Studies of quarkonia in excited states with CMS

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on behalf of the CMS Collaboration

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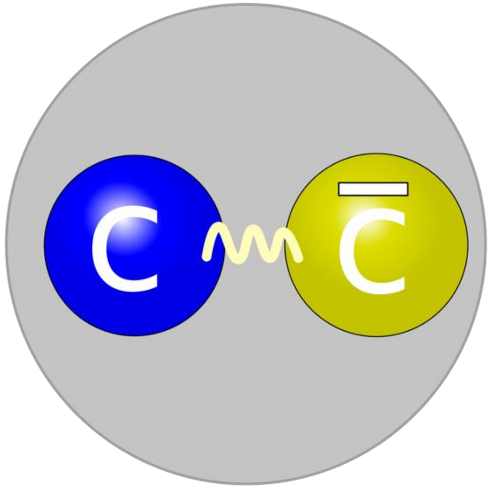
Outline

- **Quarkonium Production in heavy ion collisions**
- **Υ meson suppression in pPb and PbPb**
- **Motivation for measurement of quarkonia in excited states**
- **Existing results for excited charmonium at LHC**
- **Performance of χ_c measurement with CMS**
- **Summary**

Quarkonium production in heavy ion collisions



Quarkonia production process: Mostly initiated by gluon fusion

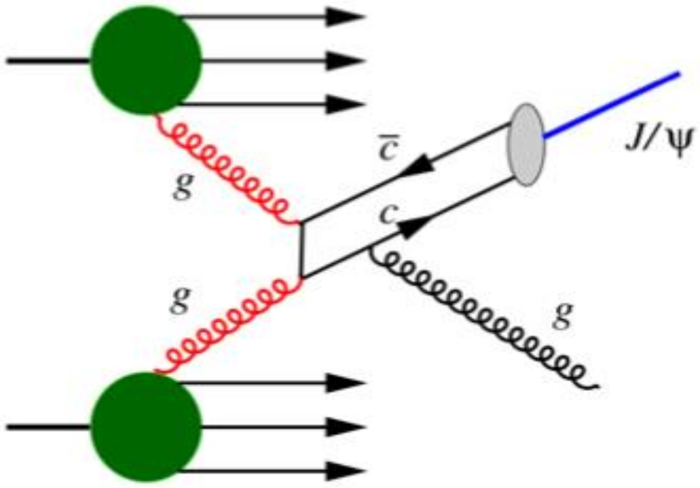
- Sensitive to the parton distribution functions (PDF)

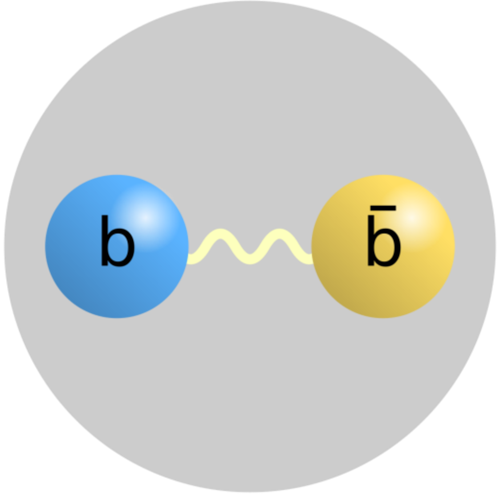
The Yields of quarkonium states

- Proposed to be suppressed due to interactions in the QGP

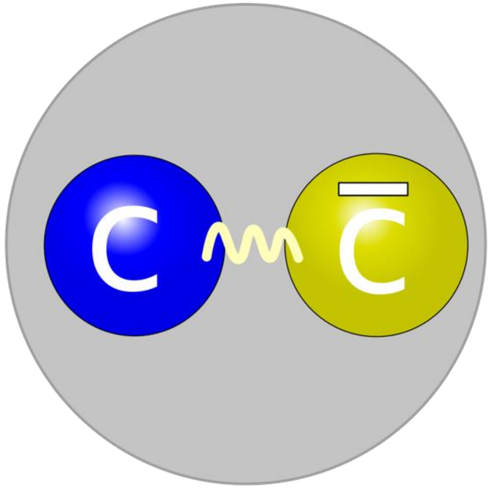
The amount of suppression

- Expected to be related to binding energies





Quarkonium production in heavy ion collisions



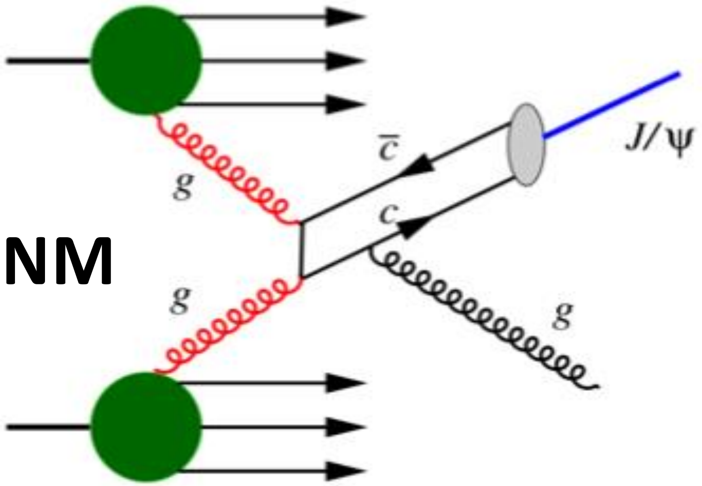
Heavy quarks experience energy loss while traveling through the nucleus

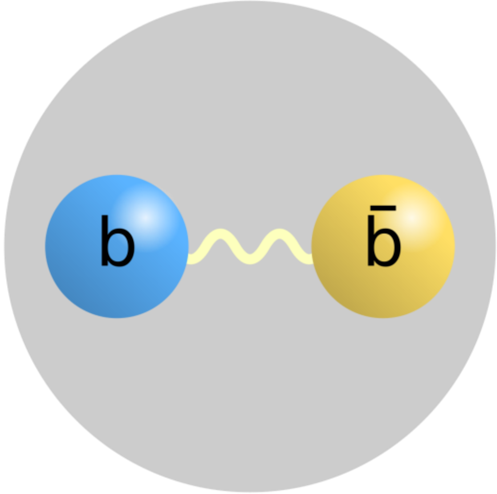
- This leads to the suppression of bound states

Heavy quark pairs interact with comoving hadrons in the late stage

- This disrupts fully formed quarkonium states.

To fully understand quarkonium production, we must distinguish the QGP effect from other effects like CNM





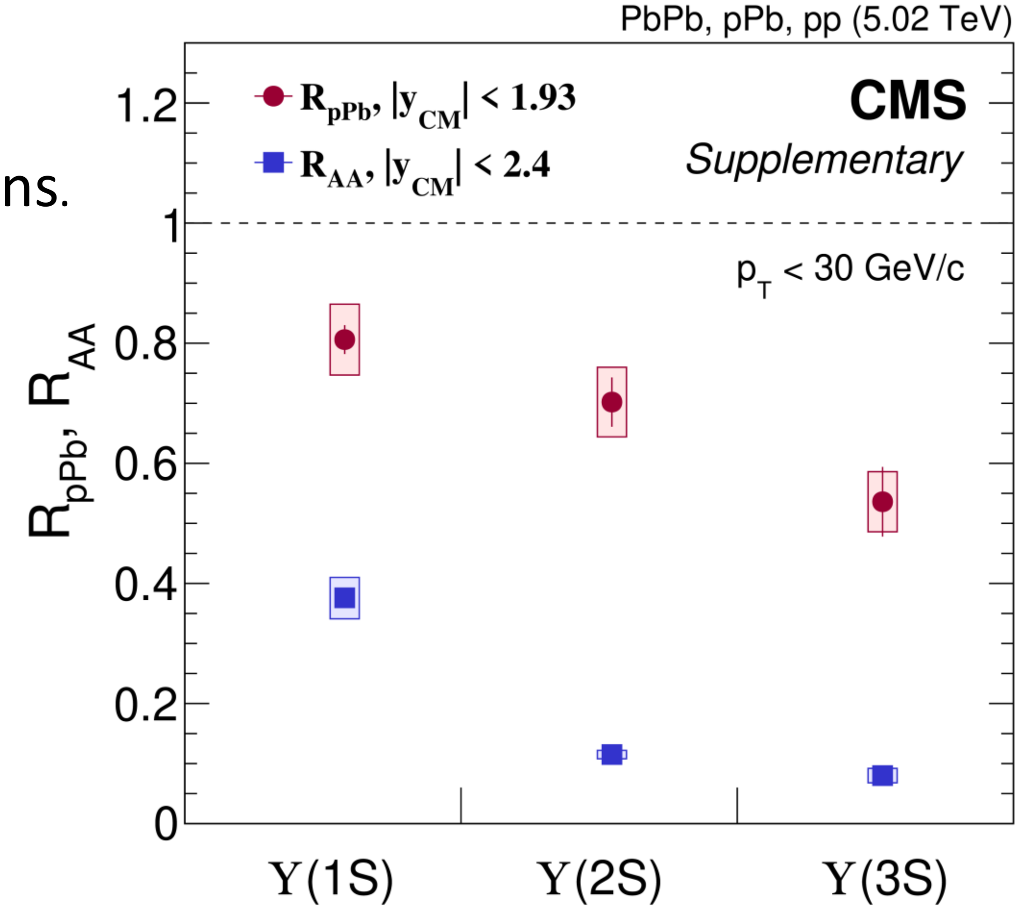
Υ meson and suppression in pPb and PbPb

CMS reported Υ states in both pPb and PbPb

- Relative suppression was also observed in pPb collisions.

Channel

- Detect bottomonium via dimuon decay channel



pPp : PLB 835(2022), 137397

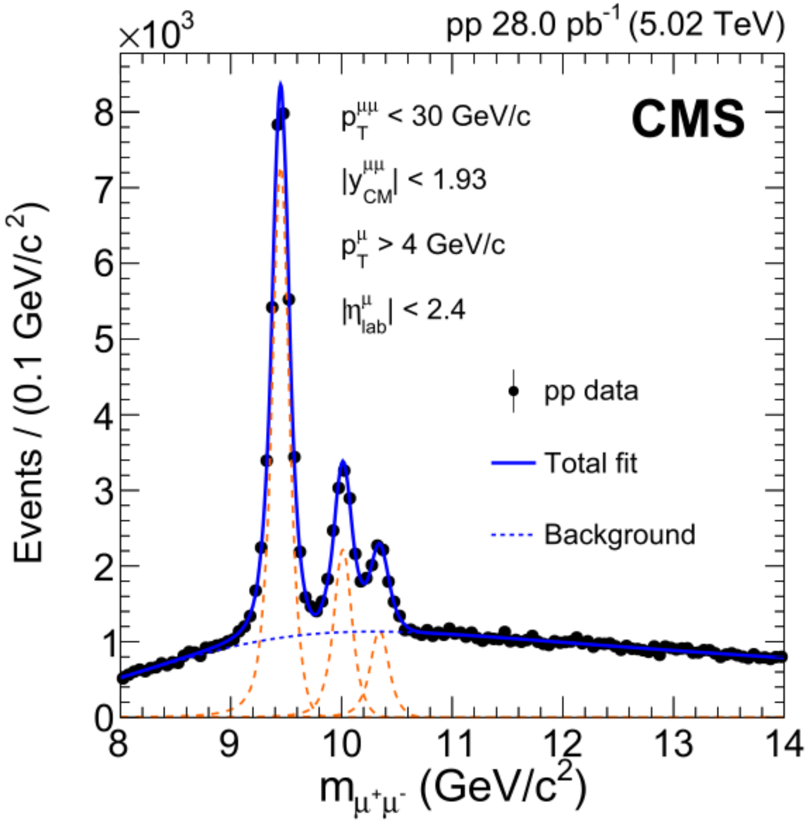
PbPb : PRL 133, 022302

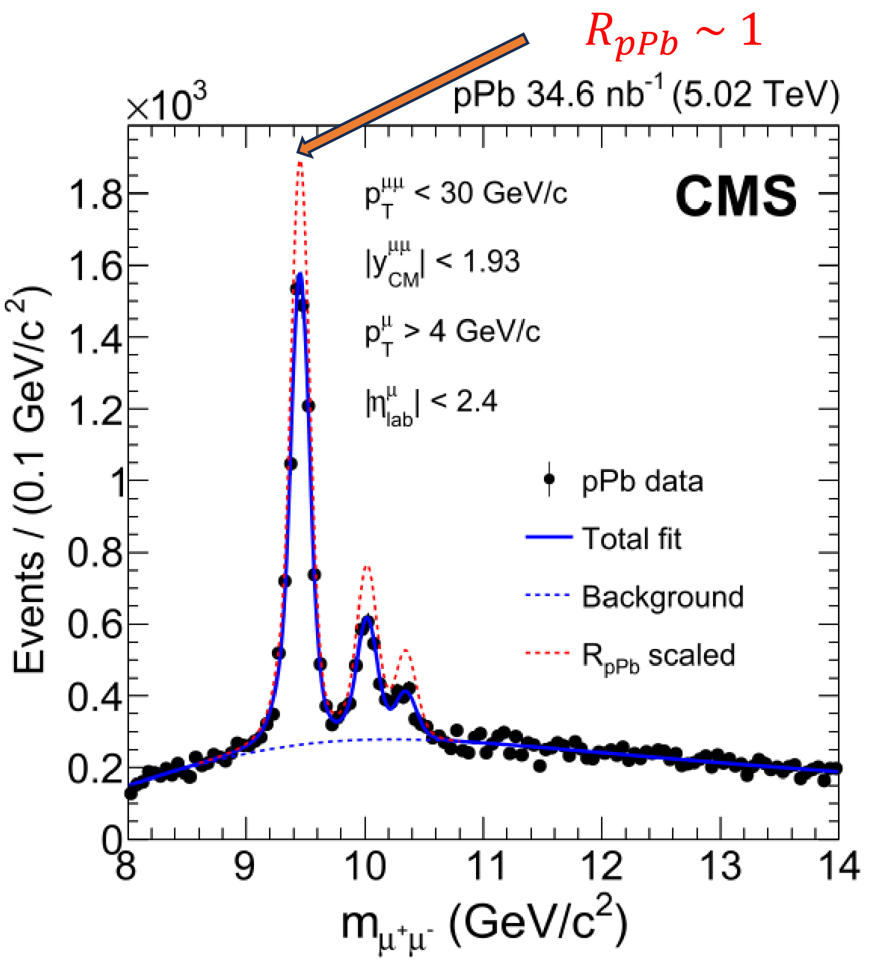
Υ meson suppression in pPb

- **Comparison of pp and pPb collisions** ($\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$)

PLB 835(2022), 137397

- **Suppression observed in pPb collisions compared to pp results**



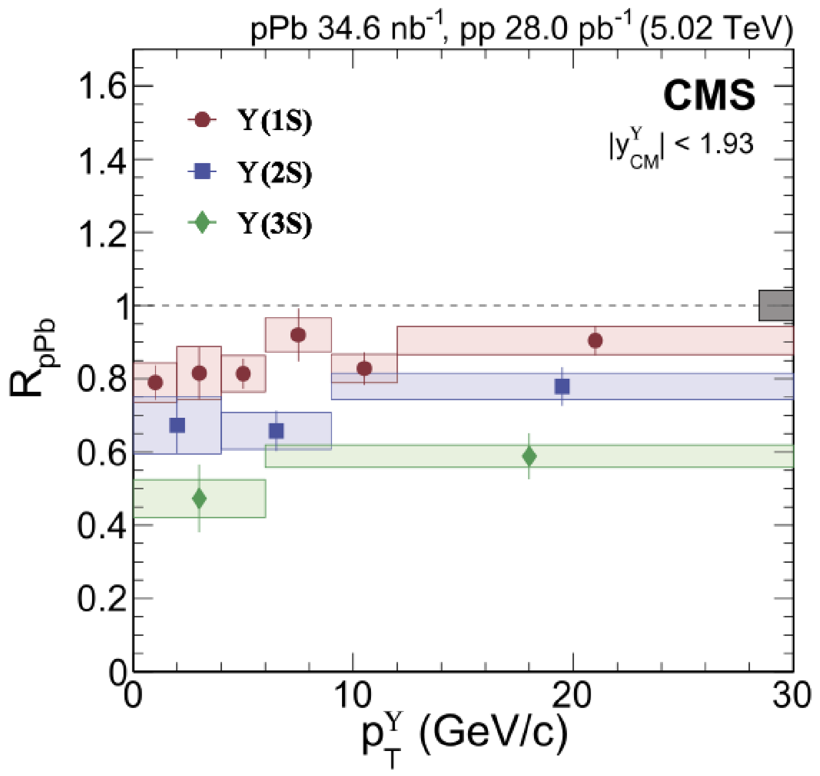


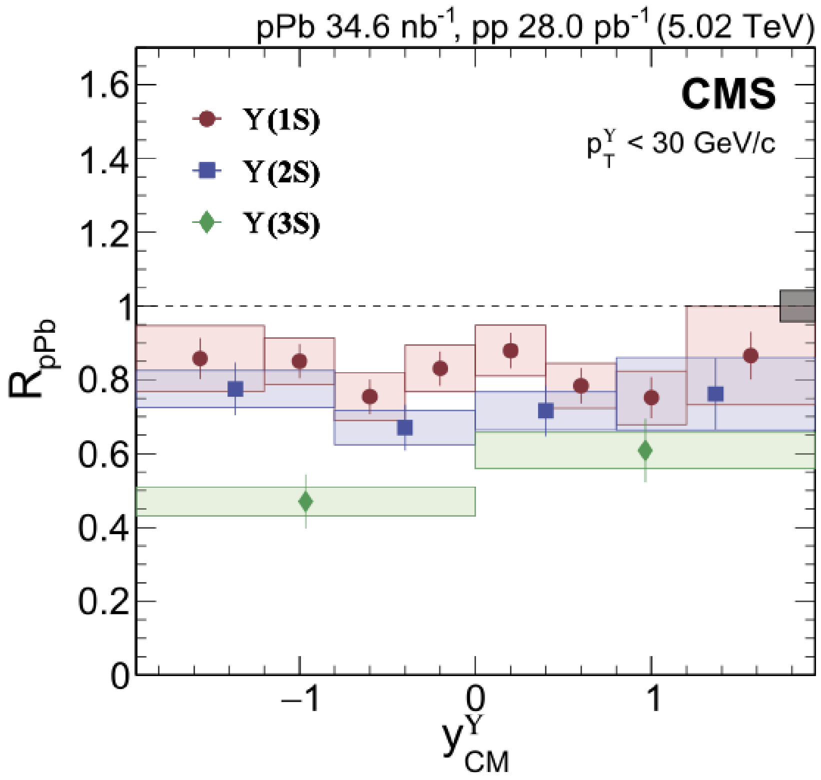
Υ meson suppression in pPb

PLB 835(2022), 137397

- **The suppression is not much dependent on both p_T and rapidity**

- $R_{pPb}(1S) > R_{pPb}(2S) > R_{pPb}(3S)$
  ->Related to the binding energy



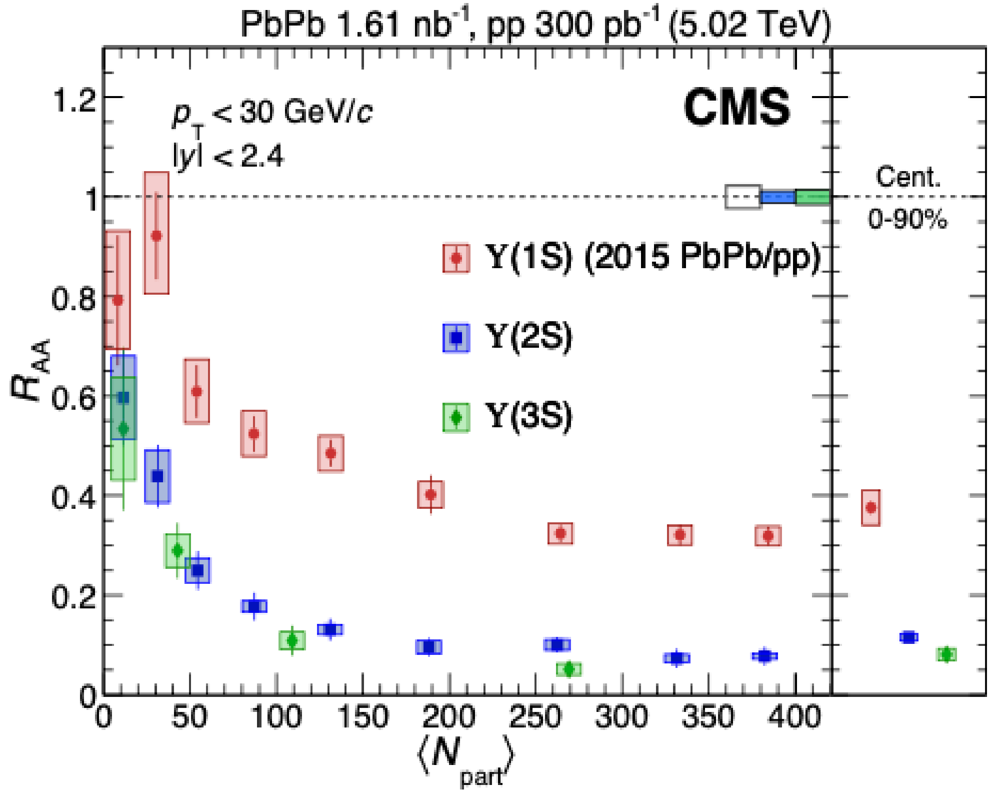


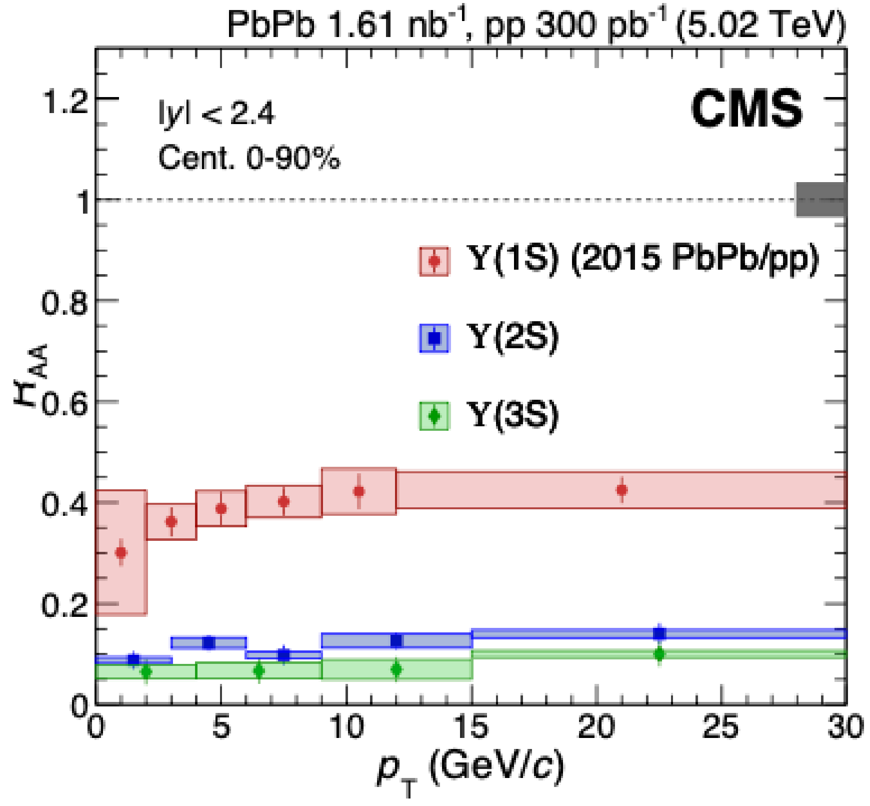
Υ meson suppression in PbPb

- The suppression is not much dependent on p_T
- Strong dependence on centrality of collision
- $R_{PbPb}(1S) > R_{PbPb}(2S) > R_{PbPb}(3S)$

->Related to the binding energy

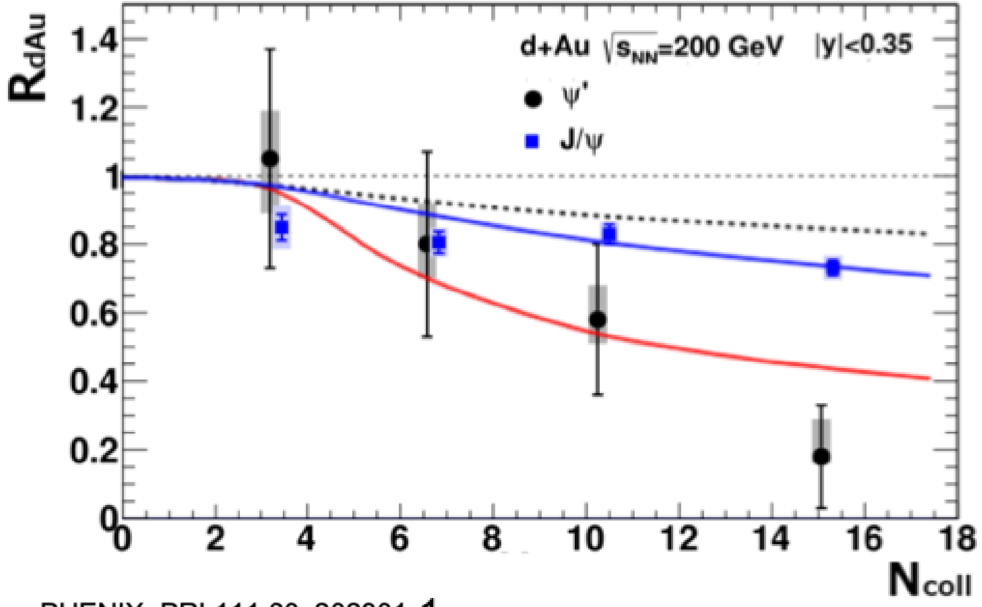
PRL 133, 022302



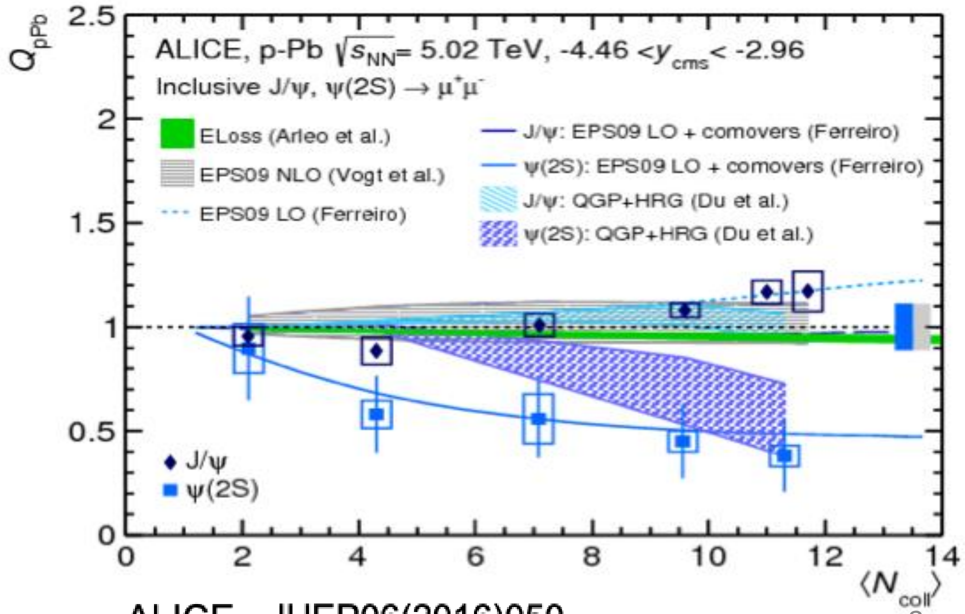


J/ψ and ψ(2S) results in pPb

- The ψ(2S) study have shown that excited state exhibit different suppression
- A trend of increasing relative suppression is observed as multiplicity (or related variables) increases
- CMS will present the multiplicity dependence of $\sigma_{\psi(2S)}/\sigma_{J/\psi}$ in pPb collisions this afternoon



PHENIX, PRL111.20, 202301 1



ALICE, JHEP06(2016)050

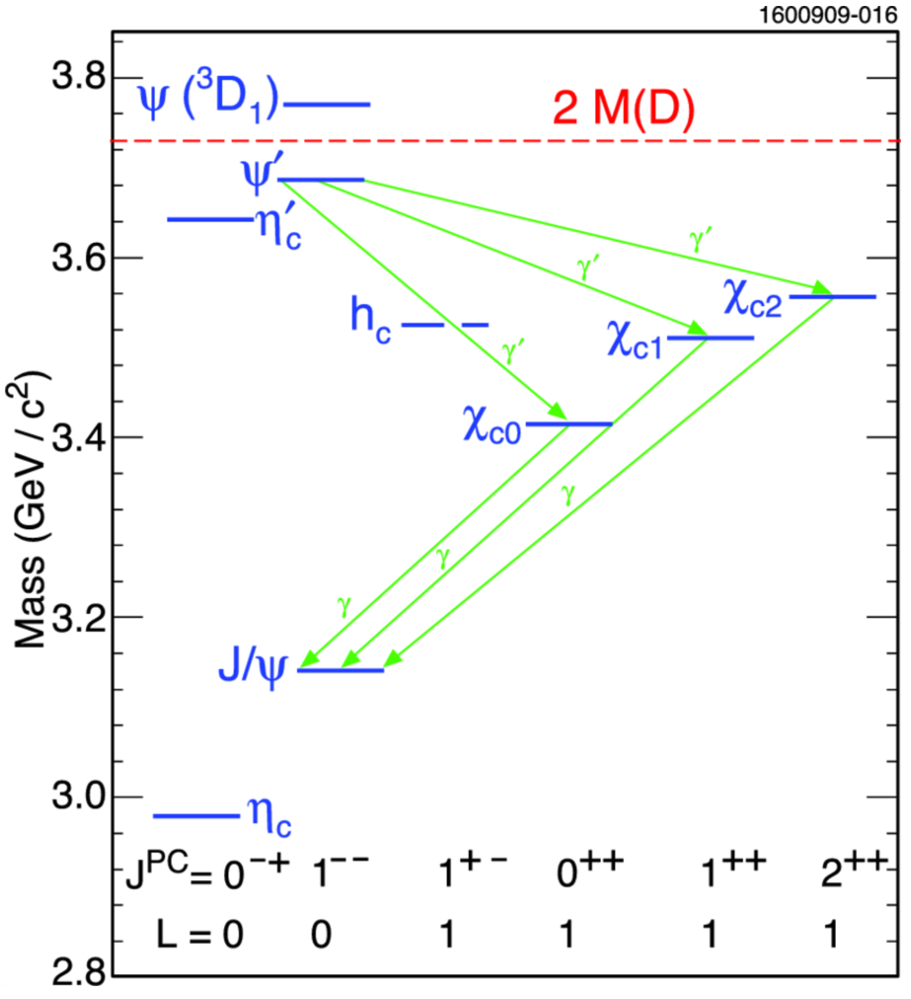
Motivation for measurement of quarkonia in excited states

Different suppression of excited quarkonium can not be explained solely by Initial state effects

- Both charmonium and bottomonium analyses demonstrate the relative suppression of excited states.

Preceding studies on nuclear modification factors for charmonium, J/ψ and ψ

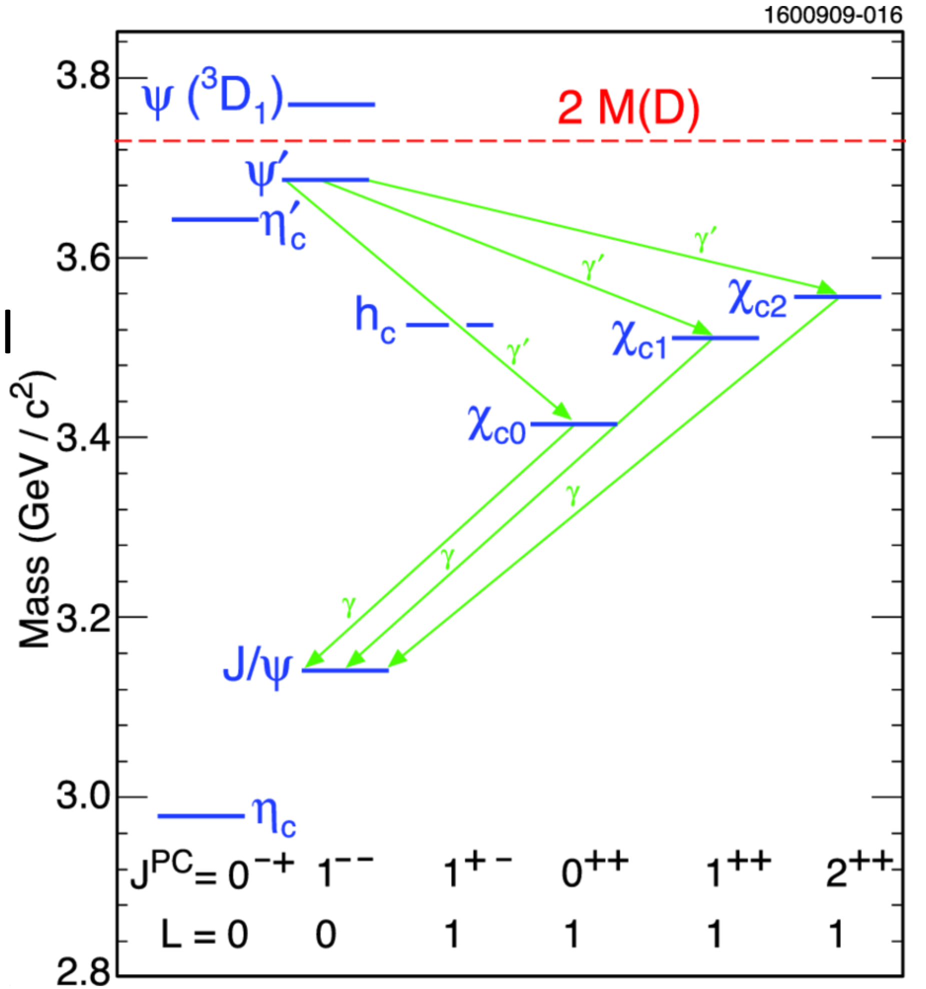
- Feed-down from the P-wave was not excluded
- Feed-down from χc is crucial to isolate the nuclear modification factor of prompt J/ψ results.



Motivation for measurement of quarkonia in excited states

To fully understand the quarkonia modification in hot or cold medium.

- Exclusive measurement of the R_{AA} for each state is crucial



Main goal

- Study of relative modification of χ_c to J/ψ in pPb
- Study of relative yields in of χ_{c1} and χ_{c2}

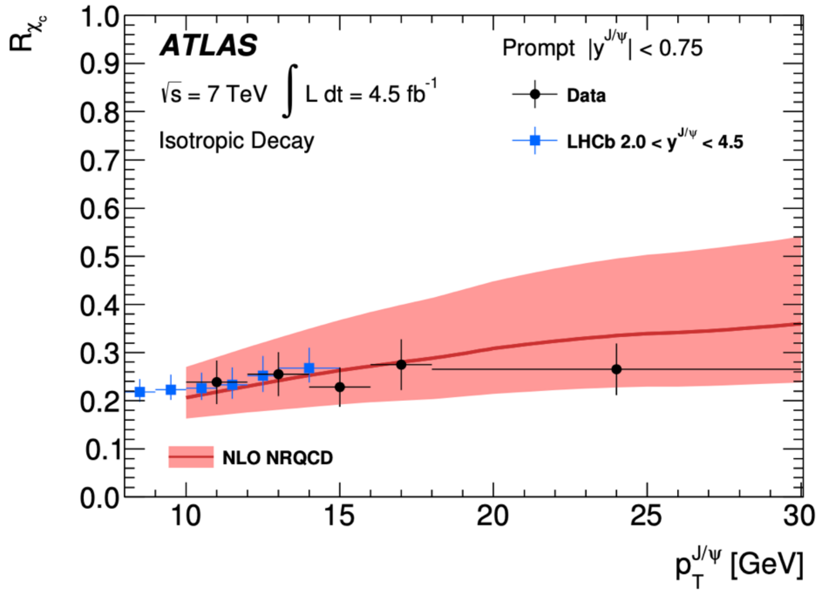
We aim to meausure χ_{c1} and χ_{c2} in pPb collision, as the step toward for the measurement in PbPb collision

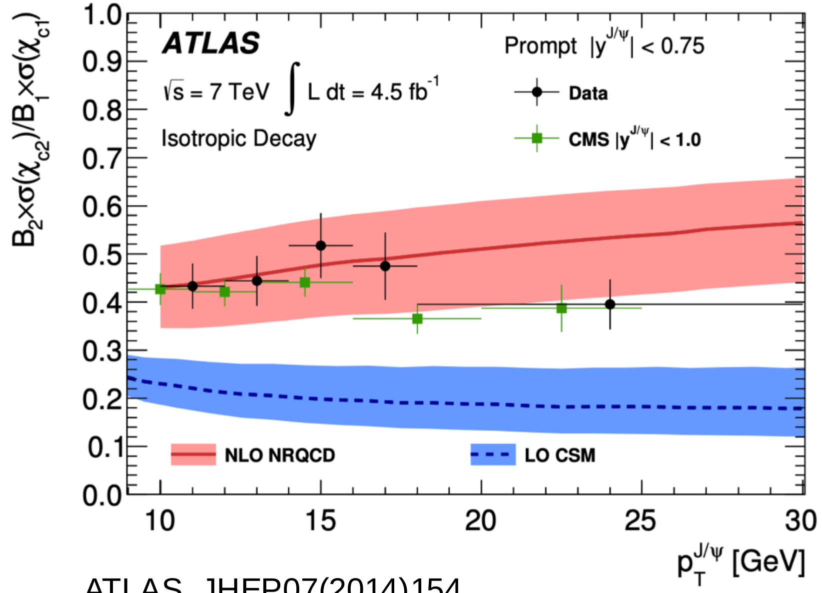
Existing results for excited charmonium at LHC

pp

ATLAS

- The cross-sections for prompt and non-prompt χ_{c1} and χ_{c2} production have been measured at 7 TeV
- Reported χ_c to J/ψ and χ_{c2} to χ_{c1} ratio.
- The measurements of prompt χ_c are combined with existing prompt J/ψ production to derive the fraction of prompt J/ψ produced in feed-down from χ_c decays.





ATLAS, JHEP07(2014)154

pp

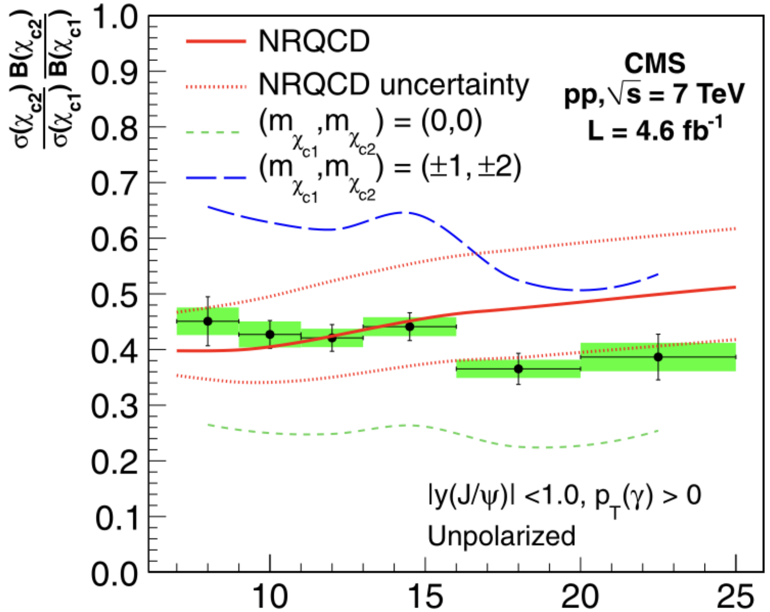
CMS

- **Measured a extend range of J/ψ P_T**

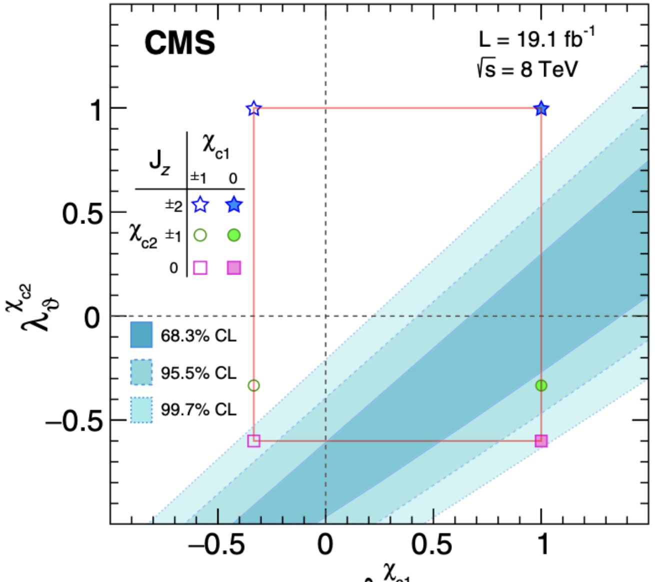
- **Studied the effect of χ_c polarization on photon reconstruction efficiency and compared to theoretical prediction.**

- **CMS observed that both χ_{c1} and χ_{c2} are strongly polarized**

- **Due to the polarization, χ_c analysis requires significantly different treatments of the acceptance correction compared to J/ψ.**



CMS, EPJC72(2012), 2251



CMS, PRL.124.162002

Existing results for excited charmonium at LHC

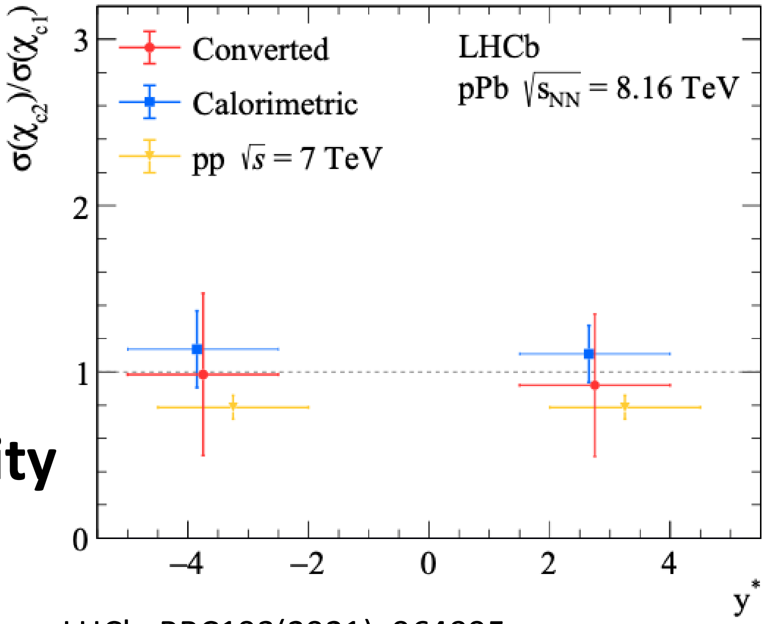
pPb

LHCb

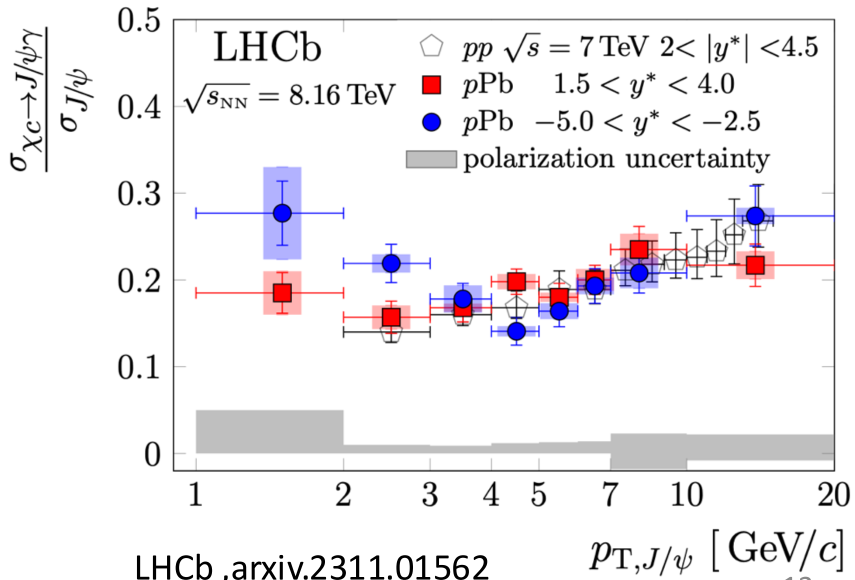
- **First measurement of χ_{c2}/χ_{c1} and χ_c / J/ψ in pPb with rapidity**
  $1.5 < y* < 4.0$
  $-5.0 < y* < -2.5$

- **Comparison with the ratio measured in pp collision.**

- **The ratio is consistent with no dissociation of χ_c states, and existing pp measurments.**



LHCb, PRC103(2021), 064905



LHCb ,arxiv.2311.01562

Existing results for excited charmonium at LHC

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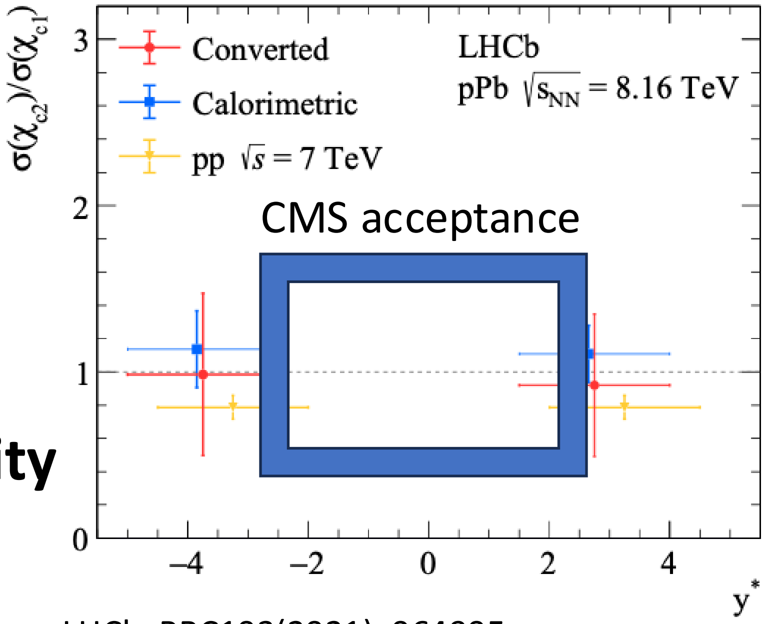
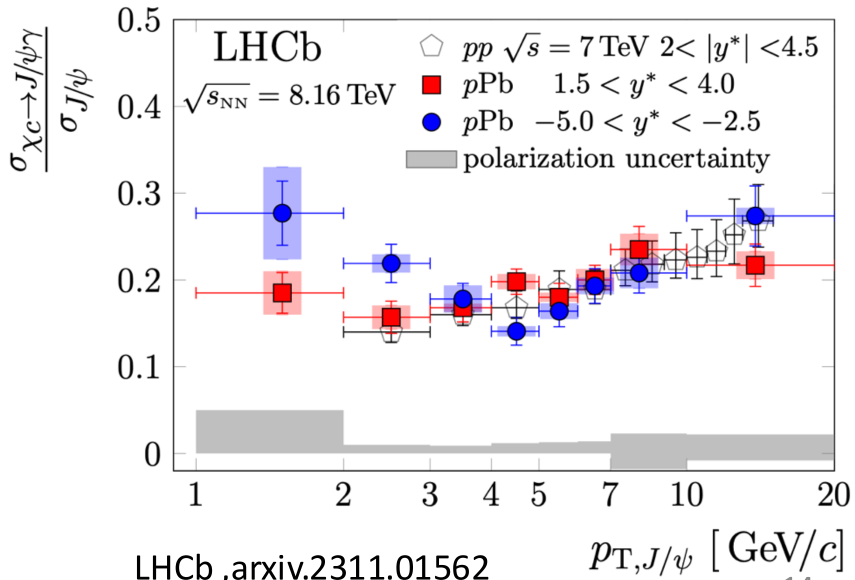


LHCb, PRC103(2021), 064905



LHCb ,arxiv.2311.01562

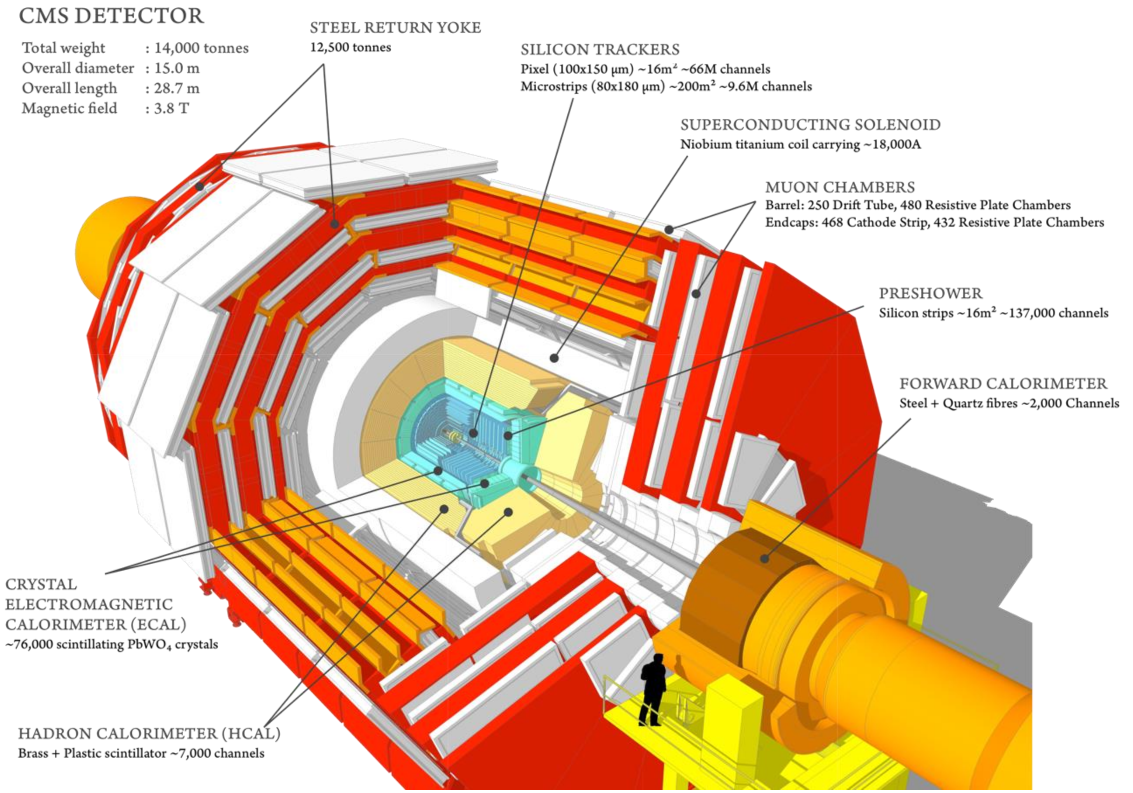
Reconstruction of χ_c in CMS

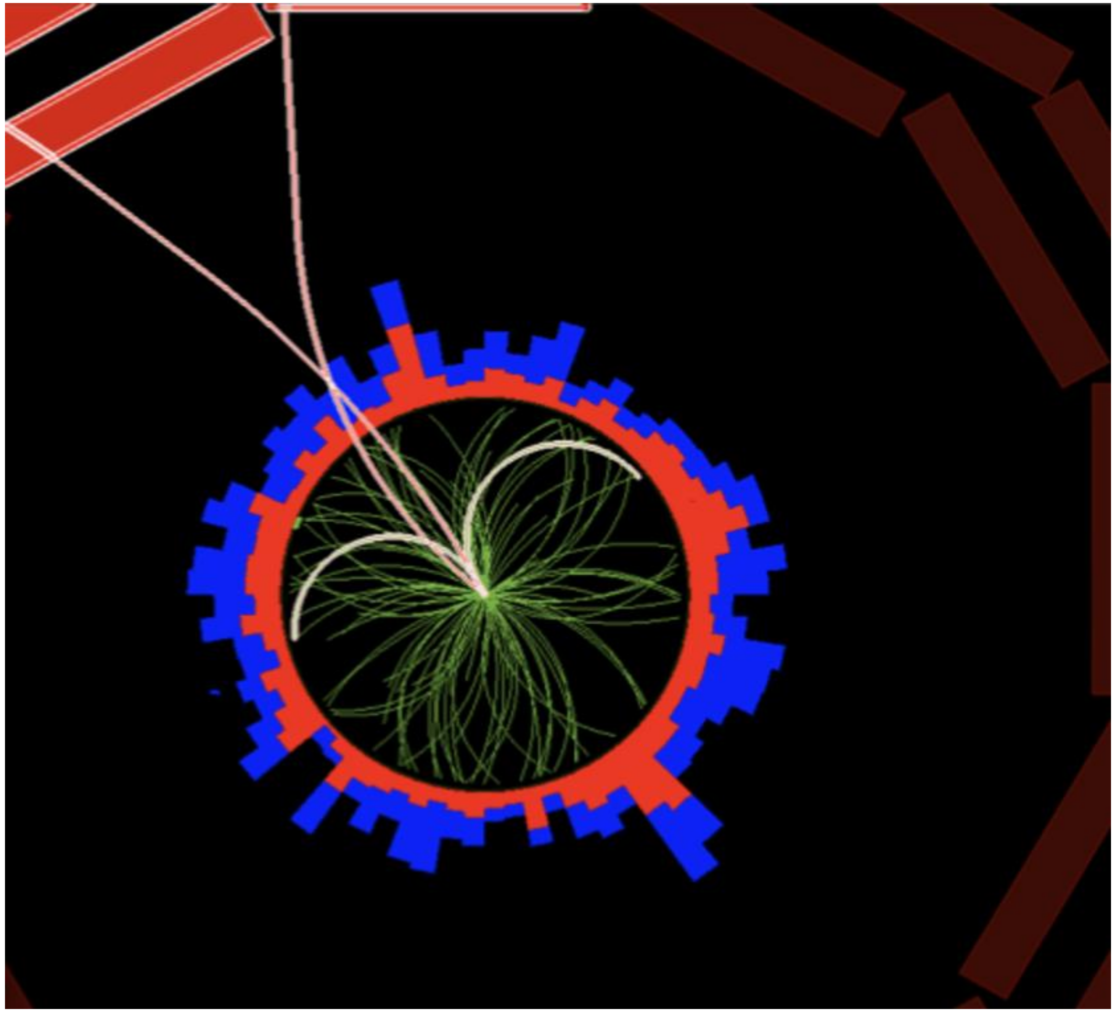
$\chi_c \to J/\psi + \gamma \to \mu^+\mu^- + e^+e^-$ (conversion)

pPb 8.16 TeV

$|\eta| < 2.4$

$\chi_c / J/\psi$ and χ_{c2}/χ_{c1}

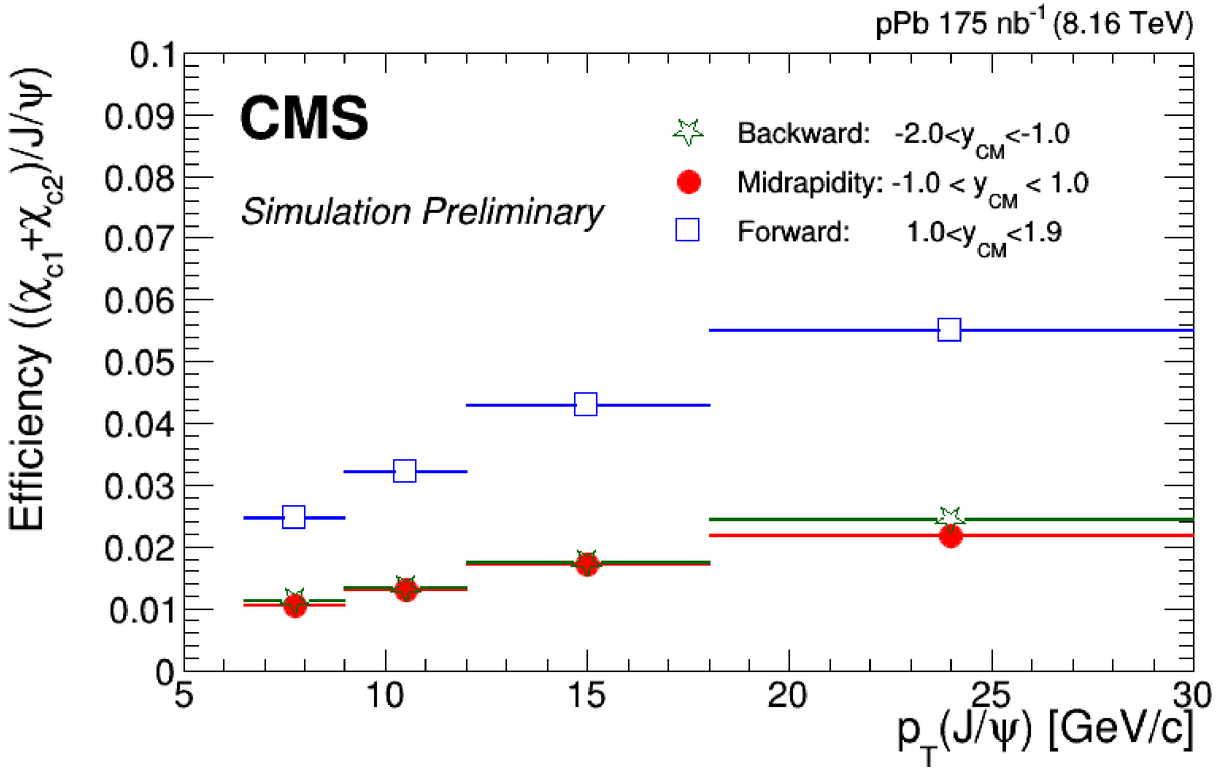




Performance of χ_c measurement with CMS

Efficiency of χ_c to J/ψ

$$\mathcal{E}_{\text{total}}(\text{bin}) = \frac{\text{prob}(\chi_c \text{ reco.})}{\text{prob}(J/\psi \text{ reco.})} = \frac{N_{\text{pass}}(\chi_c)(\text{bin})}{N_{\text{pass}}(J/\psi)(\text{bin})}$$



- **Individual muon and J/ψ efficiencies cancel out.**
- **Therefore, this plot represents γ acceptance and γ, χ_c selection efficiency.**
- **Forward rapidity exhibits higher efficiency than backward**

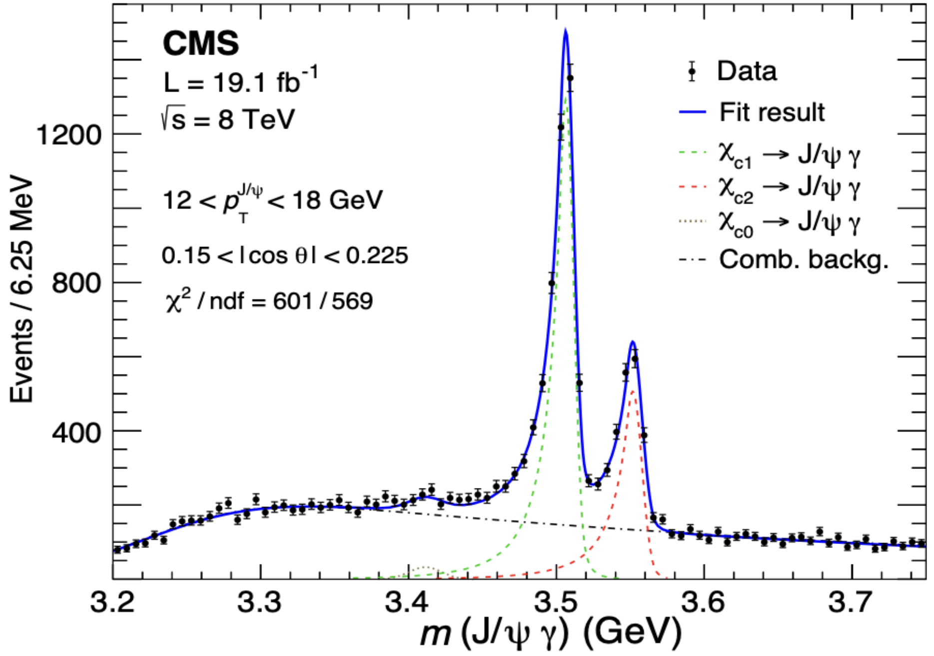
  -> Due to the target geometry, material budget of the target is much higher than the mid and backward rapidity region.

Performance of χ_c measurement with CMS

χ_c invariant mass plot for pp results and pPb simulation

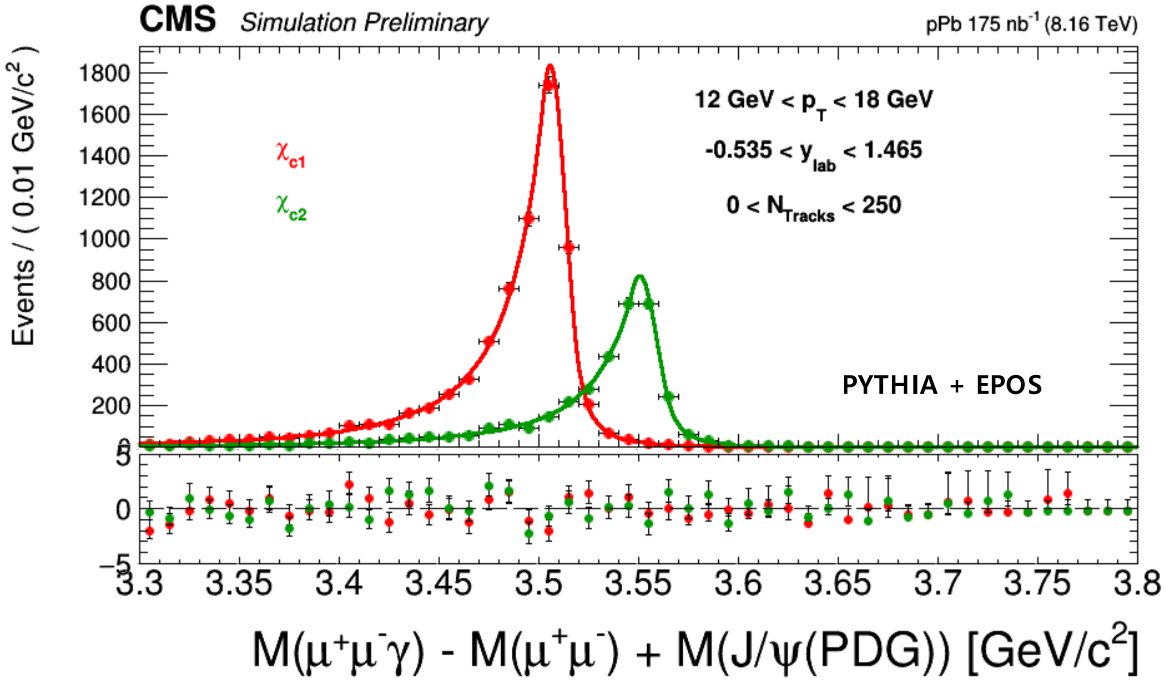
- **CMS observed clear peak of both χ_{c1} and χ_{c2} in pp collisions.**
- **χ_{c1} and χ_{c2} peak can be clearly distinguishable in the simulation studies in pPb environment.**

CMS pp invariant mass plot



(Phys. Rev. Lett. **124**, 162002)

Midrapidity($|y_{CM}|$ < 1.0) (12 < P_T < 18 GeV) pPb

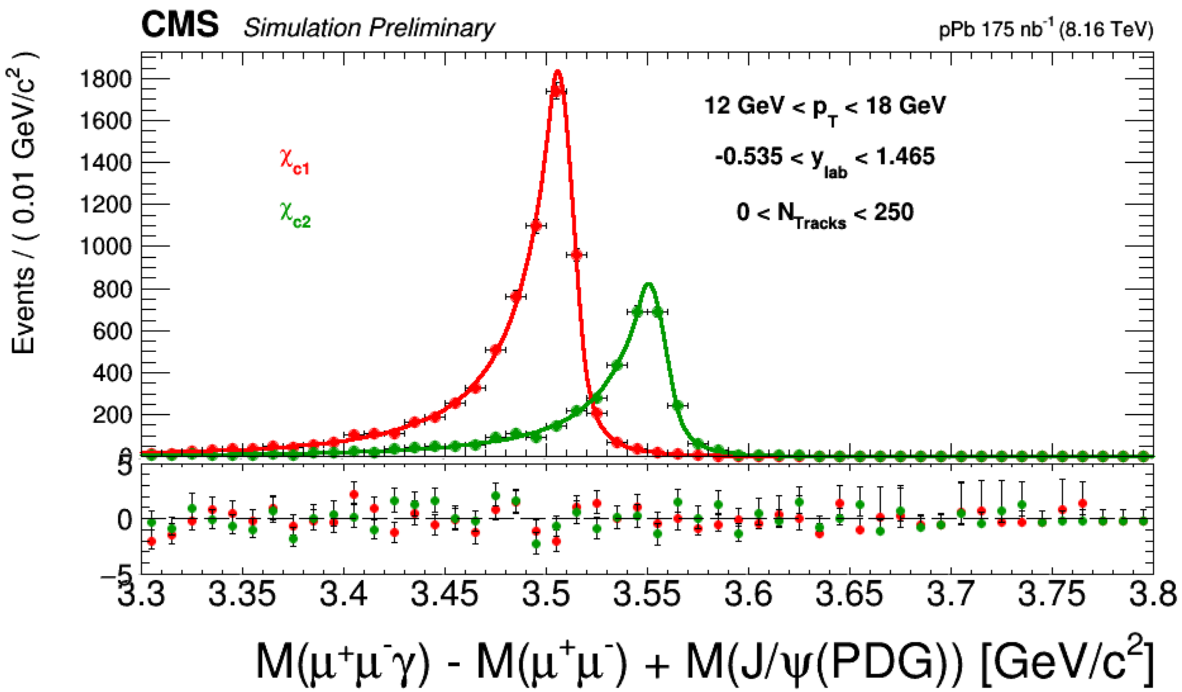


Performance of χ_c measurement with CMS

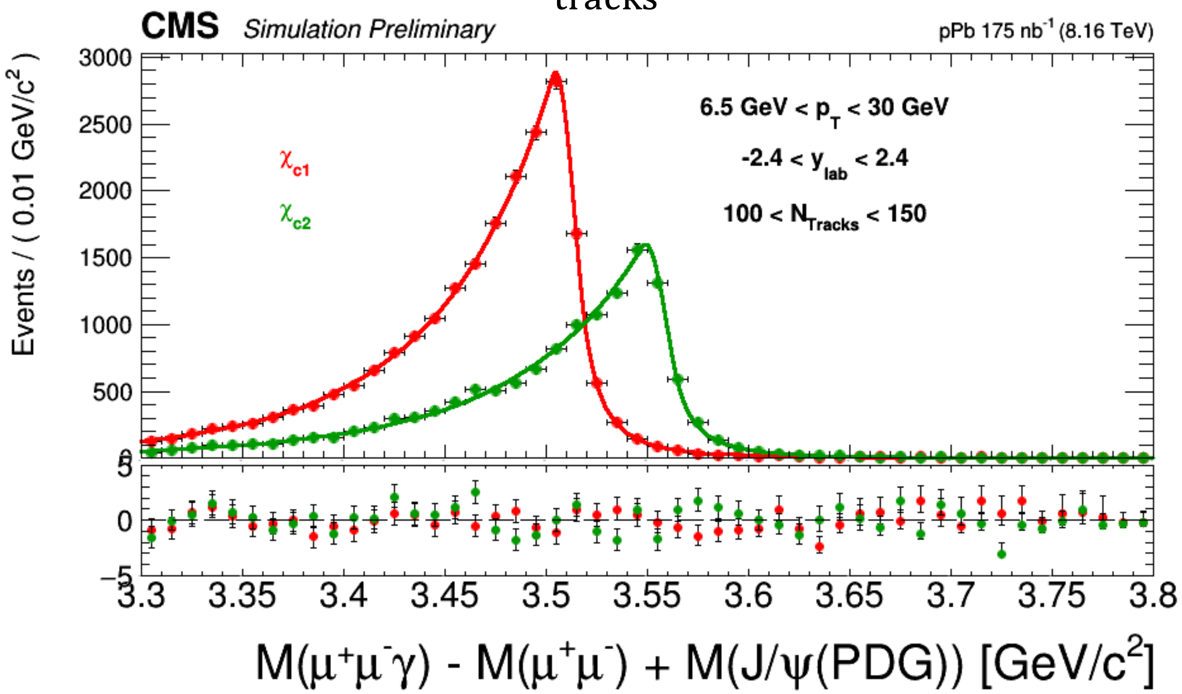
χ_c invariant mass plot in pPb simulation

- **Midrapidity (12 < P_T < 18 GeV) and High multiplicity (P_T integrated) plots.**
- **The high multiplicity plot exhibits a relatively broader peak compared to the midrapidity plot.**
- **As demonstrated, the χ_{c1} and χ_{c2} peaks remain clearly distinguishable even in high multiplicity regions.**

Midrapidity($|y_{CM}|$ < 1.0) (12 < P_T < 18 GeV)



100 < N_{tracks} < 150



Summary

- **CMS has been conducting research on the production for excited quarkonia in pPb or PbPb collisions.**

- **The study of χ_c is crucial for understanding the feed-down effect of J/ψ**

- **This analysis will serve as a baseline for nucleus-nucleus collisions.**

- **MC simulation results demonstrate that both χ_{c1} and χ_{c2} peak are clearly distinguishable.**

Backup

χ_c Charmonium P-states

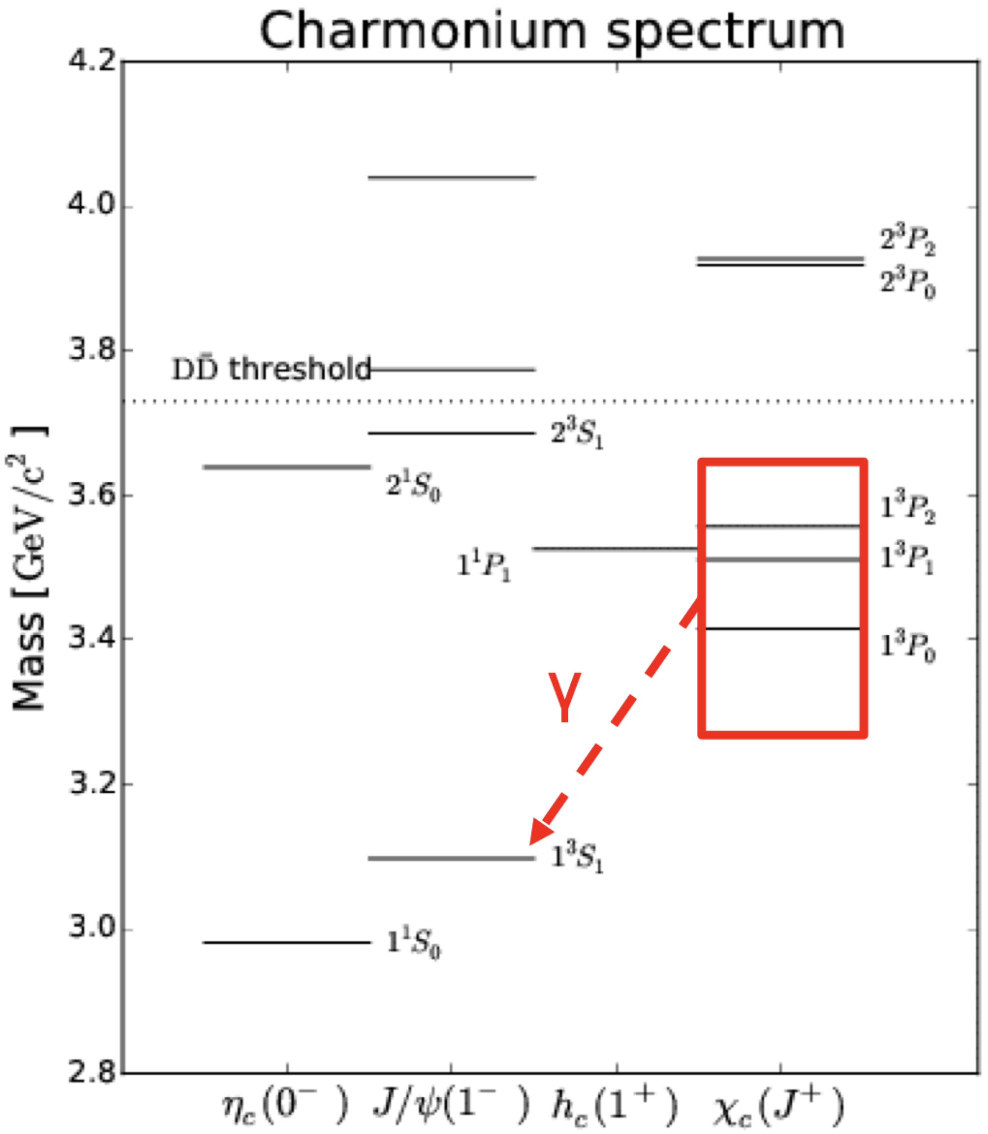
P states

- χ_{c0}(1P) m = 3415 MeV
- χ_{c1}(1P) m = 3511 MeV
- χ_{c2}(1P) m = 3556 MeV

χ_c -> $J/\psi + \gamma$ -> $\mu^+\mu^- + e^+e^-$ **(conversion)**

BR (χ_c -> $J/\psi + \gamma$) : 1.4%, 34%, 19%

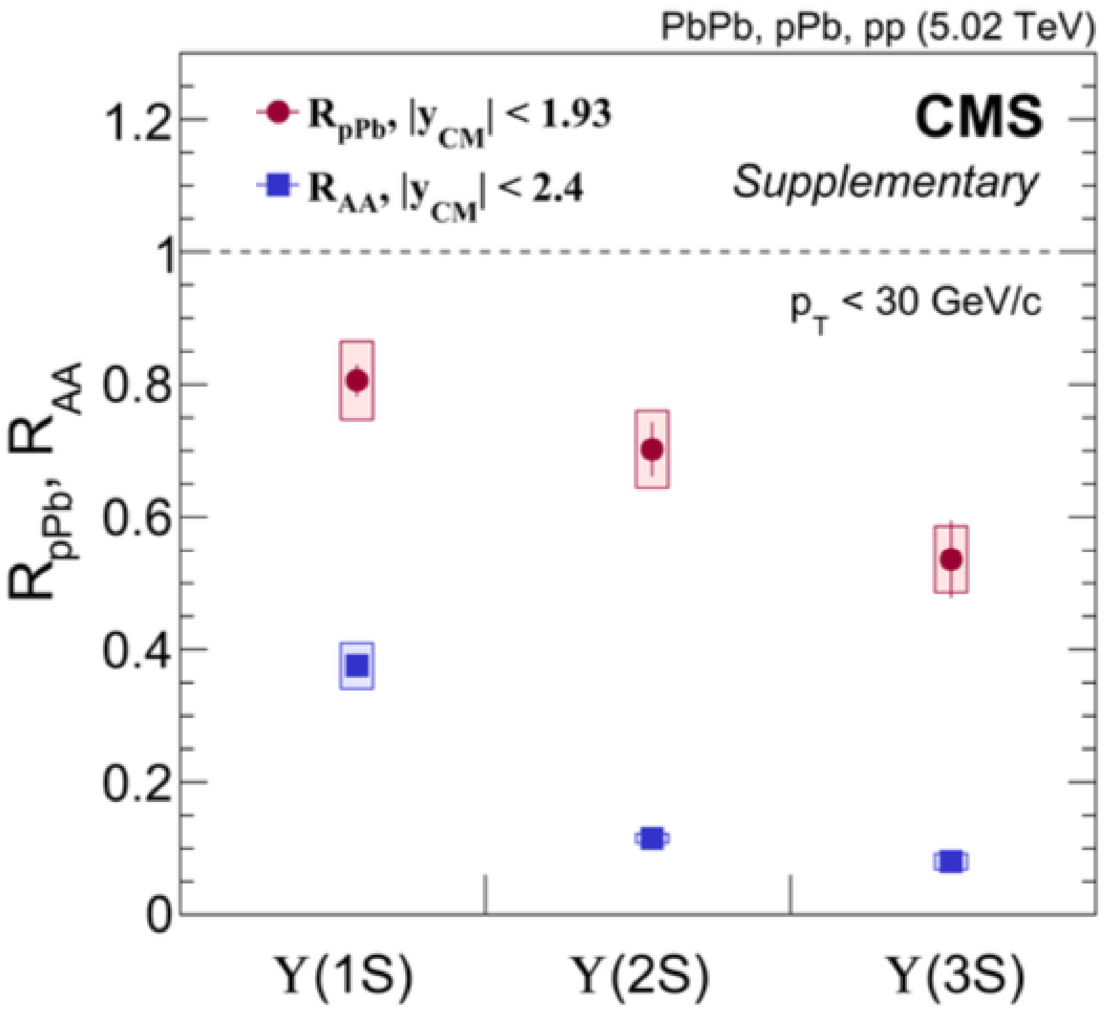
χ_{c0} **too small,** χ_{c1} **biggest peak,** χ_{c2} **smaller peak**



Υ meson suppression in pPb and PbPb

The suppression is smaller in pPb compared to PbPb

Both results shows the binding energy dependence
R(1S) > R(2S)> R(3S)



PLB 835(2022), 137397

arXiv 2303.17026

PLB 790(2019), 2070

Fitting function

Double-side crystal ball function for signal.

$$\mathrm{DCB}(m;\mu,\sigma,\alpha_L,n_L,\alpha_H,n_H) = \begin{cases} e^{-0.5\,t^2} & \text{if } -\alpha_L < t < \alpha_H \\ e^{-0.5\,\alpha_L^2}\left[\frac{\alpha_L}{n_L}\left(\frac{n_L}{\alpha_L}-\alpha_L-t\right)\right]^{-n_L} & \text{if } t < -\alpha_L \\ e^{-0.5\,\alpha_H^2}\left[\frac{\alpha_H}{n_H}\left(\frac{n_H}{\alpha_H}-\alpha_H+t\right)\right]^{-n_H} & \text{if } t > \alpha_H \end{cases}$$

$\sigma_{\chi_{c2}}$ is constrained ($\sigma_{\chi_{c2}} = 1.11\ \sigma_{\chi_{c1}}$)