Studies of relative production of χ_{c2}/χ_{c1} and $(\chi_{c1} + \chi_{c2})/(J/\psi)$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV at the CMS experiment

Andrés Muñoz Acevedo

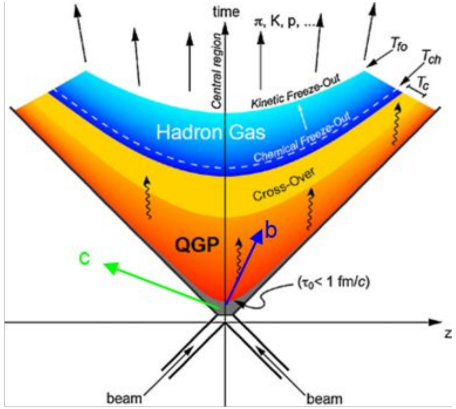
Annual Meeting of the Division of Particles and Fields (RADPyC)

21-24 May 2025, Pachuca, Hidalgo

Heavy-Ion Collisions

- The goals of ultrarelativistic **heavy ion collisions** (HICs) physics are to create **quark-gluon plasma** (QGP) and to understand its properties**.**

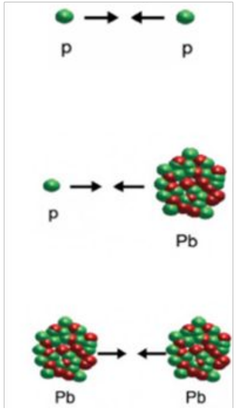
- **Charm and beauty quarks** (heavy -flavours, HF) produced in initial **hard scattering**.



Measurements in pp collisions
- Understand **particle production mechanisms**
- **Experimental reference** for heavy-ion collisions

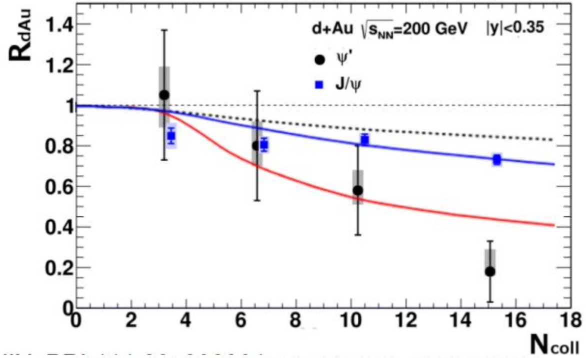
Measurements in pPb collisions
- **Cold nuclear matter** effects (CNM)
- **Experimental reference** for Hot matter effects

Measurements in PbPb collisions
- **Hot nuclear matter effects**



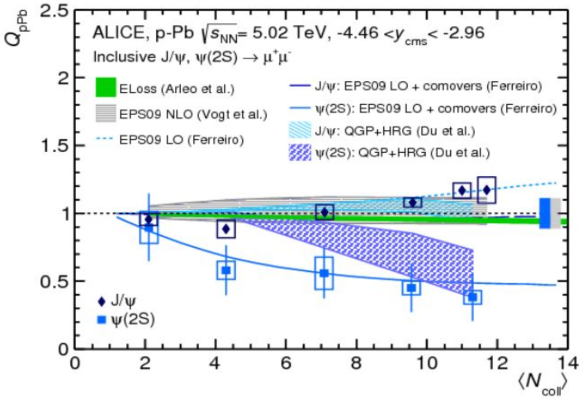
Charmonium States in pPb

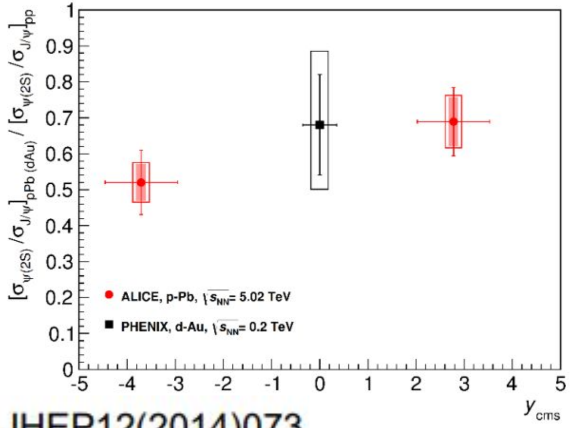
- ➔ ψ(2S) behaves differently than J/ψ
  - ψ(2S) affected more by the multiplicity (or Ncoll)
  - Trend visible across range of rapidities



PHENIX, PRL111.20, 202301

ALICE, JHEP06(2016)050

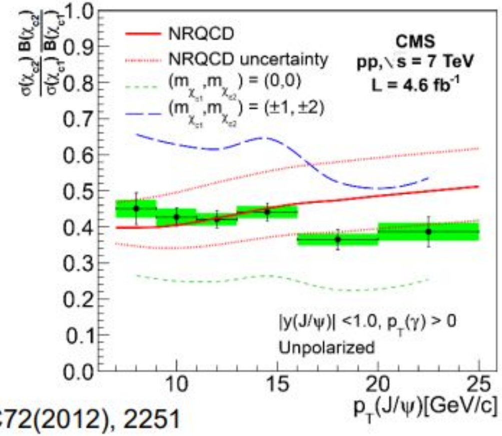




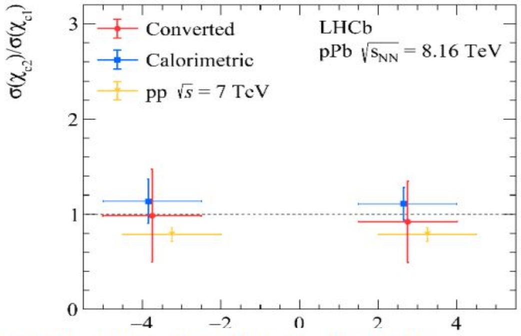
JHEP12(2014)073

Charmonium States in pPb

- ➔ Binding energy of χc between J/ψ and ψ(2S). The χcj states form an important feed-down contribution to J/Ψ production.
- ➔ Data from χc can constrain theoretical models.
- ➔ The LHCb collaboration published the first χc2, χc1 measurement in nuclear collisions at the LHC.
- ➔ Main goal is to study how is χc affected in pPb compared to pp collisions.



CMS, EPJC72(2012), 2251

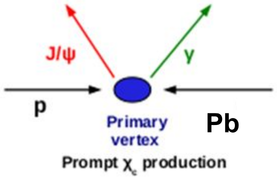


LHCb, PRC103(2021), 064905

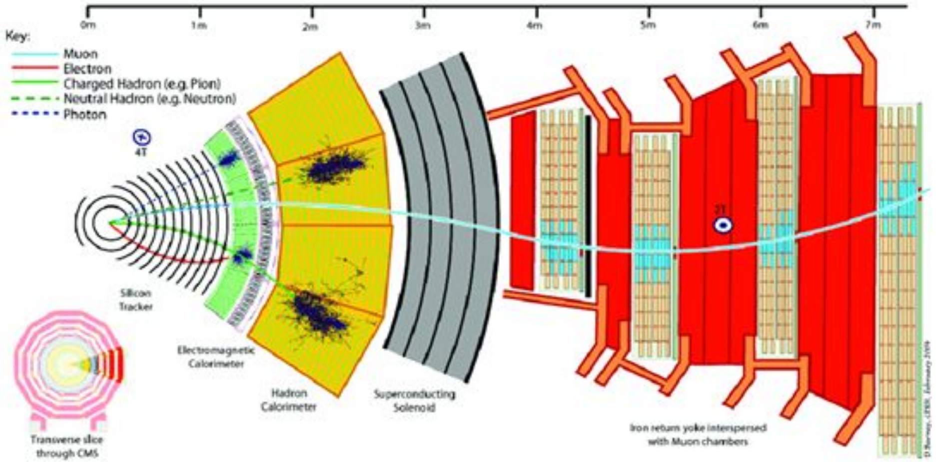
Analysis overview

$$\chi_{cJ} \rightarrow J/\psi + \gamma$$

J/ψ is reconstructed in the $\mu^+ \mu^-$ followed by the conversions of the photons into $e^+ e^-$ pairs, detected in the silicon tracker.



$$\mathcal{R} = \frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \frac{\epsilon_{\chi_{c1}}}{\epsilon_{\chi_{c2}}} \times \frac{\mathcal{B}(\chi_{c1} \rightarrow J/\psi\,\gamma)}{\mathcal{B}(\chi_{c2} \rightarrow J/\psi\,\gamma)}$$



<u>Integrated Luminosity:</u>

L = 175 / nb (2016)

Analysis dependence:

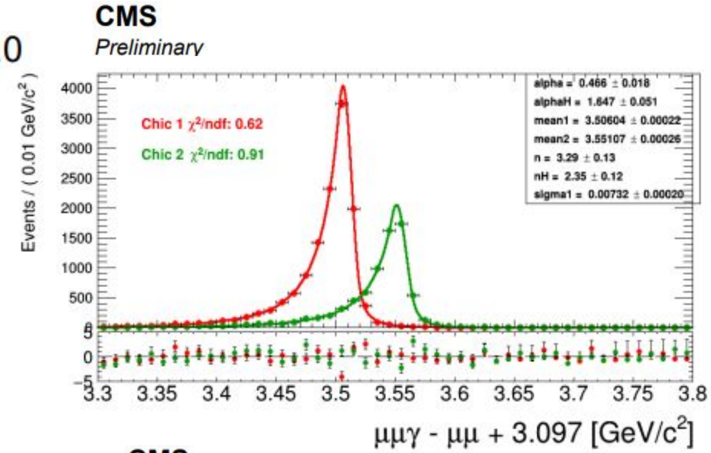
- ➔ Ntrack dependence
- ➔ Rapidity
- ➔ Transverse momentum

Signal extraction

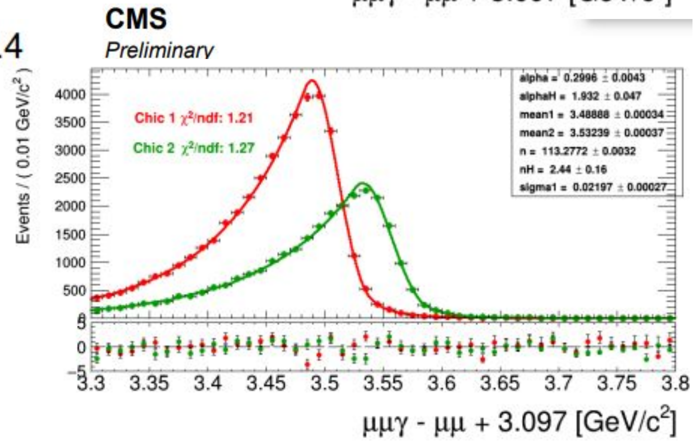
Reconstruction in Monte Carlo

- ➔ Signal: one double sided Crystal Ball function for each peak
- ➔ x_{c2} width is restricted to the x_{c1} width, based on the mass difference with respect t0 J/ψ : (x_{c2} -J/ψ) / (x_{c1} -J/ψ).
- ➔ Shape parameters set by simultaneous fit to the MC (in each bin of analysis separately)

0<y<1.0



1.6<y<2.4

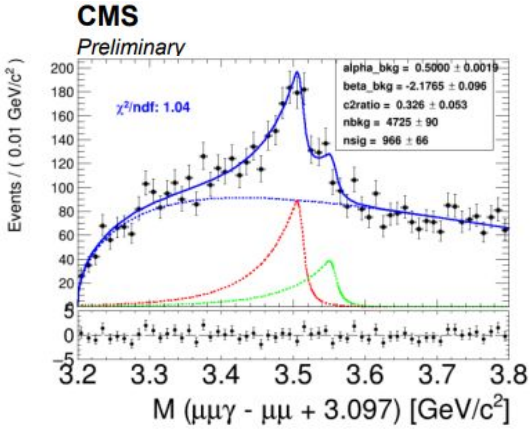


Signal extraction

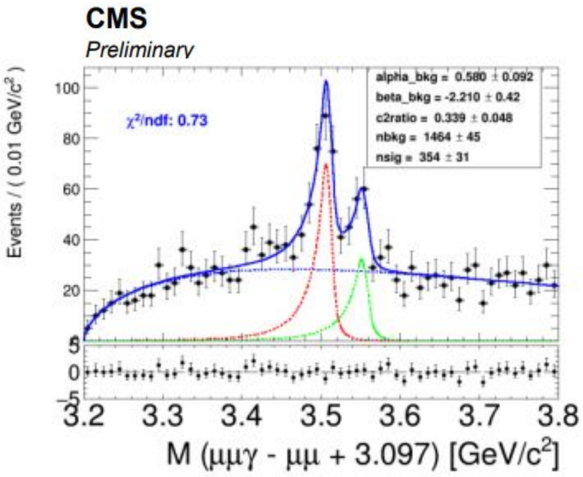
χc fitting

- ➔ **Overall fit:** DCB(χc1)+DCB(χc2)+BKG
- ➔ **Background:** “threshold function”
  - $(m - q_0)^{\alpha} \cdot e^{\beta(m - q_0)}$, q_0 = 3.2 GeV (threshold)

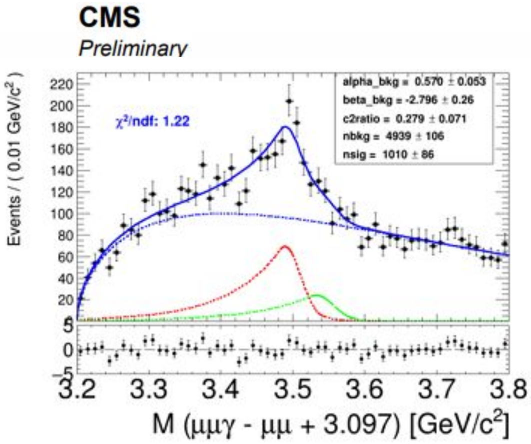
$9<p_T(J/\psi)<12$
y integrated



$0<y<1.0$
p_T integrated



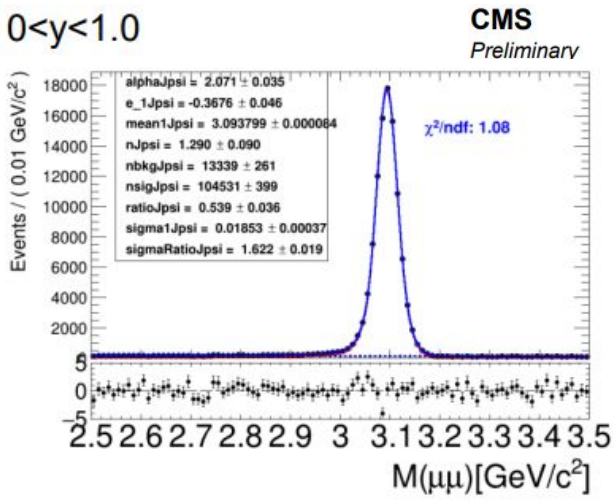
$1.6<y<2.4$
p_T integrated

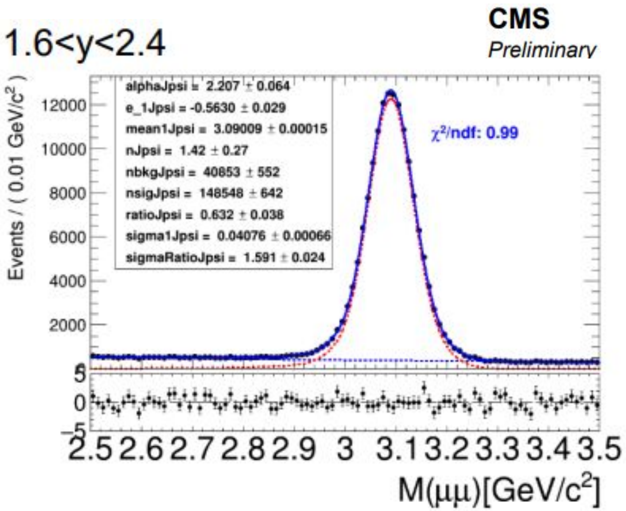


Signal extraction

J/ψ fitting

- ➔ **Signal:** two Crystal Ball functions
- ➔ **Background:** Exponential

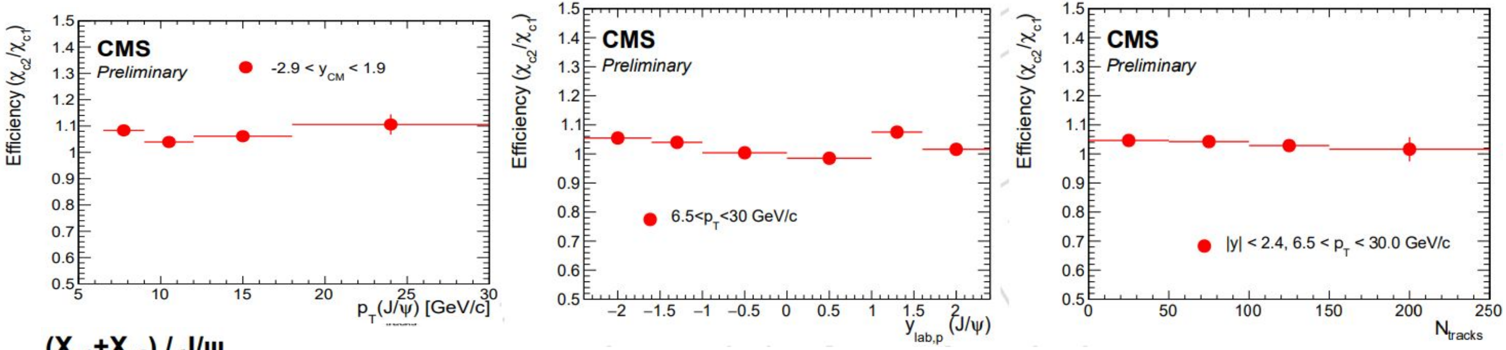




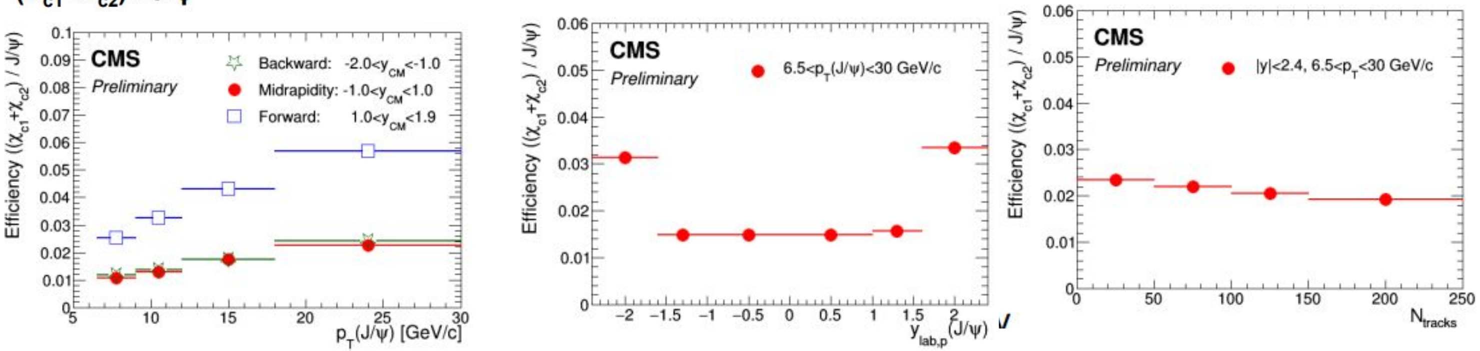
Efficiencies

➔ **Corrections calculated from MC directly for the ratios that we report**

X_{c1}/X_{c2}



$(X_{c1}+X_{c2})$ / J/ψ

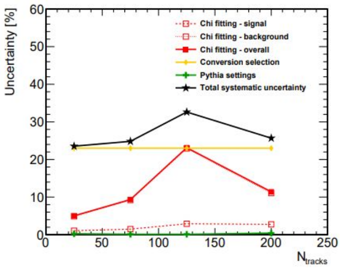


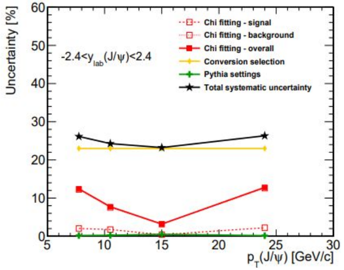
Systematic Uncertainties

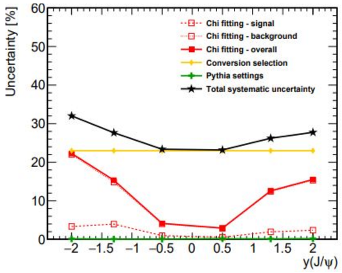
Three groups of systematics considered

- ➔ Fitting procedure
  - ◆ Signal and background models for Xc and J/ψ
- ➔ Conversion selection
- ➔ Monte carlo settings (Pythia settings)

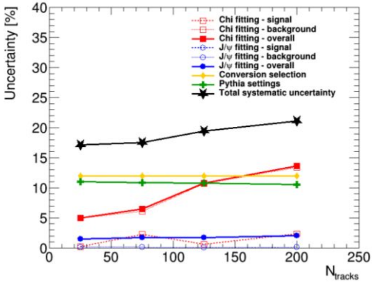
X_{c2}/X_{c1}

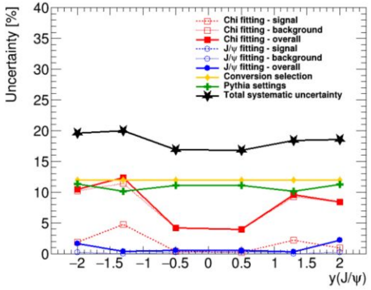


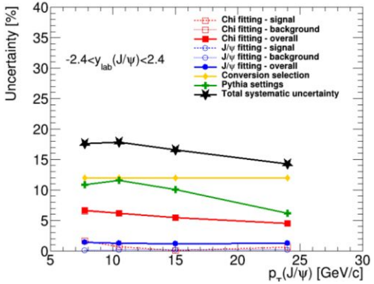




$(X_{c1}+X_{c2})$ / J/ψ



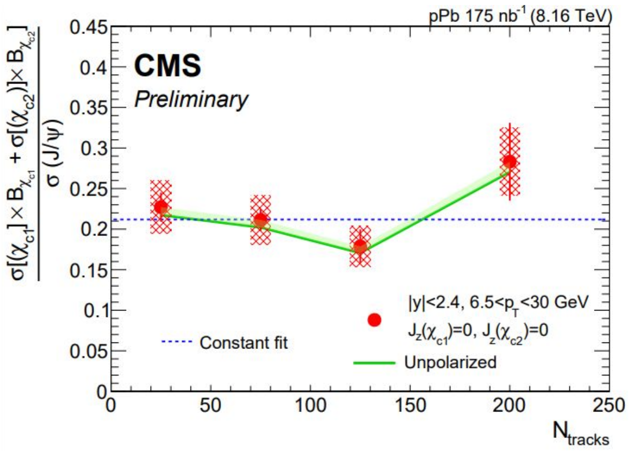


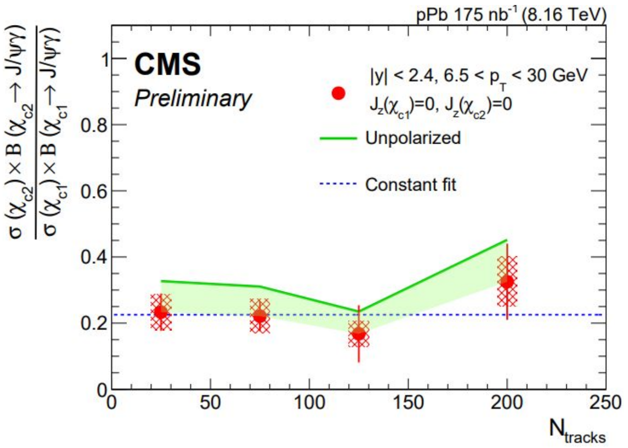


Results

Multiplicity dependence

- ➔ Xc modified vs multiplicity similarly to J/ψ, and Xc2 similarly to Xc1
- ➔ Different from what is seen for ψ(2S) (yield vs Ncoll decreases quicker than yield of J/ψ)





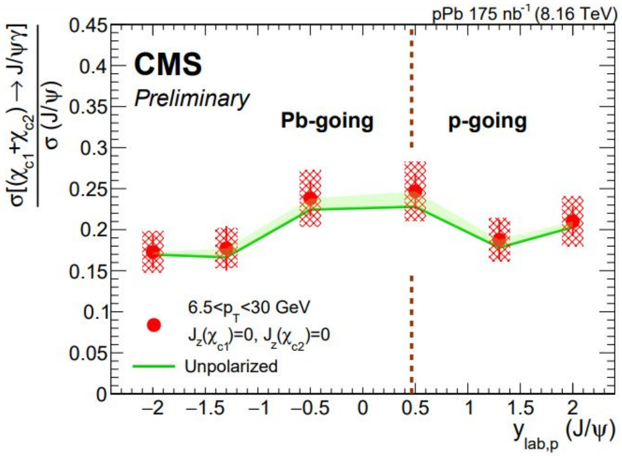
Results

Rapidity dependence

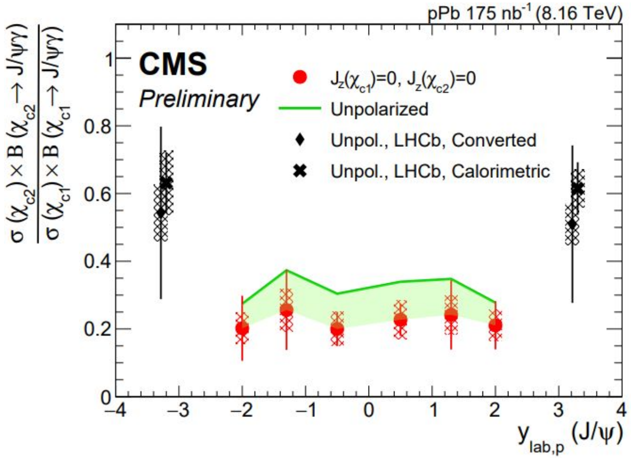
➔ Ratios flat: Xc modified vs rapidity similarly to J/ψ, and Xc2 similarly to Xc1

- Xc2/Xc1 consistent with previous LHCb pPb measurement (wider rapidity)

$(X_{c1}+X_{c2})$ / J/ψ



X_{c2}/X_{c1}

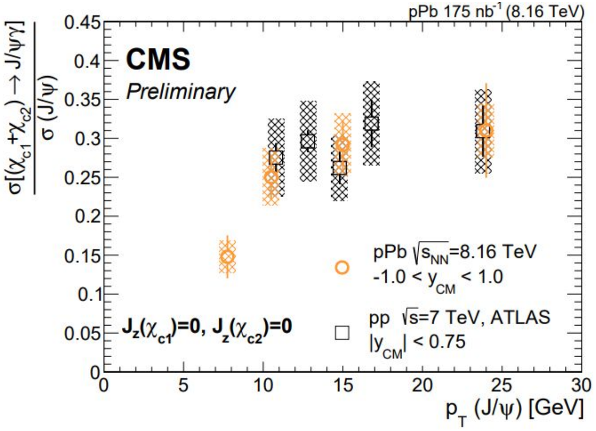


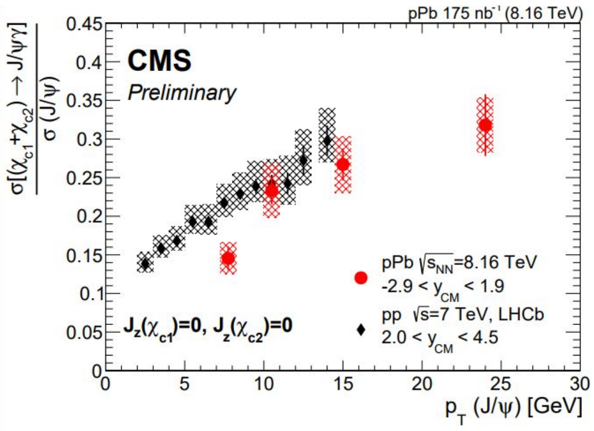
Results

Transverse Momentum dependence

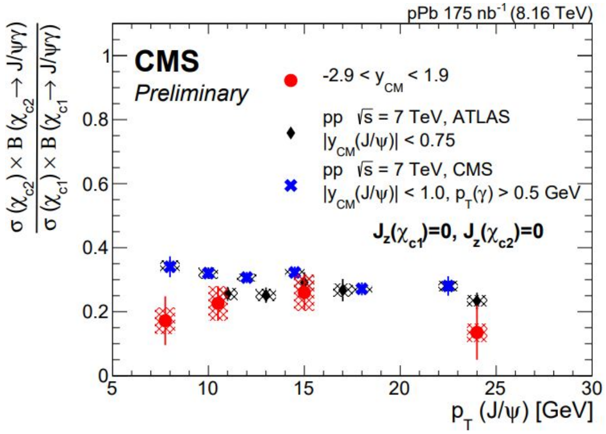
- ➔ Xc / J/ψ ratio increases with pT (J/ψ) and consistent with pp results
  - ◆ We see no evidence of any rapidity-based trend
- ➔ Results consistent with no relative suppression of Xc compared to J/ψ in pPb
- ➔ Suggests weaker dissociation effects in Xc compared to ψ(2S)
- ➔ Xc2/Xc1 flat and consistent with previous pp measurements (midrapidity, 7TeV)

$(X_{c1}+X_{c2})$ / J/ψ





X_{c2}/X_{c1}



Summary

- **We measure (Xc1+Xc2) / J/ψ and Xc2 / Xc1 in pPb 8.16 TeV**

- **Xc2 / Xc1**
  - Flat vs rapidity, Ntracks, pT
  - Same magnitude when compared to existing pp and pPb measurements
  - Consistent with no relative suppression/enhancement between the Xc states

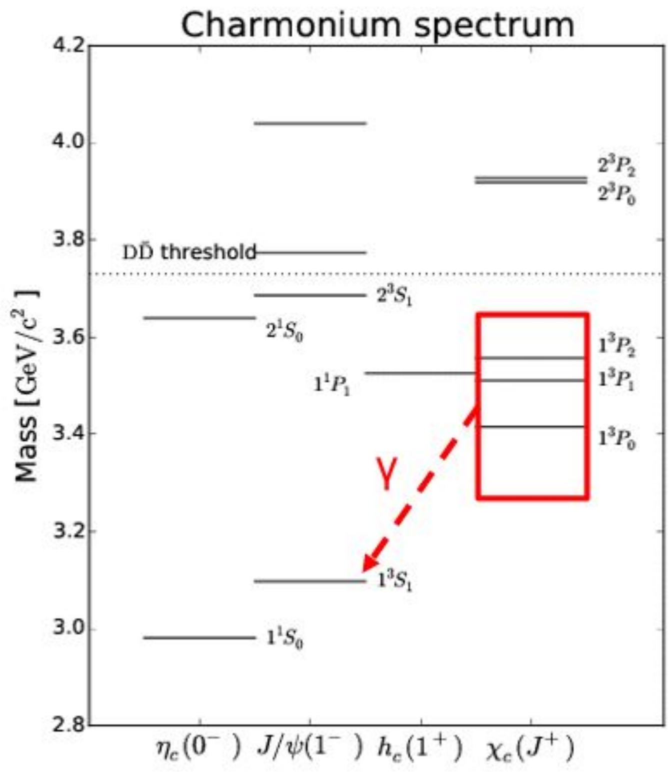
- **(Xc1+Xc2) / J/ψ**
  - Flat vs rapidity, Ntracks, but increasing with pT
  - Consistent with existing pp measurements (not exactly same comparisons)
  - Suggest no additional suppression in pPb when compared to J/ψ
    - Different from the existing pPb/dAu ψ(2S) results

Thanks for listening!

Backup

χc charmonium P-states

- ➔ (χc0(1P): m = 3415 MeV)
- ➔ χc1(1P): m = 3511 MeV
- ➔ χc2(1P): m = 3556 MeV
- ➔ Reconstructed via χc → J/ψ+γ → μ+μ- + e+e-
  - BR (χc → J/ψ+γ): 1.4%, 34%, 19%
  - χc0 too small, χc1 biggest peak, χc2 smaller



Selection

Data:

- 2016 pPb at 8.16 TeV
- Data set: /PADoubleMuon/PARun2016C-PromptReco-v1/AOD
- Trigger: HLT_PAL1DoubleMuOpen_v1
- Luminosity: 63nb-1 (pPb), 112nb-1 (Pbp)

Muon:

- Selection:
  - Soft ID
  - Trigger (HLT_PAL1DoubleMuOpen_v1)

J/ψ:

- Opposite sign muons
- Common vertex probability > 1%
- Removing non-prompt J/ψ: (cτ)/σ(cτ)<3
- |y|<2.4, 6.5<pT<30 GeV
  - Defines our fiducial region, not corrected for anywhere in the analysis
- To be considered candidate for χc: 2.9 < minv(J/ψ)<3.25 GeV

Conversion:

- Acceptance
  - |y|<2.4, pT>0.5 GeV

MC:

- Official MC samples, pPb/Pbp direction
  - Pythia for the initial hard scattering, EVTGEN for χc decays, PHOTOS for final state radiation
  - EPOS underlying event, CMS response: Geant4
- Weighted to match data
  - pPb/Pbp luminosity
  - Ntrack distribution (associated with the dimuon PV, to account for pile-up)
  - pT distribution

Efficiencies

Efficiency for ratio of Xc states

Efficiency is the number of reconstructed events after the full selection divided by the number of generated decays in the fiducial region of the analysis specified by the kinematic window.

$$\epsilon_c(p_T(J/\psi)) = \frac{N^{rec}_{\chi_c}(p_T(J/\psi))}{N^{gen}_{\chi_c}(p_T(J/\psi))|_{J/\psi\ reconstructed}}$$

$$\frac{\epsilon_{c1}}{\epsilon_{c2}} = \frac{N^{rec}_{\chi_{c1}} / N^{gen}_{\chi_{c1}}}{N^{rec}_{\chi_{c2}} / N^{gen}_{\chi_{c2}}}$$

Efficiency for Xc to J/ψ ratio

The correction is then the ratio of the probability that we reconstruct the Xc over the probability that we reconstructed J/ψ . Individual muon and J/ψ efficiencies and acceptances cancel out in this ratio, because they are present both in the numerator and in the denominator. The only remaining parts are ɣ acceptance and selection, and xc selection.

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

Analysis bins

Ntrack dependence

- ➔ Number of tracks in PV associated with dimuon
- ➔ (0, 50, 100, 150, 250)

Rapidity:

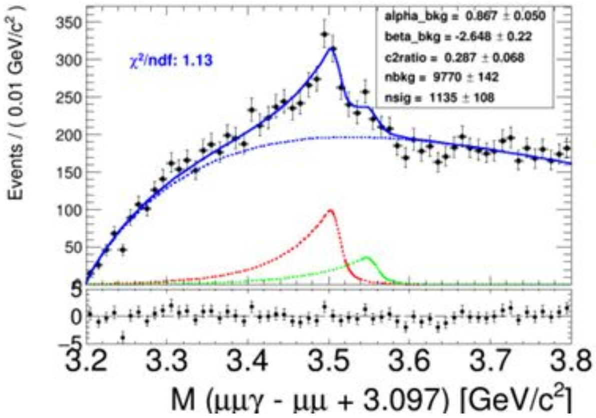
- ➔ p-going direction always positive (flip rapidity sign for Pbp session)
- ➔ (-2.4, -1.6, -1.0, 0, 1.0, 1.6, 2.4) (lab frame)

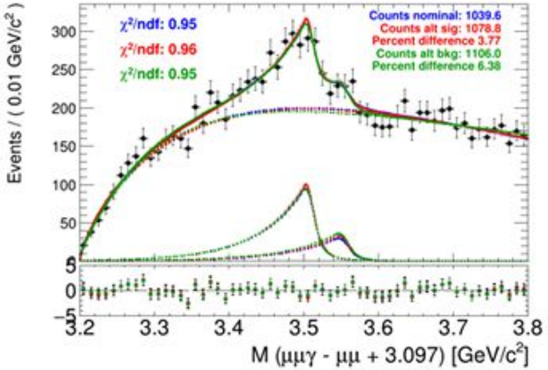
Transverse momentum:

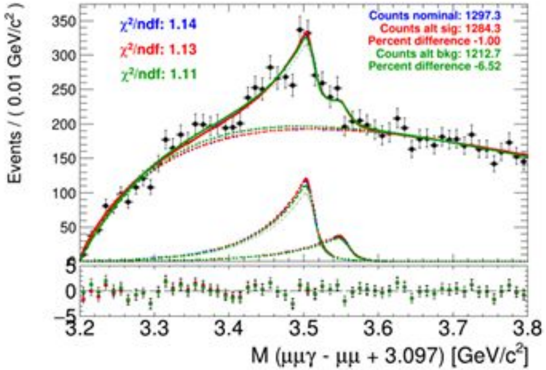
- ➔ (6.5, 9, 12, 18, 30) GeV Rapidity integrated
- ➔ Divided in 3 rapidity ranges in yCM(J/ψ), done for (Xc1+Xc2) / J/ψ only (Not enough stat. for Xc2/Xc1)
    - (-2, -1, 1, 2) (center-of-mass rapidity – offset by 0.465 from lab rapidity)

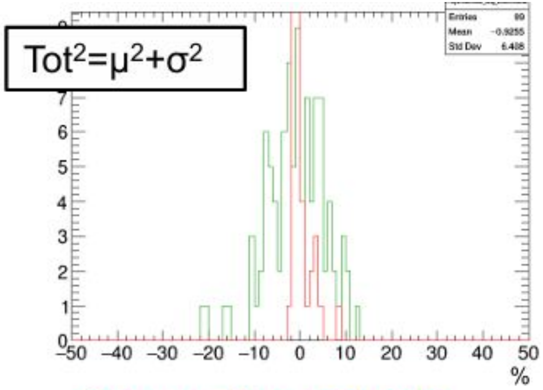
Systematics: Fitting procedure

- ➔ 100 toy data (each bin), uncertainty bin by bin
- ➔ Right: Nominal fit
- ➔ Below: 2 example toys + output
  - ◆ Grey: generating curve (original nominal fit)
  - ◆ Points: pseudodata (toys)
  - ◆ Blue: Fit with nominal settings (DCB constrained + threshold)
  - ◆ Red: Alternative signal (Hypatia constrained + threshold)
  - ◆ Green: Alternative background (DCB constrained + D0BG)









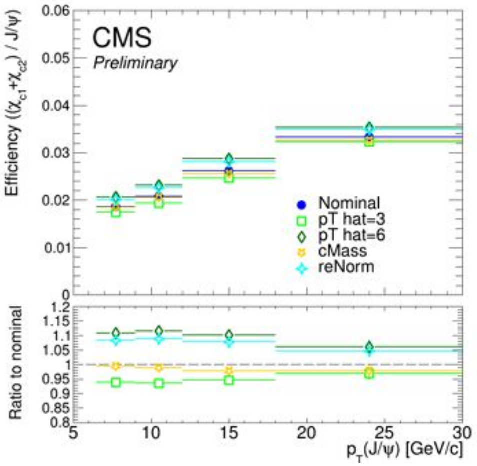
Green – bkg, red - sig

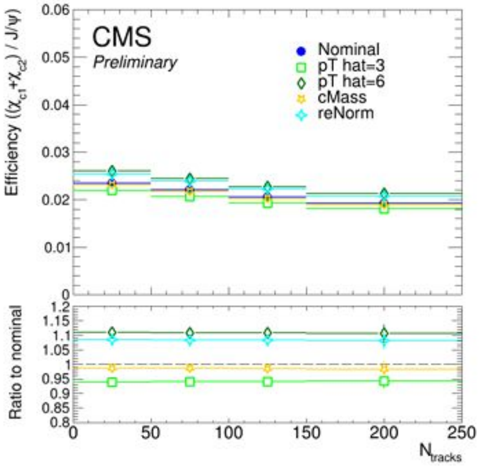
Systematics: MC settings

- ➔ MC distributions primarily affect the photon acceptance and kinematic distributions
  - ◆ We correct for it, but the correction depends fully on MC

- ➔ Approach: Vary the parameters of Pythia simulation
  - ◆ pThat, c mass, renormalization and factorization
  - ◆ Using small private MC sample derived from the official MC (gen only, changes in distributions explored in official MC)
  - ◆ Sample reweighted to match the data pT distribution

- ➔ Relevant for (Xc1+Xc2) / J/ψ
- ➔ Negligible for Xc2/Xc1





Conversions - systematics

- ➔ Trying to assign systematic uncertainty related to conversions
- ➔ Done by changing the selection
- ➔ Redo whole analysis with the new selection
  - ◆ Including the signal shape constraints (turns out it is needed)

Medium:
Quality_isGeneralTracksOnly = true
conv_compatibleInnerHitsOK = true
conv_vertexChi2Prob > 0.0005
tk1NumOfDOF > 3
tk2NumOfDOF > 3
conv_minDistanceOfApproach >-10
|conv_dzToClosestPriVtx| < 10

Loose:
Quality_isGeneralTracksOnly = true
conv_compatibleInnerHitsOK = true
conv_minDistanceOfApproach >-10
|conv_dzToClosestPriVtx| < 10

Very loose:
Quality_isGeneralTracksOnly = true