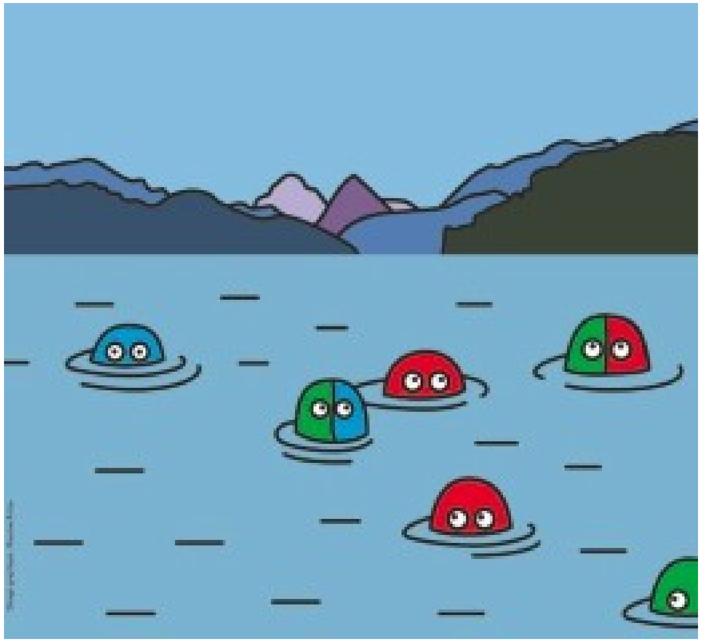
Review on charmonia in medium at the LHC



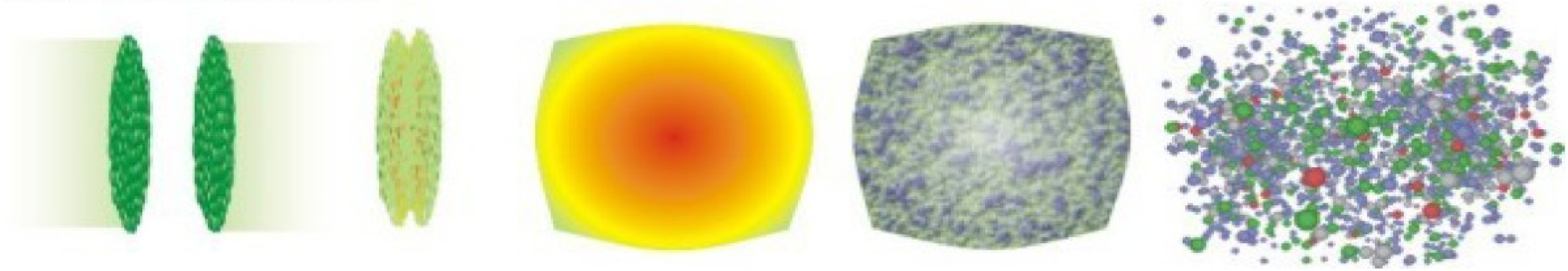
F. Fionda
University & INFN, Cagliari

Heavy Flavours from small to large system
Oct. 17th-21th, 2022 – Institut Pascal, Orsay (France)

Charmonia in (UR) Heavy Ion collisions

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

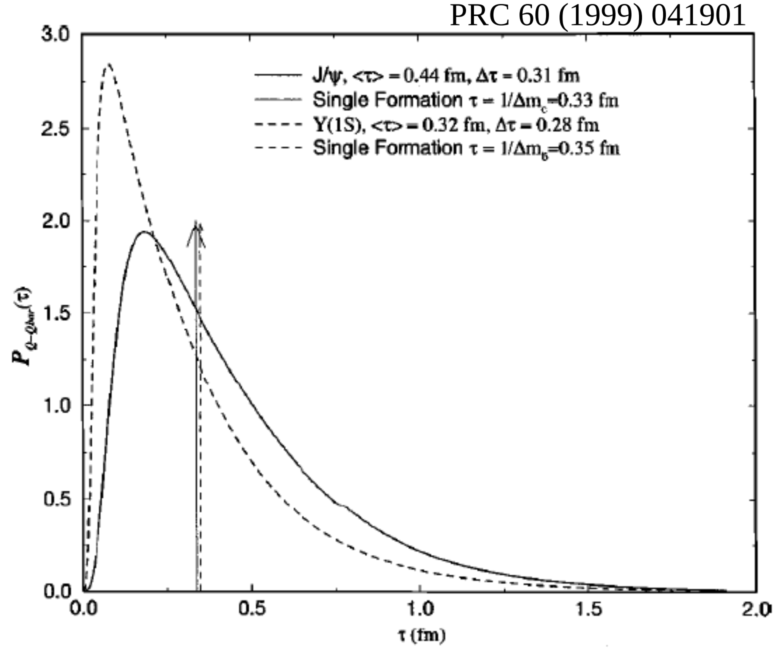
Image: S.A.Bass (Duke Univ.)



Charmonia as **probe of QGP**:

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

PRC 60 (1999) 041901



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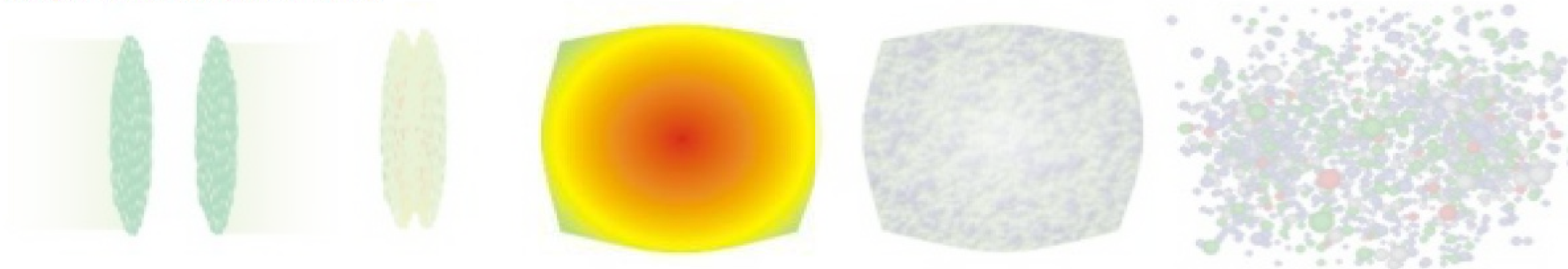
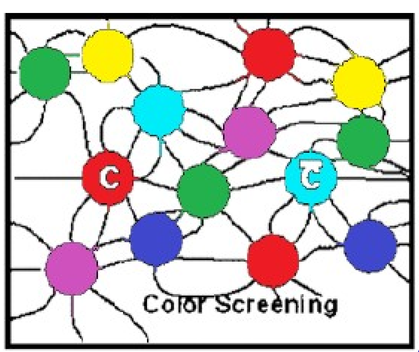


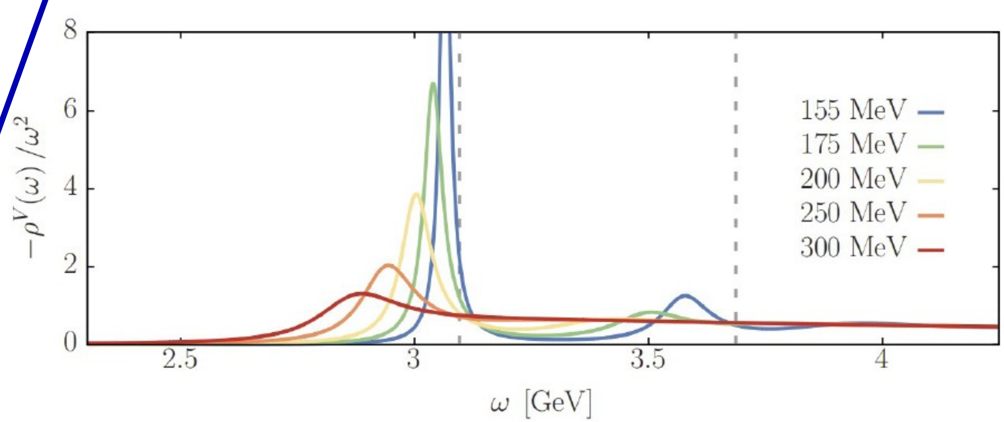
Matui & Satz, Phys.Lett. B178 (1986) 416-422

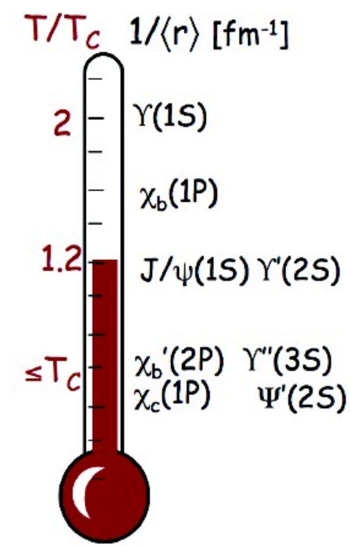
Color Debye screening



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

Quarkonia described in terms of spectral functions modified in a deconfined medium using lattice QCD calculations





[EPJC 61 (2009) 705]

→ **Sequential dissociation**

Charmonia in (UR) Heavy Ion collisions

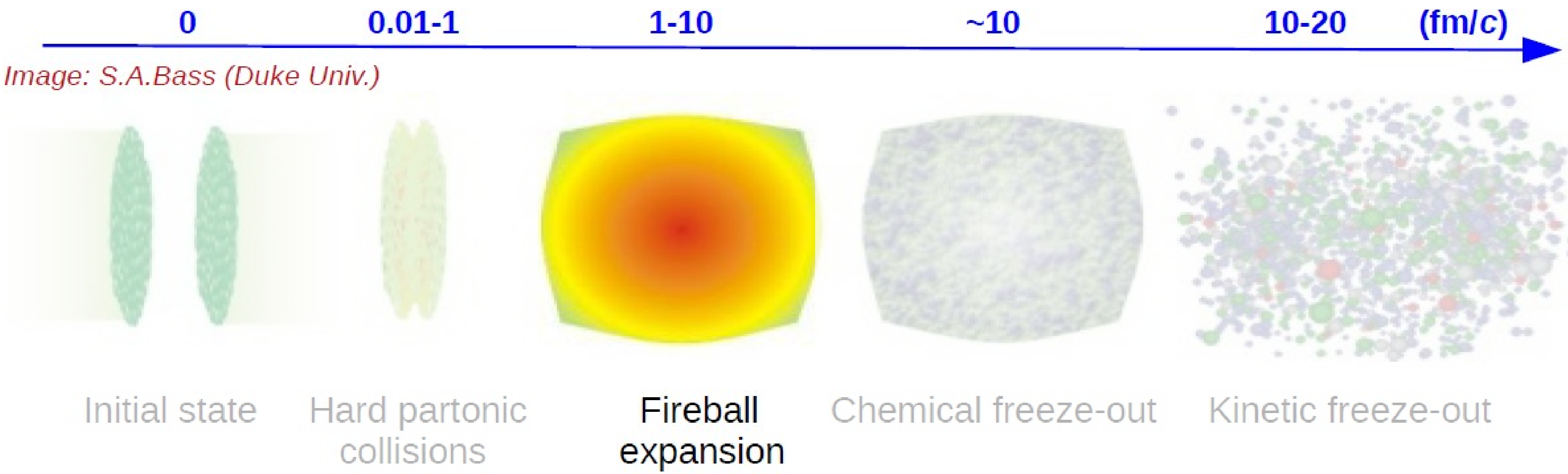
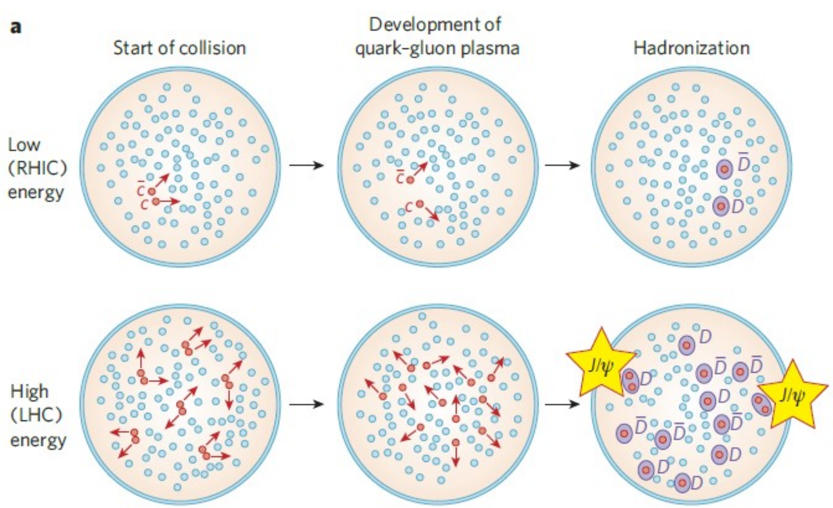


Image: S.A.Bass (Duke Univ.)

Regeneration of charmonia

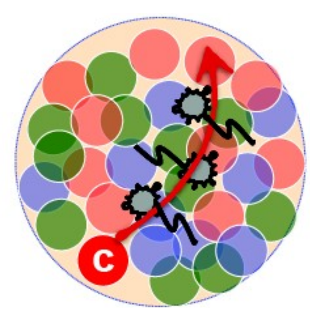
Braun-Munzinger and Stachel, PLB 490 (2000) 196
Thews et al., PRC 63 (2001) 054905



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

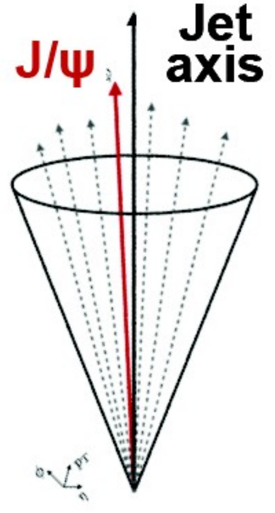


Production

Nuclear modification factor:

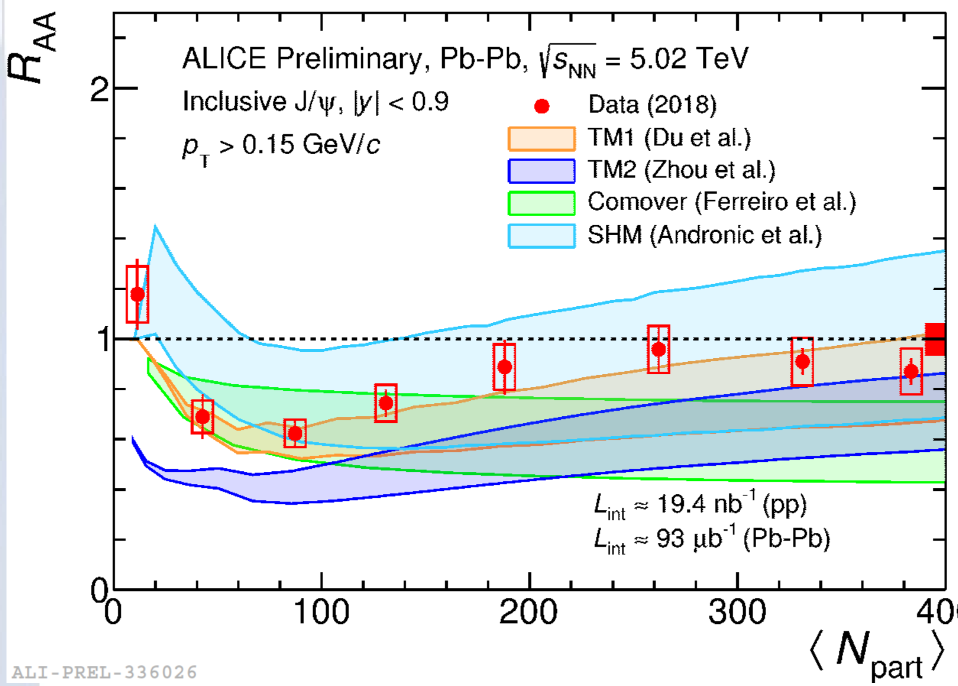
$$R_{\mathrm{AA}}(p_{\mathrm{T}}, y) = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{d^2 N_{\mathrm{AA}}/dp_{\mathrm{T}}dy}{d^2 N_{\mathrm{pp}}/dp_{\mathrm{T}}dy}$$

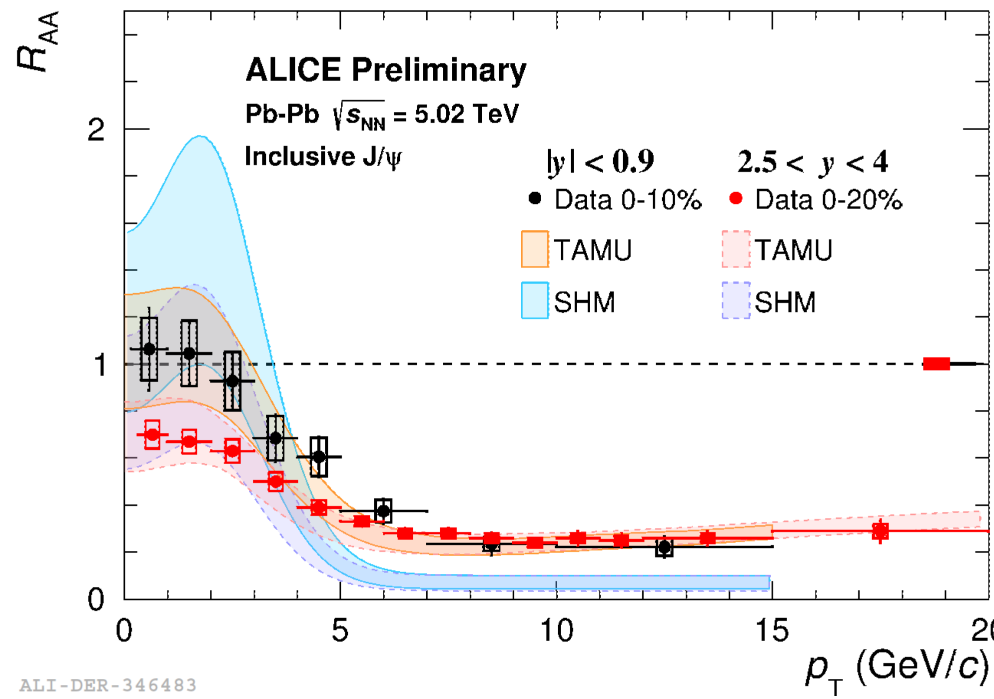
Production inside jets



Excited-to-ground state ratios
(e.g. $\psi(2S)/J/\psi$)

J/ψ R_{AA} - Comparison with models





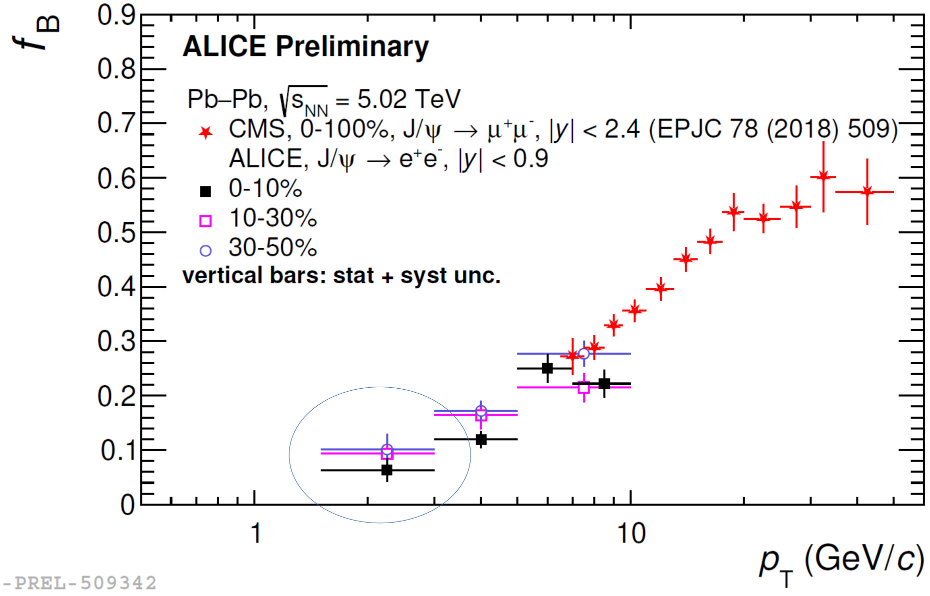
- **Models including regeneration mechanism in agreement with data**
  - Statistical Hadronization (SHM)
    - All charmonia produced at the QGP phase boundary with thermal weights
  - Transport model (TAMU)
    - Charmonium spectral functions from lattice QCD
    - Solve Boltzmann equation with gain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

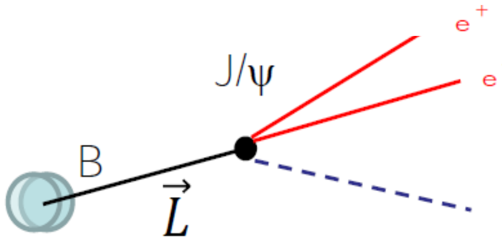
→ **Are the observed path influenced by non-prompt contribution ?**
→ **How to discriminate between the two pictures ?**

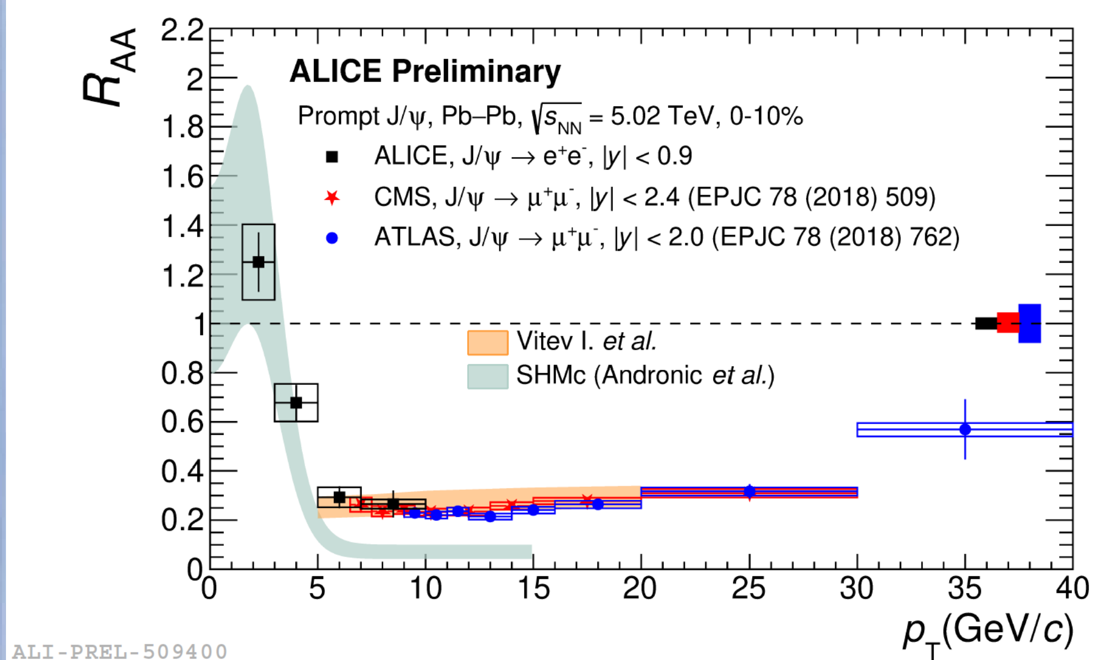
TM2: Zhou et al., Phys. Rev. C 89, 054911 (21 May 2014)
Comover: Ferreiro E. et al., PLB 731 (2014) 57

SHM: Andronic A. et al., Phys. Lett. B797 (2019) 134836,
TM1/TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158

Prompt J/ψ R_{AA}







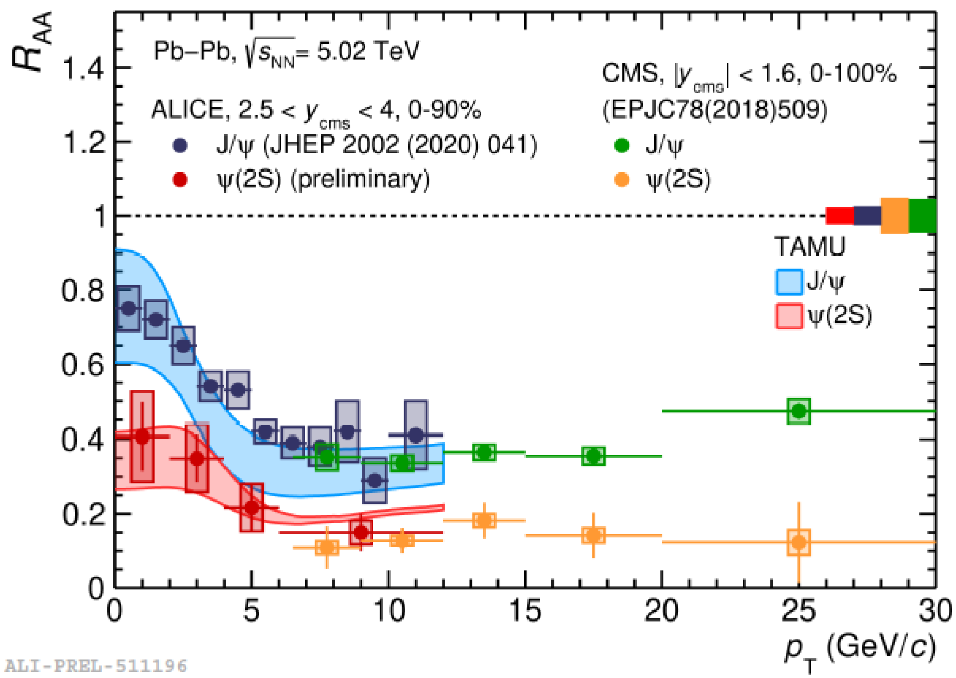
– rise of prompt J/ψ RAA at low pT → compatible with SHMc

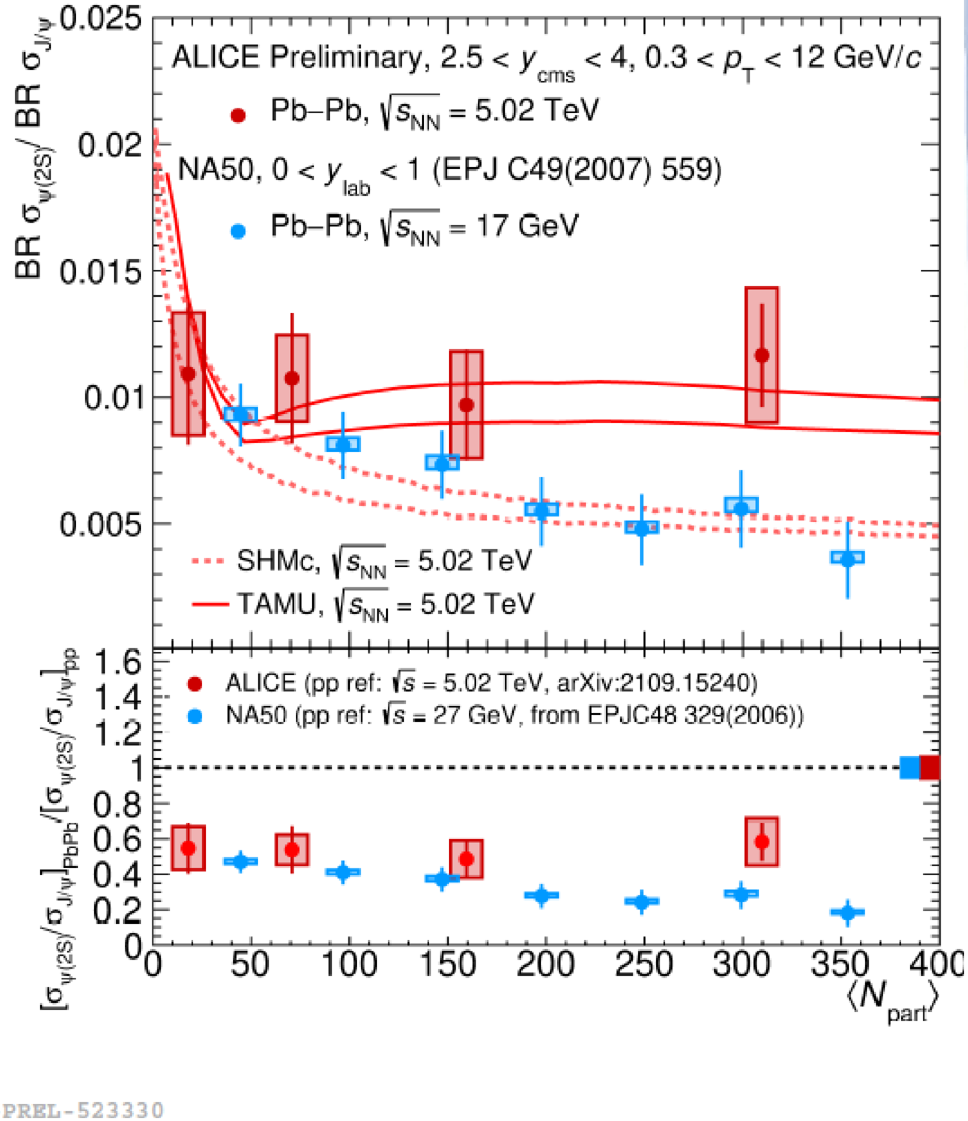
– model by Vitev et al, including dissociation, can describe results at high-pT

– 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

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

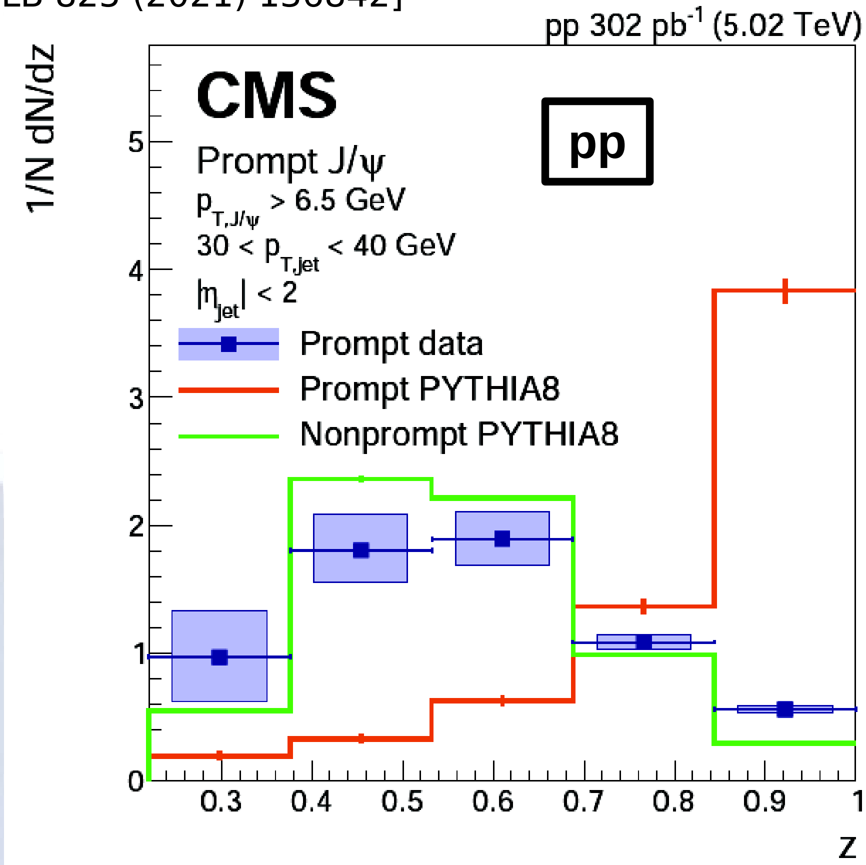
– pT dependent R_{AA} in agreement with TAMU for both charmonium states

– 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

J/ψ production inside jets

[PLB 825 (2021) 136842]

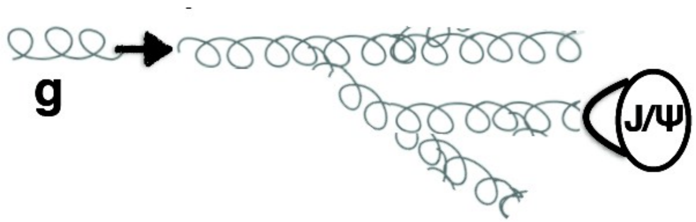


$$z = p_T\,(J/\psi)\ /\ p_T\,(jet)$$

pp collisions: prompt J/ψ produced with more jet activity as predicted by PYTHIA8 (LO)

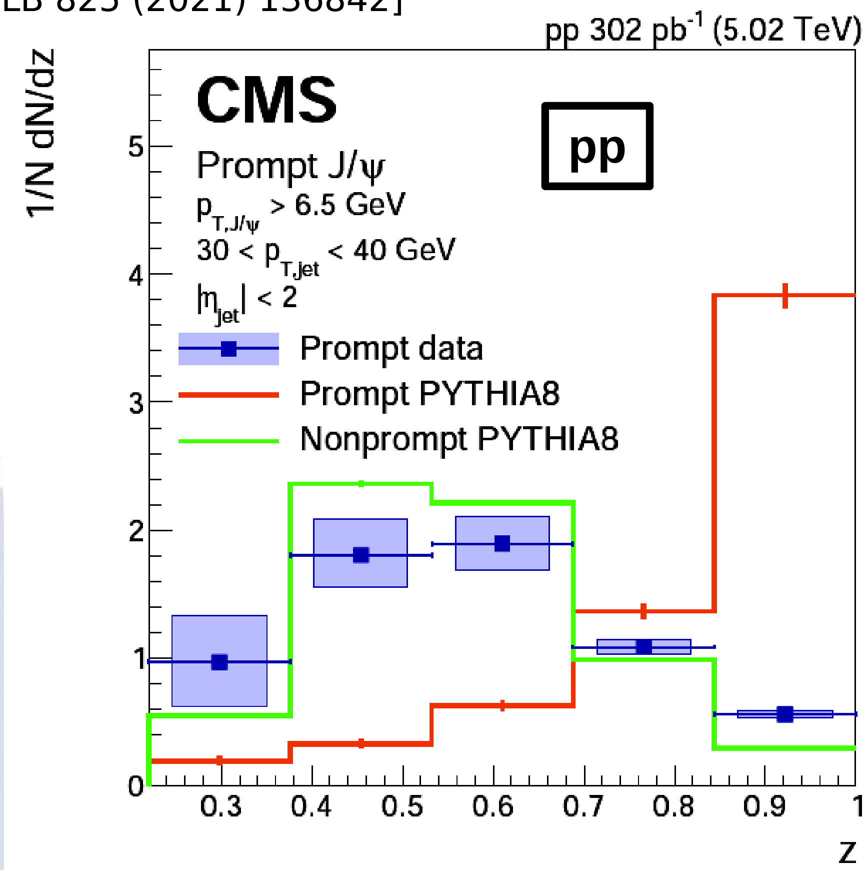
→ sizable contribution from **parton shower**

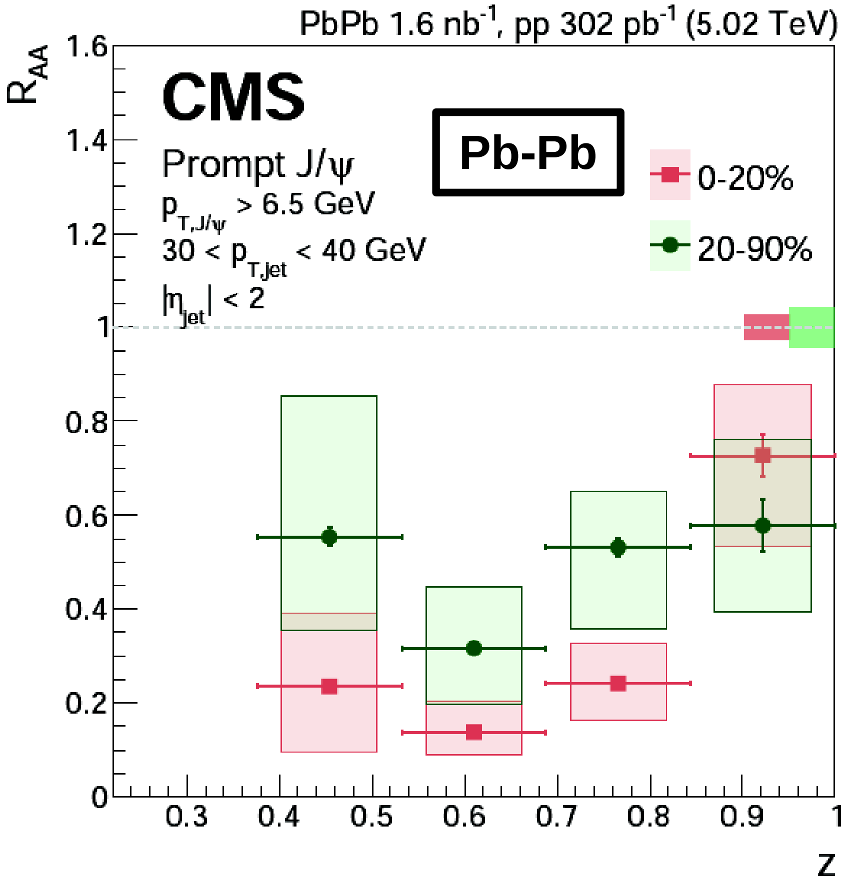
→ later formation than generally assumed! [PRL 119 (2017) 032002]



J/ψ production inside jets

[PLB 825 (2021) 136842]





pp collisions: prompt J/ψ produced with more jet activity as predicted by PYTHIA8 (LO)

→ sizable contribution from **parton shower**

→ later formation than generally assumed! [PRL 119 (2017) 032002]

Pb-Pb collisions:

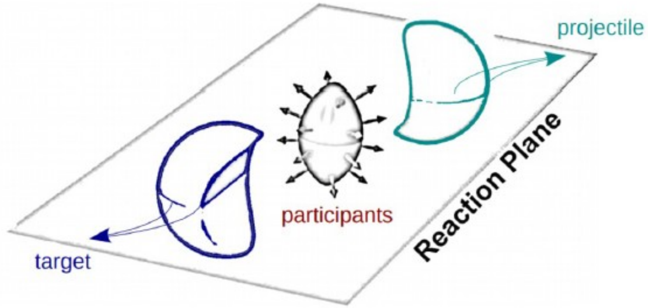
– less suppression for mostly isolated J/ψ

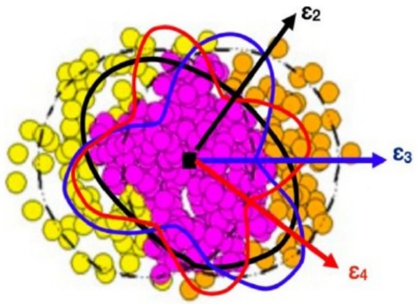
– larger effect in most central collisions

→ **suppression of J/ψ through jet quenching mechanisms**

Flow

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





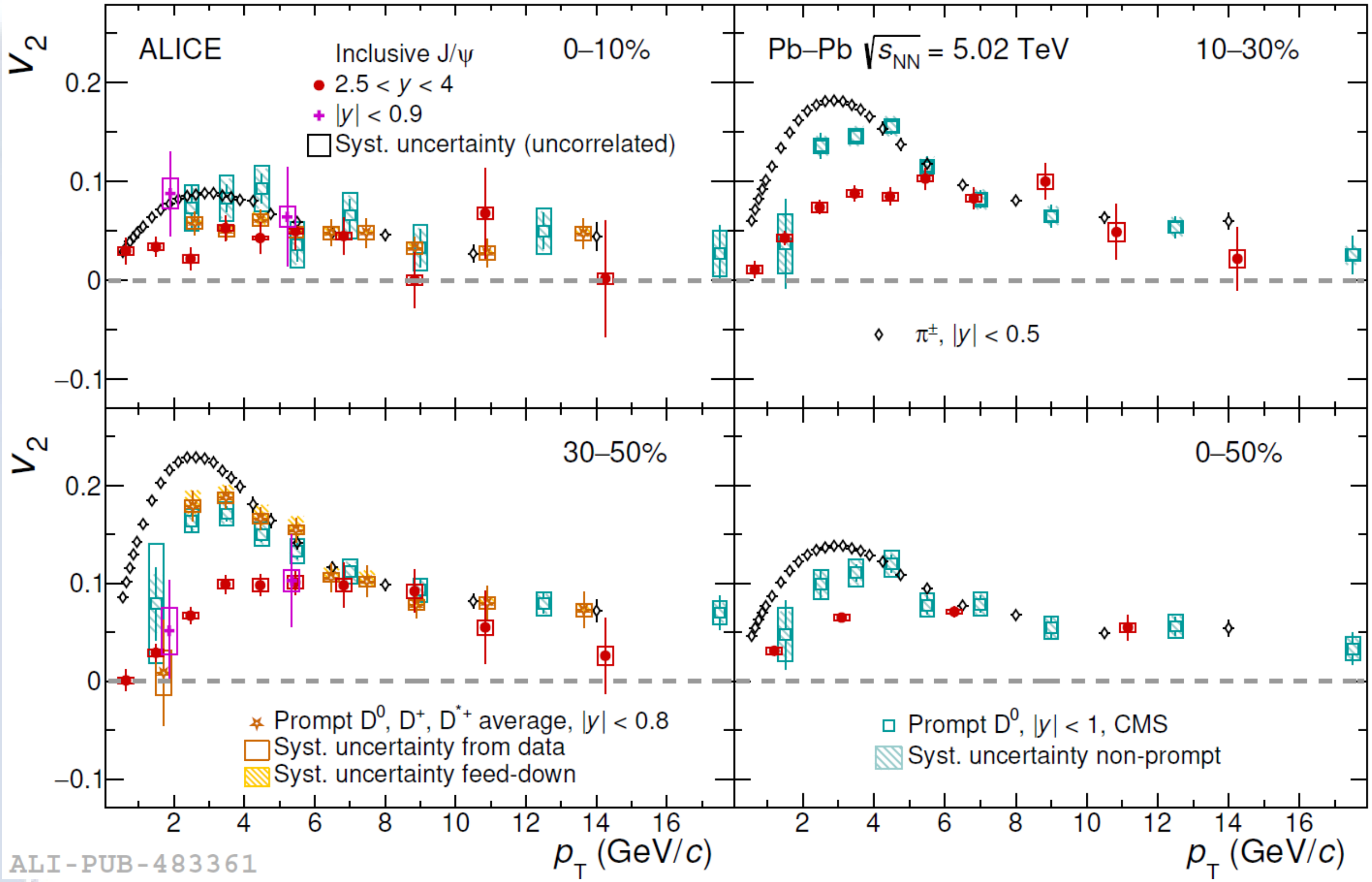
Decomposed transverse projection of participant region in Fourier series

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

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

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

JHEP 10 (2020) 141



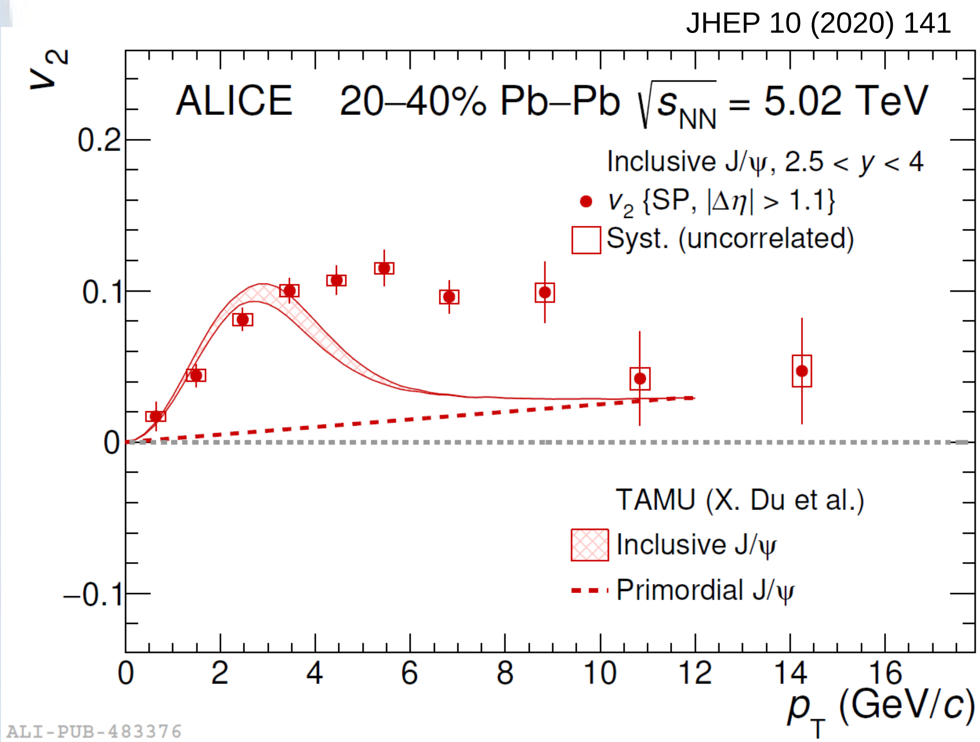
– J/ψ v_2 >0 → consistent with hydrodynamic flow of charm quarks in QGP

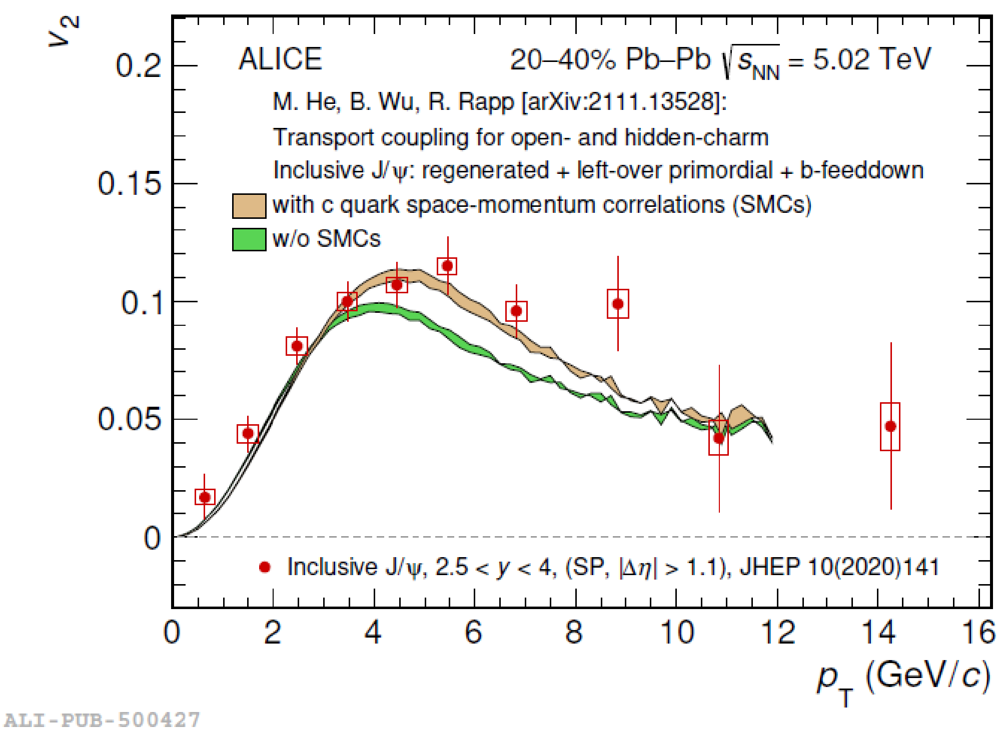
– J/ψ v_2 grows from central towards semi-central collisions, similarly as lighter particles

– 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





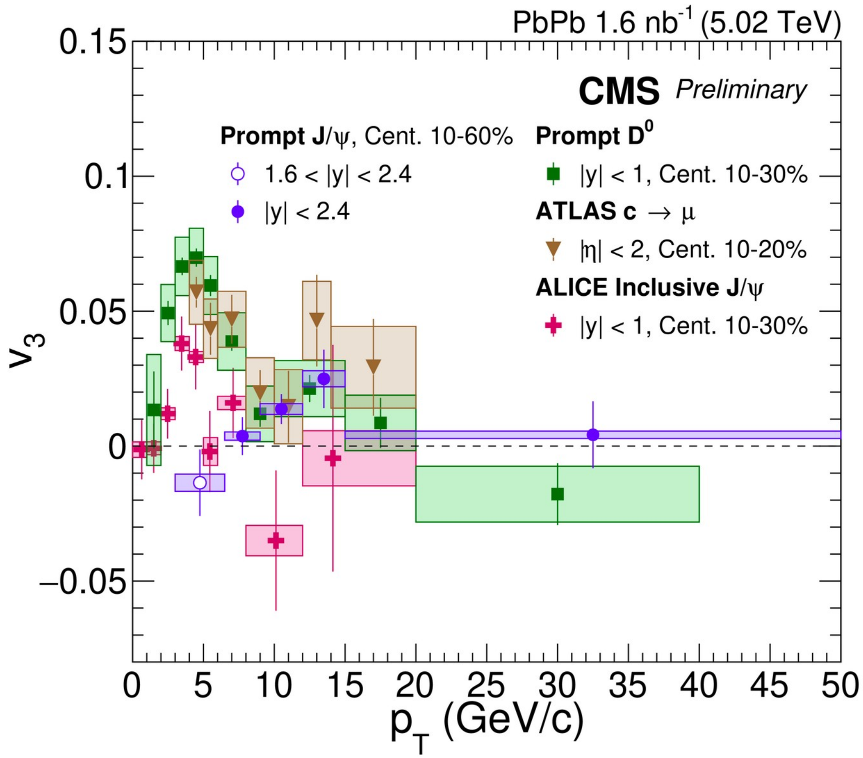
– Low p_T region described by TAMU, however tensions clearly visible at high p_T (>4 GeV/c)

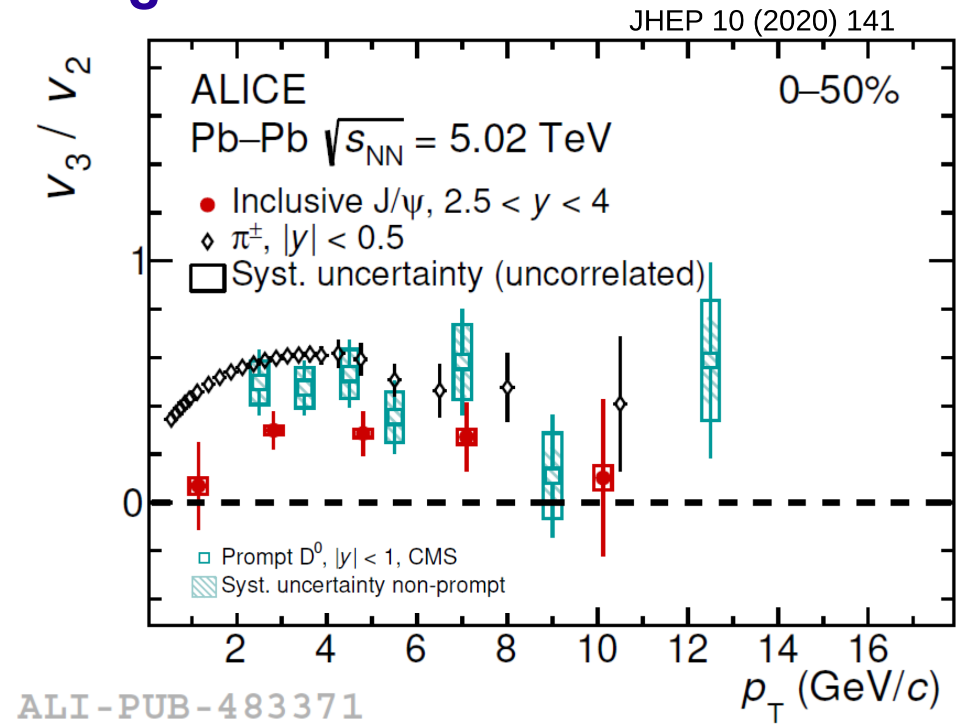
– Better agreement with the model thanks to recent improvements (p_T distribution of regenerated component and improved description of the primordial component)

– agreement further improved including charm quark space-momentum correlations

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

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

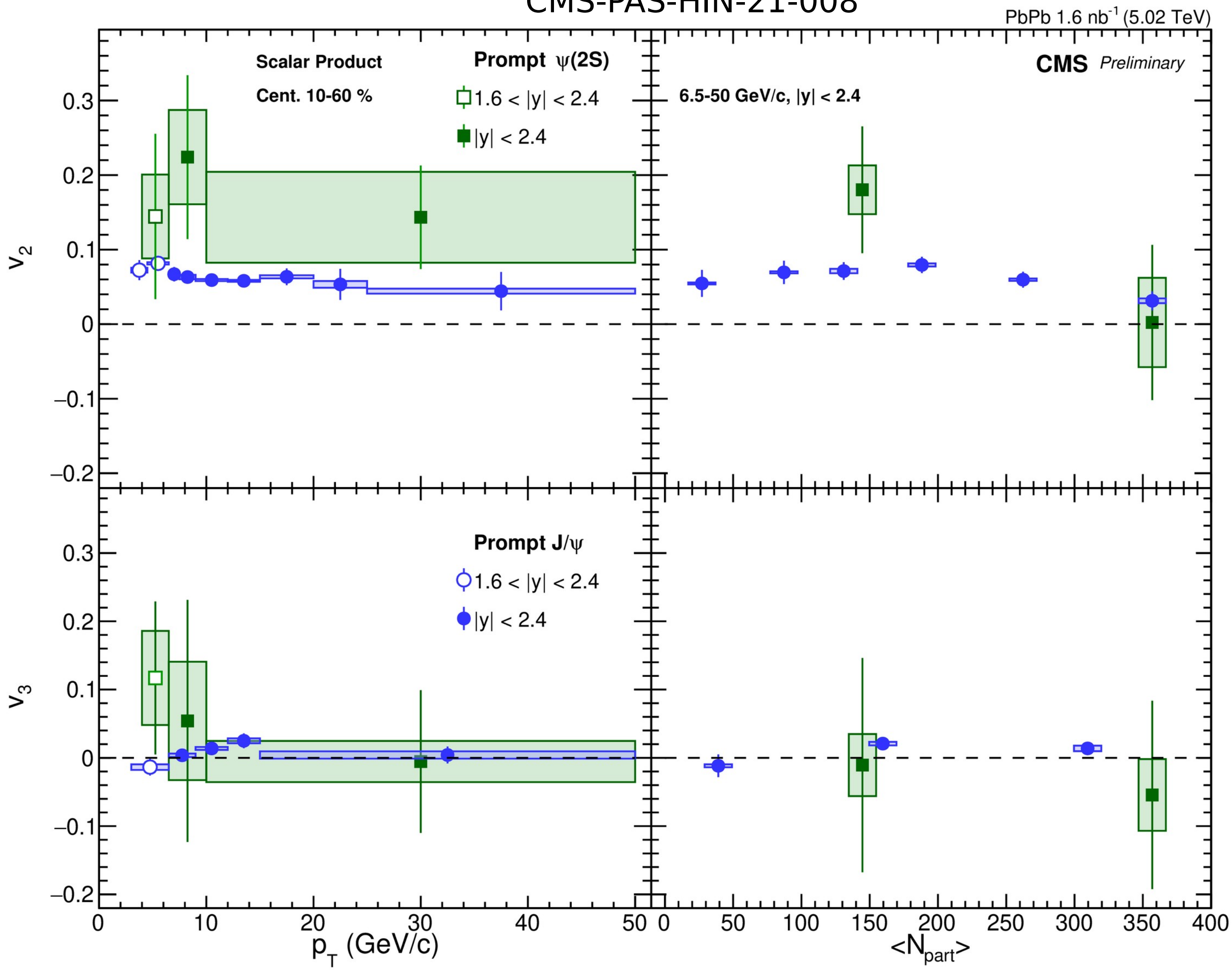
→ Less sensitivity to initial state fluctuations wrt light flavor species

v_2 and v_3: J/ψ vs ψ(2S)

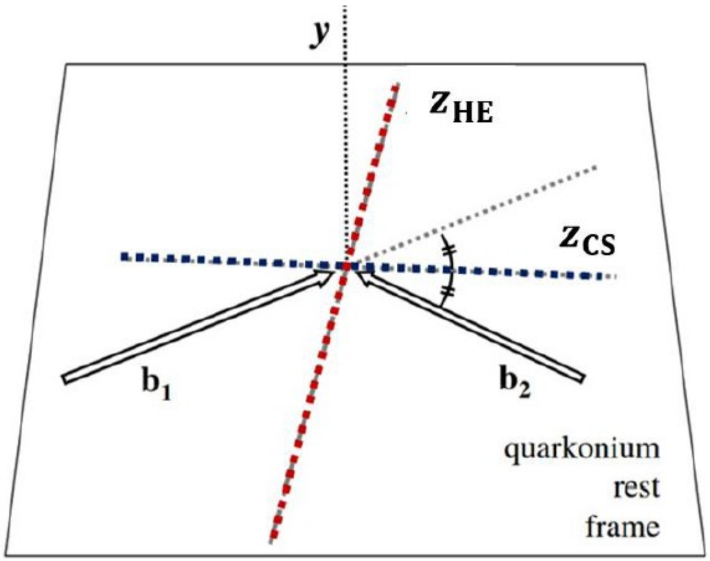
– Hint at larger prompt ψ(2S) v_2 compared to prompt J/ψ $v_2 \rightarrow$ possibility of larger contribution from regeneration for ψ(2S)

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

CMS-PAS-HIN-21-008



Polarization



Reference frames:

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

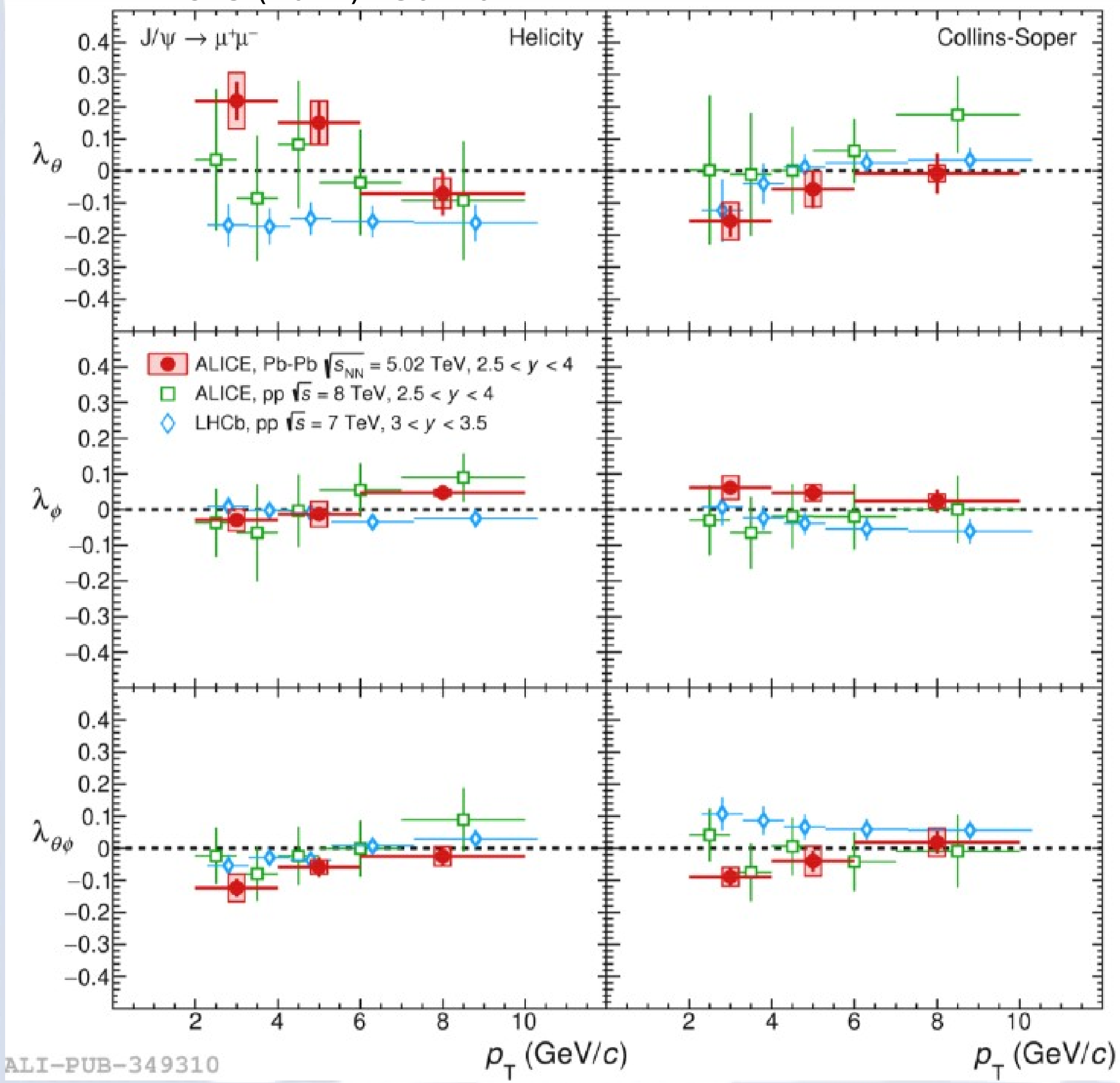
Collins-Soper (CS): the bisector of the angle between the beam and the opposite of the other beam, in the vector meson rest frame

→ **sensitive to production mechanisms**

→ **difference in Pb-Pb w.r.t. pp expected due to different mechanisms at play**

J/ψ polarization

PLB 815 (2021) 136146



– Polarization measured by ALICE in Pb-Pb collisions

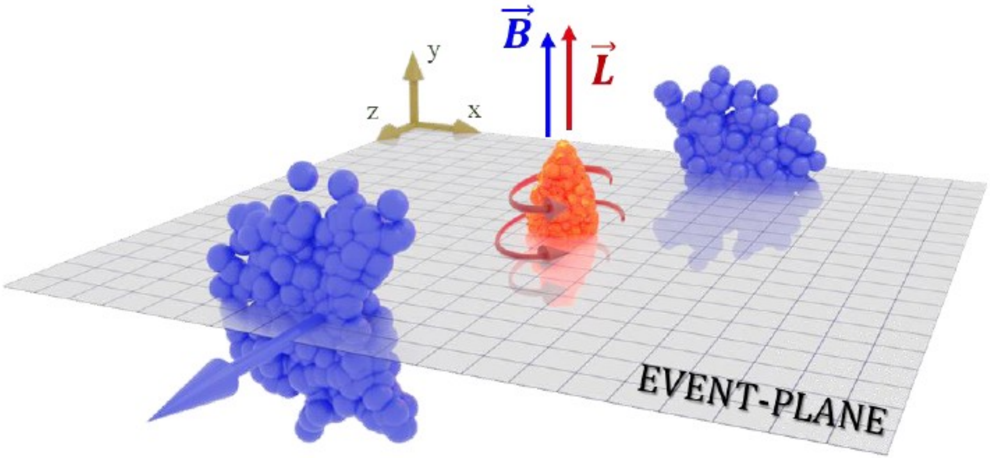
– 2σ deviation for λ_θ in 2-4 GeV/c w.r.t zero in HE and CS

– 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

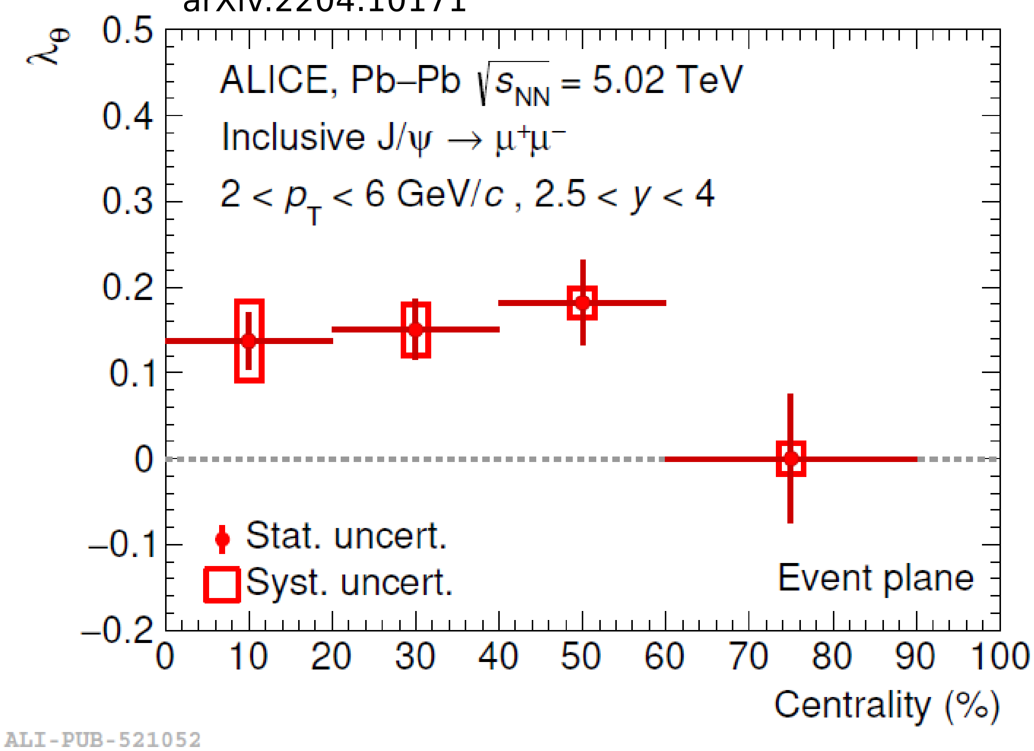


– **Event Plane based frame (EP)**: axis orthogonal to the event plane in the collision center of mass frame

– 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

Summary

- Regeneration mechanism essential at low transverse momemtum 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
- 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
- Evidence of jet quenching mechanism contributing to suppression at high pT
- Non-zero J/ψ polarization in Pb-Pb collisions at the LHC
  - Significantly different from pp $\rightarrow$ difference due to suppression / regeneration
  - Observed as a function of event plane $\rightarrow$ sensitive to initial state
  - Lacking of theoretical models

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Thank you for your attention!

BACK-UP

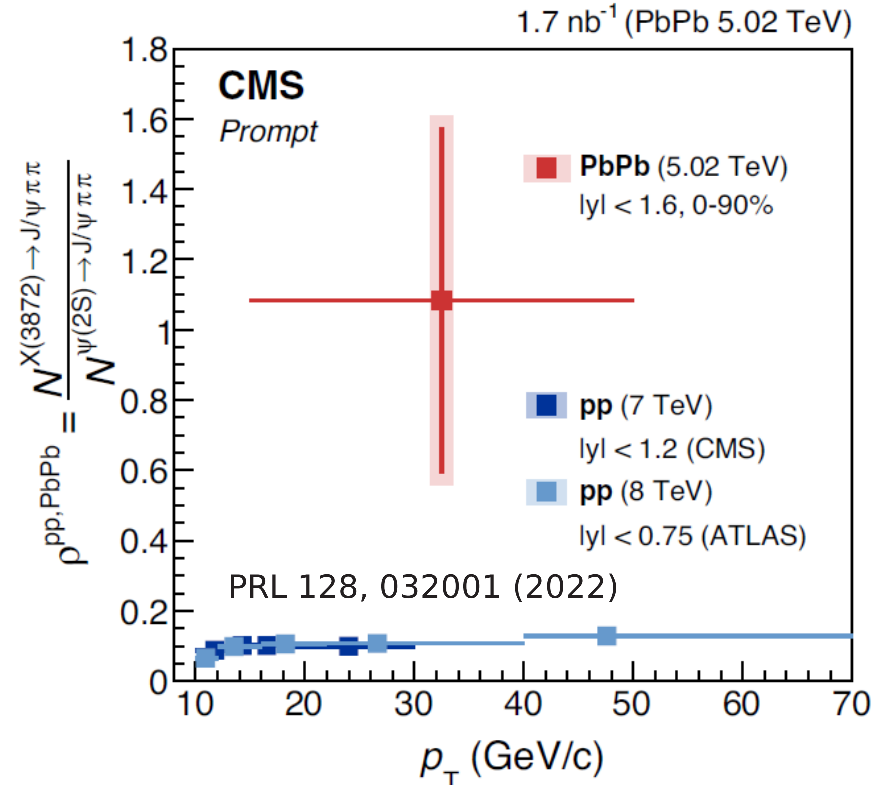
X(3872)-to-ψ(2S) ratio

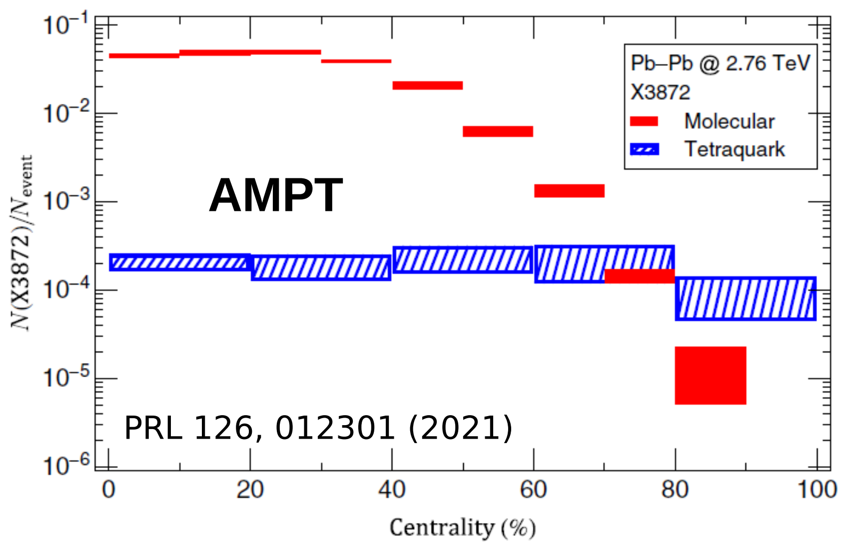
– First evidence of exotic quarkonium state X(3872) in heavy-ion collisions

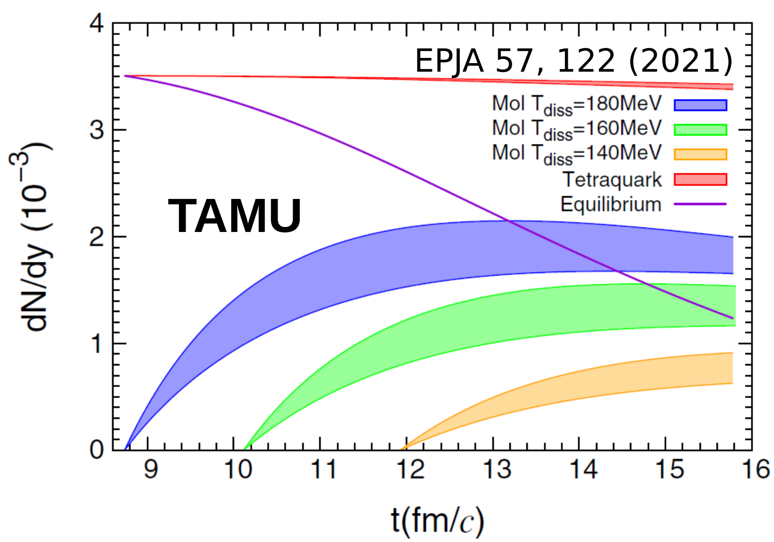
– Hint of enhanced X(3872) production compared to ψ(2S) (R_X ~ 1)

– Difficult to conclude about the nature of X(3872) (tetraquark or hadron molecule) because of the statistical limitation on the data + disagreement among models

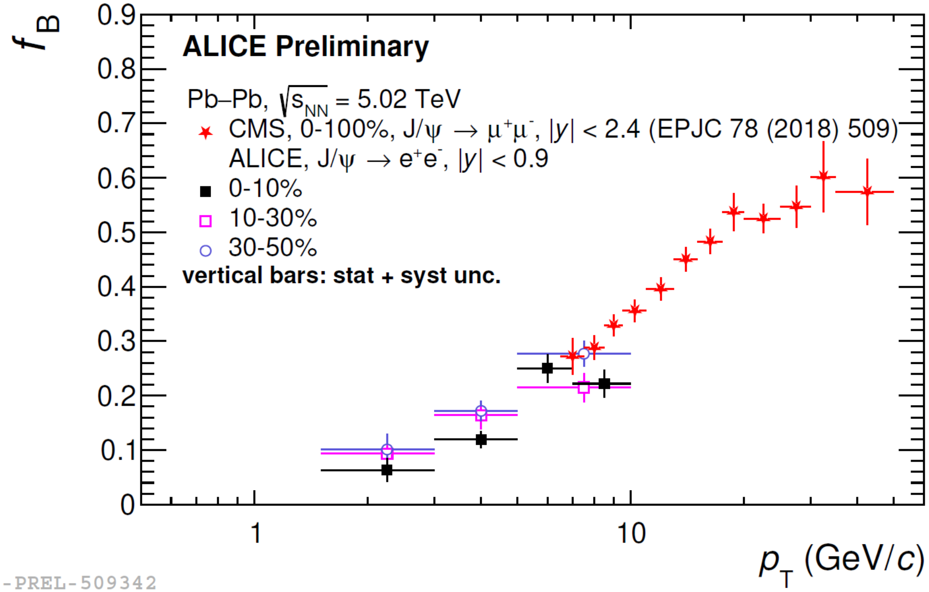
→ Future measurements with improved precision can shed light on the nature of X(3872)

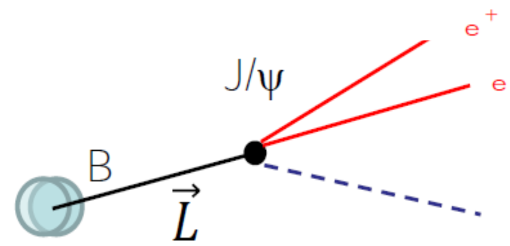






Non-Prompt J/ψ R_{AA}

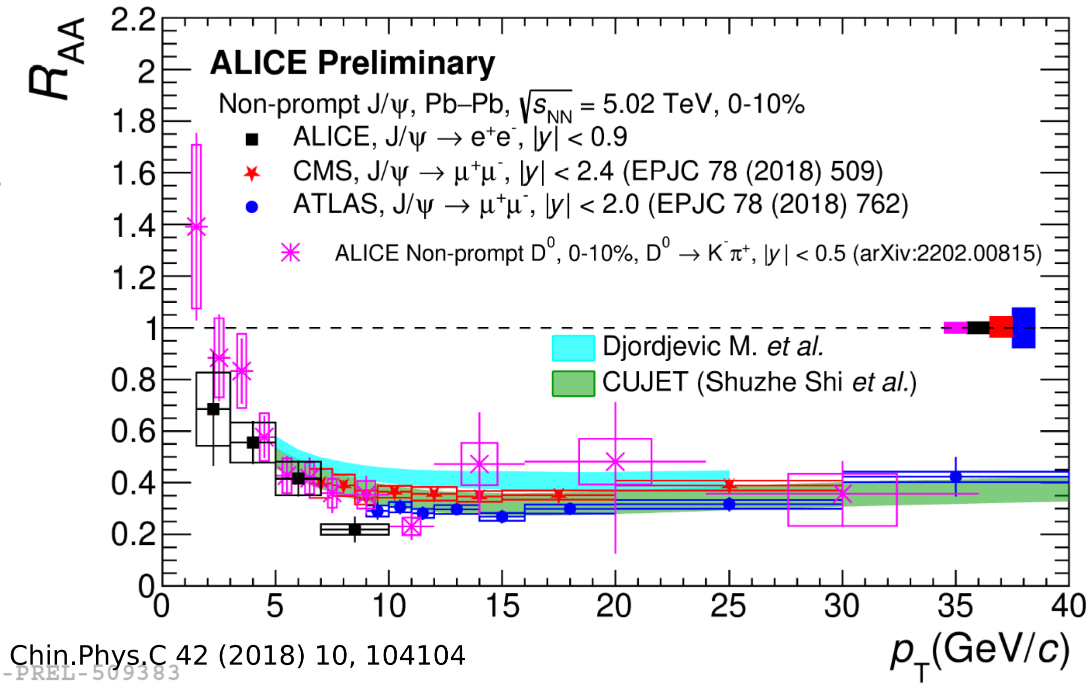




– non-prompt J/ψ R_{AA} allows to access beauty quark energy loss in the QGP

– compatible with models including collisional and radiative energy loss

– good agreement between non-prompt J/ψ and non-prompt D⁰ R_{AA}



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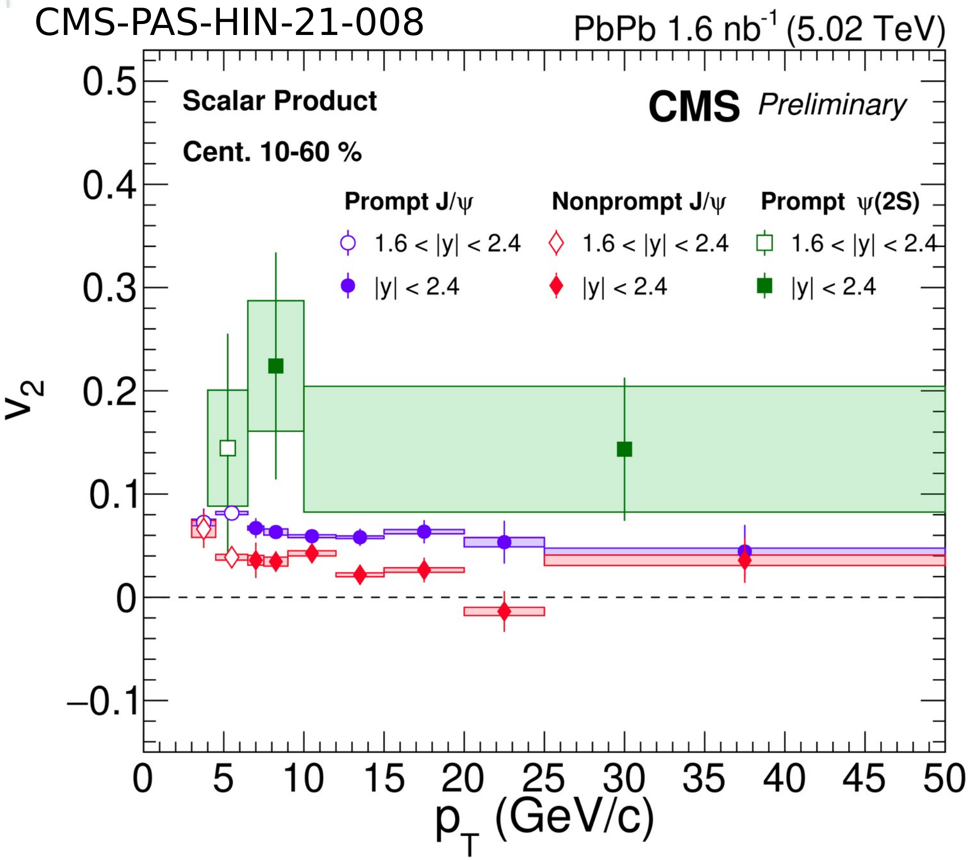
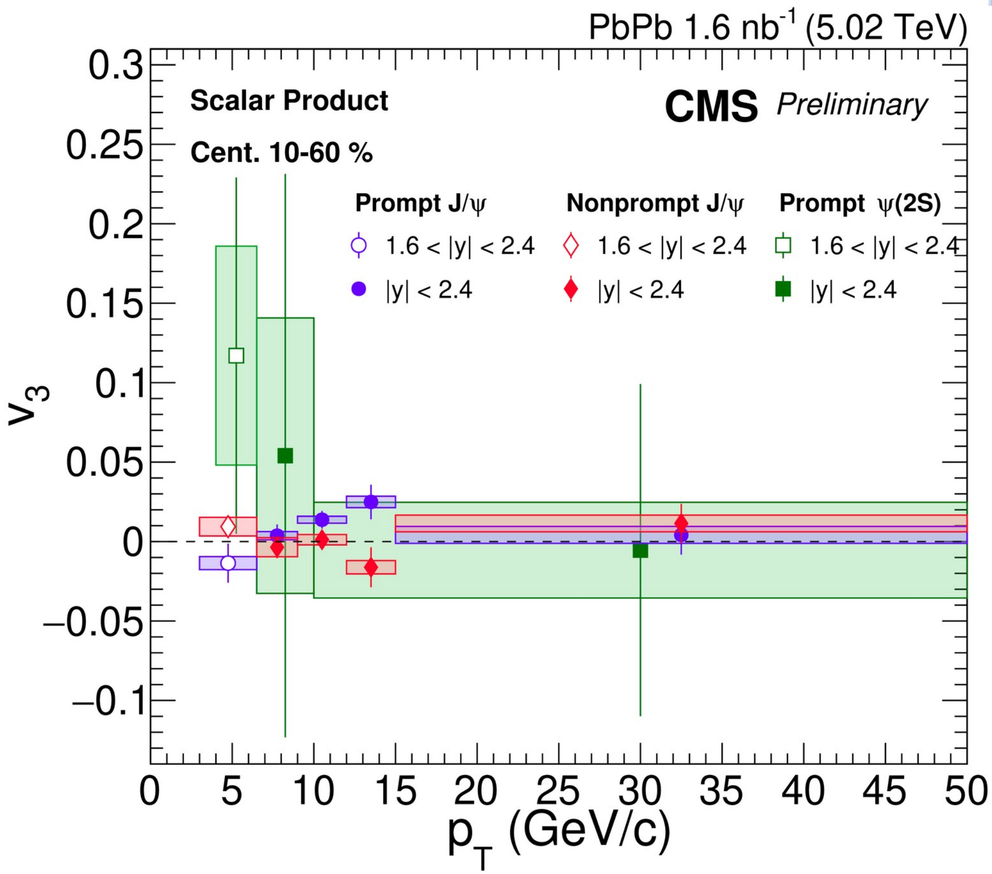
CUJET: Shuzhe S. et al. Chin.Phys.C 43 (2019) 4, 044101, Chin.Phys.C 42 (2018) 10, 104104
Djordjevic M. et al. arXiv:2110.01544

v_2 and v_3: J/ψ vs ψ(2S)



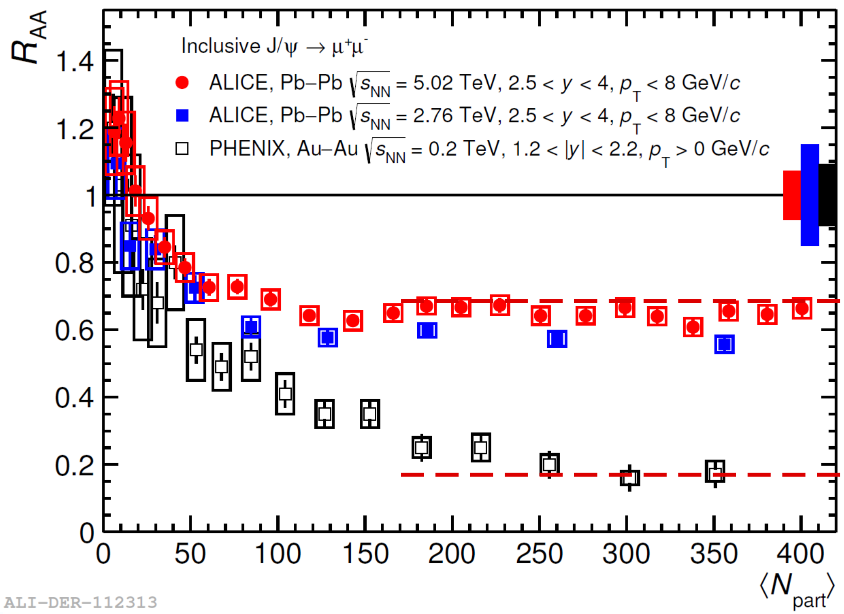


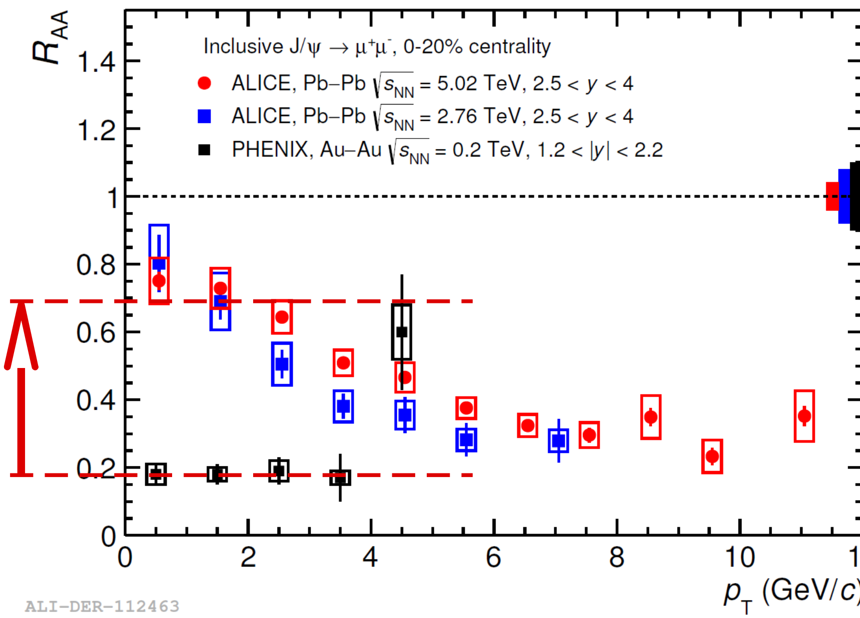
– Hint at larger prompt ψ(2S) v_2 compared to prompt J/ψ $v_2 \rightarrow$ possibility of larger contribution from regeneration for ψ(2S)

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

J/ψ R_{AA}

[PLB 766 (2017) 212]





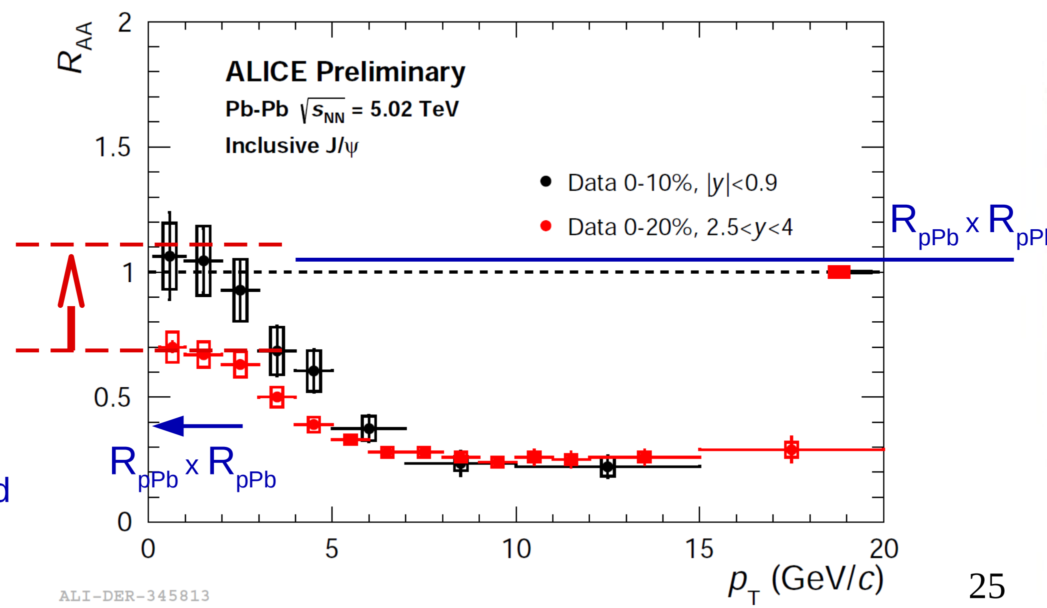
– Similar suppression observed in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV and 5.02 TeV

– Less suppression at LHC energy compared to lower RHIC energy towards more central events

– Weaker suppression at midrapidity compared to forward rapidity at the LHC

– Comparable suppression at high p_T

– Increasing R_{AA} towards lower p_T, more pronounced at midrapidity



All compatible with a regeneration scenario!