Charmonium modification in the quark-gluon plasma

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on behalf of the ALICE, ATLAS, CMS and LHCb collaborations

Outline

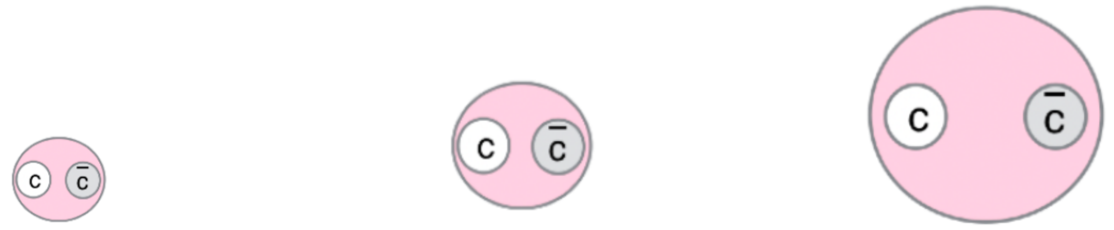
- Probing the QGP with charmonia
- Charmonium in heavy-ion collisions
  - Nuclear modification factor
  - Elliptic and triangular flow
  - J/ψ polarisation wrt Pb-Pb event plane
  - Coherent J/ψ photoproduction with nuclear overlap
  - Exotic charmonium $\chi_{c1}(3872)$ state

Selection of final/new results from ALICE, ATLAS, CMS and LHCb

Probing the QGP with charmonia

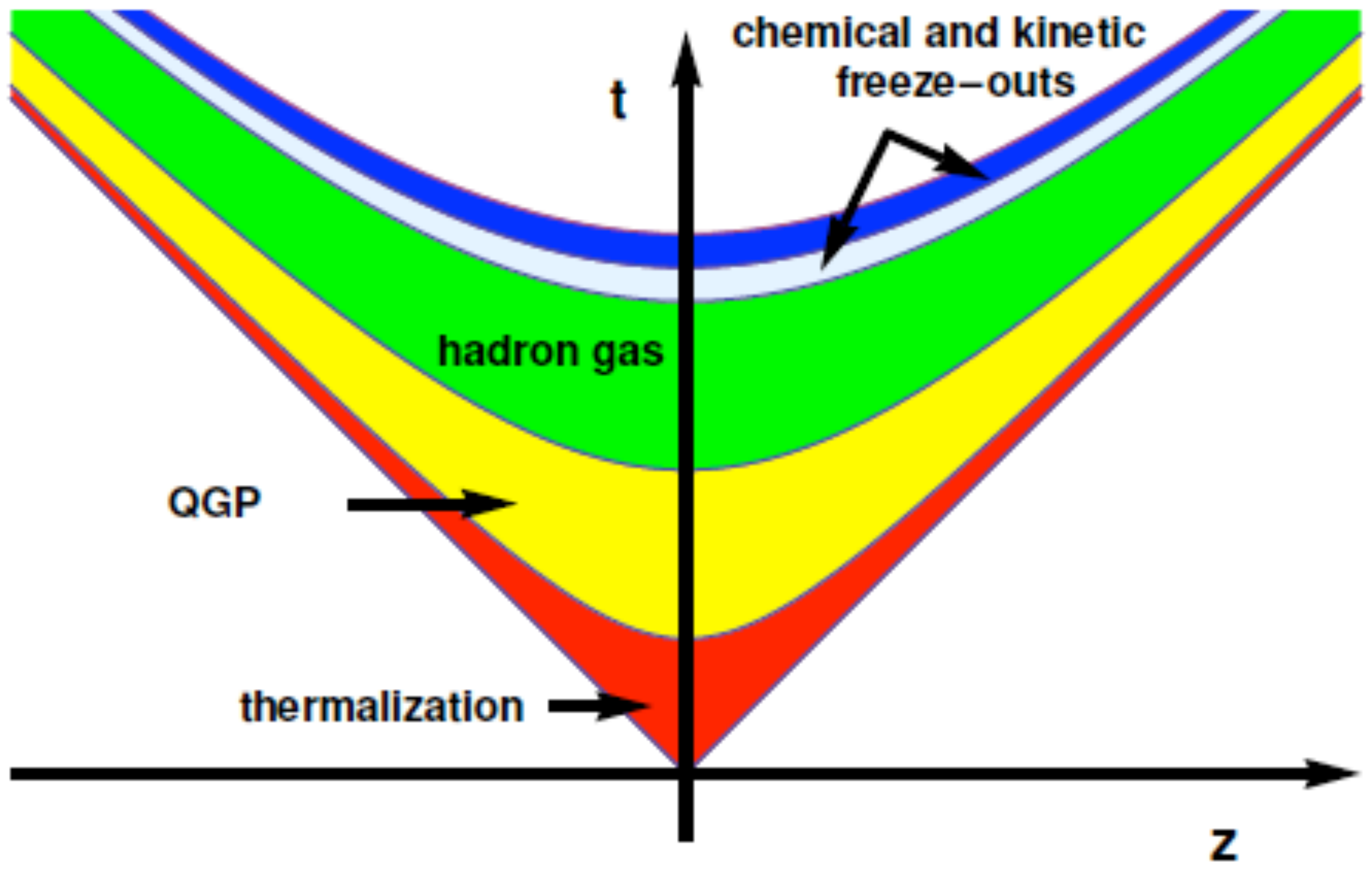
Charmonia

- Bound states of c and $\bar{c}$
- Stable and tightly bound
- Produced in the initial hard partonic collisions in the early stage of the collisions ($\tau \simeq 1/m_c$): charmonia experience the whole space-time evolution of the formed medium in heavy-ion collisions



Satz, J.Phys.G32 (2006) 3

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05



Feed-down and non-prompt charmonia

- Prompt J/ψ = direct J/ψ + J/ψ from excited states (χ_c, ψ(2S))

prompt J/ψ in pp at LHC ~ 80% direct J/ψ + 14% $\chi_c \rightarrow$ J/ψ + 6% ψ(2S) → J/ψ

Lansberg Phys.Rep.889 (2020) 1

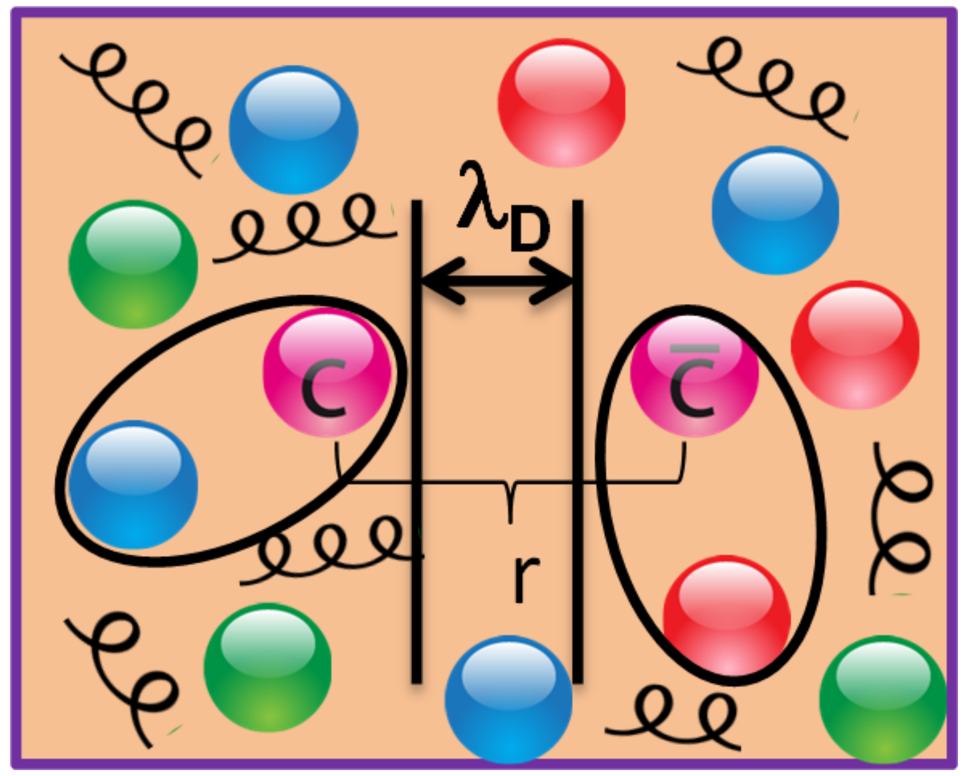
- Inclusive J/ψ (ψ(2S)) = prompt J/ψ (ψ(2S)) + J/ψ (ψ(2S)) from b-hadron decays

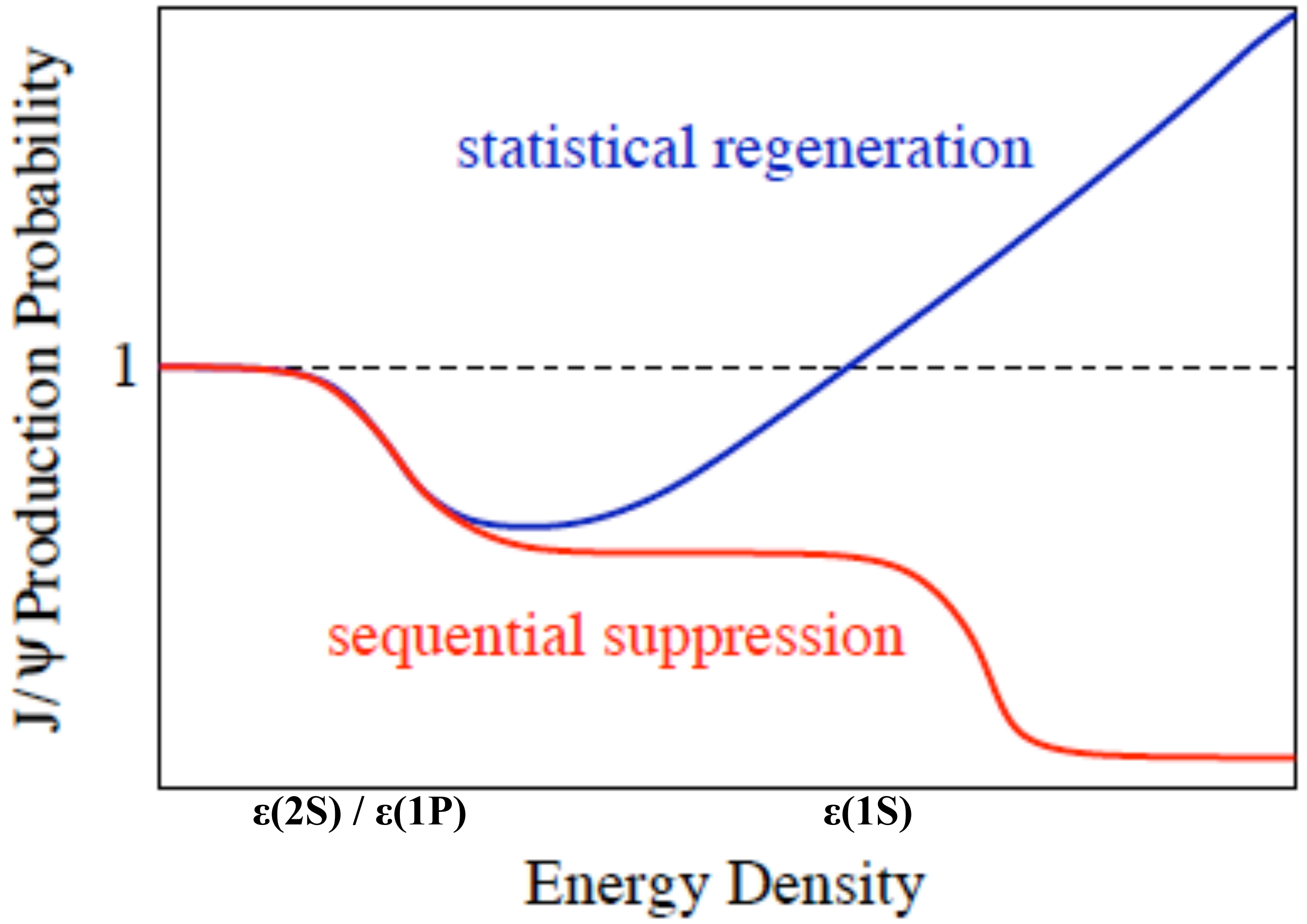
Probing the QGP with charmonia

From dissociation…

- At $T >> 0$, high density of colour charge in the medium induces Debye screening
- At $T > T_D$, melting of quarkonia *Matsui, Satz PLB178(1986)*
- Since charmonia (J/ψ, ψ(2S), …) have different binding energy
  - → sequential suppression of charmonium and bottomonium states
  - → quarkonium as a QGP thermometer

Karsch, Satz Z.Phys.C51 (1991) 209
Rothkopf Phys.Rept.858 (2020) 1





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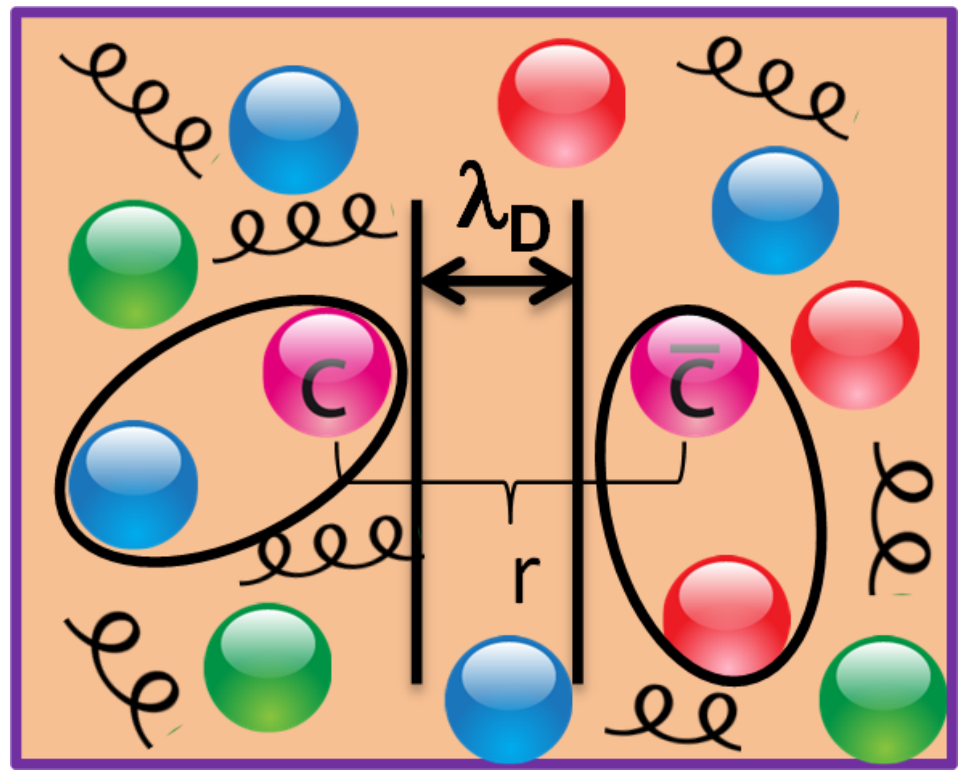
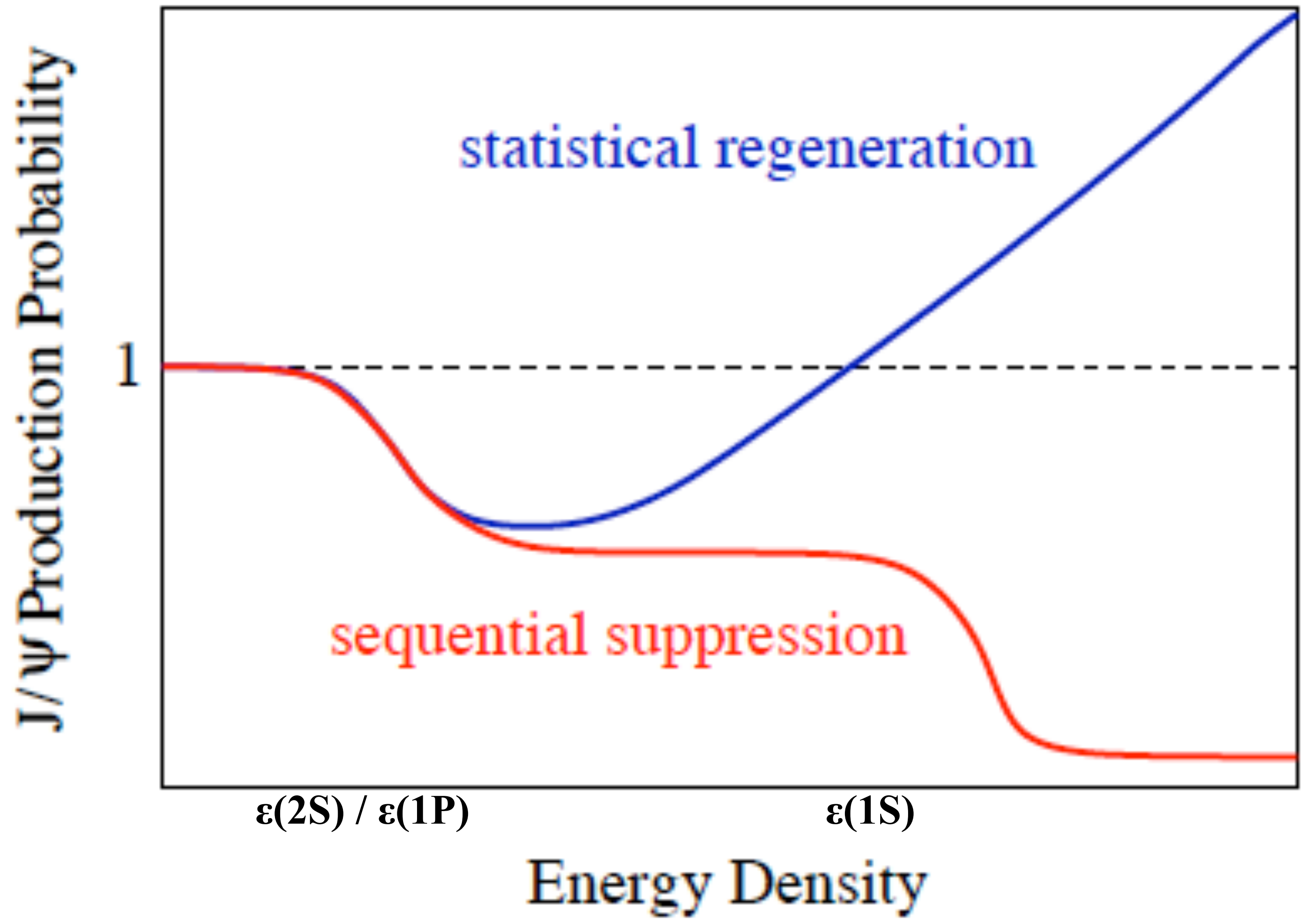
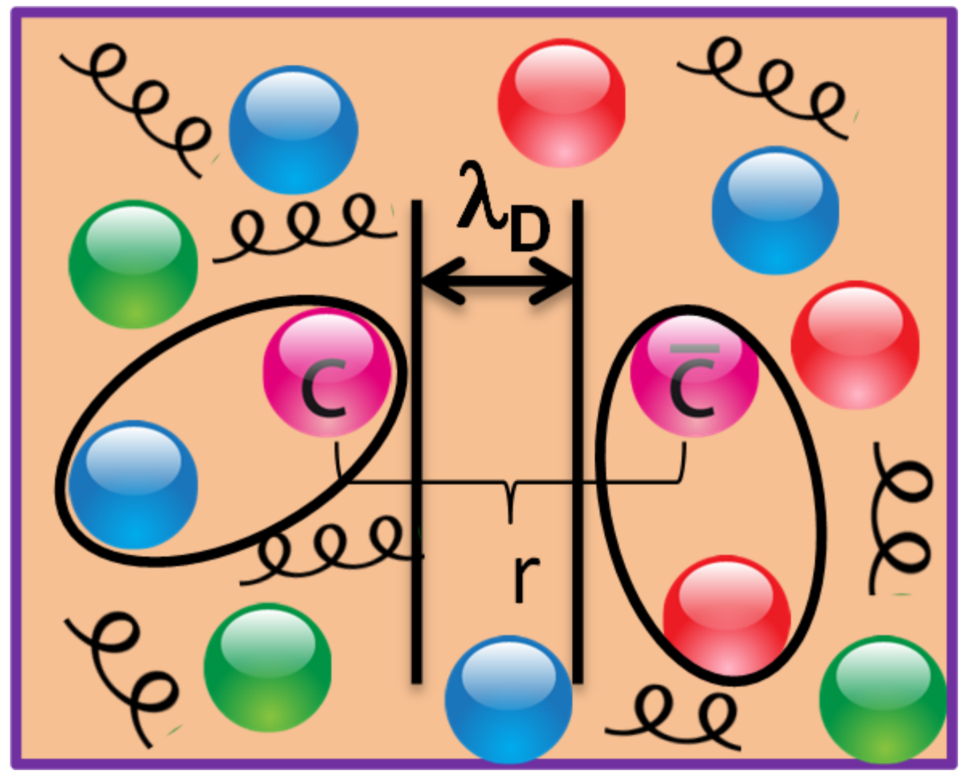




… to regeneration…

- Total charm cross-section increases with energy
- c and c̄ combination in the QGP or at the phase boundary
  - → regeneration of charmonia *Braun-Munzinger, Stachel PLB490(2000)* *Thews et al. PRC62(2000)*
  - ➡ production enhancement
  - ➡ evidence of thermalization of charm quarks
- regeneration delayed for loosely bound states (such as ψ(2S))

Probing the QGP with charmonia



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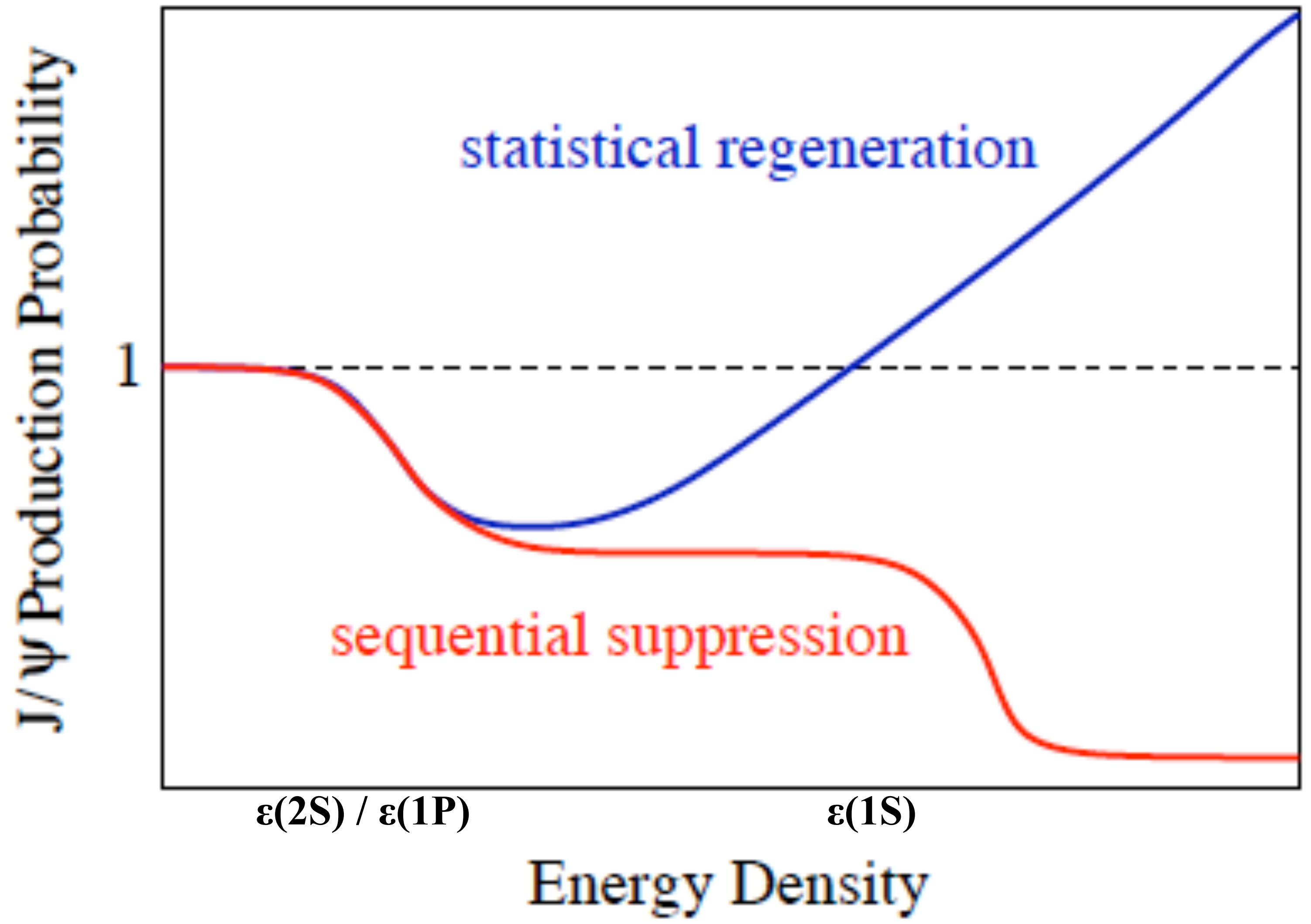

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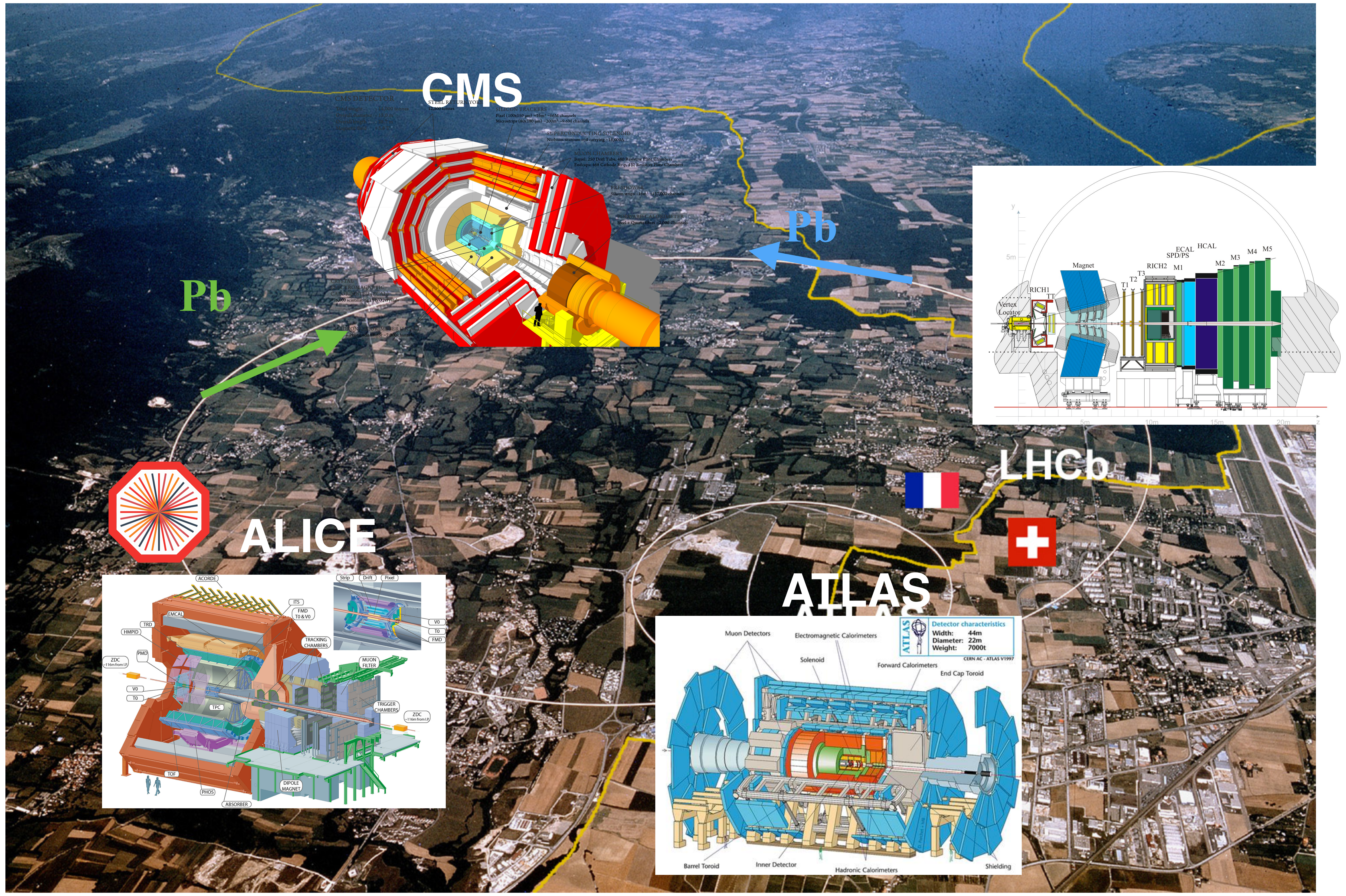
Braun-Munzinger, Stachel PLB490(2000)
Thews et al. PRC62(2000)

… and energy loss

- at large p_T, gluons can fragment into quarkonia → gluon energy loss in the QGP: suppression similar for all particles

Arleo PRL119 (2017) 062302

Charmonium measurements in heavy-ions at the LHC



ALICE
- midrapidity region with dielectron decay channel
- forward-rapidity region with dimuons

ATLAS and CMS
- midrapidity region with dimuons

LHCb
- forward-rapidity region with dimuons

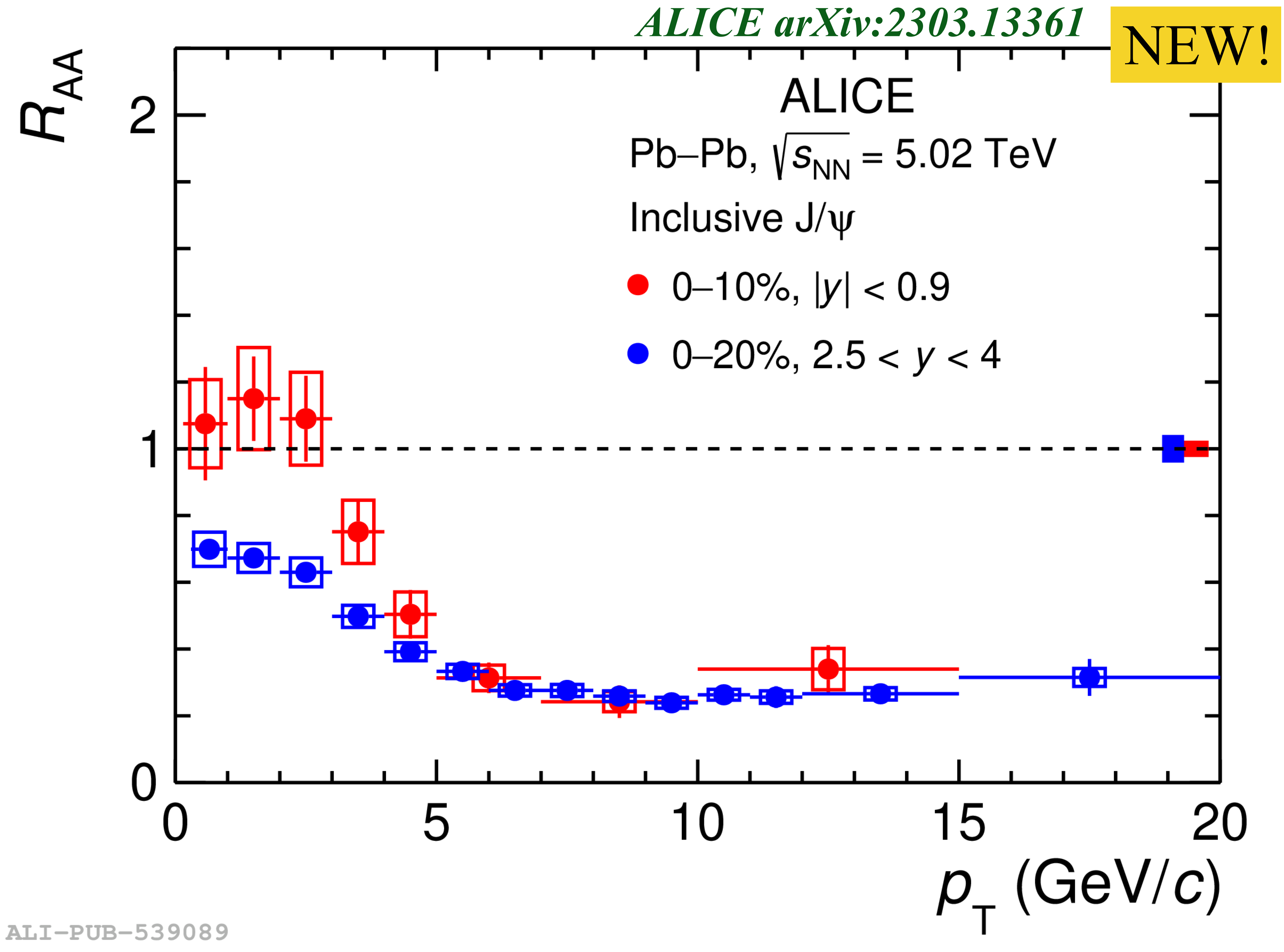
Complementary measurements !

LHC Pb-Pb collisions
- $\sqrt{s_{NN}}$ = 2.76 (Run 1), **5.02 (Run 2)**, 5.36 (Run 3/4) TeV

Inclusive J/ψ production

$$R_{AA} = \frac{d^2N^{AA}/dp_T dy}{\langle N_{coll}\rangle \, d^2N^{pp}/dp_T dy}$$

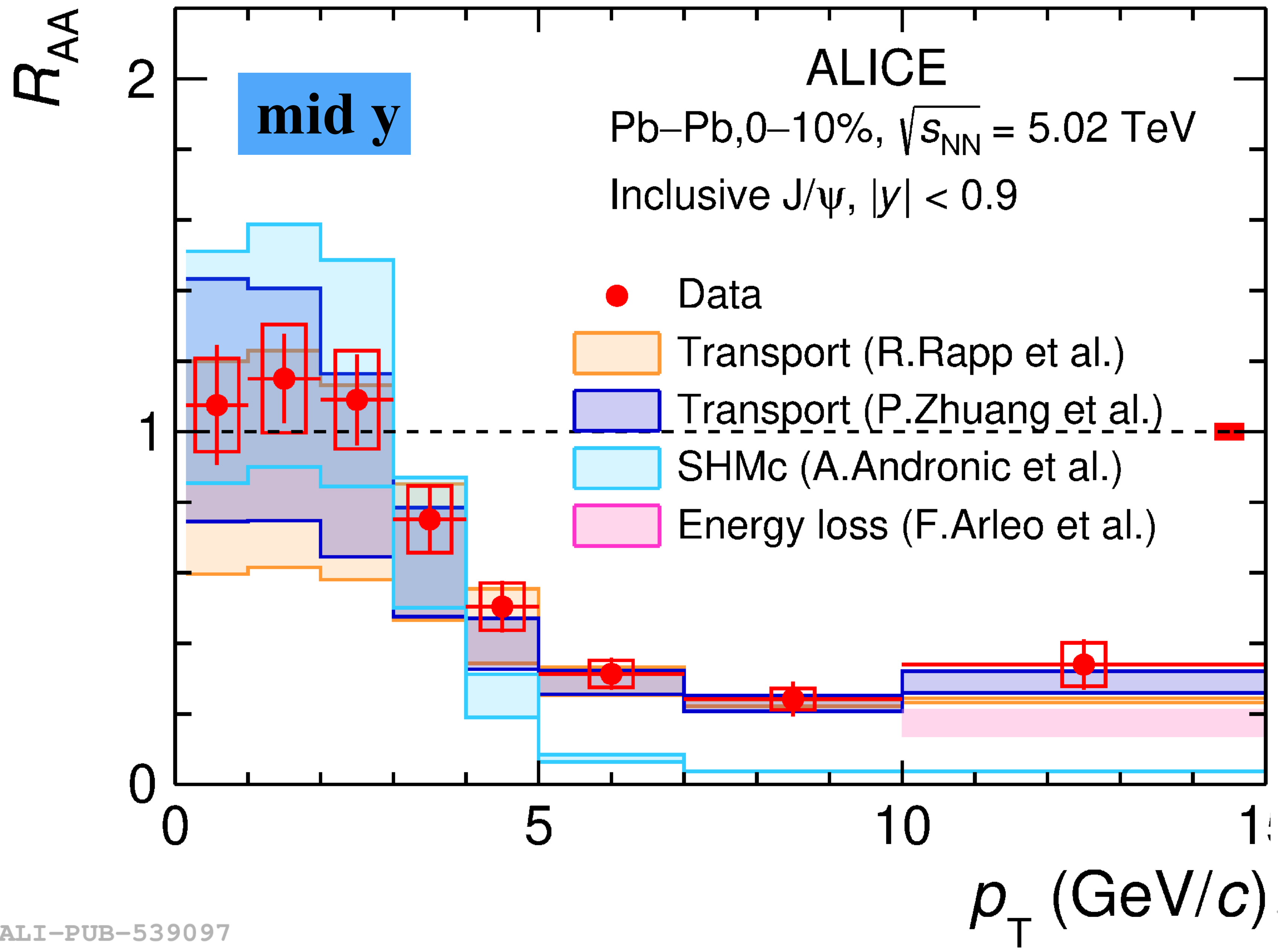
- $R_{AA} = 1$: no modification
- $R_{AA} > 1$: enhancement
- $R_{AA} < 1$: suppression



- Less suppression at low p_T and at midrapidity: expected behaviour from J/ψ recombination
- Large suppression at large p_T with no rapidity dependence : interplay of dissociation and energy loss

Model comparison

ALICE arXiv:2303.13361



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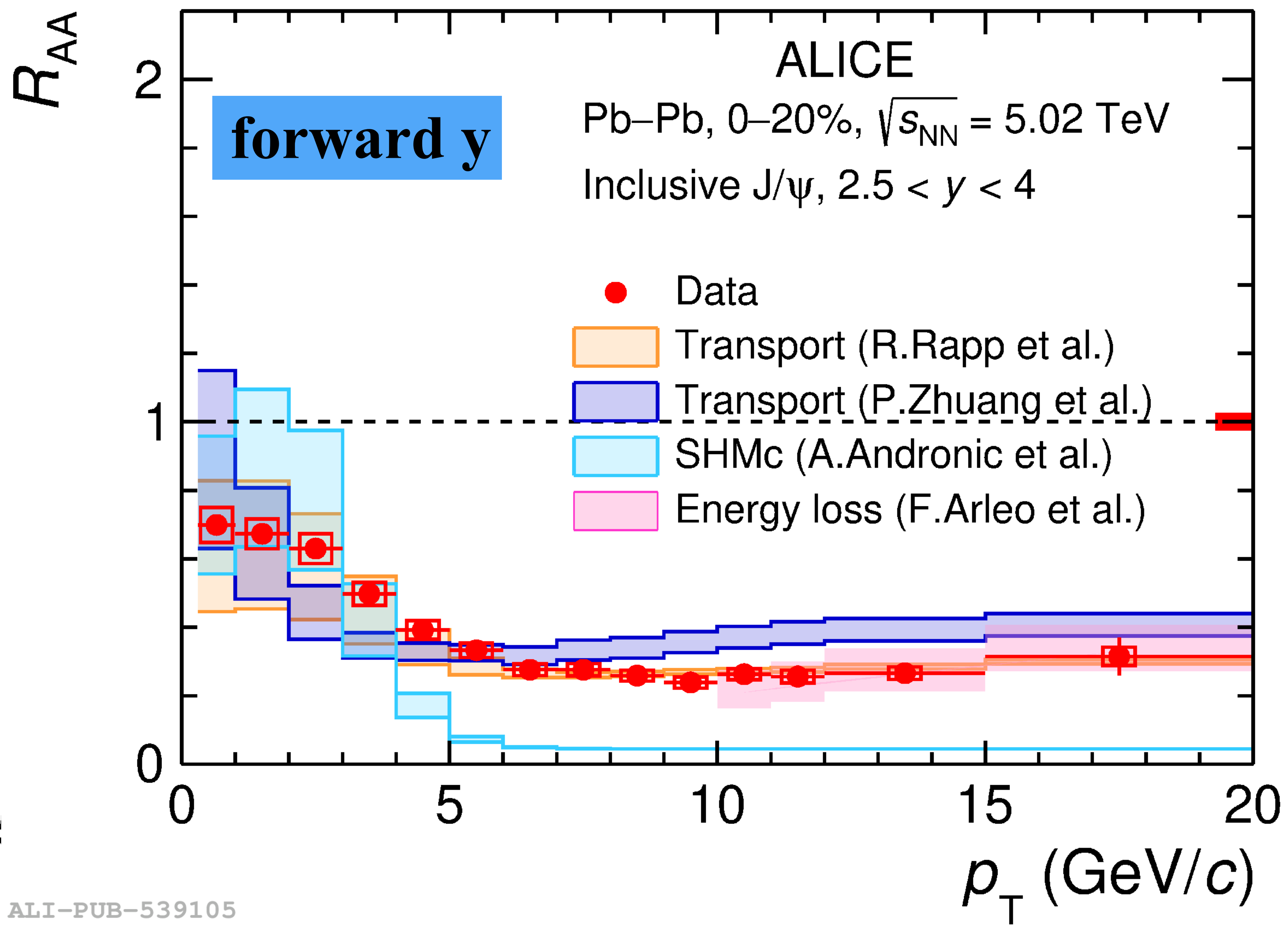

ALI-PUB-539105

Models:

Du and Rapp, Nucl.Phys.A943 (2015) 147

Zhuang et al., PRC89 (2014) 054911

Andronic et al., PLB797 (2019) 134836

Arleo, PRL119 (2017) 062302

- Good agreement with models:
  - full p_T / y ranges: transport models (regeneration, dissociation)
  - low p_T: statistical hadronization model (SHMc - regeneration)
  - high p_T: energy loss model
- Large model uncertainty at low p_T from $\sigma_{c\bar{c}}$ in Pb-Pb: need to constrain/measure it!

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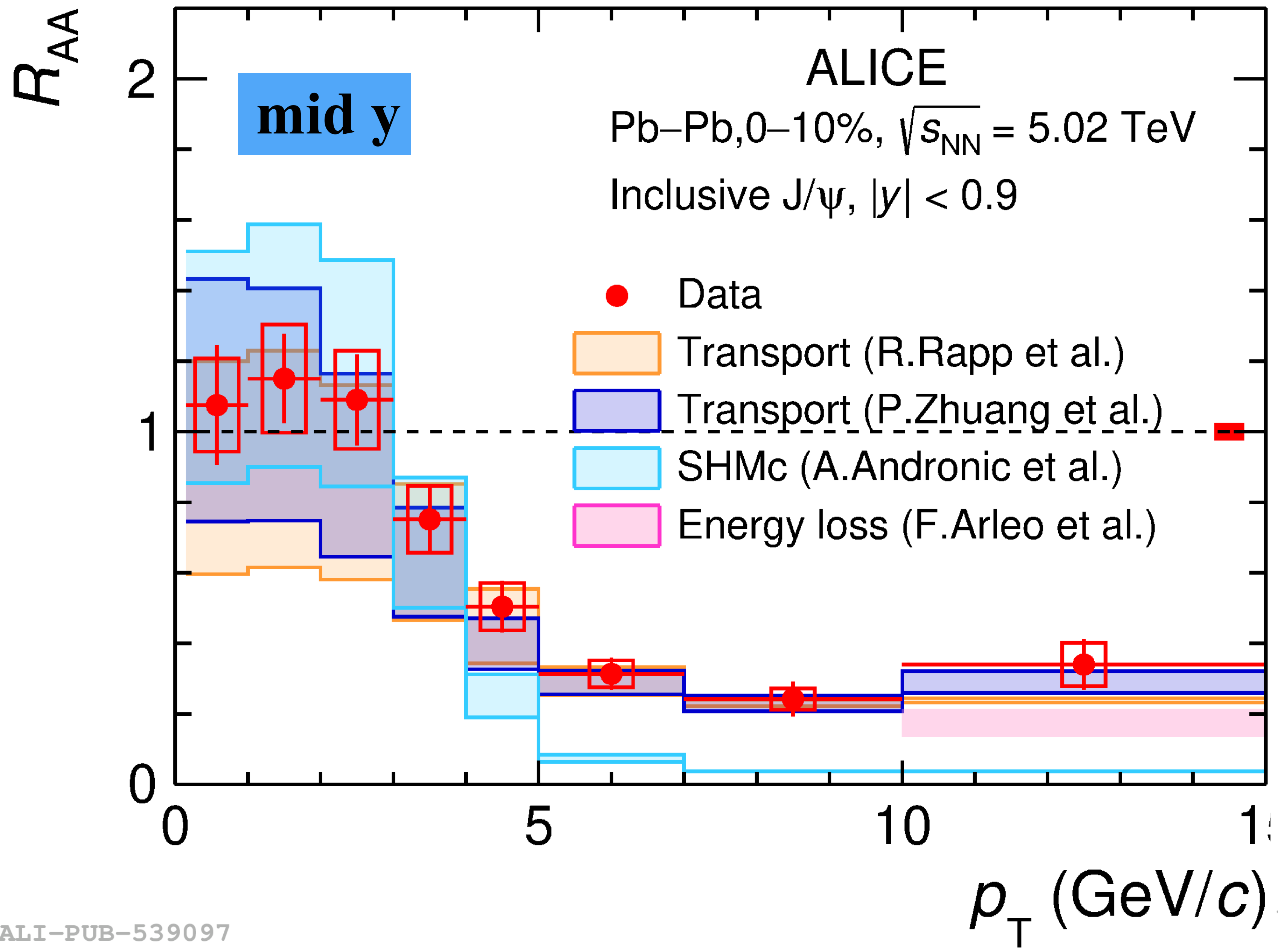

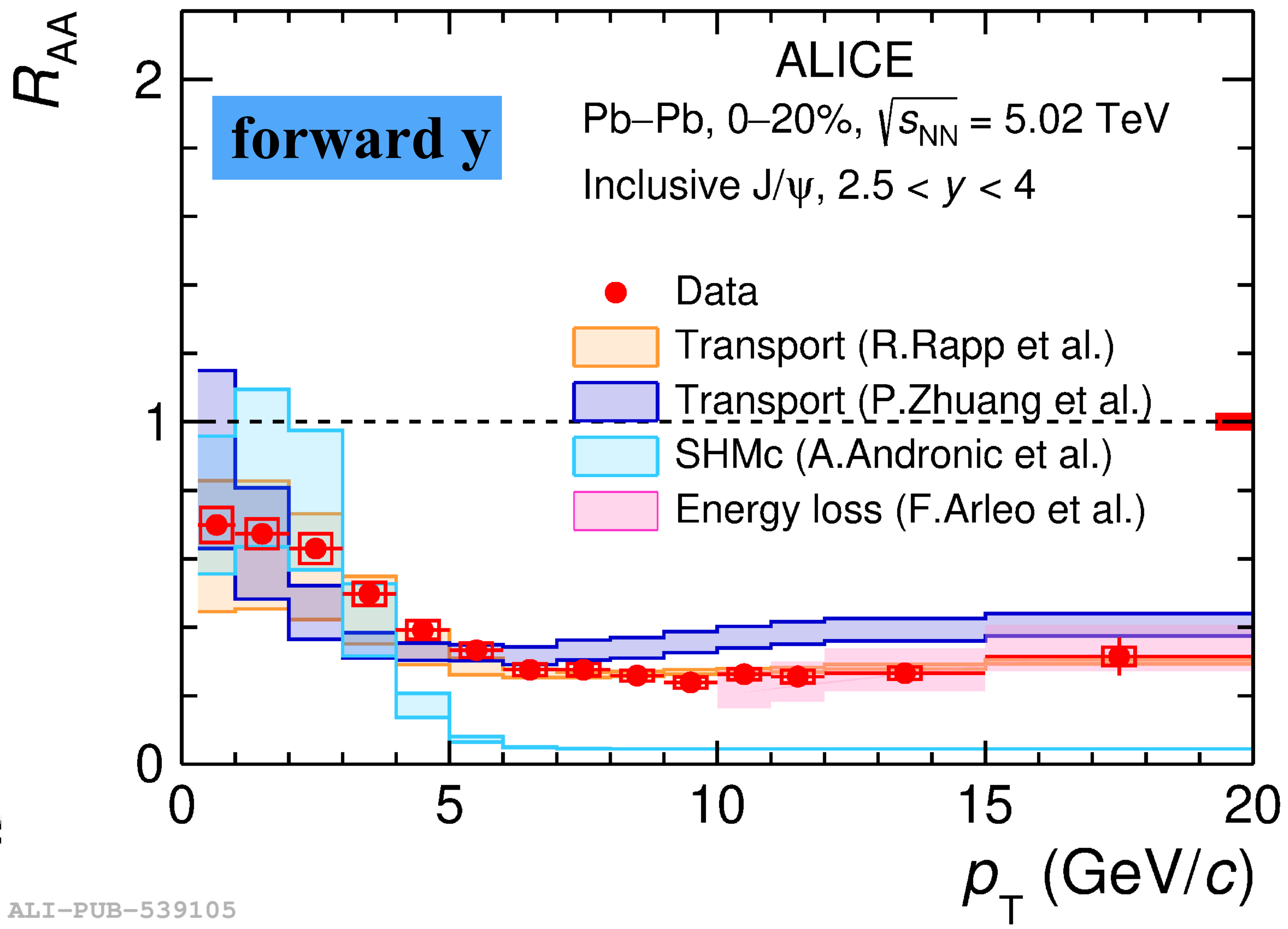

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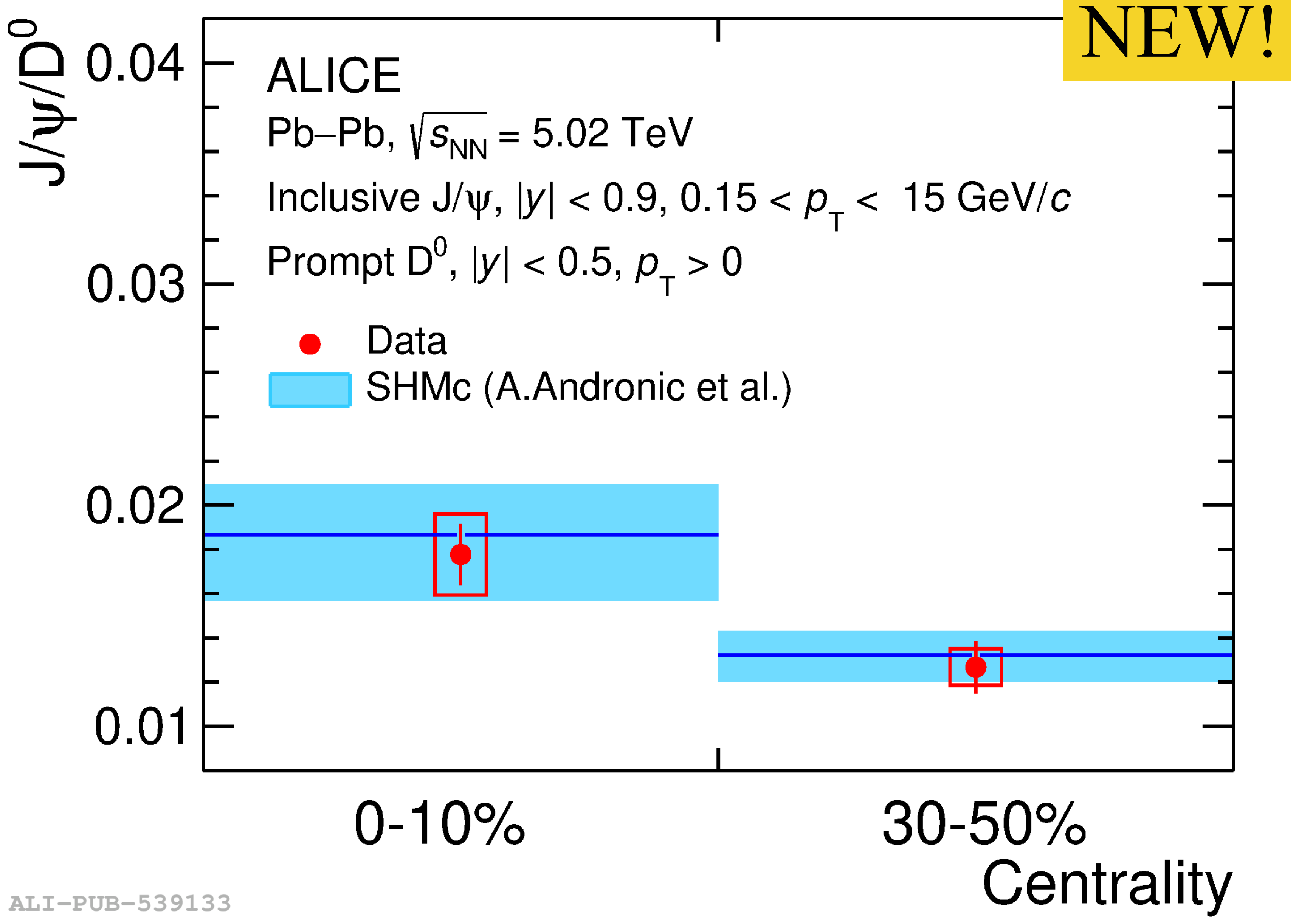
NEW!



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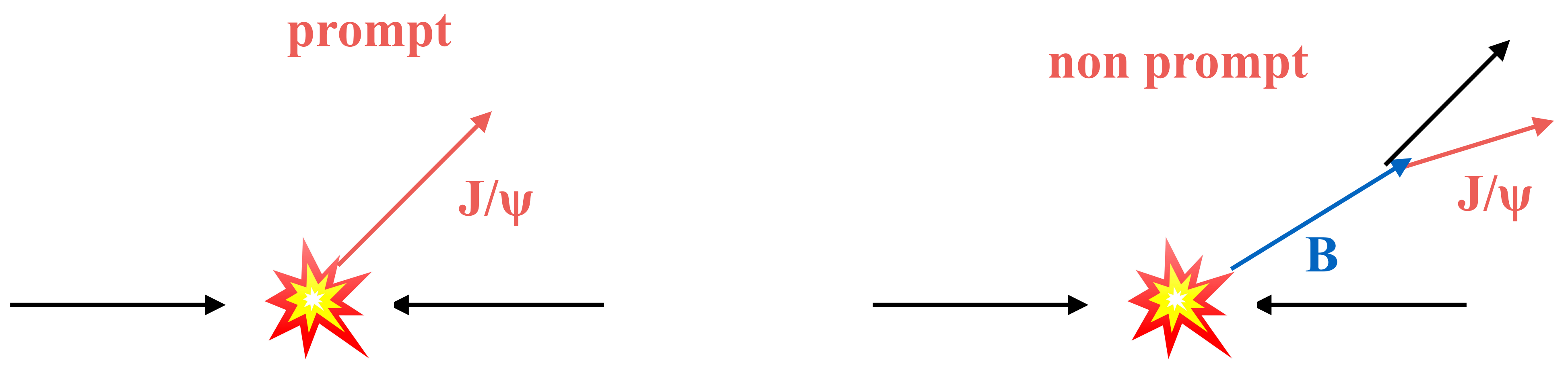
- Large model uncertainty at low p_T from $\sigma_{c\bar{c}}$ in Pb-Pb: need to constrain/measure it!

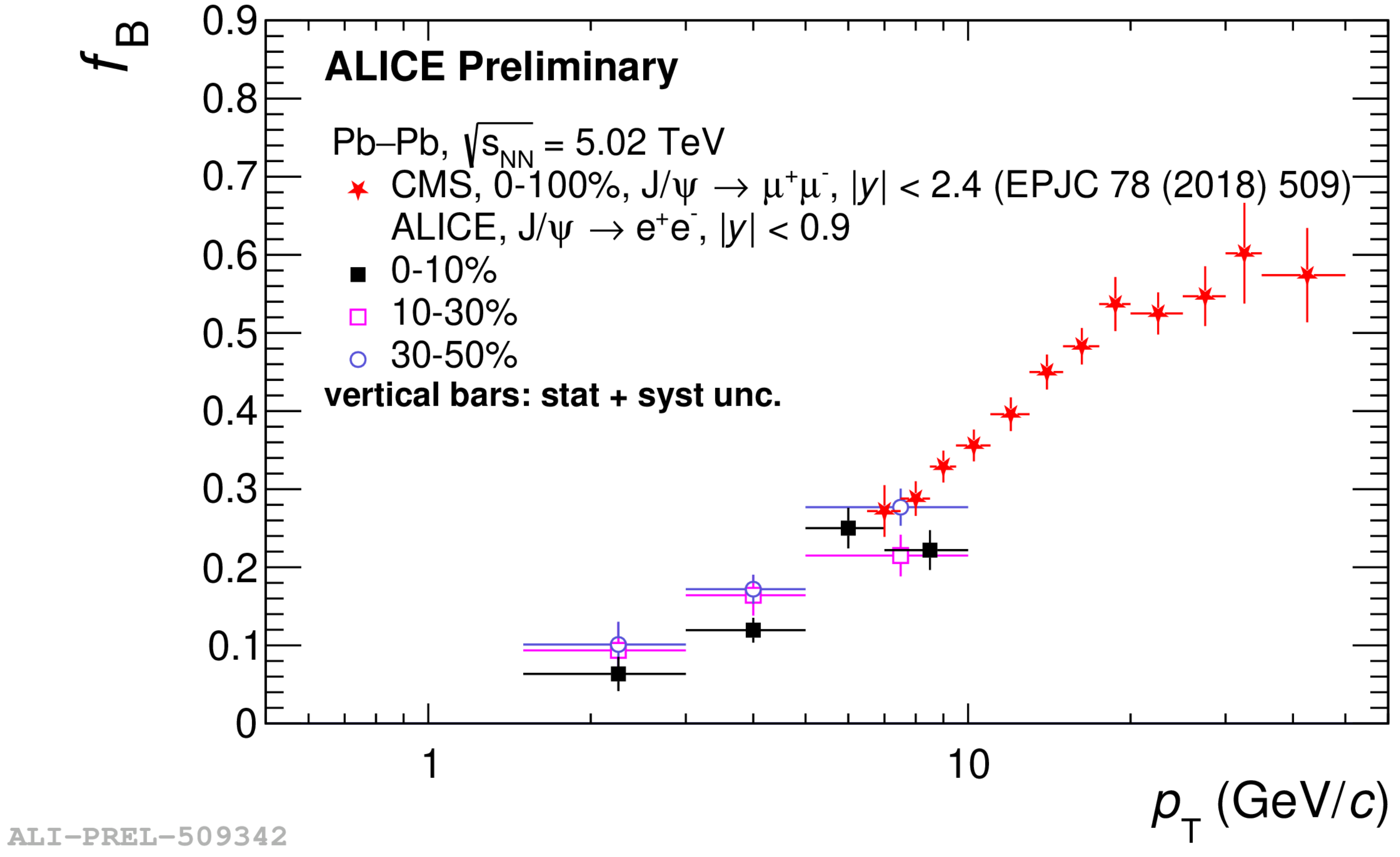
- J/ψ / D ratio provides a tight constraint to models : SHMc model gives a good description of the centrality dependence of the ratio

Prompt J/ψ production

Separation of prompt and non-prompt J/ψ with proper decay time/length

f_B = non-prompt / inclusive





- Non-prompt J/ψ fraction f_B: increasing with p_T and lower for most central collisions

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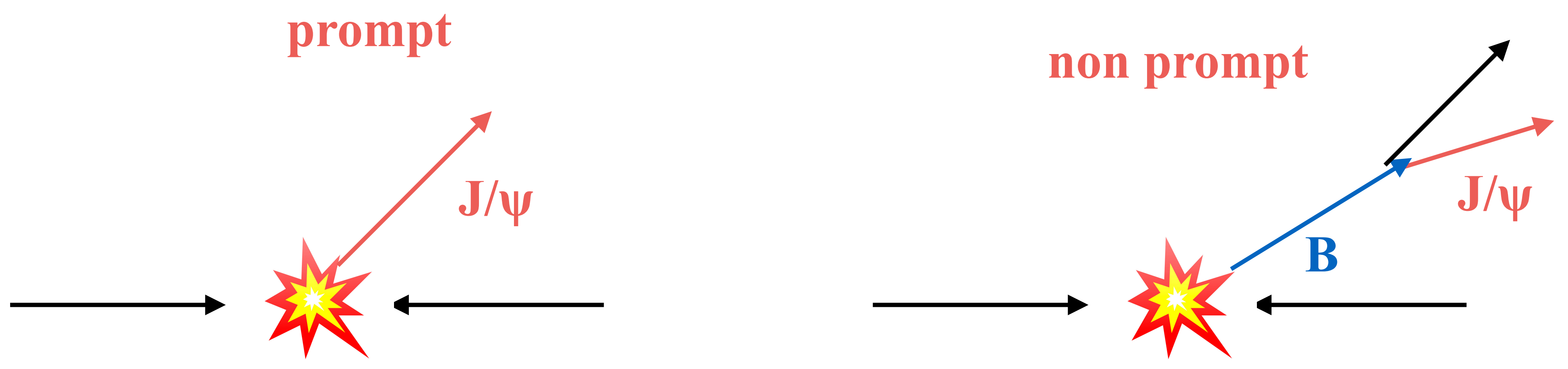
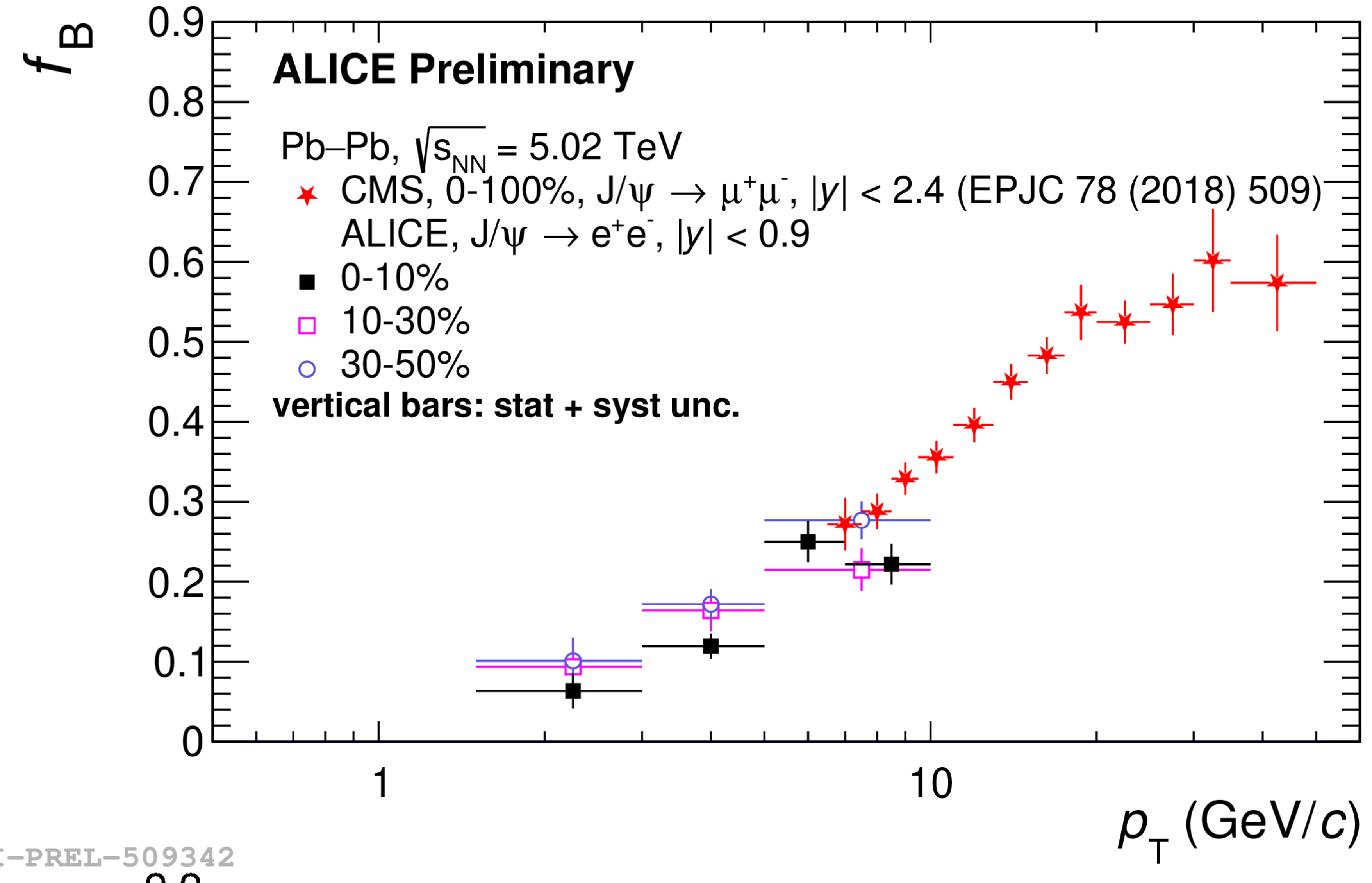


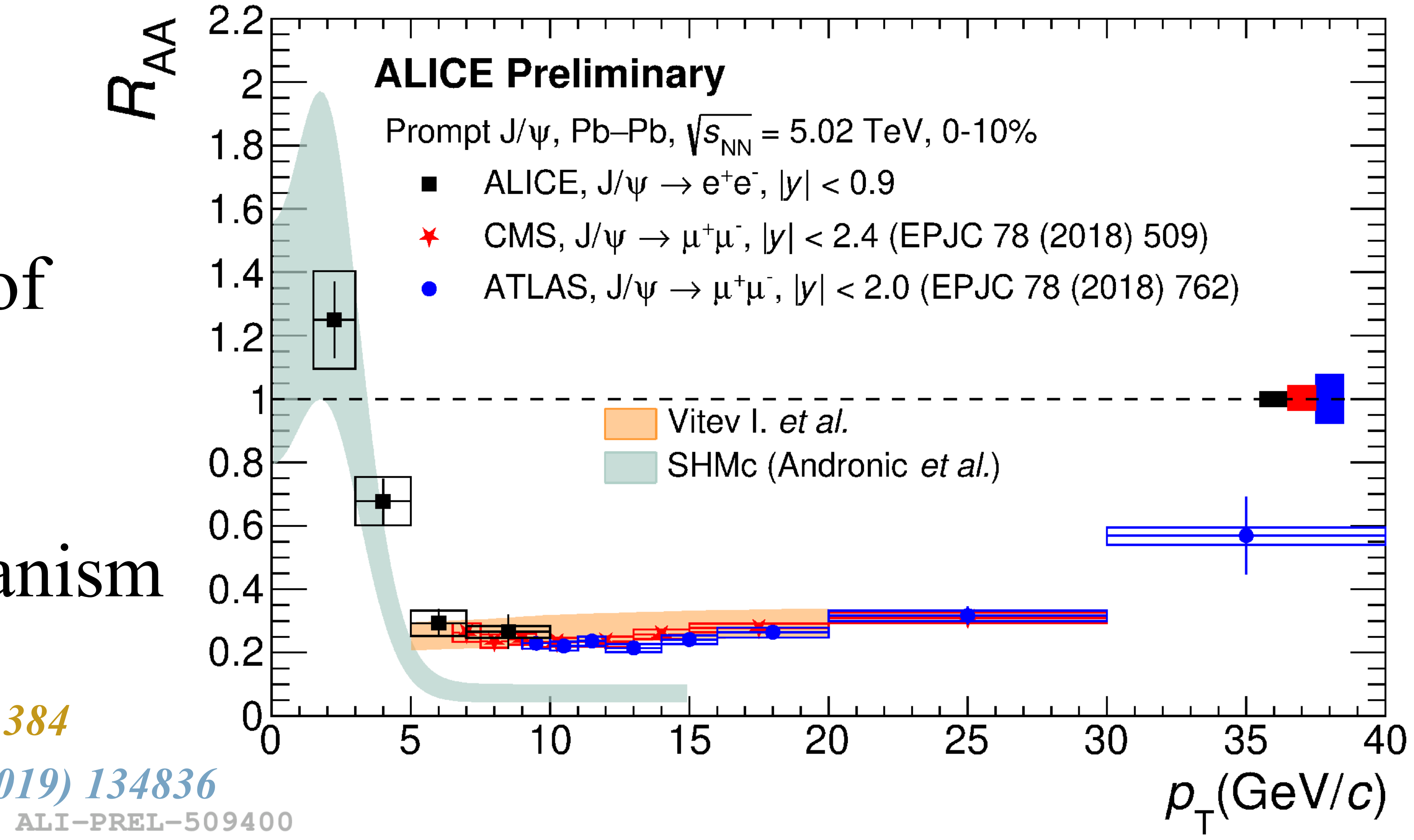


- Non-prompt J/ψ fraction f_B: increasing with p_T and lower for most central collisions
- Complementary p_T ranges between ALICE, ATLAS and CMS for R_{AA} of prompt J/ψ:
  - good agreement in overlapping region
  - almost no suppression at low p_T as expected from regeneration mechanism
  - slight increase of R_{AA} with p_T as expected from energy loss mechanism

Models:

Vitev et al., PLB778 (2018) 384

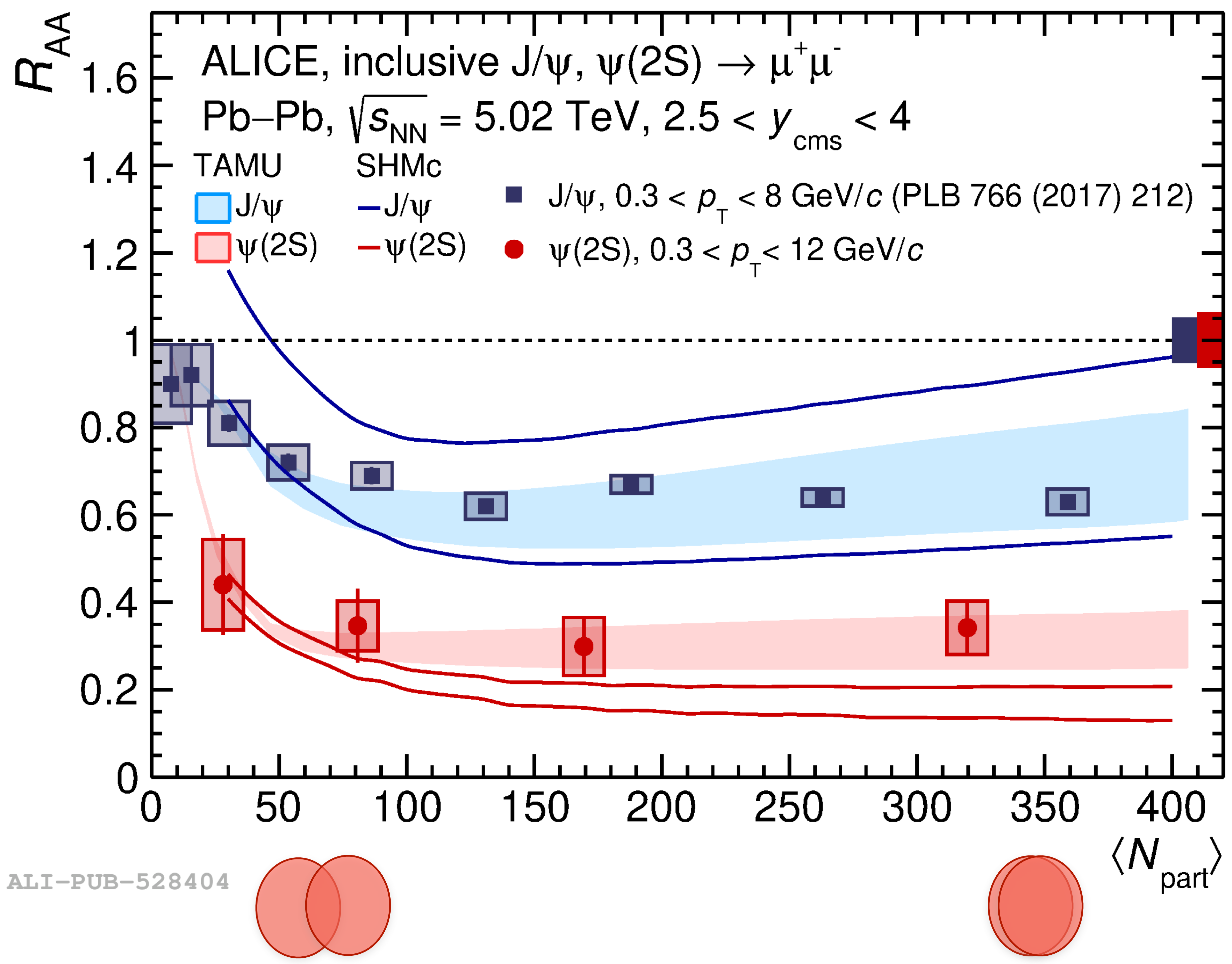
Andronic et al., PLB797 (2019) 134836

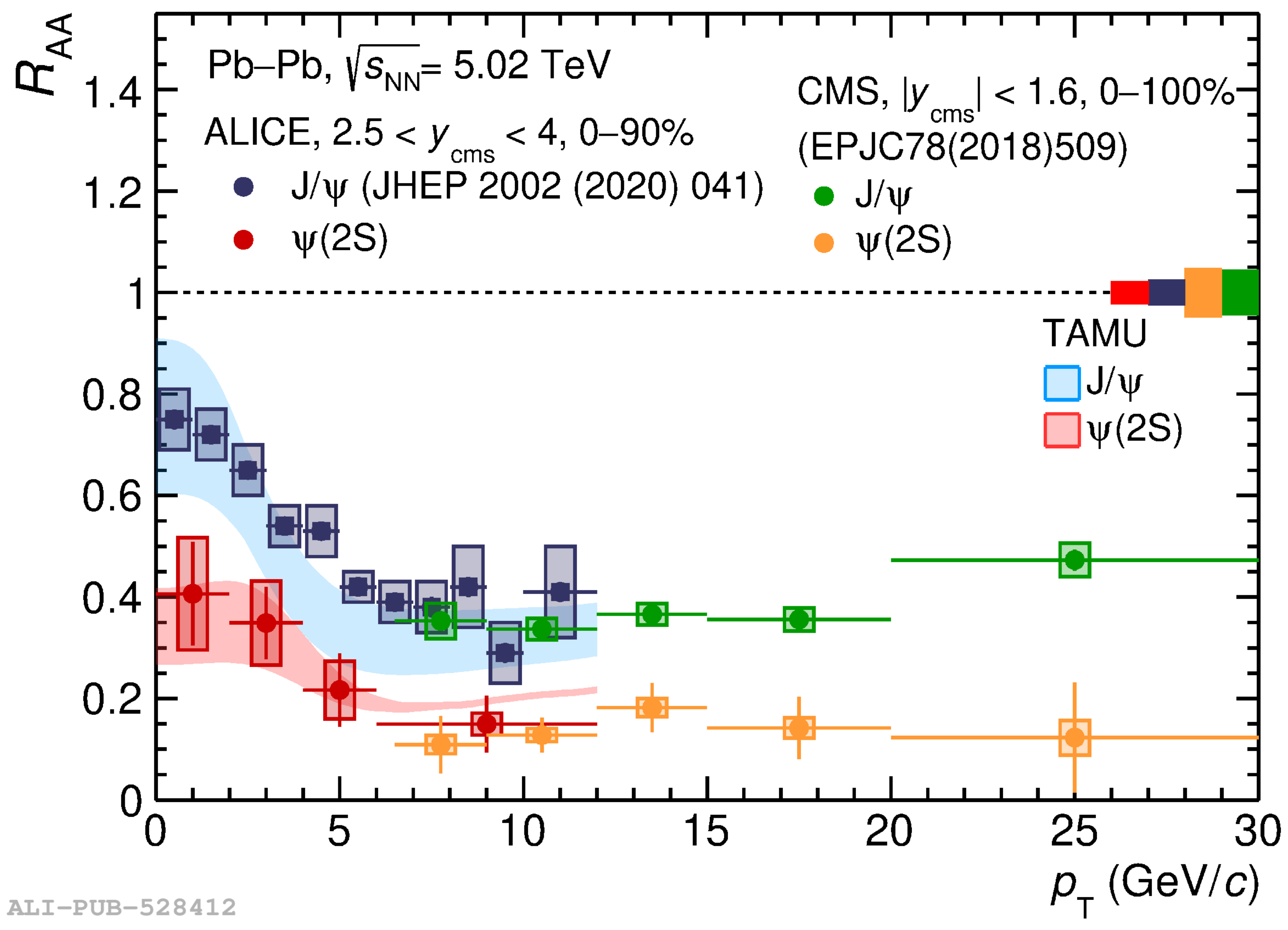


Inclusive ψ(2S) production

ALICE
CMS

ALICE arXiv:2210.08893





Models:

TAMU: Du and Rapp, Nucl.Phys.A943 (2015) 147

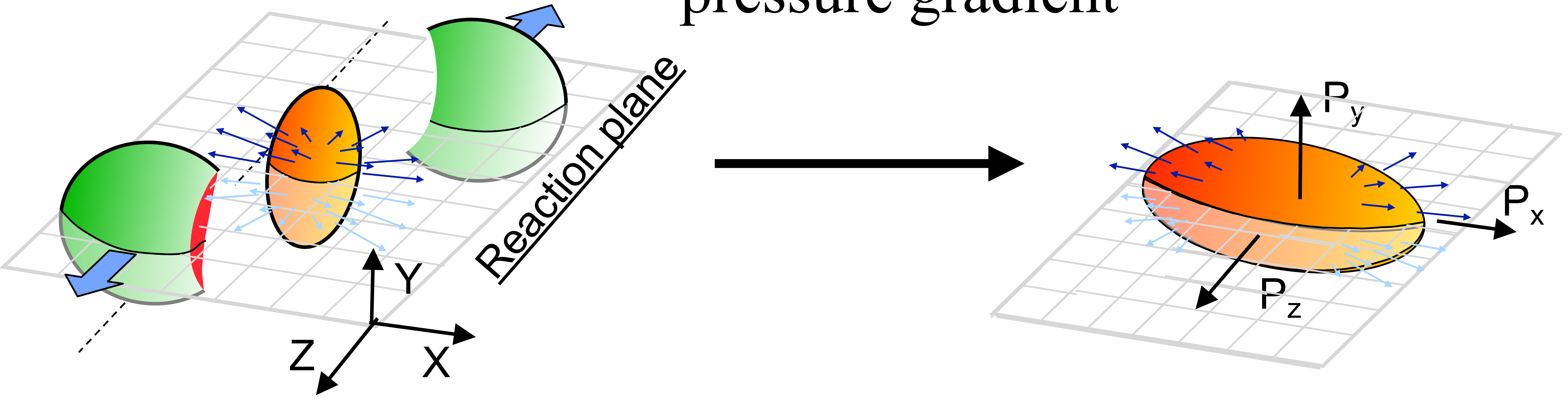
SHMs: Andronic et al., PLB797 (2019) 134836

- ψ(2S) more suppressed than the J/ψ by a factor 2 (lower binding energy for ψ(2S))
- Similar dependence vs N_{part} and p_T for J/ψ and ψ(2S) with less suppression at low p_T as expected from regeneration mechanism
- Strong ψ(2S) suppression persists up to $p_T = 30$ GeV/c

Elliptic and triangular flow of charmonia

- Another observable: azimuthal distribution of particles wrt the reaction plane
- Sensitive to initial collision asymmetry and event-by-event fluctuations
- Path length dependence at high p_T: charmonia expected to be more suppressed in longer path directions

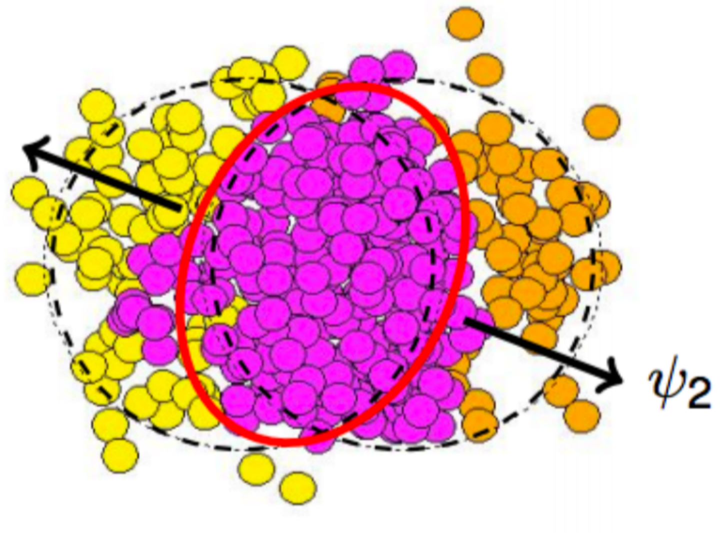
collective interaction
pressure gradient



Fourier distribution

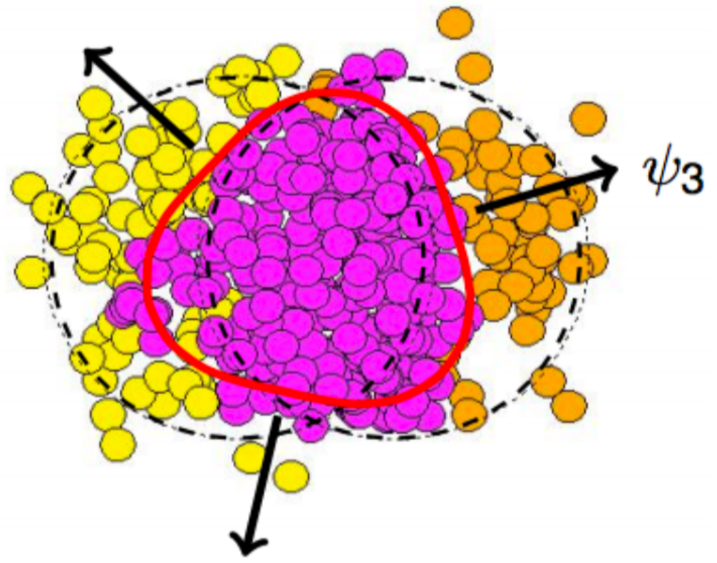
$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

n = 2: elliptic flow v_2



+

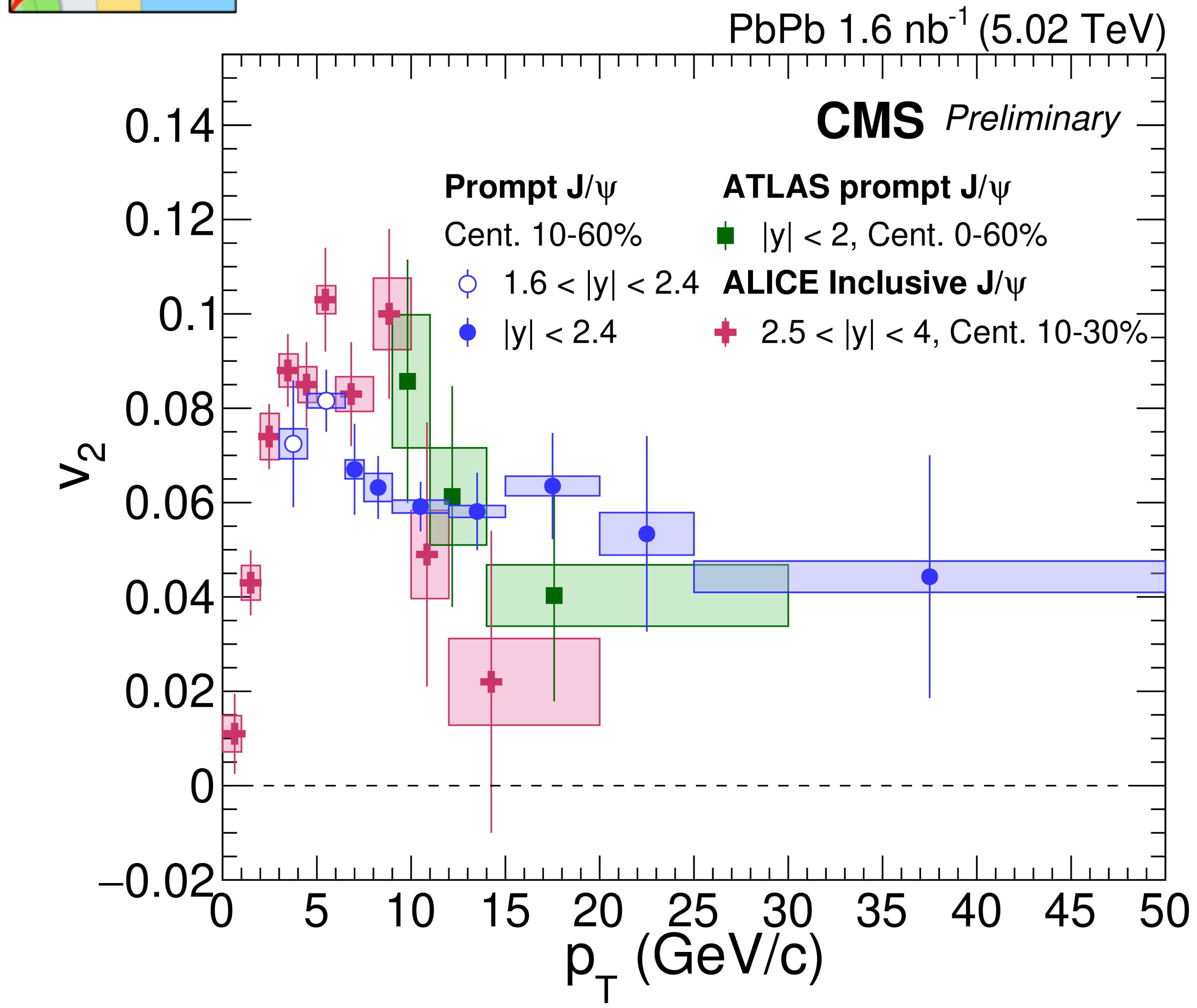
n = 3: triangular flow v_3

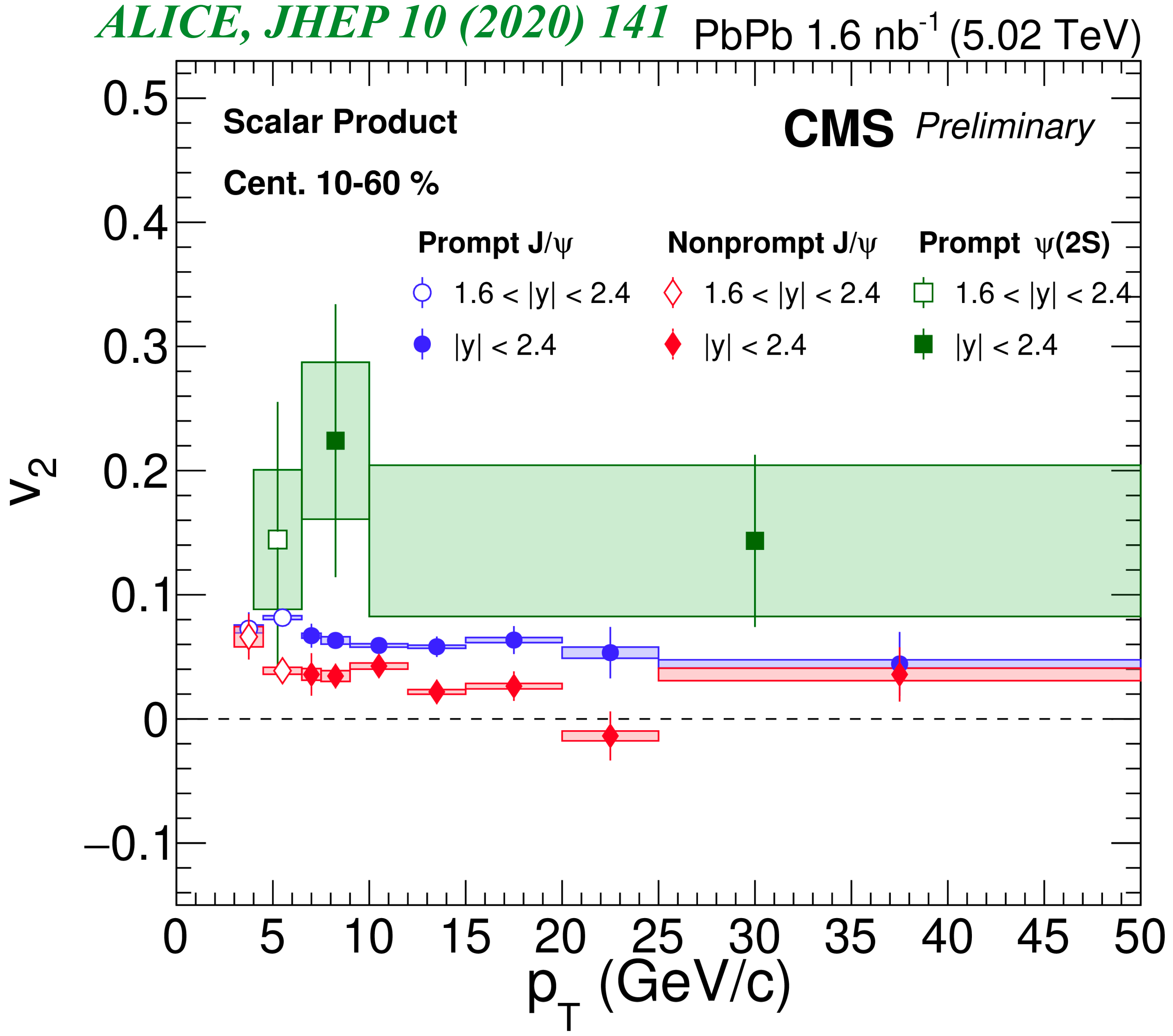


+ …

Elliptic and triangular flow of charmonia

CMS-PAS-HIN-21-008
ATLAS, EPJC 78 (2018) 784
ALICE, JHEP 10 (2020) 141





- Large J/ψ v_2 up to p_T = 50 GeV/c :
  - low p_T: indication of collective flow behaviour of charm quarks
  - high p_T: path length dependence
- First indication of prompt ψ(2S) v_2 > prompt J/ψ v_2 that may be linked to different hadronization time in the regeneration picture

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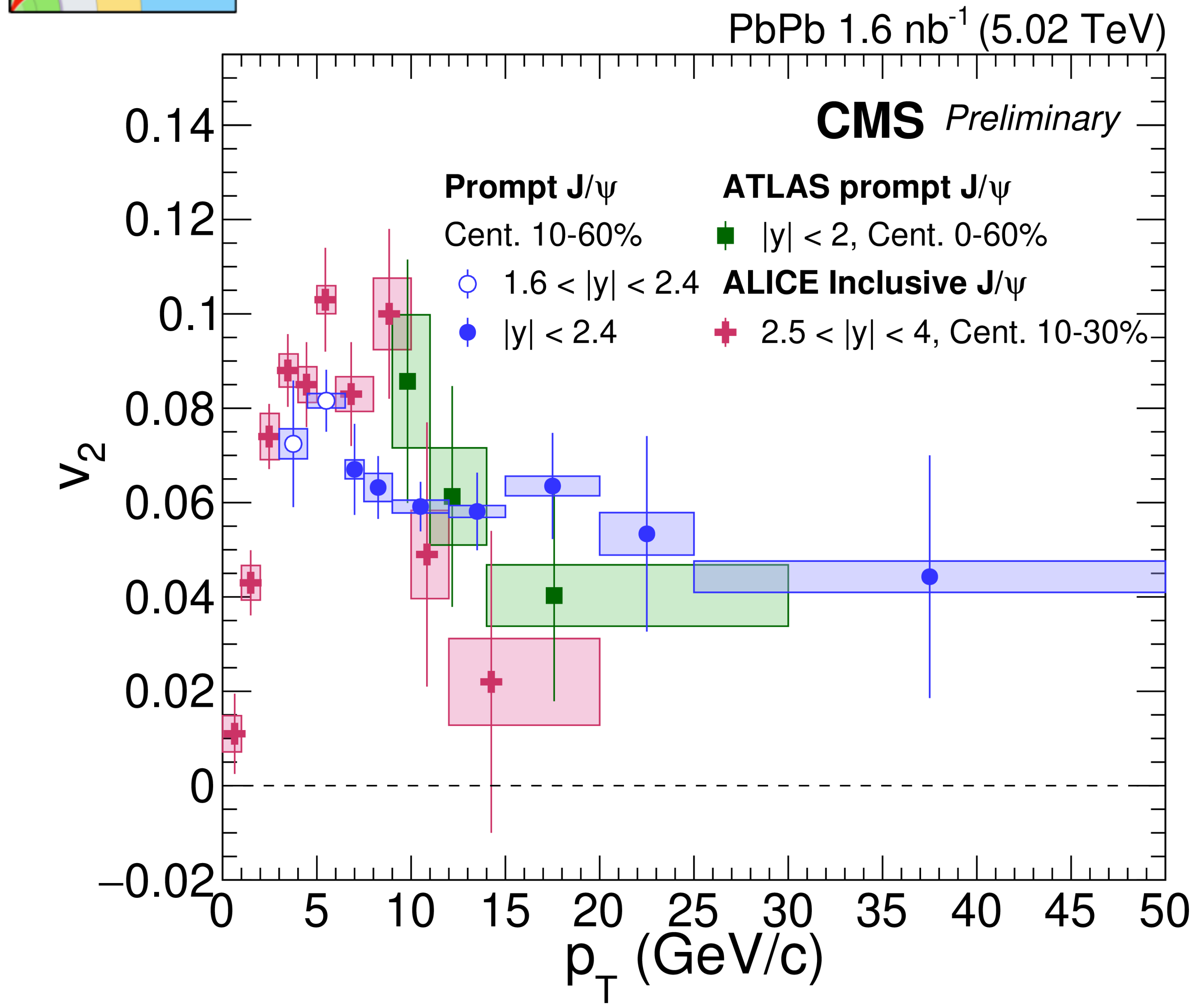

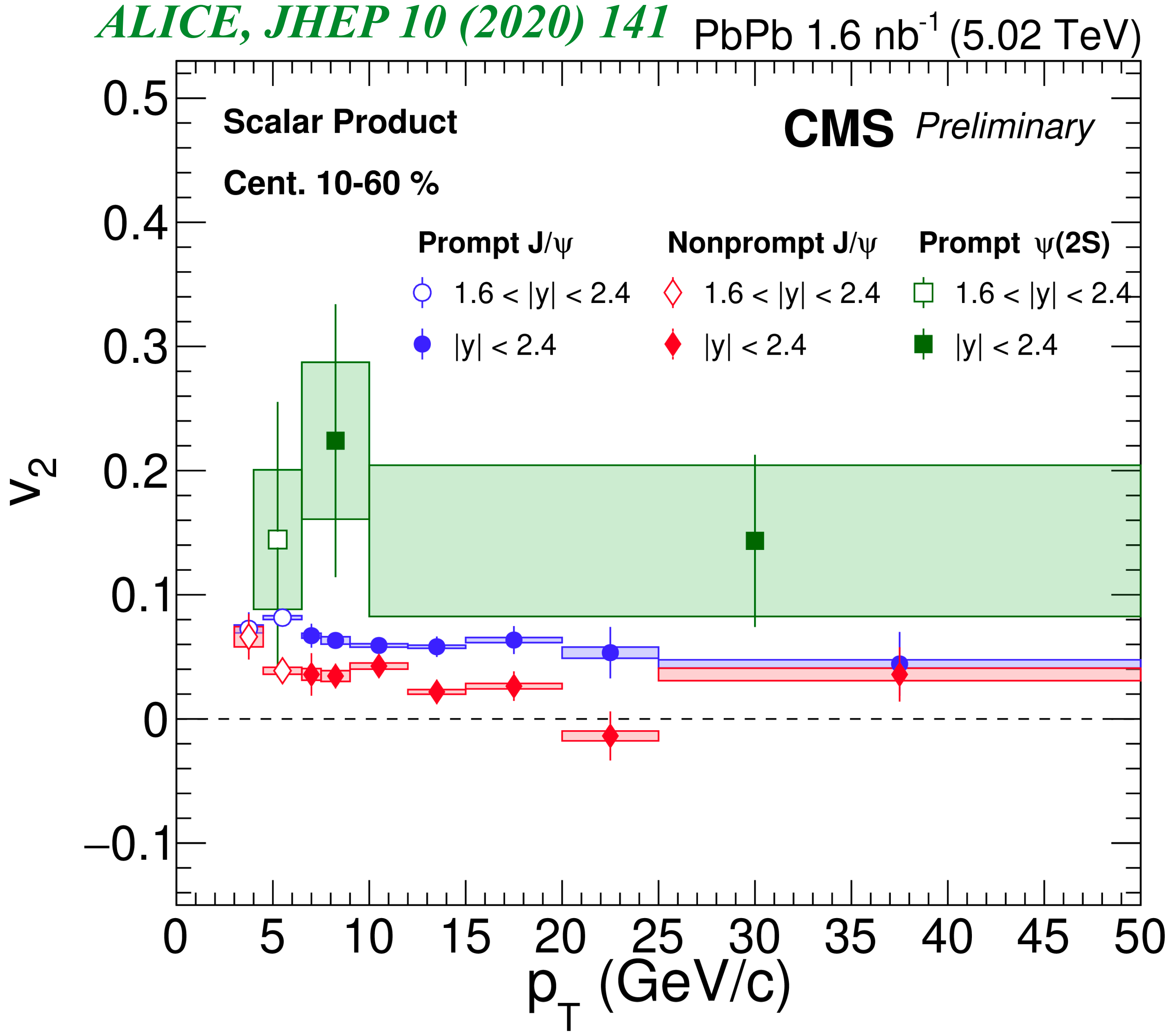

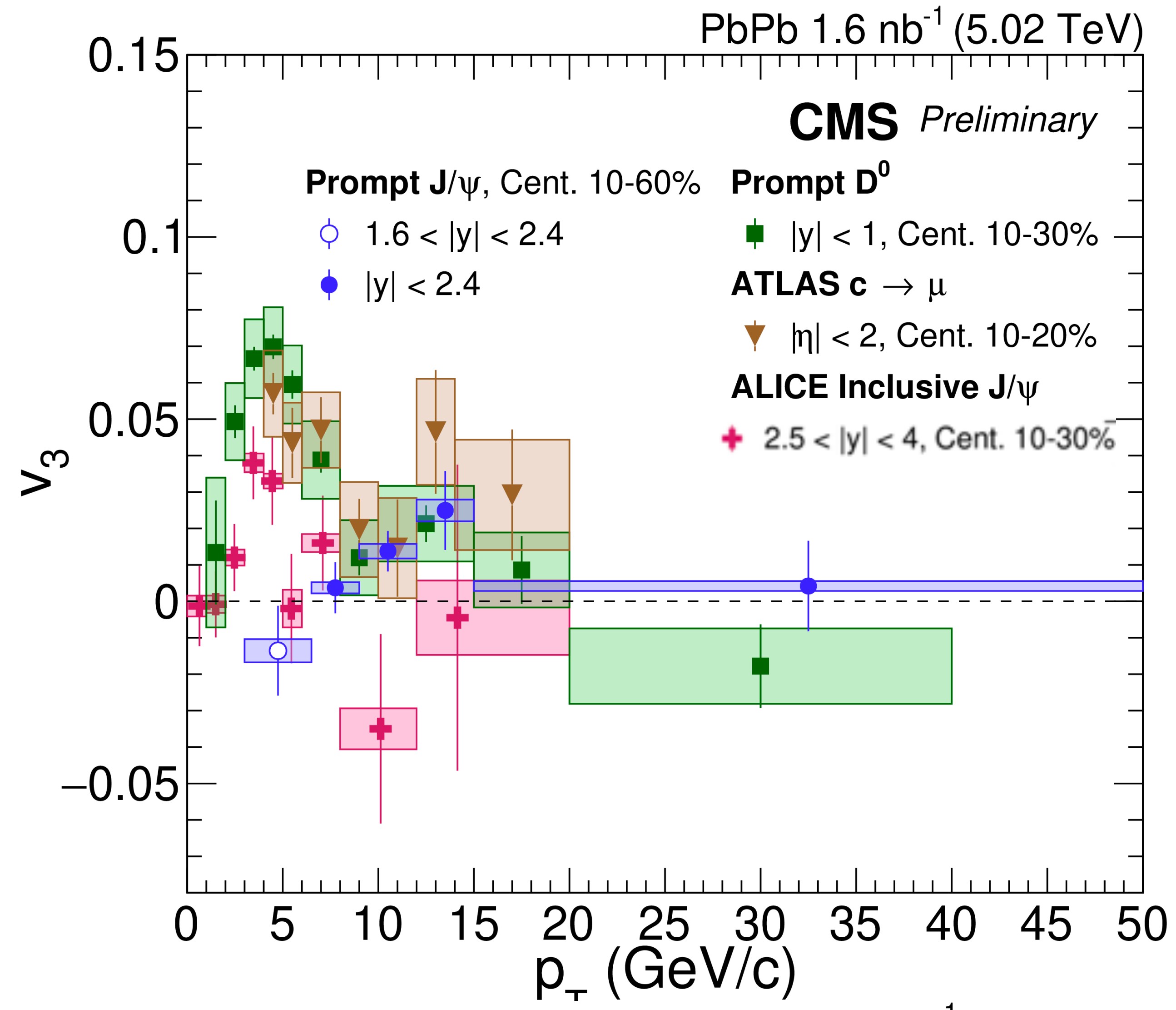

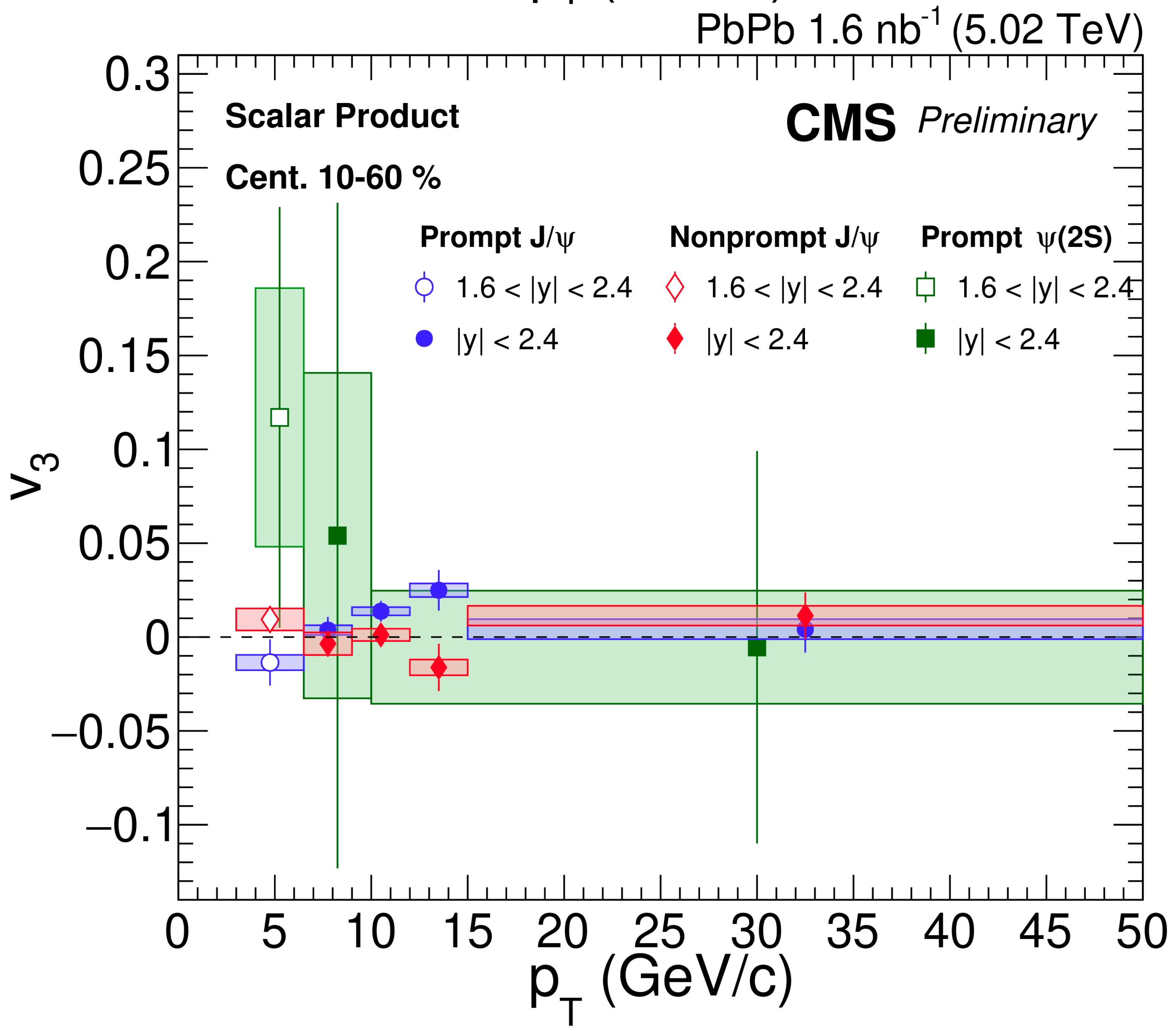

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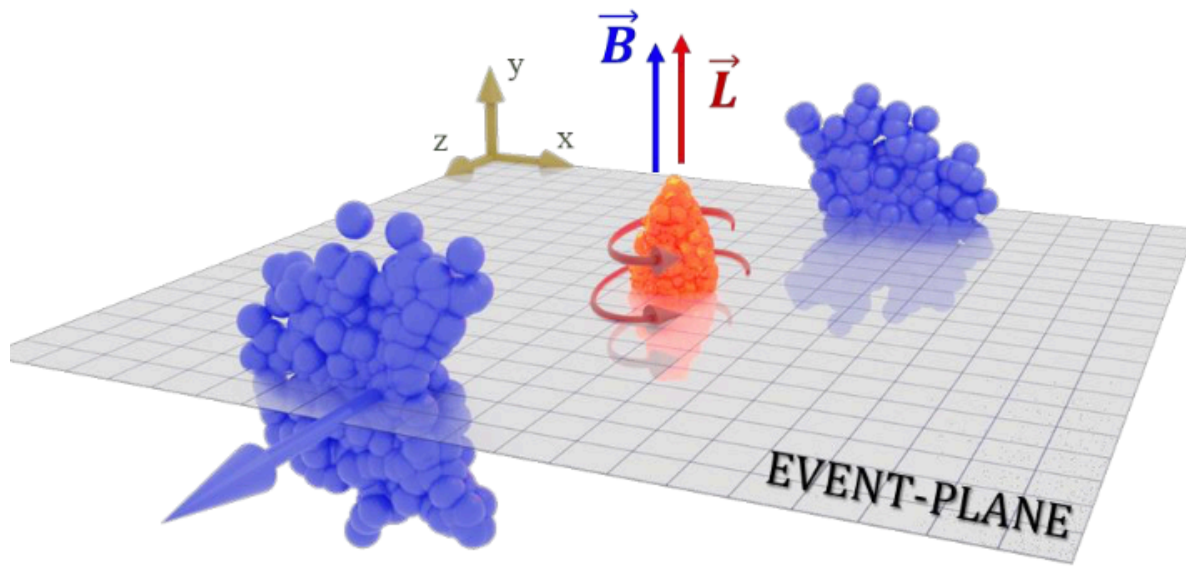
- Prompt J/ψ, ψ(2S) v_3 consistent with zero at high p_T

Polarisation wrt Pb-Pb event plane

- Large magnetic field ($\vec{B}$) and angular momentum ($\vec{L}$) produced in the early stage of the QGP formation, perpendicular to the reaction plane → can influence the polarisation of quarkonia
- B ~ 10^{14} T with short live time (1 fm/c) *Kharzeev et al., NPA803 (2008)*
- L highest in semi-central collisions, very large QGP velocity, with an effect on the system evolution up to freeze-out *Becattini et al., PRC77 (2008) 024906*



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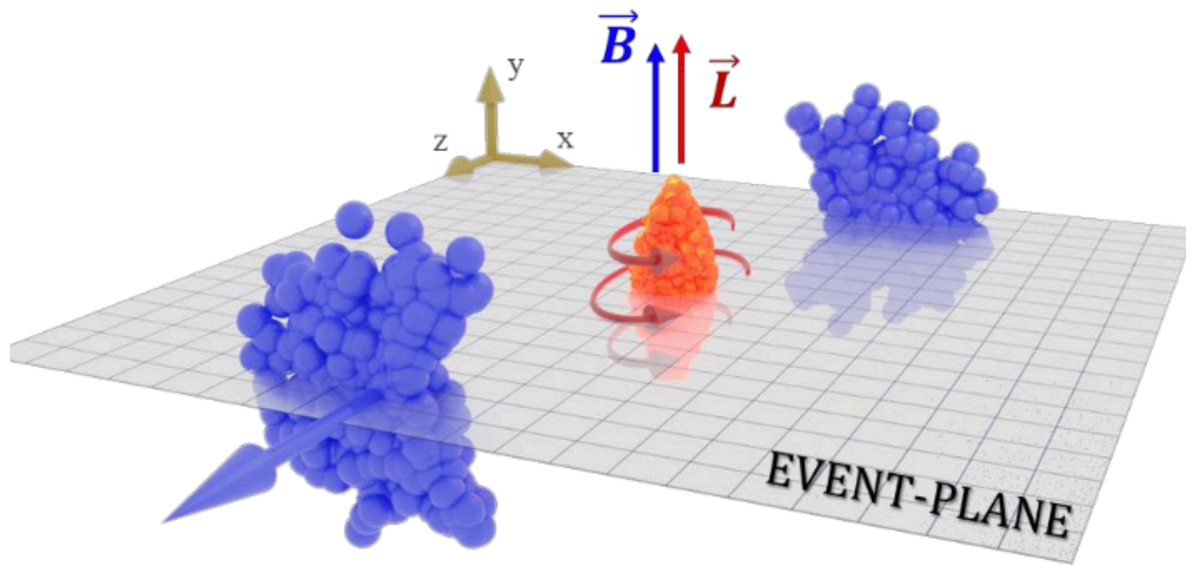

- Polarisation of J/ψ extracted along the axis perpendicular to the reaction plane

$$W(\theta) \propto \frac{1}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta\right)$$

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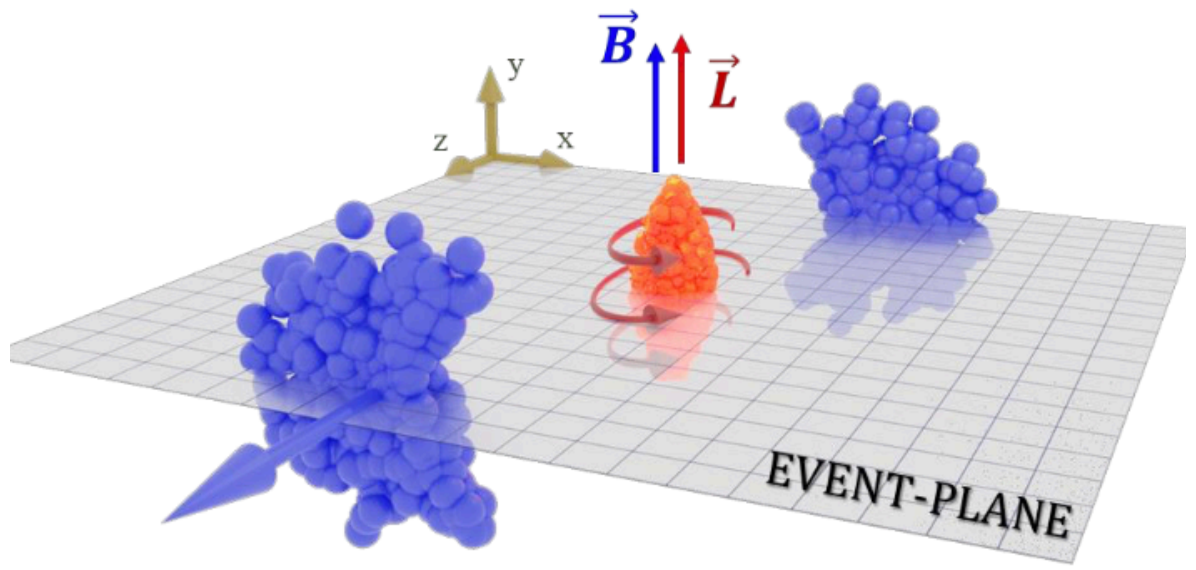
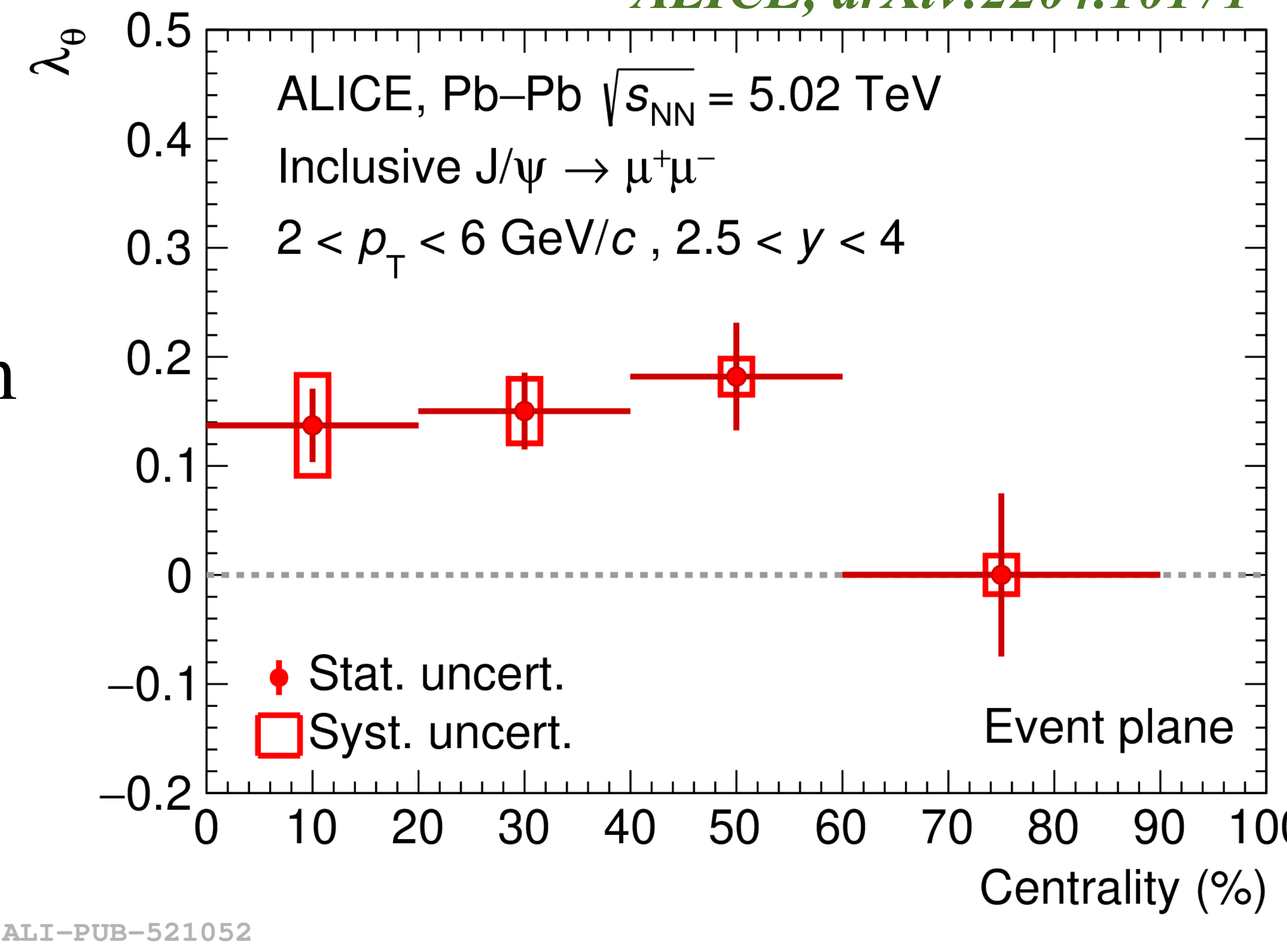


ALICE, arXiv:2204.10171



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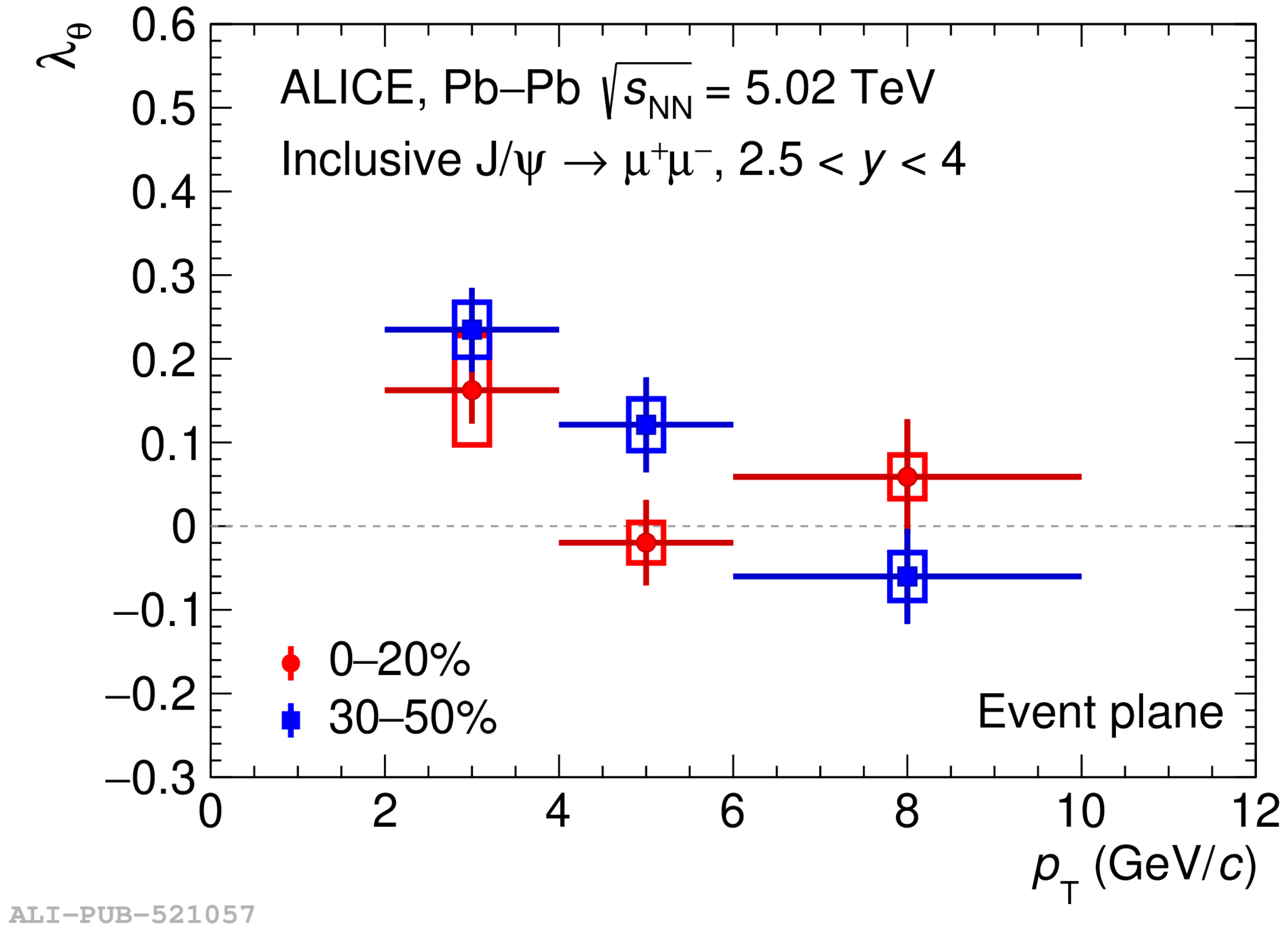
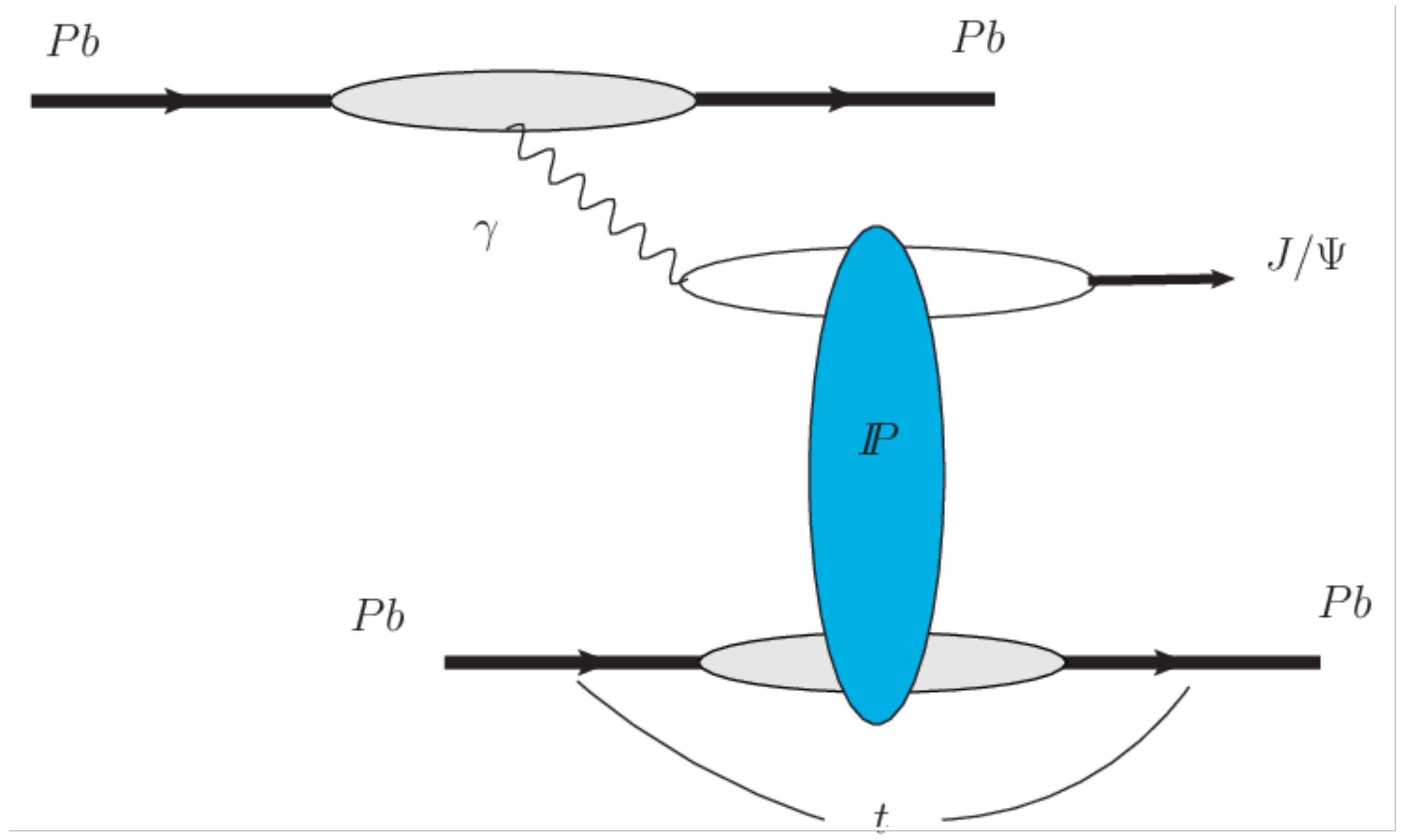
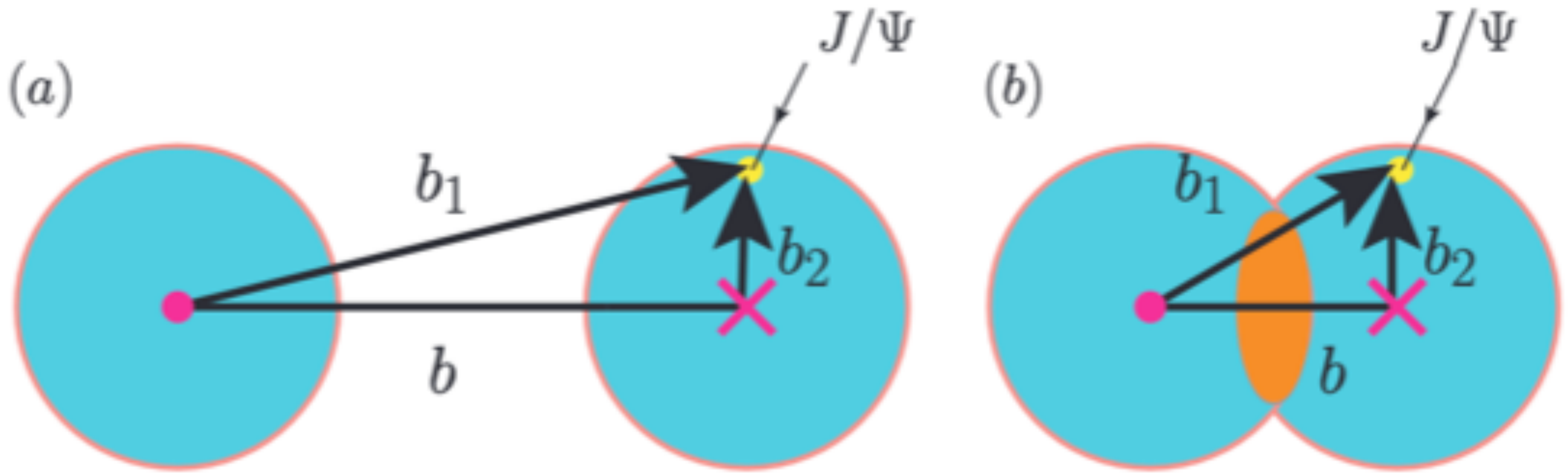


- First J/ψ measurement wrt event plane: small but significant transverse polarisation at low p_T (3.9σ effect for semi-central events and p_T ~ 3 GeV/c)
- Spin alignement observed for light vector mesons (K^{*0} and ϕ) at midrapidity and low p_T: common origin? *ALICE, PRL125 (2020) 012301*

Coherent J/ψ photoproduction with nuclear overlap

- Strong electromagnetic field from Pb nuclei: photoproduction of vector mesons with very low p_T (< 500 MeV)
- Coherent production when the photon couples coherently with the target nucleus
- Processes well studied at LHC in ultra-peripheral Pb-Pb collisions (UPC) when the incoming nuclei do not overlap: **see talk by J.G. Contreras**





Pb-Pb UPC **Pb-Pb with nuclear overlap**

- Coherent J/ψ photoproduction also measured **with nuclear overlap in peripheral collisions → theoretical challenges:**
  - does coherence condition survive for a broken nucleus?
  - do only spectator nucleons participate to coherence?
  - can this process be used as a probe of charmonium color screening in the QGP?

Coherent J/ψ photoproduction with nuclear overlap

Models:

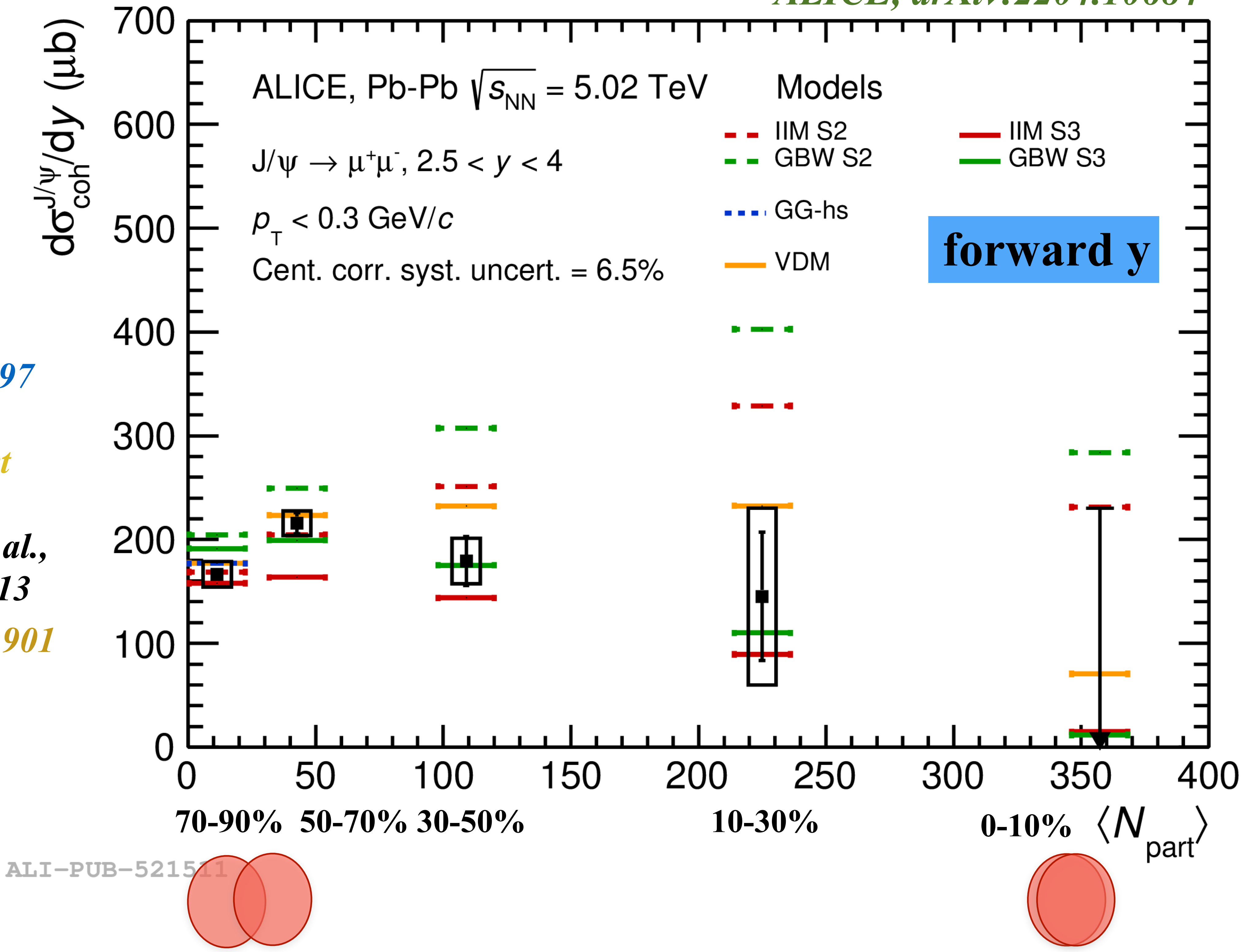
GG-hs: J. Cepila et al., PRC 97 (2018) 024901

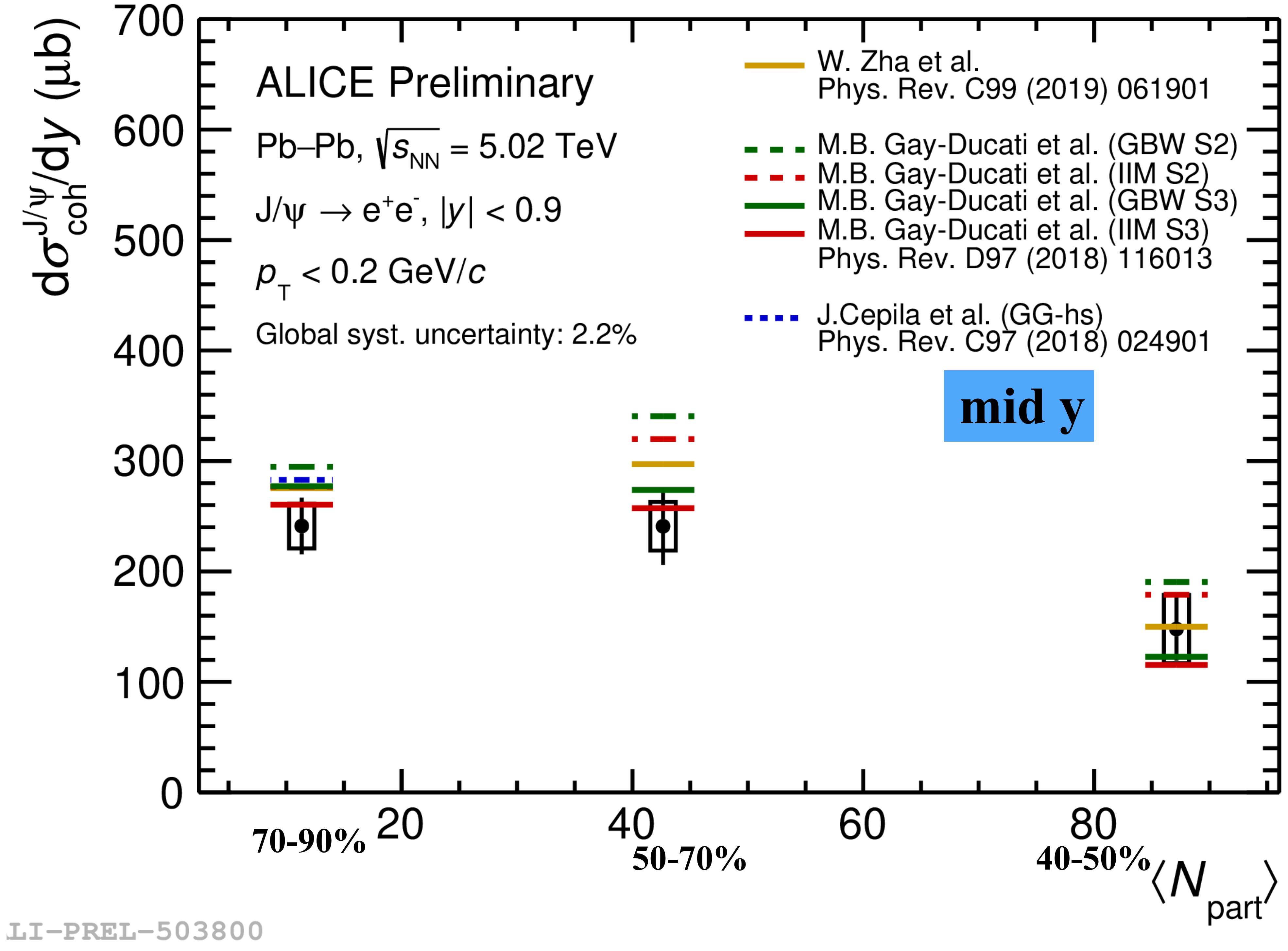
VDM: M. Klusek-Gawenda et al., PLB. 790 (2019) 339

IIM/GBW: M. Gay Ducati et al., Phys. Rev. D. 97 (2018) 116013

Zha et al., PRC99 (2019) 061901

ALICE, arXiv:2204.10684





- Cross section measured at forward and midrapidity: more than 5σ significance down to semi-central (30-50%) collisions at forward rapidity

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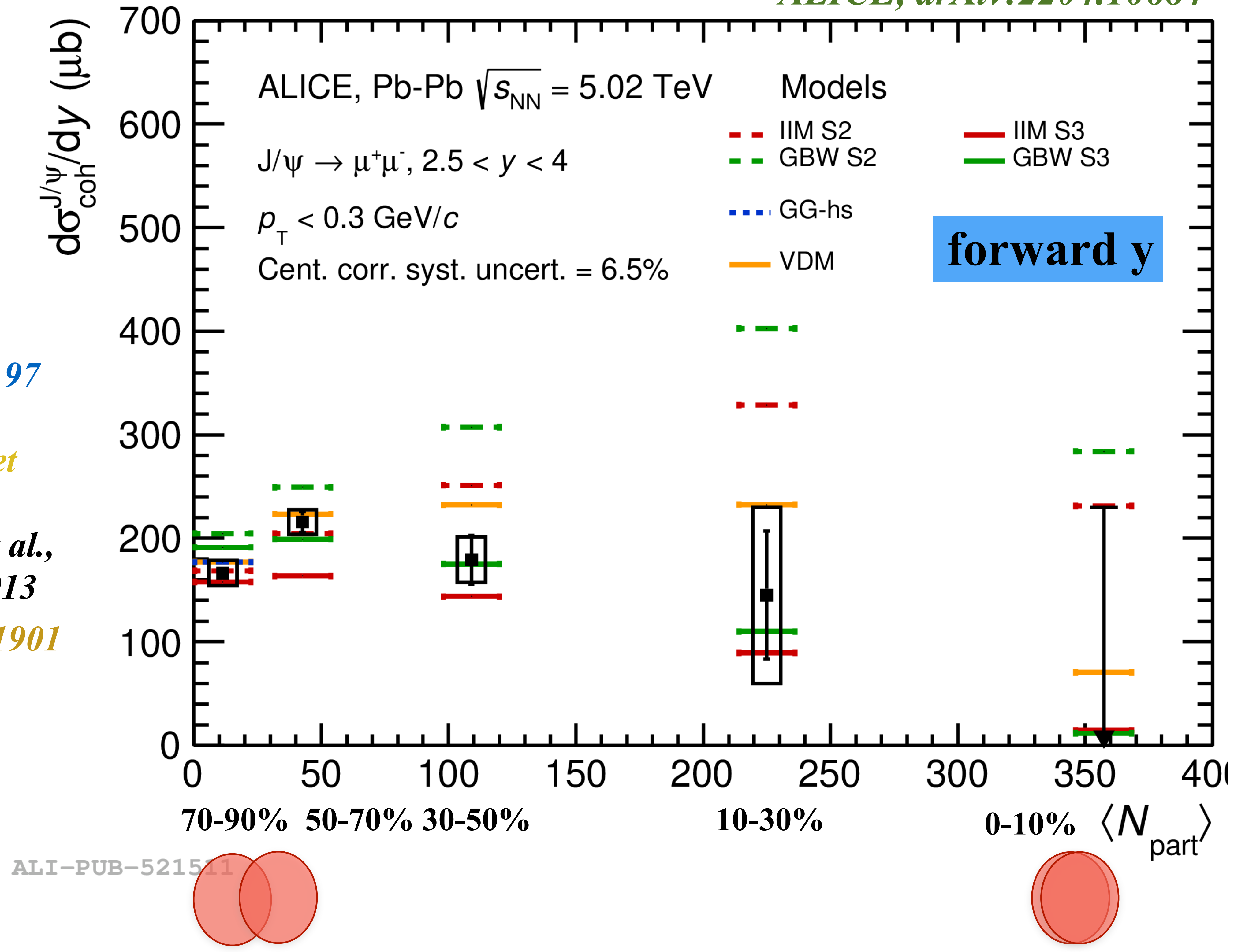
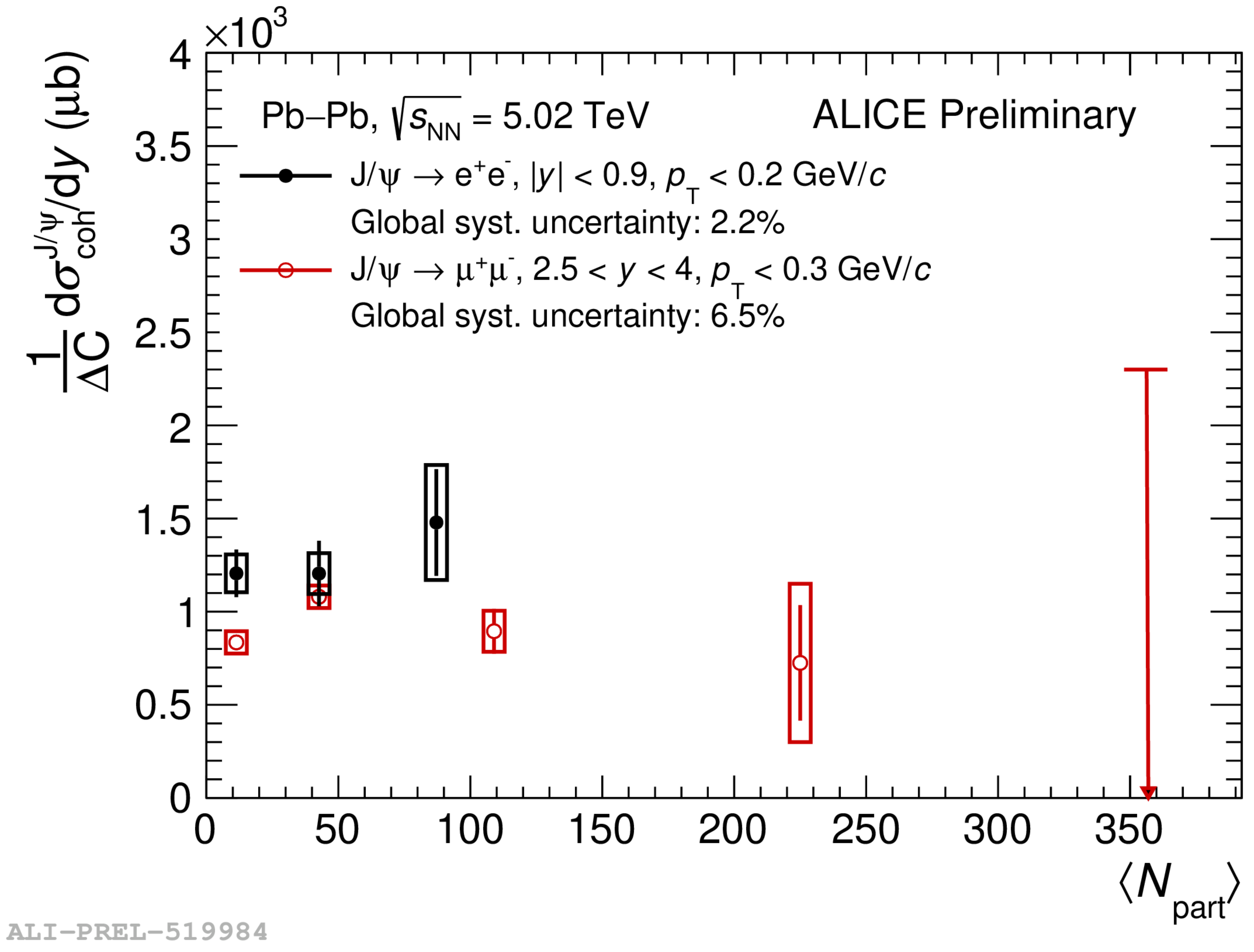
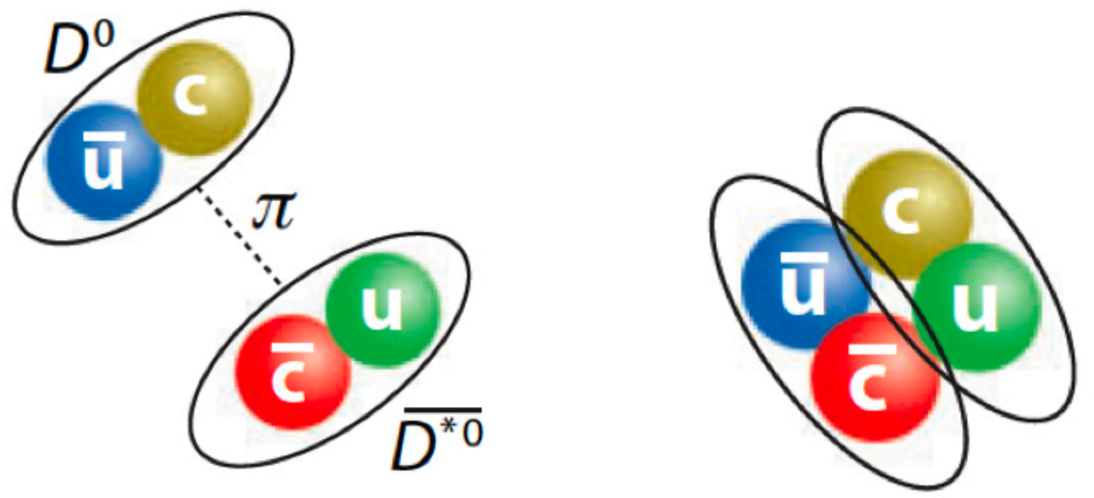
ALICE, arXiv:2204.10684





- Cross section measured at forward and midrapidity: more than 5σ significance down to semi-central (30-50%) collisions at forward rapidity
- No centrality dependence (once normalised by the centrality bin width ΔC) of the cross section: no evidence of variation from nuclear overlap or medium effects

Exotic charmonium $\chi_{c1}(3872)$ state

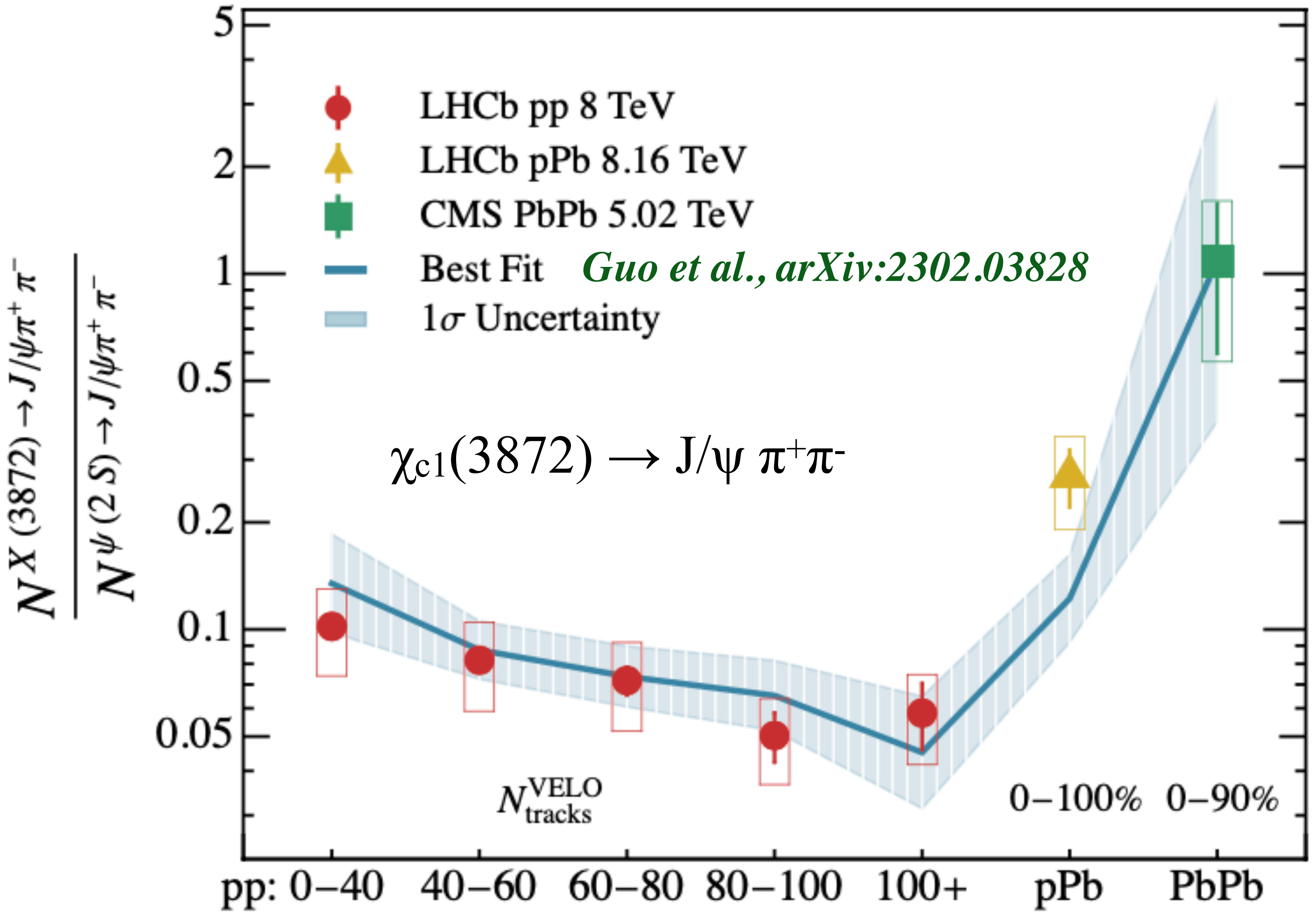


D^0–$\overline{D}^{*0}$ "molecule" **Diquark–diantiquark**

- $\chi_{c1}(3872)$: D-D* molecule or tetraquark? See **talk by A. Rakotozafindrabe**
- In heavy-ion, produced only at the hadronization stage? Regeneration for loosely bound states delayed with respect to compact tetraquarks

$$\text{Yield ratio: } \rho \equiv \frac{N_{\text{corr}}^{X(3872)\to J/\psi\pi\pi}}{N_{\text{corr}}^{\psi(2S)\to J/\psi\pi\pi}}$$

CMS, PRL 128, 032001 (2022)
LHCb-CONF-2022-001
LHCb, PRL126, 092001 (2021)



- Evidence of $\chi_{c1}(3872)$ in Pb-Pb collisions
- Yield ratio enhanced in Pb-Pb wrt pp ($\rho_{pp} \sim 0.1$)
- Competing processes: regeneration vs suppression. These two processes can explain the $\chi_{c1}(3872)$ production dependence with system size.

Summary and outlook

- LHC experiments **probe the quark gluon plasma** formed in heavy-ion collisions **with charmonium** production

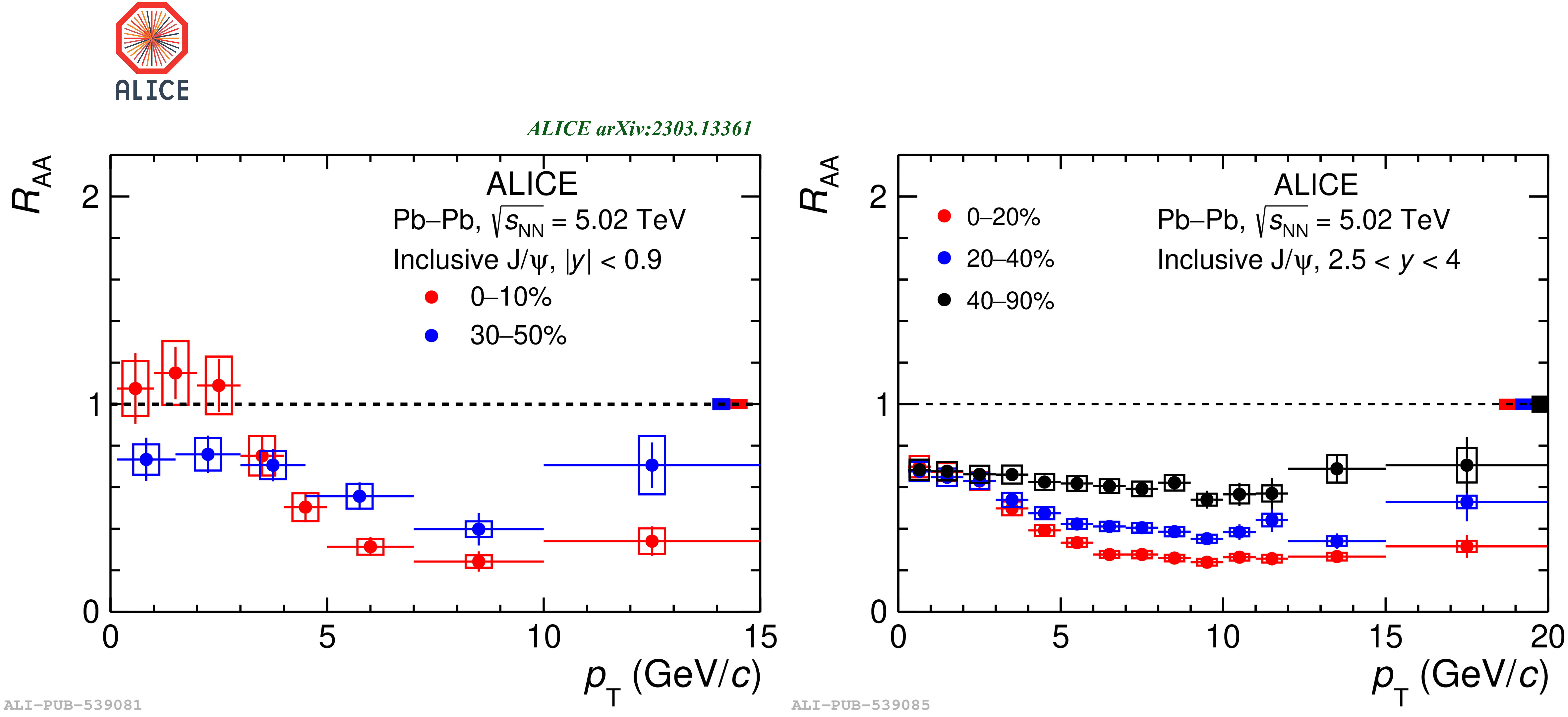
- Charmonium production measurements in heavy-ion collisions
  - Nuclear modification factor, R_{AA}
    - low p_T : J/ψ and ψ(2S) less suppressed at low p_T as expected from **regeneration mechanism**
    - mid and high p_T : large suppression as an interplay between **dissociation** and **energy loss**
    - **ψ(2S) 2x more suppressed** than J/ψ
  - Elliptic and triangular flow
    - large J/ψ v_2 and **indication of larger ψ(2S)** $\boldsymbol{v_2}$
    - J/ψ, **ψ(2S)** $\boldsymbol{v_3}$ consistent with zero at high p_T
  - Polarisation wrt event plane
    - small but **significant J/ψ transverse polarisation** at low p_T : effect from large $\vec{B}$ and $\vec{L}$ produced in the early stage?
  - Coherent J/ψ γ-production: **no dependence with centrality** of the measured cross section within uncertainties
  - Evidence of exotic charmonium $\boldsymbol{\chi_{c1}}$**(3872) in Pb-Pb** with **yield ratio to ψ(2S) enhanced wrt pp**

- LHC experiment upgrades for Run3/4 and forthcoming Pb-Pb run in fall 2023!
  - New detectors and higher rate capabilities
  - Stay tuned!

backup slides

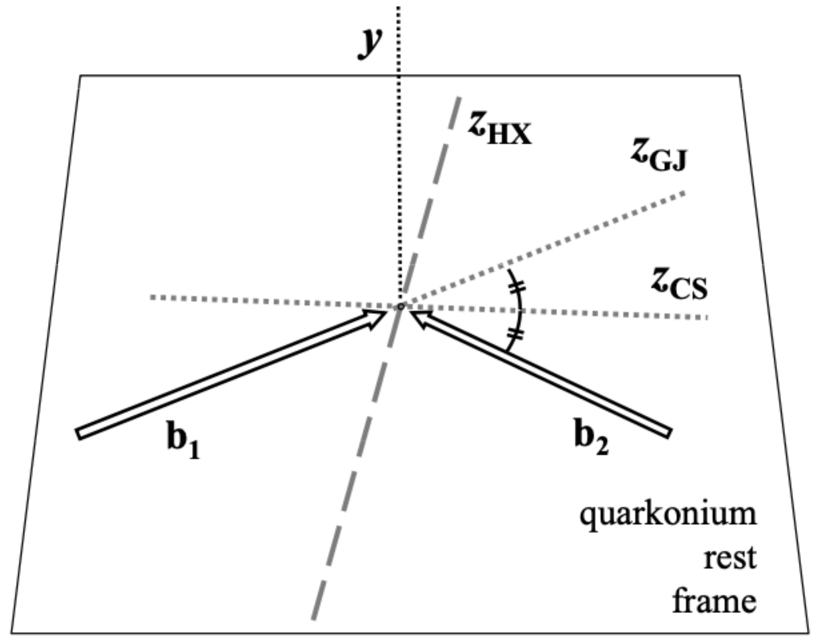
Inclusive J/ψ production

ALICE arXiv:2303.13361

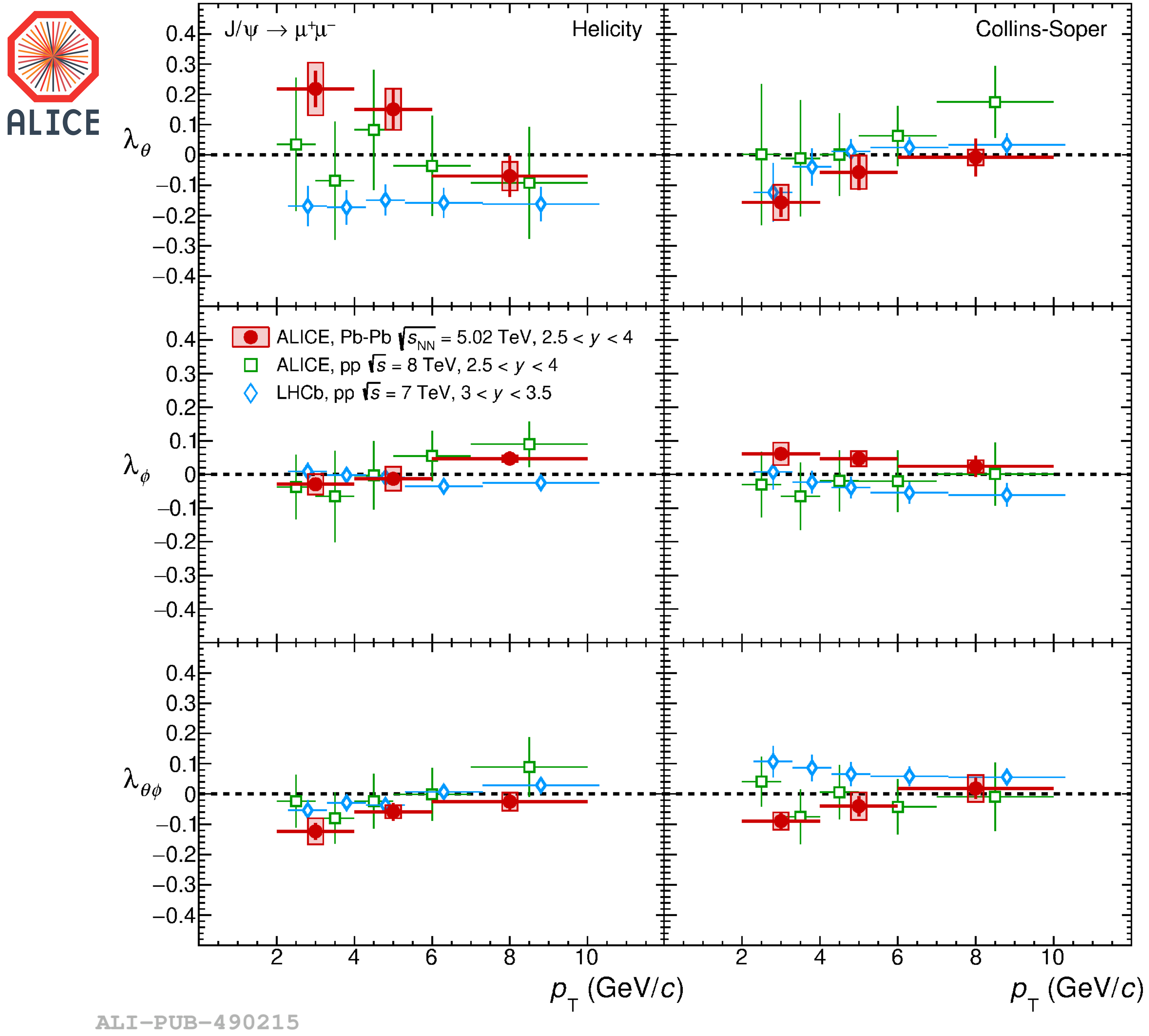


J/ψ polarisation in Pb-Pb collisions

- Polarisation provides information complementary to the yield production
- Important per se for detector effect correction
- Polarisation measured in the helicity and collins-super frame

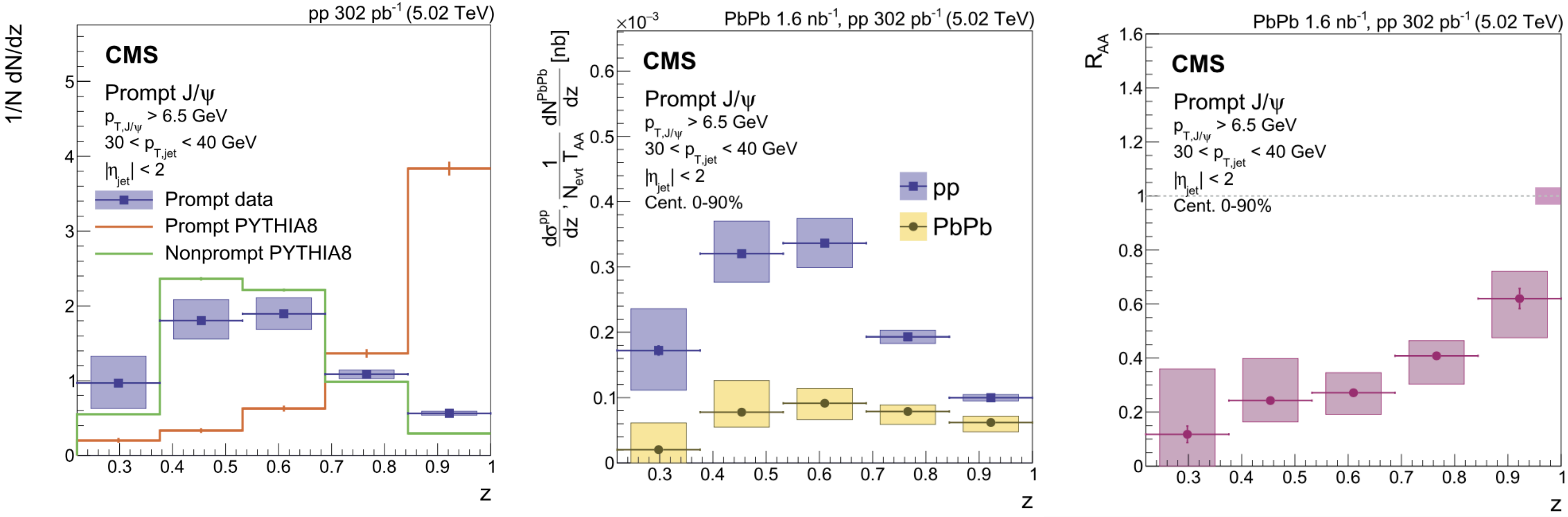


- Polarisation compatible with zero (2 sigma from 0 at low p_T) and with ALICE pp measurements: no or small modification of the polarisation with the medium

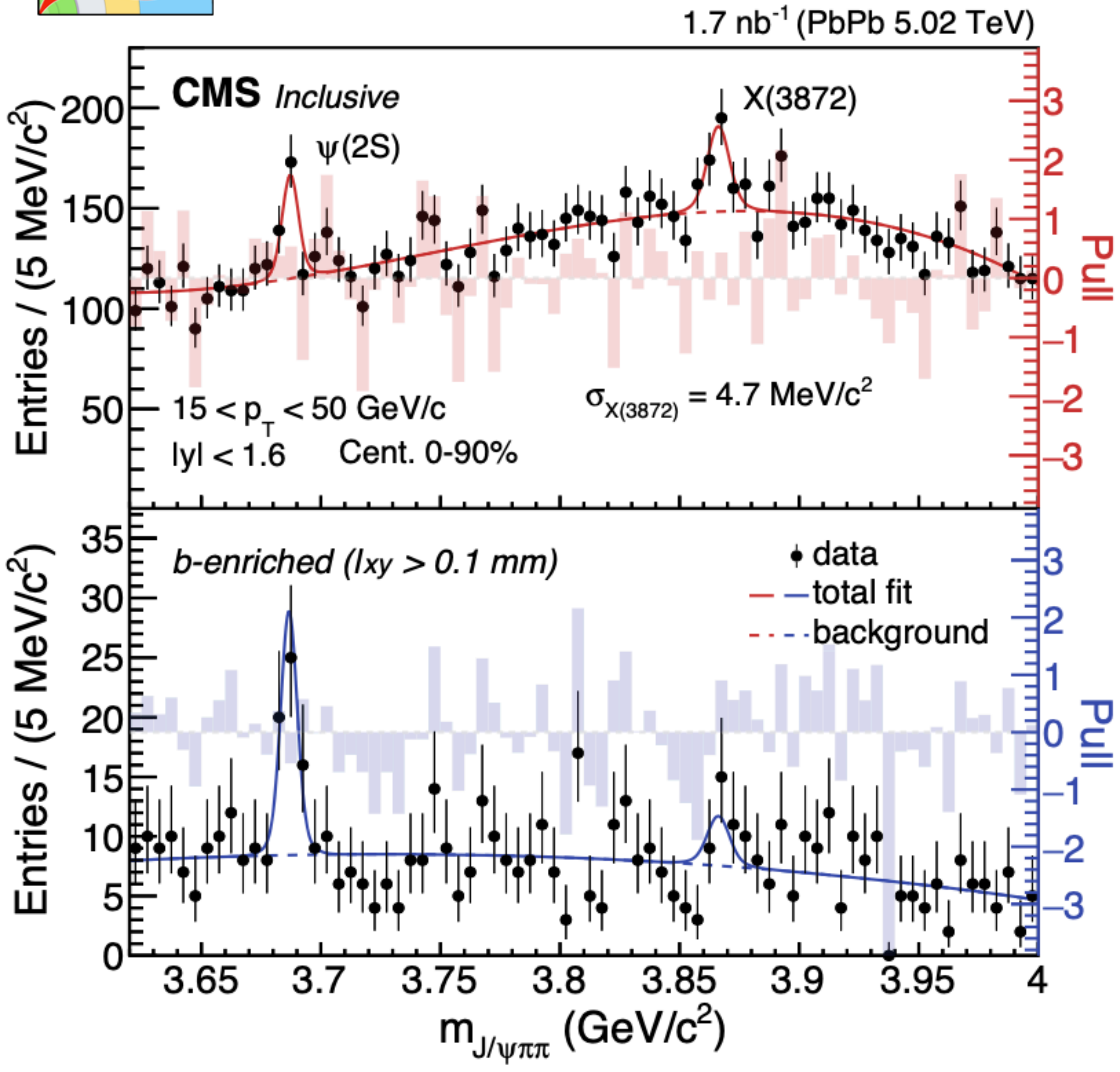


Jet fragmentation containing a prompt J/ψ

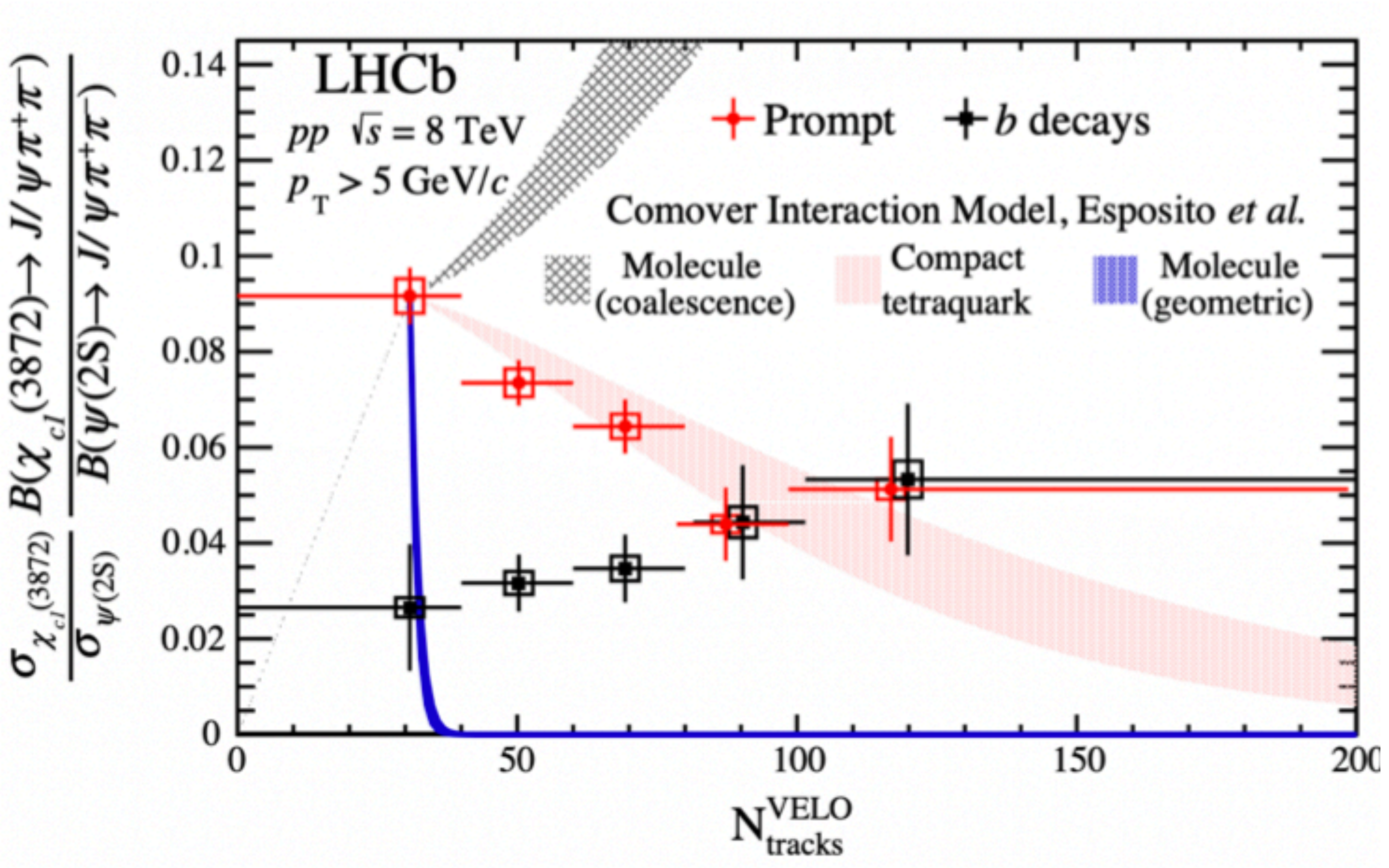
CMS PLB 825 (2022) 136842



$\chi_{c1}(3872)$



1.7 nb-1 (PbPb 5.02 TeV)
CMS Inclusive
ψ(2S)
X(3872)
15 < pT < 50 GeV/c
|y| < 1.6
Cent. 0-90%
σX(3872) = 4.7 MeV/c2
b-enriched (lxy > 0.1 mm)
data
total fit
background
Entries / (5 MeV/c2)
Pull
mJ/ψππ (GeV/c2)

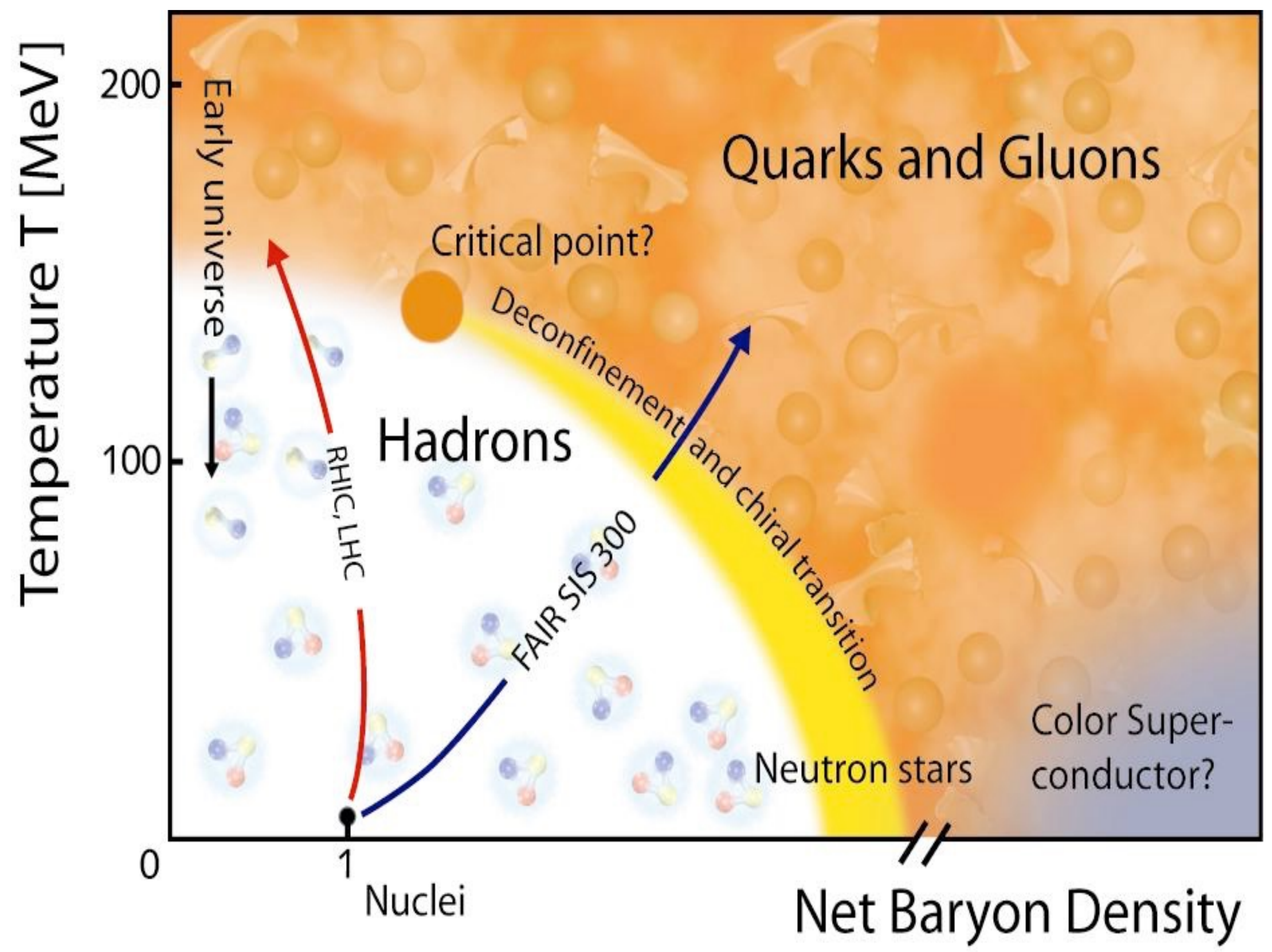


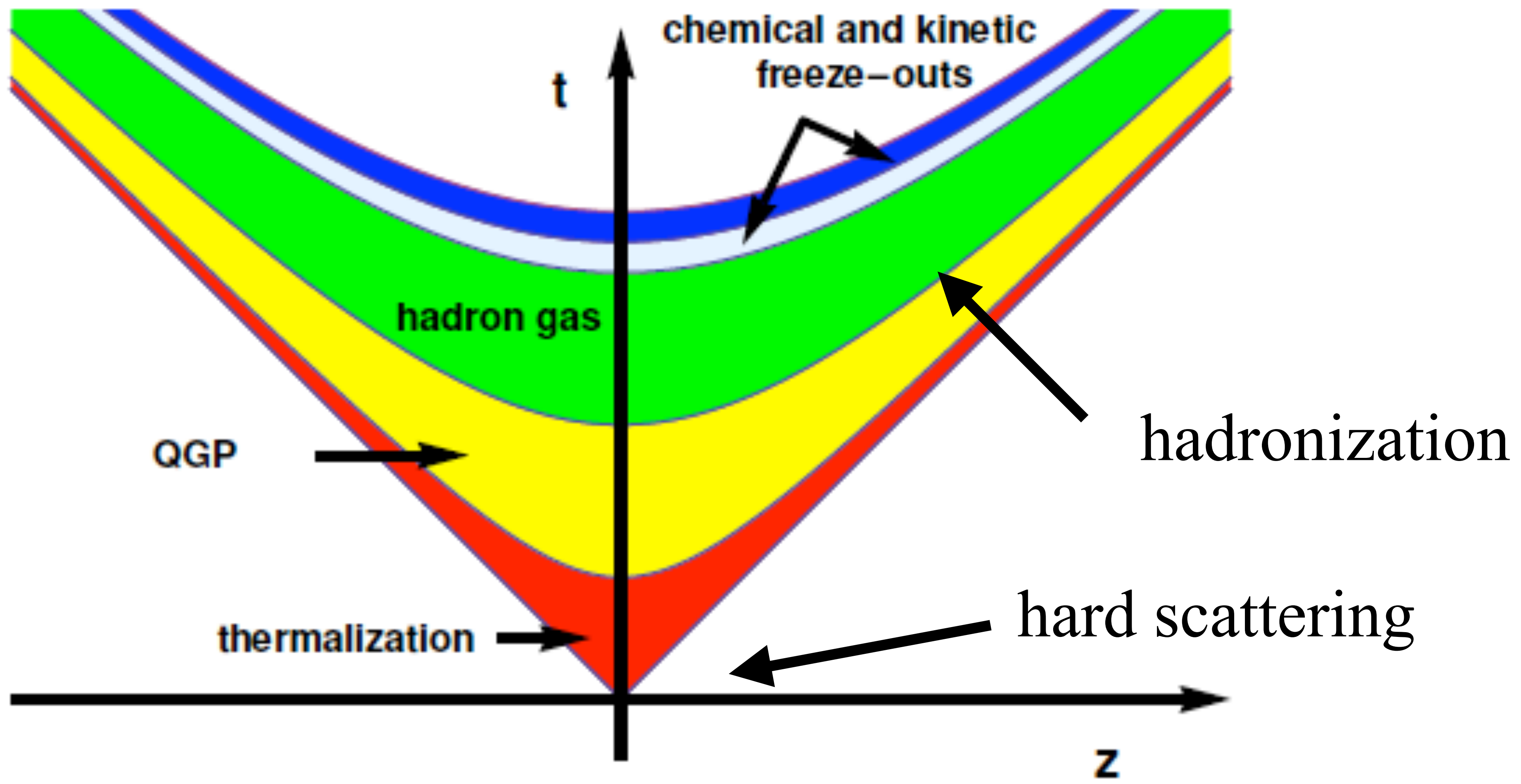
LHCb
pp √s = 8 TeV
pT > 5 GeV/c
Prompt
b decays
Comover Interaction Model, Esposito et al.
Molecule (coalescence)
Compact tetraquark
Molecule (geometric)
N VELO tracks

Coherent J/ψ photoproduction with nuclear overlap

ALICE, arXiv:2204.10684

Quark-gluon plasma in heavy-ion collisions





τ ≃ 20 fm/c
Kinetical freeze-out
Chemical freeze-out

τ ≃ 10 fm/c $T < T_c$
Hadron gas

τ ≃ 1 fm/c $T > T_c$
Thermalized QGP

τ ≃ 0
Heavy-ion collision

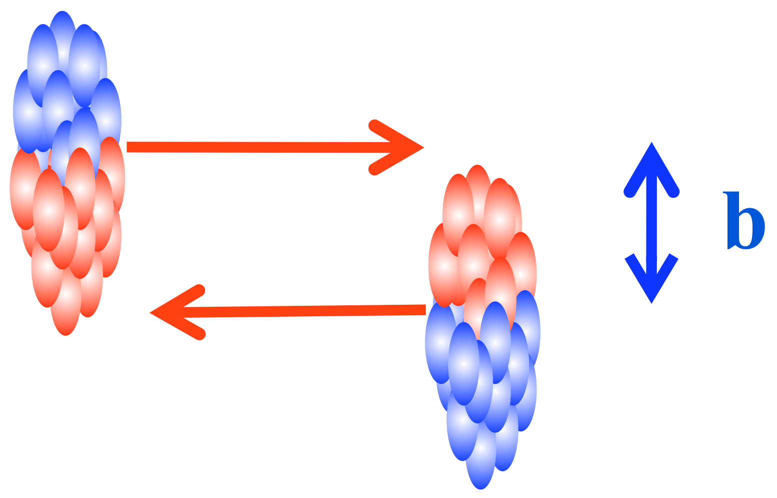
LHC size and time numbers
1 fm/c ~ 3 10^{-24} s

- Nuclear matter at high temperature and high density = Quark Gluon Plasma (QGP)
- From lattice QCD: phase transition near T_c = 170 MeV (ε_c = 1 GeV/fm^3)
- At LHC energies: most particles produced during the collisions → very low net baryon density
- Heavy ion collision experiments: characterize the QGP phase
- At large energy: large, hot, dense, long life-time plasma

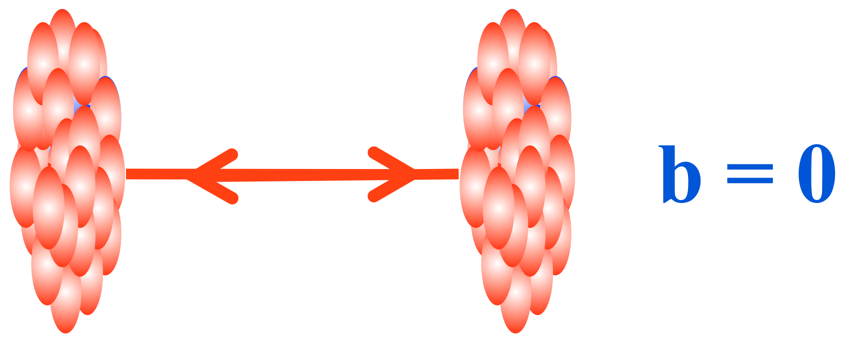
Collision geometry: few definitions

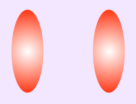
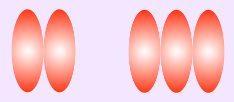
Centrality of the collisions: overlap of two nuclei

semi-central collision



central collision



	N_{part} = 2	N_{coll} = 1
	N_{part} = 5	N_{coll} = 6
Pb-Pb cent.	N_{part} = 360	N_{coll} = 1500
p-Pb cent.	N_{part} = 16	N_{coll} = 15

Impact parameter of the collision: b
Number of participants nucleons: N_{part}
Number of binary collisions: N_{coll}

Collision geometry: few definitions

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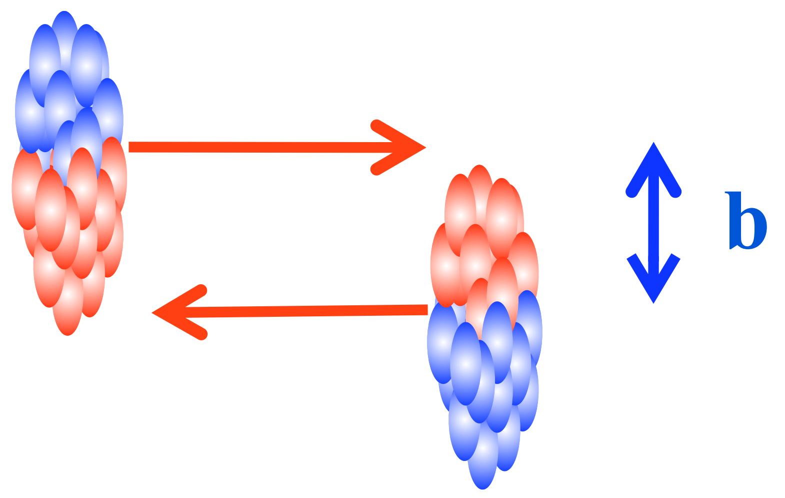
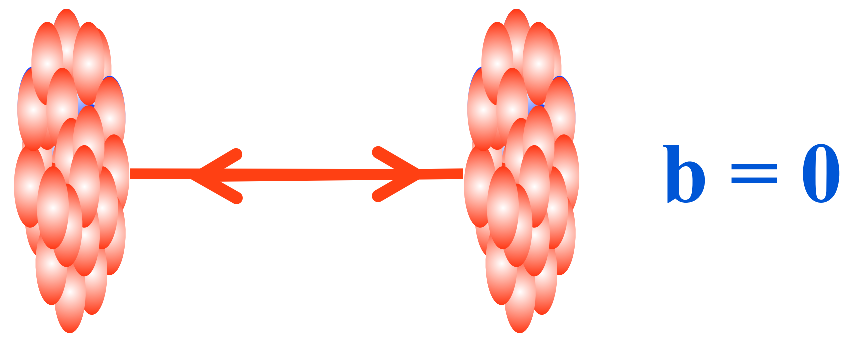
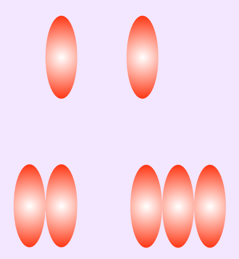


central collision





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Impact parameter of the collision: b
Number of participants nucleons: N_{part}
Number of binary collisions: N_{coll}

Event centrality determination

- Cannot measure b, N_{part}, N_{coll} directly
- Multiplicity measurements with forward or central detectors (charged particles multiplicity - π, K, p… -, spectator neutrons, …)
- Use Glauber model to map the measured multiplicities in A-A collisions to b, N_{part} and N_{coll}

Collision geometry: few definitions

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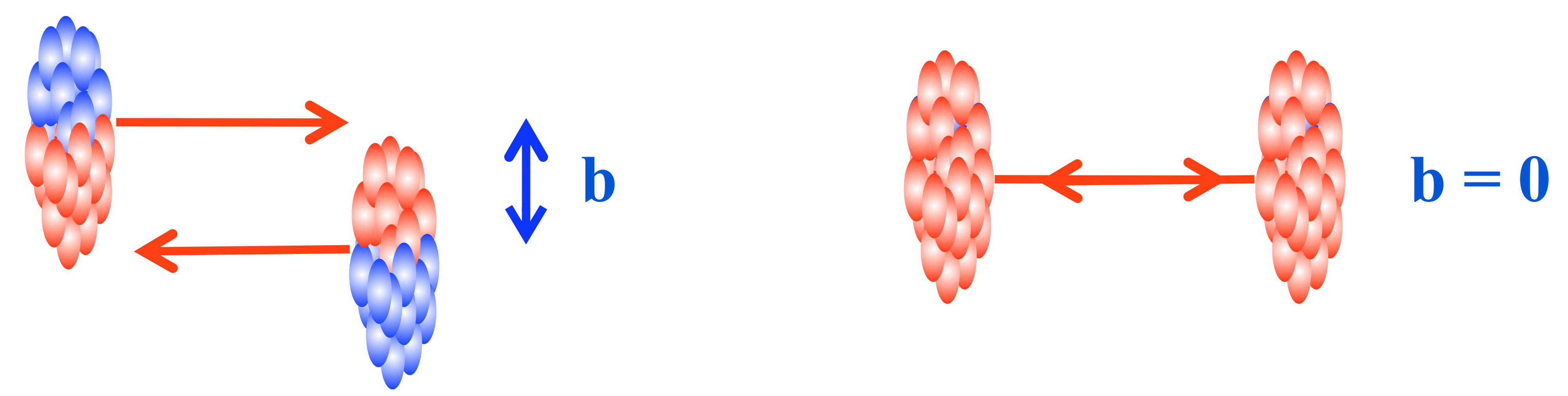

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