Production of Υ mesons in PbPb collisions with CMS

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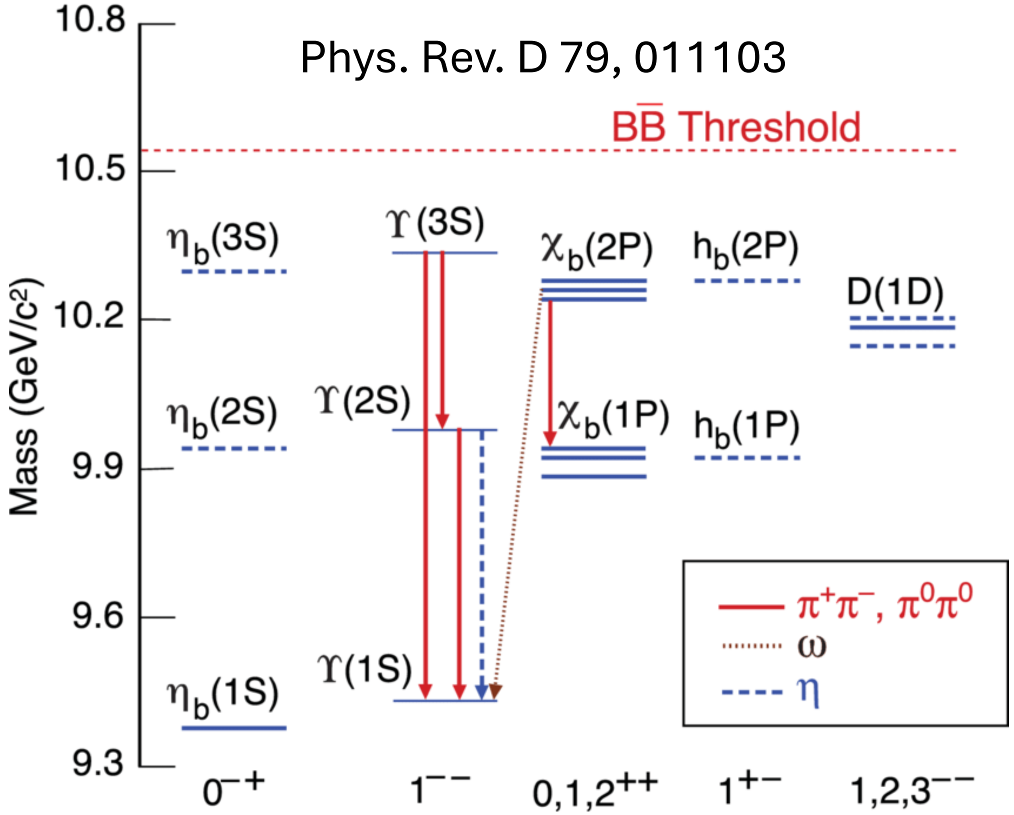
Outline

- **Motivation:**
  - Quarkonia as probes of QGP
  - Quarkonia modification in heavy-ion collisions

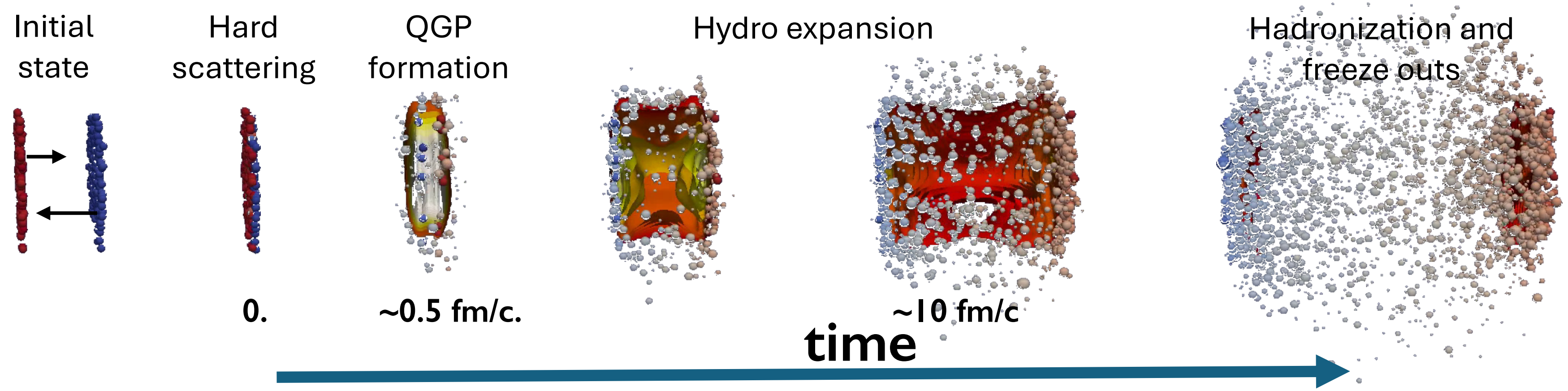
- **CMS experiment:**
  - Muon performance across collision systems
  - Quarkonia detection in CMS

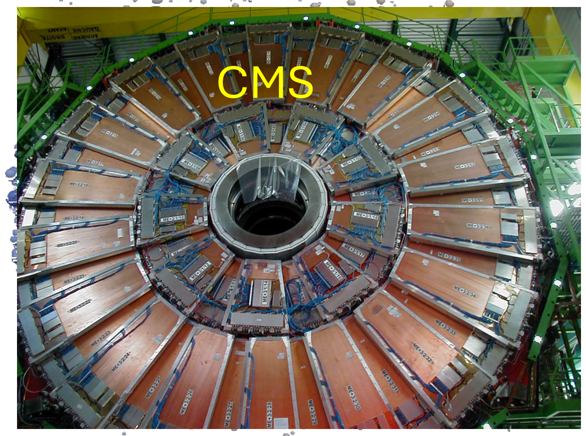
- **Bottomonium states in PbPb collisions:**
  - R_{AA} vs. $\langle N_{part} \rangle$ vs. p_T
  - Double ratio $\Upsilon(3S)/\Upsilon(2S)$ in PbPb and pp
  - Binding energies
  - Model comparisons

- **Summary**



Probing QCD matter with Quarkonia





Ultimate goal: *establishing a comprehensive picture of the in-medium microscopic interactions and formation of bound states of heavy quarks from QCD first principles*

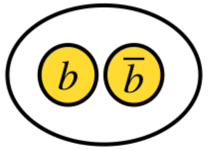
- ❑ Production of heavy quarks from hard initial scatterings ($2m_Q \gg T_{medium} > \Lambda_{QCD}$)
- ❑ Formation time of $Q\bar{Q}$ bound states < emergence of a QGP phase (~0.5 fm/c)
- ❑ Debye screening in QGP leads to sequential melting as per the binding energy
- ❑ Correlated/uncorrelated recombination of $Q\bar{Q}$ pairs in QGP

Major advances in this area are achieved due to much larger cross-section (compared to lower energies), coupled with excellent capabilities of LHC detectors!

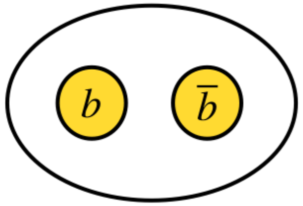
Bottomonia in heavy ion collisions

Upsilon spectroscopy

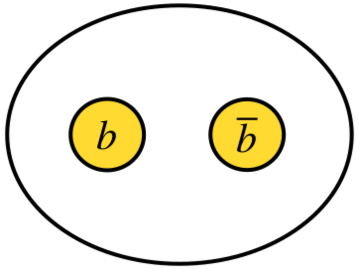
$\Upsilon(1S)$: 0.28fm



$\Upsilon(2S)$: 0.56fm



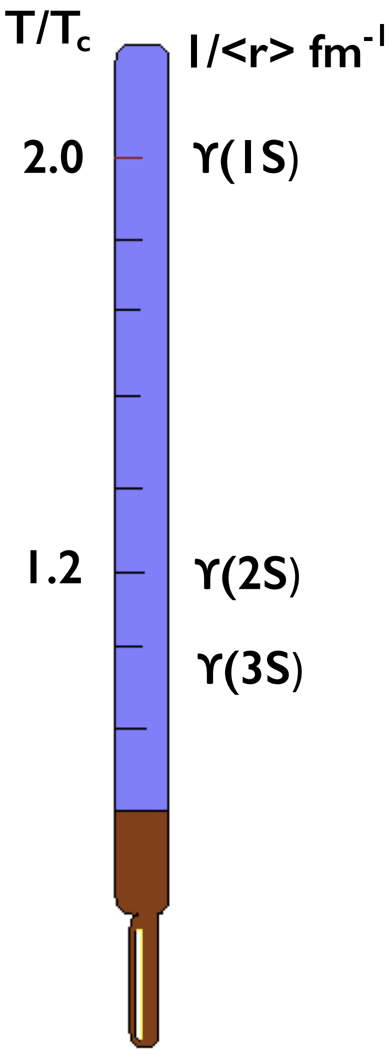
$\Upsilon(3S)$: 0.78fm



Dissociation vs. Recombination

- ***Colour screening:*** Bottomonia cannot exist inside the QGP medium → temperature probe of QGP
- ***Sequential suppression:*** Different radii/binding energies → different suppression
- ***Recombination:*** Bottomonia formed in the QGP by combination of $b\bar{b}$ pairs
- Only very small statistical enhancement compared to charmonia

Provide constraints to dynamical models including dissociation and recombination

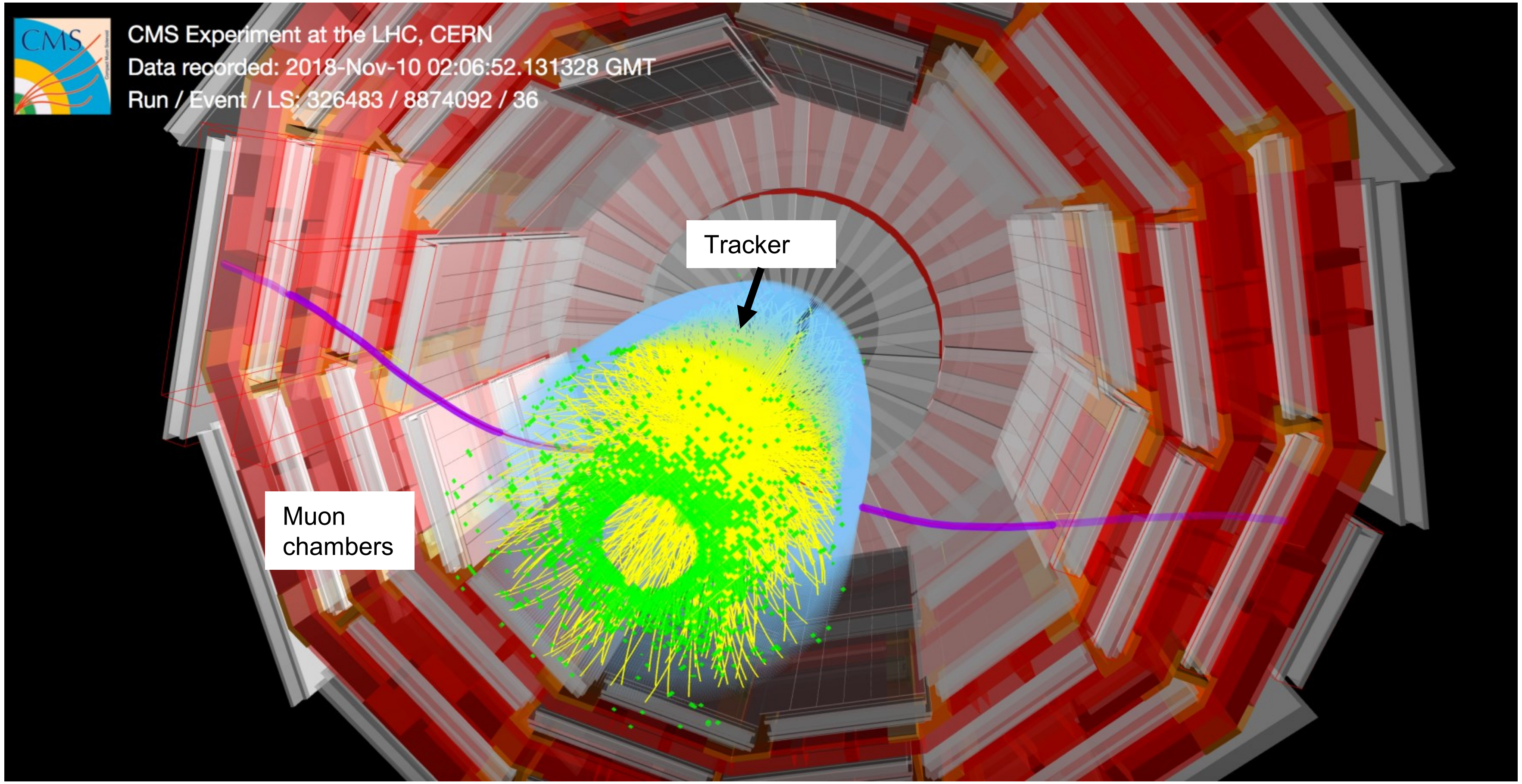


Measurement of quarkonia in CMS

- Quarkonia detected via dimuon decay channel: $Q \rightarrow \mu^{+} \mu^{-}$

- Detecting muons:
  - $|\eta| < 2.4$, $p_T \gtrsim$ 1-4 GeV
  - Inner tracker
  - Muon chambers

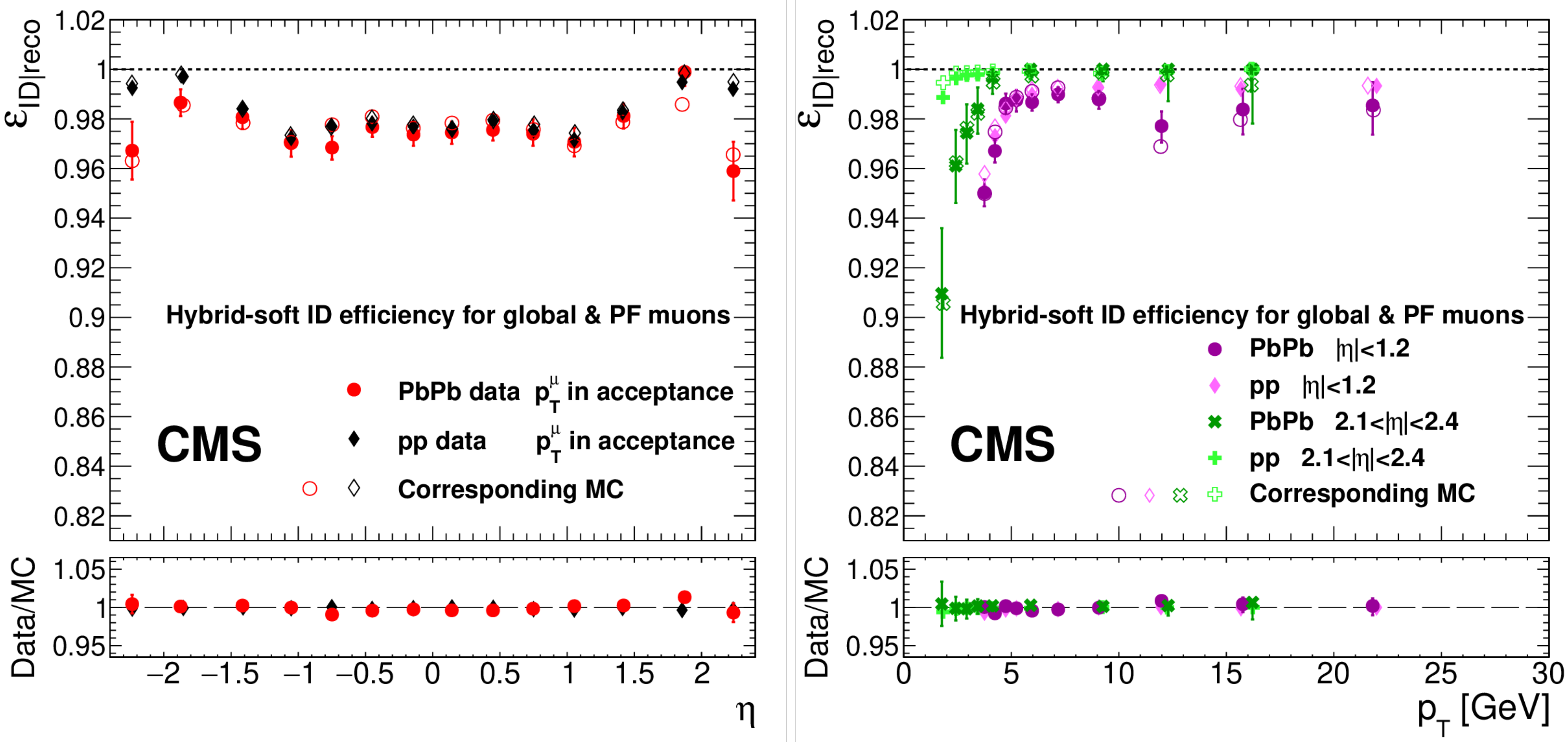
- ϒ candidate in Pb-Pb collisions 5.02 TeV (Nov – Dec 2018)
  - Measured from $p_T = 0$ GeV



- Large coverage for muons ⇒ wide coverage and better resolution for Quarkonia

- Data driven measurement of muon reconstruction, identification and triggering eff

arXiv:2404.17377



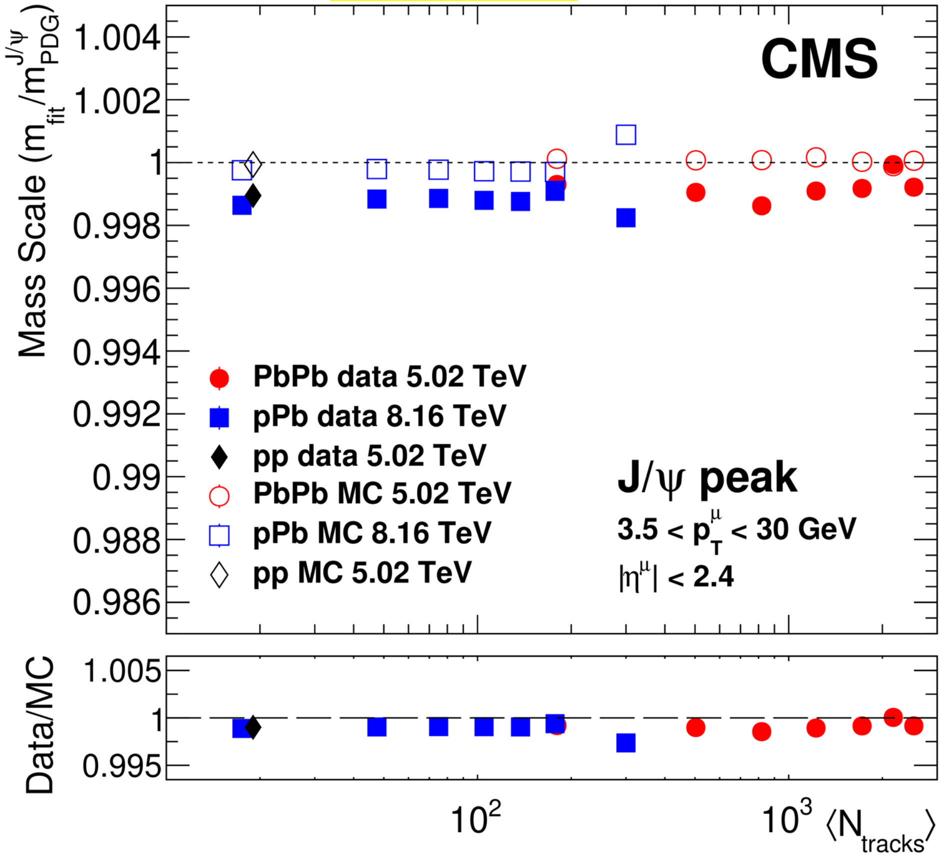
- Muon identification: PbPb performance is very good, comparable to pp
- Well described by MC simulations

Muon performance from pp to PbPb in CMS

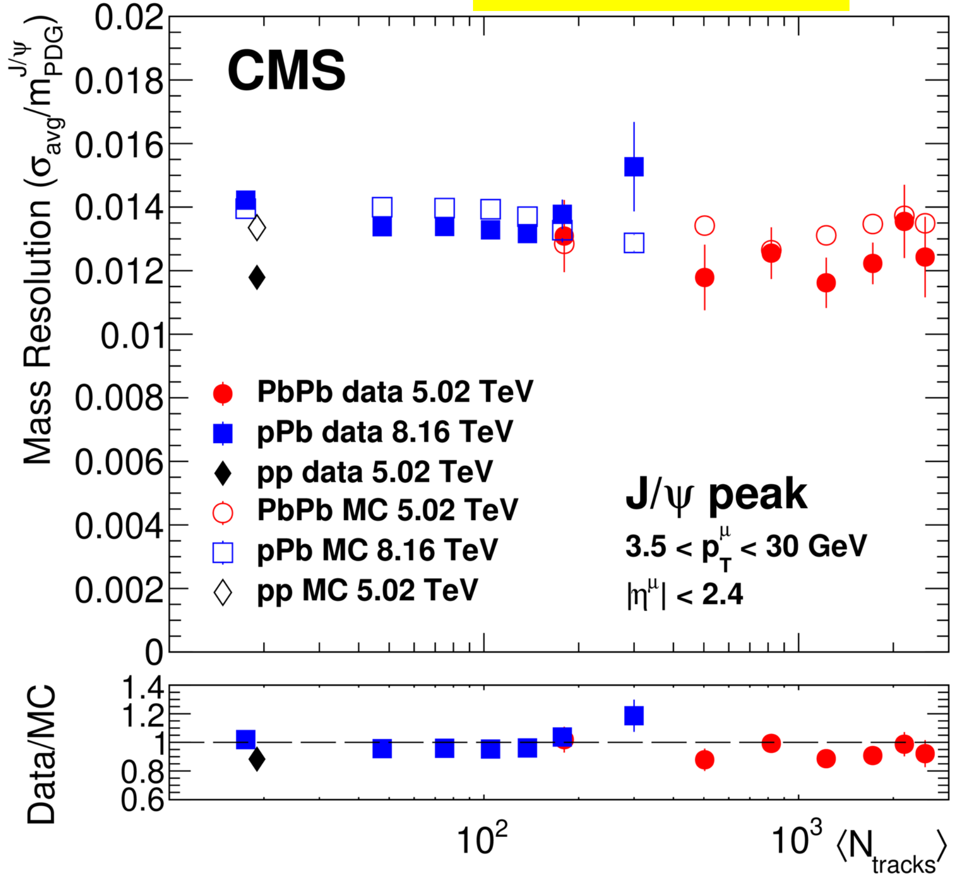
- ❑ Mass scale and resolution stable among all systems
- ❑ No dependency on detector occupancy
- ❑ Excellent mass resolution ≈ 1.4% → allowing clear separation of the excited states

arXiv:2404.17377

Mass Scale



Mass Resolution



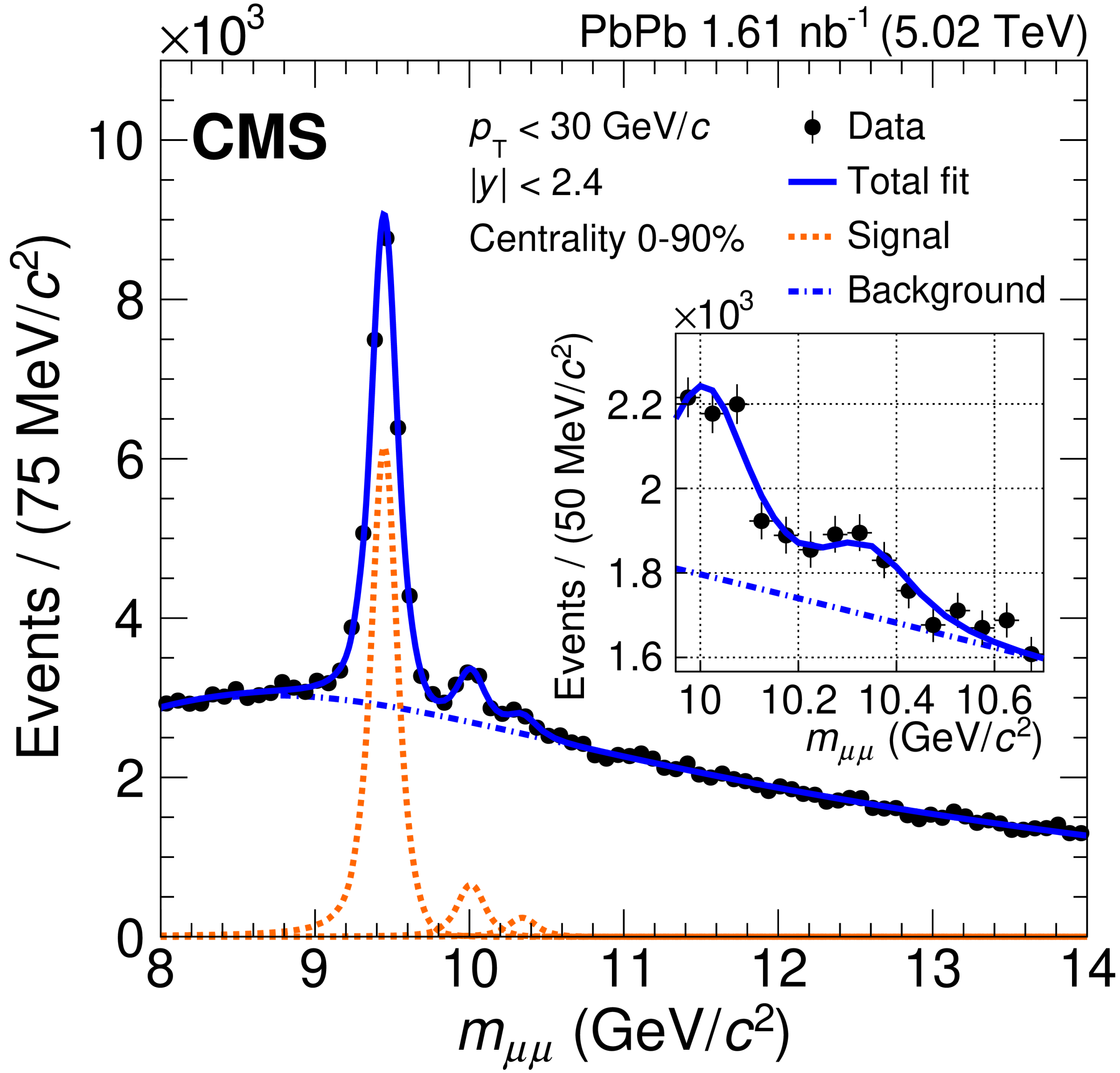
ϒ(3S) state in PbPb

arXiv:2303.17026

Accepted by PRL

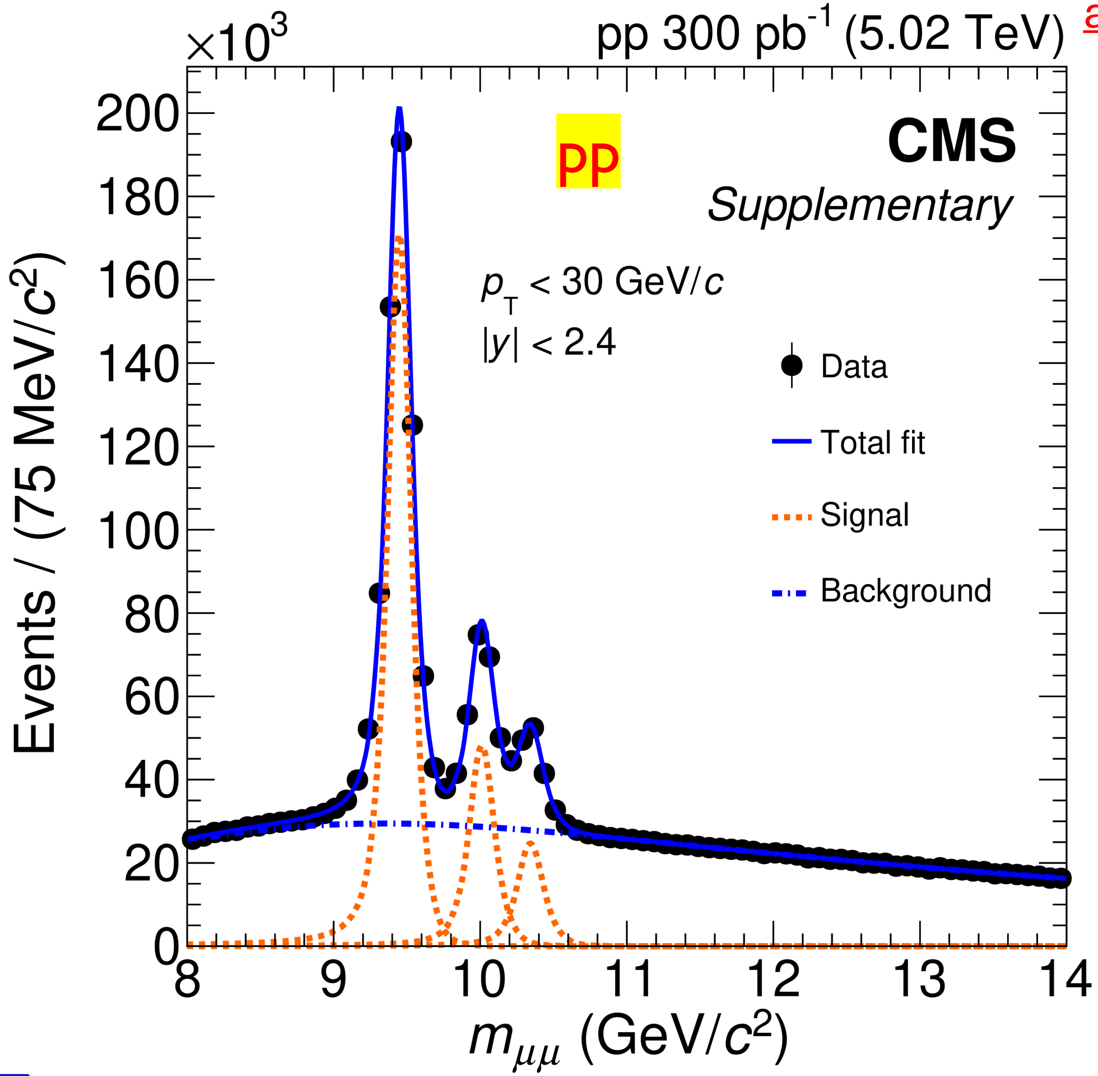
First ever measurement of ϒ(3S) in nucleus-nucleus collisions

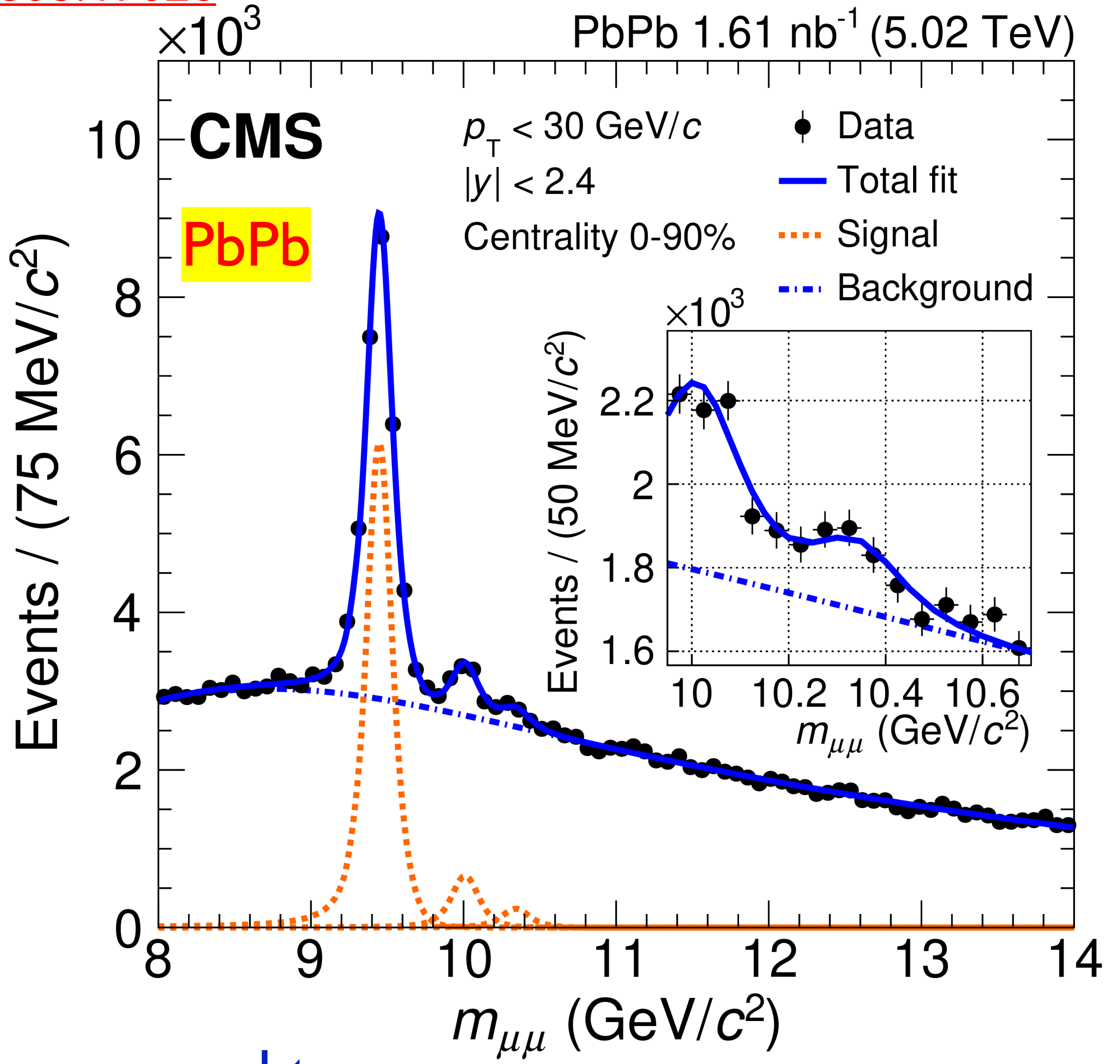
- MVA to improve signal/background ratio
  - Boosted decision trees
  - 5.6σ signal for ϒ(3S)



Bottomonium suppression in PbPb

arXiv:2303.17026



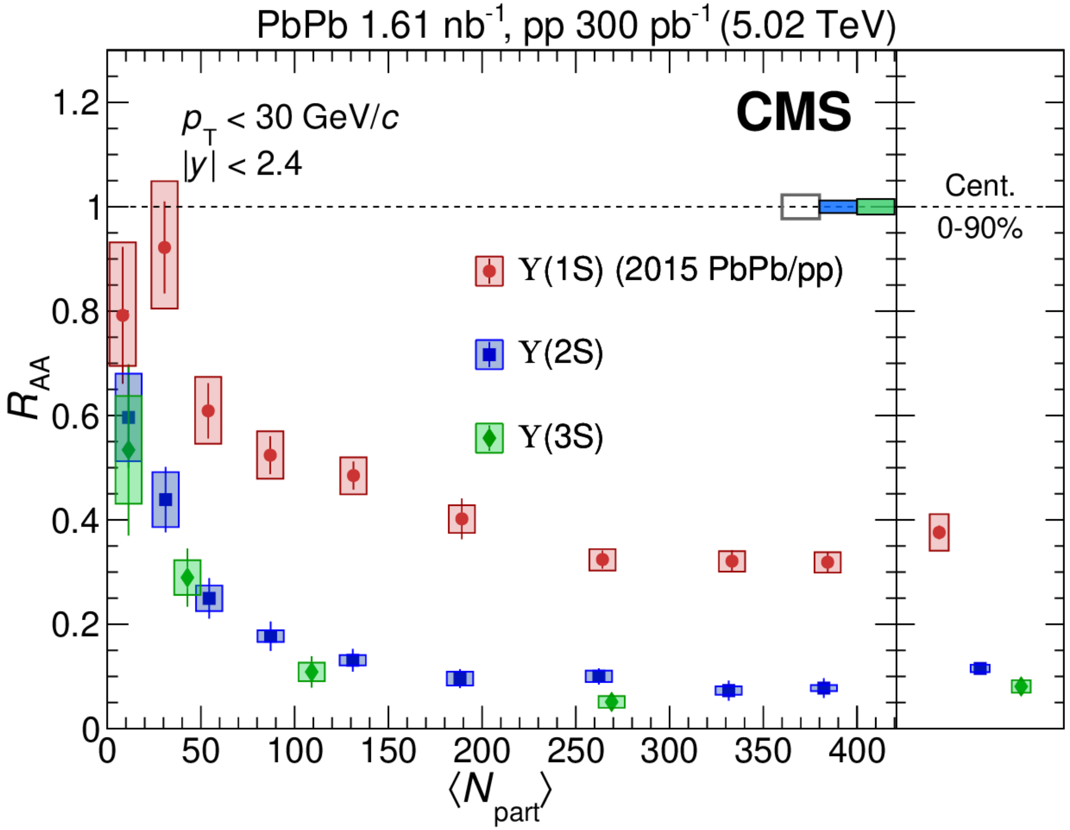


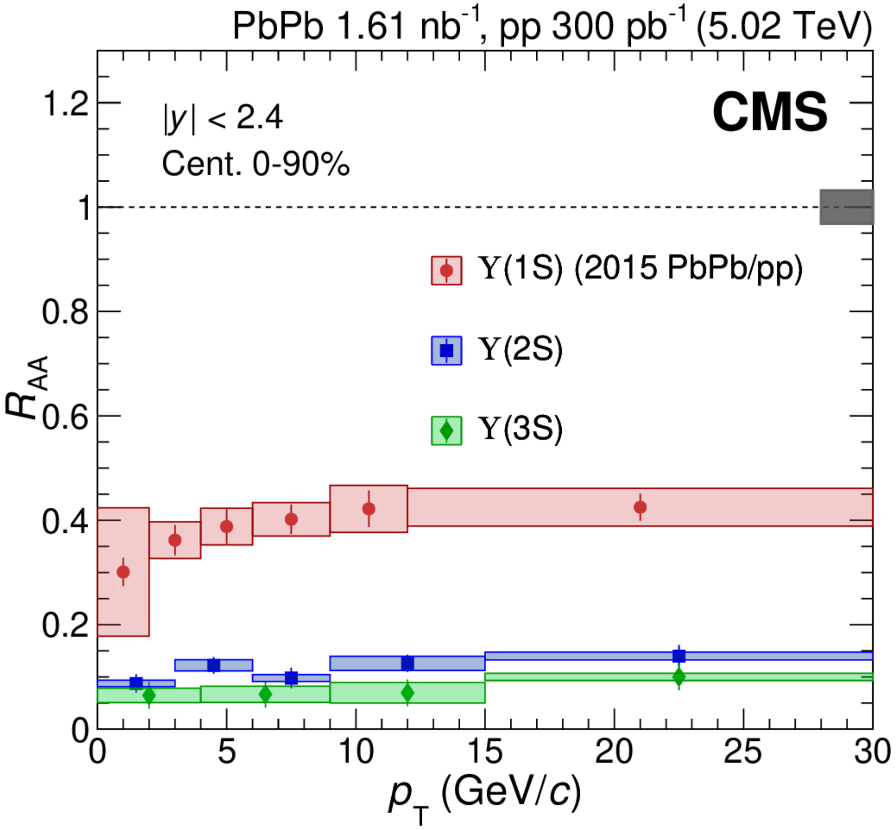
- ϒ(1S) and ϒ(2S) states are suppressed in PbPb compared to pp
- ϒ(3S) almost disappeared in PbPb!

Υ(2S) and Υ(3S) in PbPb

- Υ states are suppressed in PbPb compared to pp collisions
- R_{PbPb} (1S) > R_{PbPb} (2S) > R_{PbPb} (3S) ☞ excited states more suppressed

arXiv:2303.17026



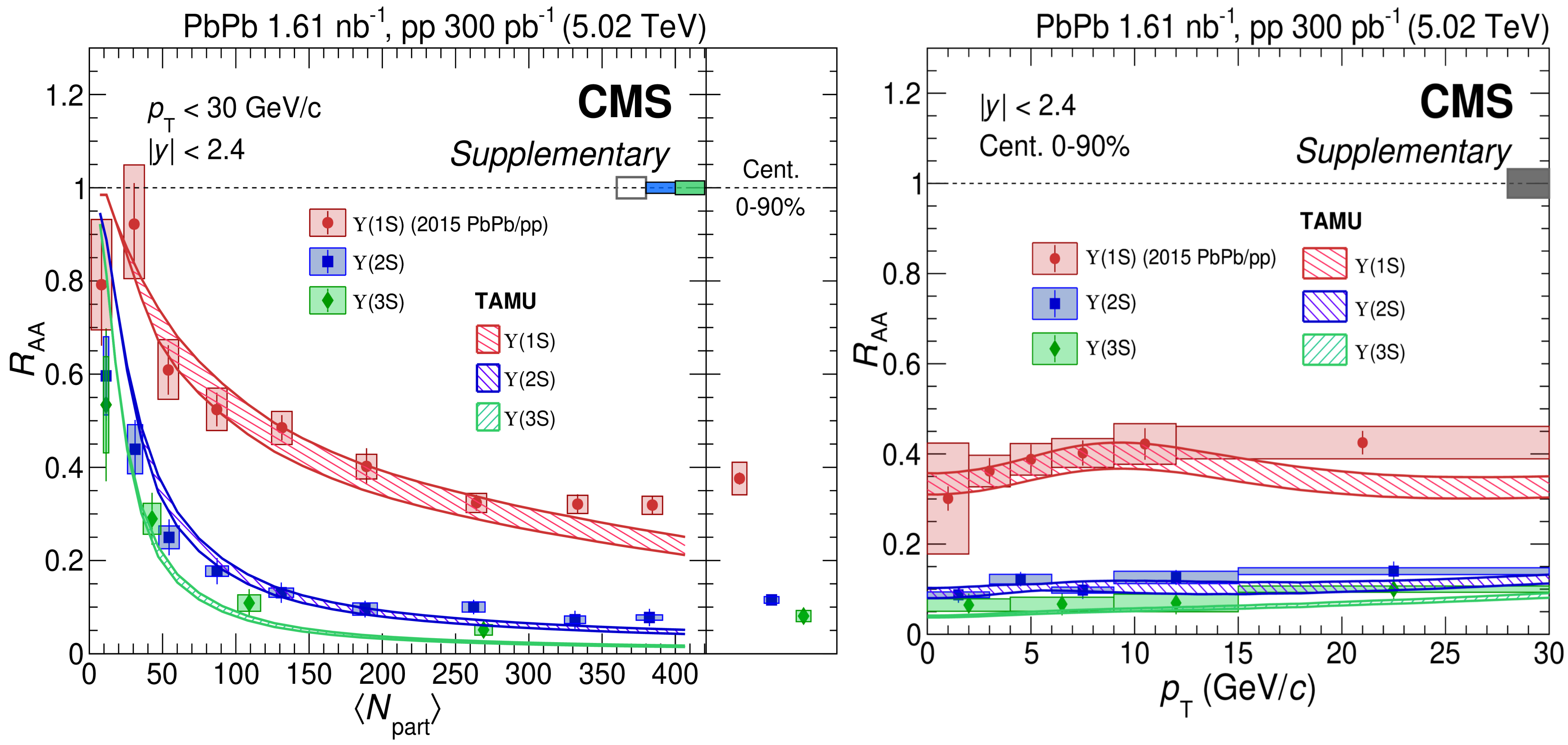


- Strong dependence on collision centrality (N_{part})
- Suppression level constant across p_T of Υ

TAMU [PRC 96 (2017) 054901]

arXiv:2303.17026

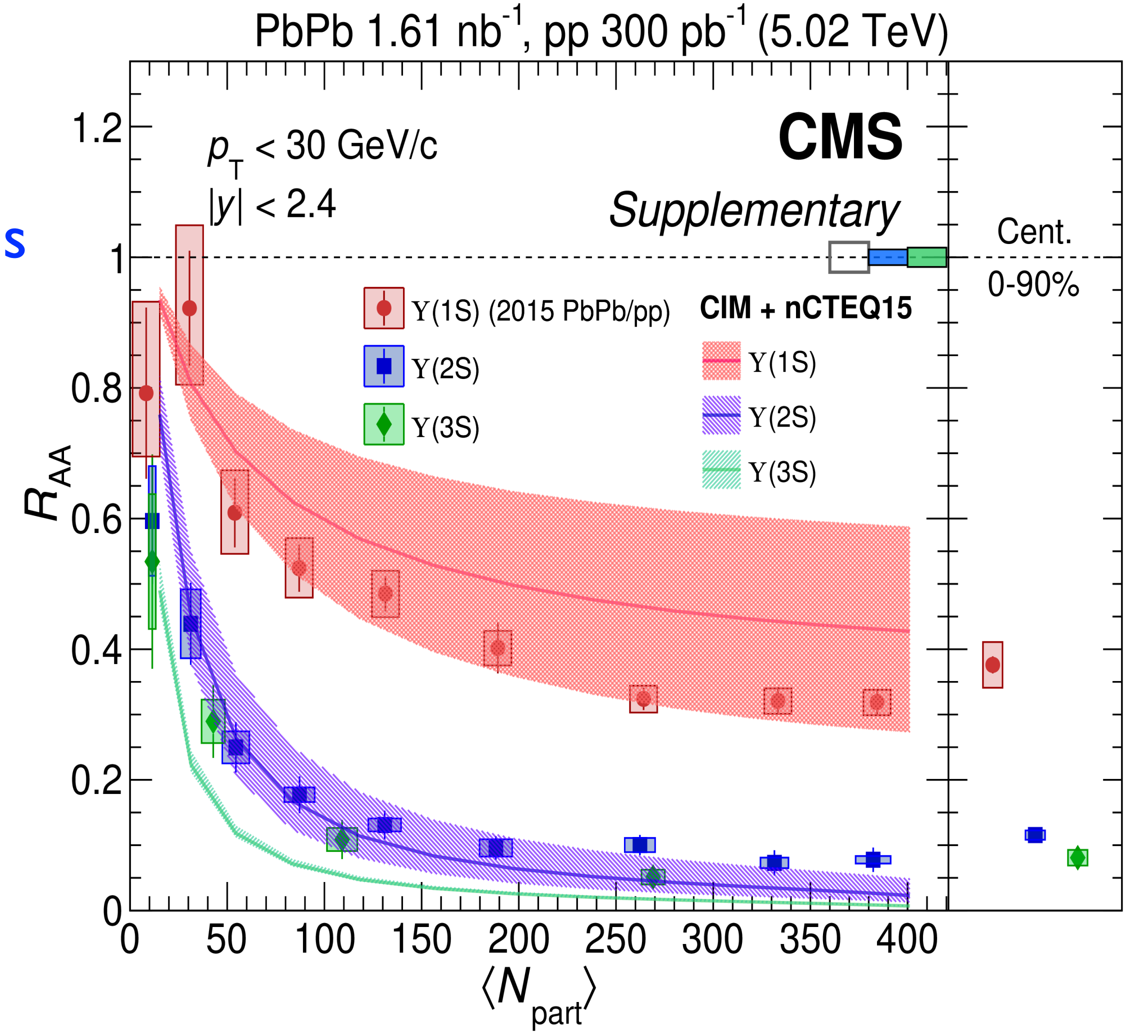
- Kinetic rate equation approach
- Includes regeneration, in-medium binding energies, and lattice QCD based EOS for fireball evolution
- Describes the trends well



Model comparison (2)

Comover Interaction Model [JHEP 10 (2018) 094]

arXiv:2303.17026



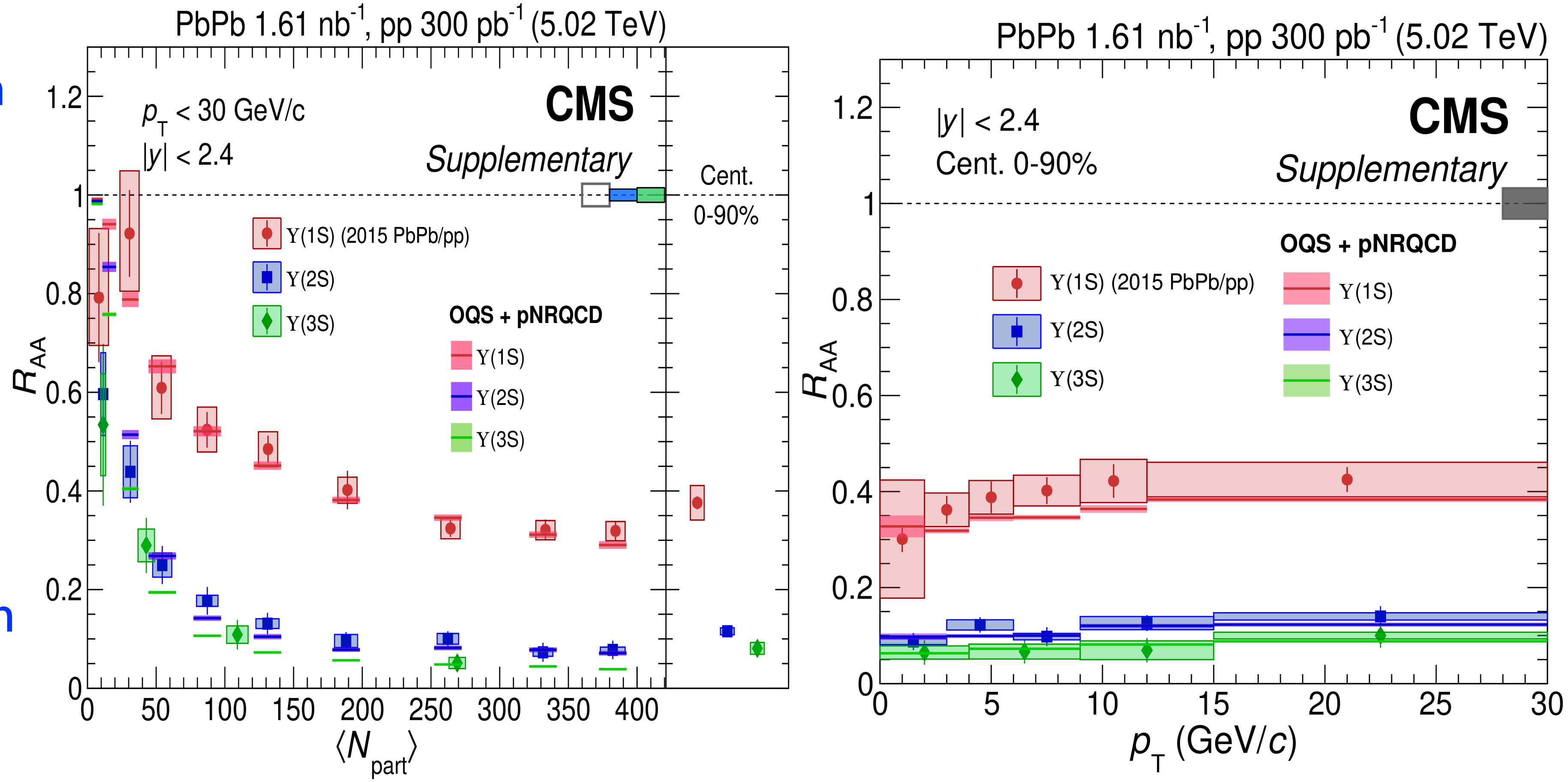
- Includes shadowing and break-up from interactions with comoving particles: nCTEQ15 [PRD 93 (2016) 085037]
- Describes the Υ(1S) and Υ(2S)
- Predicts stronger suppression for Υ(3S) for most of the centrality (N_{part}) range

Model comparison (3)

arXiv:2303.17026

OQS + pNRQCD [PRD 108 (2023) 011502]

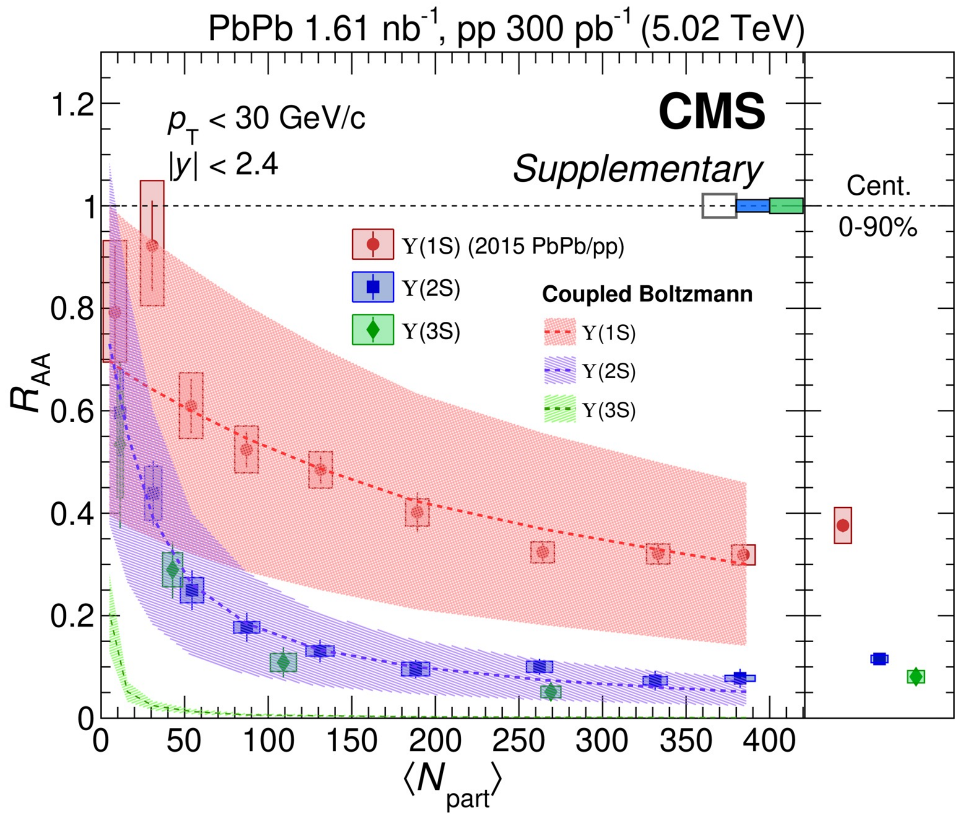
- Open quantum system framework, potential NRQCD approach
- Includes quantum regeneration
- Model describes the trends and suppression well

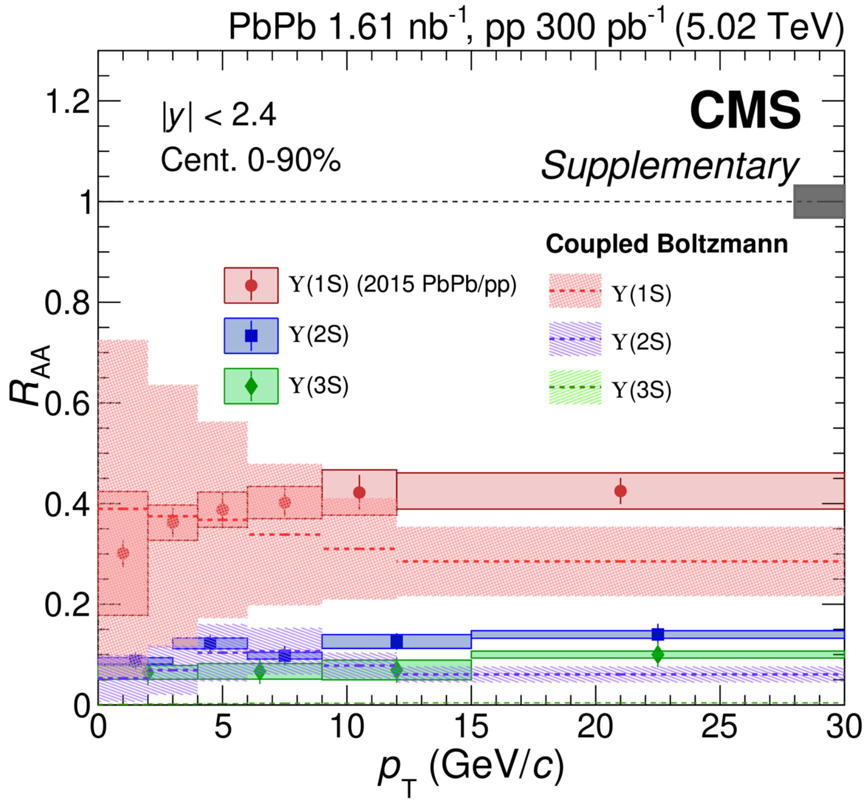


Model comparison (4)

Coupled Boltzmann [JHEP01(2021)046]

arXiv:2303.17026



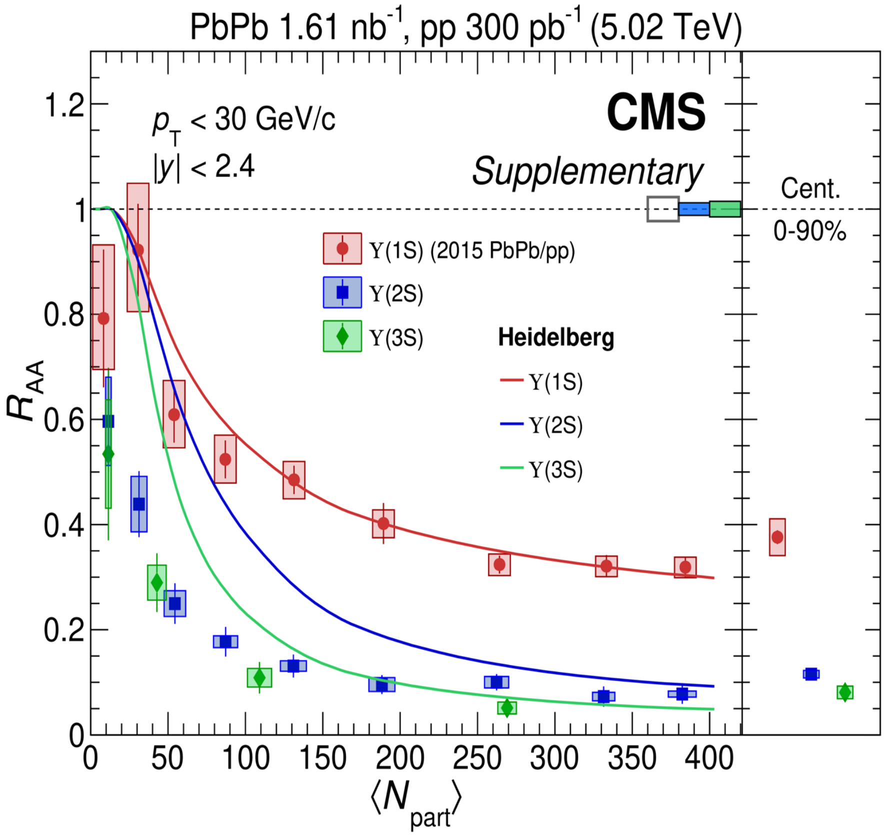


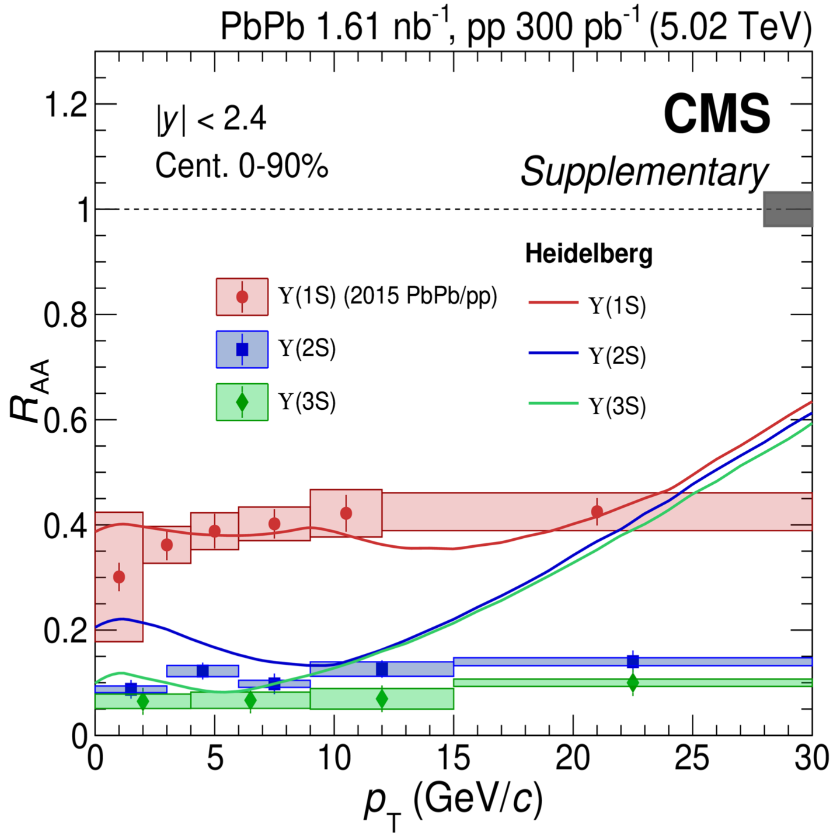
- Open quantum system framework, coupled transport equations and EPPS16 nPDF
- Includes both correlated and uncorrelated recombination
- Describe centrality dependence of 1S and 2S states, fails for 3S state

Heidelberg [IJMPA 35, 2030016 (2020)]

arXiv:2303.17026

- ❑ Model incorporates screening and gluon dissociation
- ❑ Describes 1S state well
- ❑ Overpredicts 2S and 3S states at high-p_T and peripheral collisions

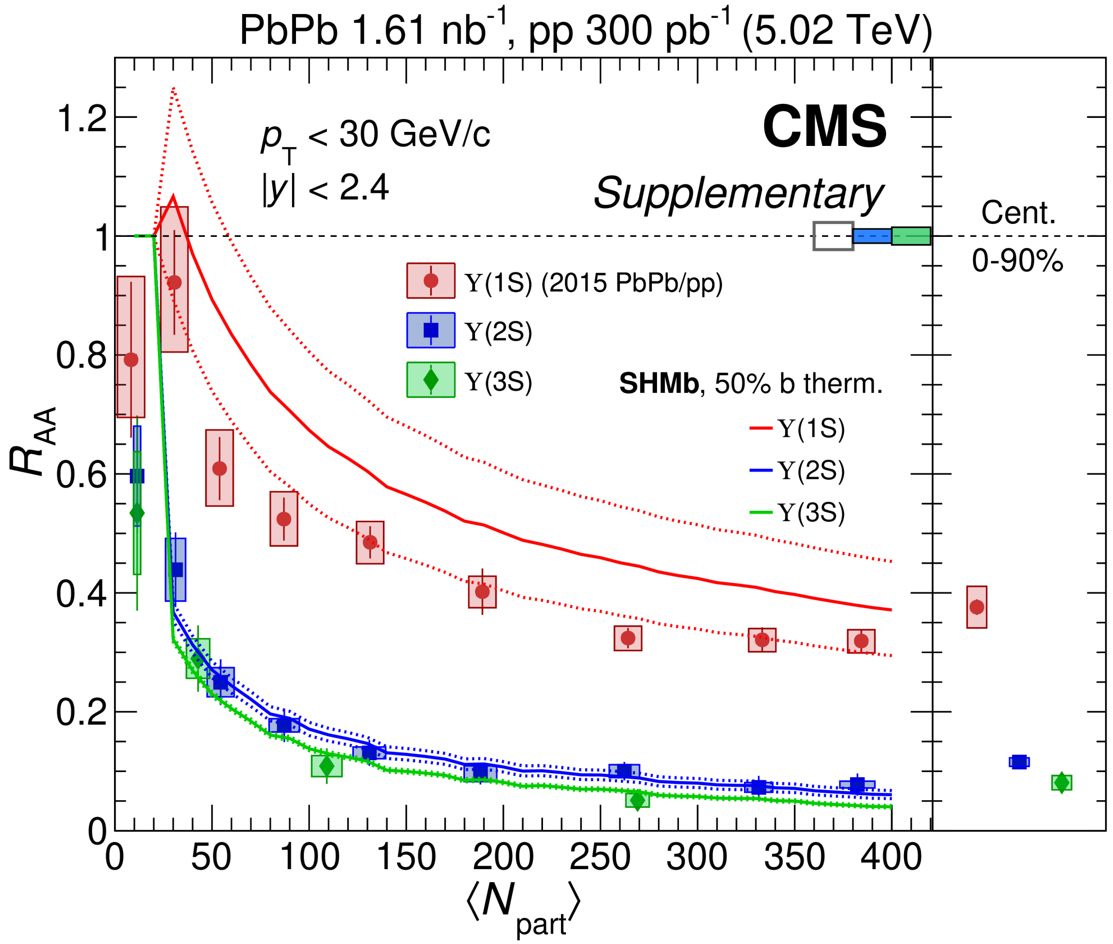




SHMb [arXiv:2209.14562v1]

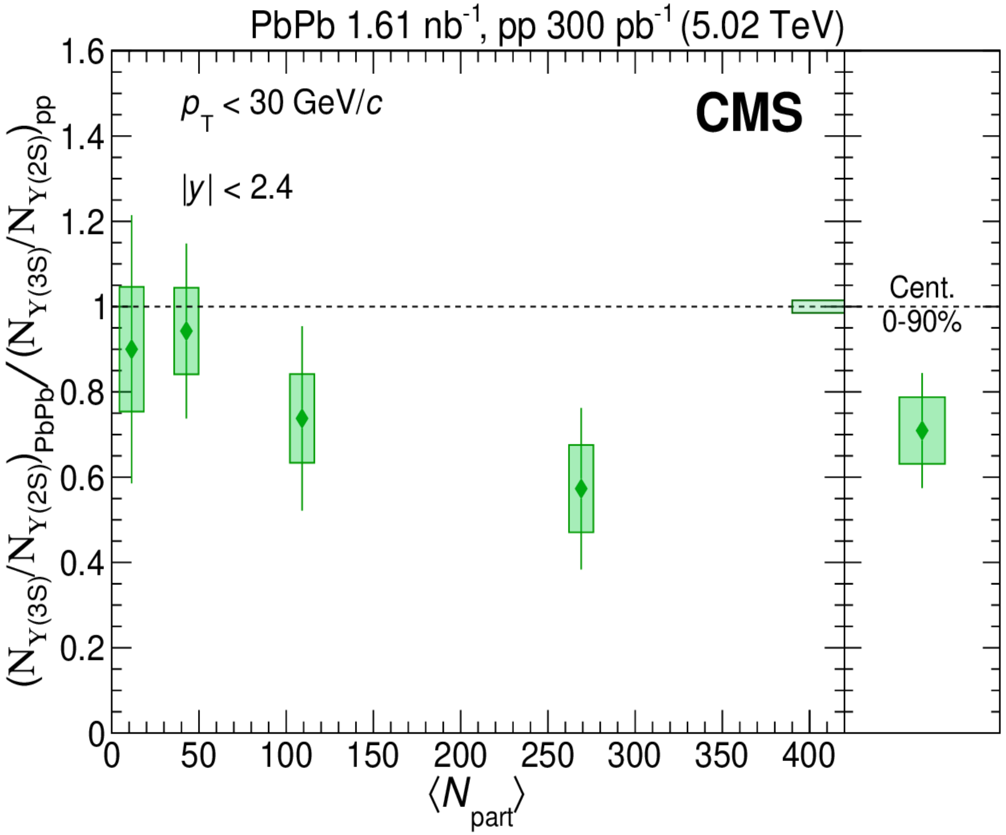
arXiv:2303.17026

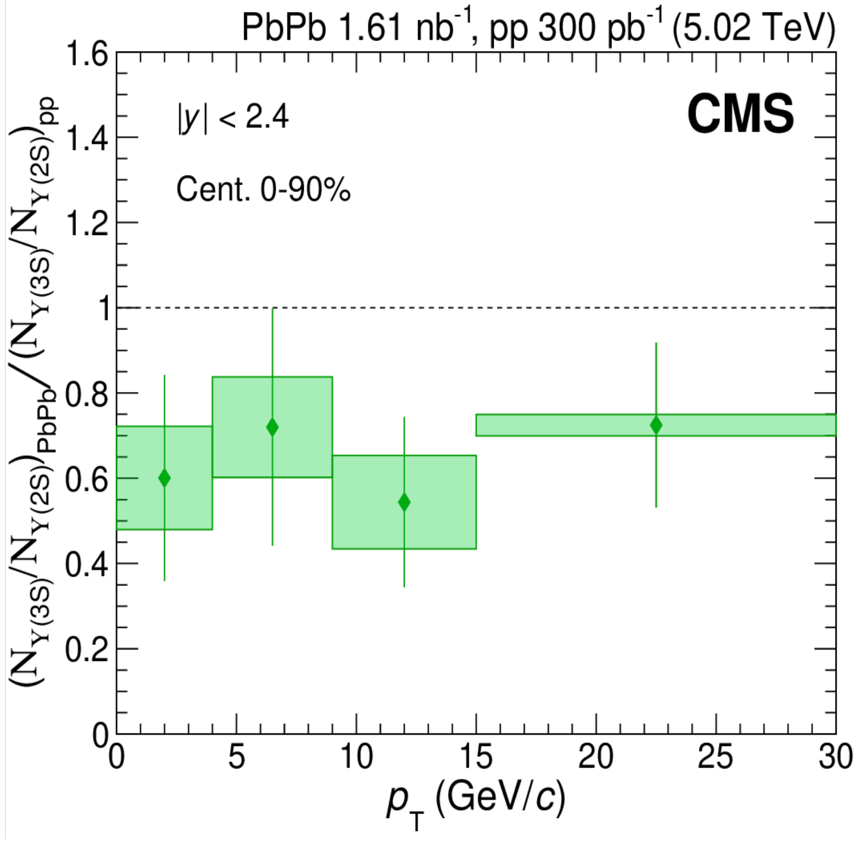
- Statistical hadronization of b-quarks in PbPb
- Effect of a partial thermalization of b-quarks:
  → SHMb incorporates an arbitrary suppression of beauty pairs at the phase boundary
- A thermalization fraction of ~50% of b-quarks explains the bottomonium data at the LHC



Double ratio in CMS PbPb

- Double ratio $\frac{[\Upsilon(3S)/\Upsilon(2S)]_{\rm PbPb}}{[\Upsilon(3S)/\Upsilon(2S)]_{\rm pp}}$ → partial cancellation of systematic uncertainties





arXiv:2303.17026

- Hint of stronger suppression for ϒ(3S) compared to ϒ(2S) for more central collisions
- Constant across p_T(ϒ)

Double ratio and models in PbPb

- Double ratio $\frac{[\Upsilon(3S)/\Upsilon(2S)]_{\mathrm{PbPb}}}{[\Upsilon(3S)/\Upsilon(2S)]_{\mathrm{pp}}}$

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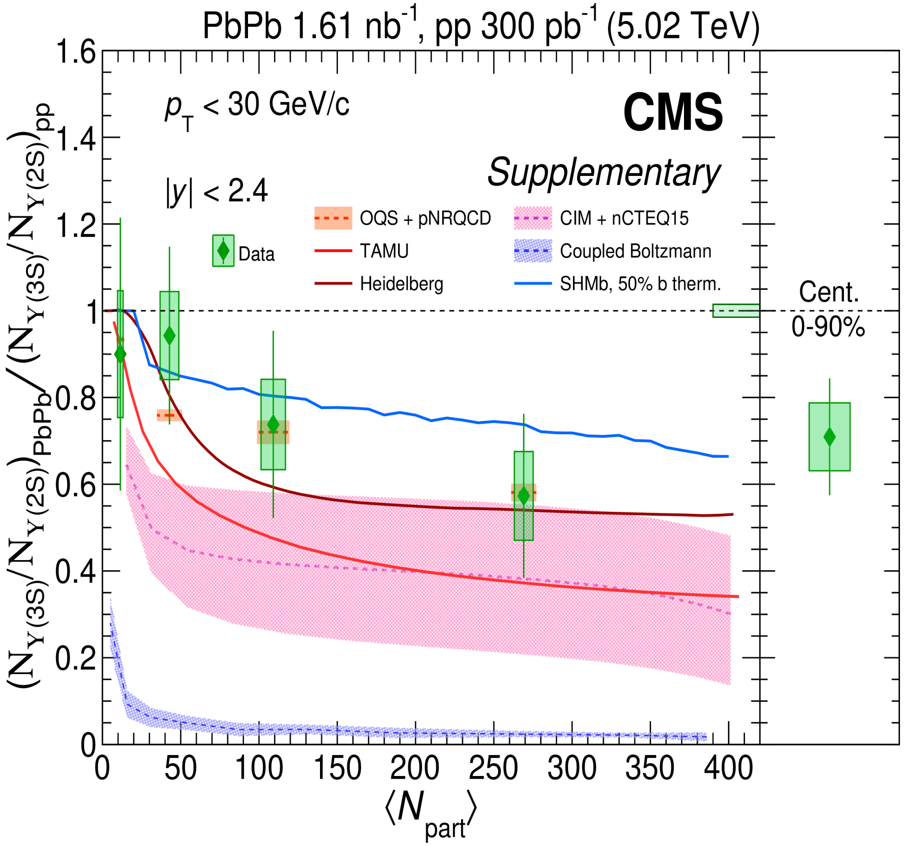
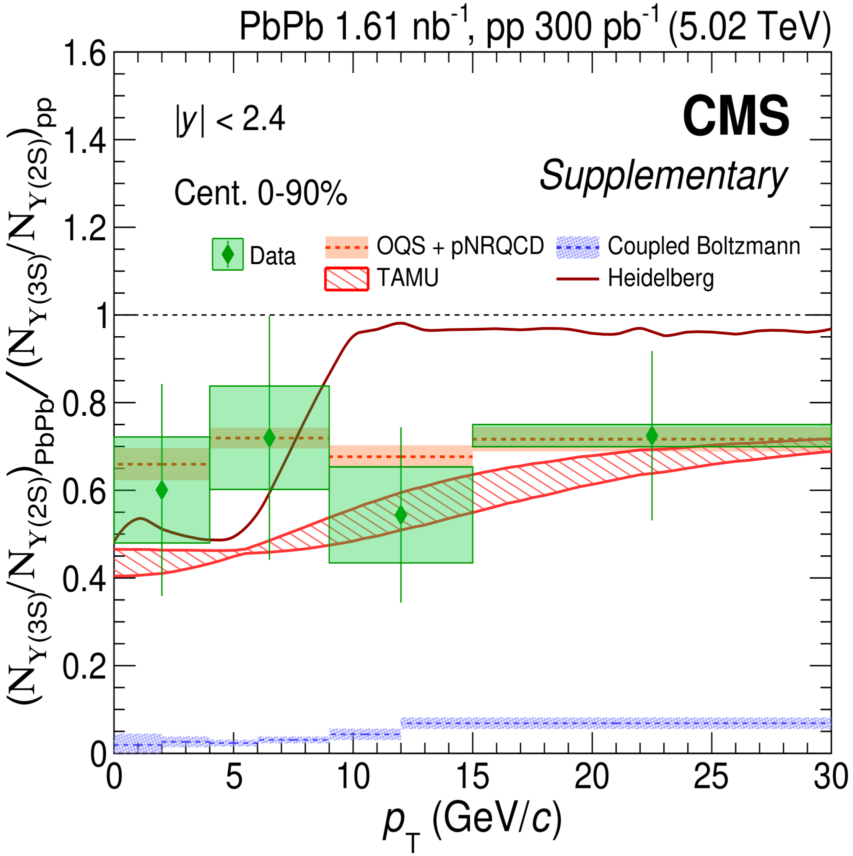
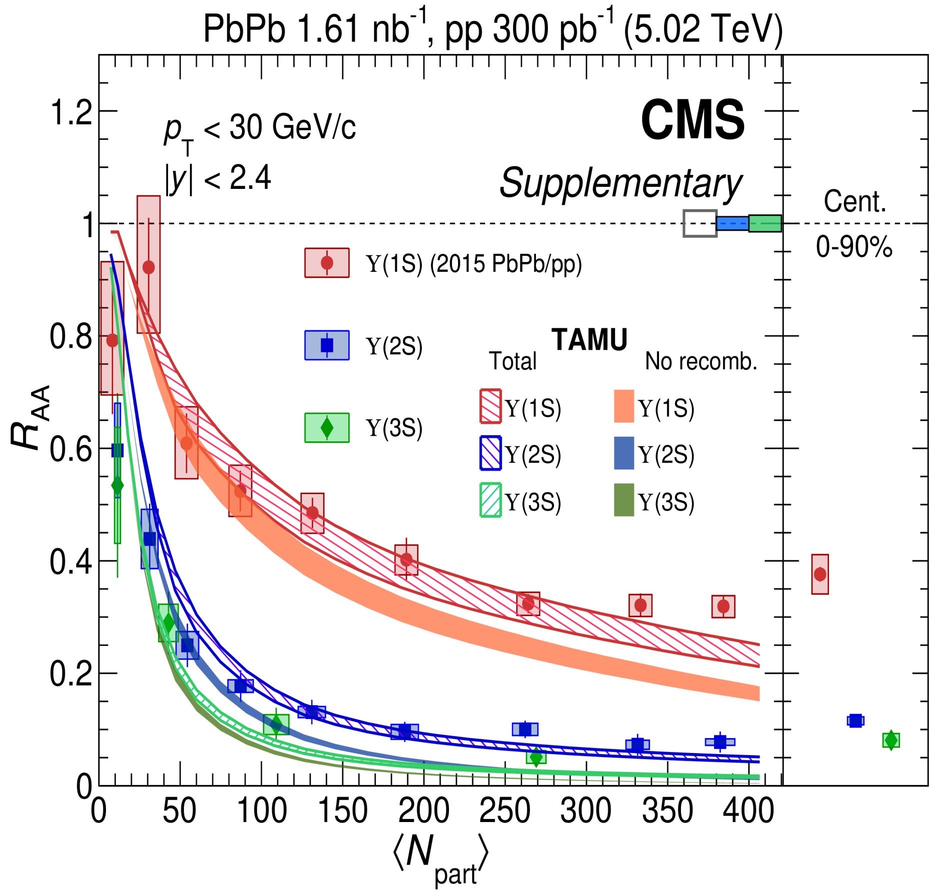
Models comparison

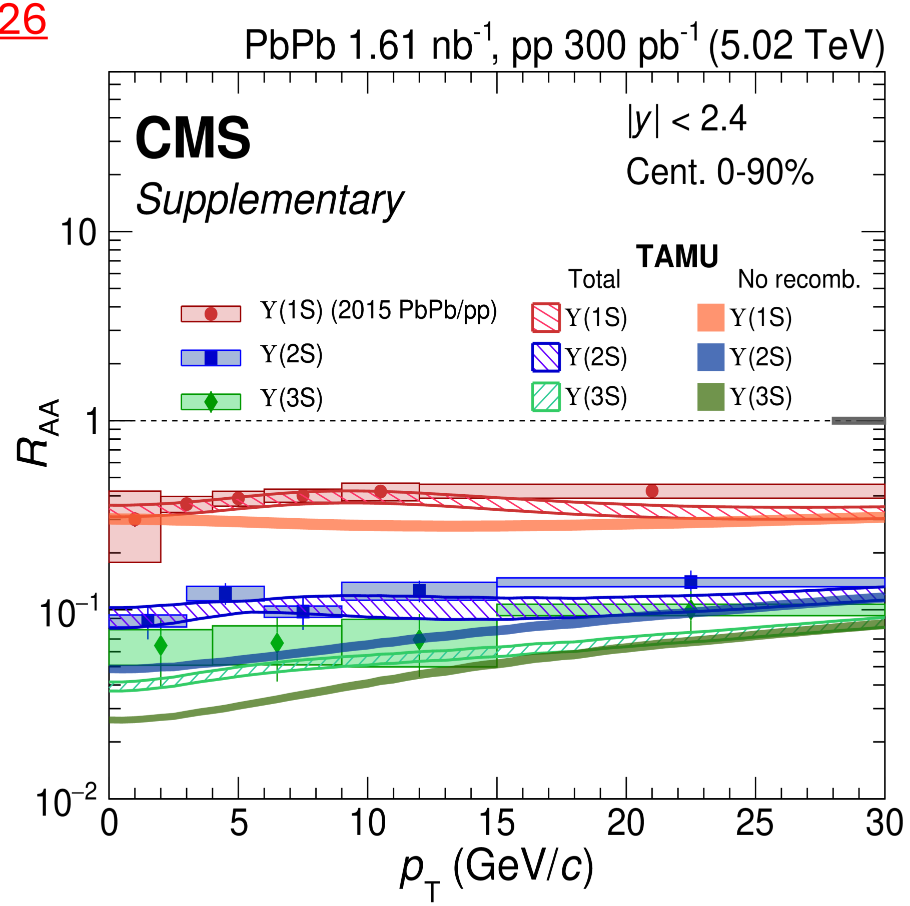




- Models that include regeneration effect explains data well!
- TAMU [PRC 96 (2017) 054901] → the correlated recombination effect is expected to be quite significant to describe the data

arXiv:2303.17026





- Models that include dynamical recombination explains PbPb data well
- OQS + pNRQCD [PRD108 (2023) 011502]

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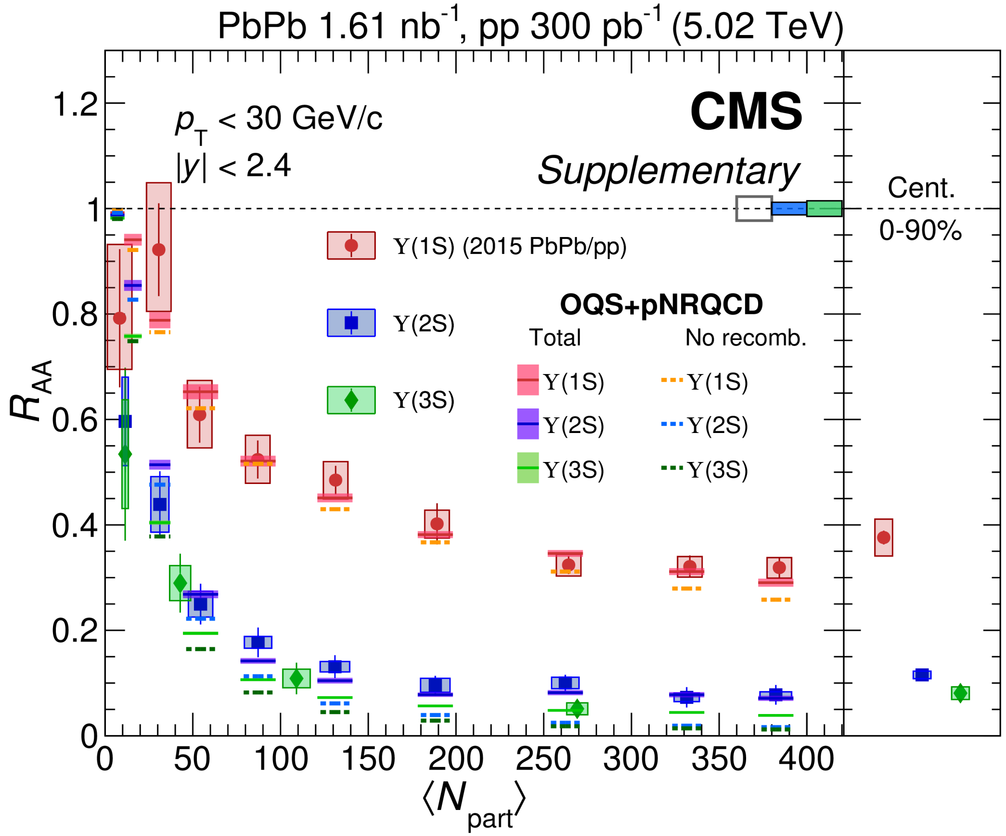
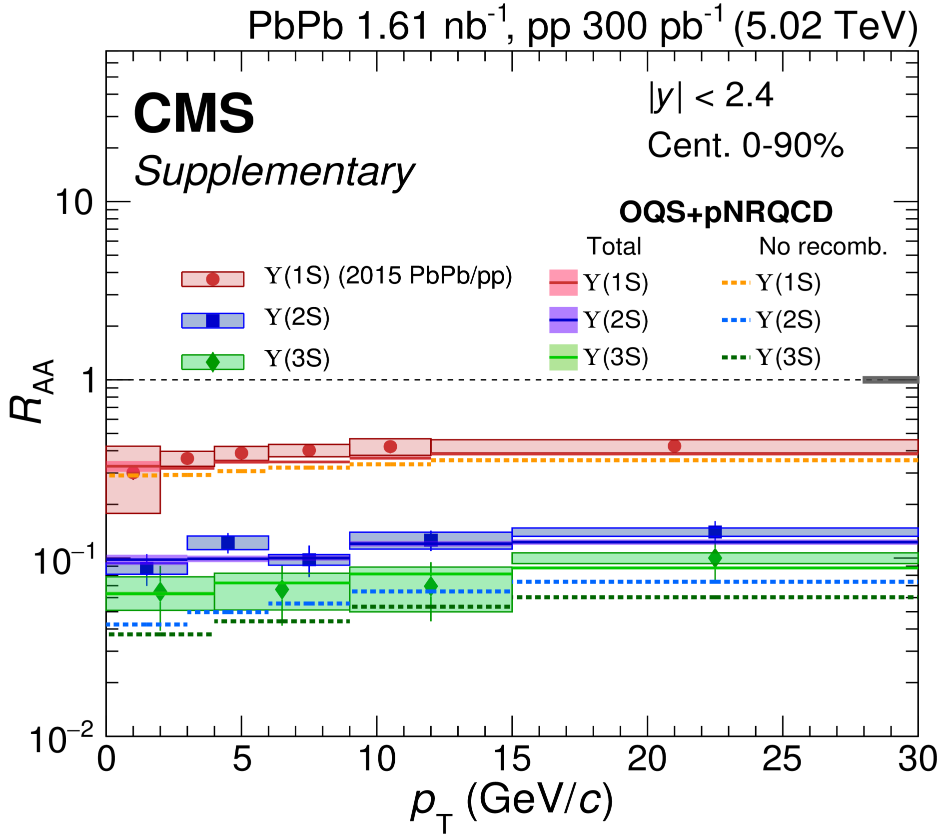
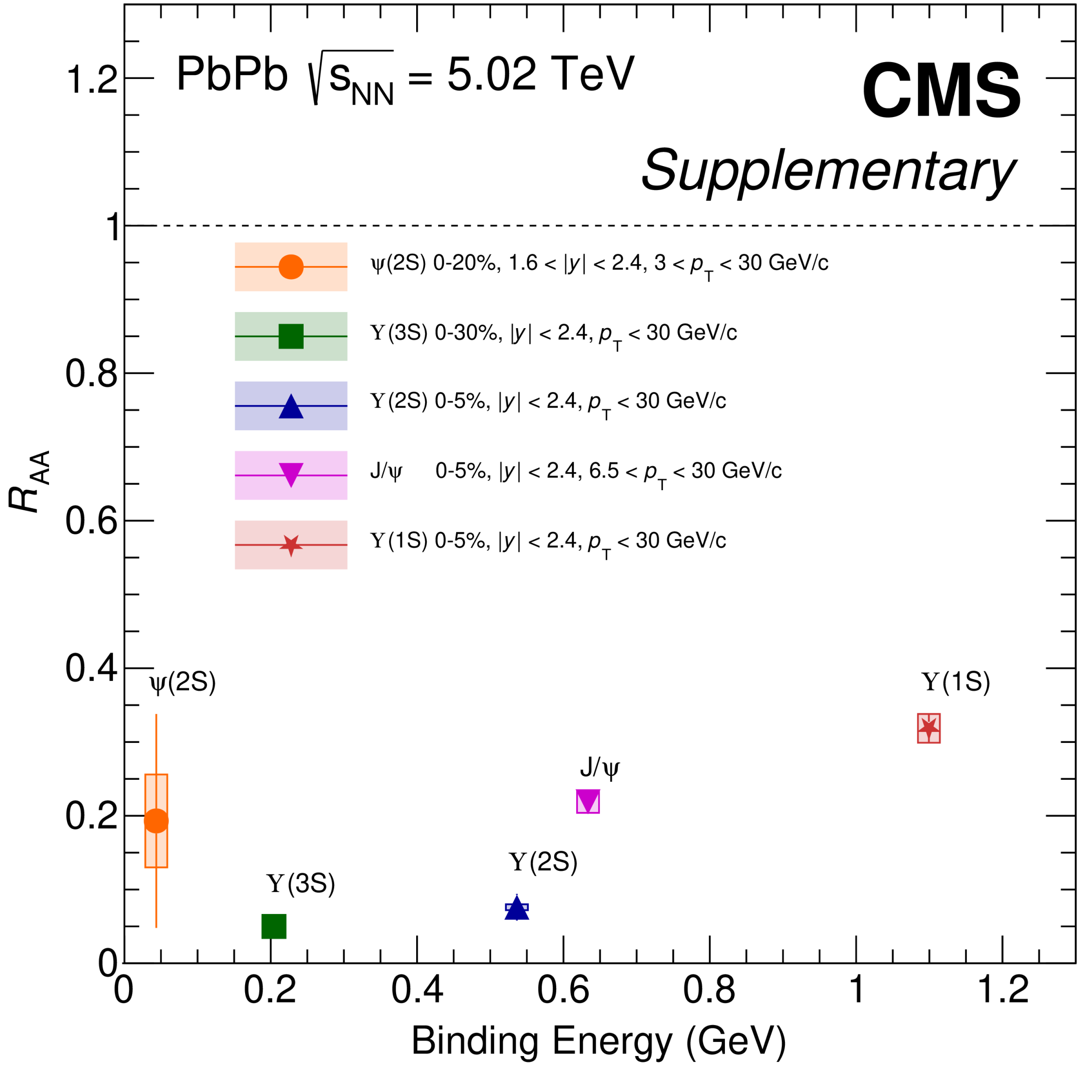




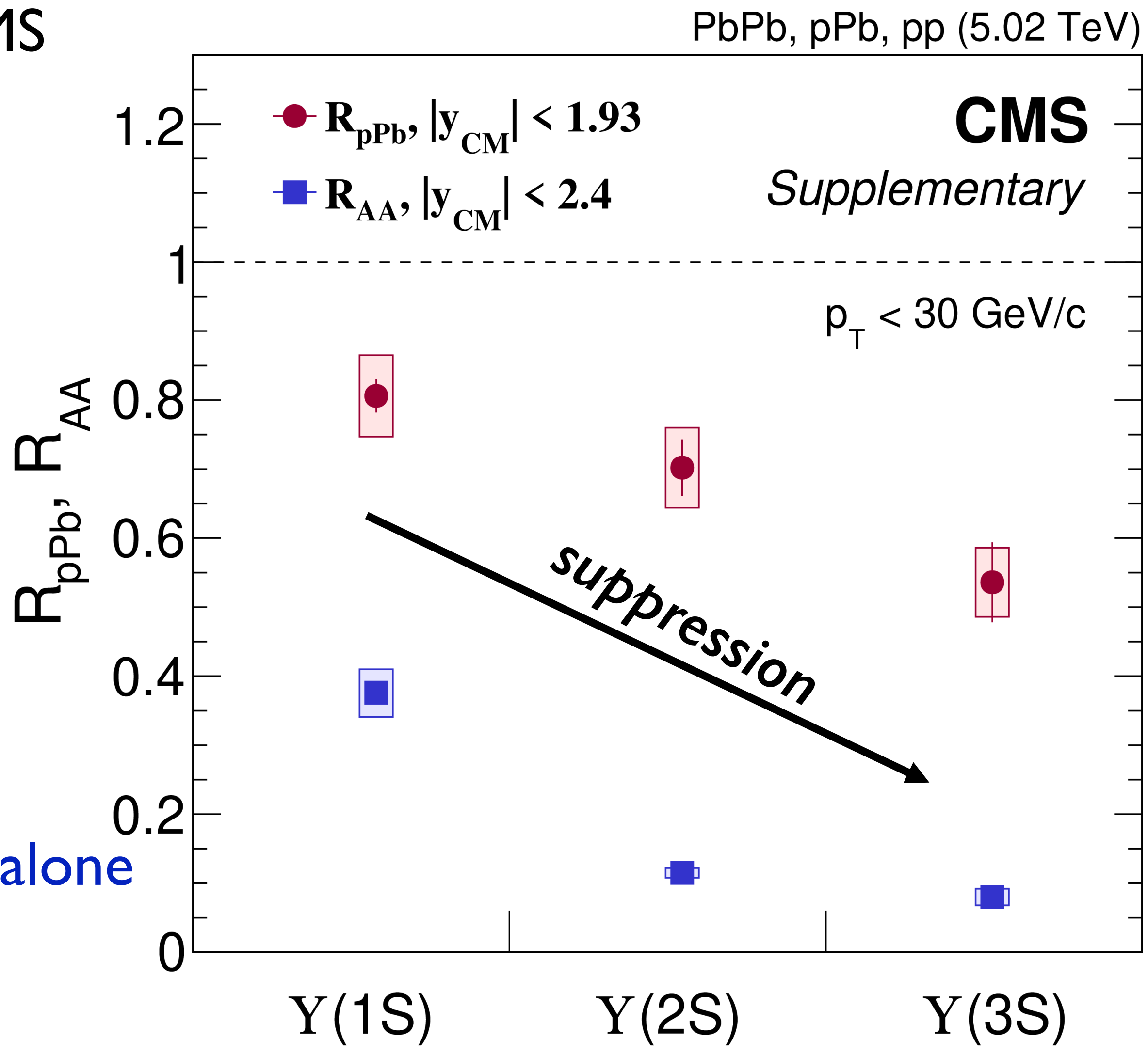
arXiv:2303.17026

- ❑ R_{PbPb} vs quarkonia binding energy
- ❑ Sequential suppression of quarkonia states → binding energy dependence
- ❑ Incomplete contributions from feed-down decays yet to be measured!



Summary

- Excellent performance for muon detection in CMS
  - Wide range of detector occupancies
- First measurement of ϒ(3S) in PbPb collisions
  - Sequential ordering of suppression $R_{PbPb}(1S) > R_{PbPb}(2S) > R_{PbPb}(3S)$
  - Follows their binding energies
  - R_{PbPb} (3S) = 0.080 ± 0.014 (stat) ± 0.012 (syst)
  - Challenging to describe with initial state effects alone



PbPb (2S) and (3S) arXiv 2303.17026

pPb: PLB 835(2022), 137397