Nuclear modification of the production of Υ mesons with CMS

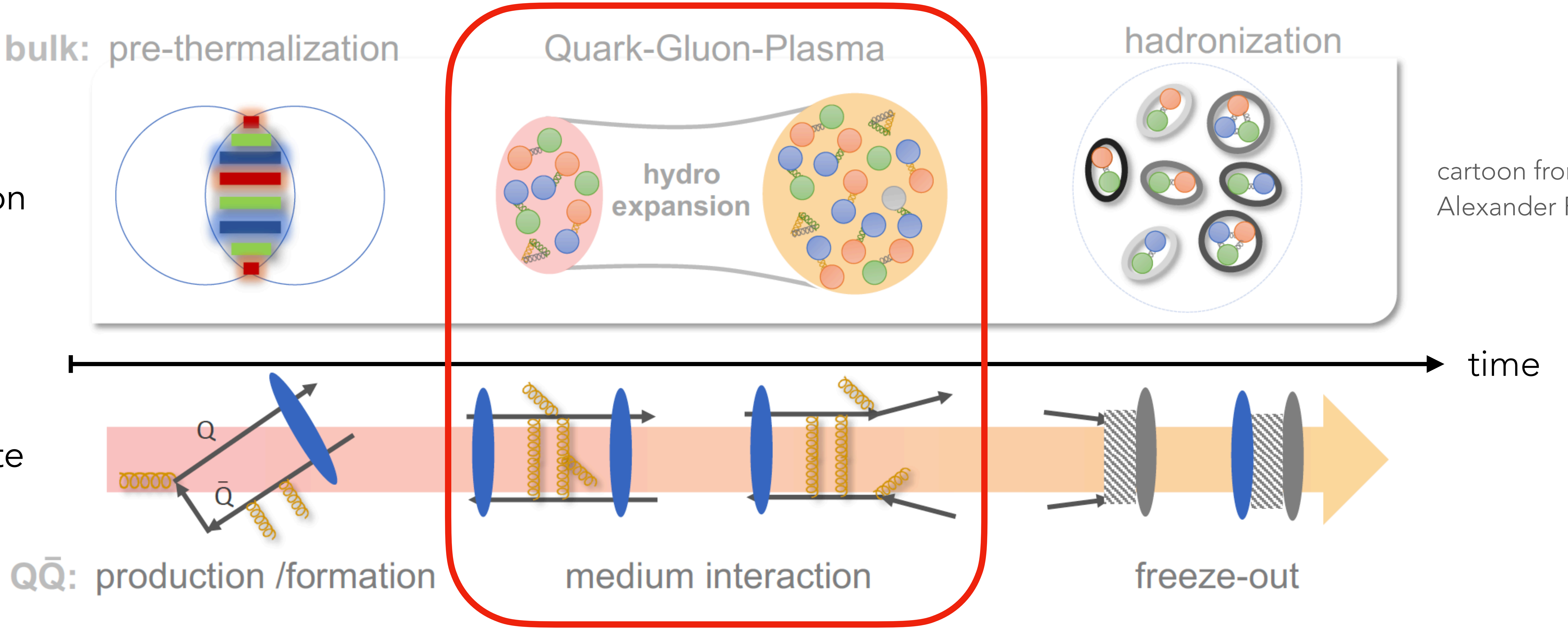
Florian Damas for the CMS Collaboration

QNP 2024, Barcelona, July 11

Probing strongly-interacting matter with quarkonia

System's evolution

Quarkonium's fate



cartoon from
Alexander Rothkopf

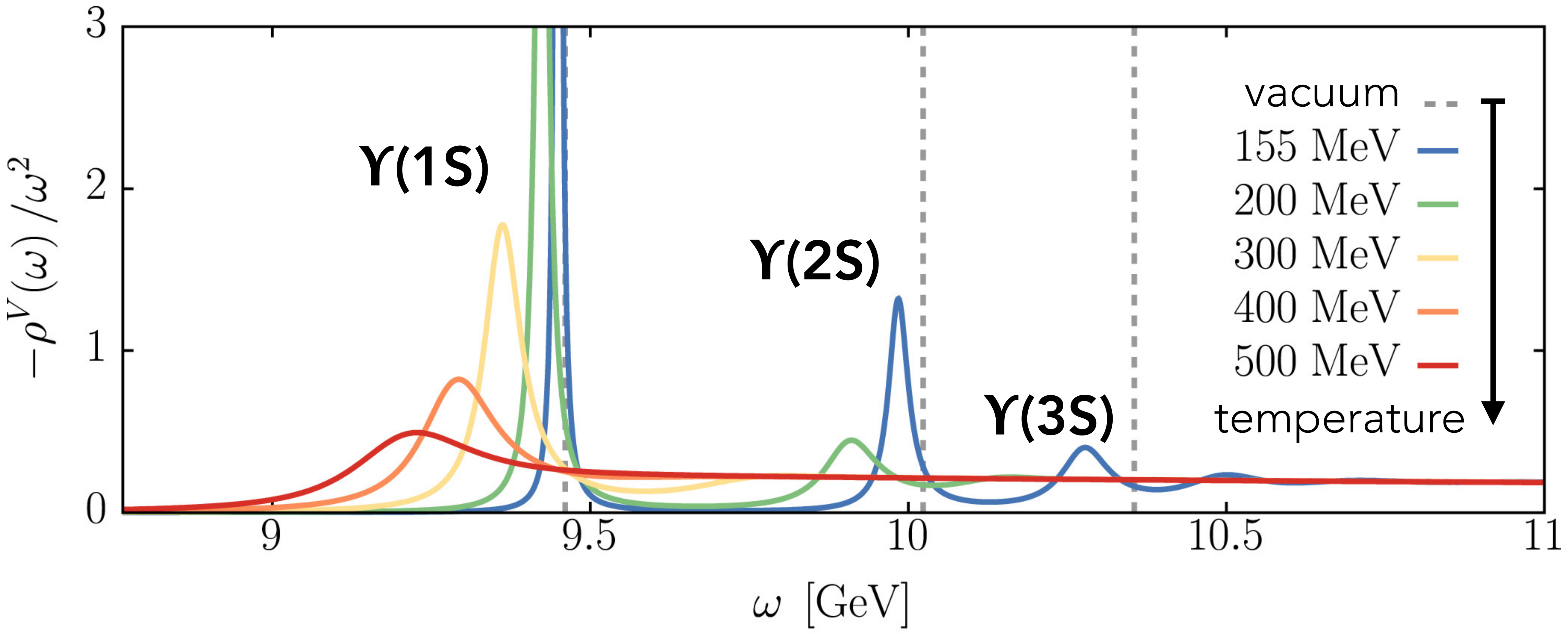
- heavy quarks experience the whole space-time evolution of heavy-ion collisions
- quarkonium states are ideal tools to study **bound states in extreme conditions**

☛ **key insights of the dynamics within deconfined matter at various scales**

Quarkonium's fate in hot QCD matter

- **Dissociation** via scatterings with QGP constituents
☛ broadening of the spectral functions leading to *sequential melting* with temperature

In-medium spectral functions of Υ states from lattice NRQCD calculations
[D. Lafferty and A. Rothkopf, PRD 101 (2020) 056010]



Quarkonium's fate in hot QCD matter

- **Dissociation** via scatterings with QGP constituents
  ☛ broadening of the spectral functions leading to *sequential melting* with temperature

- **(Re)formation of heavy quark bound states**
  - recombination of correlated pairs
    ☛ reshuffling of the population of states
  - ``regeneration'' if many heavy quarks produced
    ☛ significant for charmonia (cf. N. Oei's talk) and B_c mesons, negligible for bottomonia*

In-medium spectral functions of Υ states from lattice NRQCD calculations
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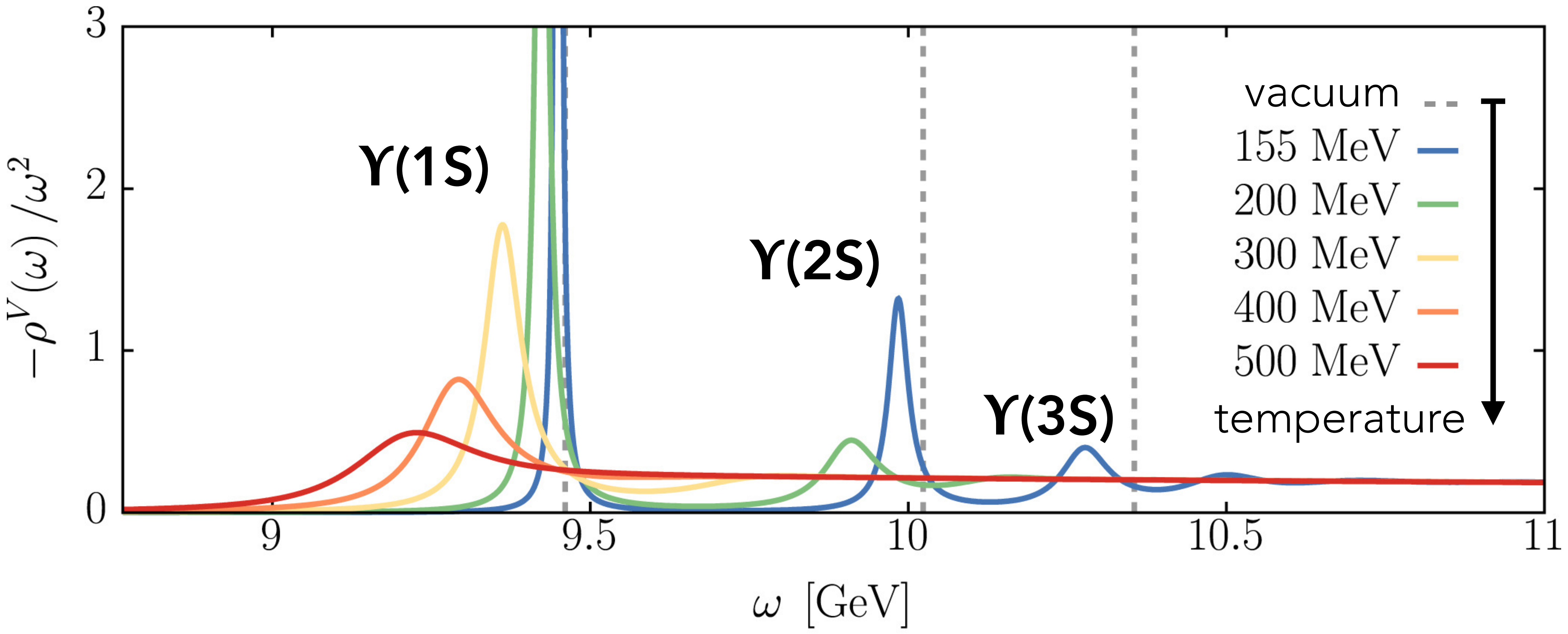

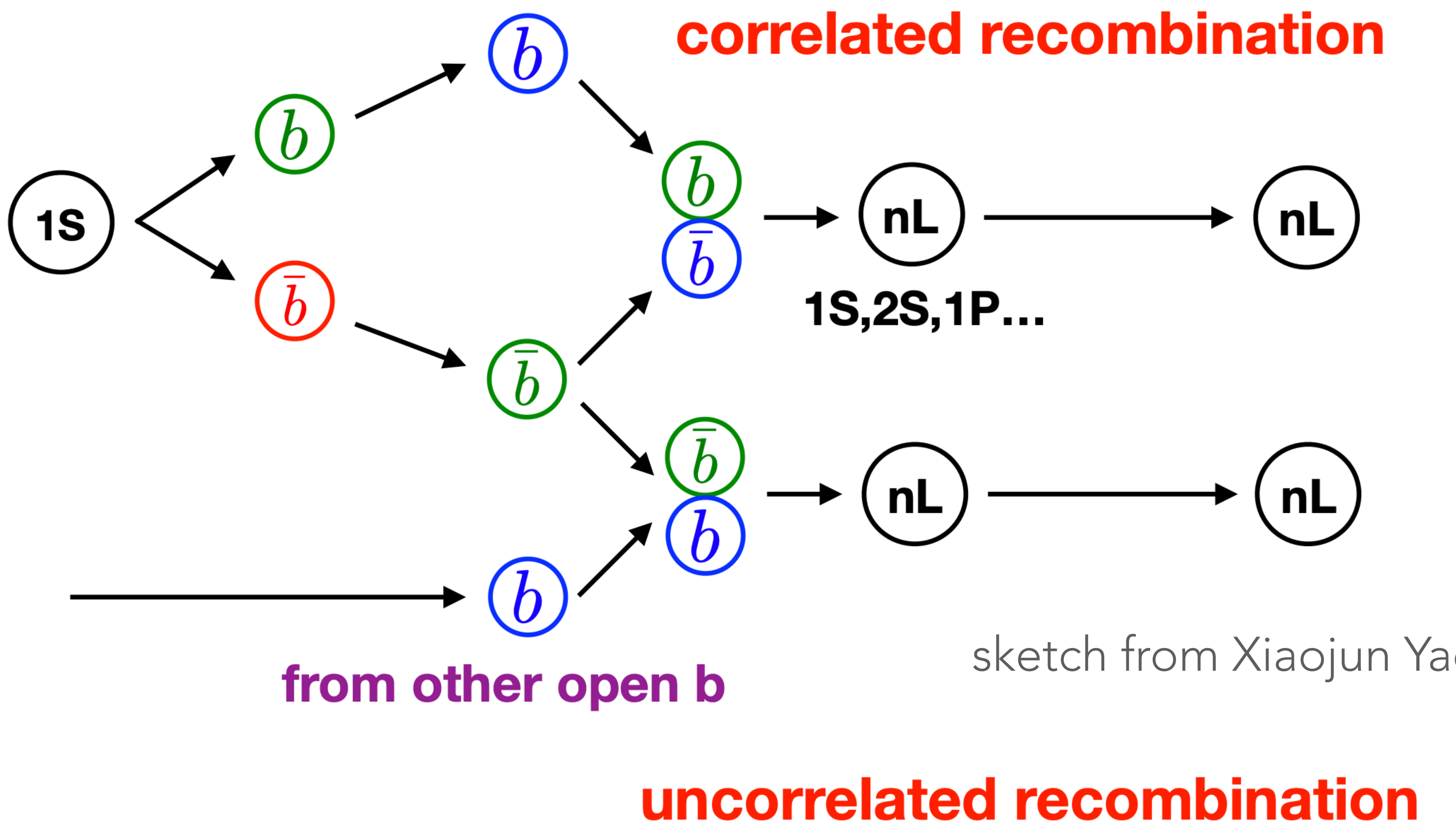

sketch from Xiaojun Yao

*one $b\bar{b}$ produced per PbPb collision at most

Quarkonium's fate in hot QCD matter

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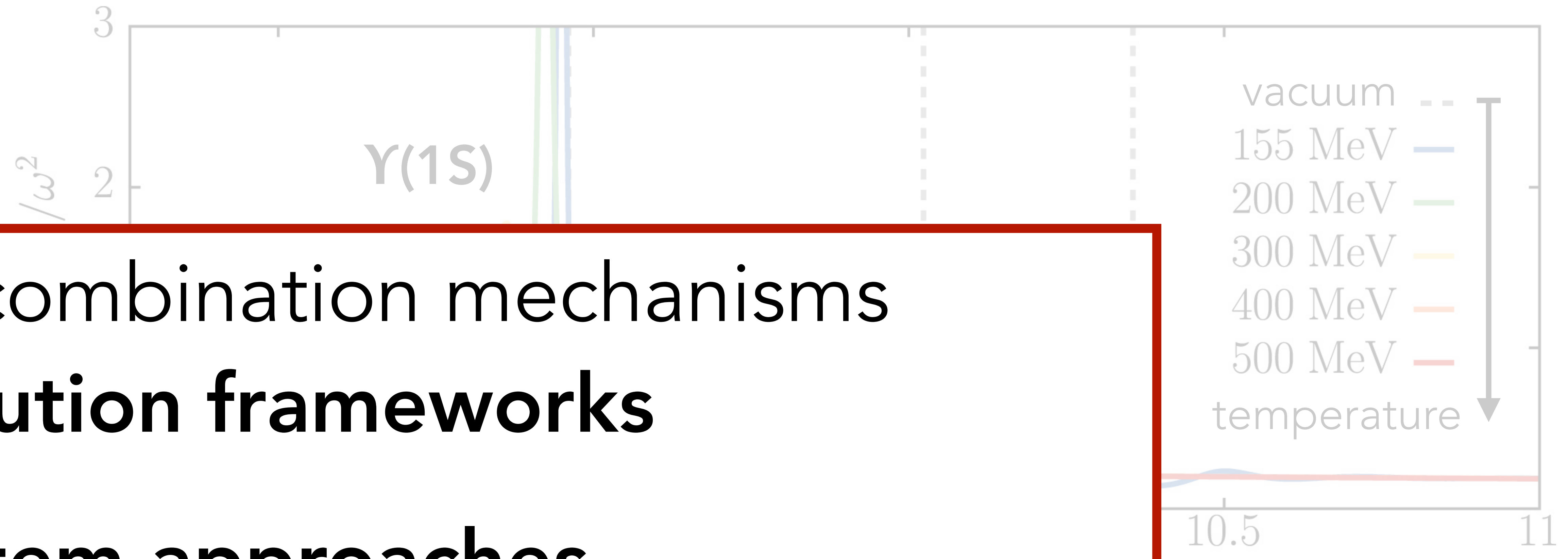


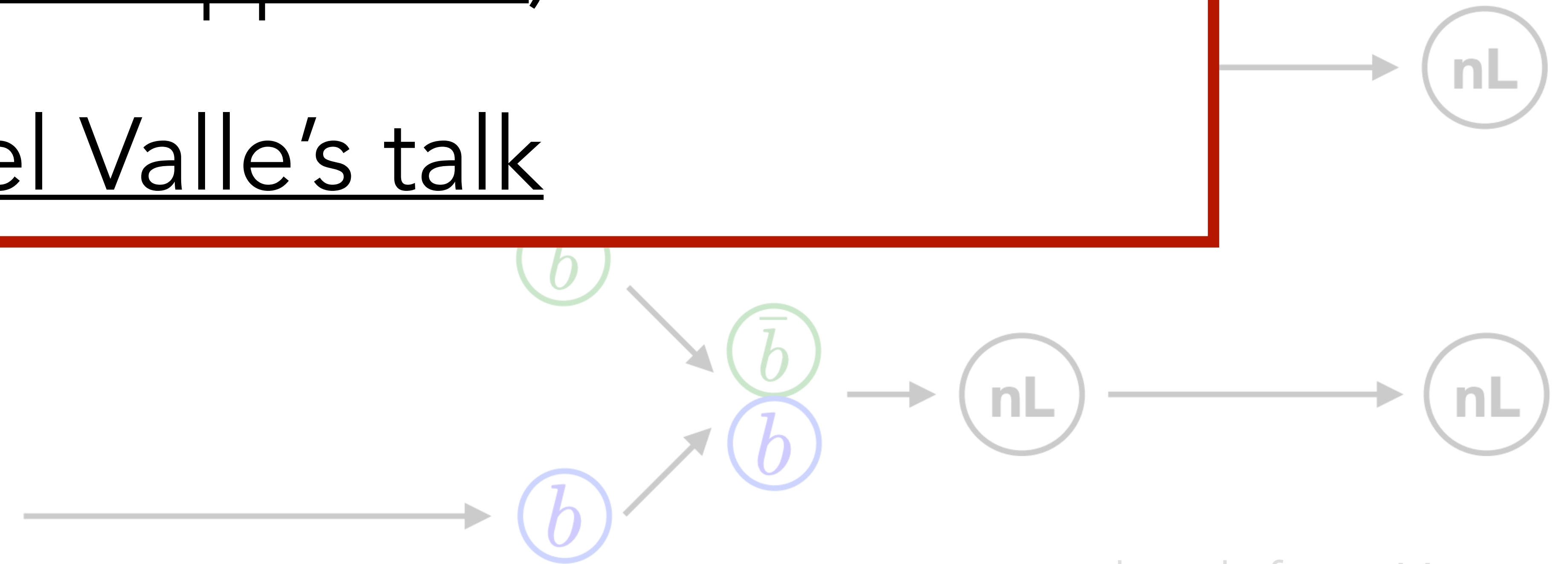
- **Dissociation** via scatterings with QGP constituents
  ☛ broad…
  sequenti…

- (Re)form…
  - recom…
    ☛ resh…
  - ``regen…
    ☛ significant for charmonia (cf. N. Oei's talk) and B_c mesons, negligible for bottomonia*

Interplay of dissociation and recombination mechanisms
calling for **real-time evolution frameworks**

- development of **open-quantum system approaches**
  (cf. talks by J.M. Martinez Vera and P-B Gossiaux and references in backup)
- connection to **heavy-flavor transport** (cf. R. Rapp's talk)
- more experimental results in Z. Conesa del Valle's talk

…ombination



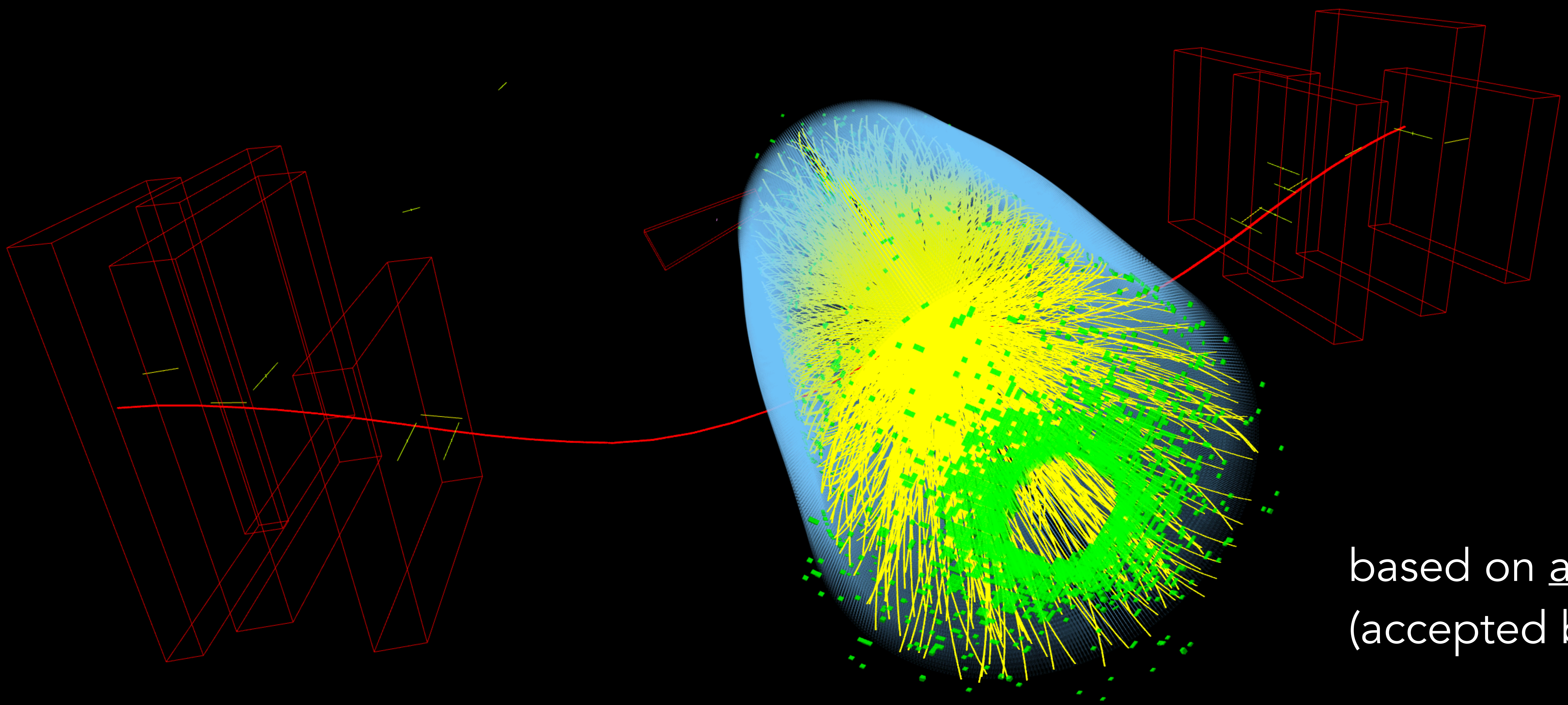
sketch from Xiaojun Yao

uncorrelated recombination

*one $b\bar{b}$ produced per PbPb collision at most

CMS Experiment at the LHC, CERN
Data recorded: 2018-Nov-10 02:06:52.131328 GMT
Run / Event / LS: 326483 / 8874092 / 36

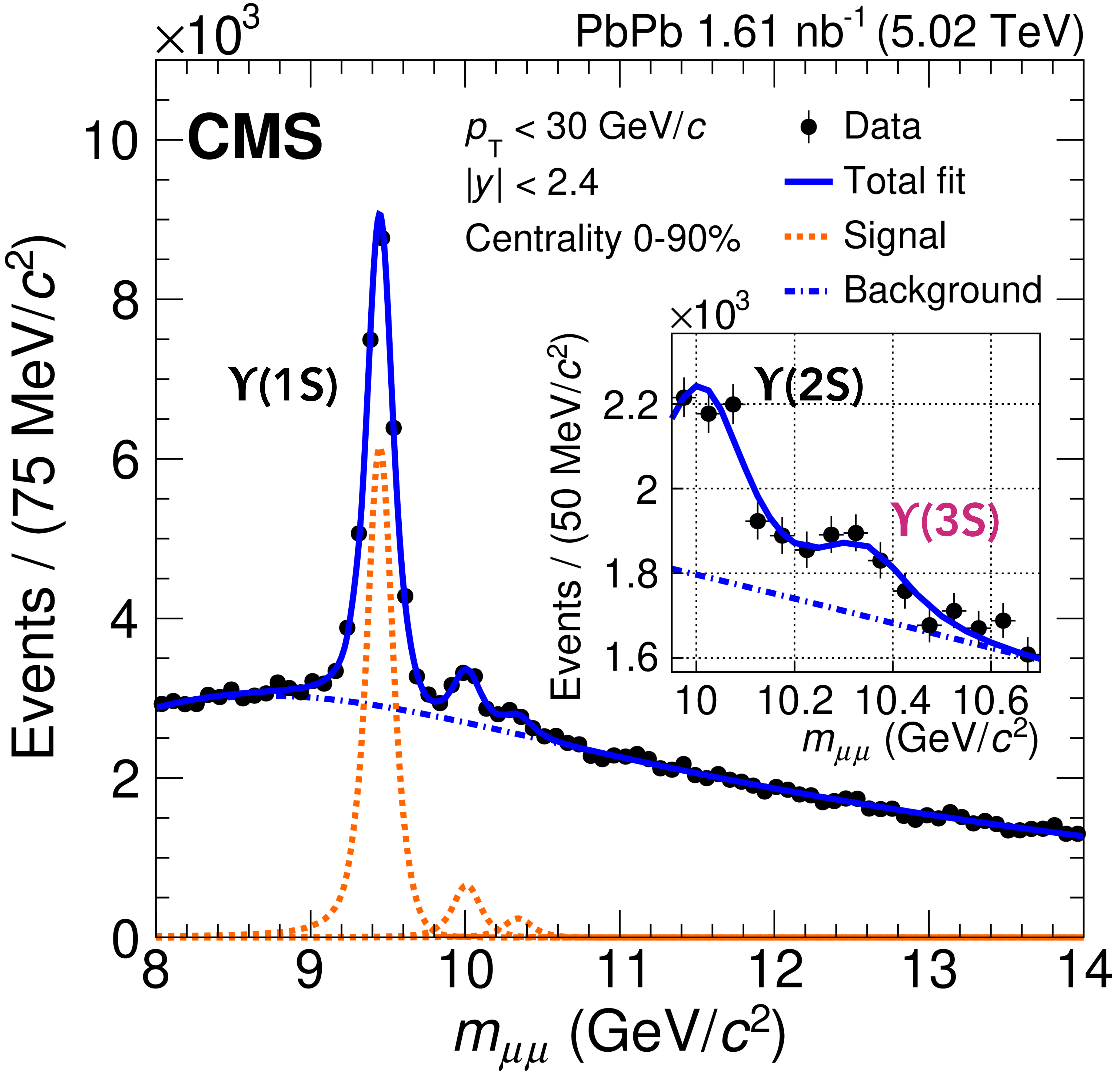
Event display of a $\Upsilon \rightarrow \mu\mu$ candidate in 2018 PbPb collisions



based on arXiv:2303.17026
(accepted by Physical Review Letters)

Observation of the Υ(3S) meson and suppression of Υ states in PbPb collisions

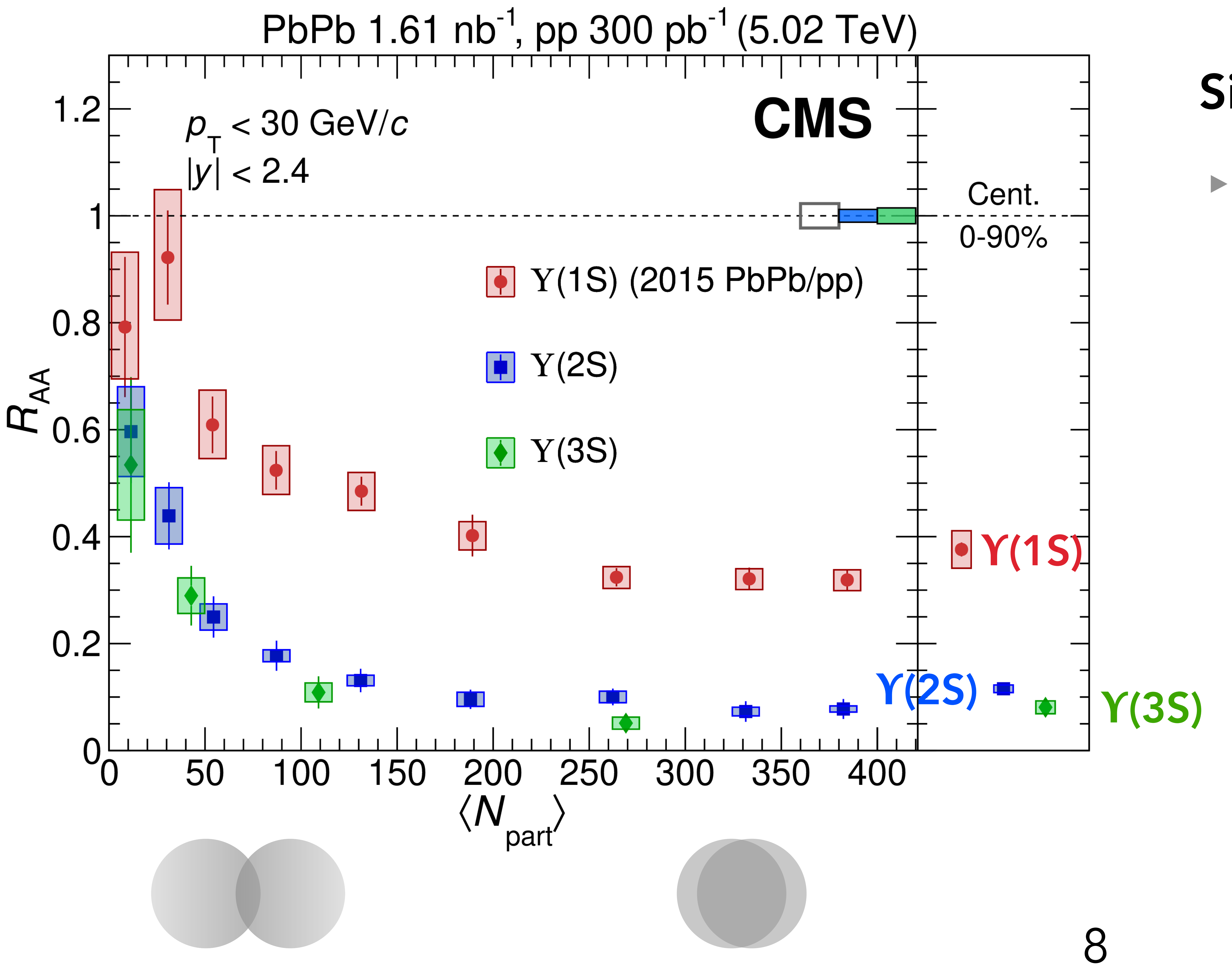
Υ mesons from pp to PbPb collisions



- Excellent performance of the CMS detector
  - very efficient muon reconstruction over a large phase space (see dedicated paper arXiv:2404.17377)
  - recording large data samples
- **All three states now available in all collisions!**
  - first observation of the elusive **Υ(3S)** meson in AA collisions!
  - unique detailed studies of the suppression of the excited states

Nuclear modification *vs* centrality

$$R_{AA} \equiv \frac{dN_{AA}/dp_T}{N_{coll} \times dN_{pp}/dp_T}$$



Significant suppression for all states!

- ordered by their binding energy
  $R_{AA}(1S) > R_{AA}(2S) > R_{AA}(3S)$

Nuclear modification *vs* centrality

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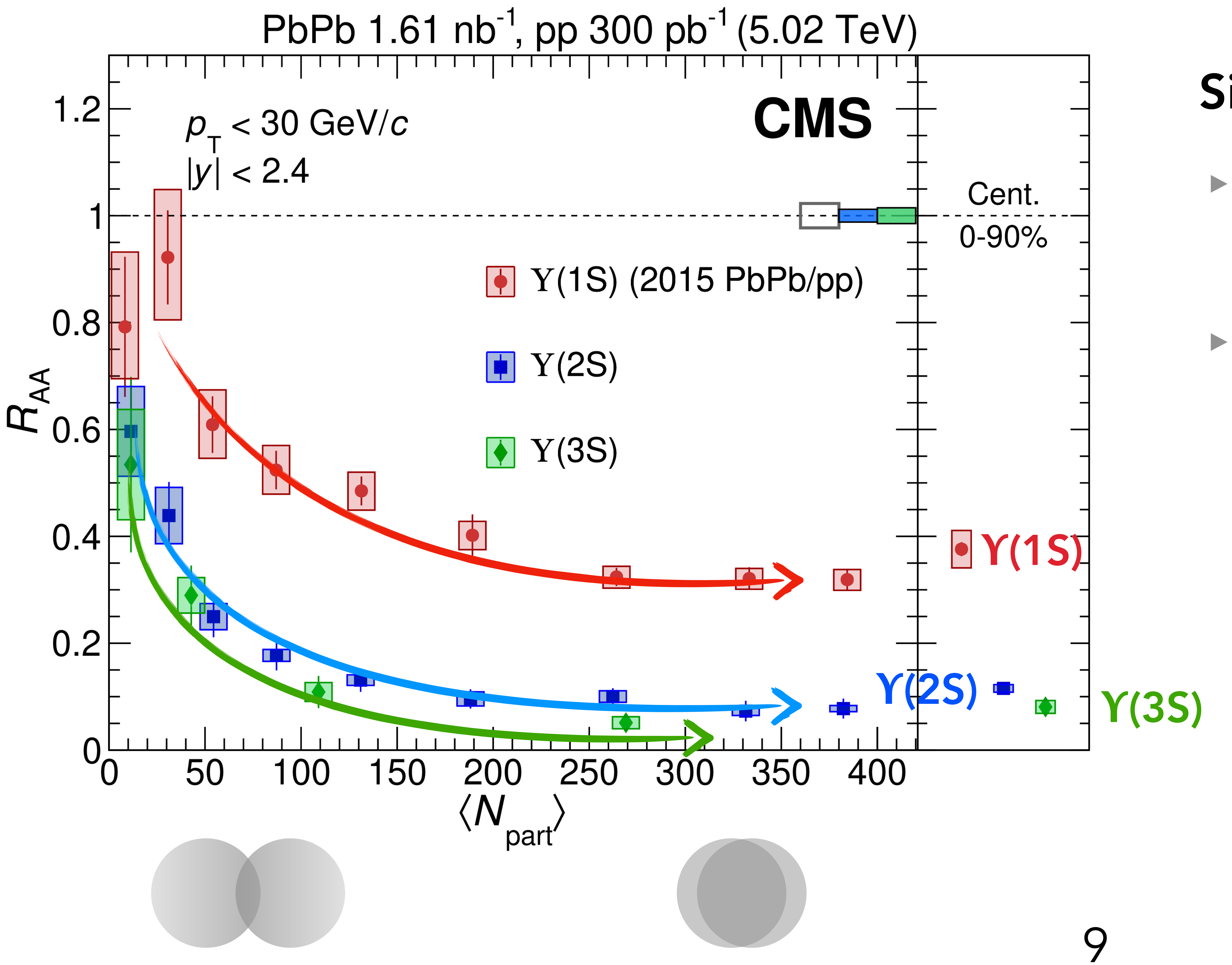
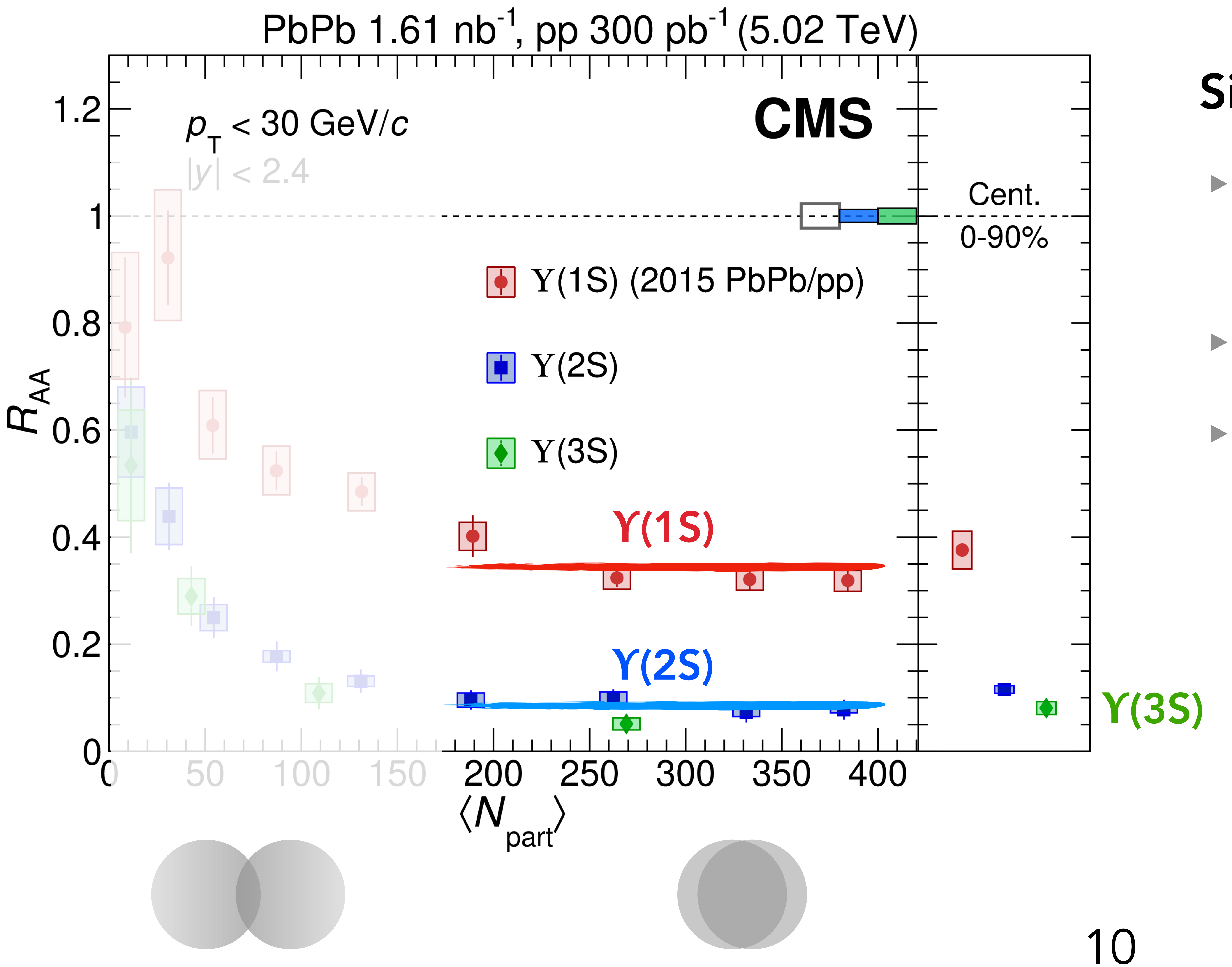


Significant suppression for all states!

- ordered by their binding energy
  $R_{AA}(1S)$ > $R_{AA}(2S)$ > $R_{AA}(3S)$
- **increasing with the number of participants**
  (bigger QGP volume, longer interaction time)

Nuclear modification *vs* centrality



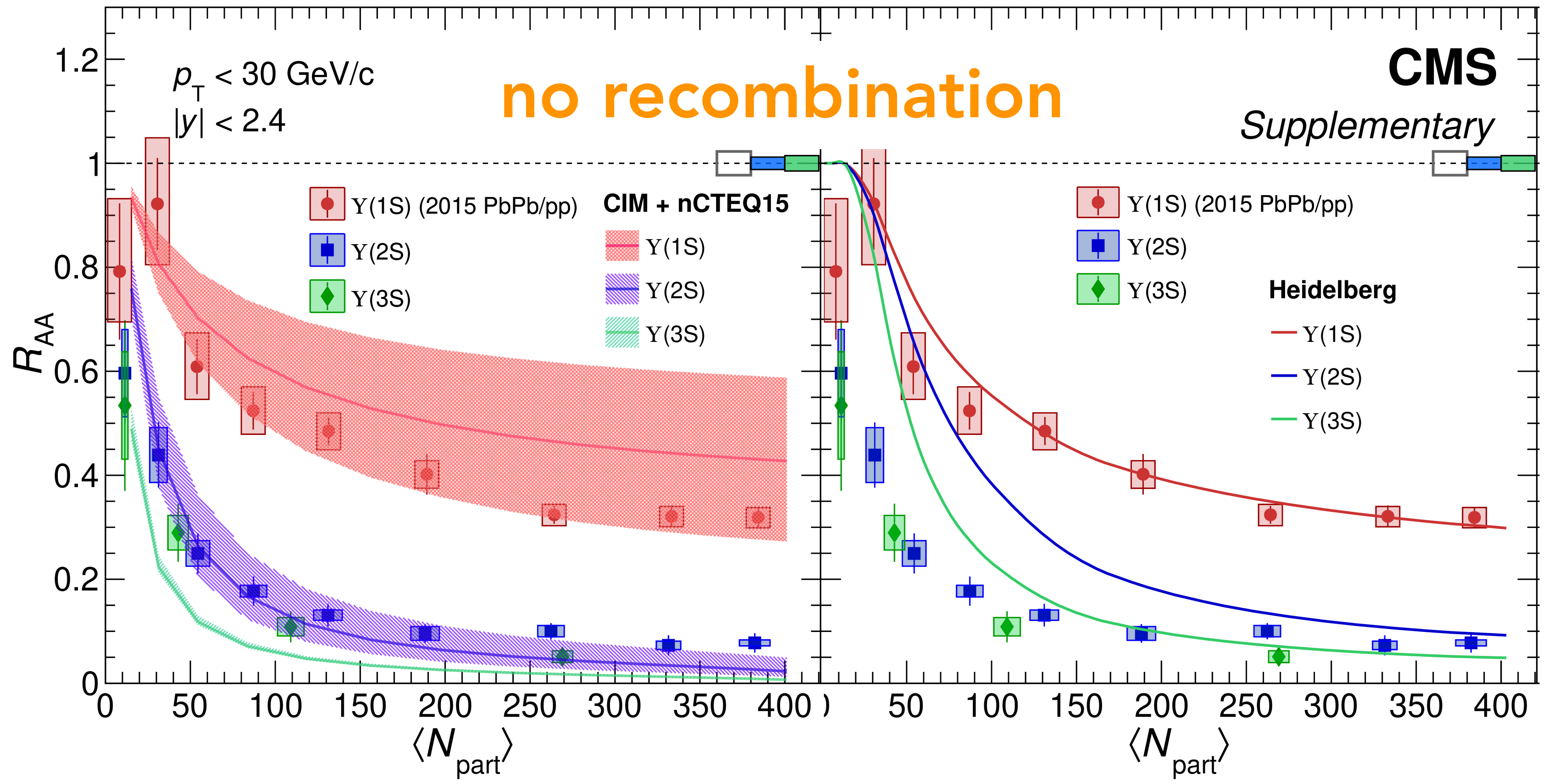
Significant suppression for all states!

- ordered by their binding energy
  $R_{AA}(1S)$ > $R_{AA}(2S)$ > $R_{AA}(3S)$
- increasing with the number of participants
- **plateau for the most central events***
  ☛ balance of physical effects?
  let's see what the models have to say!

*also observed in the forward rapidity region
[ALICE Collaboration, PLB 822 (2021) 136579]

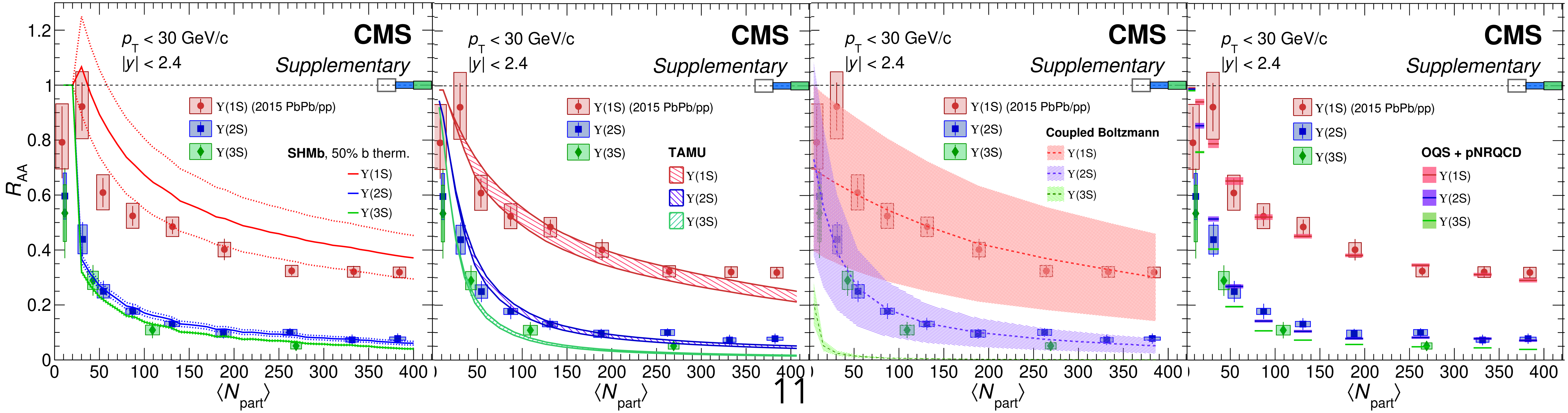
Comparison with models

detailed in backup
see also R. Rapp's talk



Many calculations and different approaches

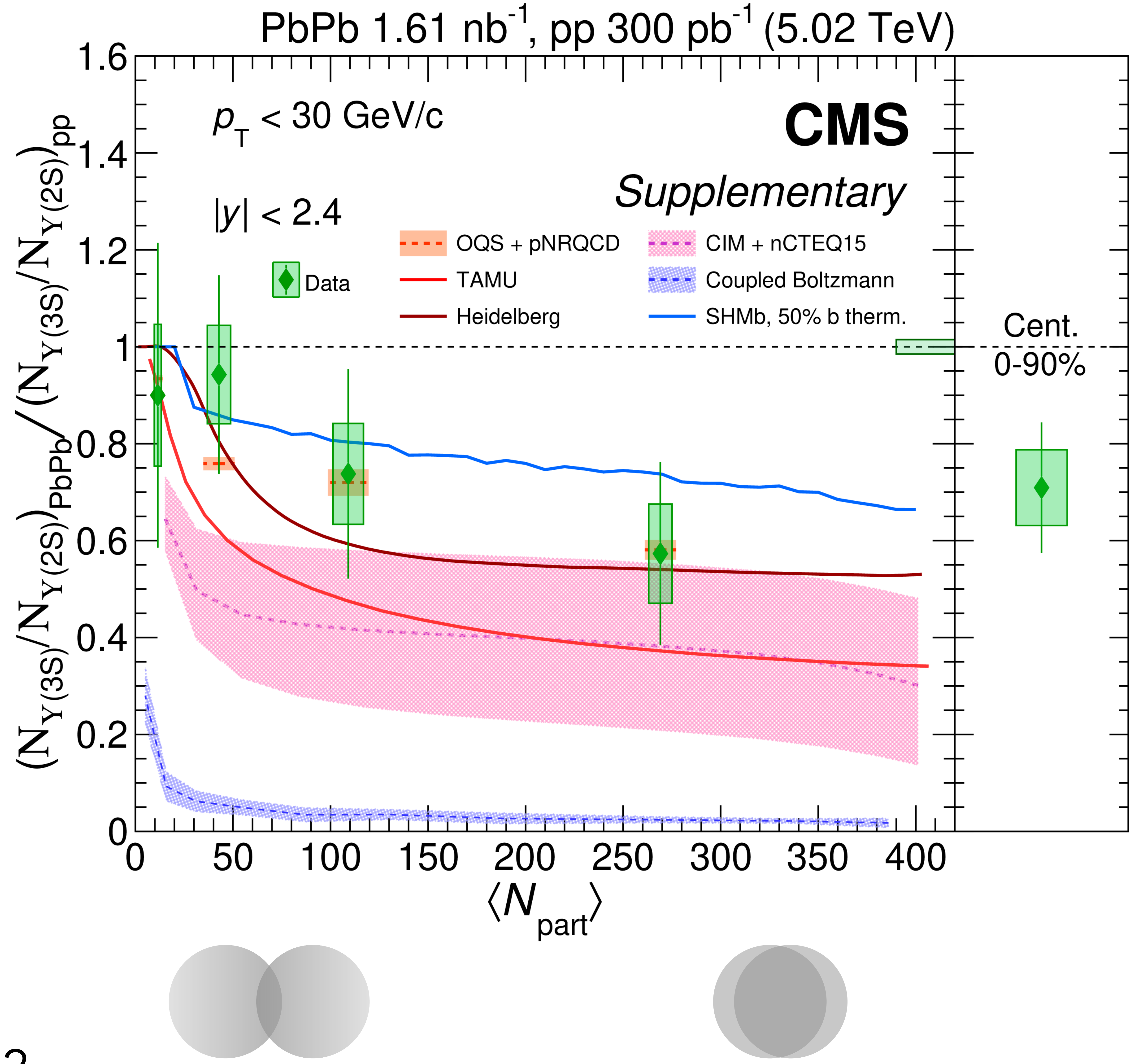
- good description of the ϒ(1S) data
- some deviations for the excited states
- **large uncertainties from external inputs** (gluon nPDF, beauty cross section)



Constraining models with yield double ratios

Observable with more **discriminating power**!

- (partial) cancellation of uncertainties common to all states
- mild centrality dependence of **Υ(3S) / Υ(2S)** to be confirmed with more data
- detailed comparison of model approaches
- recent exercise from the theory community [A. Andronic et al., EPJA 60 (2024) 4]

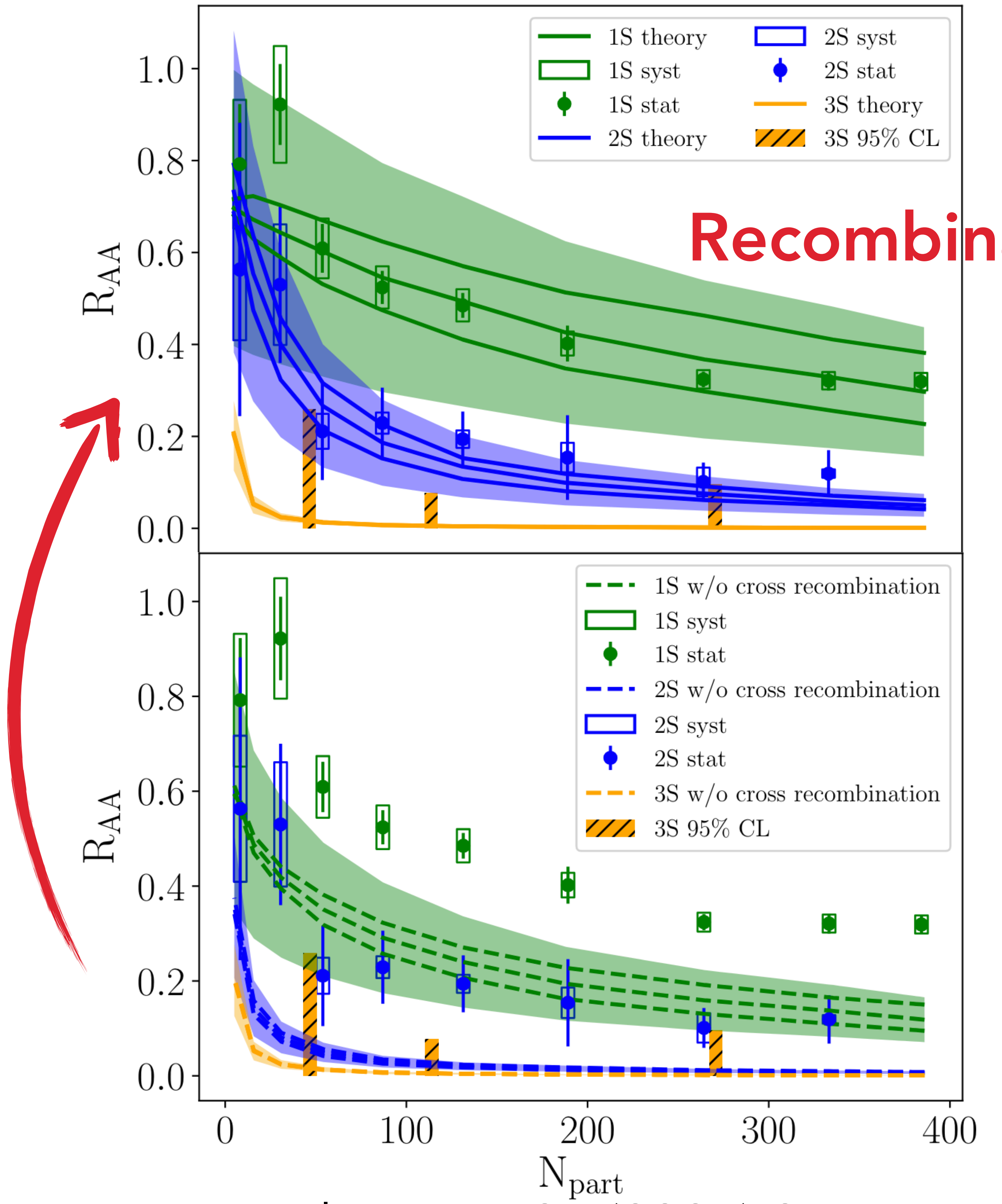


Correlated recombination of bottomonia

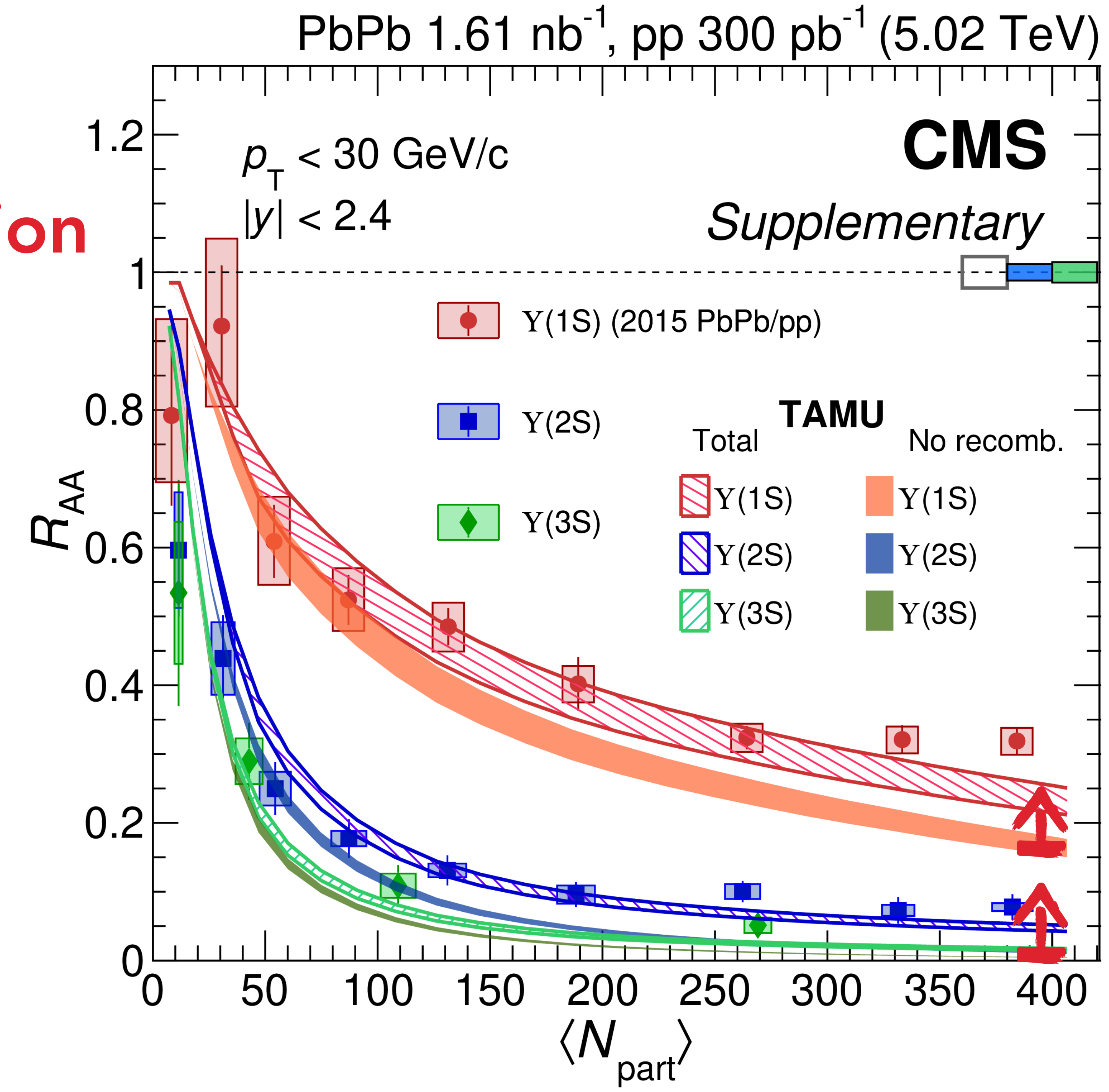
Mechanism necessary for a comprehensive description of the production of all states!

☛ relatively more important for the excited states as demonstrated by our CMS data

Transport models (semi-classical calculations)



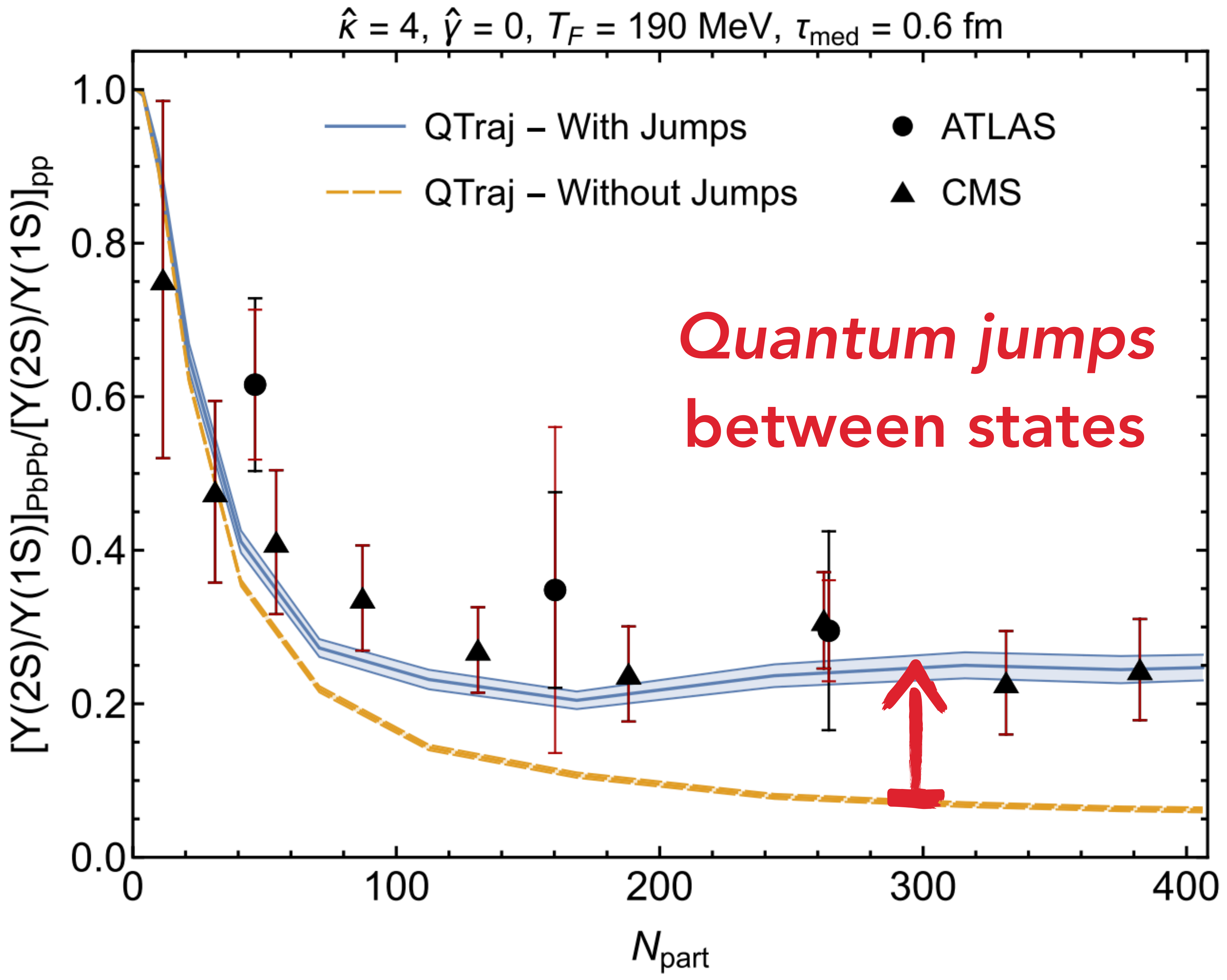
X. Yao et al., JHEP 01 (2021) 046



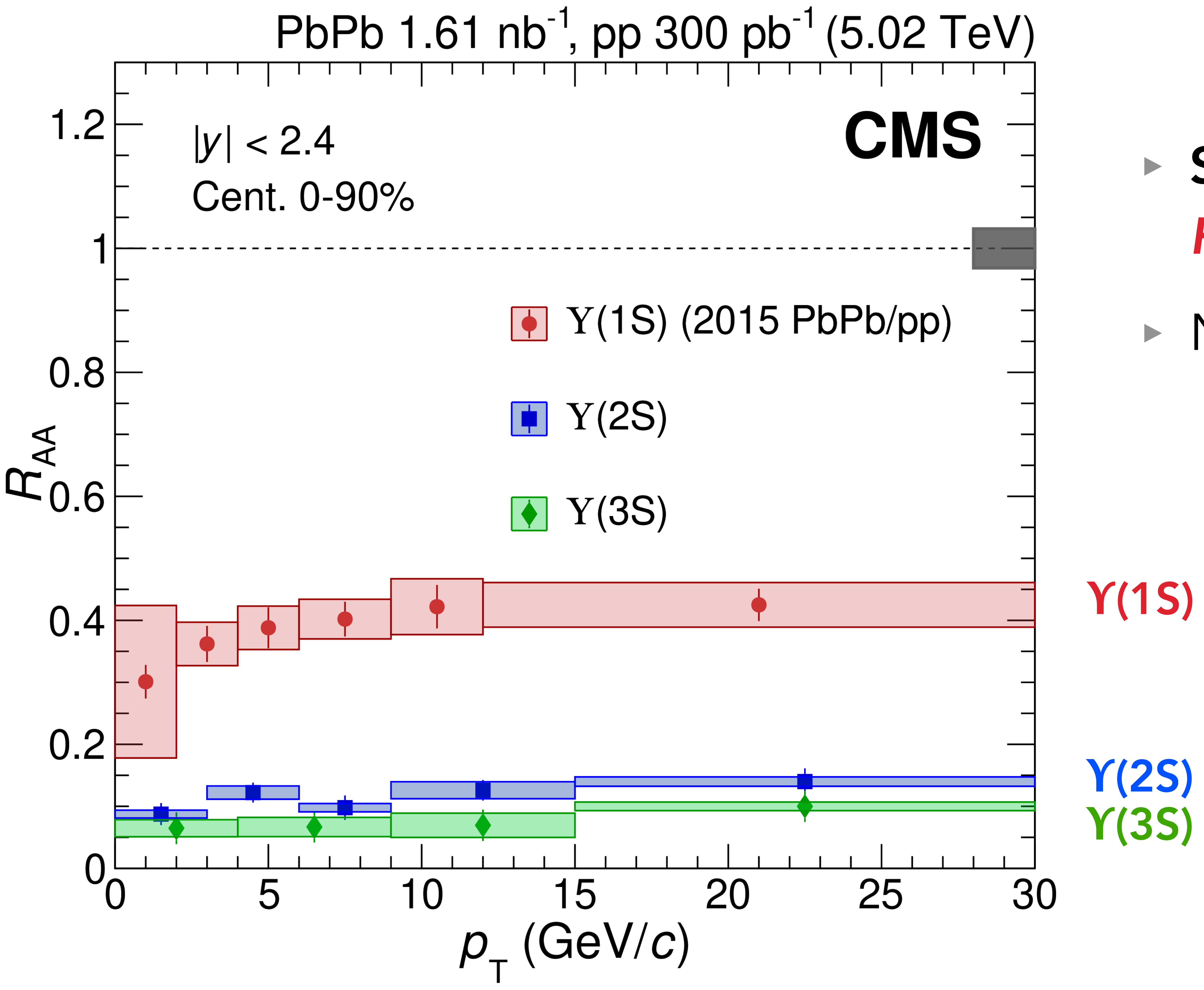
X. Du et al., PRC 96 (2017) 054901

Open-quantum system + pNRQCD

[N. Brambilla et al., PRD 108 (2023) 1]

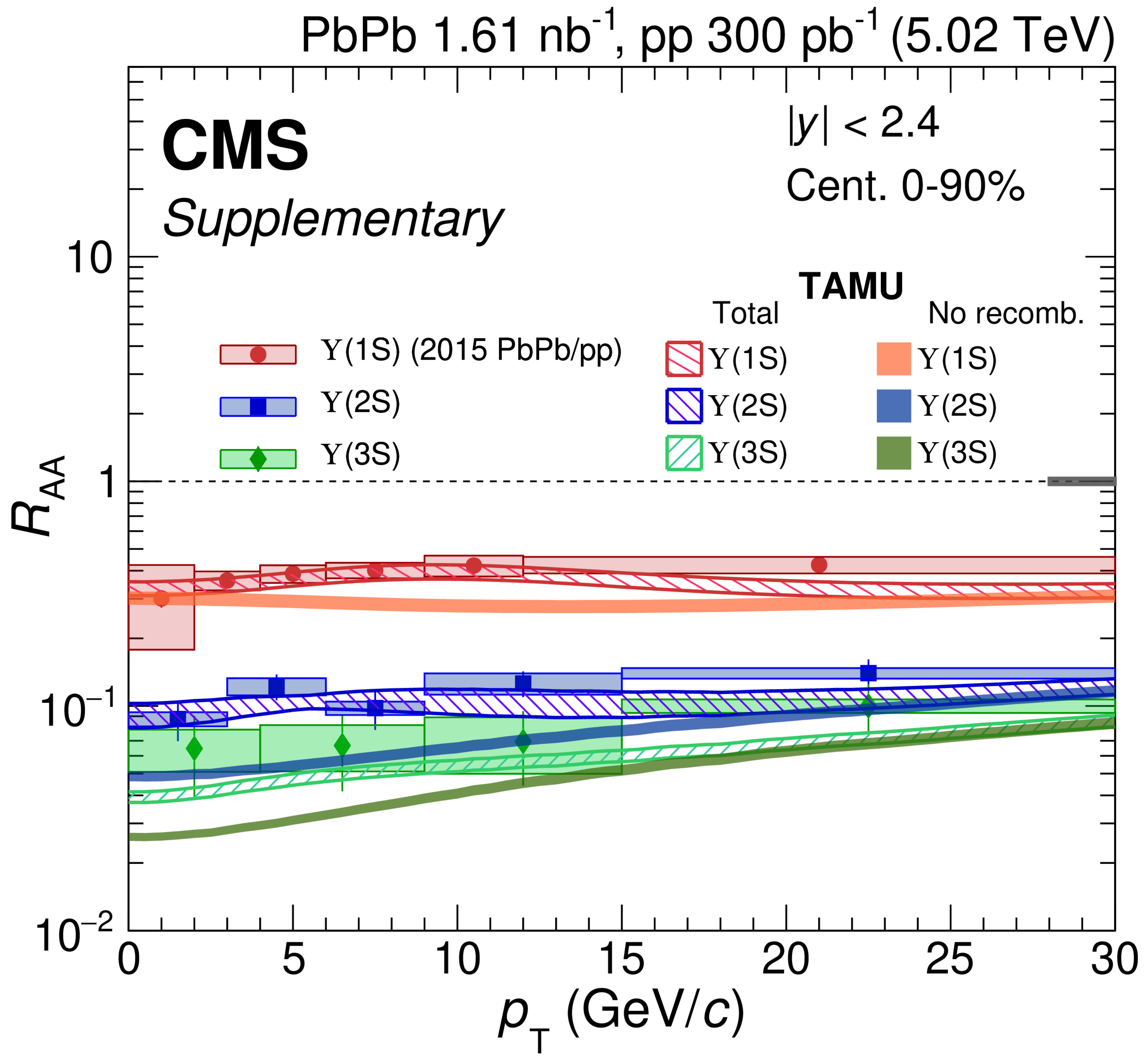


Nuclear modification vs p_T



- **Suppression ordering over the full phase space** $R_{AA}(1S) > R_{AA}(2S) > R_{AA}(3S)$
- No significant dependence with p_T

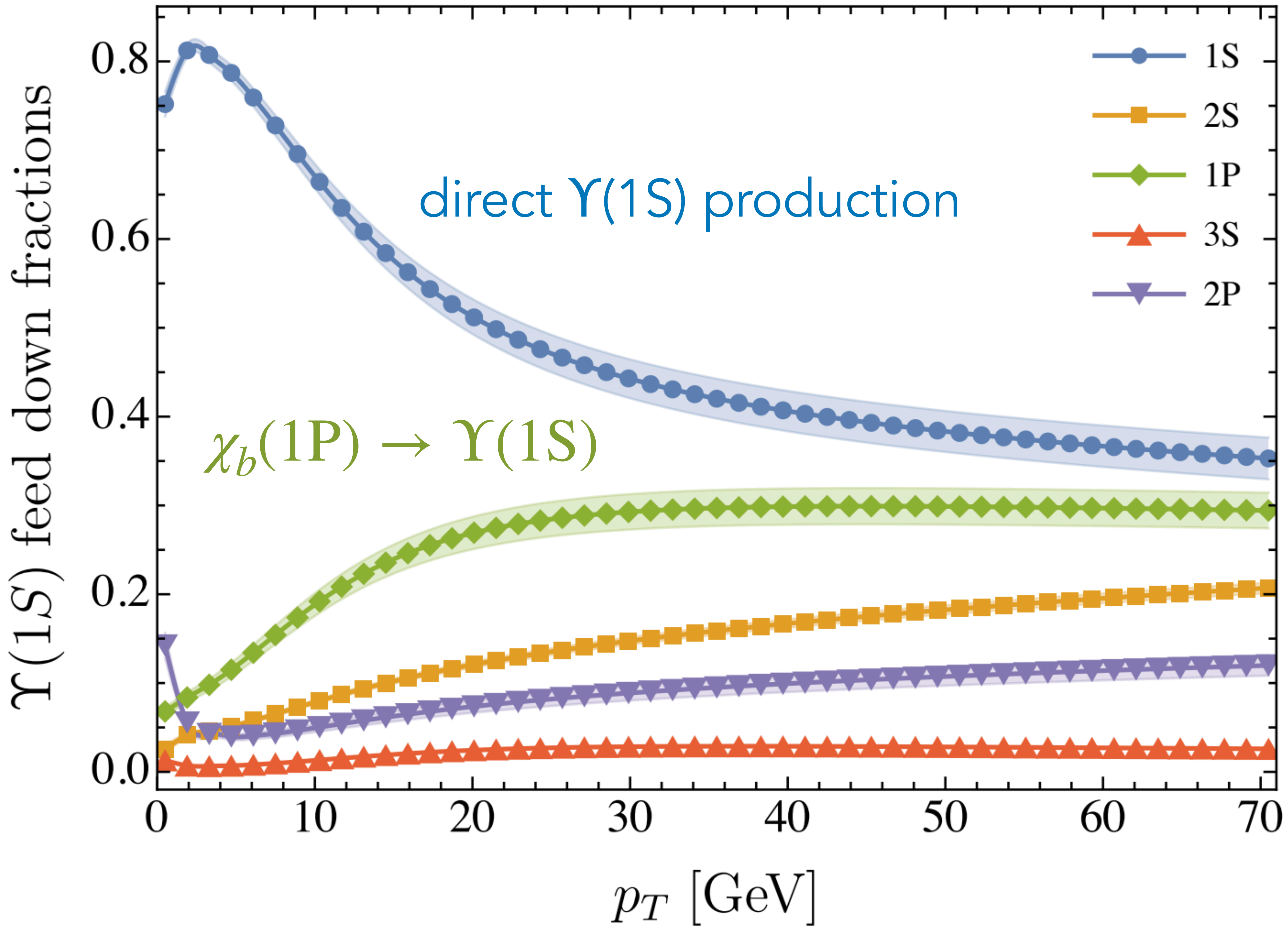
Nuclear modification vs p_T



- Suppression ordering over the full phase space
  $R_{AA}(1S) > R_{AA}(2S) > R_{AA}(3S)$
- No significant dependence with p_T
  exact compensation of many relevant effects?
  - **dissociation and recombination mechanisms**

Nuclear modification vs p_T

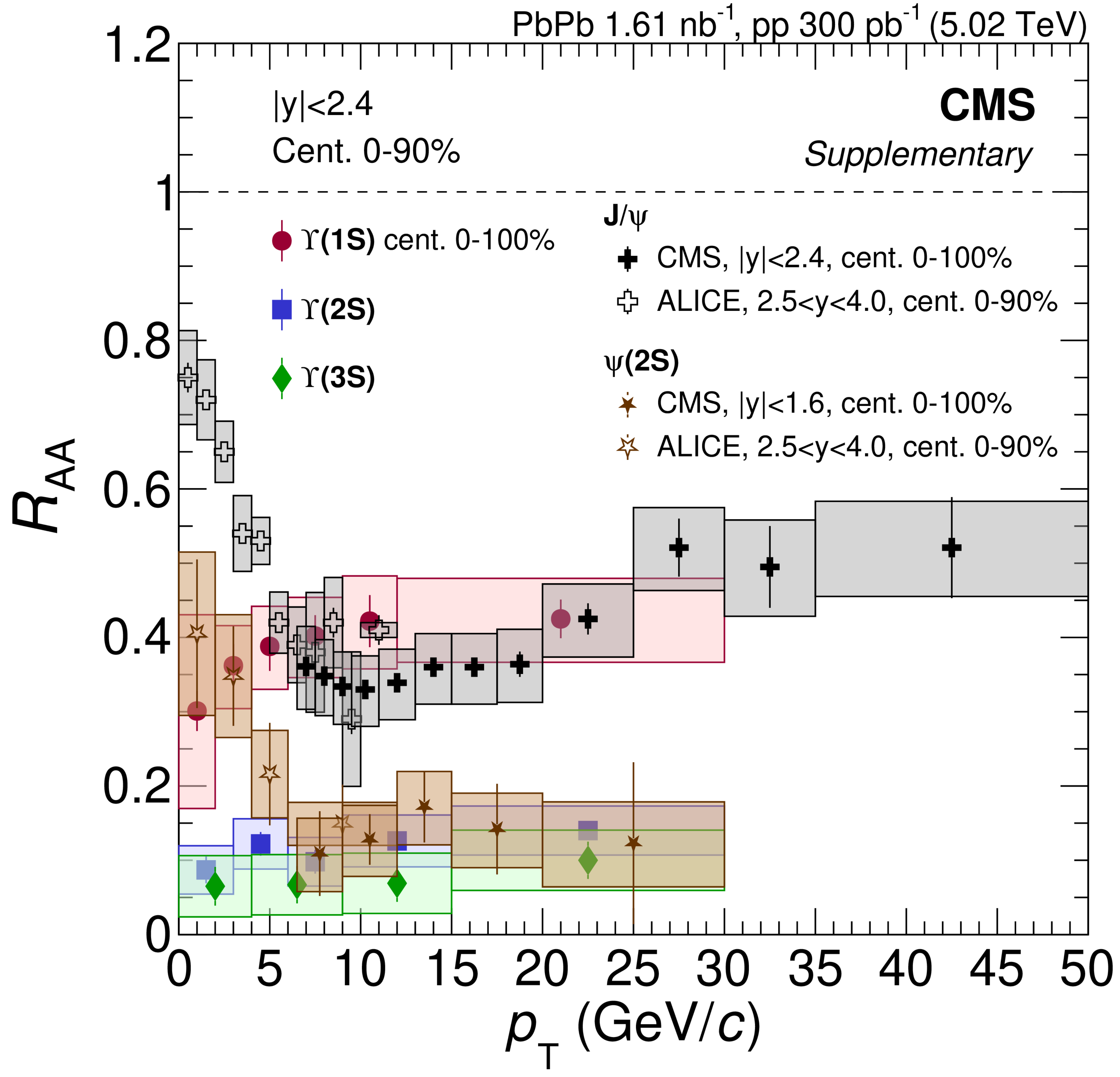
Estimated feed-down fractions to Υ(1S) in pp collisions
[J. Boyd et al., PRD 108 (2023) 094024]



- Suppression ordering over the full phase space
  $R_{AA}(1S) > R_{AA}(2S) > R_{AA}(3S)$
- No significant dependence with p_T
  exact compensation of many relevant effects?
  - dissociation and recombination mechanisms
  - time scale of the formation of bound states
  - **contributions from decays of heavier states**
    (also known as *feed-downs*)

Open questions

- **Five quarkonium states at hand, but still a lot to understand to draw a comprehensive picture**
  - feed-downs to be completed
    ☛ is the direct Υ(1S) production even suppressed or just the excited states?
  - polarization measurements
    ☛ indirect constraints on missing feed-downs
  - production from jet fragmentation
    ☛ **parton energy loss as high-p_T quarkonium suppression mechanism!**
    (see S-L Zhang et al., Science Bulletin 68 (2023) 2003 and arXiv:2403.12704)

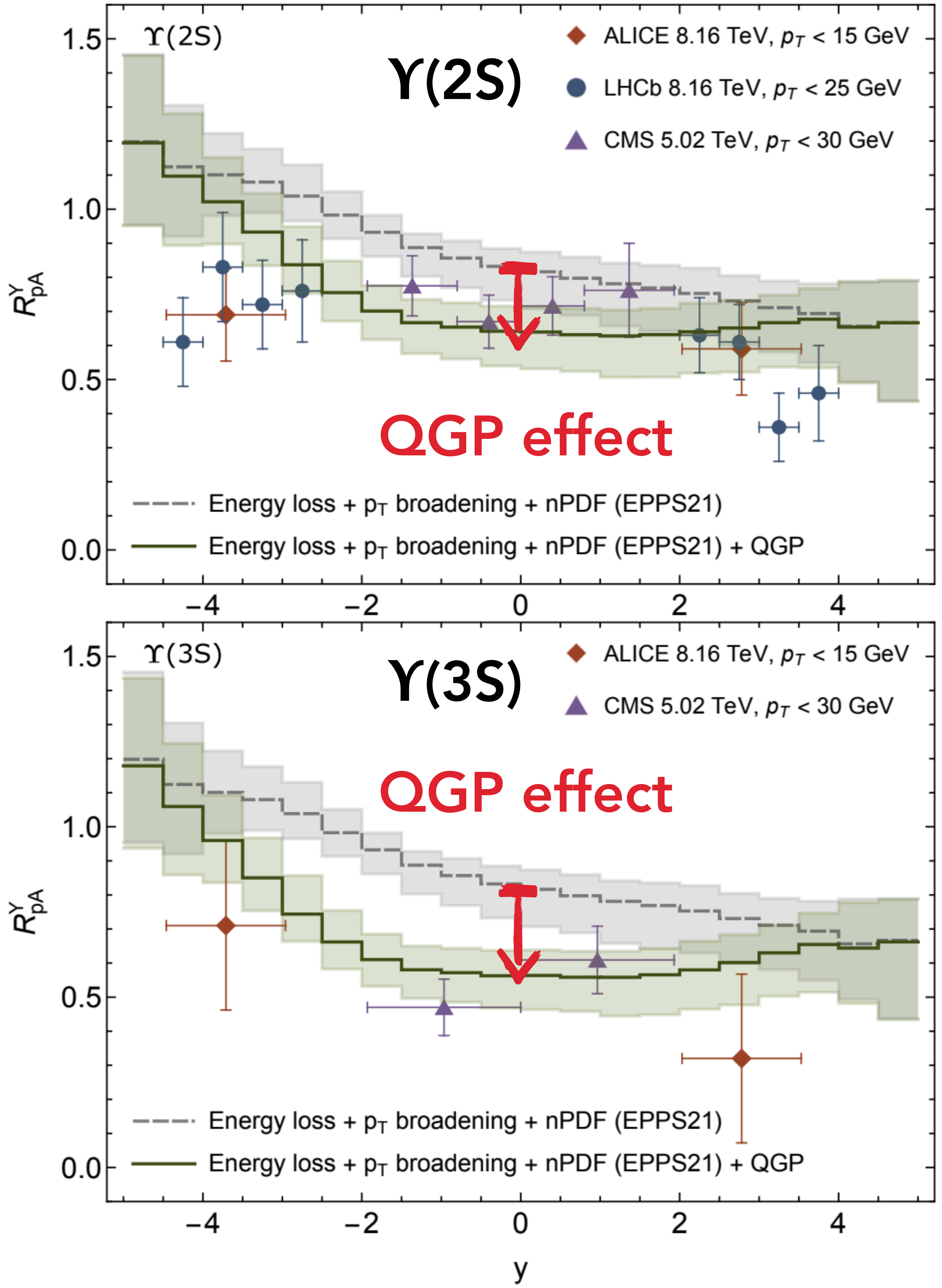


Open questions

- Five quarkonium states at hand, but still a lot to understand to draw a comprehensive picture
  - incomplete feed-down contributions
  - polarization measurements
  - production from jet fragmentation

- **Suppression ordering in proton-nucleus collisions too!**
  - how to conciliate the measurements in both systems?
  - **formation of a deconfined medium?**
    LHC data described by hydro and transport models
    [IJMPA 35 (2020) 29, PRC 107 (2023) 054905, PRC 108 (2023) 014901]

Nuclear modification factor in pPb collisions from OQS + pNRQCD [M. Strickland et al., PRD 109 (2024) 9]

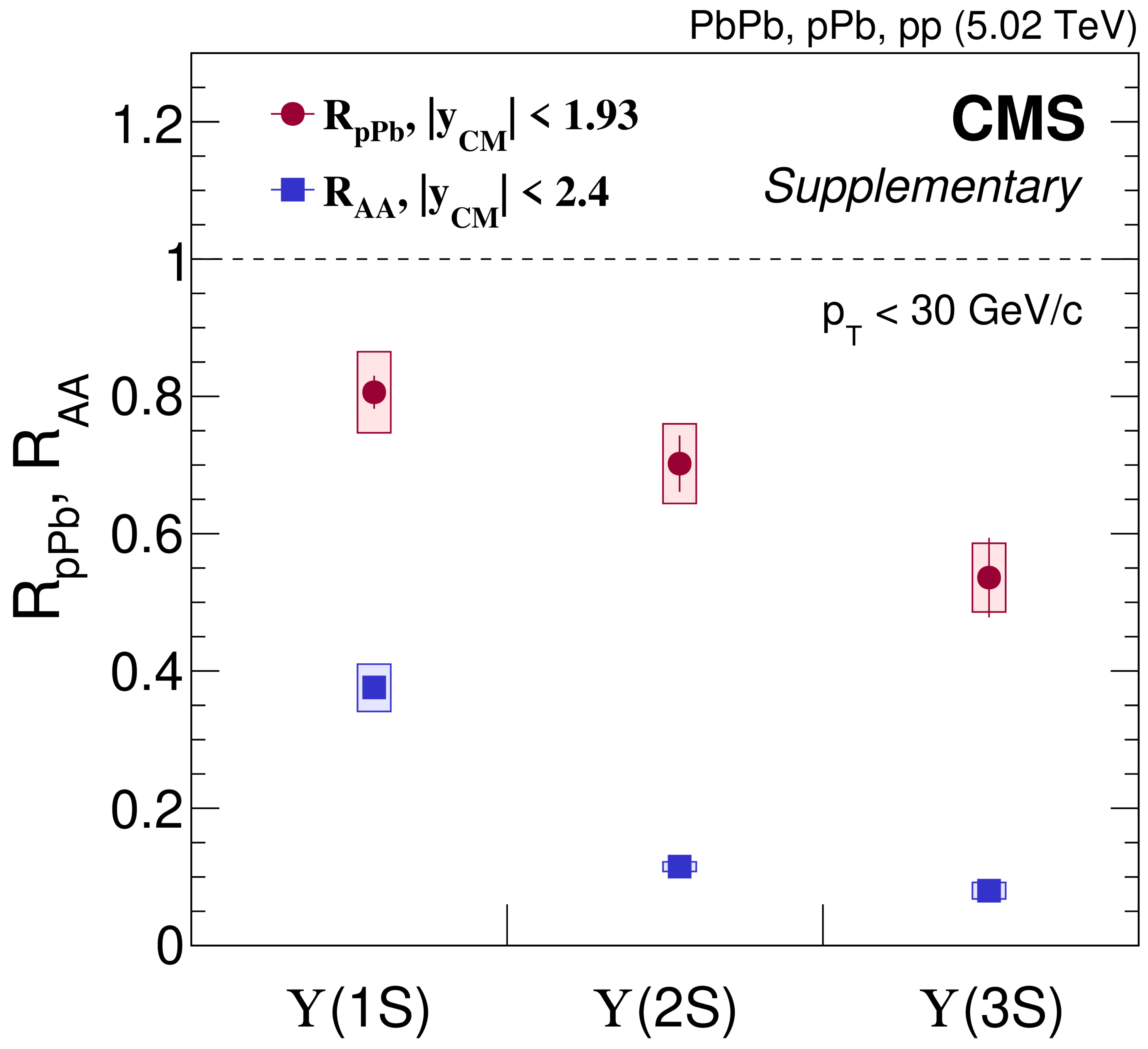


Take-away messages

PLB 825 (2022) 137397, arXiv:2303.17026

Bottomonia are privileged observables to study the **interactions and formation of bound states in hot QCD matter**

- **most precise measurements on ϒ production in all collision systems from CMS**
- suppression hierarchy extended to the ϒ(3S) meson over a large phase space in AA collisions
- significant in-medium production of excited states from **correlated recombination of beauty quarks**
- intriguing similarities in pPb data questioning on the potential formation of QGP phases in small systems



Outlook

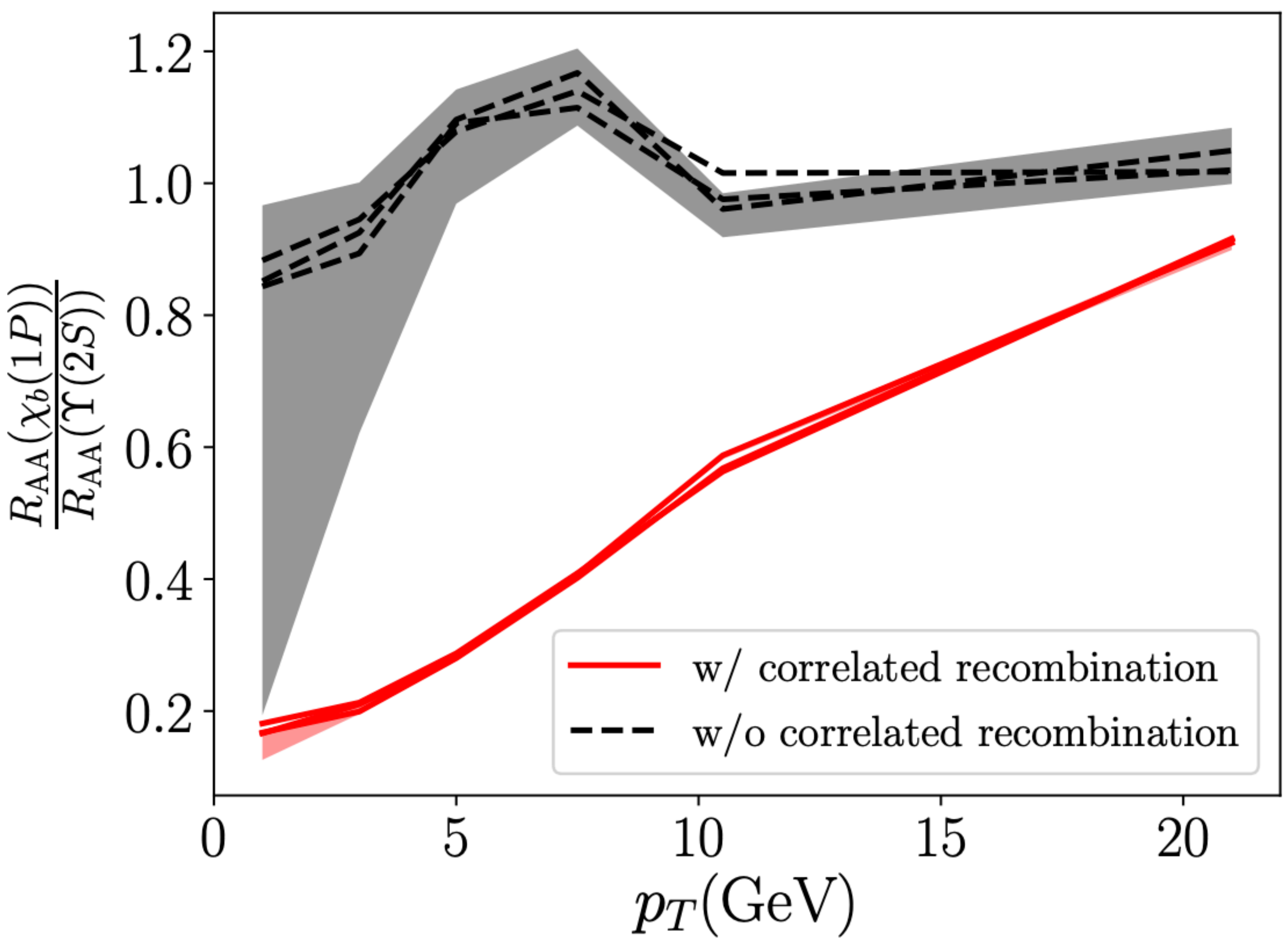
Overall L_{int} ~5 nb^{-1} of PbPb data by the end of Run 3

- differential studies with ϒ(1S) + extension to high p_T
- update of measurements for excited states
- search for P-wave state signal
  - ☛ complete feed-down patterns
  - ☛ decisive test for the correlated recombination

Almost new detector for Run 4 and beyond!

- investigation of other states thanks to hadron PID
- novel observables? physics cases for light ion runs? bring your ideas!

Predictions for the relative suppression of χ_b(1P) and ϒ(2S) [X. Yao et al., JHEP 01 (2021) 046]



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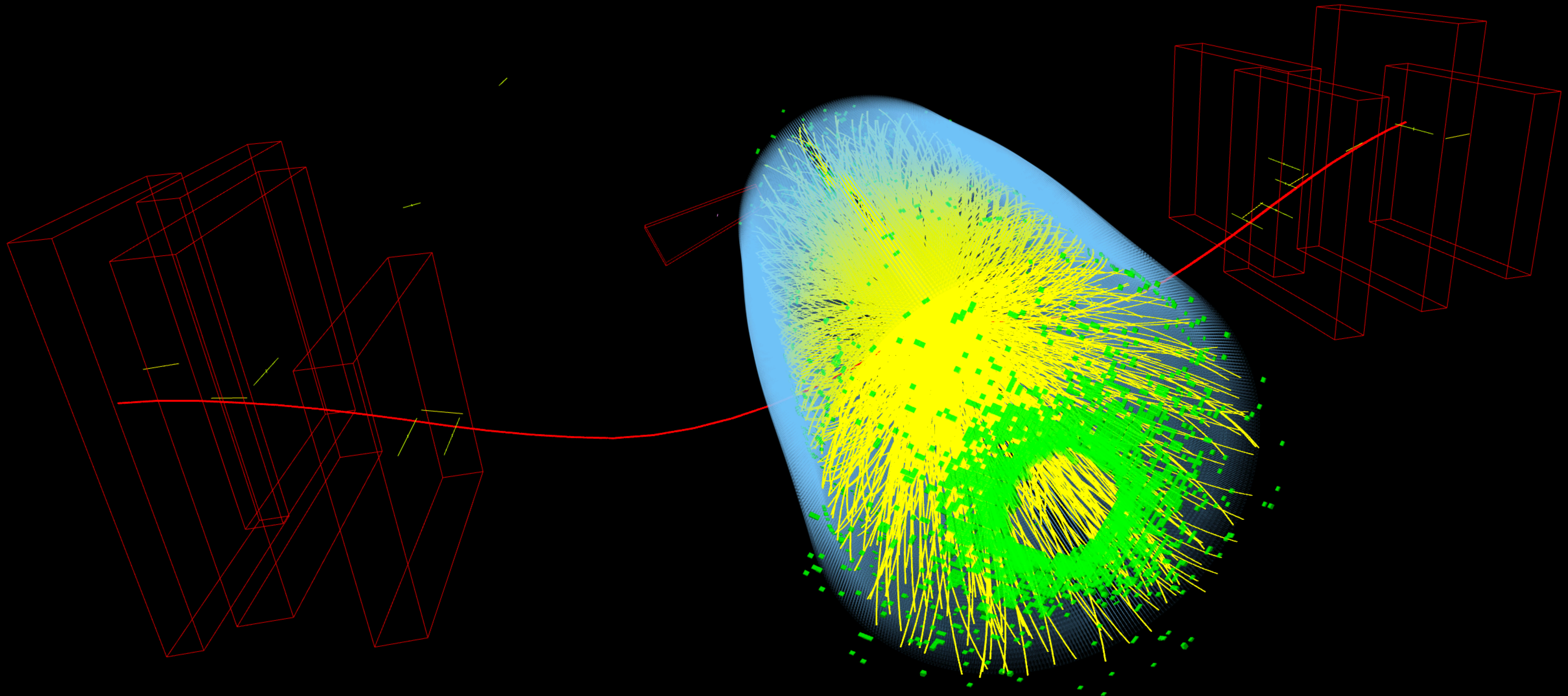


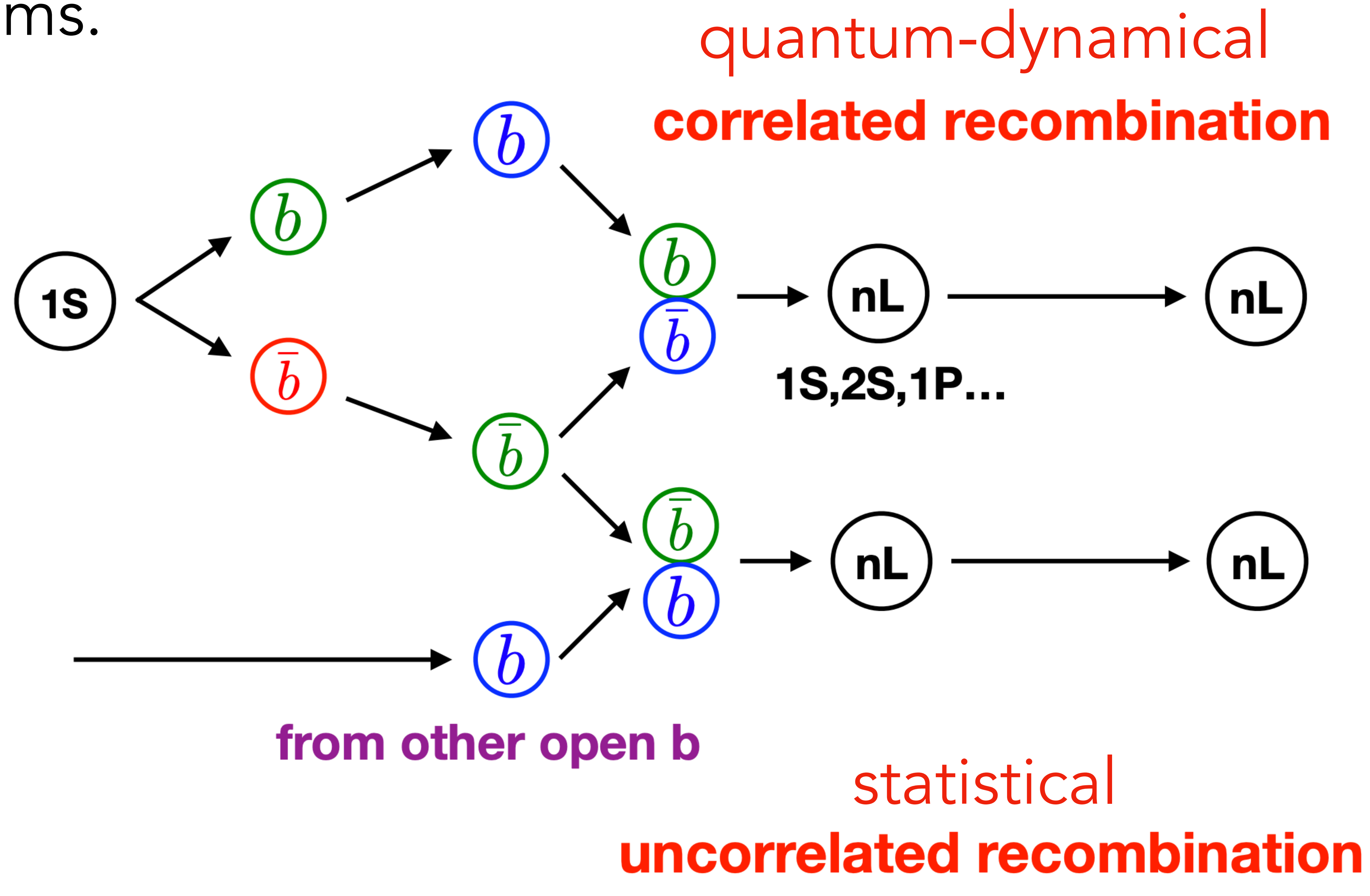
Supplementary material ahead!

References to learn further

- *Heavy Quarkonium in Extreme Conditions*, A. Rothkopf, Physics Reports 858 (2020) 1
- *Open quantum systems for quarkonia*, X. Yao, Int. Journal of Modern Physics A 36 (2021) 20
- *Comparative study of quarkonium transport in hot QCD matter*, EPJA 60 (2024) 4
- Recent theoretical overview talks: M.A. Escobedo @ Quark Matter 2023, J.Zhao @ SQM 2024, R. Rapp @ QNP 2024

Dissociation *vs* recombination

Interactions of heavy quarks with their environment
can counteract the quarkonium suppression mechanisms.



Correlated recombination

inverse process where a heavy quark-antiquark pair emits a gluon and forms a bound state again

☛ **reshuffling of the population of states!**

Uncorrelated recombination (or ``regeneration”)

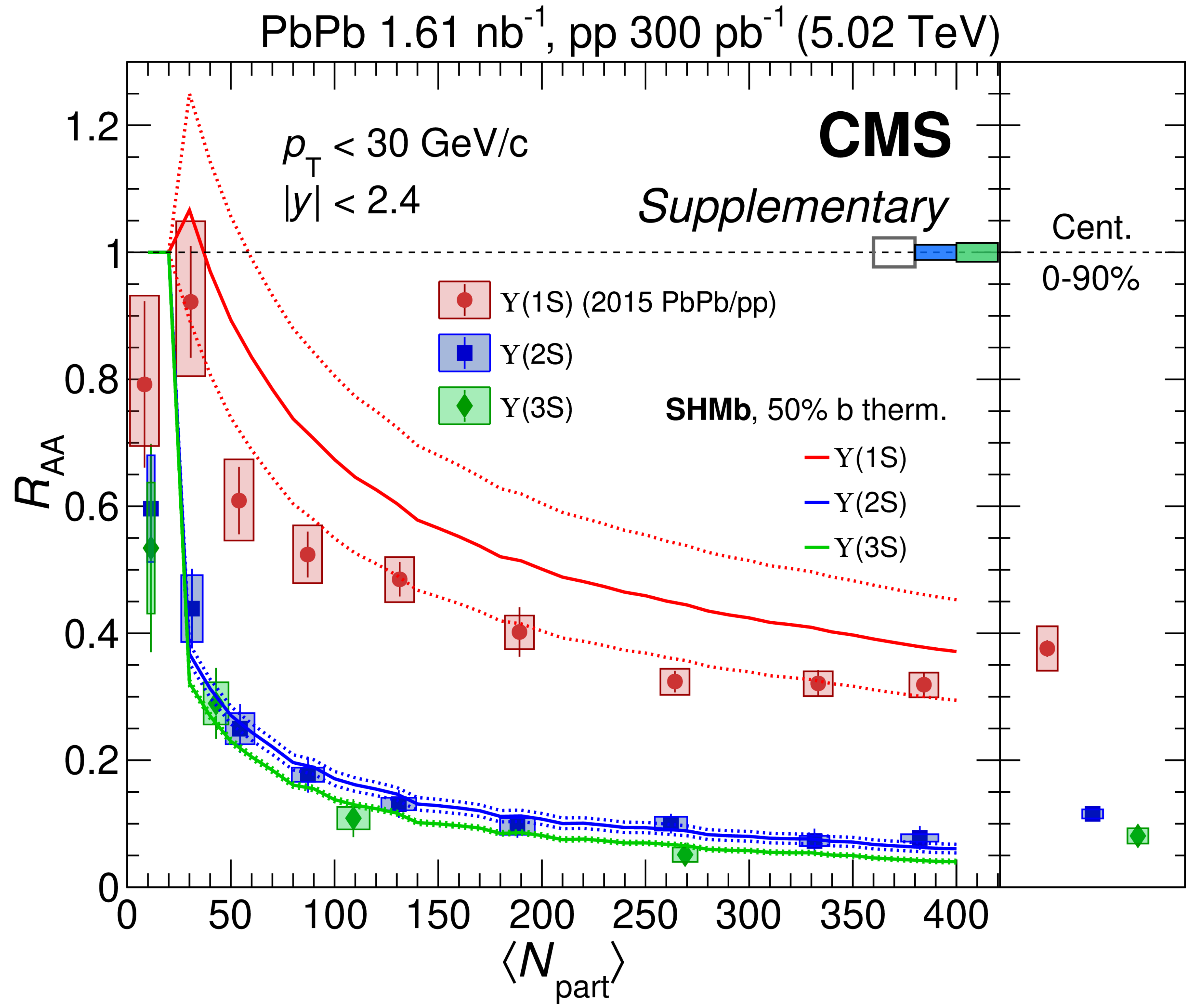
two heavy quarks produced independently
create quarkonia via coalescence as the medium cools down

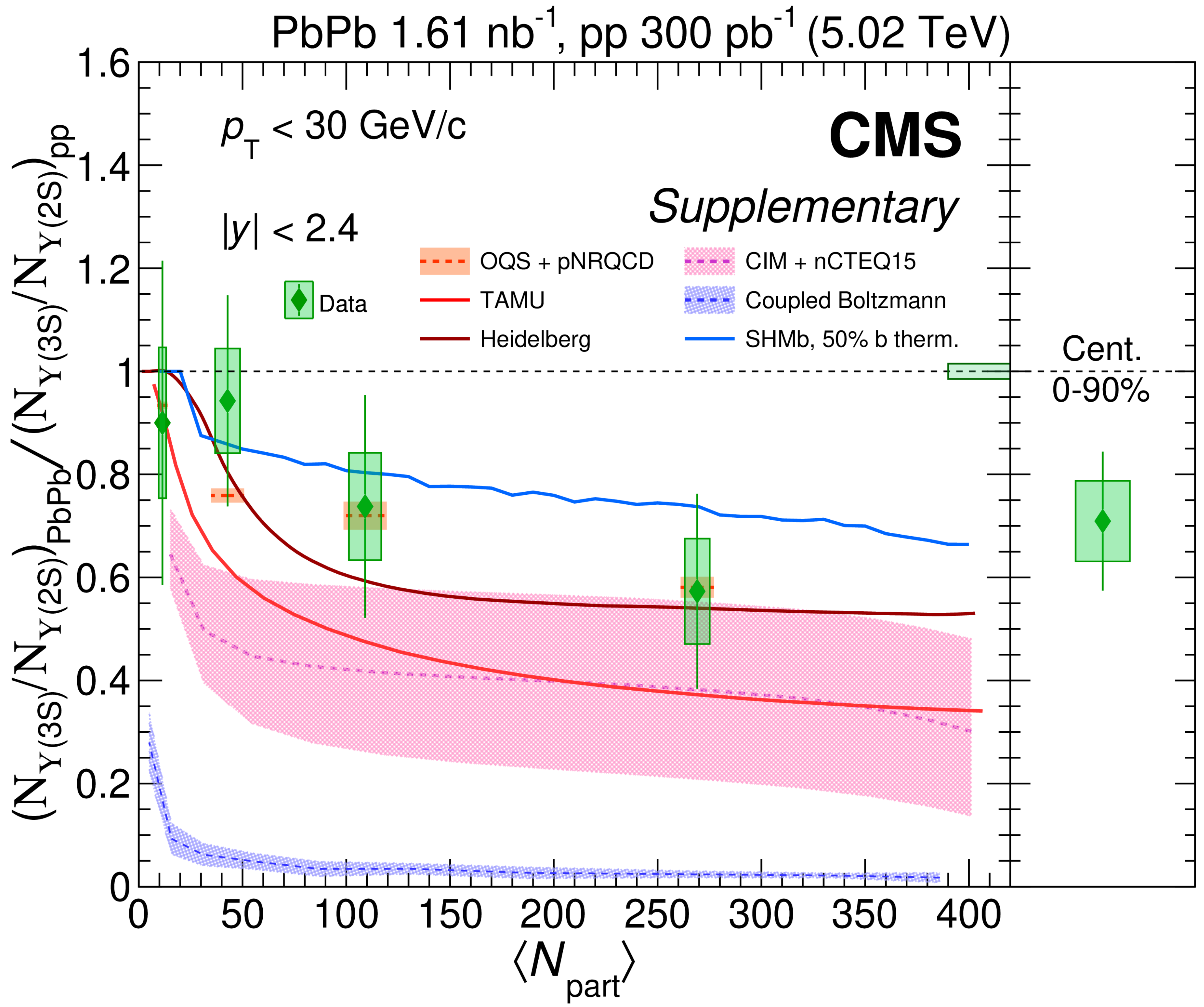
☛ **statistical enhancement prominent for charmonia at the LHC!**

sketch from Xiaojun Yao

Statistical Hadronization model [Nature 561 (2018) 7723]

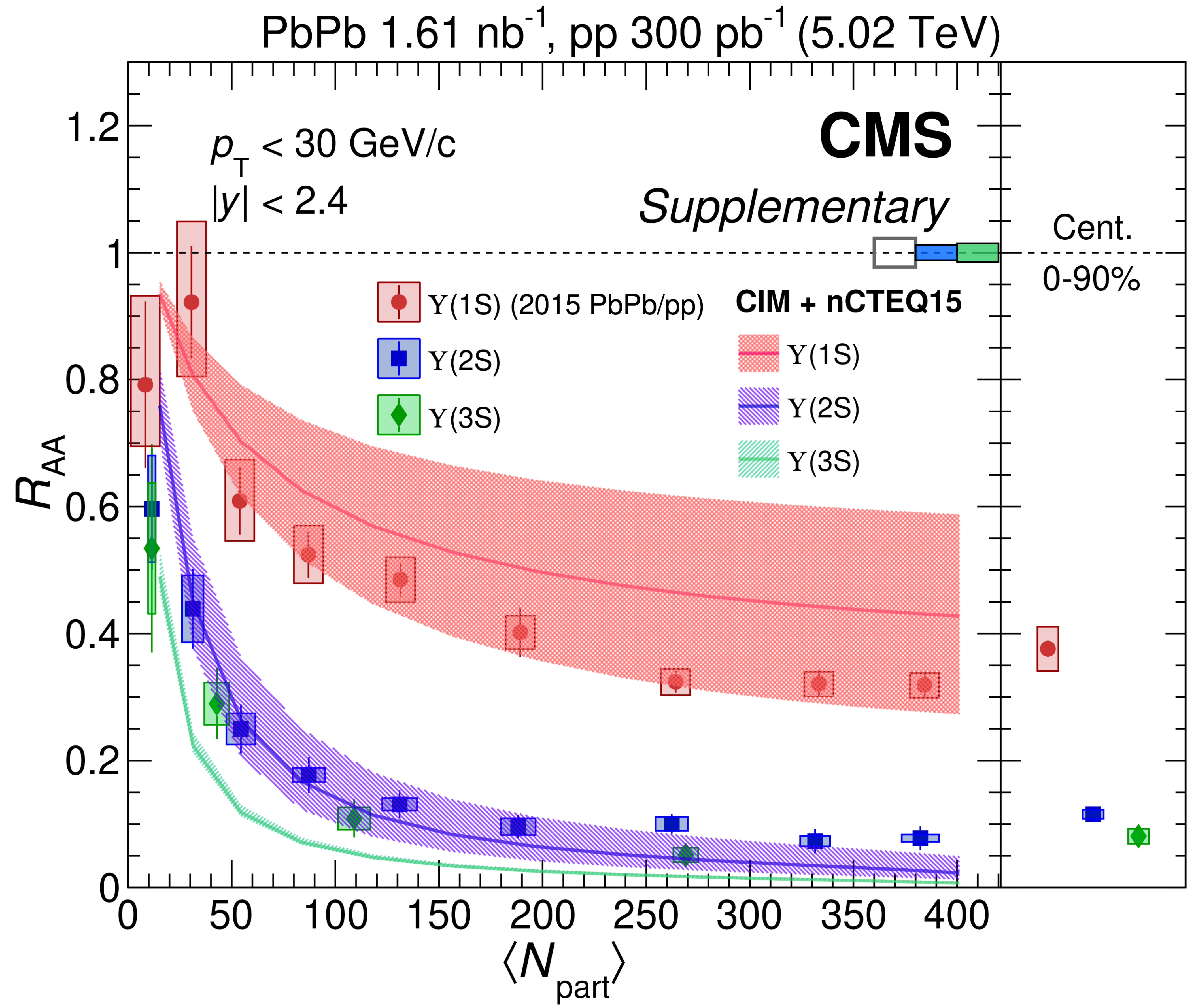
- All hadrons are produced at chemical freeze-out with yields based on thermal weights, heavy quarks reaching (partial) thermalization via kinetic equilibration inside the QGP
- pp cross section + shadowing factor as inputs

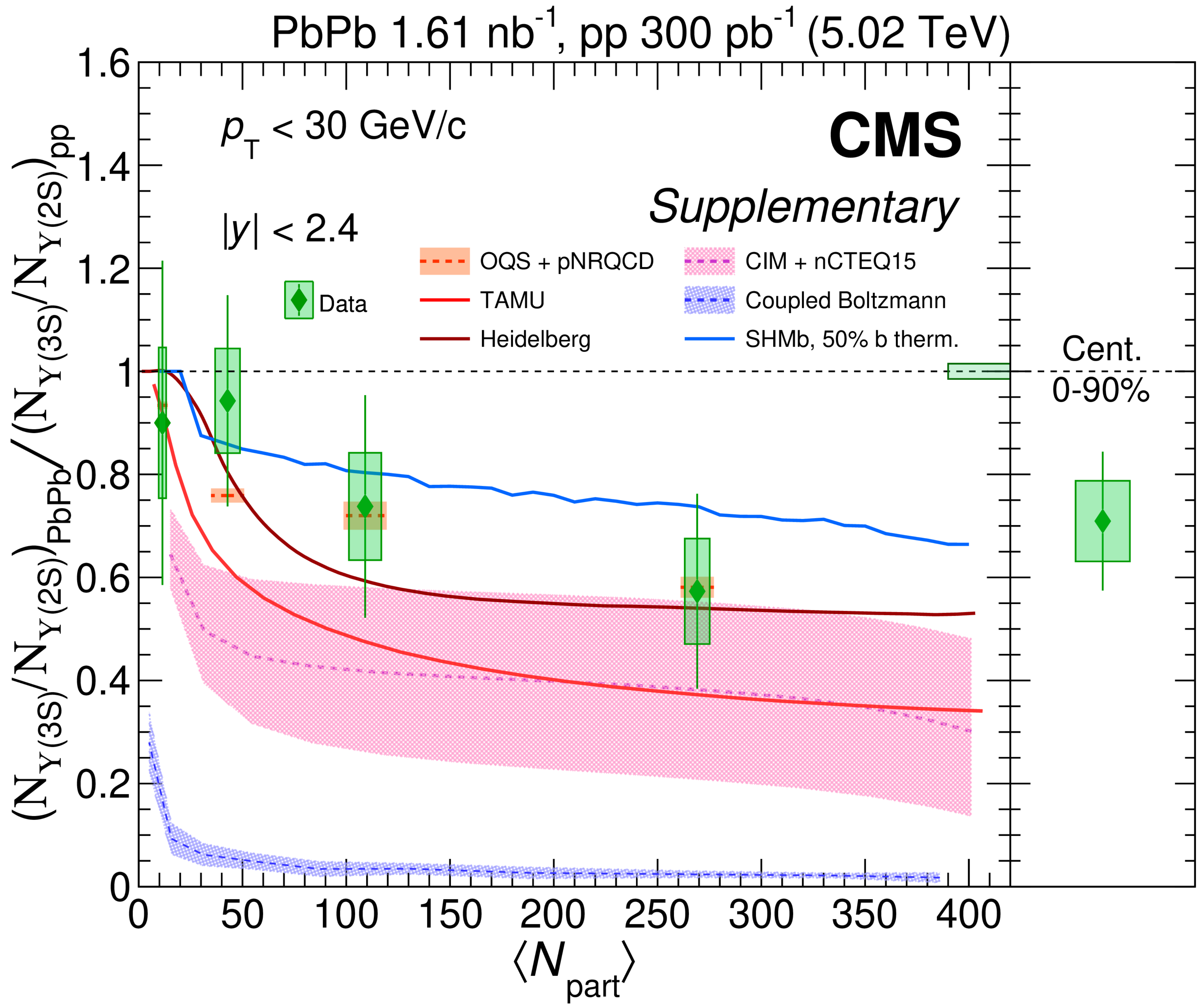




Comover Interaction Model [JHEP 10 (2018) 094]

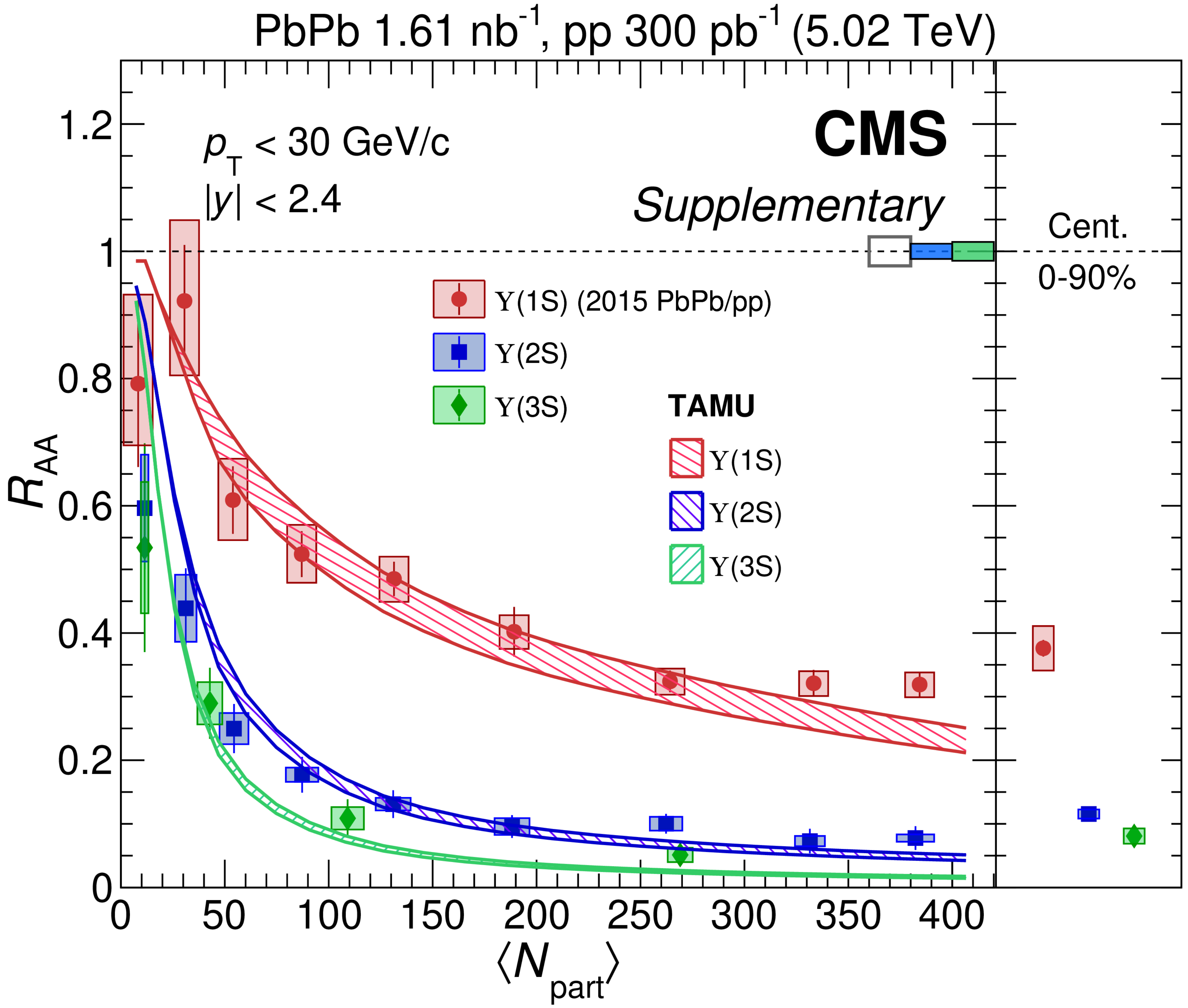
- Quarkonium suppression from scatterings with surrounding particles in the final state
- nCTEQ15 nPDF parametrisation for initial-state modification (gluon shadowing)
- Aims to describe pPb and PbPb data from the same assumptions

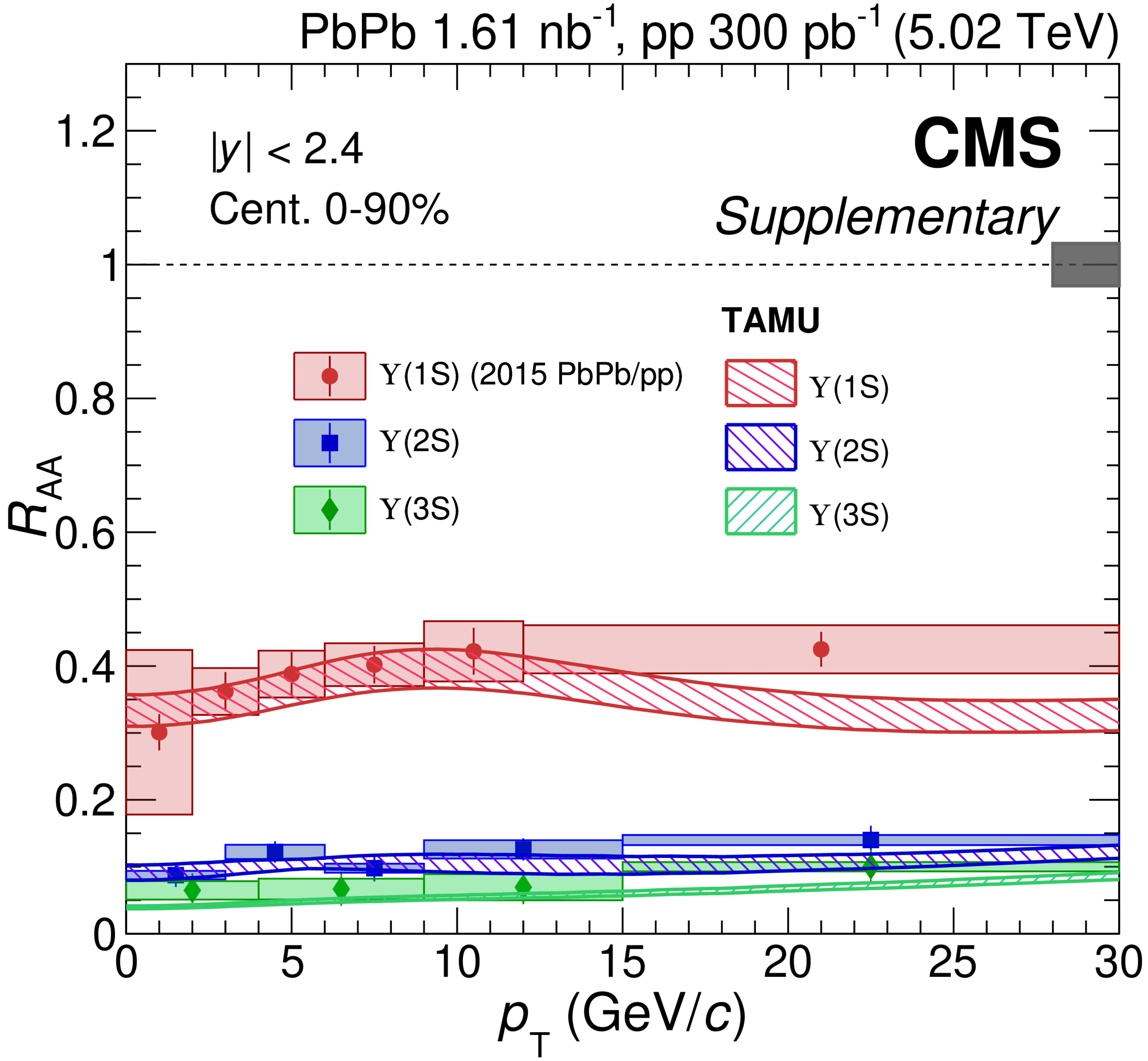




TAMU transport model [PRC 96 (2017) 054901]

- In-medium dissociation and recombination processes
- Isotropic fireball with lattice QCD based equation of state + effective absorption
- Undershoots the data for the most central collisions

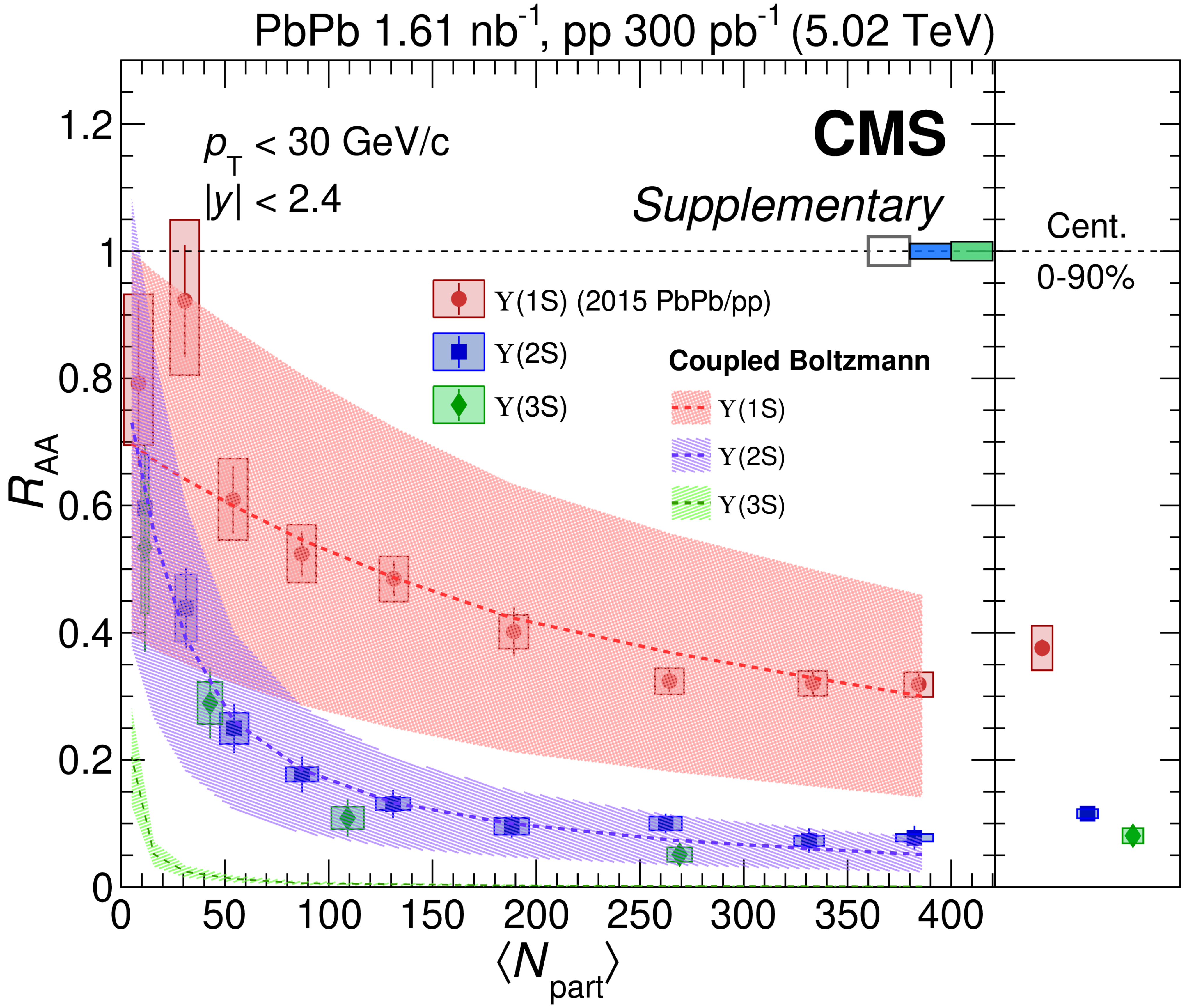




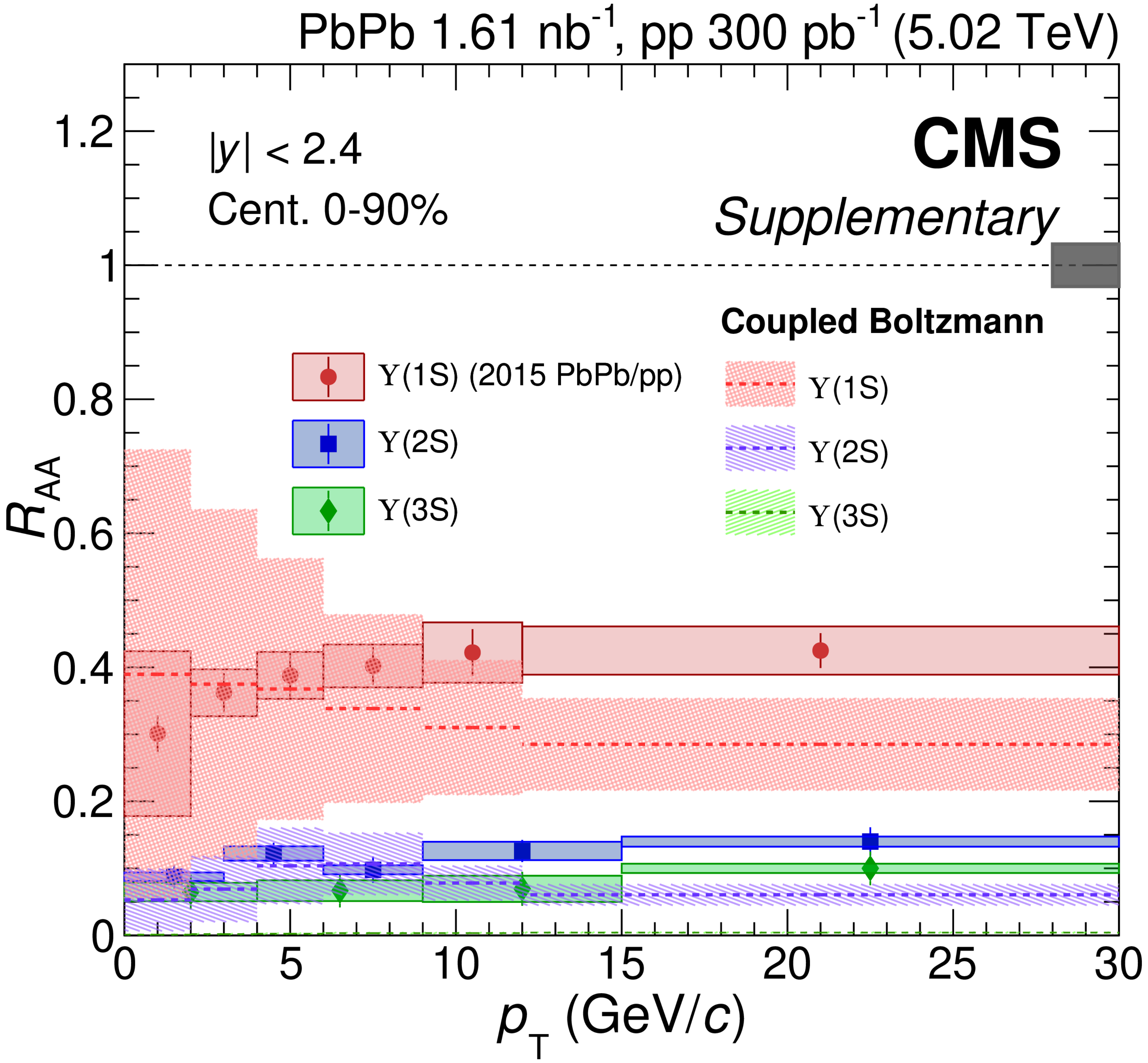
Coupled Boltzmann Equations [JHEP 01 (2021) 046]

- Continuous dissociation and recombination of heavy-quark pairs through the QGP evolution
- 2+1D viscous hydrodynamics for medium description, EPPS16 nPDF for initial HQ modification

No regeneration for Υ(3S)

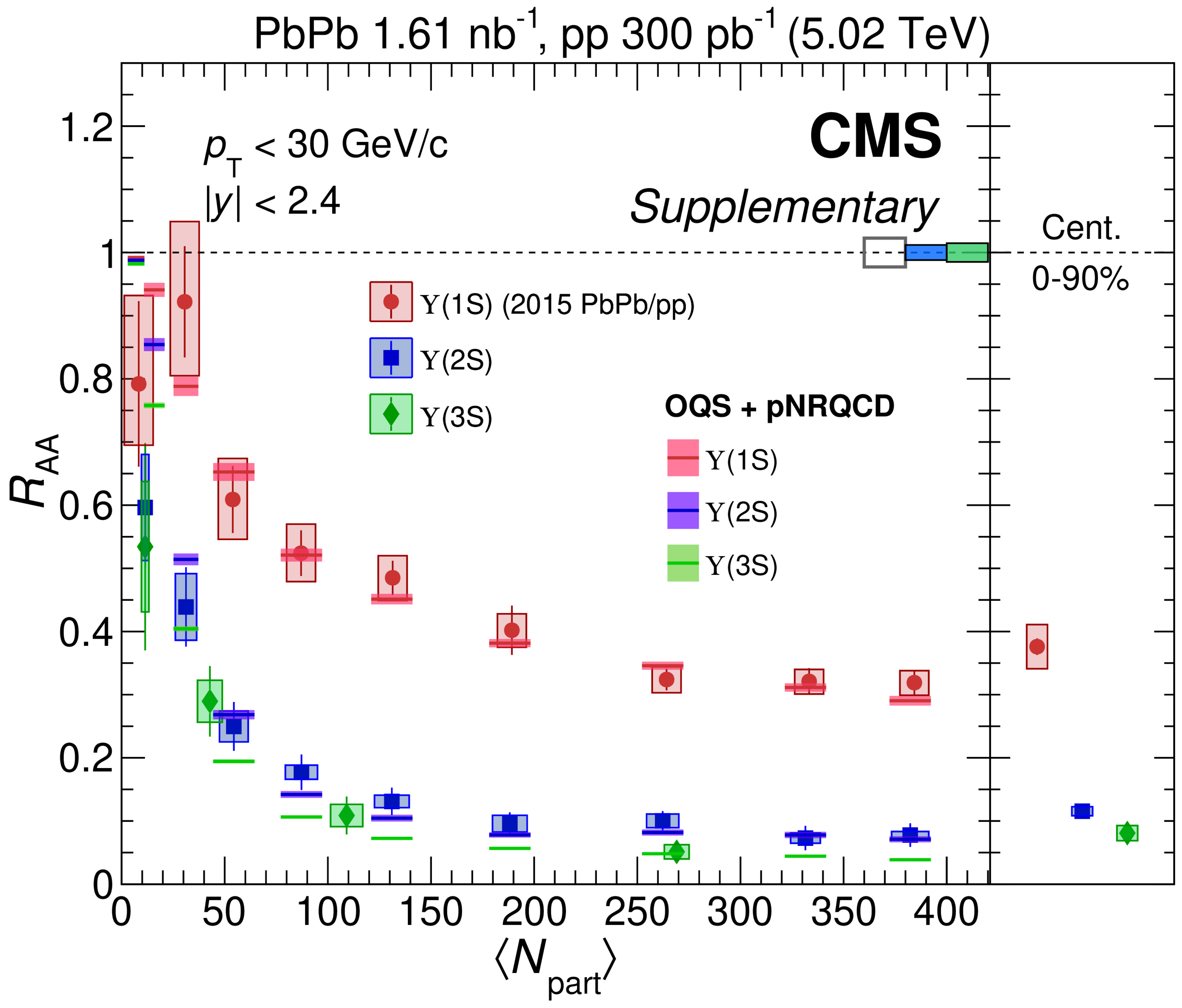


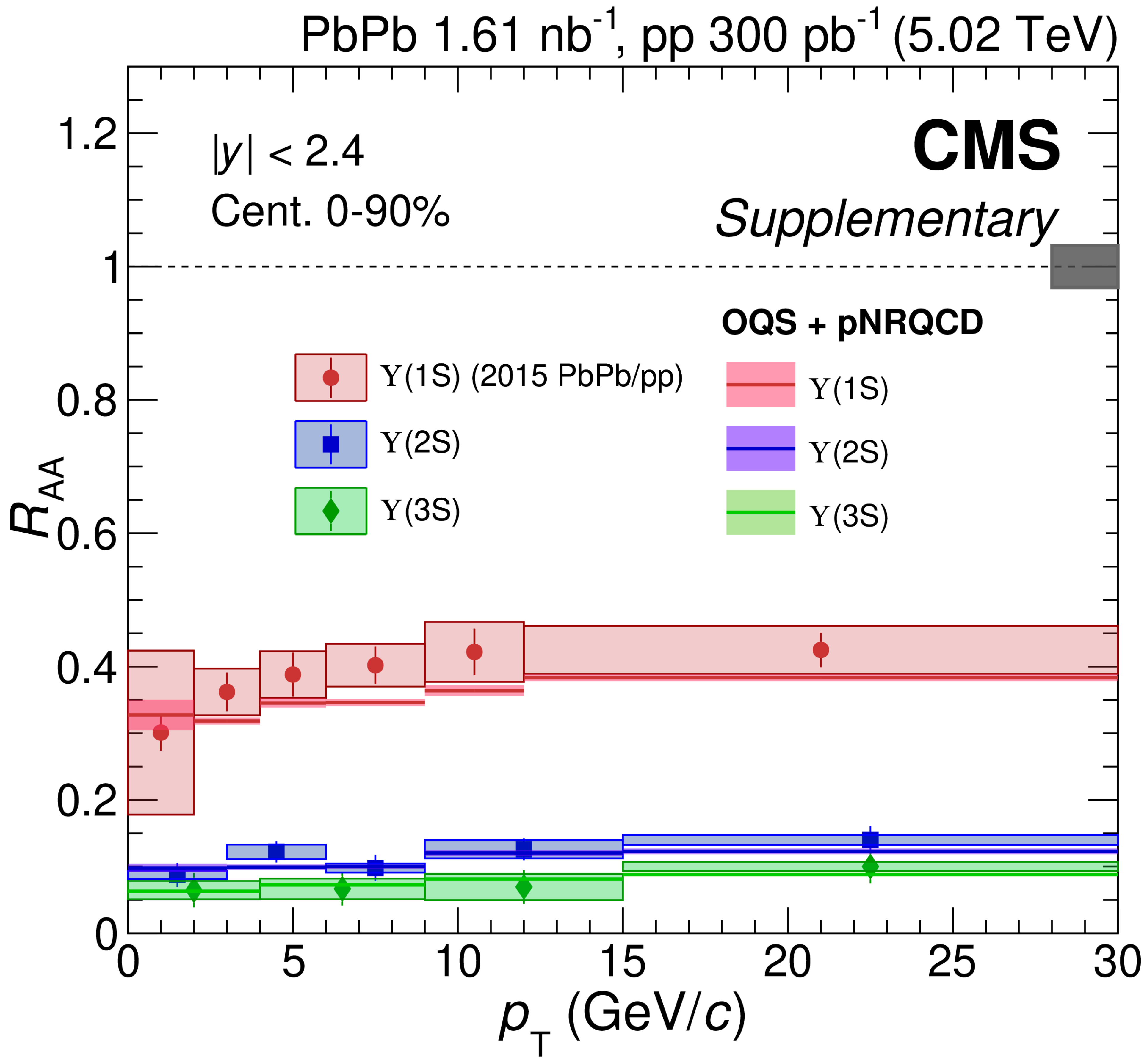
Breakdown of NRQCD formalism at high p_T?



Open-Quantum System [PRD 104 (2021) 094049]

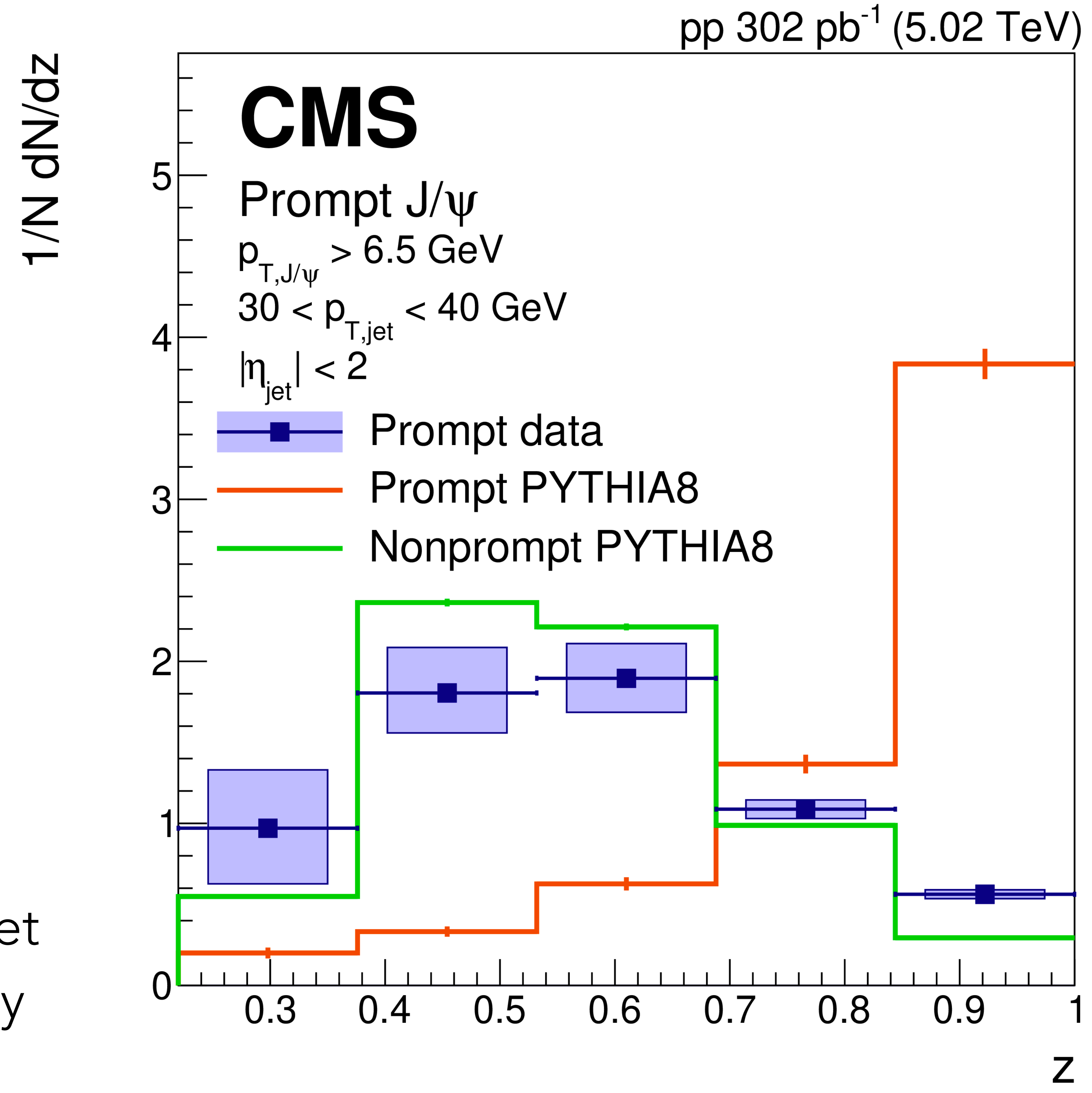
- Continuous dissociation and recombination through the QGP evolution (Linblad equation)
- 3+1D anisotropic hydrodynamics to model the bulk expansion

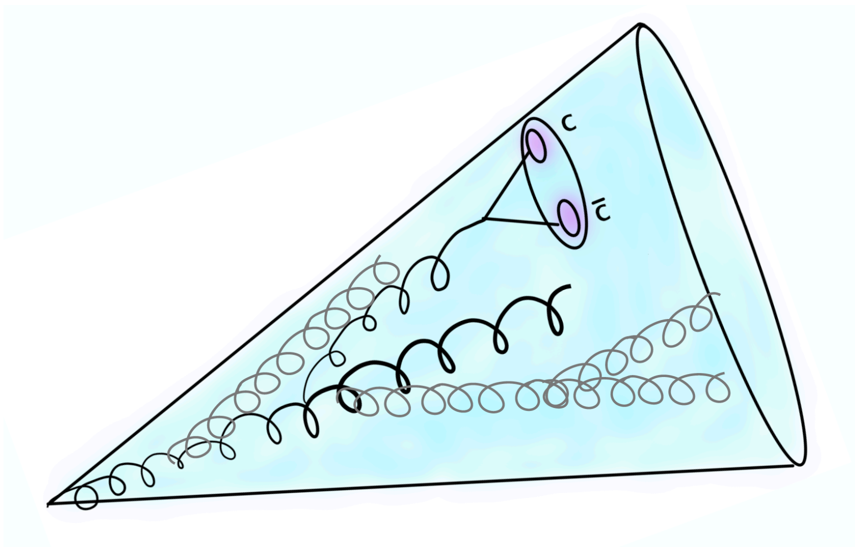


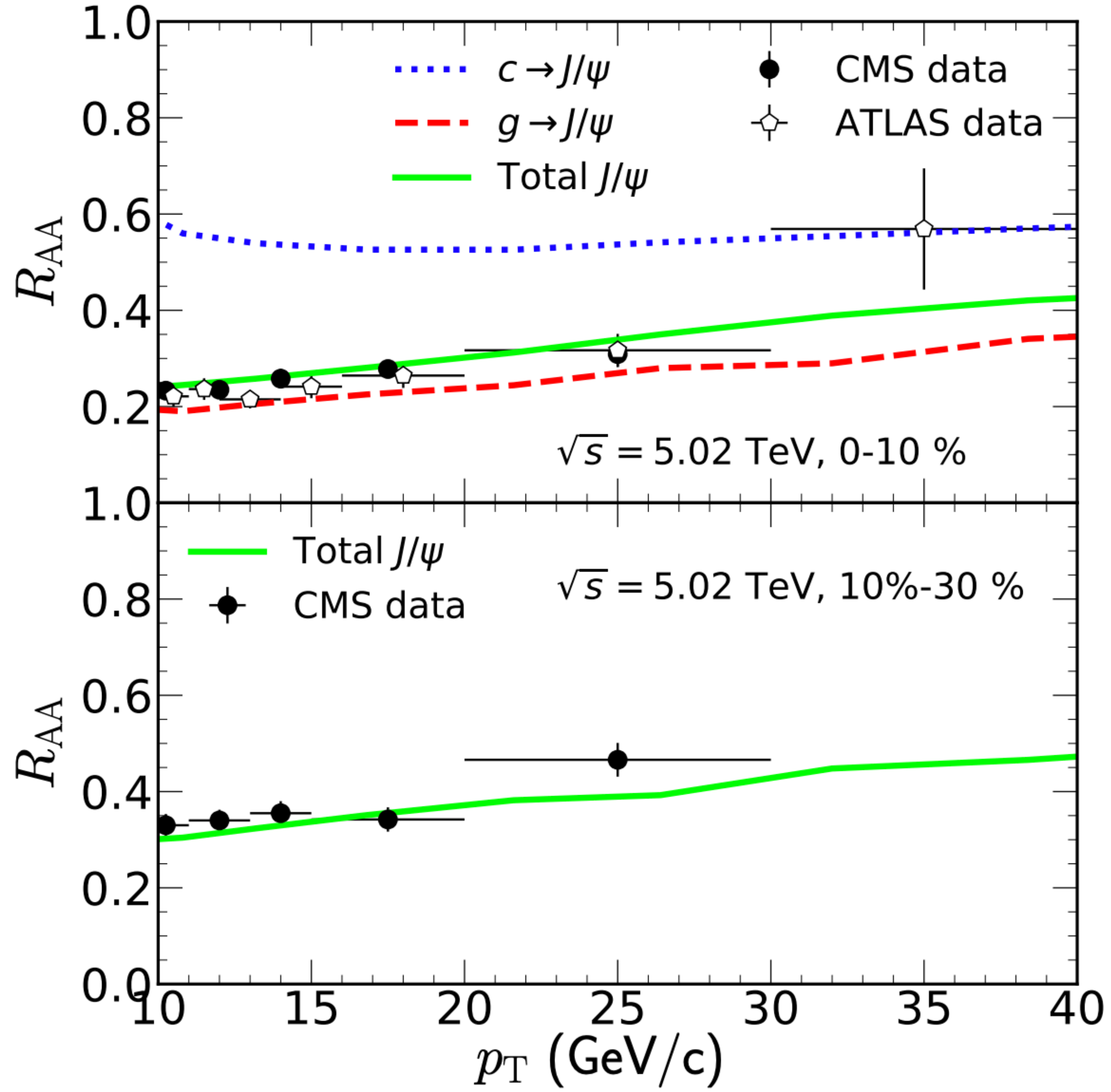


Quarkonium production inside jets

- Prompt J/ψ comes with large jet activity ☛ delayed formation of quarkonia inside jets
- In-medium parton energy loss prior to fragmentation into heavy-quark bound states







large jet activity

isolated J/ψ

J/ψ-jet fragmentation variable **z = p_T (J/ψ) / p_T (jet)**

S-L Zhang et al., Science Bulletin 68 (2023) 2003