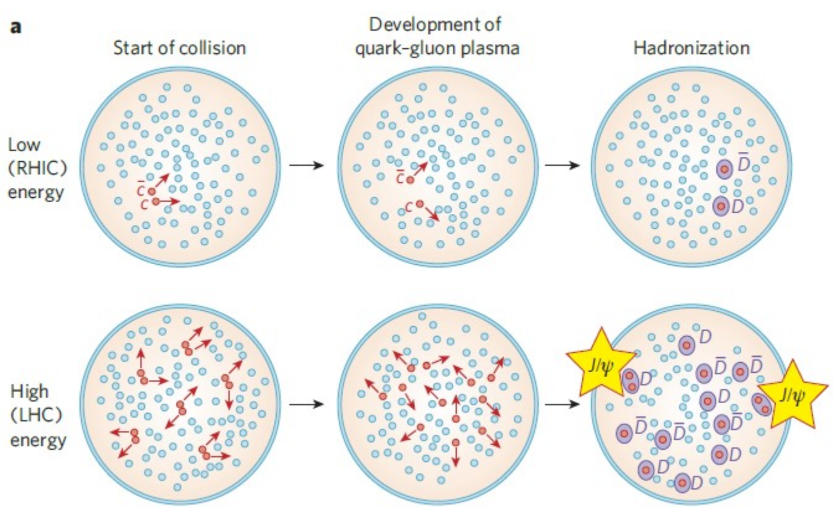
0 0.01-1 1-10 ~10 10-20 (fm/c)

*Image: S.A.Bass (Duke Univ.)*




## Regeneration of quarkonia

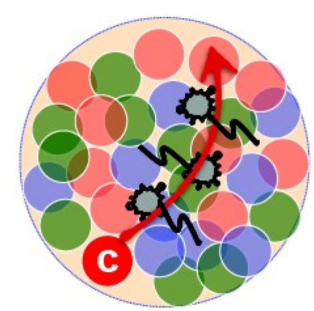
Braun-Munzinger and Stachel, PLB 490 (2000) 196
Thews et al., PRC 63 (2001) 054905




Nature 448 (2007) 302-309

## Parton energy loss (at high pT)

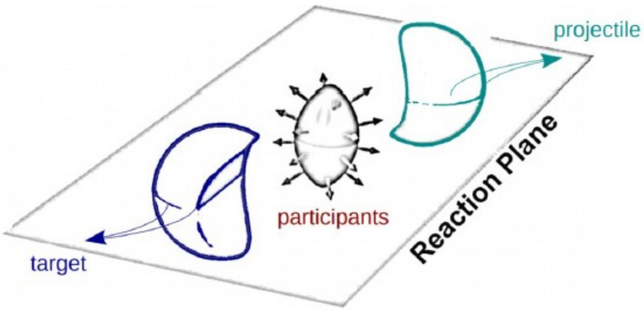
M. Gyulassy and M. Plumer, Phys. Lett. B243 (1990) 432
M. H. Thoma and M. Gyulassy, Nucl. Phys. B351 (1991) 491.
E. Braaten and M. H. Thoma, Phys. Rev. D44 (1991) 1298;
Phys. Rev. D44 (1991) 2625

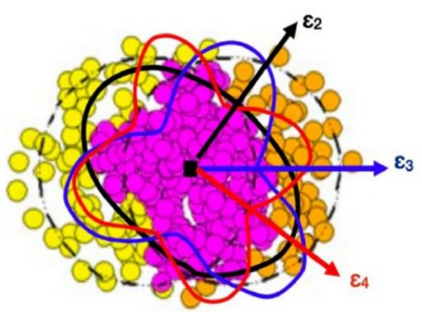


# Key Observables

1) $$R_{AA}(p_T, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2N_{AA}/dp_T dy}{d^2N_{pp}/dp_T dy}$$

2) $$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cdot \cos[n(\varphi - \Psi_{RP})] \quad v_n = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$




*Decomposed transverse projection of participant region in Fourier series*

– **Initial spatial anisotropy**:

– Almond shape of the participant region → generates ellipticity ($\varepsilon_2$)

– Energy density fluctuations in the overlap region → generates triangularity ($\varepsilon_3$)

– Higher harmonics → mainly arising from the combination of the lower order components

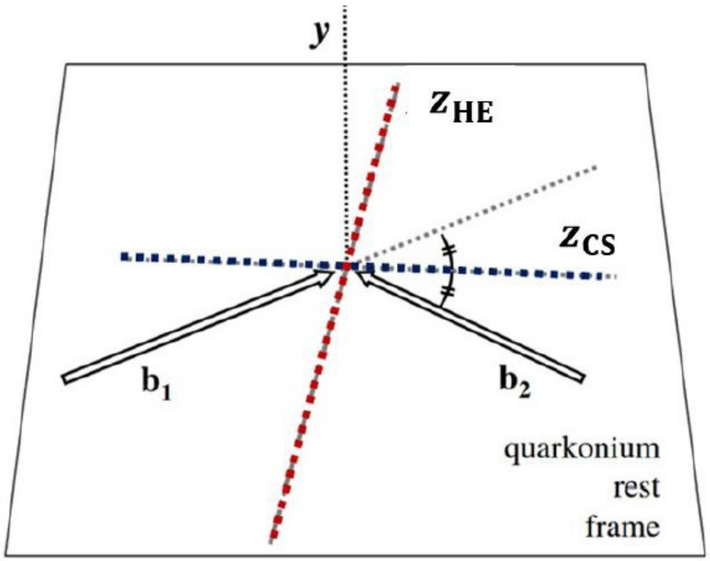
→ **low-$p_T$: sensitive to bulk QGP properties**

→ **high-$p_T$: sensitive to the in medium energy loss (path-lenght dependence)**

# Key Observables (1)

3) Excited-to-ground state ratios (e.g. ψ(2S)/J/ψ) → **experimental and theoretical uncertainties partially cancel out in the ratio**

4) Polarization




**Reference frames:**

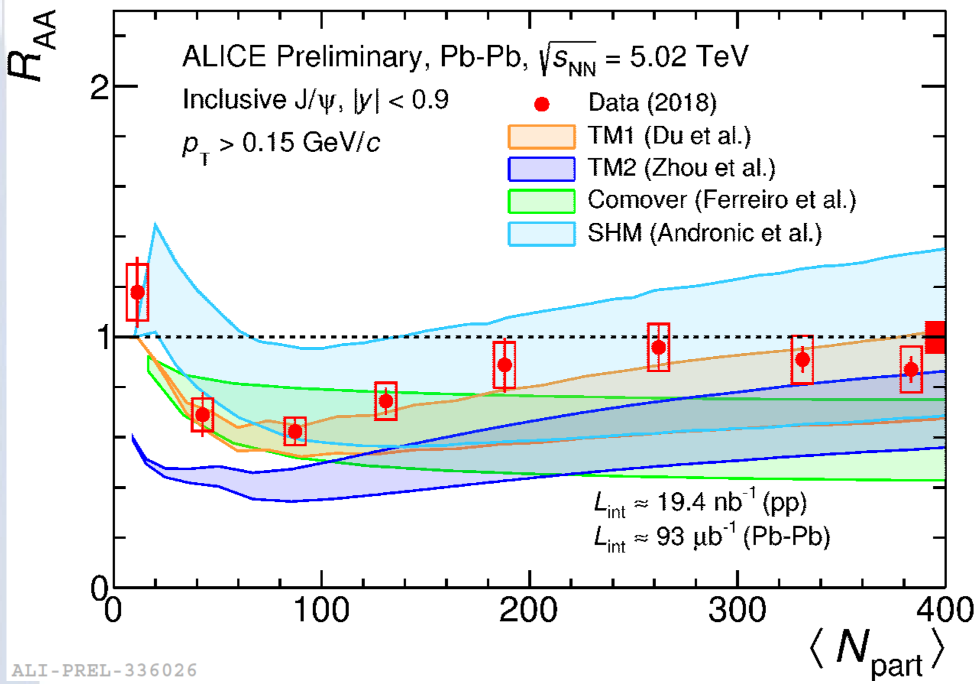
**Helicity (HE)**: direction of vector meson in the collision center of mass frame

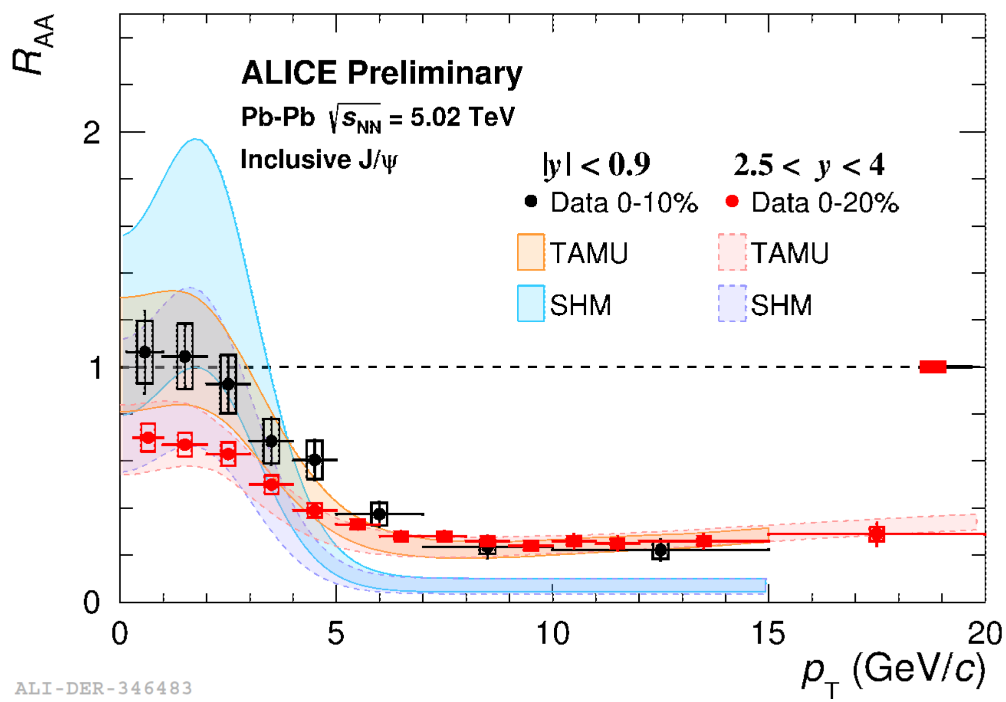
**Collins-Soper (CS)**: the bisector of the angle between the beam and the opposite of the other beam, in the vector meson rest frame

→ **sensitive to production mechanisms**

→ **difference in Pb-Pb w.r.t. pp expected due to suppression / regeneration**

# J/ψ $R_{AA}$ - Comparison with models




- **Models including regeneration mechanism in agreement with data**
  - Statistical Hadronization (SHM)
    - All charmonia produced at the QGP phase boundary with thermal weights
  - Transport model (TAMU)
    - Charmonium spectral functions from lattice QCD
    - Solve Boltzmann equation with gain (regeneration) and loss (melting) terms
- **large uncertainties on the models arise from charm cross sections and poor constrained nPDF**

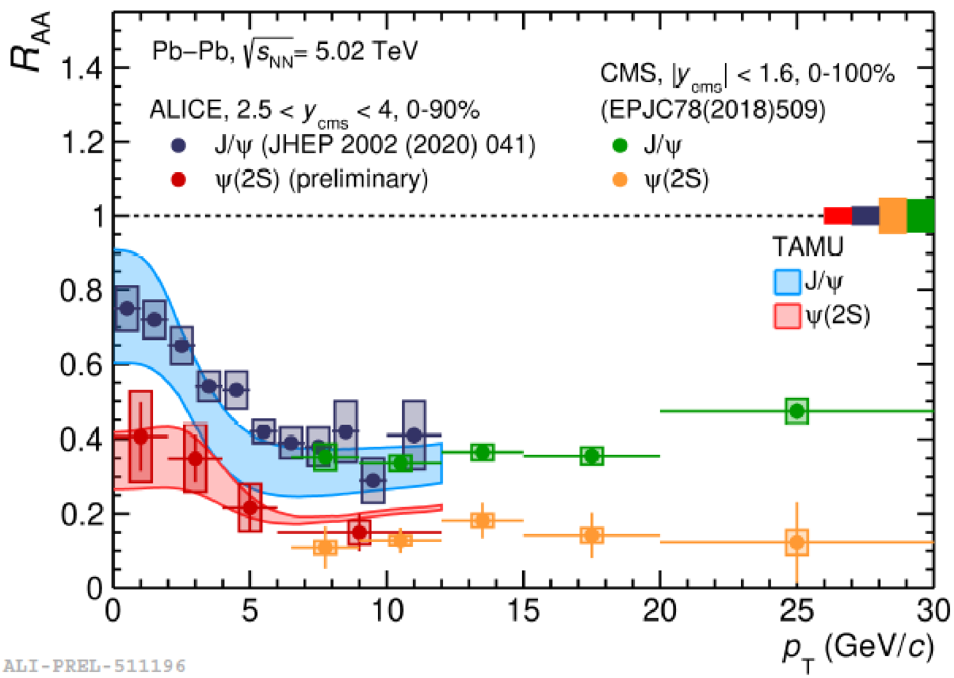
→ **Discriminate between the two pictures**

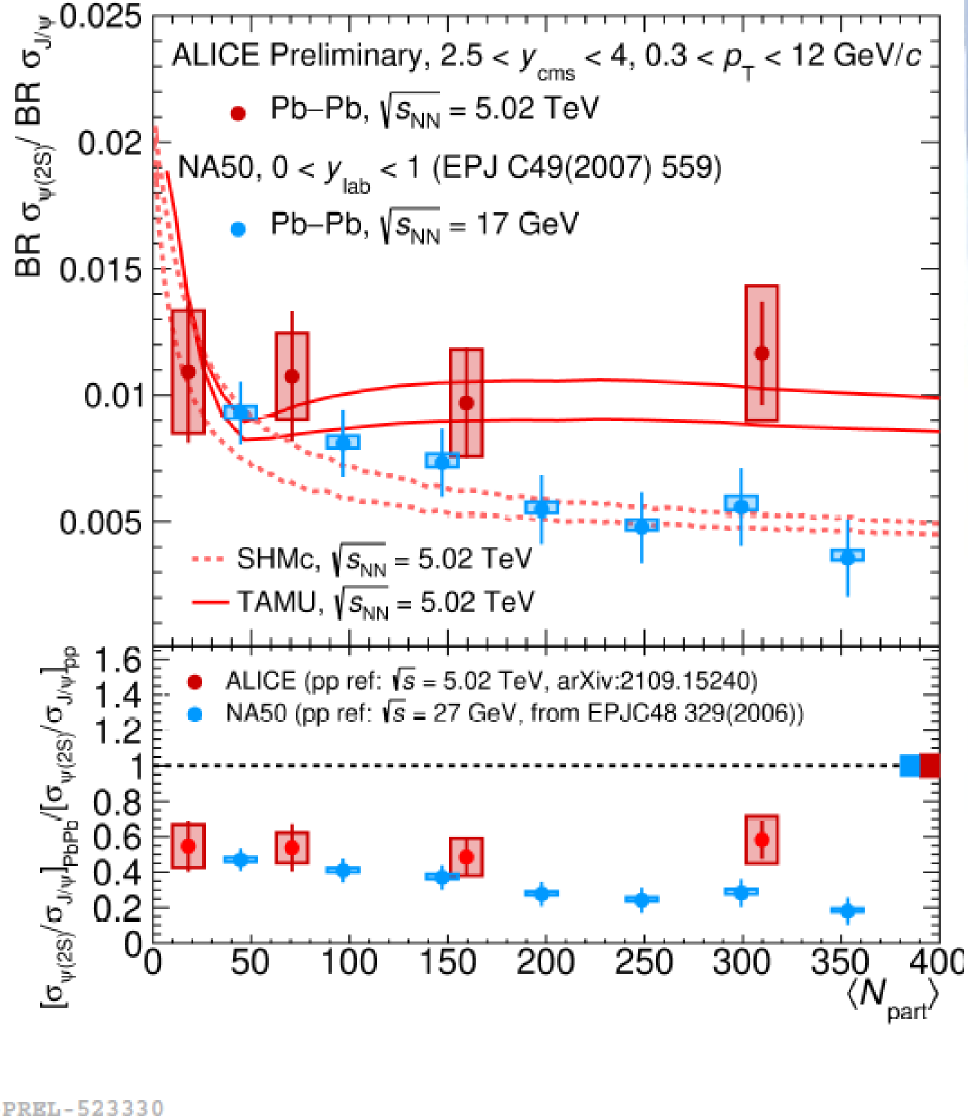
→ **Separate prompt and non-prompt charmonia**




TM2: Zhou et al., Phys. Rev. C 89, 054911 (21 May 2014)
Comover: Ferreiro E. et al., PLB 731 (2014) 57
SHM: Andronic A. et al., Phys. Lett. B797 (2019) 134836,
TM1/TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158

# ψ(2S) $R_{AA}$ and ψ(2S)-to-J/ψ ratio




– ψ(2S) more suppressed compared to J/ψ; rise of J/ψ and ψ(2S) RAA towards low pT

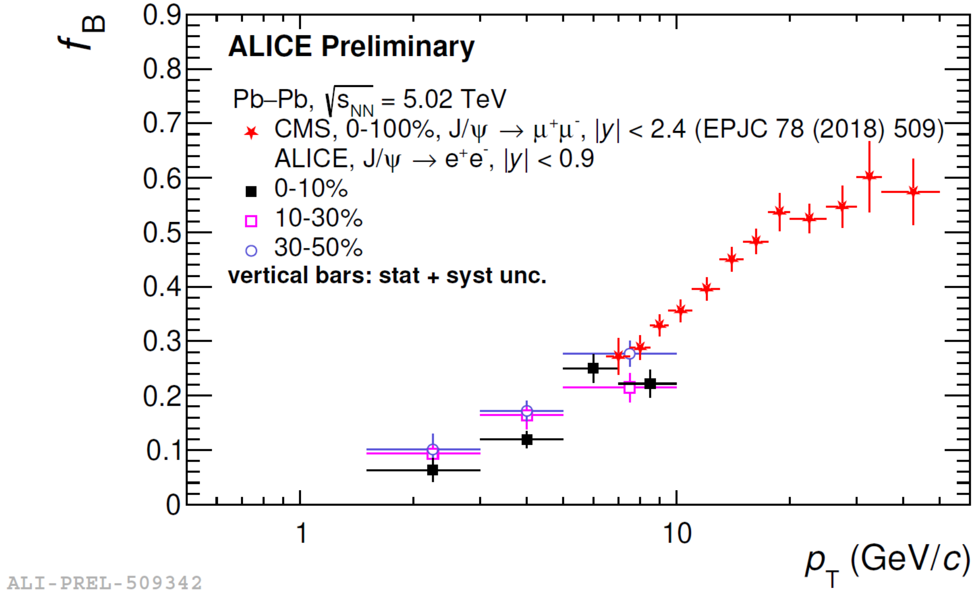
– pT dependent $R_{AA}$ in agreement with TAMU for both charmonium states

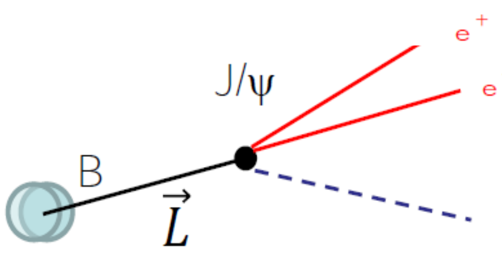
– ψ-to-J/ψ ratio at LHC in agreement with TAMU; tensions visible with SHMc at higher centralities

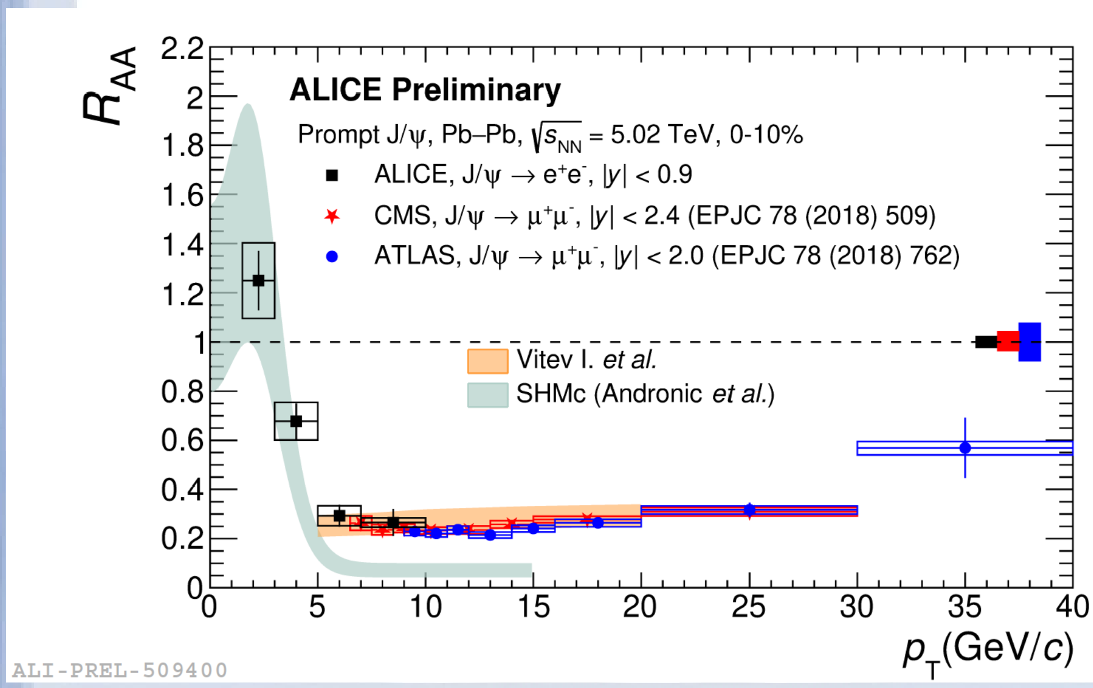


TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158
SHMc: A. Andronic et al., JHEP07 (2021) 035

# Prompt J/ψ $R_{AA}$



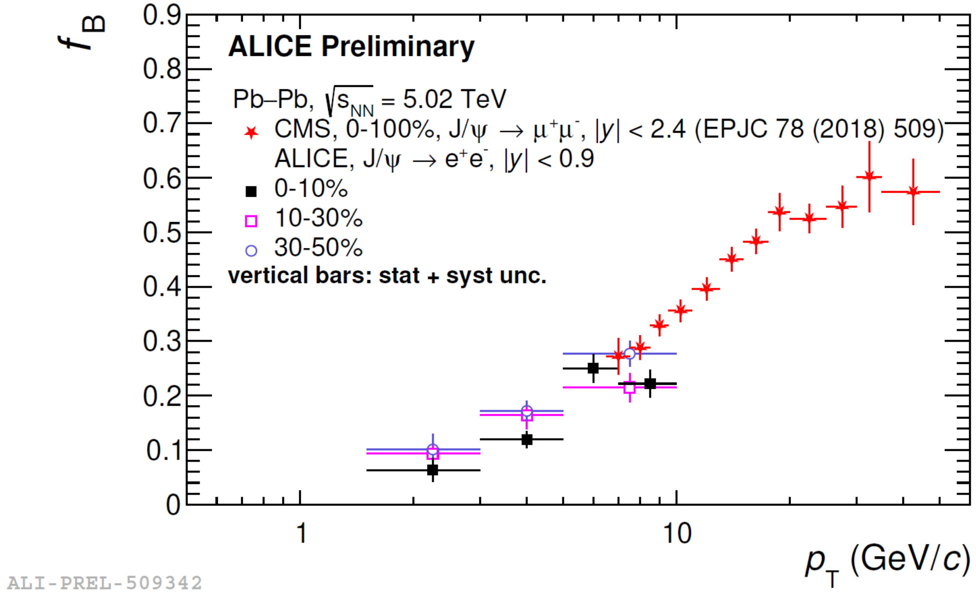

– rise of prompt J/ψ RAA at low pT → compatible with SHMc

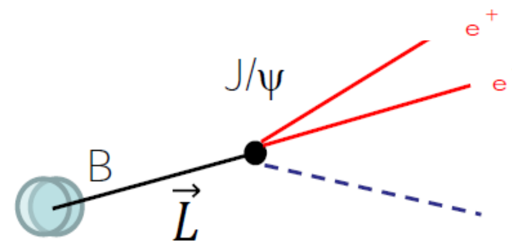
– model by Vitev et al, including dissociation, can describe results at high-pT

– compatible with ATLAS and CMS in the overlapping pT range

SHMc: A. Andronic et al., JHEP07 (2021) 035
Vitev I. et al. arXiv:1709.02372, arXiv:1906.04186

# Non-Prompt J/ψ $R_{AA}$

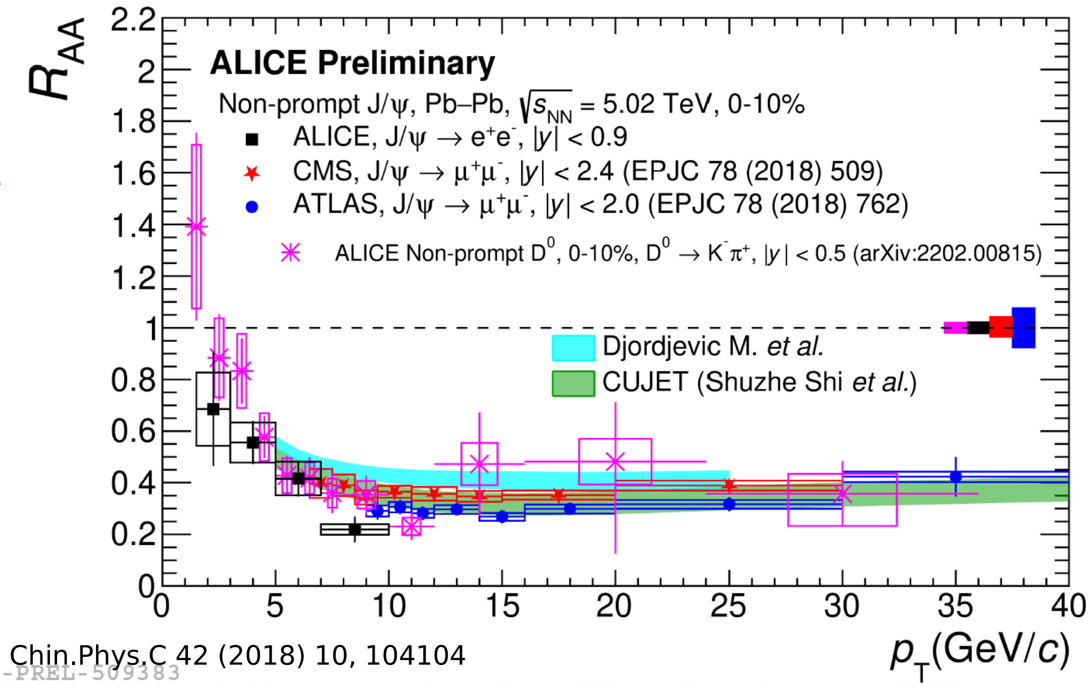



– non-prompt J/ψ $R_{AA}$ allows to access beauty quark energy loss in the QGP

– compatible with models including collisional and radiative energy loss

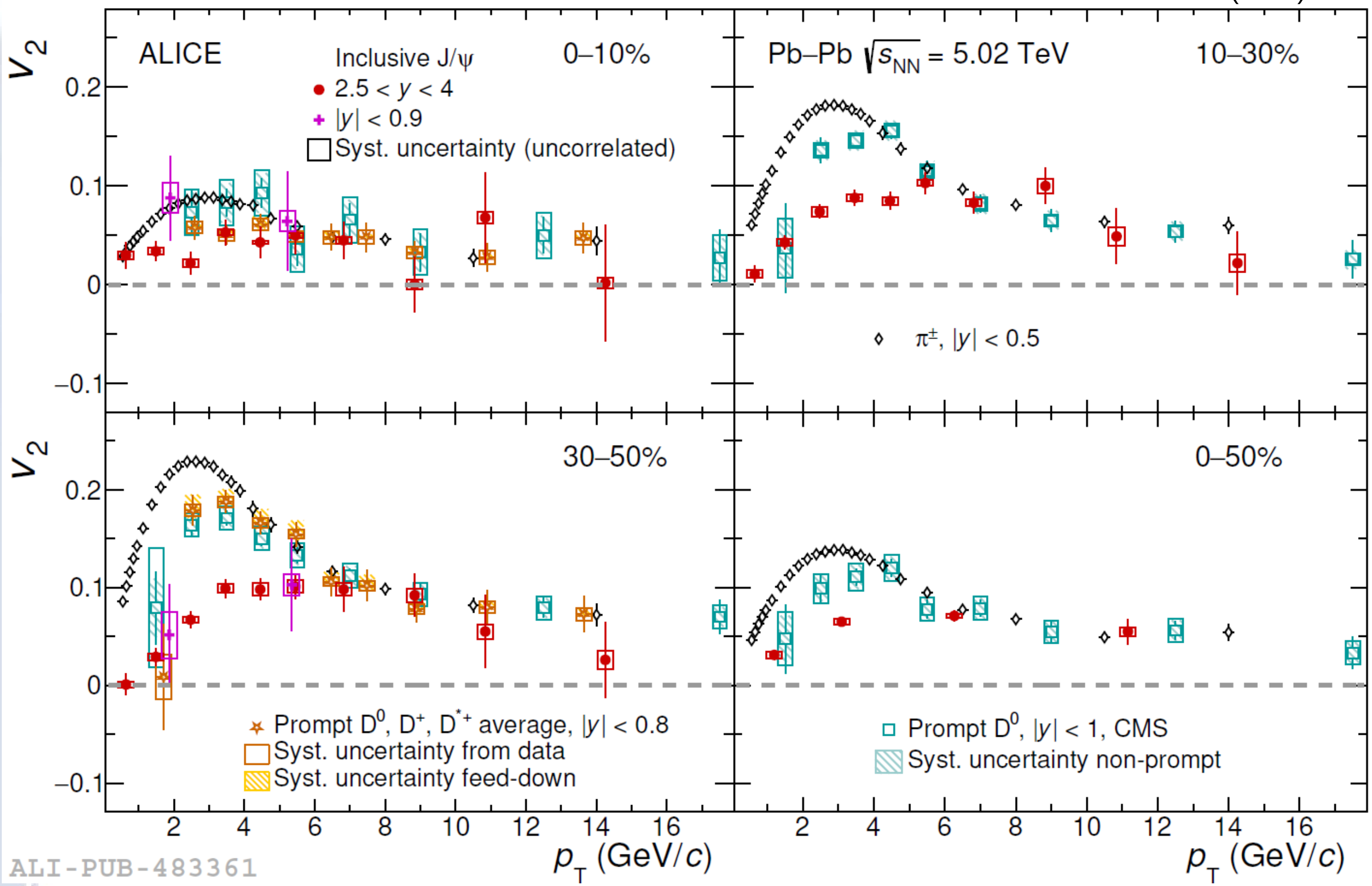
– good agreement between non-prompt J/ψ and non-prompt $D^0$ $R_{AA}$




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

# J/ψ $v_2$ – comparison to D-mesons and π

JHEP 10 (2020) 141



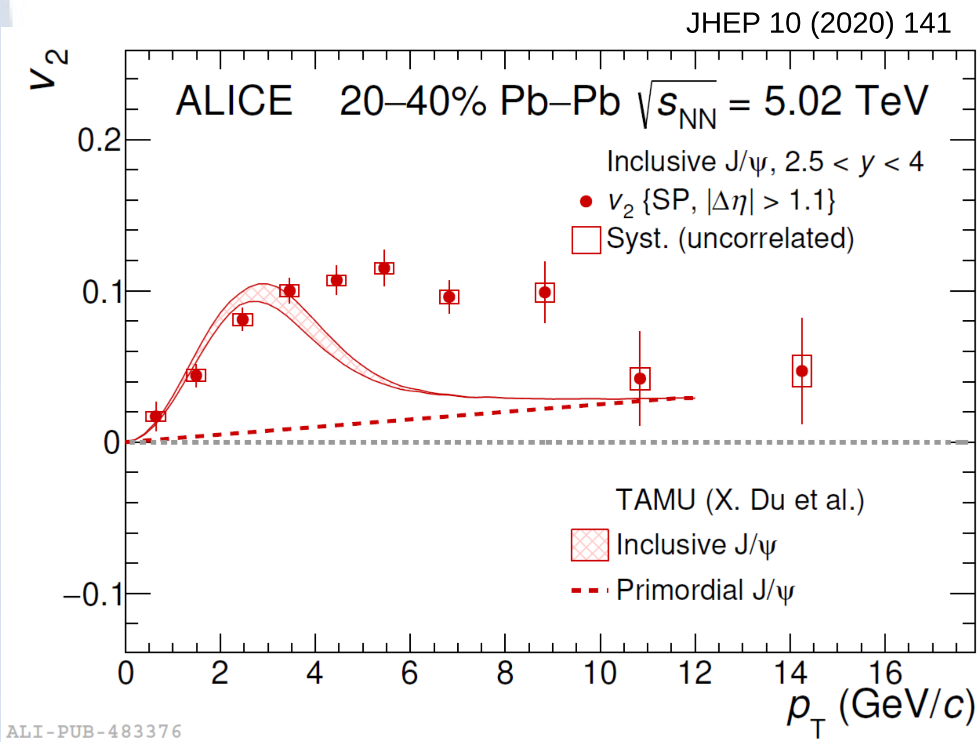

– J/ψ $v_2$ >0 → consistent with hydrodynamic flow of charm quarks in QGP

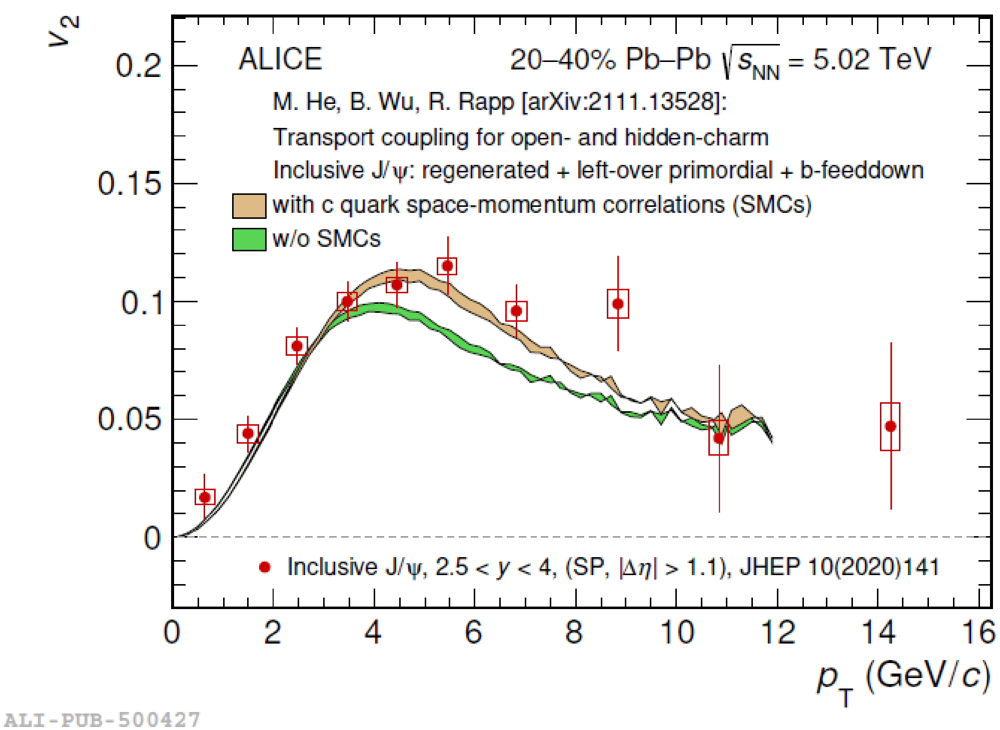
– J/ψ $v_2$ grows from central towards semi-central collisions, similarly as lighter particles

– Clear mass hierarchy at low-pT: $v_2(\pi)>v_2(D)>v_2(J/\psi)$

– Specie independent $v_2$ at high-$p_T$

# J/ψ $v_2$ – comparison with models



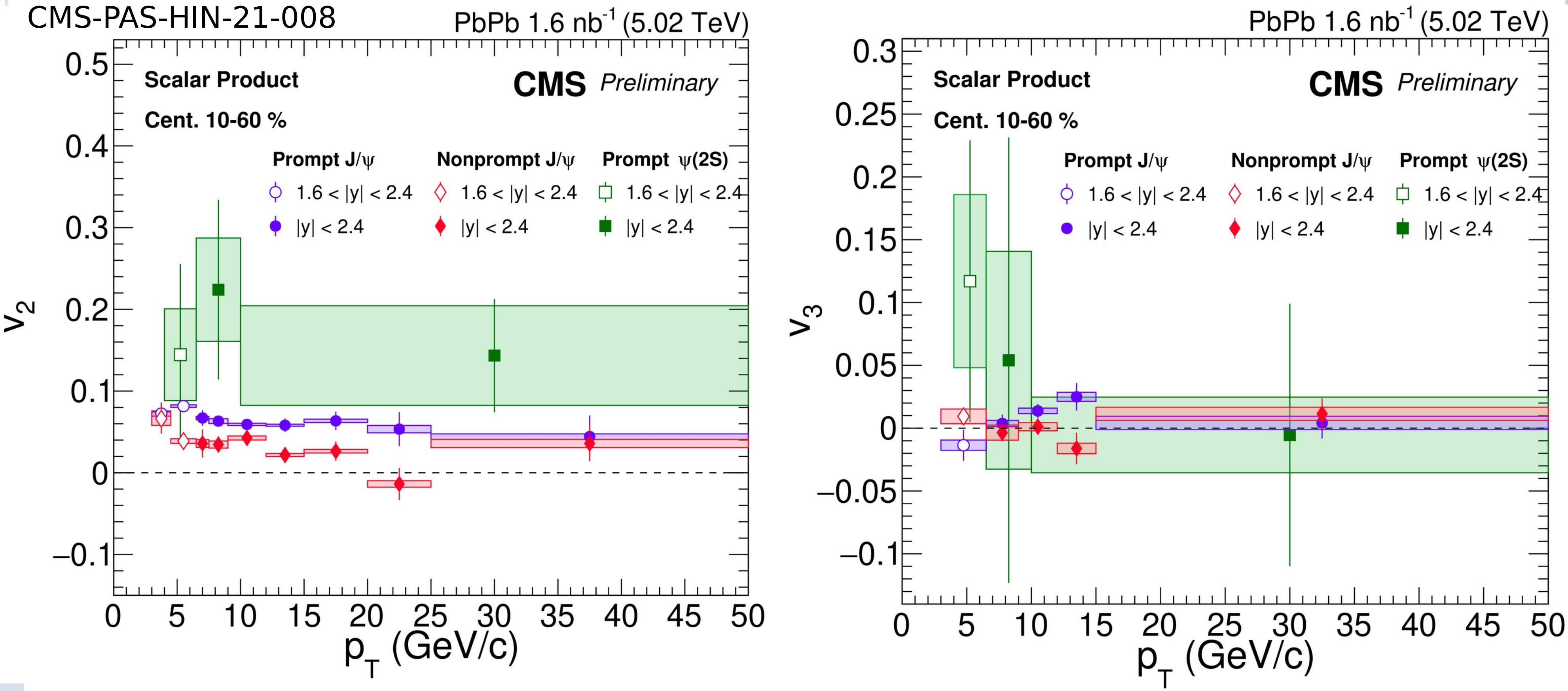




– Low $p_T$ region described by TAMU, however tensions clearly visible at high pT (>4 GeV/c)

– Better agreement with the model thanks to recent improvements, in particular including charm quark space-momentum correlations

TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158
TAMU+SMCc: arXiv:2111.13528

# $v_2$ and $v_3$: J/ψ vs ψ(2S)

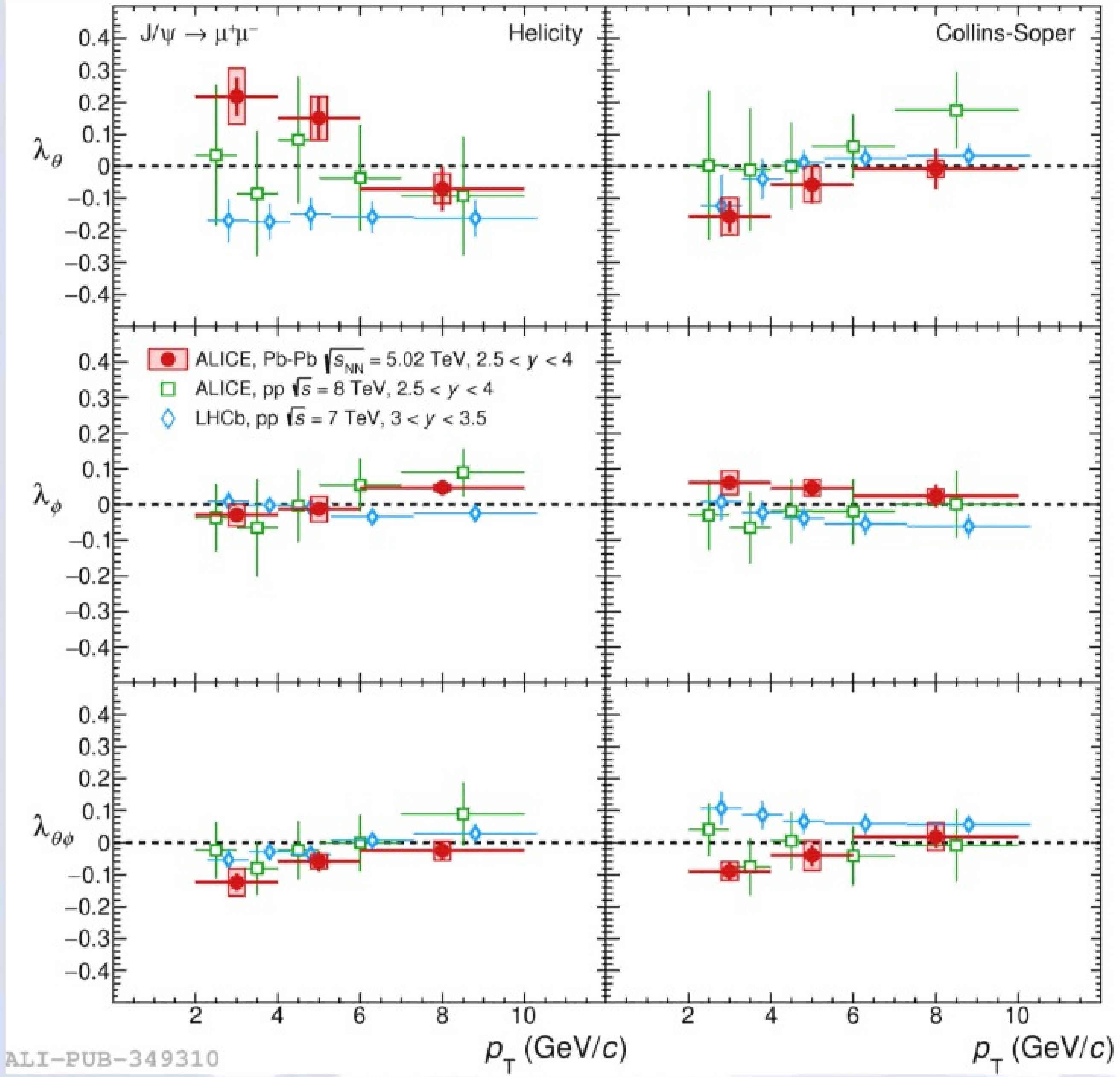



– Hint at larger prompt ψ(2S) $v_2$ compared to prompt J/ψ $v_2 \rightarrow$ possibility of larger contribution from regeneration for ψ(2S)

– ψ(2S) $v_3$ consistent with zero and with prompt J/ψ $v_3$, however uncertainties are large for concluding

# J/ψ polarization

PLB 815 (2021) 136146




– Polarization measured by ALICE in Pb-Pb collisions

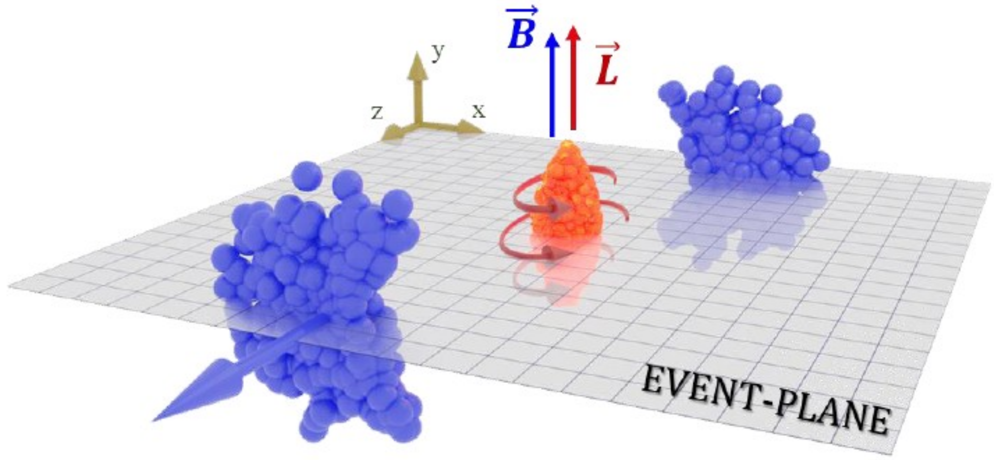
– 2σ deviation for $\lambda_\theta$ in 2-4 GeV/c w.r.t zero in HE and CS

– compatible with ALICE in pp colllisions [EPJC 78 (2018) 562]

– significant difference w.r.t. LHCb pp measurements [EPJC 73 (2013) 11]

→ difference due to suppression / regeneration in Pb-Pb ?

# J/ψ polarization w.r.t. event plane

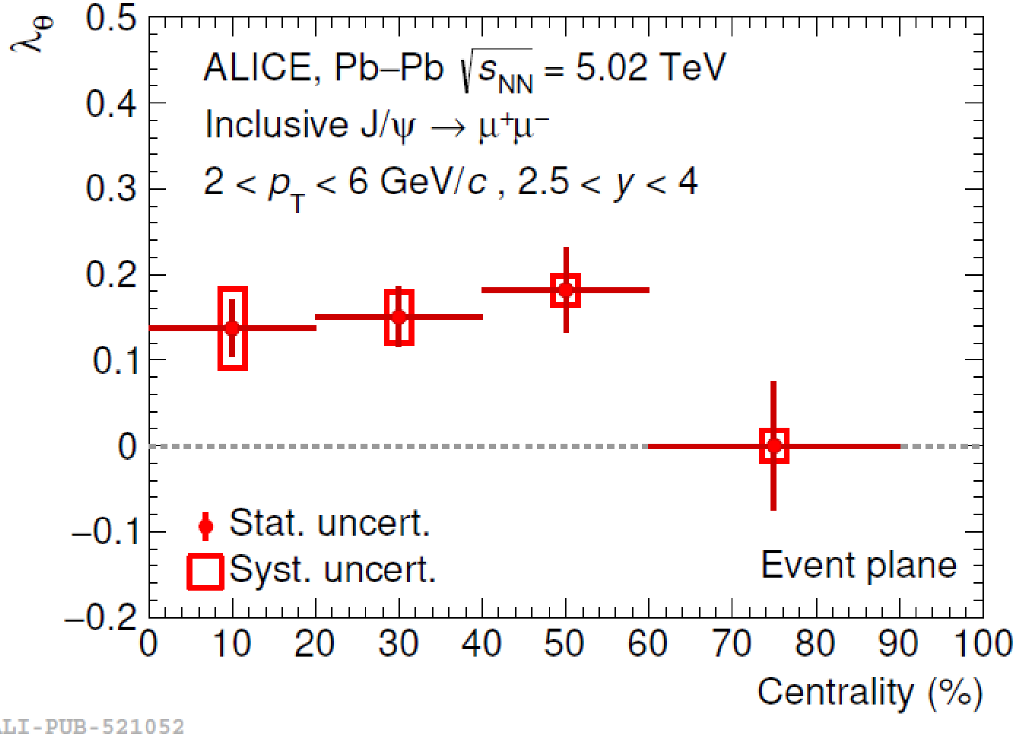



– **Event Plane based frame (EP)**: axis orthogonal to the event plane in the collision center of mass frame

– Event Plane normal to **B** and **L**

– Heavy quarks produced early in the collisions → can experience both **B** and **L**

arXiv:2204.10171



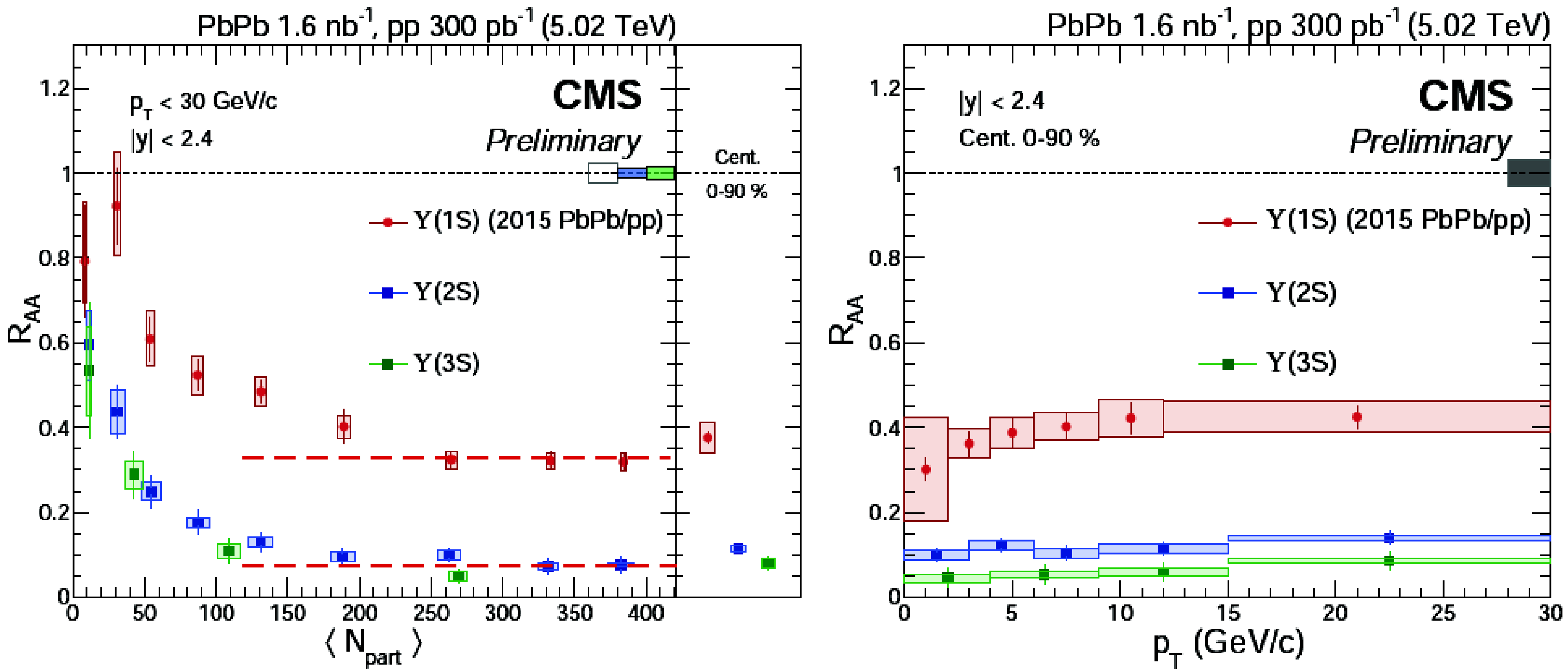

– Small centrality dependence

– Significant polarization (3.5σ) in 40-60% and 2 < $p_T$ < 6 GeV/c

– **Theoretical description of vector meson polarization in heavy ion collisions still missing**

# Bottomonium $R_{AA}$

[CMS-PAS-HIN-21-007]



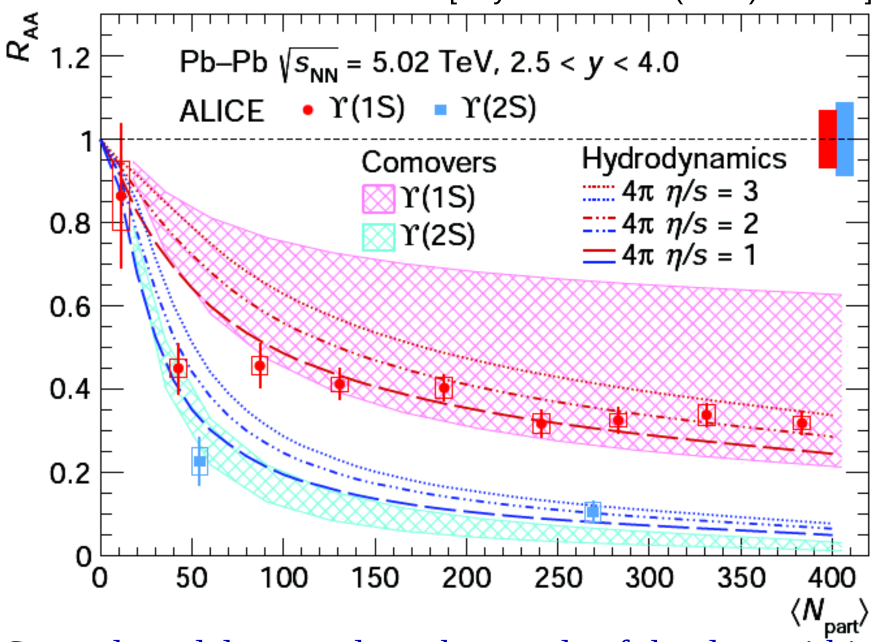

– Increasing suppression of ϒ(nS) with centrality; saturation of $R_{AA}$ at higher centralities

– $R_{AA}$ of ϒ(1S) saturates to ~0.35 (factor ~3 suppression), $R_{AA}$ of ϒ(2S) suppressed by a factor ~10

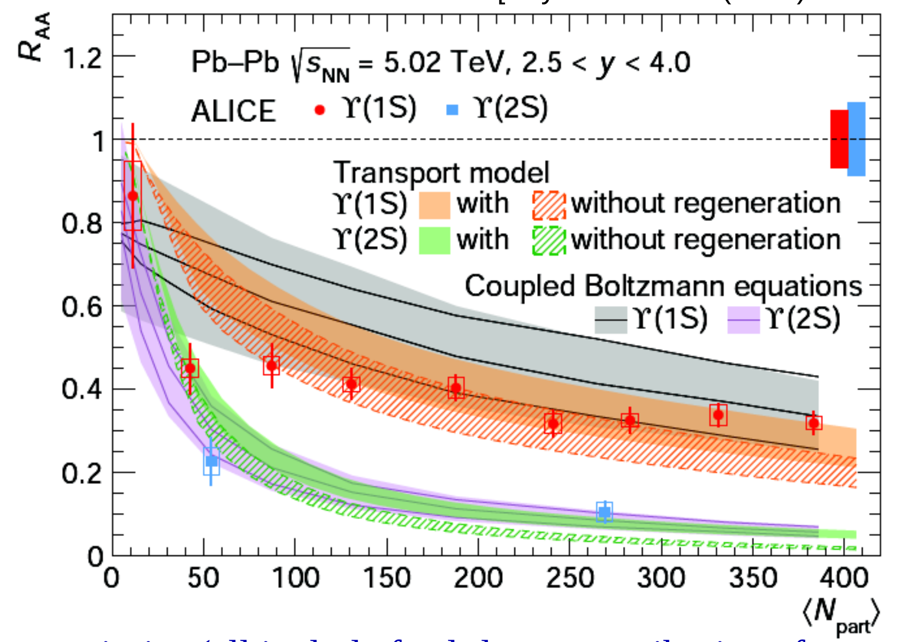
– compatible with a sequential ordering of the suppression

# Bottomonium $R_{AA}$

[Phys.Lett.B 822 (2021) 136579]




[Phys.Lett.B 822 (2021) 136579]




– Several models reproduce the trends of the data within uncertainties (all include feed-down contributions from higher states):

– **hydrodynamics:** thermal modification of a complex heavy-quark potential inside an anisotropic plasma (no modification of nuclear PDFs / no regeneration included)

B. Krouppa, M. Strickland, Universe 2(3) (2016) 16, arXiv:1605 .03561

– **transport models:** interplay of dissociation and regeneration mechanisms, modification of nPDF included (available with and without regeneration)

Coupled Boltzmann Eq.: X. Yao et al., JHEP 01 (2021) 046, arXiv:2004.06746.
Transport: X. Du, R. Rapp, M. He, Phys. Rev. C 96(5) (2017) 054901, arXiv:1706.08670

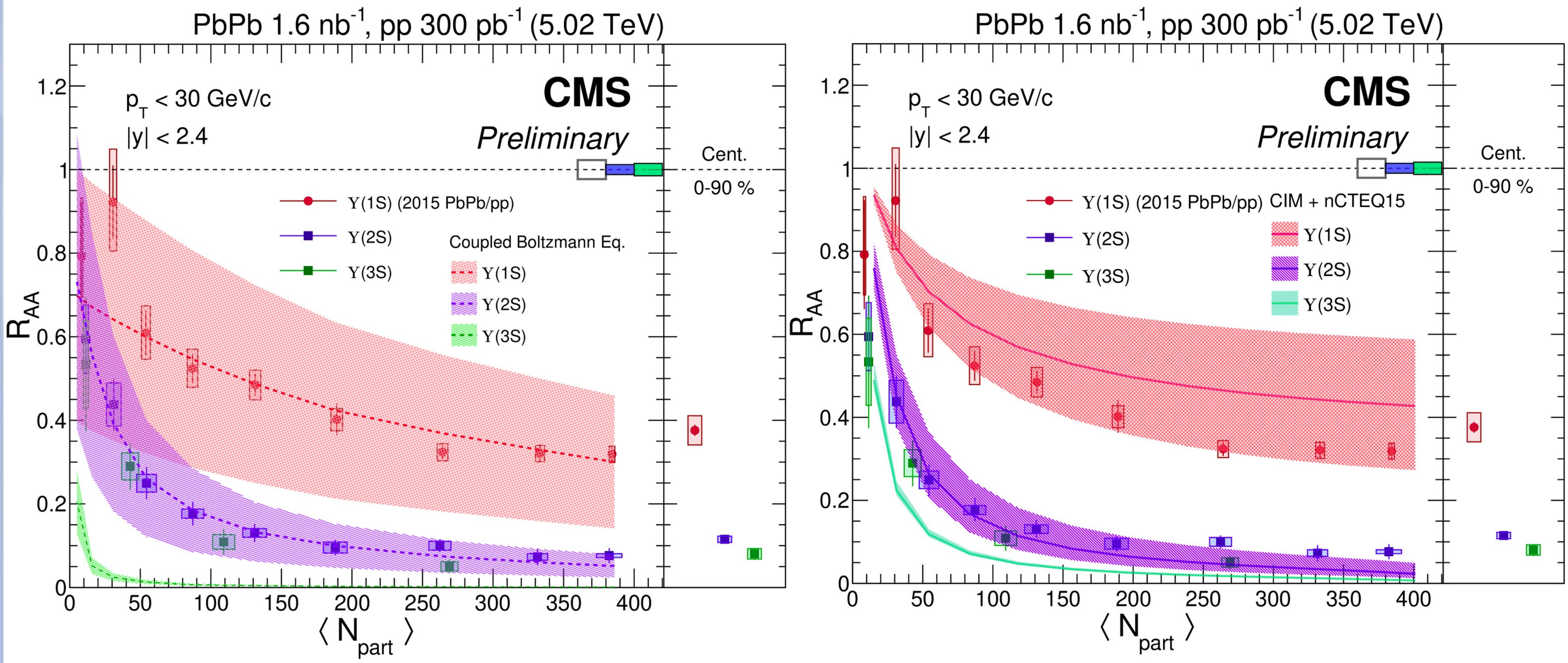
– **comovers:** break-up by interactions with comover particles, nCTEQ15 parametrisation for nPDF

Comovers: E. Ferreiro, J.-P. Lansberg, JHEP 10 (2018) 094, arxiv:1804.04474

→ **fair agreement also when regeneration is not included**

[CMS-PAS-HIN-21-007]

# Bottomonium $R_{AA}$



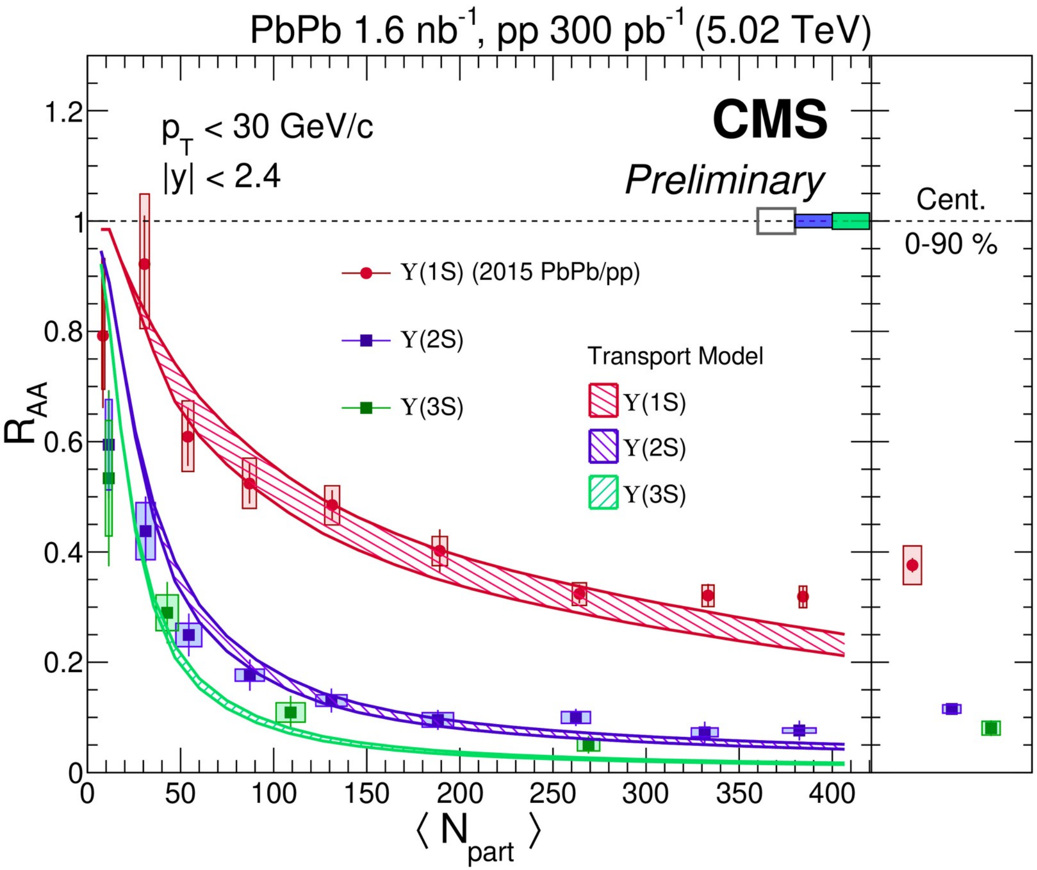

– **Coupled Boltzmann Eq.** and **CIM + nCTEQ15** models reproduce the trends of the Υ(1S) and Υ(2S) RAA within uncertainties

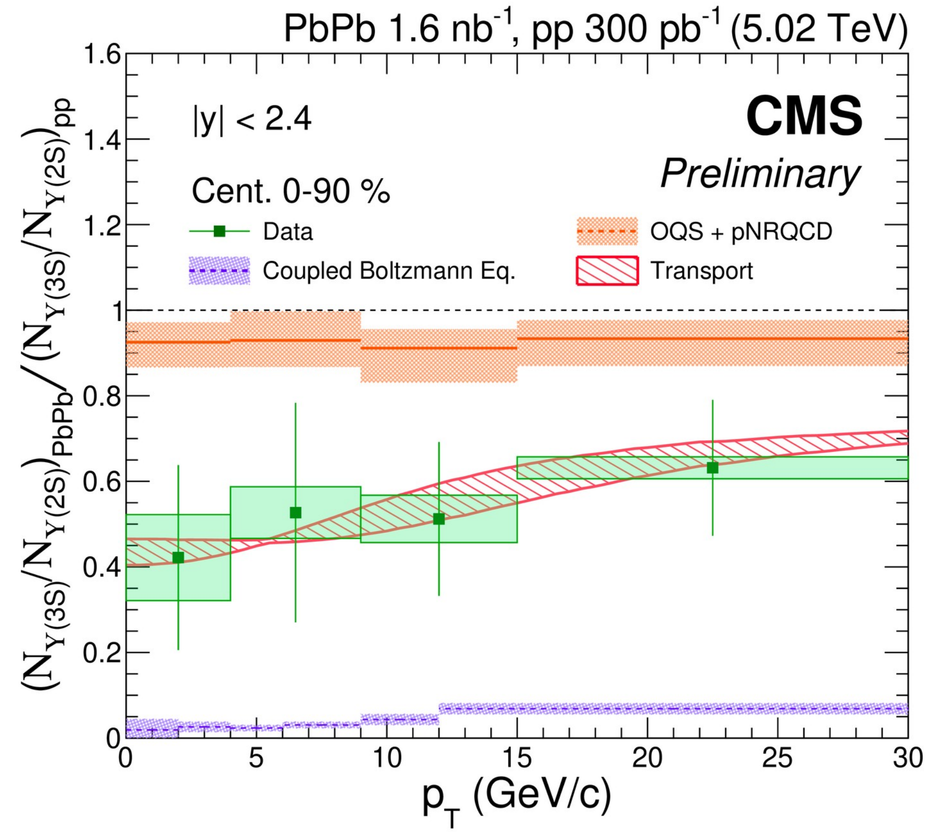
– tensions observed for Υ(3S)

Coupled Boltzmann Eq.: X. Yao et al., JHEP 01 (2021) 046, arXiv:2004.06746.
Comover Interaction Model (+nCTEQ15): E. Ferreiro, J.-P. Lansberg, JHEP 10 (2018) 094, arxiv:1804.04474

# Bottomonium $R_{AA}$

[CMS-PAS-HIN-21-007]



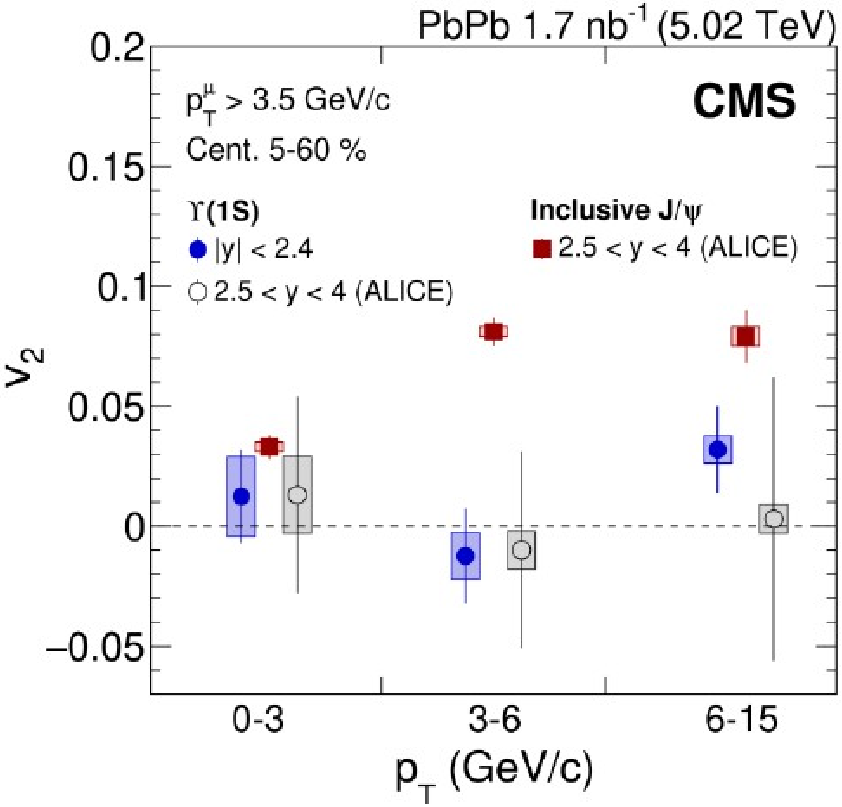

– Better agreement, including also Υ(3S), with **transport model**

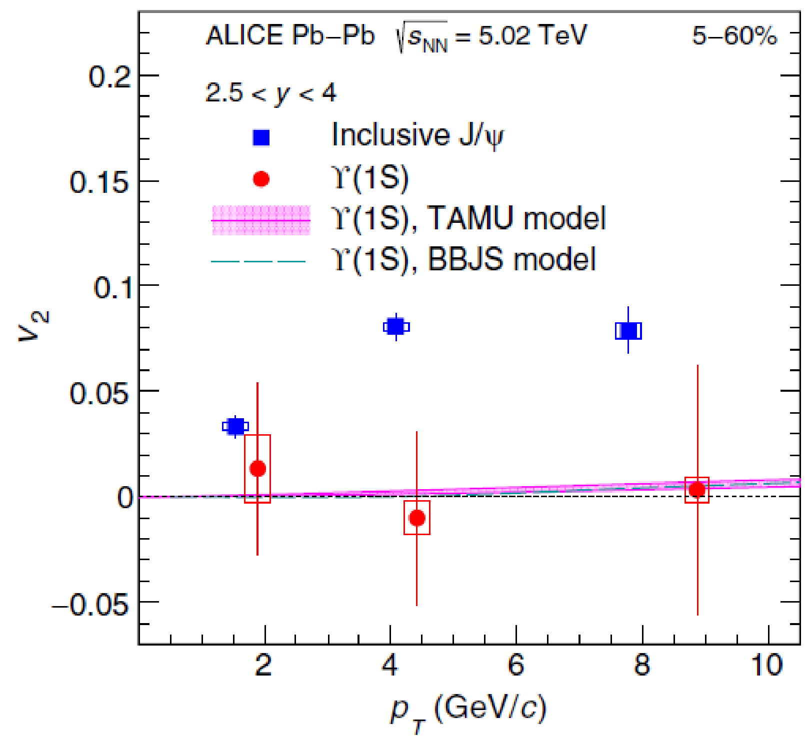
– Effect of regeneration negligible on the overall trend in all cases

Coupled Boltzmann Eq.: X. Yao et al., JHEP 01 (2021) 046, arXiv:2004.06746.
Transport: X. Du, R. Rapp, M. He, Phys. Rev. C 96(5) (2017) 054901, arXiv:1706.08670
Comover Interaction Model (+nCTEQ15): E. Ferreiro, J.-P. Lansberg, JHEP 10 (2018) 094, arxiv:1804.04474
OQS + pNRQCD: N. Brambilla et al., PRD 104 (2021) 094049, arXiv:2107.06222

# Υ(1S) $v_2$

[CMS: Phys. Lett. B 819 (2021) 136385]
[ALICE: Phys. Rev. Lett. 123 (2019) 192301]




– Υ(1S) $v_2$ compatible with zero and smaller than that of inclusive J/ψ

  – different relative importance of production mechanisms (dissociation vs regeneration) for J/ψ and Υ(1S) ?

– Results compatible within uncertainties with values predicted by theoretical models:

  – regeneration included in TAMU, but it gives no significant contribution to the Υ(1S) $v_2$



TAMU: X. Du, R. Rapp, and M. He, Phys. Rev. C 96, 054901 (2017)
BBJS: P. P. Bhaduri, N. Borghini, A. Jaiswal, and M. Strickland, arXiv:1809.06235

# Take-home notes: Quarkonia in Pb-Pb collisions

**Charmonia:**

- Regeneration mechanism essential for describing suppression patterns observed for J/Ψ at the LHC
  - First ψ(2S)-to-J/ψ ratio measurements from ALICE tend to favourite transport model
  - One of the main goal of Run3 / Run4
- Significant non-zero $v_2$ measured at the LHC for J/Ψ:
  - Consistent with the regeneration scenario, assuming thermalization of charm quarks in QGP
  - Recent version of transport model is able to reproduce the trend in the whole pT range

**Bottomonia:**

- Larger suppression observed for excited bottonium states → compatible with a sequential ordering of the suppression
  - Patterns in models not affected significantly by regeneration
- Υ(1S) $v_2$ compatible with zero and much smaller compared to J/Ψ $v_2$:
  - Consistent with small or negligible contribution from regeneration

# Quarkonia in p-Pb collisions

## Cold Nuclear Matter (CNM) effects

$$R_{\mathrm{pA}}(y, p_{\mathrm{T}}) = \frac{1}{A}\frac{\mathrm{d}^2\sigma_{\mathrm{pA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}$$

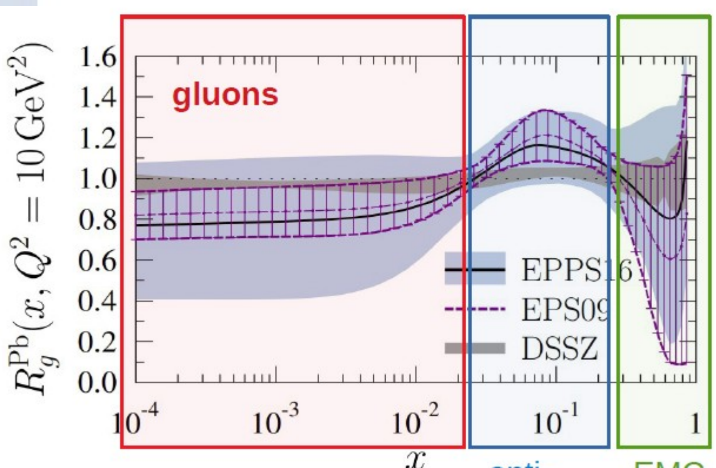
$\mathrm{d}^2\sigma_{\mathrm{pA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}$: cross section in pA

$\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}$: cross section in pp

$A$: cross section in pp

### nPDF modification

Eskola et al., EPJC77 (2017) 163



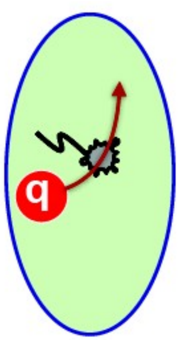

"shadowing"

anti - "shadowing"

EMC effect

### Coherent energy loss

F. Arleo, S. Peigne', JHEP 03 (2013) 122.

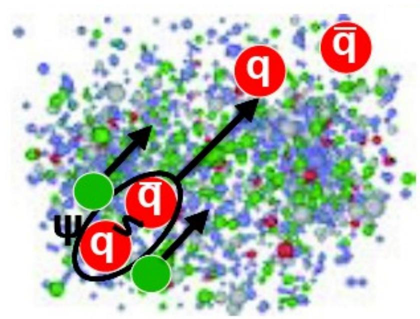



**Nuclear medium**

### Dissociation with comovers

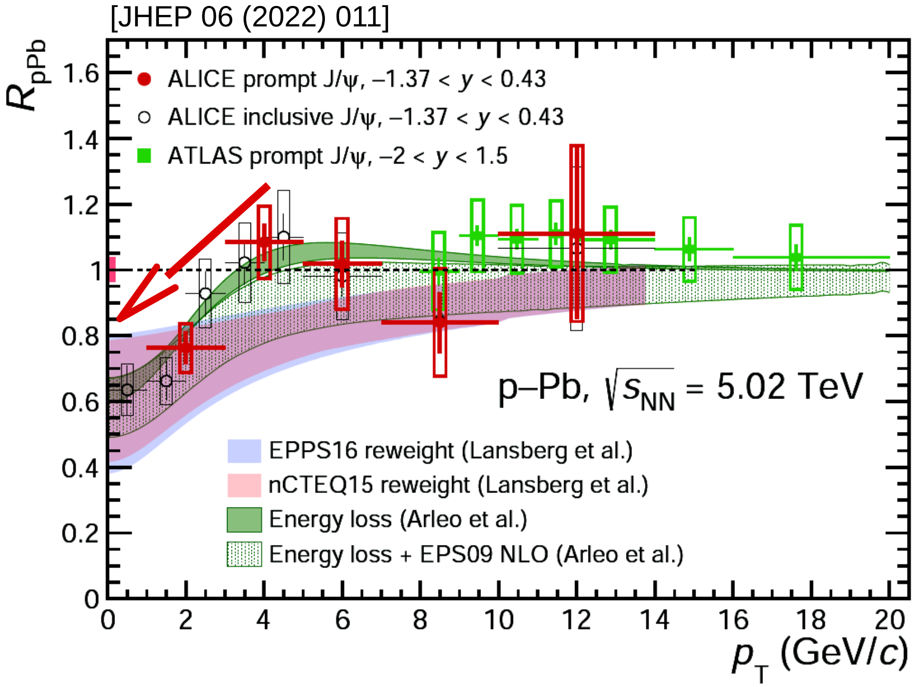
E. G. Ferreiro, PLB 731 (2014) 57

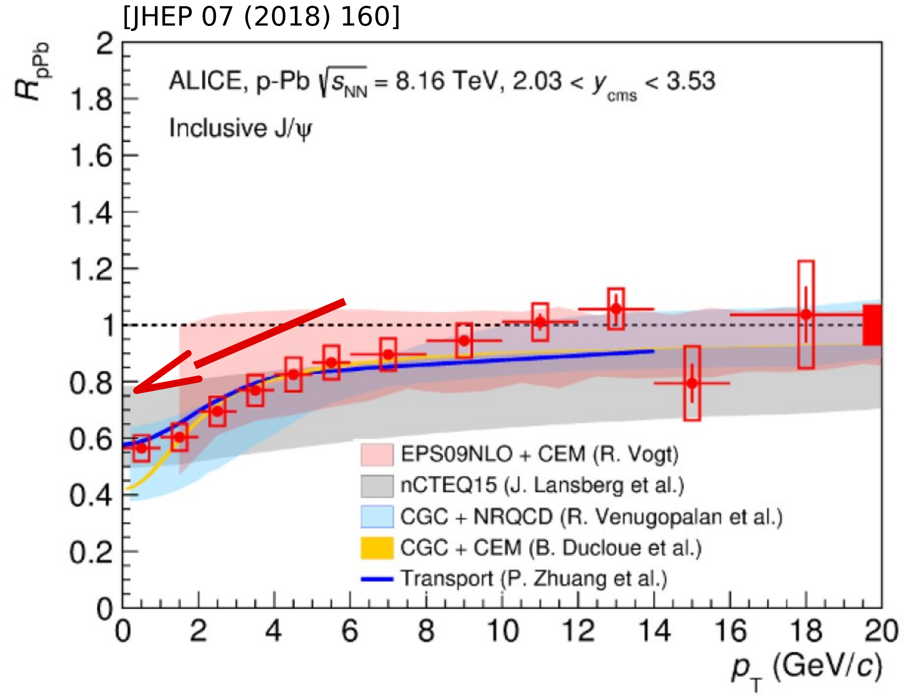
E. G. Ferreiro and J. P. Lansberg, JHEP 1810 (2018) 094




**Hadronic matter**

# J/ψ nuclear modification factor



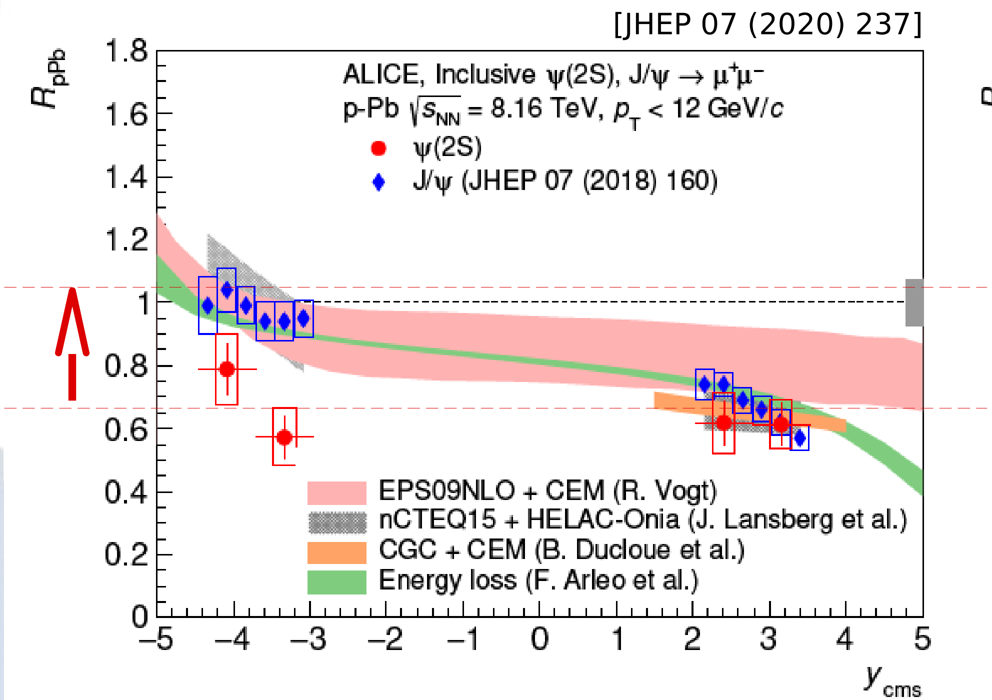

– J/Ψ production suppressed at low $p_T$ at both midrapidity and forward rapidity

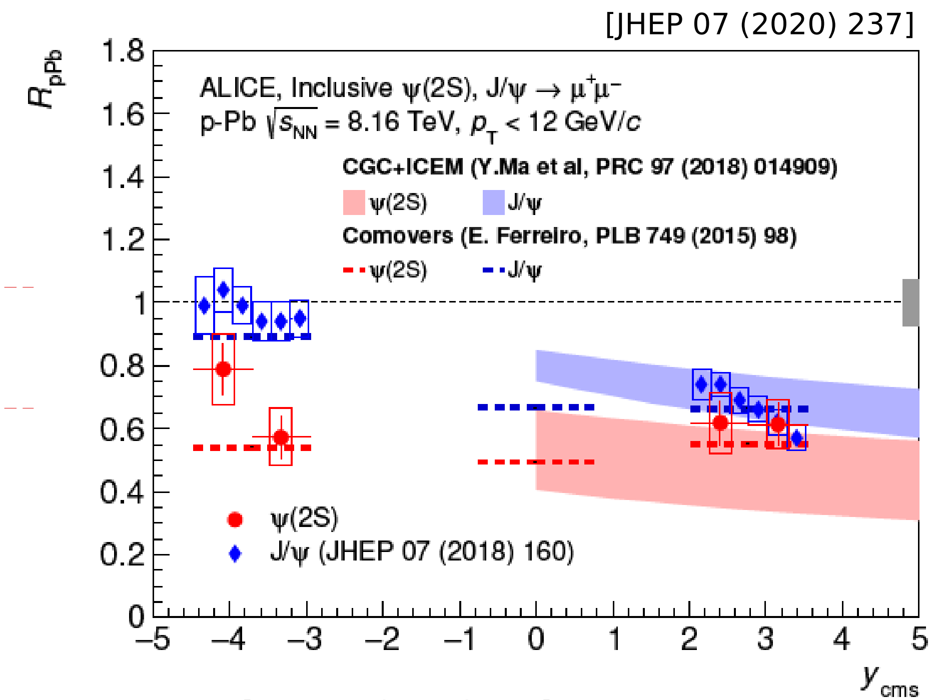
– Models implementing nPDF modifications are able to describe qualitatively the trend at low $p_T$

– Model including coherent energy loss also catches the deplation at low $p_T$ at midrapidity

  – larger uncertainties when combined with EPS09NLO nPDFs

# J/ψ and ψ(2S) nuclear modification factor

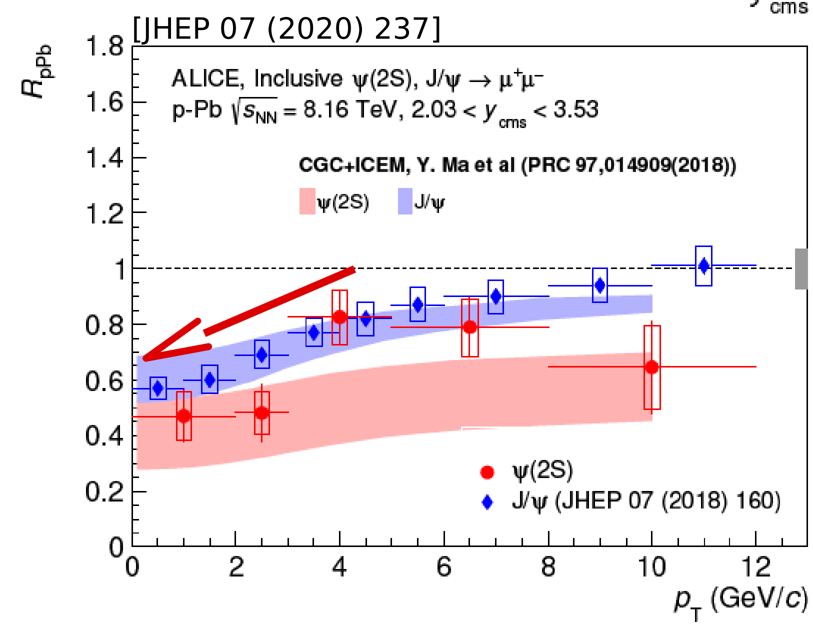



– larger Ψ(2S) nuclear suppression w.r.t. J/Ψ at backward rapidity

– Calculations implementing initial state CNM effects (CGC or nPDF modifications) and coherent energy loss do not distinguish between charmonium states

– they are able to describe rapidity dependence of RpPb of J/Ψ but fail for Ψ(2S)!



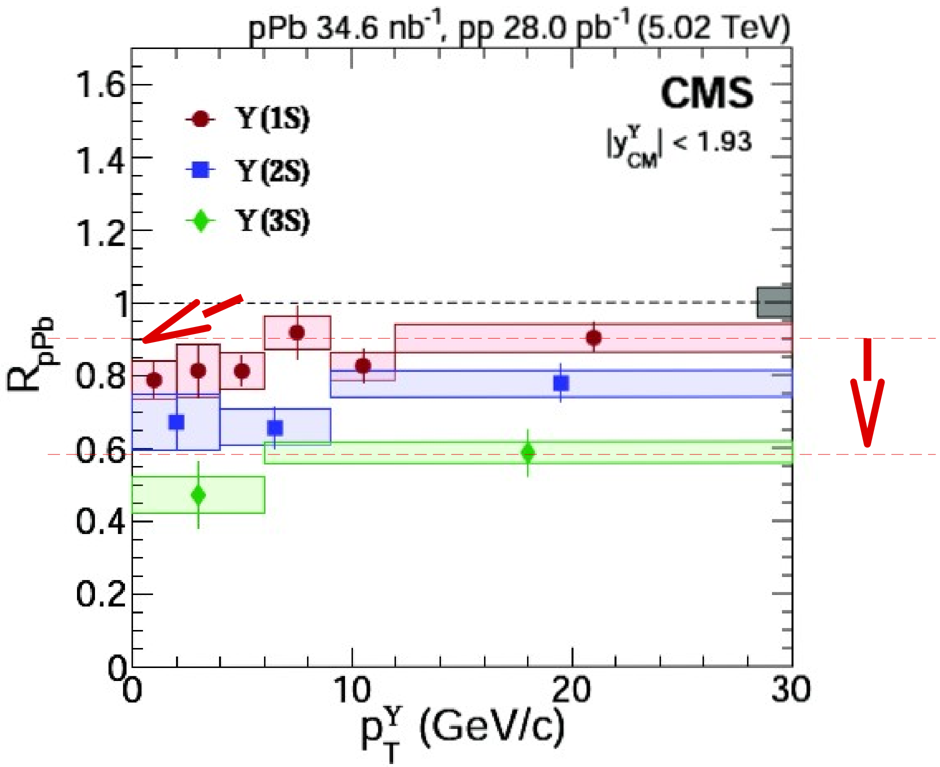

– Ψ(2S) suppression described by models which implement further **interactions in the final state**:

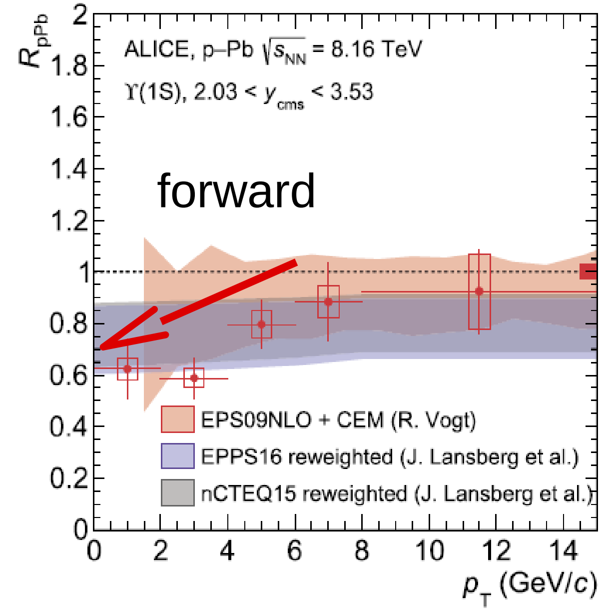
– soft color exhanges during the cc hadronization

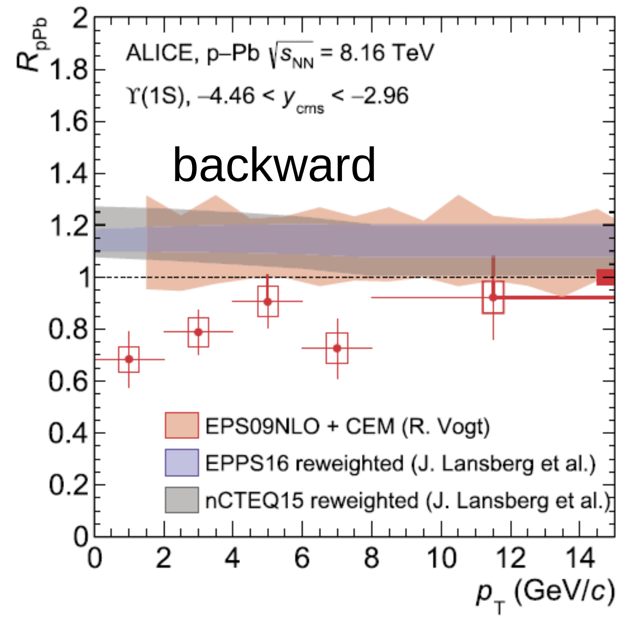
– interaction with comovers

# Υ(nS) production in p-Pb

[arXiv:2202.11807]



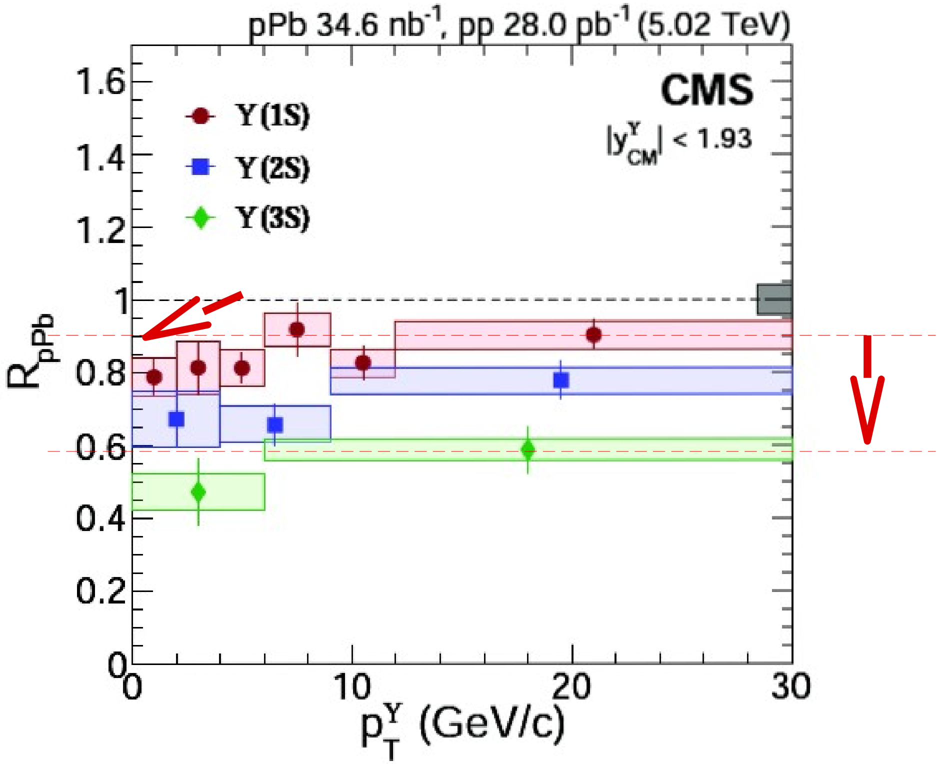



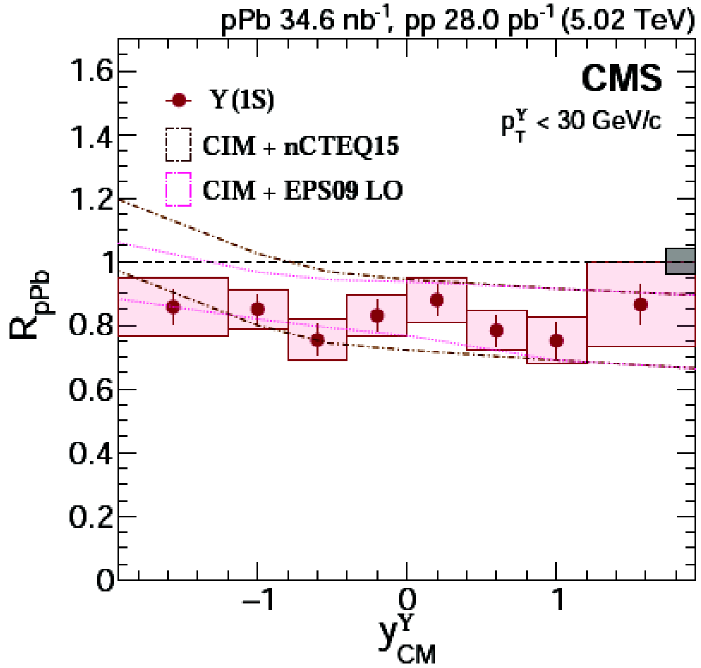

– sequential suppression observed for Υ(nS) states also at midrapidity by CMS

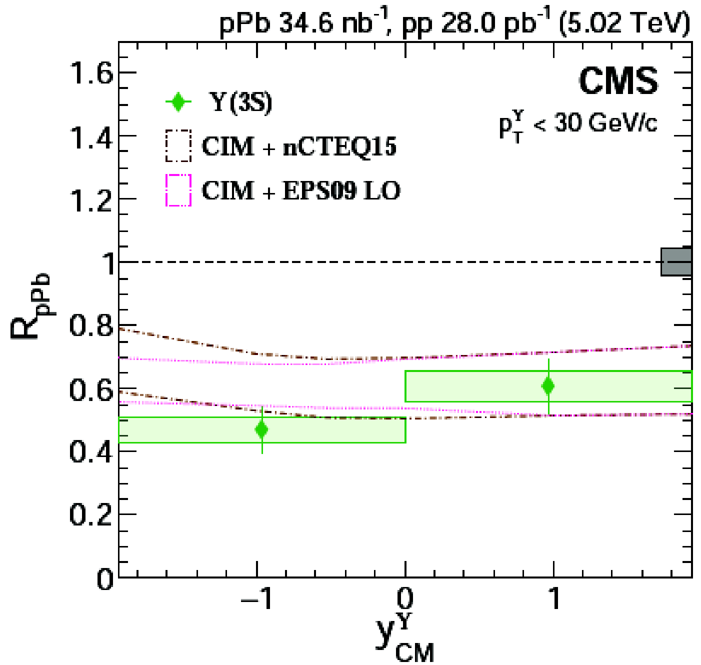
– coherent energy loss catches forward rapidity when EPS09 nuclear shadowing is considered, but fail at backward-y

# Υ(nS) production in p-Pb

[arXiv:2202.11807]




– sequential suppression observed for Υ(nS) states also at midrapidity by CMS

– coherent energy loss catches forward rapidity when EPS09 nuclear shadowing is considered, but fail at backward-y

– in general good agreement with comover model

# Quarkonia in p-Pb collisions

## Cold Nuclear Matter (CNM) effects

$$R_{\mathrm{pA}}(y, p_{\mathrm{T}}) = \frac{1}{A}\frac{\mathrm{d}^2\sigma_{\mathrm{pA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}$$

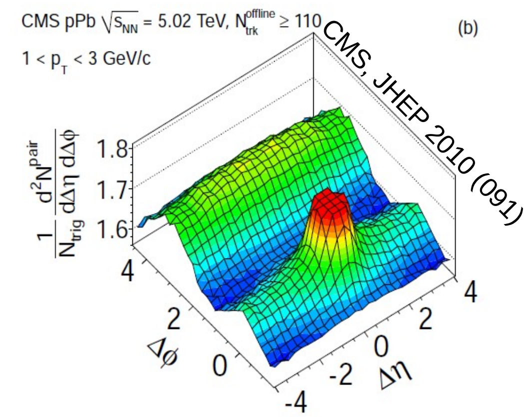
$\mathrm{d}^2\sigma_{\mathrm{pA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}$: cross section in pA

$\mathrm{d}^2\sigma_{\mathrm{pp}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}$: cross section in pp

$A$: cross section in pp

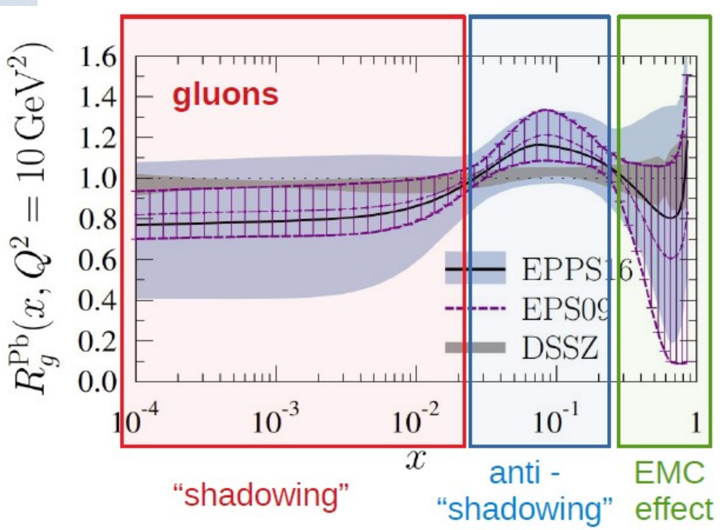
## Search for collectivity in small systems

- ✔ Open questions: QGP formation in small systems ? Collectivity ?



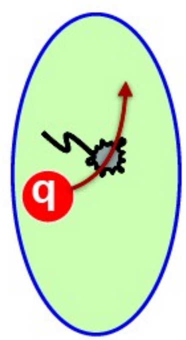

### nPDF modification

Eskola et al., EPJC77 (2017) 163




### Coherent energy loss

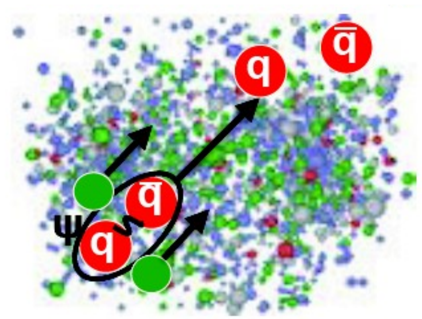
F. Arleo, S. Peigne', JHEP 03 (2013) 122.




**Nuclear medium**

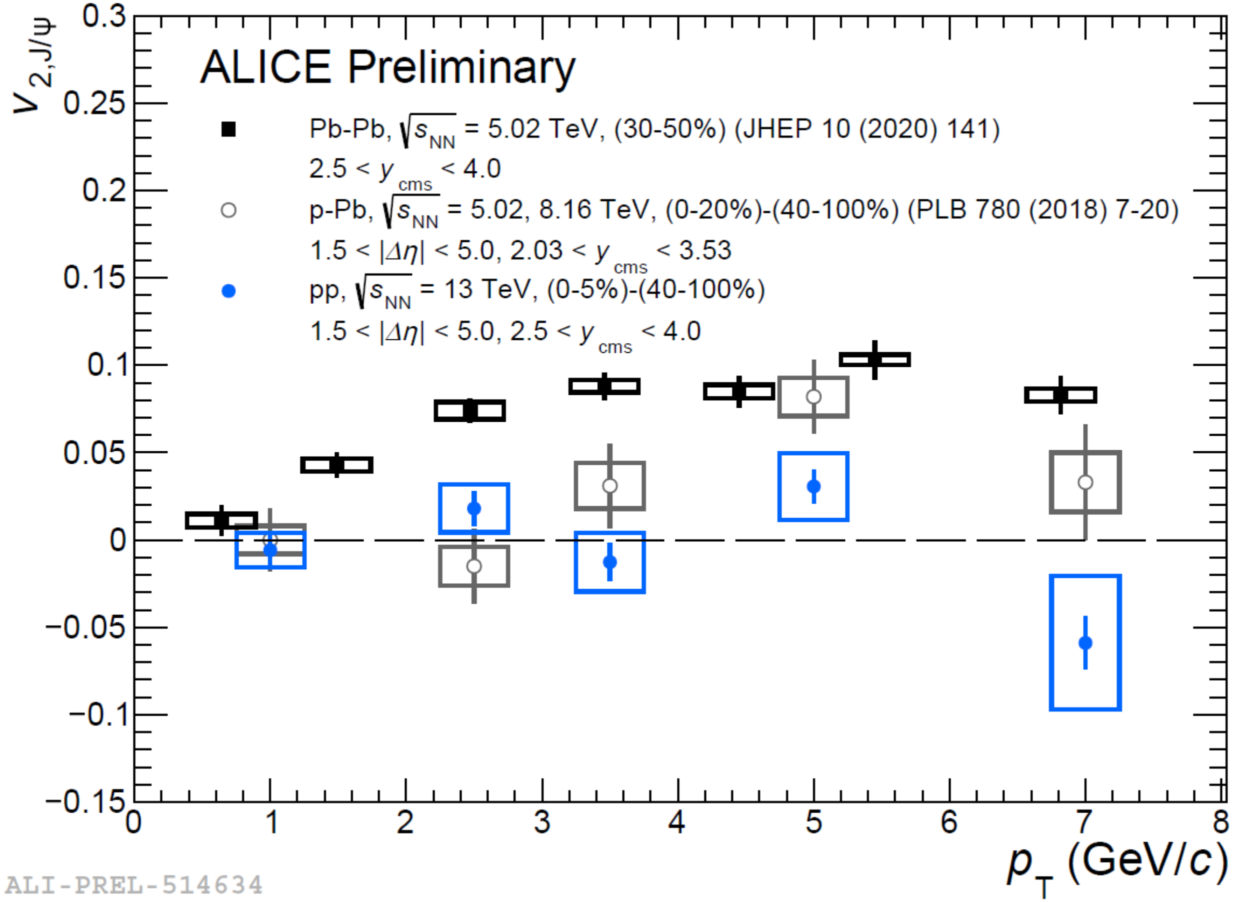
### Dissociation with comovers

E. G. Ferreiro, PLB 731 (2014) 57
E. G. Ferreiro and J. P. Lansberg, JHEP 1810 (2018) 094




**Hadronic matter**

# J/ψ $v_2$ in small systems



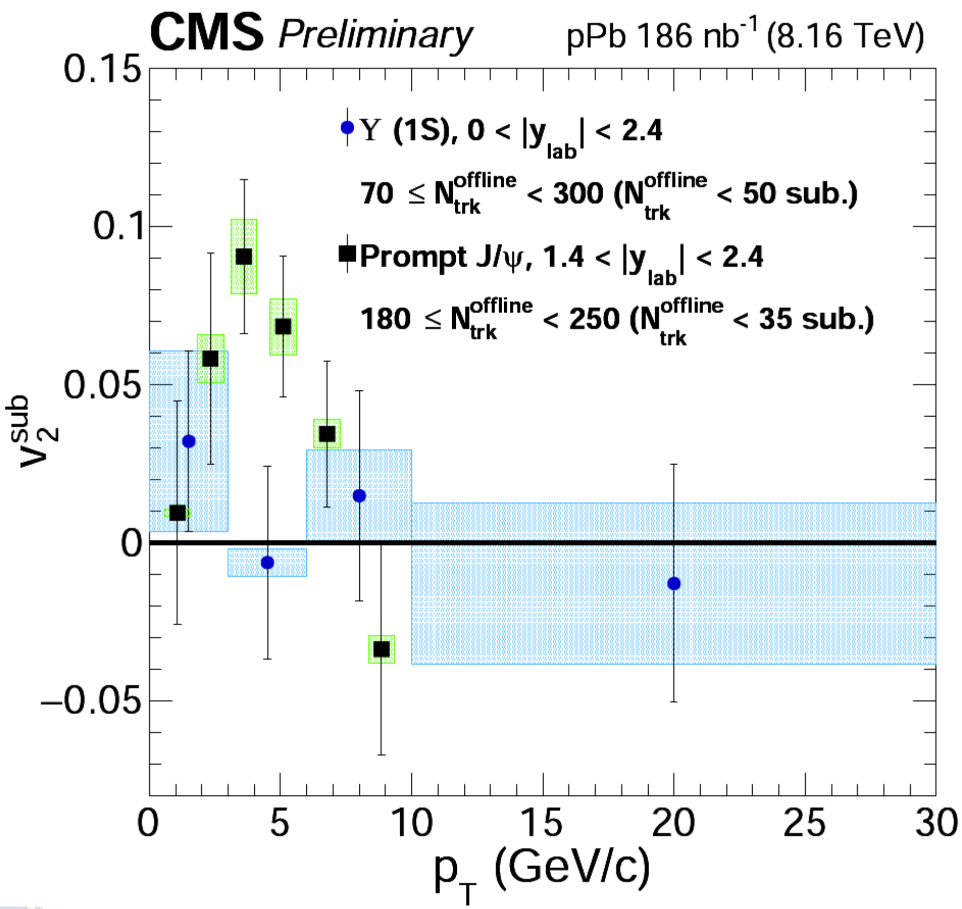

– collectivity observed in the light flavour sector → interest to look at heavy flavours

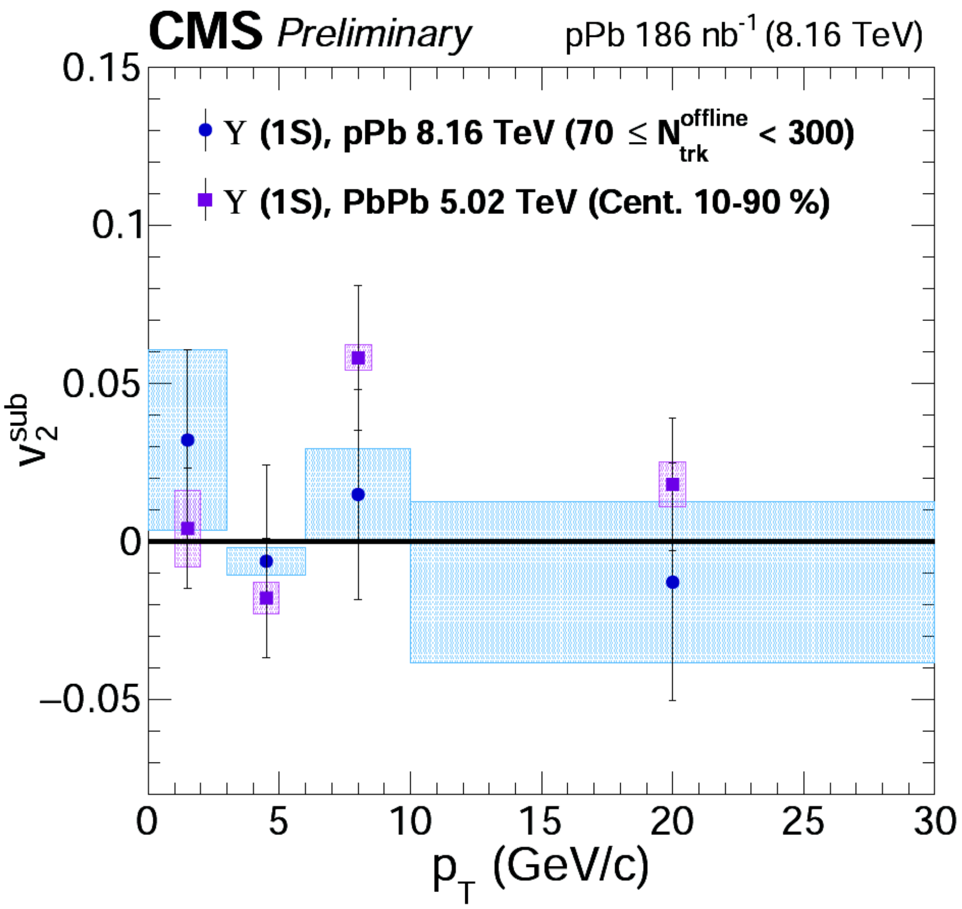
– J/psi v2 compatible with 0 in pp collisions, with no significant pT dependence

– Significant v2 at high-pT observed in p-Pb collisions, compatible with similar results in Pb-Pb → common mechanisms at play ?

# Υ(1S) $v_2$ in p-Pb collisions

[CMS-PAS-HIN-21-001]




– first measurement of Υ(1S) $v_2$ in p-Pb collisions

– compatible with zero on the full pT range, significantly different from J/ψ $v_2$

– compatible with Pb-Pb collisions, where it is found also to be zero

# Take-home notes: Quarkonia in p-Pb collisions

**Charmonia:**

- J/Ψ suppressed at low $p_T$; reproduced by models implementing nPDF modifications and coherent energy loss
- Ψ(2S) nuclear suppression described by models implementing further interactions in the final state, e.g. comovers
- Significant J/Ψ $v_2$ observed at high-$p_T$

**Bottomonia:**

- larger suppression observed for higher bottomonium states
- models implementing shadowing and / or coherent energy loss fail to predict $R_{pPb}$ at backward rapidity (also for the ground state)
- in general in good agreement with comovers model
- Υ(1S) $v_2$ compatible with zero within uncertainties, and with Pb-Pb measurements

# Take-home notes: Quarkonia in p-Pb collisions

**Charmonia:**

- J/Ψ suppressed at low $p_T$; reproduced by models implementing nPDF modifications and coherent energy loss
- Ψ(2S) nuclear suppression described by models implementing further interactions in the final state, e.g. comovers
- Significant J/Ψ $v_2$ observed at high-$p_T$

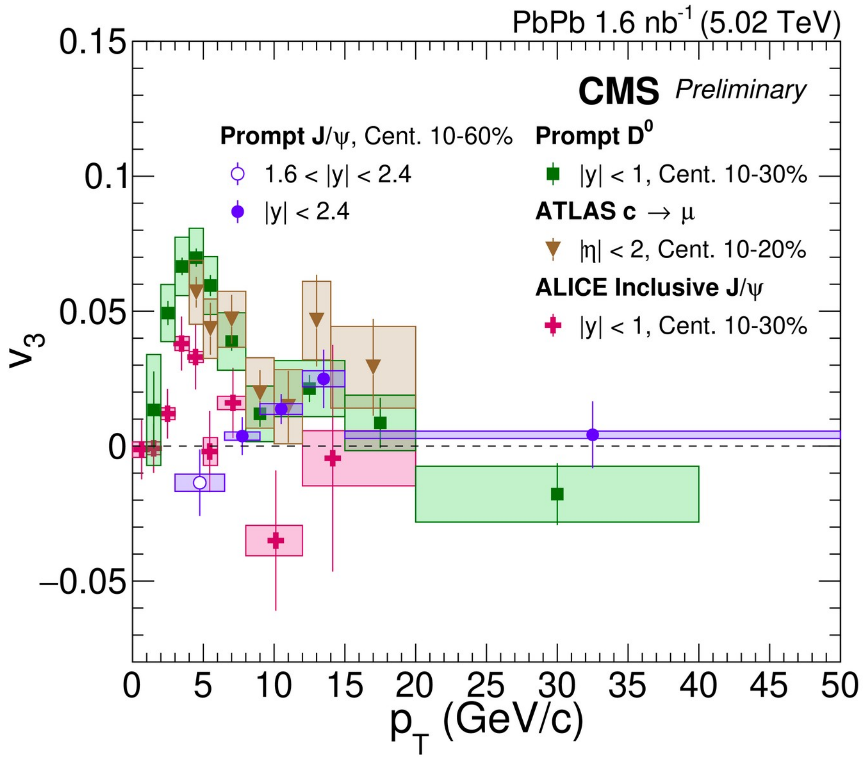
**Bottomonia:**

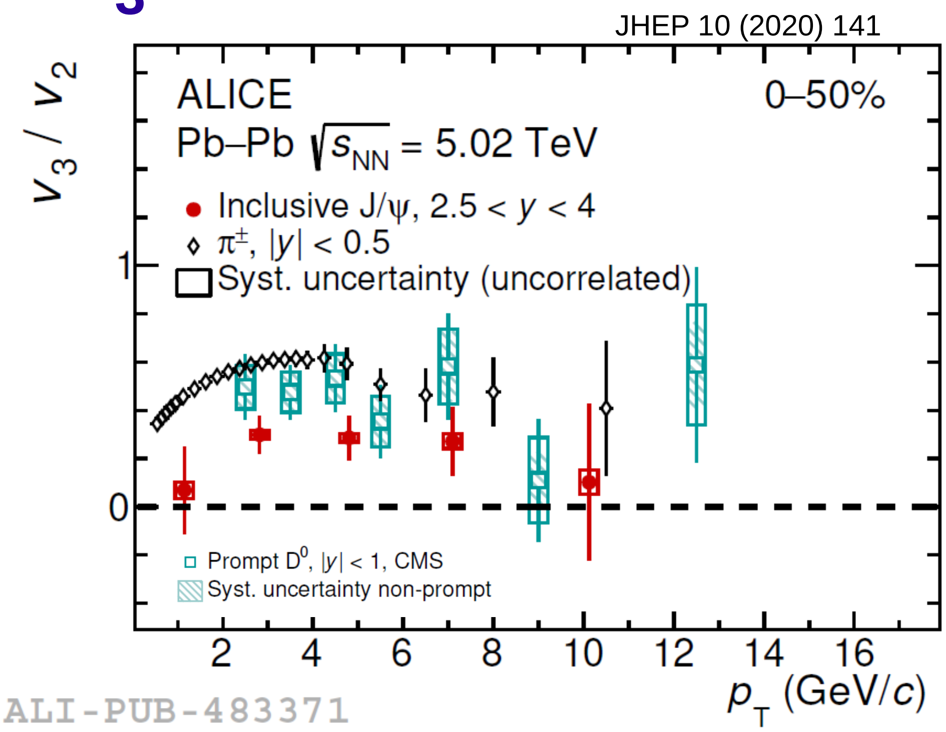
- larger suppression observed for higher bottomonium states
- models implementing shadowing and / or coherent energy loss fail to predict $R_{pPb}$ at backward rapidity (also for the ground state)
- in general in good agreement with comovers model
- Υ(1S) $v_2$ compatible with zero within uncertainties, and with Pb-Pb measurements

**Takk !**

# BACK-UP

# J/ψ $v_3$




– Significant J/ψ $v_3$ observed at low $p_T$

– Similar hierarchy observed for $v_3$ / $v_2$ → higher harmonics are damped faster for heavy quarks than for the light ones

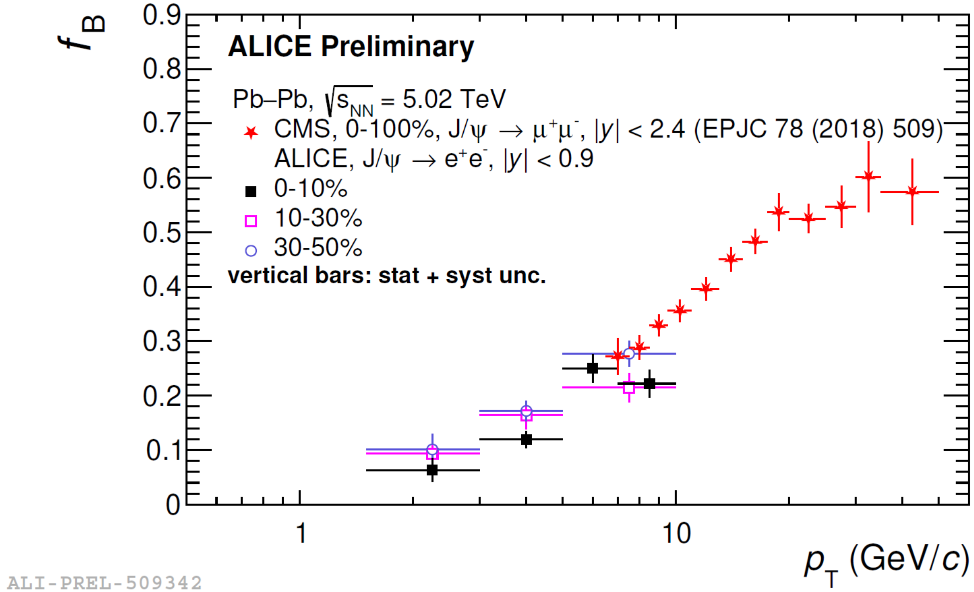
– Nearly species independent for light flavor particles

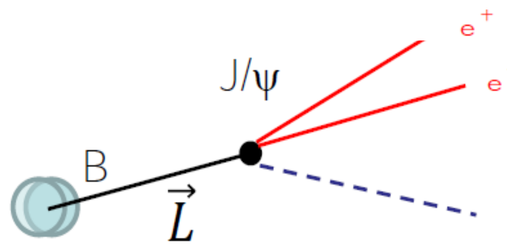
– Heavy-flavour hadrons (both J/ψ and D mesons) deviate from this expectation

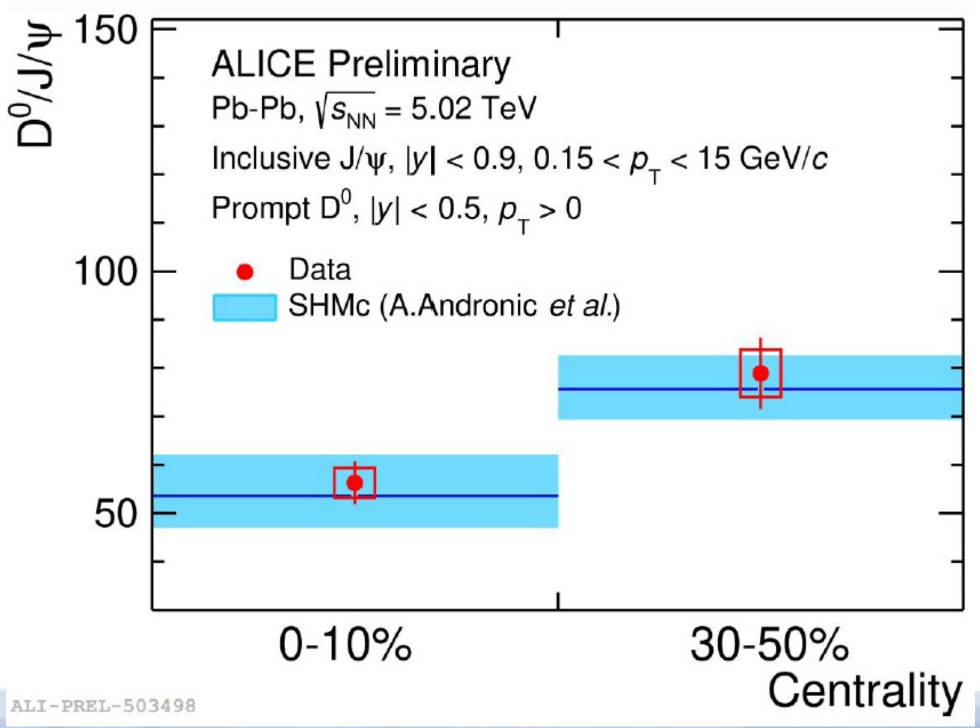
  – Less sensitivity to initial state fluctuations wrt light flavor species

  – Possible consequence of a late or incomplete charm thermalization

# Prompt J/ψ $R_{AA}$




– sensitive to hadronization mechanisms

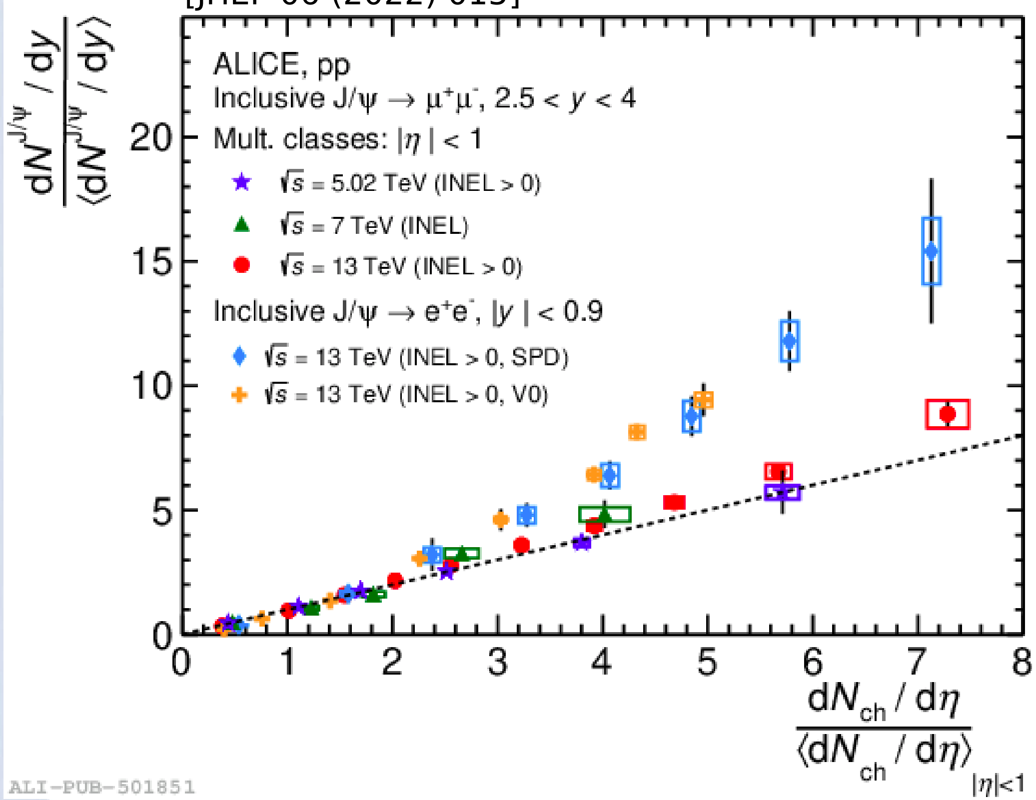
– common uncertainties cancel out in the ratio

– good agreement with SHMc predictions

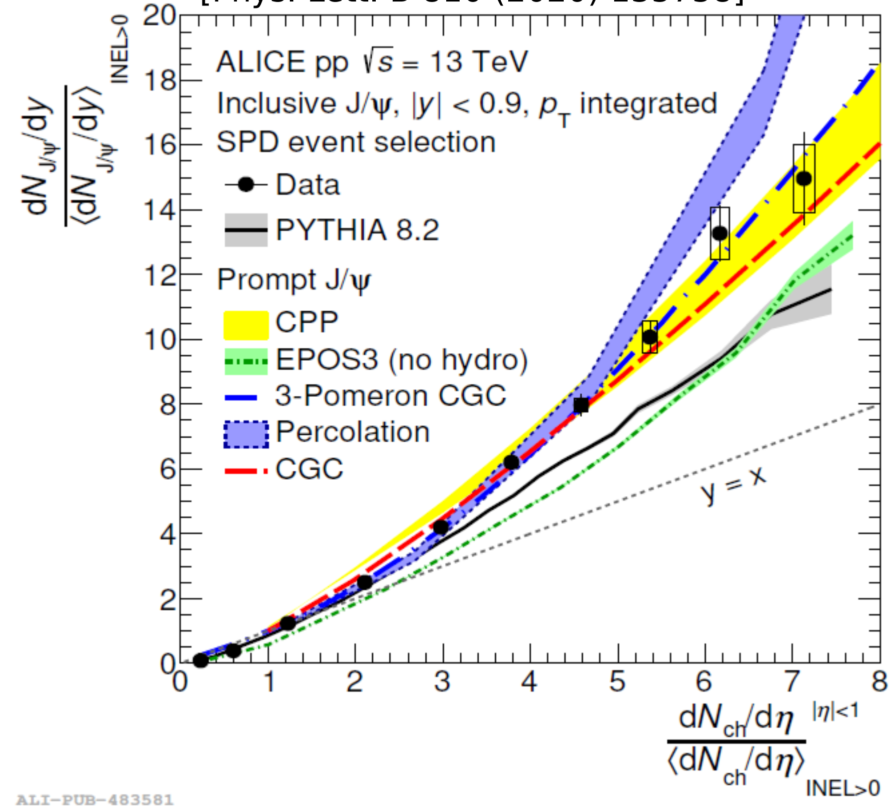
SHMc: A. Andronic et al., JHEP07 (2021) 035

# Quarkonia vs multiplicity in pp

[JHEP 06 (2022) 015]




[Phys. Lett. B 810 (2020) 135758]



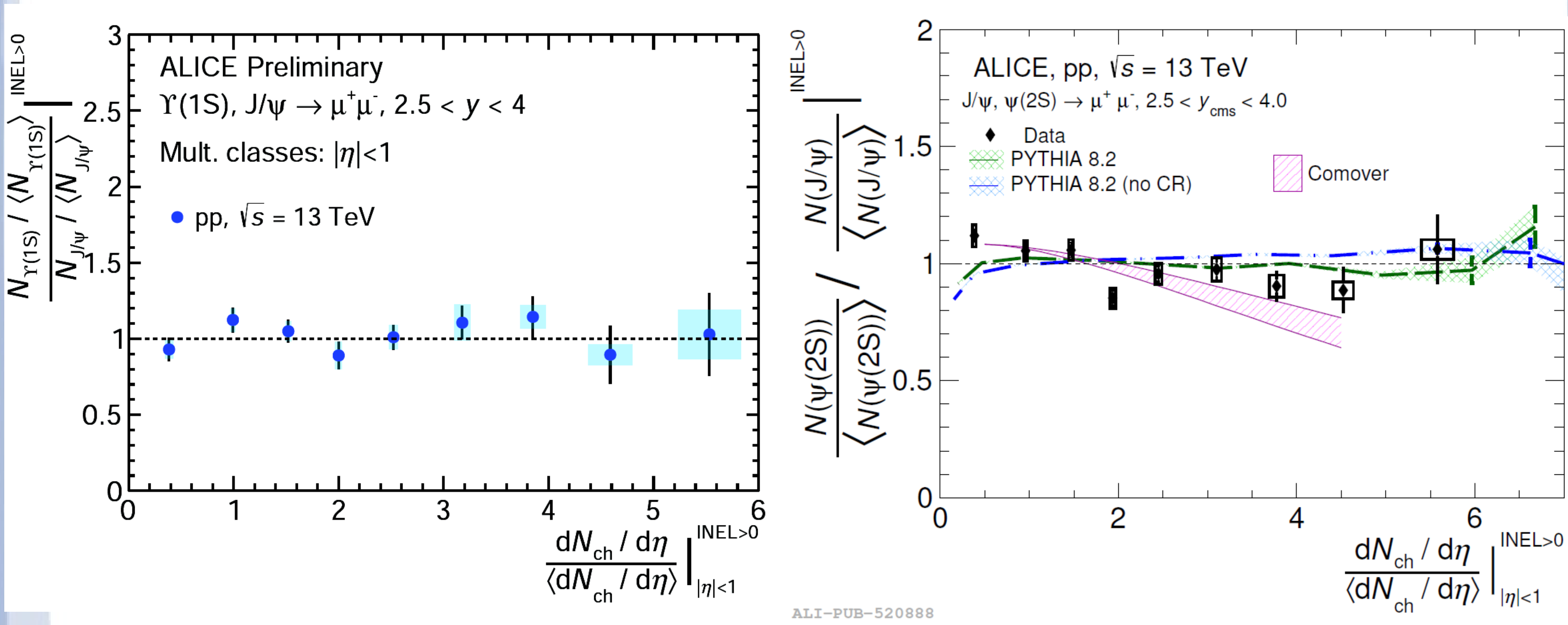

– Faster than linear increase at midrapidity, while self-normalized J/ψ yields at forward rapidity show a linear trend with multiplicity (multiplicity measured at midrapidity in both cases)

– Comparison with models at midrapidity:

  – CPP, CGC, and 3-Pomeron models in agreement within uncertainties

  – different mechanisms responsible for the faster than linear trend in the models

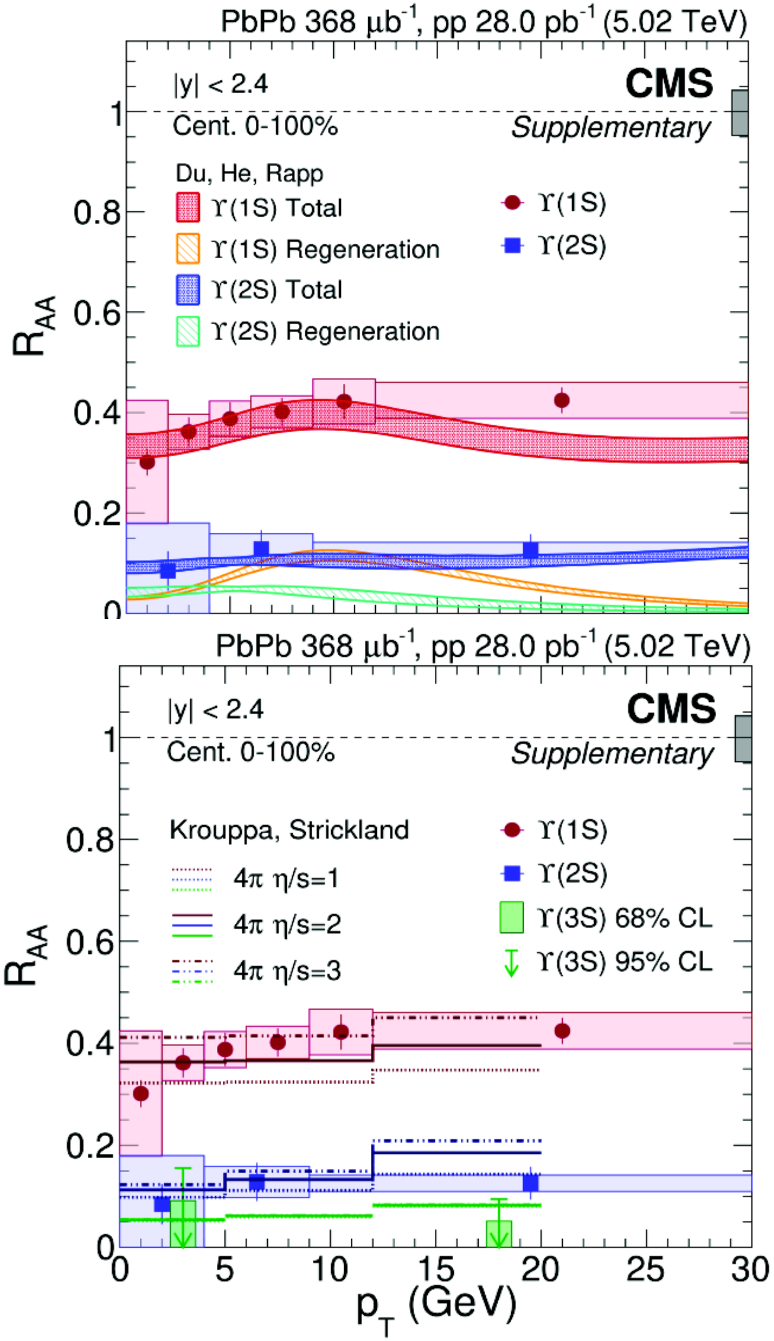
# Quarkonia vs multiplicity in pp

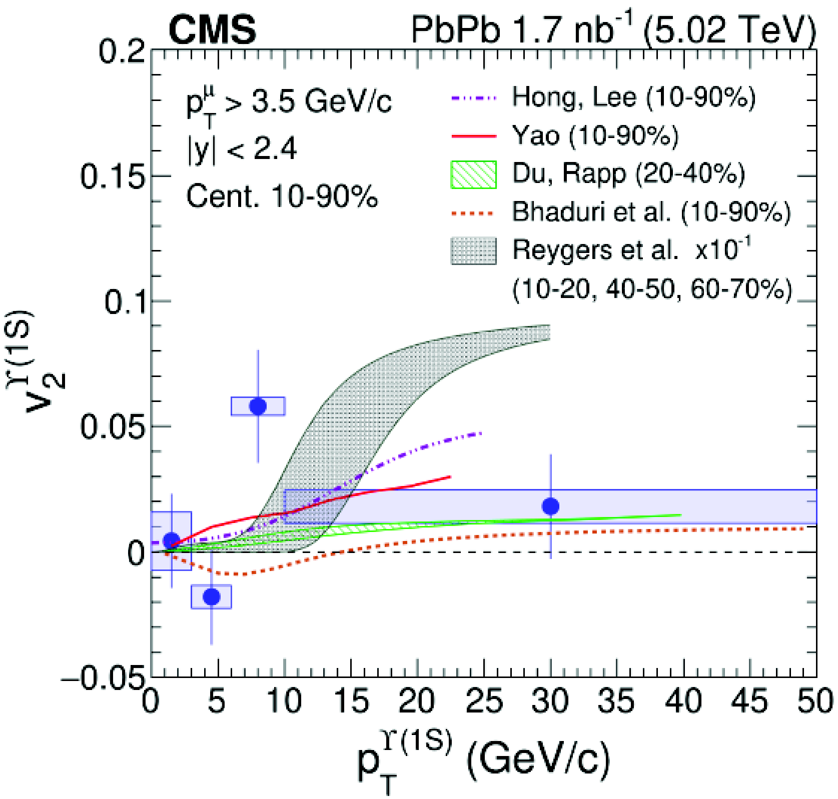



– Excited to ground state ratios show a flat trend as a function of multiplicity → point to a weak dependence on the hadronization

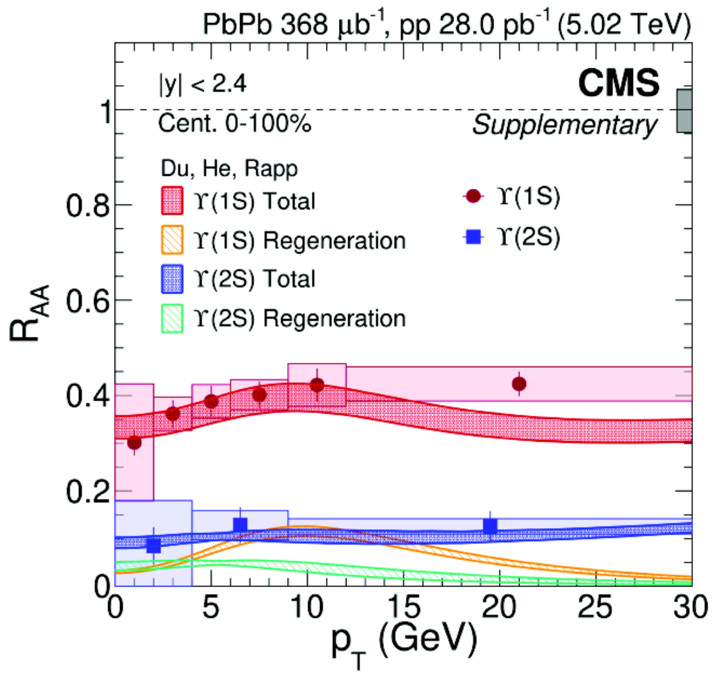
– Double ratios described by PYTHIA models, with and without color reconnections, at low multiplicity

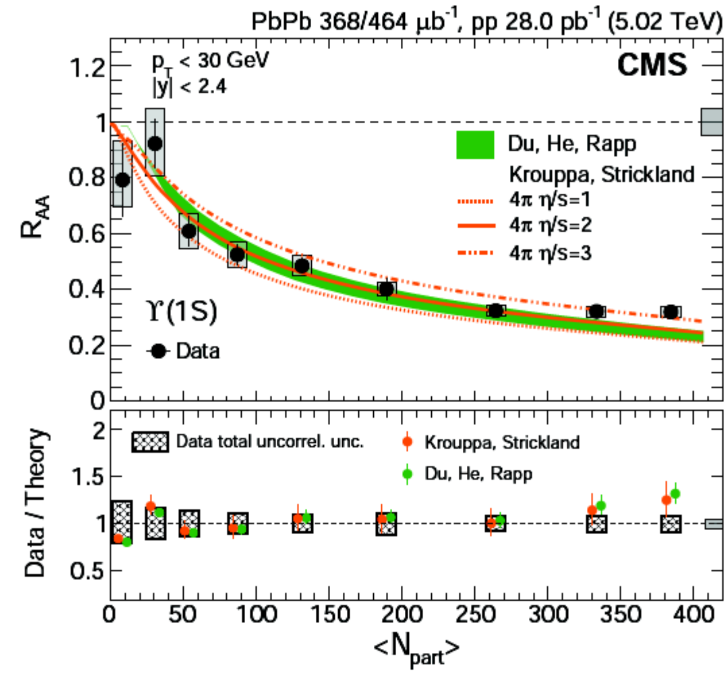
# Bottonomium $v_2$ / $R_{AA}$



# Bottonomium $R_{AA}$



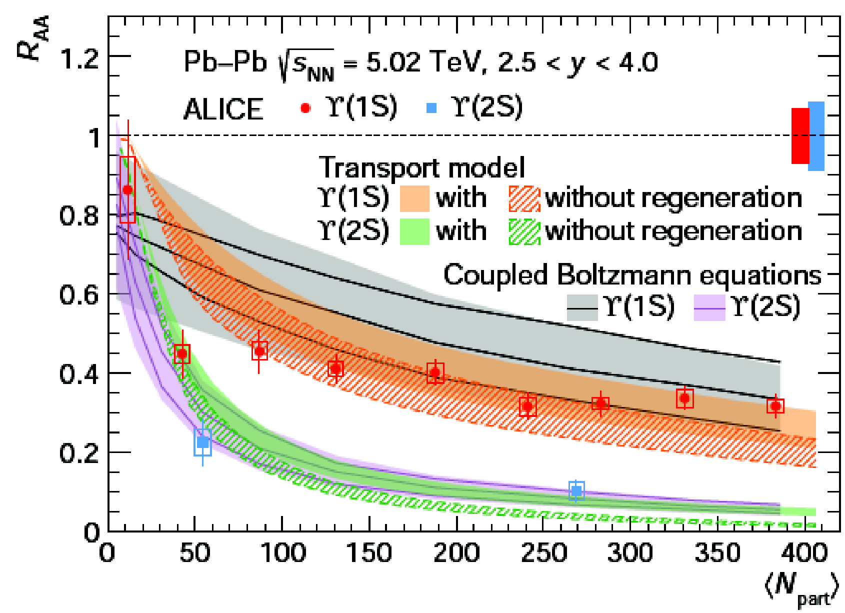




– Sequenzial suppression observed for ϒ(nS) states

– Models based on hydrodynami and transport models reproduce the trends of the data within uncertainties (both include color screening and feed-down from higher states):

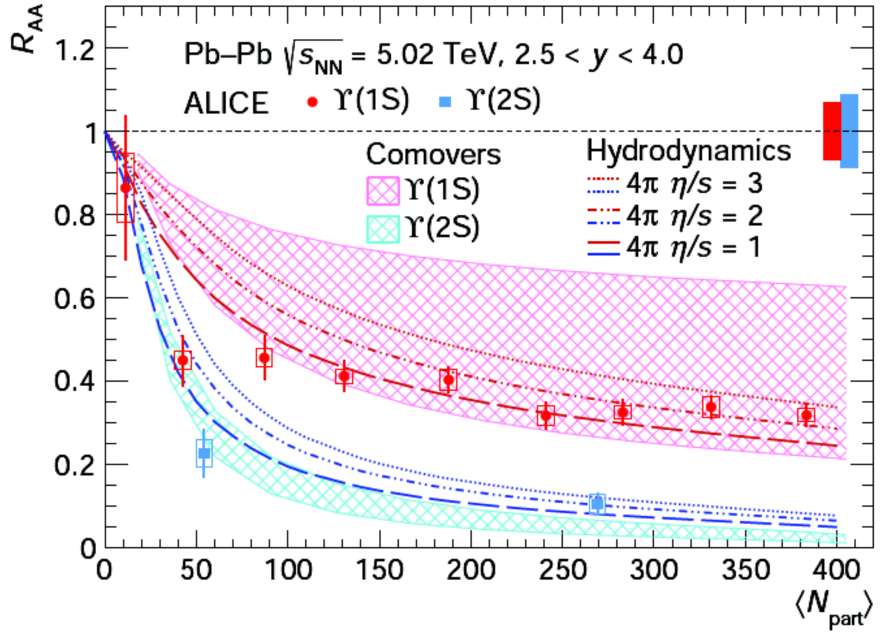
– hydro: thermal modification of a complex heavy-quark potential inside an anisotropic plasma → no modification of nuclear PDFs / no regeneration included

– transport models → interplay of dissociation and regeneration mechanisms regulating → moderate contribution from regeneration

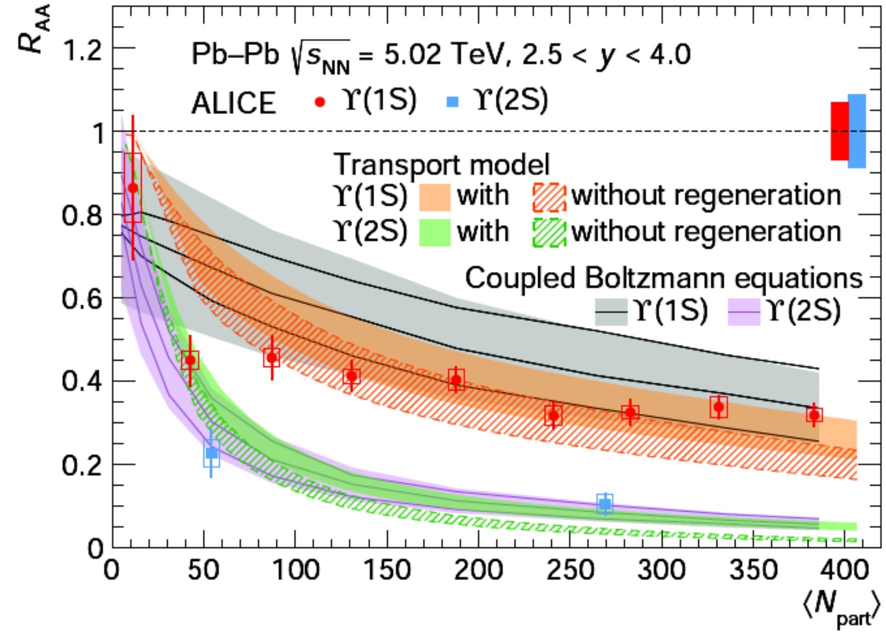


# Bottonomium $R_{AA}$

[Phys.Lett.B 822 (2021) 136579]




[Phys.Lett.B 822 (2021) 136579]




– Comparison of **Υ(2S)-to-Υ(1S) double ratio** with models:

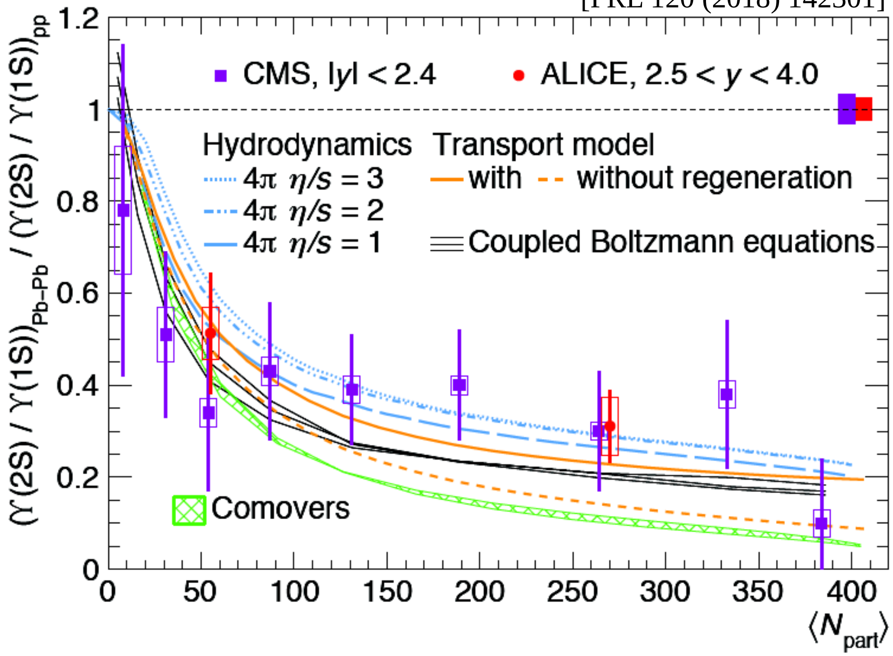
– tension observed with comovers

– hydro calculations describe the data within uncertainties

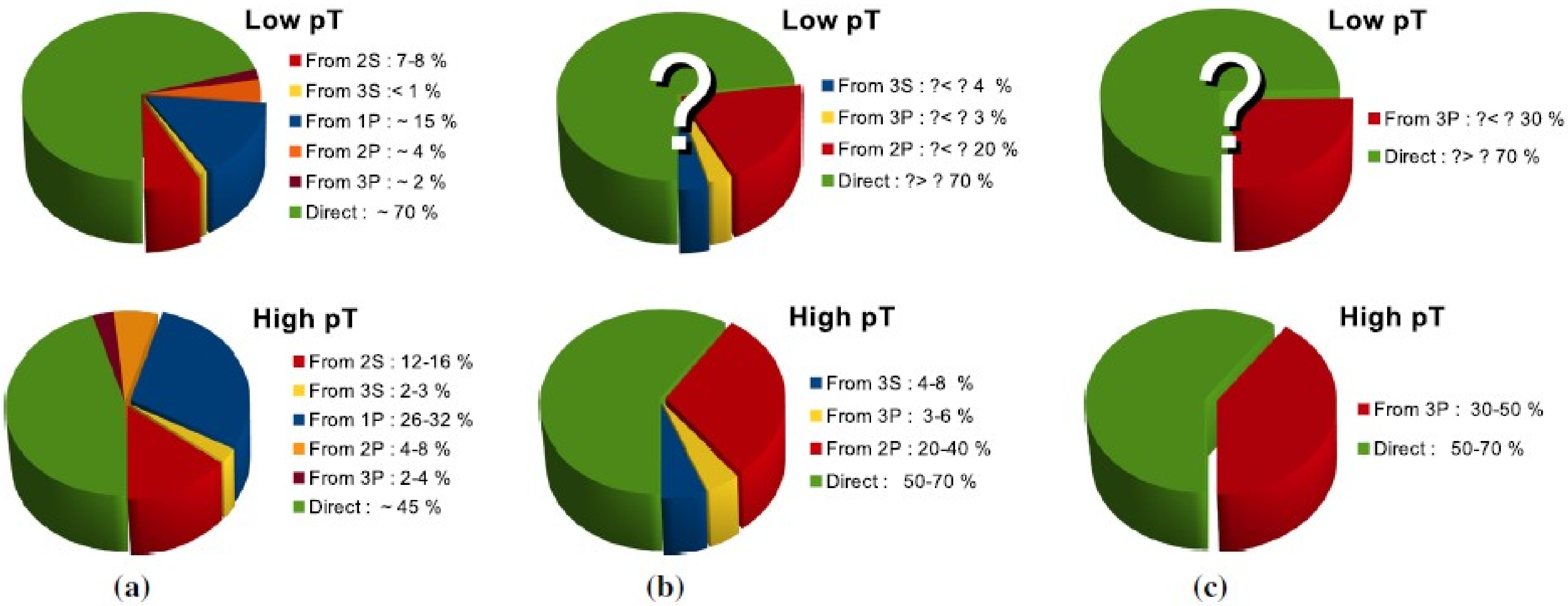
– transport model with regeneration component included in better agreement

→ with more precise measurements could serve as a model discriminator

[PRL 120 (2018) 142301]



# Bottomonium feed-down fractions at the LHC

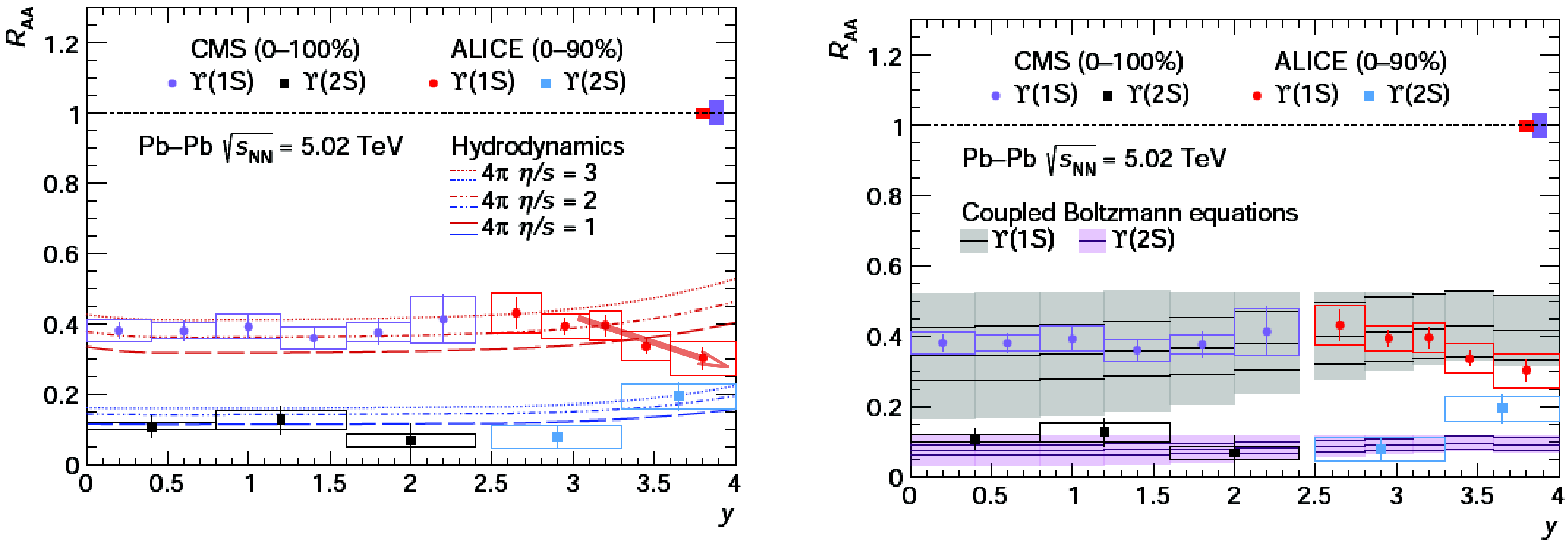





A. Andronic, et al., Eur. Phys. J. C 76(3) (2016) 107, arXiv:1506 .03981[nucl -ex].

# Bottonomium $R_{AA}$

[Phys.Lett.B 822 (2021) 136579]



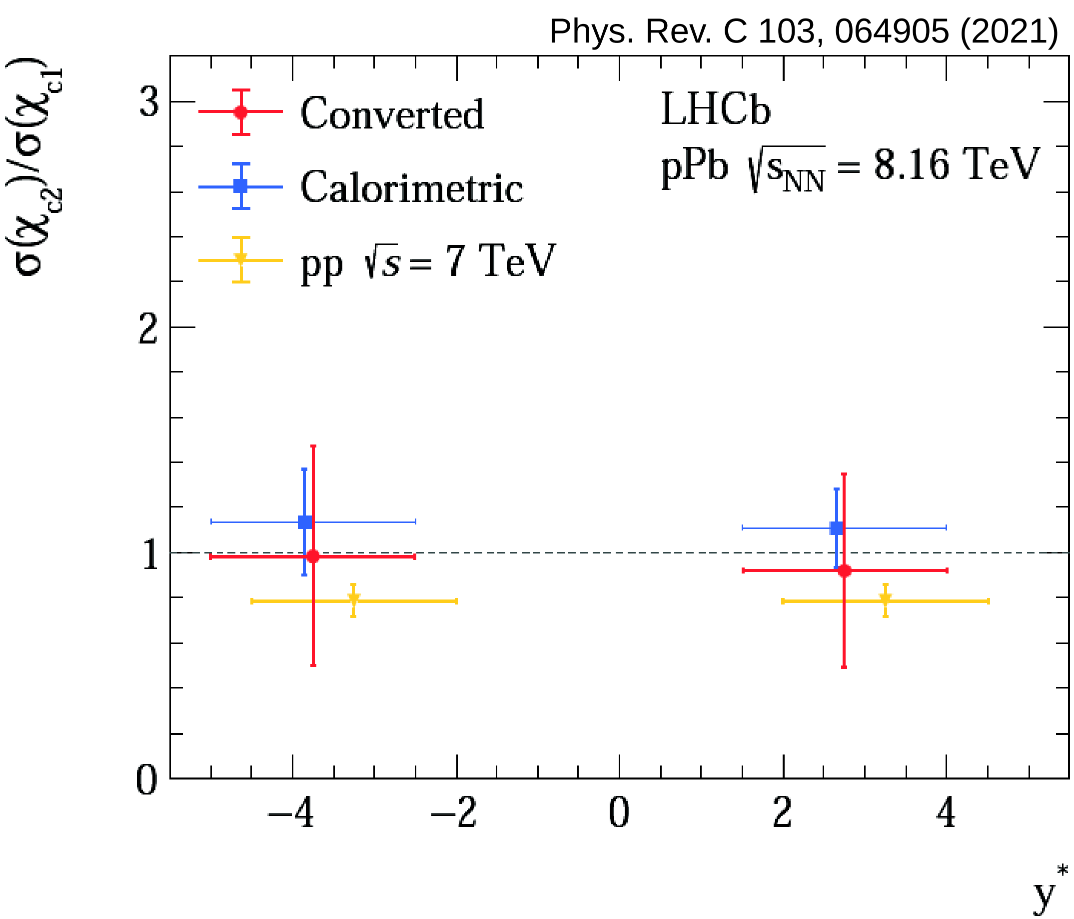

– Constant $R_{AA}$ for ϒ(2S) as a function of rapidity in agreement with models within large uncertainties

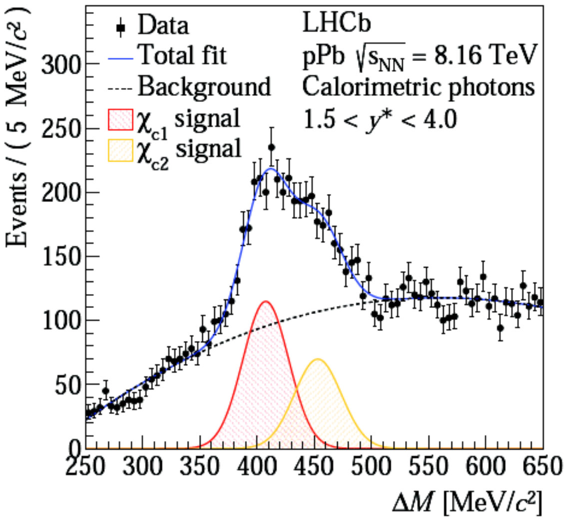
– Flat $R_{AA}$ as a function of rapidity for ϒ(1S) with a dropping from ~0.4 to ~0.3 at forward rapidity

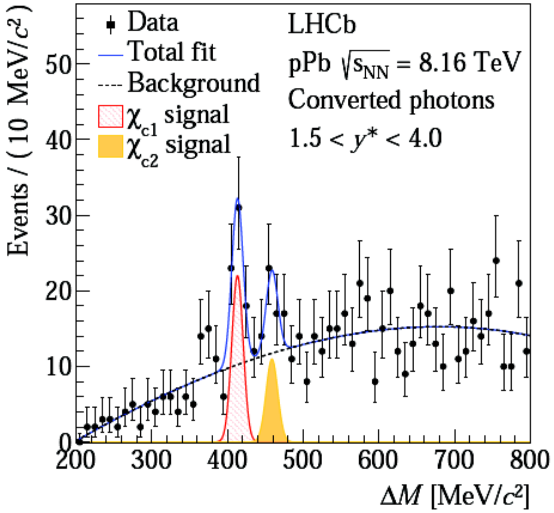
– not reproduced by hydrodynamics (opposite trend) and Coupled Boltzmann equations

→ **could point to missing mechanism in available models**

# $\chi_c$ production in p-Pb



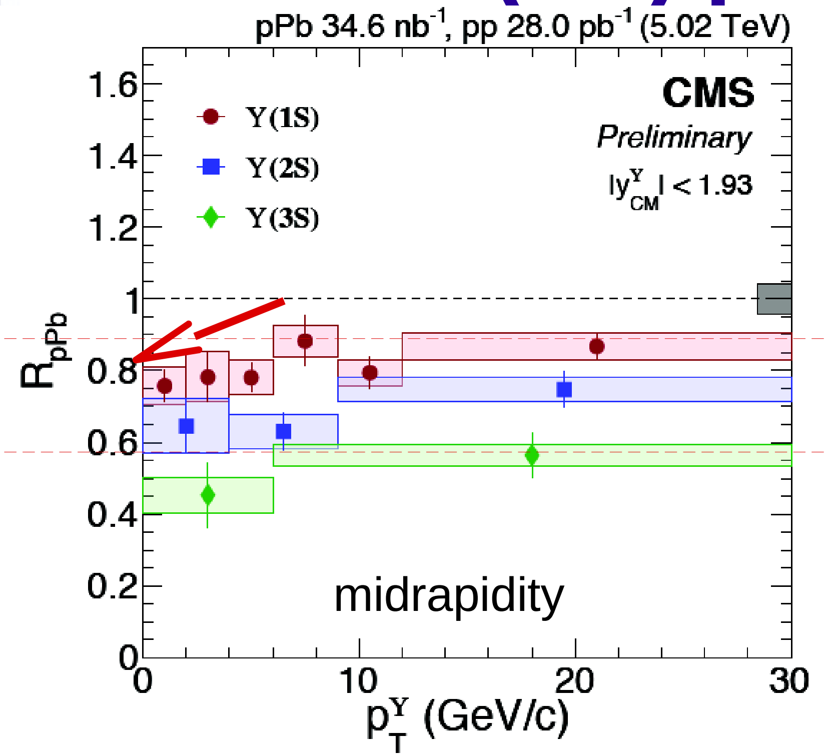



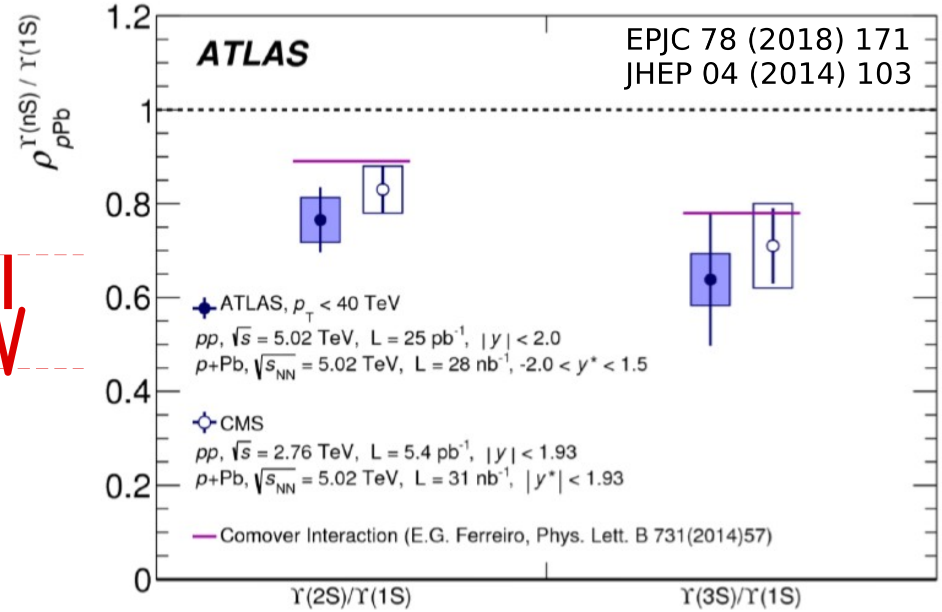




– Prompt $\sigma_{\chi c1}/\sigma_{\chi c2}$ ratio in pPb collisions sensitive to final state effects (similar binding energies for $\chi_{c1}$ and $\chi_{c2}$)

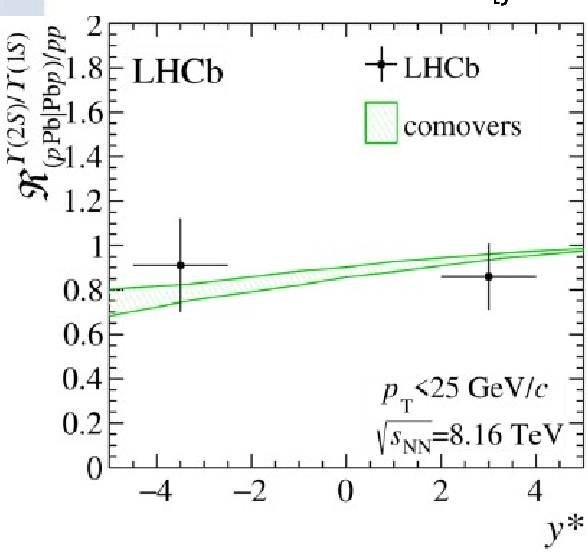
– consistent with unity and pp within uncertainties at bit forward and mid rapidity → similar CNM effects for the two states

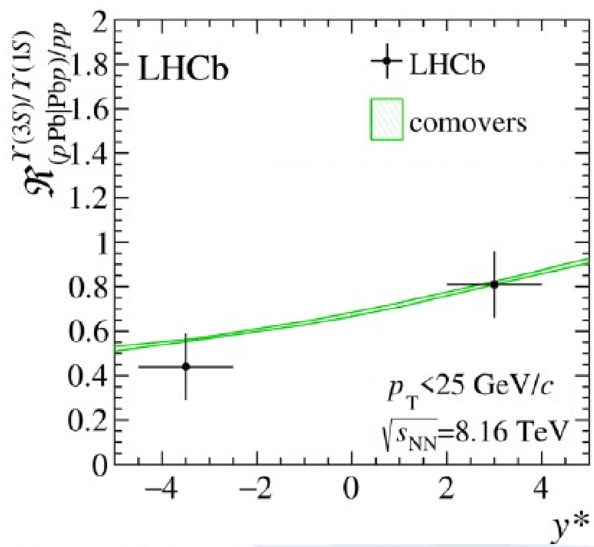
# Υ(nS) production in p-Pb




[JHEP 11 (2018) 194]



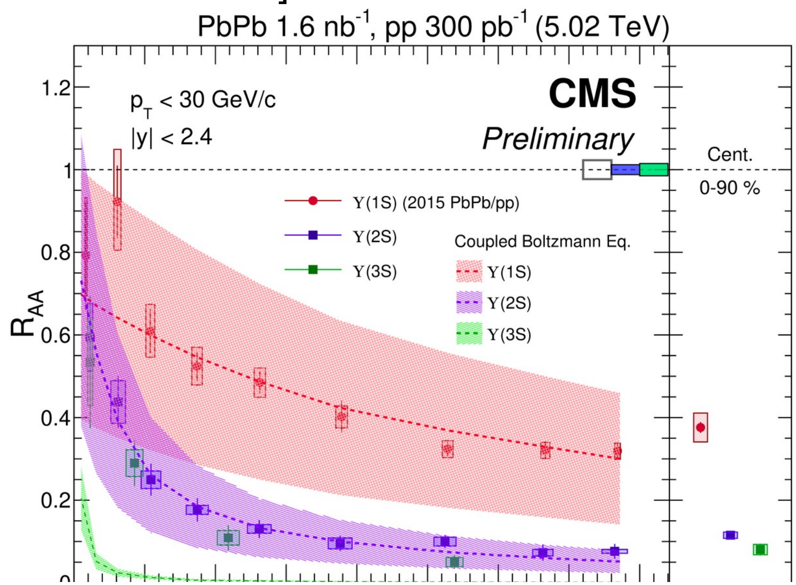



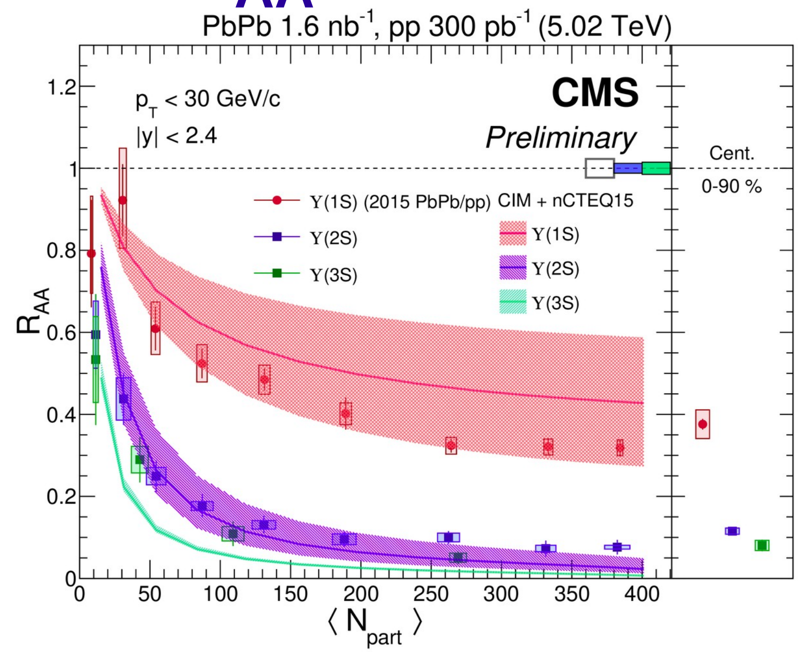

– sequential suppression observed for Υ(nS) states also at midrapidity by CMS

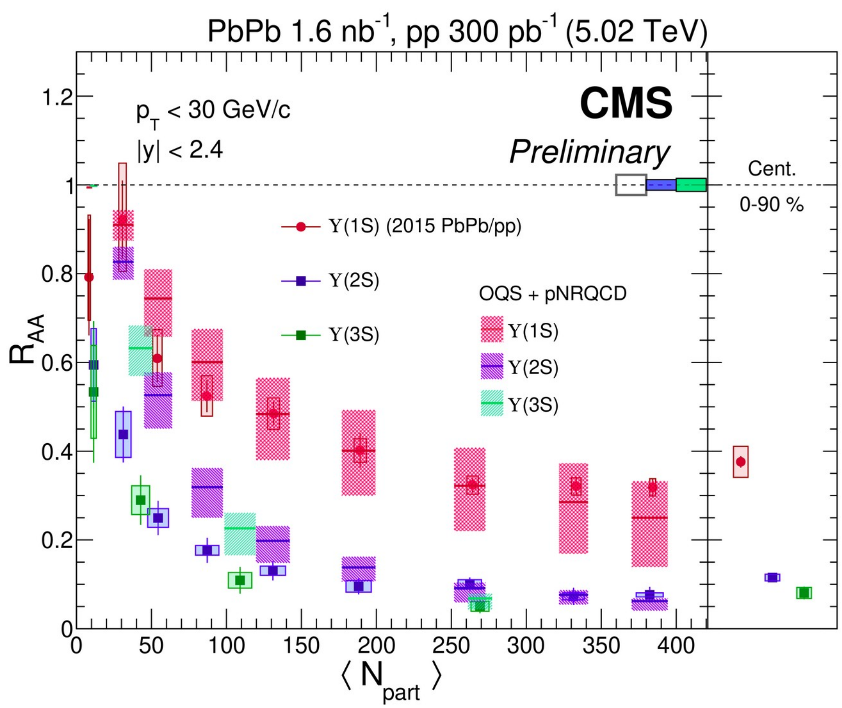
– in general good agreement with comover model

# Bottomonium $R_{AA}$

[CMS-PAS-HIN-21-007]




– **Coupled Boltzmann Eq.** and **CIM + nCTEQ15** models reproduce the trends of the Υ(1S) and Υ(2S) RAA within uncertainties

– tensions observed for Υ(3S)




Coupled Boltzmann Eq.: X. Yao et al., JHEP 01 (2021) 046, arXiv:2004.06746.
Comover Interaction Model (+nCTEQ15): E. Ferreiro, J.-P. Lansberg, JHEP 10 (2018) 094, arxiv:1804.04474
OQS + pNRQCD: N. Brambilla et al., PRD 104 (2021) 094049, arXiv:2107.06222