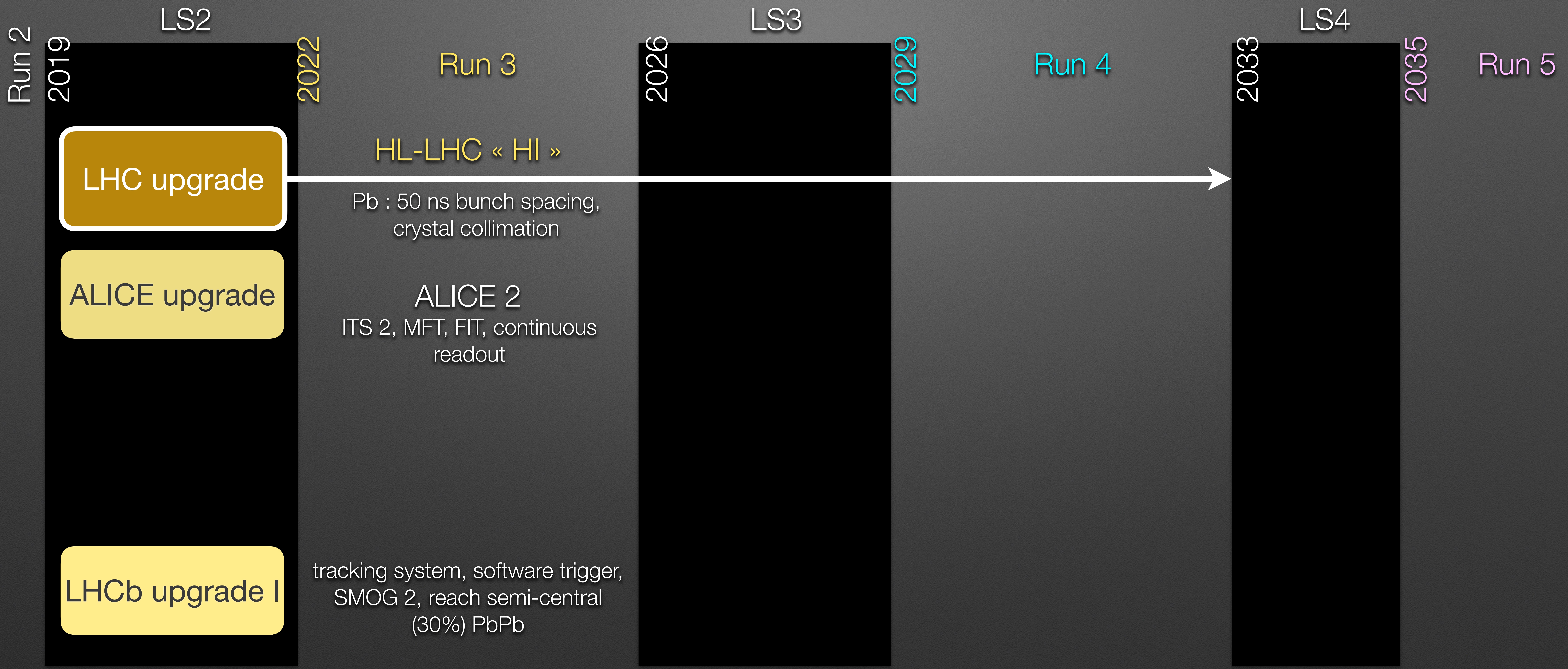
Synergies between LHC and EIC for quarkonium physics,
July 2024, ECT* Trento (Italy)

HL-LHC quarkonium prospects in pA, AA

Andry Rakotozafindrabe

cea irfu

High luminosity for heavy ions : Run 3 + Run 4



LHC upgrade

HL-LHC « HI »

Pb : 50 ns bunch spacing,
crystal collimation

ALICE upgrade

ALICE 2
ITS 2, MFT, FIT, continuous
readout

LHCb upgrade I

tracking system, software trigger,
SMOG 2, reach semi-central
(30%) PbPb

High luminosity for heavy ions : Run 3 + Run 4

Run 2

LS2

2019

2022

LHC upgrade

ALICE upgrade

LHCb upgrade I

Run 3

HL-LHC « HI »

Pb : 50 ns bunch spacing, crystal collimation

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ITS 2, MFT, FIT, continuous readout

tracking system, software trigger, SMOG 2, reach semi-central (30%) PbPb

LS3

2026

2029

ALICE upgrade

LHC upgrade

ATLAS, CMS phase 2 upgrades

Run 4

ALICE 2.1

ITS 3, FOCAL

HL-LHC « pp »

pp : 5 to 7 x LHC nominal luminosity, 140 to 200 pile-up / bunch x-ing

LS4

2033

2035

Run 5

High luminosity for heavy ions : Run 3 + Run 4

Run 2

LS2

2019

2022

Run 3

LS3

2026

2029

Run 4

LS4

2033

2035

Run 5

LHC upgrade

HL-LHC « HI »

Pb : 50 ns bunch spacing, crystal collimation

HI ?

ALICE upgrade

ALICE 2
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ALICE upgrade

ALICE 2.1
ITS 3, FOCAL

ALICE upgrade

ALICE 3

LHC upgrade

HL-LHC « pp »

LHCb upgrade I

tracking system, software trigger, SMOG 2, reach semi-central (30%) PbPb

ATLAS, CMS phase 2 upgrades

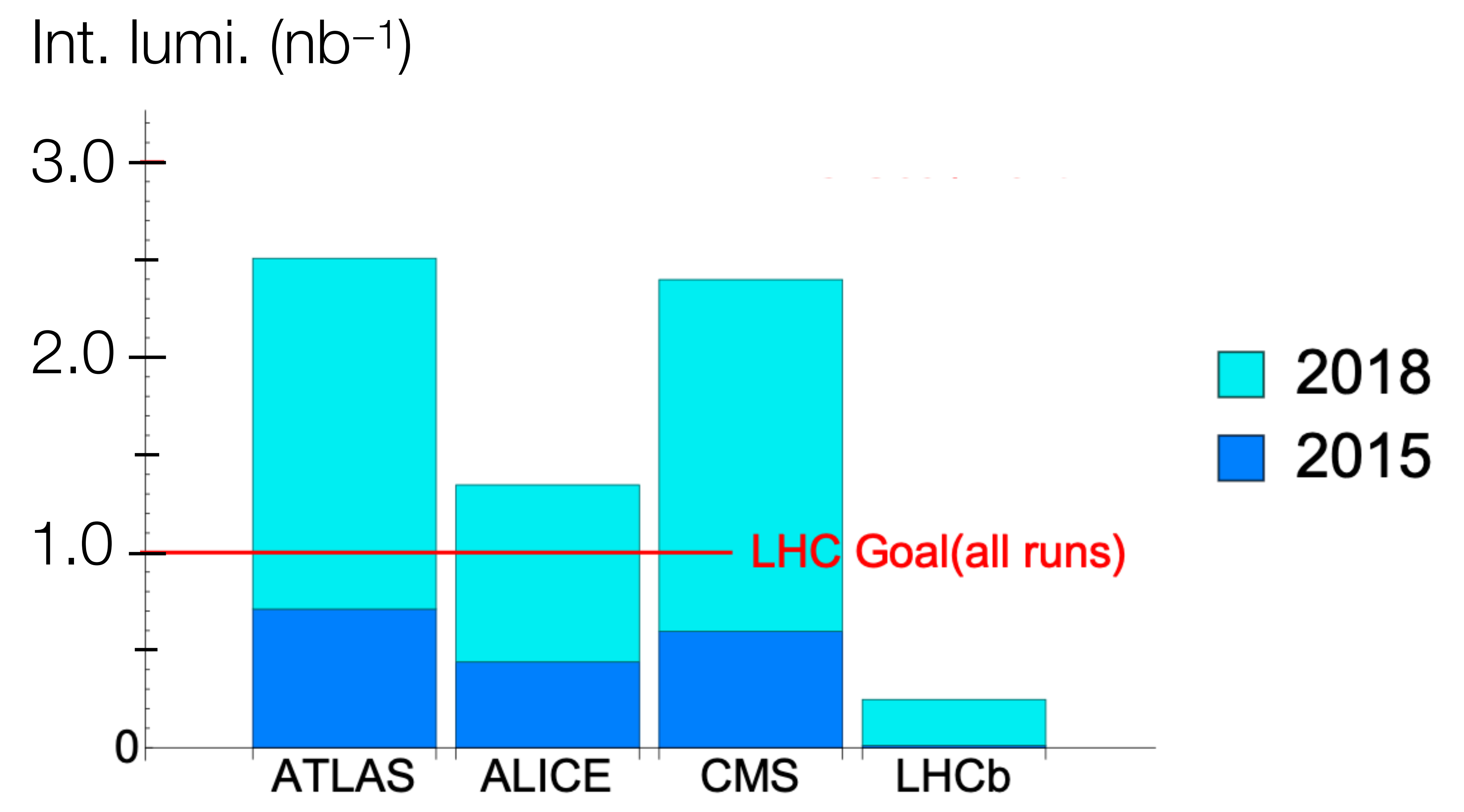
pp : 5 to 7 x LHC nominal luminosity, 140 to 200 pile-up / bunch x-ing

LHCb upgrade II

precision timing, improved PID, increased granularity

Collider mode : past vs future Pb-Pb

Run 2, delivered Pb-Pb 5.02 TeV in 2015 and 2018



J.M. Jowett et al. *[IPAC 2019 proceedings]*

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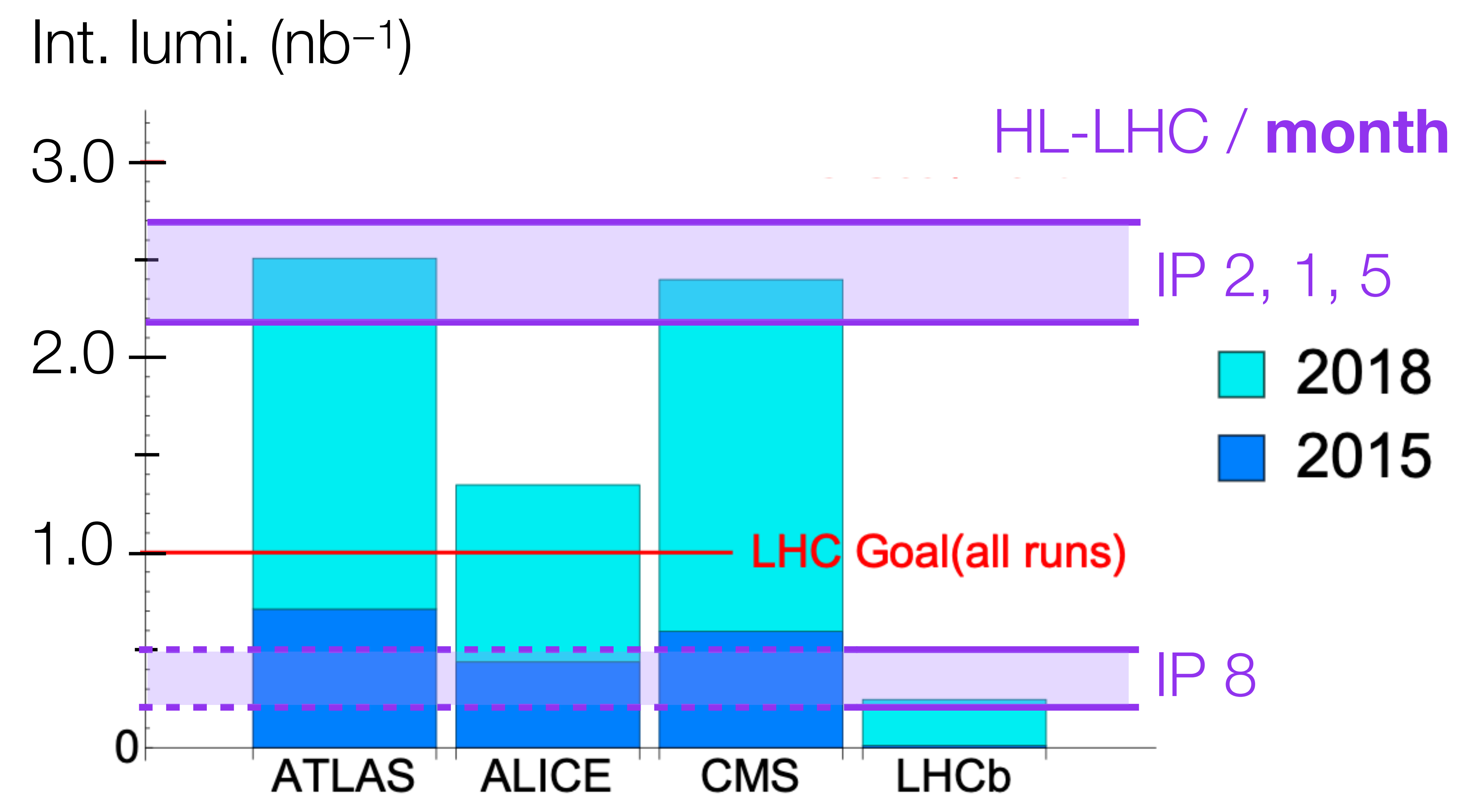
CERN yellow report, WG5 [CERN-2019-007]

Predicted Pb-Pb delivered luminosity per month



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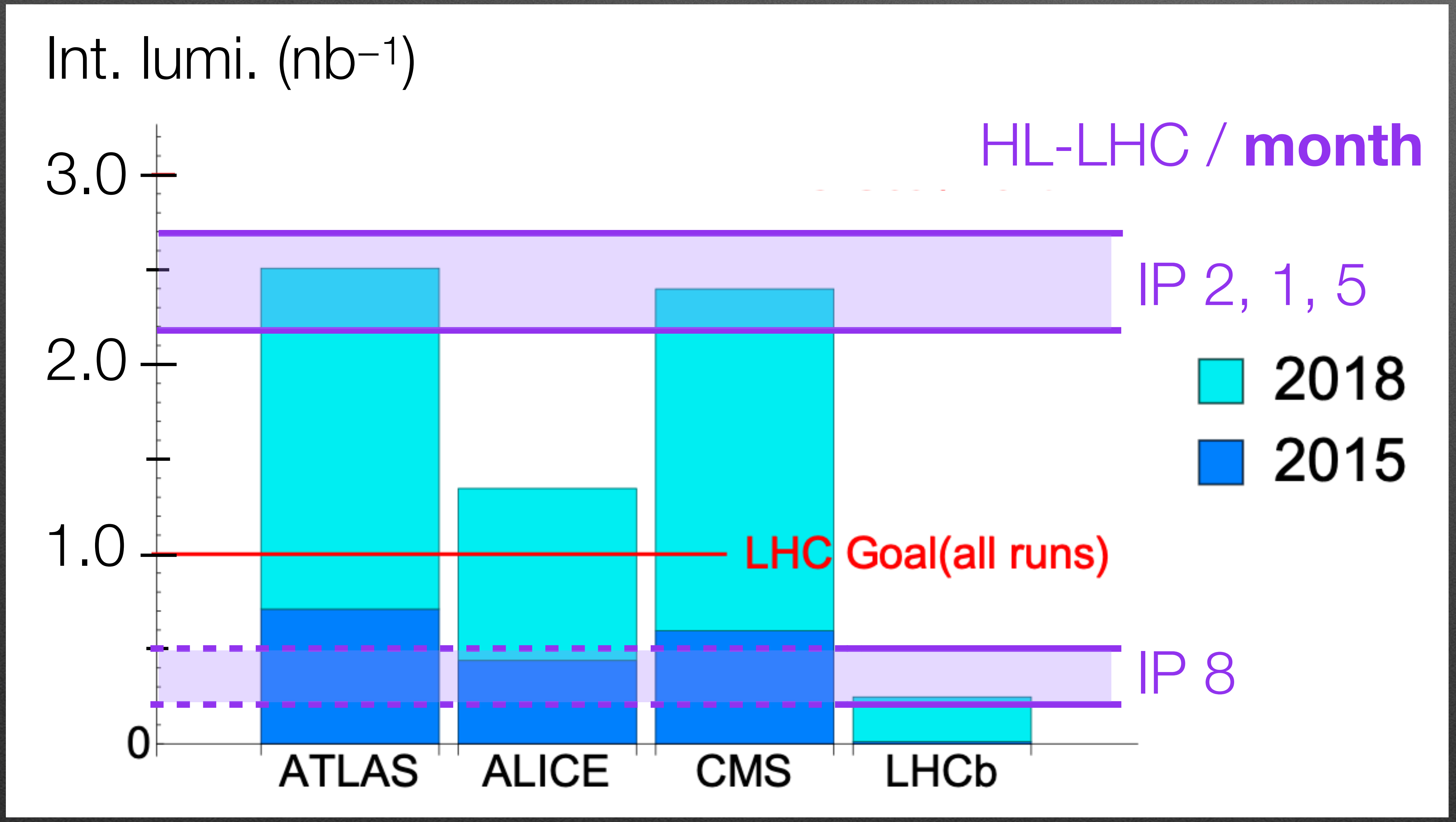

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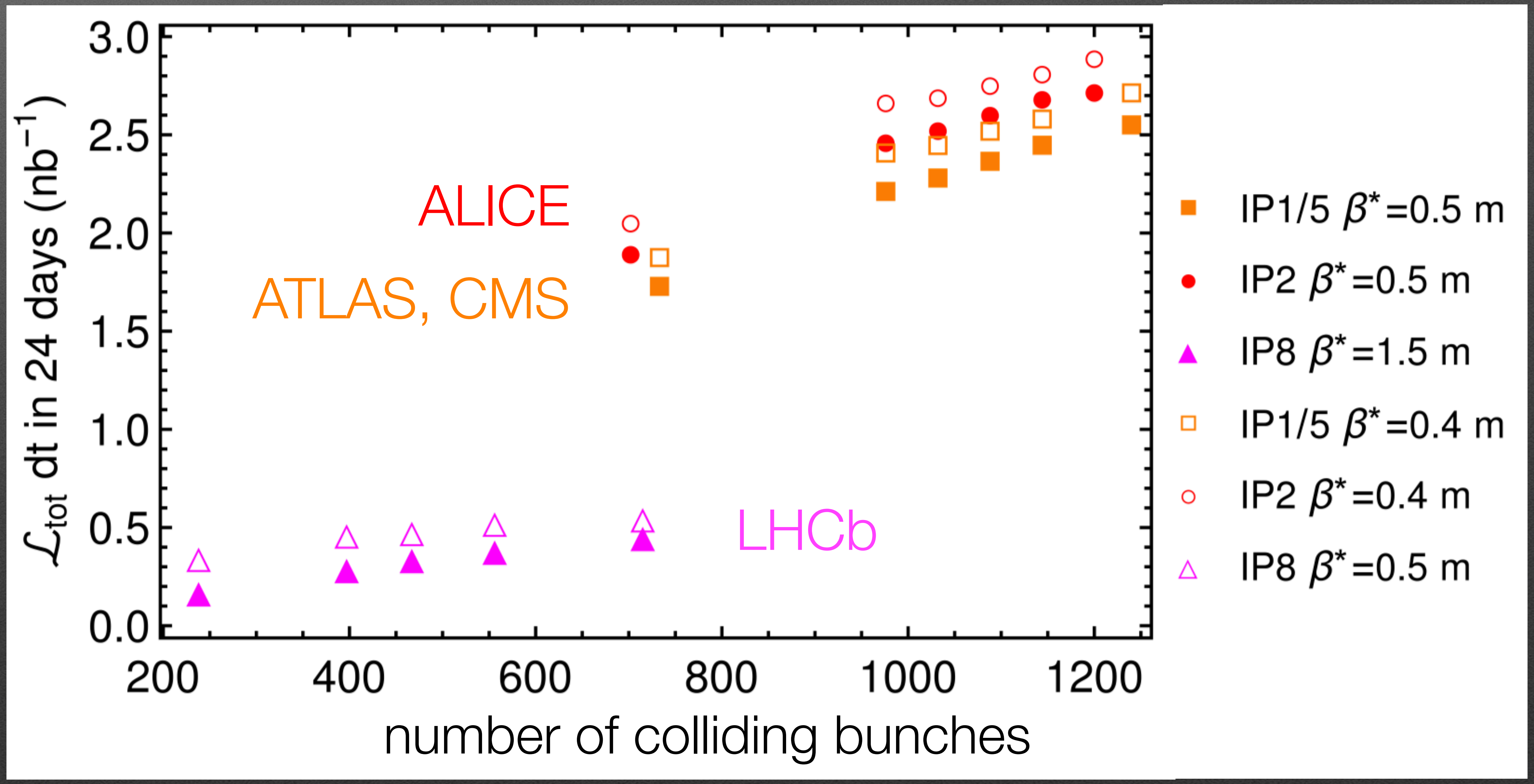
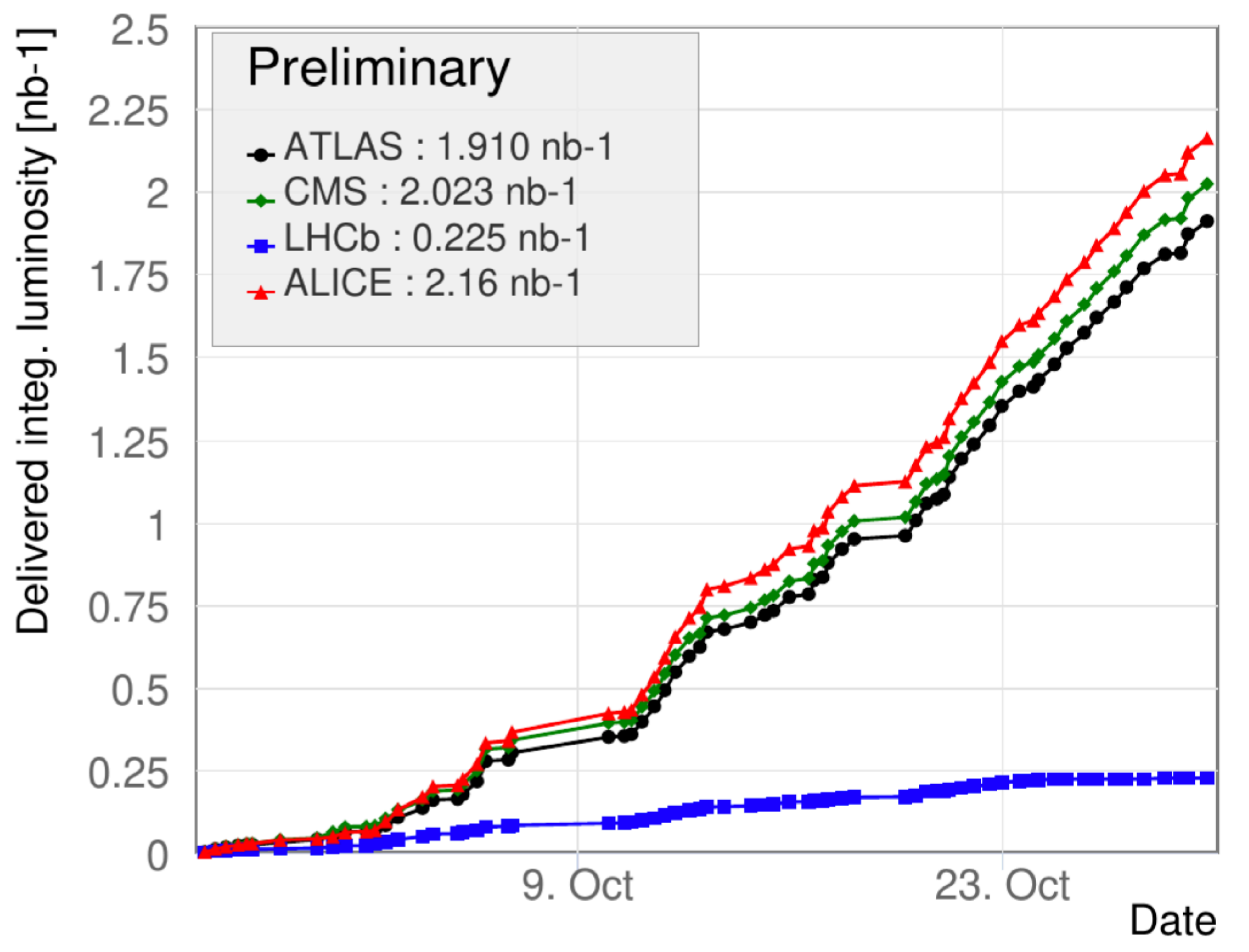


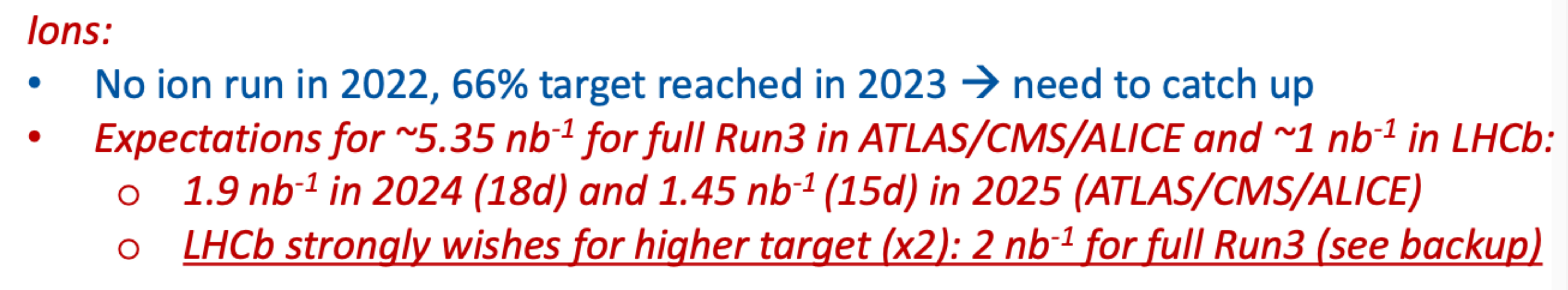
R. Bruce et al. [EPJ P 136 (2021) 7, 745]

Collider mode : Pb-Pb in 2023

All experiments collected more data than in the last Run 2 Pb-Pb run

Useable luminosity in ALICE is reduced to 1.96 nb^{-1} after beam background (*) mitigation




Ions:

- No ion run in 2022, 66% target reached in 2023 → need to catch up
- *Expectations for ~5.35 nb^{-1} for full Run3 in ATLAS/CMS/ALICE and ~1 nb^{-1} in LHCb:*
    - ○ *1.9 nb^{-1} in 2024 (18d) and 1.45 nb^{-1} (15d) in 2025 (ATLAS/CMS/ALICE)*
    - ○ *LHCb strongly wishes for higher target (x2): 2 nb^{-1} for full Run3 (see backup)*

F. Alessio [Chamonix workshop 2024]

(*) particle shower resulting from beam remnants (Pb207) hitting tertiary collimators in IR2 and reaching the detectors

Collider mode : past vs future p-Pb

Run 2, p-Pb/Pb-p 8.16 TeV in 2016, delivered approx. 39 (32) nb^{-1} ALICE (LHCb), 194 (186) nb^{-1} ATLAS (CMS)

J. Jowett et al. [IPAC 2017 proceedings]

Run 3 + Run 4, p-Pb 8.8 TeV, requested 600 nb^{-1} ALICE/LHCb, 1200 nb^{-1} ATLAS/CMS

CERN yellow report, WG5 [CERN-2019-007]

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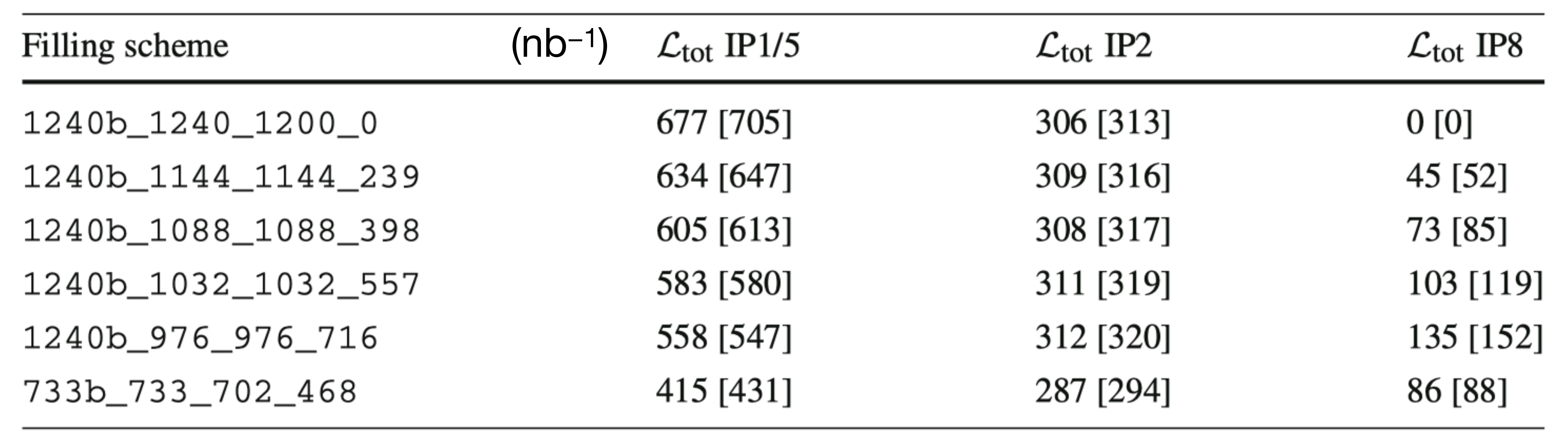
CERN yellow report, WG5 [CERN-2019-007]

Run 3 : no p-Pb scheduled *R. Bruce [Physics with HL-LHC pA , 2024 workshop]*

Run 4 : one month p-Pb run ? maybe two ? w. or w/o beam reversal ?

R. Bruce et al. [EPJ P 136 (2021) 7, 745]

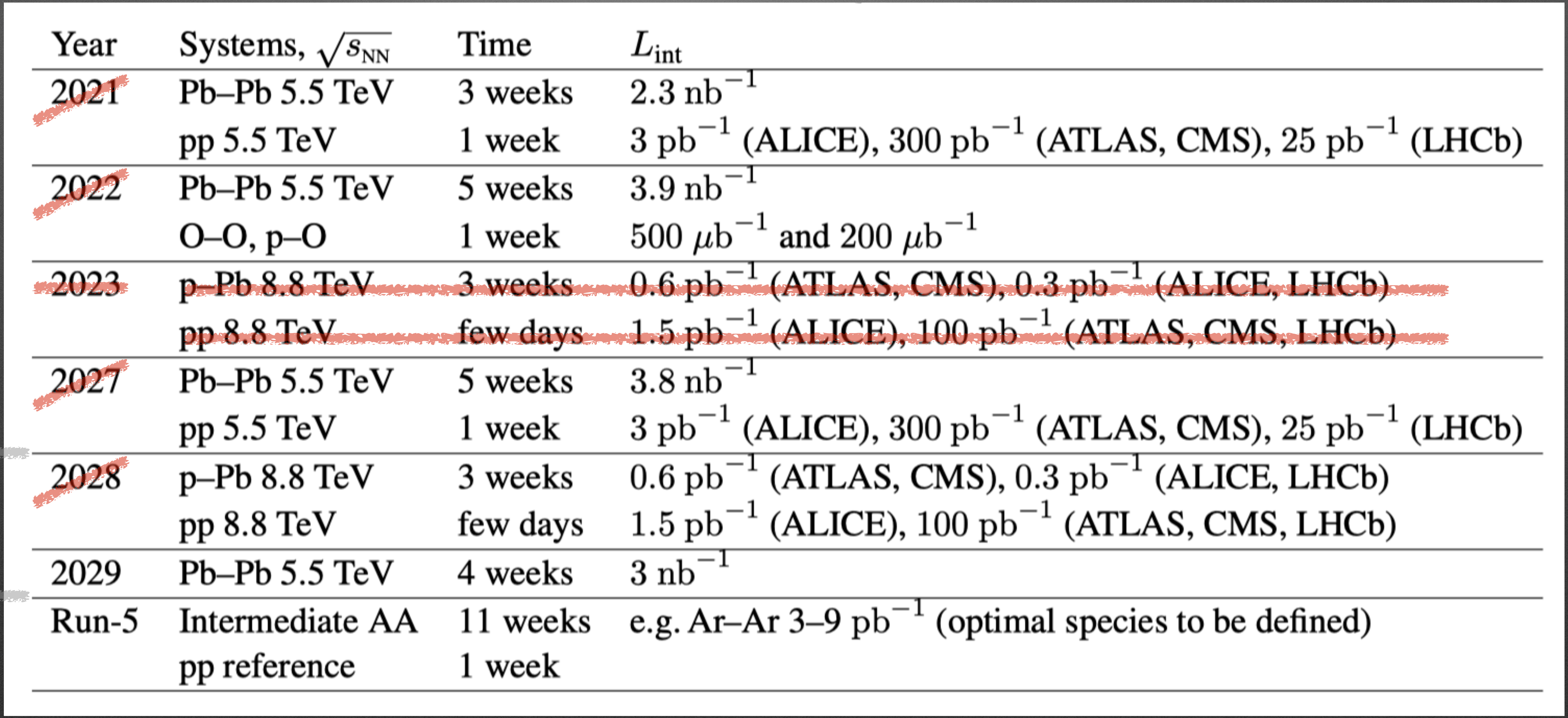


Filling scheme (nb^{-1})	$\mathcal{L}_{\text{tot}}$ IP1/5	$\mathcal{L}_{\text{tot}}$ IP2	$\mathcal{L}_{\text{tot}}$ IP8
`1240b_1240_1200_0`	677 [705]	306 [313]	0 [0]
`1240b_1144_1144_239`	634 [647]	309 [316]	45 [52]
`1240b_1088_1088_398`	605 [613]	308 [317]	73 [85]
`1240b_1032_1032_557`	583 [580]	311 [319]	103 [119]
`1240b_976_976_716`	558 [547]	312 [320]	135 [152]
`733b_733_702_468`	415 [431]	287 [294]	86 [88]

Collider mode : a (vintage) calendar

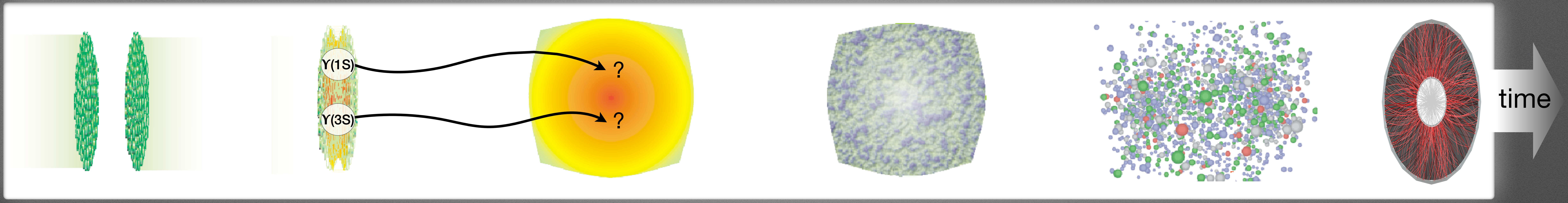
CERN yellow report, WG5 [CERN-2019-007]

Run 3
2023
2024
2025
2029
Run 4
2032
2035
Run 5



Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
~~2021~~	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
~~2022~~	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 $\mu\mathrm{b}^{-1}$ and 200 $\mu\mathrm{b}^{-1}$
~~2023~~	~~p–Pb 8.8 TeV~~	~~3 weeks~~	~~0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)~~
	~~pp 8.8 TeV~~	~~few days~~	~~1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)~~
~~2027~~	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
~~2028~~	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

Heavy quarkonia as **hard probes** of the medium



initial conditions

hard scatterings
pre-equilibrium
dynamics

QGP
hydrodynamic
expansion

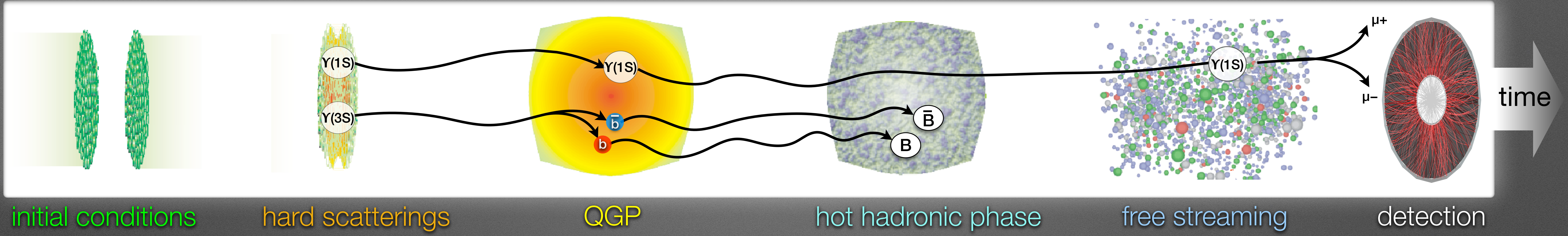
hot hadronic phase
ch. freeze-out

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

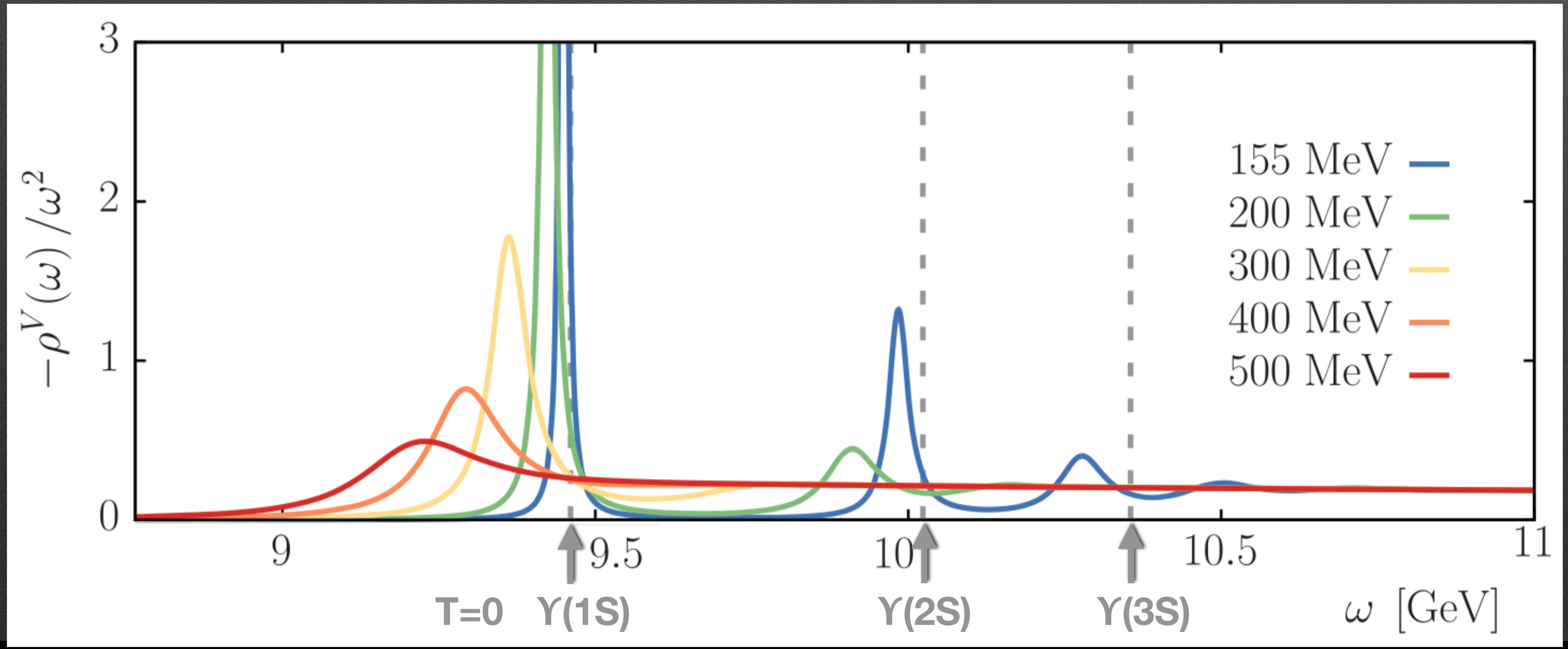
Heavy quarkonia as hard probes of the **medium**



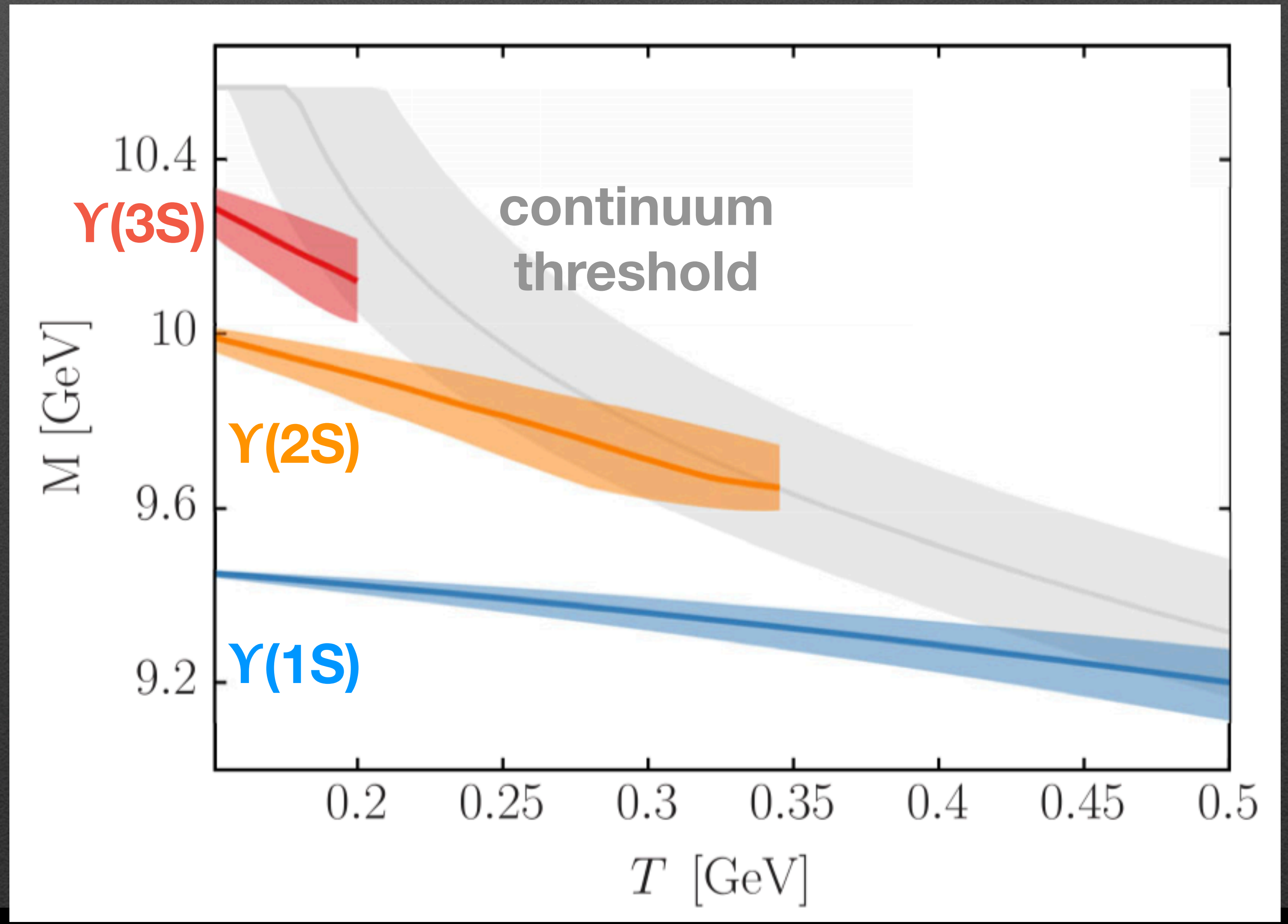
- In-medium dynamics: progressive dissolution of the quarkonium states, depending on their binding strength and the bath temperature, for e.g. Υ(nS) :

Lafferty, Rothkopf [PRD 101 (2020) 056010]

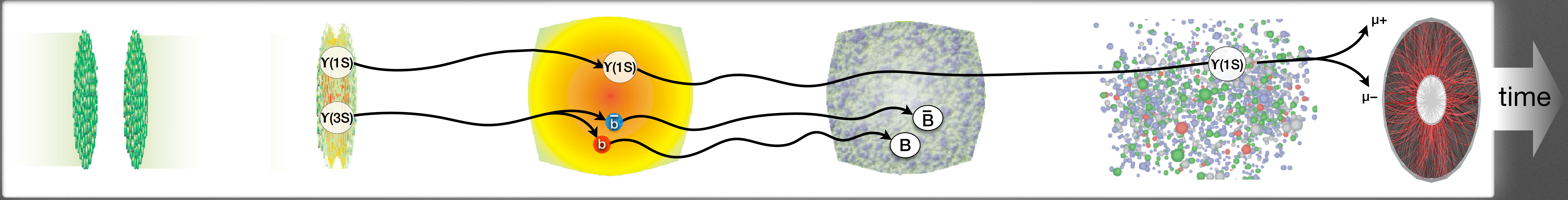
lattice in-medium spectral functions



lattice in-medium masses vs T



Heavy quarkonia as hard probes of the medium



initial conditions hard scatterings QGP hot hadronic phase free streaming detection

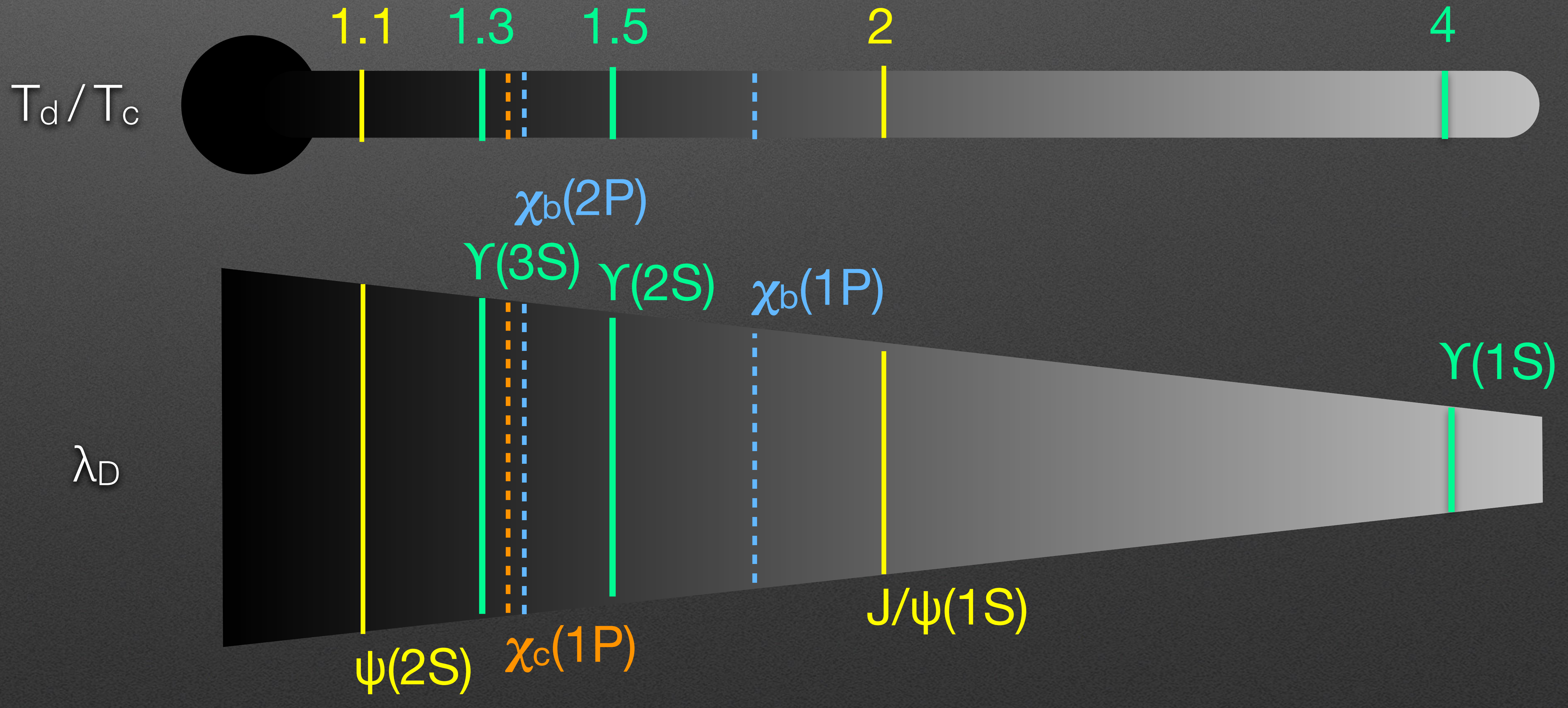
- Can be used as a QGP « thermometer » ?
- For e.g. the Υ(nS) family :
  - In PbPb relative to pp collisions, Υ(1S) and Υ(2S) were observed by ALICE, ATLAS, CMS

    CMS [PLB 790 (2019) 270]

    ALICE [PLB 822 (2021) 136579]

    ATLAS [PRC 107 (2023) 054912]
  - Υ(3S) totally suppressed at LHC ?

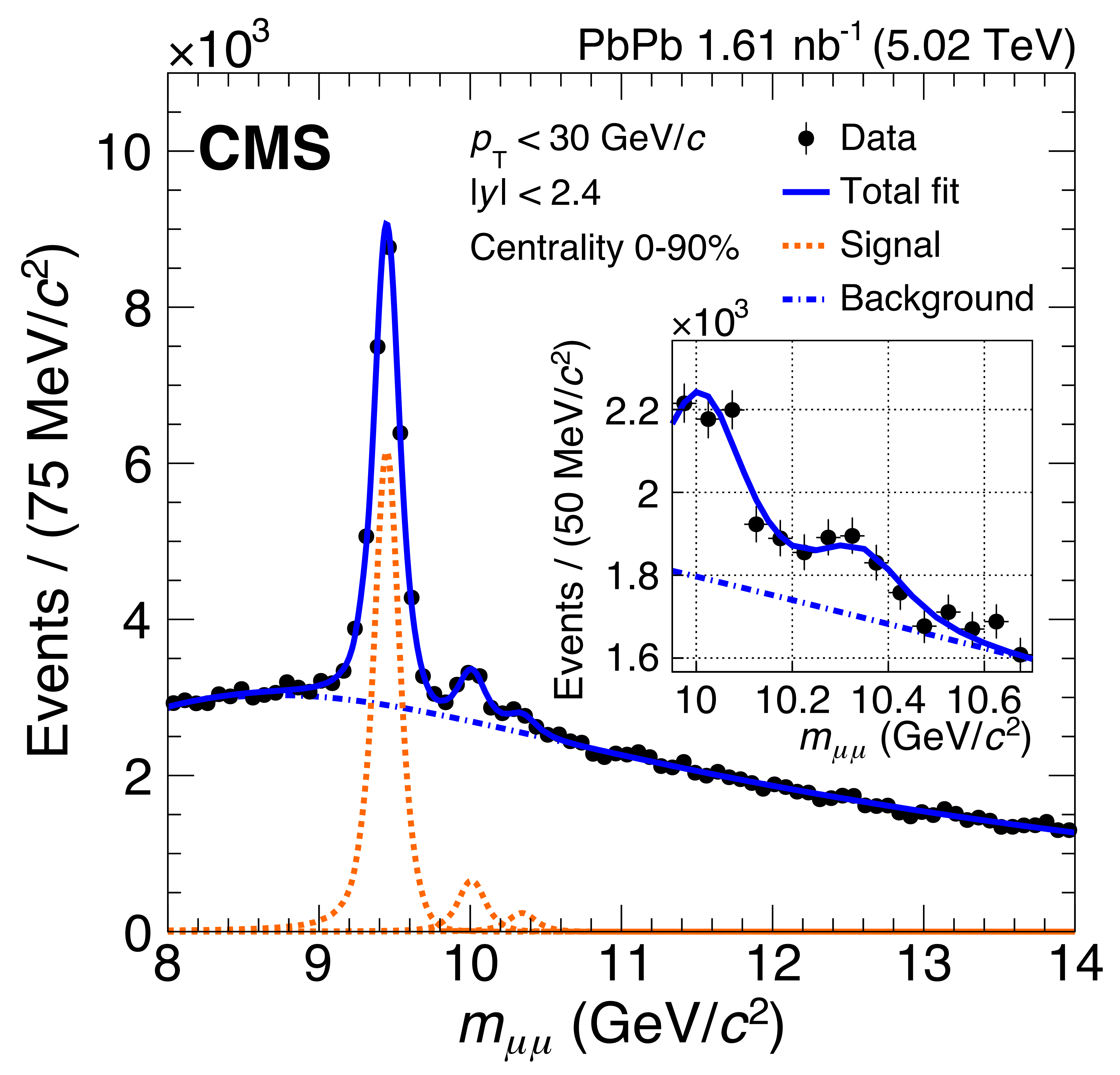
T_d from hydro + lattice QCD



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

ϒ(3S) in PbPb collisions at LHC

CMS [arXiv : 2303.17026]



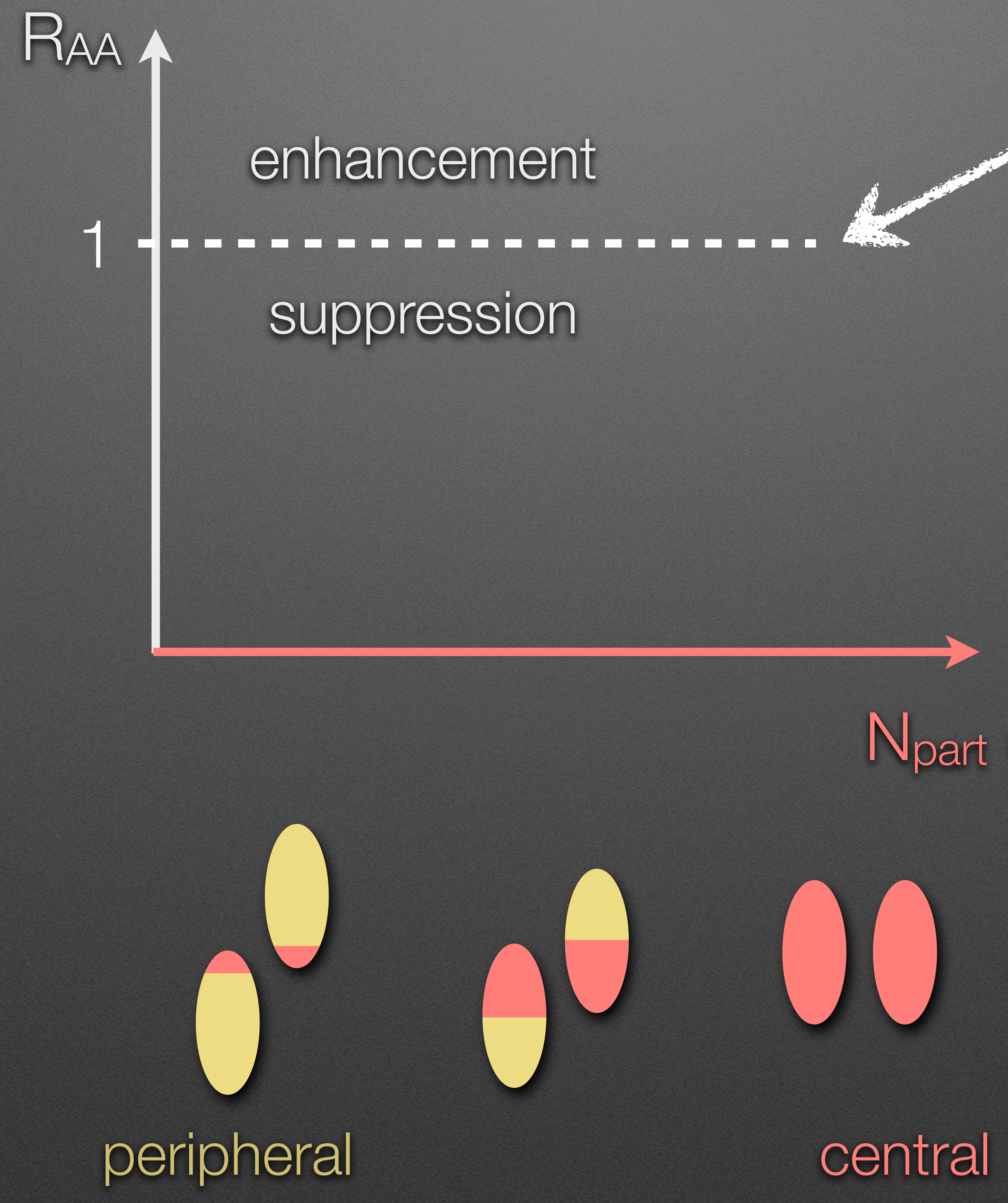
- First ϒ(3S) measurement in AA collisions
- 5.6σ signal for ϒ(3S)

Our favourite observable

Nuclear modification factor for a quarkonium in AA collisions

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

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



no deviation from
a simple superposition of pp collisions

N_{part} = # nucleons participating in the collision

geometry of an AA collision

increasing $dN_{\mathrm{ch}}/d\eta \propto \varepsilon$ (GeV/fm^3)

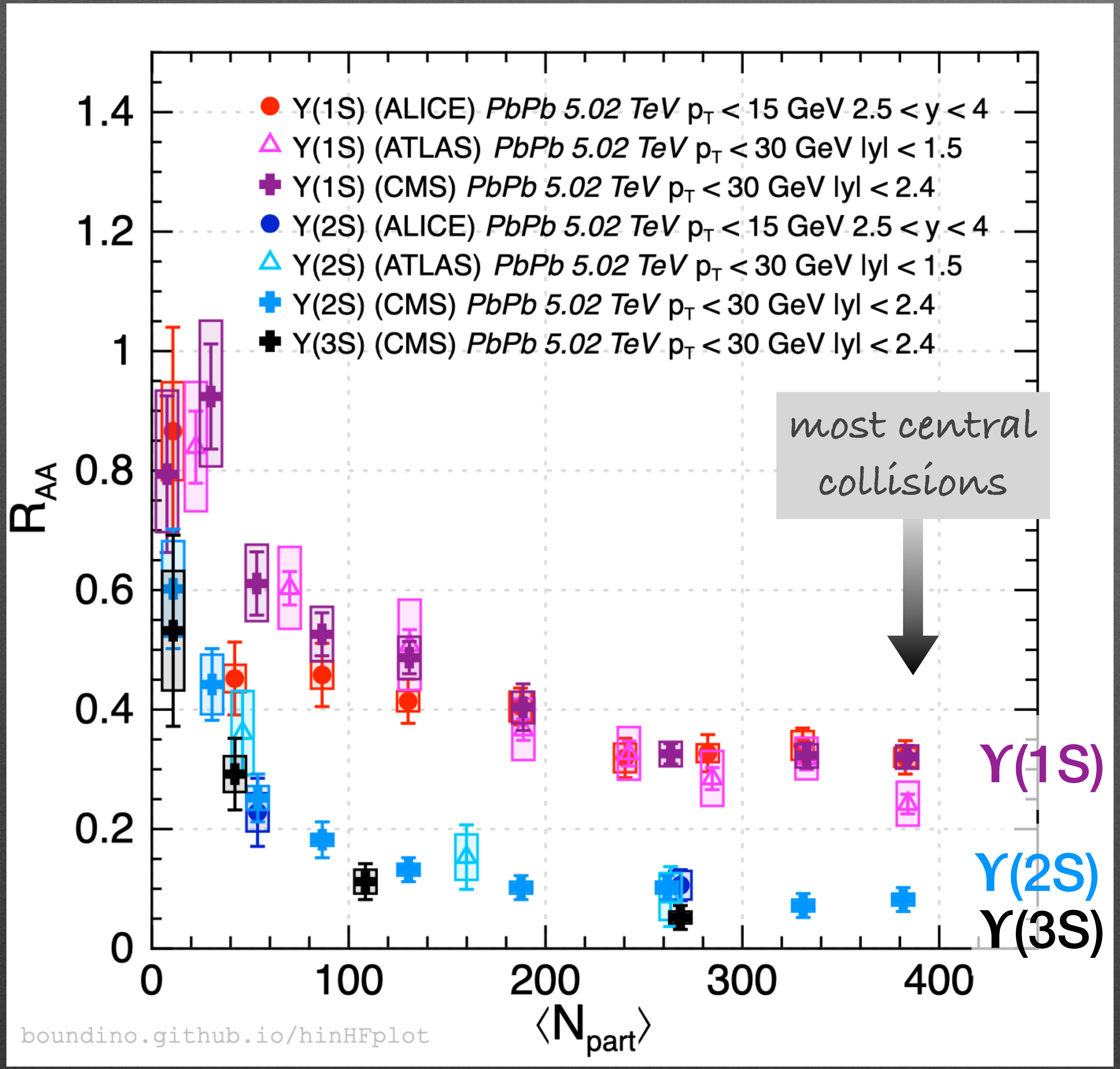
ϒ(nS) : a GQP thermometer in PbPb ?

ϒ(1S) CMS [PLB 790 (2019) 270]

ALICE [PLB 822 (2021) 136579]

ATLAS [PRC 107 (2023) 054912]

ϒ(2S) and ϒ(3S) CMS [arXiv : 2303.17026]



most central collisions

ϒ(nS) : a GQP thermometer in PbPb ?

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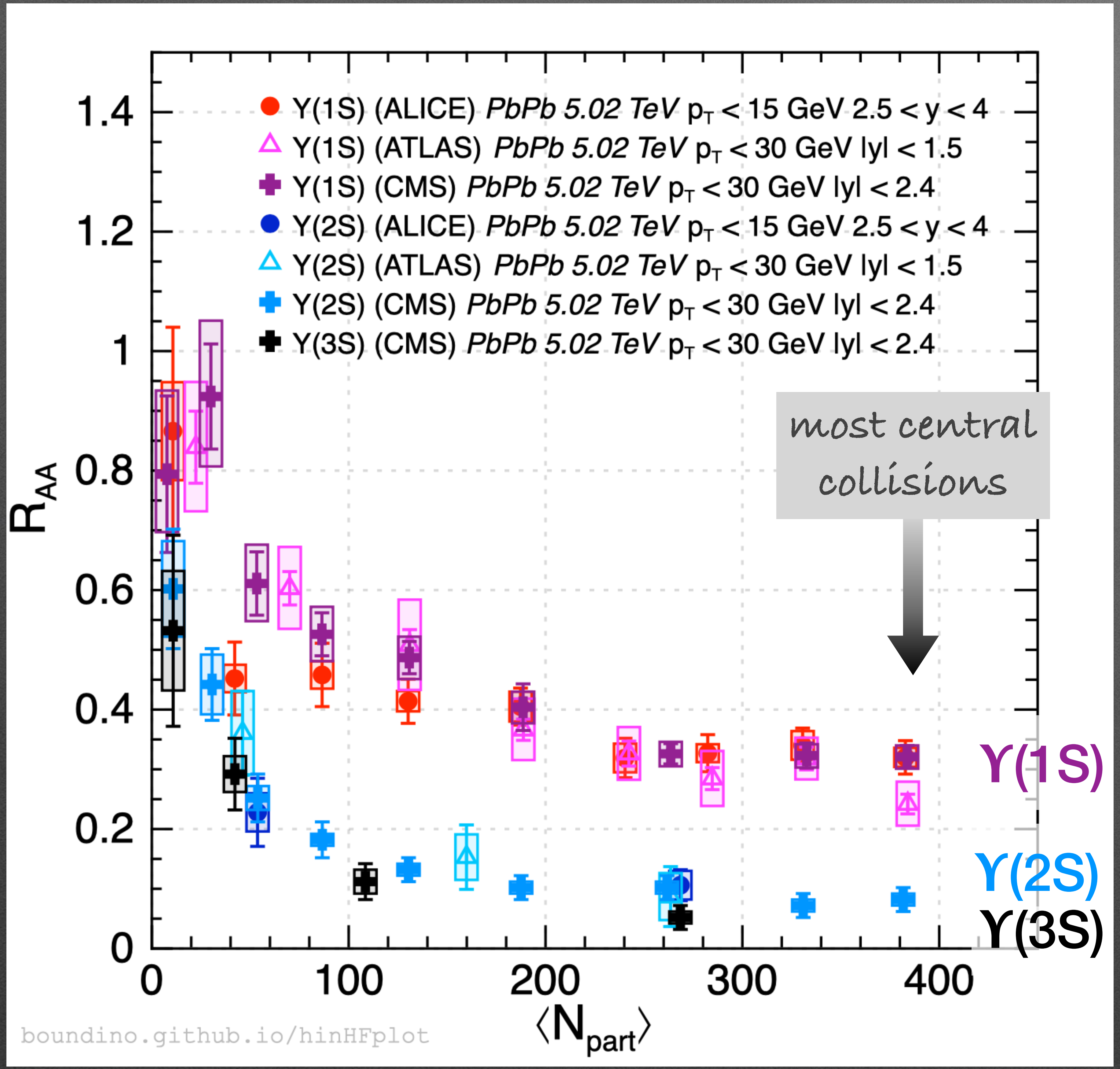
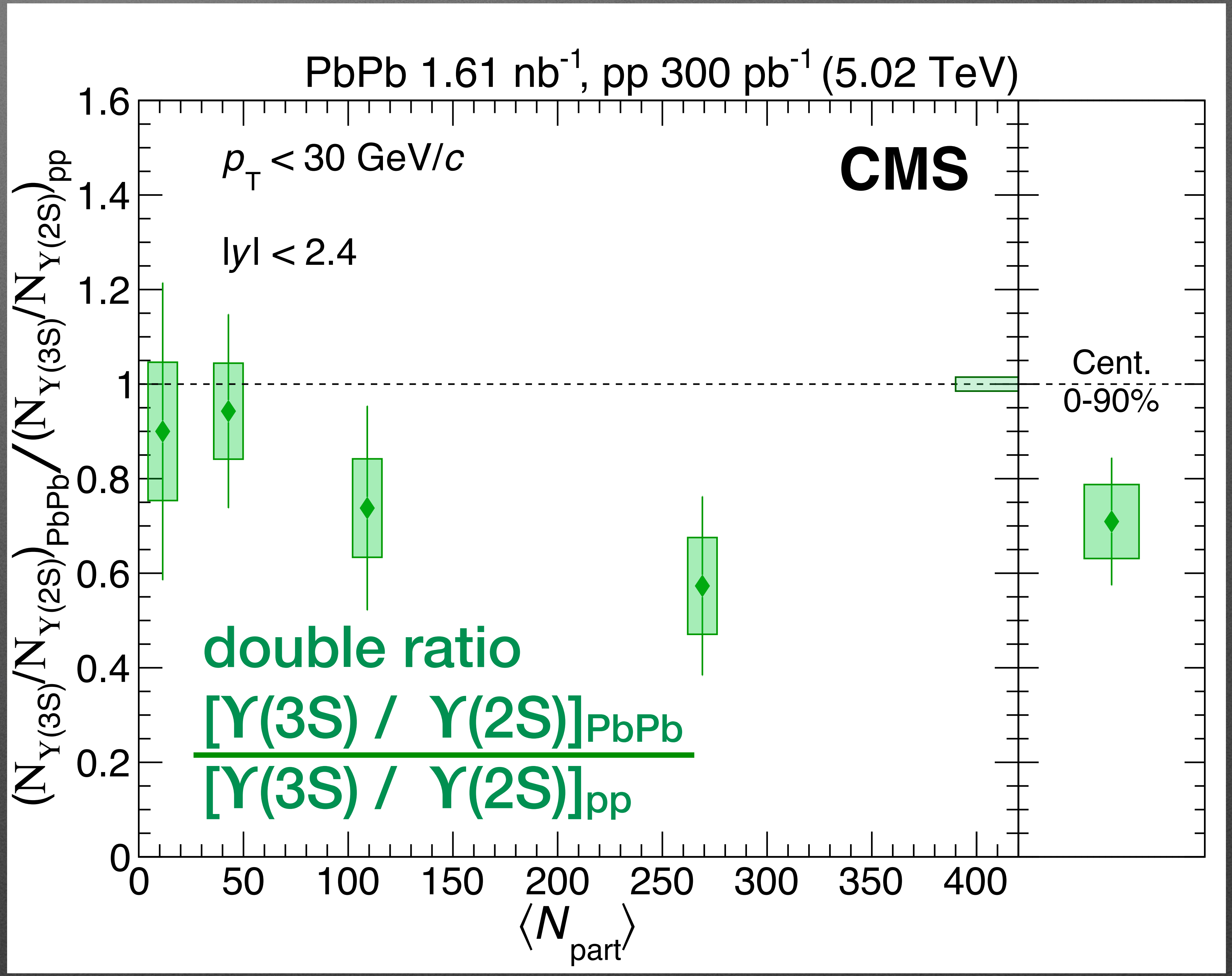
ATLAS [PRC 107 (2023) 054912]

ϒ(2S) and ϒ(3S) CMS [arXiv : 2303.17026]

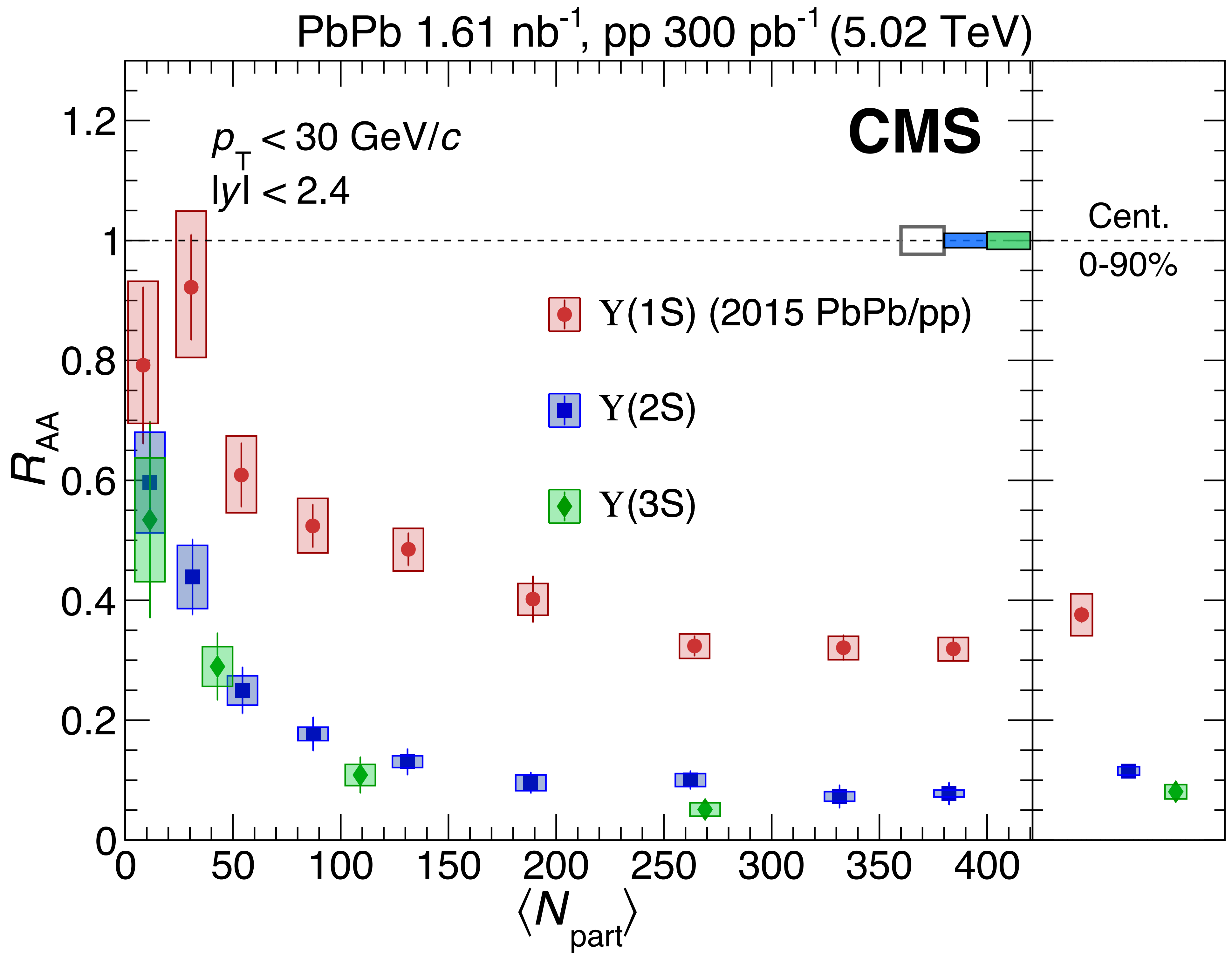




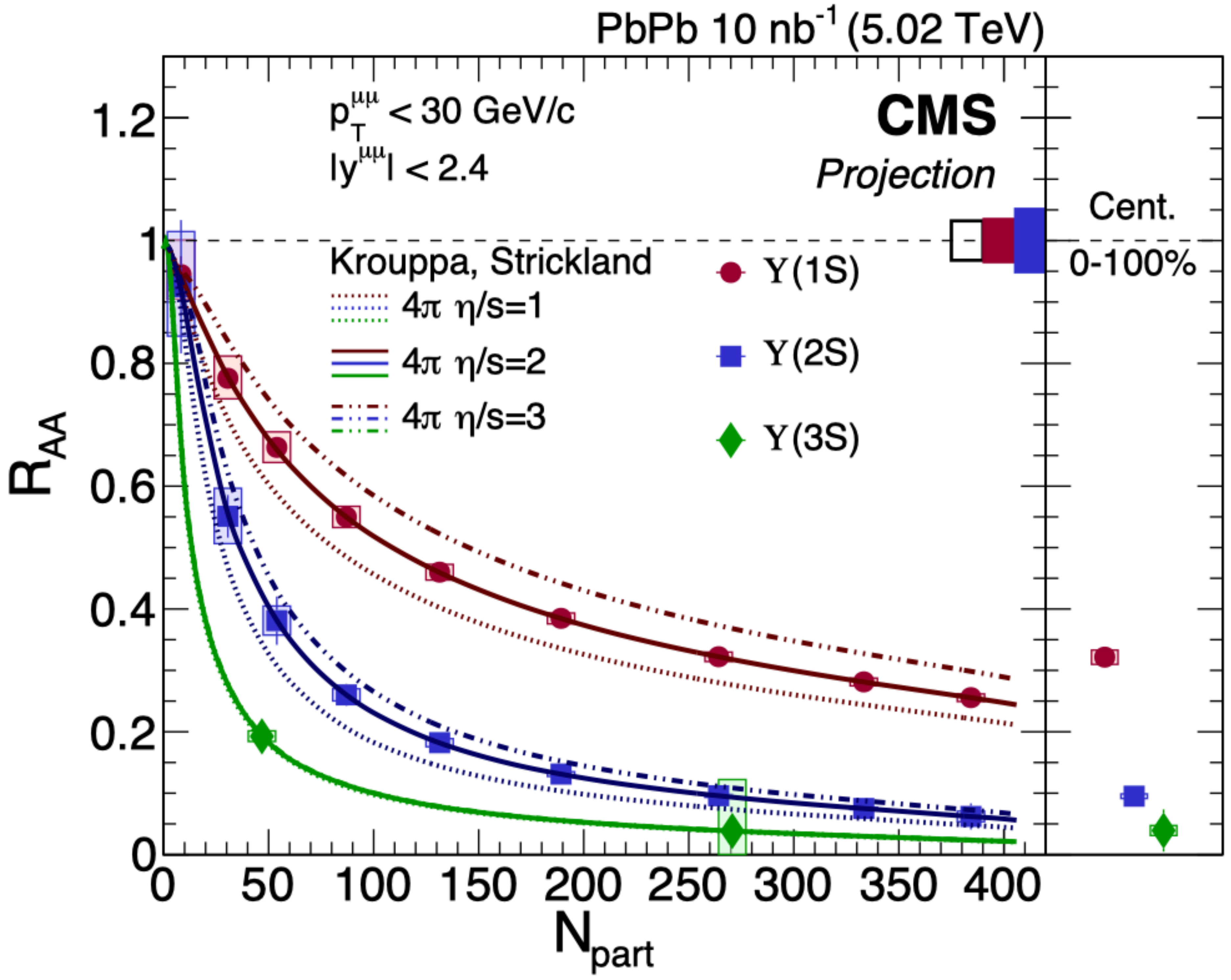
- Sequential suppression pattern in more central events i.e. ordered by binding energy :
  - All states are suppressed, with a larger suppression observed for the excited states
  - ϒ(3S) seems more suppressed than ϒ(2S)

Υ(nS) in PbPb: future improvements in Run 3 + Run 4

CMS [arXiv : 2303.17026]



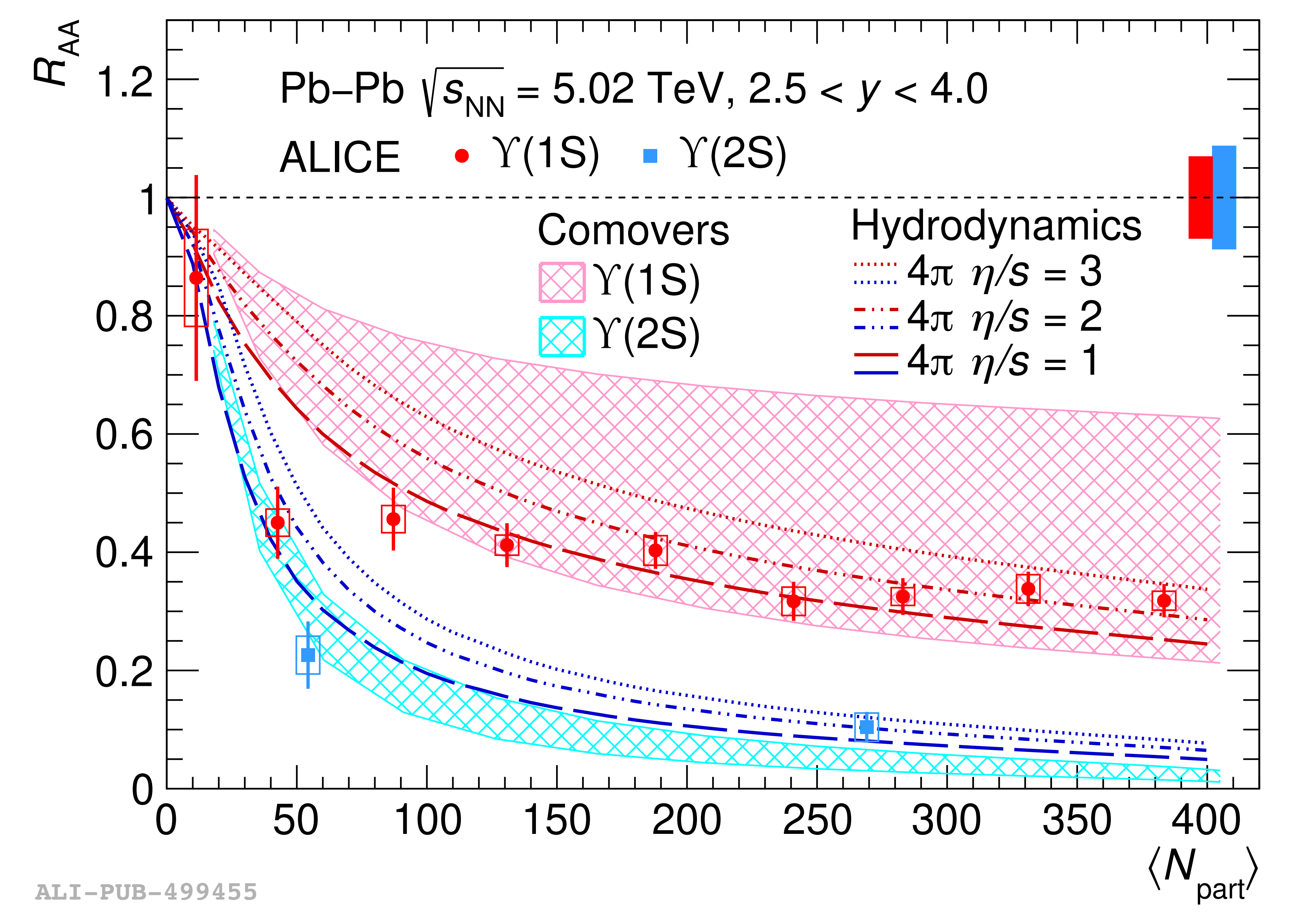
ATLAS and CMS [10.23731/CYRM-2019-007.Addendum]



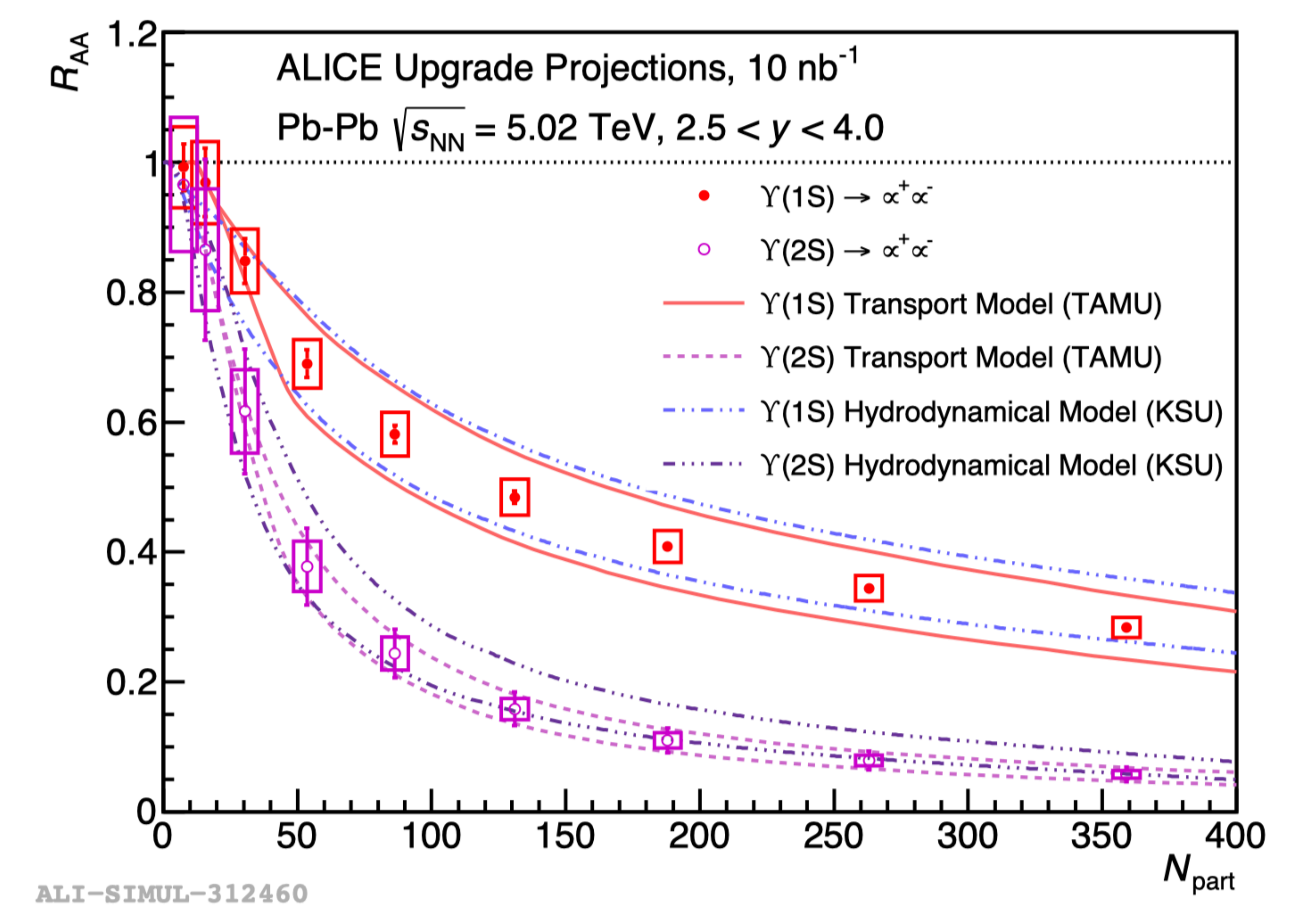
- Quite conservative Υ(3S) projections in the 2019 Cern Yellow Report Addendum

Υ(nS) in PbPb: future improvements in Run 3 + Run 4

ALICE [PLB 822 (2021) 136579]



ALICE, CERN yellow report, WG5 [CERN-2019-007]

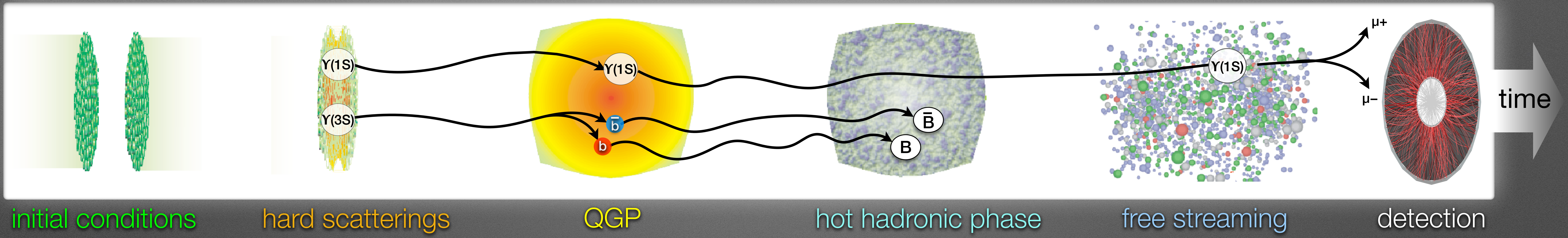


E.G. Ferreiro, J.P. Lansberg [JHEP 10 (2018) 094, JHEP 03 (2019) 063]
B. Krouppa, M. Strickland [Universe 2 (2016) 3]

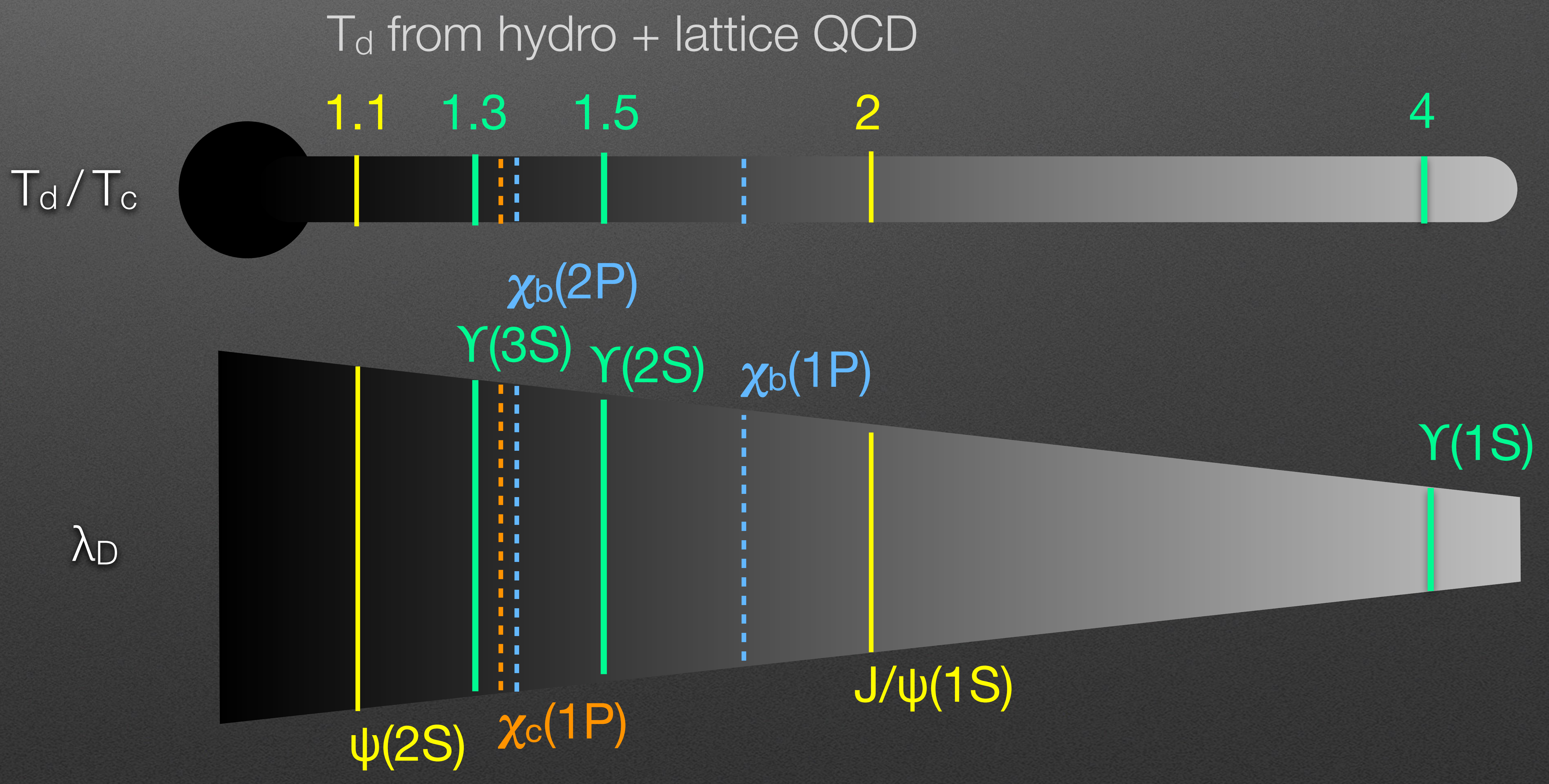
X. Du, M. He, R. Rapp [Phys.Rev.C 96 (2017) 5]

- Significant improvement for the Υ(2S) statistics

Heavy quarkonia as hard probes of the medium



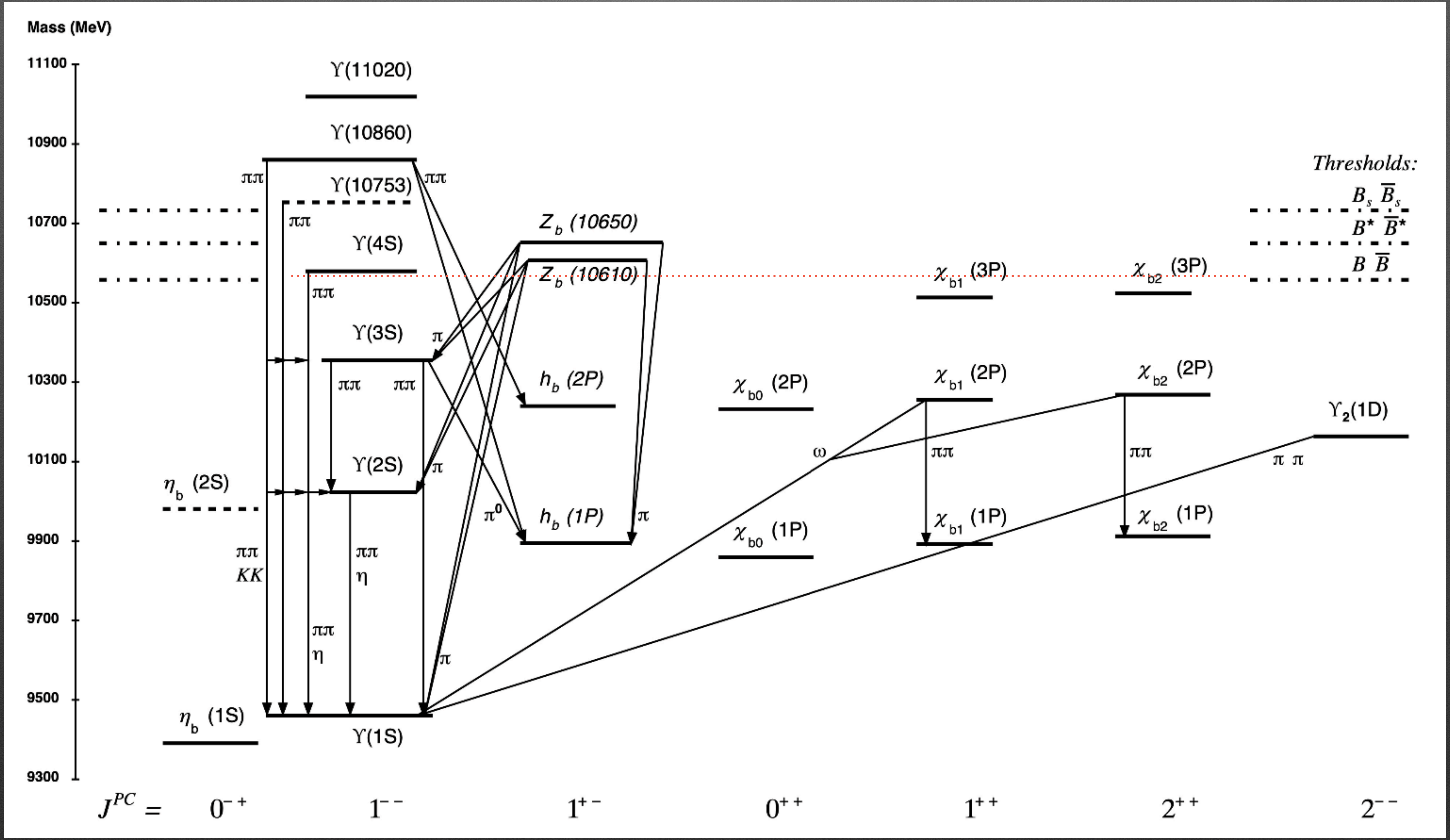
- Can be used as a QGP « thermometer » ?
- Quite straightforward if quarkonium states were only directly produced
- Complicated by feed-down :
  - in-family, from higher resonances
  - cross-family, i.e. non-prompt charmonium from b-hadron feed-down



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

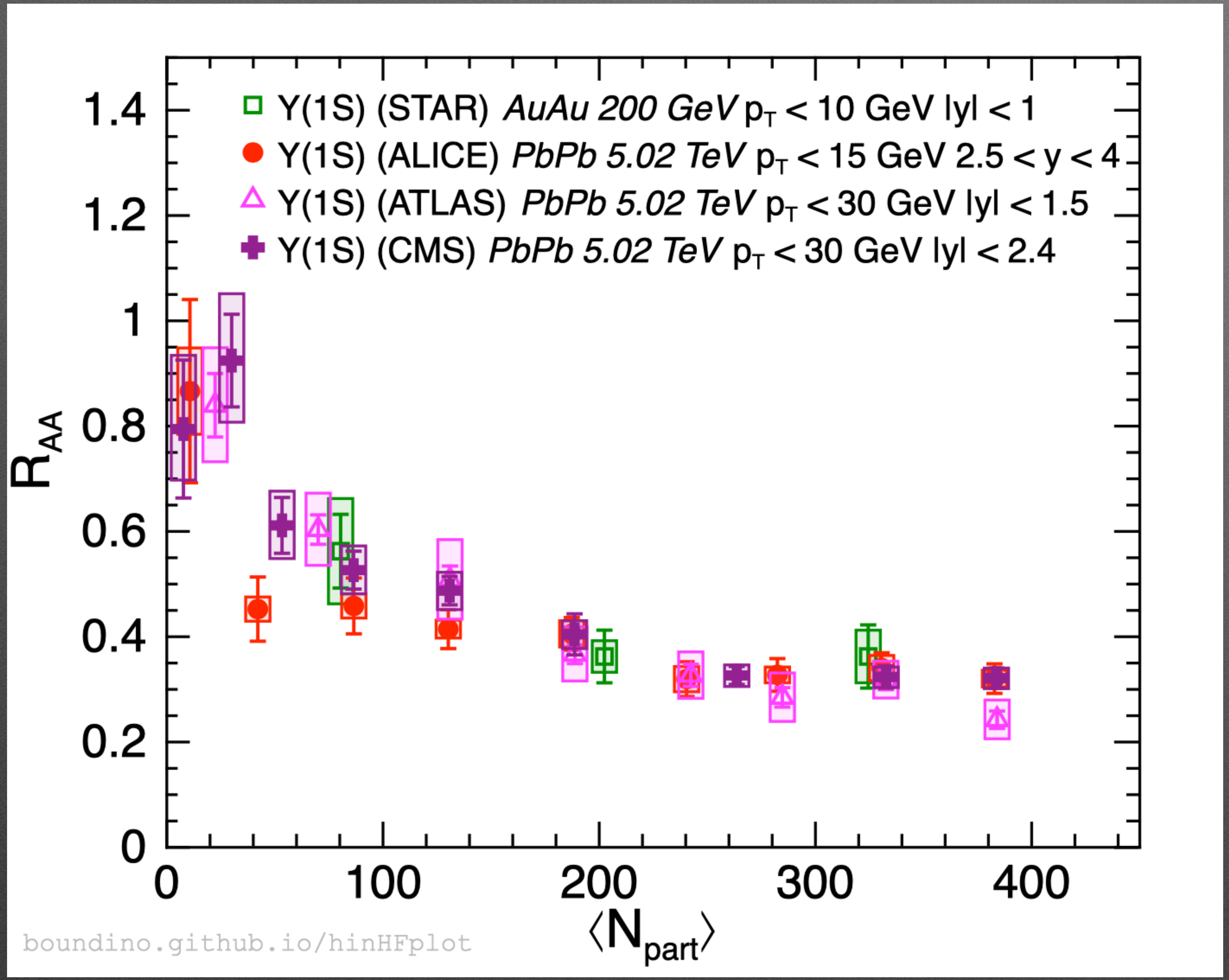
Bottomonium system

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



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

ALICE [PLB 822 (2021) 136579]
ATLAS [PRC 107 (2023) 054912]
CMS [PLB 790 (2019) 270]
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) ?
  - need precise measurements of the suppression of excited states and feed-down fractions

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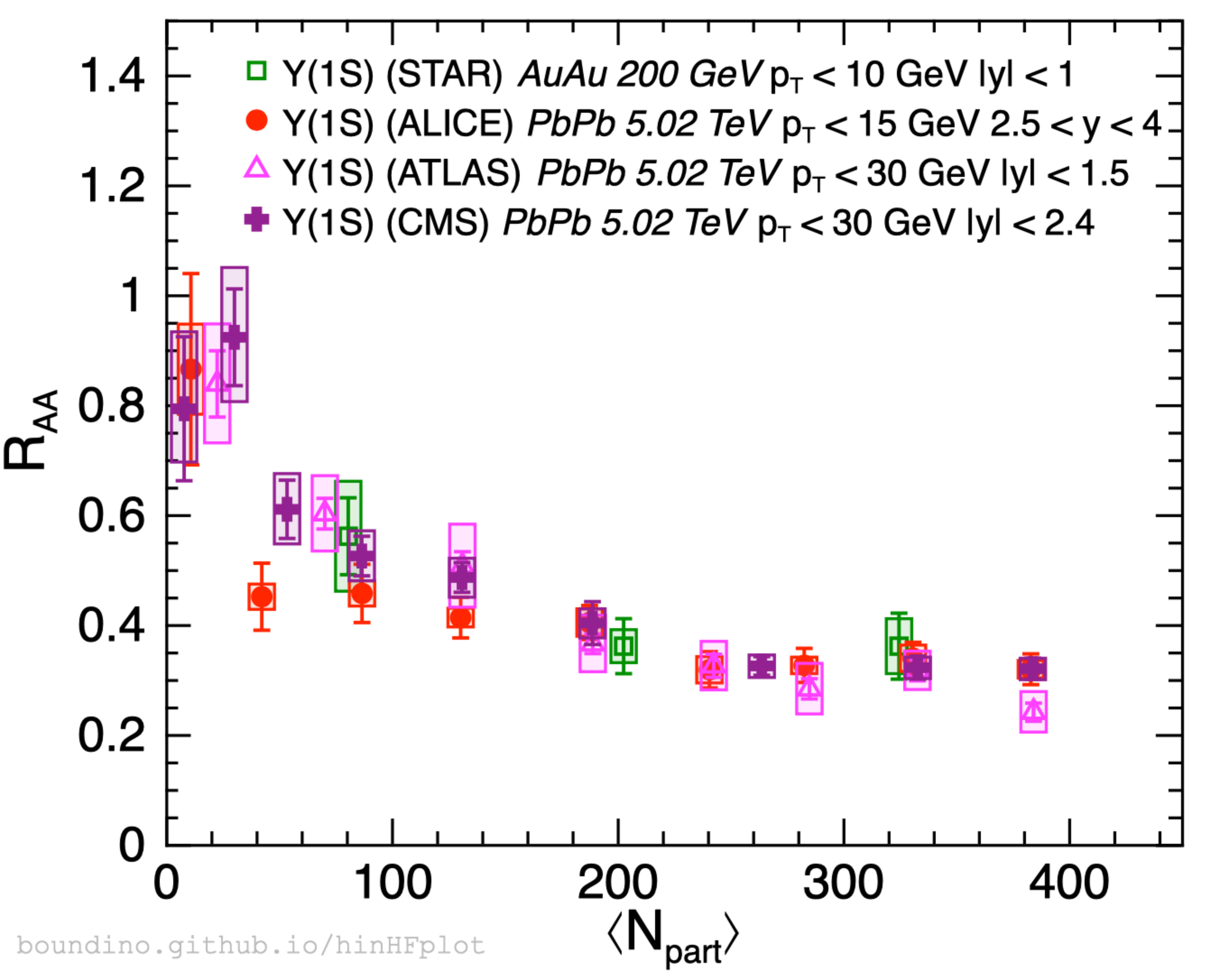
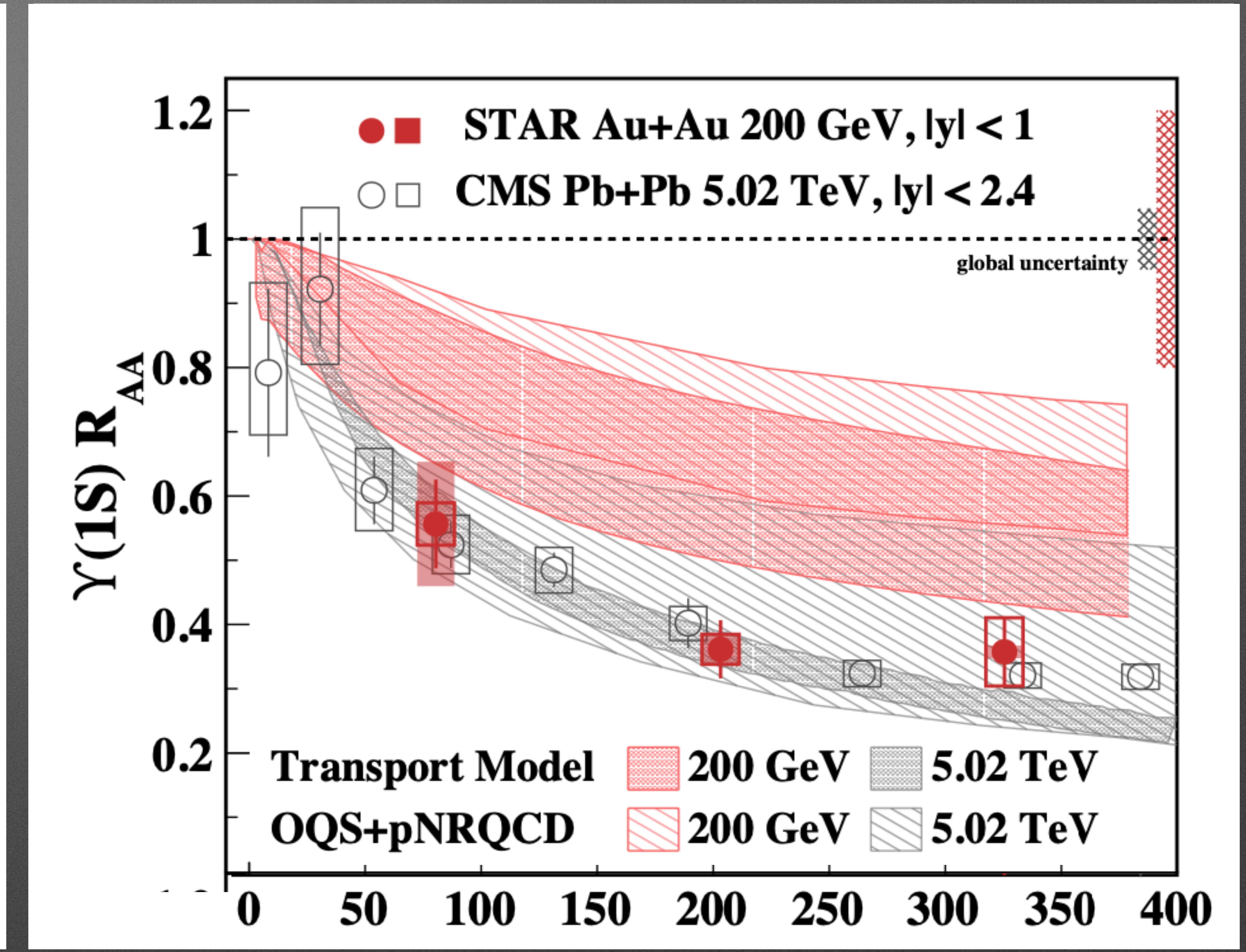
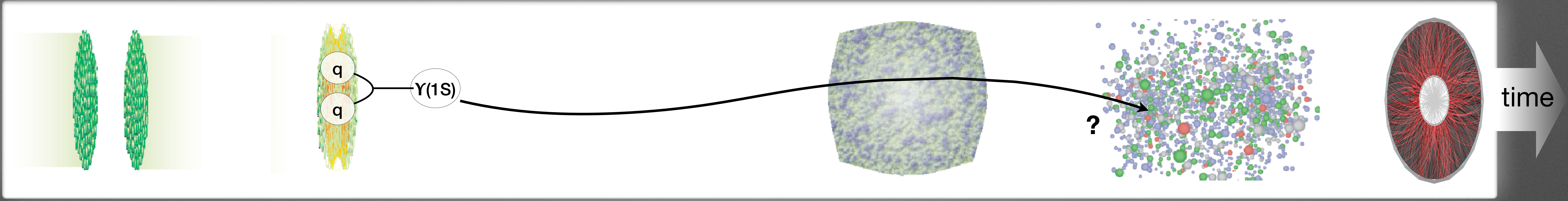




- Similar suppression seen at RHIC and at LHC (x 25 in √s):
  - in favour of a negligible melting of the direct Υ(1S) (i.e. dissociation temperature not reached yet at LHC) ?
  - need precise measurements of the suppression of excited states and feed-down fractions
  - models tend to underestimate the suppression at RHIC energy
  - and different CNM effects at play

Cold Nuclear Matter effects on Heavy quarkonia



initial conditions

hard scatterings

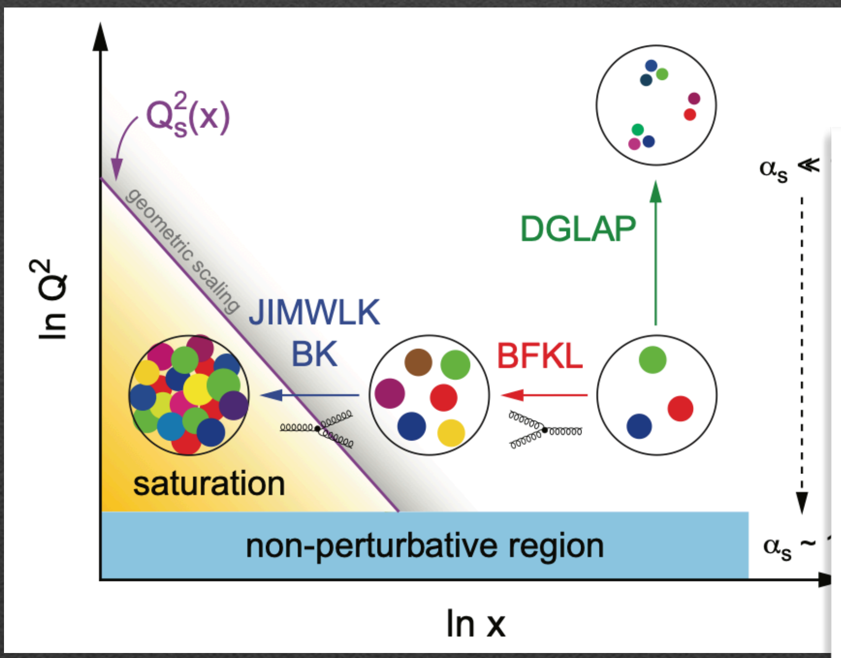
hadronisation

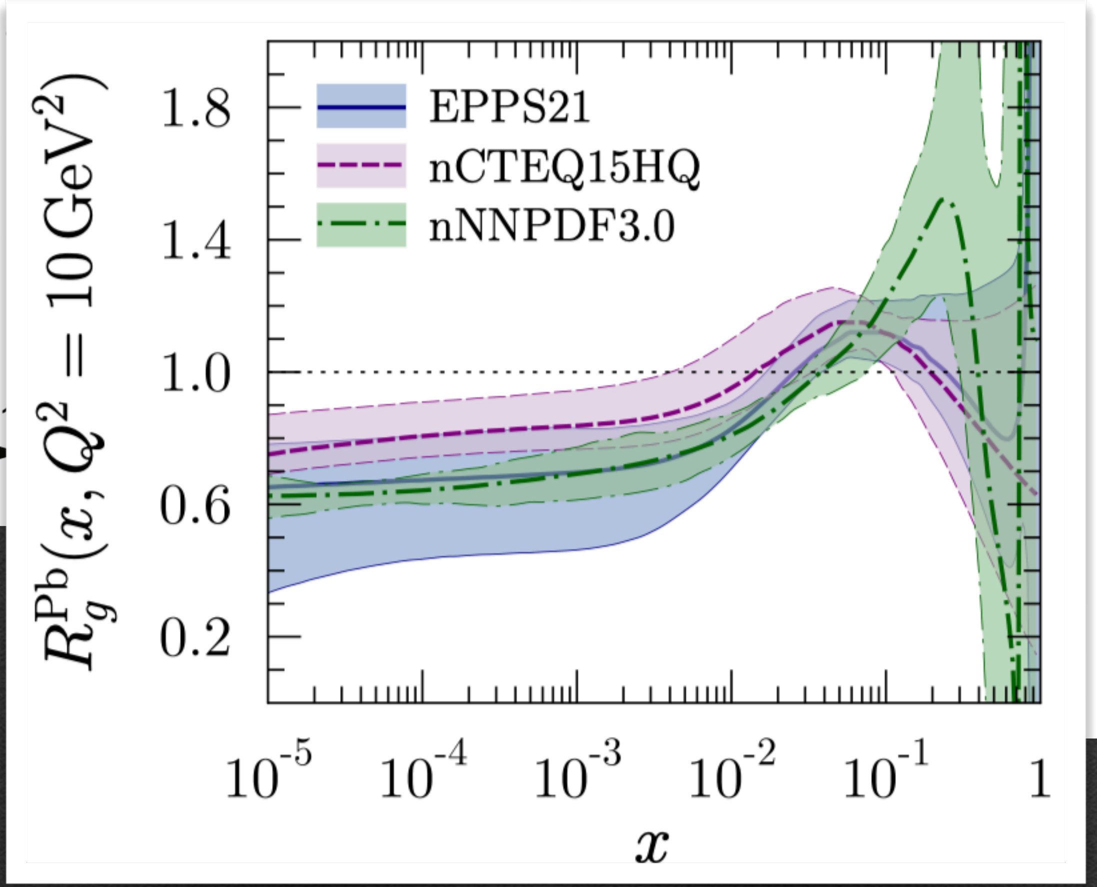
free streaming

detection

initial state-effect

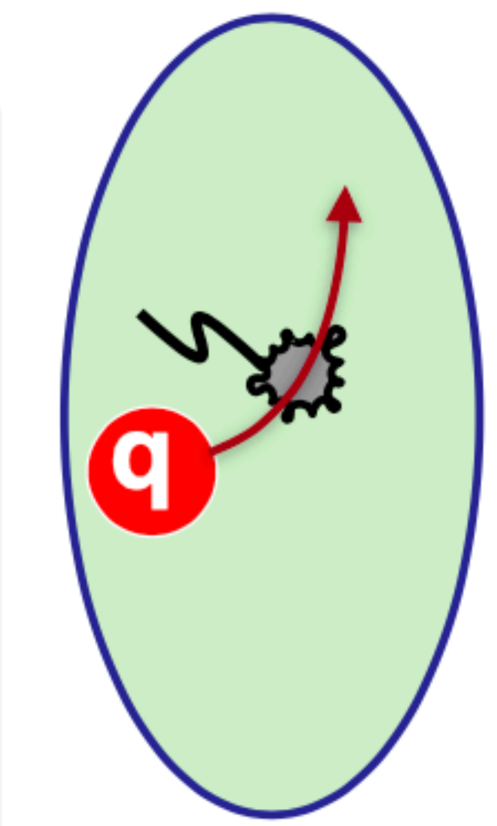
nPDF modification, saturation





interplay initial/final state-effect

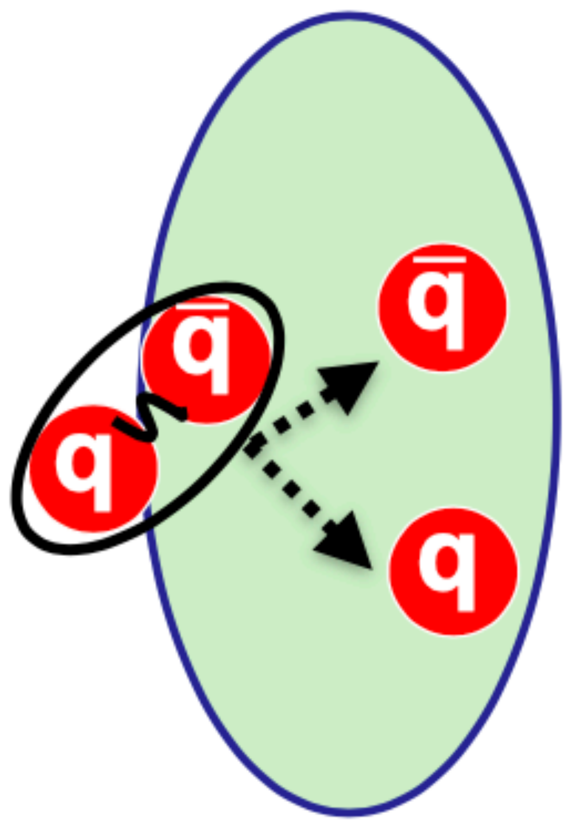
Coherent energy loss



nuclear medium

final state-effect

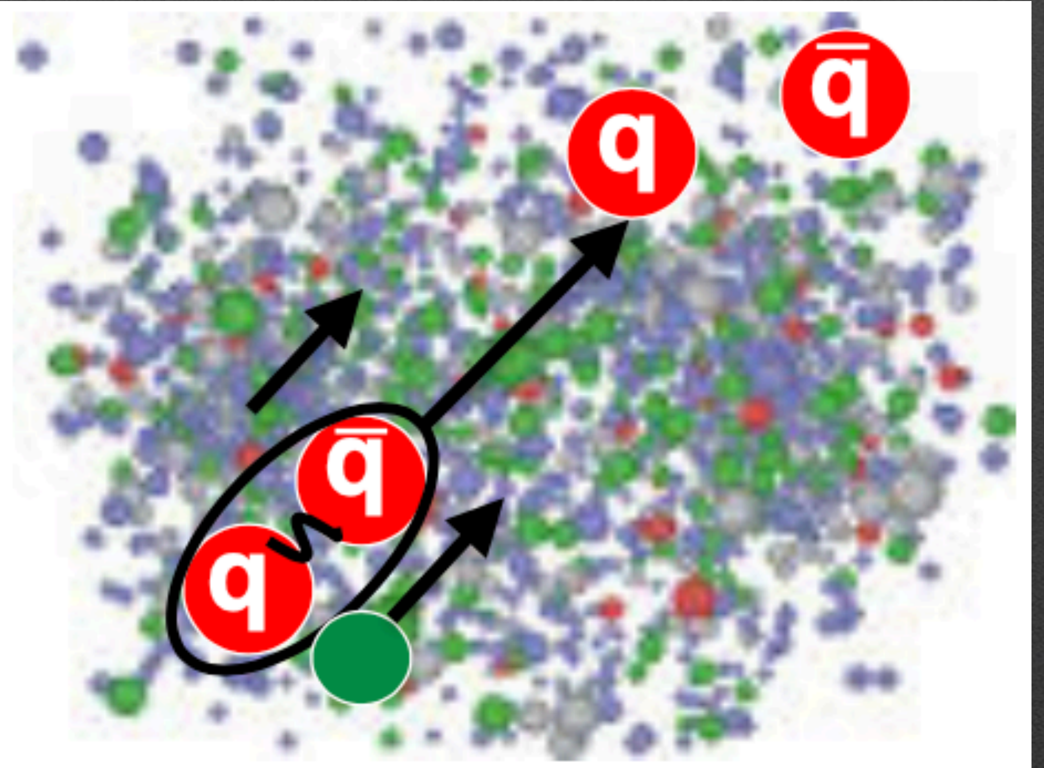
Nuclear absorption



nuclear medium

final state-effect

Co-mover break-up



hadronic matter

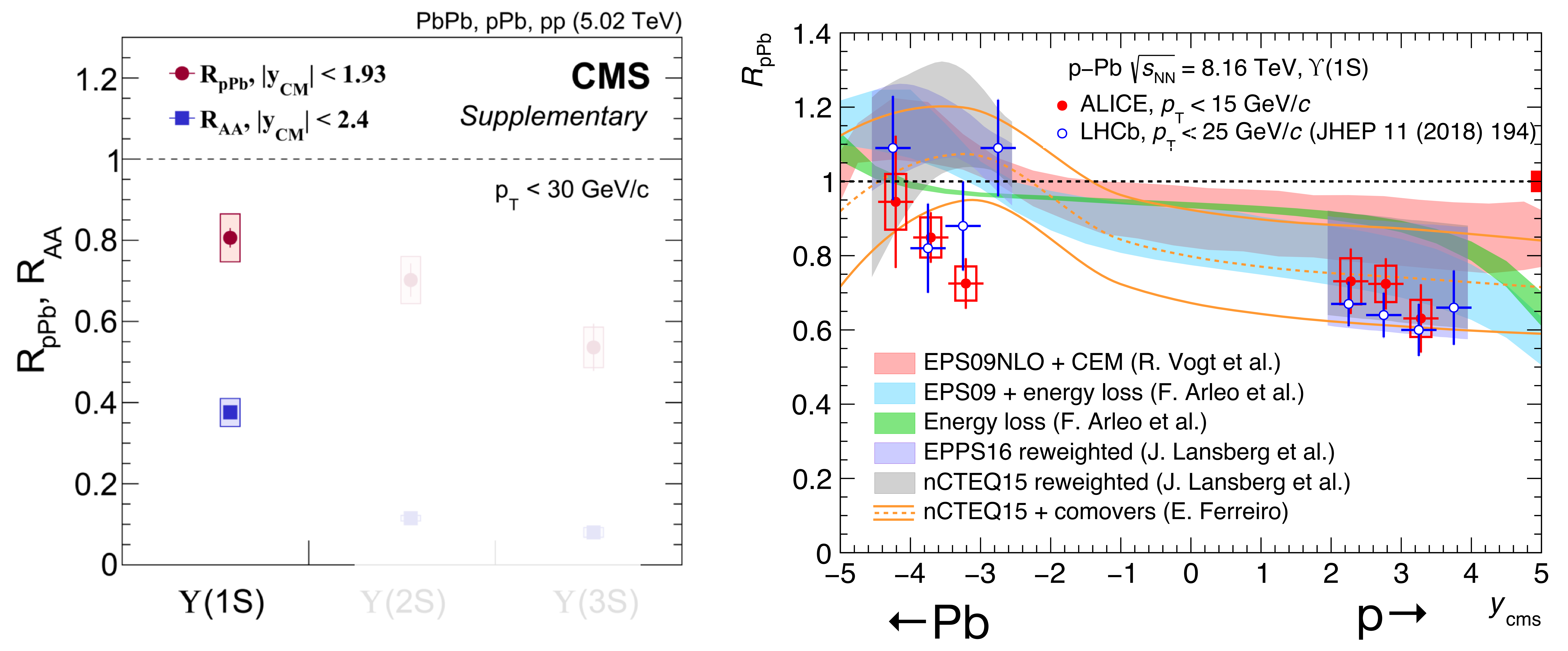
CMS [arXiv : 2303.17026]

CMS [PLB 835 (2022) 137397]

ϒ(1S) in p-Pb vs Pb-Pb

ALICE [PLB 806 (2020) 135486]

LHCb [JHEP 11 (2018) 194, JHEP 02 (2020) 093]



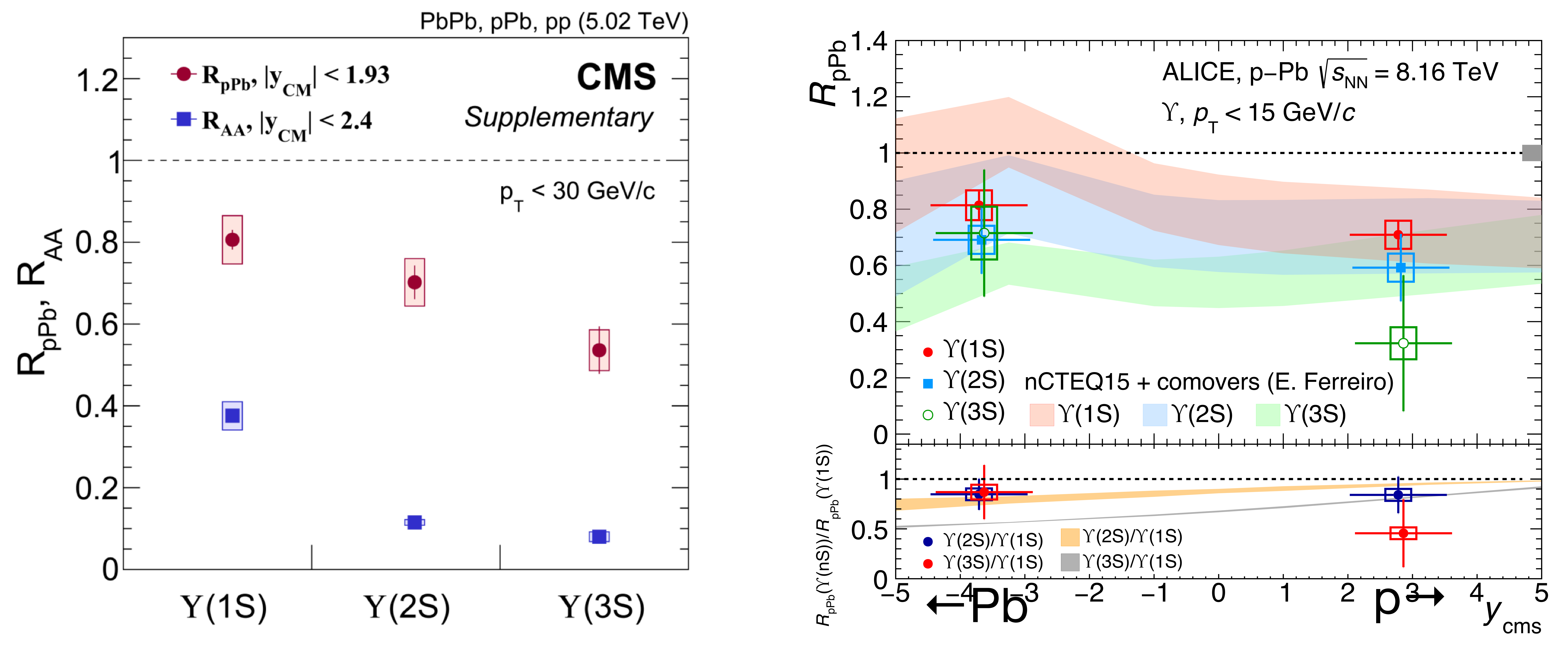
- ϒ(1S) much less suppressed in p-Pb than in Pb-Pb
  - even compatible with unity at backward rapidity
  - measurements with enhanced precision in Run 3 + Run 4 will put stringent constraints on the models

CMS [arXiv : 2303.17026]

CMS [PLB 835 (2022) 137397]

Υ(nS) in pPb

ALICE [PLB 806 (2020) 135486]

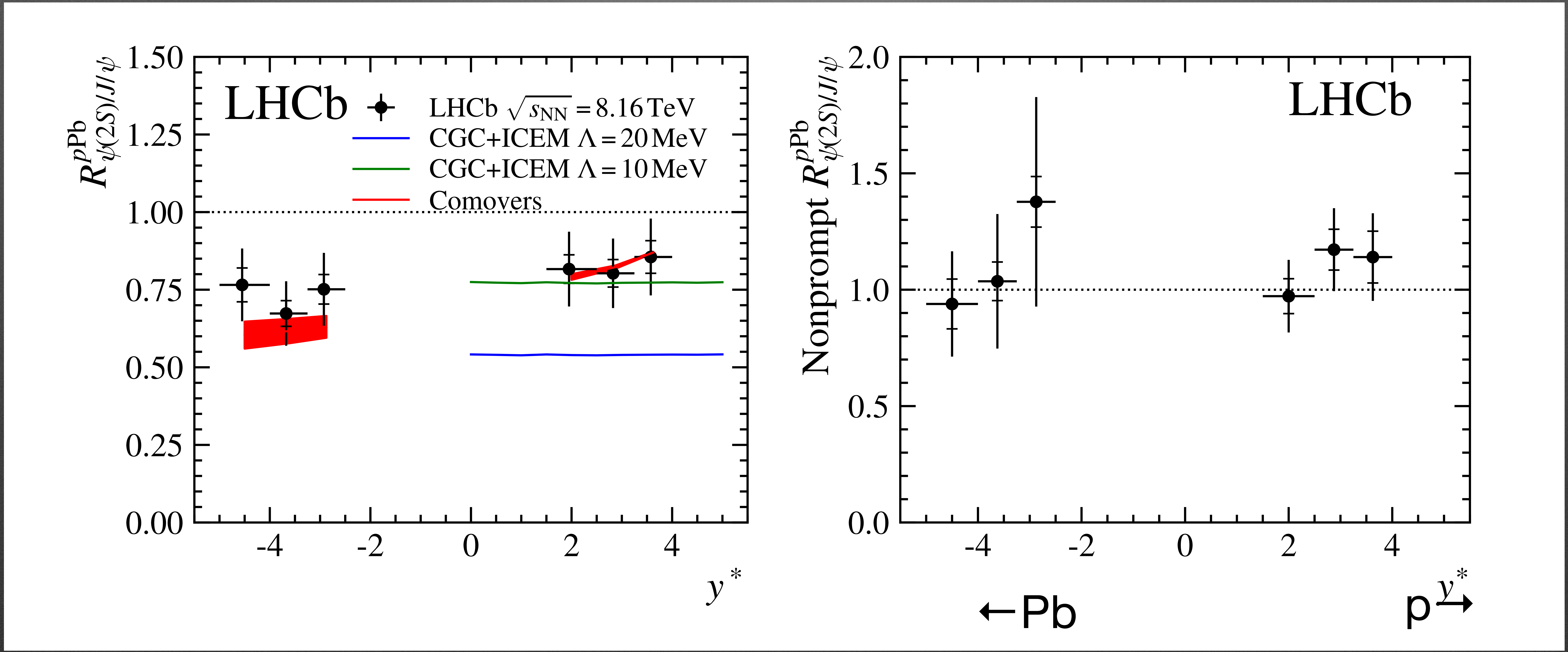


- In p-Pb and increasing rapidity, excited states suffer more suppression from CNM effects

Double ratios J/ψ / ψ(2S) in p-Pb

LHCb [JHEP 04 (2024) 111]

Prompt | Non-prompt



- Non-prompt double ratio : large uncertainties, can benefit from Run 3 + Run 4 p-Pb run
- Prompt double ratio : excited state more affected by CNM effects

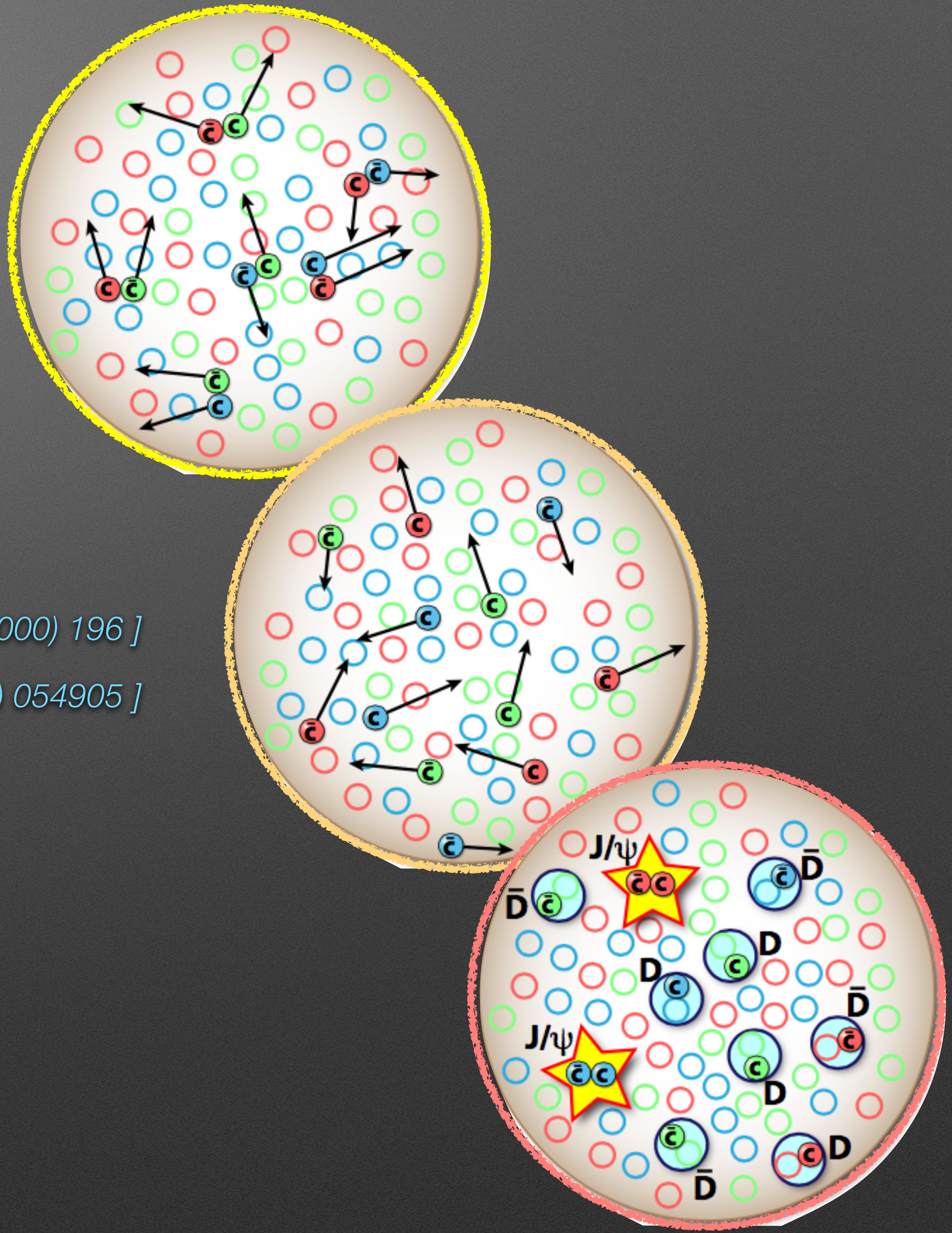
Charmonium regeneration

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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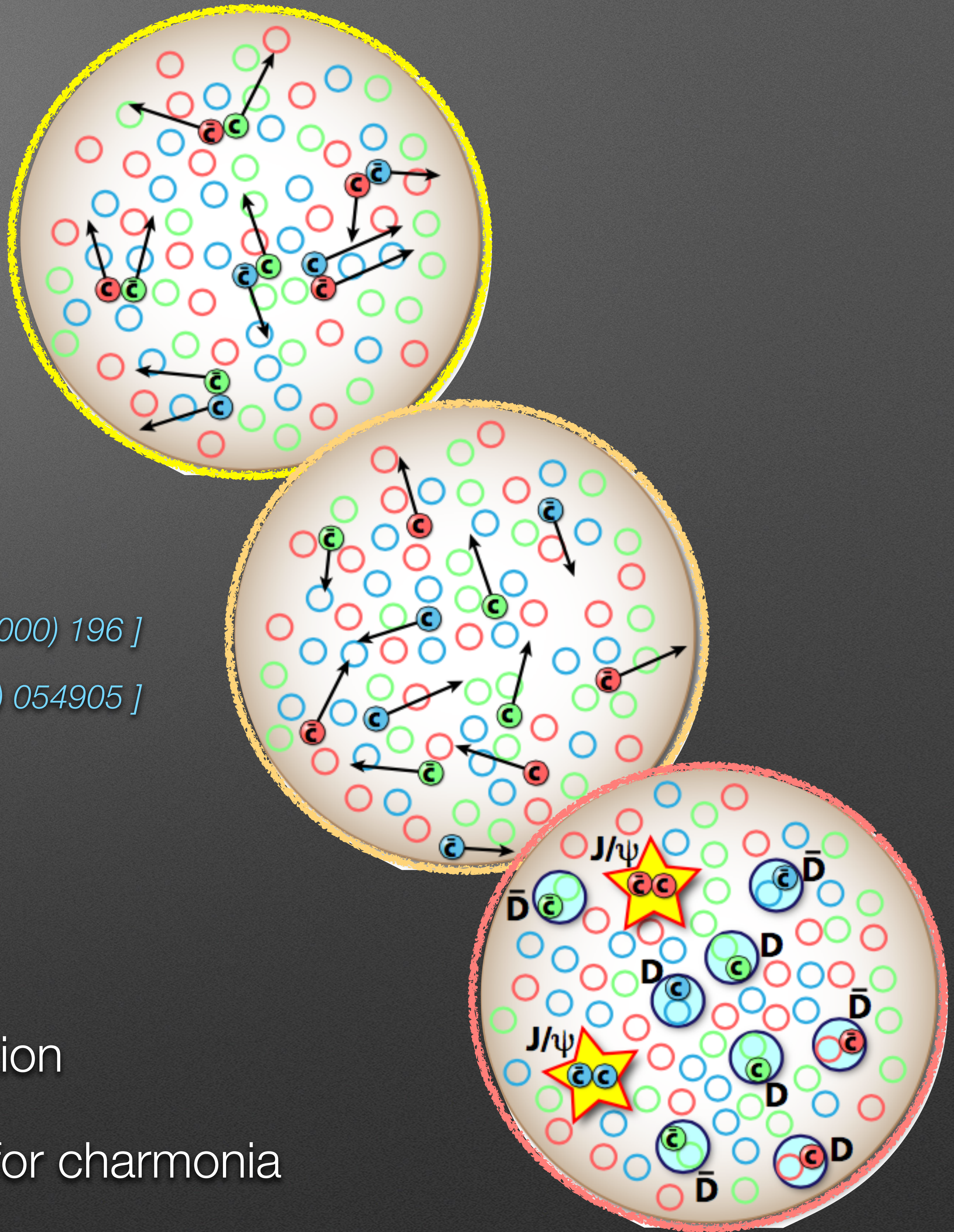


P. Braun-Munziger, J.Stachel [PLB 490 (2000) 196]

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]

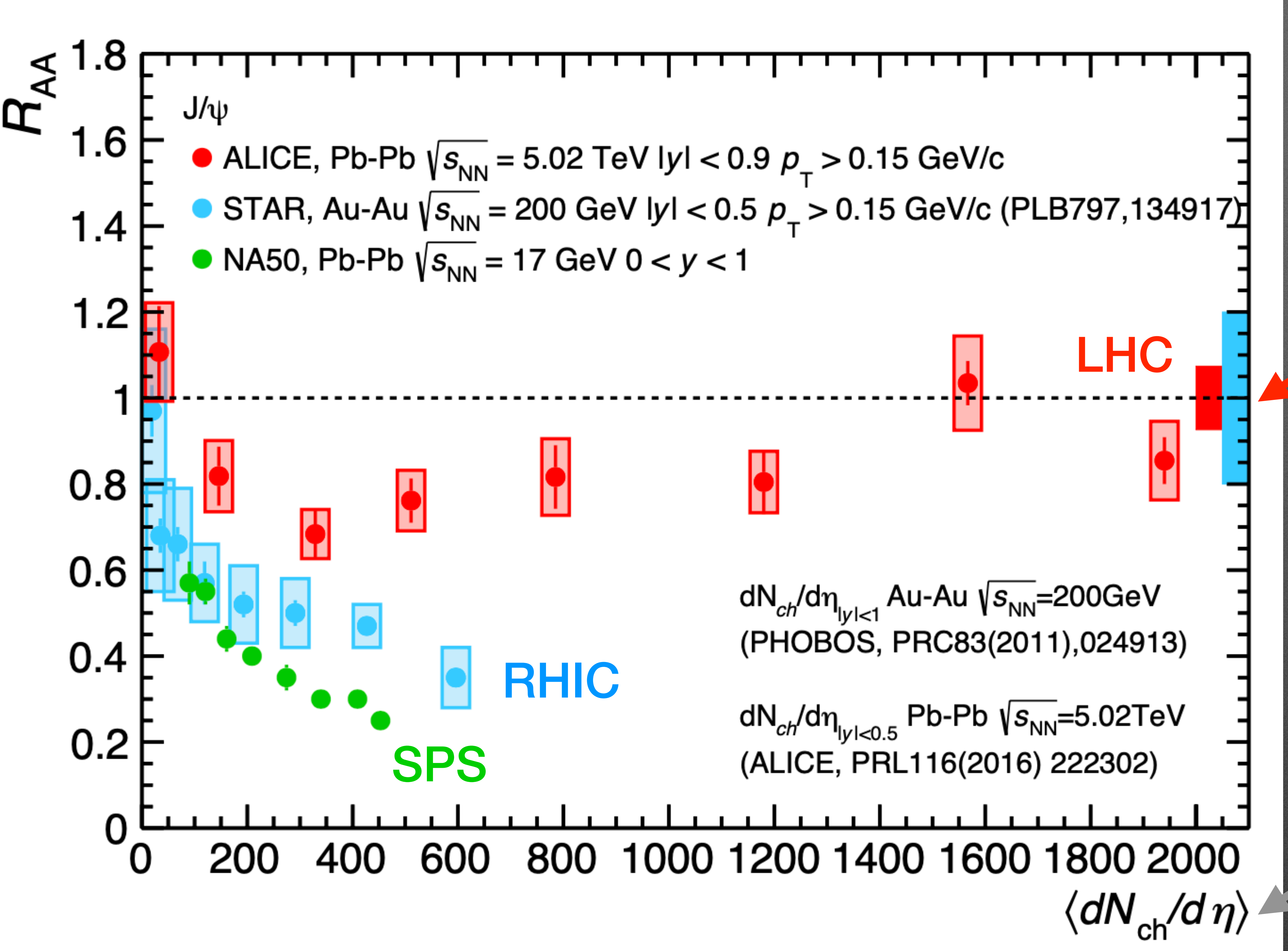
PHOBOS [PRC 83 (2011) 024913]

ALICE [PRL 116 (2016) 222302]

STAR [PLB 797 (2019) 134917]

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

ALICE *[arXiv:2303.13361]*



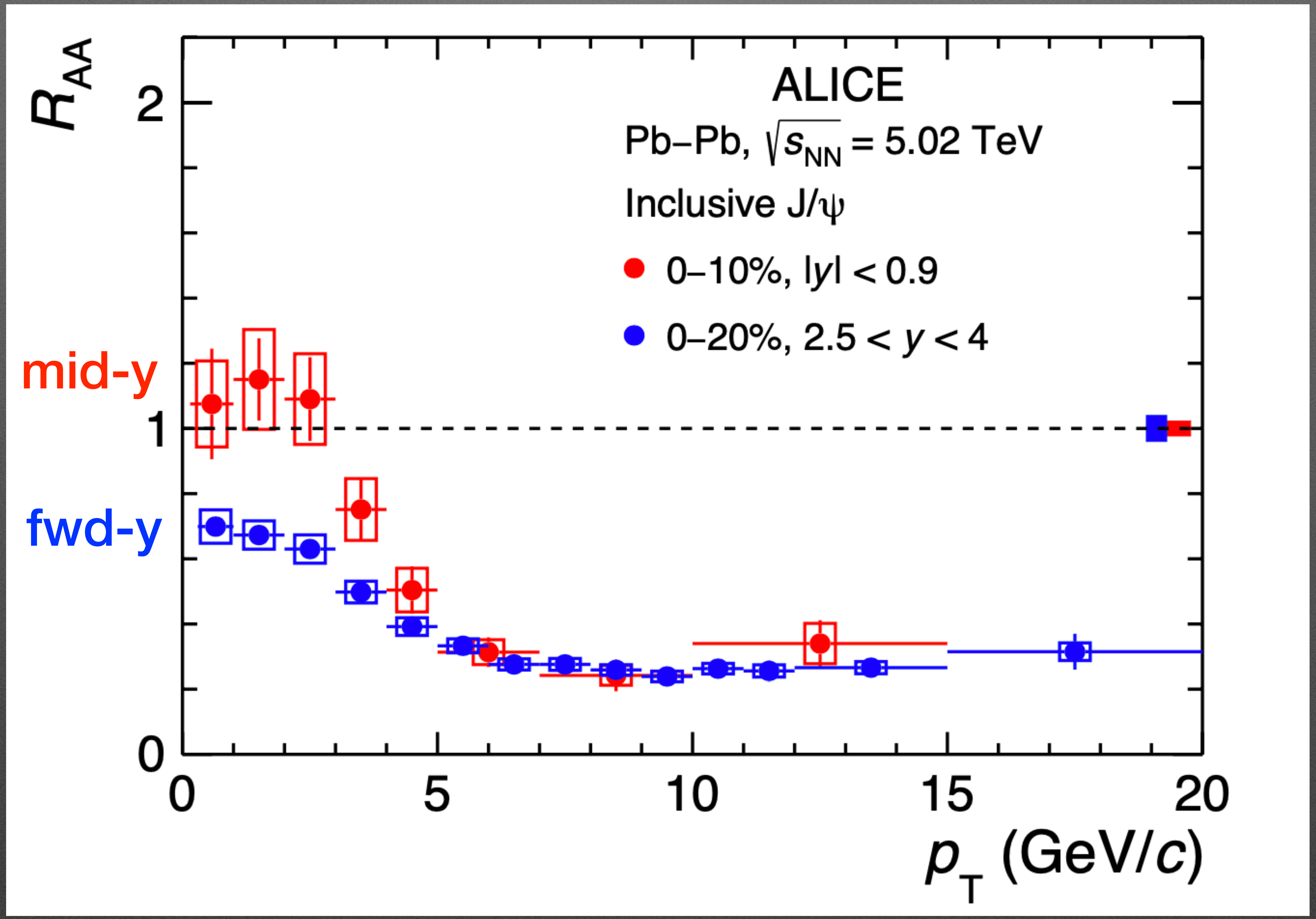
R_{AA} ~ 1 at mid-y in central collisions at LHC

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]*

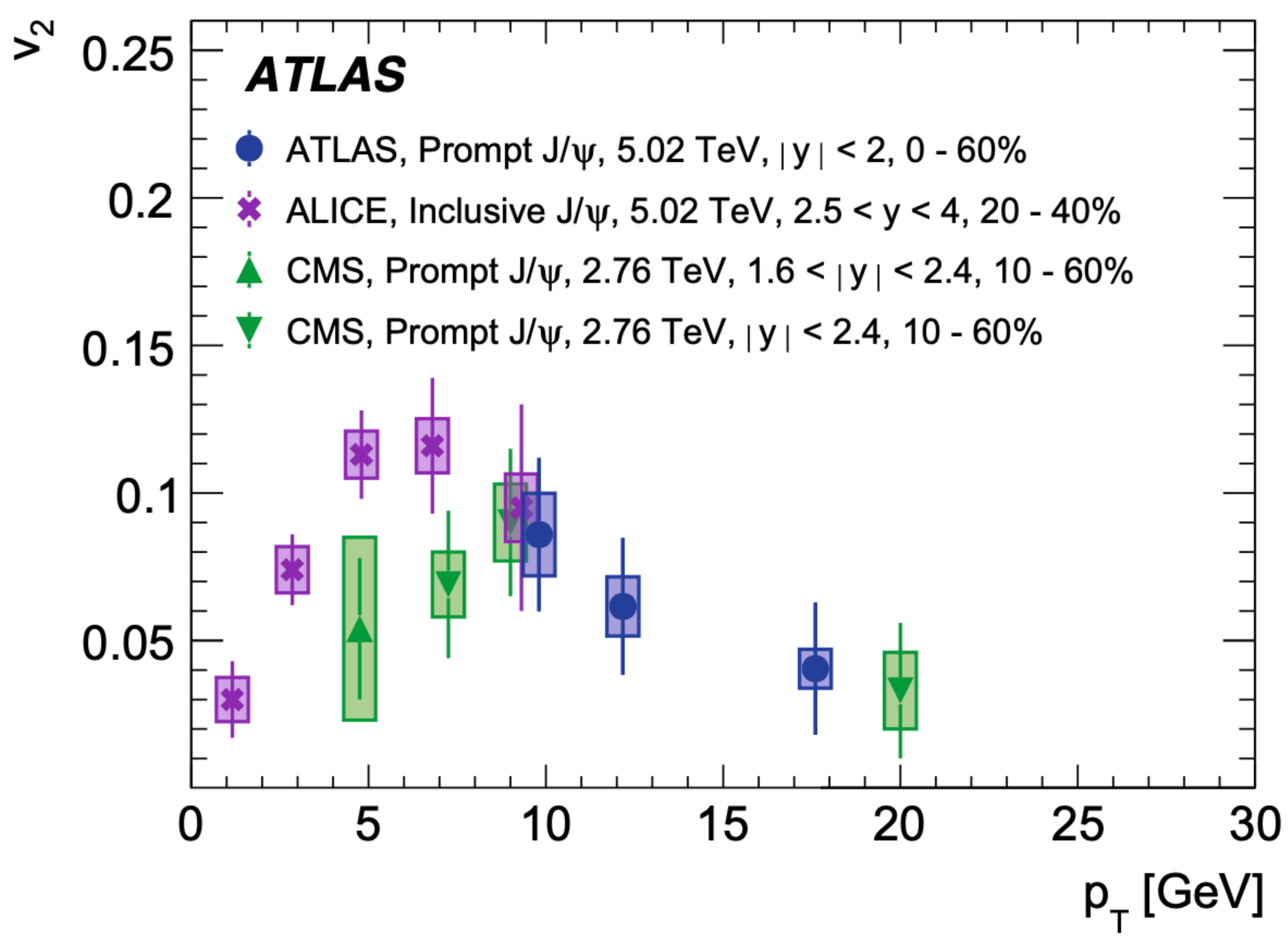


- The density of charm quarks is larger at mid-y and at low p_T
- Therefore, we can expect an enhanced regeneration component at mid-y compared to fwd-y at low p_T
- At low p_T, R_{AA} (mid-y) > R_{AA} (fwd-y)

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]*

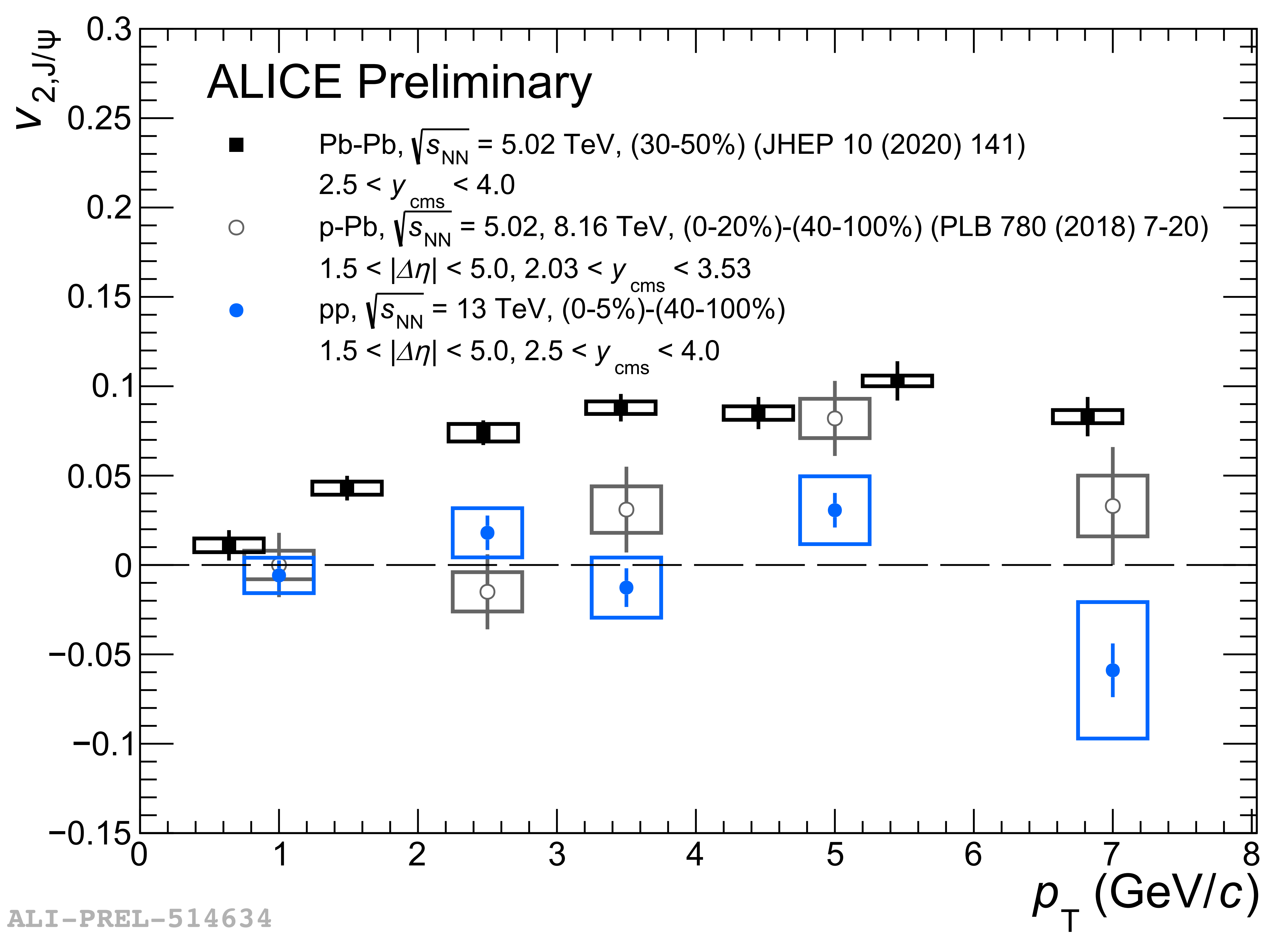
CMS *[EPJC 77 (2017) 252]*

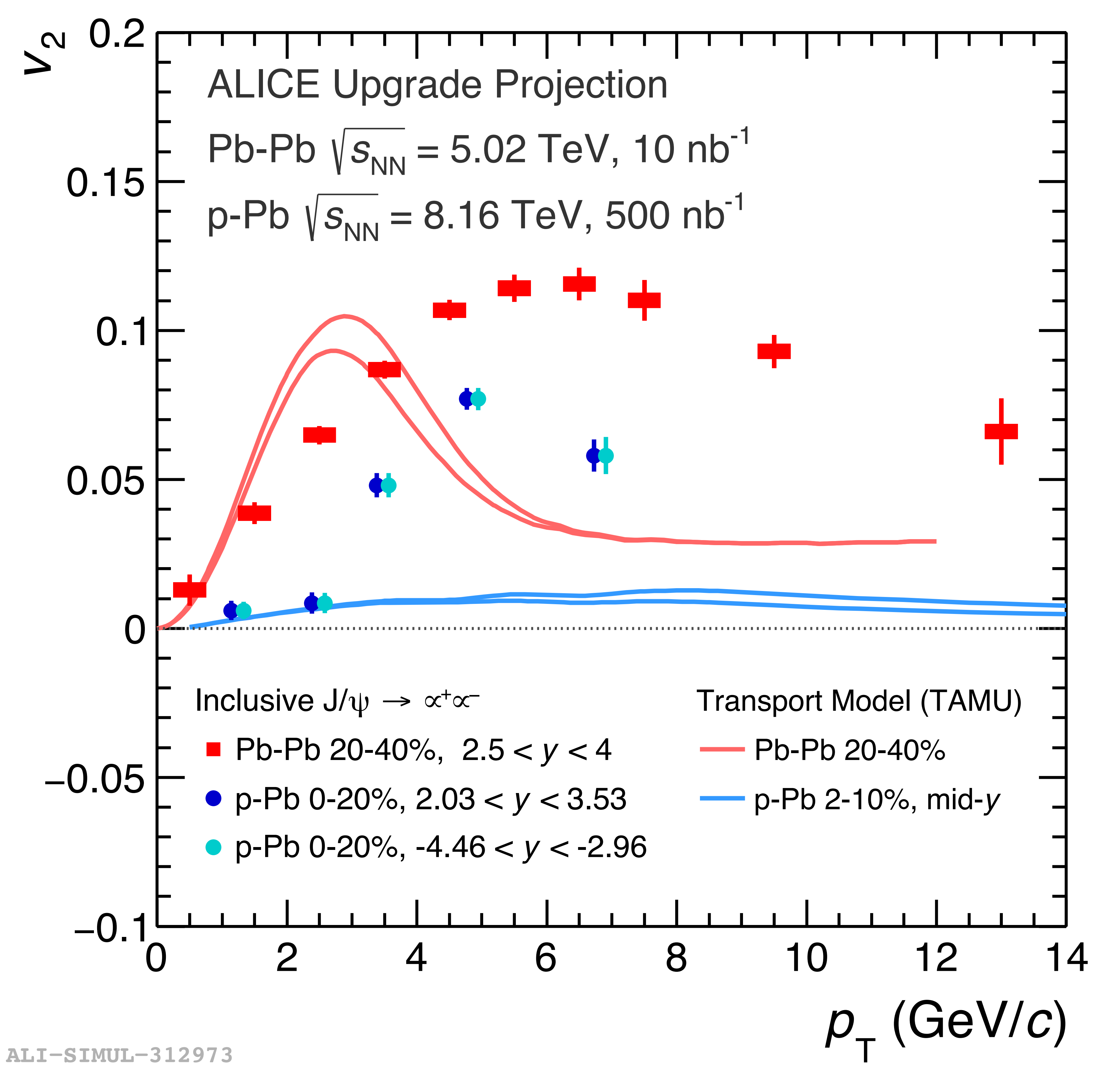
ATLAS *[EPJC 78 (2018) 784]*

- (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 v_2 : prospects in Run 3 + Run 4

ALICE *[ALI-SIMUL-312973]*





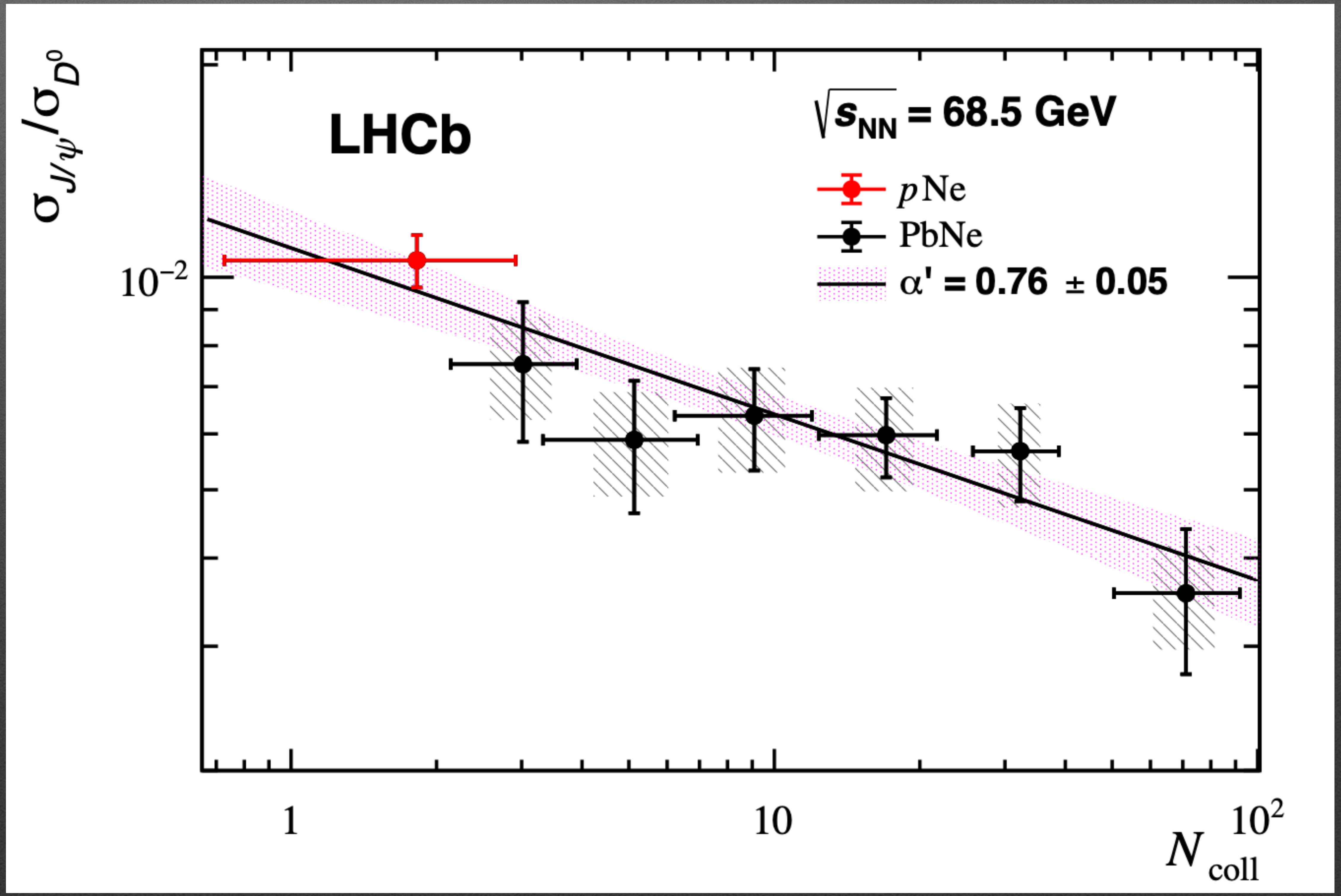
- Pb-Pb : v_2 measurements at high p_T are desirable to check if any mechanism can build collectivity at high p_T for hidden charm
- p-Pb : is there an onset of collective effects in small system ? can it be transferred to hidden charm ?

Fixed-target at LHCb : J/ψ / D^0 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 p-Pb, Pb-Pb collisions

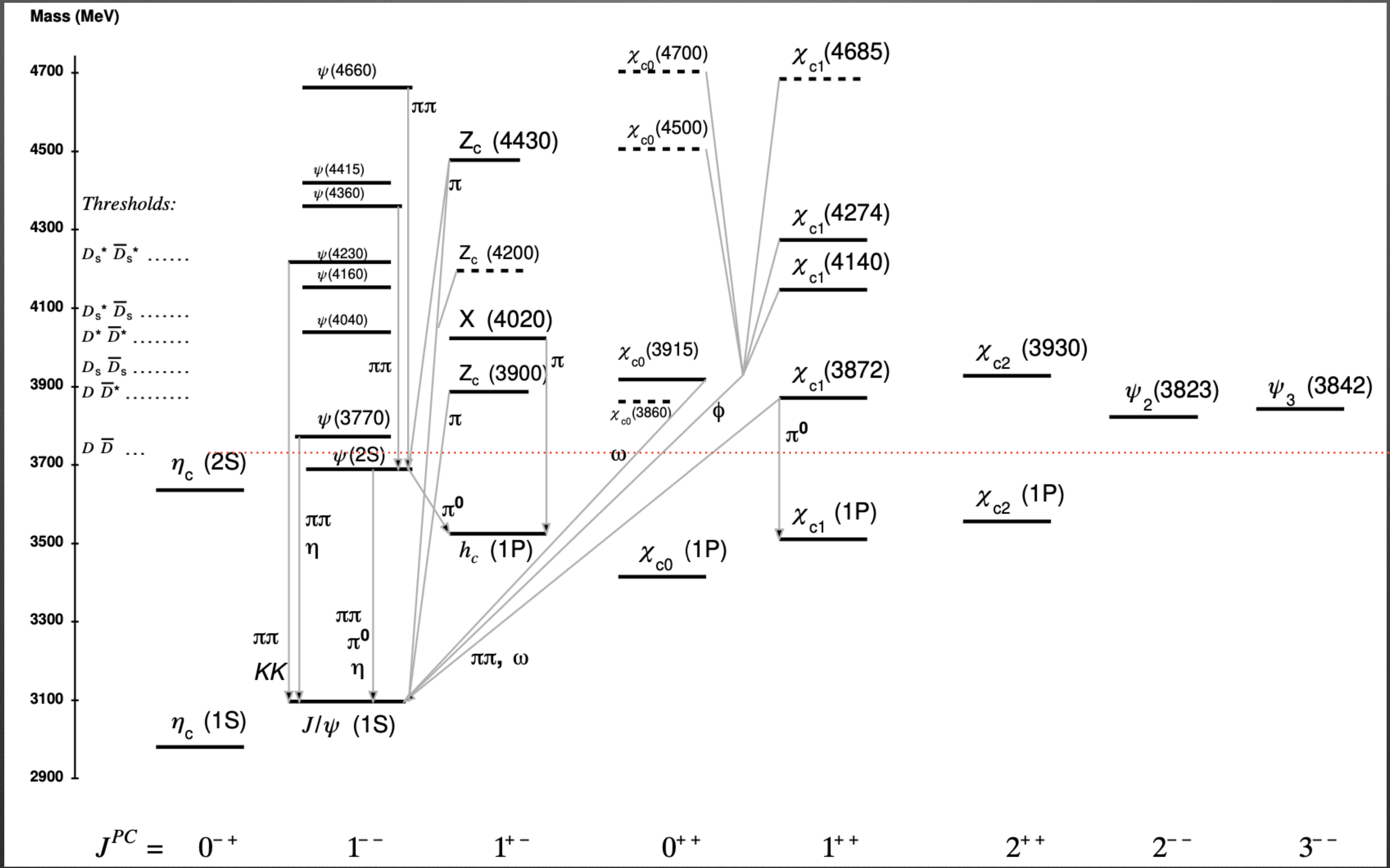
- This QCD laboratory provides :
  - harvest of results involving ground and excited states, from all LHC experiments
  - many opportunities at reach with Run 3 + Run 4 data

Thanks for your attention

SPARE SLIDES

Charmonium system

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

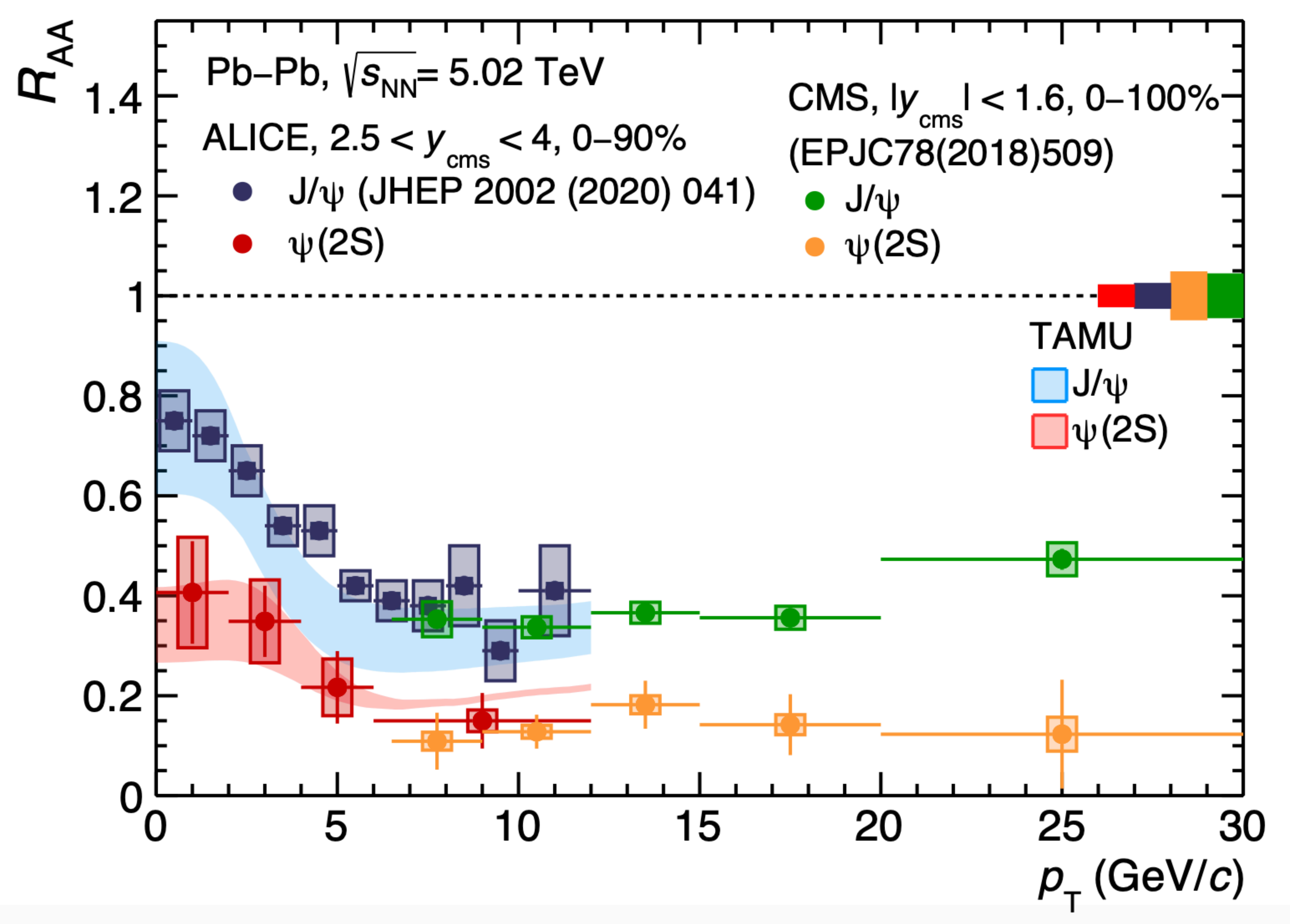


J/ψ vs ψ(2S)

(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]*

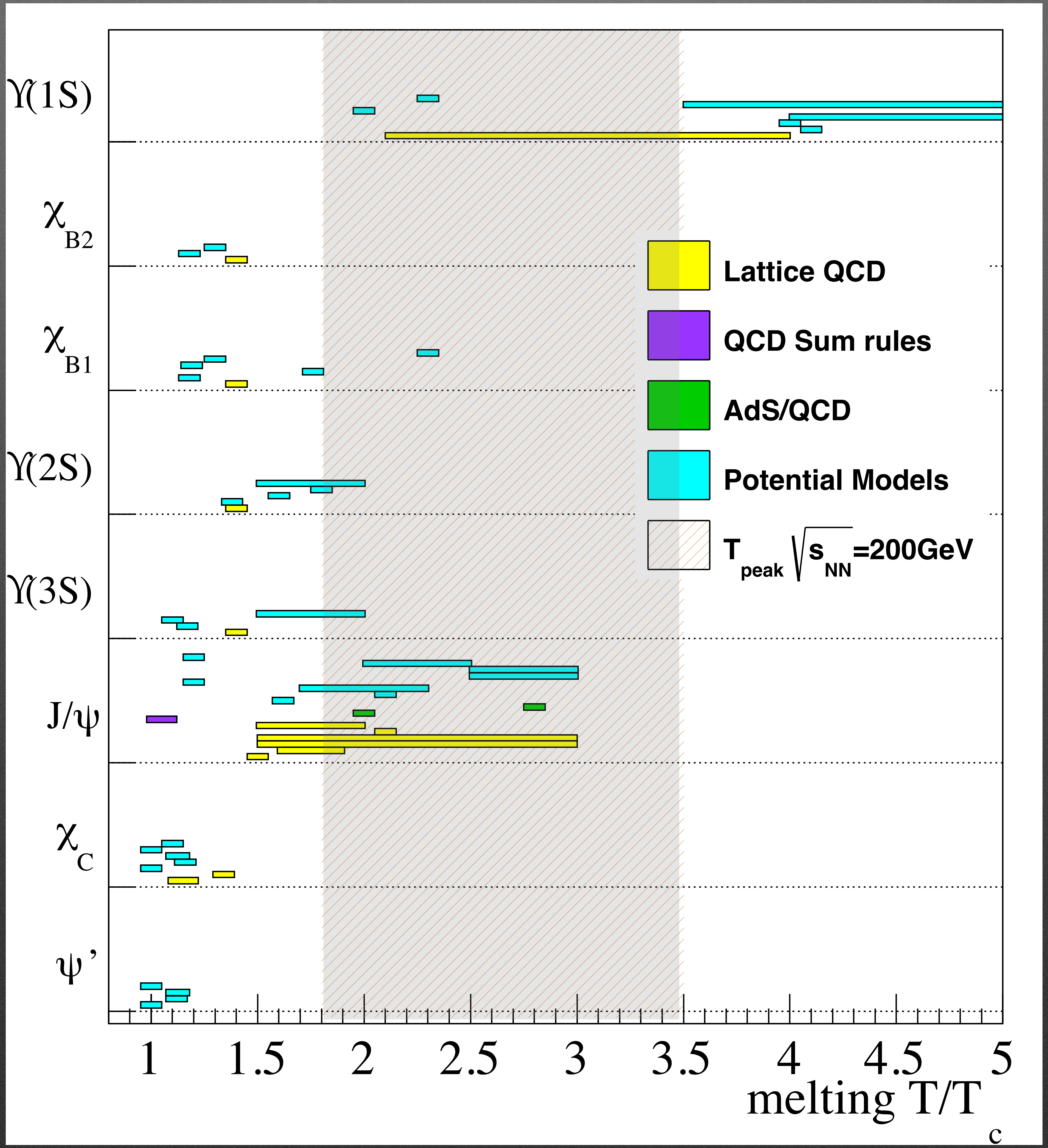
ALICE *[JHEP 02 (2020) 041]*

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

Uncertainties on the dissociation temperature

PHENIX *[PRC 91 (2015) 02413]*



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

- Using S-wave differential cross-section measurements from ATLAS or CMS in pp at √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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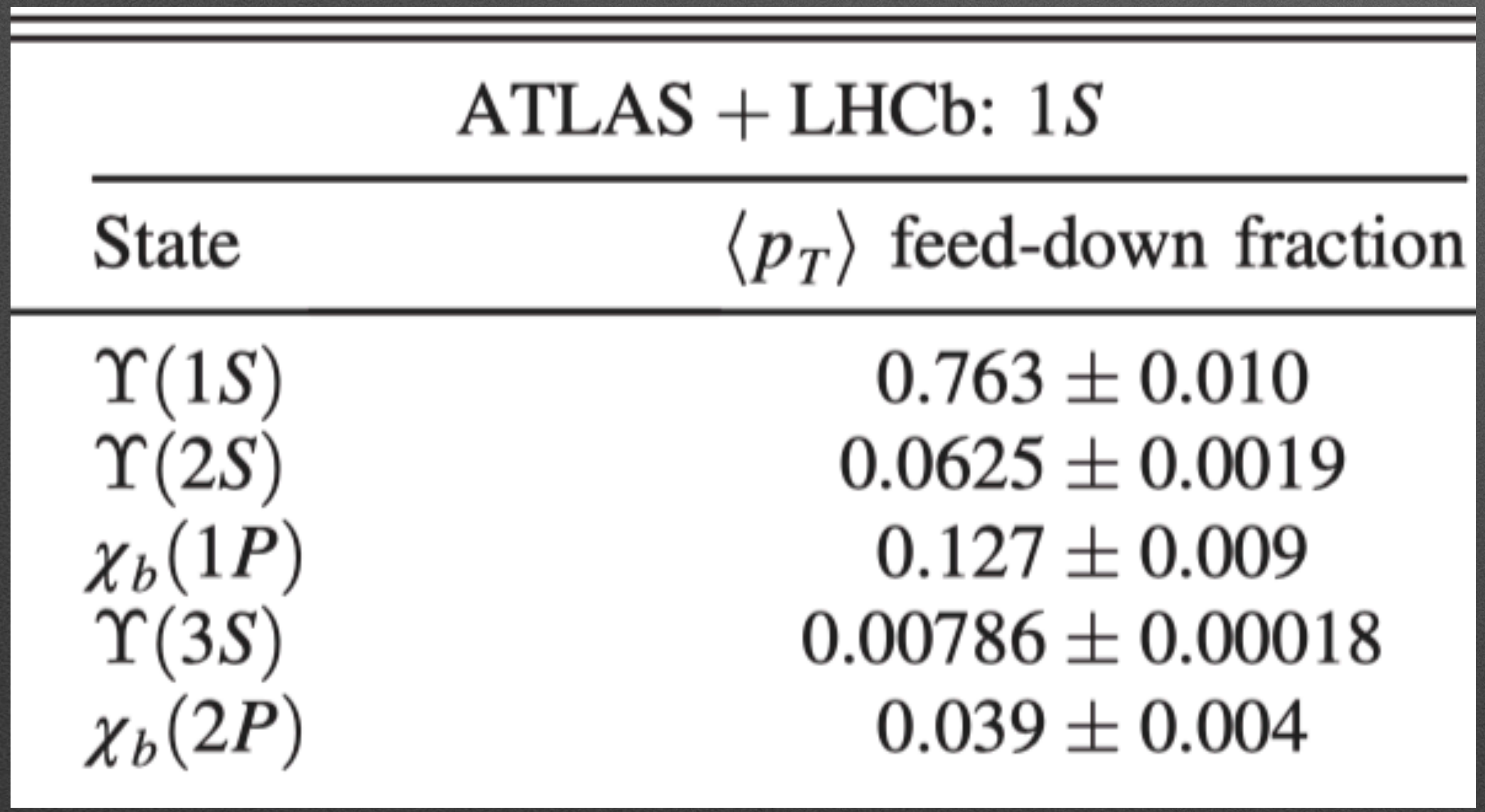
Υ(1S) feed-down fraction at $< p_T >_{\Upsilon(1S)}$ ~ 5.8 GeV



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

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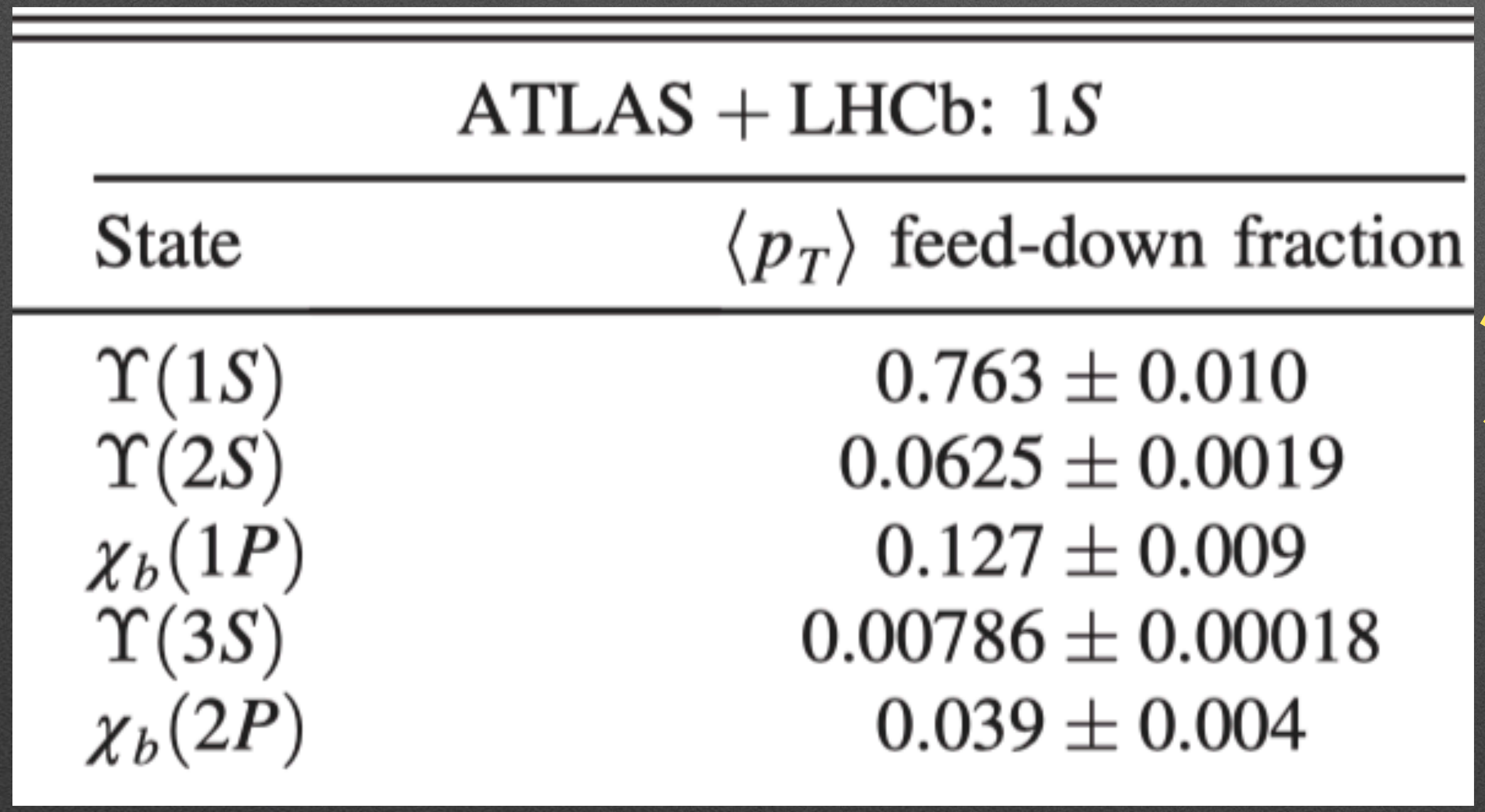

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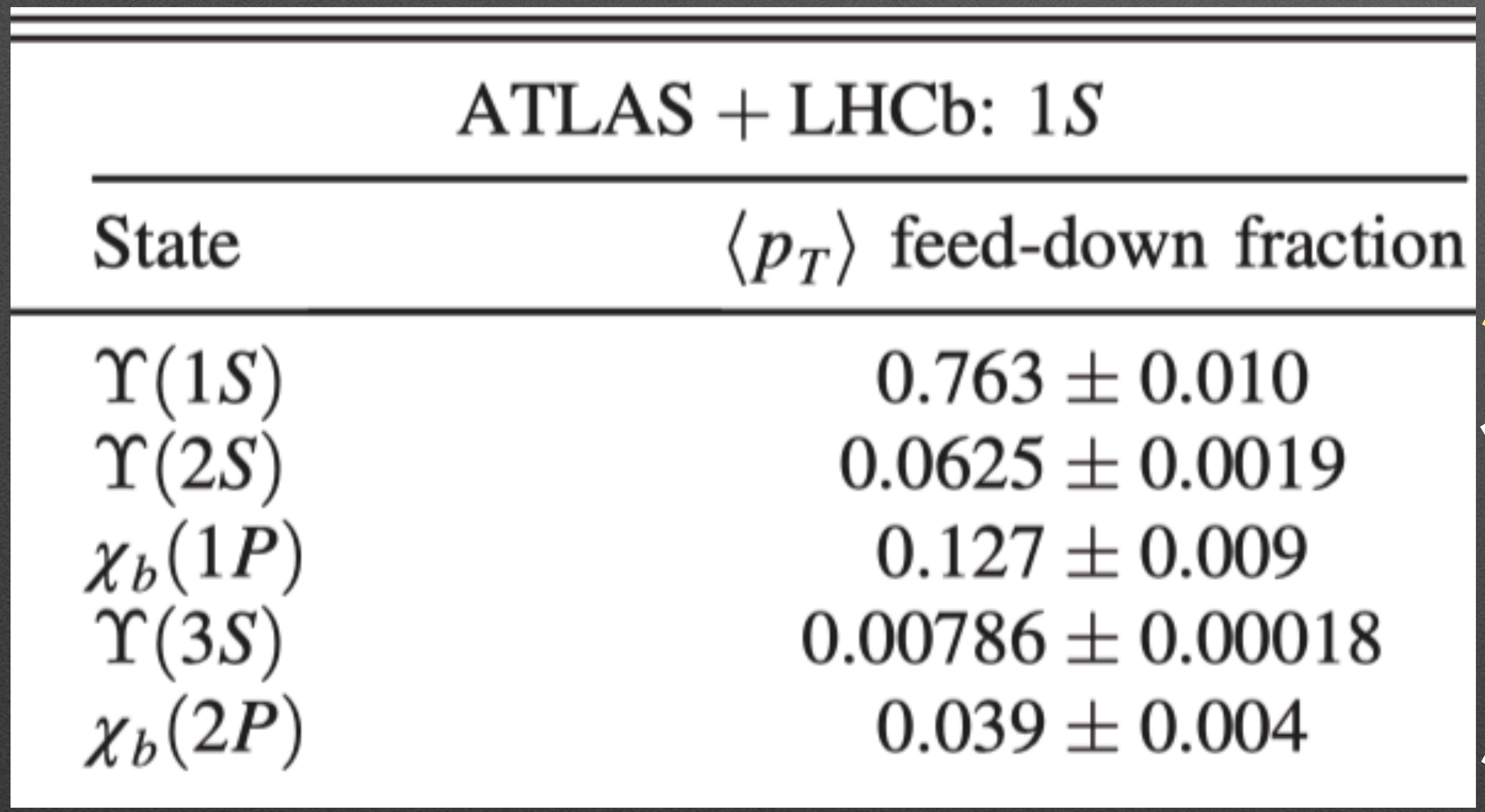

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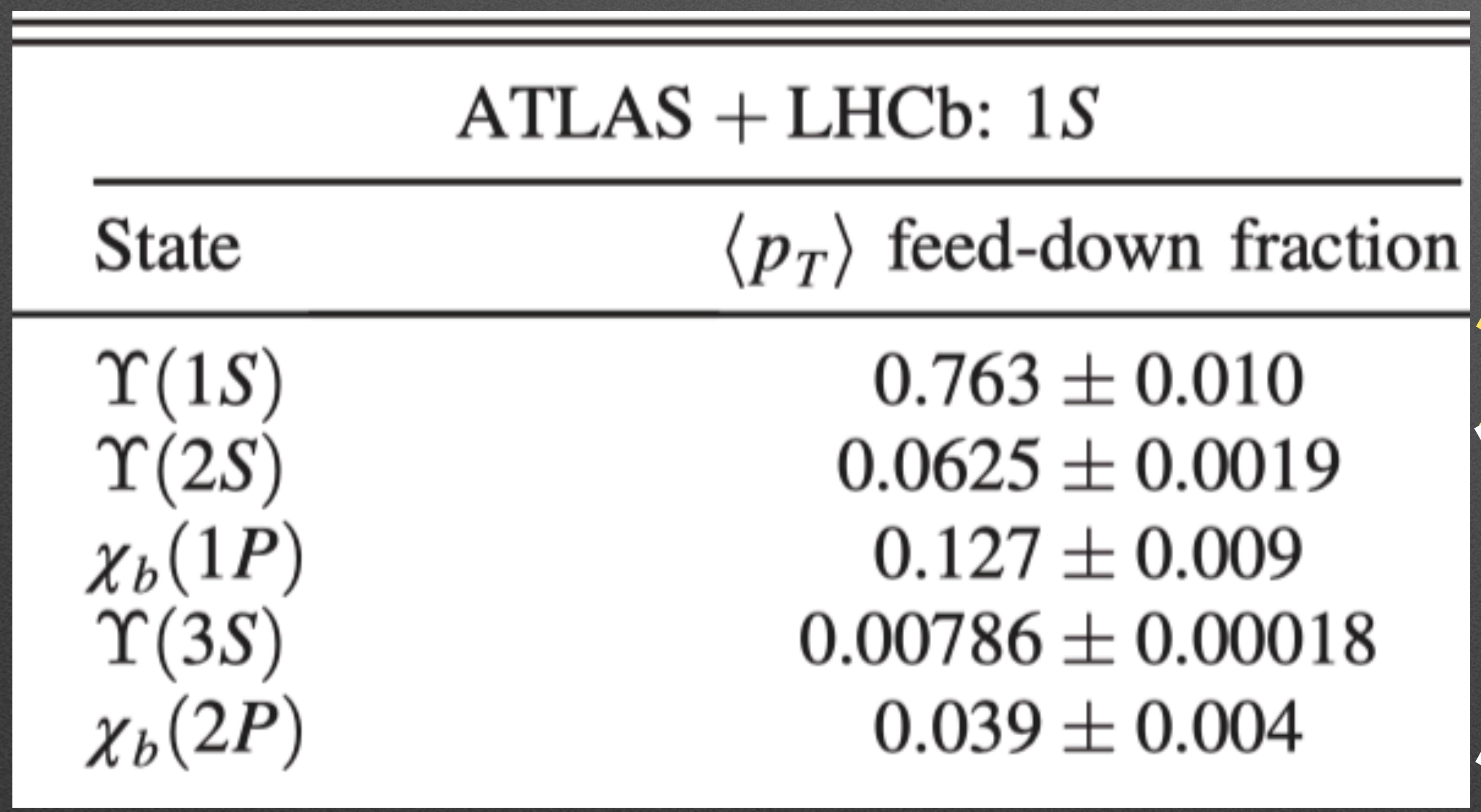

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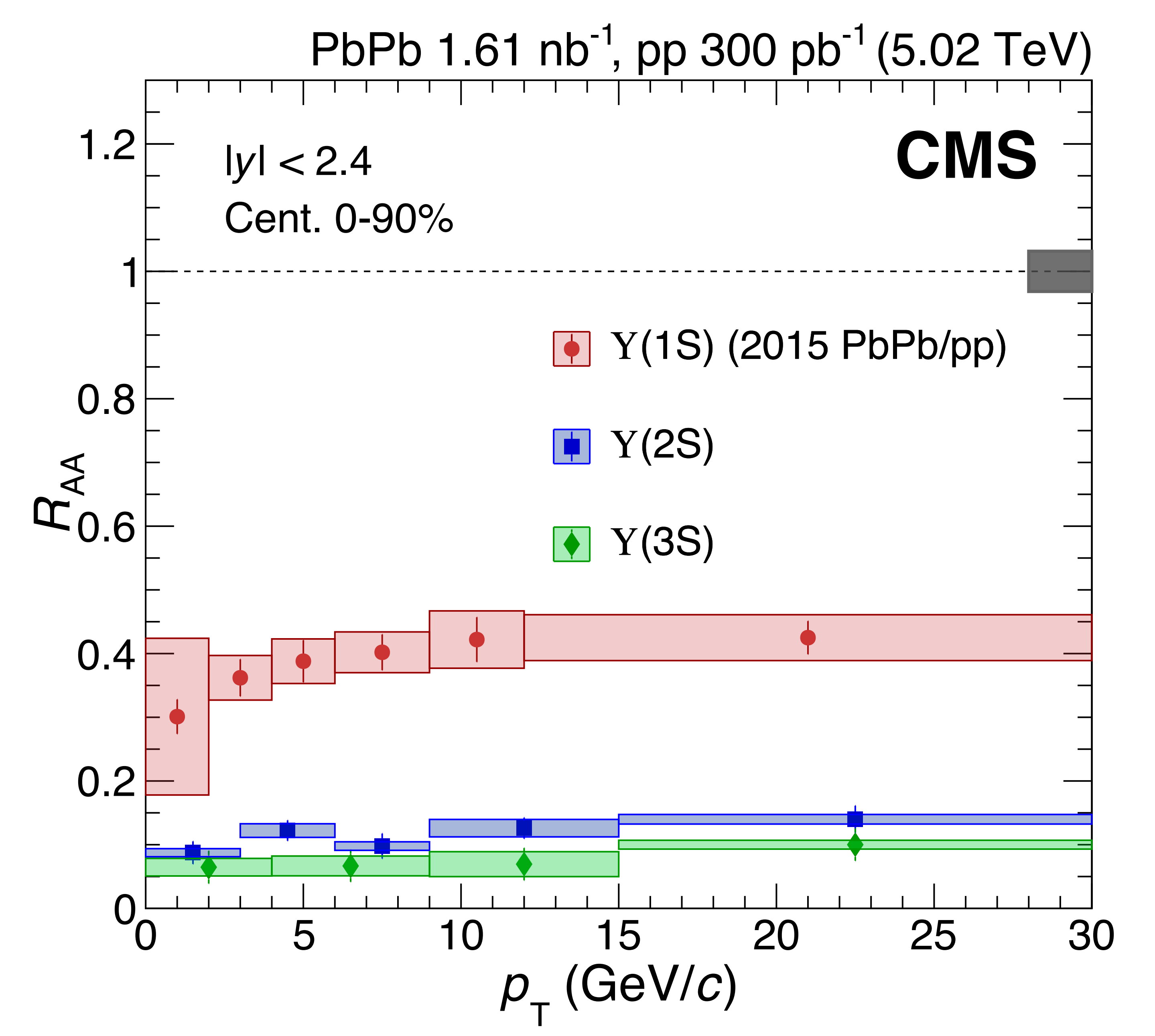
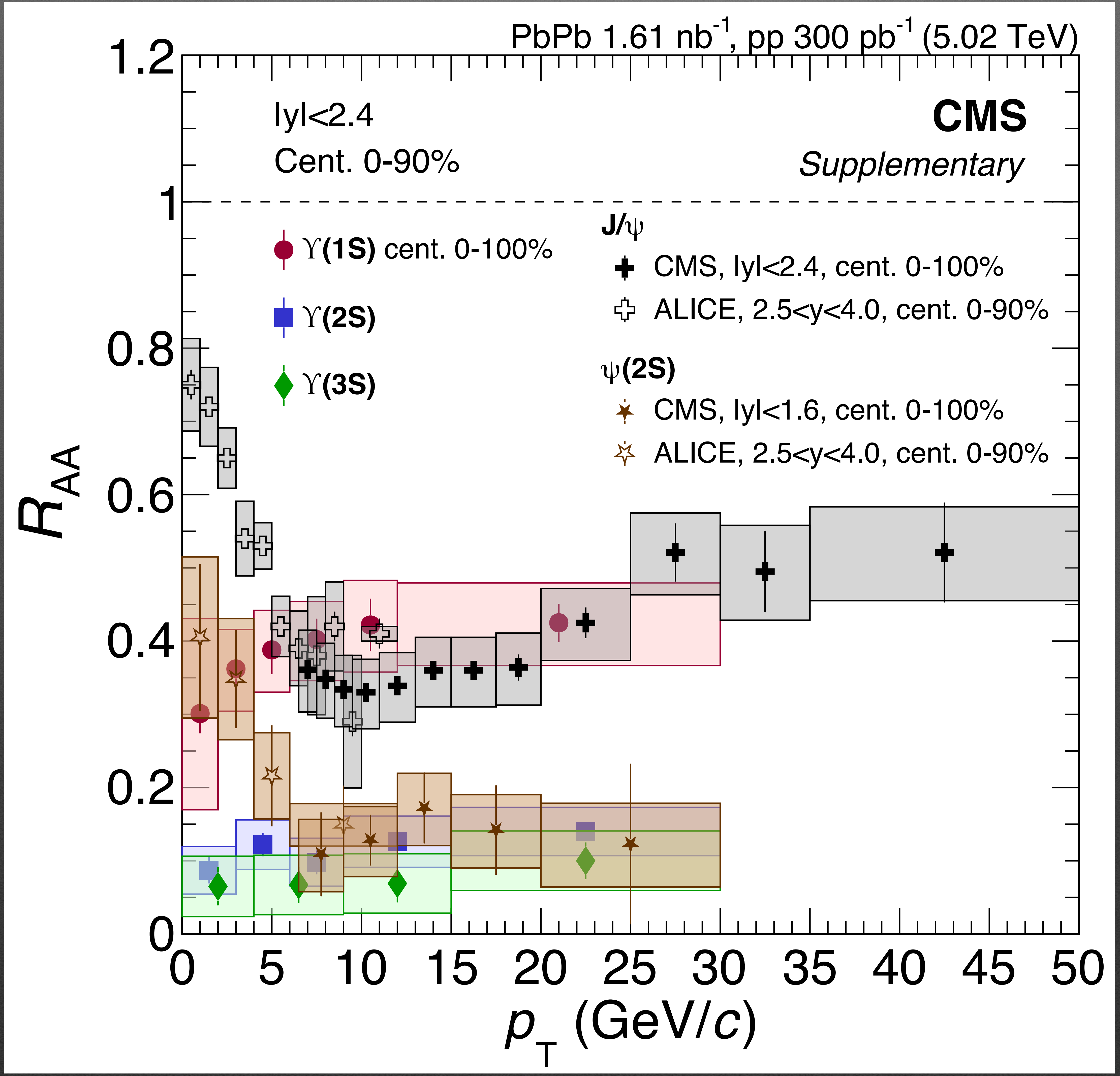


CMS [arXiv : 2303.17026]

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

Charmonia vs bottomonia in Pb-Pb, pT dependence



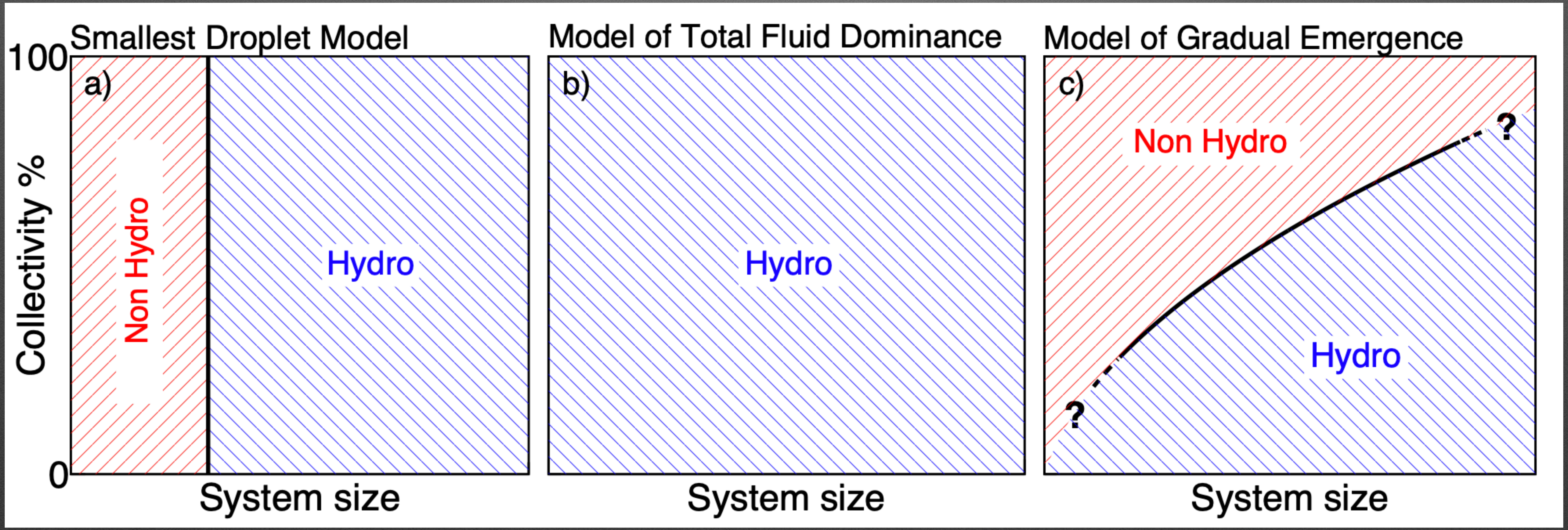
CMS [arXiv : 2303.17026]

CMS [EPJC 78 (2018) 509]

ALICE [JHEP 02 (2020) 041]

ALICE [arXiv:2210.08893]

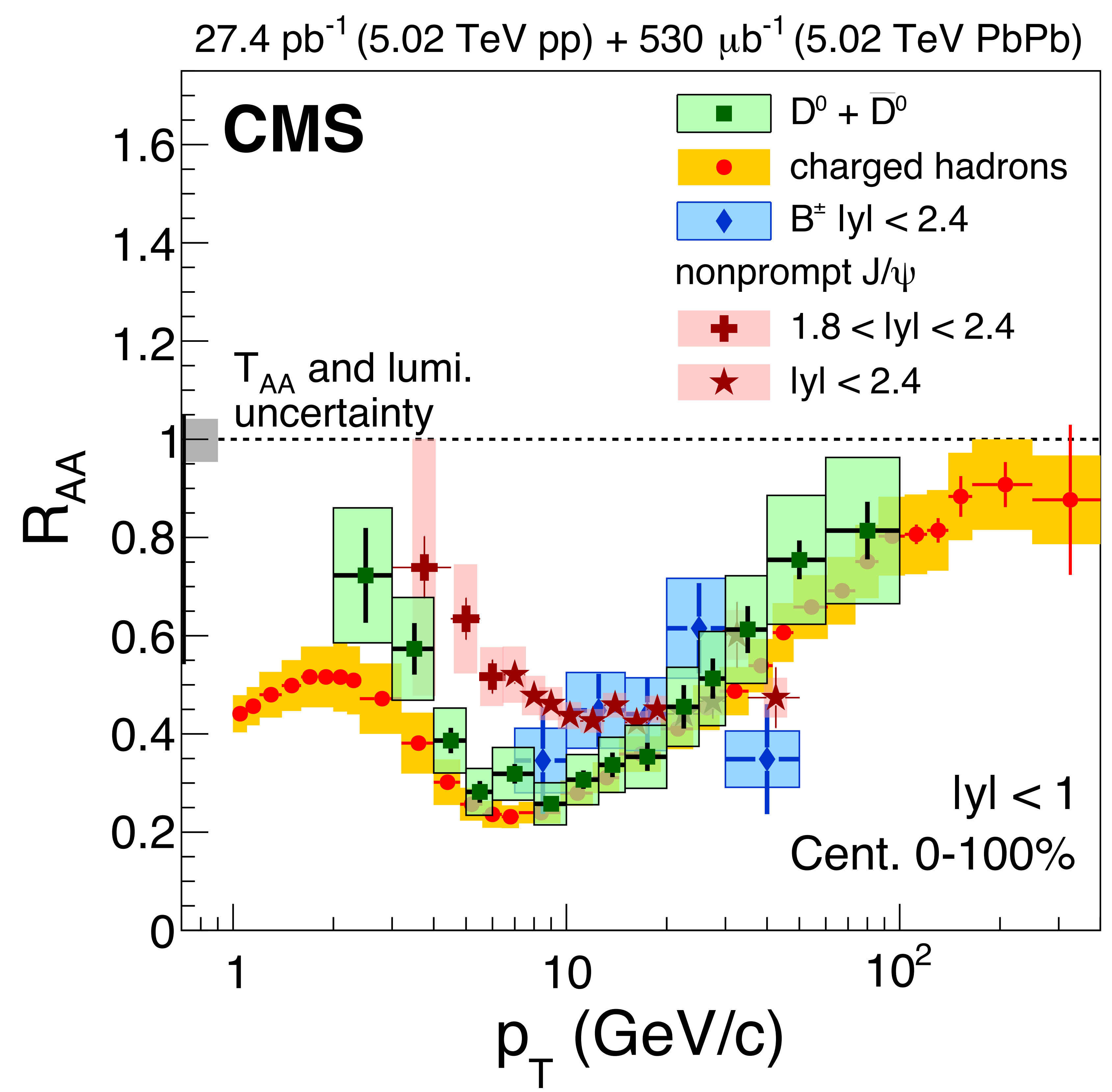
Small systems : collectivity and hydrodynamics



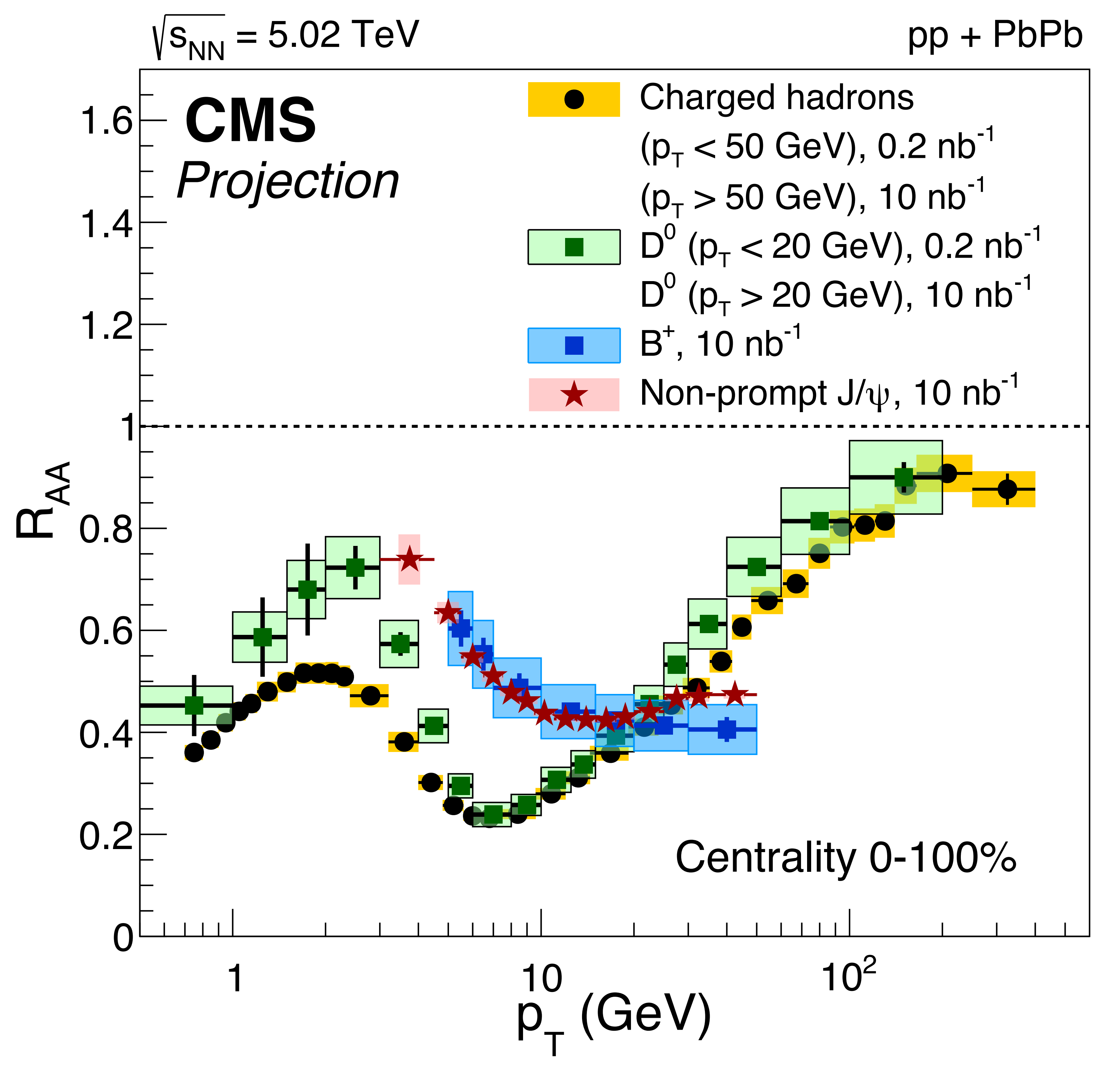
J.F. Grosse-Oetringhaus, U.A. Wiedemann *[arXiv:2407.07484]*

What about J/ψ from B feed-down ?

Current and projected measurements for B and non-prompt J/ψ



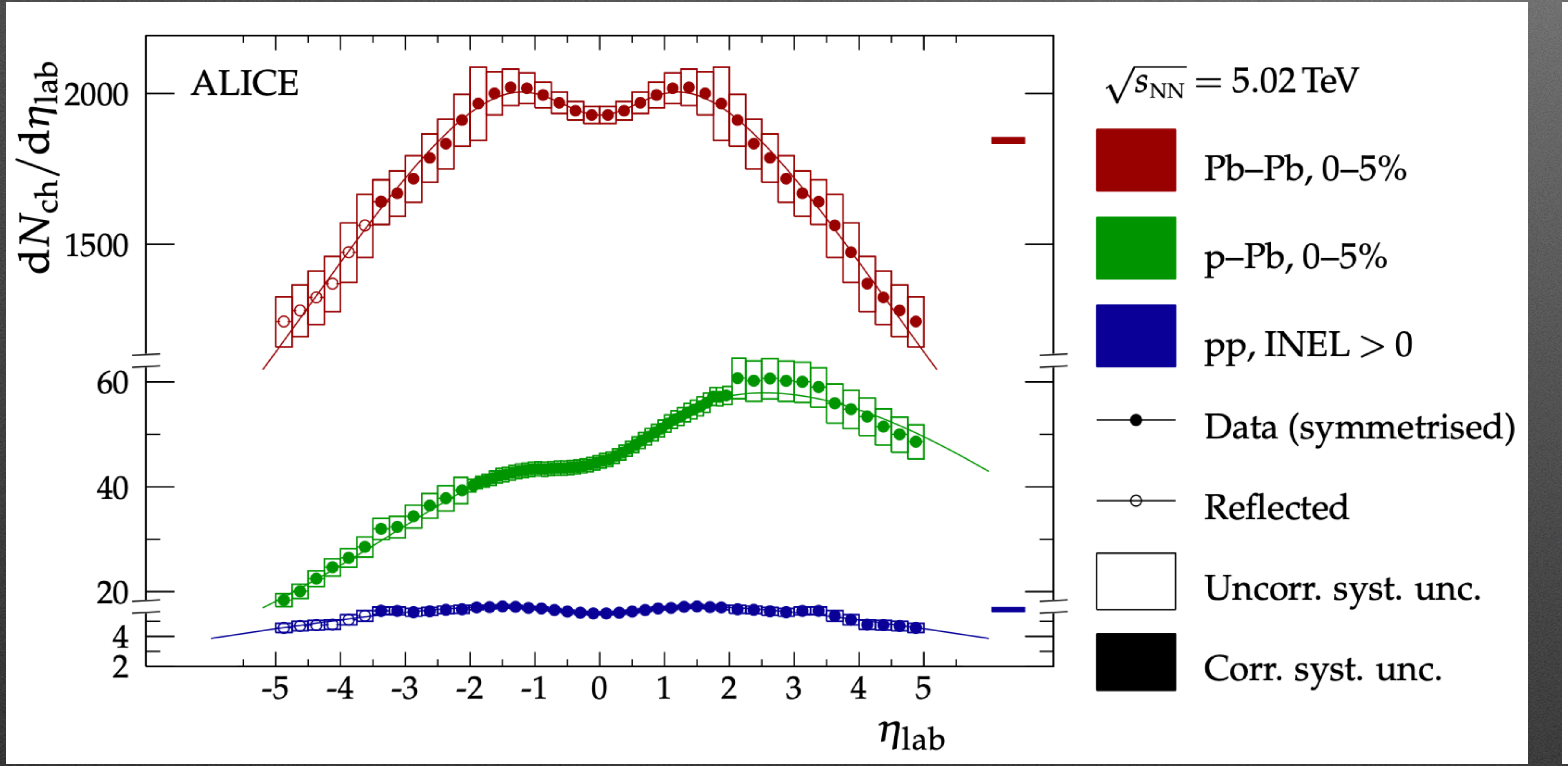
CMS [PLB 790 (2019) 270]



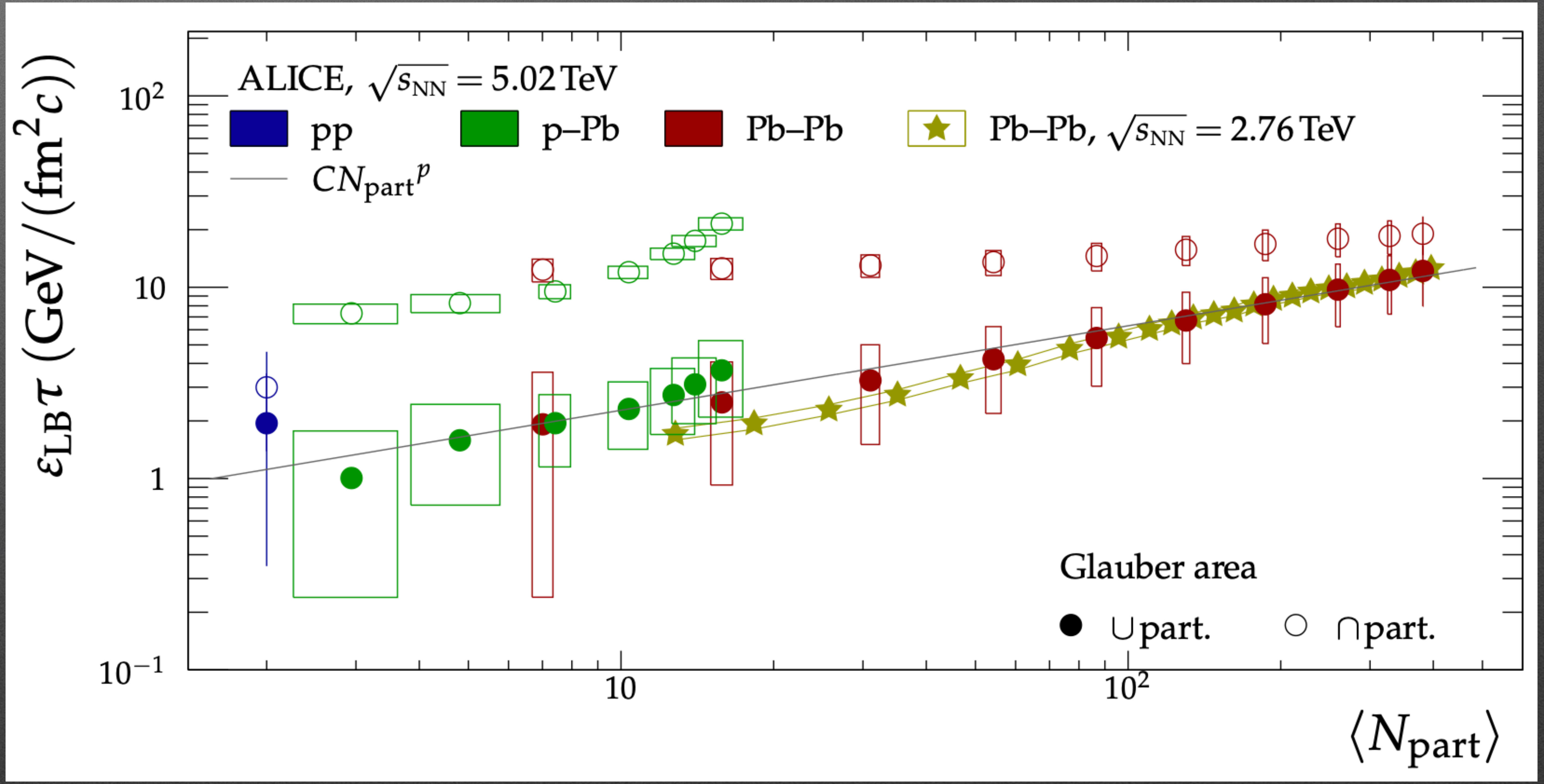
CMS [PLB 790 (2019) 270]

Pseudo-rapidity density, energy density at LHC

ALICE *[PLB 845 (2023) 137730]*



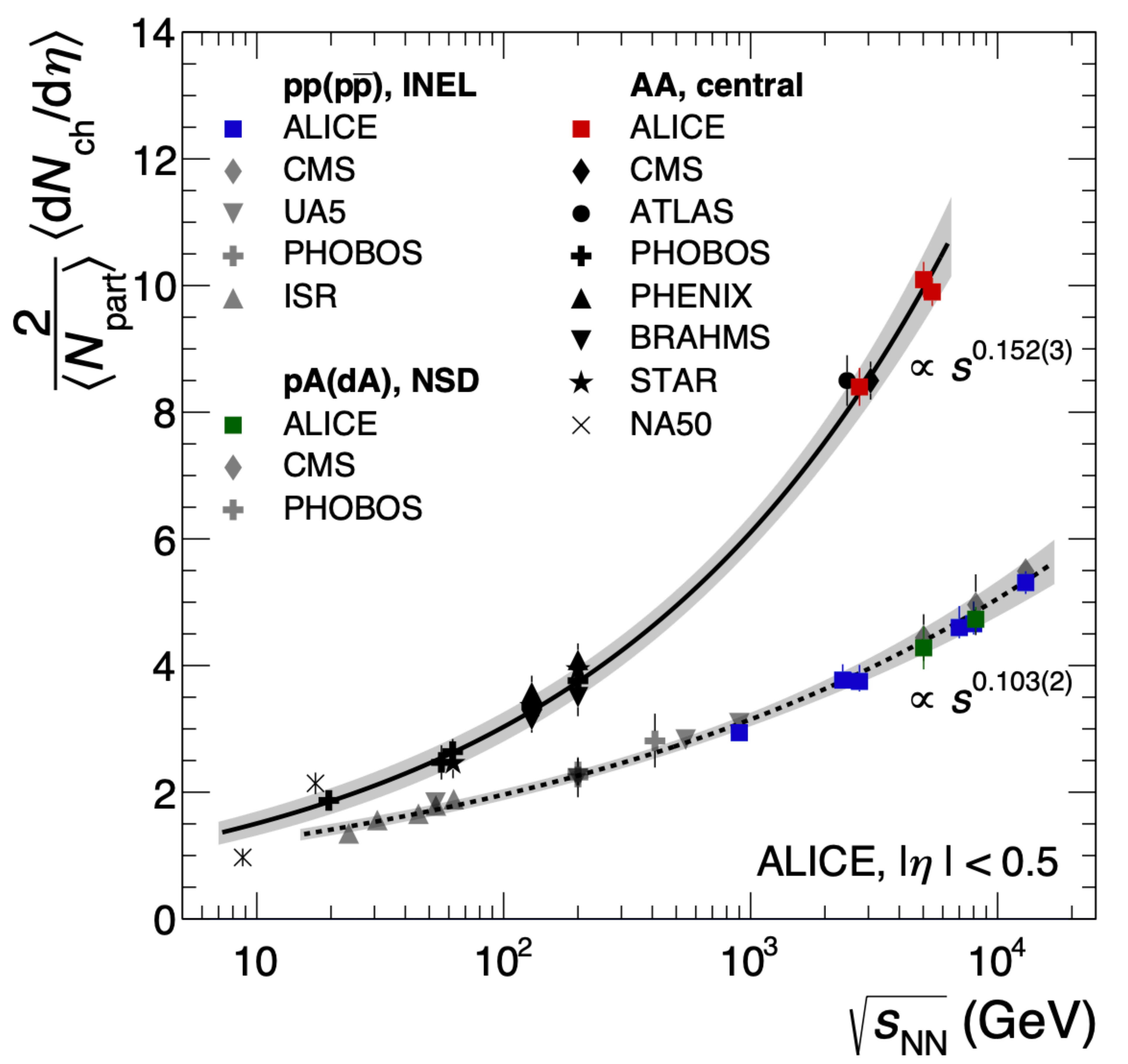
Charged-particle pseudo-rapidity density



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)