Bottomonium production in heavy-ion collisions at the LHC

Overview of Run 2 measurements from ALICE and CMS

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Gluodynamics

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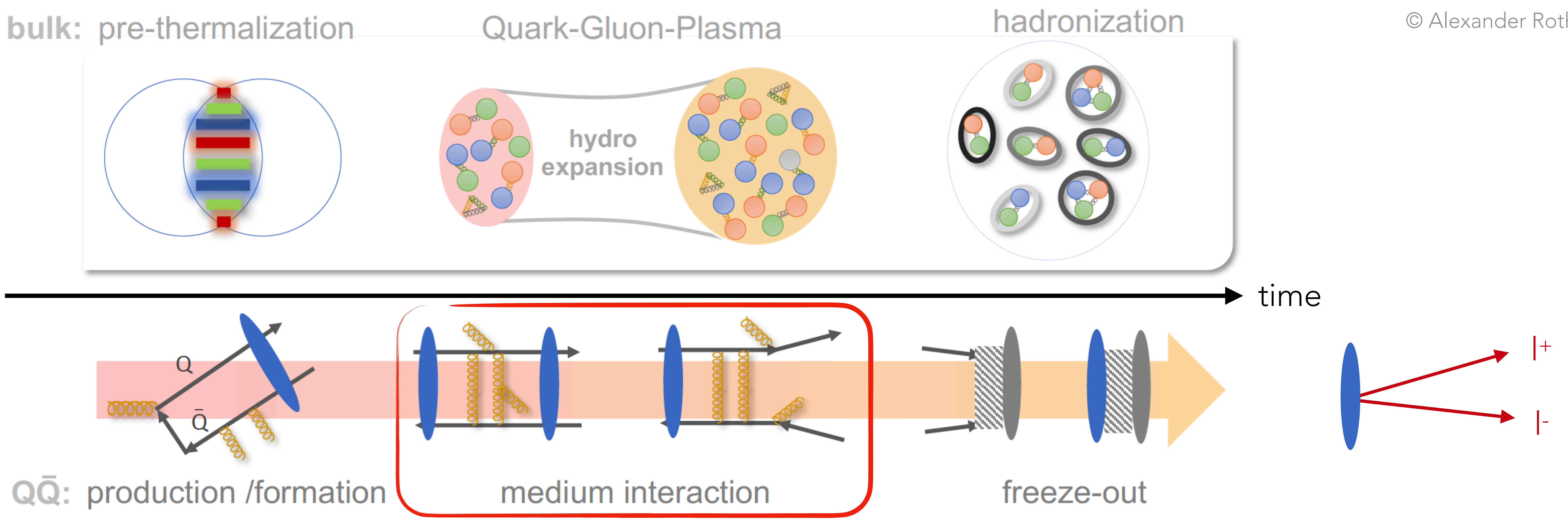
STRONG-2020

Quarkonia as probes of the QGP

Collision evolution

Quarkonium history



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- production of heavy quarks from initial hard gluon scatterings ($2m_Q \gg T_{\text{medium}} > \Lambda_{QCD}$)
- formation time of bound states* ≲ QGP emergence (~1 fm/c)

  ☛ experience the whole evolution of the thermodynamic system
- dilepton decay = clean experimental signal

☛ **insights of in-medium phenomena**

*reasonable argument for Υ(nS)
debatable for J/ψ (Batoul's talk)

A dynamical interplay

Medium-induced suppression

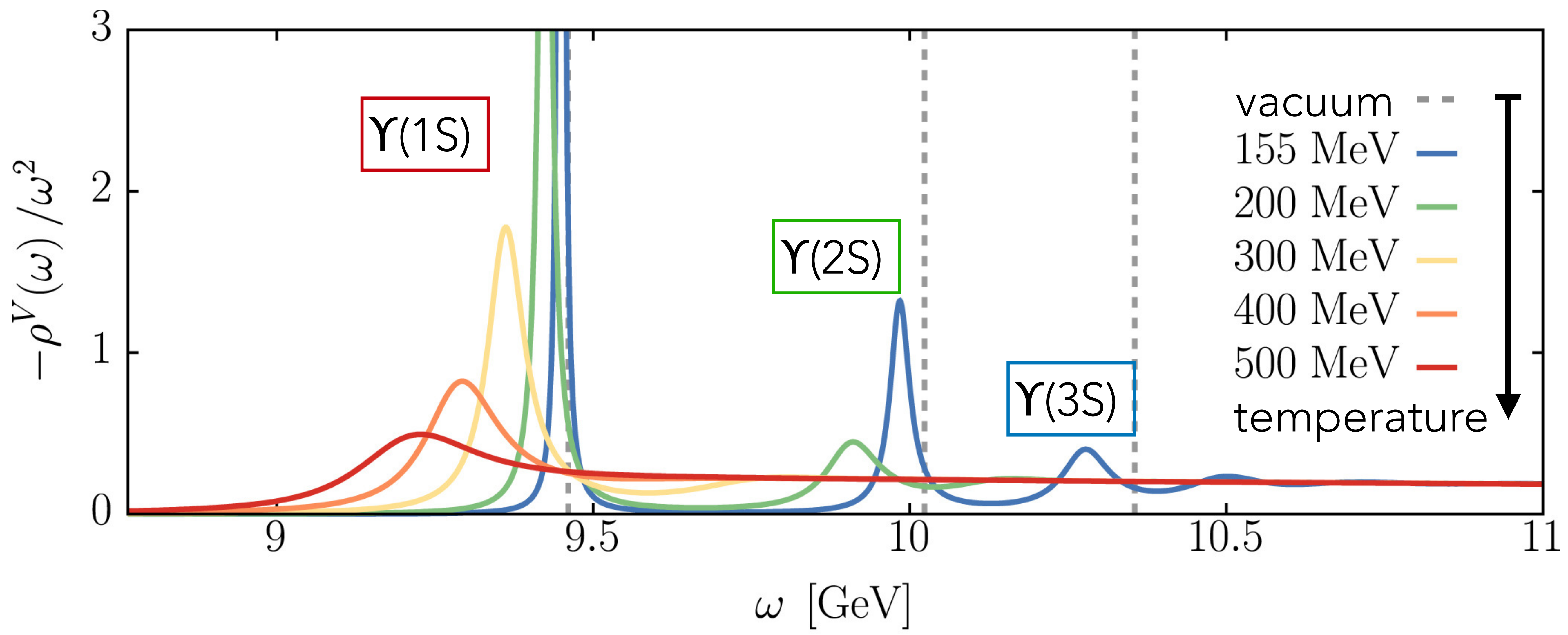
- modification of the inter-quark potential
  ➠ pair dissociation for $T_{QGP} > T_D$
- scattering interactions with plasma constituents
  ☛ illustration: broadening of the spectral functions and *sequential melting*

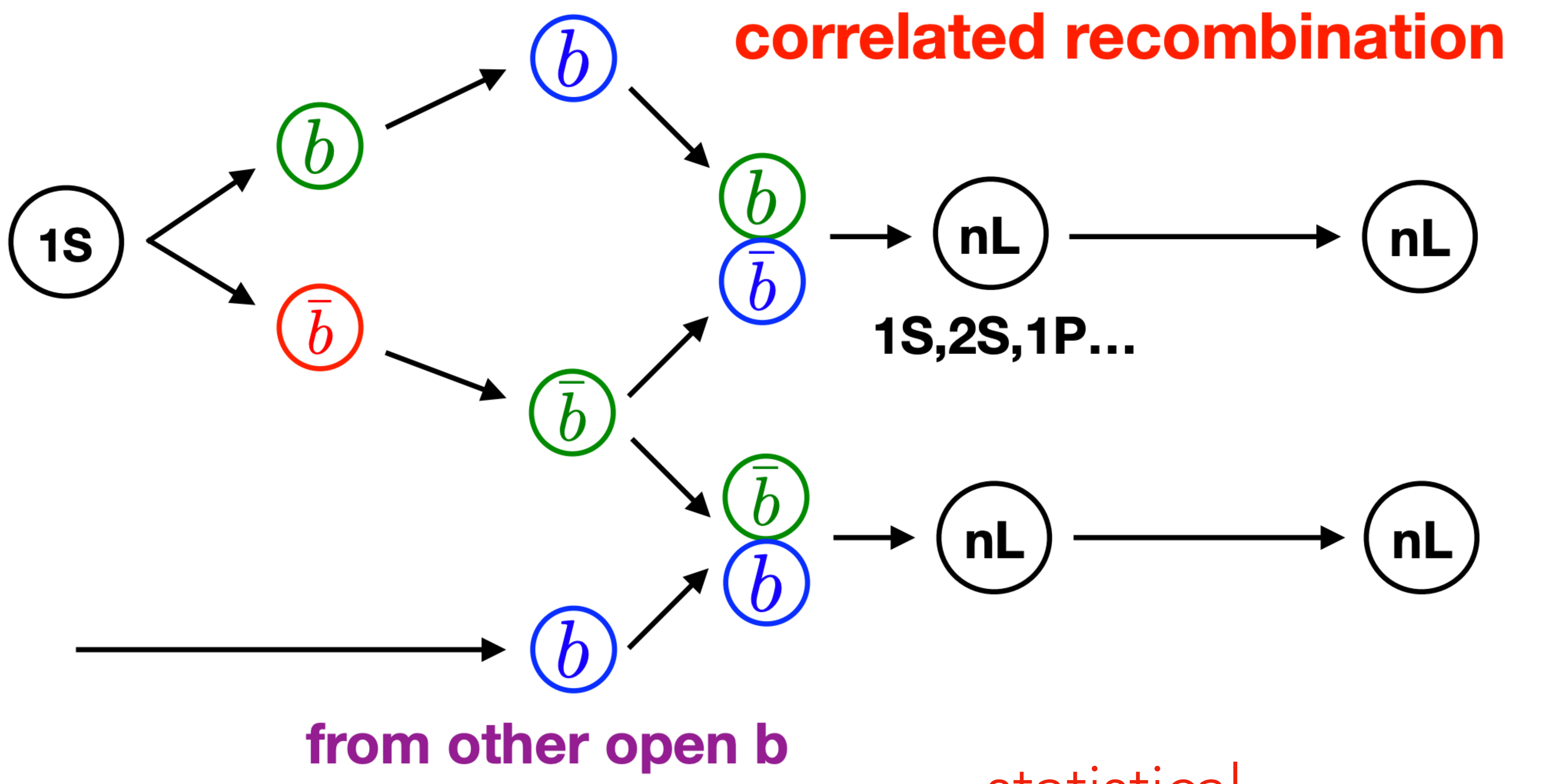
Regeneration

quarkonium (re-)formation from unbound heavy quarks via medium interactions

☛ theoretical frameworks to treat all these phenomena!

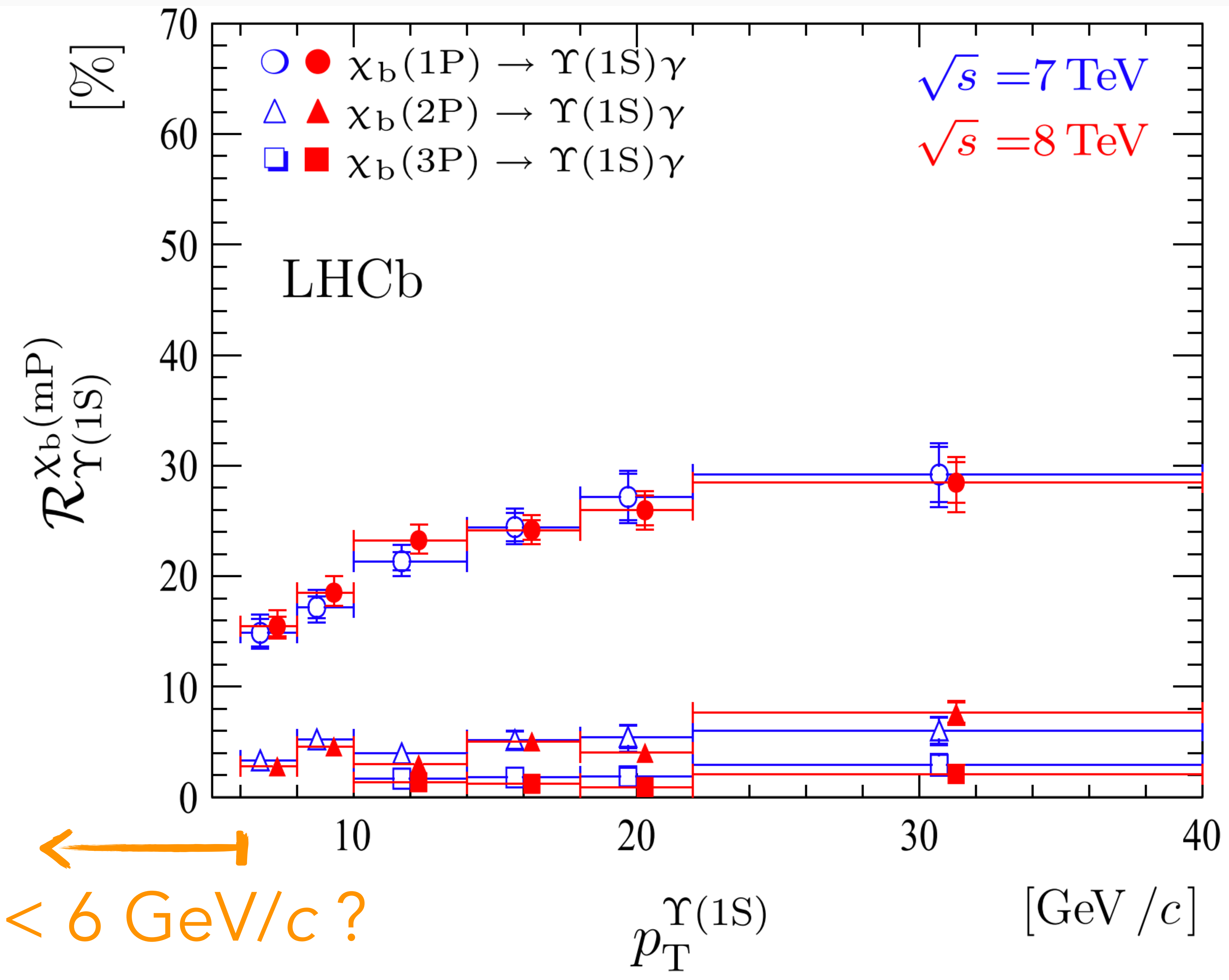
In-medium spectral functions of Υ resonances from lattice NRQCD calculations [PRD 101 (2020) 056010]



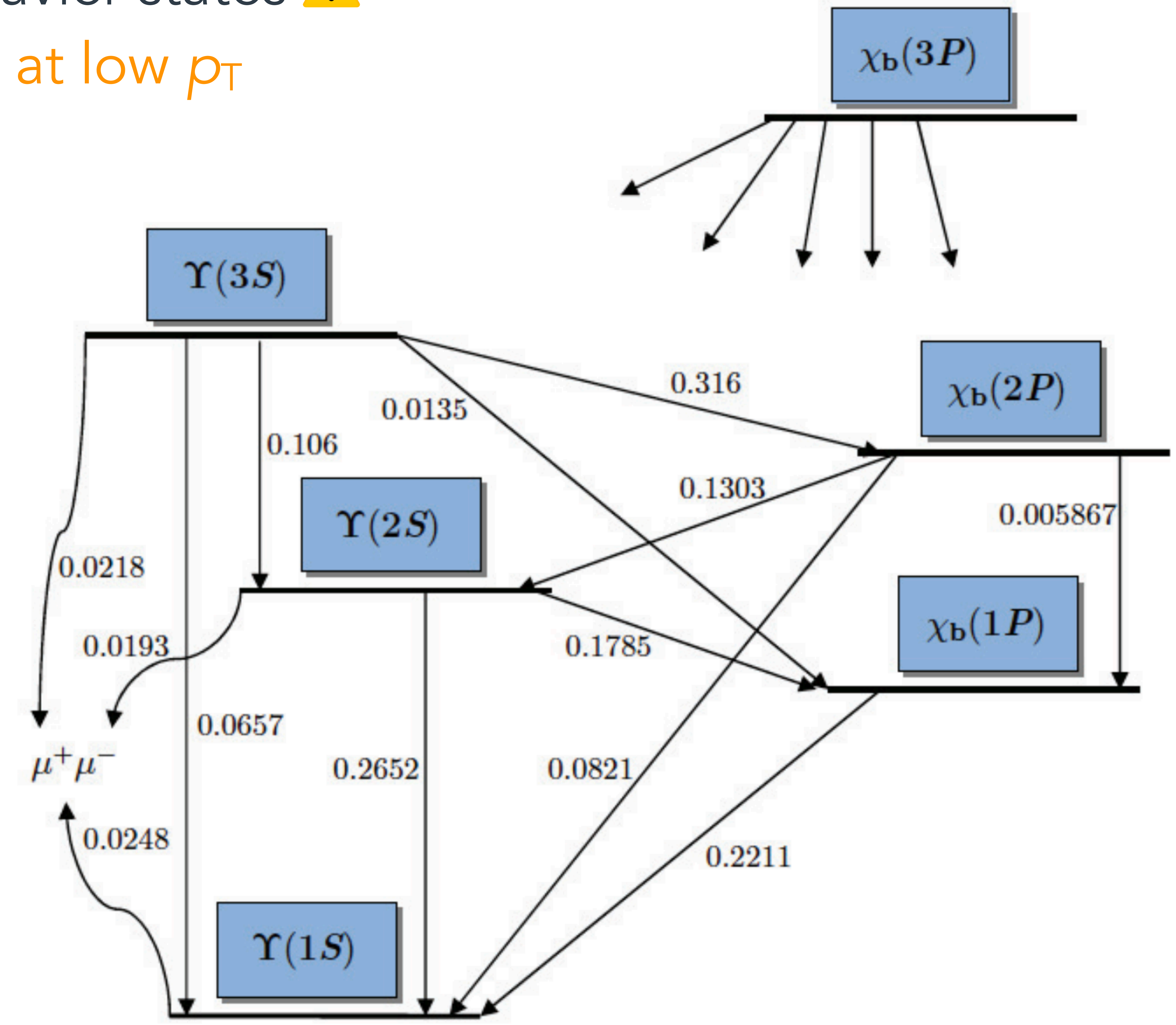


Bottomonium production at the LHC

- **ϒ resonances measured down to p_T = 0 GeV/c** by all four experiments (dimuon decay channel)
  ☛ complementary rapidity coverages
- **inclusive production = direct + feed-down** from heavier states ⚠
  complex pattern with P-wave contributions unknown at low p_T
  ☛ implications when interpreting heavy-ion data!



p_T < 6 GeV/c ?

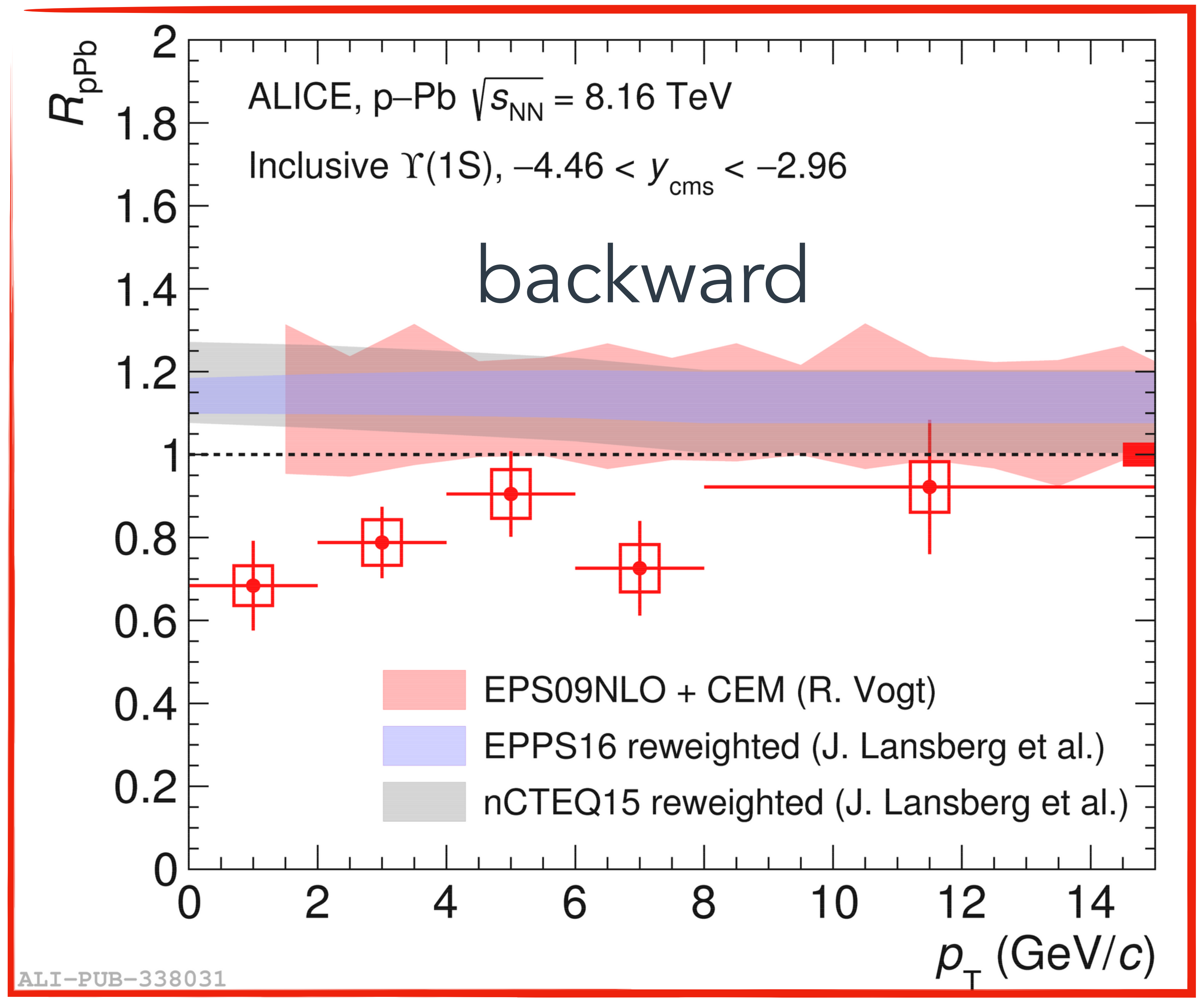


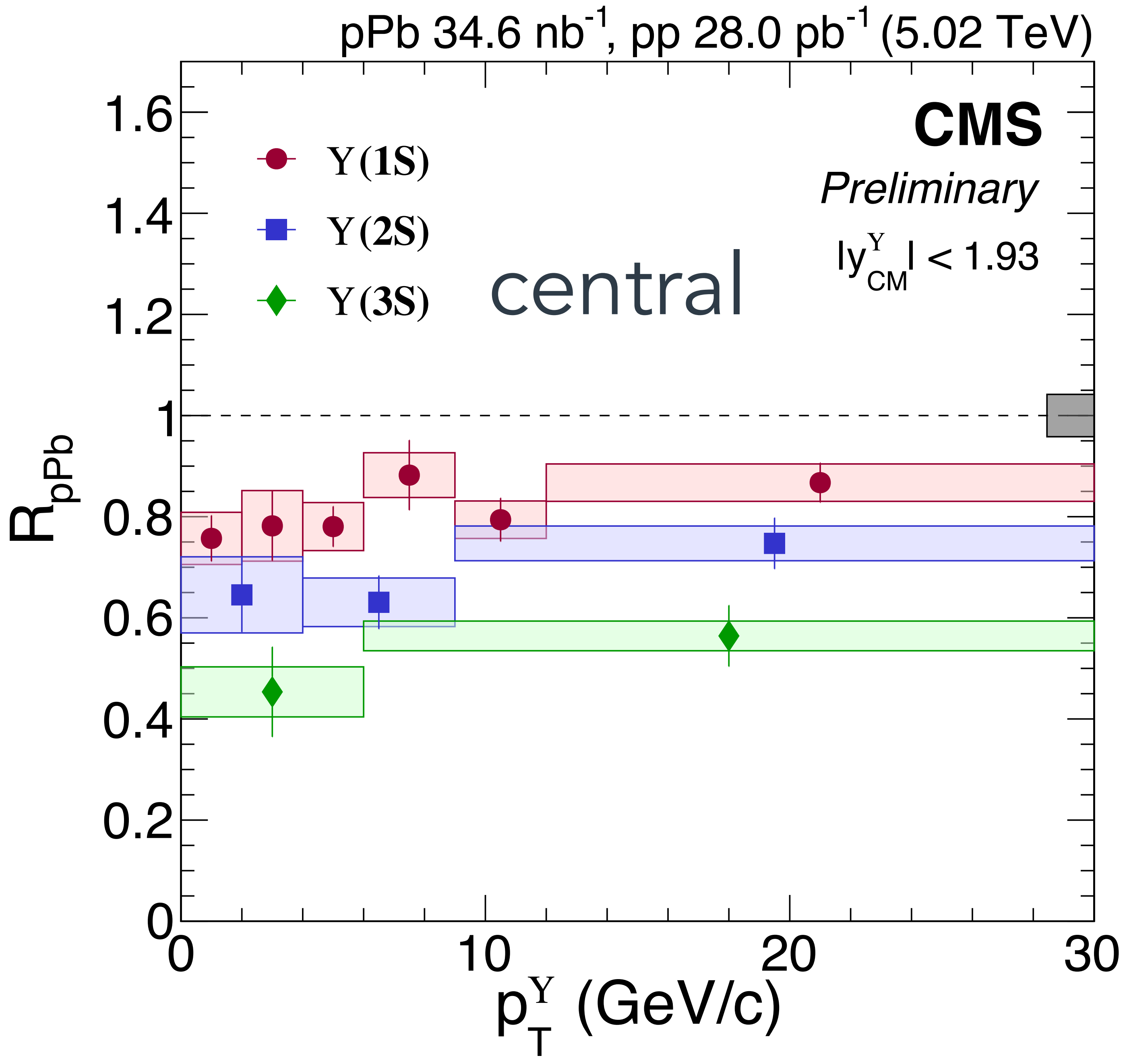
Υ production in pPb collisions

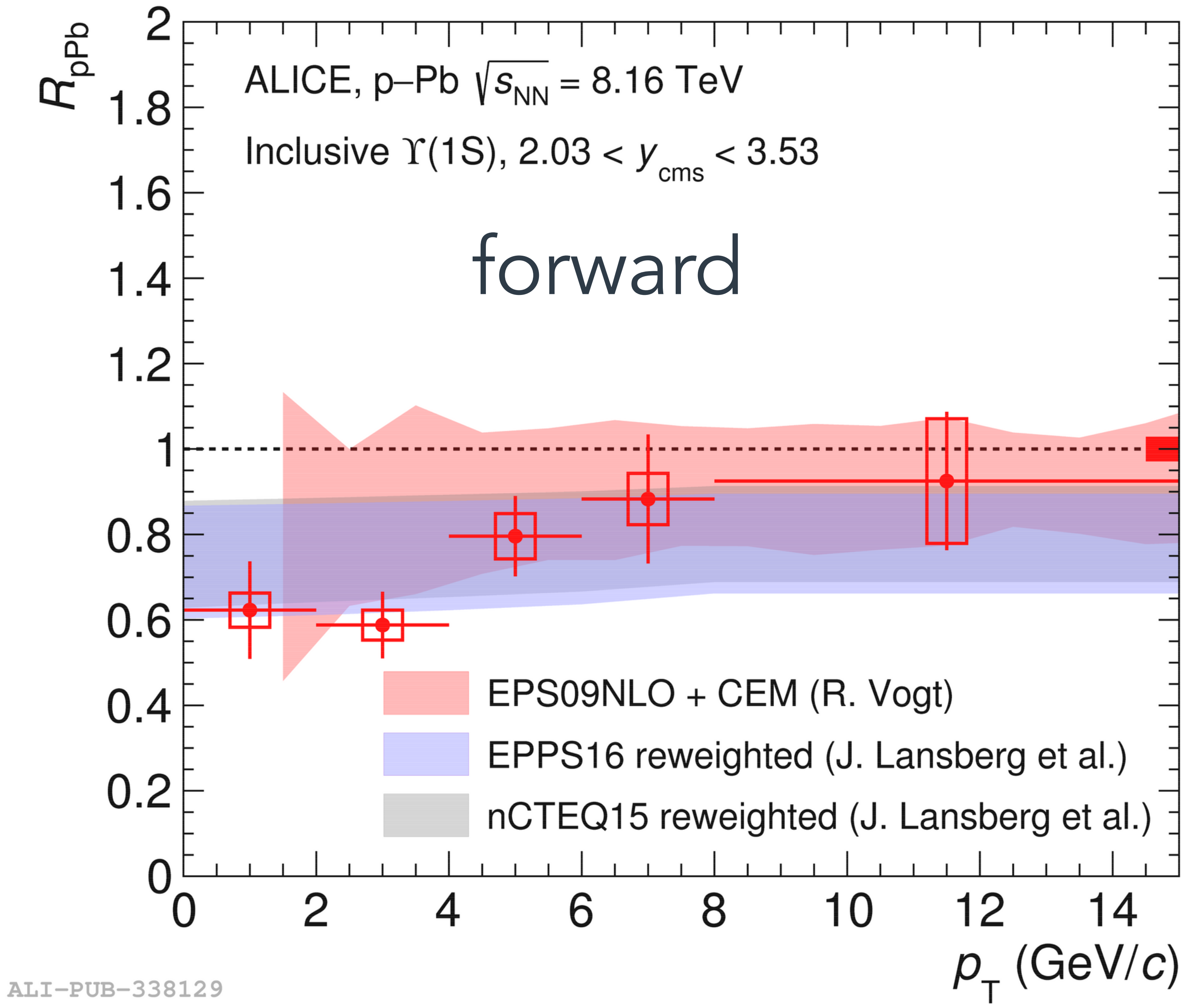
Already modified in proton–nucleus collisions

- $R_{\mathrm{pPb}} < 1$ for p_{T} below 4–6 GeV/c for all rapidities
- cannot be described by nPDF parametrisations in the backward region (no antishadowing?)
- stronger suppression for excited states

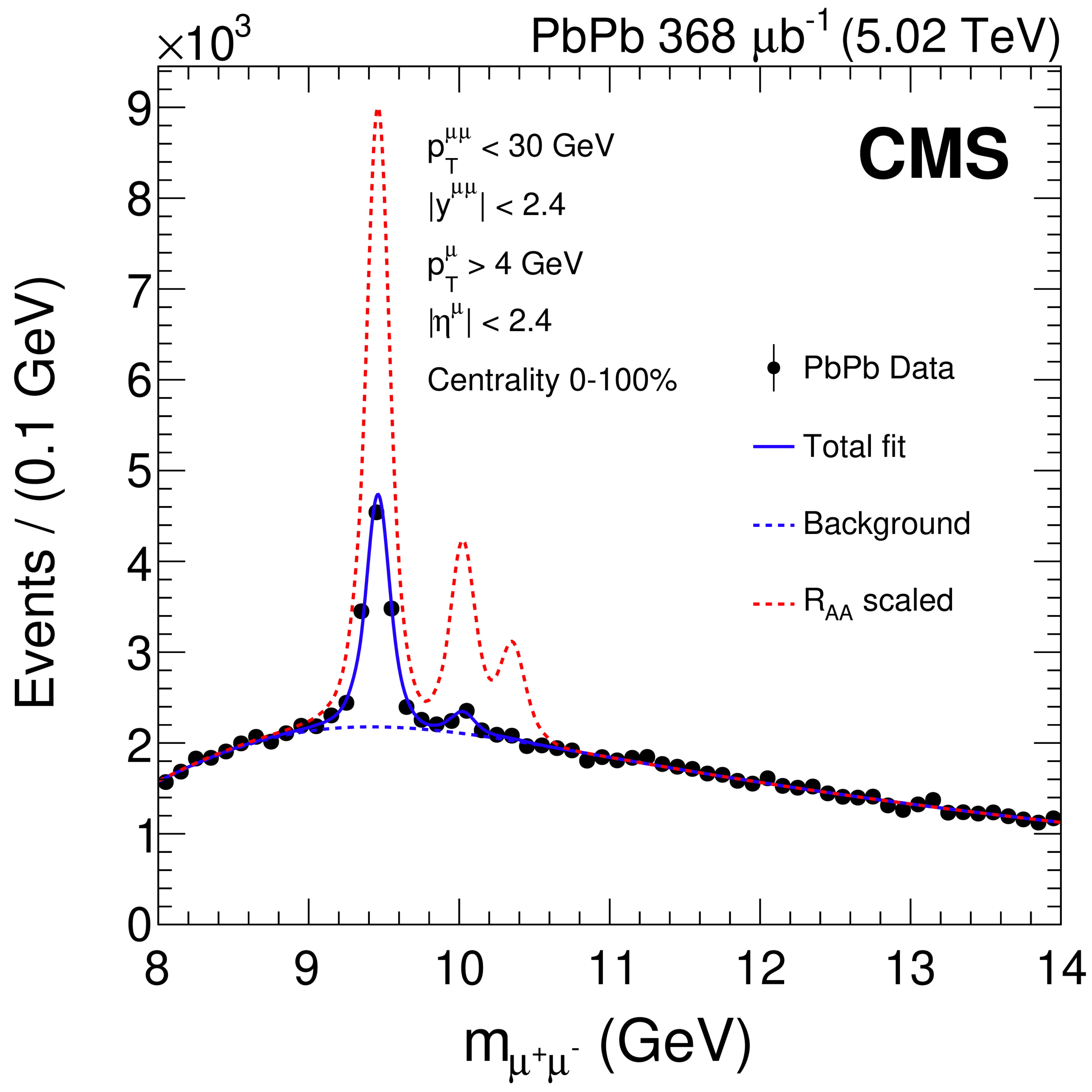
☛ **must be taken into account by models** describing production in nucleus–nucleus collisions







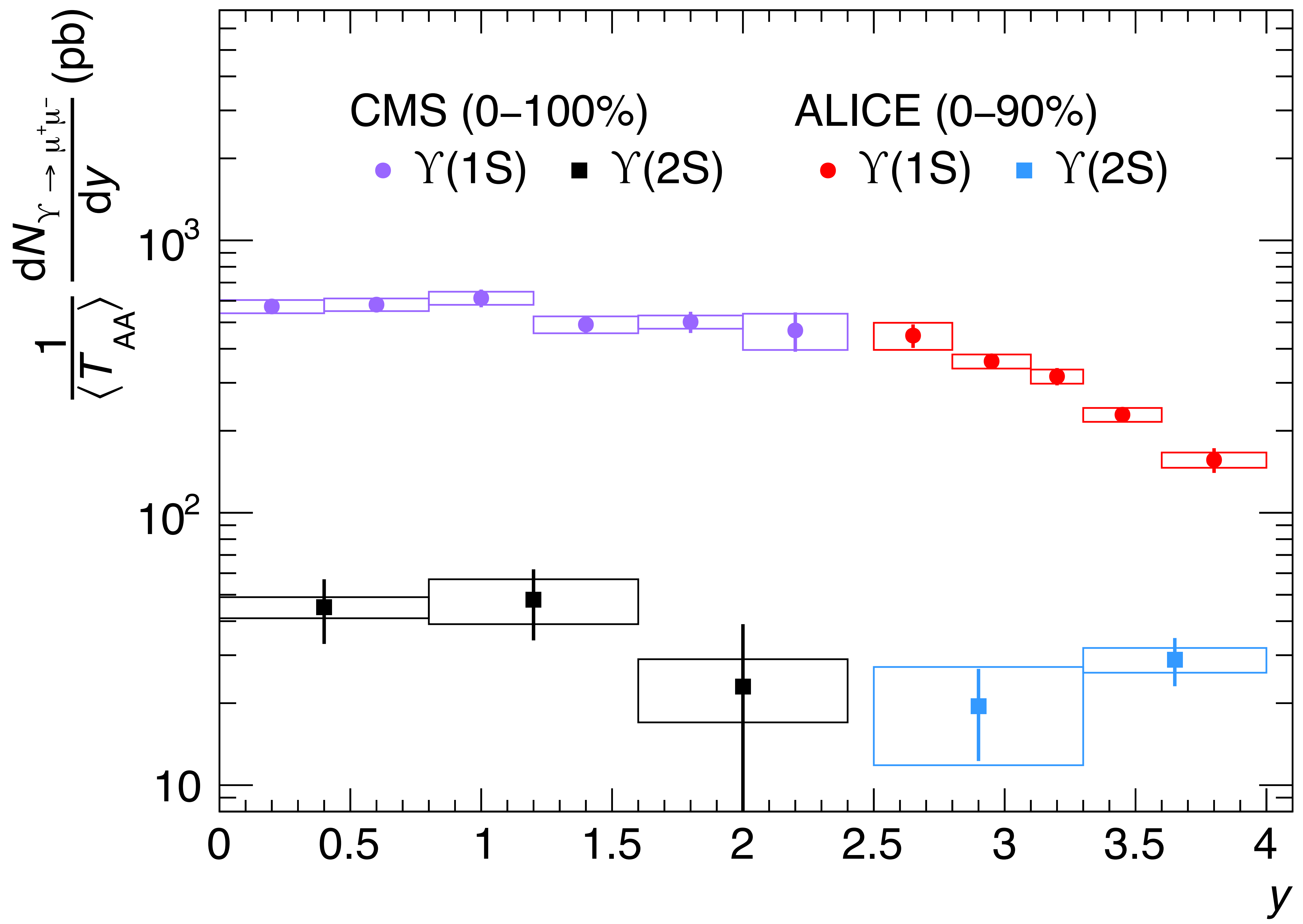
Nuclear modification of Υ production in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

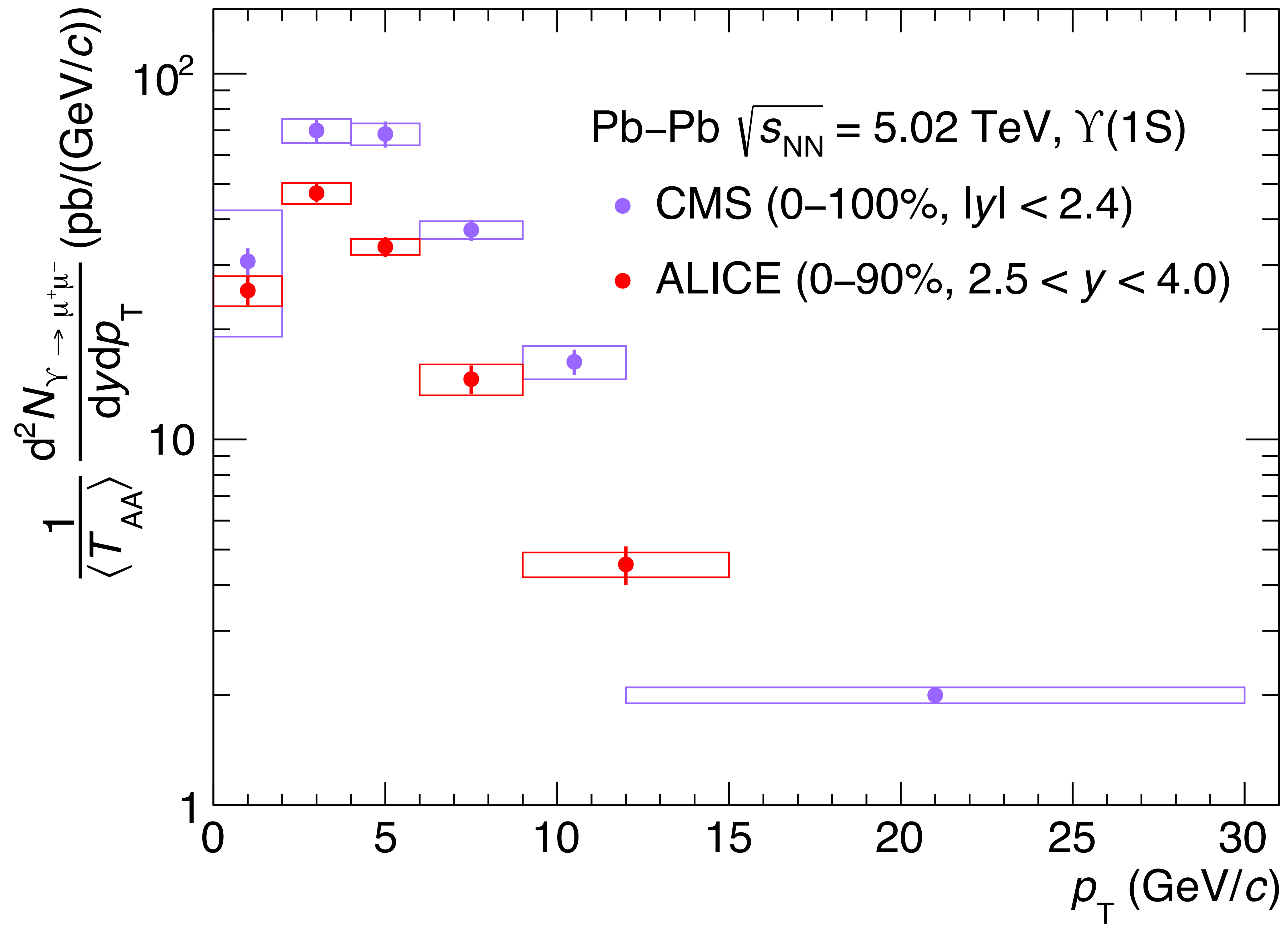


Based on the references:

- CMS collaboration, *Suppression of excited Υ states relative to the ground state in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, PRL 120 (2018) 142301
- CMS collaboration, *Measurement of nuclear modification factors of Υ(1S), Υ(2S), and Υ(3S) mesons in PbPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, PLB 790 (2019) 270
- ALICE collaboration, *Υ production and nuclear modification at forward rapidity in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV*, arXiv:2011.05758

Differential yields (centrality-integrated)

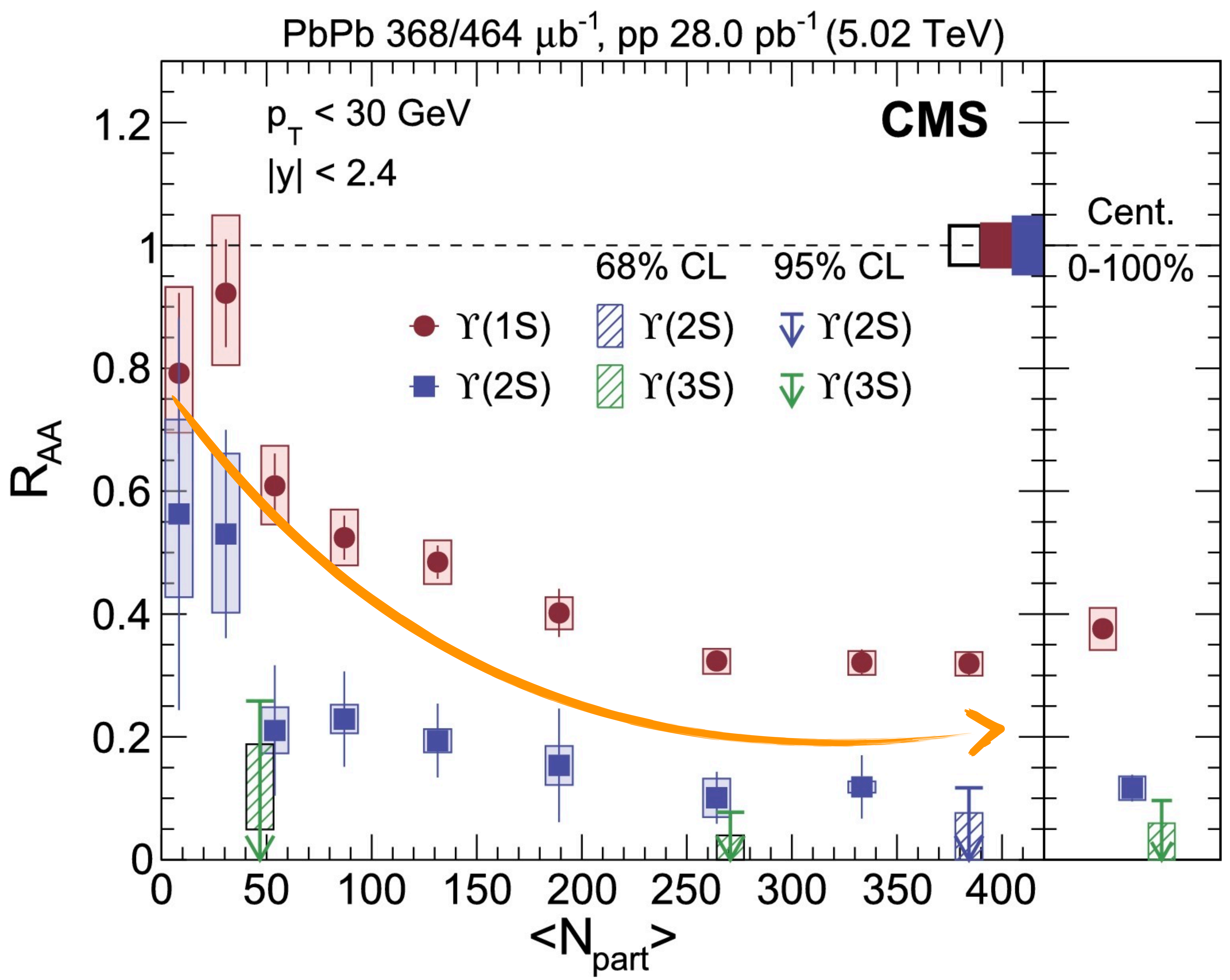


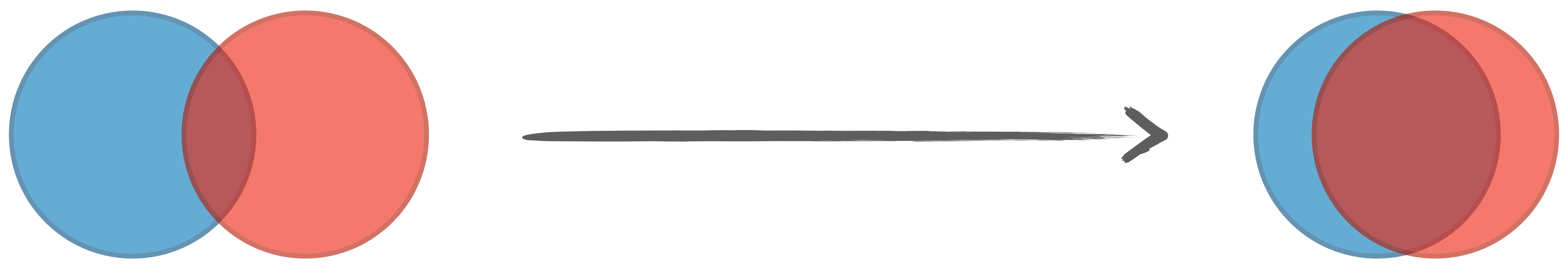


- ϒ(1S) production decreasing from a midrapidity plateau down to the forward ALICE acceptance
- no significant rapidity dependence for ϒ(2S) within sizeable uncertainties

- ϒ signal **measurable down to p_T = 0 GeV/c**
- p_T spectrum at forward rapidity softer than at midrapidity (as in other systems)

Nuclear modification factors





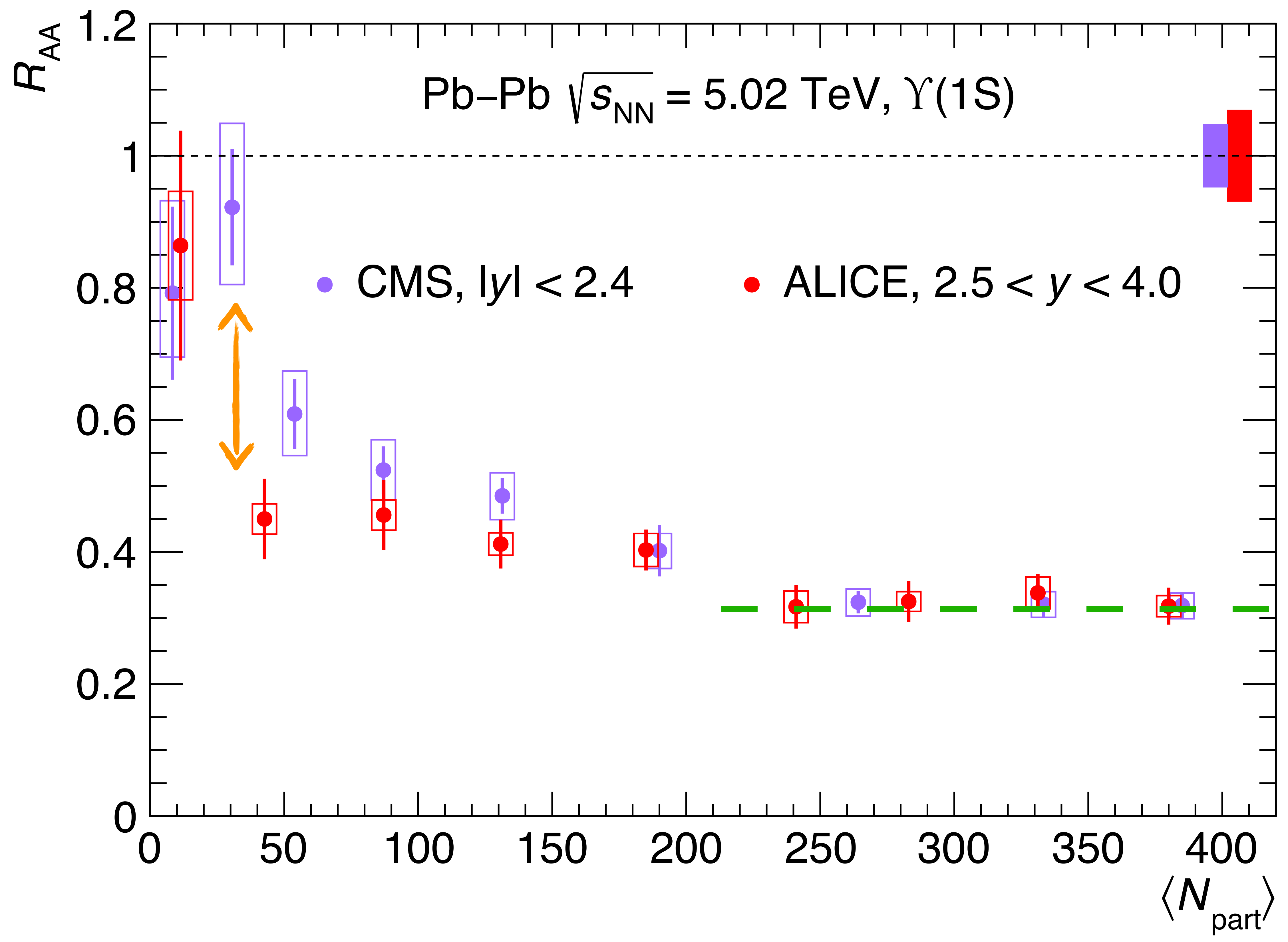
Strong suppression of ϒ production increasing with the centrality

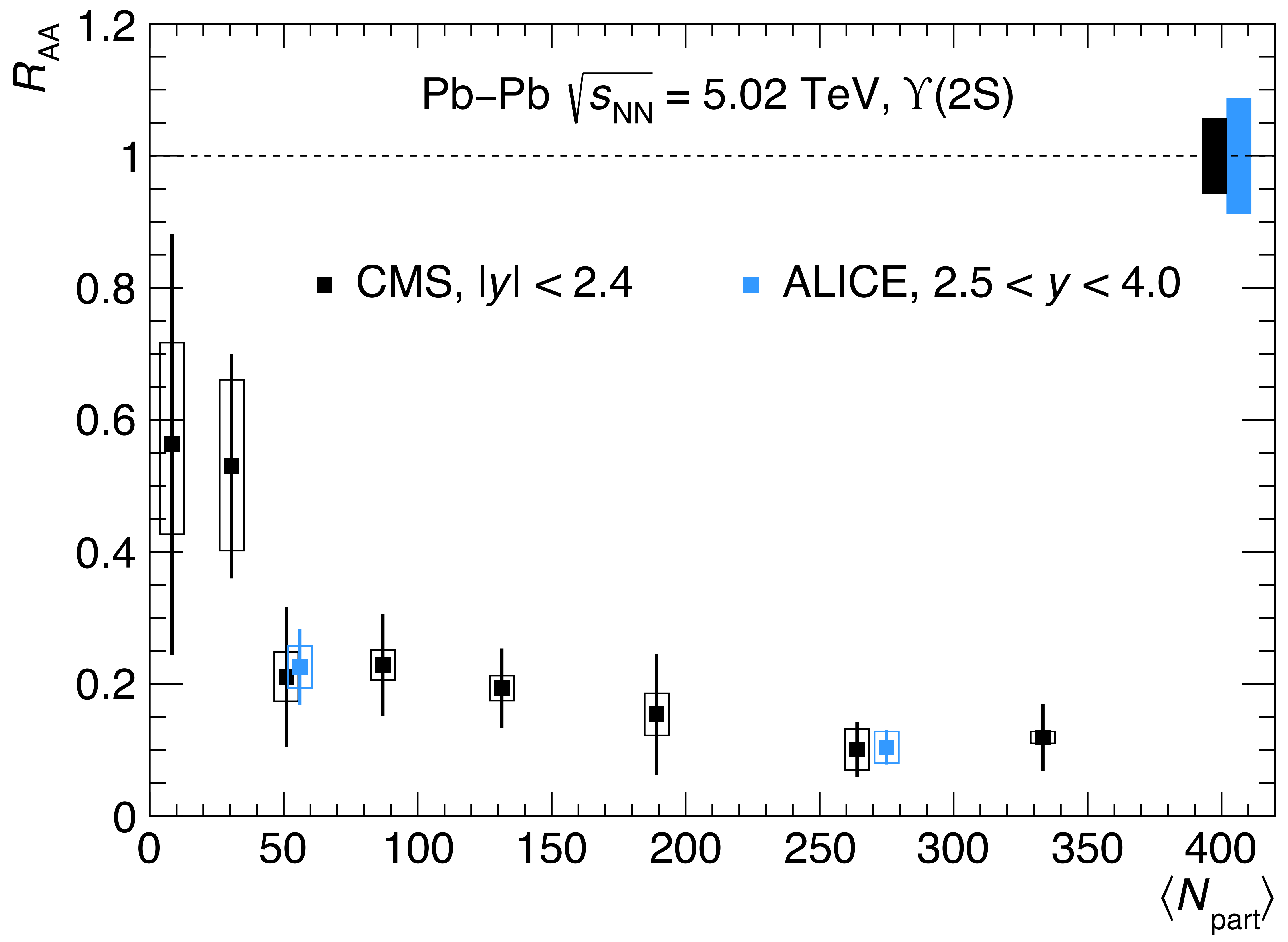
- down to a plateau of R_{AA}~0.3 for ϒ(1S)
  ☛ is the direct contribution even affected?
- ϒ(2S) production suppressed by a factor 10 for the most central collisions
- no evidence for ϒ(3S) production to date (R_{AA} < 0.096 at 95% CL)

☛ ordering following the *sequential melting* picture

Consistency between experiments

- **similar observations** within the forward rapidity ALICE acceptance
- intriguing plateau for the 0–30% most central collisions
- start of deviation for more peripheral events? room for improvement though

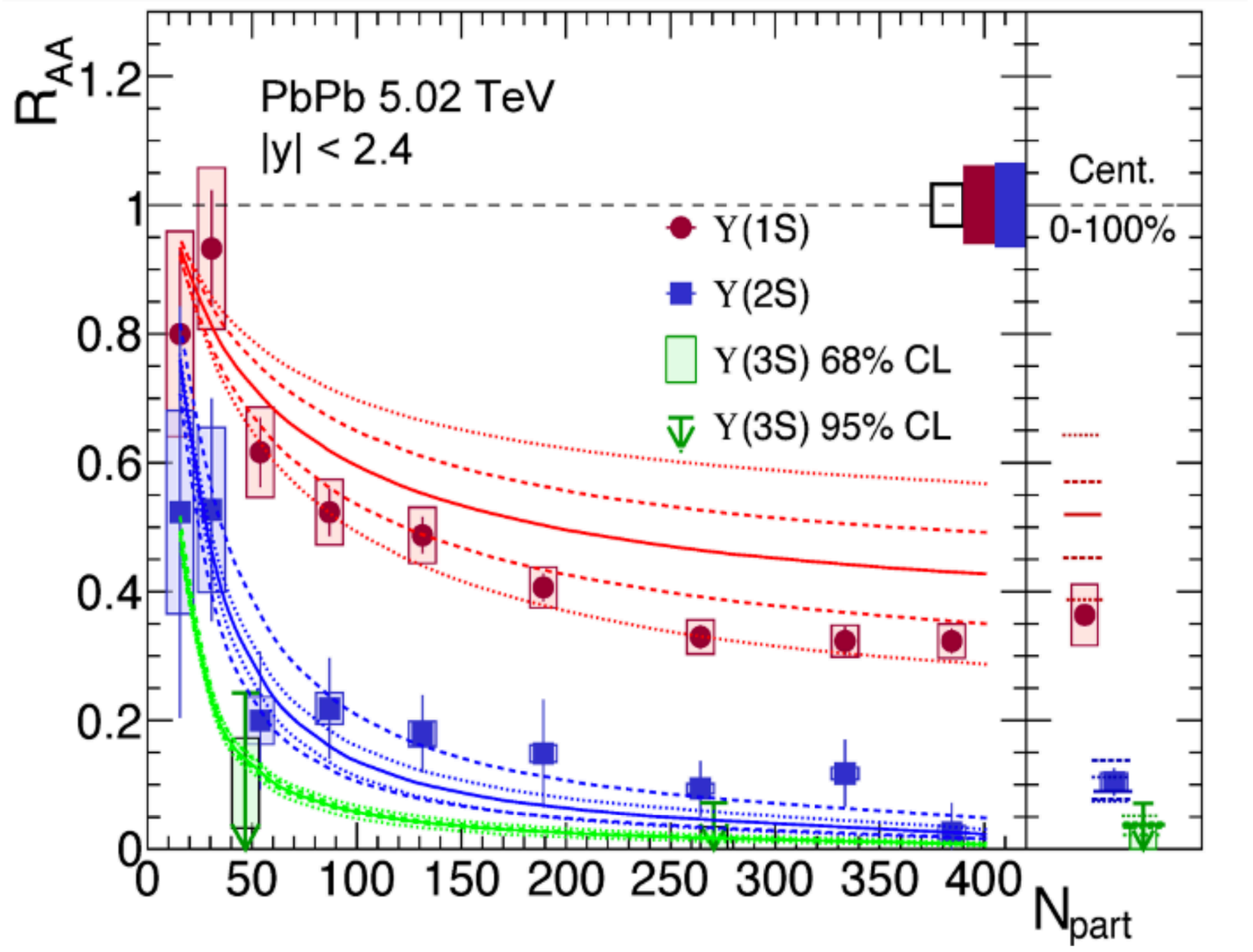




Comparison with phenomenology

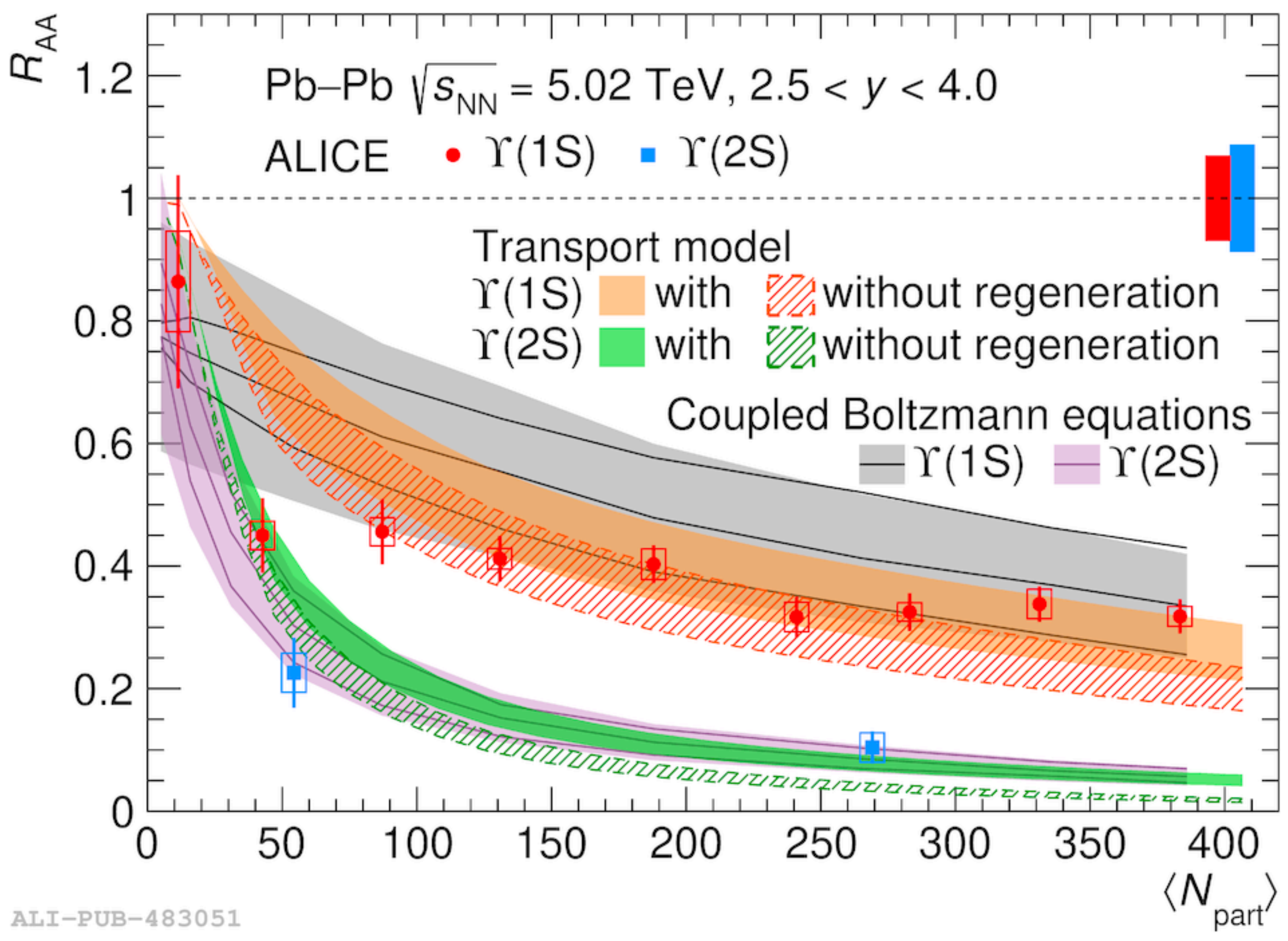
Many available calculations with different approaches and ingredients (detailed in backup)

☛ globally reproducing the experimental trends but within **large uncertainties**



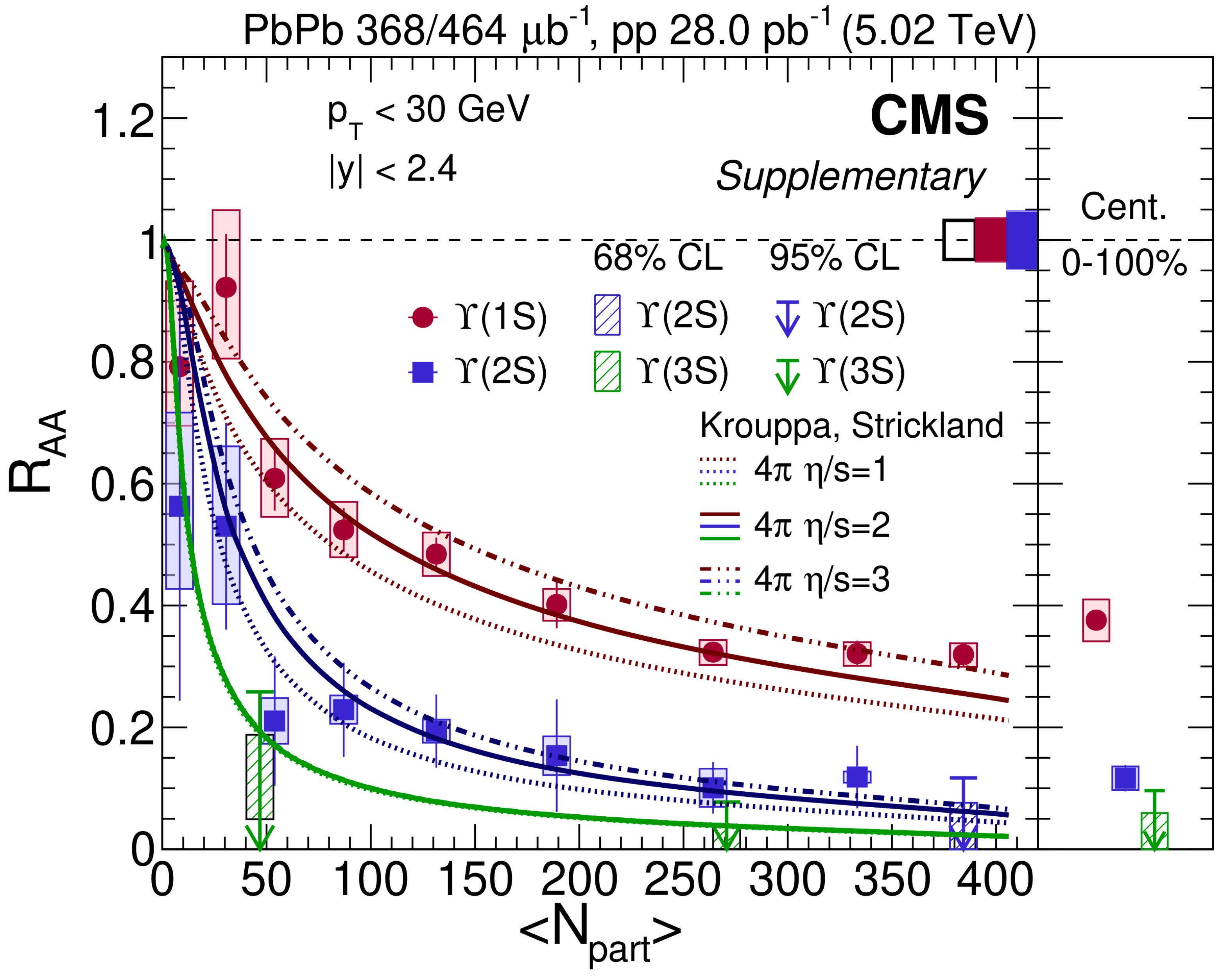
Break-up by **comover interaction**

+ nCTEQ15 parametrisation



Transport descriptions

in-medium dissociation and recombination + nPDF sets

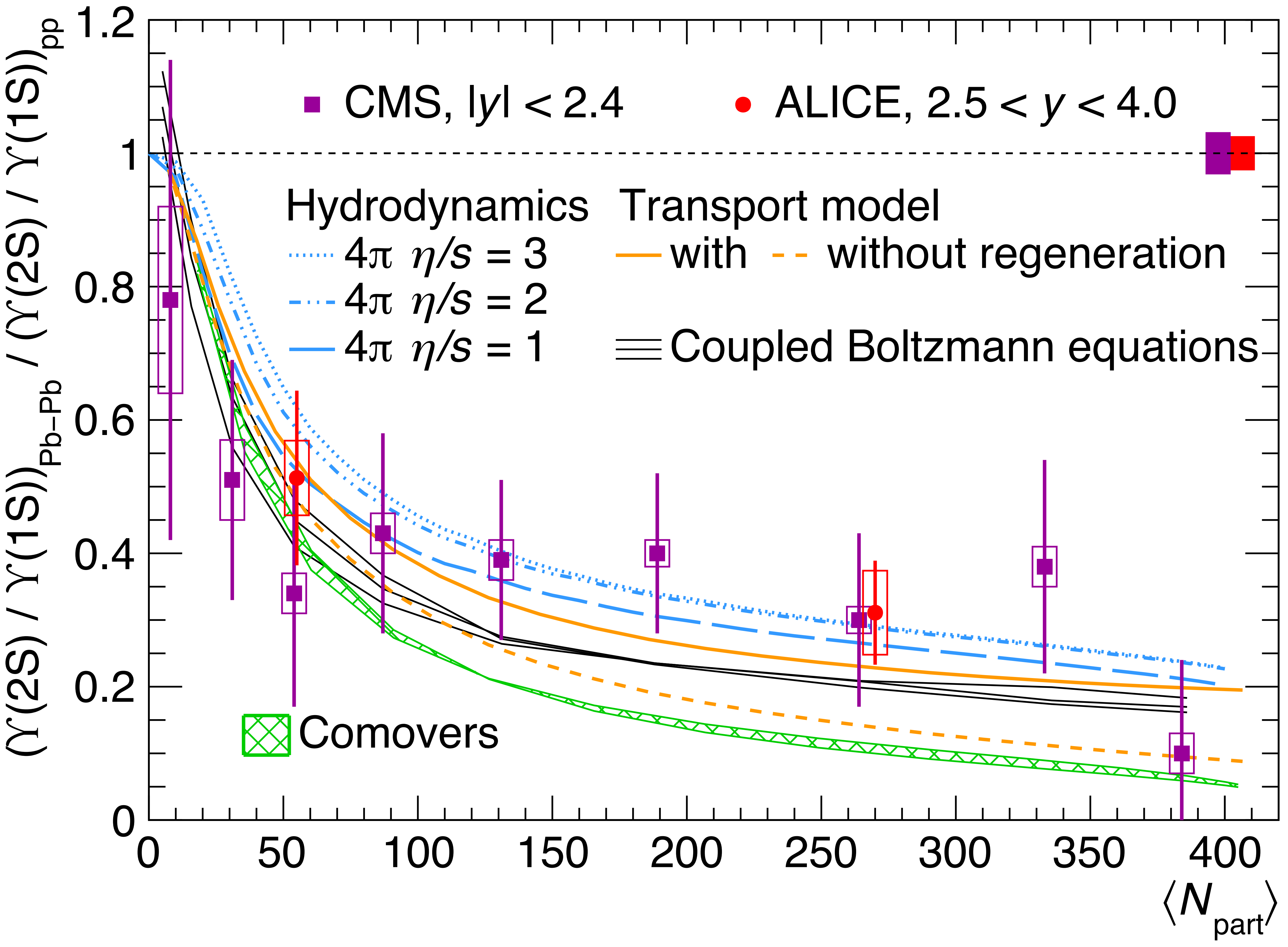


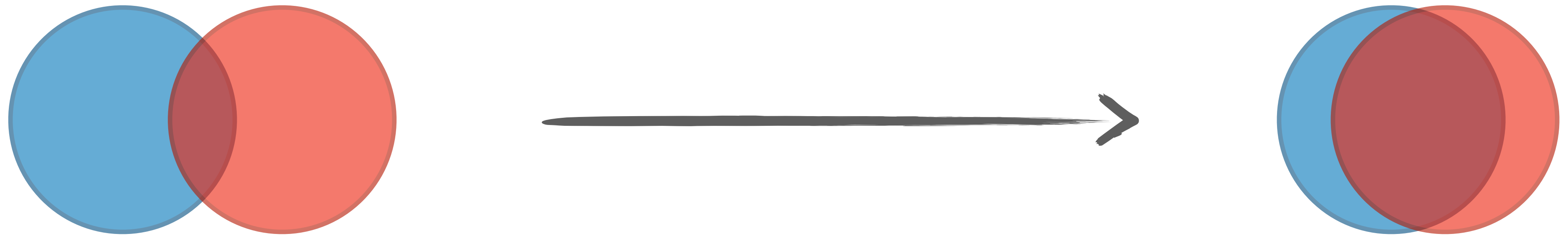
Hydrodynamic framework

modification of the heavy-quark potential

Υ(2S)-to-Υ(1S) double yield ratio

Appropriate observable to confront the different approaches thanks to the **cancellation of effects and uncertainties common to both states**



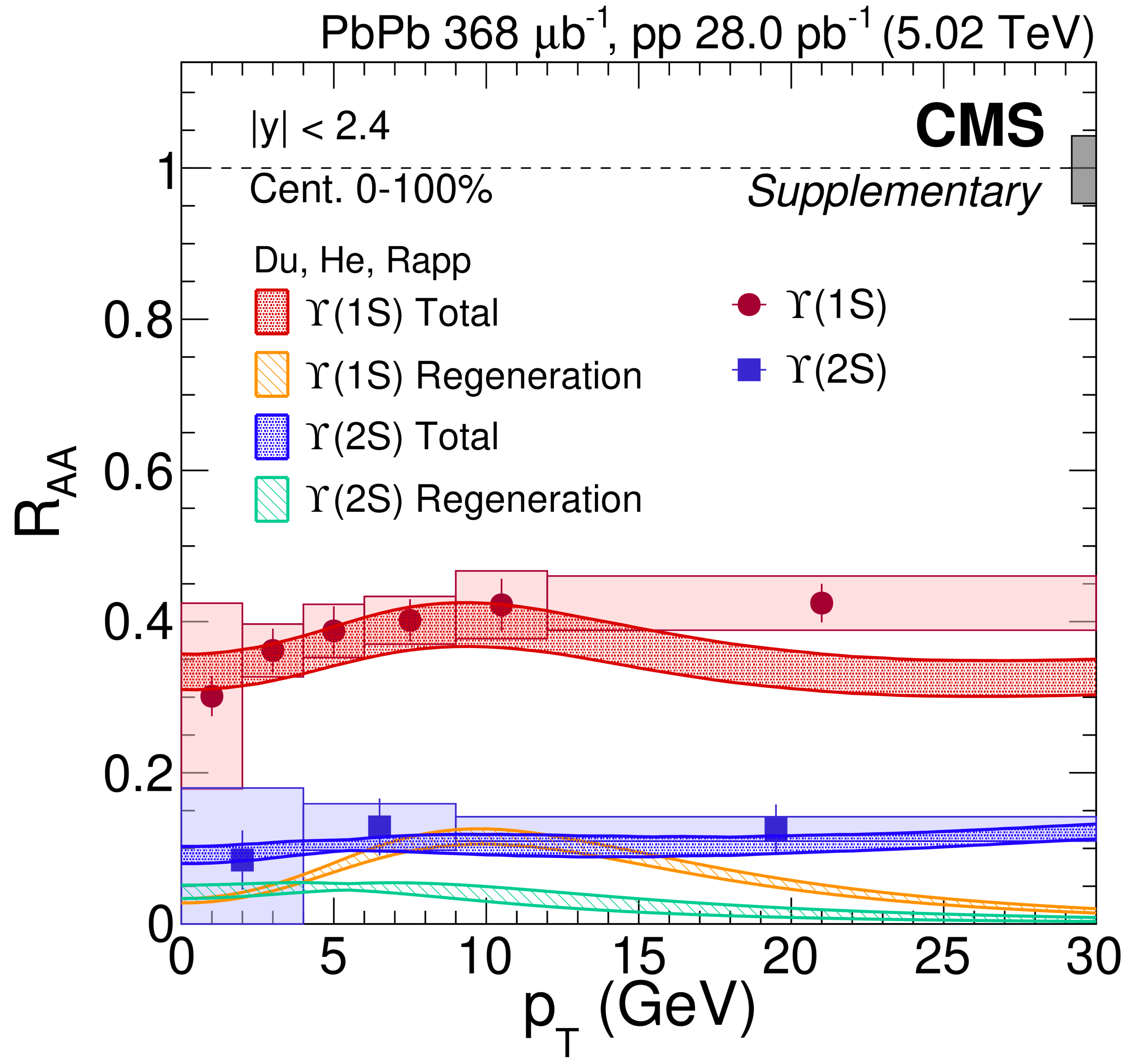


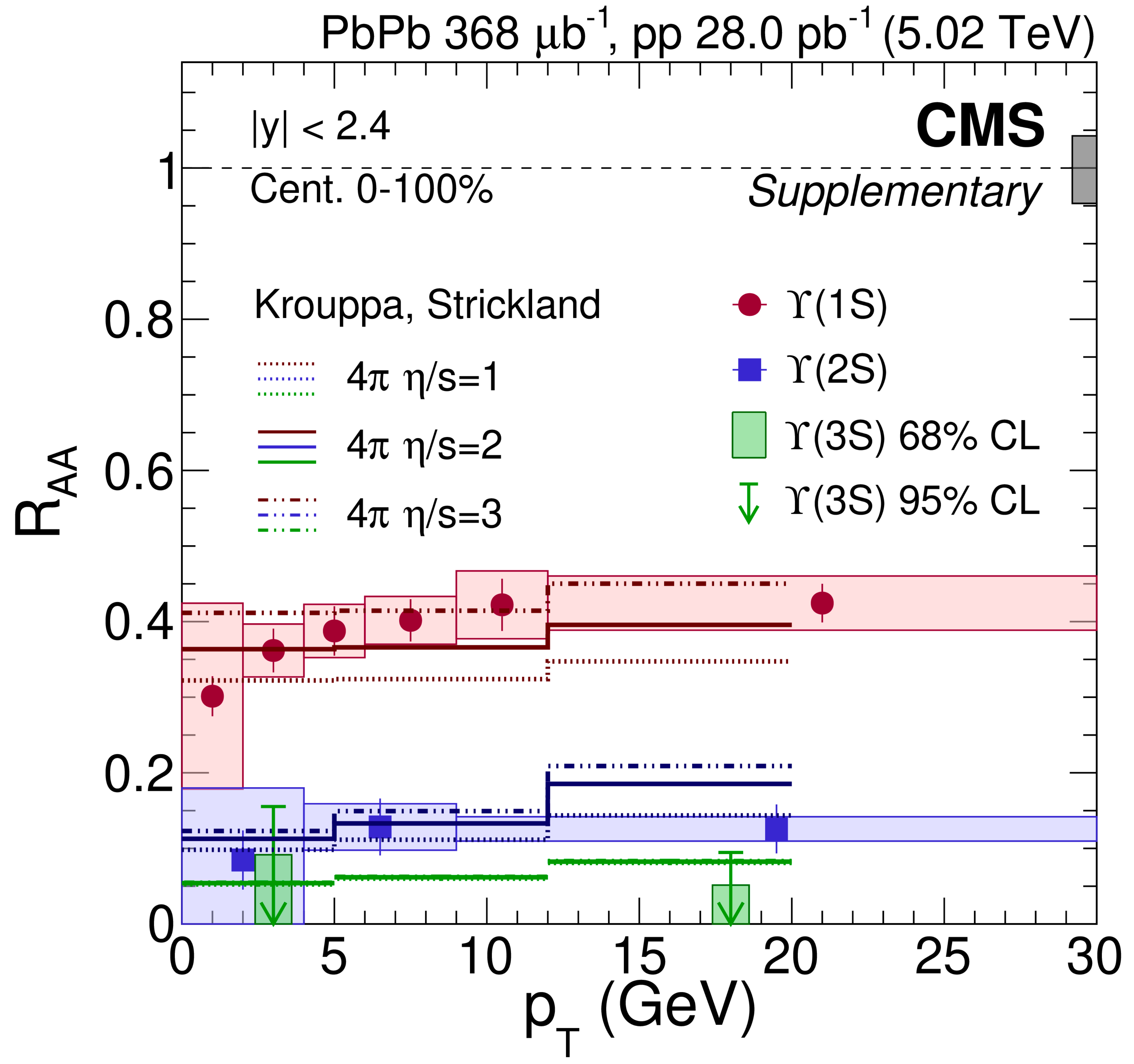
- qualitatively described by the calculations
- in tension with comovers for central events (2σ with ALICE measurement)
- favours the presence of a regeneration component for the transport descriptions…
- … but the hydrodynamic calculations do not need it to describe the data

☛ ***model discriminator* with more precise measurements** (statistically limited!!!)

Transverse momentum dependence

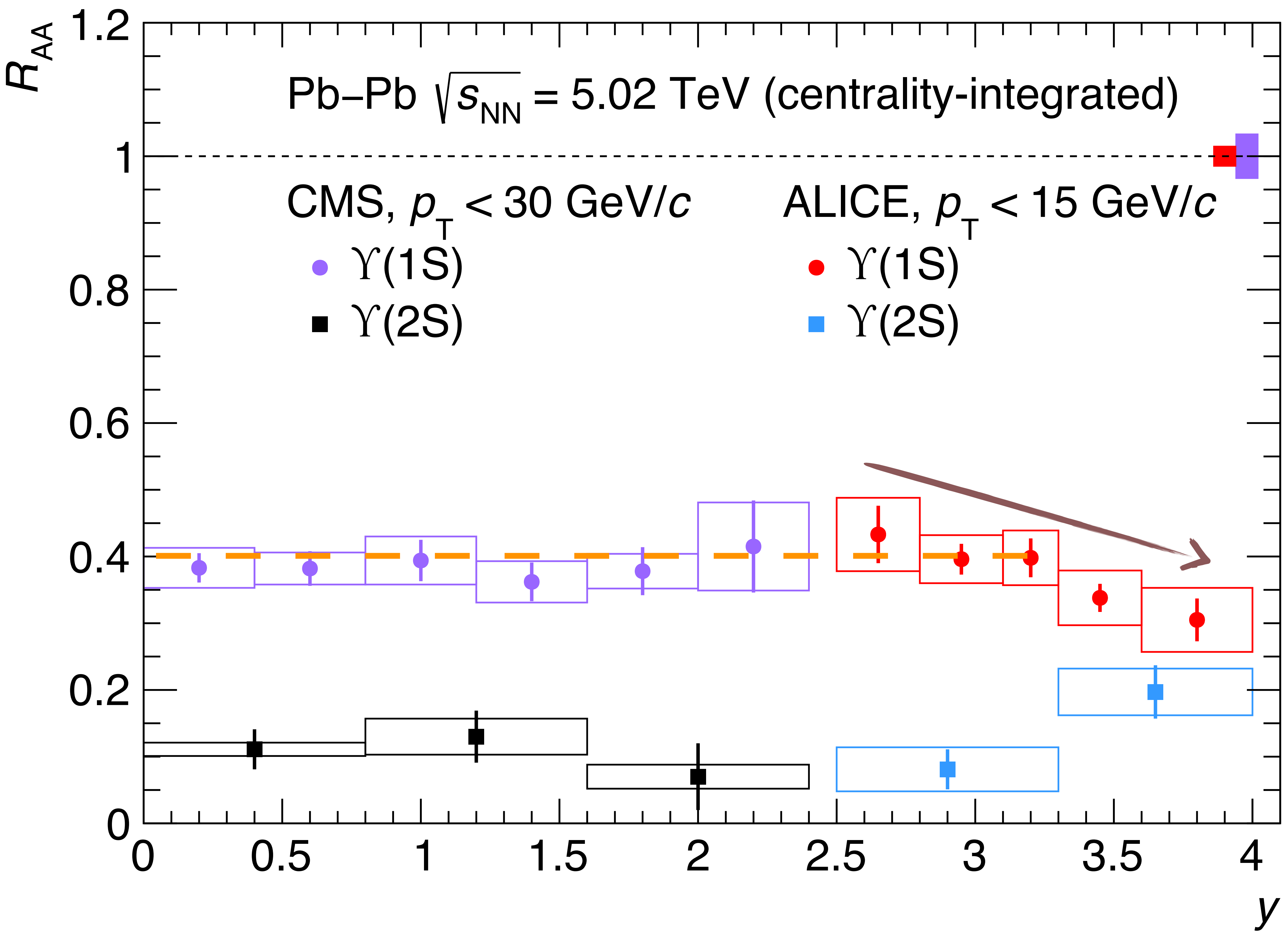
- **flat R_{AA} up to p_T = 30 GeV/c**
  - in line with calculations from transport (left) and hydrodynamic (right) models





Rapidity-differential measurements

Continuous suppression observable **over 4 units of rapidity** thanks to CMS and ALICE acceptance



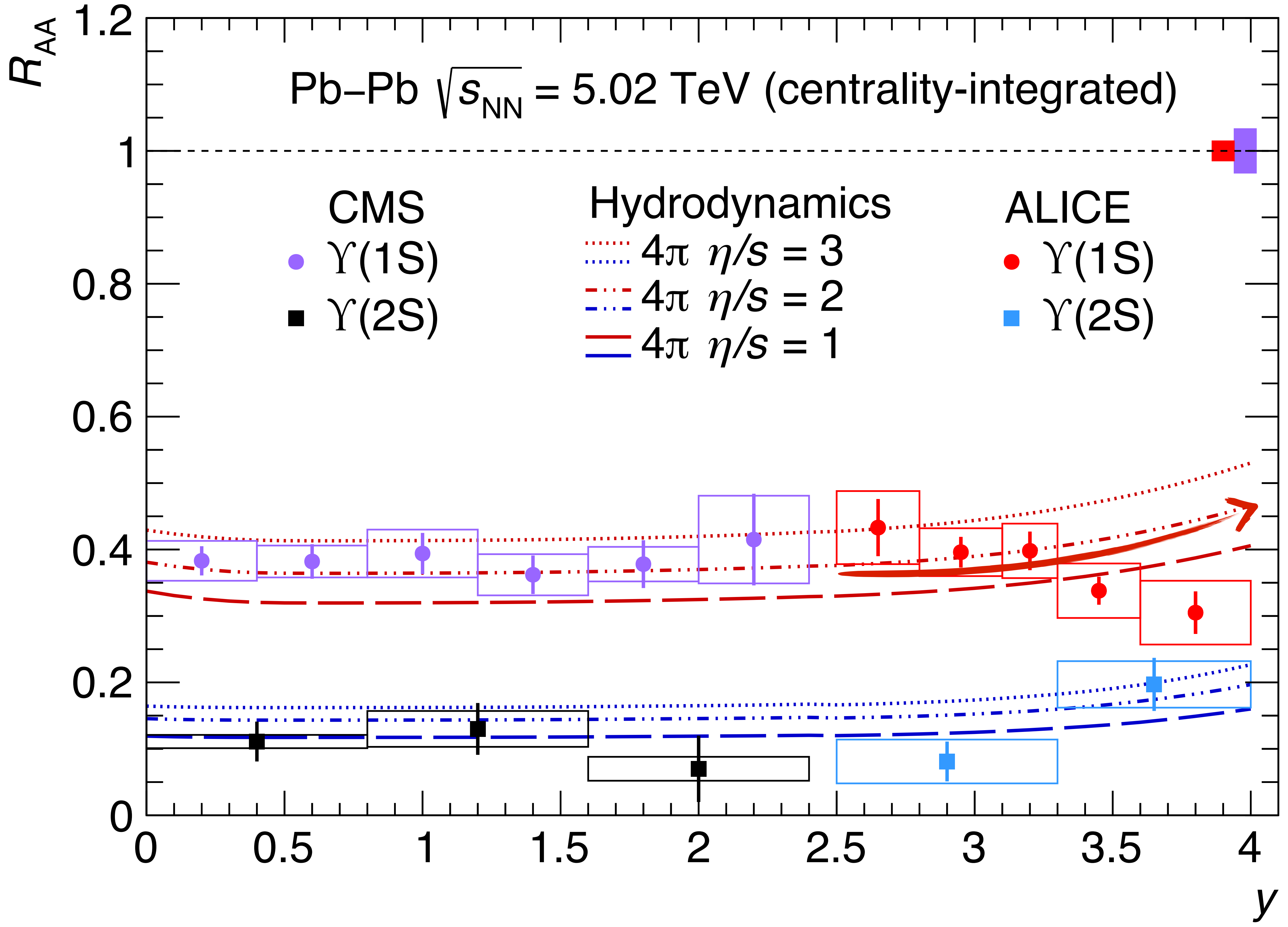
- ϒ(1S) nuclear modification factor
  - plateau ~0.4 from midrapidity to $y \approx 3.3$
  - dropping down to ~0.3 for the most forward rapidity interval
    ☛ 2σ for a decreasing trend (⚠️ correlations)
  - expected behaviour?
- constant R_{AA} for ϒ(2S) within large uncertainties

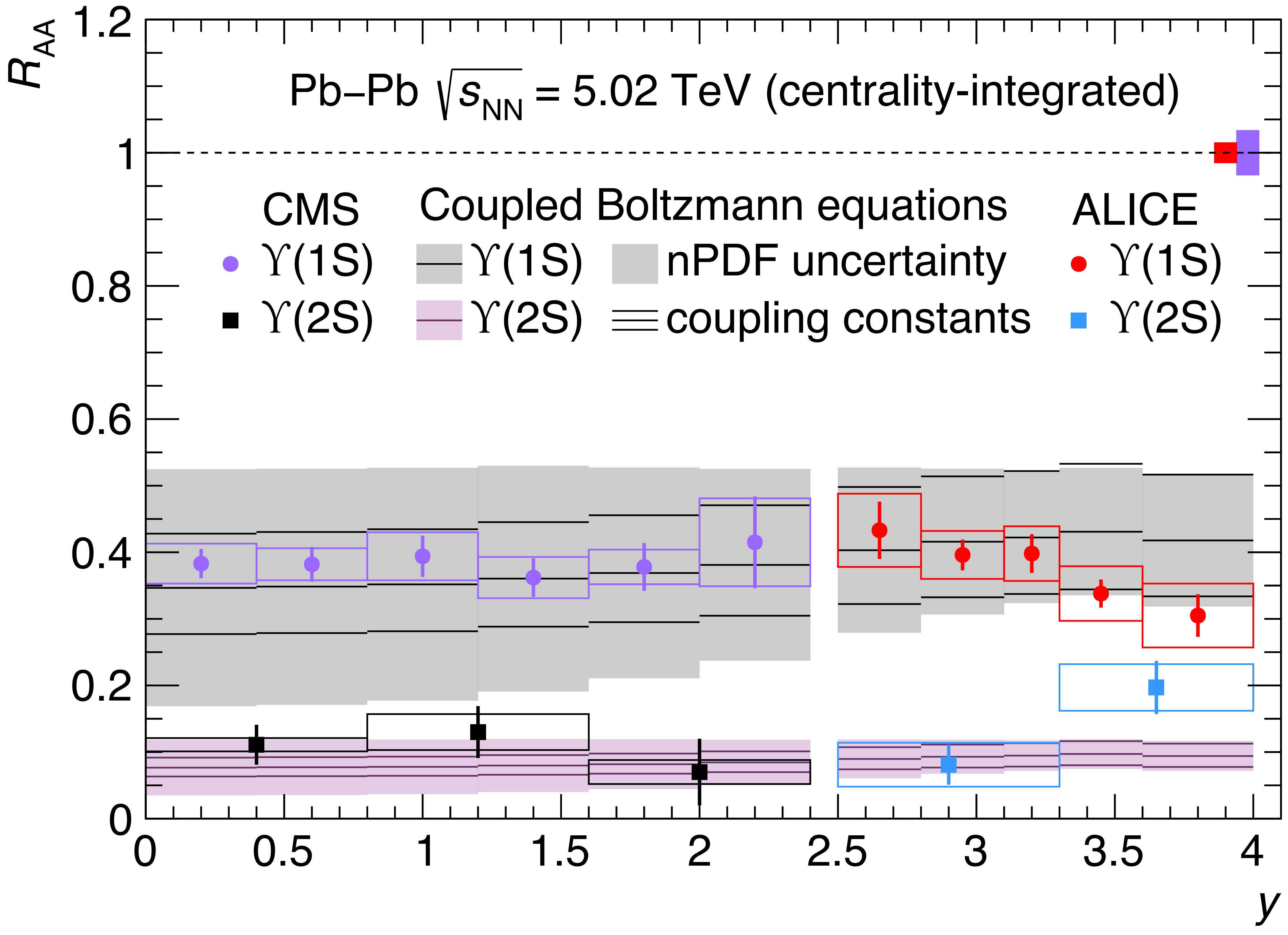
Rapidity-dependent suppression?

Experimental decreasing trend **not captured by available models ☛ missing mechanism?**

Hydrodynamic calculations = initial temperature profile of the simulated medium ☛ **weaker suppression** going forward

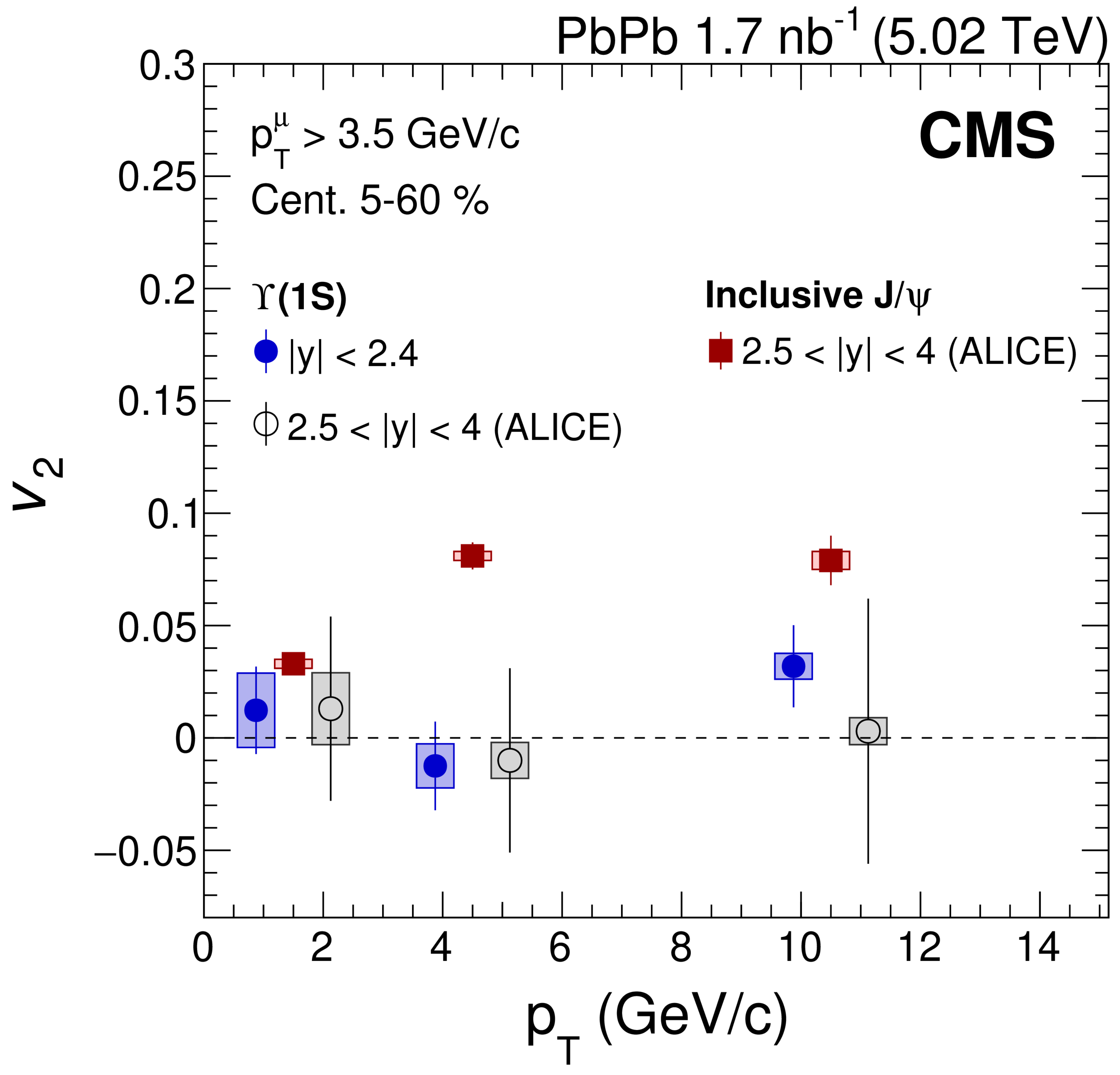
Coupled Boltzmann equations = EPPS16 parametrisation **cannot describe both CMS and ALICE data consistently**

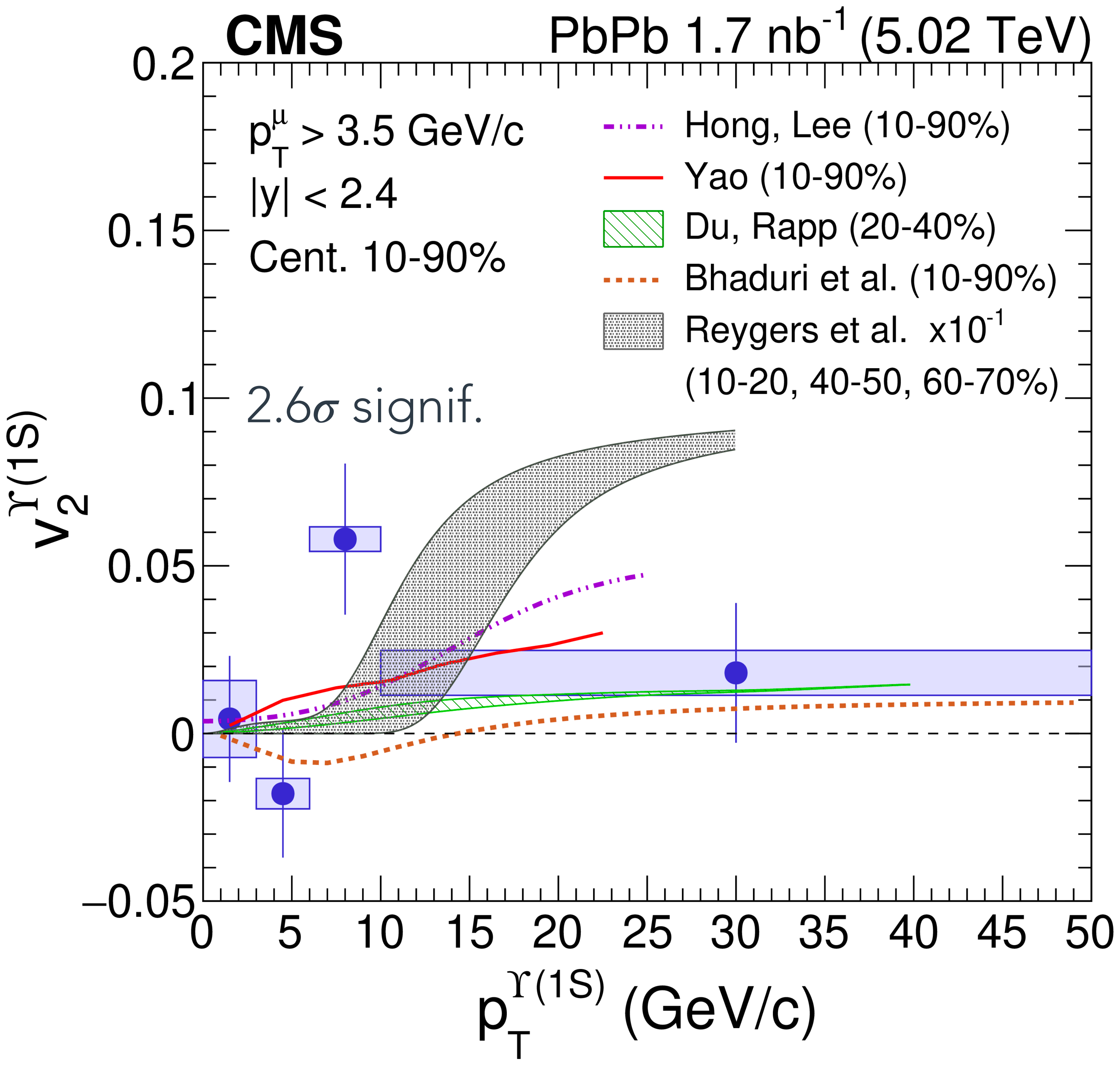




Here comes a new challenger!

First measurement of ϒ(1S) elliptic flow by ALICE [PRL 123 (2019) 192301] and CMS [PLB 819 (2021) 136385]





- v_2 coefficient **consistent with 0 for all p_T**
- unlike J/ψ ☛ bottom / charm quark collectivity
- also consistent with many approaches
- non-zero signal expected at high p_T

Wrap-up

Bottomonium production in heavy-ion collisions is a priviliged observable to study and constrain the *microscopic phenomena* in the quark–gluon plasma (review: Physics Reports 858 (2020) 1)

- **detailed measurement of ϒ(1S) production in PbPb collisions at the LHC**
  - strong suppression increasing with centrality, reproduced by various calculations
  - no significant variation as a function of transverse momentum
  - CMS ⊕ ALICE data contraining the rapidity dependence

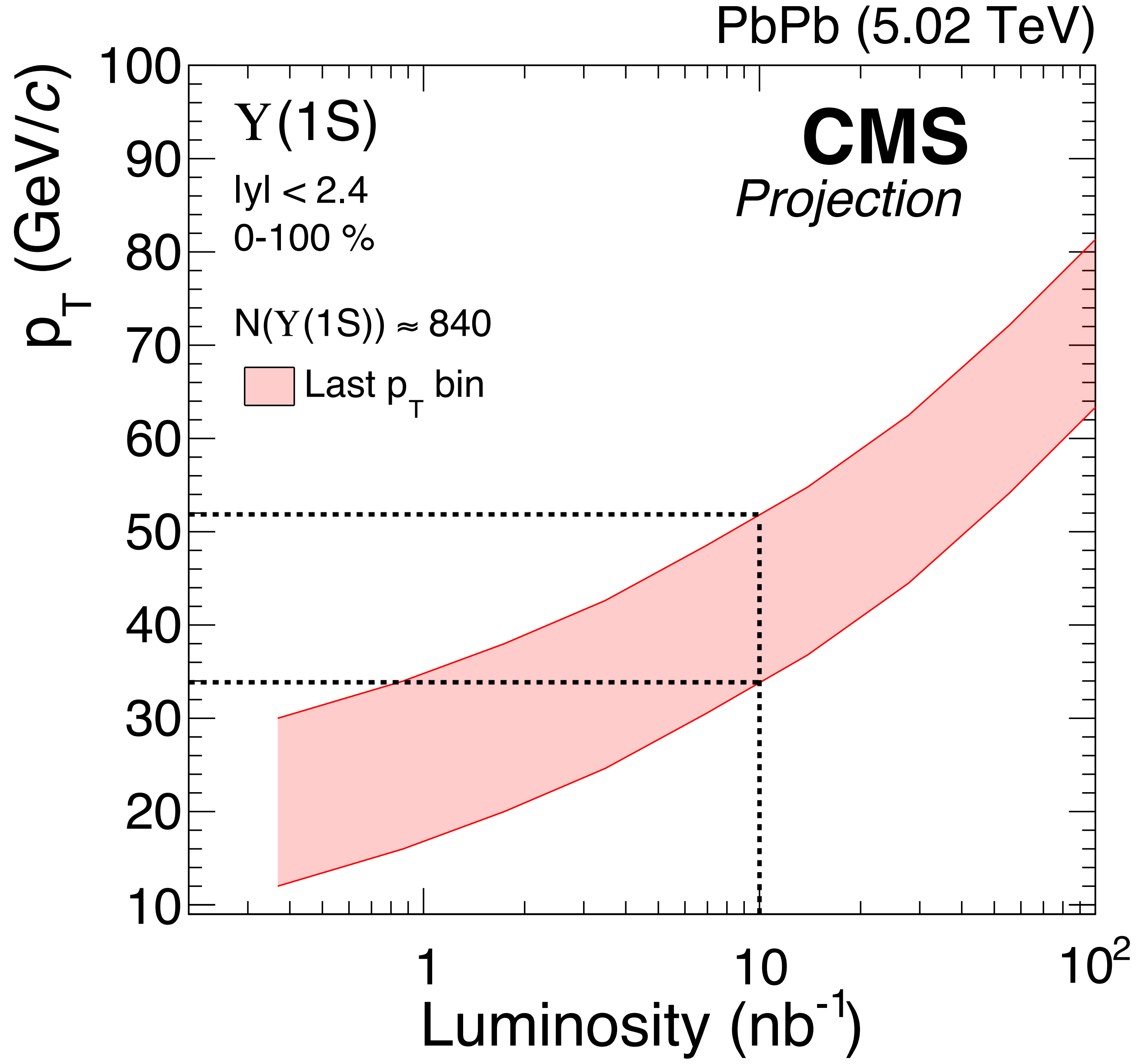
    ☛ *hint* for a stronger suppression towards forward rapidities opposite to model expectations

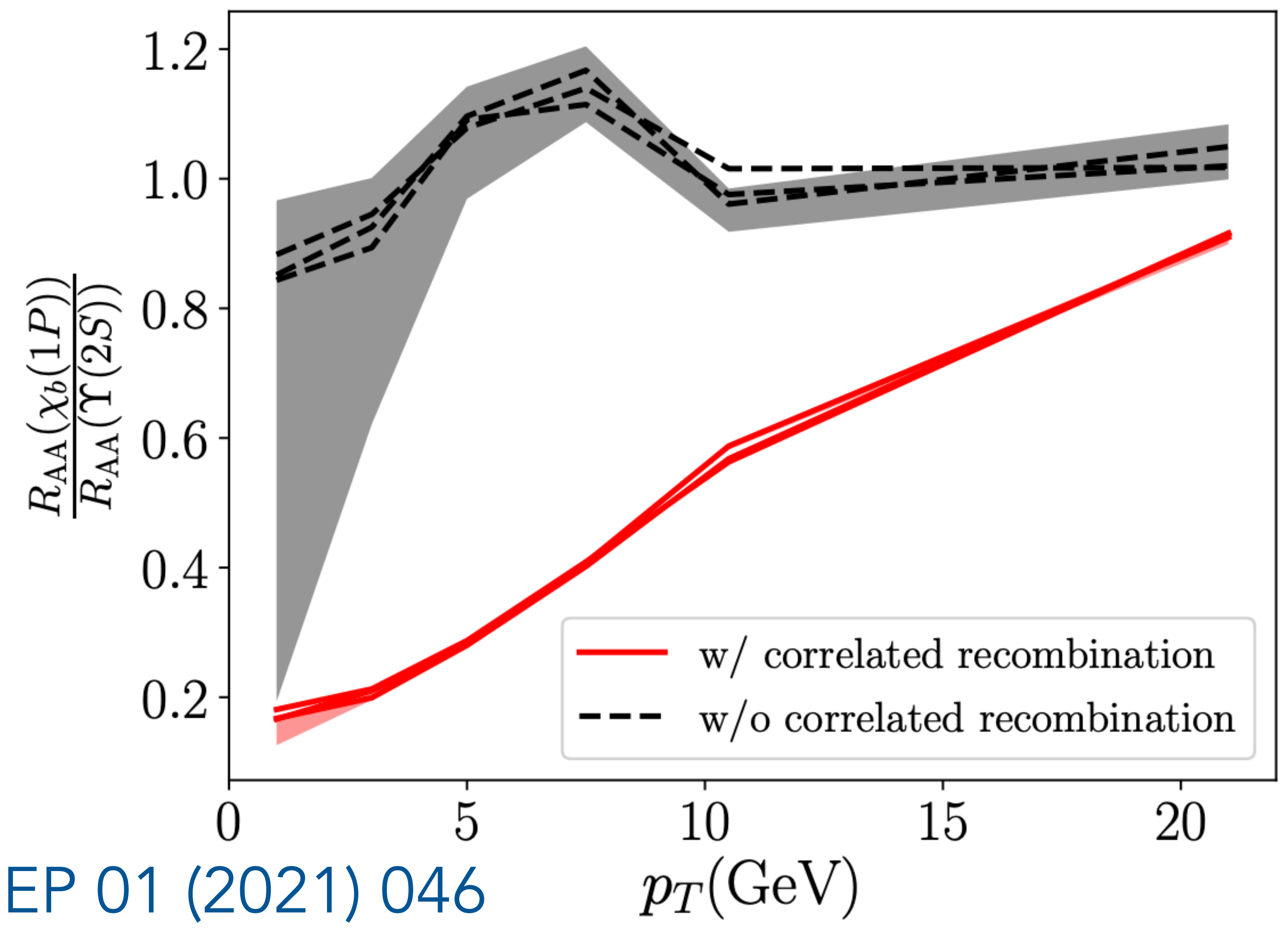
- **stronger suppression for the excited states**
  - data interpretation statistically limited
  - excited-to-ground state double yield ratio as a *model discriminator*

    ☛ regeneration as the dominant source of ϒ(2S) production? very model dependent…

Perspectives… with CMS

- **Complete analysis of Run 2 data** ($L_{int} \approx 1.7$ nb^{-1})
  - (more) precise measurement of ϒ(2S) suppression
  - apparatus better suited for p_T-differential measurements
- **Prospects for Run 3 & 4** [CERN Yellow Report 7 (2019) 1159]
  - projected luminosity $L_{int} \approx 10$ nb^{-1}
    ☛ extension of the p_T reach up to 50 GeV/c
    ☛ observation of ϒ(3S) production?
  - new opportunities with the Phase 2 upgrade?
- Other observables to further constrain the models
  - flow coefficients, polarisation and combination
  - **dream measurement: χ_b production**
    ☛ test of the underlying recombination mechanism

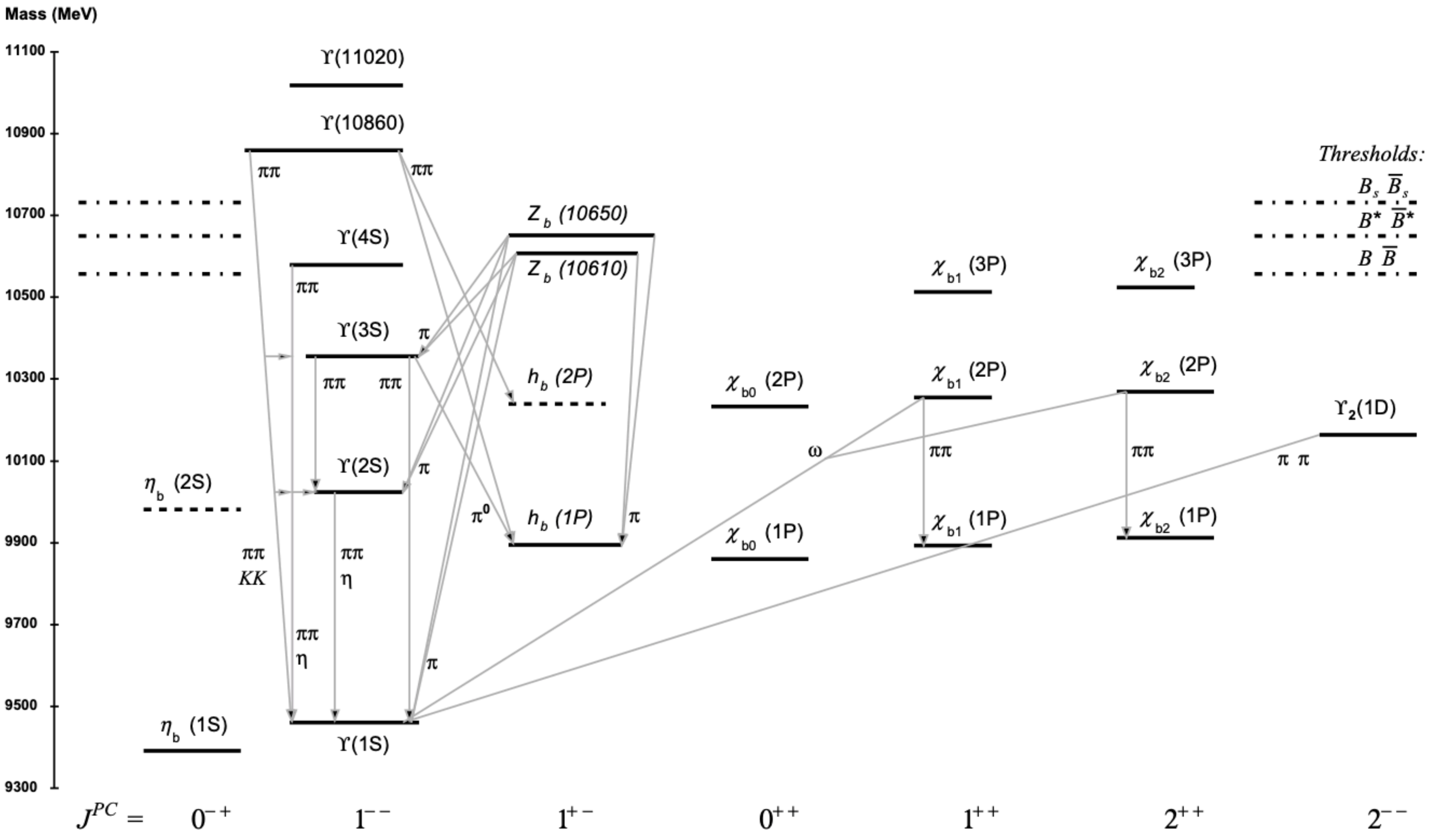




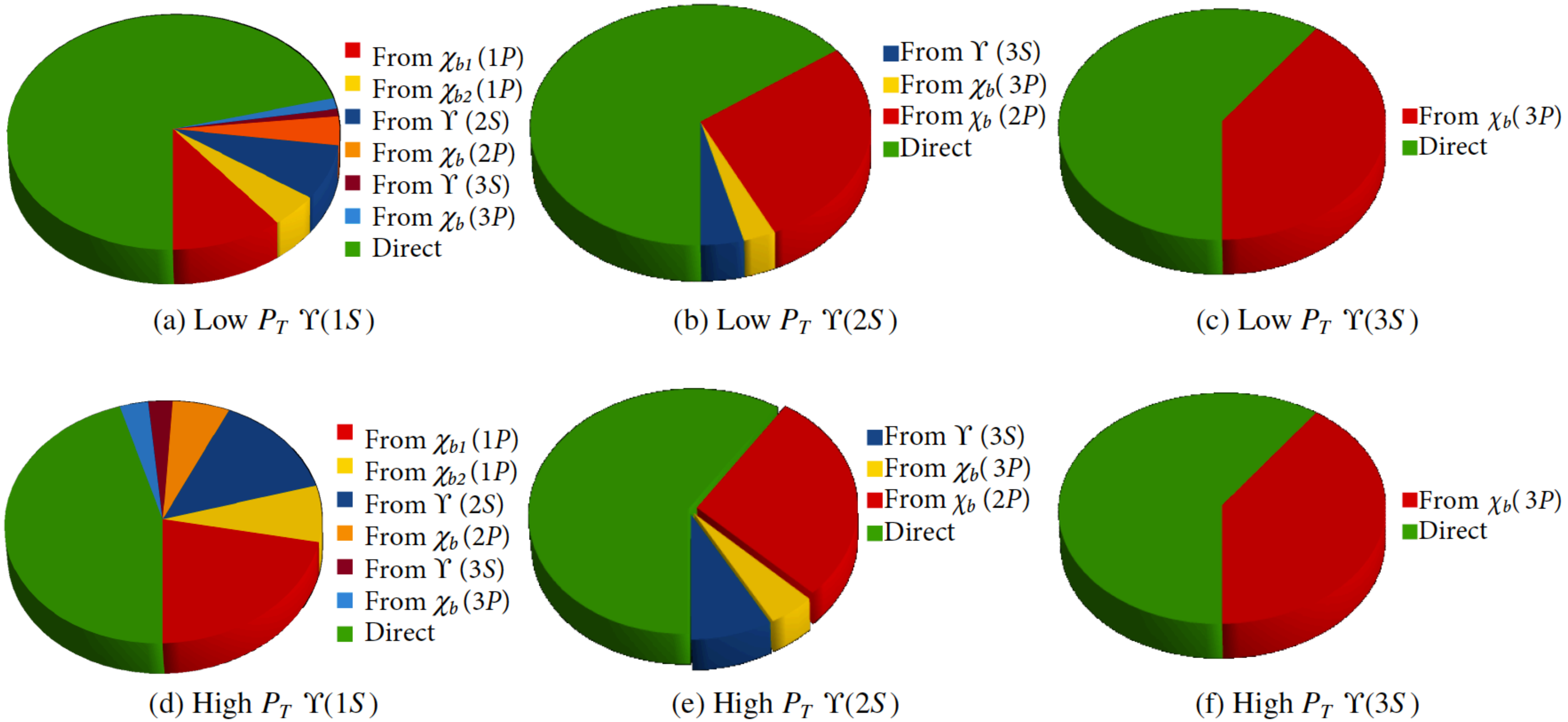
JHEP 01 (2021) 046

Thank you for your attention!

Bottomonium spectroscopic scheme



Feed-down contributions



Compilation from the review Physics Reports 889 (2020) 1

	$F^{\text{direct}}_{\Upsilon(1S)}$	$F^{\chi_{b1}(1P)}_{\Upsilon(1S)}$	$F^{\chi_{b2}(1P)}_{\Upsilon(1S)}$	$F^{\Upsilon(2S)}_{\Upsilon(1S)}$	$F^{\chi_b(2P)}_{\Upsilon(1S)}$	$F^{\Upsilon(3S)}_{\Upsilon(1S)}$	$F^{\chi_b(3P)}_{\Upsilon(1S)}$
“low” P_T	71 ± 5	10.5 ± 1.6	4.5 ± 0.8	7.5 ± 0.5	4 ± 1	1 ± 0.5	1.5 ± 0.5
“high” P_T	45.5 ± 8.5	21.5 ± 2.7	7.5 ± 1.2	14 ± 2	6 ± 2	2.5 ± 0.5	3 ± 1

Phenomenological models

nuclear effects / nPDF
regeneration term

Semi-classical calculations based on transport or rate equations

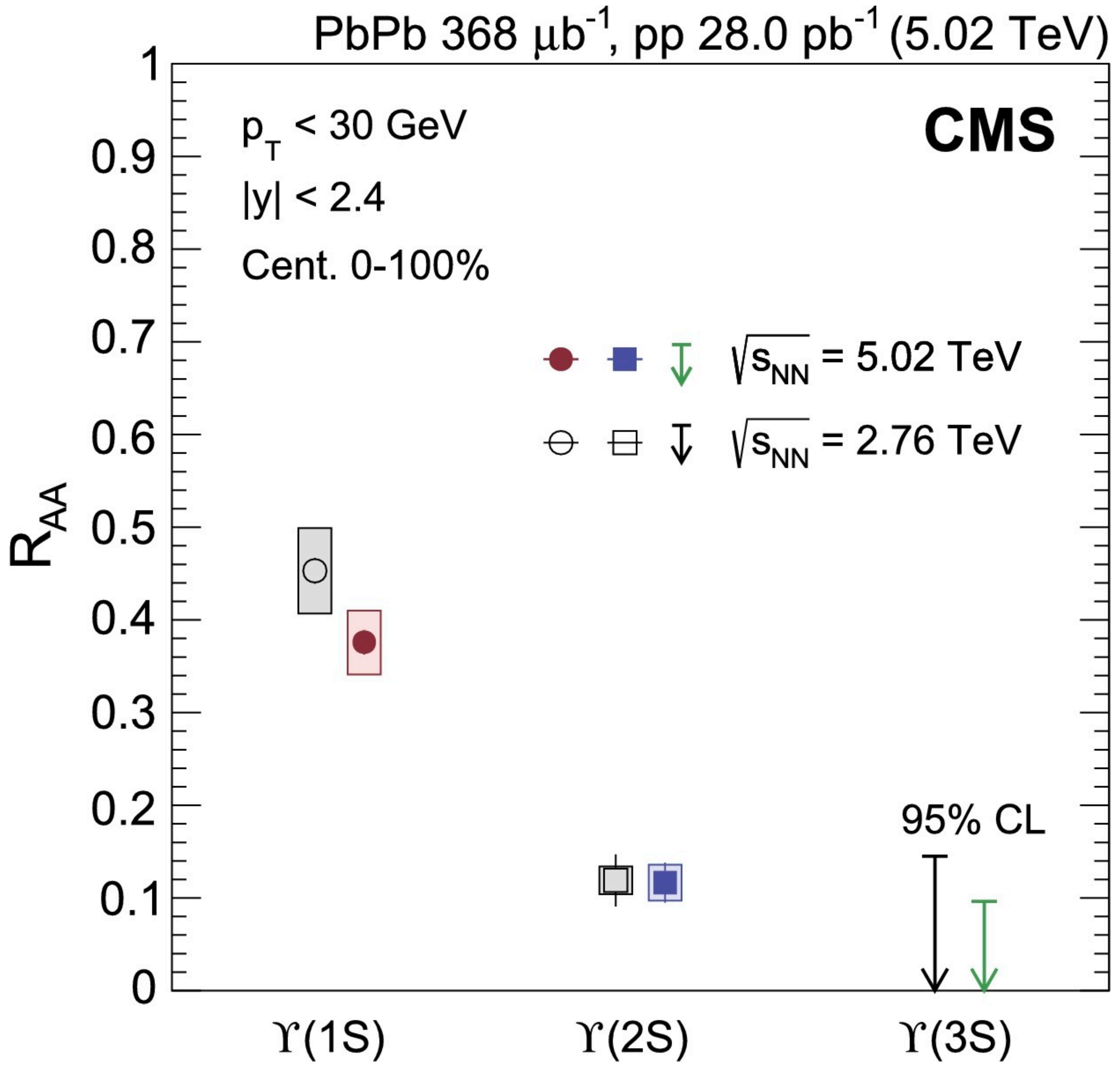
- **Comover interaction model** [JHEP 10 (2018) 094]
  Final-state suppression by interaction with *comoving* particles + nCTEQ15 parametrisation

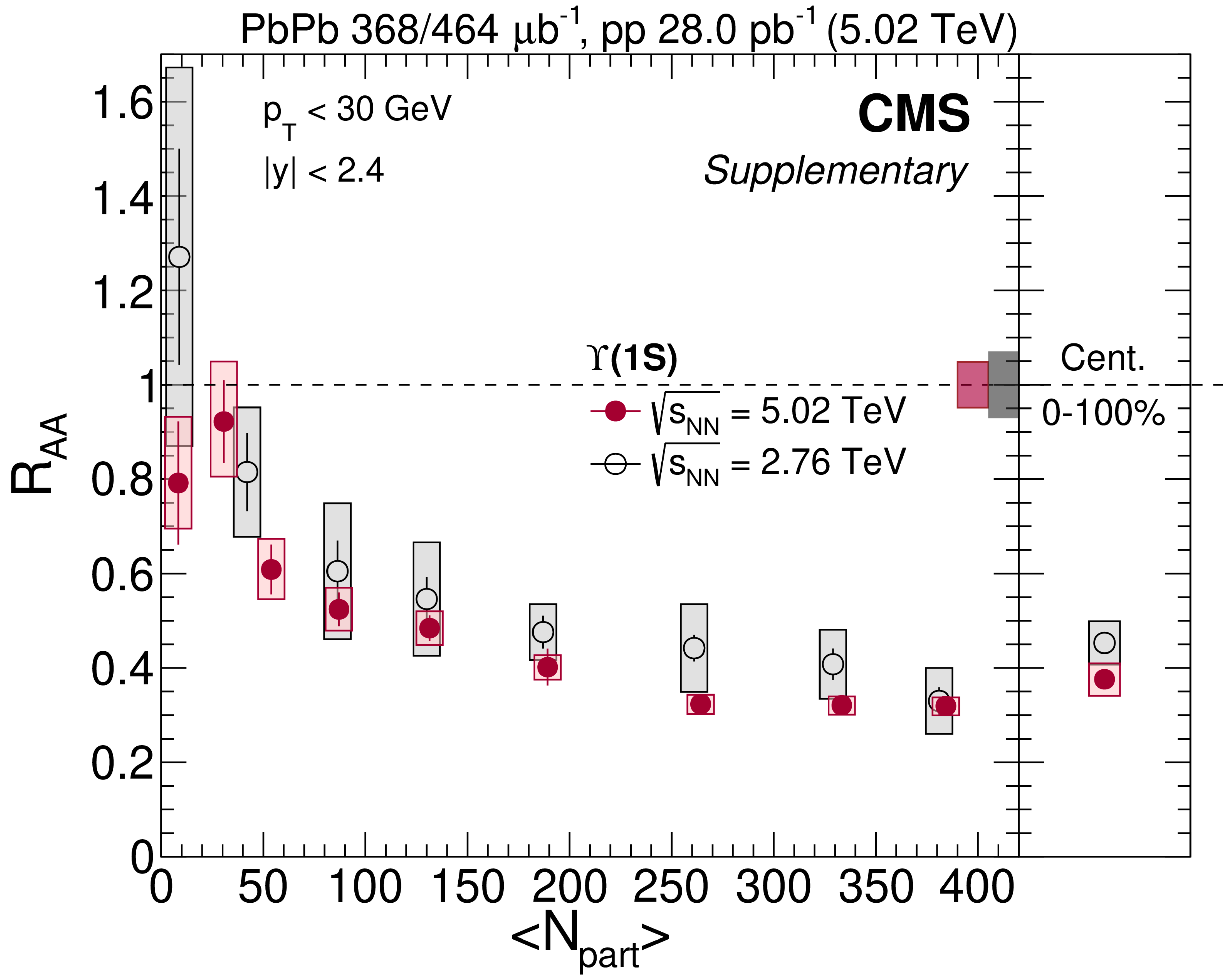
- **Transport descriptions**: in-medium dissociation and recombination processes
  - « transport model » a.k.a TAMU = isotropic fireball + effective absorbtion [PRC 96 (2017) 054907]
  - « coupled Boltzmann equations » = 2+1d viscous hydrodynamics + EPPS16 parametrisation [JHEP 01 (2021) 046]

- **Hydrodynamic calculations** [Universe 2 (2016) 3]
  Thermal modification of the heavy-quark potential inside a 3+1d anisotropic medium.
  No nPDF parametrisation nor regeneration mechanism.

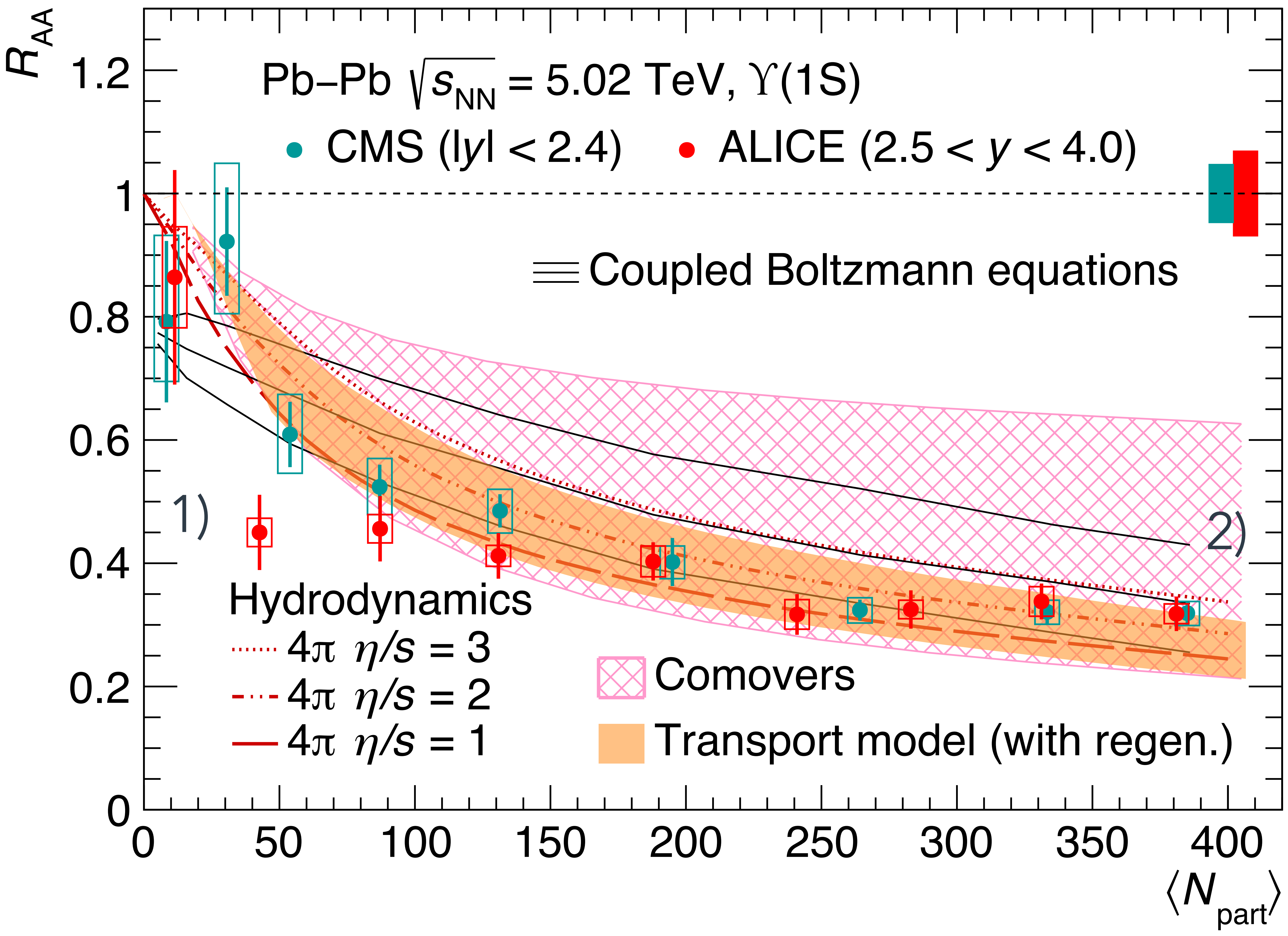
<u>All account for the suppression of feed-down contributions</u> but with different treatments.

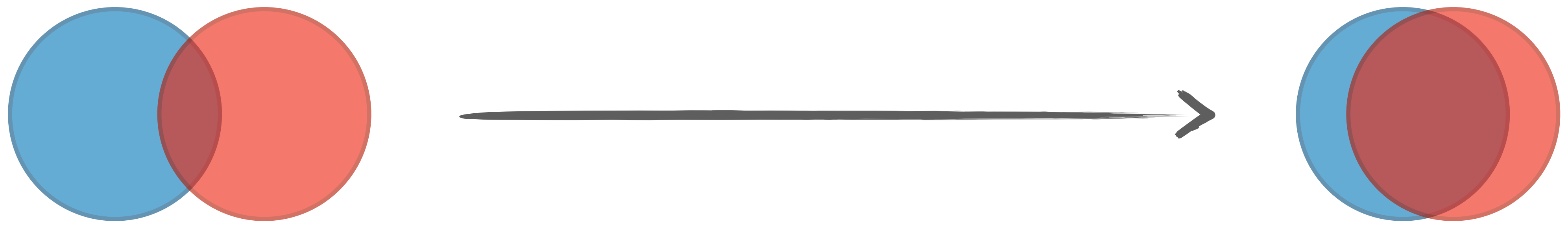
Comparison with Run 1 measurements





Centrality dependence of Υ(1S) suppression

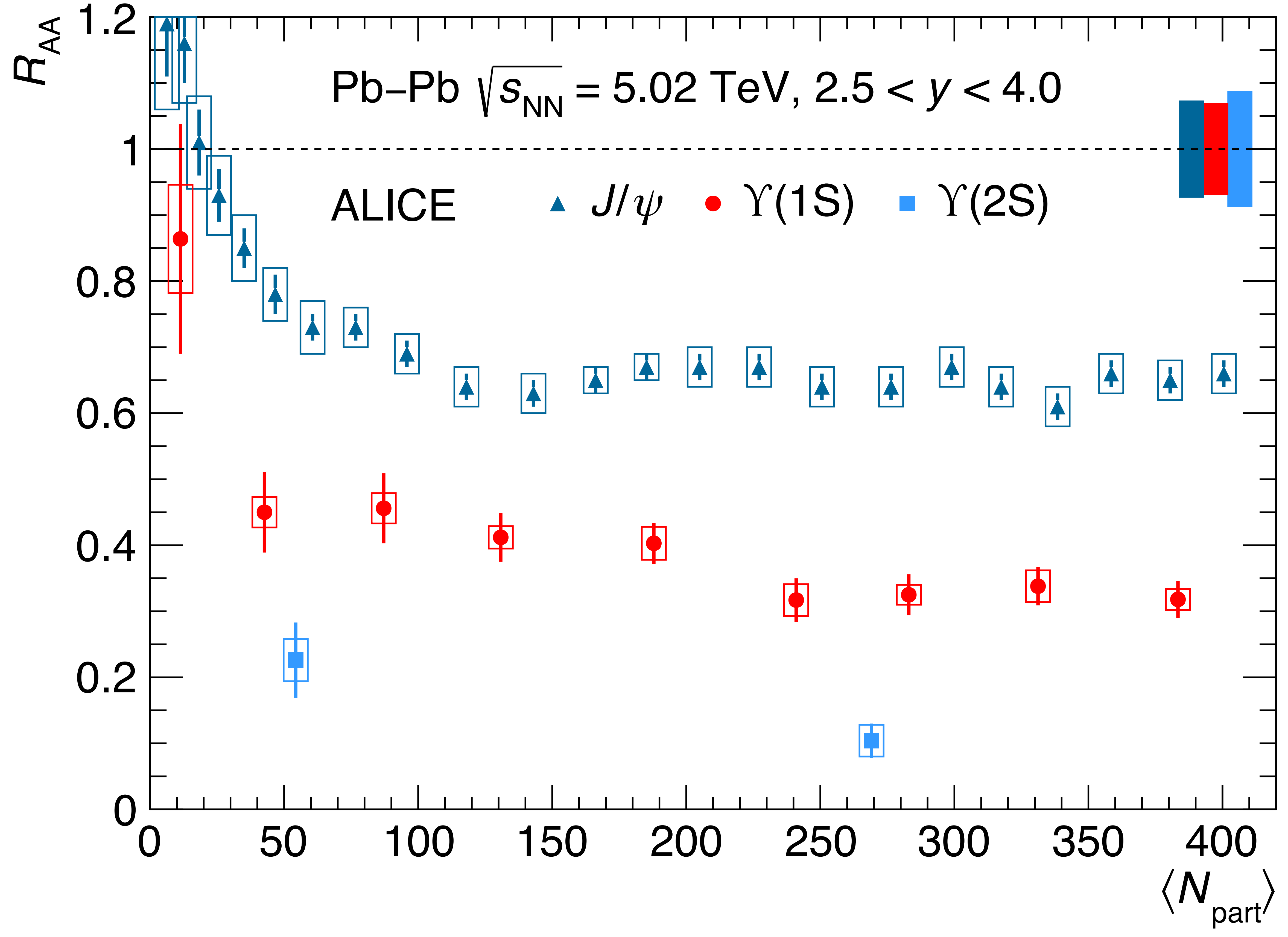


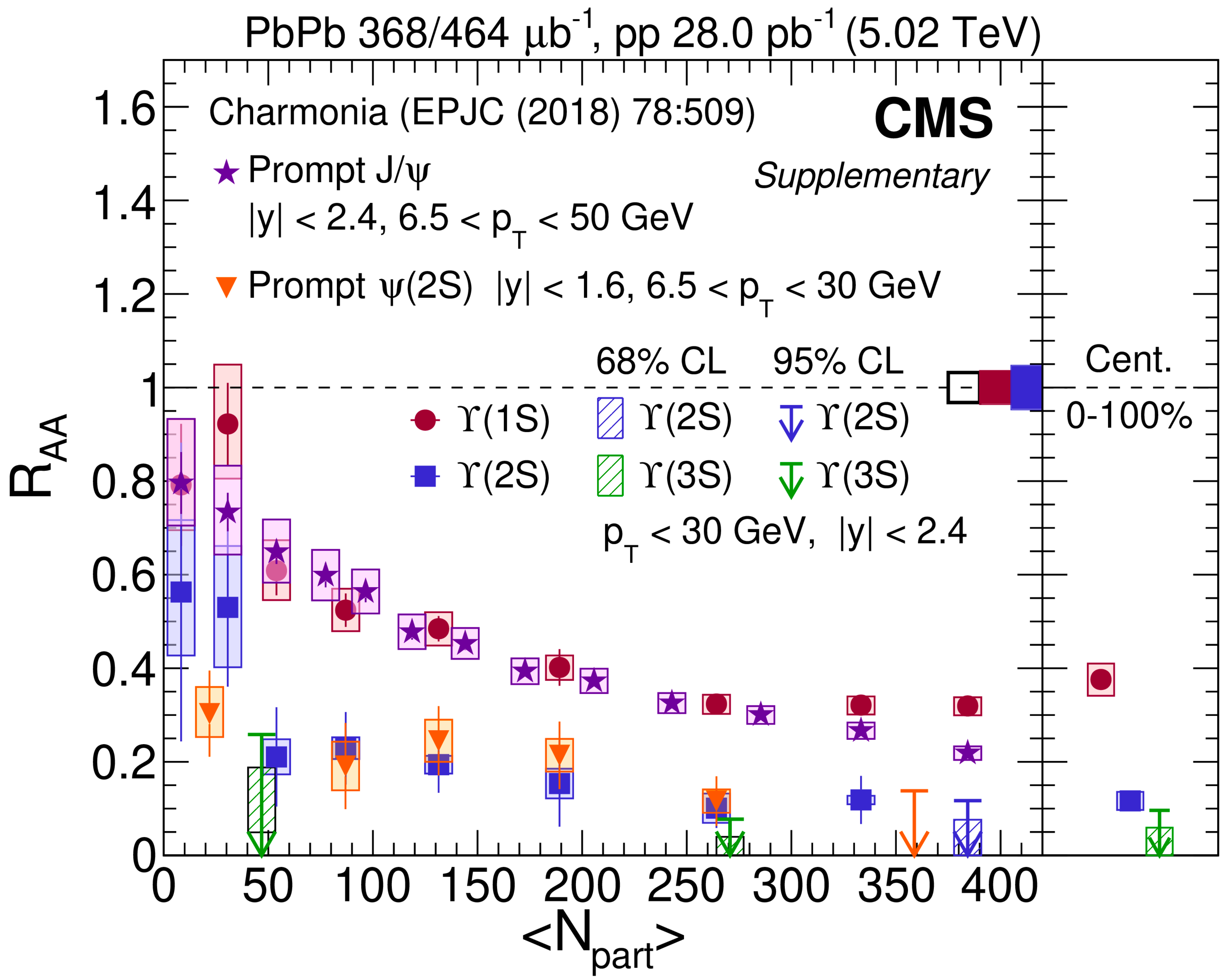


1) deviation for peripheral collisions? (50–70% centrality)
   - event-selection bias leading to an apparent suppression in peripheral collisions? (cf. PLB 793 (2019) 420)
   - need for impact-parameter dependent nPDF? (e.g. EPS09s)
   - stronger forward suppression?

2) plateau ~0.32 for ⟨N_{part}⟩ > 200 (20% most central collisions)
   - continuous suppression in the models (i.e. no threshold effect)
   - from a complete suppression of the feed-down contributions?

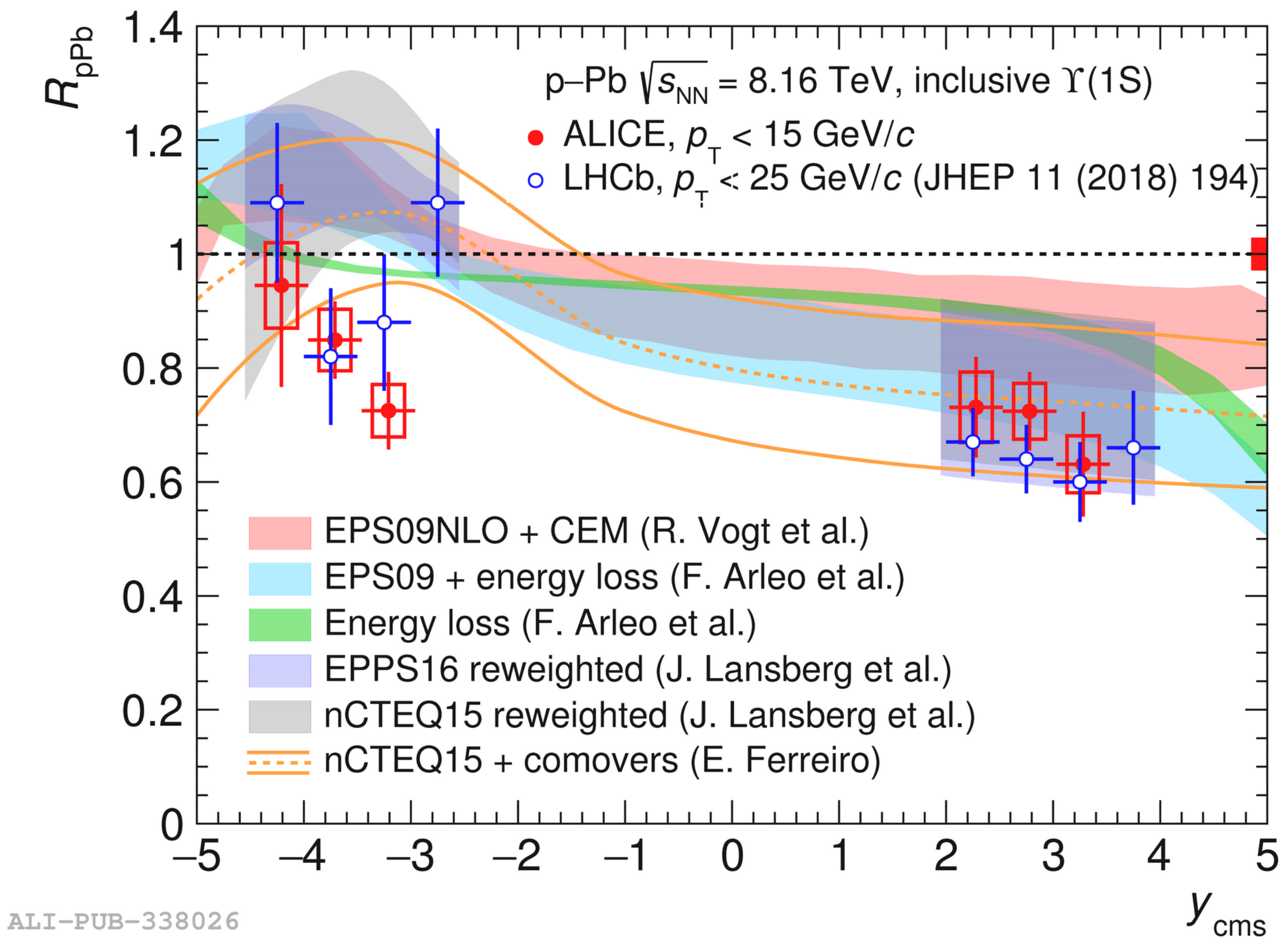
Comparison with charmonia

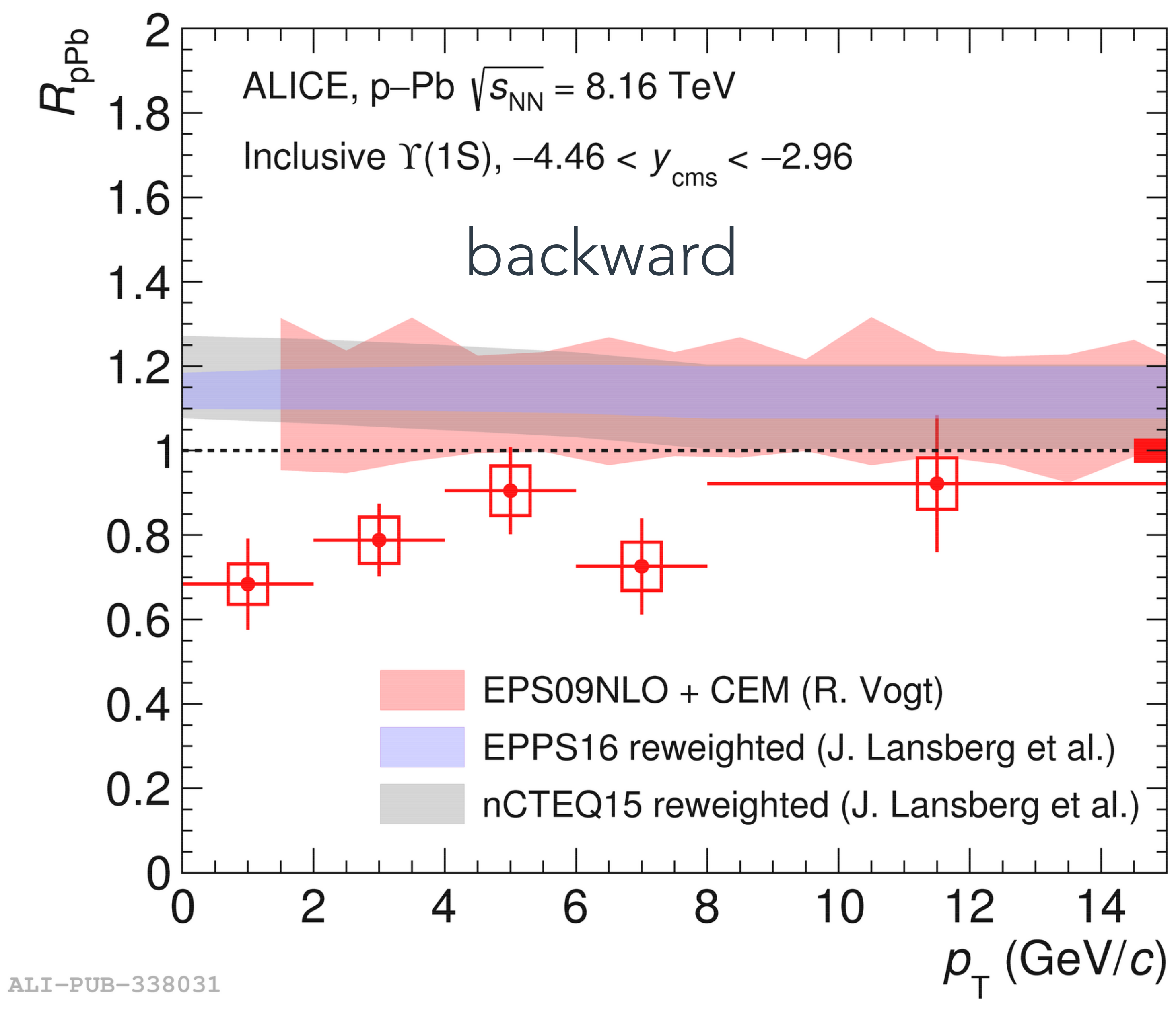


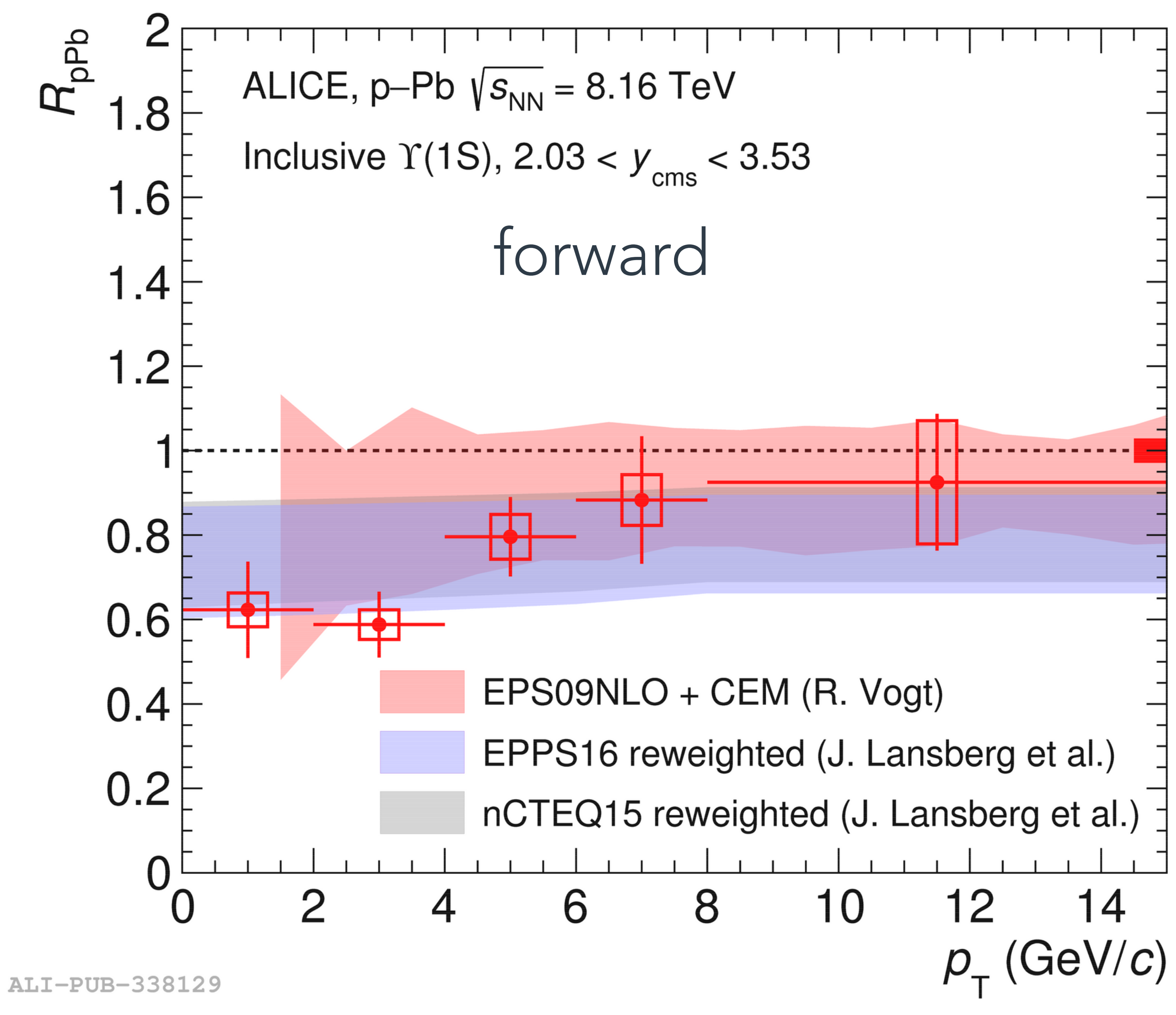


Production in p–Pb collisions [PLB 806 (2020) 134586]

- Υ(1S) production **already suppressed in p–Pb collisions**, no antishadowing?
- R_{pPb} compatible with unity and with fits of nuclear PDFs at intermediate p_T
- **significant modification of the p_T distribution** below 4 GeV/c not observed in the nPDF parametrisations (especially at backward rapidity)
- dependence in contrast to the measurements in Pb–Pb collisions

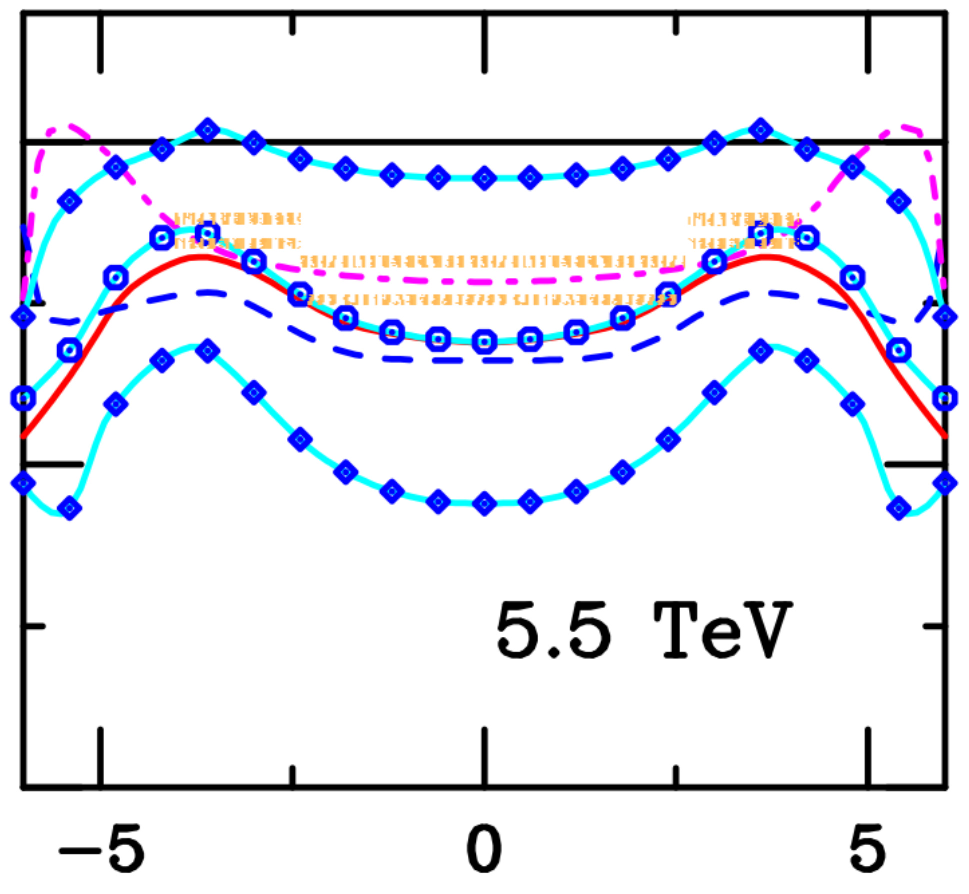






Rapidity-dependent suppression expected?

- Comover interaction model [JHEP 10 (2018) 094], no predictions available but
  - particle multiplicity decreasing going forward ☛ smaller interaction cross sections ☛ **weaker suppression**
  - caveat: shadowing modeling
- Transport model [PRC 96 (2017) 054901], no predictions available but
  - lower initial temperature ☛ **weaker final-state suppression**
  - caveat: shadowing modeling
- Coupled Boltzmann equations [JHEP 01 (2021) 046]
  - hydro framework = boost invariance (i.e. **no rapidity-dependent hot medium effect**)
  - EPPS16 nPDF parametrisation ☛ (anti-)shadowing?!
- Hydrodynamic calculations [Universe 2 (2016)]
  *"[…] a **slight increase in ~~suppression~~ (R_{AA} !) for forward rapidities**, which is due to the increased plateau halfwidth used in the initial conditions"*



Shadowing factor in Pb-Pb collisions as a function of rapidity for different models

Coherent energy loss? JHEP 10 (2014) 073