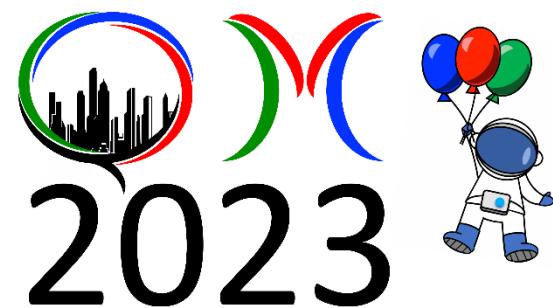
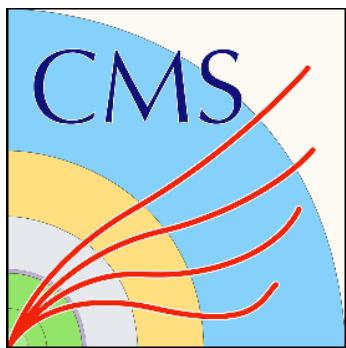


Studies of the relative suppression of excited quarkonium states with CMS

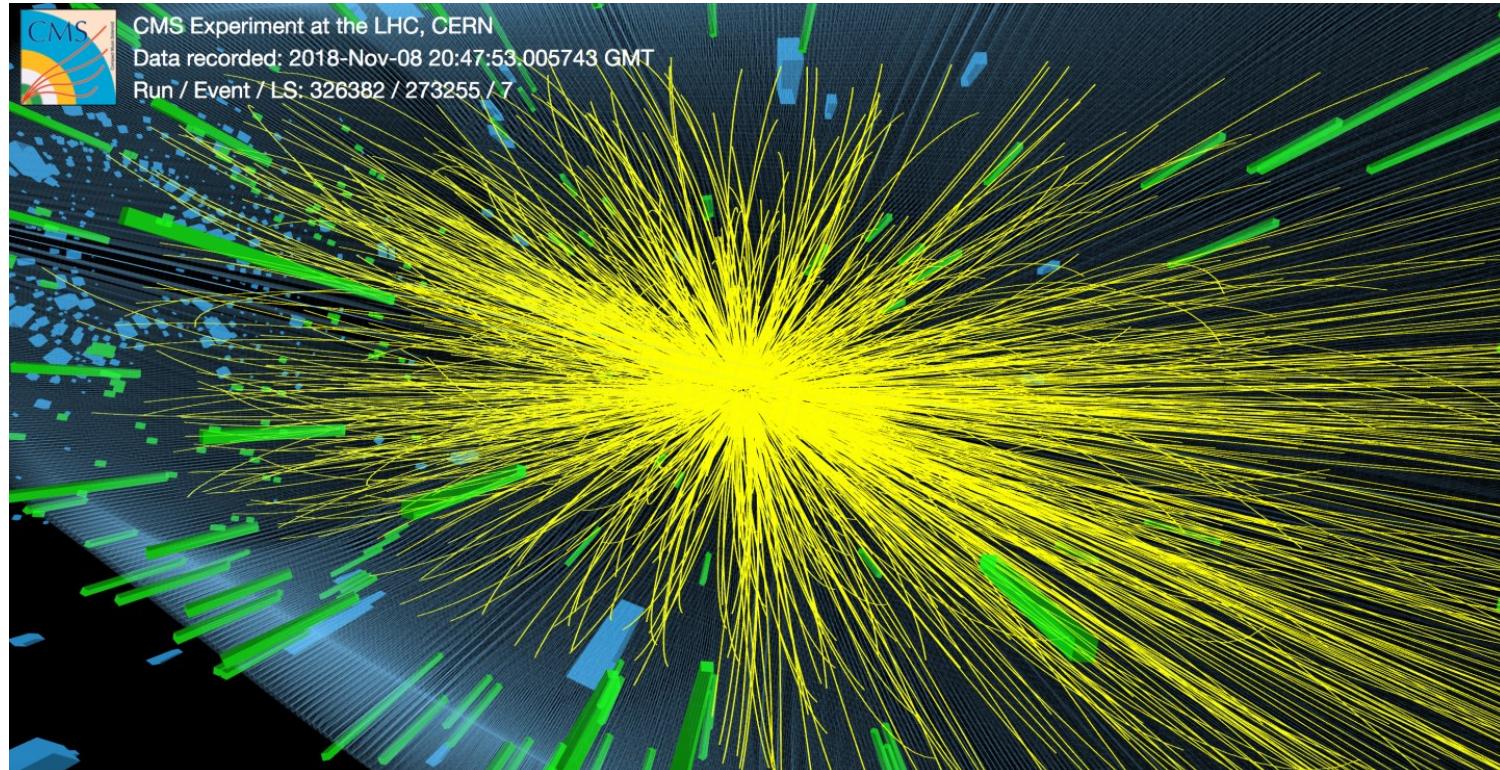
Ota Kukral

on behalf of the CMS Collaboration



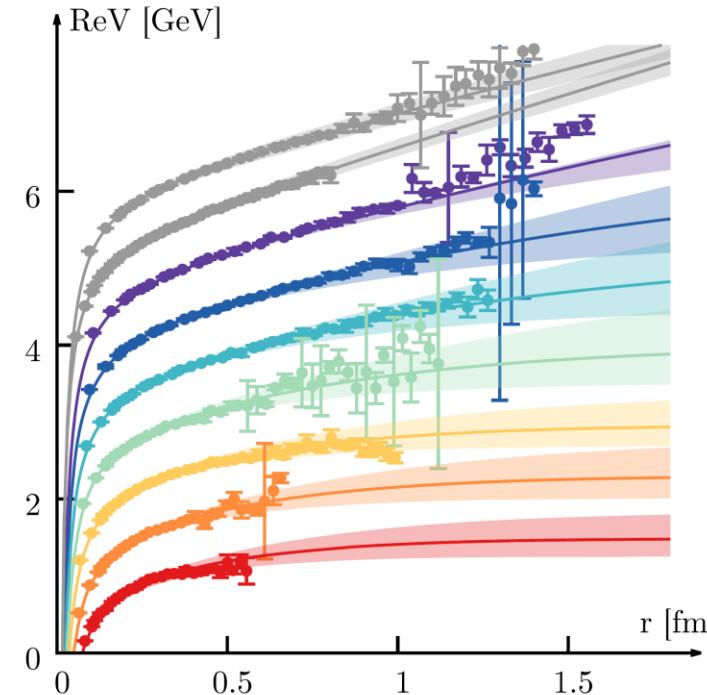
Outline

- Motivation
- CMS experiment
 - Quarkonia detection at CMS
 - Muon performance at CMS
- Y states in pPb collisions
 - p_T , rapidity and multiplicity trends
 - Model comparisons
- Y(2S) and (3S) in PbPb collisions
 - R_{AA}
 - Double ratio $Y(3S)/Y(2S)_{\text{PbPb}/\text{pp}}$
 - Model comparisons
- Summary

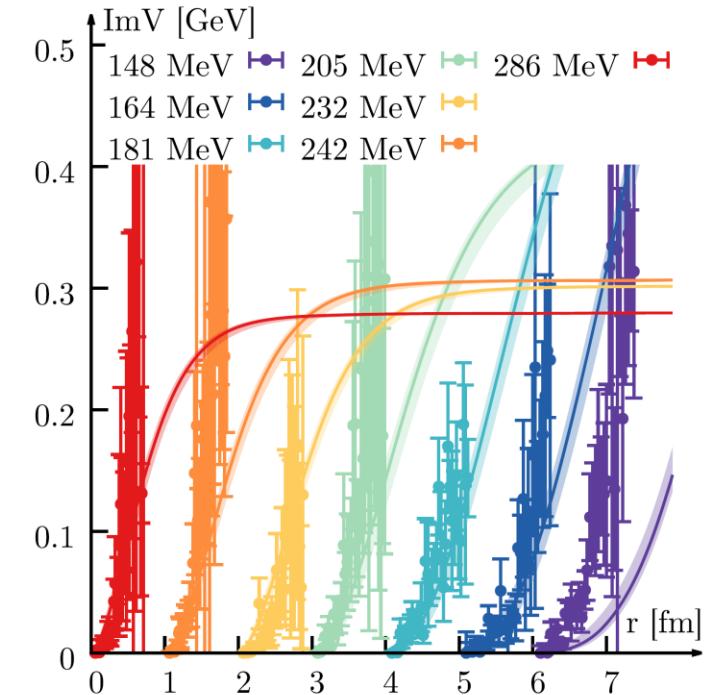


Motivation

- Quarkonia binding potential modified in-medium
 - In-medium dissociation
 - Different states affected differently
- Bottomonium
 - Produced mostly in initial hard scattering
 - Only very small stat. recombination compared to charmonia
 - Measured from $p_T = 0$ GeV in CMS
- Studying effects across various collisions systems
 - Relative suppression also observed in pPb collisions?



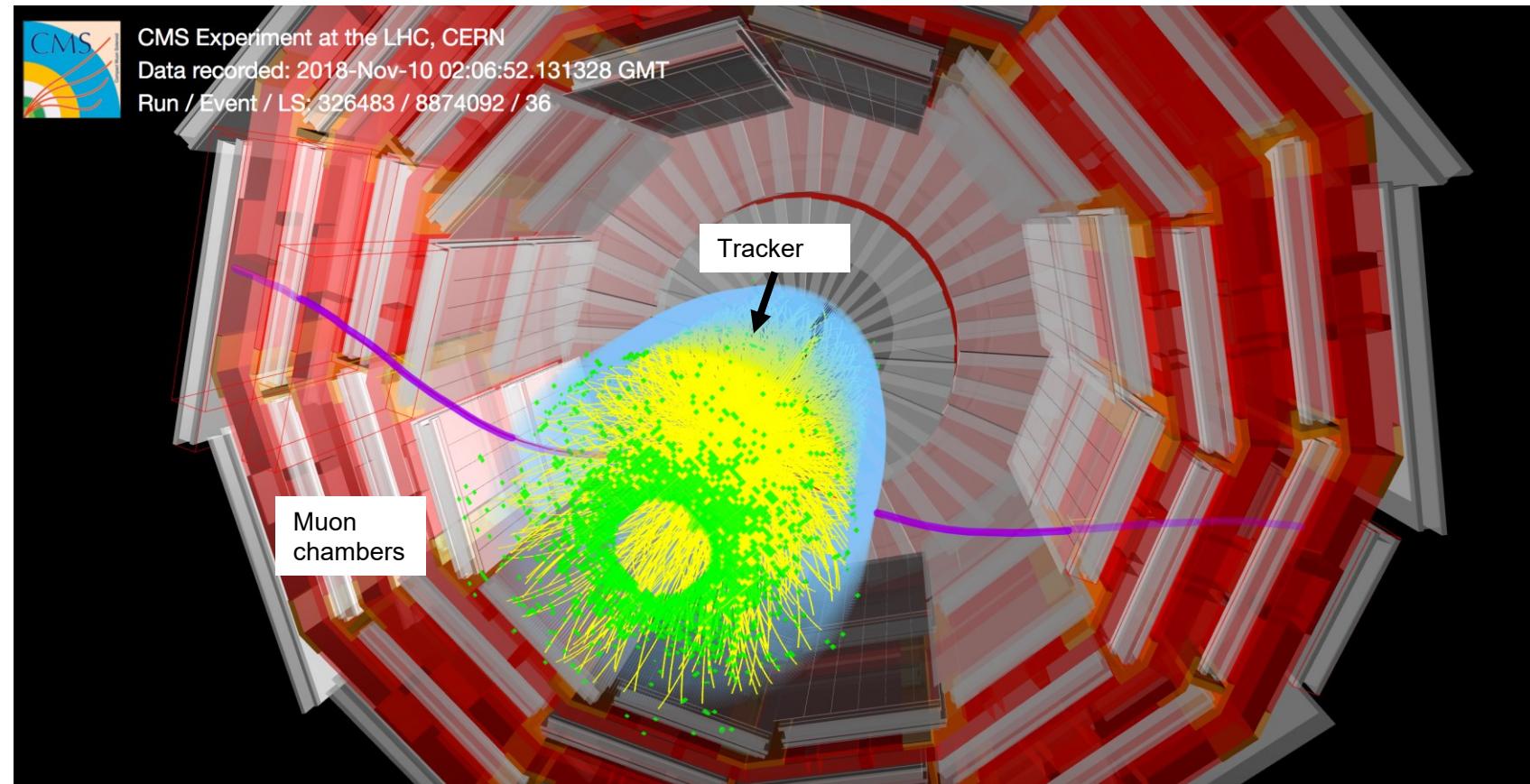
PRD101, 056010 (2020)



Measurement of quarkonia in CMS

- Quarkonia detected via dimuon decay channel: $Q \rightarrow \mu^+ \mu^-$
- Detecting muons
 - $|\eta| < 2.4$, $p_T \gtrsim 1\text{-}4 \text{ GeV}$
 - Inner tracker
 - Muon chambers

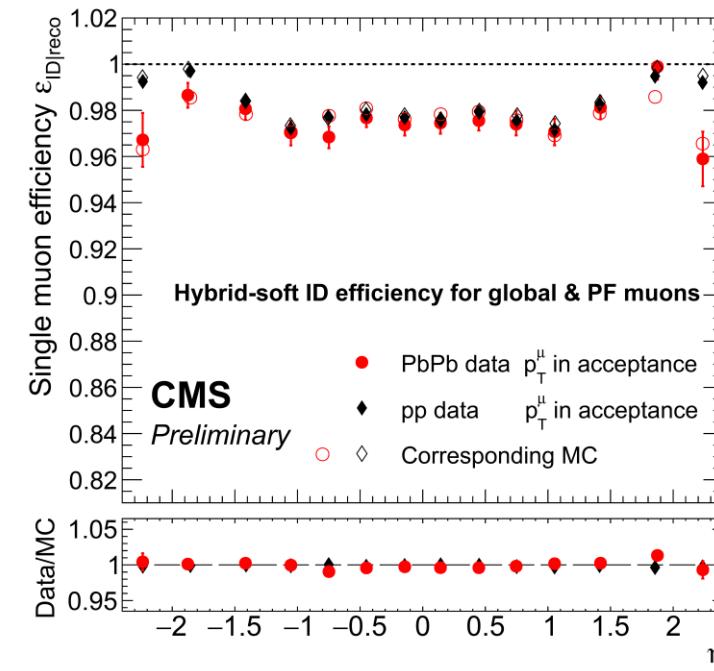
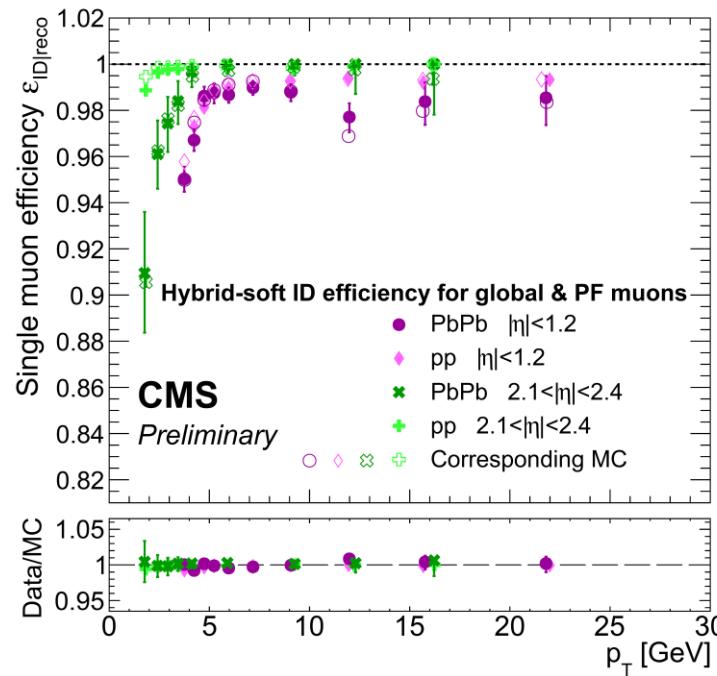
Υ candidate
in PbPb



Muon performance from pp to PbPb

- Data driven measurement of muon reconstruction, identification, and triggering efficiency
- Muon identification
 - PbPb performance very good, comparable to pp
 - Well described by Monte Carlo simulations
 - Efficiency very high even in challenging regions

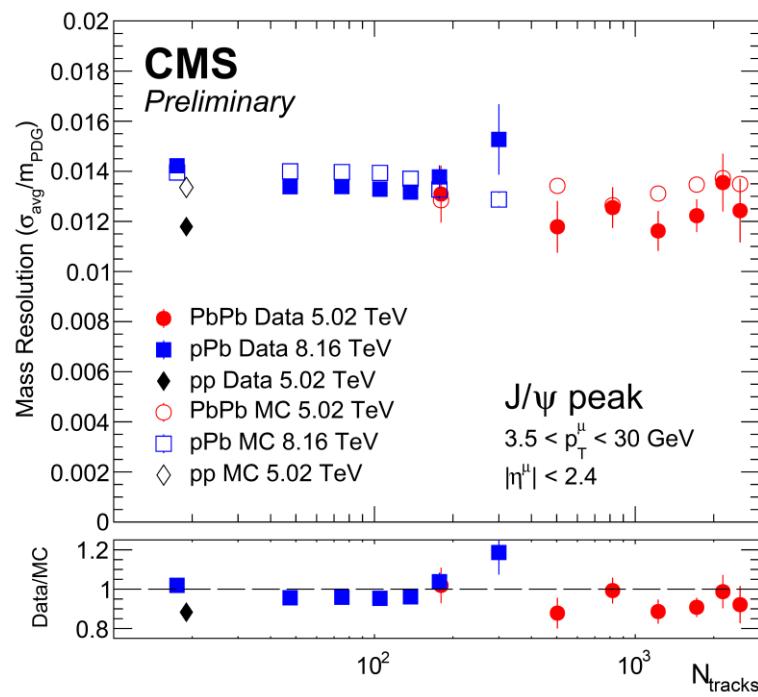
CMS-PAS-MUO-21-001



Muon performance from pp to PbPb

- Comparisons between pp, pPb and PbPb collisions
- Mass scale and resolution stable among the systems
 - No dependency on particle occupancy
 - Mass resolution critical for resolving quarkonia states
 - Excellent, only $\approx 1.4\%$

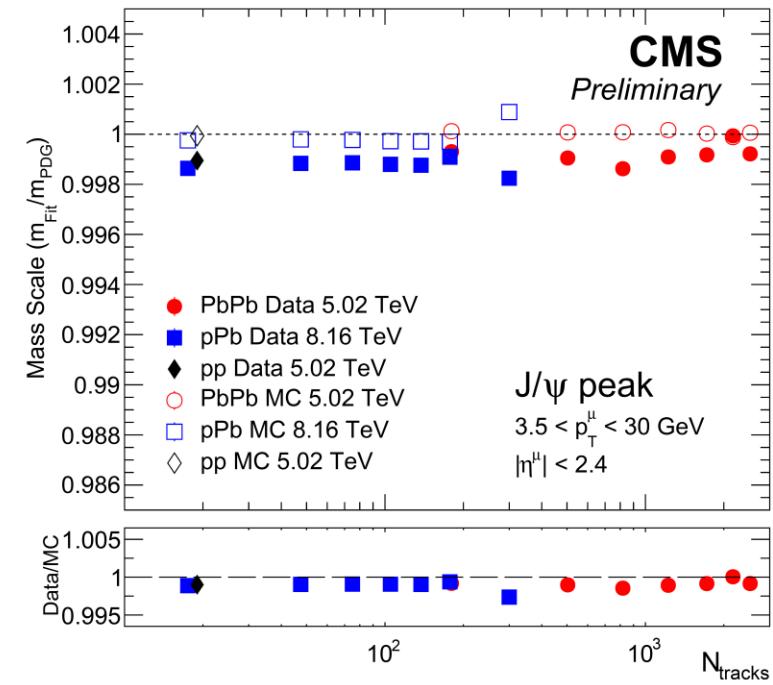
CMS-PAS-MUO-21-001



Mass resolution



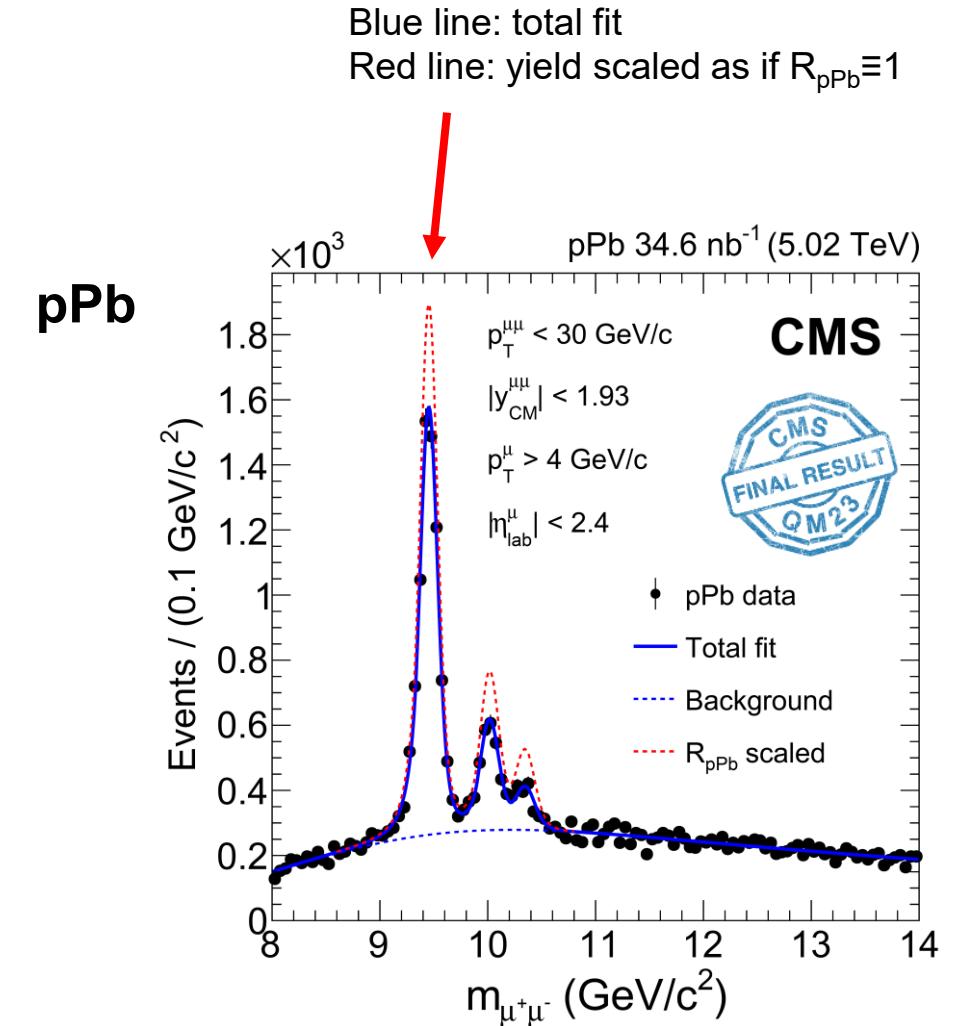
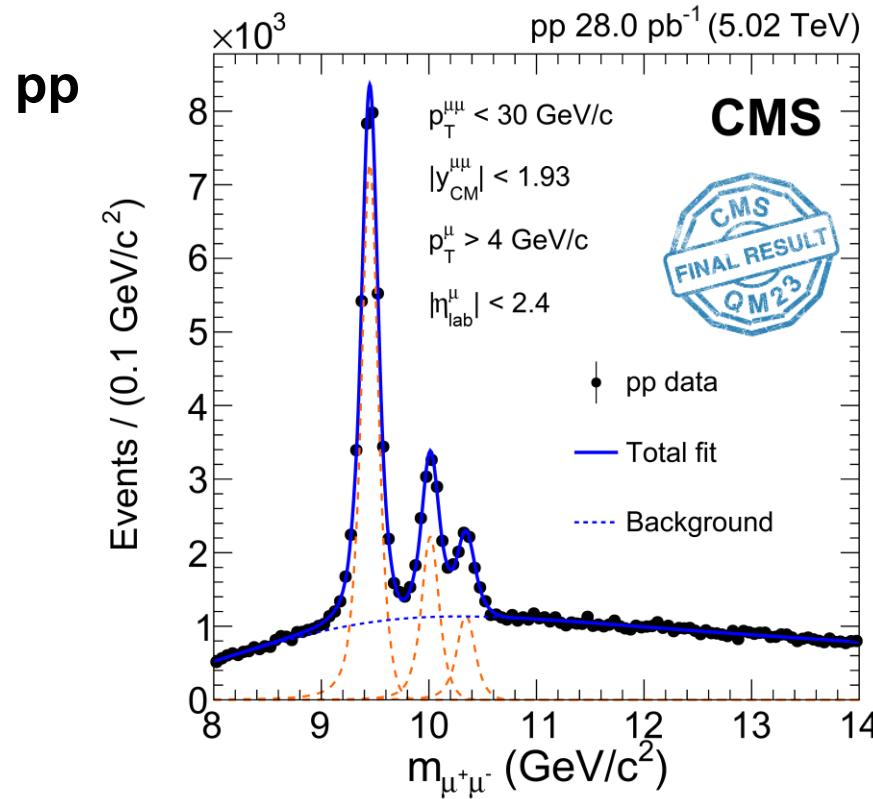
Mass scale



Υ states in pPb

PLB 835(2022), 137397

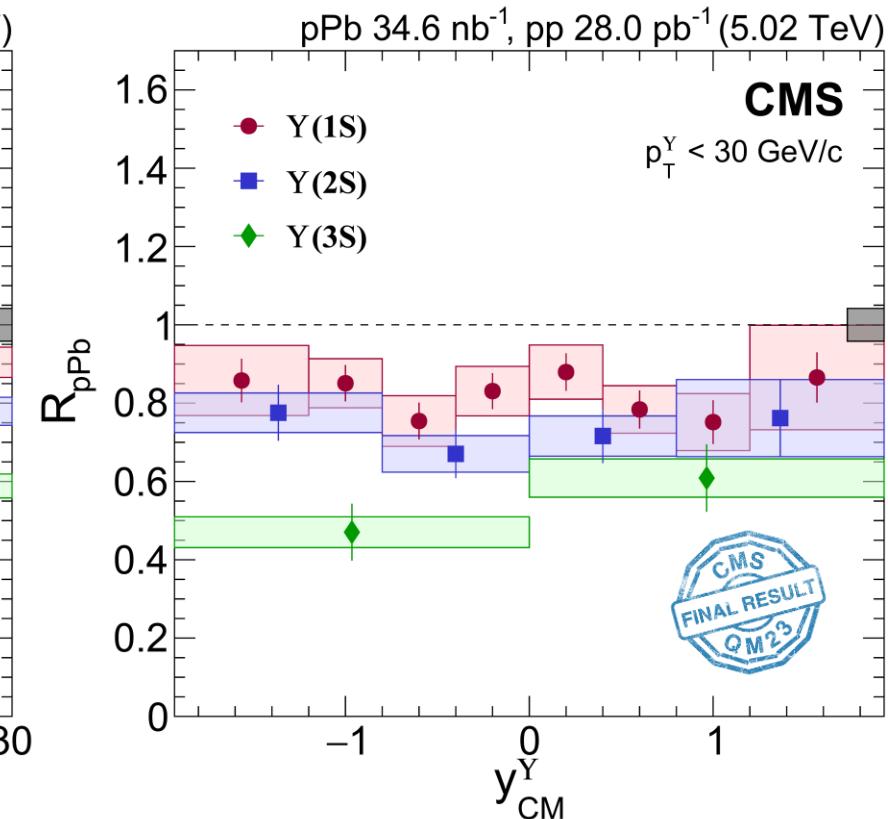
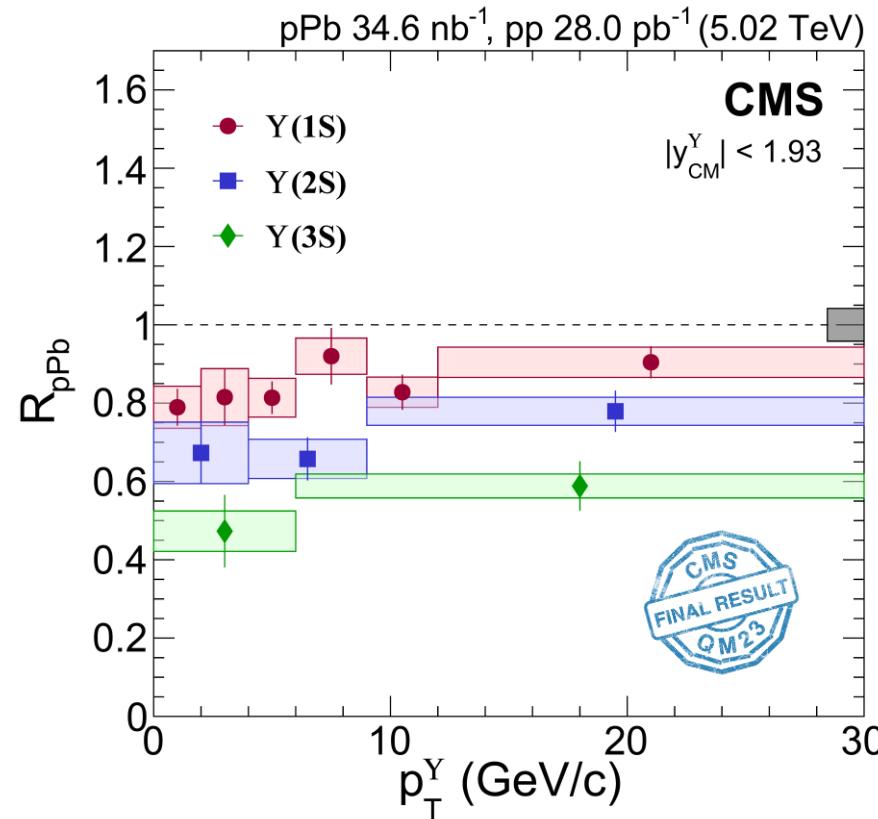
- pp and pPb collisions
- $\sqrt{s_{NN}} = 5.02$ TeV
- Suppression observed in pPb collisions



Y states in pPb

PLB 835(2022), 137397

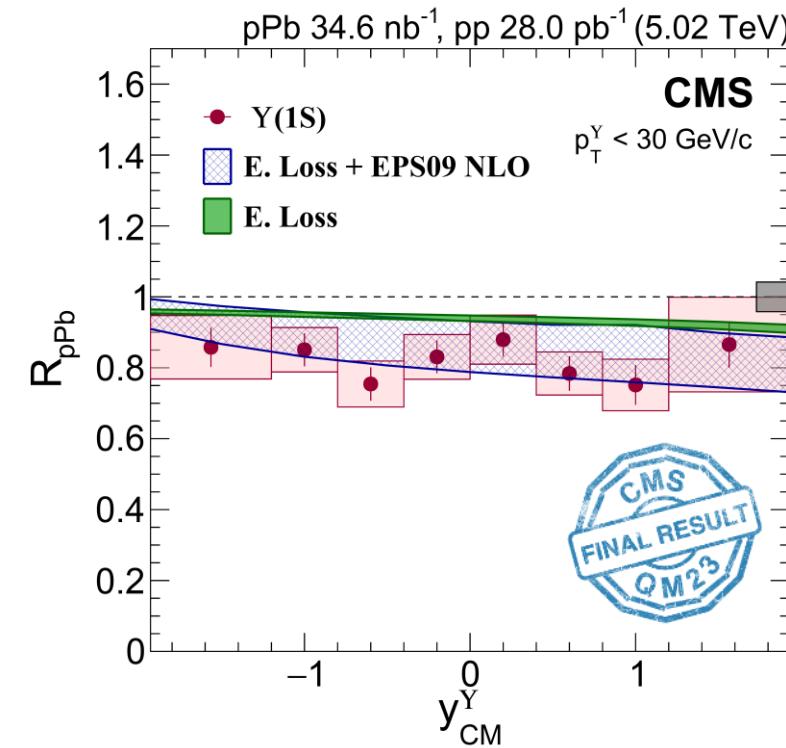
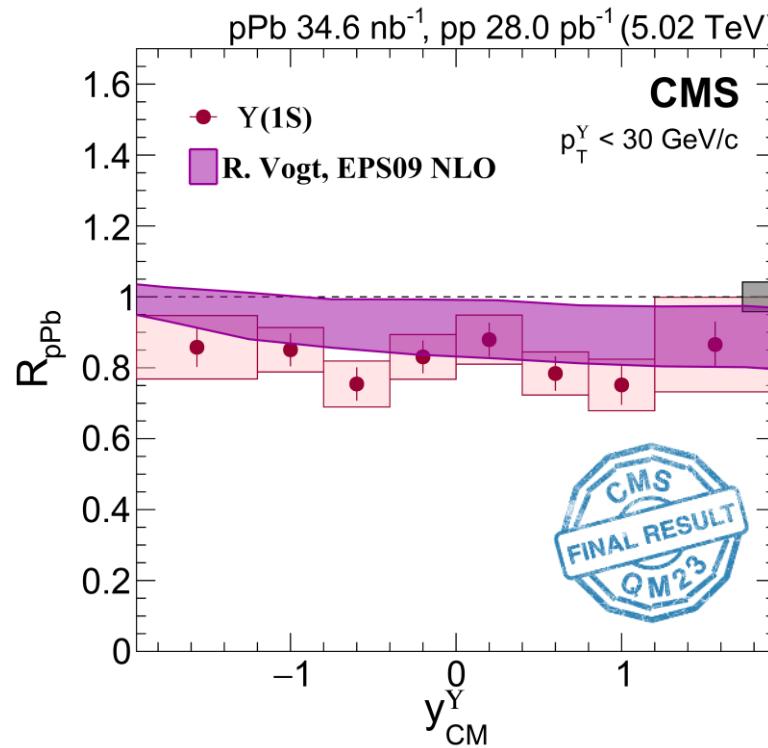
- Y states suppressed in pPb collisions
 - Suppression level constant across $p_T(Y)$ and $y_{CM}(Y)$
- $R_{pPb}(1S) > R_{pPb}(2S) > R_{pPb}(3S)$
 - Excited states more suppressed
 - Follows order of binding energies



Υ states in pPb

PLB 835(2022), 137397

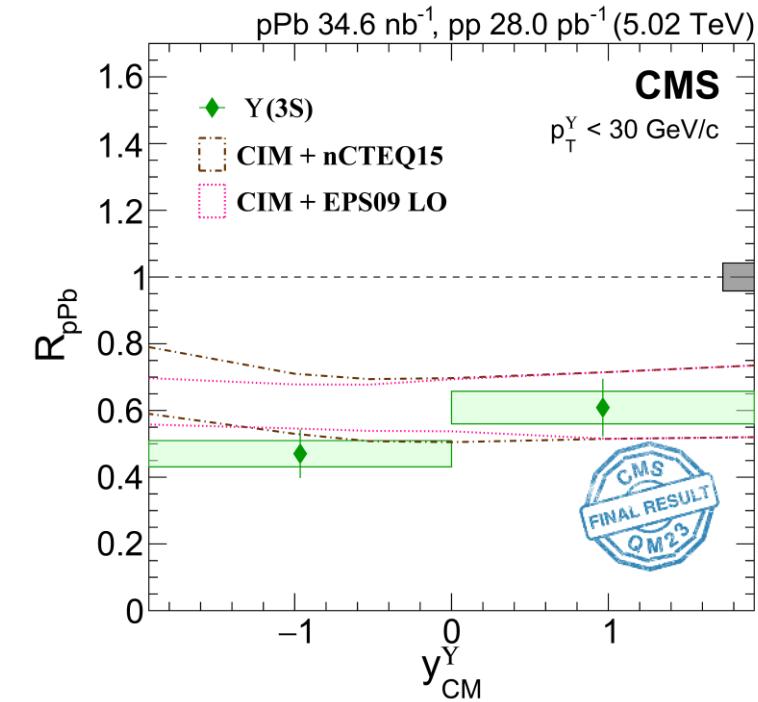
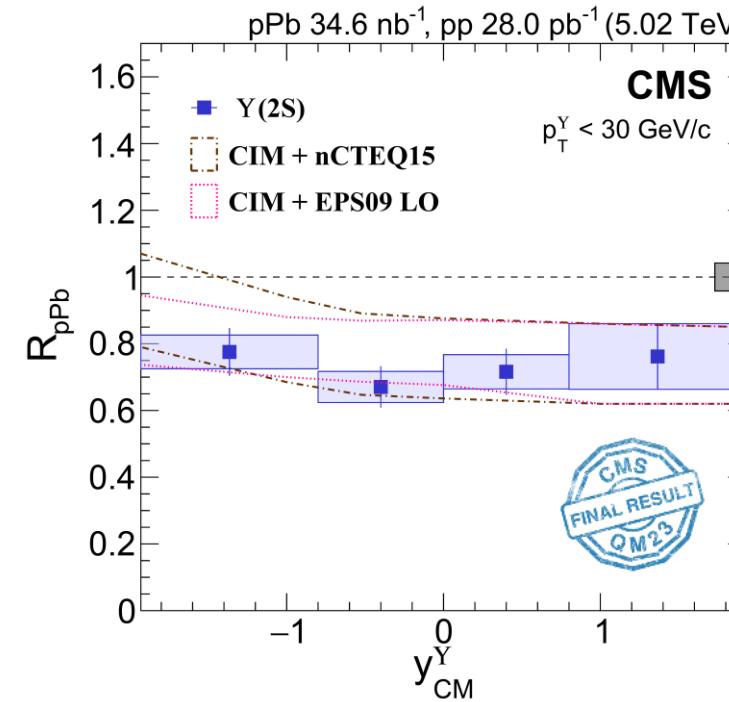
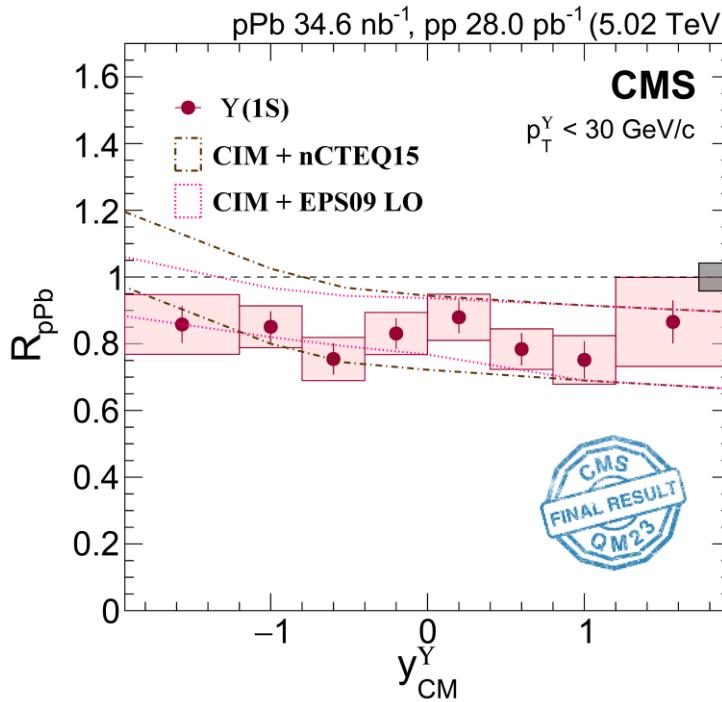
- $\Upsilon(1S)$ model comparison
 - Left: nPDF modifications (EPS09 NLO) [PRC 92, 034909]
 - Right: energy loss (with and without shadowing corrections) [JHEP 10 (2014) 073]
- Similar suppression in these models for $\Upsilon(2S)$ and $\Upsilon(3S)$



Υ states in pPb

PLB 835(2022), 137397

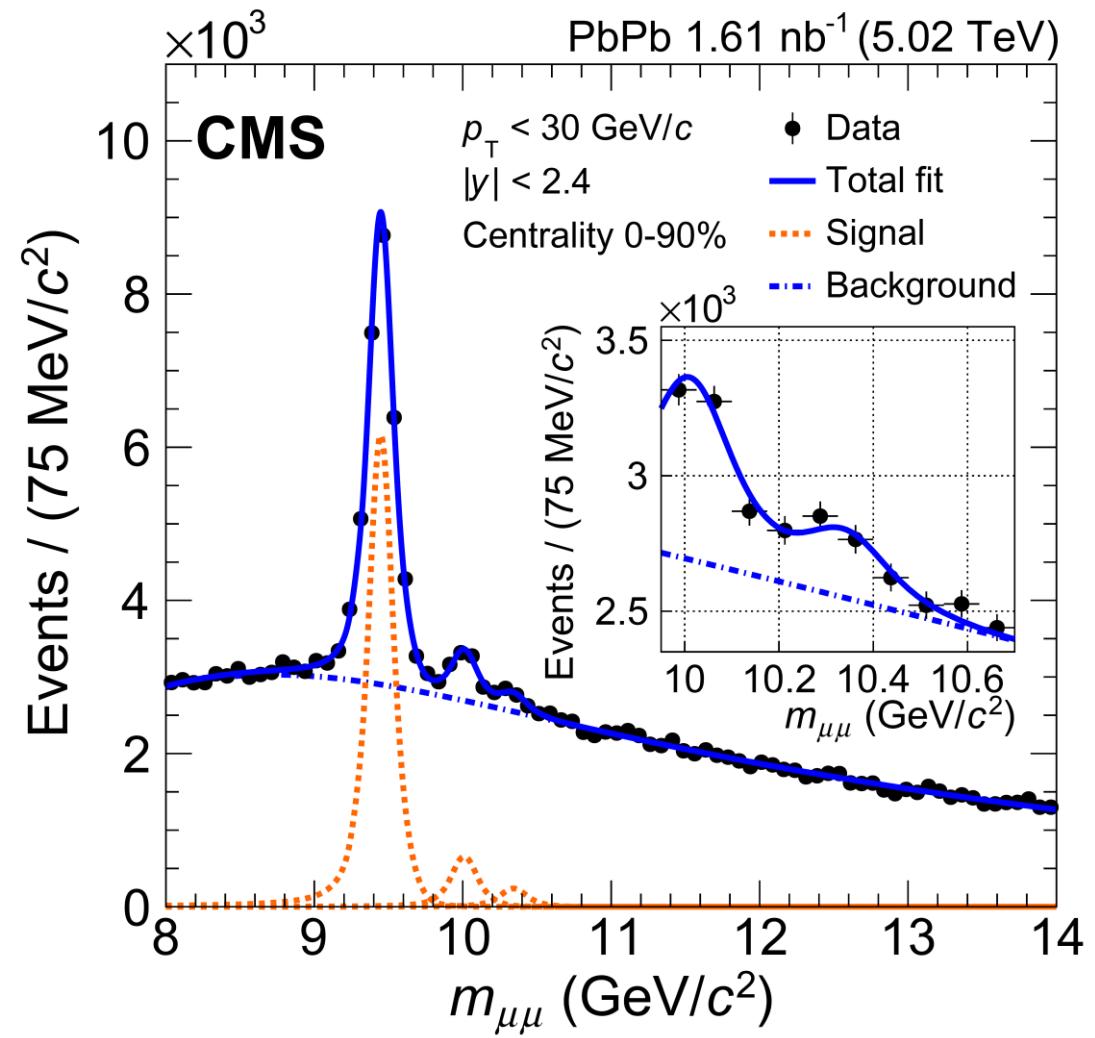
- Results compared to the comover interaction model (CIM) [JHEP10 (2018) 094, JHEP03 (2019) 063]
 - Final-state interaction – different magnitude for 2S and 3S state
 - 2 different nPDFs: nCTEQ15 [PRD 93 (2016) 085037] and EPS09 LO [EPJC 71 (2011) 1534]
 - Model calculation consistent with our observation



Y(2S) and Y(3S) in PbPb

arXiv 2303.17026

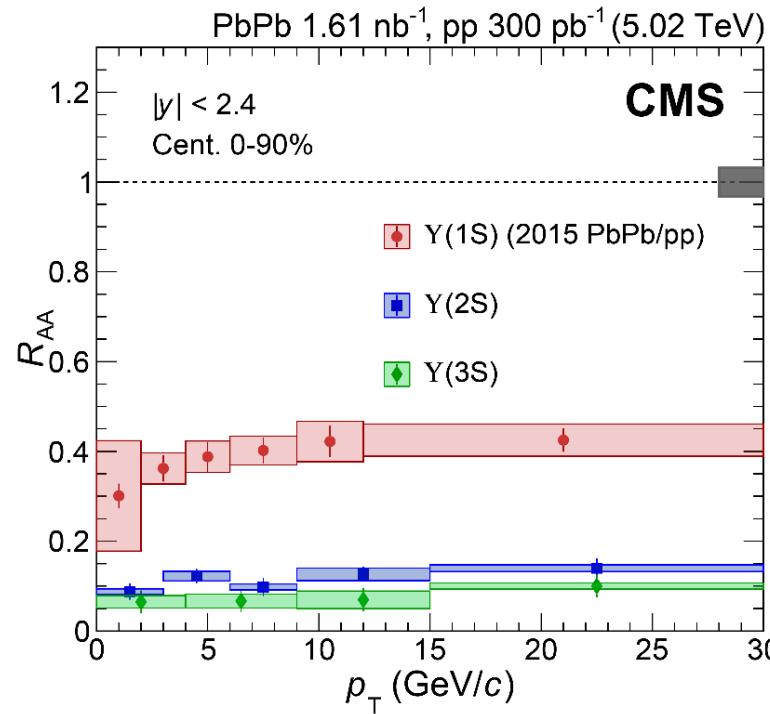
- First ever measurement of Y(3S) in nucleus-nucleus collisions
- $\sqrt{s_{NN}} = 5.02 \text{ TeV}$
 - 2017 pp, 2018 PbPb
- MVA to improve signal/background ratio
 - Boosted decision trees
- 5.6σ signal for Y(3S)



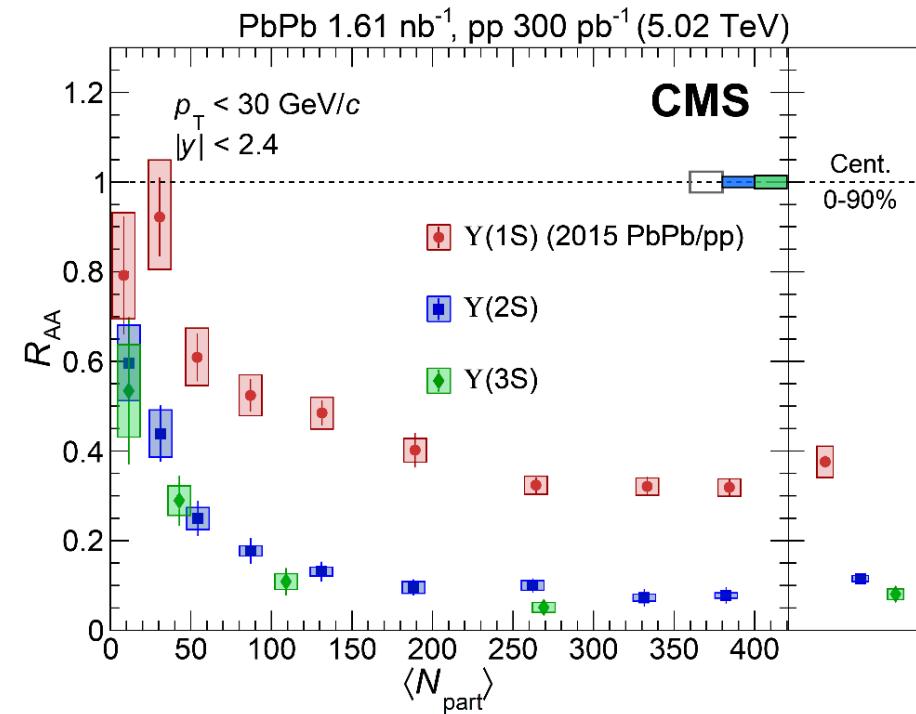
$\Upsilon(2S)$ and $\Upsilon(3S)$ in PbPb

arXiv 2303.17026

- Υ states are suppressed in PbPb collisions, all states melt
 - Suppression level constant across $p_T(\Upsilon)$
 - Strong dependence on centrality of collision (N_{part})
- $R_{\text{PbPb}}(1S) > R_{\text{PbPb}}(2S) > R_{\text{PbPb}}(3S)$
 - Excited states more suppressed



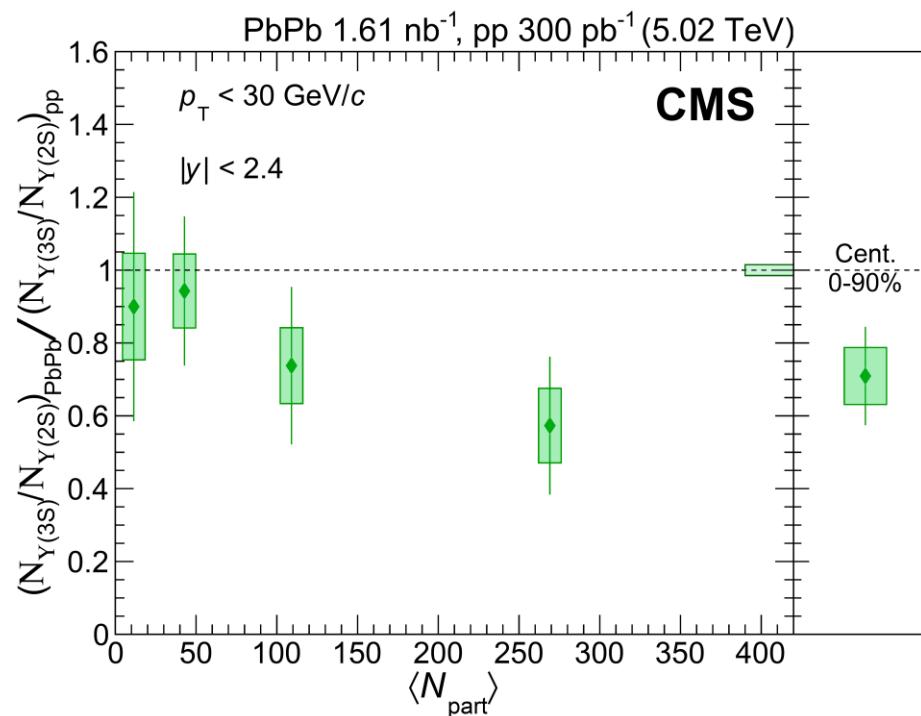
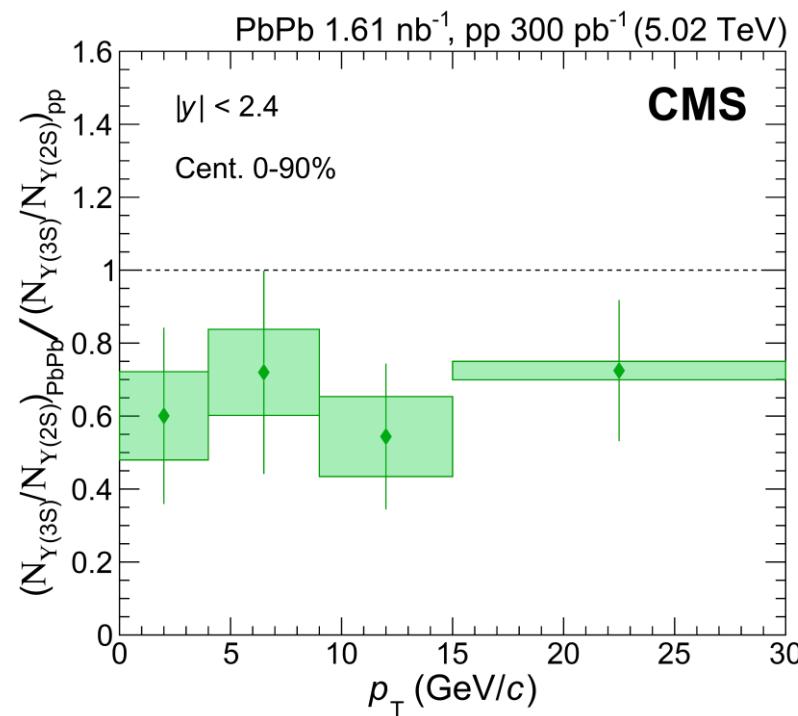
0-90% centrality
 $R_{\text{PbPb}}(3S) = 0.080 \pm 0.014 \text{ (stat)} \pm 0.012 \text{ (syst)}$



Y(2S) and Y(3S) in PbPb

arXiv 2303.17026

- Double ratio $\frac{[\Upsilon(3S)/\Upsilon(2S)]_{\text{PbPb}}}{[\Upsilon(3S)/\Upsilon(2S)]_{\text{pp}}}$
 - Constant across $p_T(\Upsilon)$
 - Hint of stronger suppression for $\Upsilon(3S)$ compared to (2S) for more central events

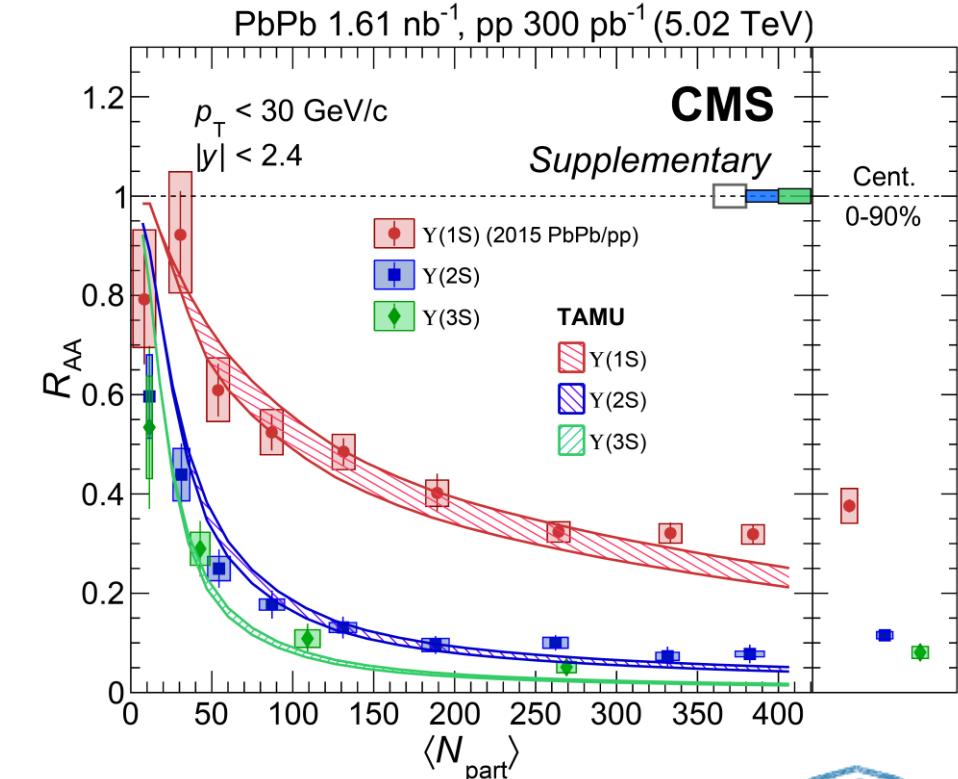
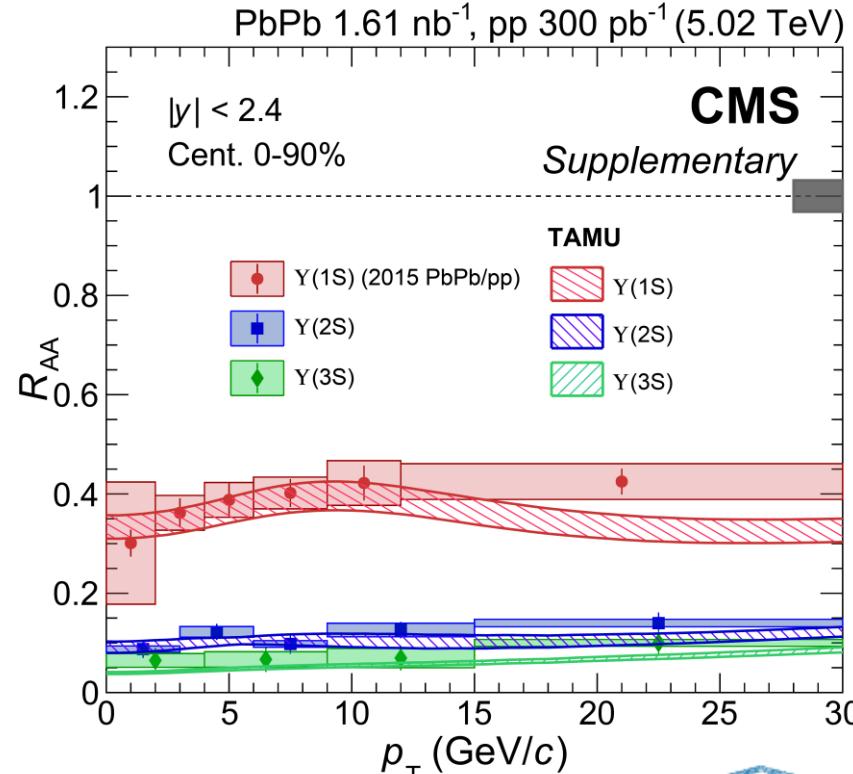


$\Upsilon(2S)$ and $\Upsilon(3S)$ in PbPb

arXiv 2303.17026

Model comparisons (1)

- TAMU [PRC 96 (2017) 054901]
 - Kinetic rate equation approach
 - Includes regeneration, in-medium binding energies, and lattice QCD based EOS for fireball evolution
 - Describes the trends well

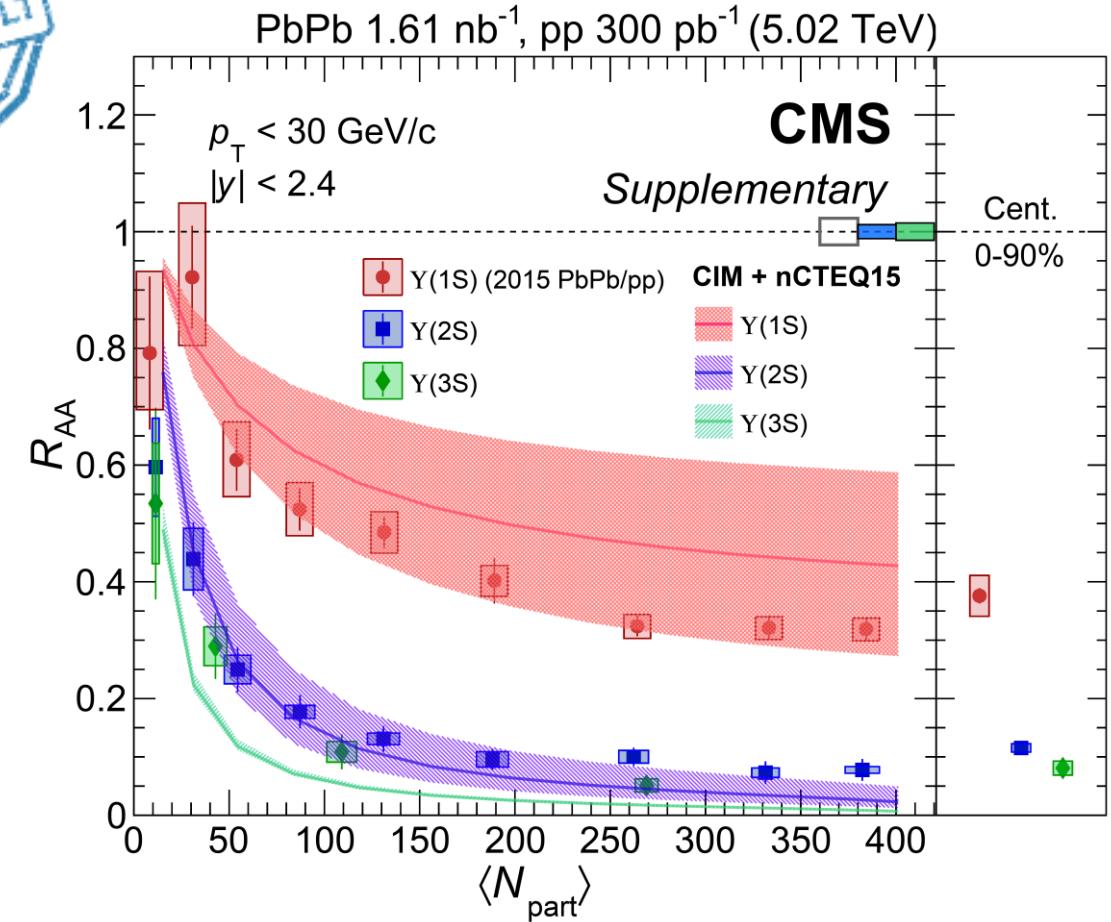


$\Upsilon(2S)$ and $\Upsilon(3S)$ in PbPb

arXiv 2303.17026

Model comparisons (2)

- Comover interaction model [JHEP10 (2018) 094]
 - Same model used for pPb collisions
 - Includes shadowing nCTEQ15 [PRD 93 (2016) 085037]
 - Describes the $\Upsilon(1S)$ and $\Upsilon(2S)$
 - Predicts stronger suppression for $\Upsilon(3S)$ for most of the centrality range



Comparison to other models
in the back-up slides

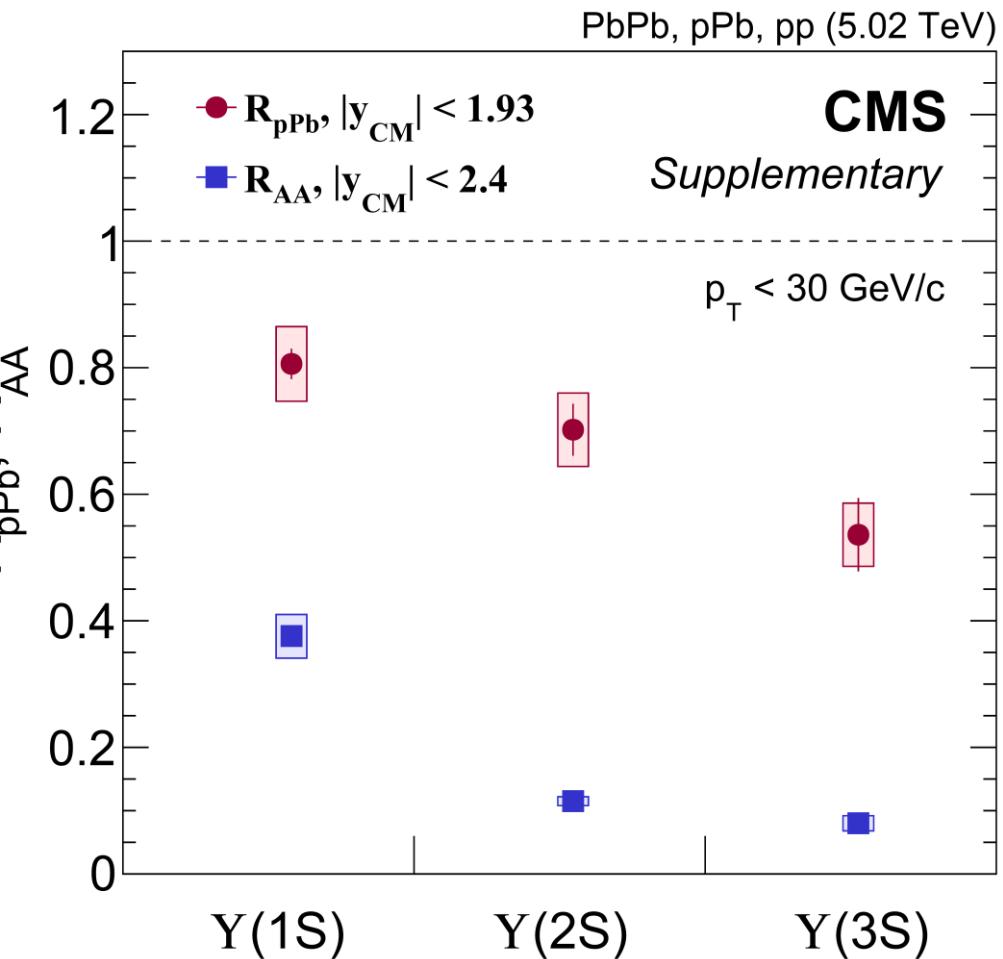
Y states in pPb and PbPb

- Suppression smaller in pPb compared to PbPb
- Similar ordering present
 - $R_{pPb/PbPb}(1S) > R_{pPb/PbPb}(2S) > R_{pPb/PbPb}(3S)$

PbPb (2S) and (3S)
[arXiv 2303.17026](https://arxiv.org/abs/2303.17026)

pPb:
[PLB 835\(2022\), 137397](https://doi.org/10.1016/j.plb.2022.137397)

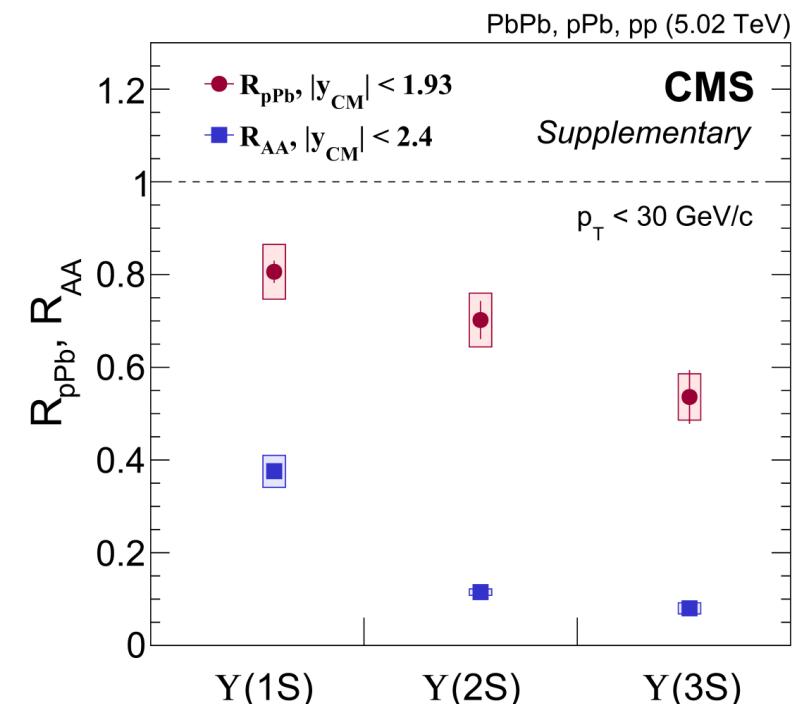
PbPb (1S): PLB 790(2019), 2070



Summary

- Excellent performance for muon detection by the CMS experiment
 - Across pp, pPb and PbPb collisions, and wide range of detector occupancies
- Y states in pPb collisions
 - Sequential ordering of suppression
 $R_{p\text{Pb}}(1S) > R_{p\text{Pb}}(2S) > R_{p\text{Pb}}(3S)$
 - Follows their binding energies
 - Challenging to describe with initial state effects alone
- First measurement of Y(3S) in PbPb collisions
 - $R_{\text{PbPb}}(3S) = 0.080 \pm 0.014 \text{ (stat)} \pm 0.012 \text{ (syst)}$
 - Same ordering as in pPb: $R_{\text{PbPb}}(1S) > R_{\text{PbPb}}(2S) > R_{\text{PbPb}}(3S)$
 - Overall suppression much larger than in pPb

[CMS-PAS-MUO-21-001](#)



PbPb (2S) and (3S) [arXiv 2303.17026](#)

pPb: [PLB 835\(2022\), 137397](#)

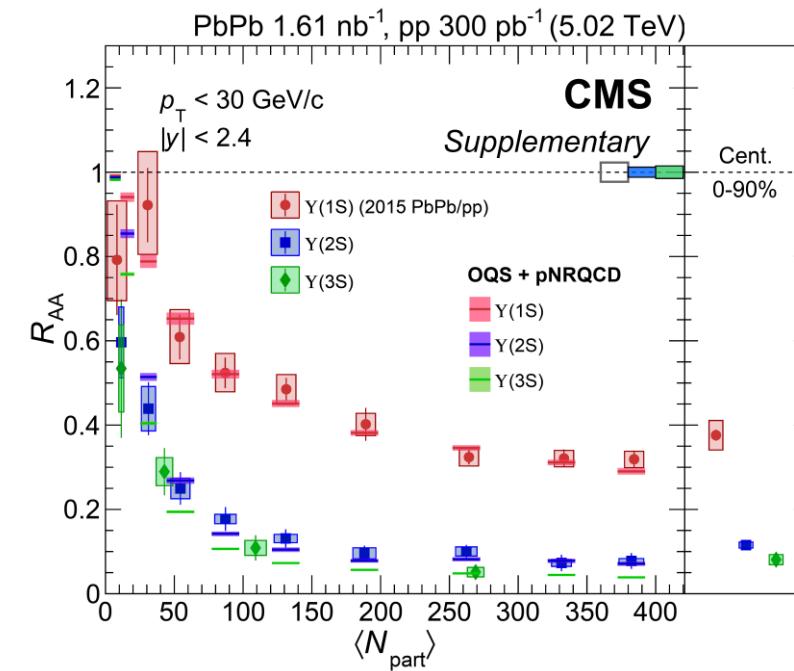
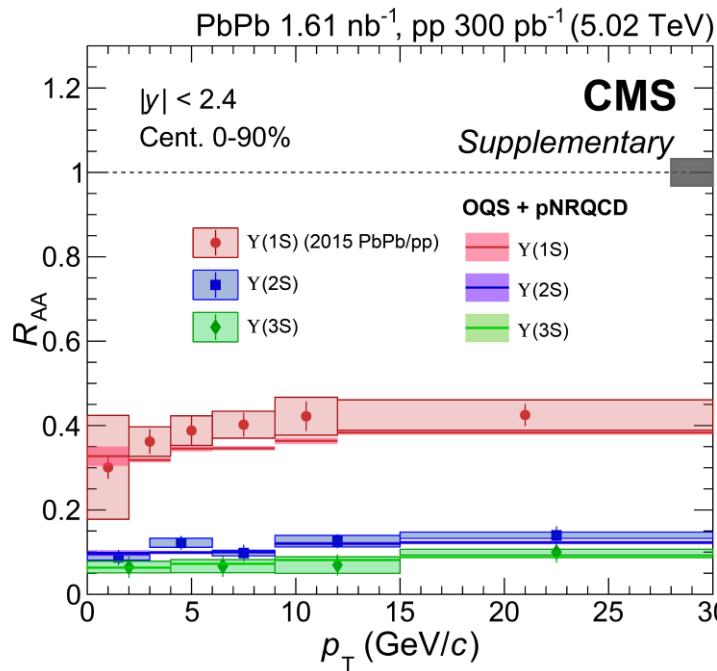
Back up

Y(2S) and Y(3S) in PbPb

arXiv 2303.17026

Model comparisons (3)

- OQS + pNRQCD [PRD108 (2023) 011502]
 - ▣ Open quantum system framework, potential NRQCD approach
 - ▣ Includes quantum regeneration
 - ▣ Model describes the trends and suppression well

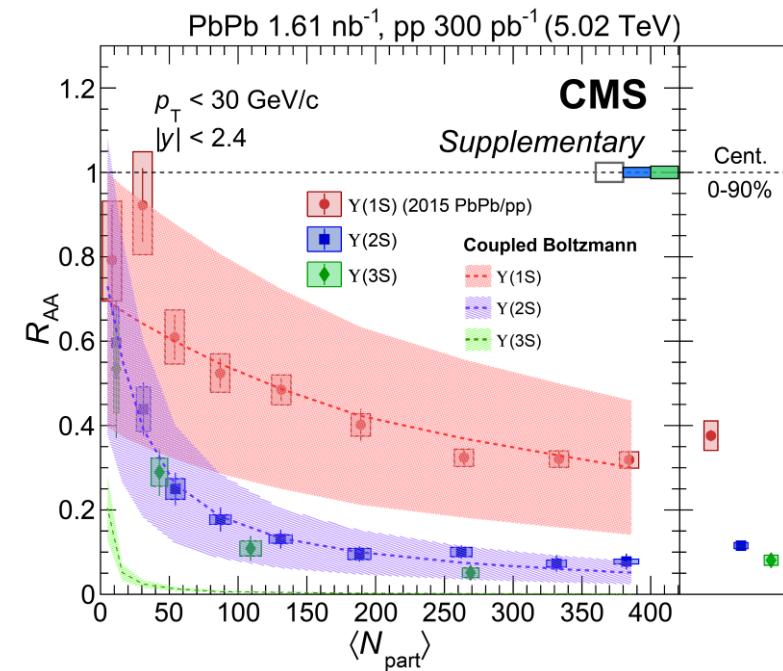
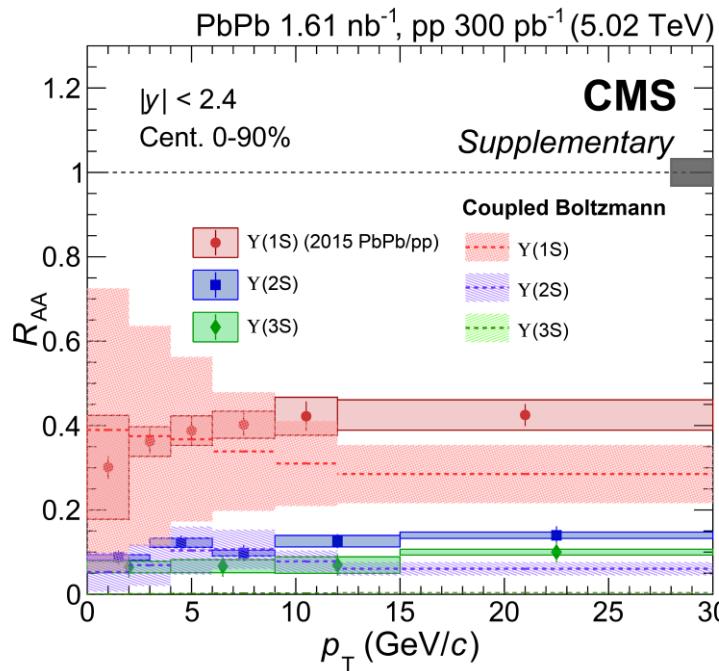


$\Upsilon(2S)$ and $\Upsilon(3S)$ in PbPb

arXiv 2303.17026

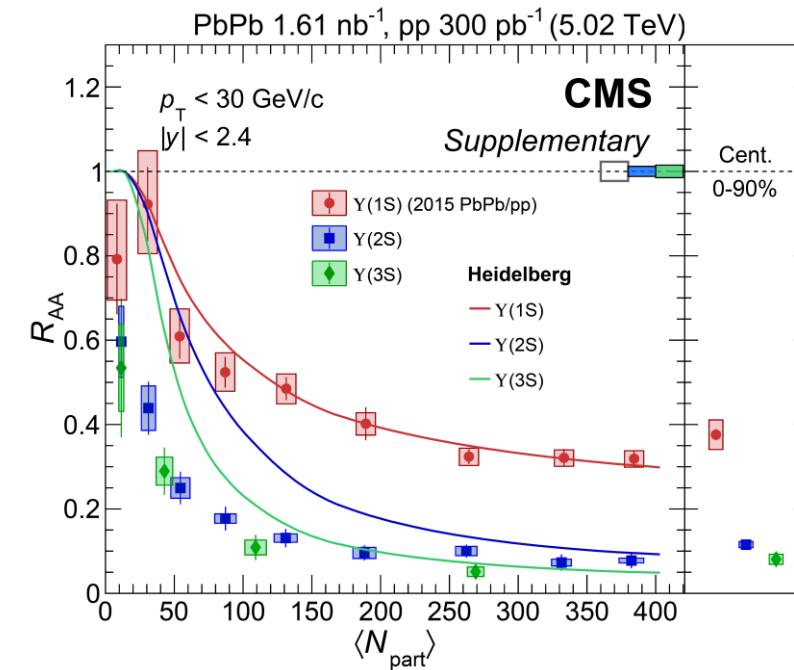
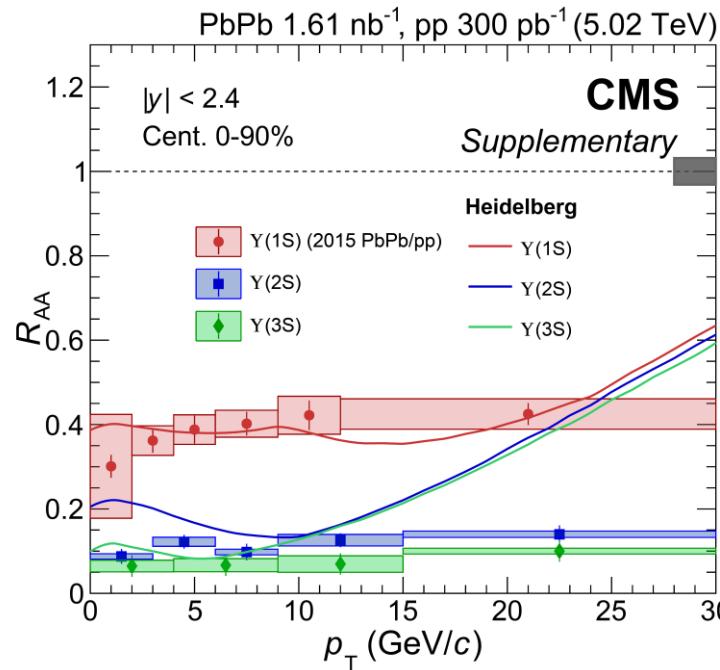
Model comparisons (4)

- Coupled Boltzmann [JHEP01(2021)046]
 - Open quantum system framework, coupled transport equations
 - Includes both correlated and uncorrelated recombination
 - Describes centrality dependence of 1S and 2S state, fails for 3S state



Model comparisons (5)

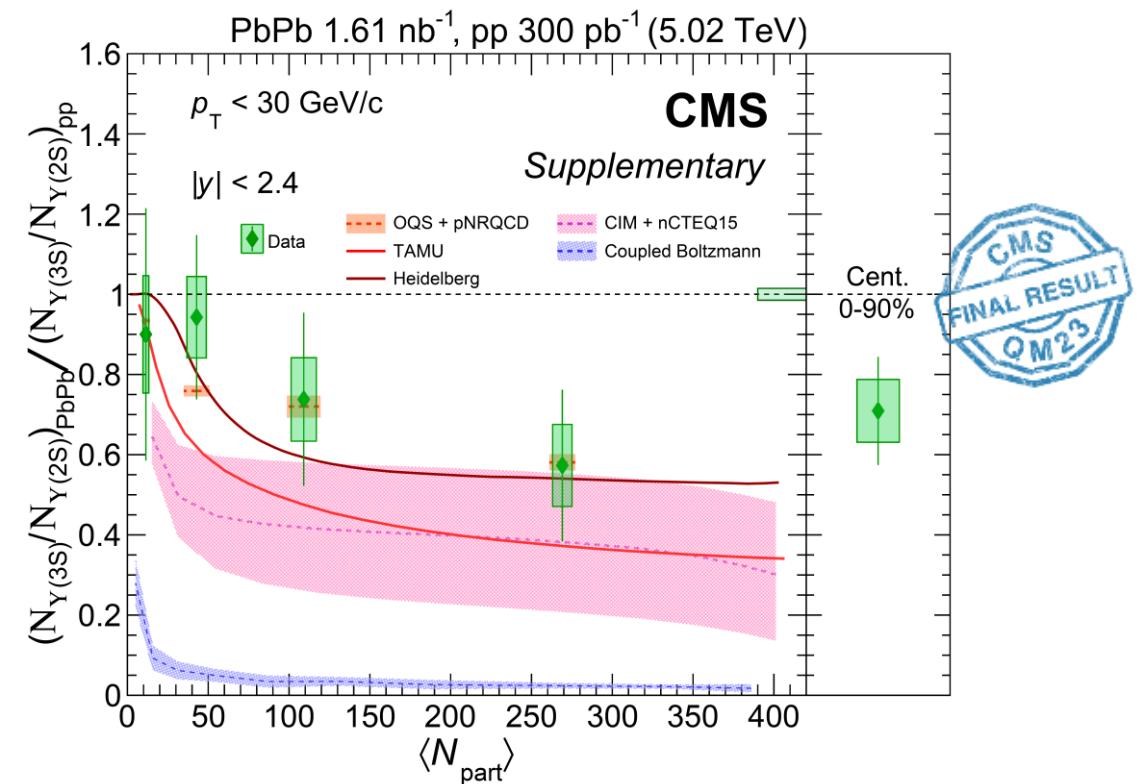
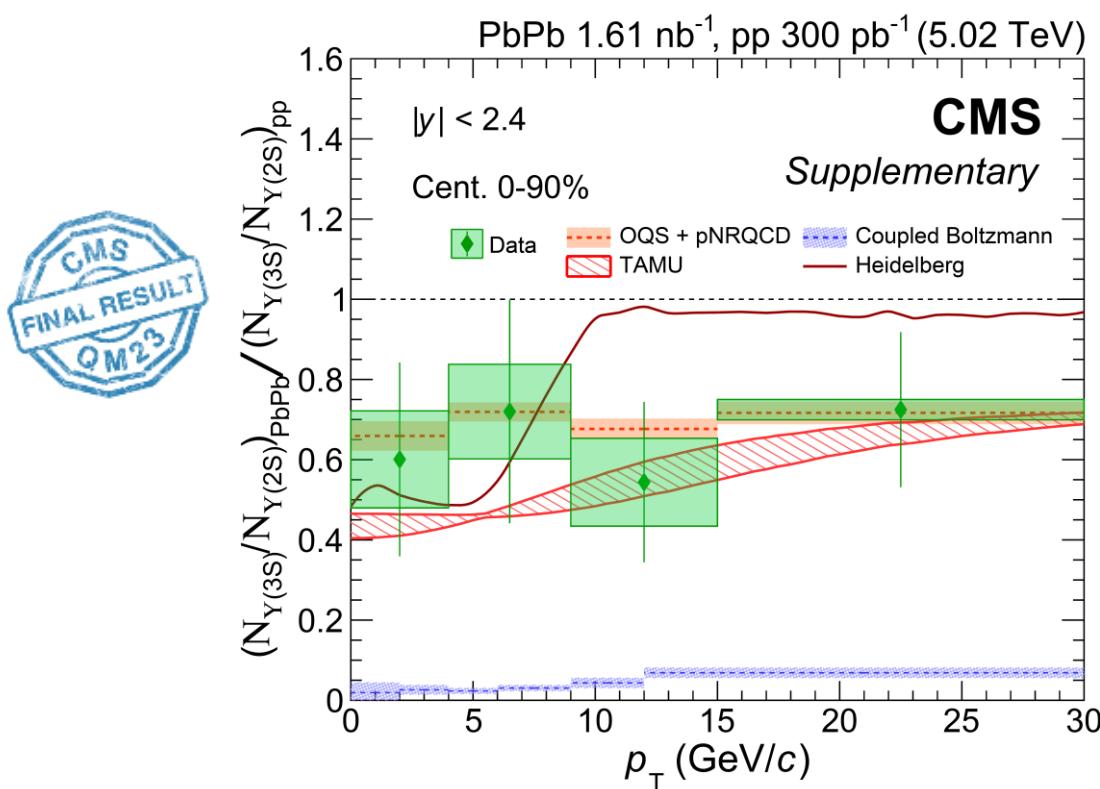
- Heidelberg [IJMPA 35, 2030016 (2020)]
 - ▣ Model incorporating screening, gluodissociation and changes to feed-down
 - ▣ Describes 1S state well
 - ▣ Overpredicts 2S and 3S states at high- p_T and peripheral collisions



Double ratio and models

arXiv 2303.17026

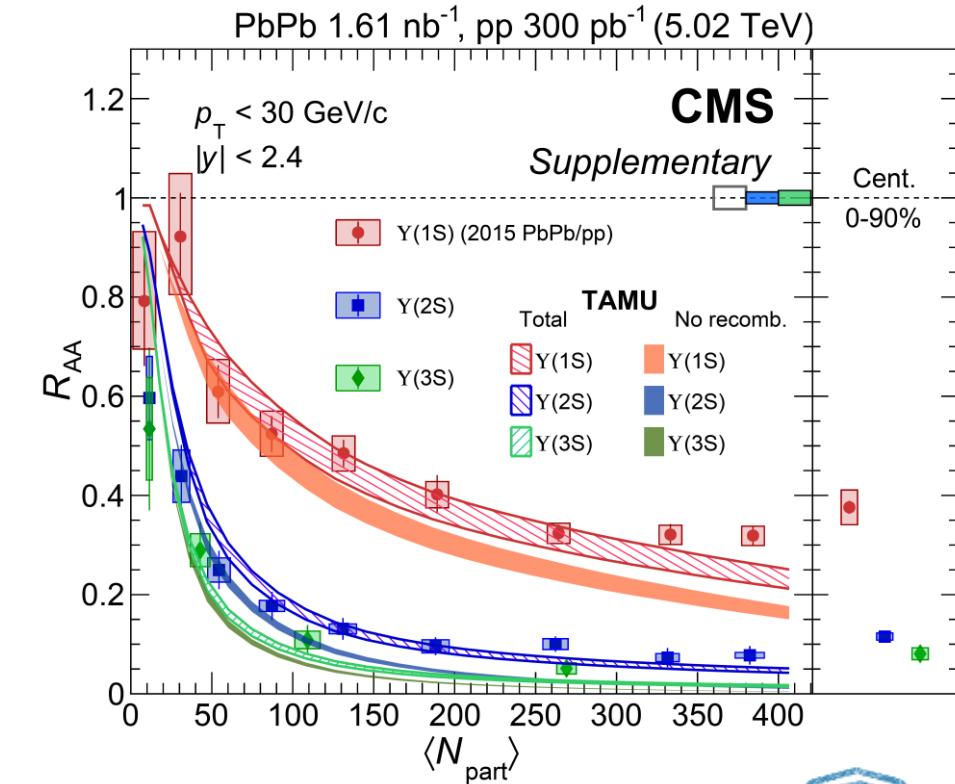
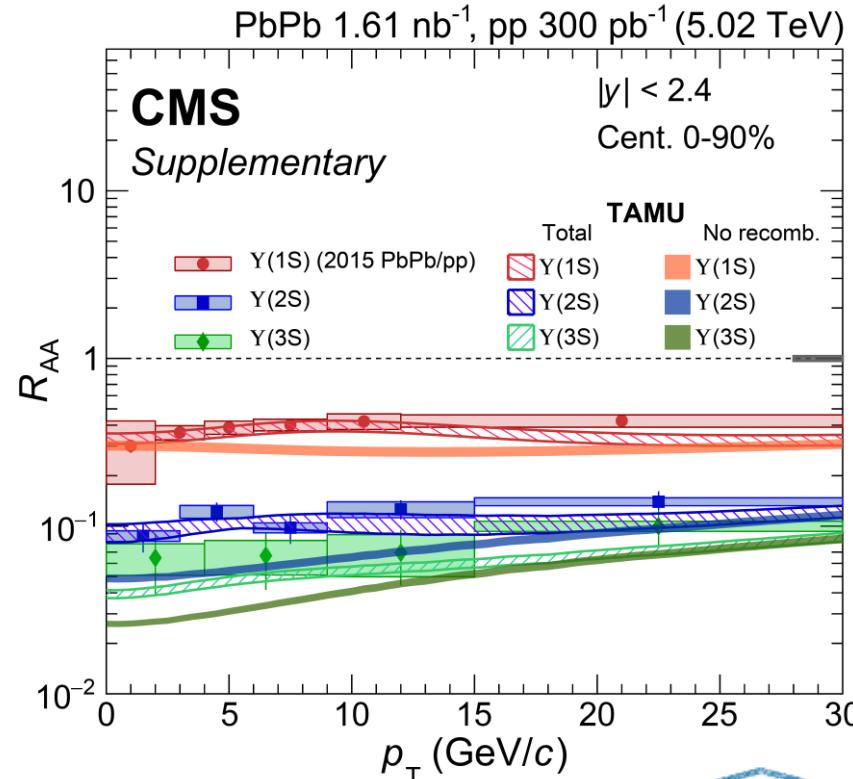
□ Double ratio $\frac{[\Upsilon(3S)/\Upsilon(2S)]_{\text{PbPb}}}{[\Upsilon(3S)/\Upsilon(2S)]_{\text{pp}}}$



Y in PbPb – regeneration (1)

arXiv 2303.17026

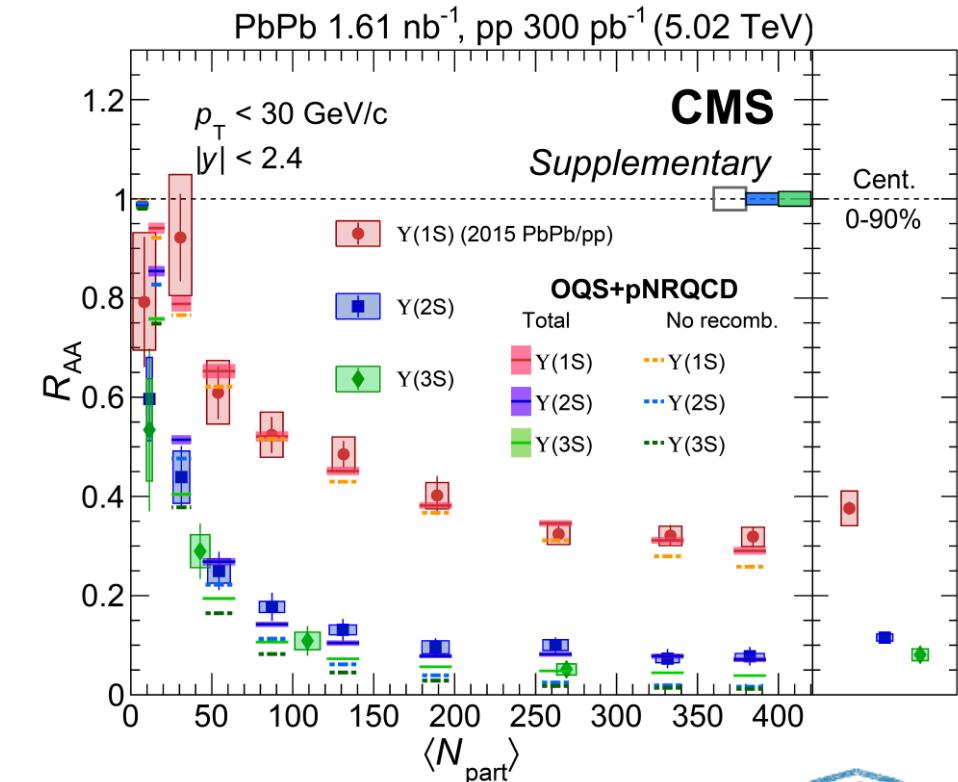
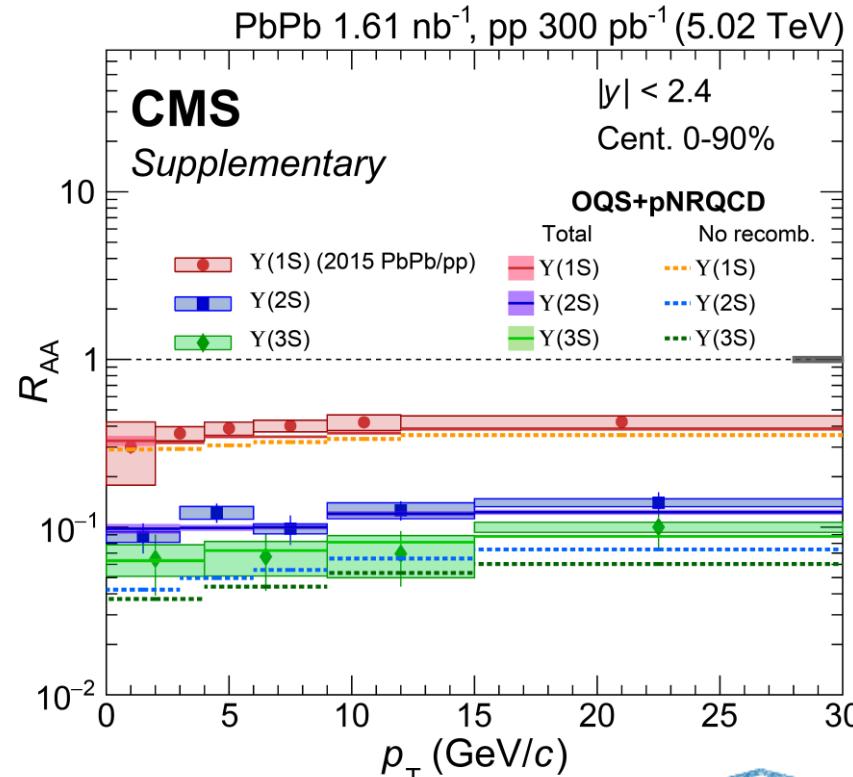
- Regeneration important in models that include it
- TAMU [PRC 96 (2017) 054901]



Y in PbPb – regeneration (2)

arXiv 2303.17026

- Regeneration important in models that include it
- OQS + pNRQCD
[PRD108 (2023) 011502]



Quarkonia in PbPb – binding E

arXiv 2303.17026

- R_{AA} vs quarkonia state binding energy

