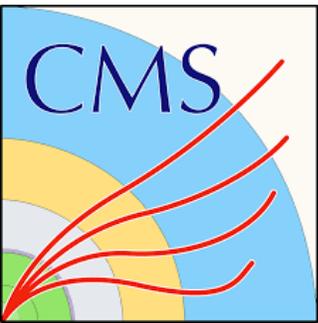


# Measurement of $\chi_c$ production in pPb collisions at $\sqrt{s_{NN}} = 8.16 \text{ TeV}$

Jeongho Kim (Sejong University)

On behalf of the CMS collaborations



# Presentation Outline

## **Motivation and Overview**

## **Analysis Details**

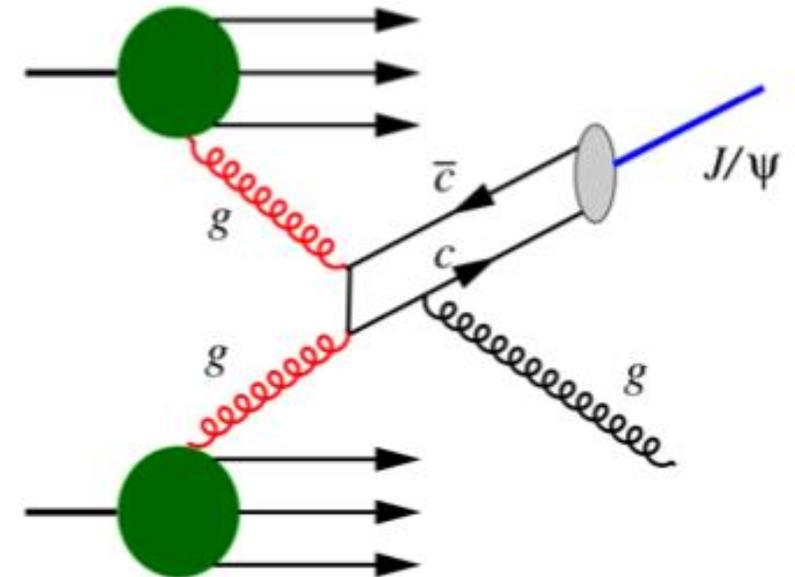
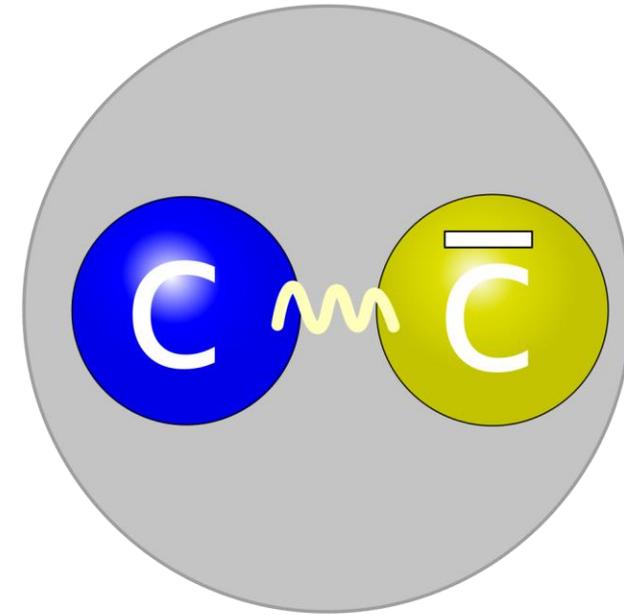
- Signal Extraction
- Efficiencies
- Polarization
- Results

## **Summary**

# Analysis Motivation

**Main goal: To study how is  $\chi_c$  ( $c\bar{c}$  P-states) affected in pPb compared to pp collisions.**

**Quarkonia production process:** Typically initiated by gluon fusion  
-> Sensitive to a modification of the parton distribution functions (PDF).

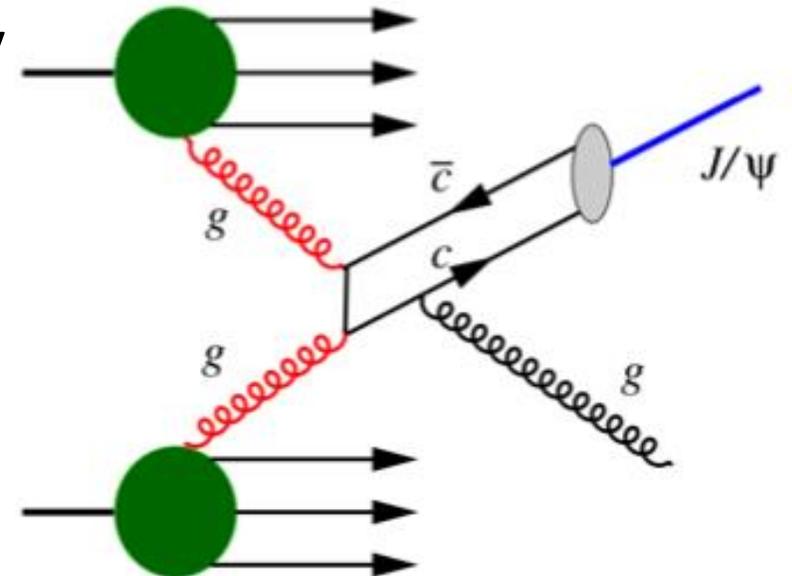
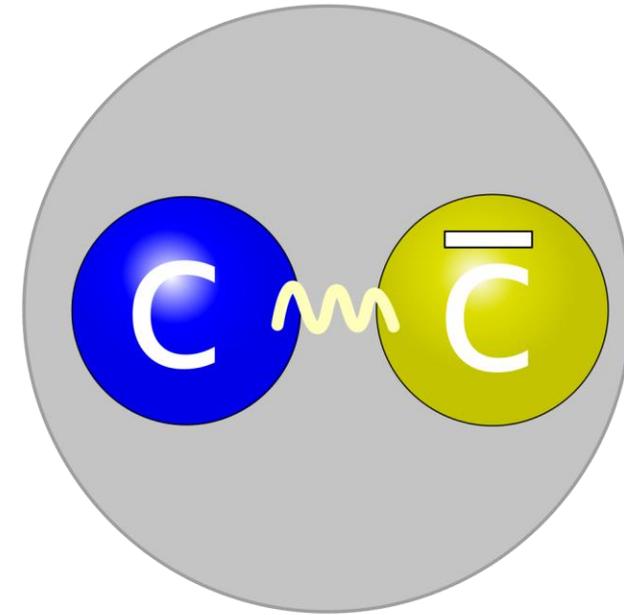


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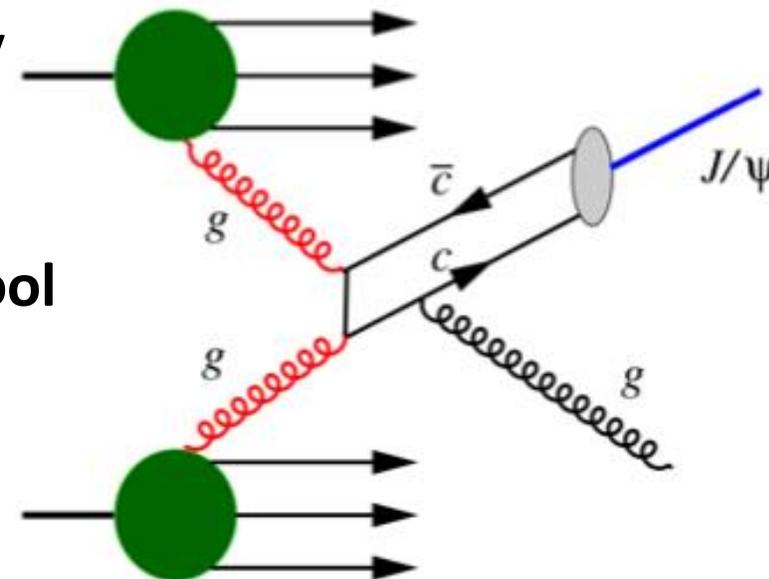
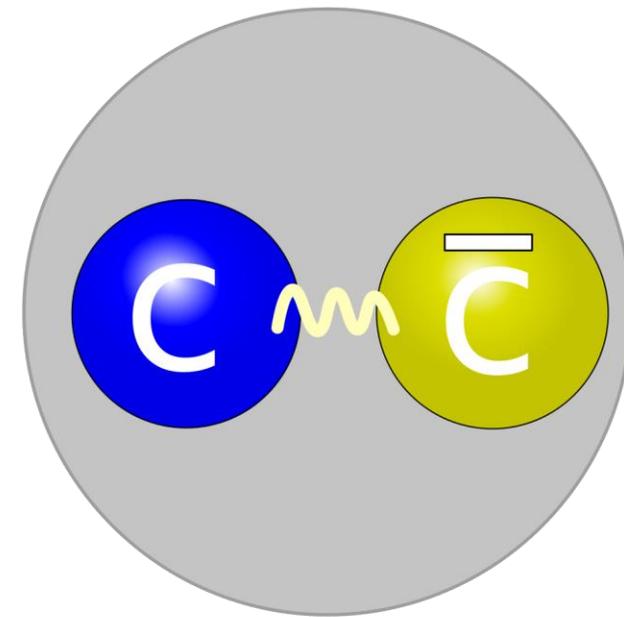
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In addition, Heavy quarkonia are also subject to coherent energy loss while traversing the nucleus (**Cold nuclear matter effect**)

**Measurements in proton-nucleus collisions could be a useful tool to understand modifications of quarkonia states in nucleus-nucleus collisions.**



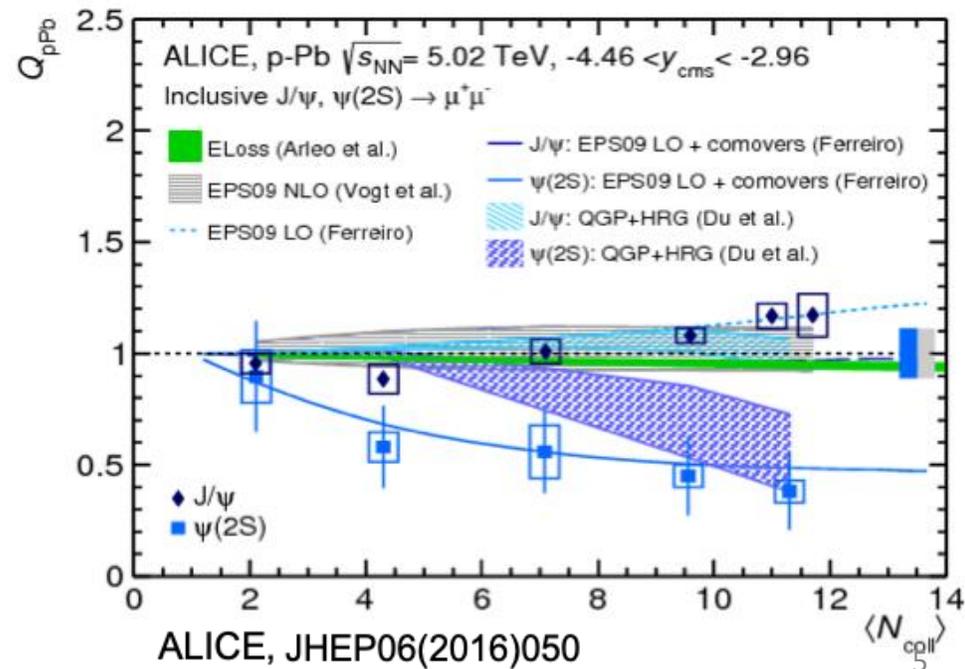
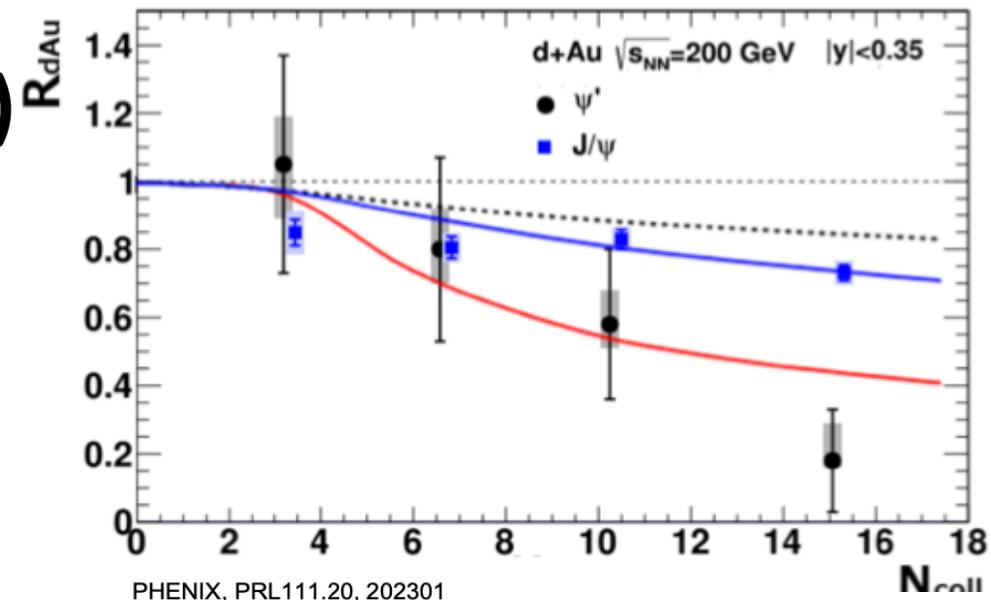
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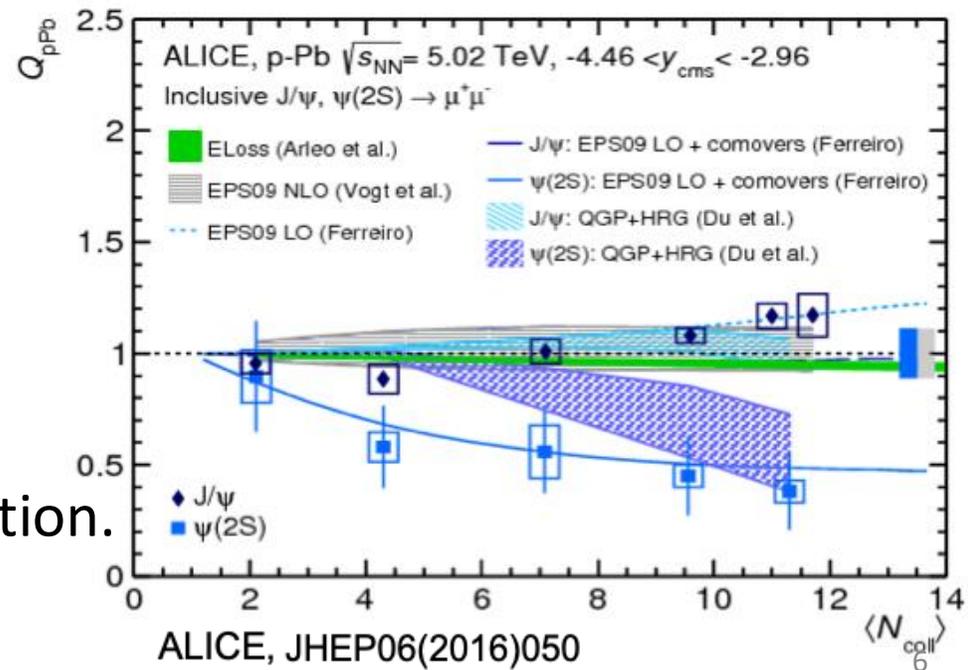
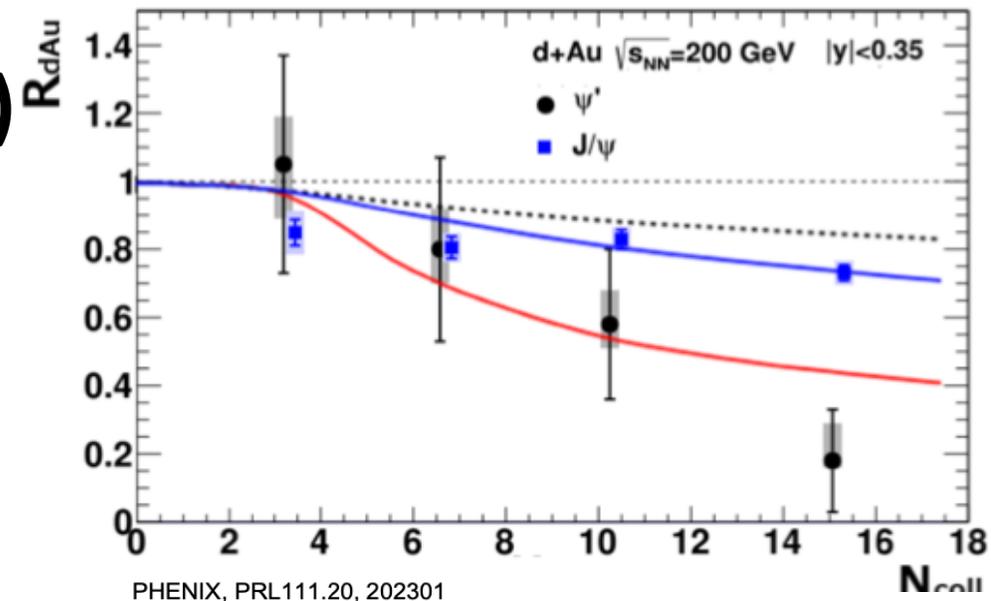
Previous measurement are done mostly in S-states.

The  $\psi(2S)$  Study have shown that excited state has a different suppression.

**(Which is not explain only by Initial-state effect)**

This relative suppression is increased by multiplicity (or related variables).

With various observable (other charmonium family),  
We can understand more detail about charmonium production.

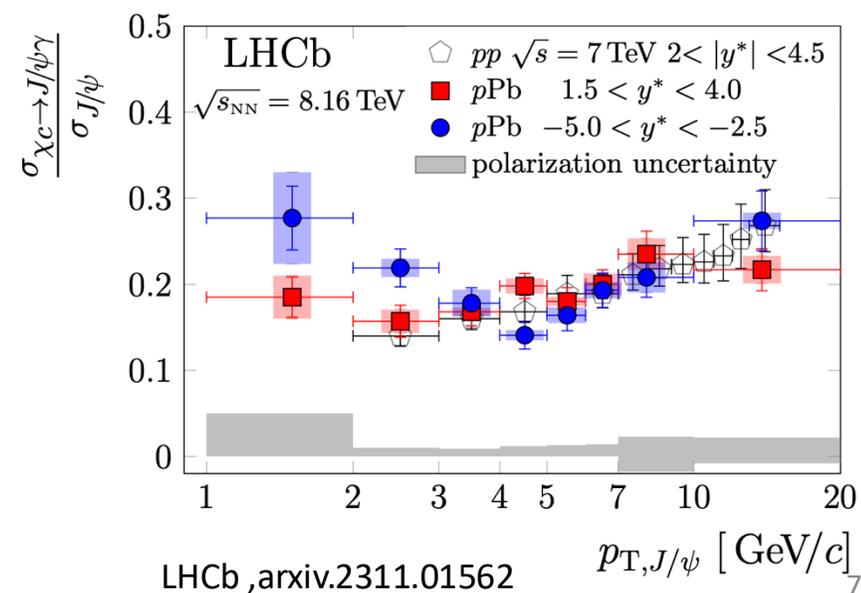
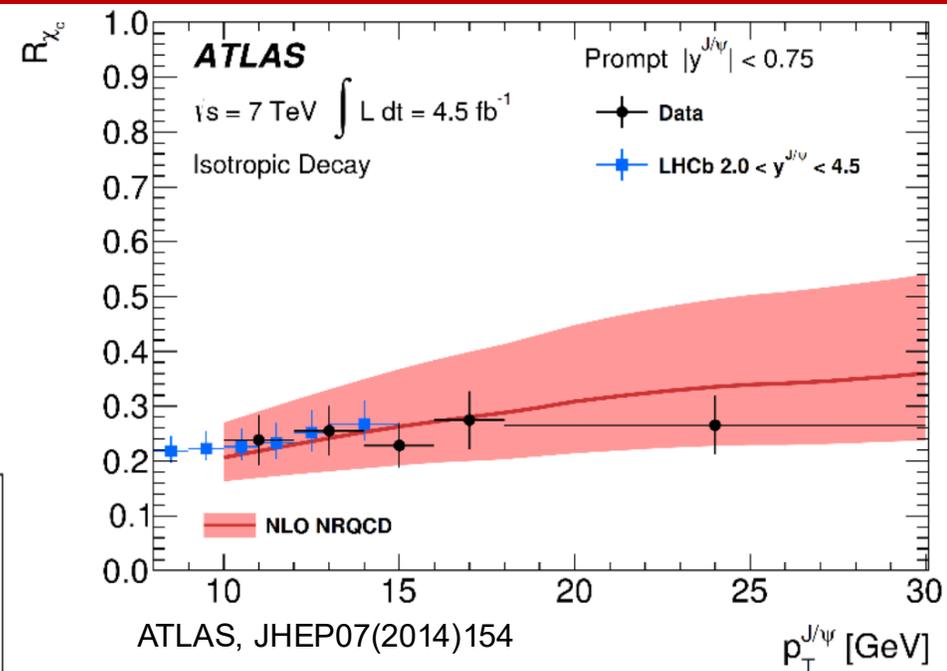
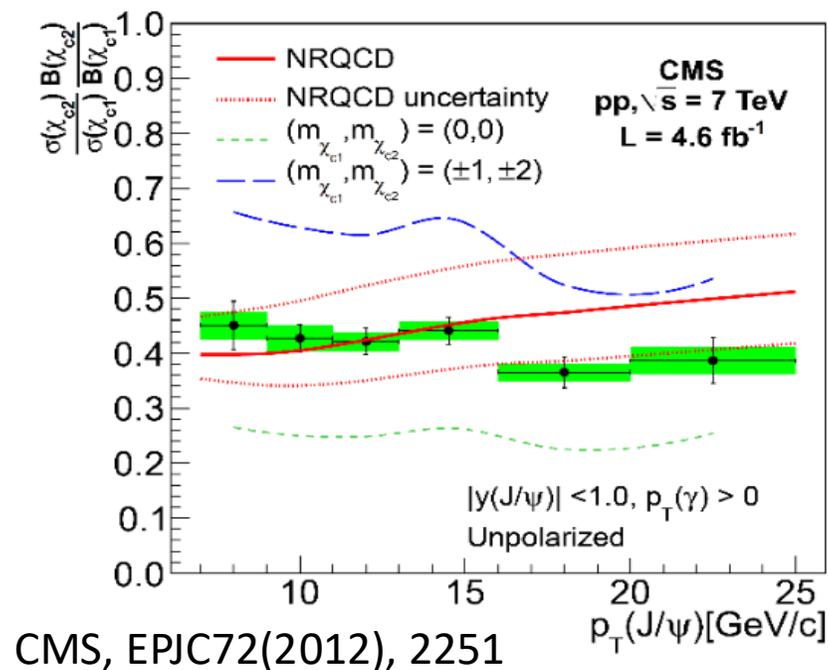


# Analysis Motivation

**Main goal: To study how is  $\chi_c$  ( $c\bar{c}$  P-states) affected in pPb compared to pp collisions.**

**pPb :  $\chi_{c2}/\chi_{c1}$  (LHCb)  
 $\chi_c / J/\psi$  (LHCb)**

**pp :  
 $\chi_{c2}/\chi_{c1}$   
(CMS, ATLAS, LHCb)  
 $\chi_c / J/\psi$   
(ATLAS, LHCb)**



# Analysis Overview

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

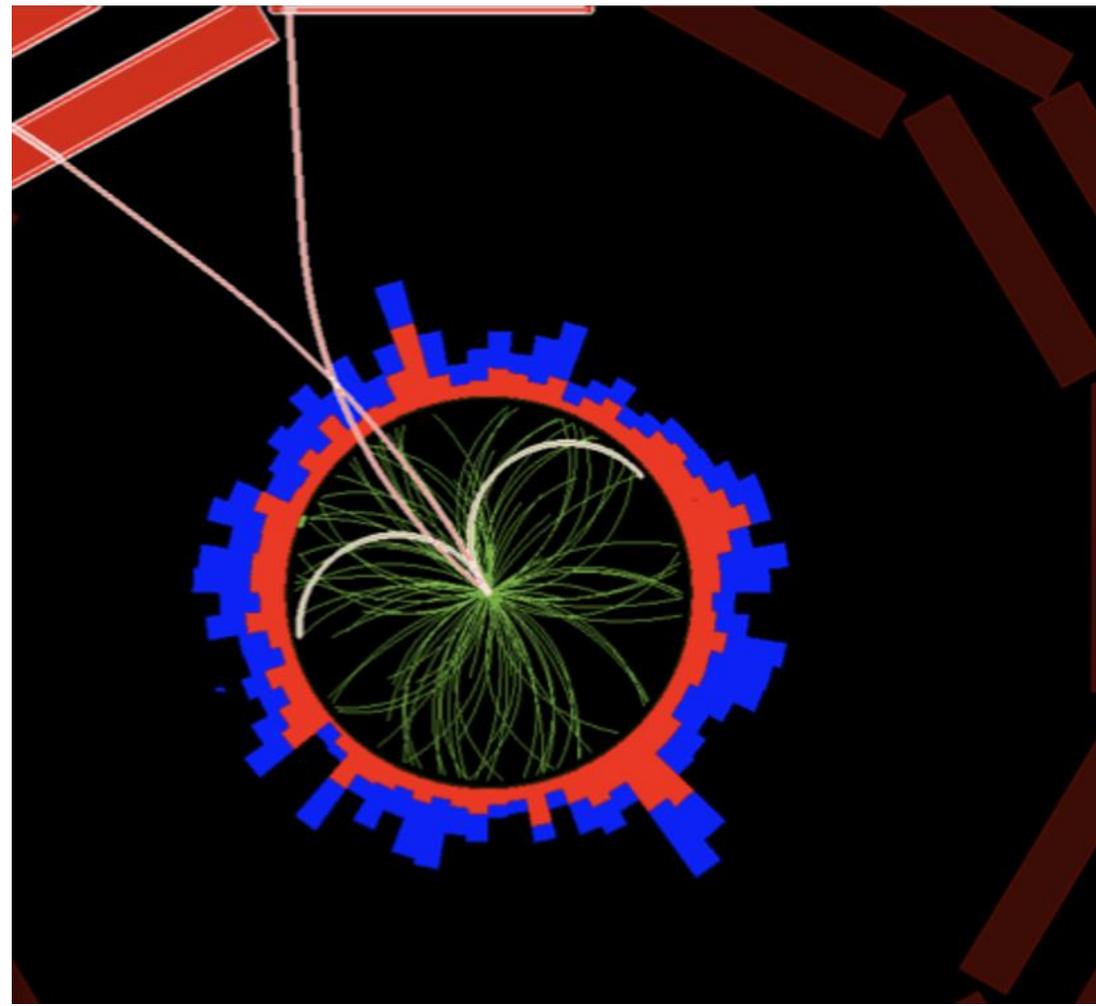
pPb 8.16 TeV

Reporting  $\chi_c / J/\psi$  and  $\chi_{c2} / \chi_{c1}$

$$\frac{[\sigma(\chi_{c1}) \times \mathcal{B}(\chi_{c1} \rightarrow J/\psi\gamma)] + [\sigma(\chi_{c2})\mathcal{B}(\chi_{c1} \rightarrow J/\psi\gamma)]}{\sigma(J/\psi)}$$

$$\frac{\sigma(\chi_{c1}) \times \mathcal{B}(\chi_{c1} \rightarrow J/\psi\gamma)}{\sigma(\chi_{c2})\mathcal{B}(\chi_{c1} \rightarrow J/\psi\gamma)}$$

\* Note that  $\mathcal{B}(J/\psi \rightarrow \mu^+ \mu^-)$  is canceled out



# Signal Extraction

## Motivation and Overview

## Analysis Details

- **Signal Extraction**
- Efficiencies
- Polarization
- Results

## Summary

# Analysis Bins

## $N_{\text{trk}}$ Dependence

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

## Rapidity

- p-going direction always positive (flip rapidity 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  $y_{CM}(J/\psi)$ , only for  $\chi_c / J/\psi$  due to low statistics for  $\chi_{c2} / \chi_{c1}$ 
    - (-2, -1, 1, 2) Center of mass rapidity

# Analysis Bins

**Note : Kinematic variables of  $\chi_c$  is expressed in values of J/ $\psi$  daughter**

- It makes ratio of  $\chi_c / J/\psi$  well defined, (this definition used in past)
- Photon doesn't change the kinematic that much

## **N<sub>trk</sub> Dependence**

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- (0, 50, 100, 150, 250)

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- p-going direction always positive (flip rapidity for Pbp session)
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# J/ψ Fitting

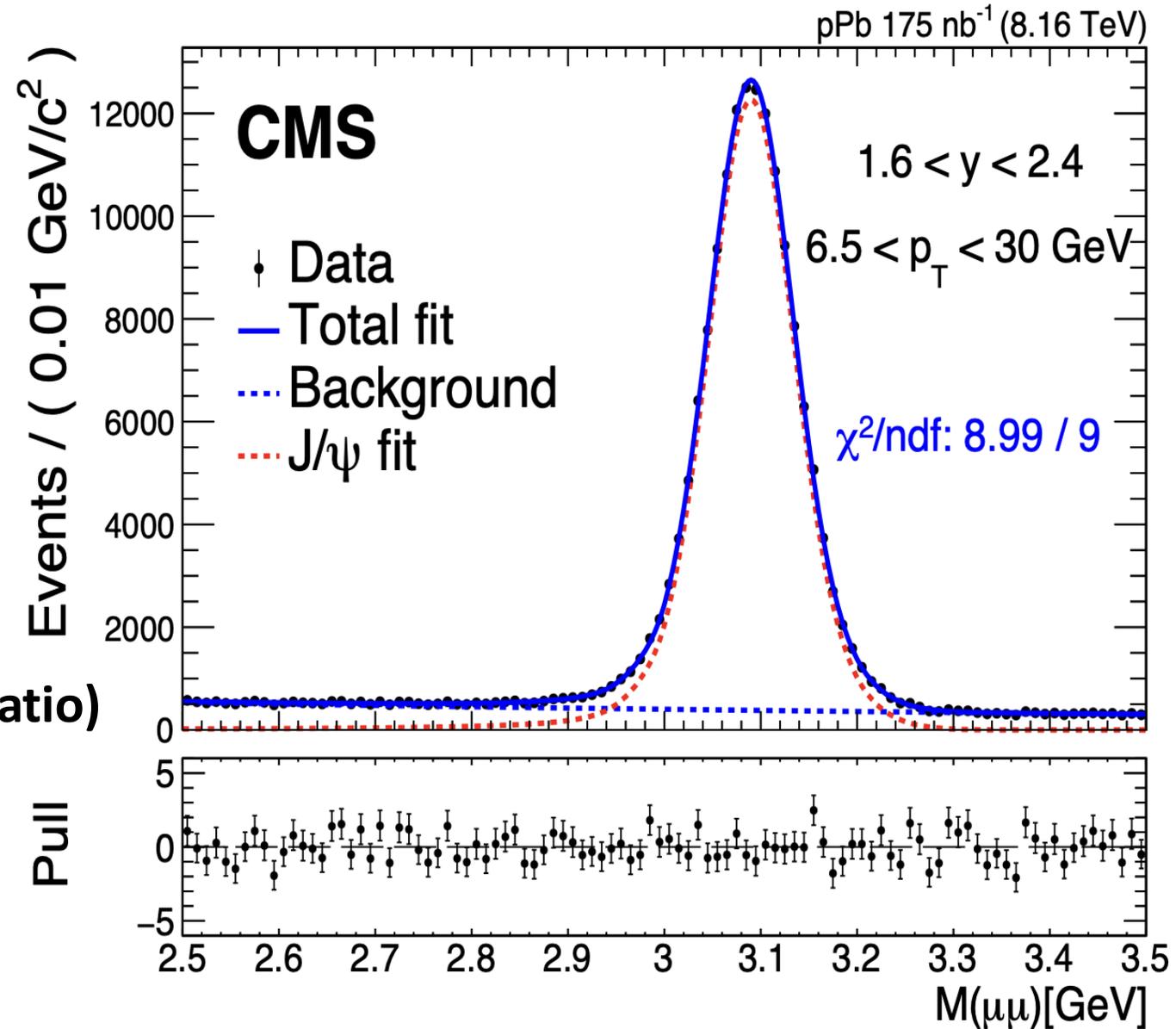
## Signal : Crystal Ball function

- Gaussian core to describe the detector resolution
- one -sided tail to model the energy loss by the decay muons via final-state photon radiation.

## Background : Exponential

Relatively straightforward (very good S/B ratio)

$$CB(m; \mu, \sigma, \alpha, n) = \begin{cases} e^{-0.5 t^2} & \text{if } t > -\alpha \\ e^{-0.5 \alpha^2 \left[ \frac{n}{\alpha} \left( \frac{n}{\alpha} - \alpha - t \right) \right]^{-n}} & \text{if } t < -\alpha \end{cases}$$



## Using MC to constrain the shape

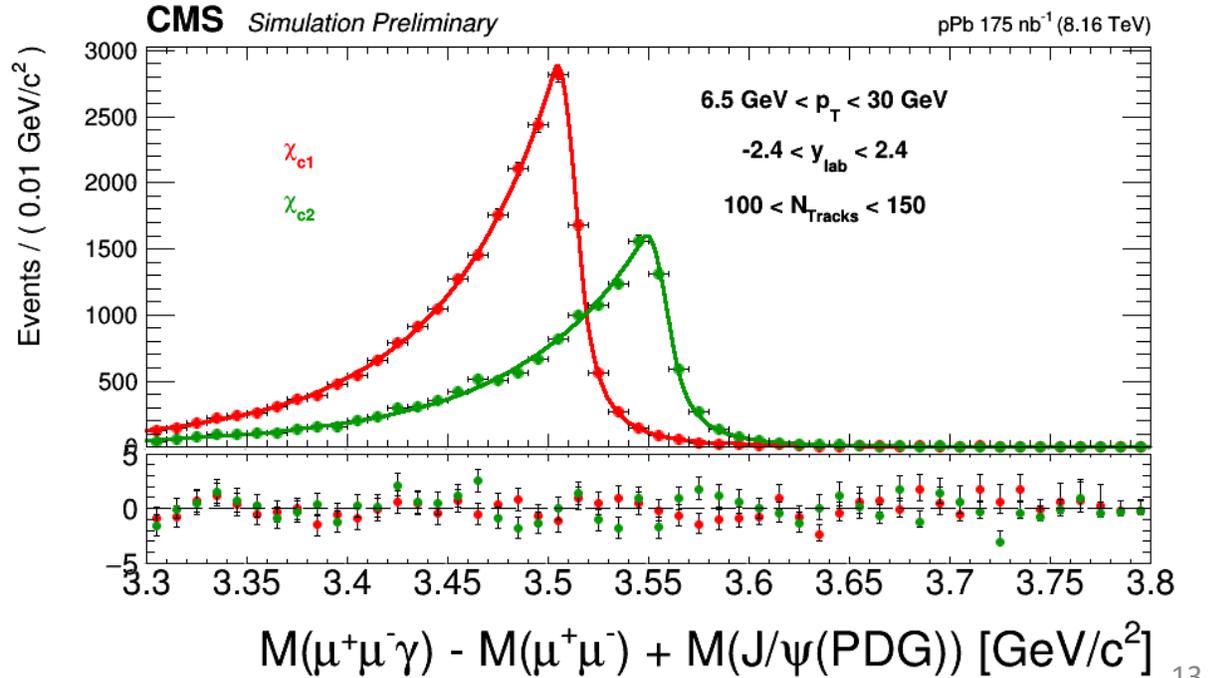
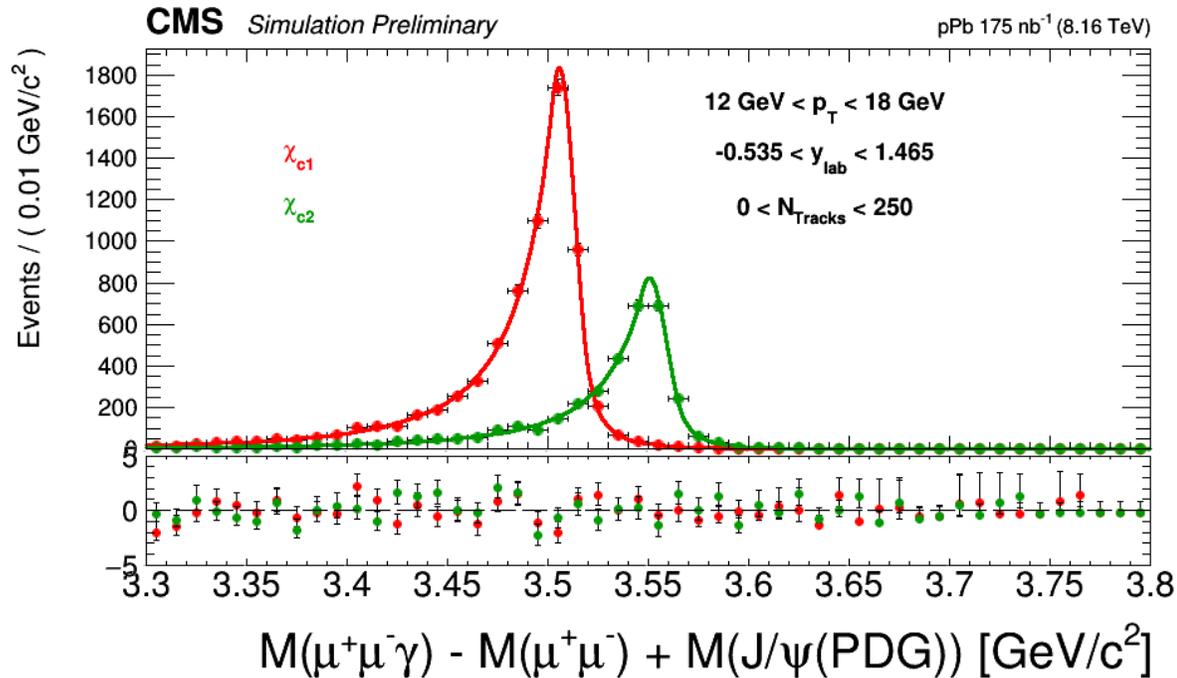
- Due to low particle yields

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

$t = (m - \mu) / \sigma$

## Signal : Double side Crystal Ball function for each peak

- Crystal Ball function with one tail at low-mass end and one at high-mass end
- Inspired by previous  $\chi$  analysis
- Shape parameters set by simultaneous fit to the MC



# $\chi_c$ Fitting

## Background : threshold function

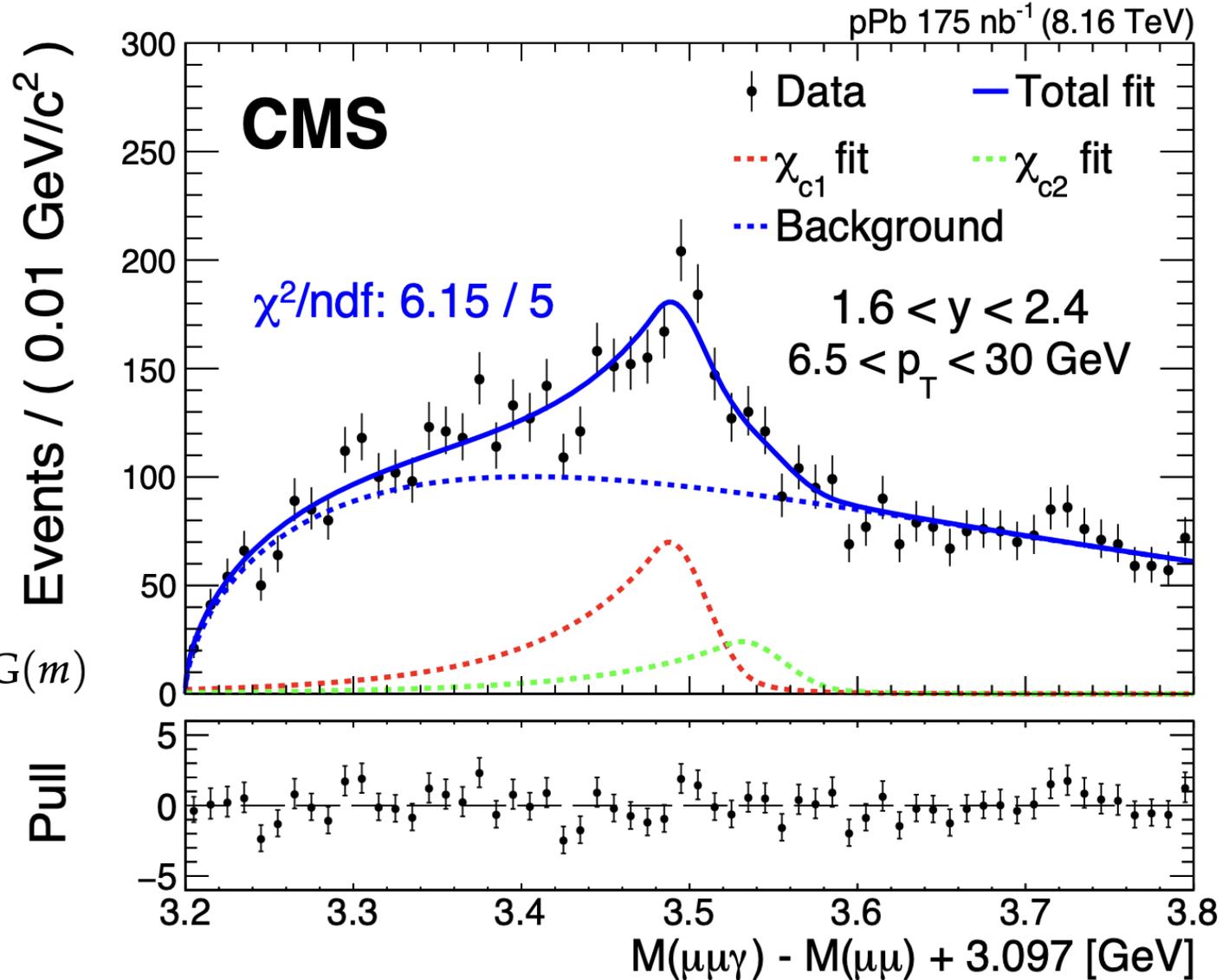
- Used previous analysis

$$\text{BKG}(m) = (m - q_0)^{\alpha_1} \cdot e^{(m - q_0) \cdot \beta_1}$$

$q_0$  is fixed to 3.2 GeV

## Overall Fit

$$N_{\chi_{c1}} \cdot \text{DCB}_{\phi_{c1}}(m) + N_{\chi_{c2}} \cdot \text{DCB}_{\phi_{c2}}(m) + N_{\text{bkg}} \cdot \text{BKG}(m)$$



## Motivation and Overview

## Analysis Details

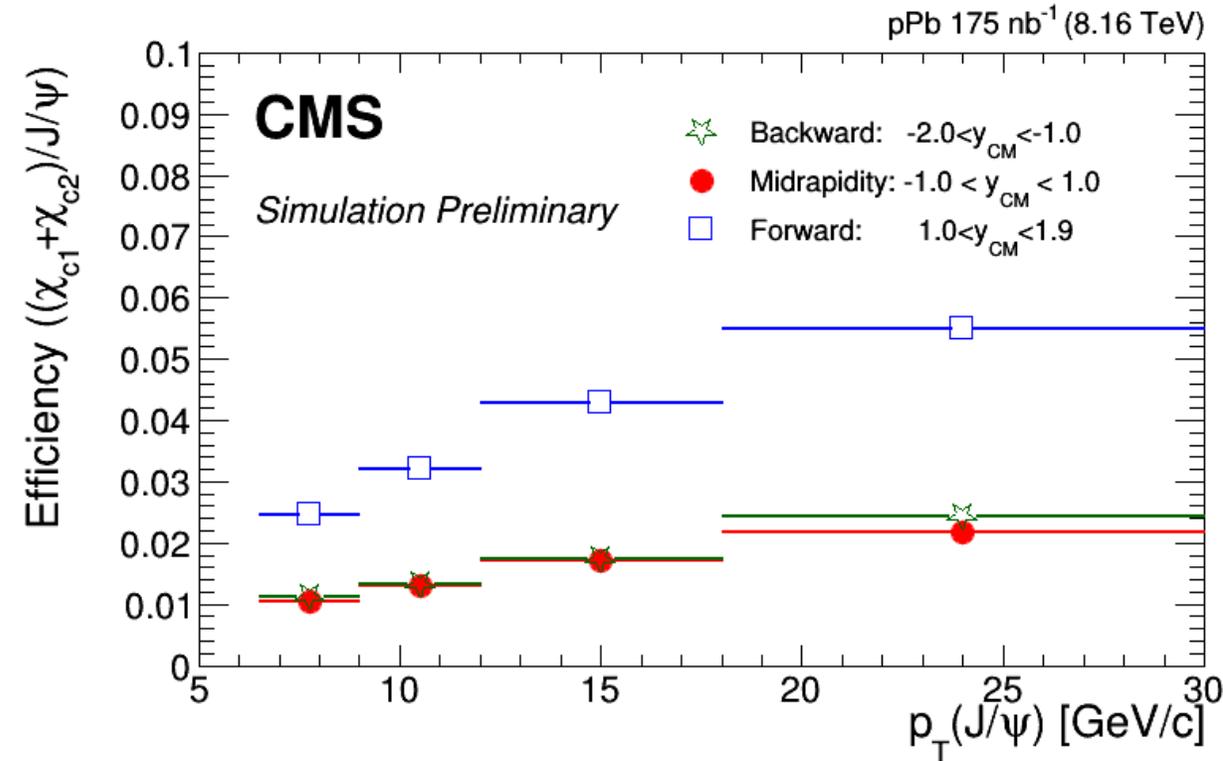
- Signal Extraction
- **Efficiencies**
- Polarization
- Results

## Summary

## Efficiency of $\chi_c$ to $J/\psi$

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

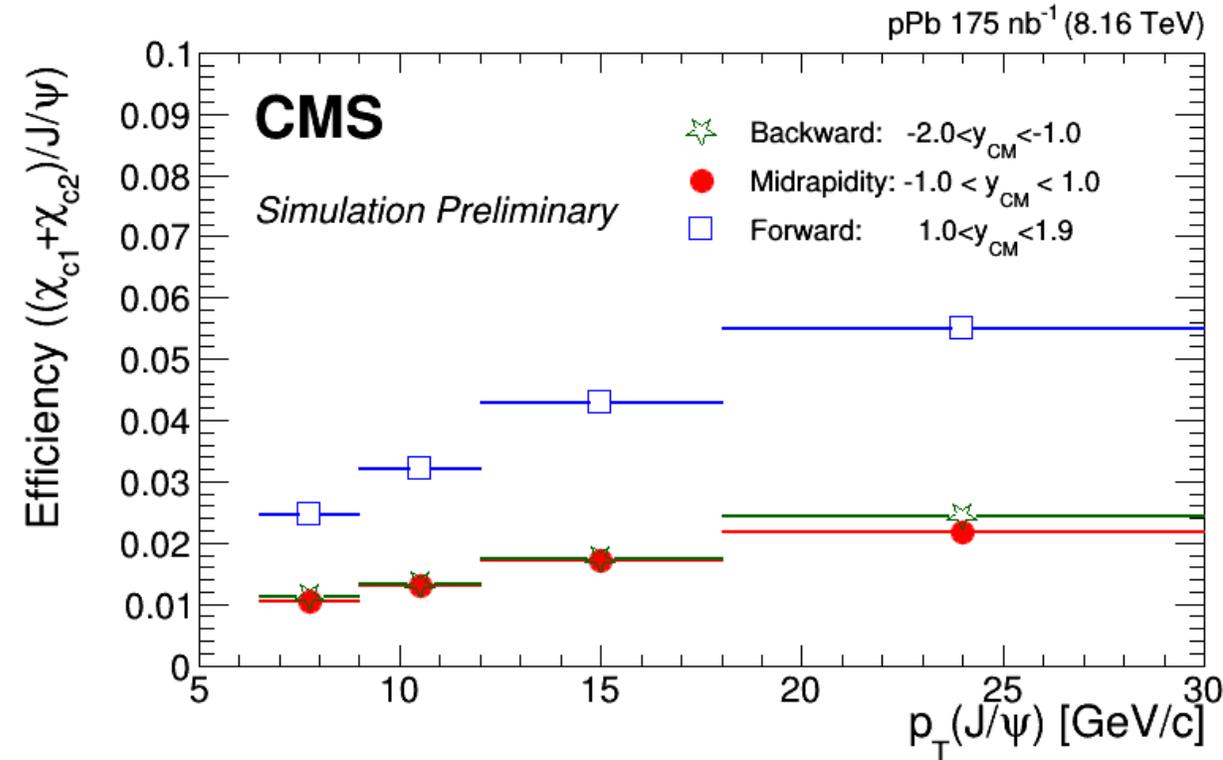
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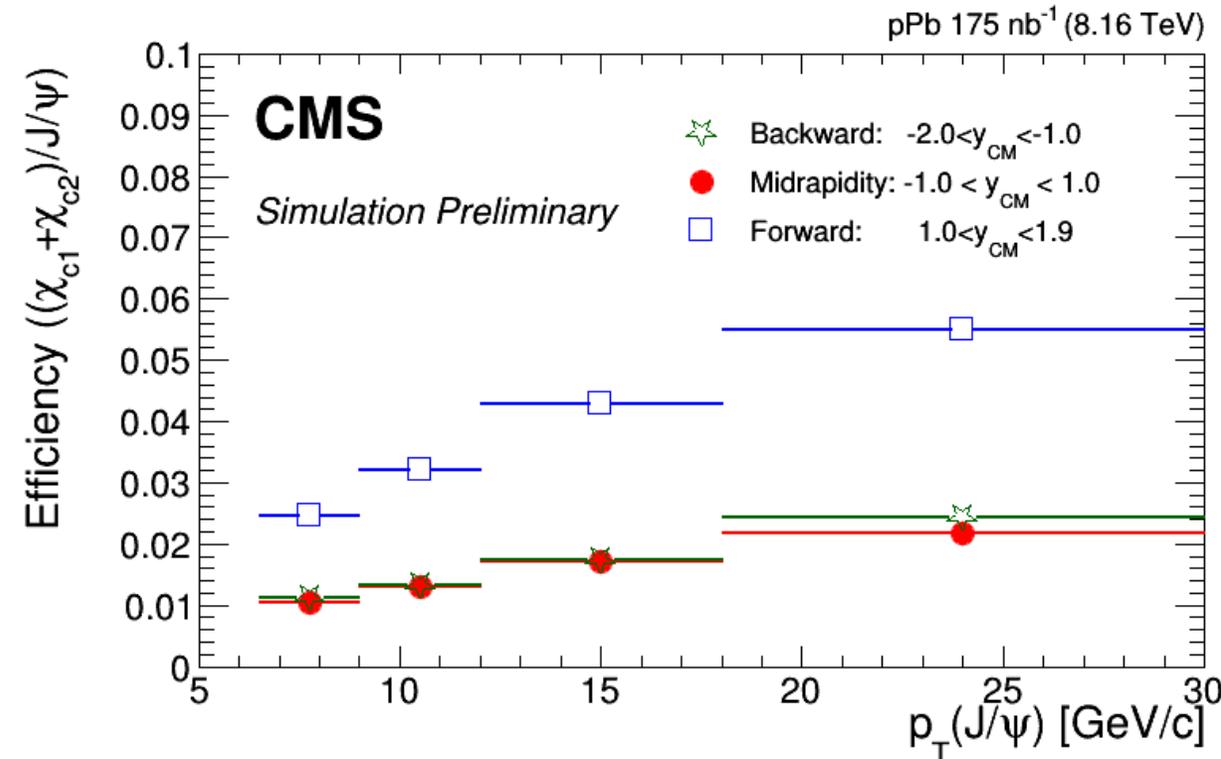
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- Individual muon and  $J/\psi$  efficiencies cancel out.
- Therefore, this plot represents  $\gamma$  acceptance and  $\gamma, \chi_c$  selection efficiency.
- Forward rapidity exhibits higher efficiency than backward
  - > Due to the target geometry, material budget of the target is much higher than the mid and backward rapidity region.

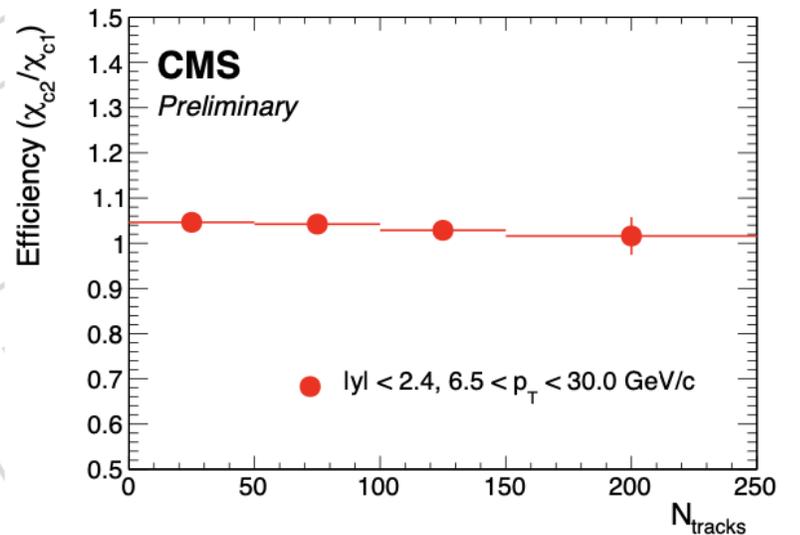
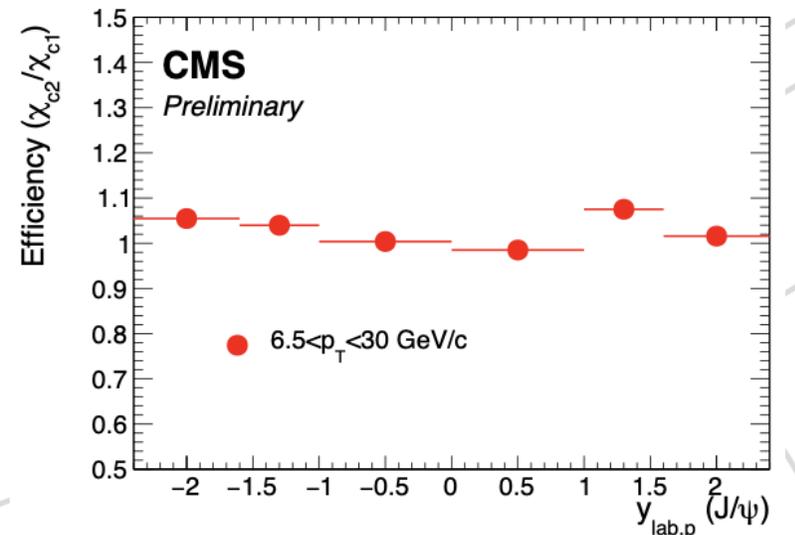
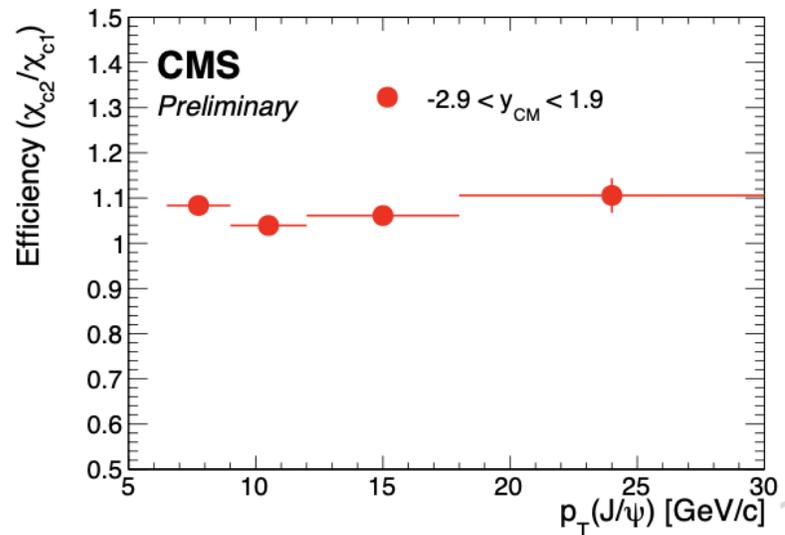


# Efficiencies- $\chi_{c2}/\chi_{c1}$

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

$N_{\chi}^{rec}$  is the number of reconstructed  $\chi$  and  $N_{\chi}^{gen}$  is the number of generated  $\chi$ , after the corresponding  $J/\psi$  has been reconstructed.

The efficiencies are relatively flat across all kinematic region.



## Motivation and Overview

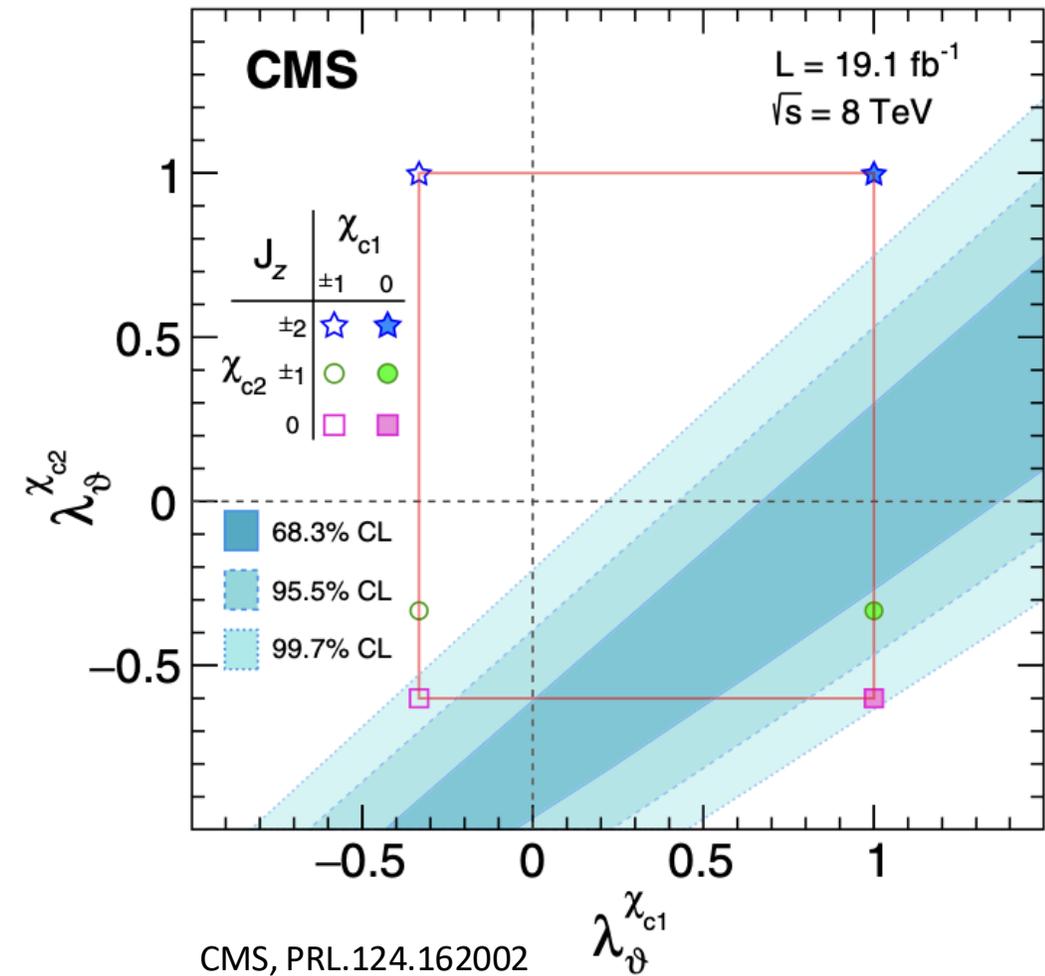
## Analysis Details

- Signal Extraction
- Efficiencies
- **Polarization**
- Results

## Summary

# Polarization

CMS observed that both  $\chi_{c1}$  and  $\chi_{c2}$  are strongly polarized

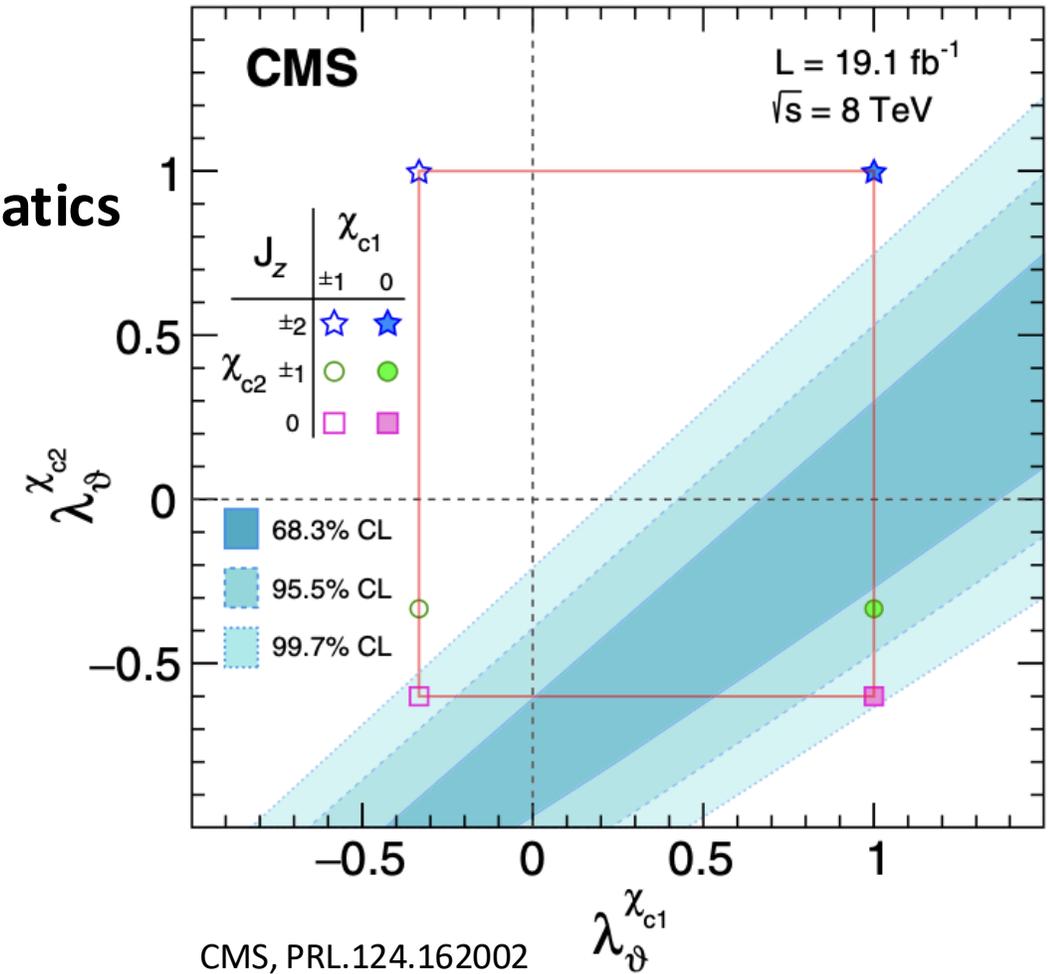


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A different polarization scenario can vary the kinematics of muons and photons

-> can change the  $p_T$  distribution



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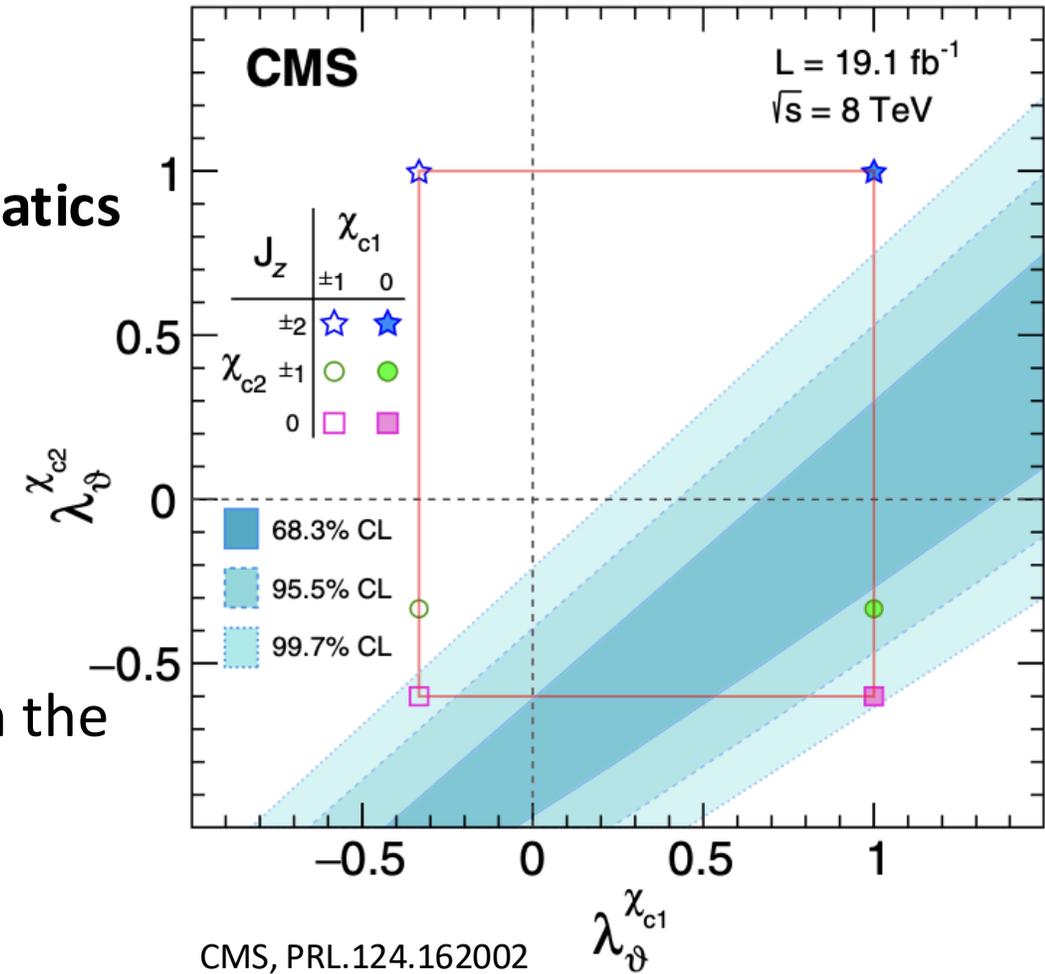
A different polarization scenario can vary the kinematics of muons and photons

-> can change the  $p_T$  distribution

Use reweighting factor  $1 + \lambda_{\theta} \cos^2 \theta$  for  $\chi_c$  reconstruction efficiency within the acceptance.

( $\theta$  is the polar angle of the positive muon direction in the  $J/\psi$  frame)

( $\lambda_{\theta 1} = 1.0, \lambda_{\theta 2} = -0.6$  which is  $J_{z1} = 0, J_{z2} = 0$ )



## Motivation and Overview

## Analysis Details

- Signal Extraction
- Efficiencies
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- **Results**

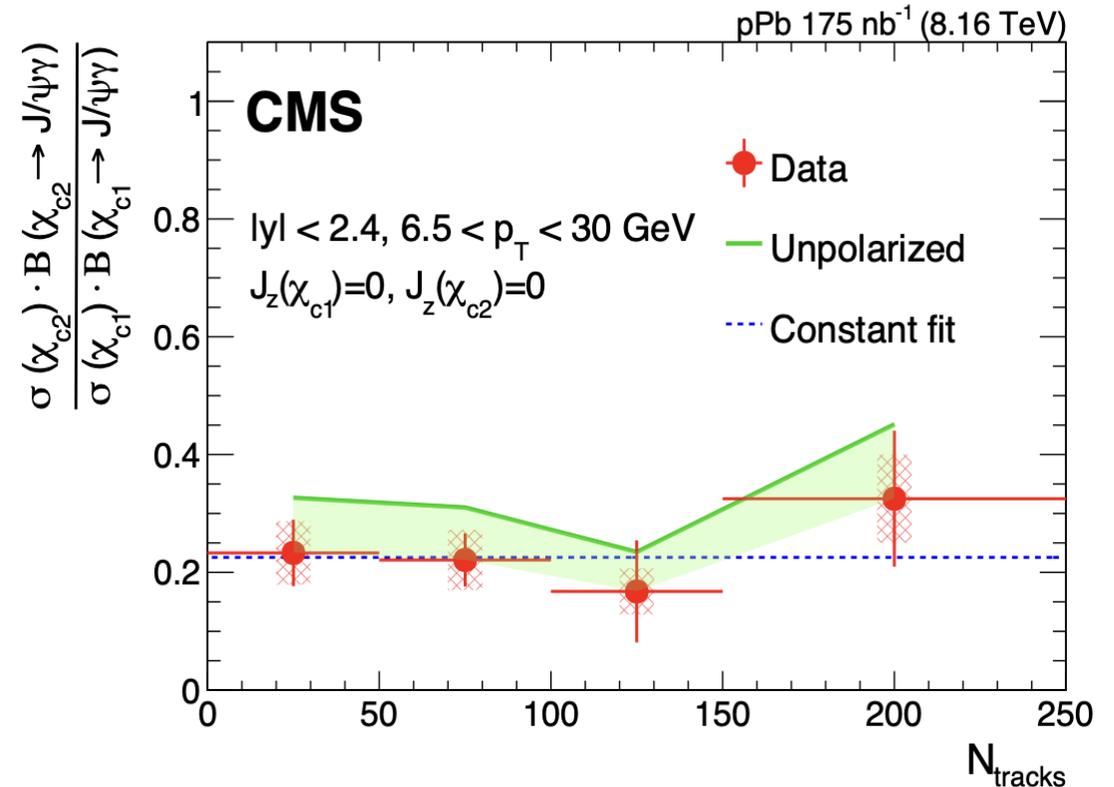
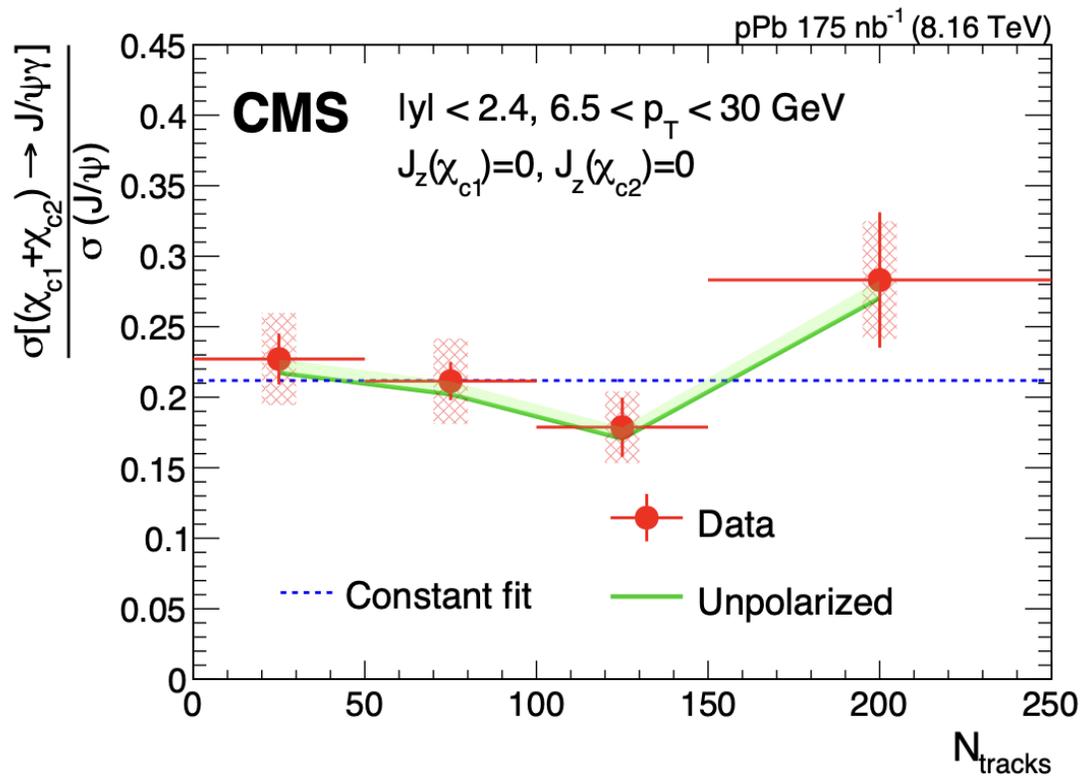
## Summary

# Result- $N_{\text{trk}}$ dependence

Both ratios are flat

- $\chi_c$  modified vs multiplicity similarly to  $J/\psi$  and  $\chi_{c2}$  similarly to  $\chi_{c1}$
- Different from what is seen for  $\psi(2S)$

Green line – Unpolarized scenario, Blue line – Constant fit



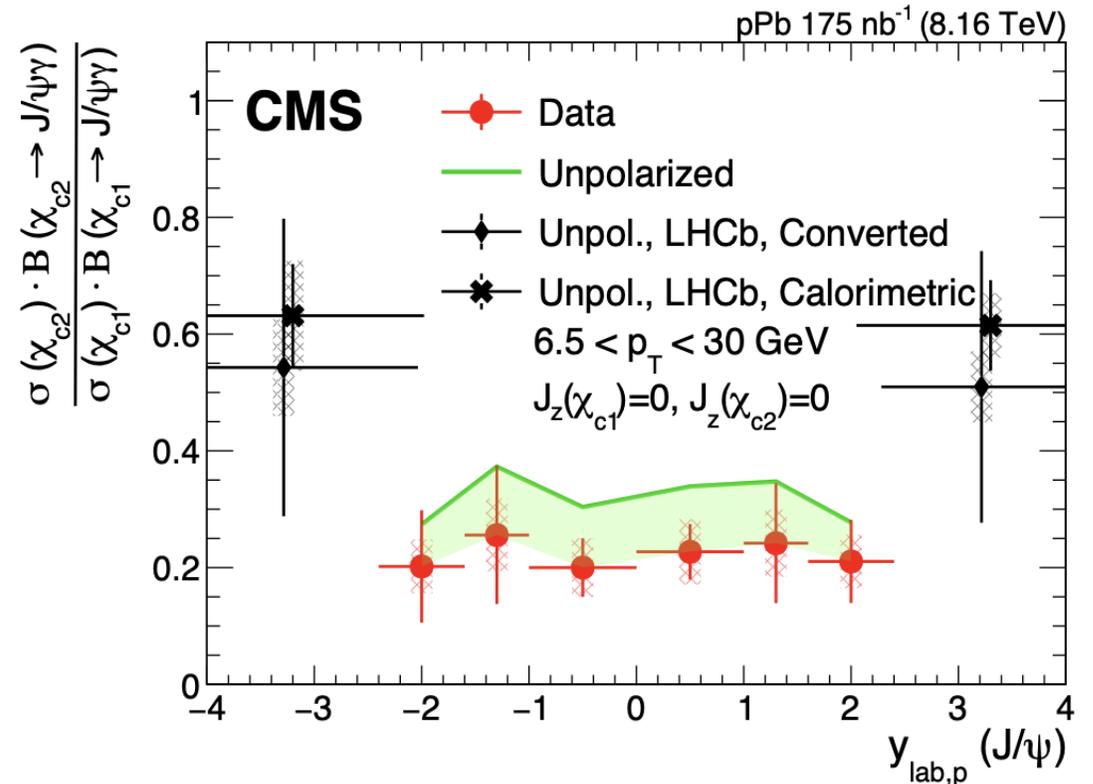
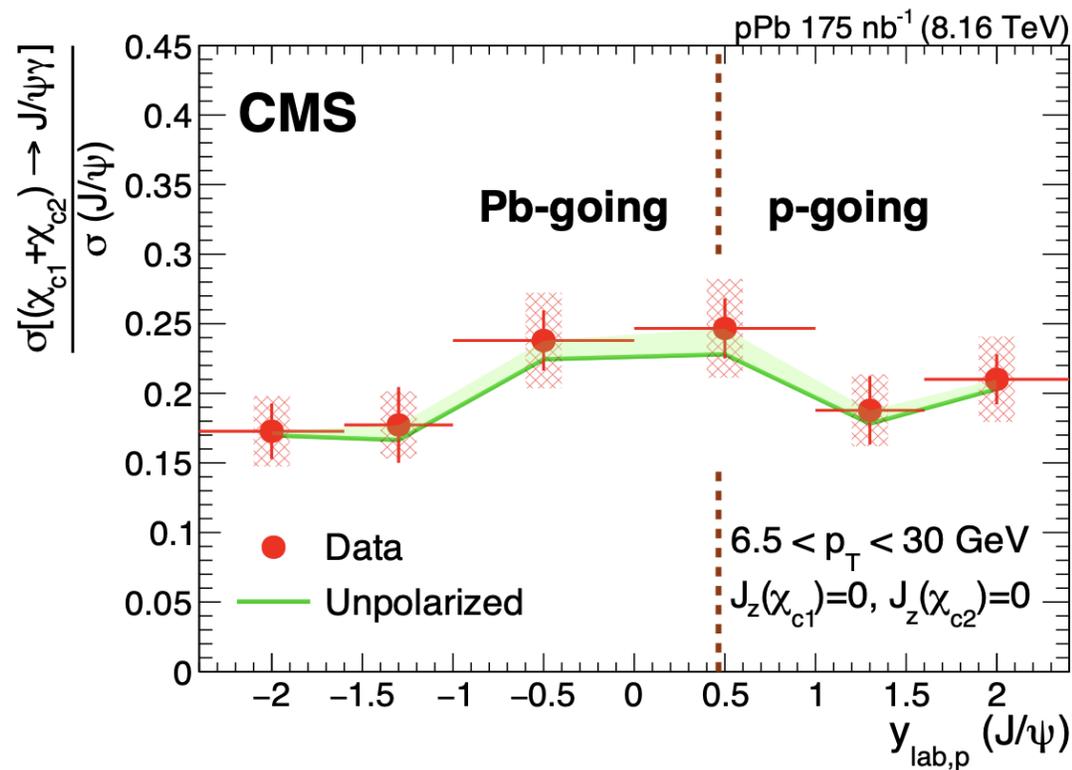
# Result – Rapidity dependence

In  $\chi_c / J/\psi$ , Given current uncertainties, the hypothesis of no rapidity dependence cannot be excluded

- p-value = 0.07

$\chi_{c2} / \chi_{c1}$  is flat within the uncertainties

- Both  $\chi_c$  states are similarly modified

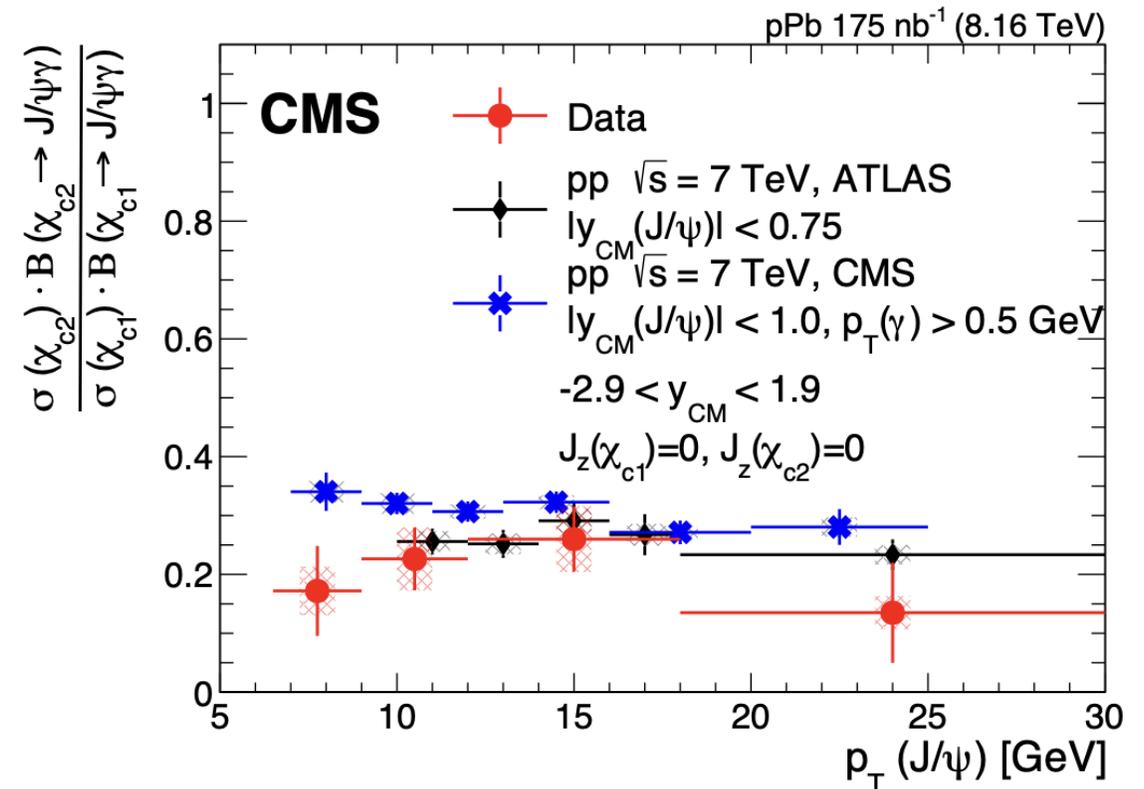
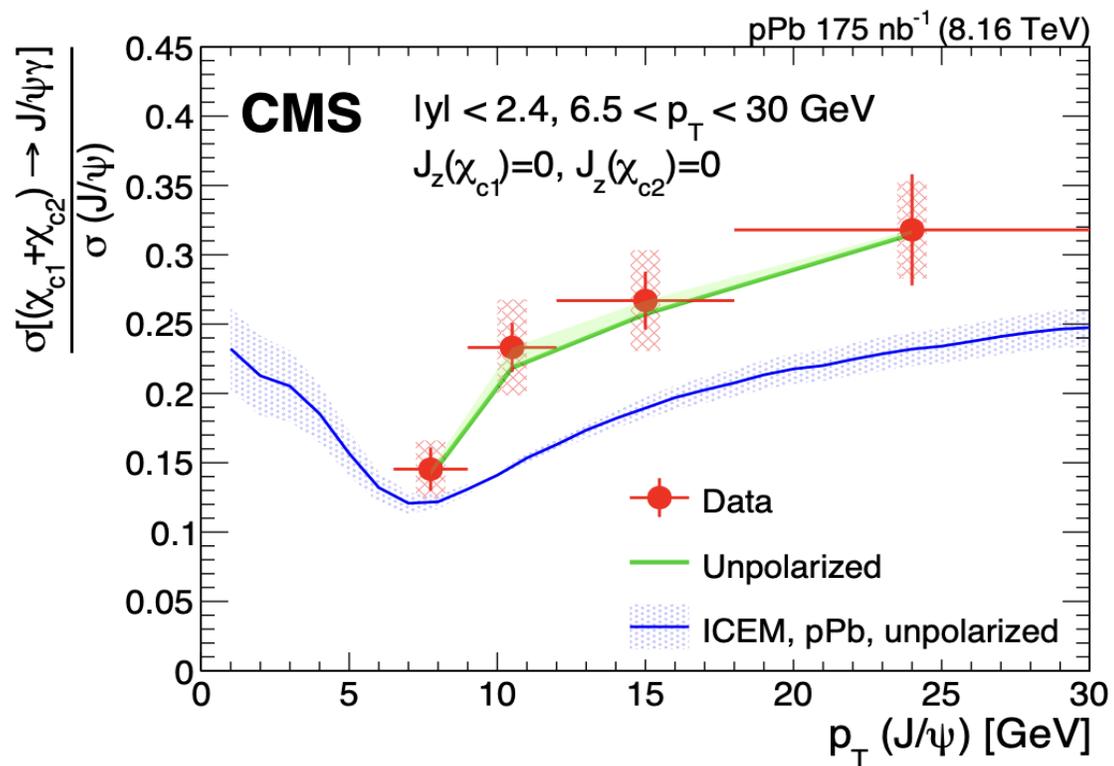


# Results – $p_T$ dependence

$\chi_c / J/\psi$  increases with  $p_T$

- ICEM model describes the shape well, but underpredicts the values  
(PRD98.11 (2018) 114029)

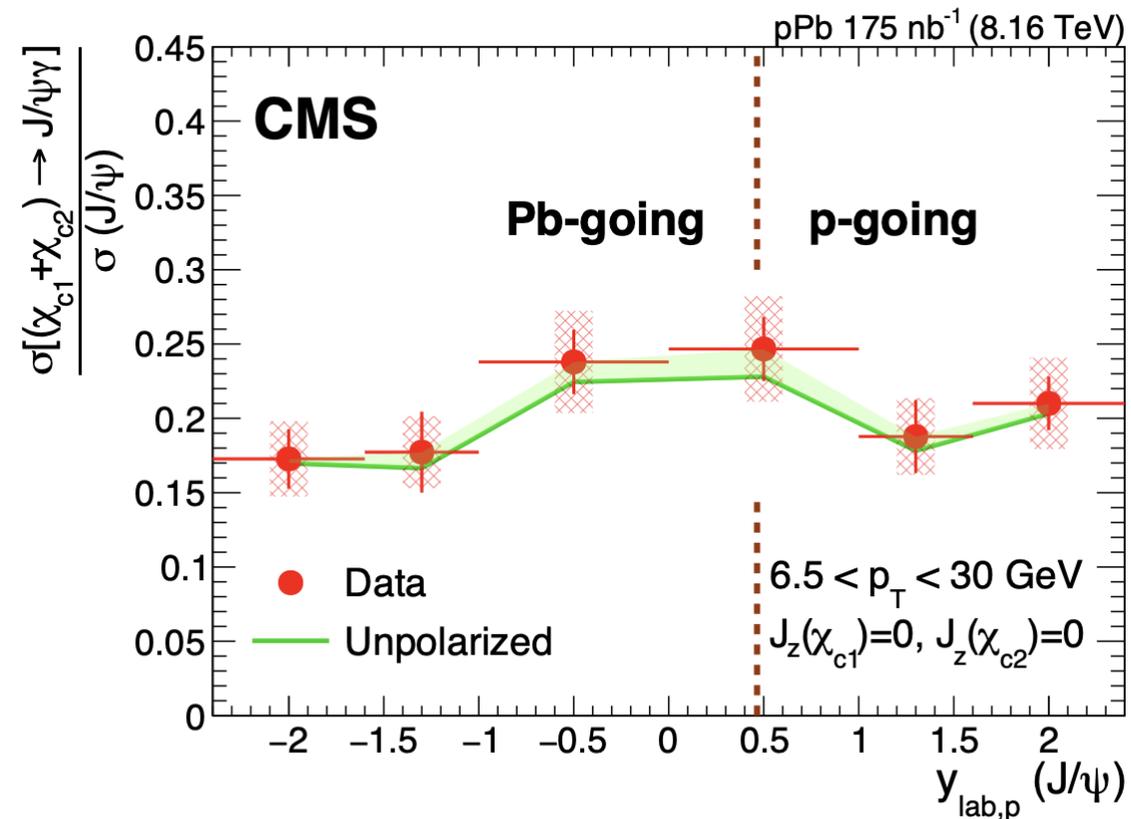
$\chi_{c2} / \chi_{c1}$  is flat and consistent with previous pp measurement



# Results – $p_T$ dependence (rapidity subrange)

## Divided results in Pb-going, p-going and midrapidity region

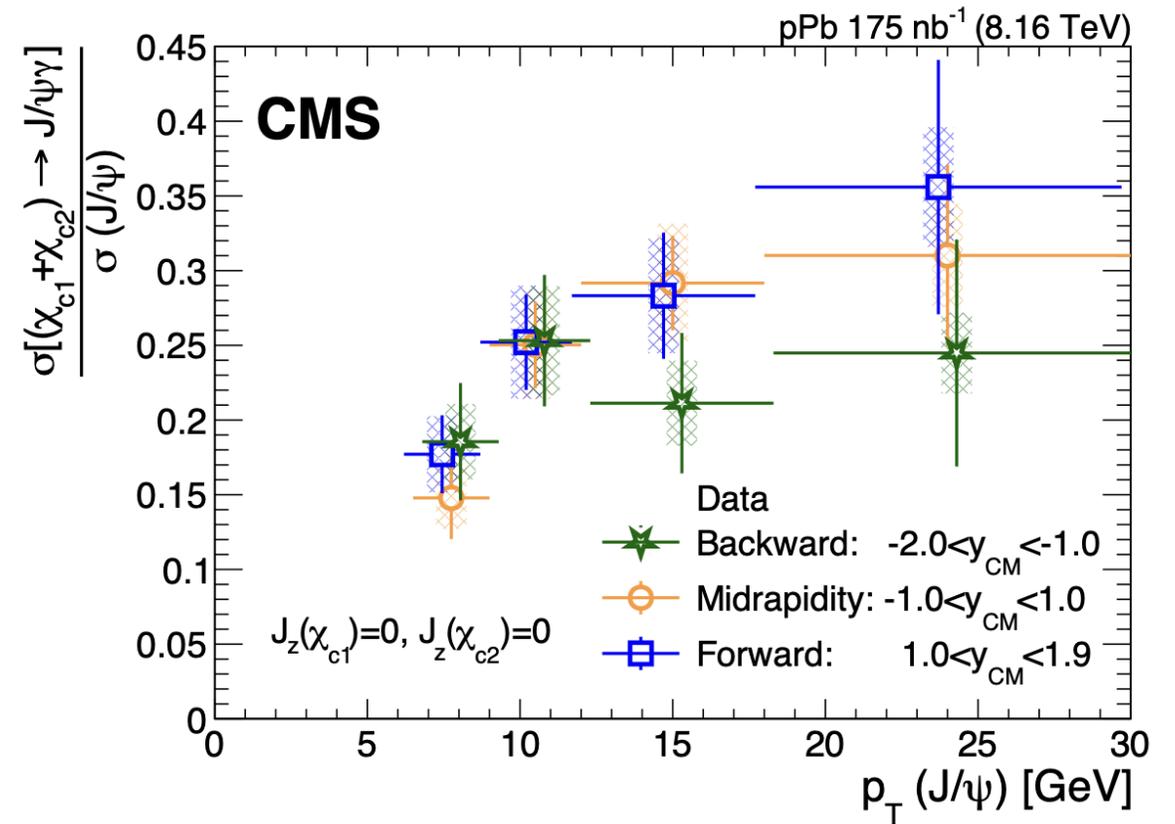
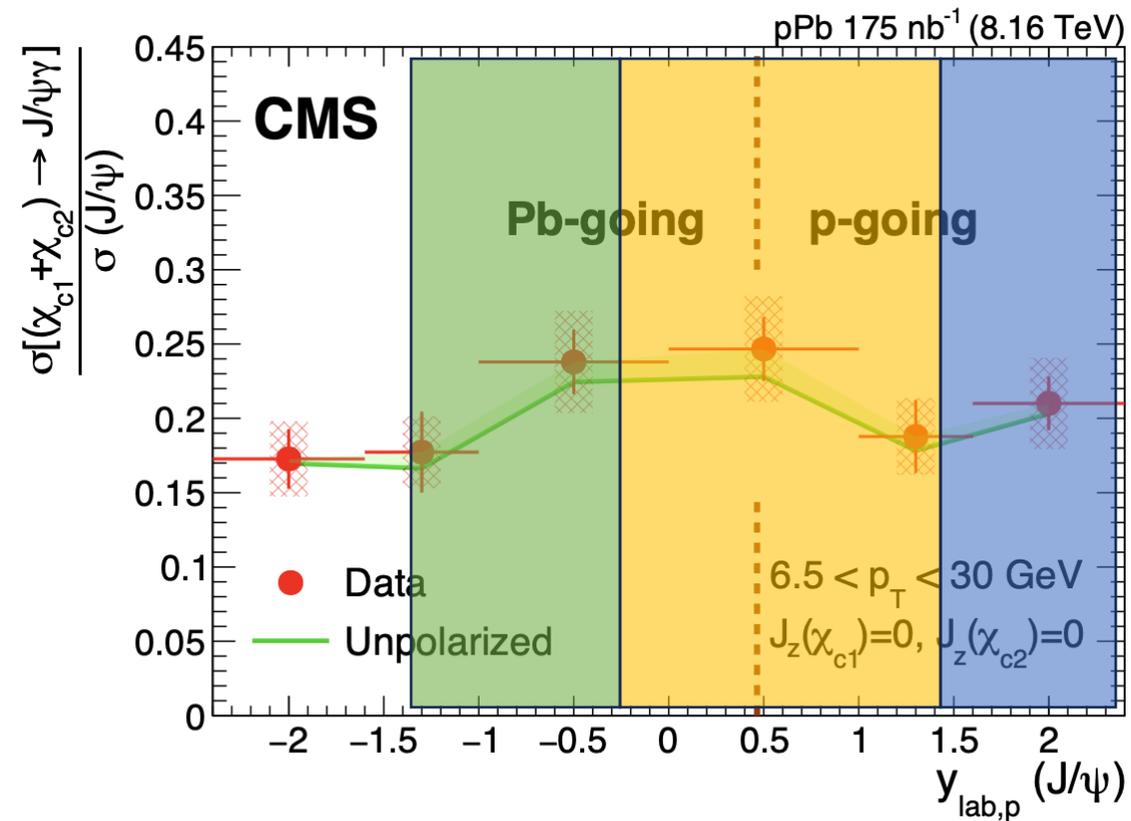
- Exploring the potential direction-related effects
- There is no significant rapidity-dependent trend.



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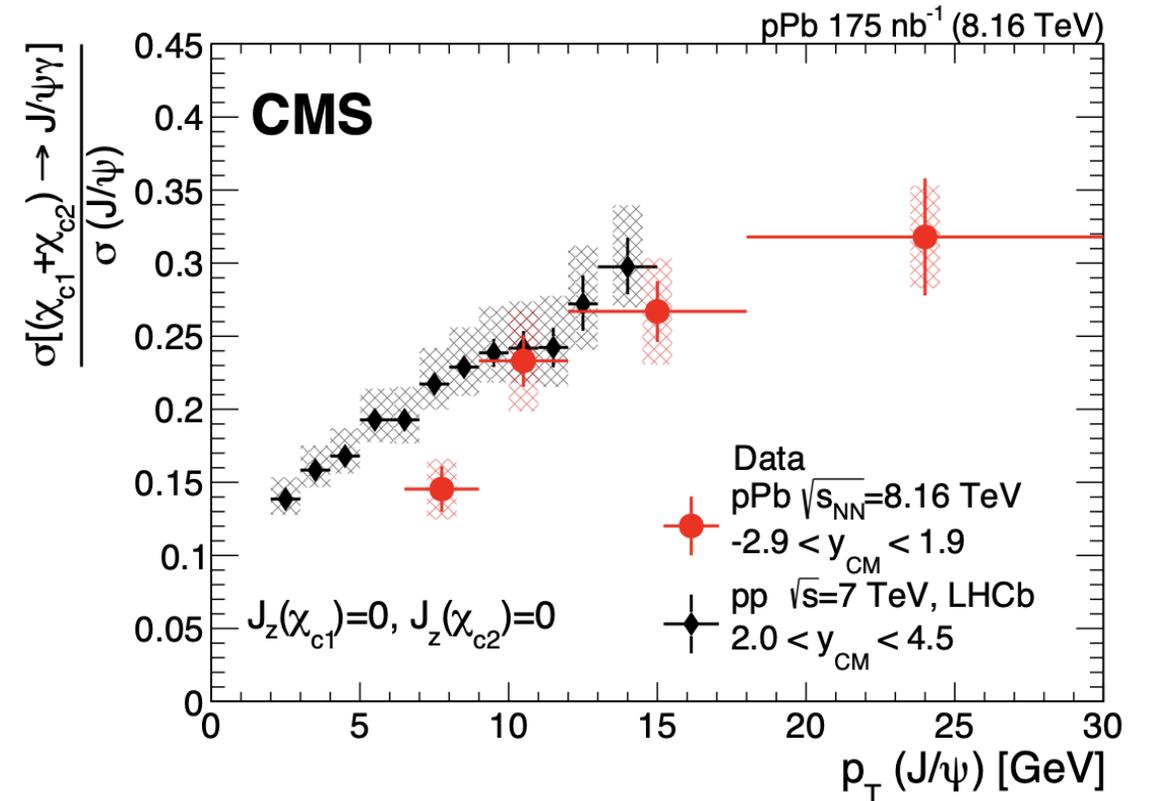
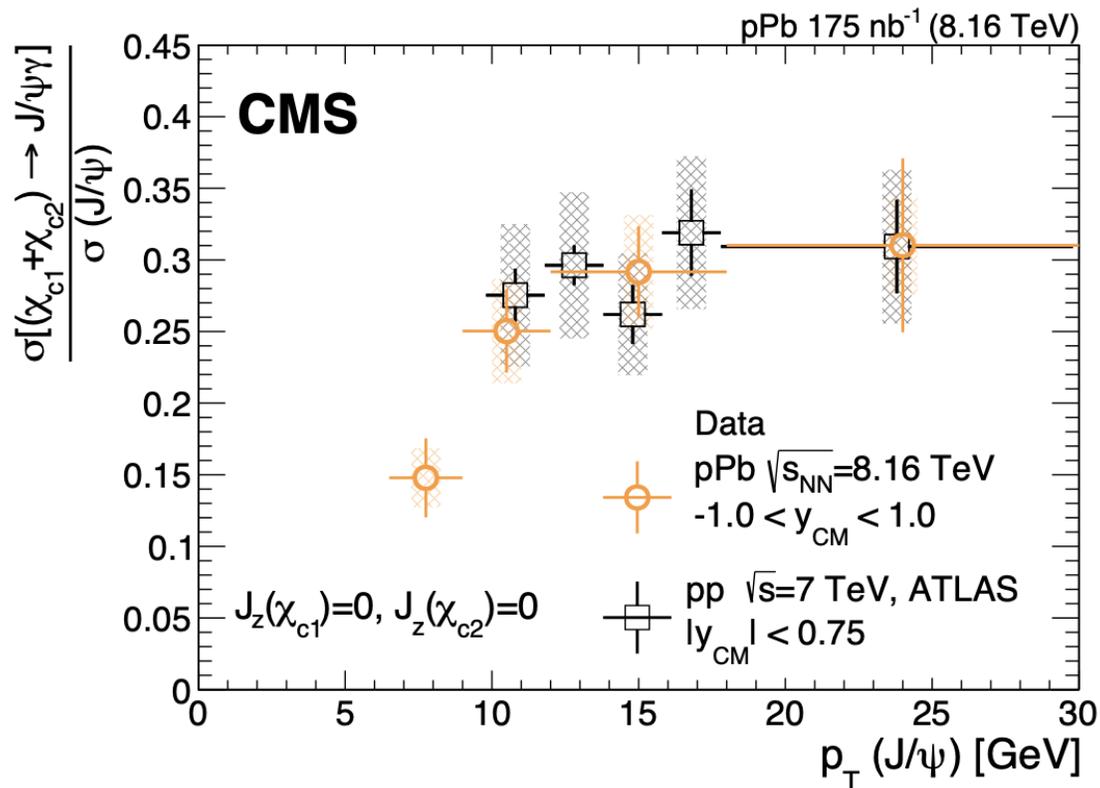


# Results – $p_T$ dependence (pp comparison)

$\chi_c / J/\psi$  is consistent with pp results

- Left plot shows similar rapidity region and right shows different rapidity region (integrated)

Results show there's no relative suppression of  $\chi_c$  compared to  $J/\psi$  in pPb



## $\chi_c / J/\psi$

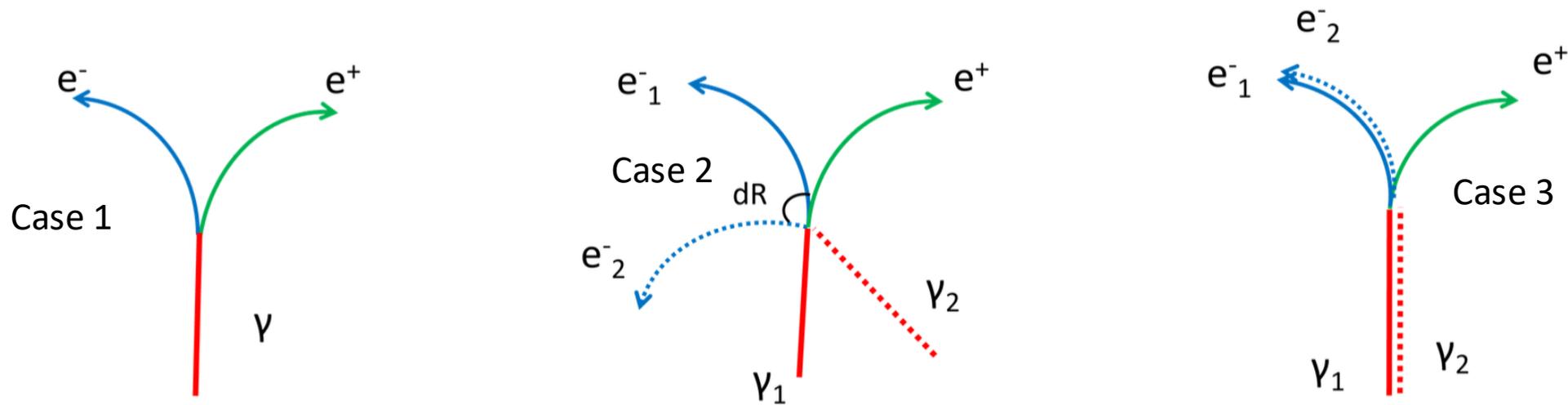
- The ratio is flat vs  $N_{\text{trk}}$ , rapidity but increase with  $p_T$
- The ratio is consistent with two previous pp measurements ATLAS (midrapidity) and LHCb (forward rapidity)
- Suggesting that weaker modification effects for  $\chi_c$  states compared to the  $\psi(2S)$  state in pPb collisions

## $\chi_{c2}/\chi_{c1}$

- The ratio is flat vs  $N_{\text{trk}}$ , rapidity and  $p_T$
- Within uncertainties, we found no significant differences between  $\chi_{c2}/\chi_{c1}$  ratio results and those in existing pp studies
- Suggesting that there's no strong relative modification between the  $\chi_c$  states in pPb collisions

# Backup

# Photon conversion - duplicate rejection



1. If the conversion doesn't share either track with any other, it is kept.

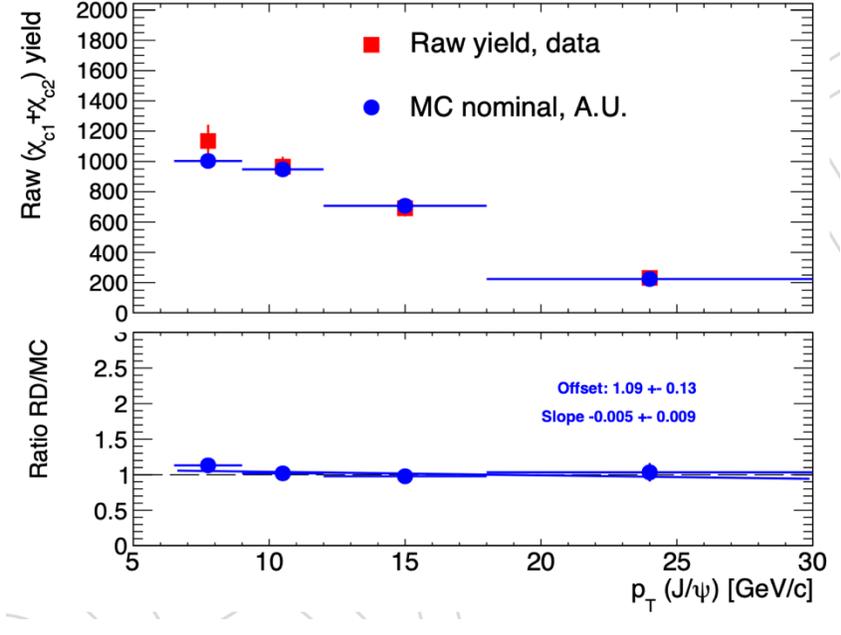
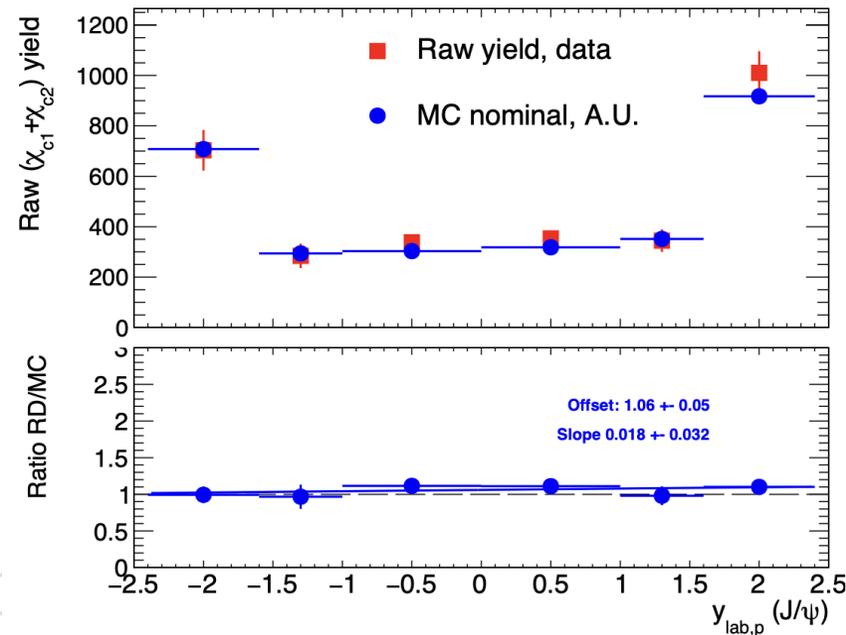
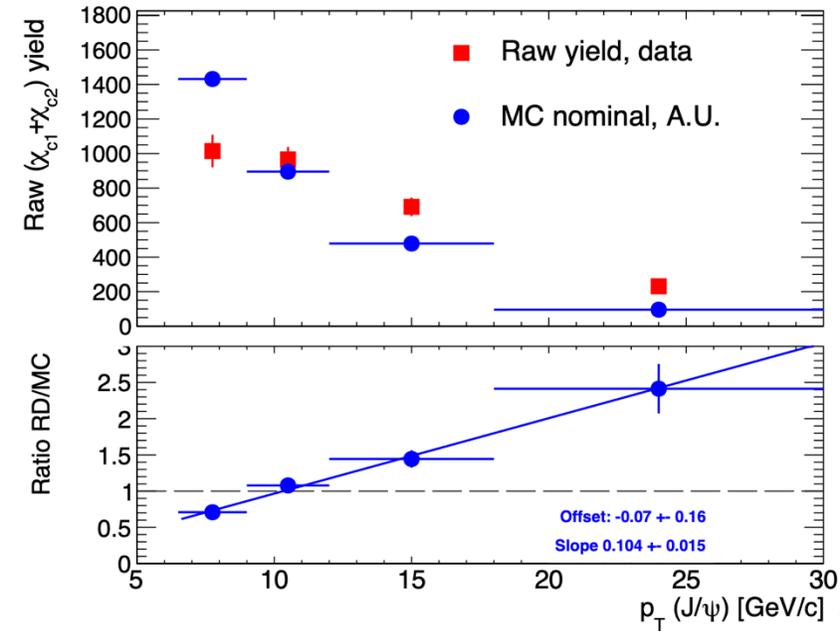
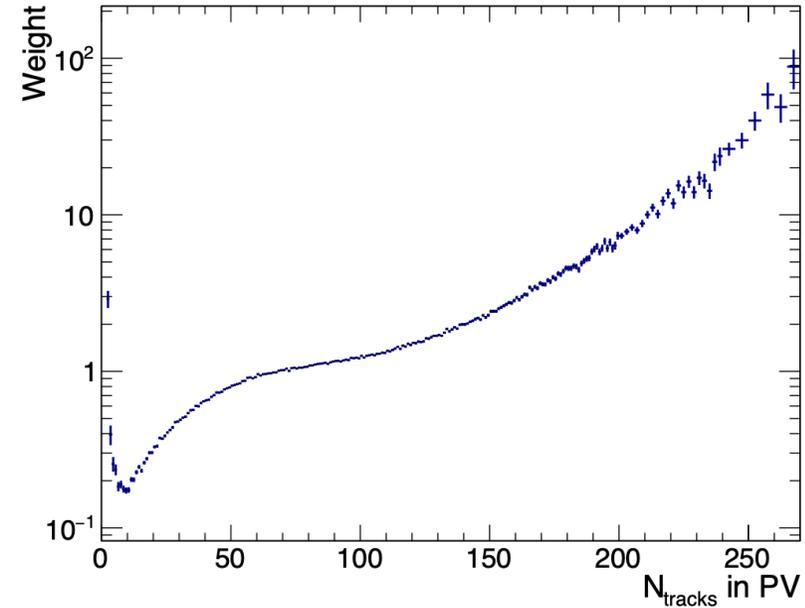
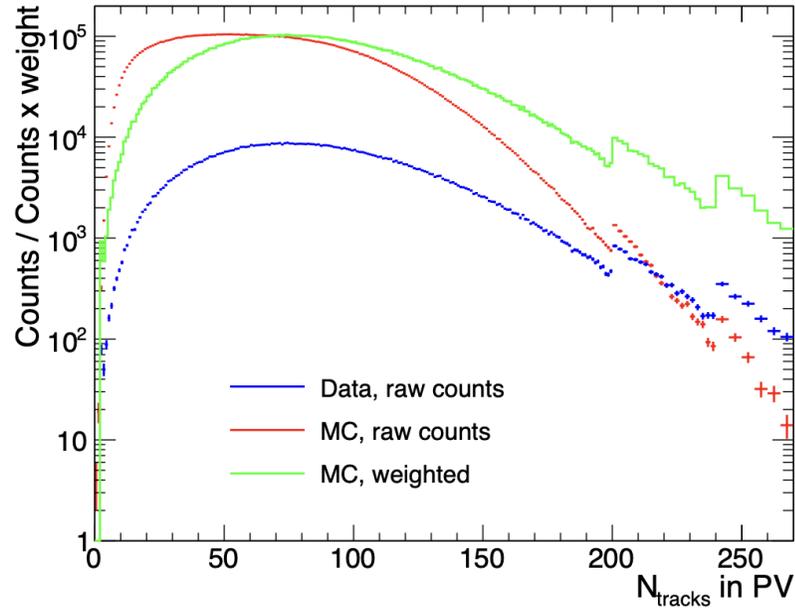
2. If the conversion shares a single track with another conversion, but the other (non-shared) track is different, the conversion is considered to be genuine systematic and is kept.

3. If the conversion shares a track with another conversion, and the other track is almost identical, then the conversions are considered duplicate. The number of valid tracker hits in the split track is compared, and the conversion with higher number is kept, while the other is removed.

In case of a tie in number of valid hits, the conversion vertex probability is used as a tie-breaker.

(This track is defined as having difference of  $pT < 0.1$  GeV/c and difference in direction  $dR = \sqrt{\Delta(\eta)^2 + \Delta(\phi)^2} < 0.05$ )

# MC Weighting

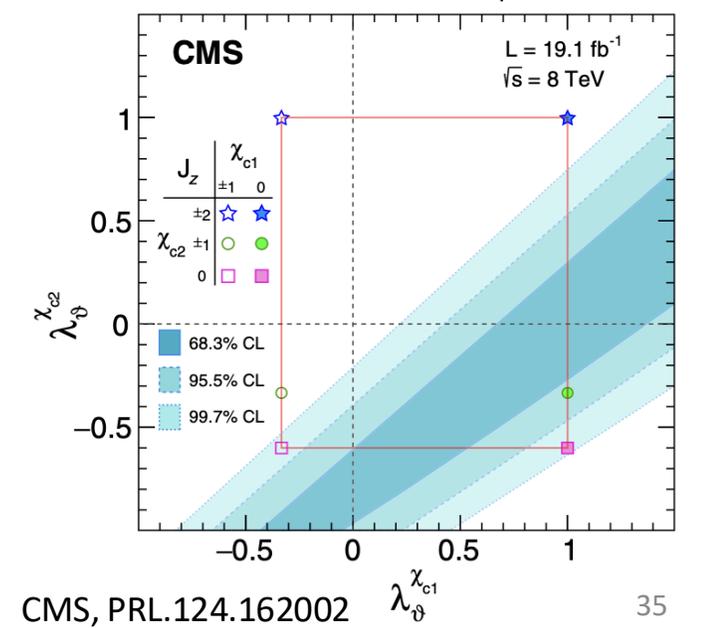
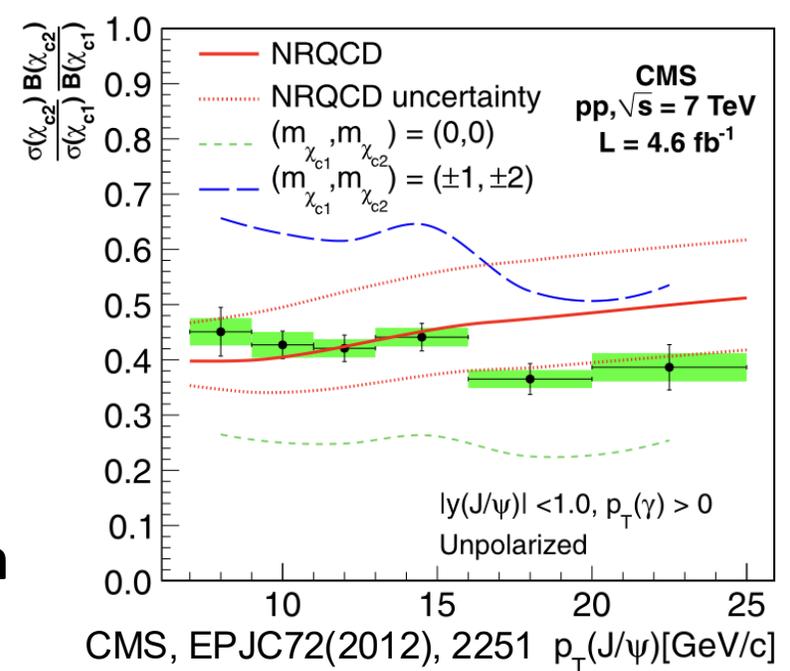


# Existing results for excited charmonium at LHC

pp

CMS

- Measured a extend range of  $J/\psi$   $P_T$
- Studied the effect of  $\chi_c$  polarization on photon reconstruction efficiency and compared to theoretical prediction.
- CMS observed that both  $\chi_{c1}$  and  $\chi_{c2}$  are strongly polarized
- Due to the polarization,  $\chi_c$  analysis requires significantly different treatments of the acceptance correction compared to  $J/\psi$ .



## Data

- 2016 pPb at 8.16 TeV
- Data set: /PADoubleMuon/PARun2016C-PromptReco-v1/AOD
- Trigger: HLT\_PAL1DoubleMuOpen\_v1
- Luminosity: 63nb<sup>-1</sup> (pPb), 112nb<sup>-1</sup> (Pbp)

## MC

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

# $\chi_c$ Charmonium P-states

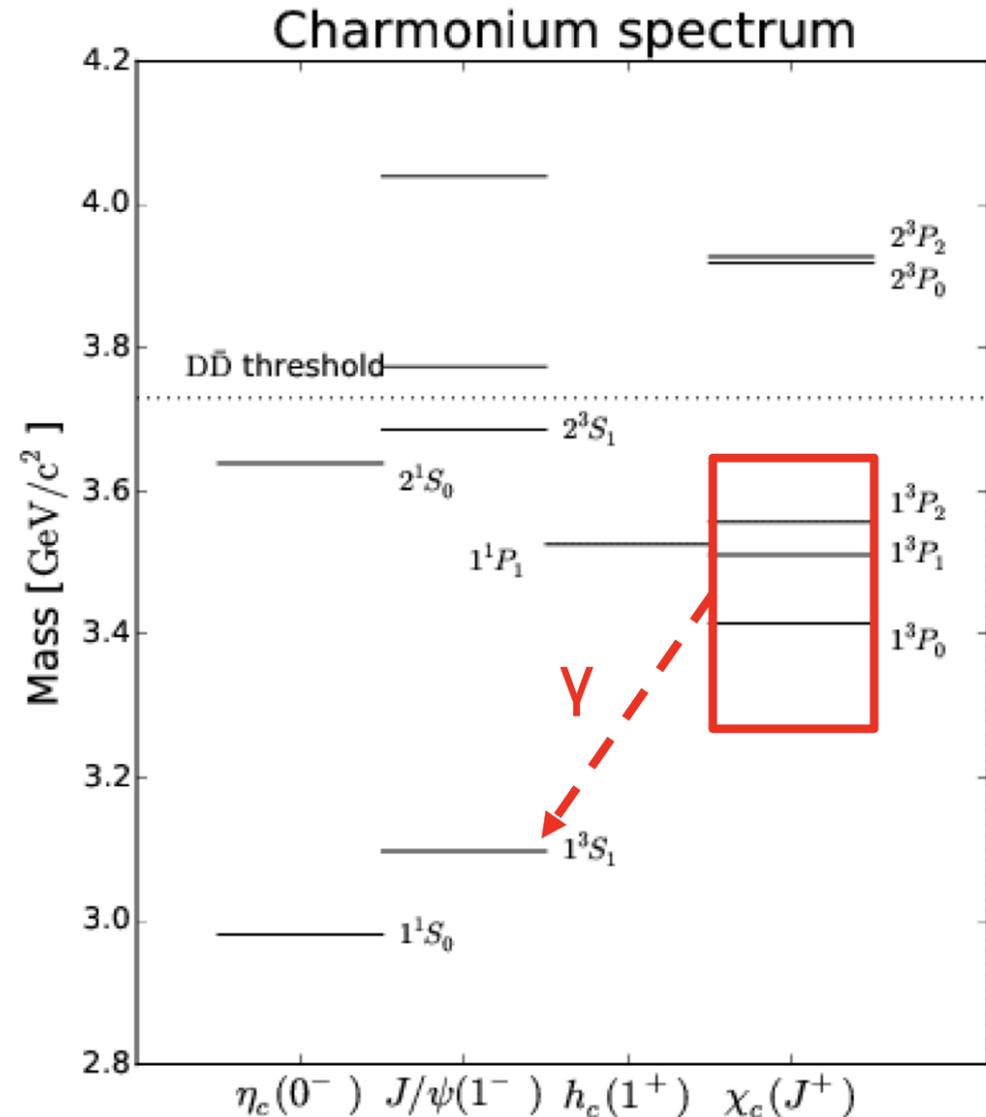
## P states

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

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

BR ( $\chi_c \rightarrow J/\psi + \gamma$ ) : 1.4%, 34%, 19%

$\chi_{c0}$  too small,  $\chi_{c1}$  biggest peak,  $\chi_{c2}$  smaller peak



# Conversion Selections

- **Tight corresponds to the previous pp selection**
- **Medium and Loose based on the signal/background variable distributions**
- **Keeping variables that seemed the most promising in distinguishing signal vs background**

## Tight:

Quality\_isGeneralTracksOnly = true  
Quality\_isHighPurity = true  
conv\_vertexPositionRho > 1.5  
conv\_sigmaTkVtx1(2) < 5  
conv\_compatibleInnerHitsOK = true  
conv\_vertexChi2Prob > 0.0005  
tk1NumOfDOF > 3  
tk2NumOfDOF > 3  
conv\_track1(2)Chi2 < 10  
conv\_minDistanceOfApproach >-0.25  
conv\_minDistanceOfApproach <1.00

## 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

# Efficiency and background rejection

- The loose selection provided the most significant yields from the cut-based selections
  - BDT method provide slightly better efficiency
- > However it wasn't deemed sufficient to warrant the increased complexity

**Tight**

**Signal eff 29%**

**Bkg rejection 78%**

**Medium:**

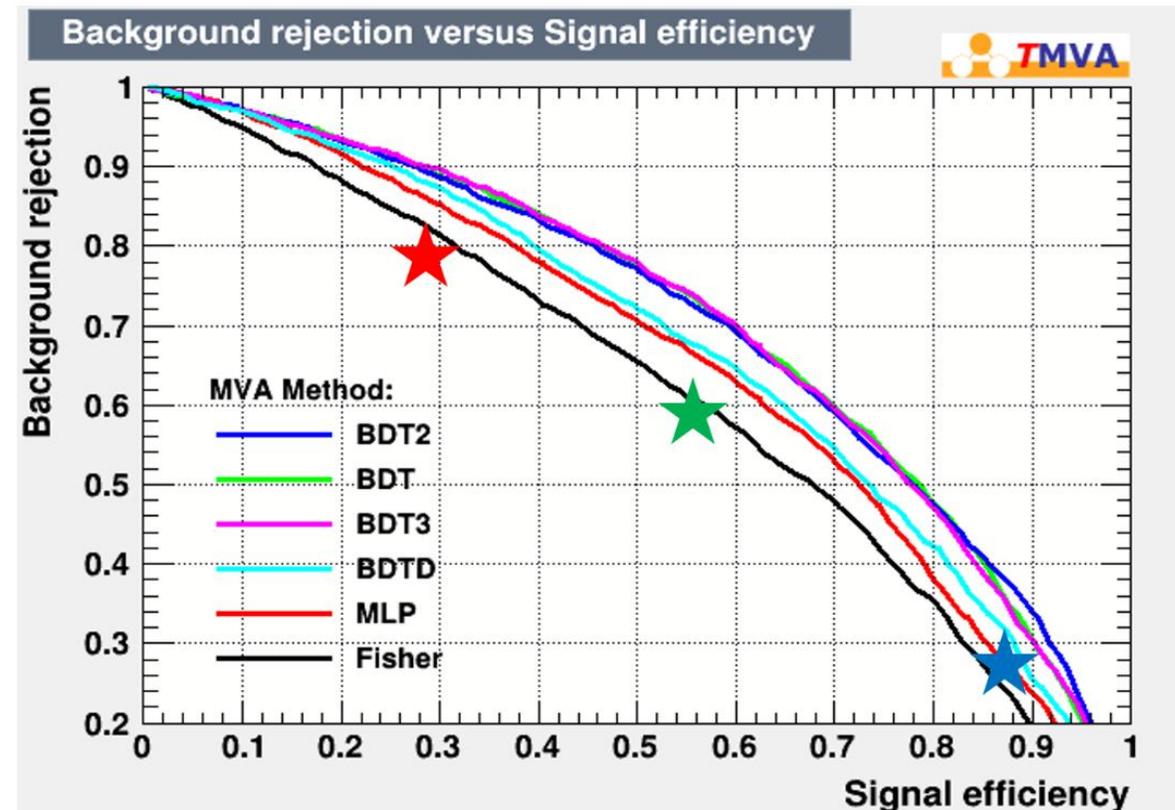
**Signal eff 56%**

**Bkg rejection 59%**

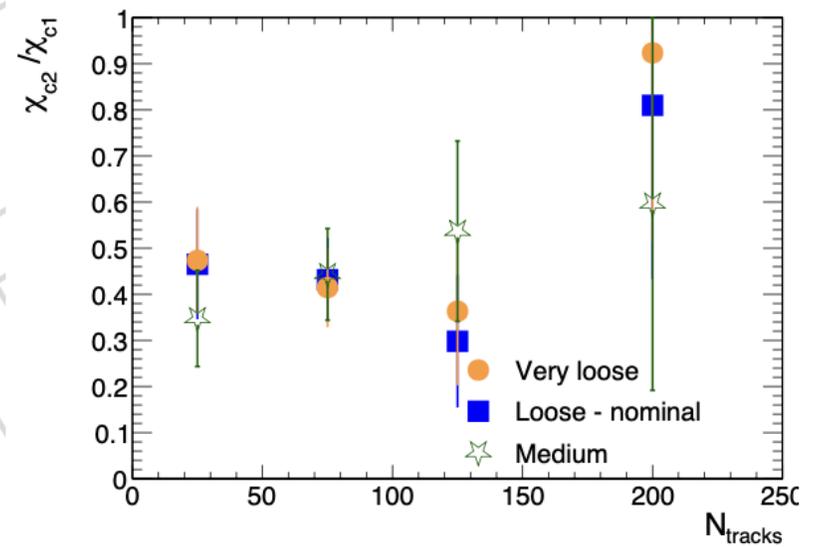
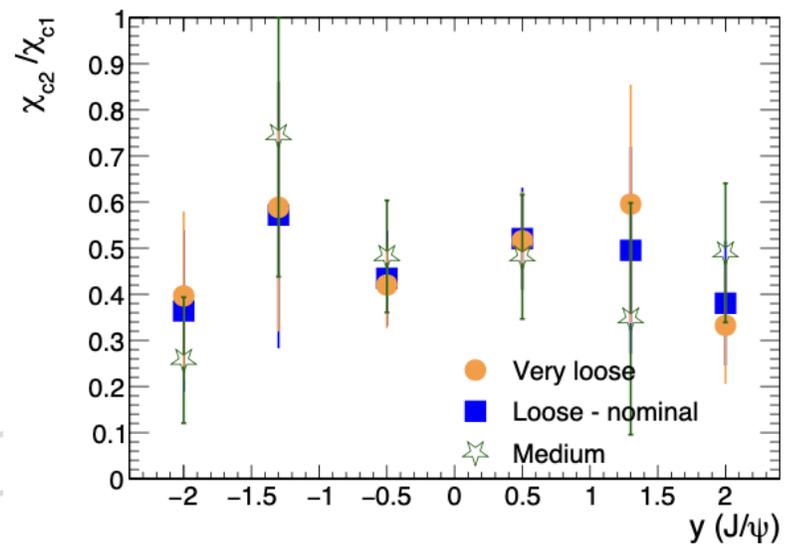
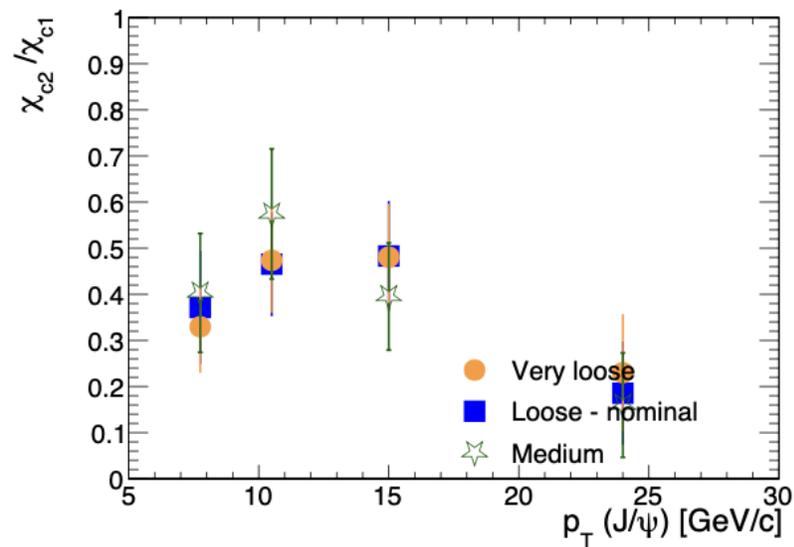
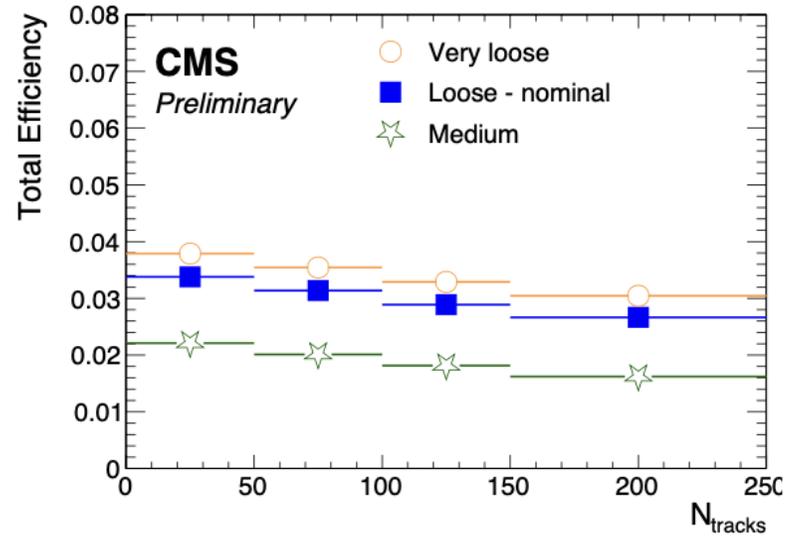
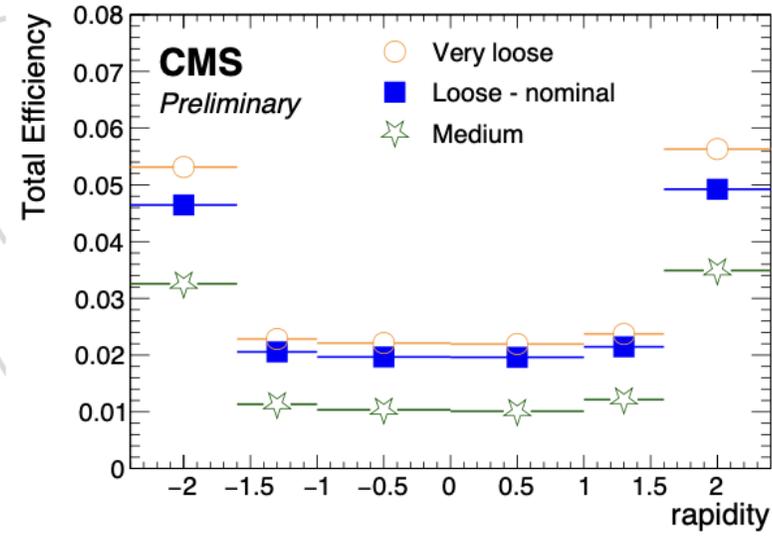
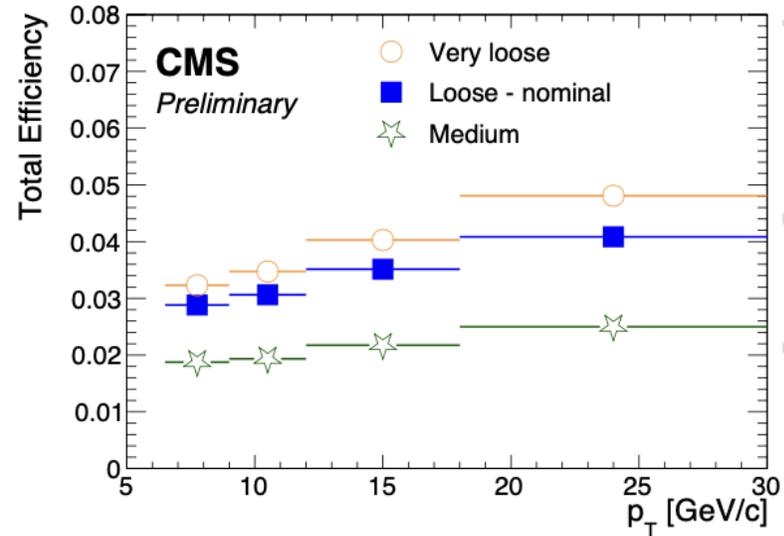
**Loose:**

**Signal eff 87%**

**Bkg rejection 28%**



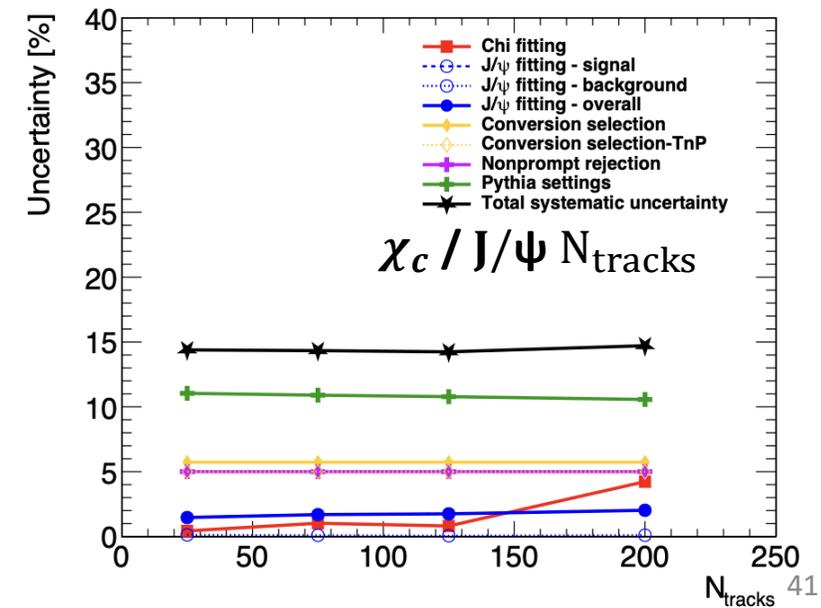
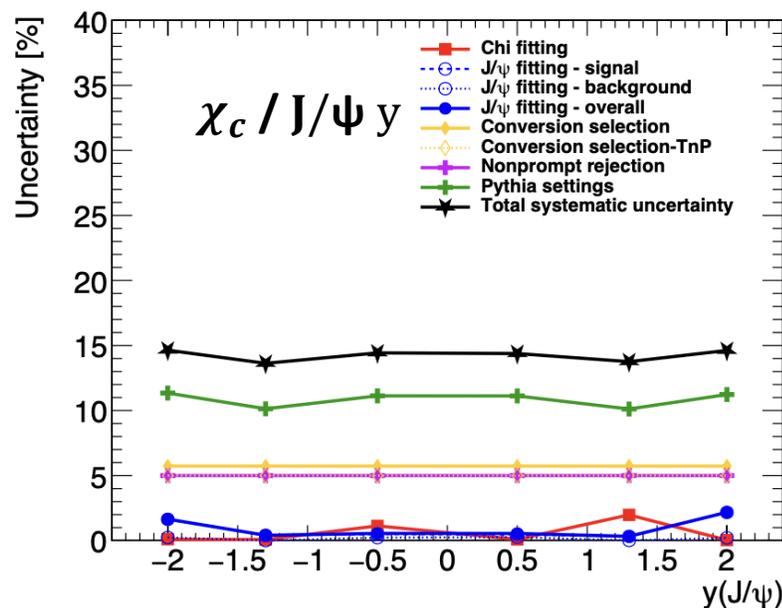
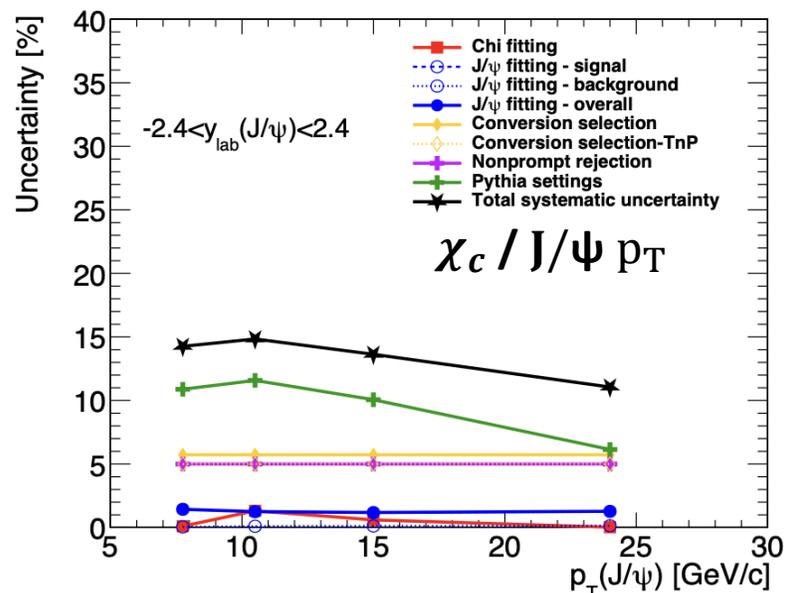
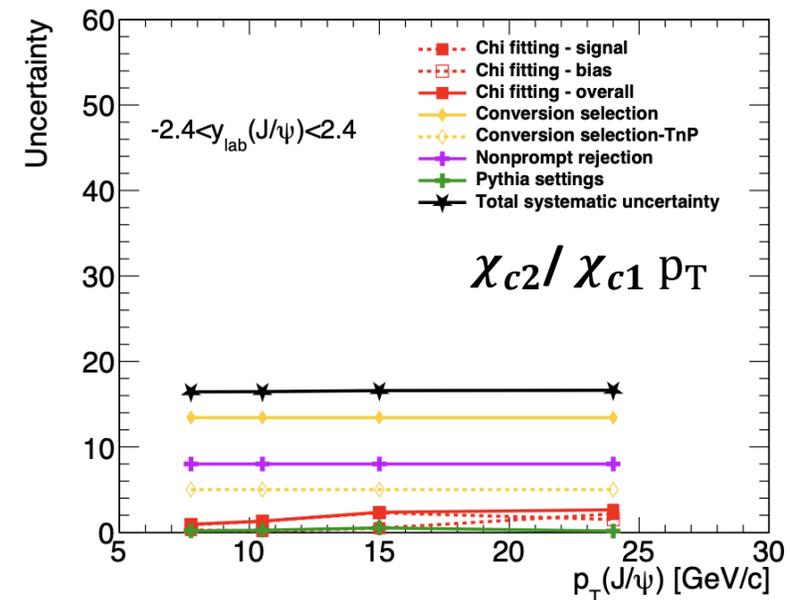
# Conversion Selection – medium alternative



# Systematic Uncertainties – Overview

## Three Main groups of systematic uncertainties

- Fitting procedure for both  $\chi_c$  and  $J/\psi$
- Conversion Selection
- Monte Carlo (Pythia settings, Non-prompt rejection)



# Systematic Uncertainties – $J/\psi$ Fitting

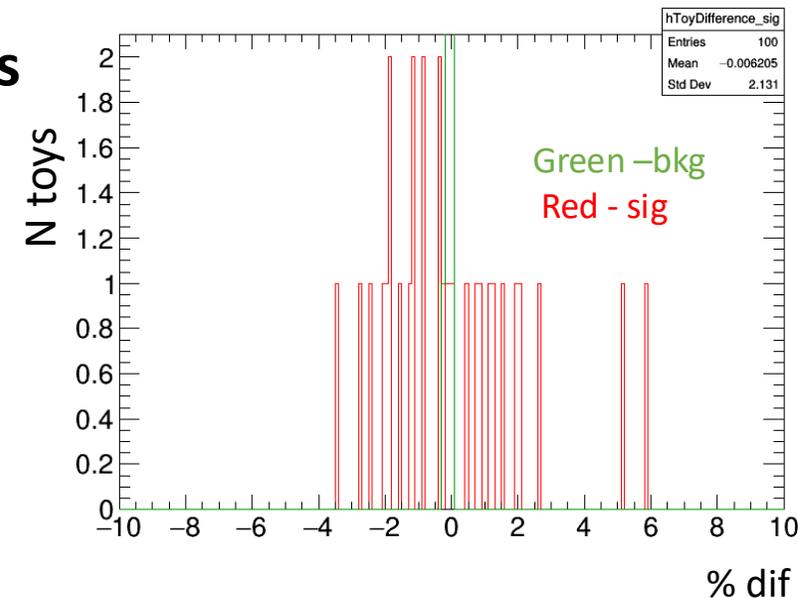
## Using toy data (each bin) to compare alternative fitting functions

1. The nominal fit (signal+background) is used to generate toy pseudodata with the same number of overall counts as the real data
2. The pseudodata are fitted with the nominal fit performing the fit in exactly the same manner as if they were the real data
3. The pseudodata are fitted with the alternative signal and background
4. Steps 1-3 are repeated 100 times.
5. We set 1 sigma of the difference as the uncertainty

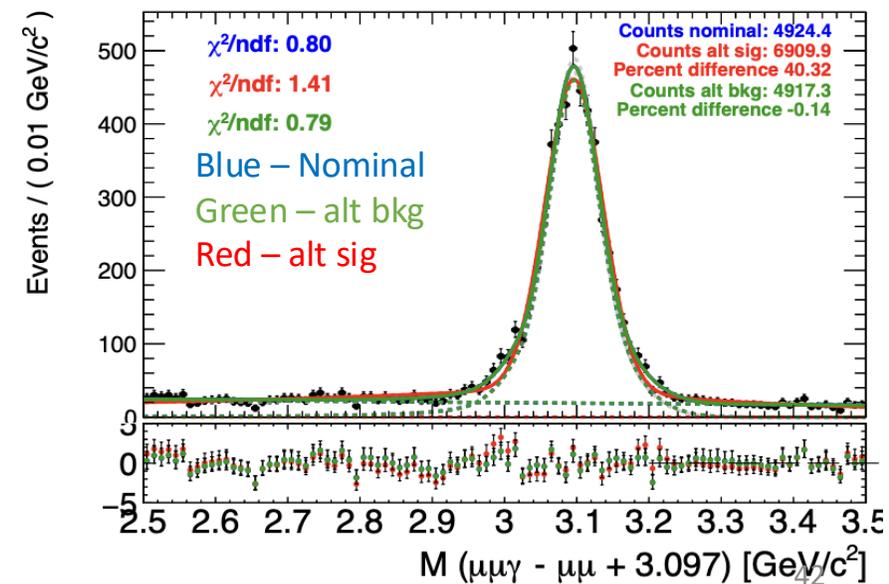
Alternative Signal – Hypatia + Gaussian

Alternative Background – First-order polynomial

|            | Nominal              | Alternative signal   | Alternative background |
|------------|----------------------|----------------------|------------------------|
| Signal     | CB+CB                | Hypatia + Gaussian   | CB+CB                  |
| Background | Exponential function | Exponential function | First-order polynomial |

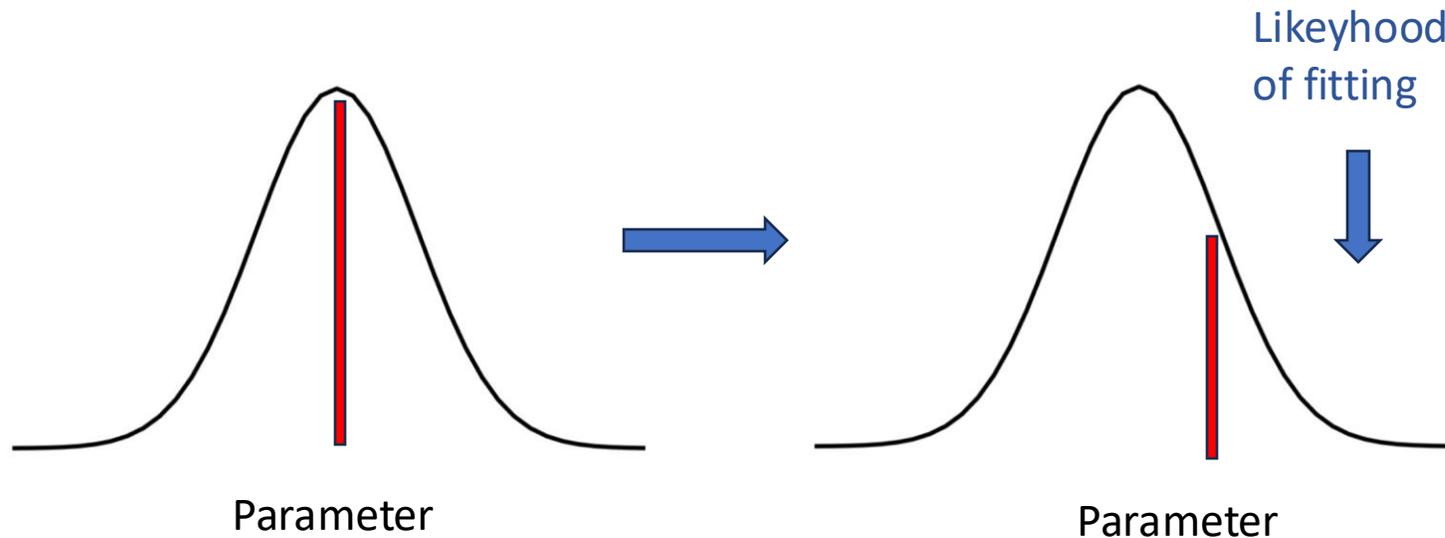


Example toy fit at  $-2.4 < \gamma < -1.6$



# Systematic Uncertainties - $\chi_c$ Fitting

- Applied Gaussian constraint to all parameters which is constrained before.
- By applying Gaussian weights to each parameter, if the parameter deviates too much from the mean value, the likelihood of fitting is reduced.  
-> The parameter does not deviate significantly from the range and is adjusted while being corrected by the given Gaussian function.
- The mean and sigma value of the Gaussian function for the parameter is based on a MC constrained value and its uncertainty.



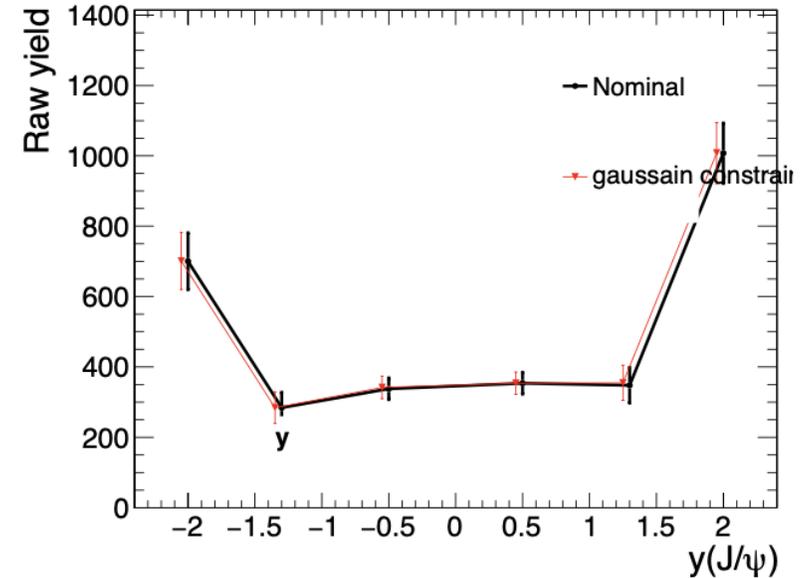
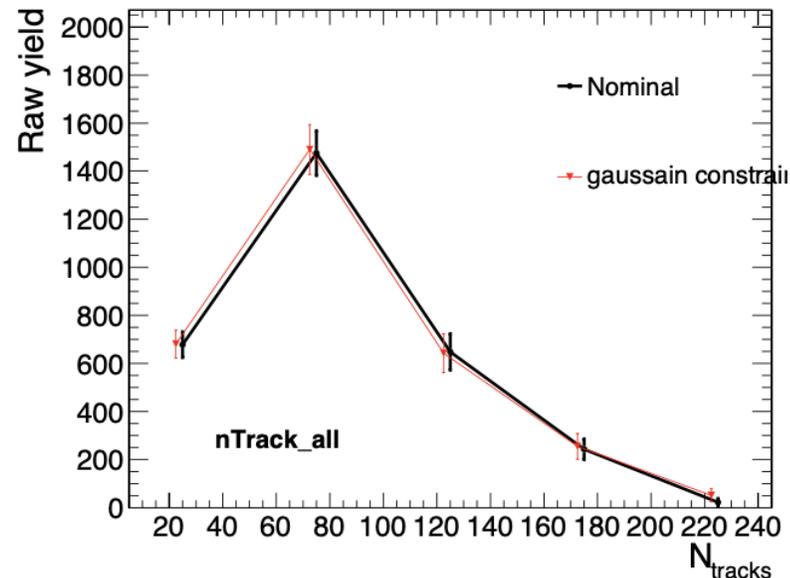
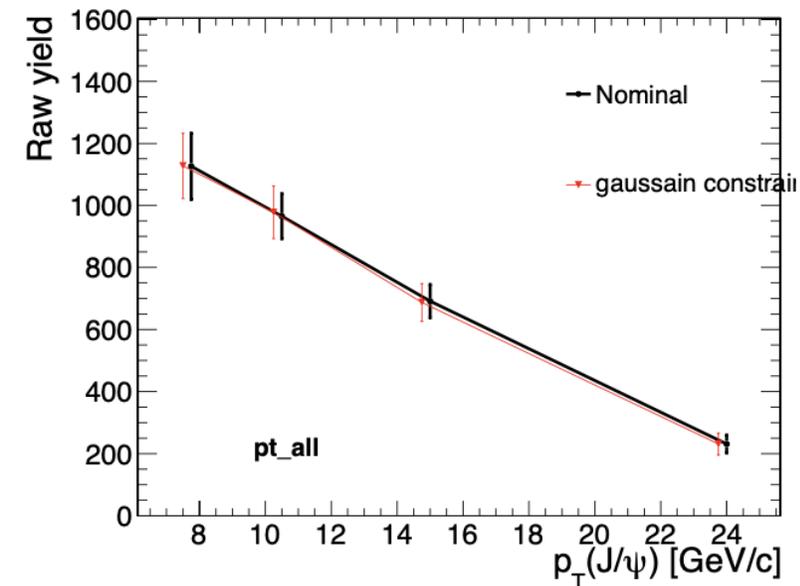
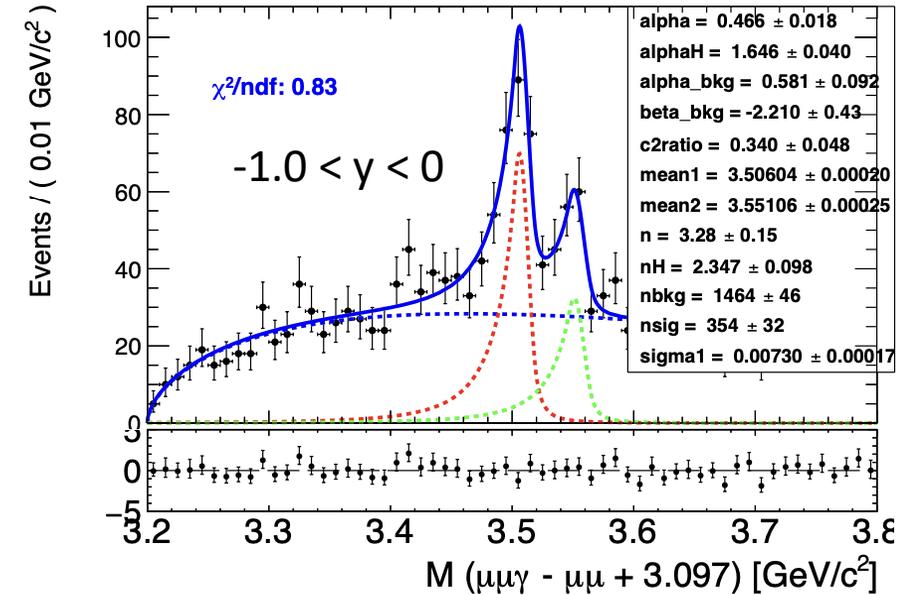
$$\mathcal{L}(\mu) = \prod f(m|\mu) * \text{Gaussian}(\mu_0; \mu, \sigma_\mu)$$

# Systematic Uncertainties - $\chi_c$ Fitting

In general, the deviation is in the range of 1%-4%

- Calculate Uncertainties with  $\sigma = \frac{N_{Gaussian} - N_{Nominal}}{N_{Nominal}}$

In  $\chi_{c2}/\chi_{c1}$  the low particle yields make statistical bias non-negligible.



# Systematic Uncertainties – Conversion Selection

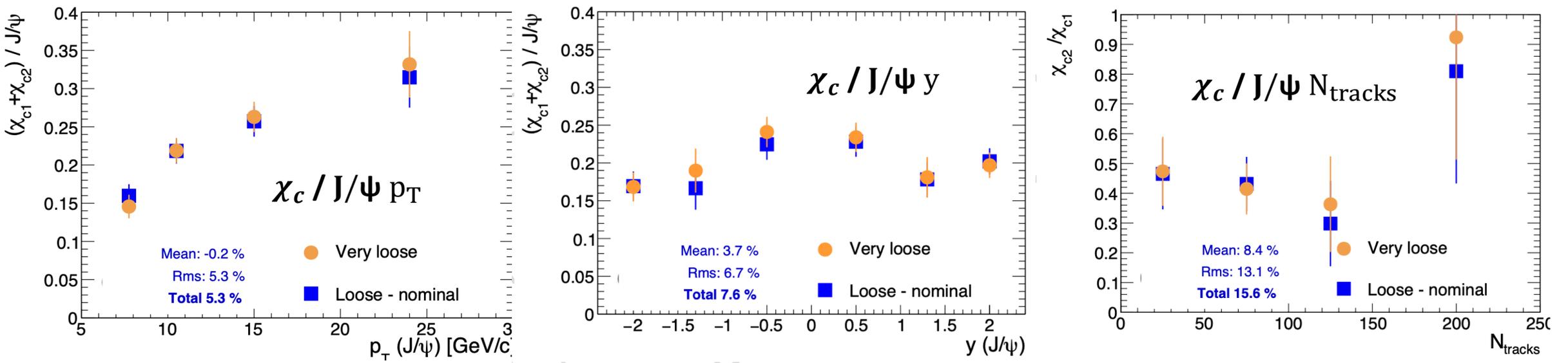
Varying the selection from nominal (**loose**) to a looser (**Very loose**) version

The analysis is redone using an alternative selection.

- Record differences

Uncertainties for  $p_T$ -differential, rapidity-differential and  $N_{\text{trk}}$ -differential are 5.3 %, 7.6 %, and 4.3 %

- These come from projections of the same total data-set and the differences are unlikely to be meaningful.
- Average to a single number 5.73 %



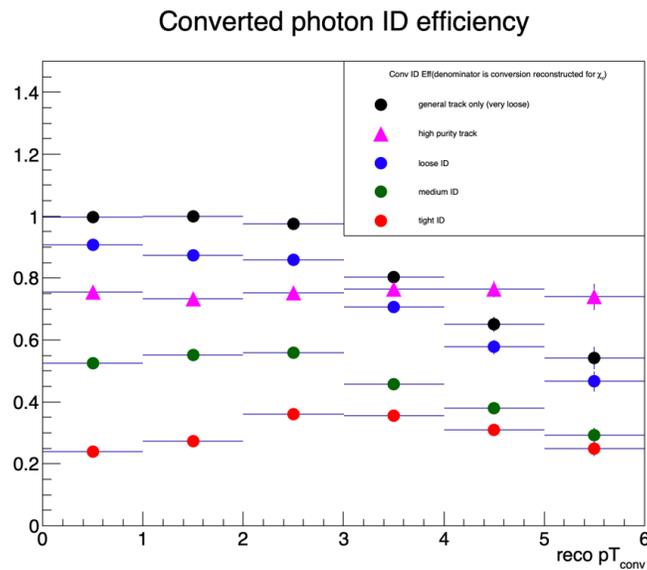
# Systematic Uncertainties – T&P method for Conversion Selection

Using the TnP data-driven method, we can assess the conversion efficiency directly from  $\pi_0$  candidates. ( $\pi_0 \rightarrow \gamma\gamma$ )

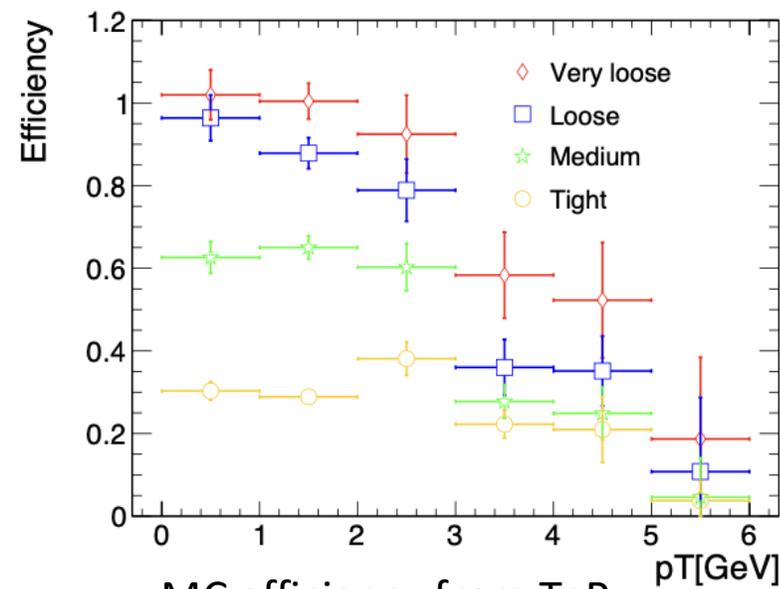
We calculated the  $\pi_0$  conversion efficiency for both MC and Data to determine whether MC is consistent with Data.

MC conversions was verified directly from  $\chi_c$  to crosscheck the results.

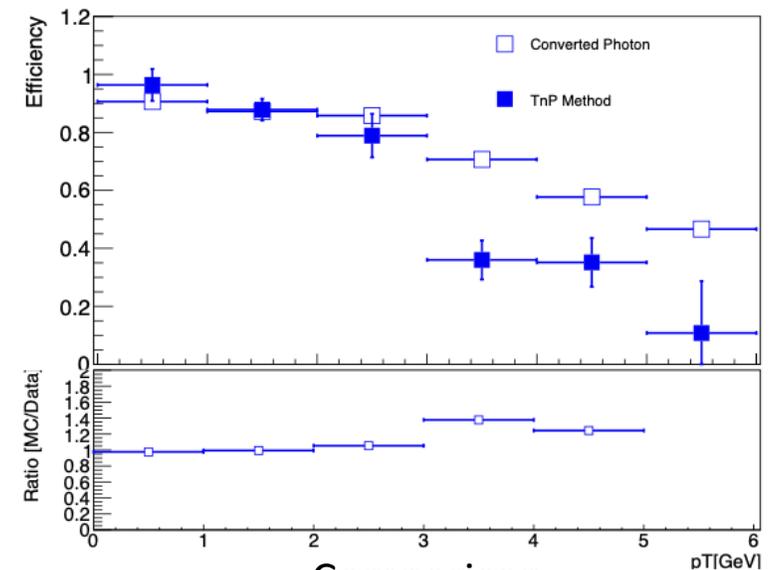
->The trends are quite similar at low pT. Since there are not much candidates at high pT, we consider this discrepancy to be negligible.



MC efficiency from  $\chi_c$



MC efficiency from TnP



Comparison

# Systematic Uncertainties – T&P method for Conversion Selection

## Comparison of data vs MC – T&P

Reconstruct invariant mass of  $\gamma\gamma$  conversion pair  
-> one must pass the loose selection (Tag)

Tag - photon pass the loose selection

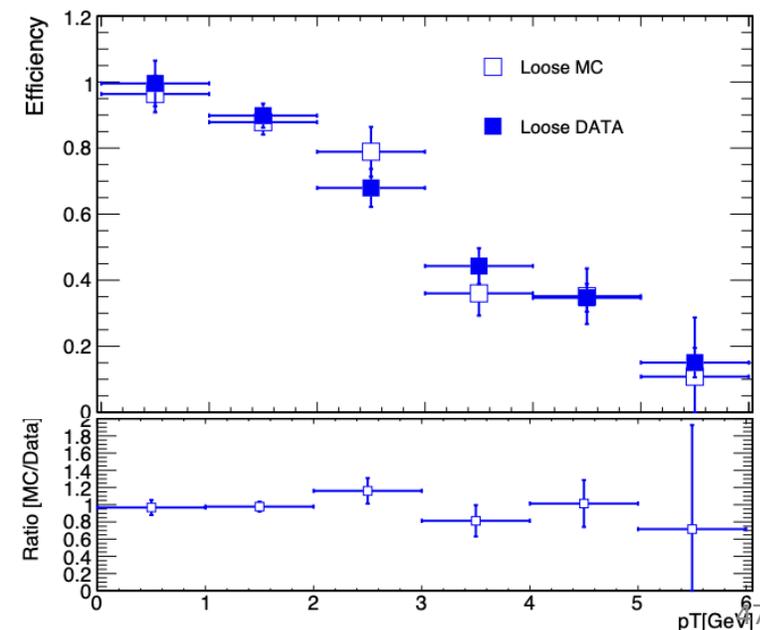
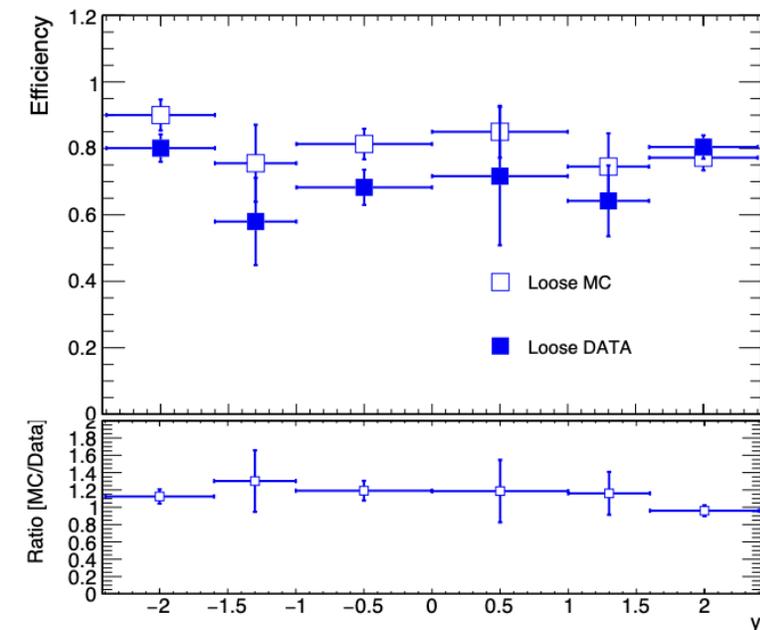
Probe – photon pass the analysis criteria

$$\sigma = \frac{\text{Candidate passed certain selection}}{\text{All Candidate(no selection)}}$$

Given the strong correlation at low  $p_T$ ,  
and the relatively minor ratio deviations across each rapidity bin

we conclude that deriving uncertainty through integrated bins  
(as the difference between MC and data)

-> 5 % uncertainty was added as the difference between MC and data.



# Systematic Uncertainties – MC settings

MC distributions primarily affect the photon acceptance and kinematic distributions

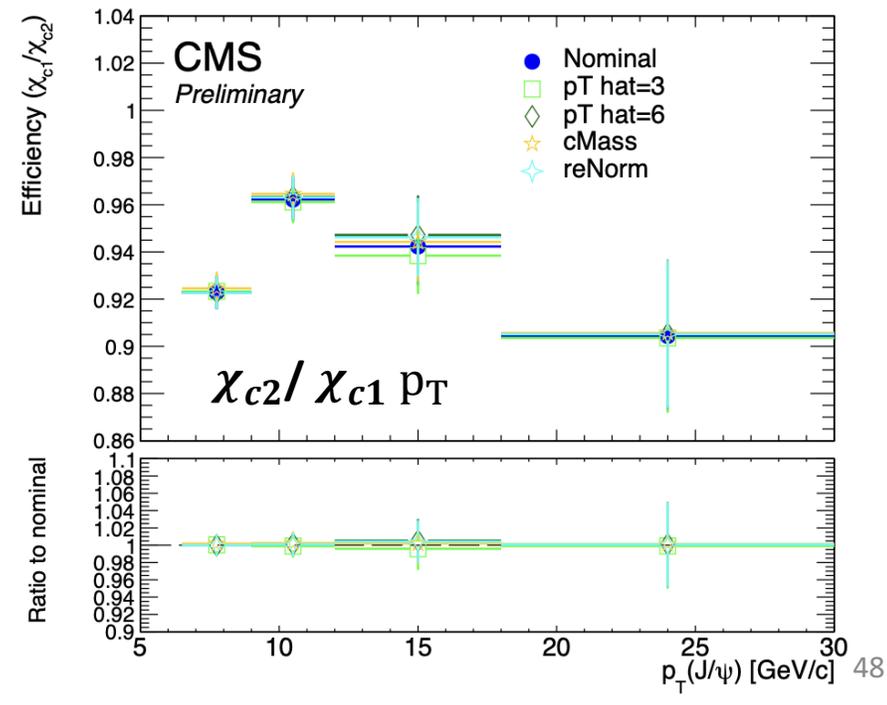
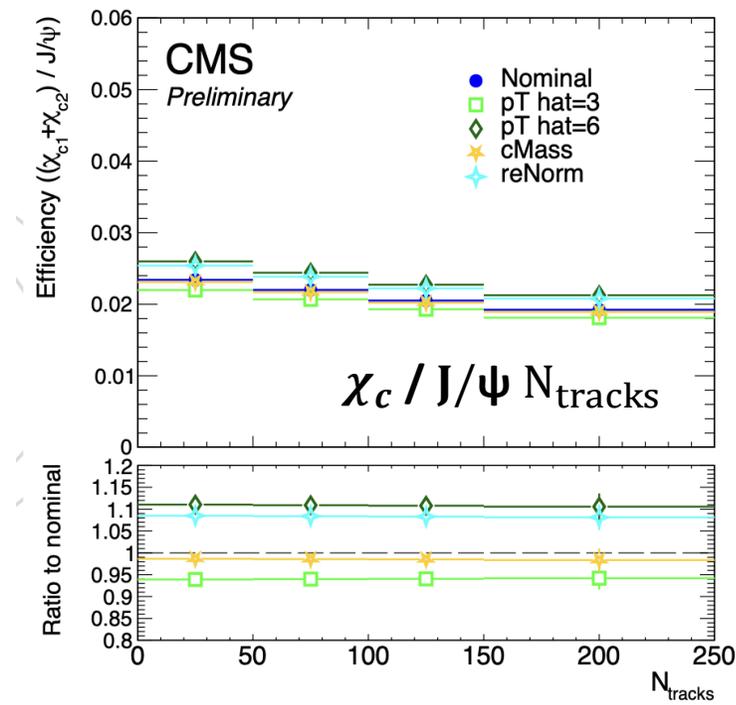
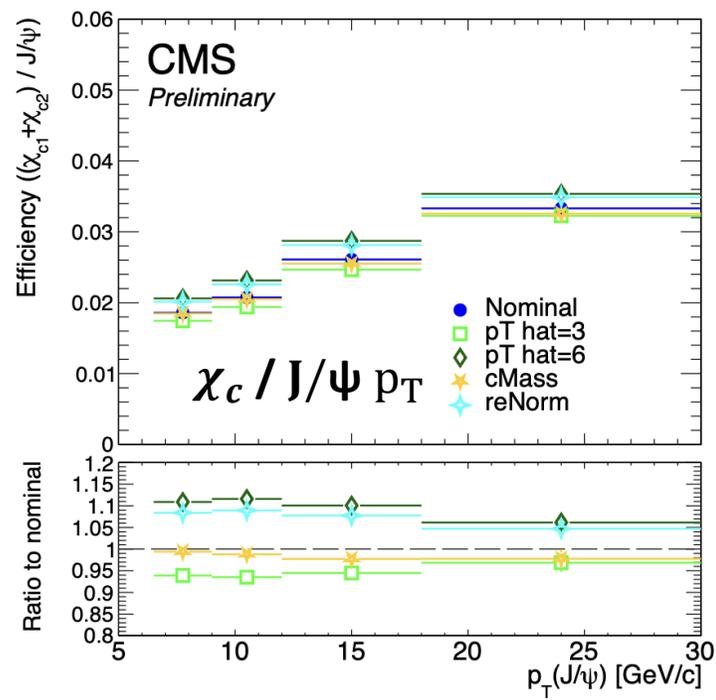
Approach: Vary the parameters of Pythia simulation

|                  | Nominal       | Alternative 1<br>pThat3 | Alternative 2<br>pThat6 | Alternative 3<br>c-mass | Alternative 4<br>reNorm |
|------------------|---------------|-------------------------|-------------------------|-------------------------|-------------------------|
| $pTHatMin$ [GeV] | 4.5           | 3.0                     | 6.0                     |                         |                         |
| $c$ -quark mass  | 1.5 (default) |                         |                         | 1.43                    |                         |
| $renormScale$    | 2 (default)   |                         |                         |                         | 3                       |
| $factorScale$    | 2 (default)   |                         |                         |                         | 3                       |
| $renormMultFac$  | 1 (default)   |                         |                         |                         | 2                       |
| $factorMultFac$  | 1 (default)   |                         |                         |                         | 2                       |

pThat c-quark – the value used in the similar study

Renormalization – Pythia 6 settings.

Relevant for  $\chi_c / J/\psi$   
Negligible for  $\chi_{c2} / \chi_{c1}$



# Systematic Uncertainties – Non-Prompt Contamination

## Non-prompt production cannot be neglected at LHC energy

We measured the  $\chi_c / J/\psi$  and  $\chi_{c2} / \chi_{c1}$  in datasets with different cuts and estimated the non-prompt fraction.

The uncertainty is determined by the difference between the ratio at the nominal non-prompt cut and at the point where the contamination is zero

