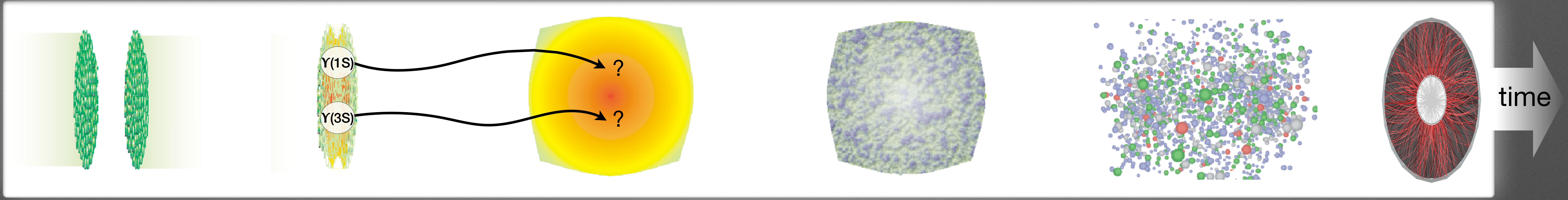
Quarkonia as Tools, Jan. 2024, Aussois (France)

Recent quarkonium results in AA collisions at the LHC

Andry Rakotozafindrabe

cea irfu

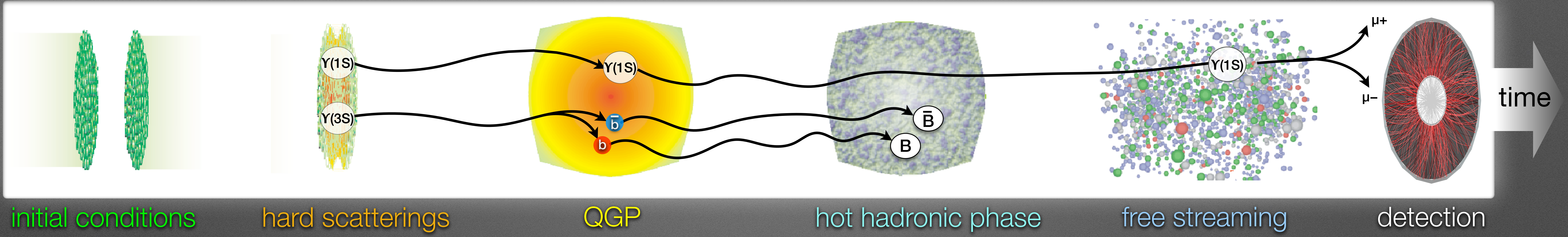
Heavy quarkonia as hard probes of the medium



initial conditions | hard scatterings pre-equilibrium dynamics | QGP hydrodynamic expansion | hot hadronic phase ch. freeze-out | free streaming kin. freeze-out | detection

- Large b(c) mass → produced in the early hard scattering stage
- High density of color charges in QGP → bounded $Q\bar{Q}$ pairs undergo color screening → their binding is weakened

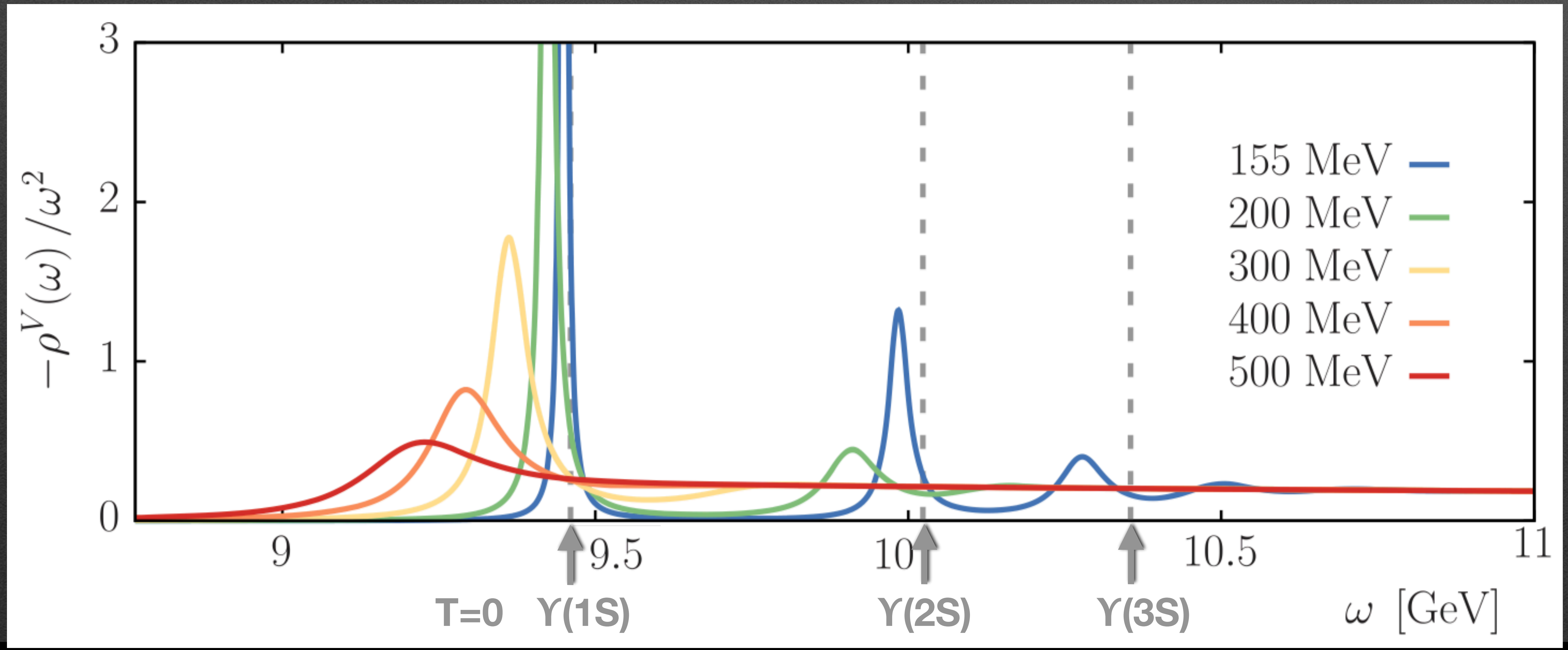
Heavy quarkonia as hard probes of the medium



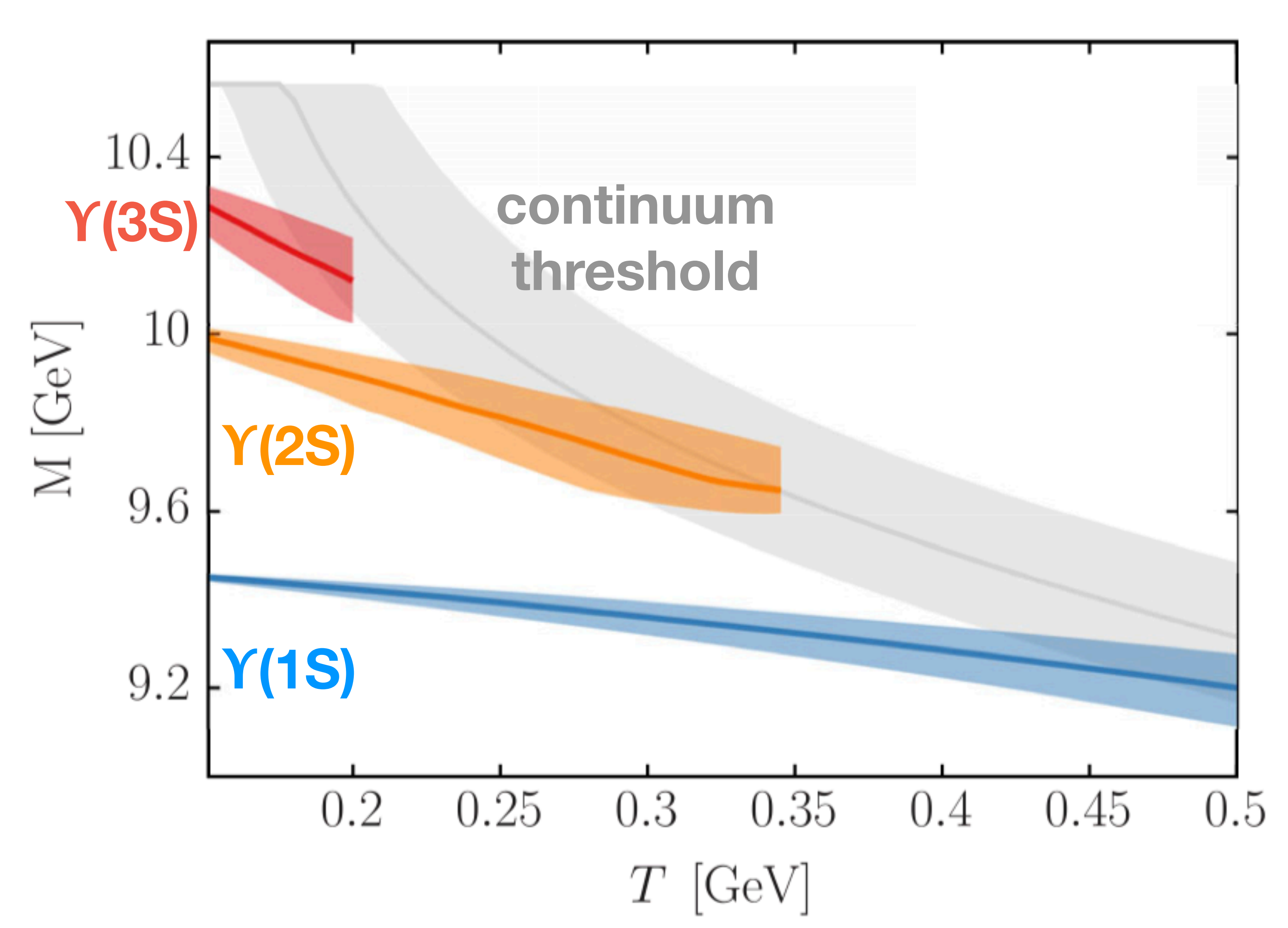
- In-medium dynamics: progressive dissolution of the quarkonium states, depending on their binding strength and the bath temperature, for e.g. Υ(nS) :

Lafferty, Rothkopf [PRD 101 (2020) 056010]

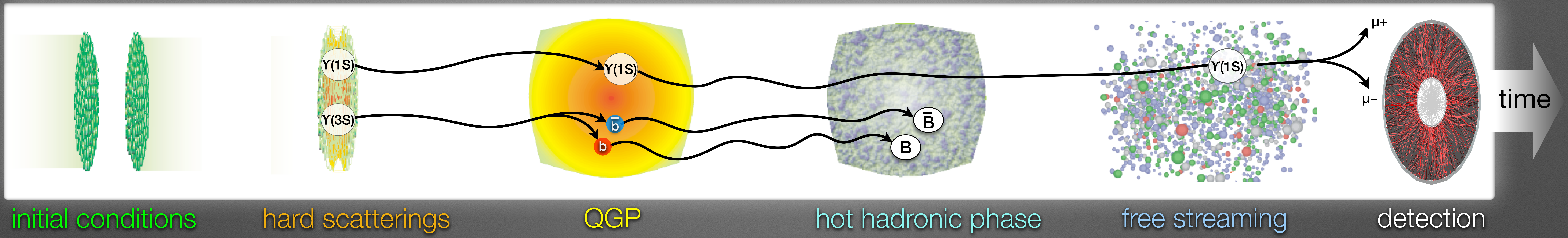
lattice in-medium spectral functions



lattice in-medium masses vs T



Heavy quarkonia as hard probes of the medium



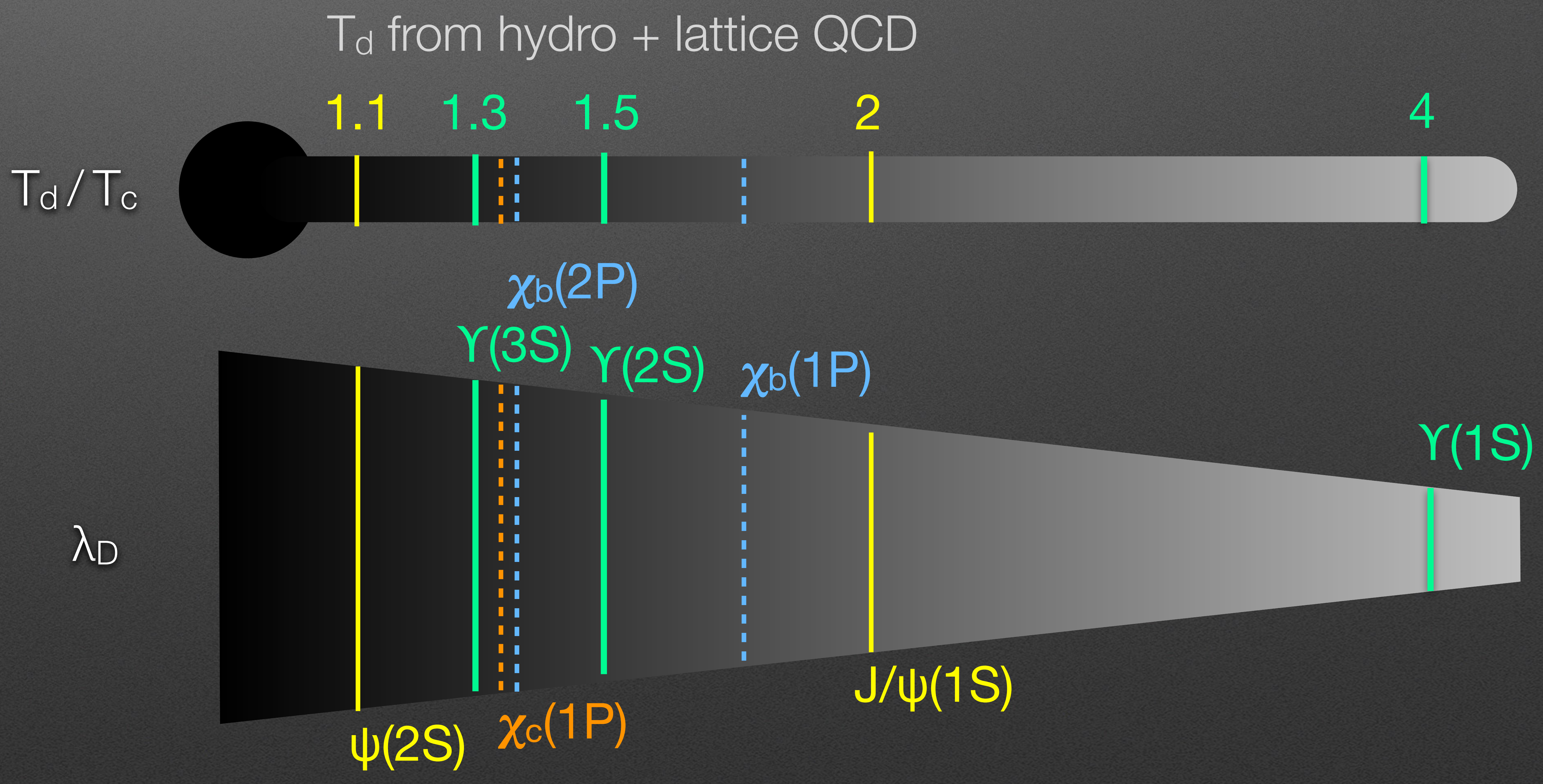
- Can be used as a QGP « thermometer » ?
- For e.g. the Υ(nS) family :
  - In PbPb relative to pp collisions, Υ(1S) and Υ(2S) were observed by ALICE, ATLAS, CMS

    CMS [PLB 790 (2019) 270]

    ALICE [PLB 822 (2021) 136579]

    ATLAS [PRC 107 (2023) 054912]

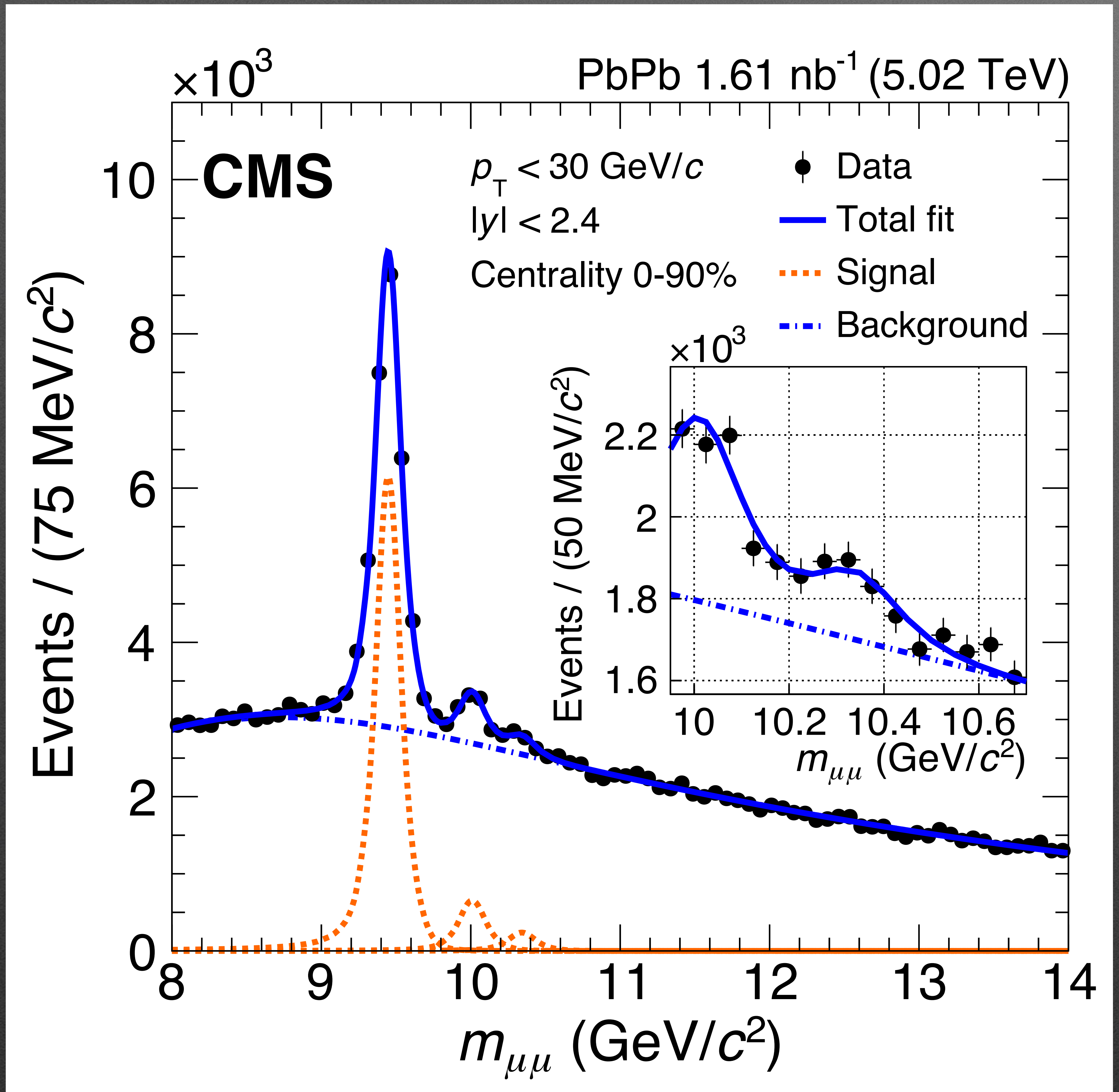
  - Υ(3S) totally suppressed at LHC ?



Mocsy et al., [Int.J.Mod.Phys.A 28 (2013) 1340012]

Υ(3S) in PbPb collisions at LHC

CMS [arXiv : 2303.17026]



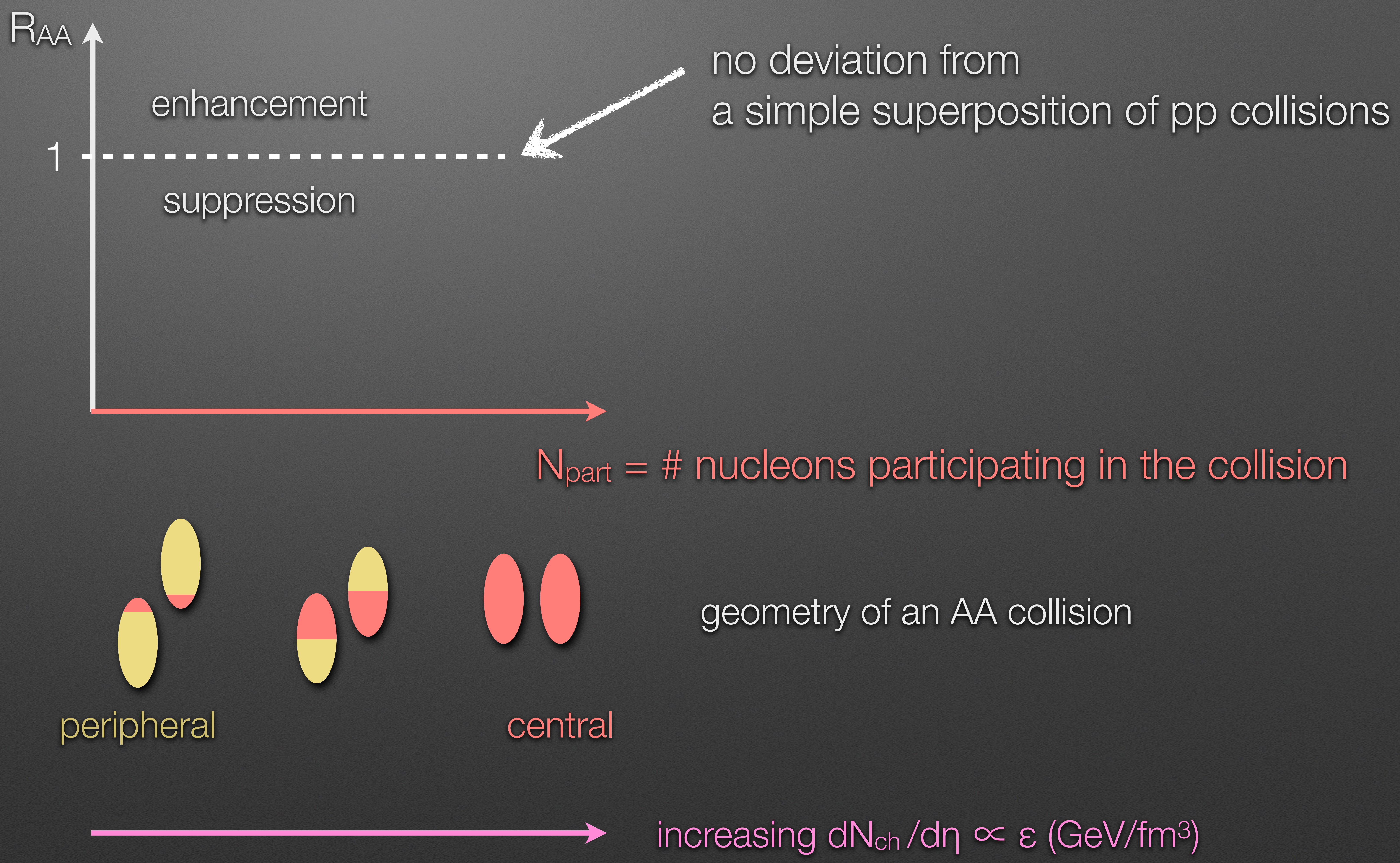
- First Υ(3S) measurement in AA collisions
- 5.6σ signal for Υ(3S)

Our favourite observable

Nuclear modification factor for a quarkonium in AA collisions

$$R_{\rm AA} = \frac{{\rm yield}_{AA}^{Q\bar{Q}}}{\langle T_{AA}\rangle \times \sigma_{pp}^{Q\bar{Q}}}$$

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



ϒ(nS) : a GQP thermometer in PbPb ?

ϒ(1S) CMS [PLB 790 (2019) 270]
ALICE [PLB 822 (2021) 136579]
ATLAS [PRC 107 (2023) 054912]
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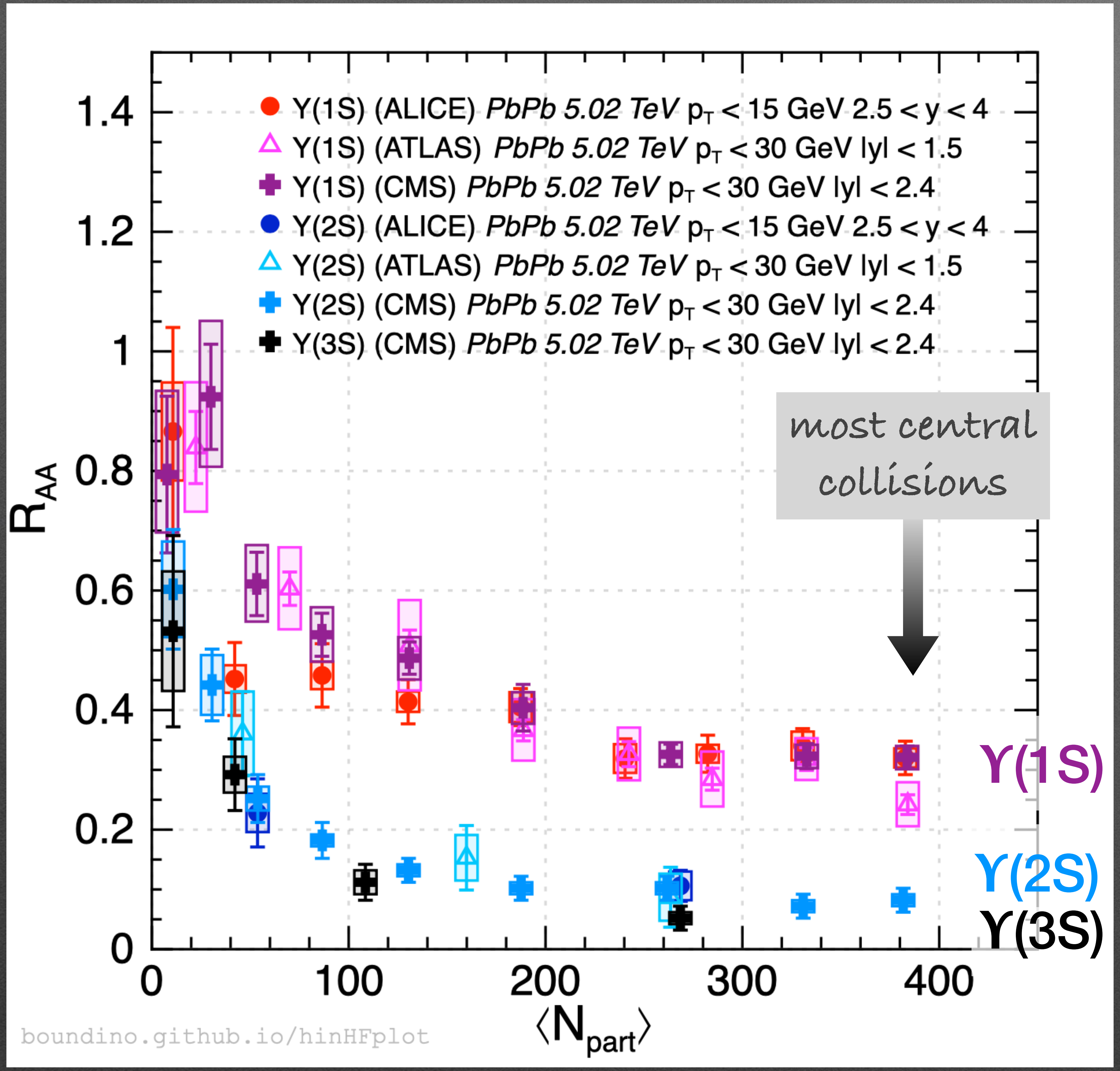

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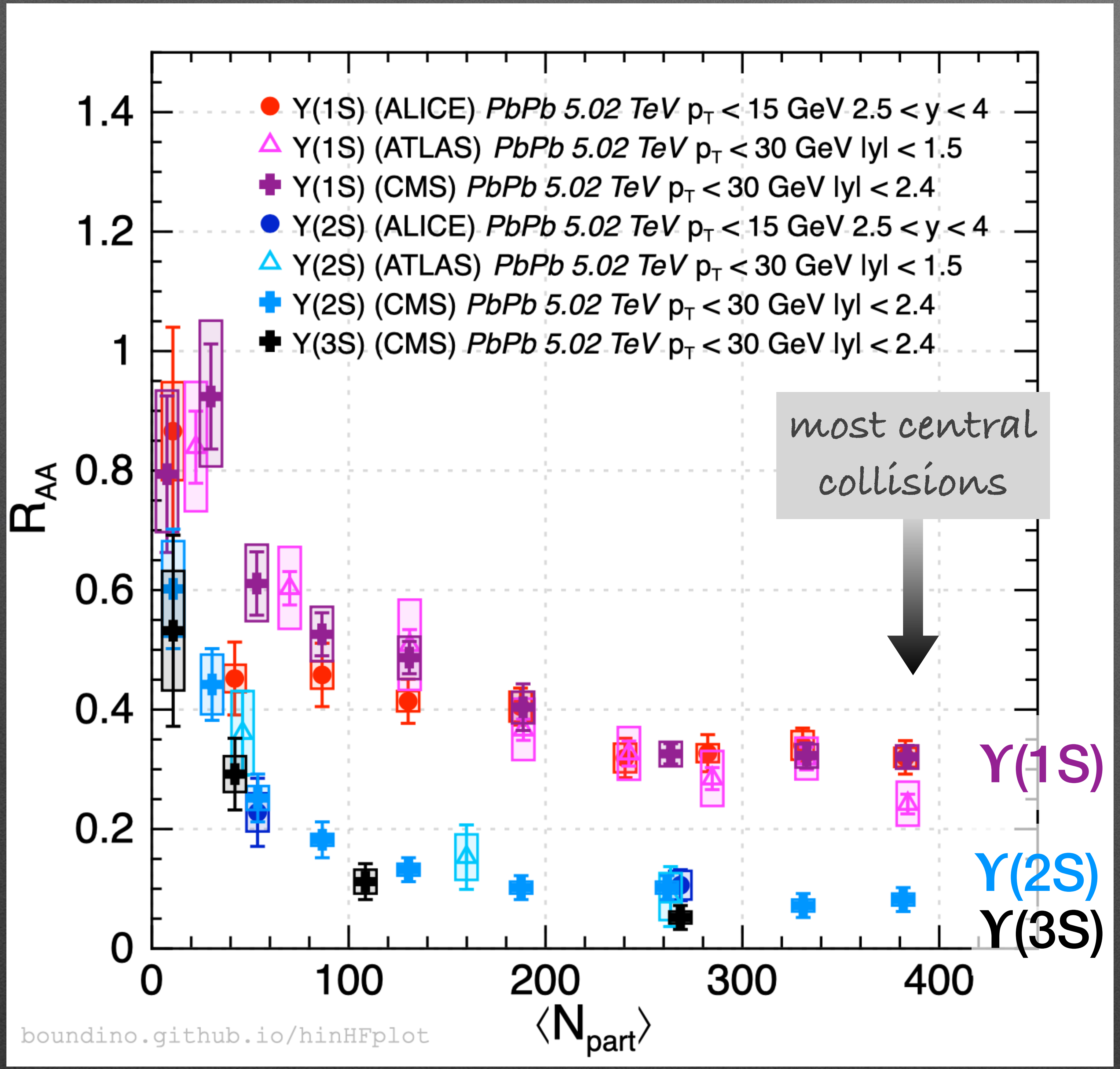
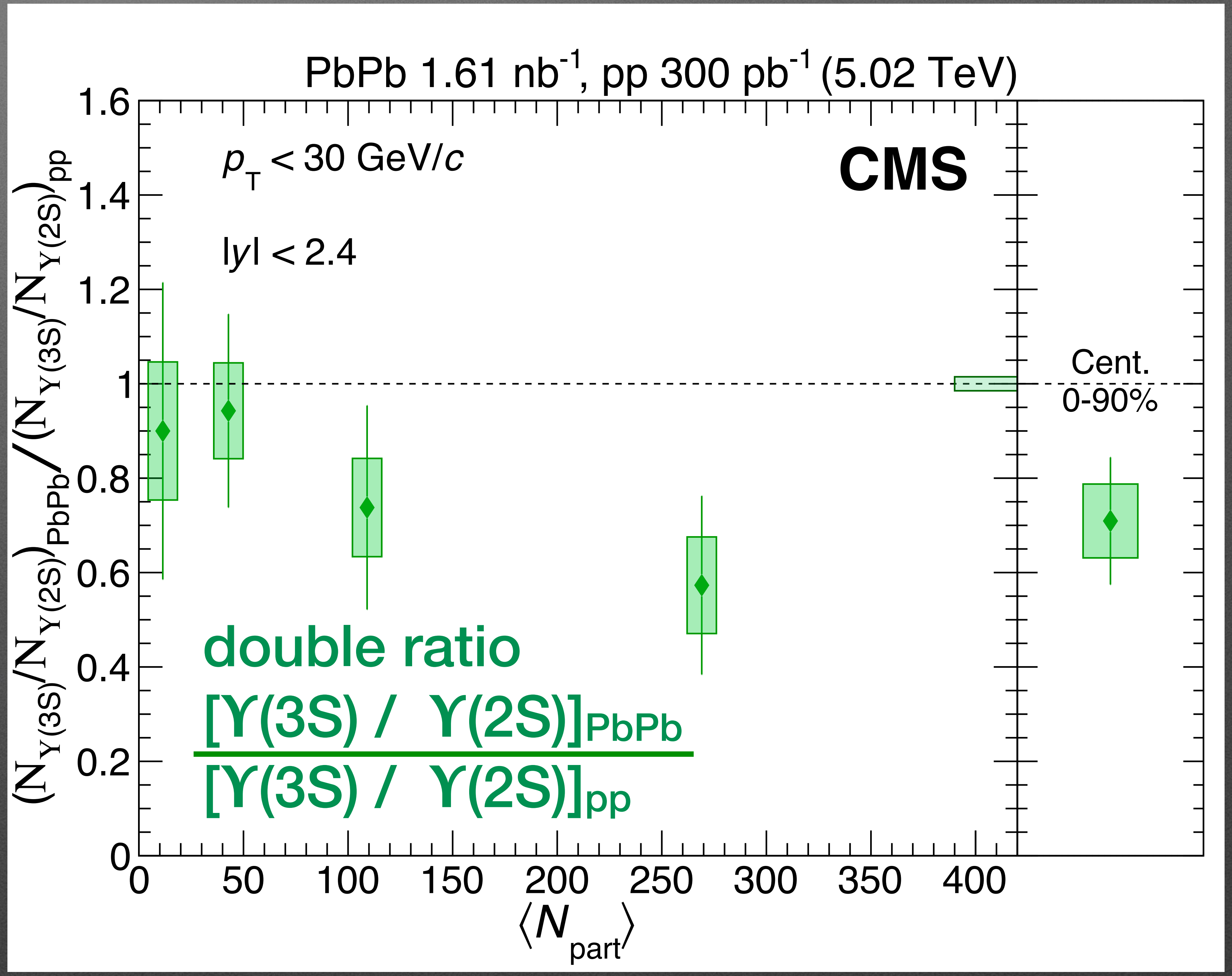
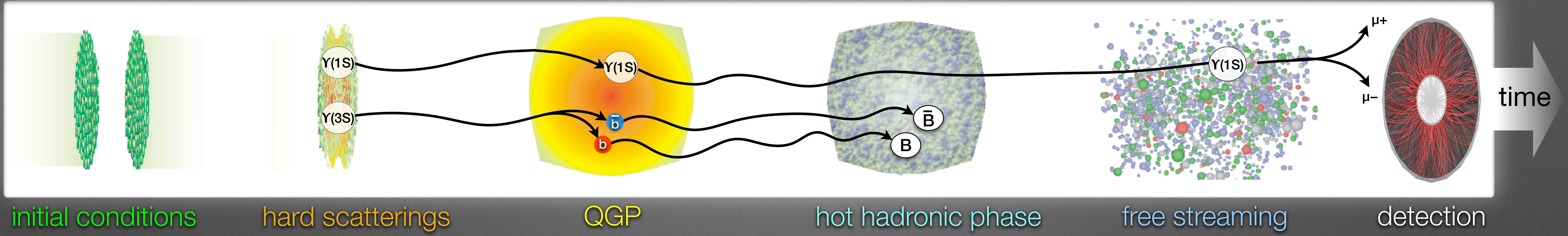


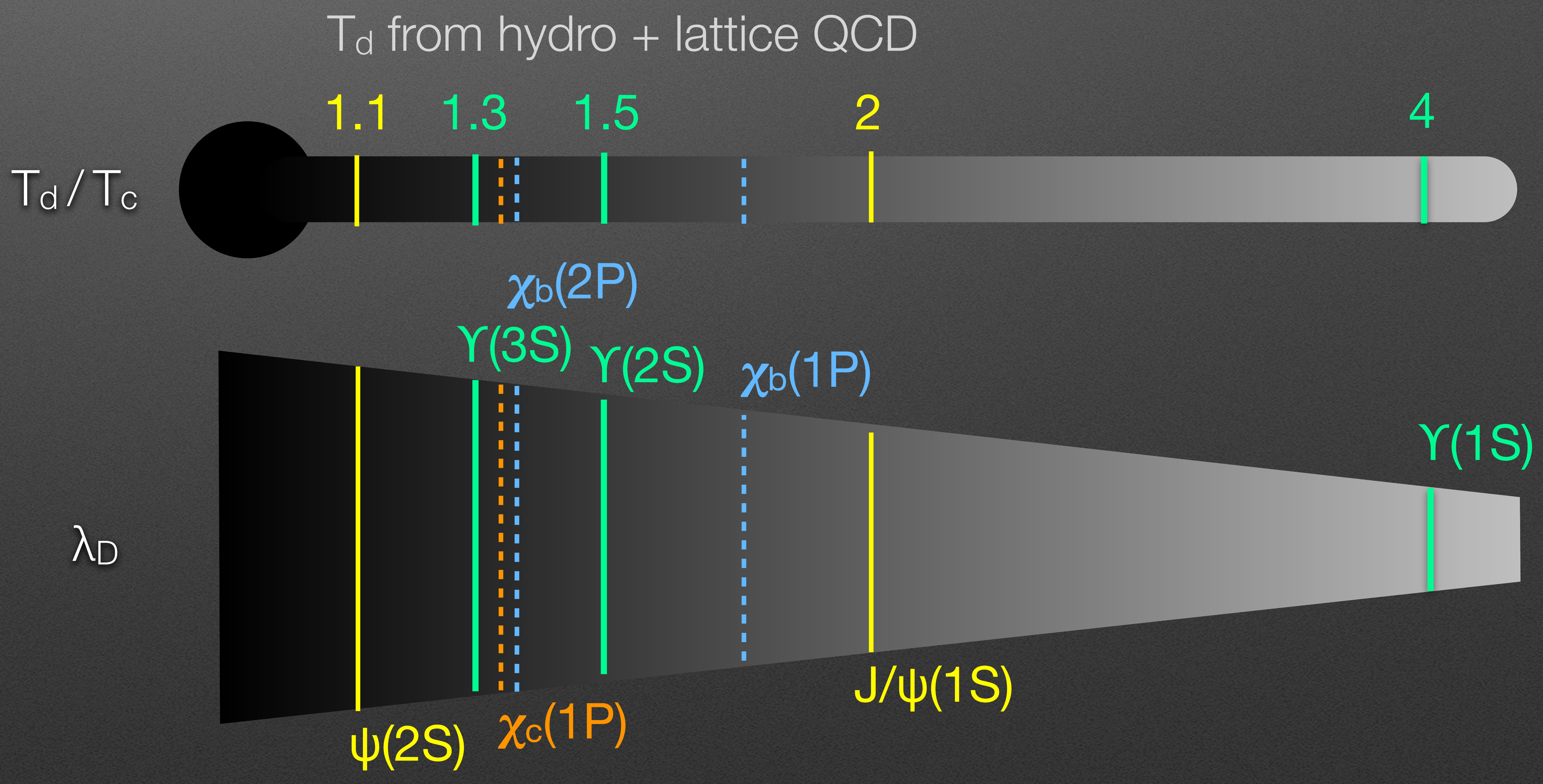


- Sequential suppression pattern in more central events i.e. ordered by binding energy :
  - All states are suppressed, with a larger suppression observed for the excited states
  - ϒ(3S) seems more suppressed than ϒ(2S)

Heavy quarkonia as hard probes of the medium



- Can be used as a QGP « thermometer » ?
- Quite straightforward if quarkonium states were only directly produced
- Complicated by feed-down :
  - in-family, from higher resonances
  - cross-family, i.e. non-prompt charmonium from b-hadron feed-down



Mocsy et al., [Int.J.Mod.Phys.A 28 (2013) 1340012]

Feed-down to Υ(nS) from measurements in pp collisions

- Using S-wave differential cross-section measurements from ATLAS or CMS in pp at $\sqrt{s}$ = 7 TeV + LHCb P-wave to S-wave ratio measurements

ATLAS [PRD 87 (2013) 052004] *CMS [PLB 727 (2013) 101]* *CMS [PLB 749 (2015) 14]* *LHCb [EPJC 74 (2014) 3092]*

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- Extract feed-down fraction from fits to S-wave and P-wave diff. cross-section and PDG branching ratios

Υ(1S) feed-down fraction at $< p_T >_{\Upsilon(1S)}$ ~ 5.8 GeV

ATLAS + LHCb: 1S

State	$\langle p_T \rangle$ feed-down fraction
$\Upsilon(1S)$	0.763 ± 0.010
$\Upsilon(2S)$	0.0625 ± 0.0019
$\chi_b(1P)$	0.127 ± 0.009
$\Upsilon(3S)$	0.00786 ± 0.00018
$\chi_b(2P)$	0.039 ± 0.004

Boyd et al. [PRD 108 (2023) 094024]

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direct

feed-down

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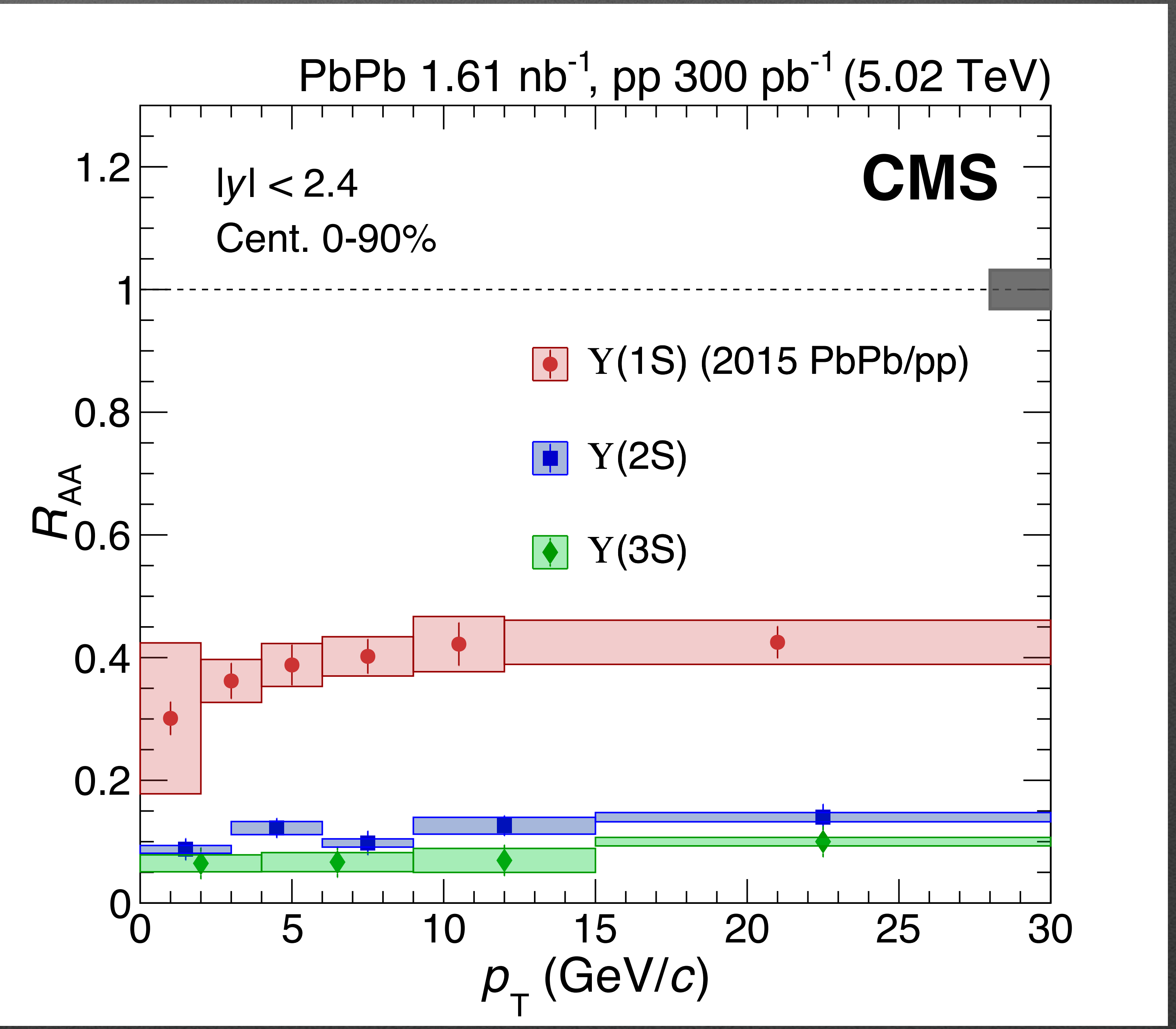
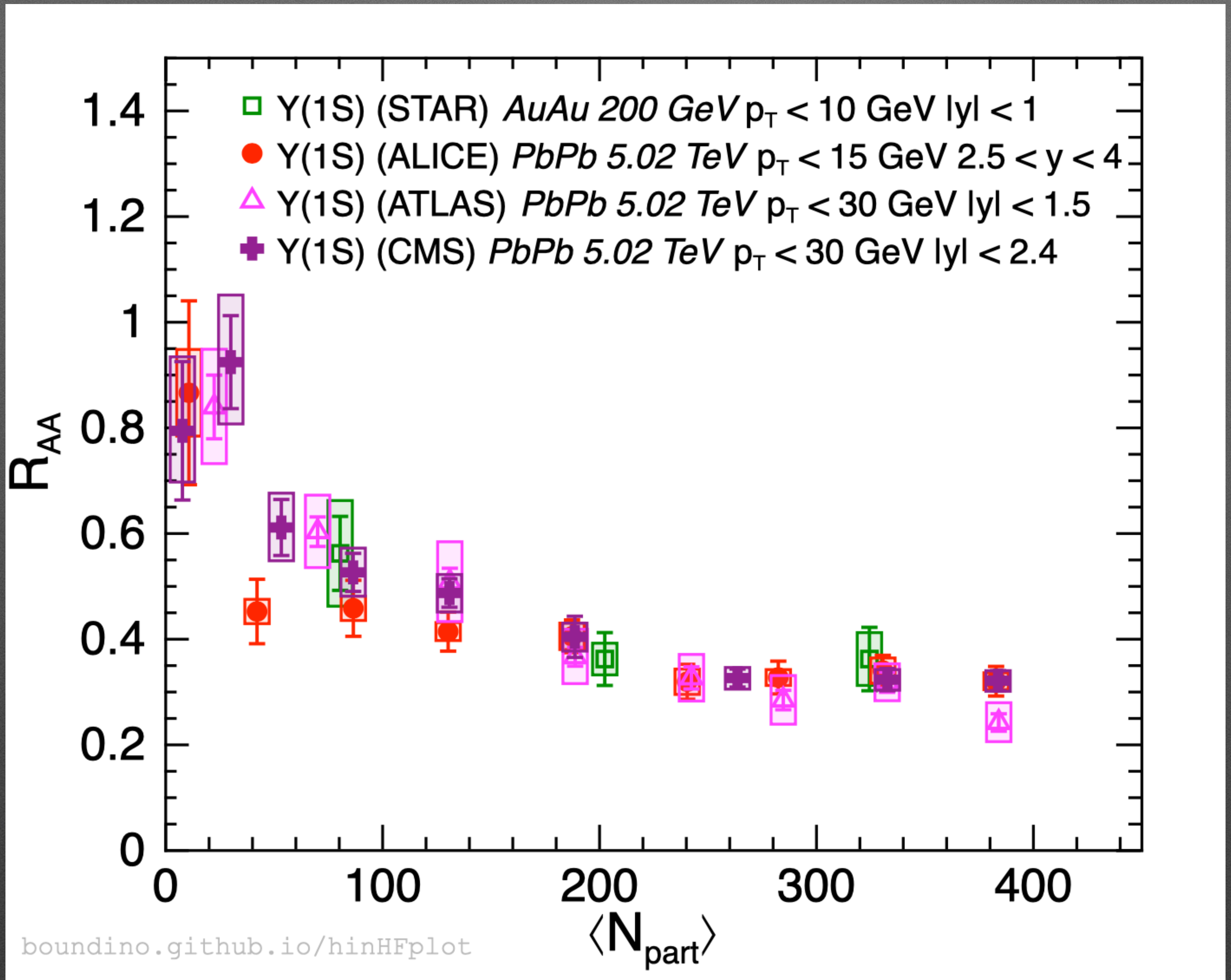


CMS [arXiv : 2303.17026]

- Only conjecturing the melting of the excited states feeding down ϒ(1S) is not enough
  - cold nuclear matter (CNM) effects ? direct ϒ(1S) melting ?

Υ(1S) : RHIC (200 GeV) vs LHC (5.02 TeV)



CMS [PLB 790 (2019) 270]

ALICE [PLB 822 (2021) 136579]

ATLAS [PRC 107 (2023) 054912]

STAR [PRL 130 (2023) 112301]

- Similar suppression seen at RHIC and at LHC (x 25 in √s):
  - in favour of a negligible melting of the direct Υ(1S) (i.e. dissociation temperature not reached yet at LHC)
  - but different CNM effects

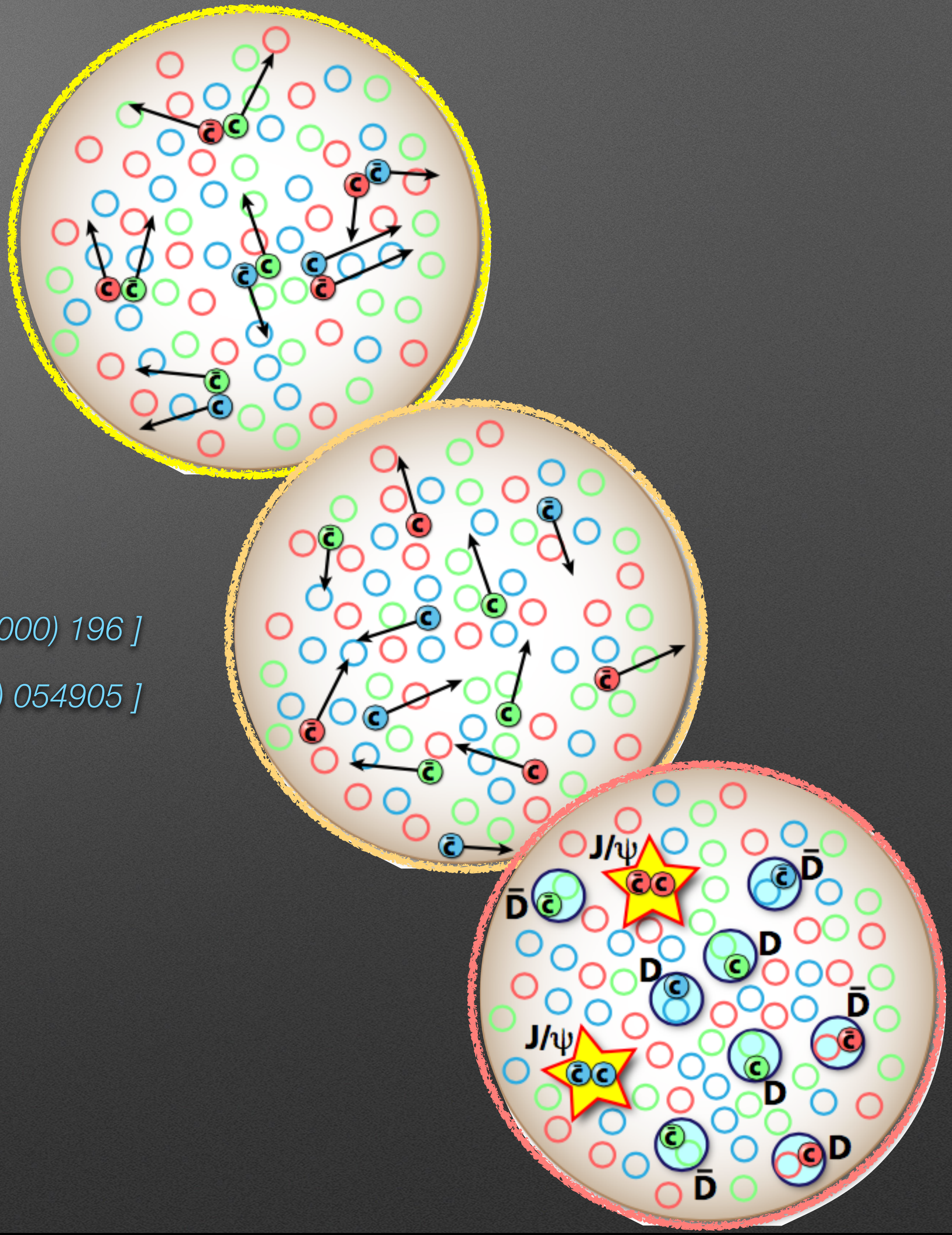
Charmonium regeneration

Up to 100 $c\bar{c}$ pairs in central Pb-Pb collisions @ 5.5 TeV

(x10 RHIC @ 0.2 TeV)

+ Color charges mobility in the QGP

- Possible (re)combination of uncorrelated c and $\bar{c}$
- during QGP evolution and/or at hadronization (chemical freeze-out)



P. Braun-Munziger, J.Stachel [PLB 490 (2000) 196]

R. Thews et al. [PRC 63 (2001) 054905]

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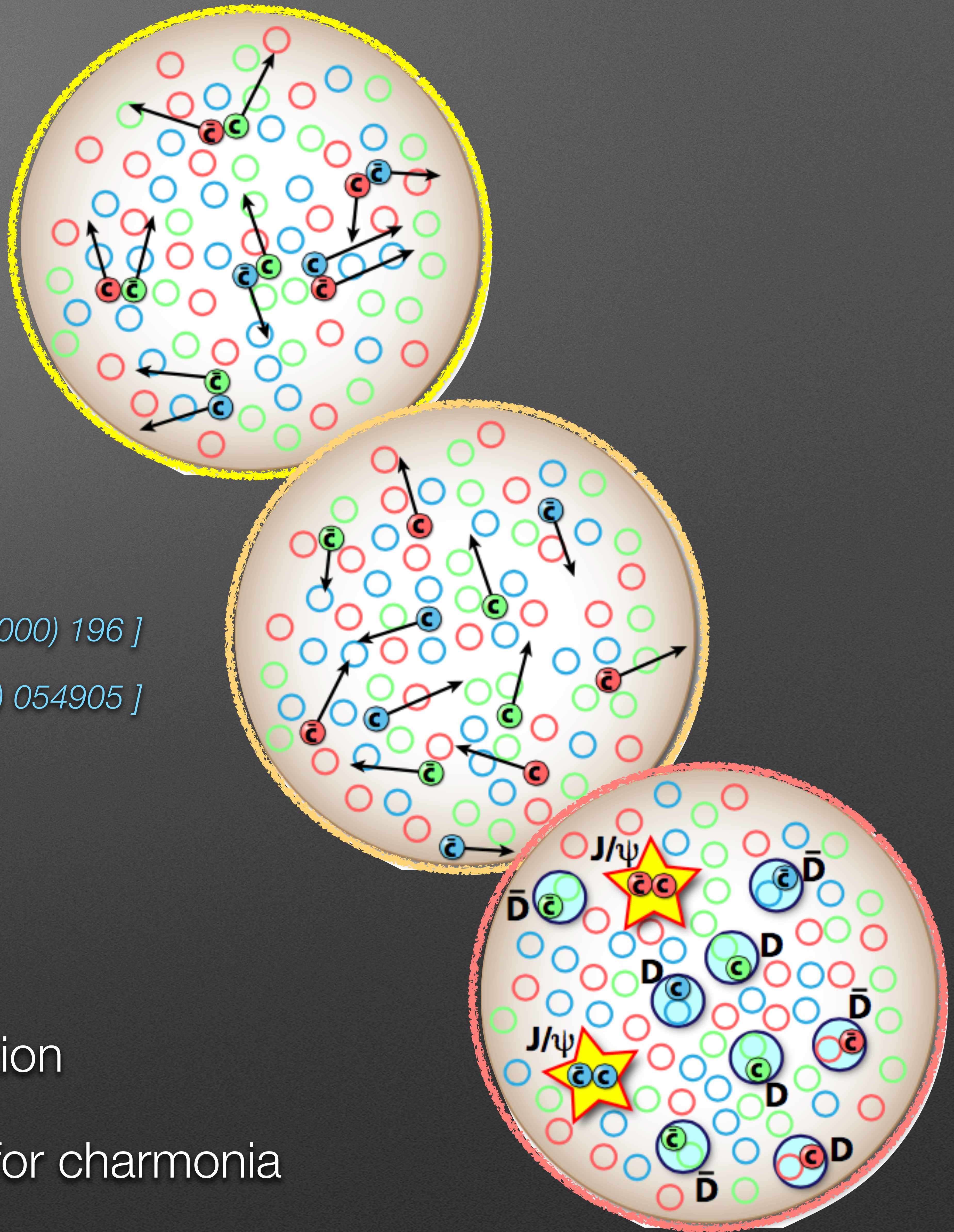


P. Braun-Munziger, J.Stachel [PLB 490 (2000) 196]

R. Thews et al. [PRC 63 (2001) 054905]

- To first approximation : $\frac{dN_{J/\psi}}{dy} \propto \left(\frac{dN_{c\bar{c}}}{dy}\right)^2$
- Crucial parameter of the models : the charm production cross-section
- Regeneration will interfere with the sequential suppression pattern for charmonia

At LHC : higher ε, but moderate suppression of inclusive J/ψ

NA50 [EPJC 39 (2005) 335]

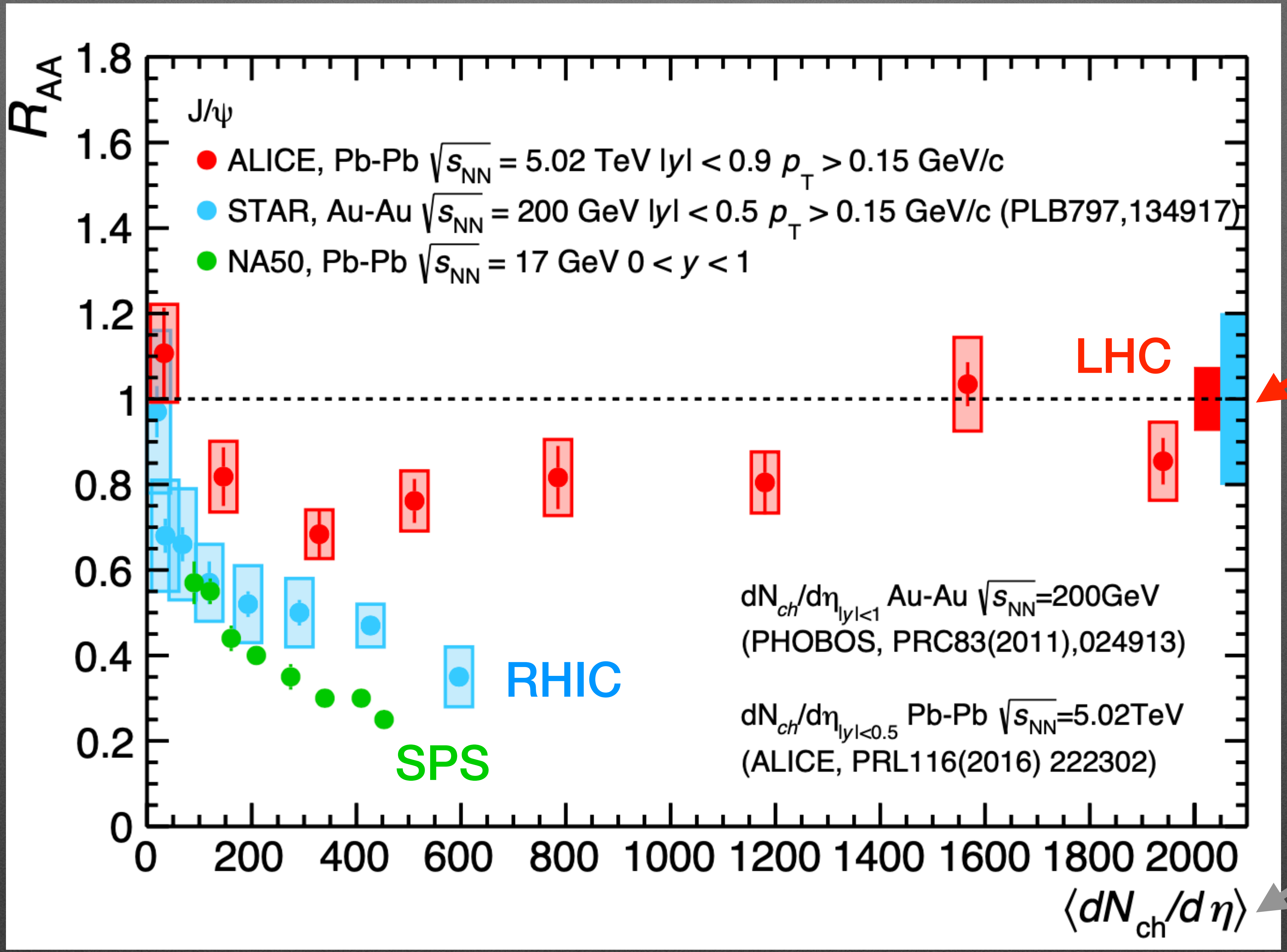
PHOBOS [PRC 83 (2011) 024913]

ALICE [PRL 116 (2016) 222302]

STAR [PLB 797 (2019) 134917]

ALICE Run 1-2 review *[arXiv:2211.04384]*

ALICE *[arXiv:2303.13361]*



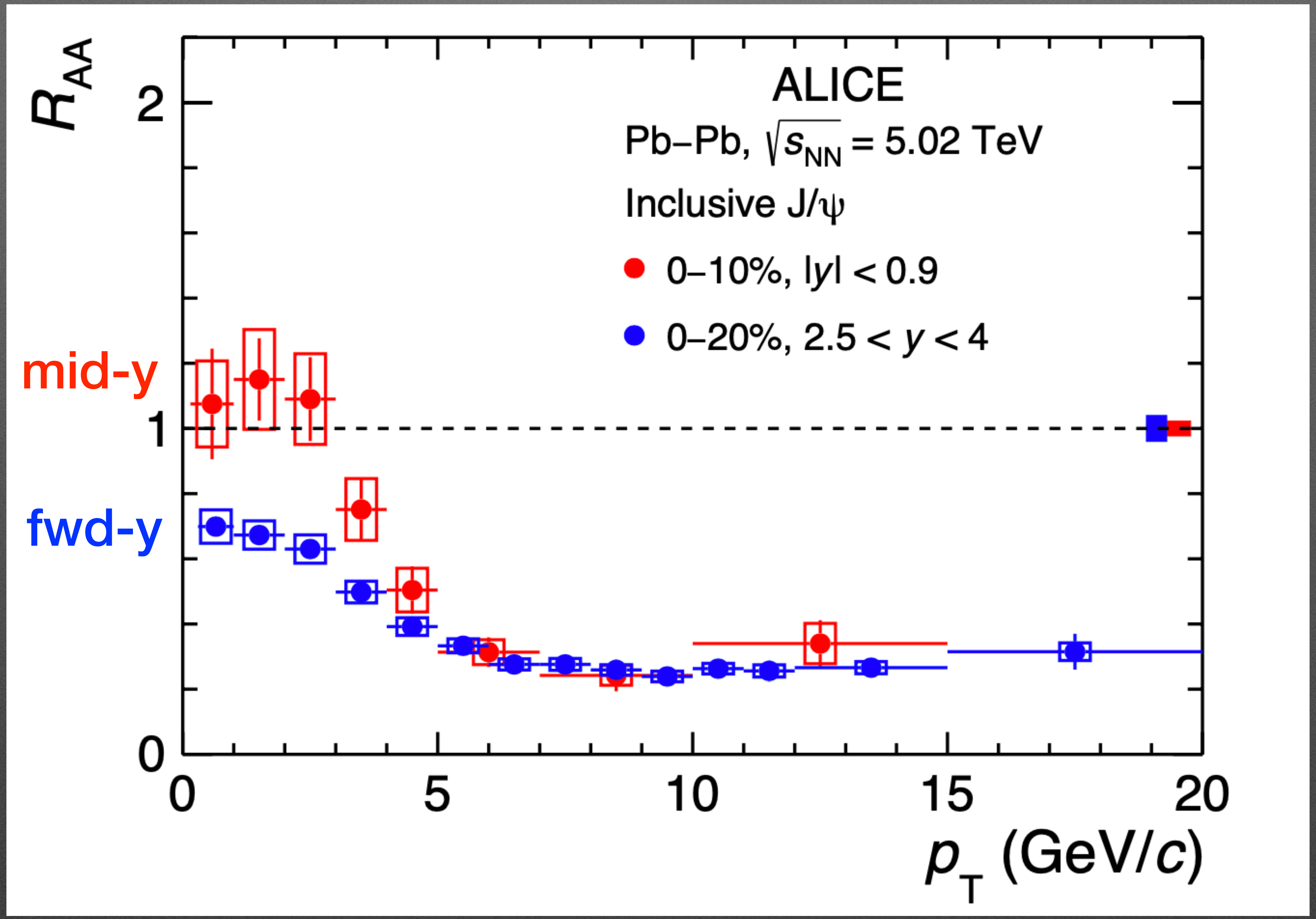
R_{AA} ~ 1 at mid-y in central collisions at LHC

charged-particle pseudo-rapidity density averaged per centrality bin

- At LHC, the (presumably) larger suppression from color screening at higher ε is compensated by a sizeable regeneration
- Regeneration $\propto \left(\frac{dN_{c\bar{c}}}{dy}\right)^2$ increases by ~10^6 from SPS to LHC

J/ψ regeneration vs y and vs p_T

ALICE [arXiv:2303.13361]

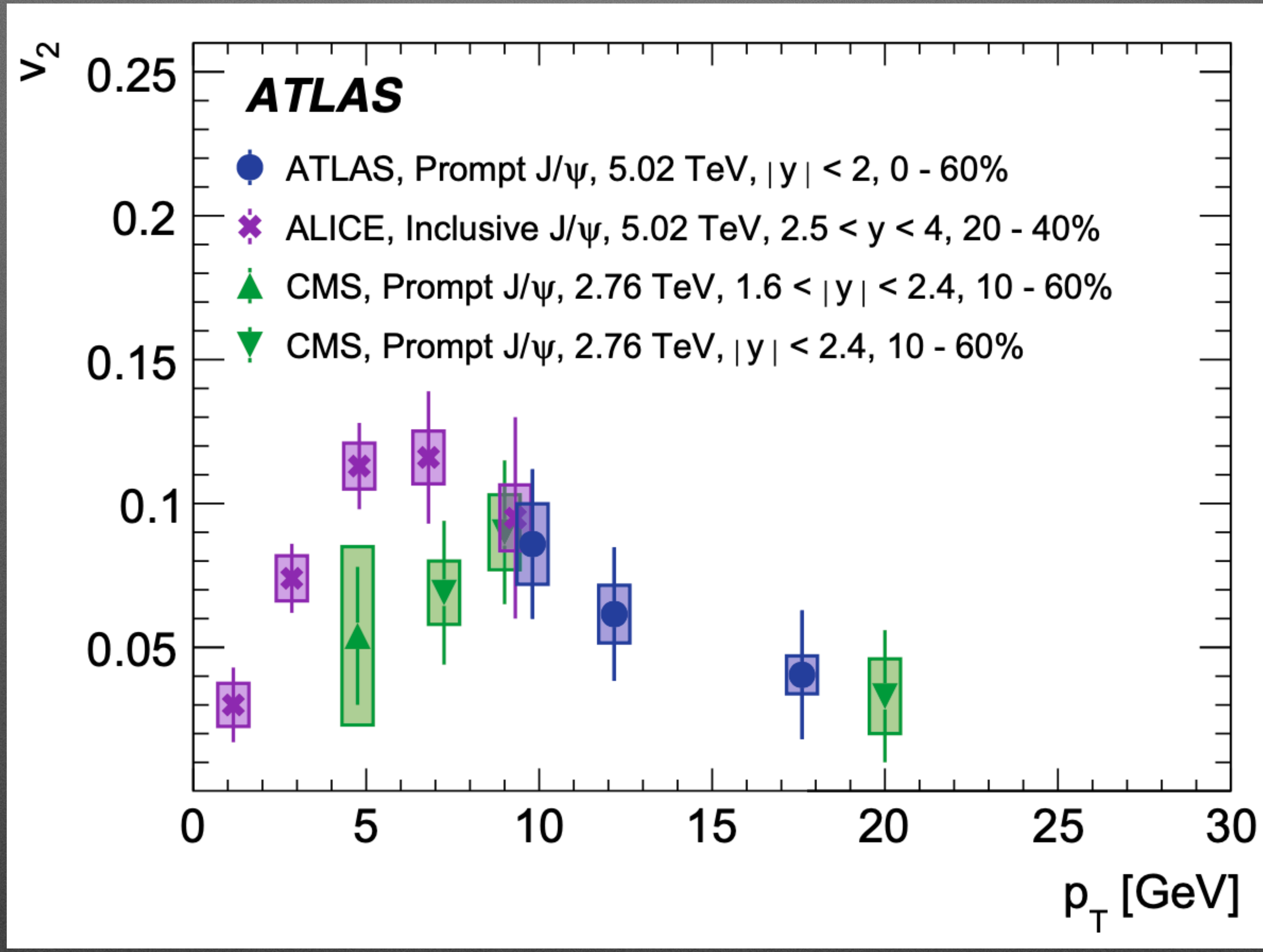


- The density of charm quarks is larger at mid-y and at low p_T
- Therefore, we can expect an enhanced regeneration component at mid-y compared to fwd-y at low p_T
- At low p_T, R_{AA} (mid-y) > R_{AA} (fwd-y)

J/ψ regeneration : inherit parent (anti)charm elliptic flow

Elliptic flow v_2 :

- second-order coefficient of the Fourier decomposition of the azimuthal angle distribution
- measured w.r.t. event plane



ALICE *[PRL 119 (2017) 242301]*

CMS *[EPJC 77 (2017) 252]*

ATLAS *[EPJC 78 (2018) 784]*

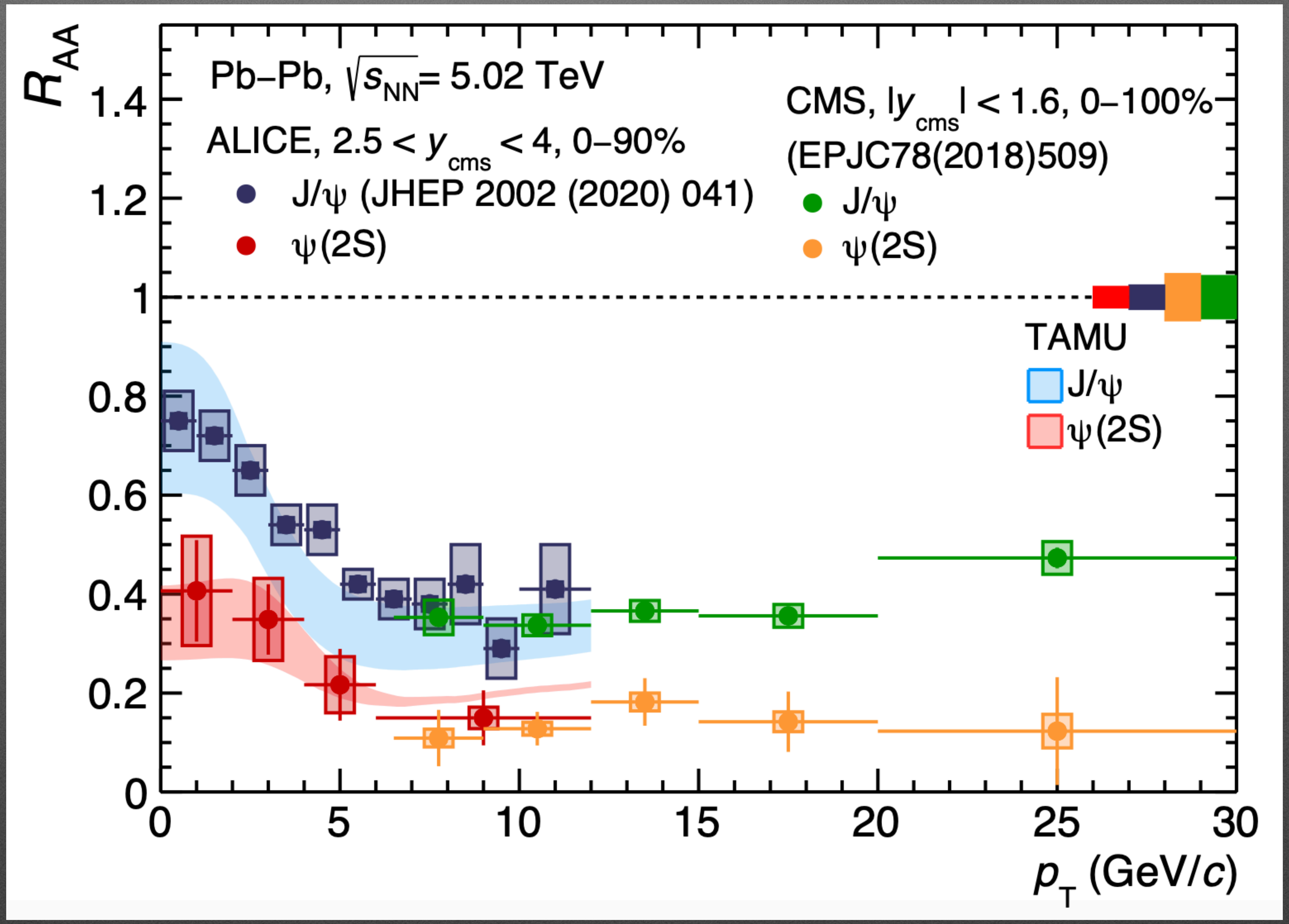
- (Anti)charm quarks (at least partially) participate to the motion in-medium collective dynamics (as seen in the v2 measurement of prompt D hadrons)
- We can expect J/ψ from regeneration mechanism to inherit (at least part of) their parent (anti)charm elliptic flow, in particular at low p_T
- Regeneration models : test vs both the measured R_{AA} and v_2

J/ψ vs ψ(2S)

(TAMU) Du and Rapp [NPA 943 (2015) 147]

Transport model TAMU:

Continuous charmonium dissociation and regeneration in the QGP, described by a rate equation



CMS [EPJC 78 (2018) 509]

ALICE [JHEP 02 (2020) 041]

ALICE [arXiv:2210.08893]

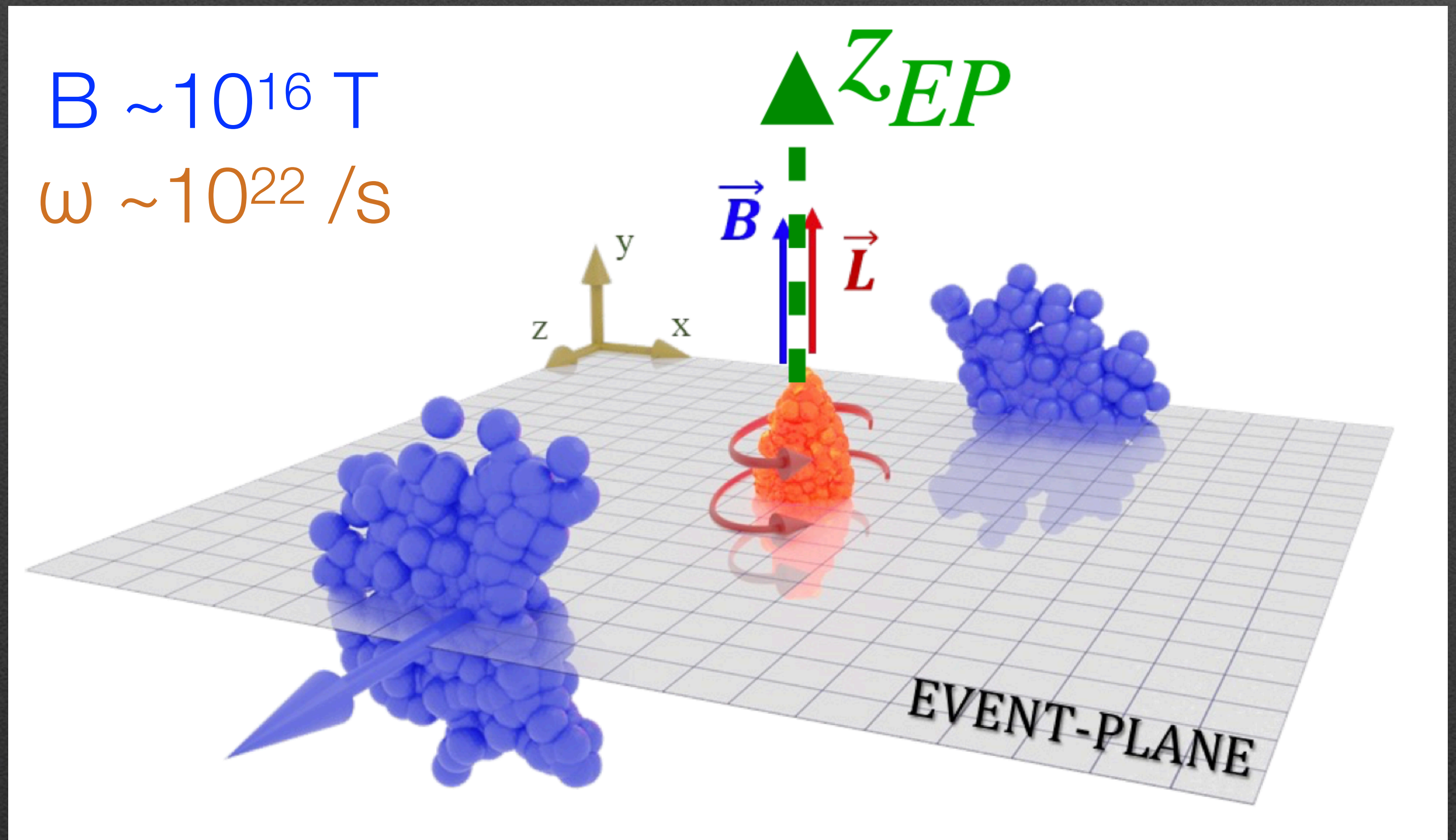
- Larger suppression of ψ(2S) with respect to J/ψ, on the whole p_T range
- Both states are enhanced at low p_T, which is successfully described by the TAMU model which includes a regeneration component

J/ψ polarisation measured w.r.t event plane

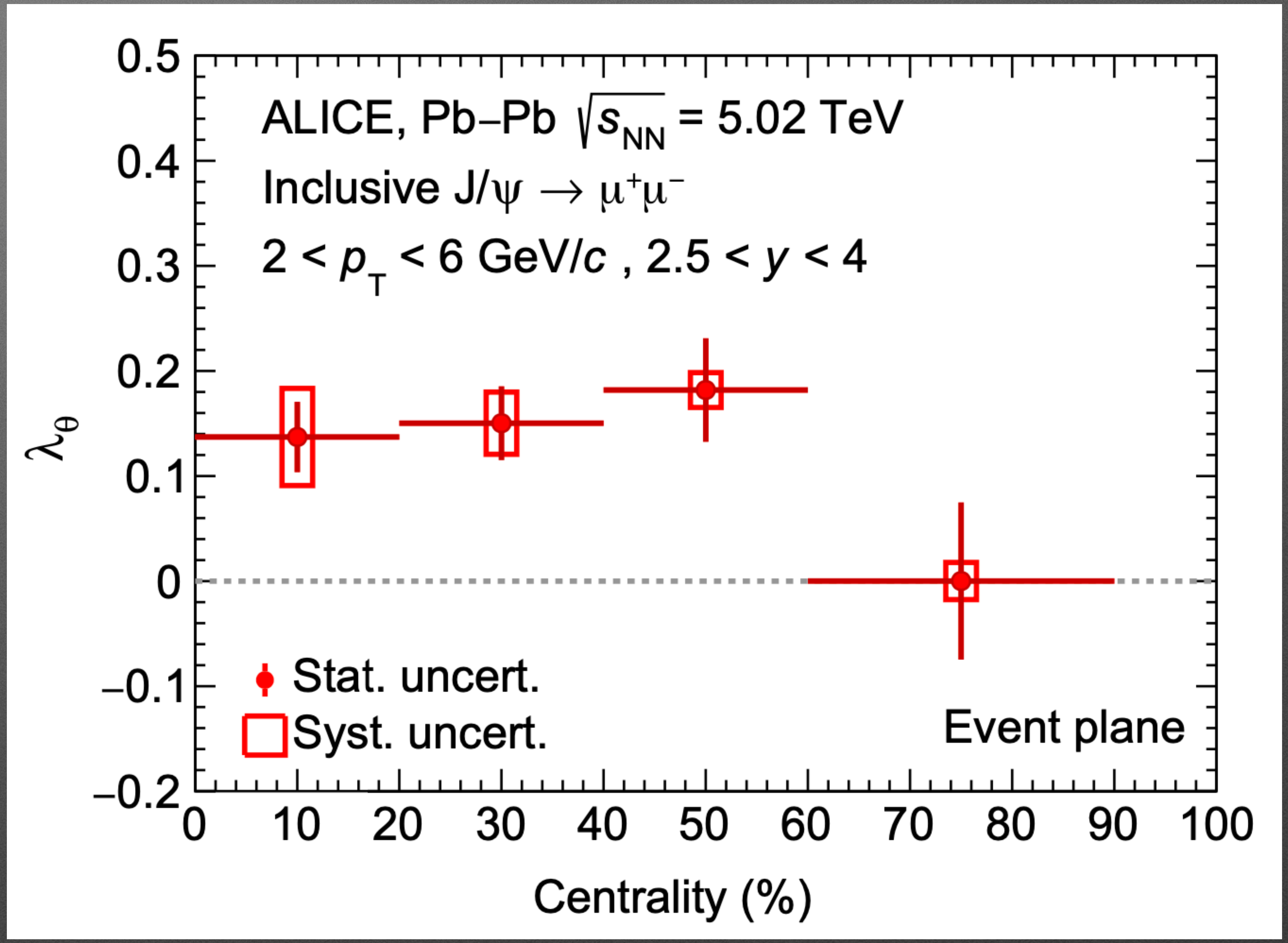
Huge magnetic field (short lived) and very large angular momentum (highest in semi-central collisions)

- present at the QGP formation
- in the direction orthogonal to the event-plane in the center of mass of the colliding beams
- may affect the system evolution

Kharzeev et al. [NPA 803 (2008) 227]
Becattini et al. [PRC 77 (2008) 024906]



ALICE [PRL 131 (2023) 042303]



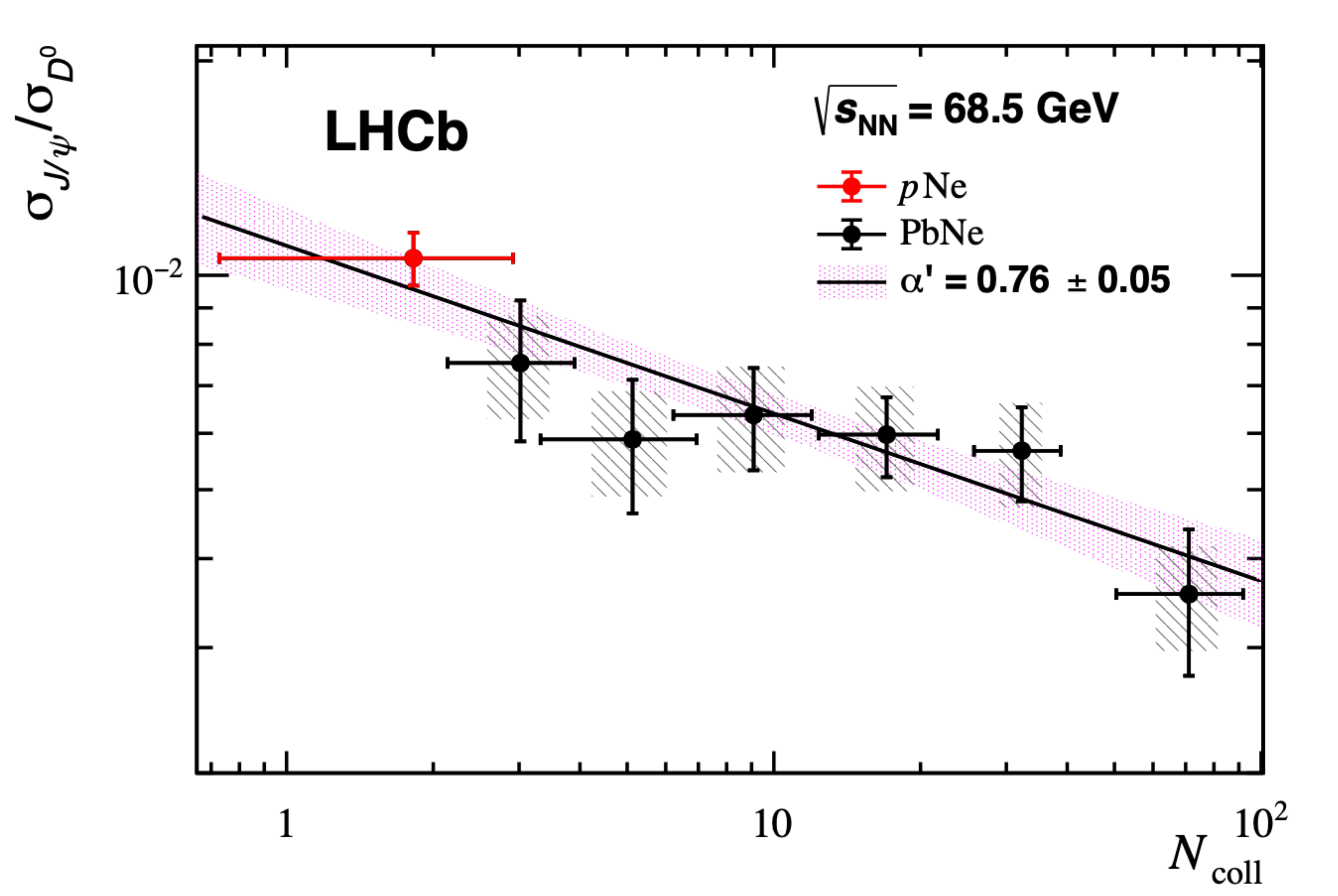
- Small but significant polarisation, particularly in the 40-60% centrality range (3σ effect)
- Theoretical models needed to distinguish between ***B*** and ***L*** contributions

Fixed-target at LHCb : J/ψ / D⁰ in PbNe at √s = 68.5 GeV

To better understand charmonium suppression: measure of charmonium yields and the overall charm quark production.

Most of the charm quarks hadronise into open charm D^0 mesons.

➡ Use D^0 production yield as reference for the study of the charmonium yield modification, assuming that D0 production is not modified by the medium.



LHCb [EPJC 83 (2023) 658]

‣ Linear trend of J/ψ / D^0 ratio in pNe vs PbNe → consistent with nuclear absorption

Summary

- Today : a biased selection of recent LHC results on hidden charm and beauty in the quarkonium system in PbPb collisions

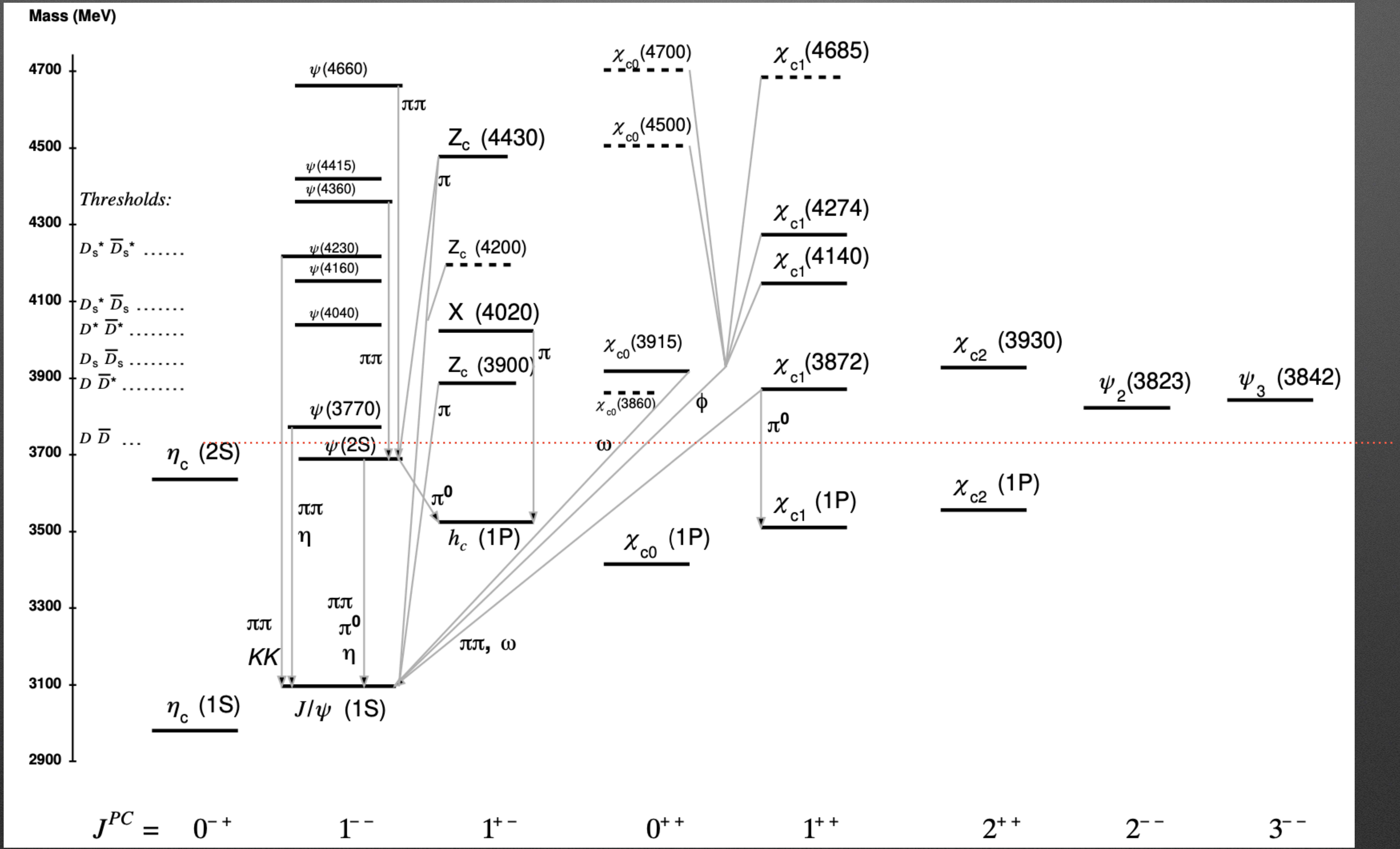
- This QCD laboratory provides :
  - harvest of results involving ground and excited states, from all LHC experiments
  - means to study the hot medium, in particular the dynamics in the suppression and regeneration mechanisms, confront them to EFT on the lattice, hydrodynamic and transport models

Thanks for your attention

Spare slides

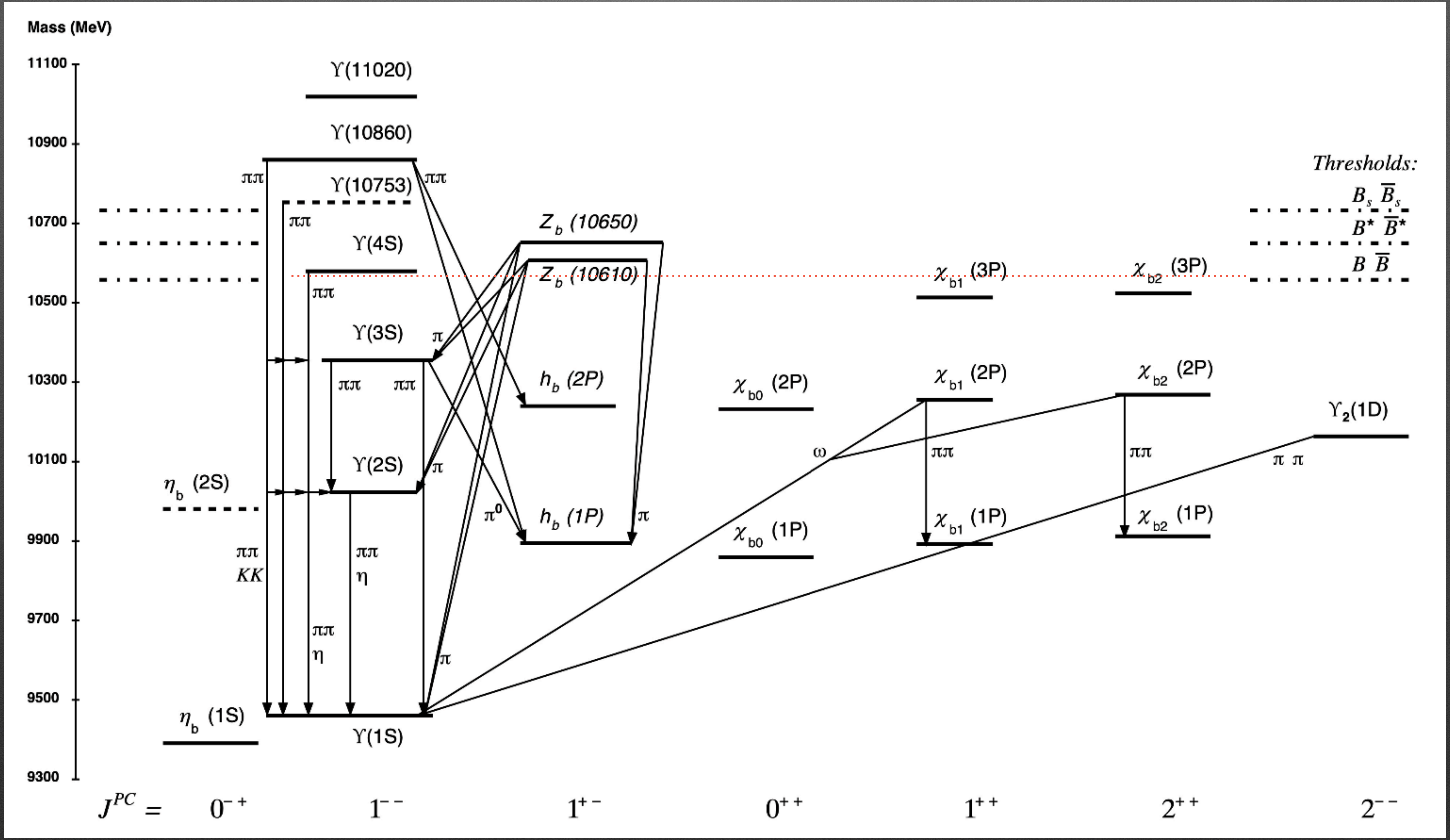
Charmonium system

PDG *[Prog.Theor.Exp.Phys. 2022, 083C01]*



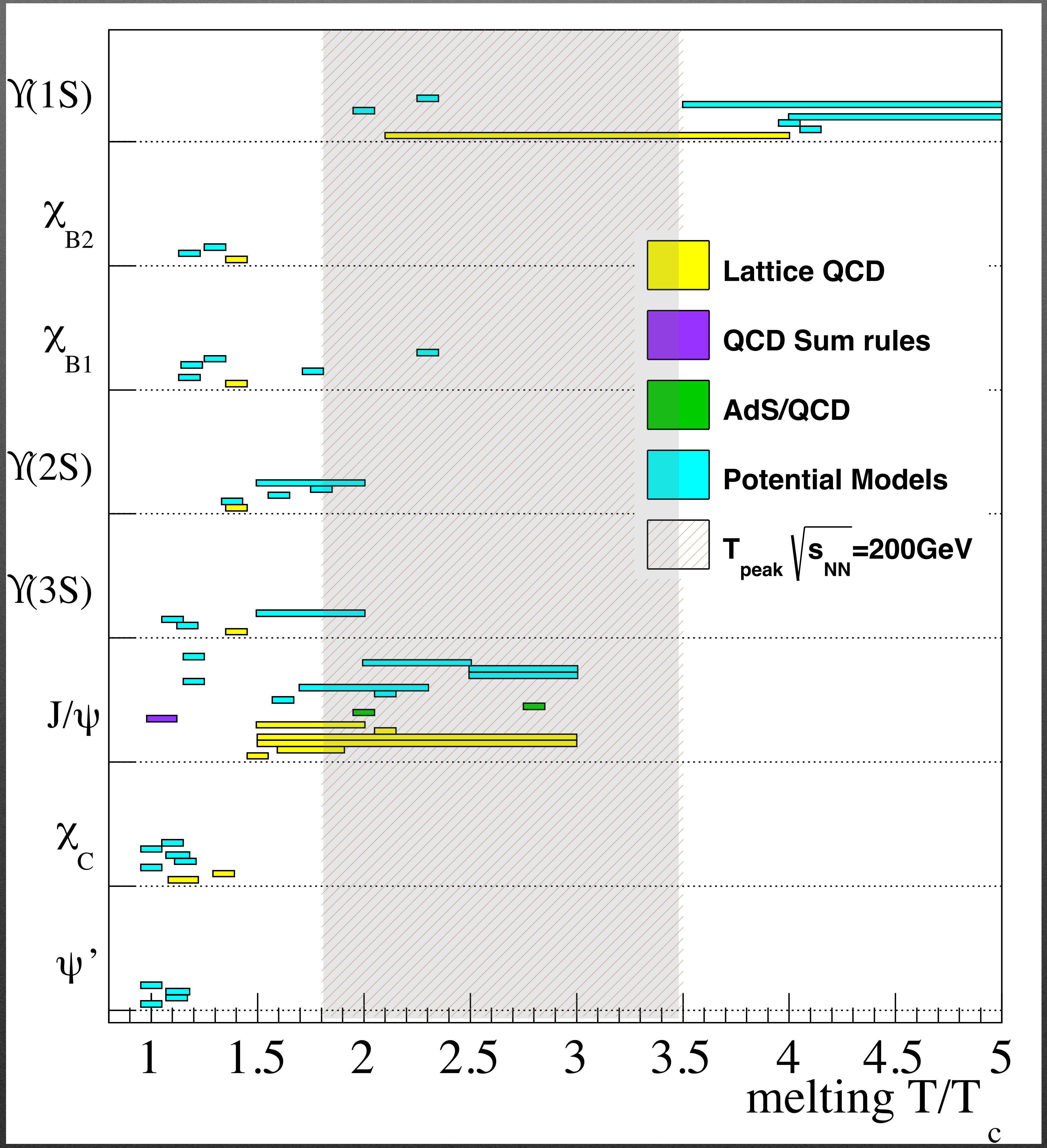
Bottomonium system

PDG [Prog.Theor.Exp.Phys. 2022, 083C01]



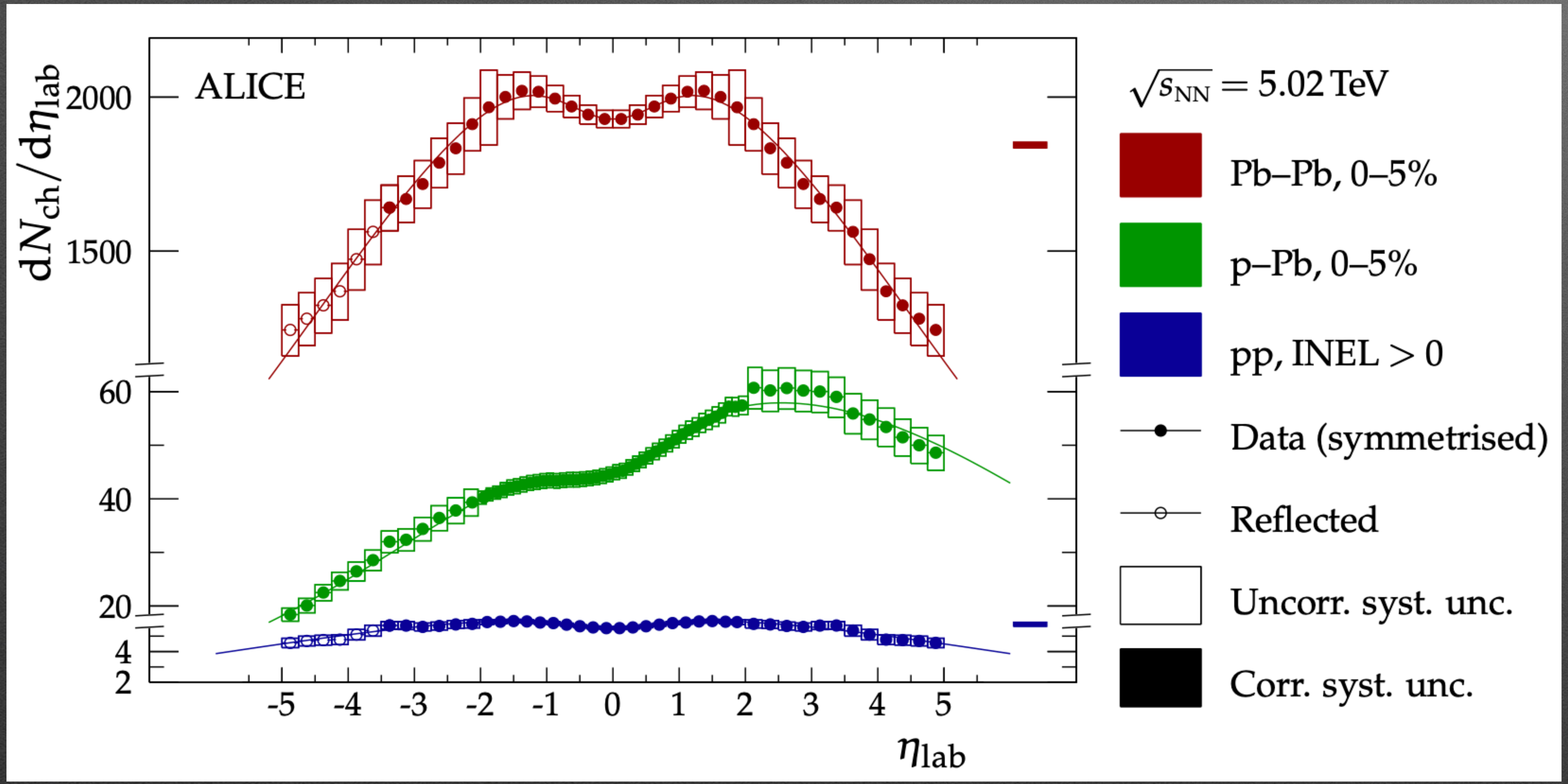
Uncertainties on the dissociation temperature

PHENIX *[PRC 91 (2015) 02413]*

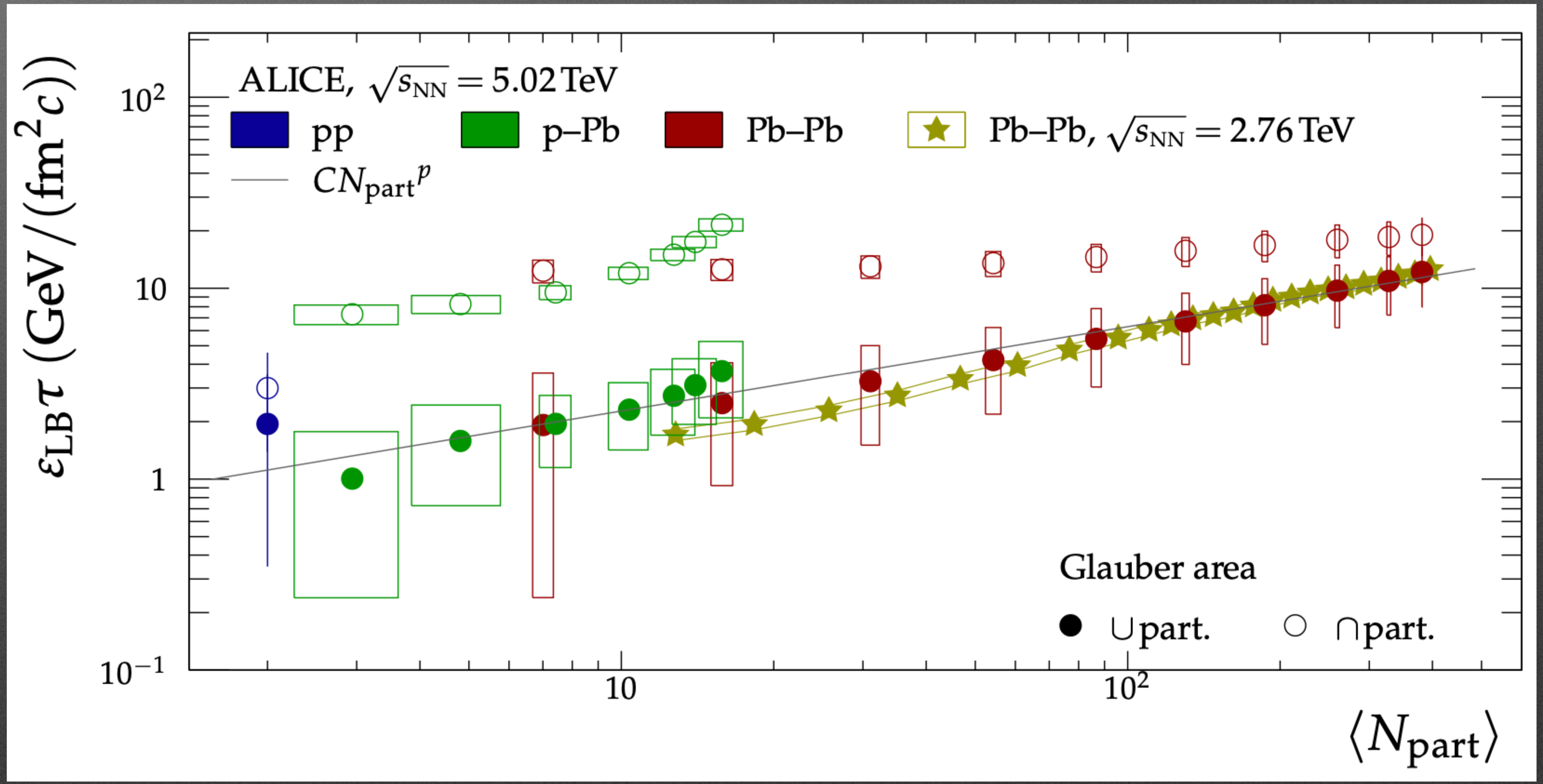


Pseudo-rapidity density, energy density at LHC

ALICE *[PLB 845 (2023) 137730]*



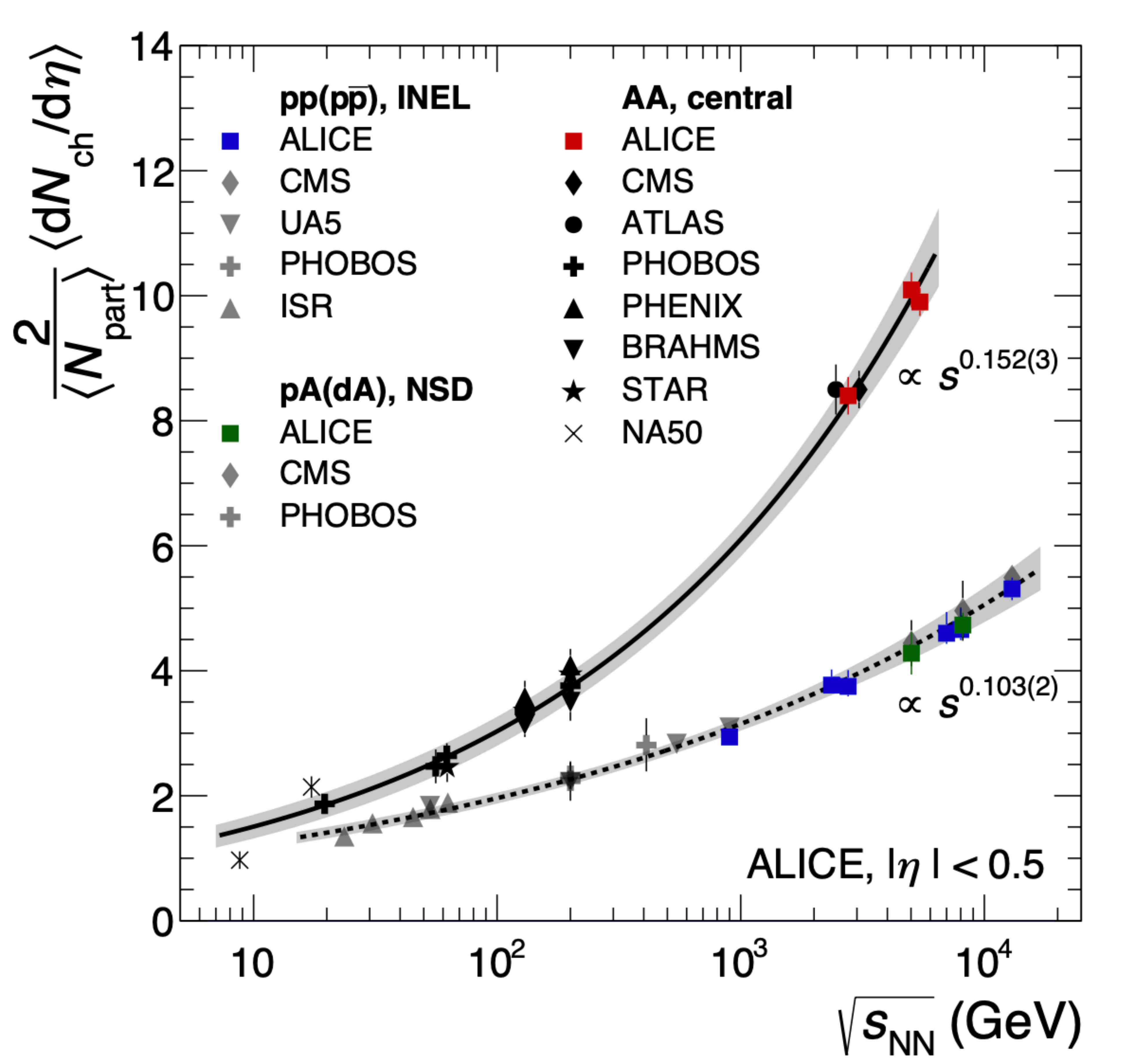
Charged-particle pseudo-rapidity density



Estimate of the lower bound of the Bjorken transverse energy density

Pseudo-rapidity density vs collision energy

ALICE [arXiv:2211.04384]

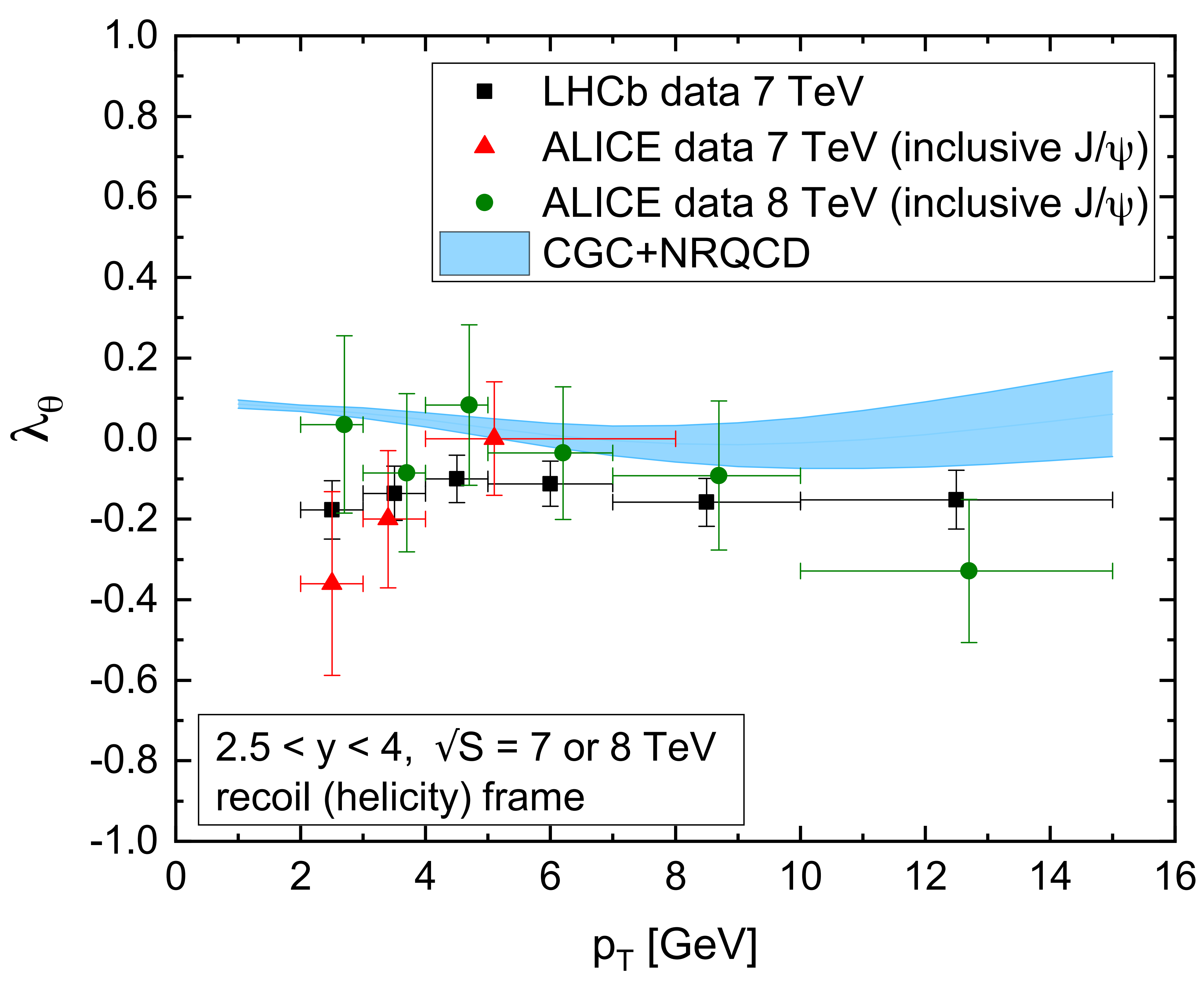


Collision energy dependence of the charged-particle pseudo-rapidity density at mid-rapidity normalised to the average number of participants, for different systems (pp, pA, AA)

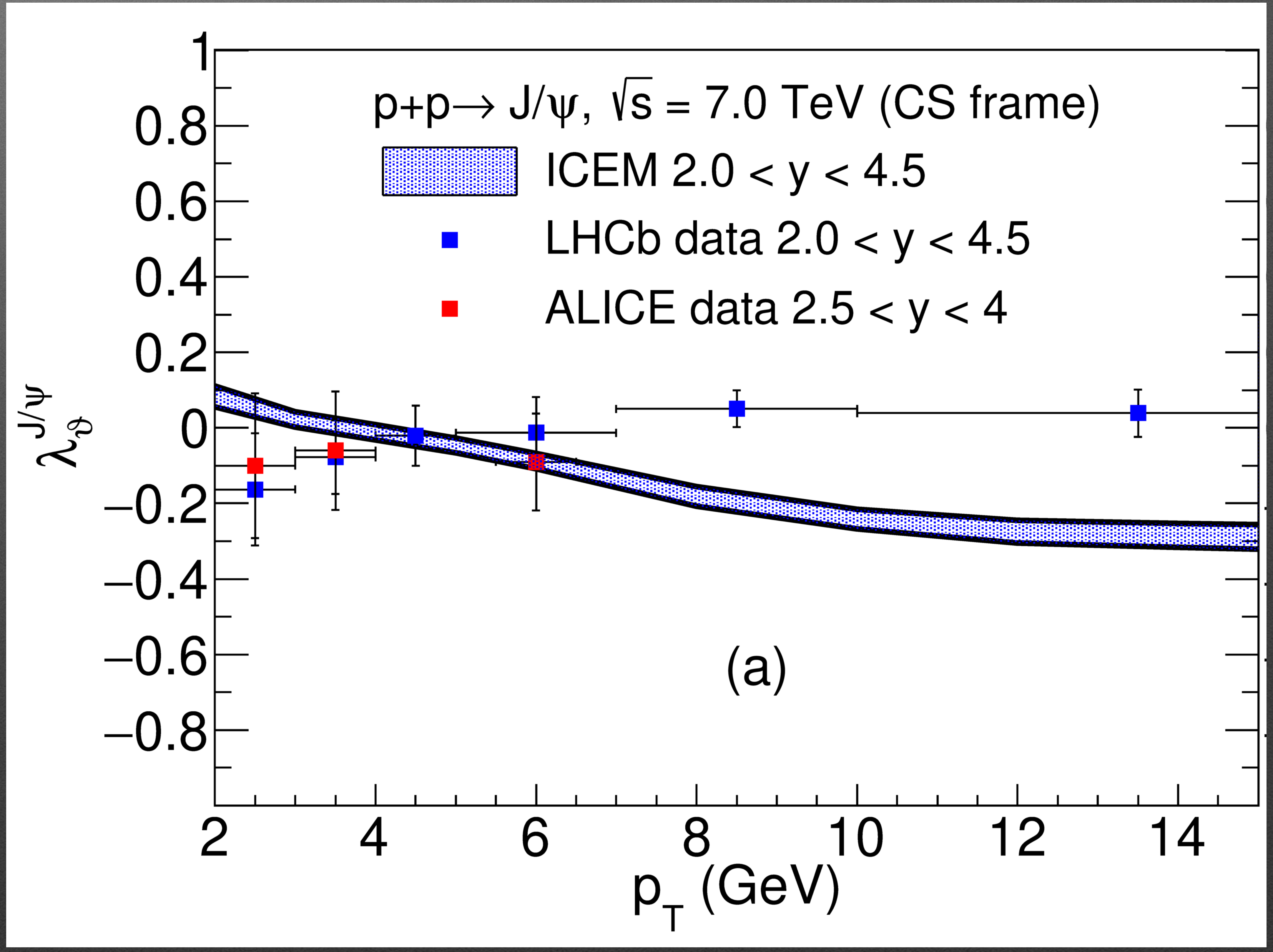
J/ψ polarisation in pp collisions

$\sqrt{s}$ = 7, 8 TeV, forward-y

ALICE [PRL 108 (2012) 082001]
ALICE [EPJ C 78 (2018) 7, 562]
LHCb [EPJ C 73 (2013) 11, 2631]



CGC + NRQCD, Ma et al. [JHEP 12 (2018) 057]



ICEM, Cheung, Vogt [PRD 104 (2021) 9, 094026]