Recent Quarkonia Results of CMS Heavy Ion Experiment

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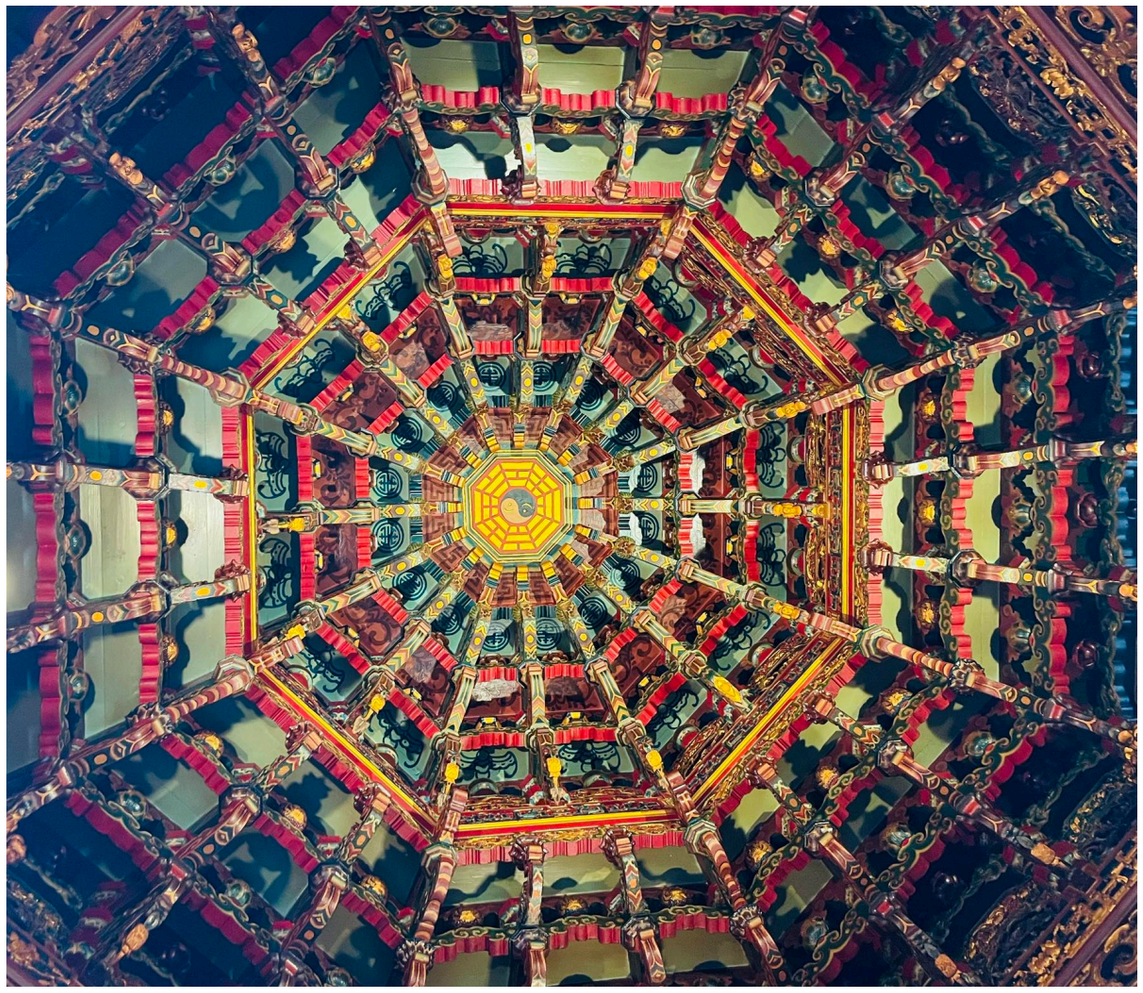
ANPhA symposium, Taipei, Nov 28, 2025

新竹都城隍廟

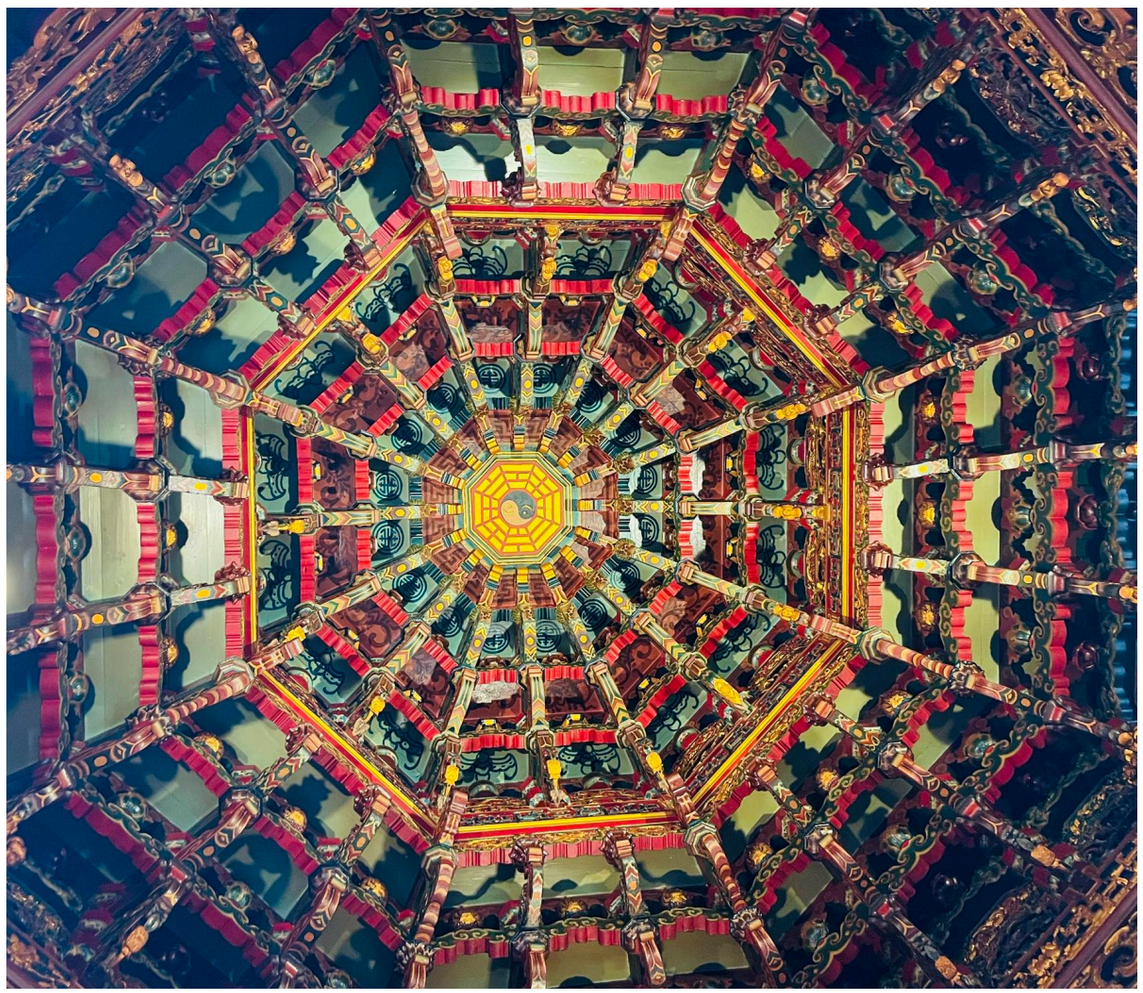
Hsinchu Governor City God Temple



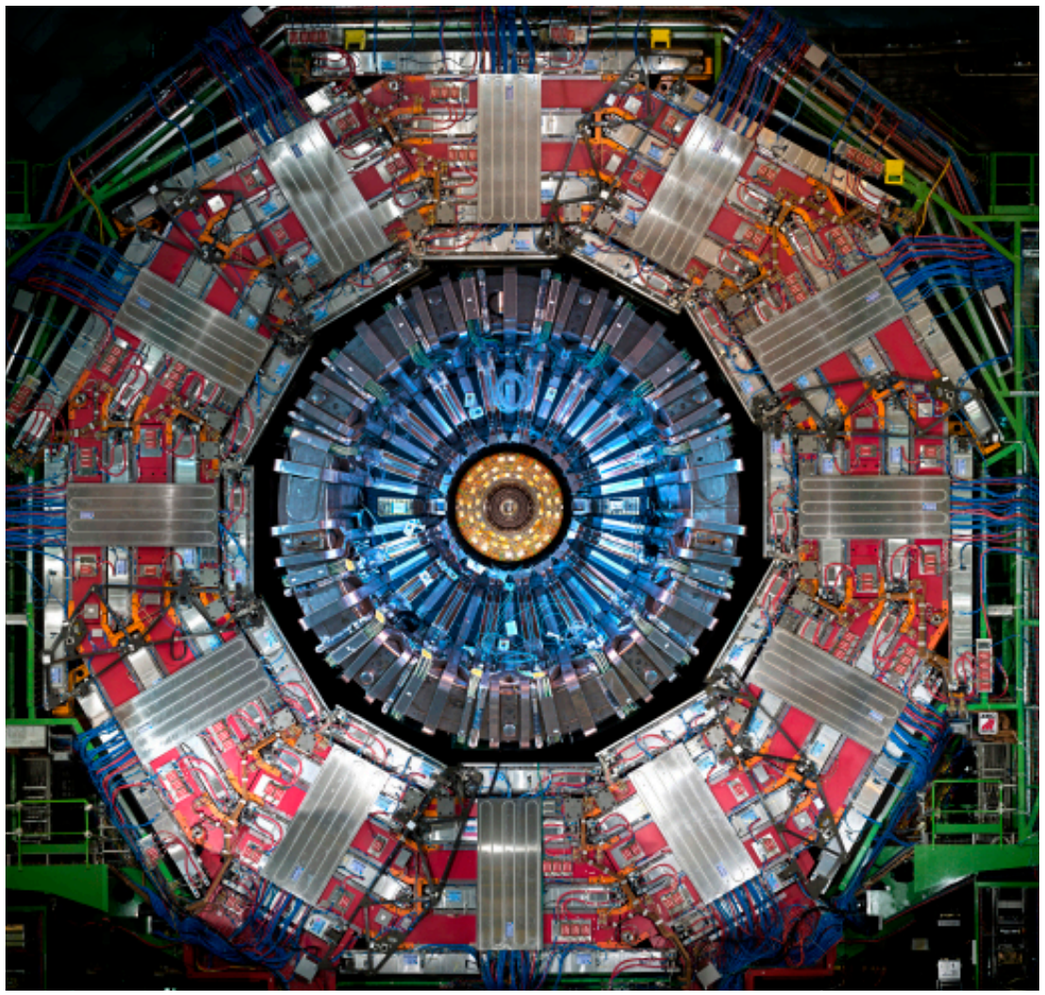
Decoration of the ceiling

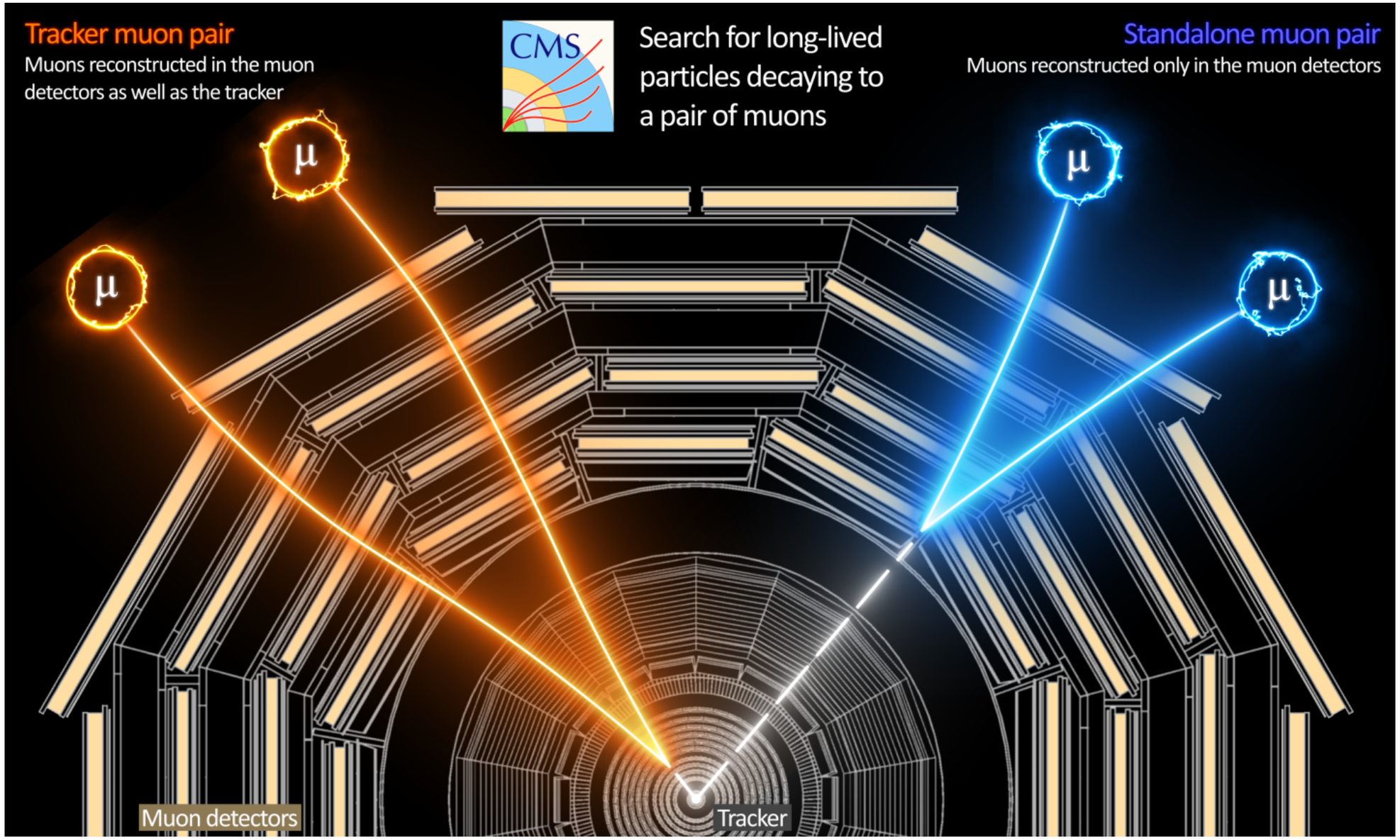
新竹都城隍廟

Hsinchu Governor City God Temple



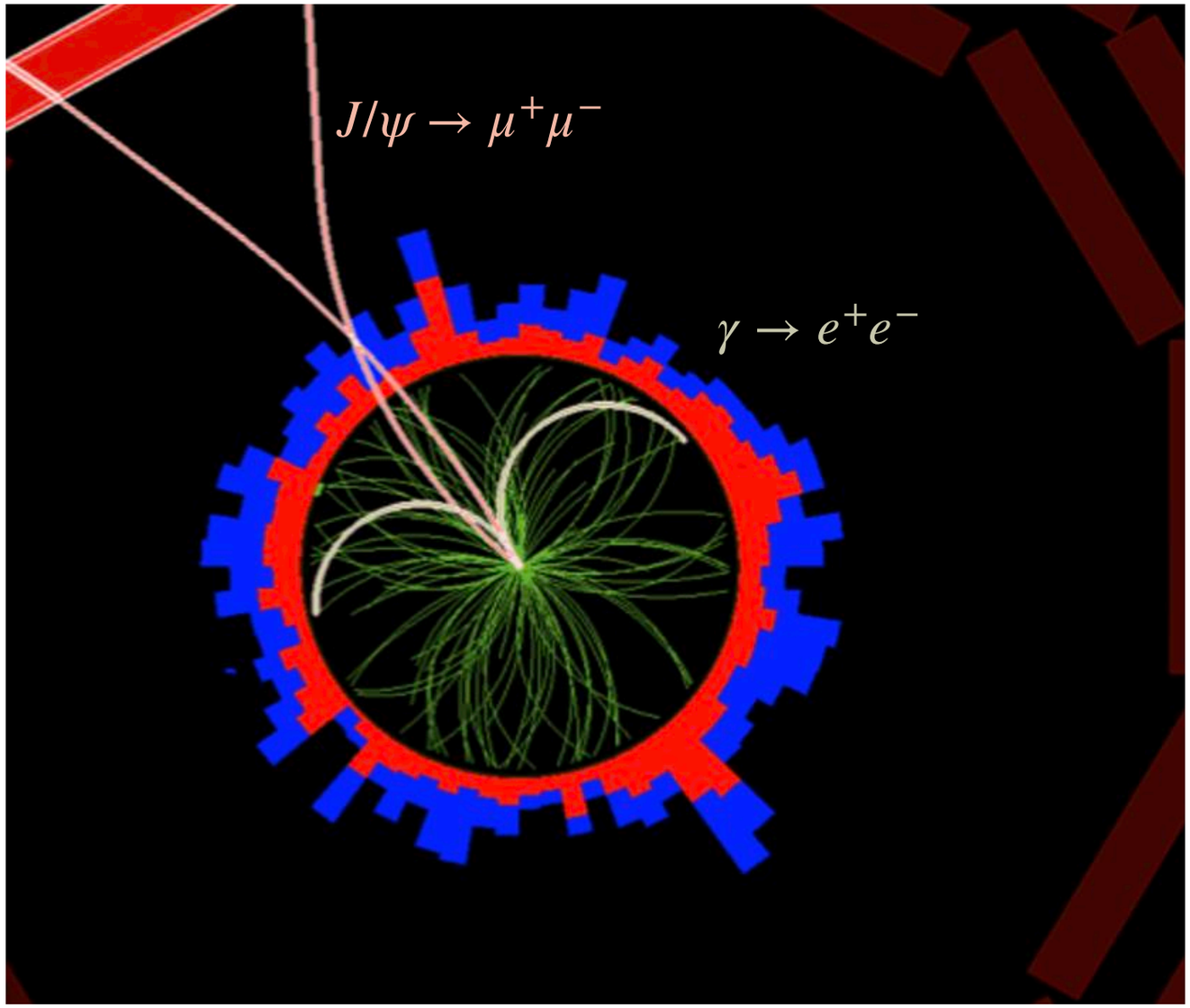
Decoration of the ceiling

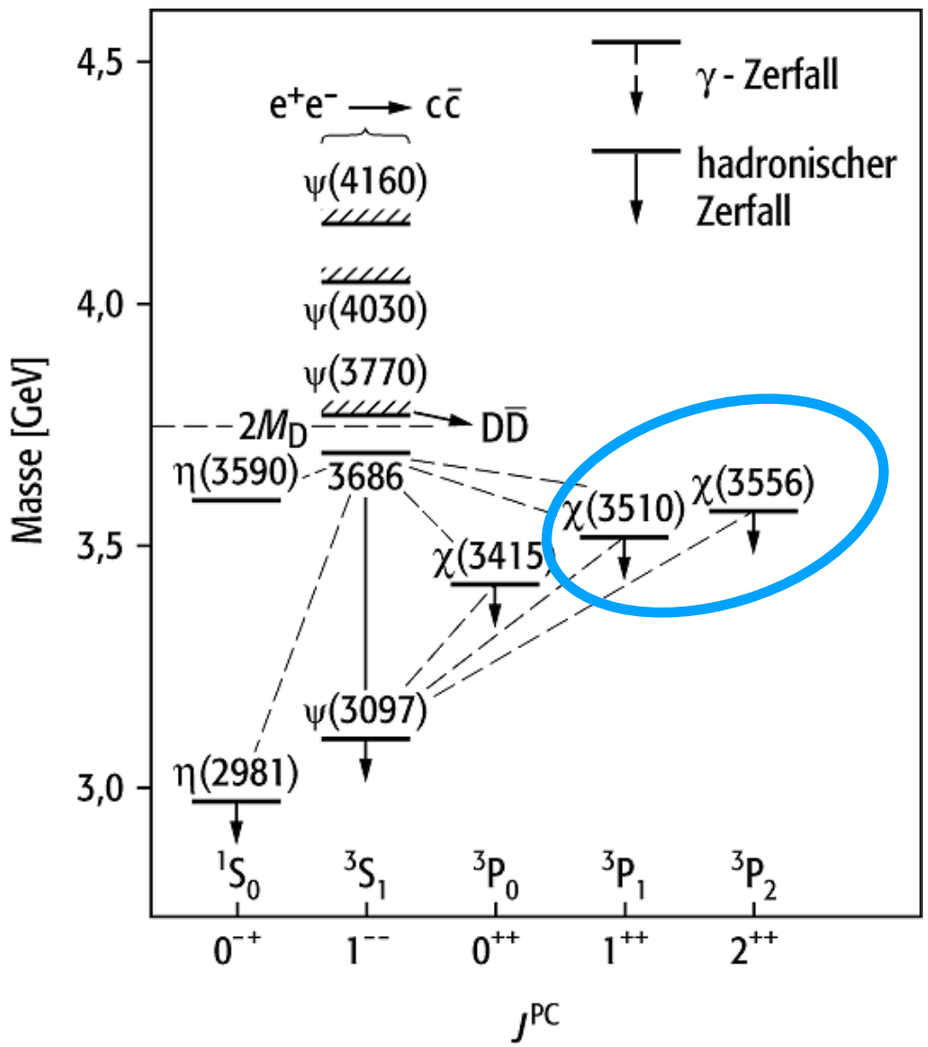




Quarkonia measurement in CMS (S-wave)

- J/ψ, $\psi(2S)$ $\rightarrow \mu^+\mu^-$
- Υ(1S), Υ(2S), Υ(3S) $\rightarrow \mu^+\mu^-$





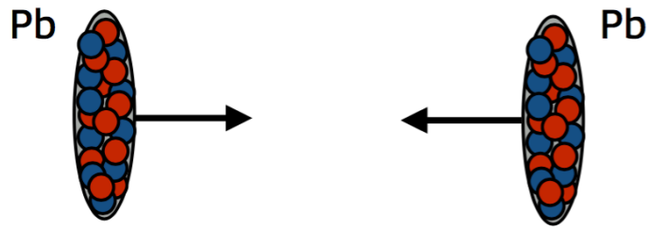
Quarkonia measurement in CMS (P-wave)

- $\chi_c \rightarrow J/\psi + \gamma \rightarrow \mu^+\mu^- + e^+e^-$

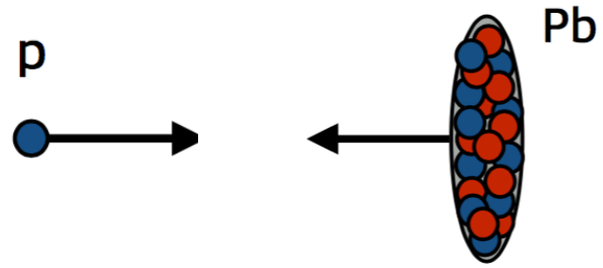
(Photons can be converted to e^+e^- pairs by the tracker material)

Outline

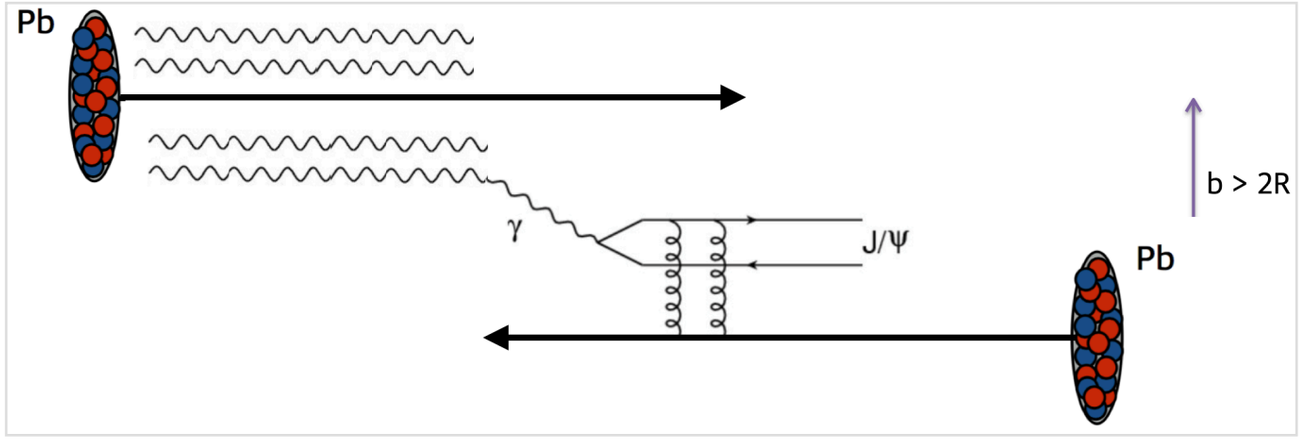
Y(nS) in PbPb



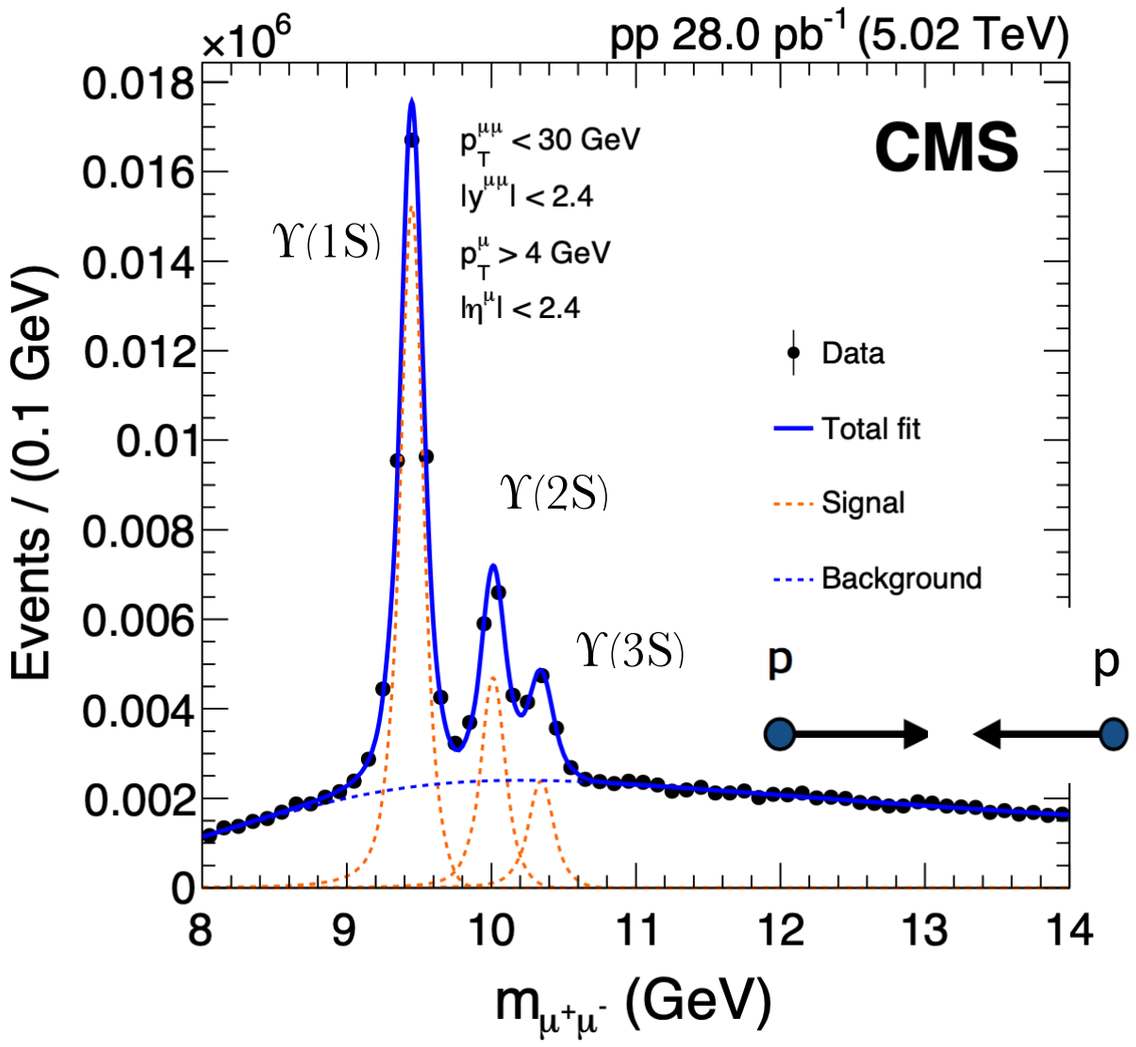
Y(nS), χ_c(nS) in pPb

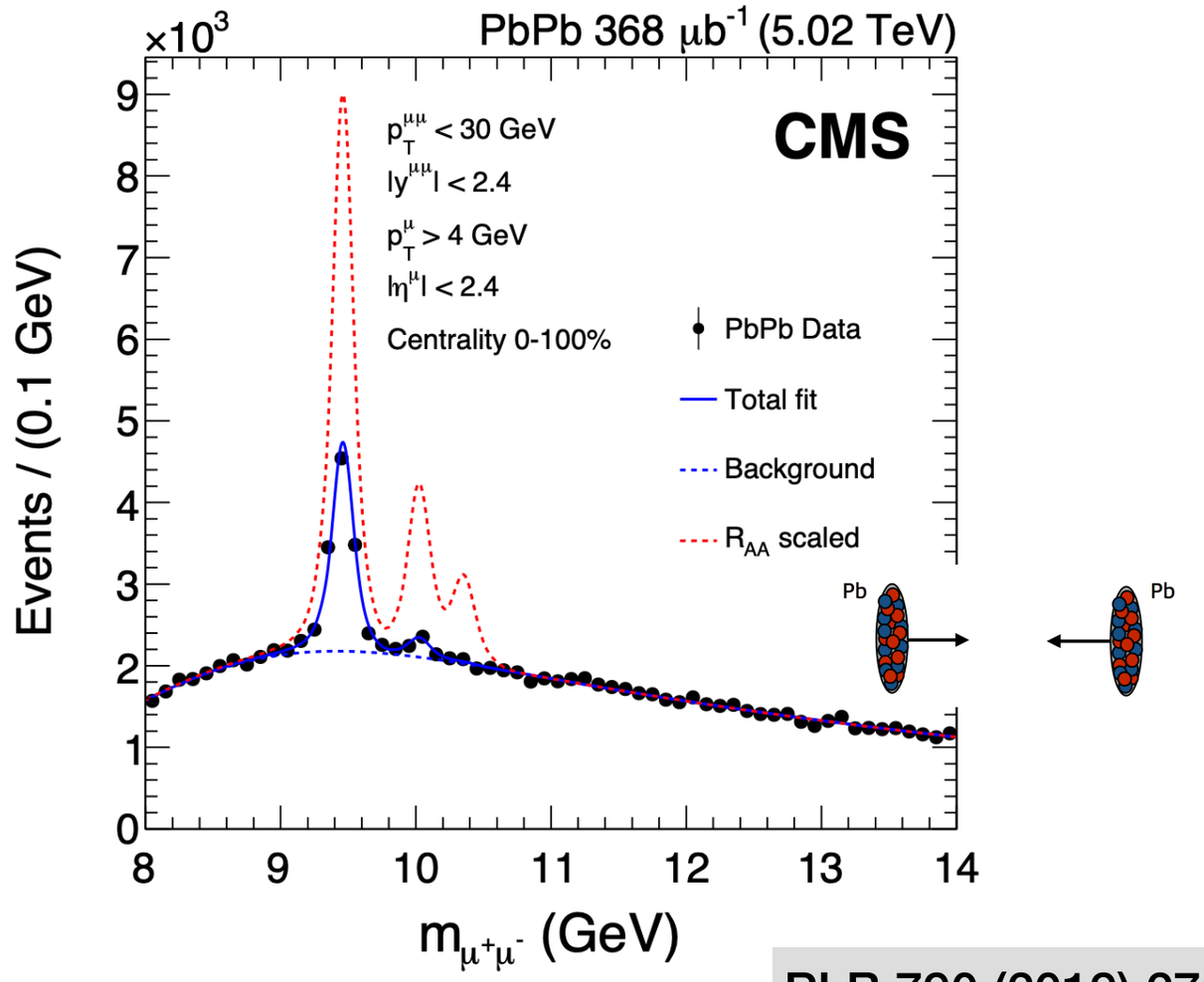


Quarkonia in UPC



Υ(nS) mesons in heavy ion collision





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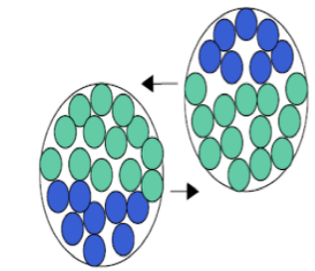
- Invariant mass distribution of $\mu^+\mu^-$ pairs measured in PbPb data, compared with pp data at the same energy.
- Signature of Quark Gluon Plasma formation due to color screening

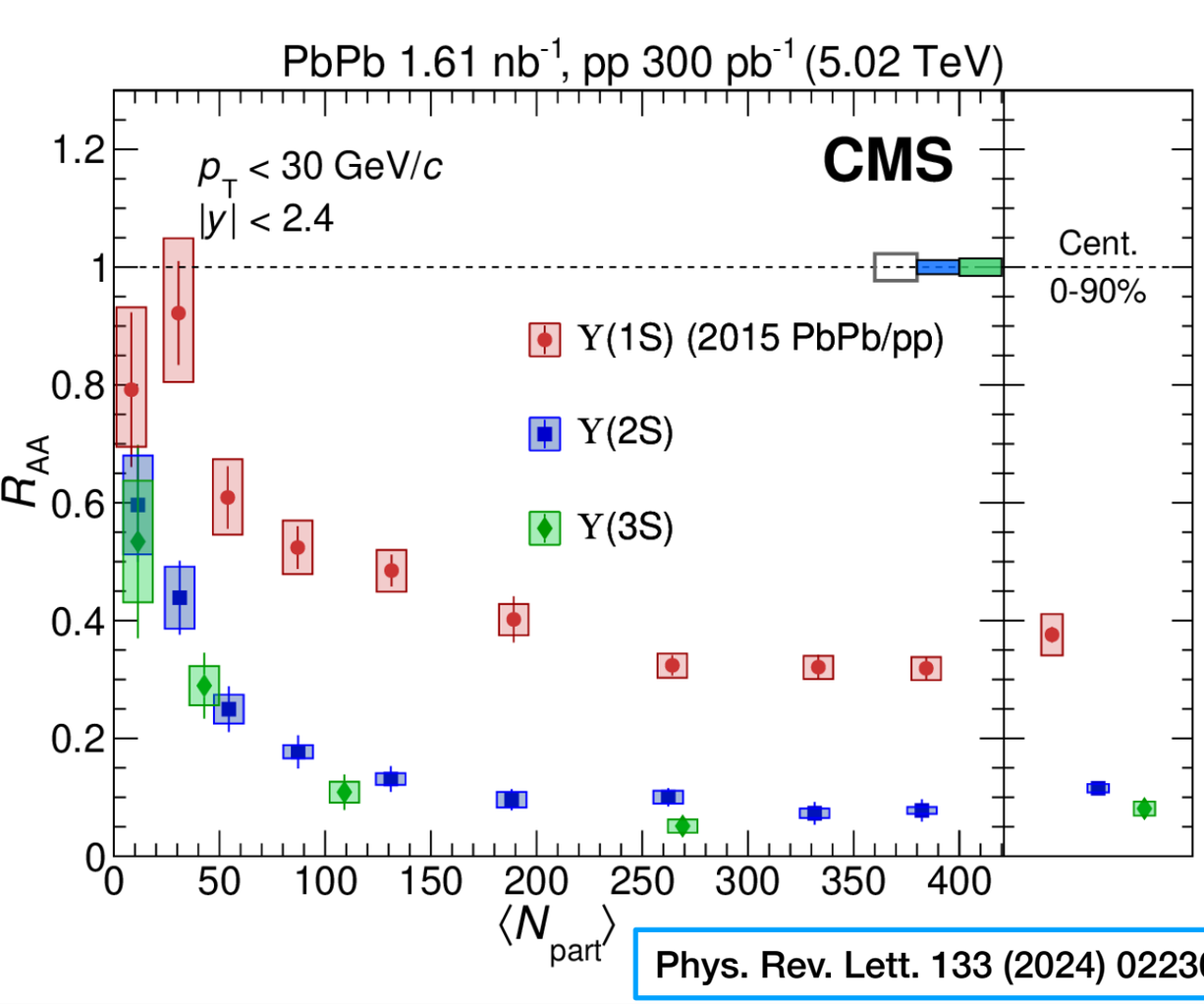
Nuclear Modification factor (R_{AA})

- Ratio of production cross section in AA (pA) to pp, normalized by the collision system's binary *NN* collision numbers (N_{coll})
- N_{coll} depends on the collisional centrality and is proportional to the nuclear thickness function T_{AA}

$$R_{AA} = \frac{d^2 N_{AA} / dp_T d\eta}{\langle T_{AA} \rangle d^2\sigma_{pp} / dp_T d\eta}$$

$R_{AA} > 1$ (enhanced production)
$R_{AA} = 1$ (consistent with pp)
$R_{AA} < 1$ (suppressed production)





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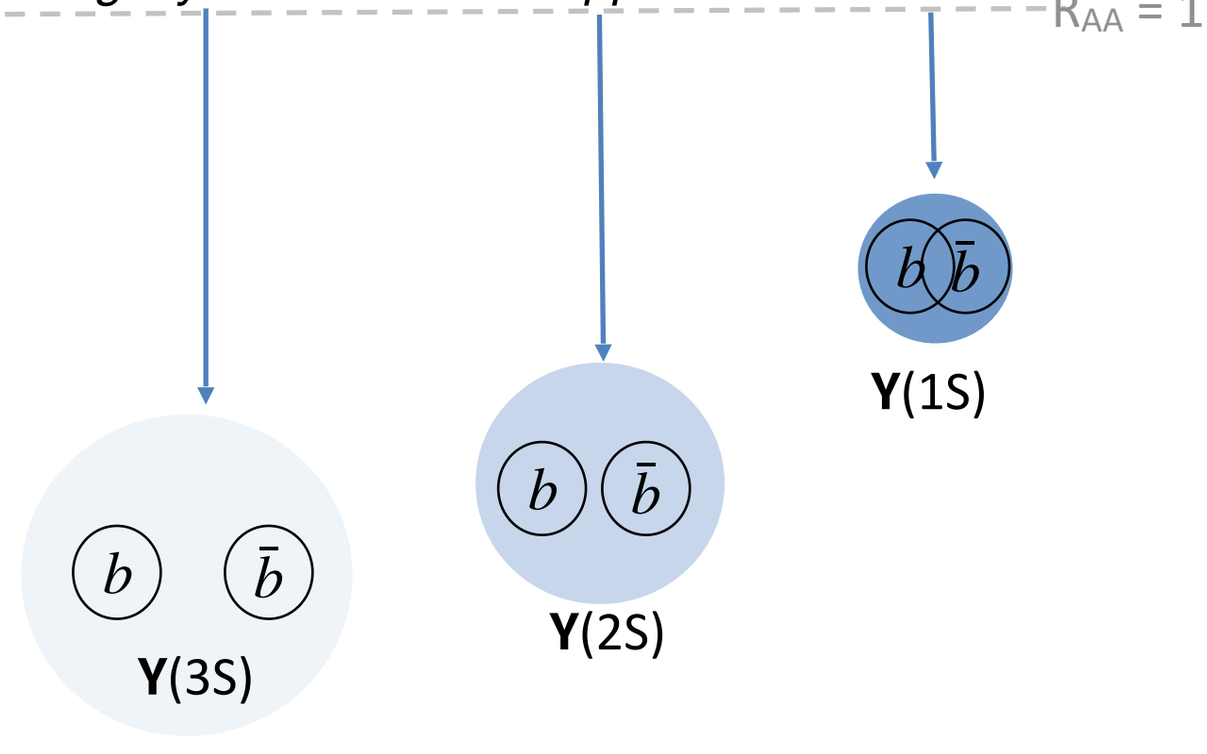
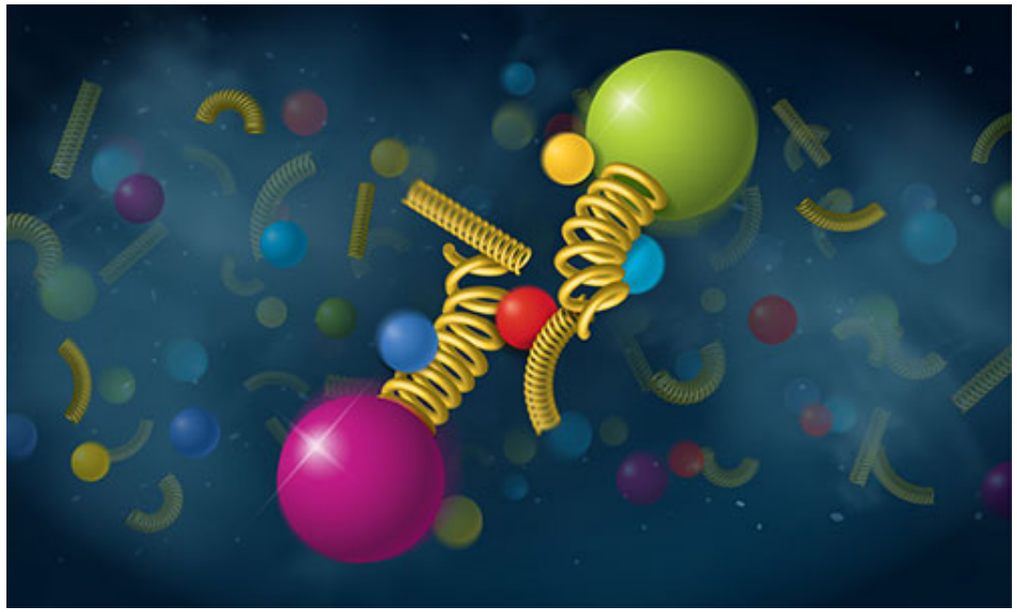
More tightly bound = less suppressed

$R_{AA} = 1$

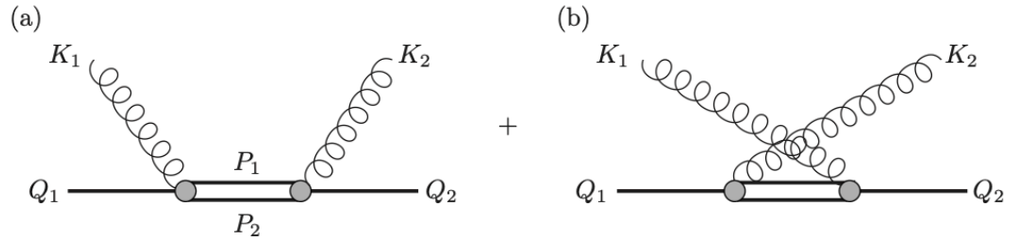


Y(nS) mesons in heavy ion collision

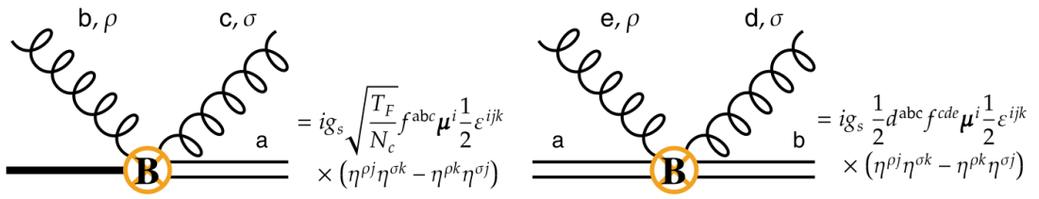
- CMS has continuously measured bottomonia and charmonia in pp, pPb, PbPb since 2010 seeking for cutting edge precision. *Why?*
- Several distinct factors affects quarkonia production
  - Color screening (Debye screening)
  - Gluon dissociation (thermal break-up)
  - Quasi-free parton scattering
  - Comover interaction (co-moving hadrons)
  - Regeneration / recombination
  - Energy loss of heavy quarks before binding
  - Modification of Parton distribution (nPDF)
- They happen in different time-scale, different dependence on T and μ
- More equations can better disentangle the effects



Debye screening (Courtesy of STAR collaboration)



Energy loss by elastic collision (Hong, Lee)

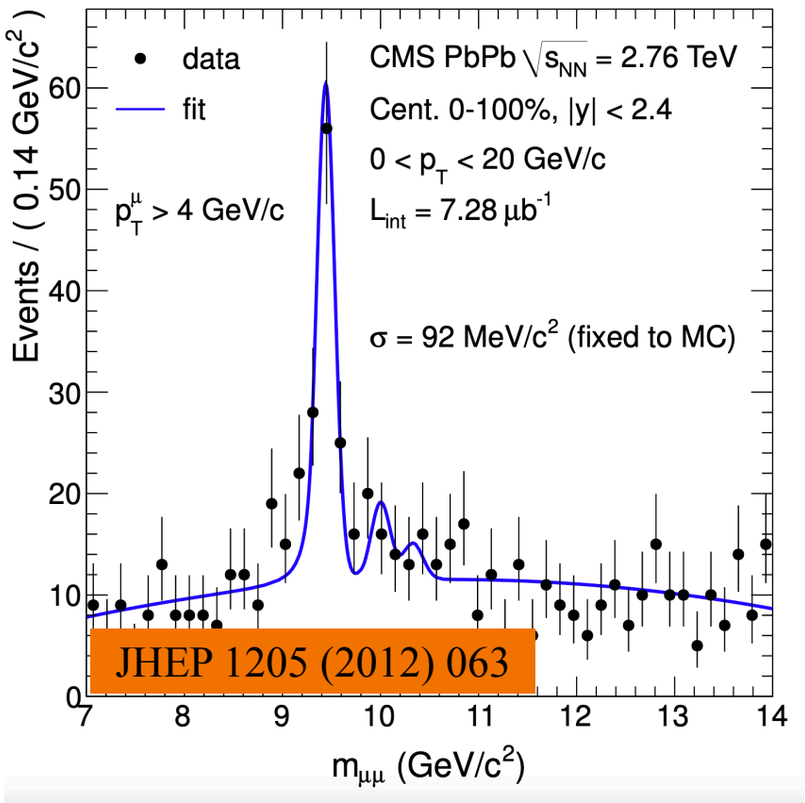


Gluo-dissociation (Chen, Lin)

Brief history of Υ(nS) in CMS

2012

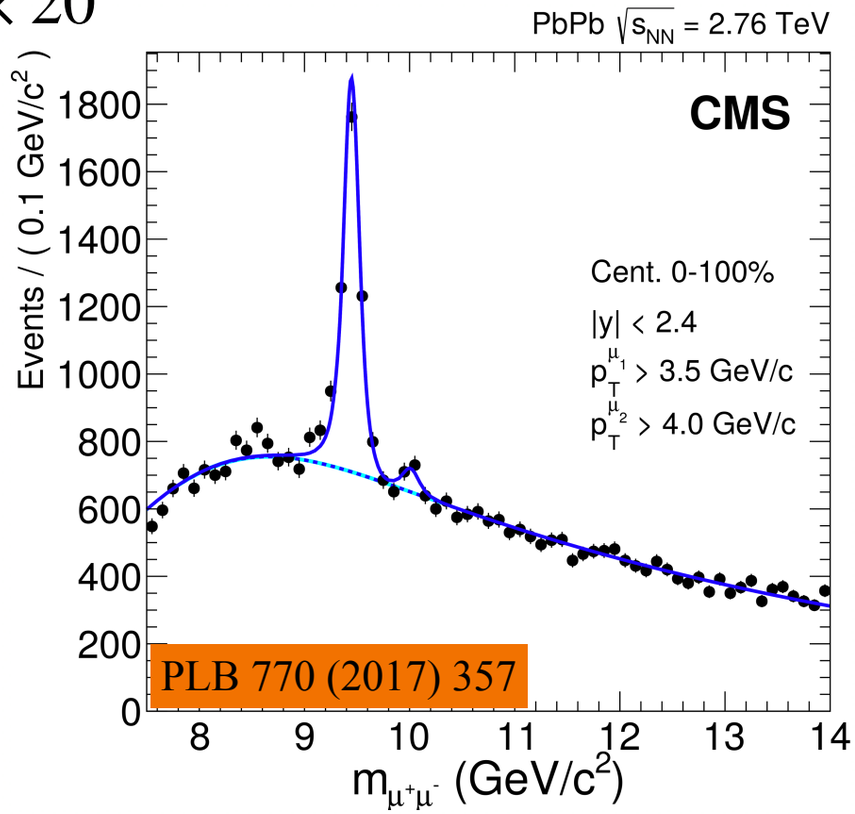
$7.28\ \mu b^{-1}$



× 20

2017

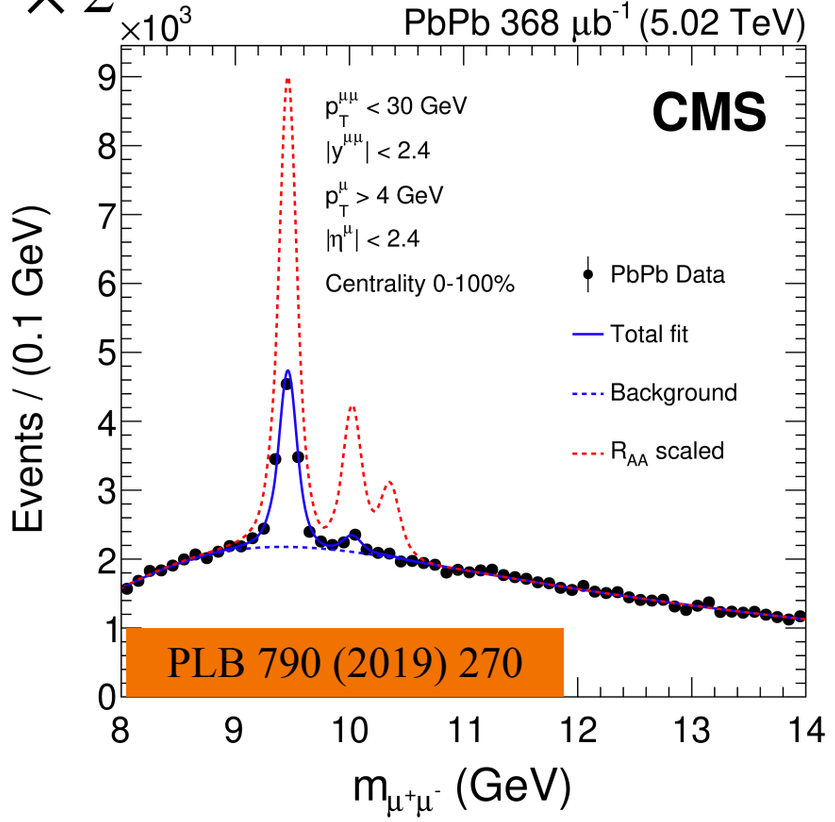
$166\ \mu b^{-1}$



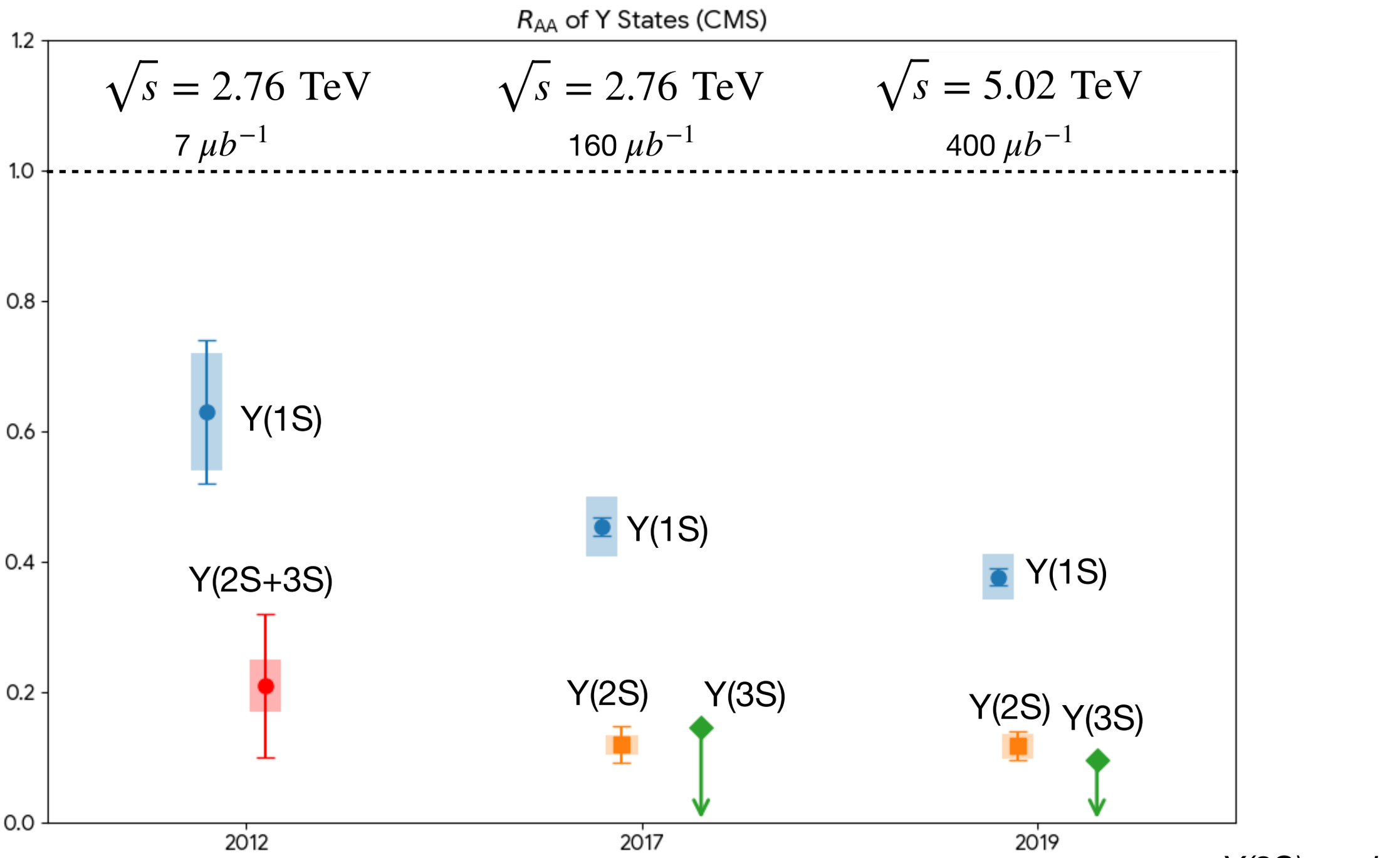
× 2

2019

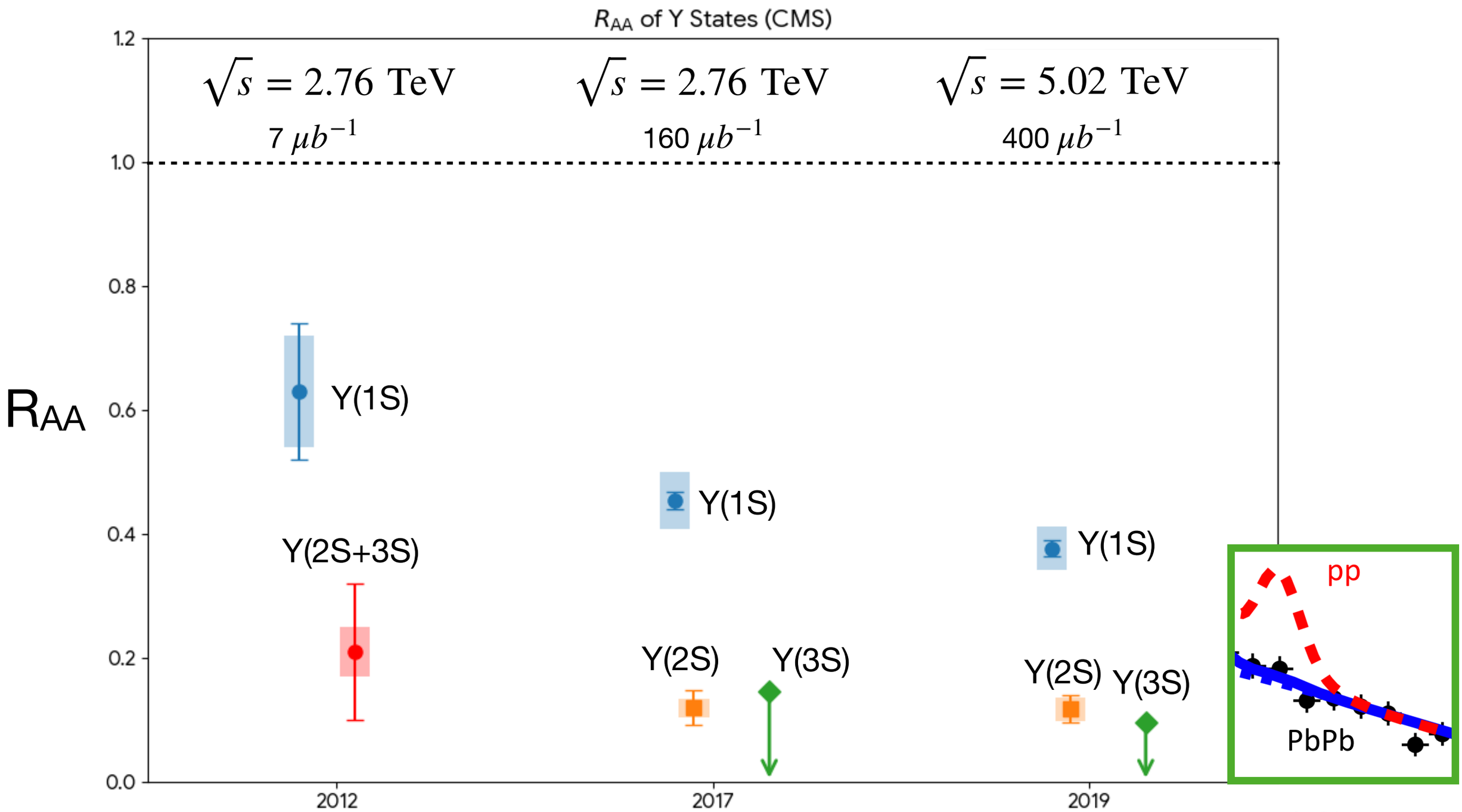
$368\ \mu b^{-1}$



Brief history of Υ(nS) in CMS



Brief history of Υ(nS) in CMS

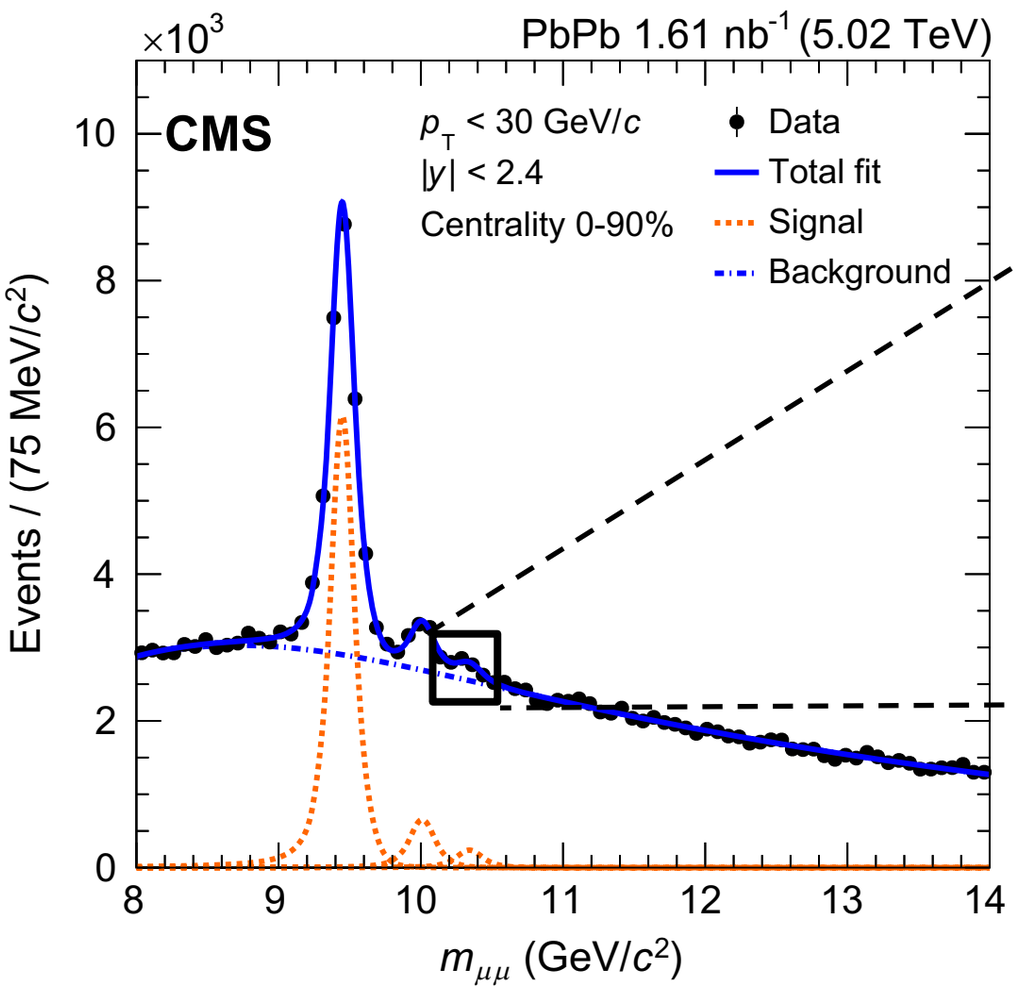


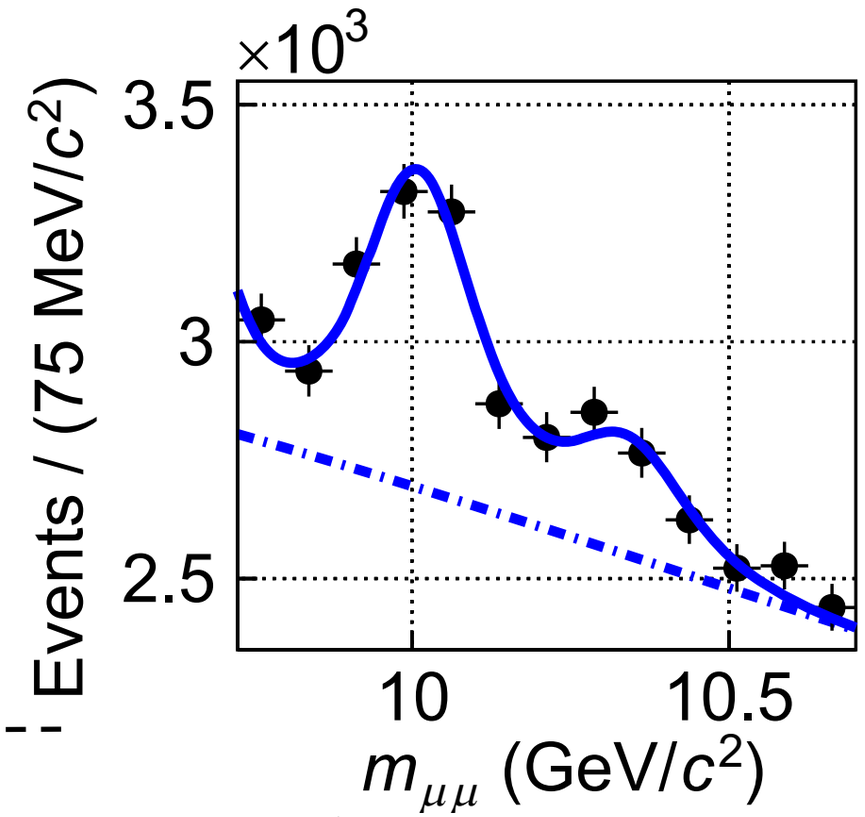
Brief history of Υ(nS) in CMS

2024

$\sqrt{s} = 5.02$ TeV

1600 μb^{-1}





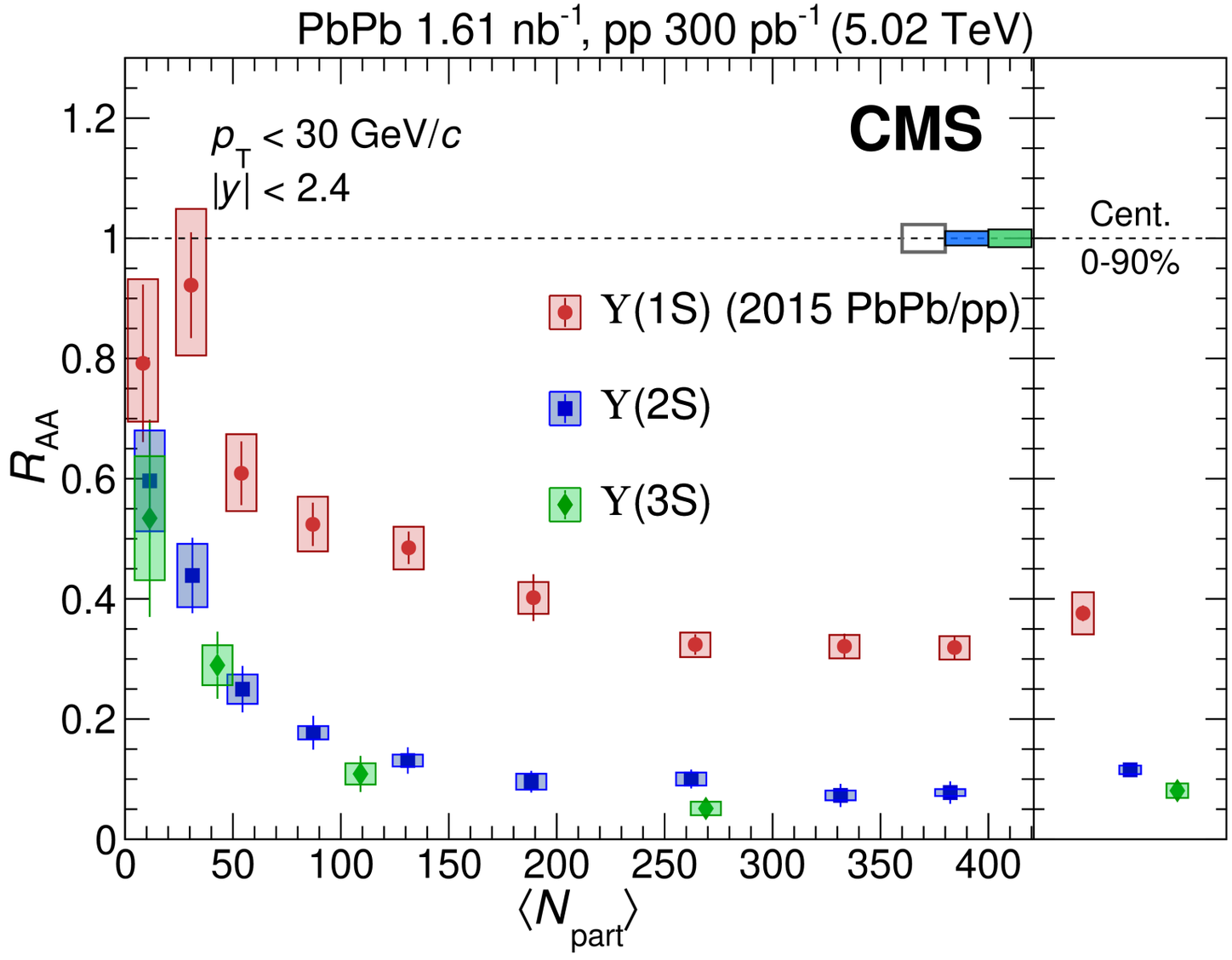
CMS is the only experiment that observes Υ(3S) peak in PbPb

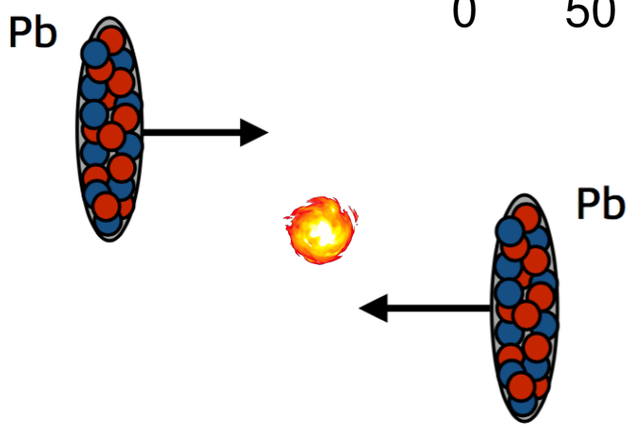
PRL133 (2024) 022302

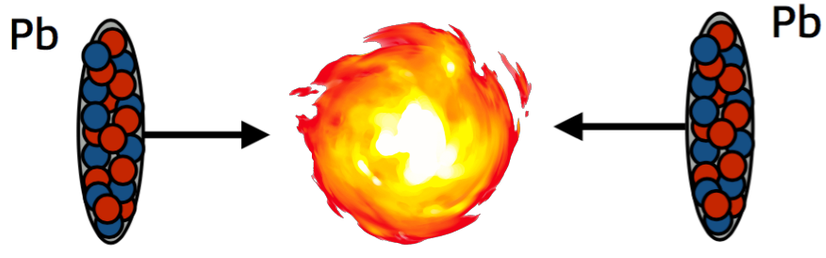
Observation of the Y(3S) meson and suppression of Y states in PbPb collisions

Brief history of Υ(nS) in CMS

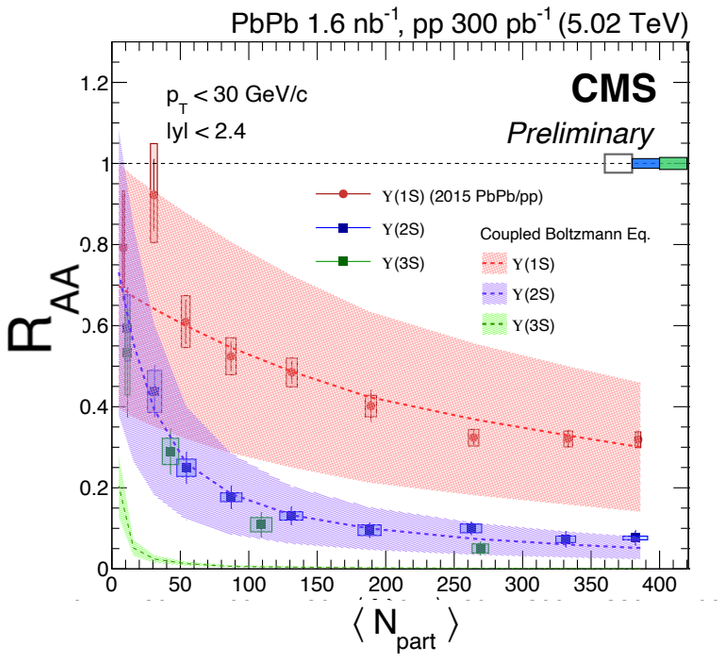
PRL133 (2024) 022302





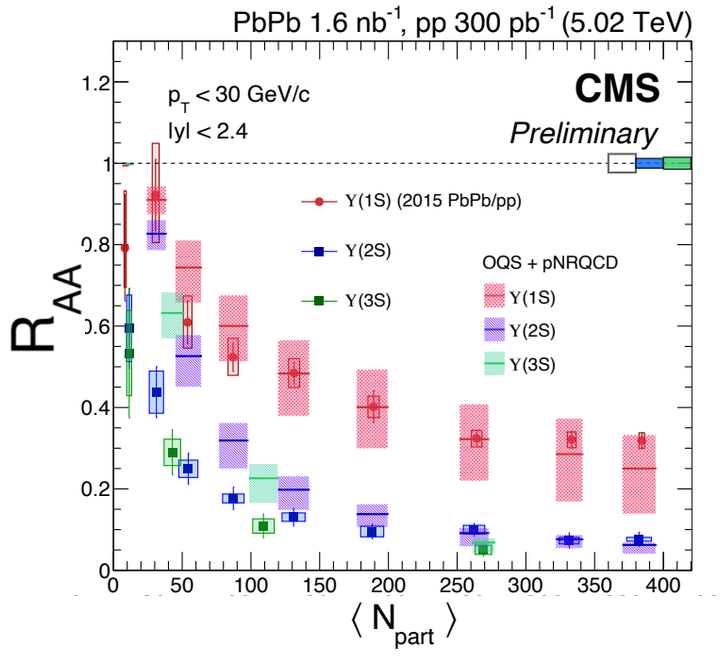


Comparison with theoretical calculations



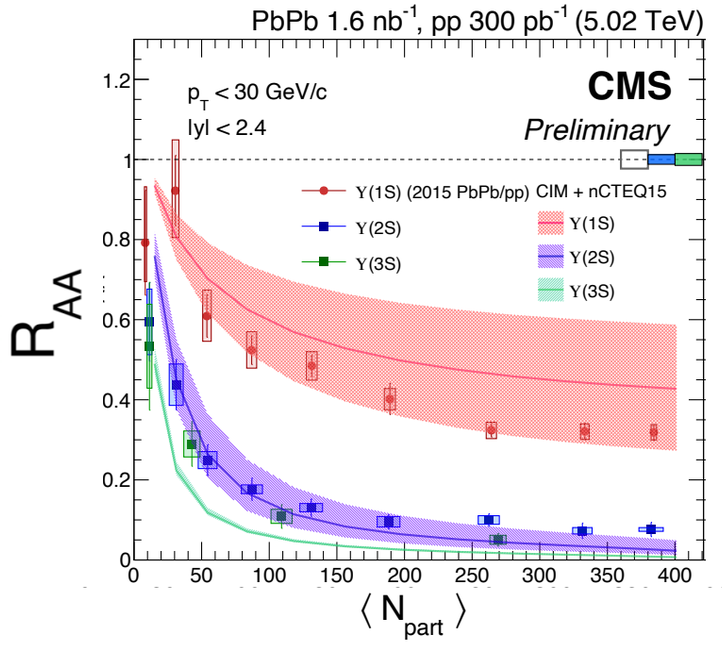
Coupled Boltzmann Eqn

- *JHEP 01(2021) 046*
- Dissociation and regeneration
- Large uncertainties from nPDF



Open quantum system + pNRQCD

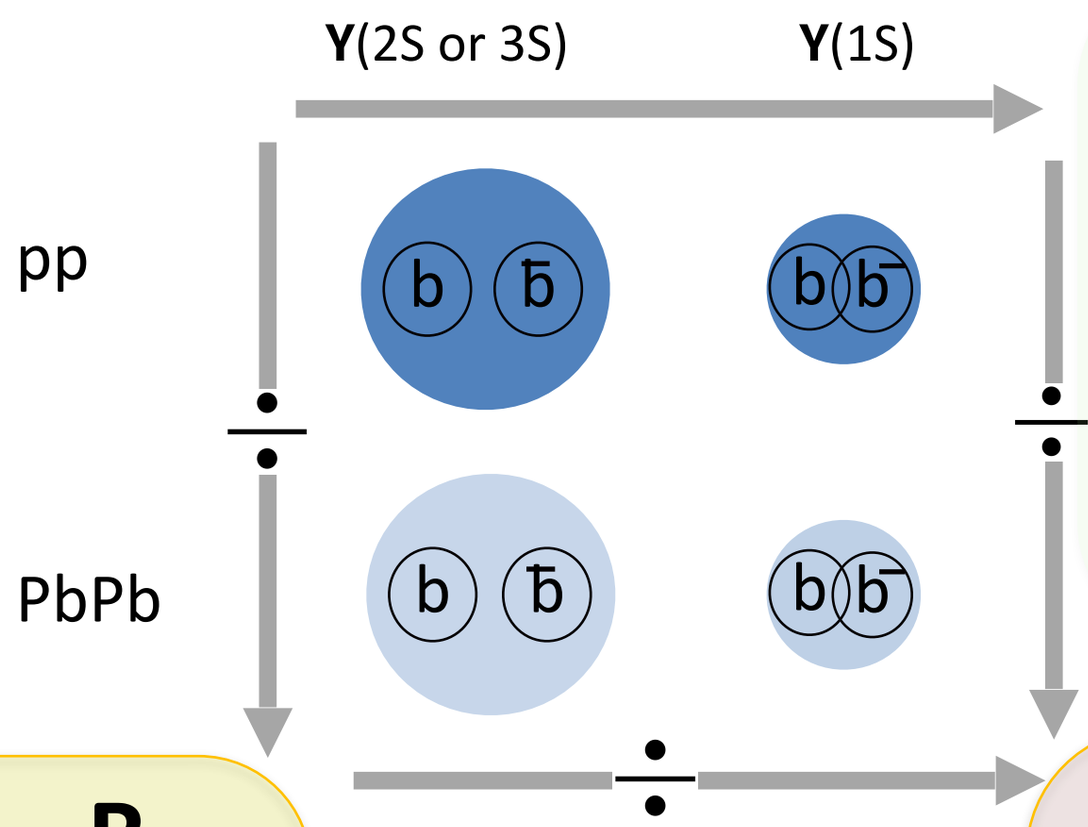
- *PRD 104 094049*
- Dissociation and regeneration
- No CNM effects



Comover effects + nCTEQ15

- *JHEP 10(2018) 094*
- Gluon behaved like pion for comover effects
- No regeneration

Observable 2, 3: Single ratio & Double ratio



SR $\dfrac{\text{Yield of } \Upsilon(nS)}{\text{Yield of } \Upsilon(1S)}$

- **EX:** Partial cancellation of uncertainties by detector efficiency/geometry
- **TH:** Cancels uncertainties in HQ distribution

$\dfrac{\text{Yield in PbPb}}{\text{Yield in pp}}$ **R_{AA}**

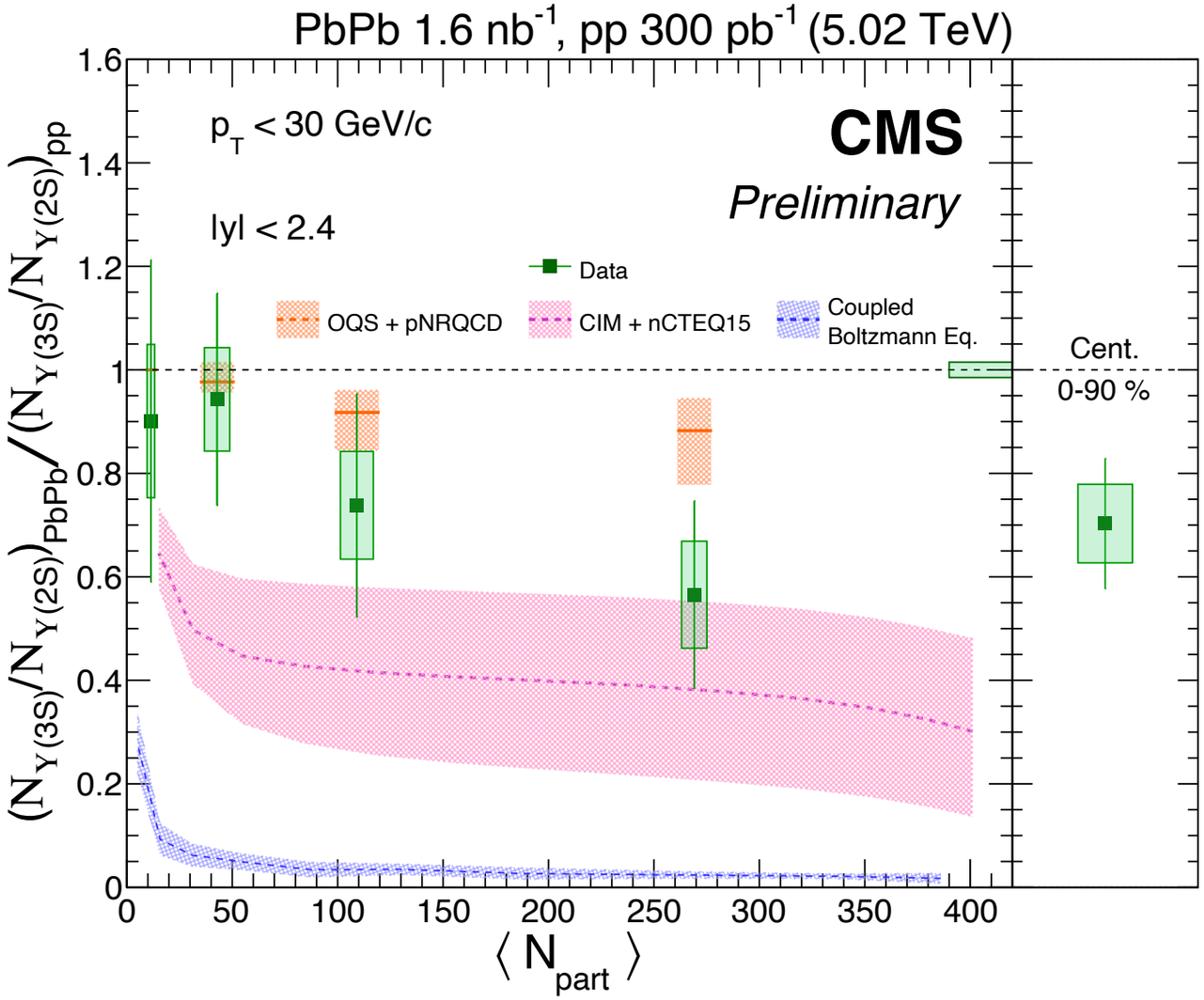
- **EX:** Several sources of uncertainties exist
- **TH:** Best reference for theorists

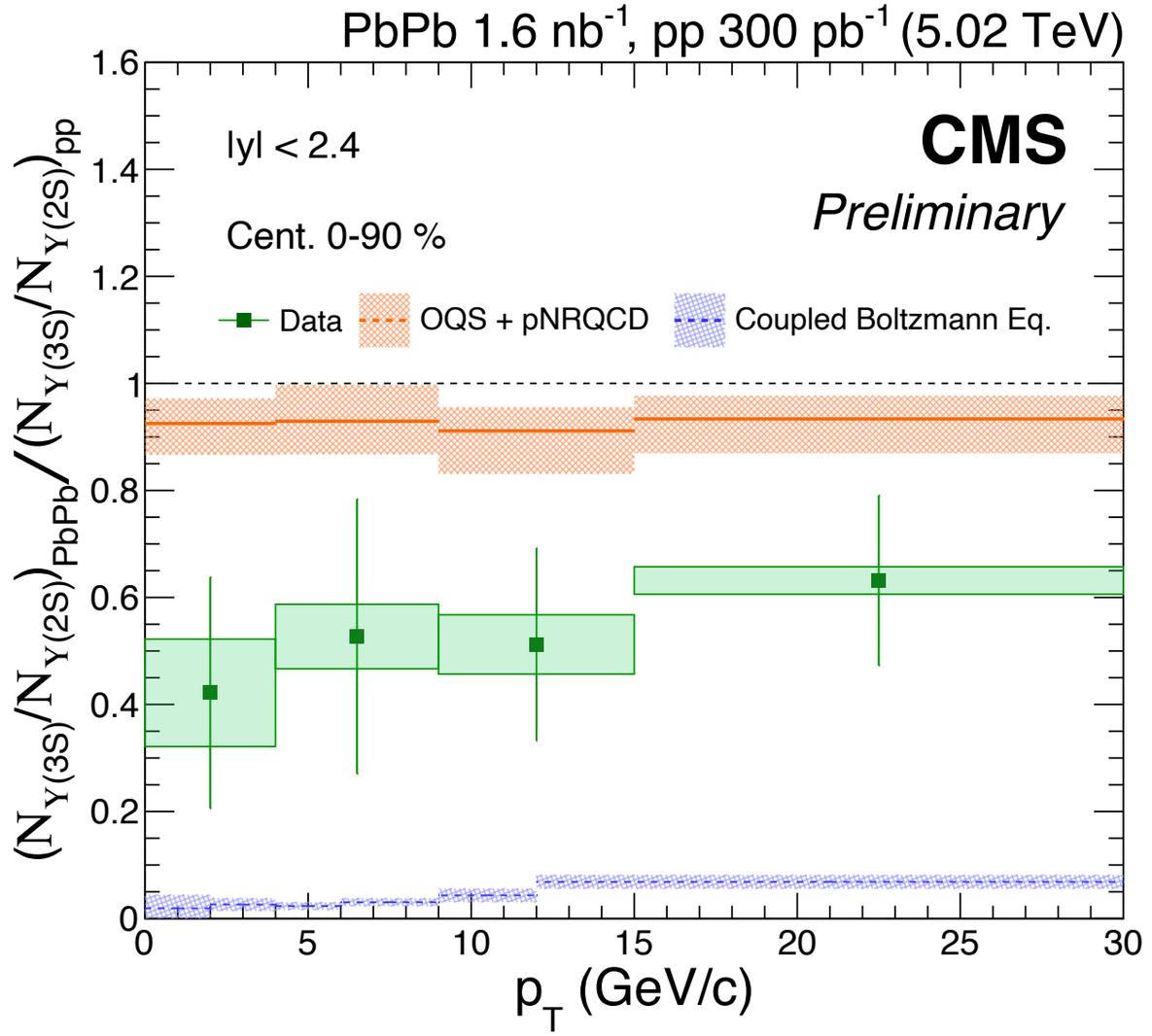
DR $\dfrac{R_{AA} \text{ of } \Upsilon(nS)}{R_{AA} \text{ of } \Upsilon(1S)}$

- **EX:** Precision measurement for very little correction beyond signal counting
- **TH:** Isolates the final state effects from production mechanism

Double ratio: $\Upsilon(3S)/\Upsilon(2S)$

***Before** the data were released*

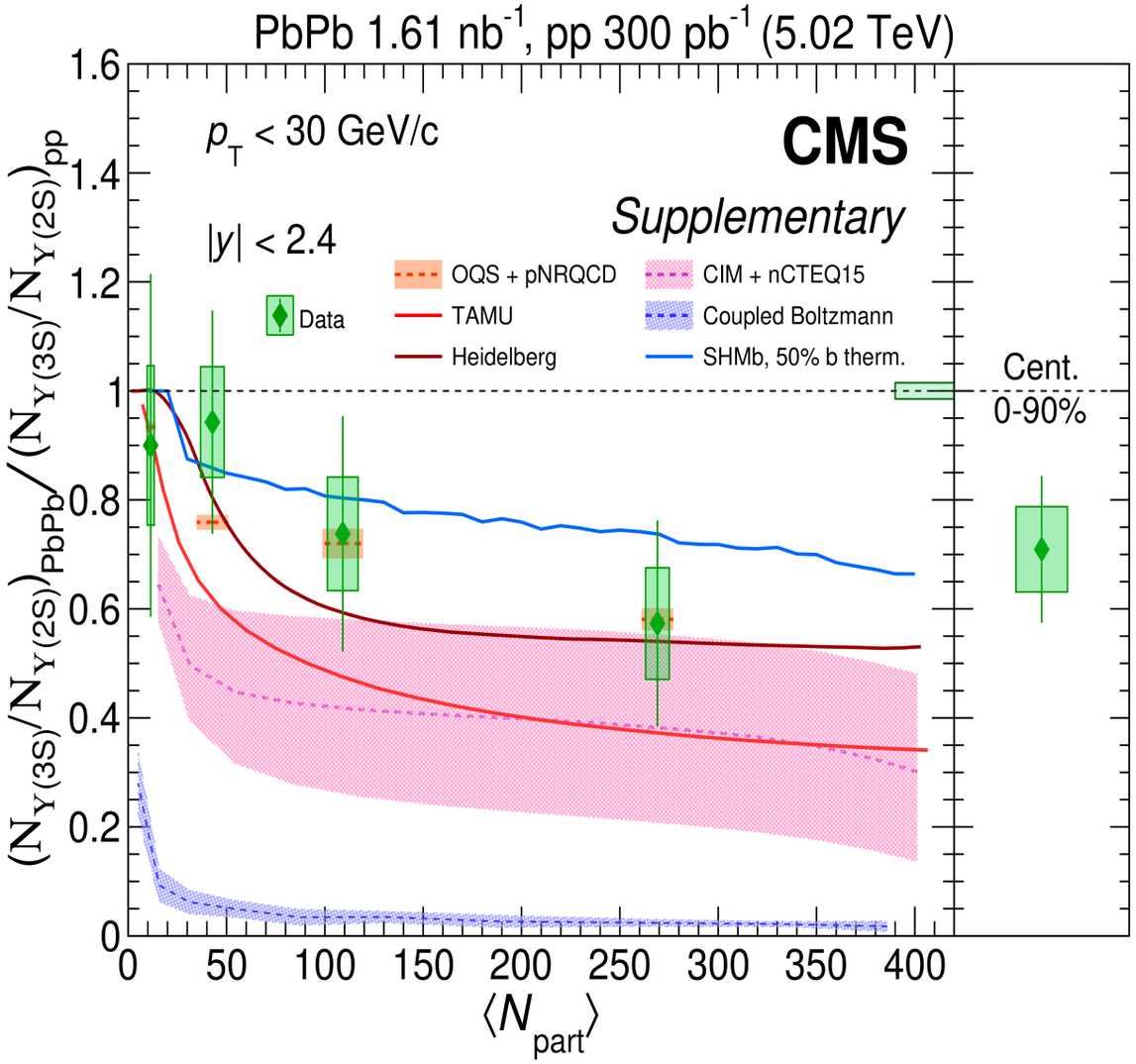


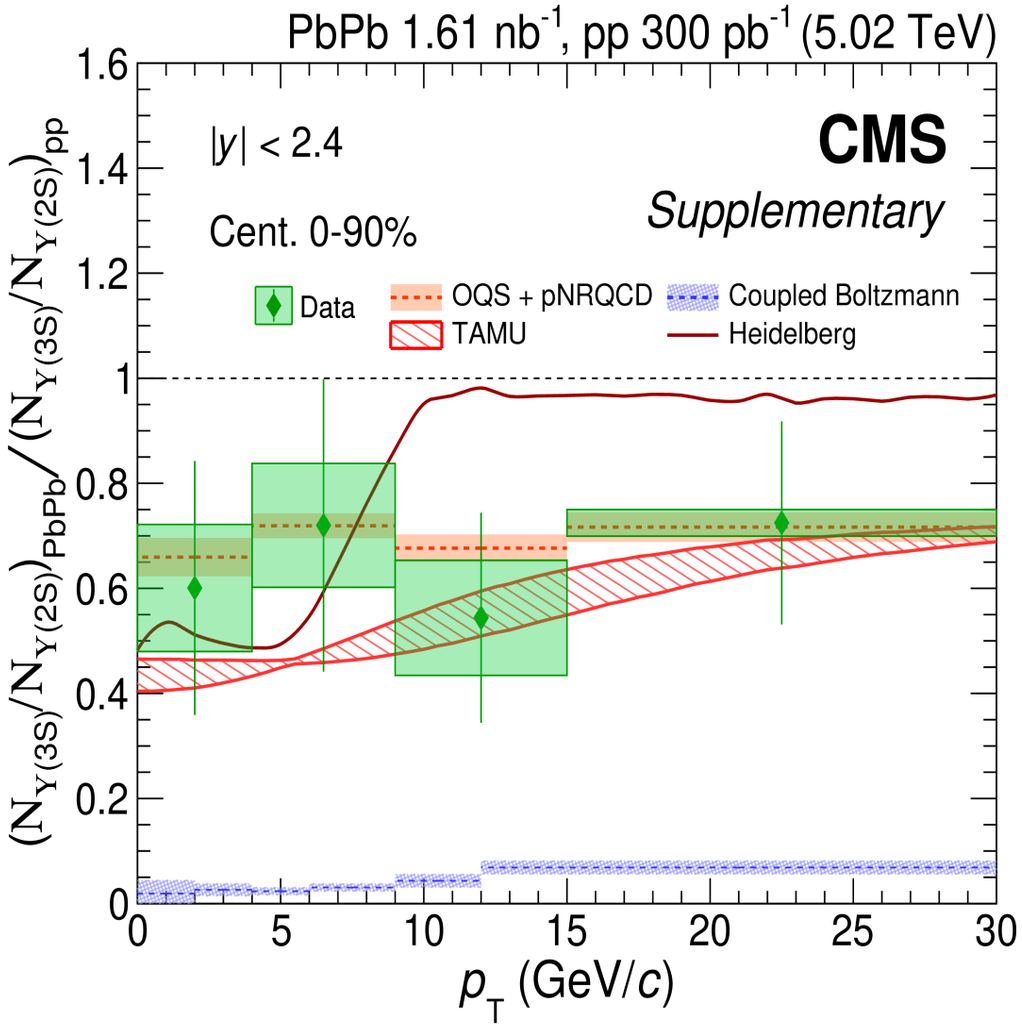


- **Double ratio** = relative suppression of Y(3S) compared to Y(2S)

Double ratio: $\Upsilon(3S)/\Upsilon(2S)$

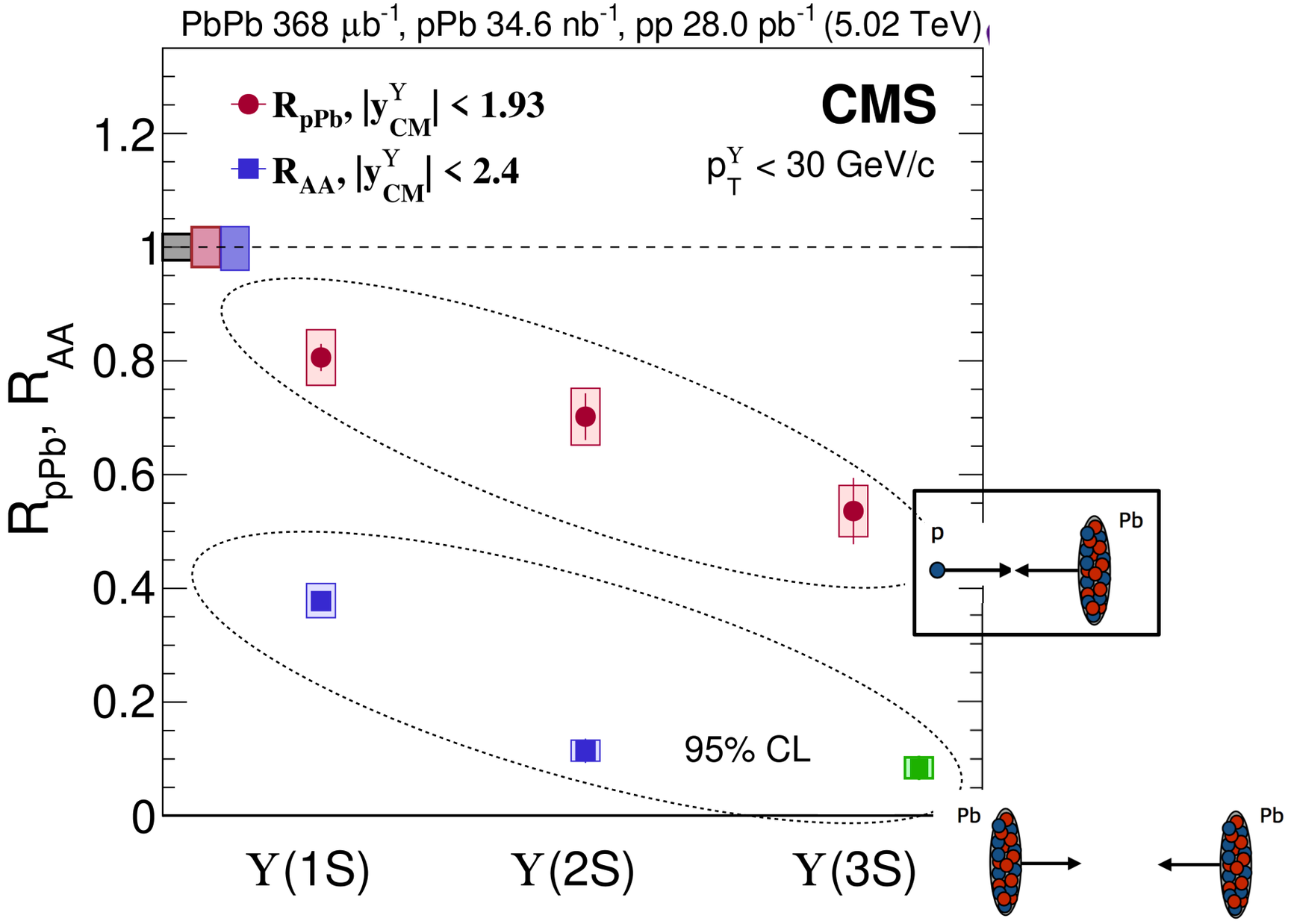
***After** the data were released*





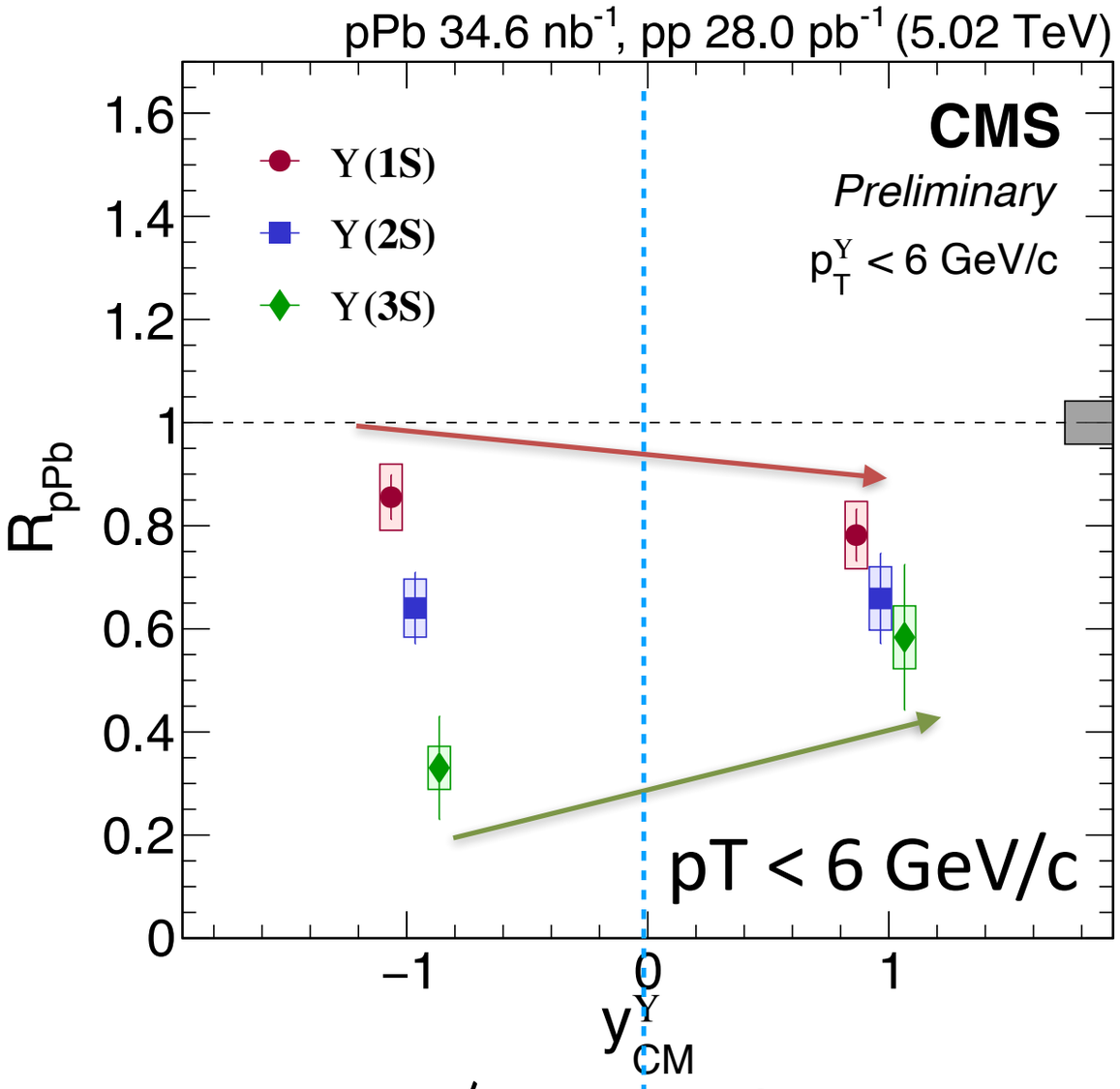
- **Double ratio** = relative suppression of Y(3S) compared to Y(2S)

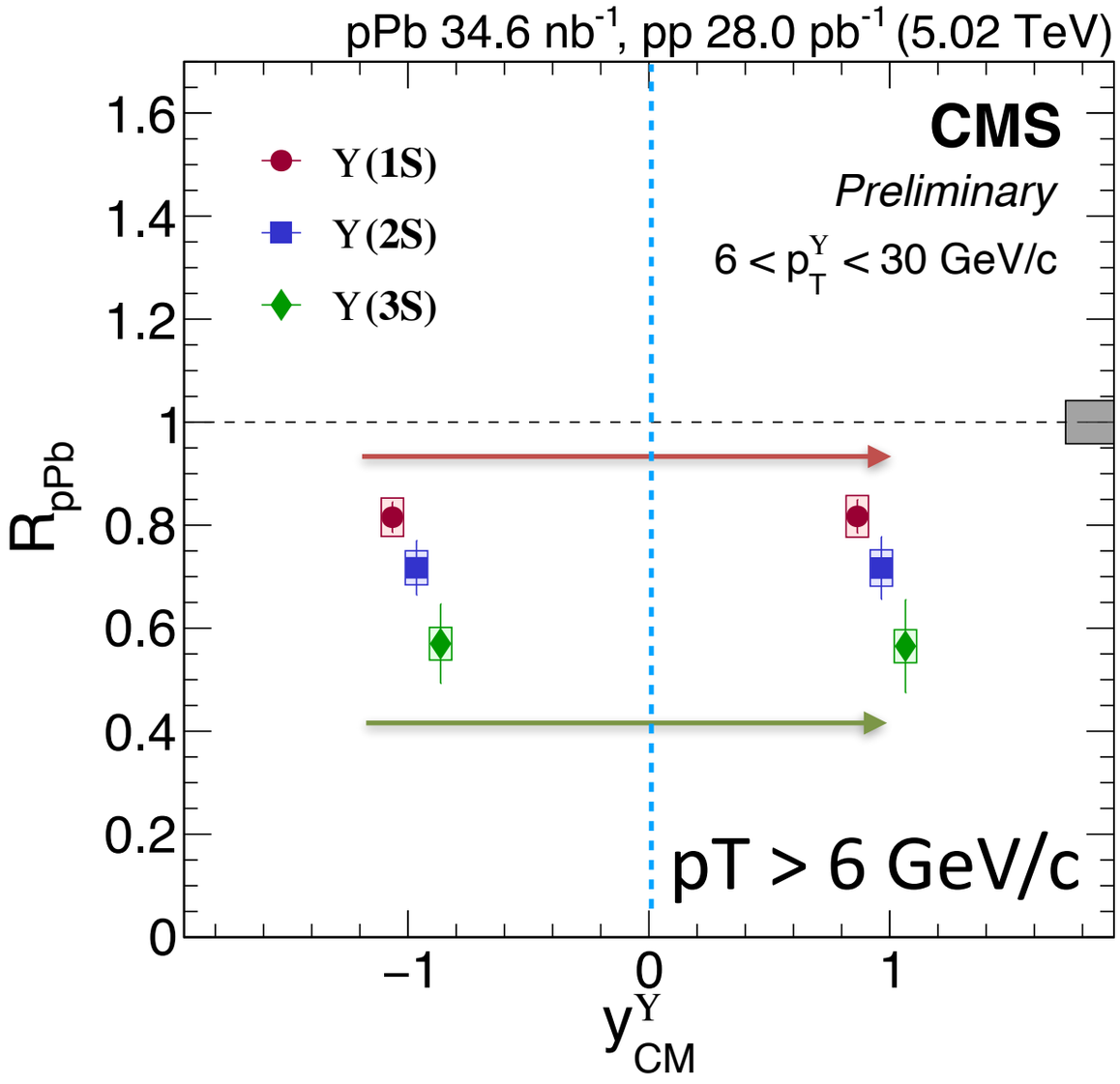
Results in pPb

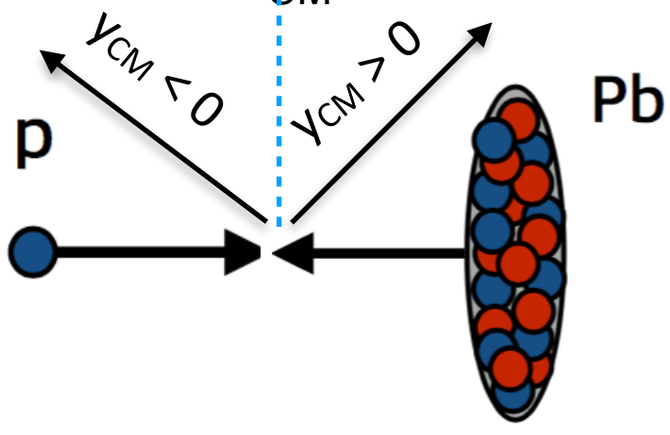


- Modest Sequential suppression of Y(nS) observed in pPb collision
- Production of small QGP?

Difference in low and high p_T revisions

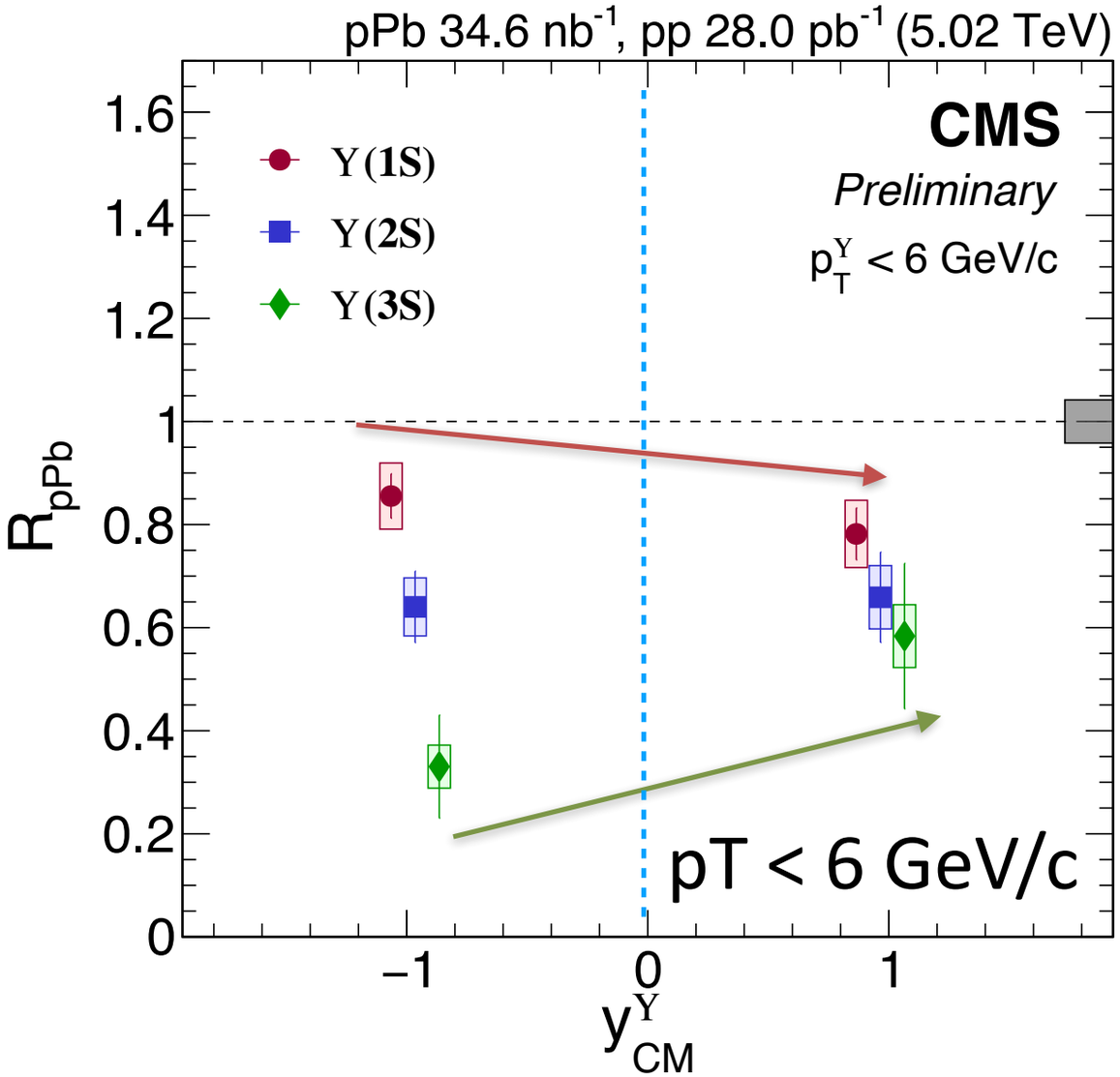


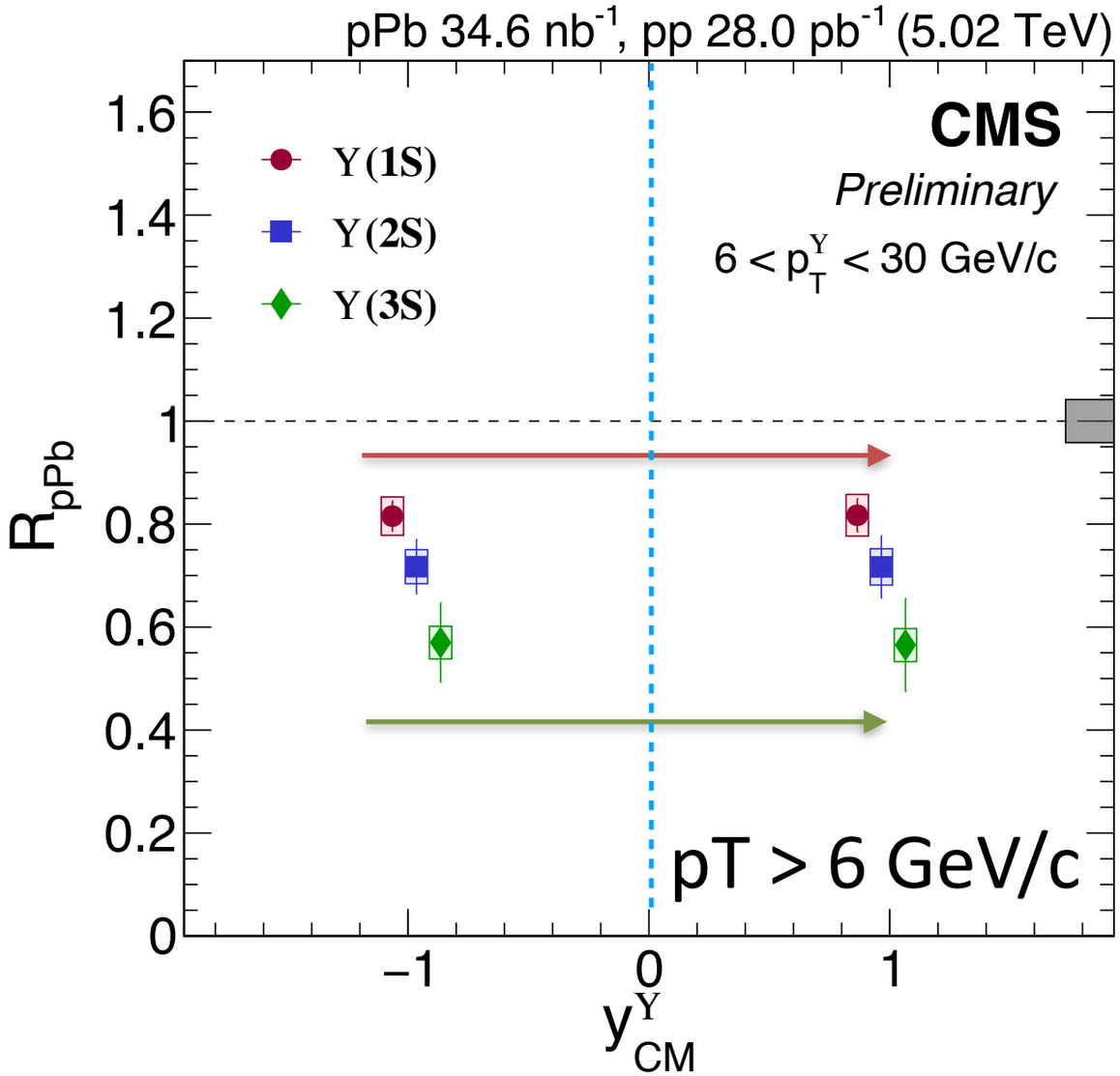


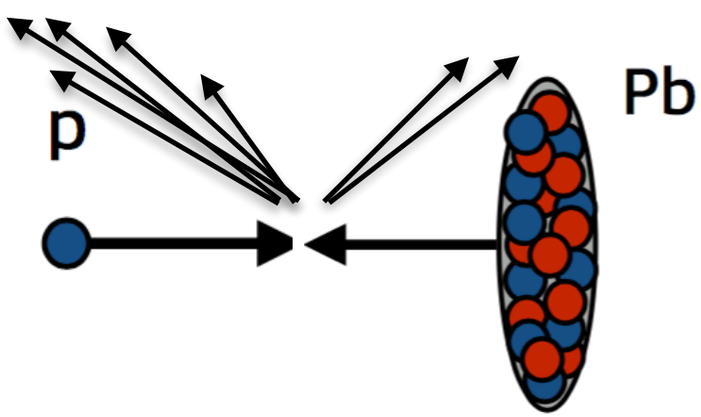


- *Different suppression pattern for low p_T region*

Difference in low and high p_T revisions

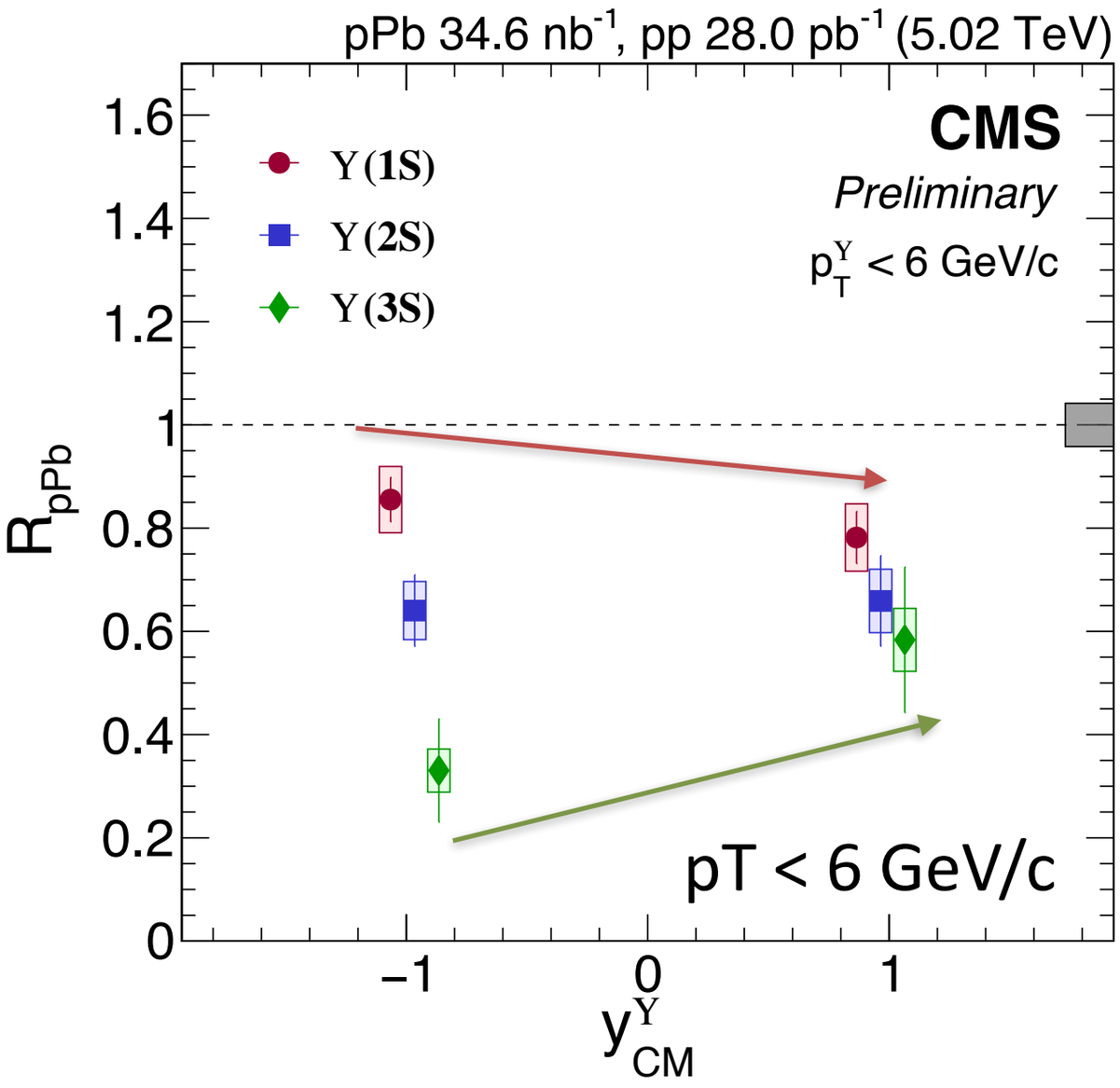


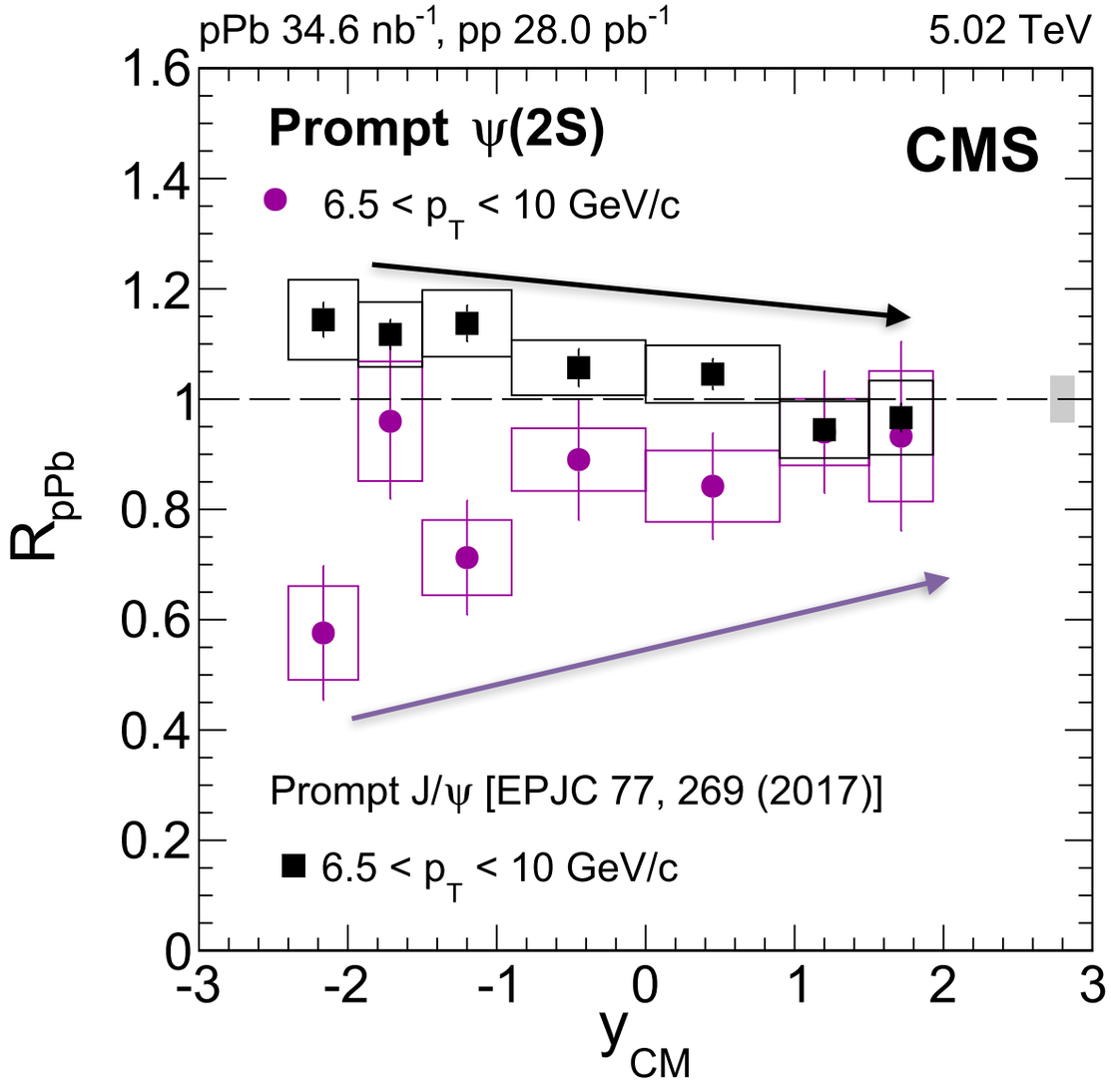




- Indication for co-mover suppression?

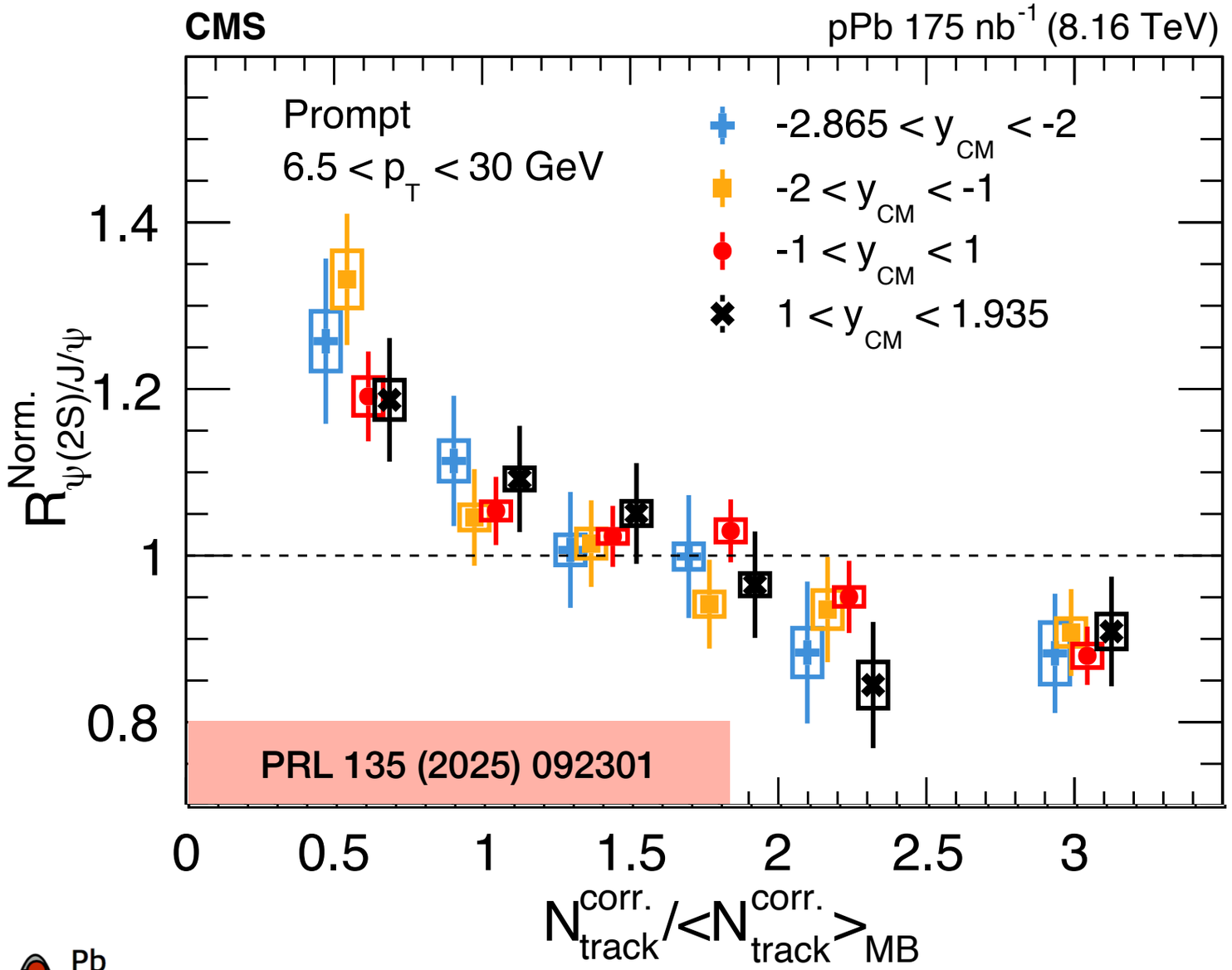
ψ(2S) / J/ψ ratio

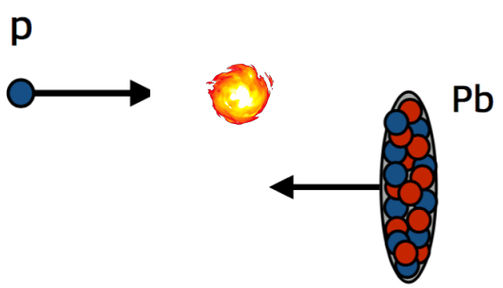


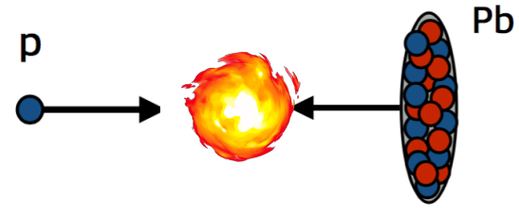


- Similar phenomena observed in ψ(2S) / J/ψ ratio
- The comover model can be one explanation
  - Can happen without production of QCD medium (*Capella, Sousa, Ferreiro, Linnyk*)

Multiplicity dependence of ψ(2S) / J/ψ

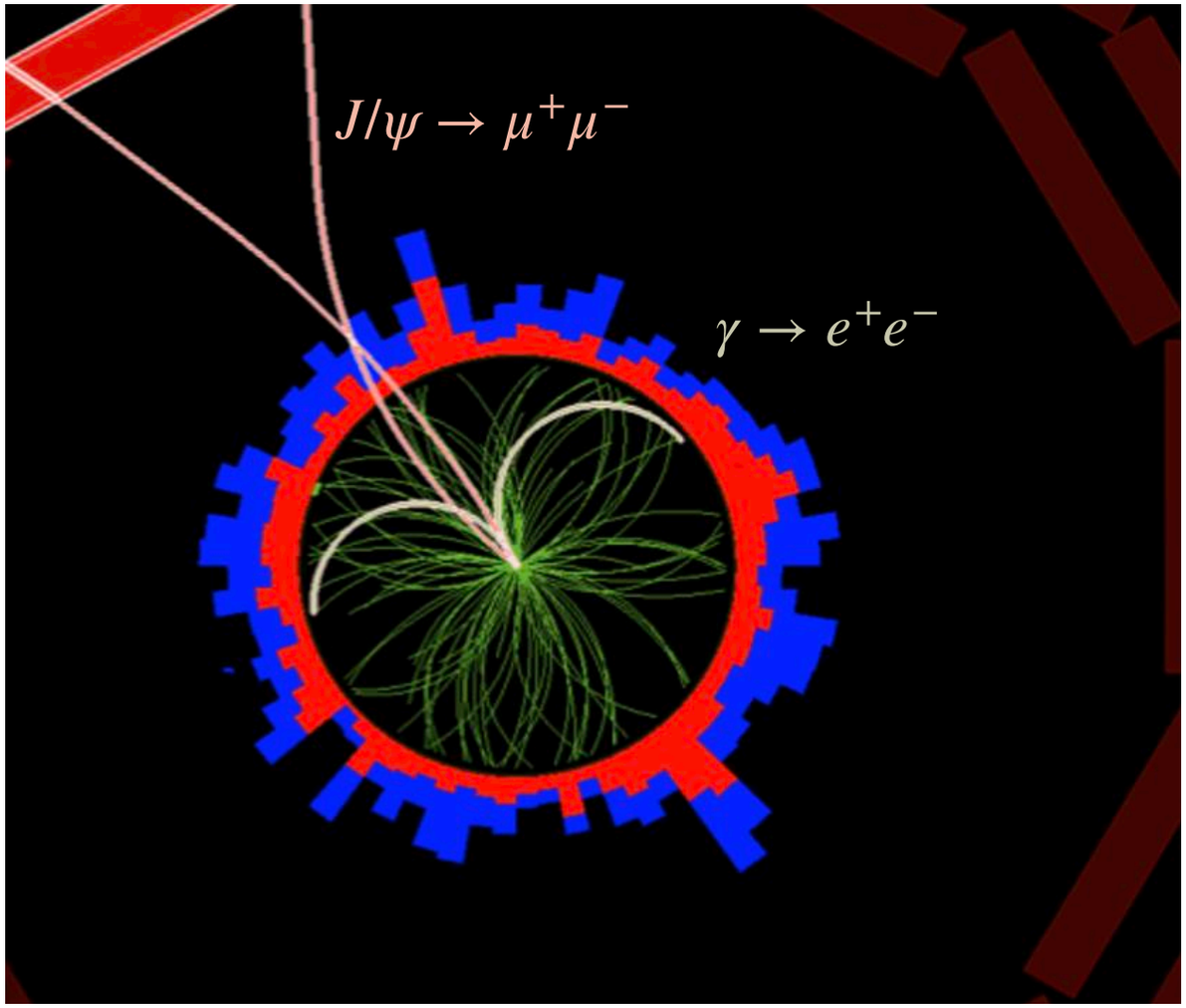


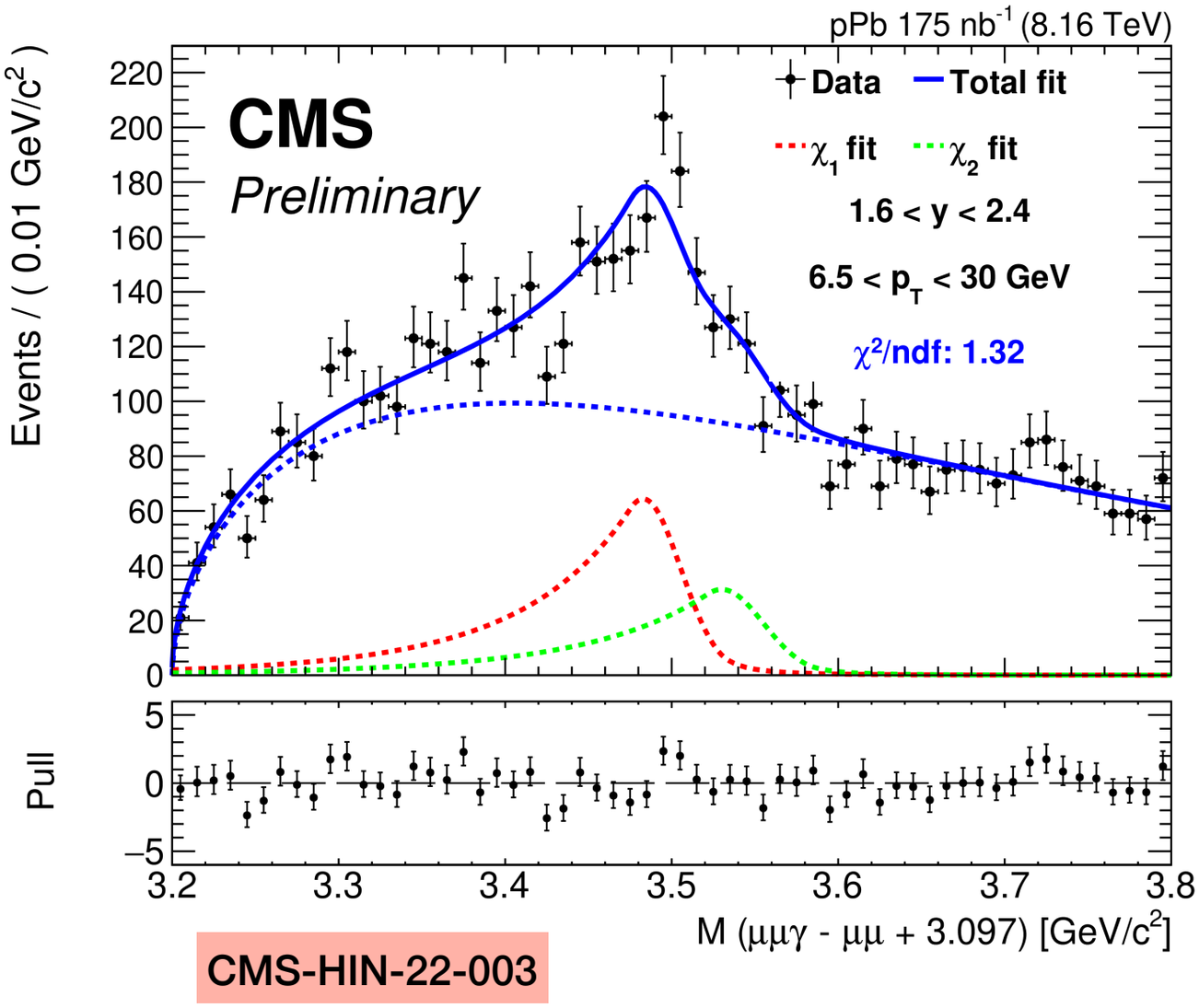




- A larger suppression of ψ(2S) compared to J/ψ is observed across all rapidity ranges (-2.9 < y < 1.9)

Measurement of χ_c : P-wave state



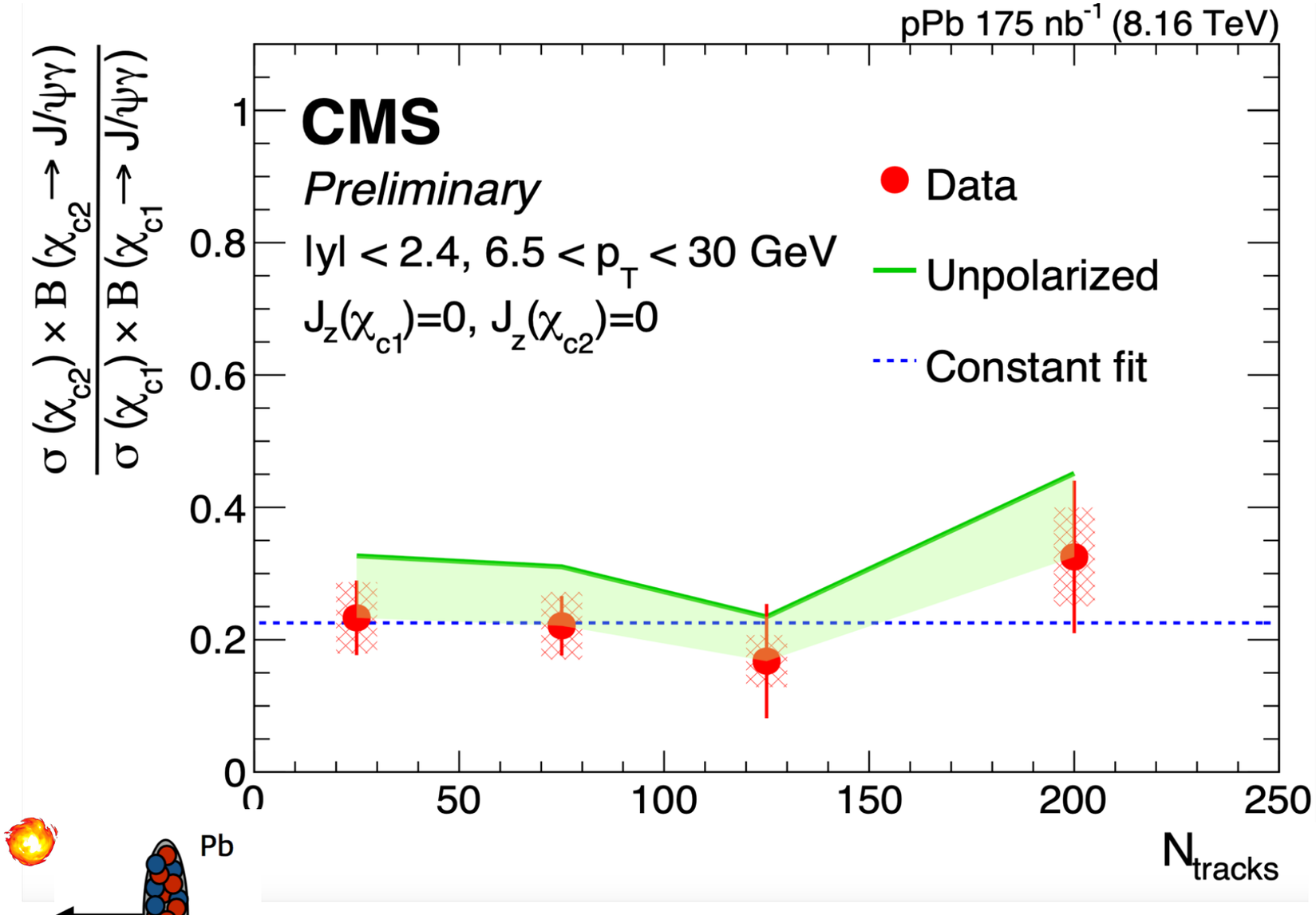


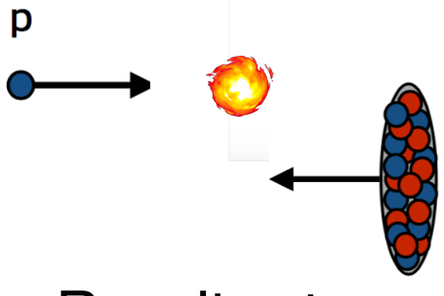
CMS-HIN-22-003

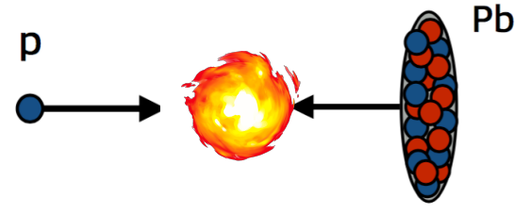
- First measur

Ratio of χ_c/ψ and χ_{c2}/χ_{c1}

Single ratio results

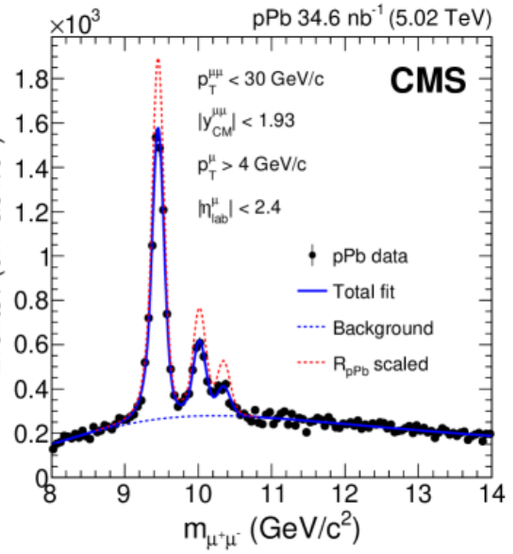


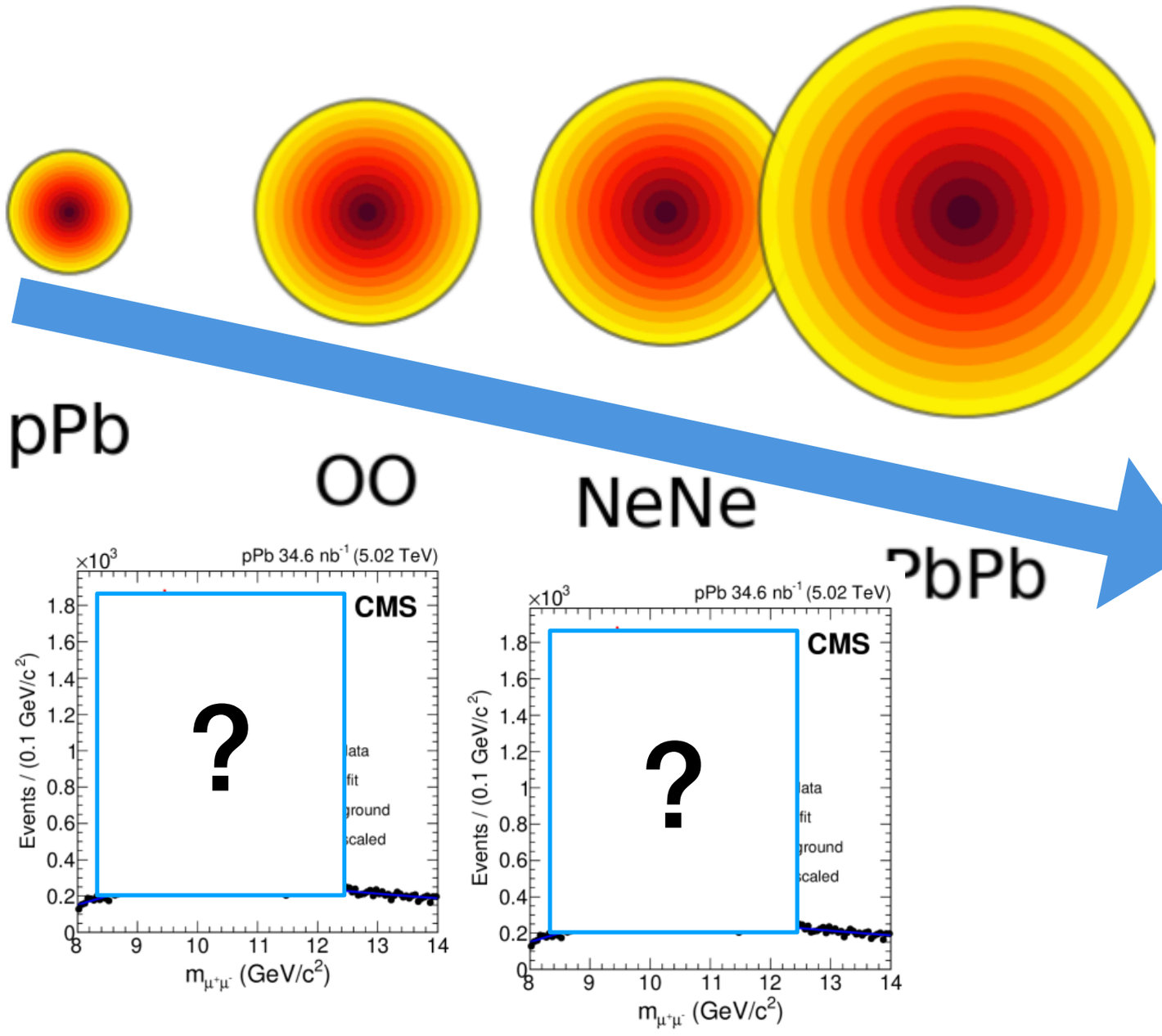


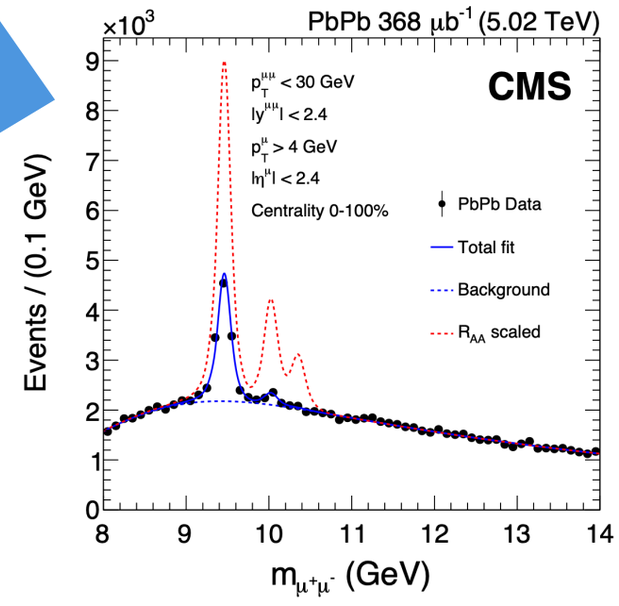


- Results show no clear dependence on the centrality
- Different nuclear effects for p-waves and s-waves? We need more data!

What is next?





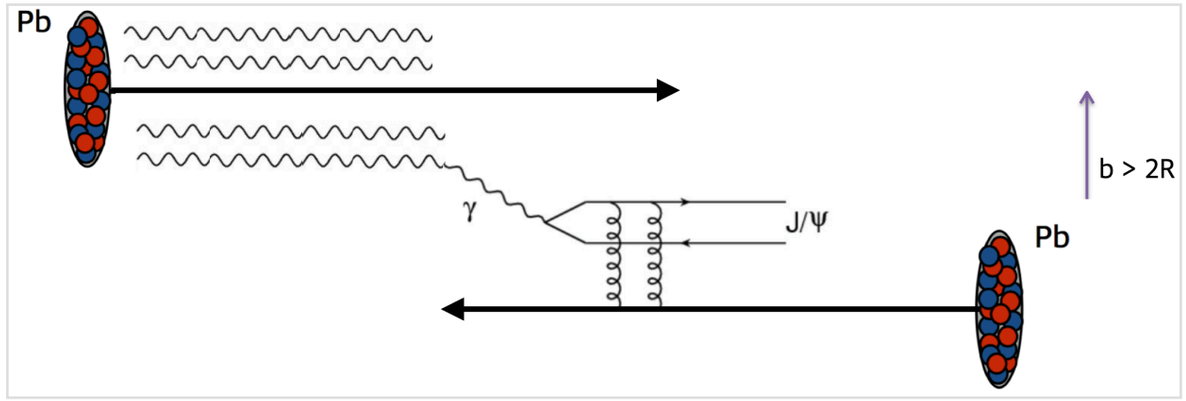


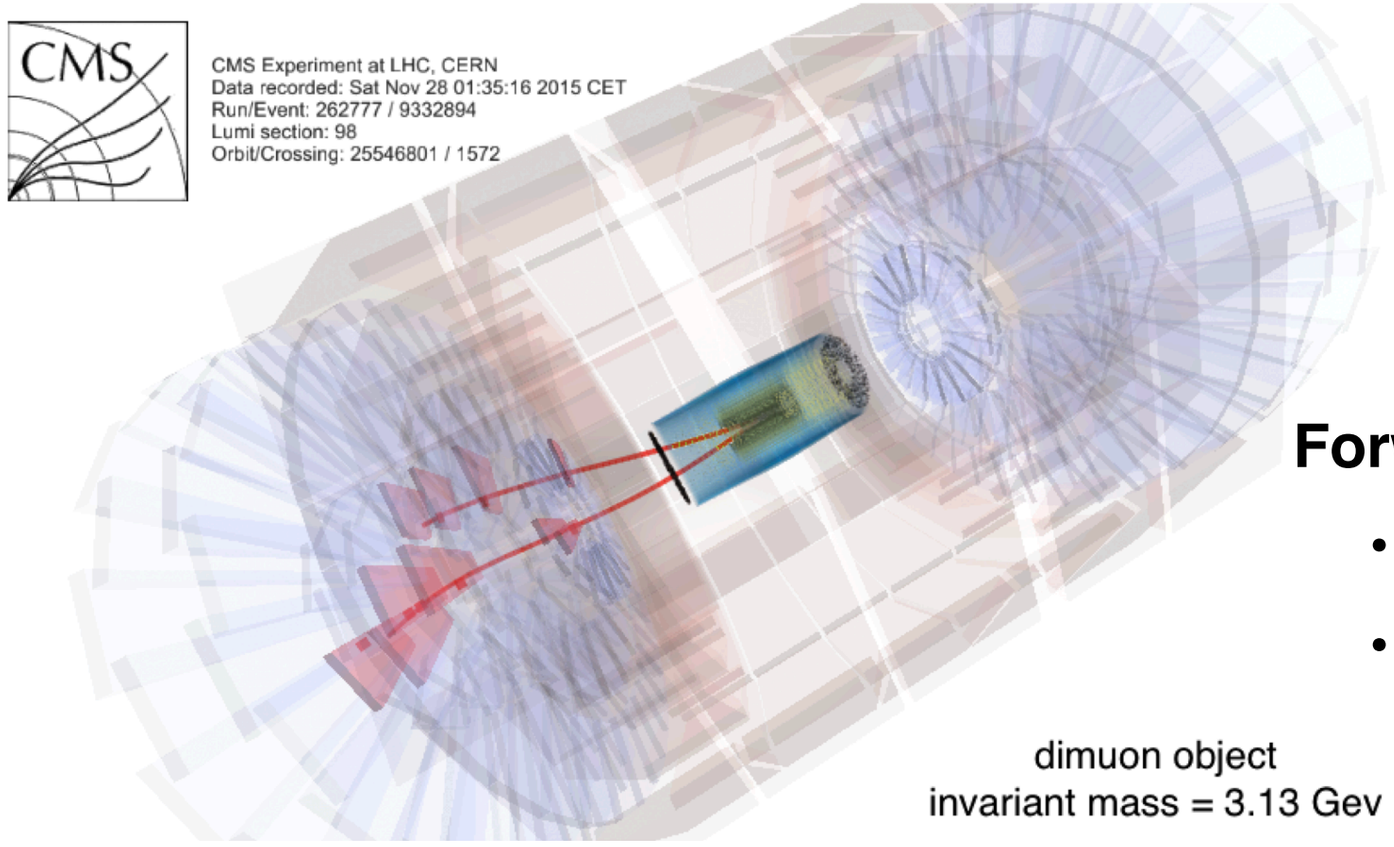
Dependence of Upsilon suppression in intermediately small system is of big interest.

Stay tuned!

Quarkonia in UPC

Quarkonia production in UPC





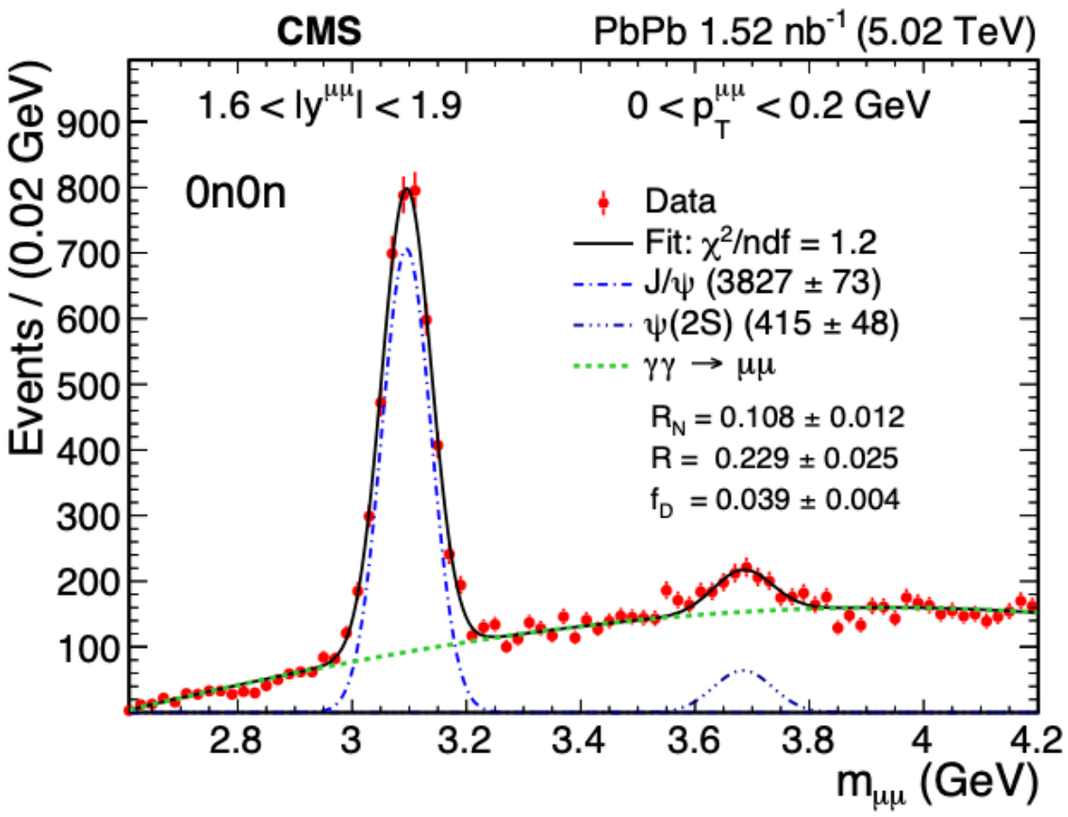
Ultra-peripheral Collision

- A clean probe of the gluon distribution in nuclei through photon–nucleus interactions
- Access to x ~ 10^{-5} using J/ψ
  - gluon saturation manifests
  - shadowing effect happens in nuclei

Forward detectors

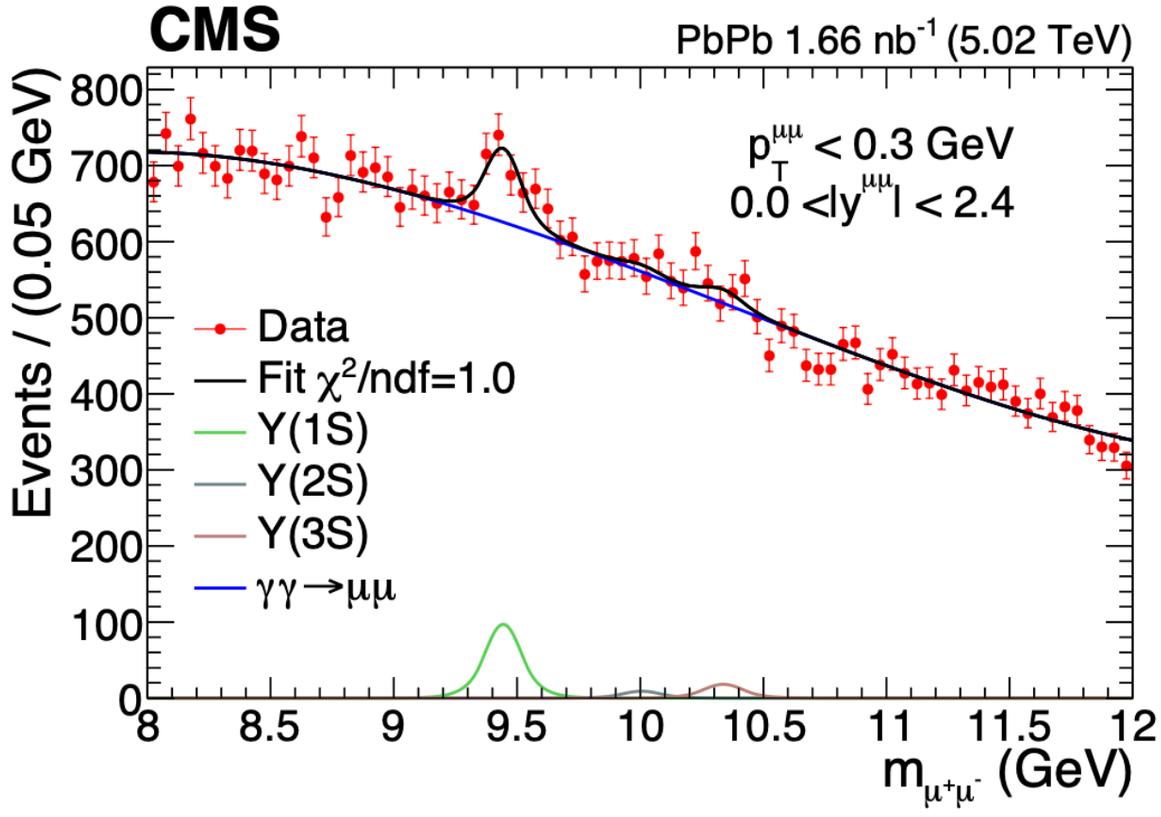
- HF to veto hadronic collisions
- ZDC measures zero degree neutrons to identify nuclear breakup

Quarkonia production in UPC



Coherent J/Ψ for $p_T^{\mu\mu} < 0.2$ GeV in 0n0n class

- PRL 131, 262301 (2023)
- PRL 135 (2025) 11, 112301

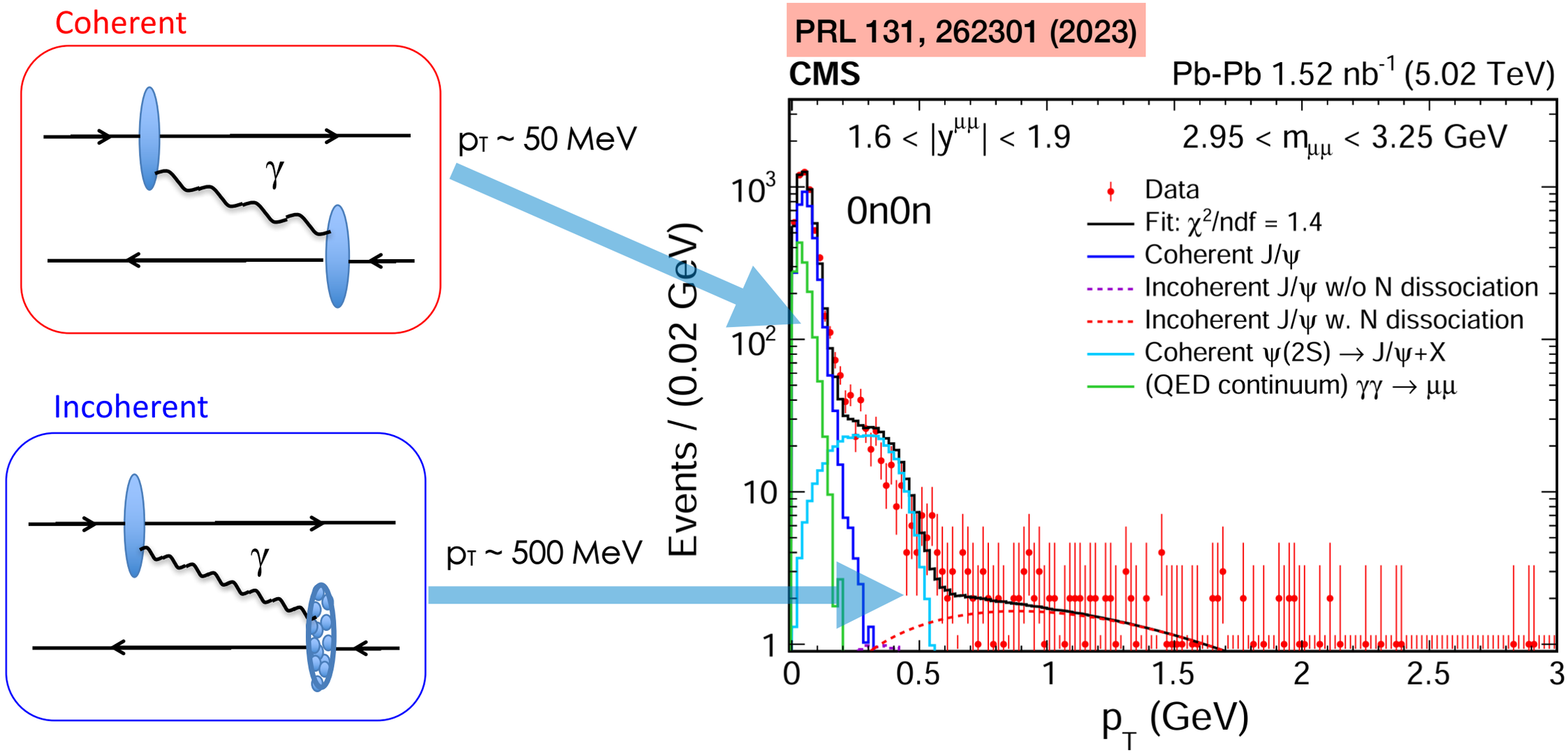


Υ(1S) for $p_T^{\mu\mu} < 0.3$ GeV

- HIN-24-013

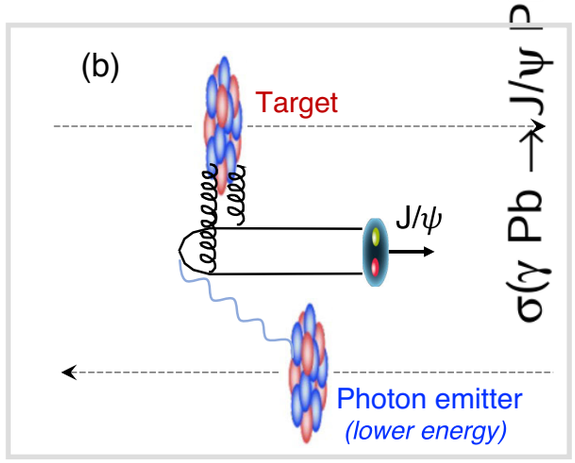
Quarkonia production in UPC

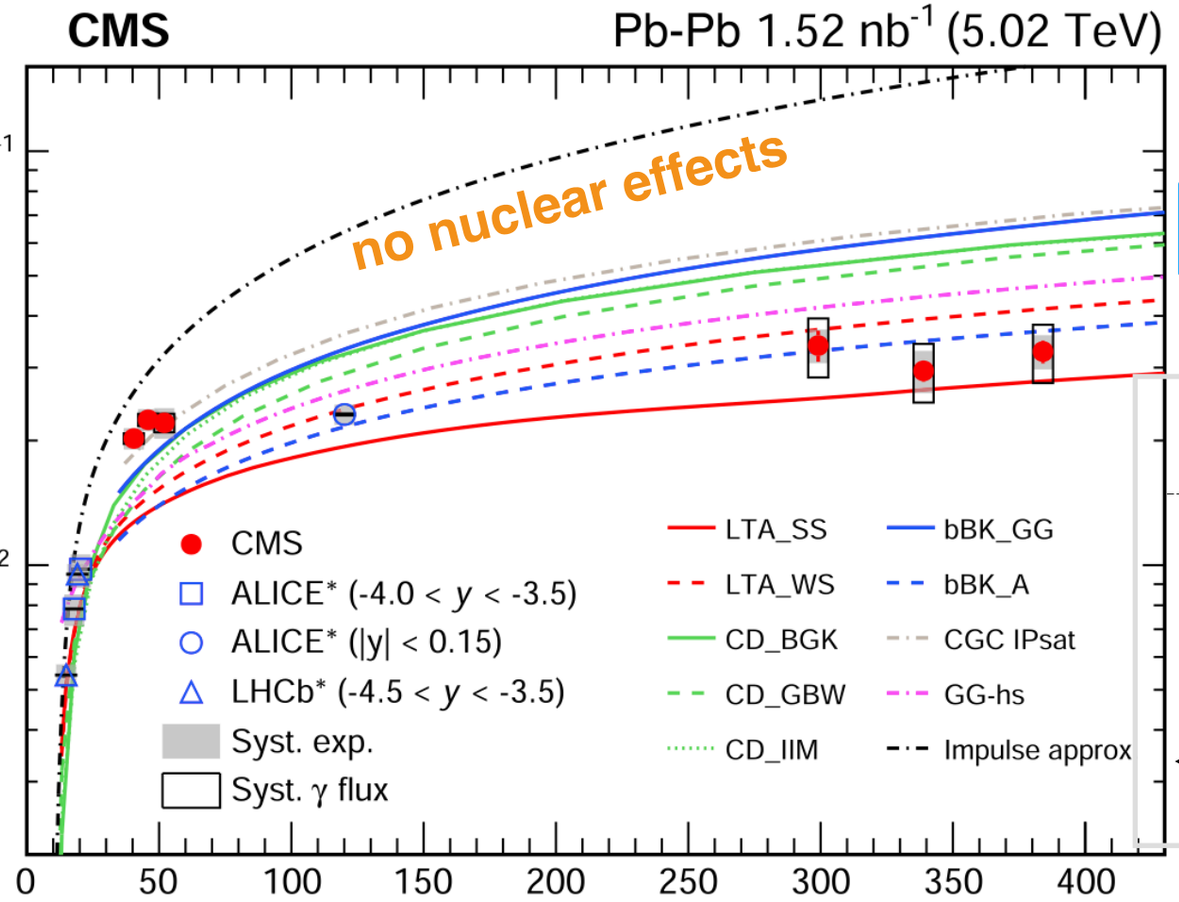
- Coherent production measures the average gluon density at a given scale, while incoherent production is sensitive to local fluctuations and spatial structure

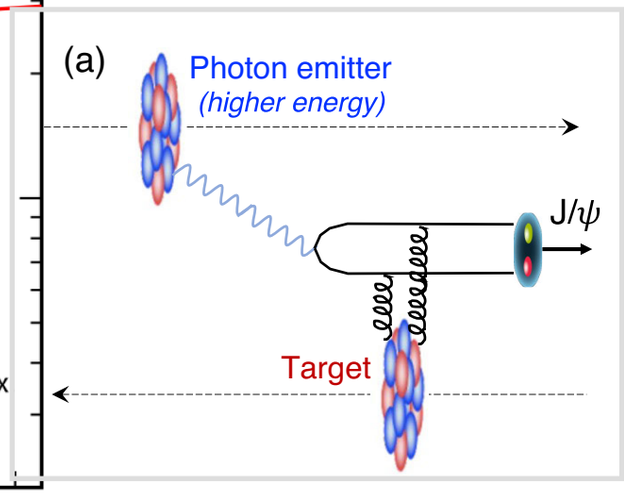


- These are distinguished by fitting the p_T distribution of vector mesons using spectra from STARLIGHT for the coherent component, and an empirical function based on ALICE and H1 data for the incoherent component

Coherent J/ψ in UPC







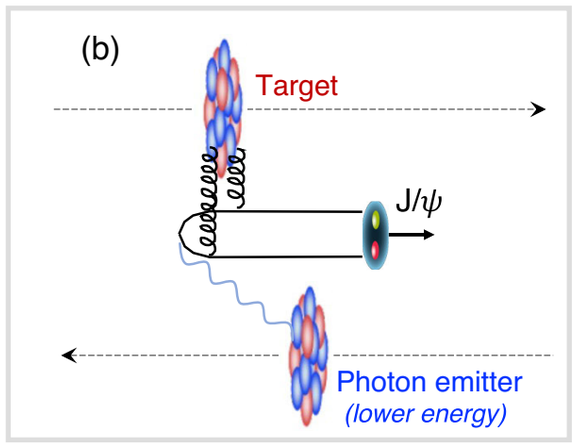
PRL 131, 262301 (2023)

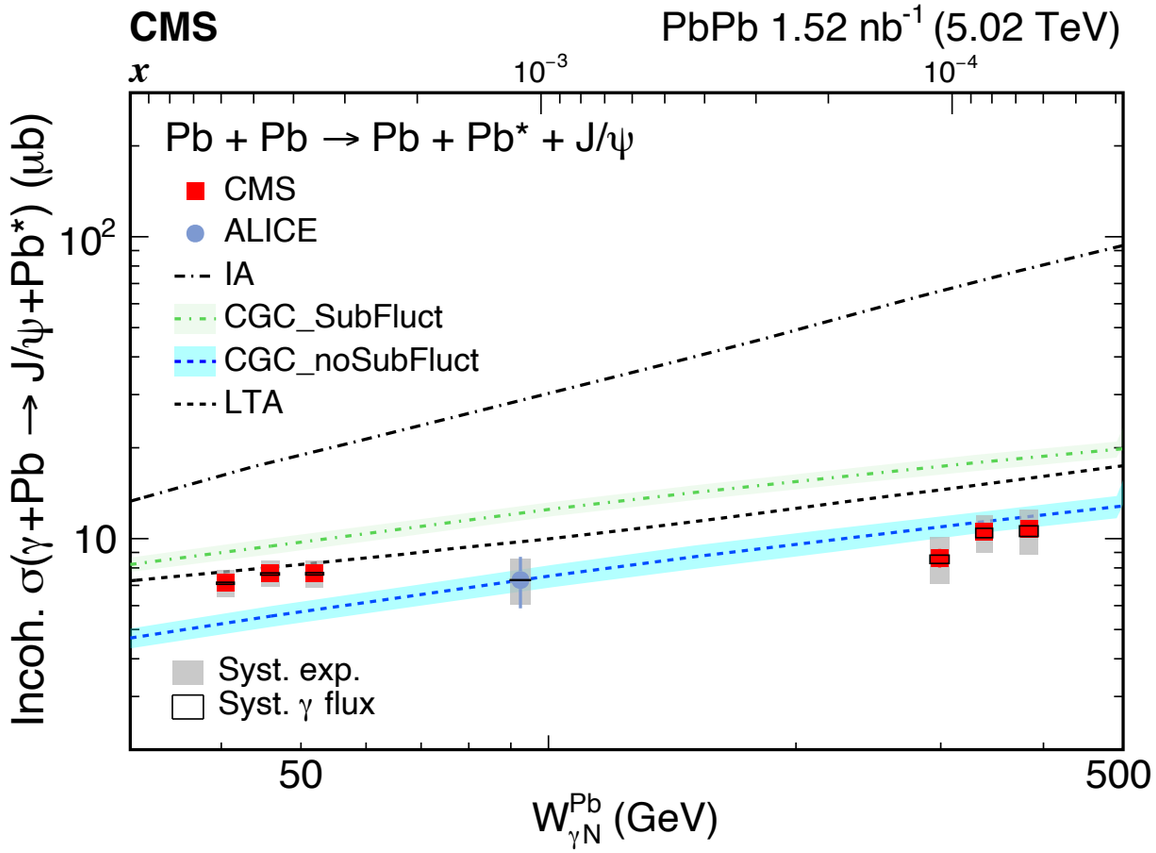
High-x

Low-x

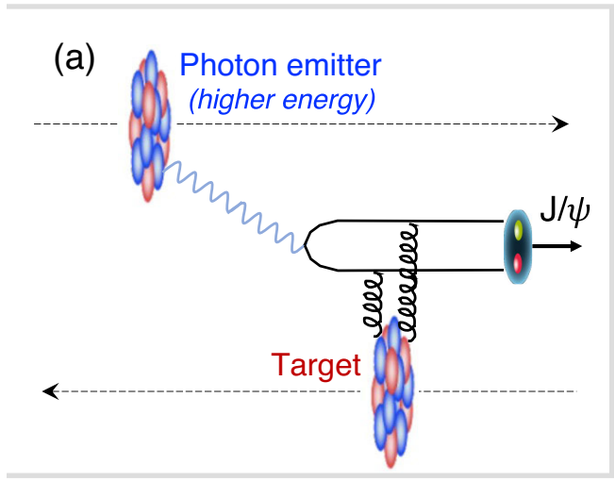
- By forward neutron measurement, we can identify the target nucleus and photon-emitter nucleus, which determines the $W_{\gamma N}$, center of mass energy in γ+N system
- Along with ALICE and LHCb data, the cross section describes the x-dependence of gluon density well
- Strong suppression observed compared to impulse approximation model (IA)
- Cross section slowly rises for very high $W_{\gamma N}$

Incoherent J/ψ in UPC





PRL 135 (2025) 11, 112301



High-x **Low-x**

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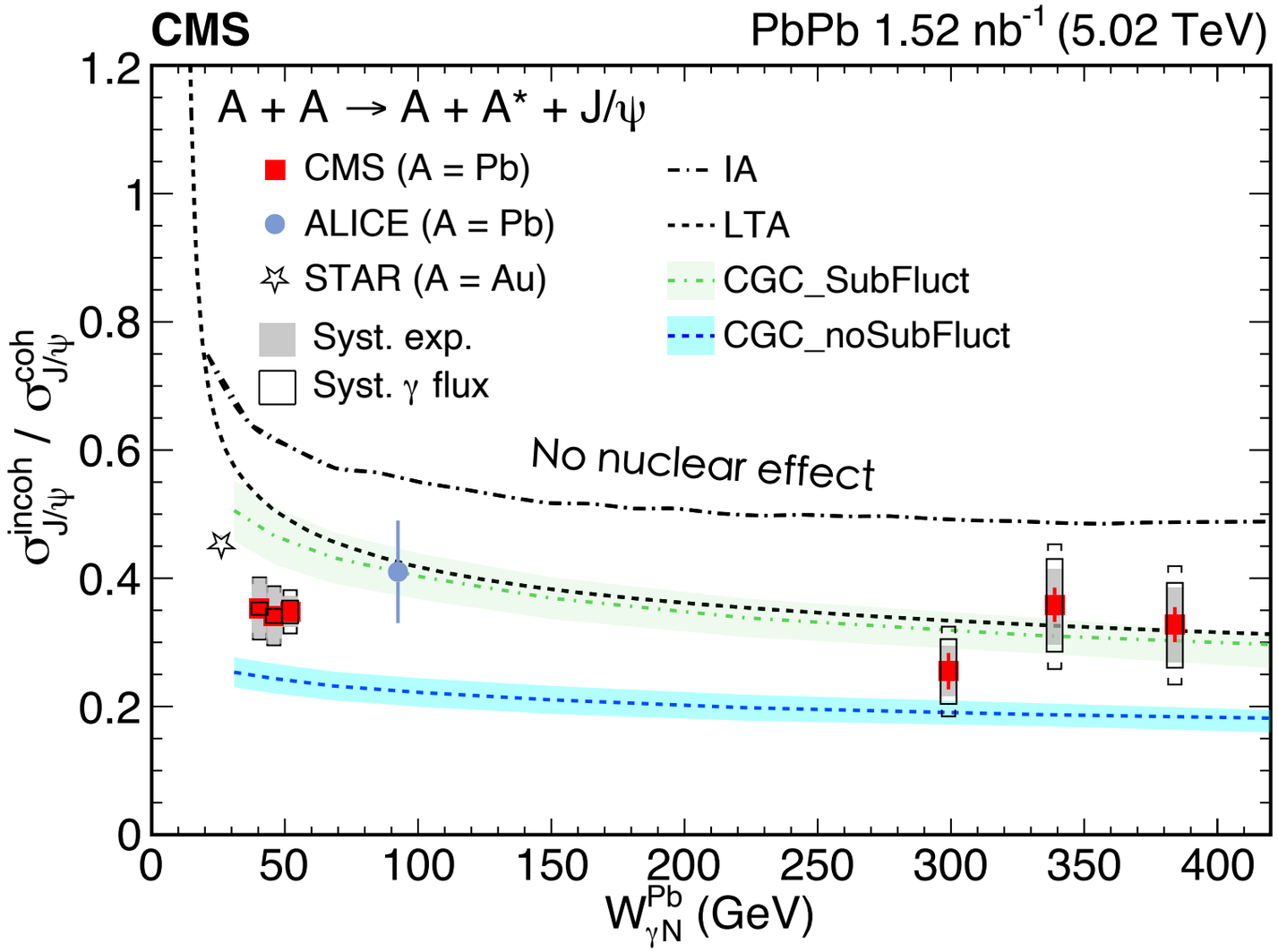
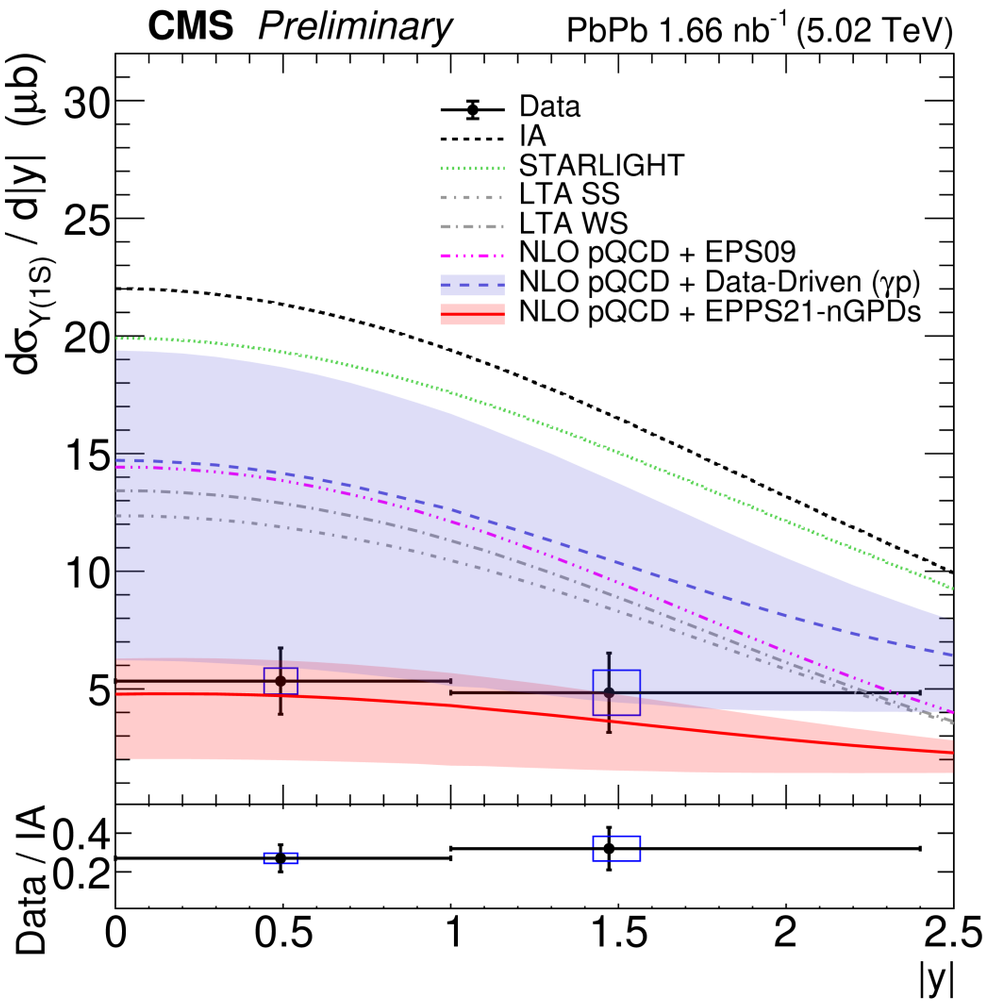
- Strong suppression observed compared to impulse approximation model (IA)
- Cross section slowly rises for very high $W_{\gamma N}$

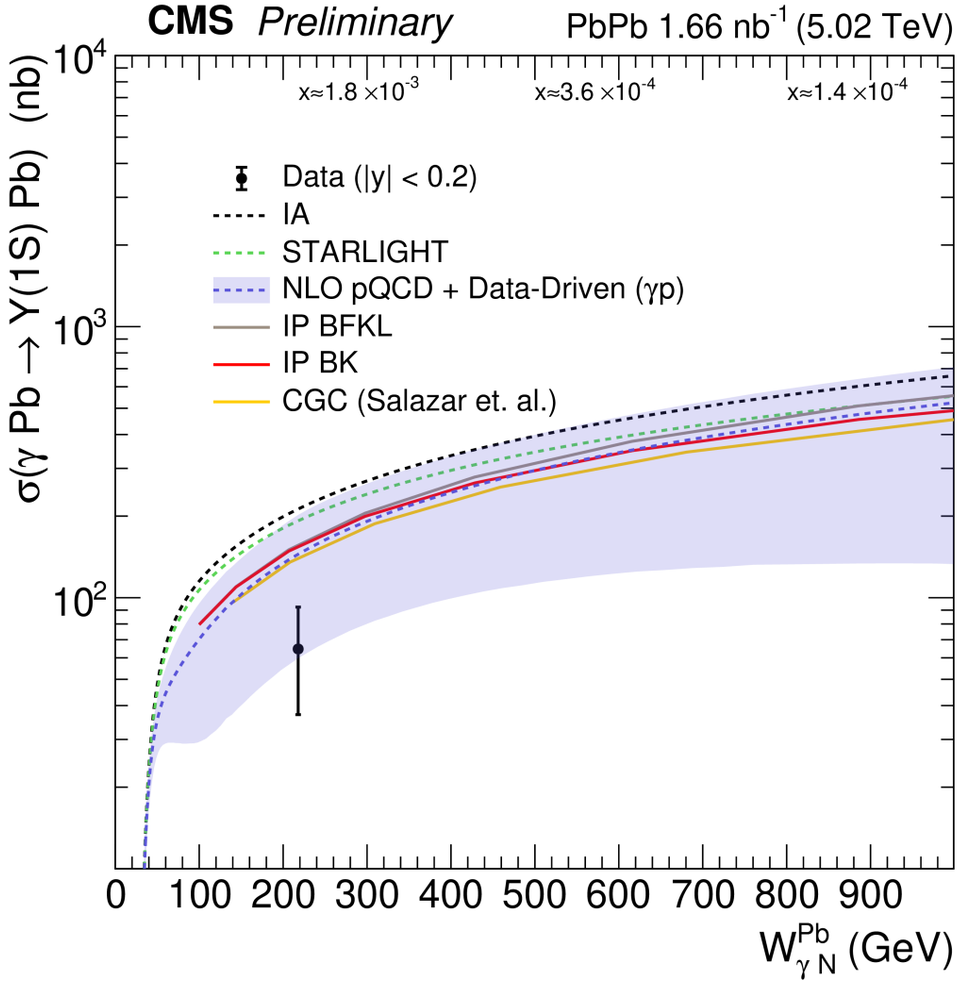
Ratio of Incoherent to Coherent yields of J/ψ



- Cross section ratio of incoherent and coherent J/ψ in UPC is almost flat for wide W range
- The result provides [fluctuation]/[average] information of gluon distribution, thus constraining models with nuclear effects

Coherent Υ(1S) in UPC





CMS-HIN-24-013

- $R_g^{Pb} = \sqrt{\sigma^{\gamma Pb}/\sigma^{IA}}$ (Guzey et al)
- We also measured coherent Υ(1S)
- $R_g^{Pb} = 0.53 \pm 0.11$, another evidence for strong shadowing effects
- Results are compared with BK, BKFL and CGC models

Summary

- Precision measurements of Υ(1S), Υ(2S) and Υ(3S) in PbPb collisions provide strong constraints on theoretical models of quarkonia dissociation

- Similar trends observed in the excited-to-ground state ratio for the charmonia and bottomonia states, which supports the co-mover effect.

- χ_c was newly measured for pPb, and χ_{c2}/χ_{c1} ratio values consistent with those in pp data

- Coherent and incoherent J/ψ, as well as coherent Υ (1S), photo-production in UPCs provide unique inputs for exploring low-x phenomena