Measurement of χ_c production in pPb collisions at $\sqrt{S_{\mathrm{NN}}} = 8.16\ \mathrm{TeV}$

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On behalf of the CMS collaborations

Presentation Outline

Motivation and Overview

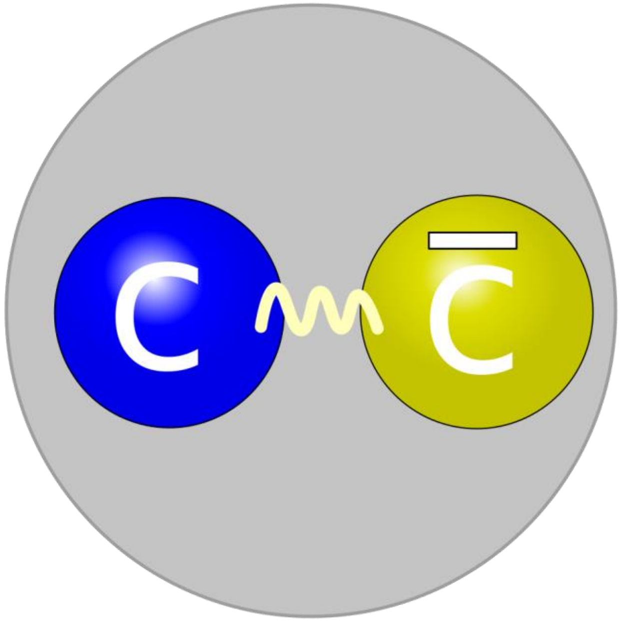
Analysis Details

- Signal Extraction
- Efficiencies
- Systematic Uncertainties
- Polarization
- Results

Summary

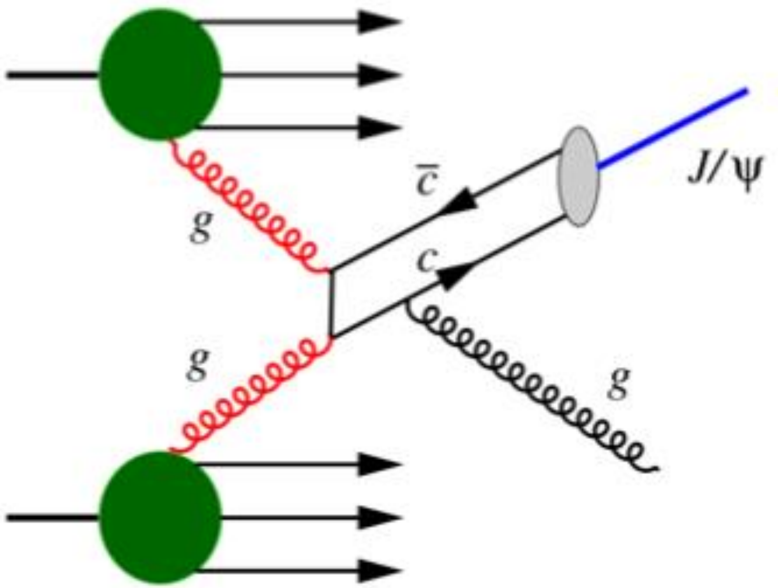
Analysis Motivation

Main goal: To study how is χ_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).

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.

Analysis Motivation

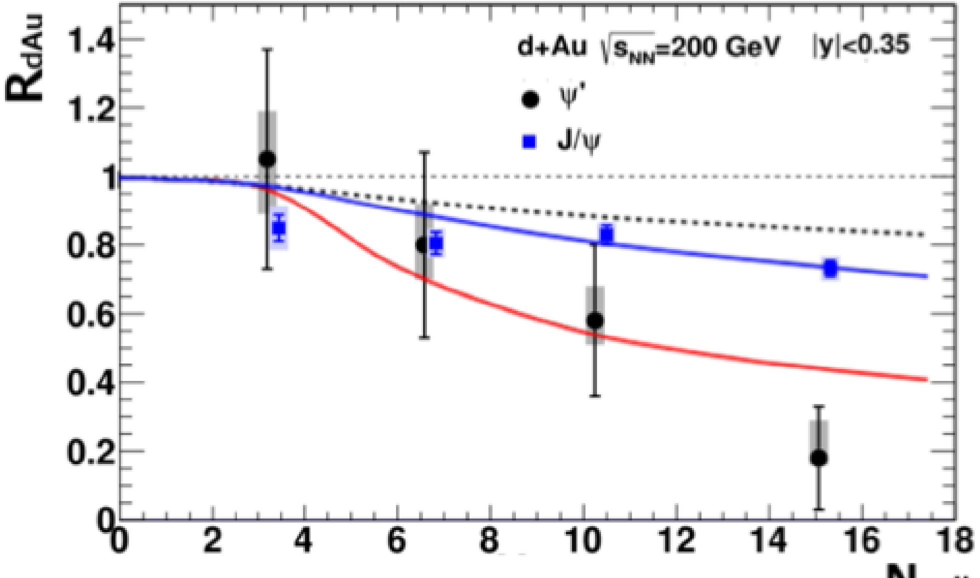
Main goal: To study how is χ_c ($c\bar{c}$ P-states) affected in pPb compared to pp collisions.

Previous measurement are done mostly in S-states.

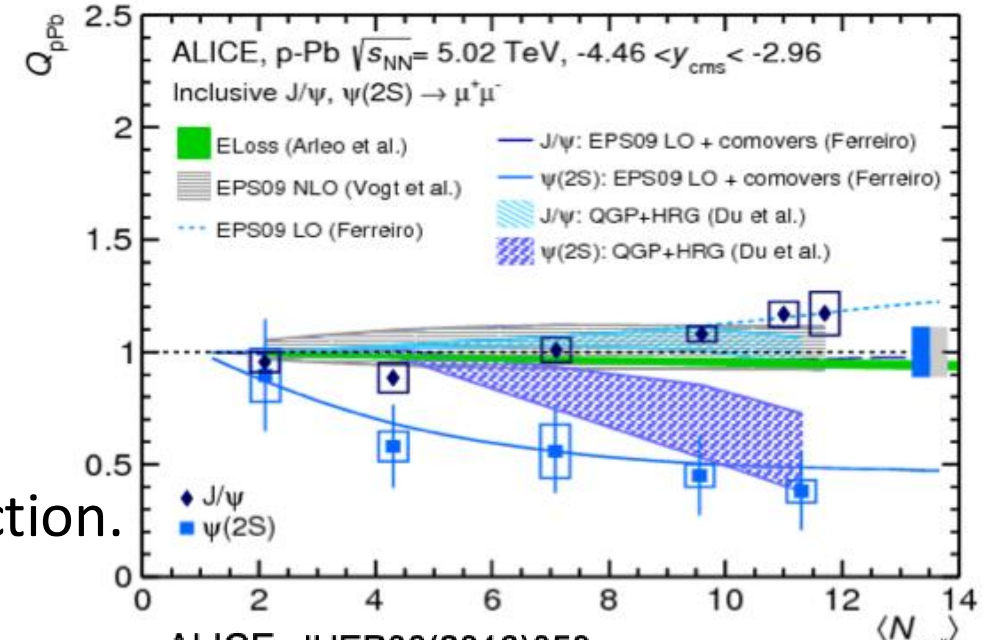
The ψ(2S) Study have shown that excited state has a different suppression.
(Which is not explain only by Initial-state effect)

A trend of increasing relative suppression is increased when multiplicity(or related variables) increases.

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



PHENIX, PRL111.20, 202301



ALICE, JHEP06(2016)050

Analysis Motivation

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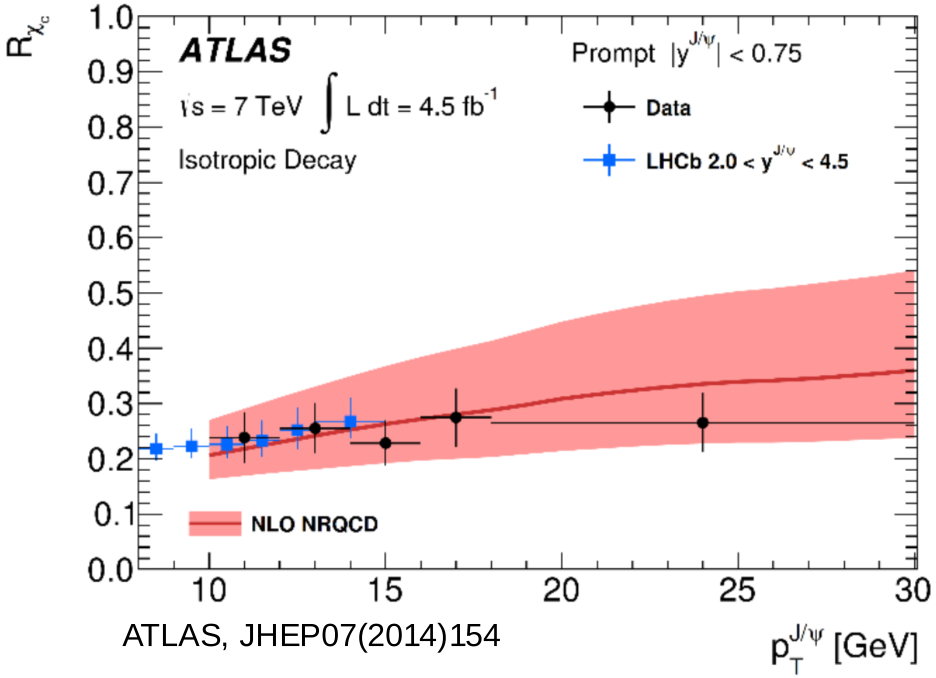
Previous measurement are done mostly in S-states.

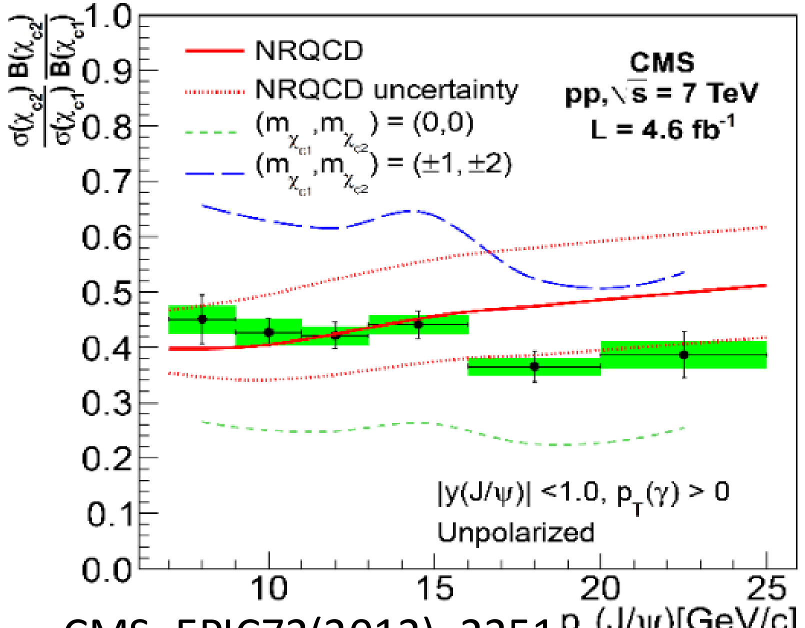
Not much data on χ_c at LHC energies



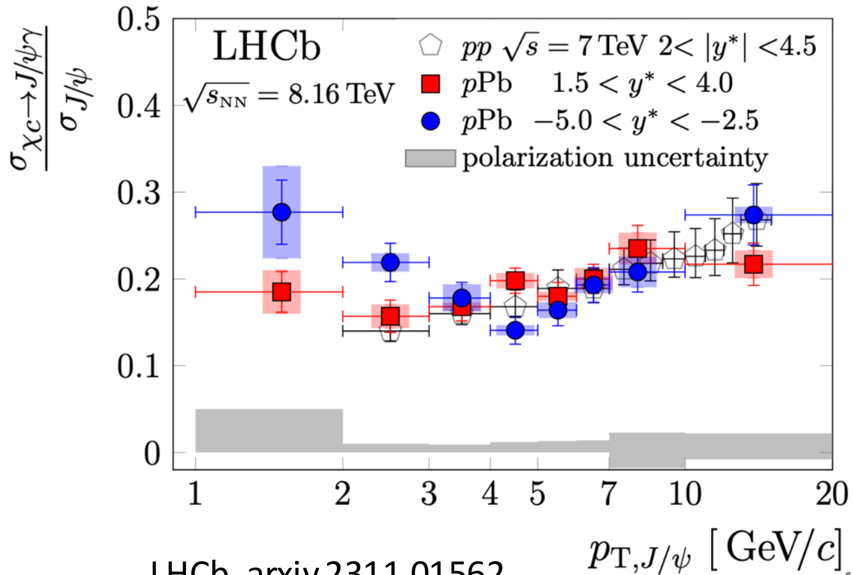
ATLAS, JHEP07(2014)154

pPb : χ_{c2}/χ_{c1}(LHCb)
χ_c / J/ψ(LHCb)

pp :
χ_{c2}/χ_{c1}
(CMS, ATLAS, LHCb)
χ_c / J/ψ
(ATLAS, LHCb)



CMS, EPJC72(2012), 2251



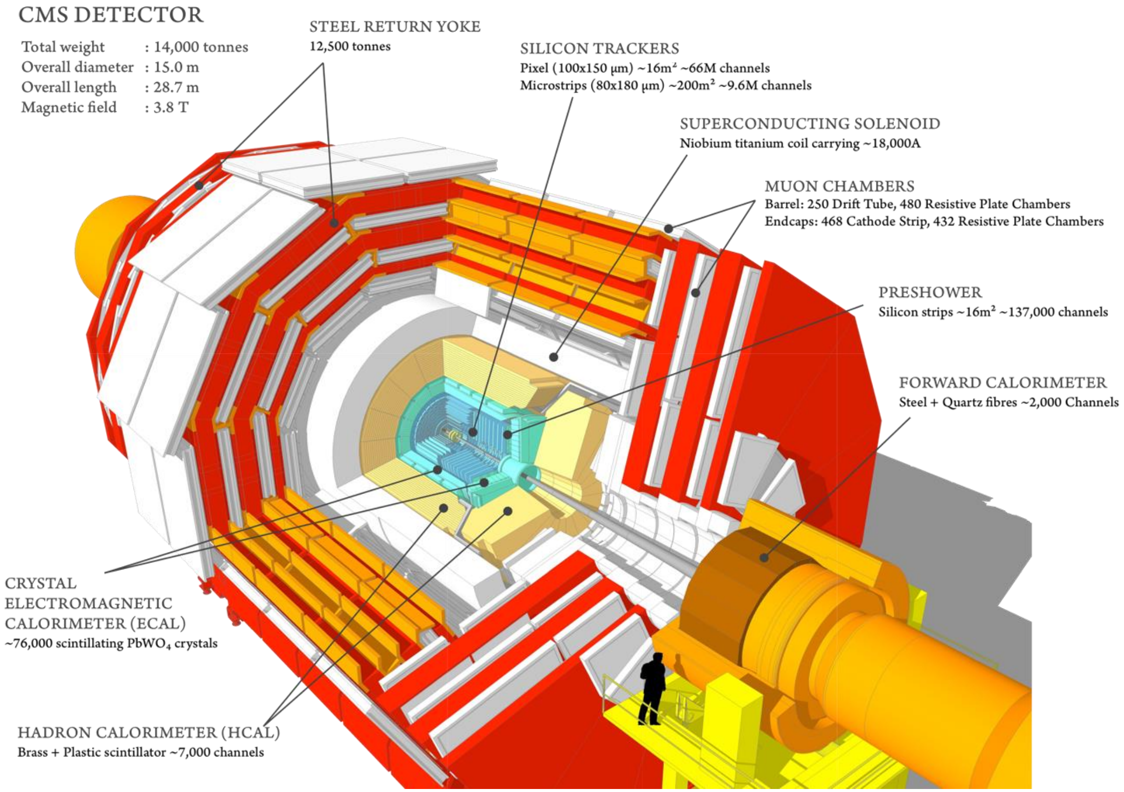
LHCb ,arxiv.2311.01562

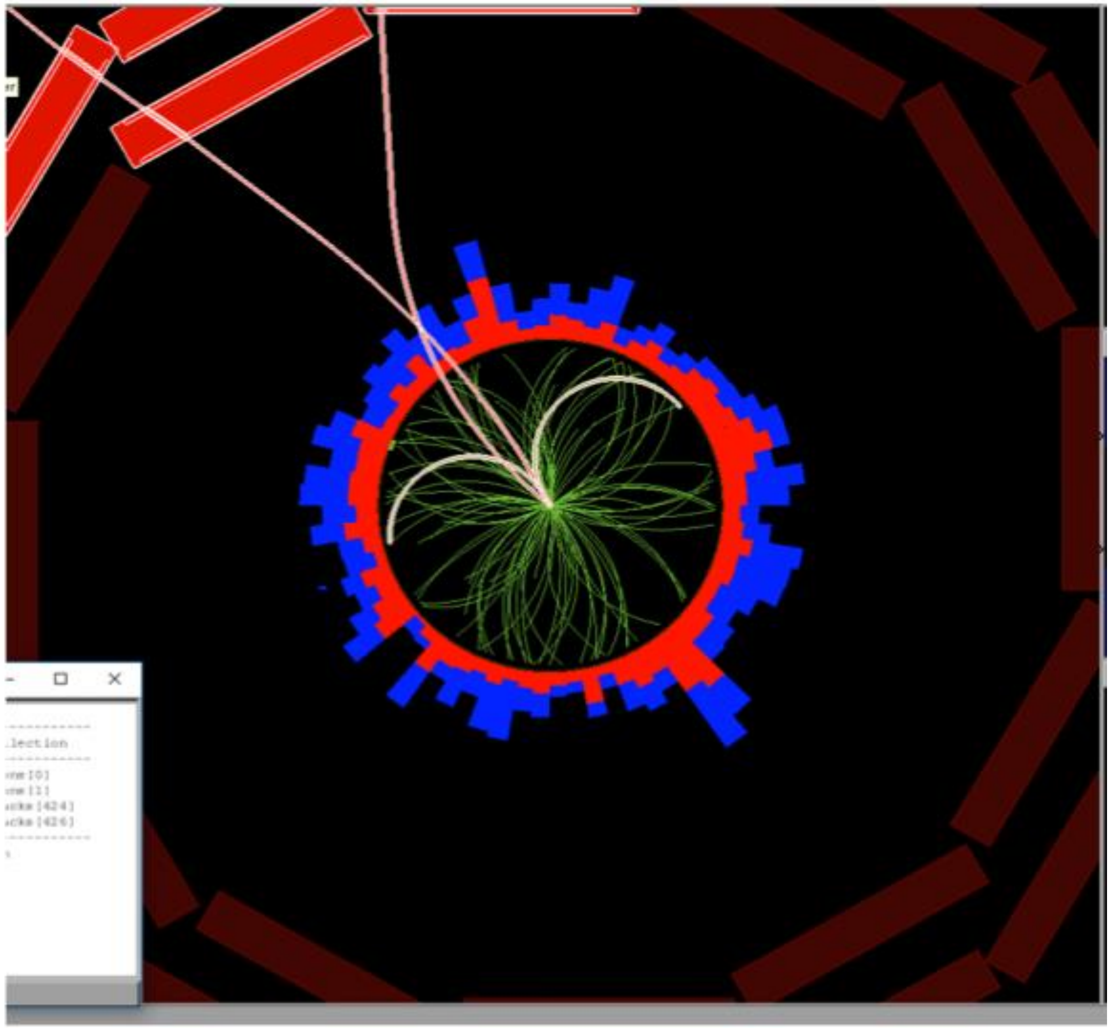
Analysis Overview

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

pPb 8.16 TeV

Reporting χ_c / J/ψ and χ_{c2}/ χ_{c1}





Signal Extraction

Motivation and Overview

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Analysis Bins

Note : Kinematic variables of χ_c is expressed in values of J/ψ daughter

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

Ntrack 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/ψ), only for χ_c / J/ψ due to low statistics for χ_{c2} / χ_{c1}
    - (-2, -1, 1, 2) Center of mass rapidity

J/ψ Fitting

Signal : Crystal Ball function

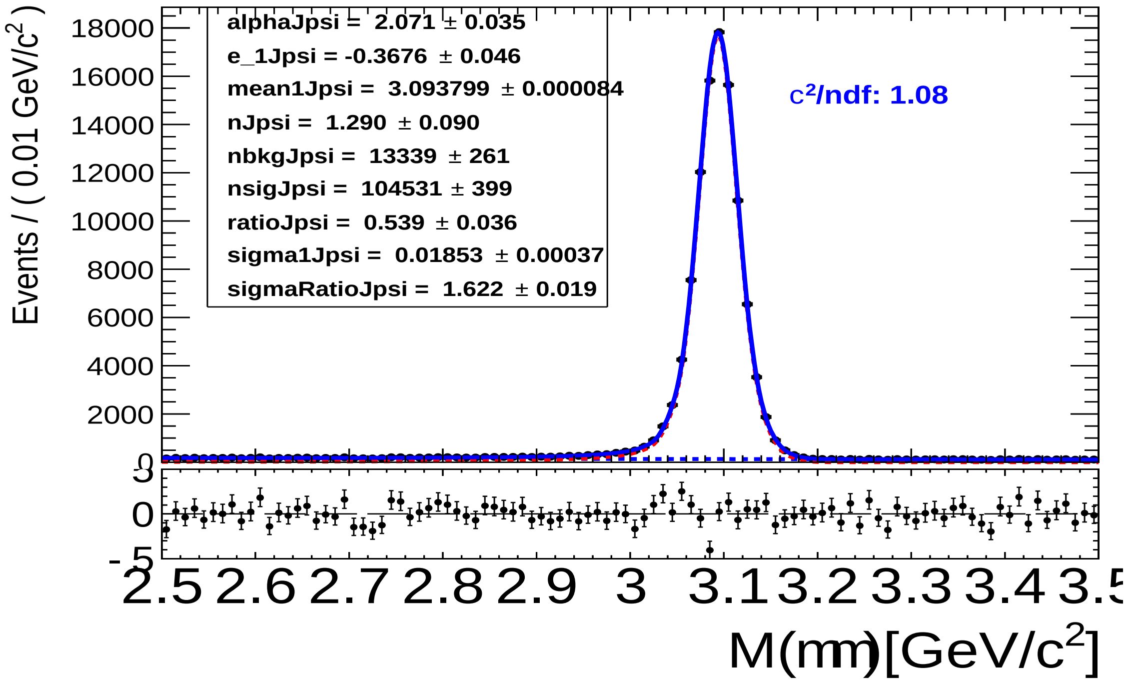
- Gaussain core to describe the detector resolution
- one -sided tail to model the energy loss by the decay muons via final-state photon radiation.

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

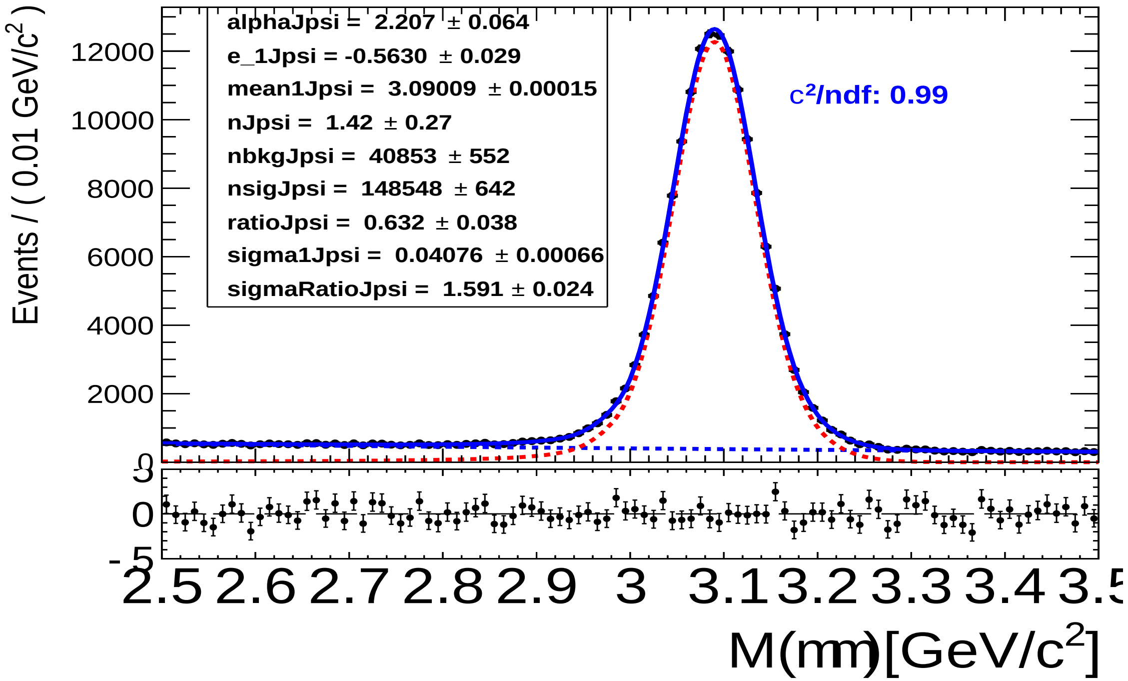
Background : Exponential

Relatively straightforward (very good S/B ratio)

0 < y < 1.0



1.6 < y < 2.4



χ_c Fitting

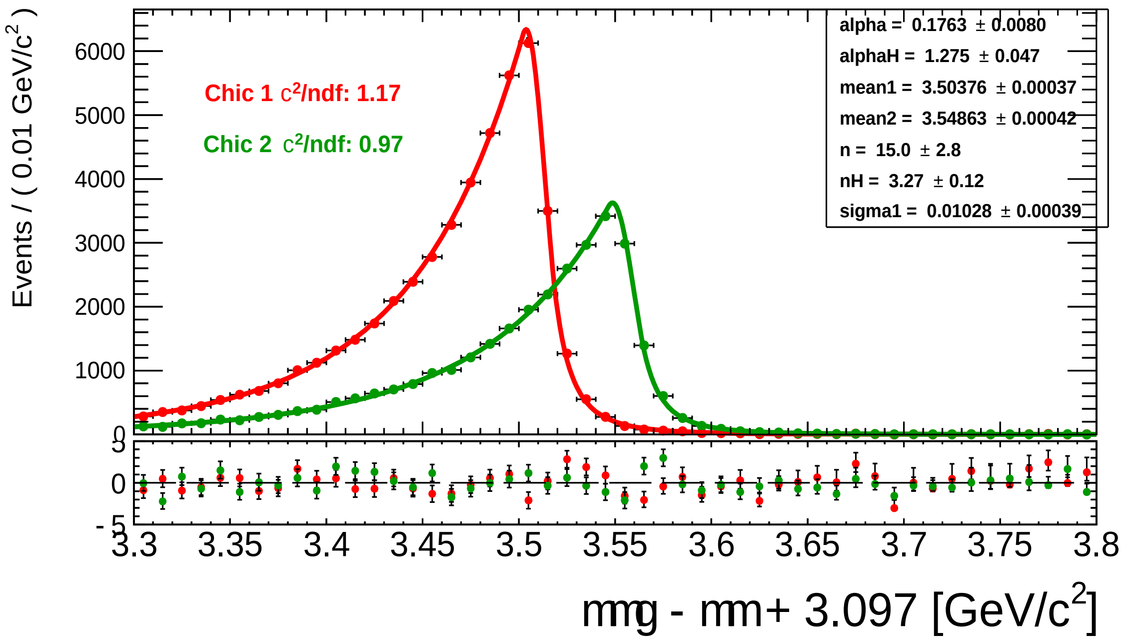
Using MC to constrain the shape

- **Due to low S/B**

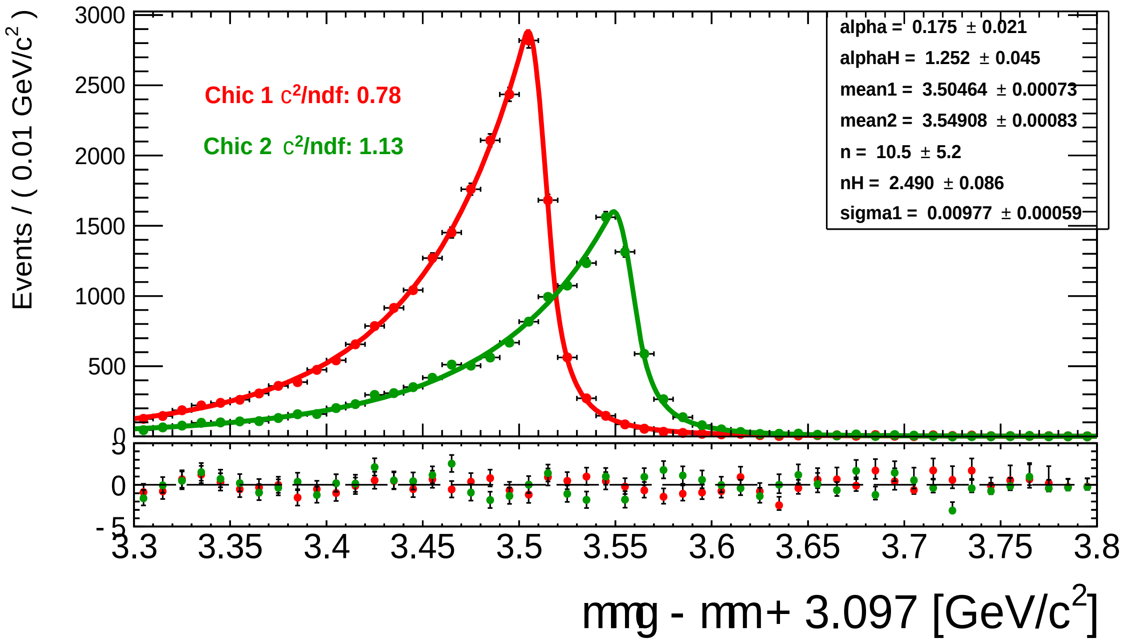
Signal : Double side Crystal Ball function for each peak

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

$0 < N_{tracks} < 50$



$100 < N_{tracks} < 150$



χ_c Fitting

Background : threshold function

- Used previous analysis

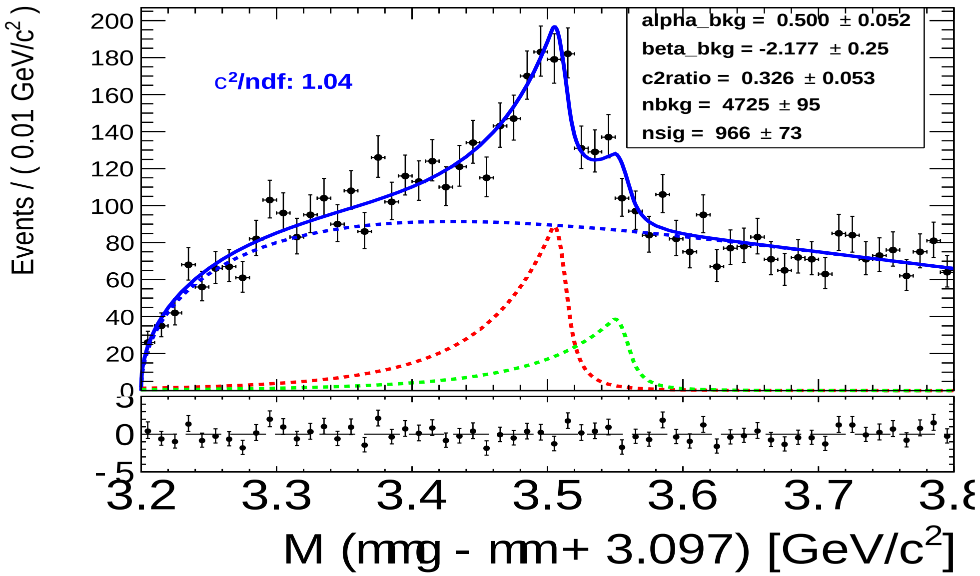
$$\mathrm{BKG}(m) = (m - q_0)^{\alpha_1} \cdot e^{(m-q_0)\cdot\beta_1}$$

q_0 is fixed to 3.2 GeV

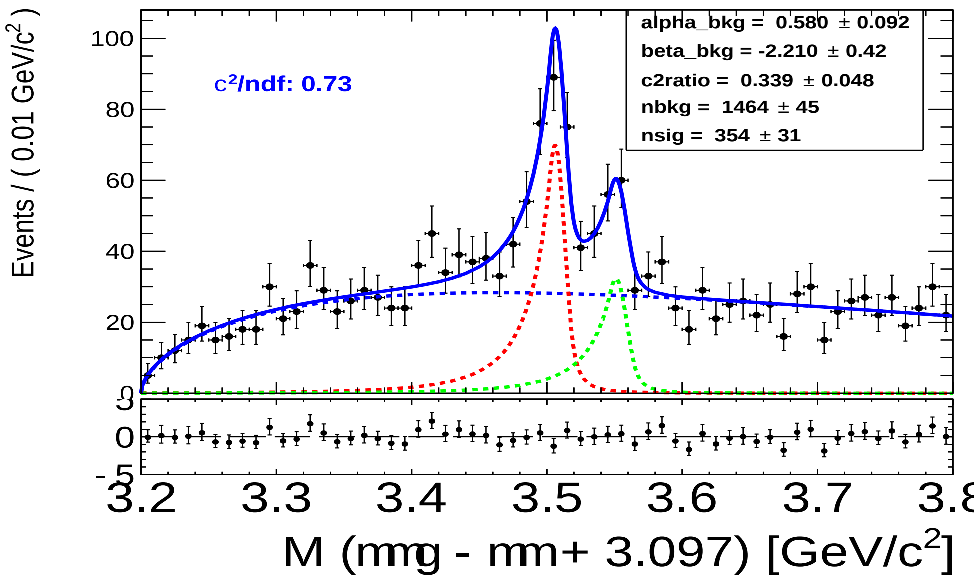
Overall Fit

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

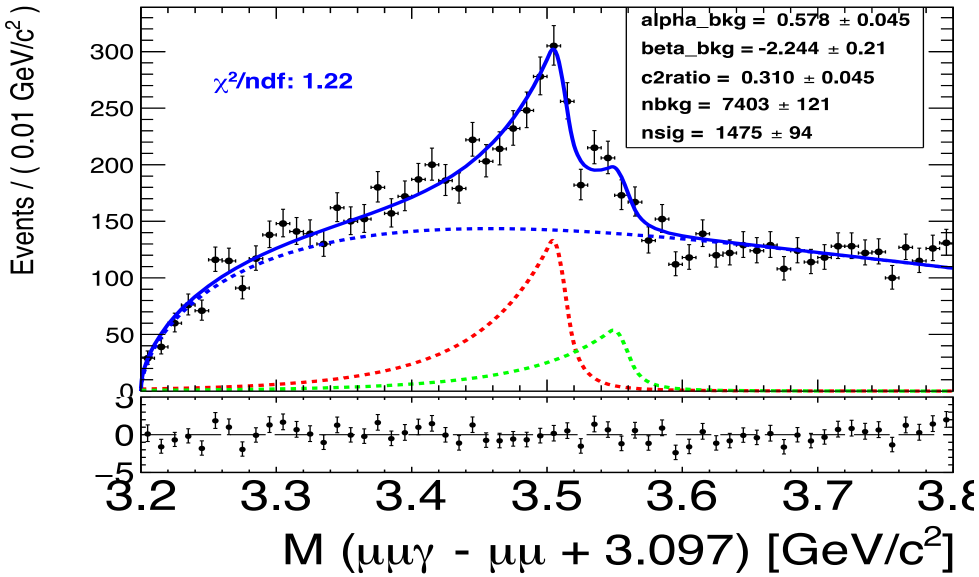
$50 < N_{\mathrm{tracks}} < 100$



0 < y < 1.0



$9 < p_T < 12$ GeV



Efficiencies

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Efficiencies

Corrections calculated from MC directly for the ratio we use

-Both χ_{c2}/χ_{c1} and χ_c / J/ψ

χ_{c2}/χ_{c1} p_T

Take advantage of cancelation of some contributions

Efficiency trends mainly driven by the photon efficiency

χ_c / J/ψ p_T

χ_c / J/ψ y

χ_c / J/ψ N_{tracks}

Systematic Uncertainties

Motivation and Overview

Analysis Details

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- **Systematic Uncertainties**
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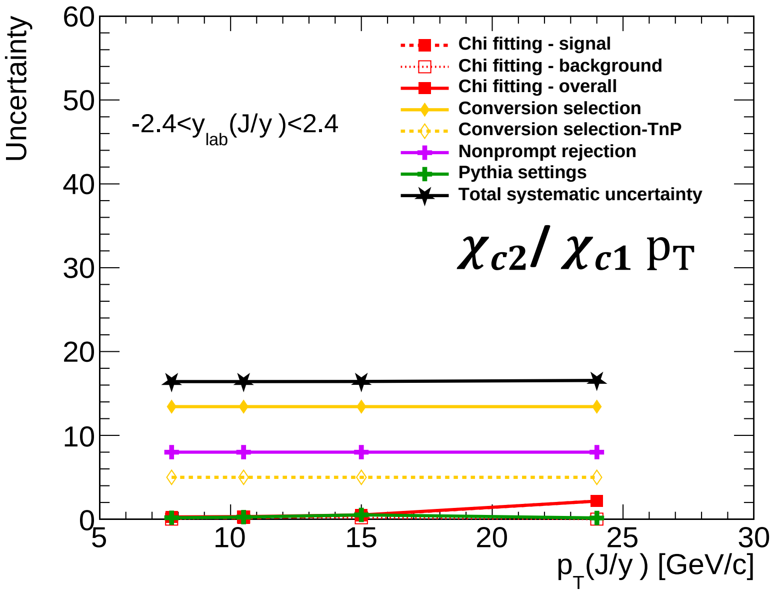
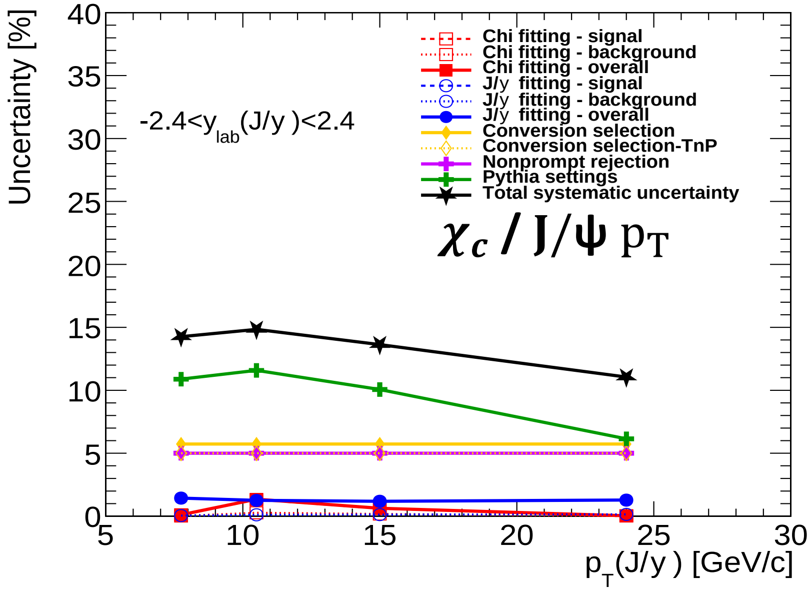
Summary

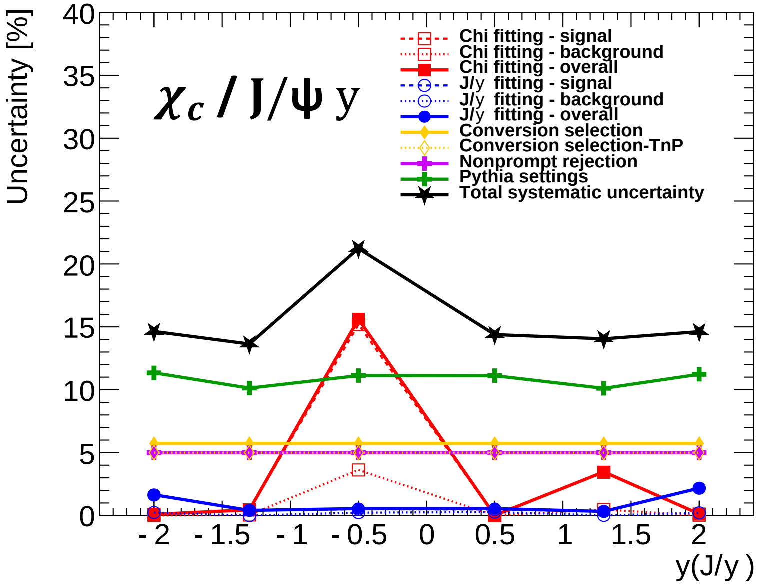
Systematic Uncertainties - Overview

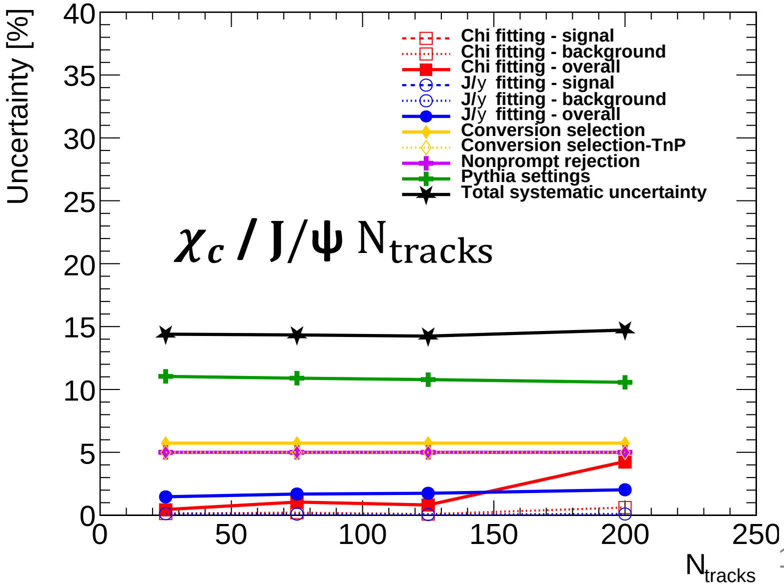
Four main groups of systematic uncertainties

- **Fitting procedure for both χ_c and J/ψ**
- **Conversion Selection**
- **Monte Carlo Settings (Pythia settings)**
- **Non-prompt rejection**









Systematic Uncertainties – J/ψ Fitting

Using 100 toy data (each bin) to compare alternative signal and background

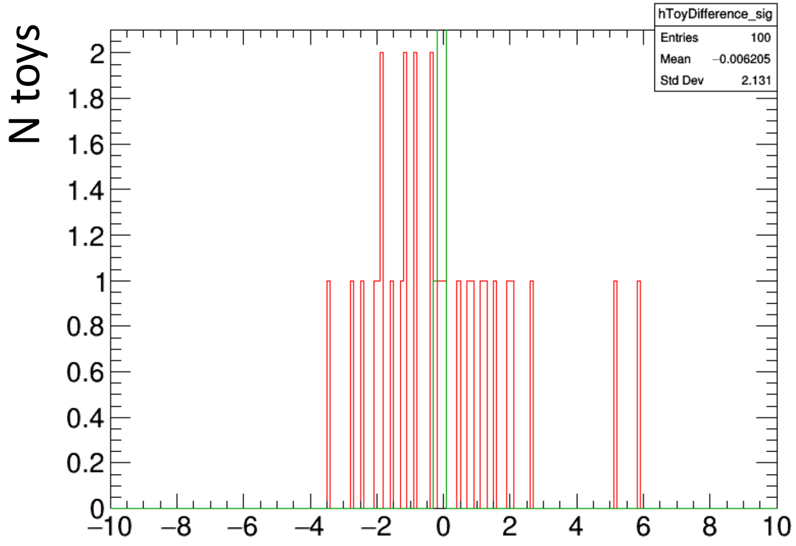
1. Generate the pseudodata and fit with nominal function.
2. Fit the pseudodata with alternative signal function.
3. Fit the pseudodata with alternative background function.
4. Repeat 100 times.
5. Calculate systematic uncertainties as $\epsilon = \sqrt{mean^2 + RMS^2}$

Alternative Signal – Hypatia + Gaussian

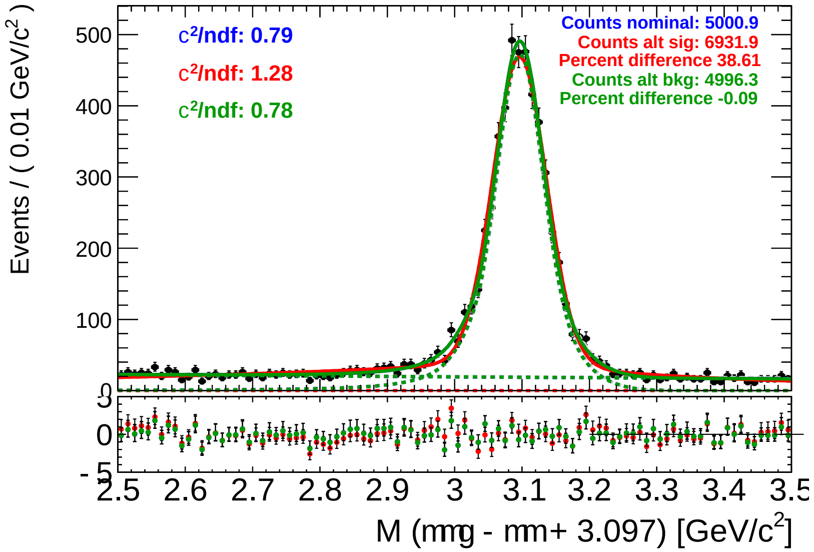
Alternative Background – First-order polynomial

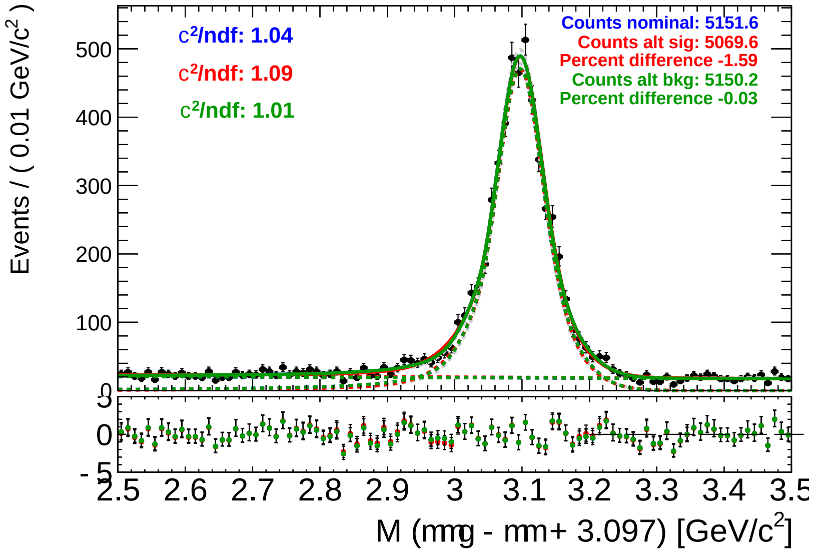
	Nominal	Alternative signal	Alternative background
Signal	CB+CB	Hypatia + Gaussian	CB+CB
Background	Exponential function	Exponential function	First-order polynomial

2 example toys at -2.4 < y < - 1.6



Green –bkg , Red - sig % dif





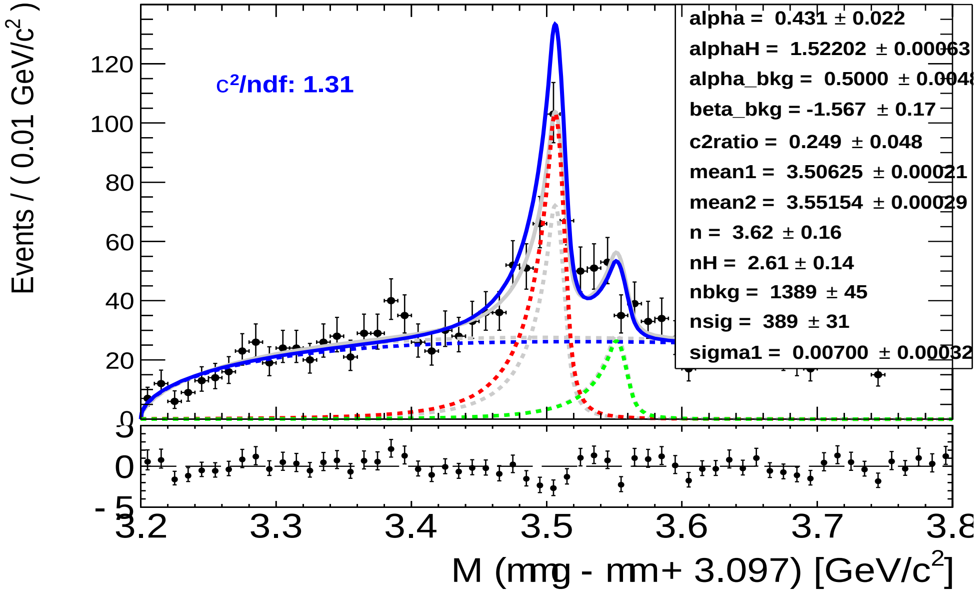
Blue – Nominal Green – alt bkg , Red – alt sig

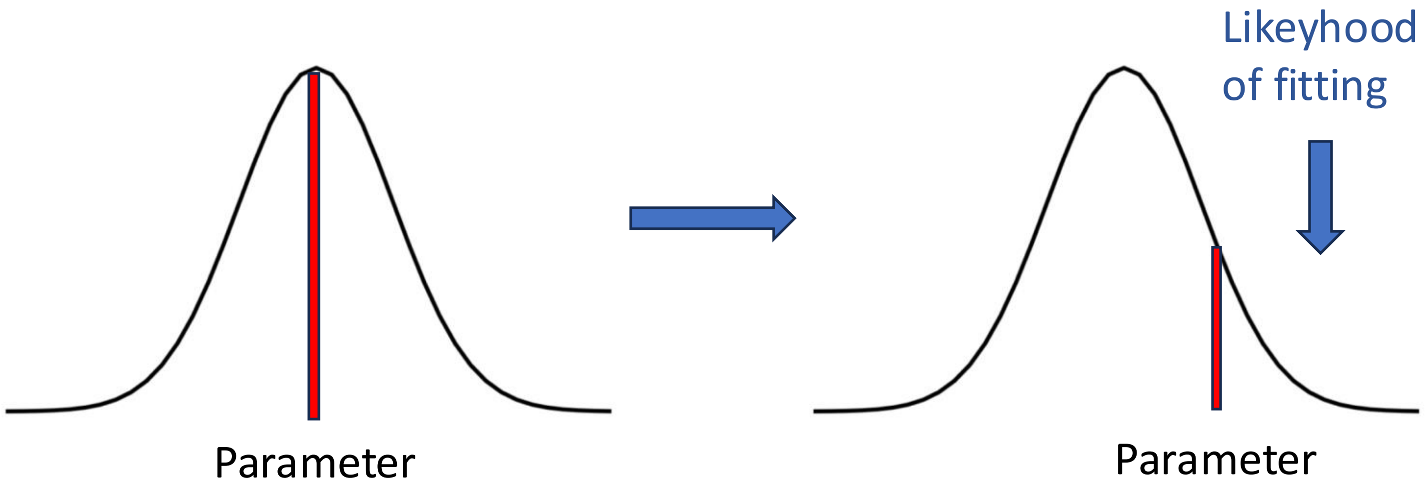
Systematic Uncertainties - χ_c Fitting

- **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.**





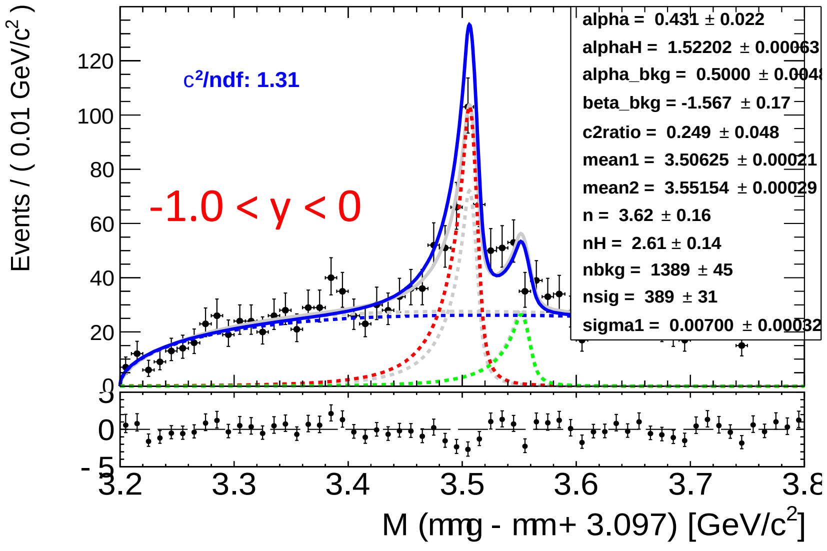
(The gray line is the Nominal result which used constrained parameter by MC.
The fitting function doesn't deviate too much)

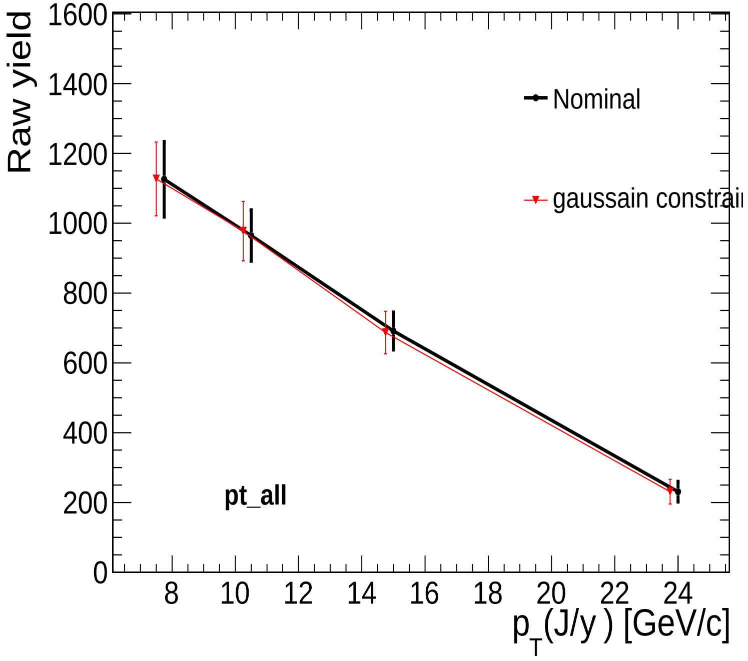
Systematic Uncertainties - χ_c Fitting

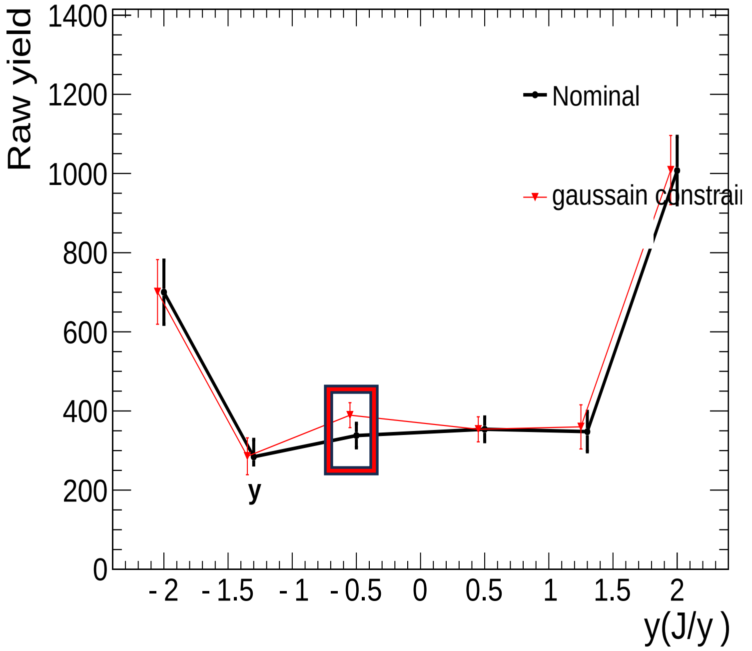
Overall there's not much deviation for each bin

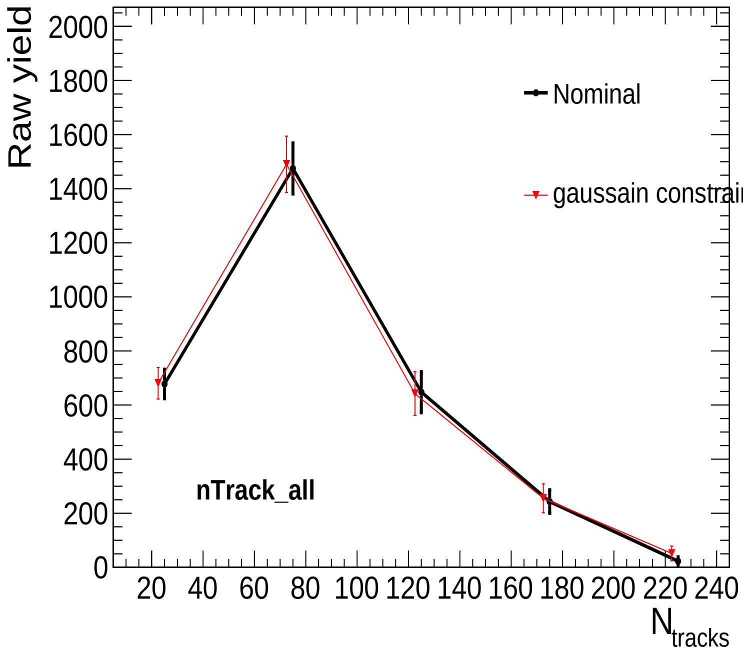
- Some bin shows relatively large deviation compared to others but the fitting seems reasonable

- Calculate Uncertainties with $\epsilon = \dfrac{N_{Gaussian} - N_{Nominal}}{N_{Nominal}}$









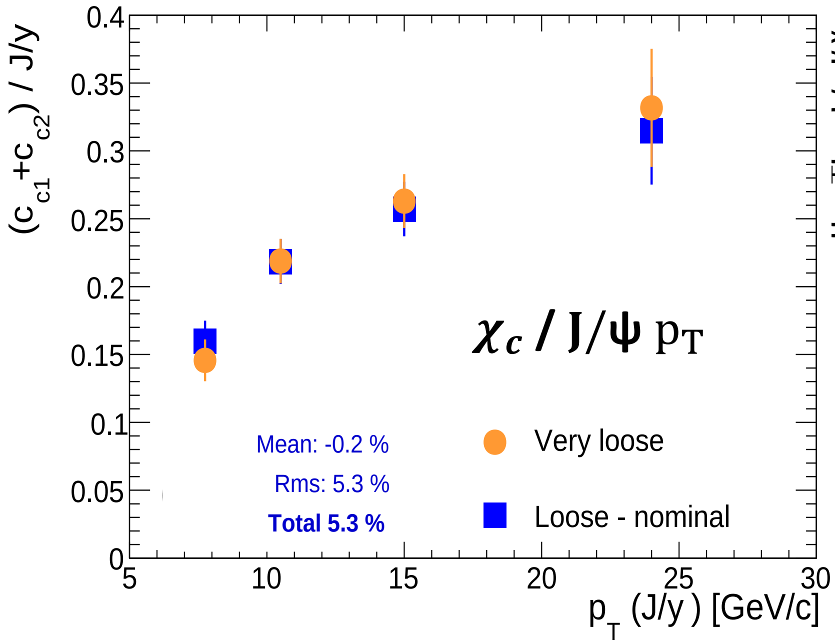
Systematic Uncertainties – Conversion Selection

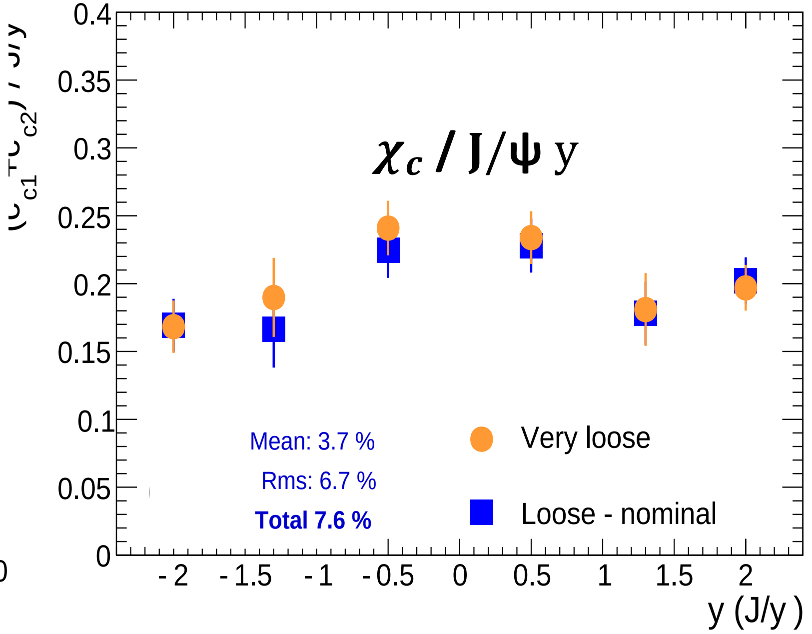
Varying the selection from nominal (loose) to a looser (Very loose) version

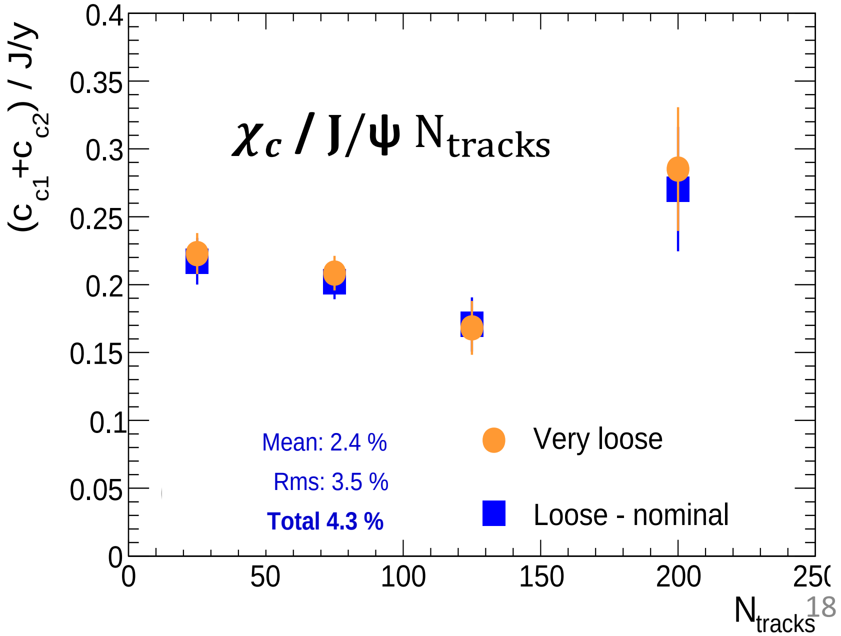
Redo the analysis with alternative selection and record the difference

Uncertainties for pT, rapidity and Ntracks 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 %





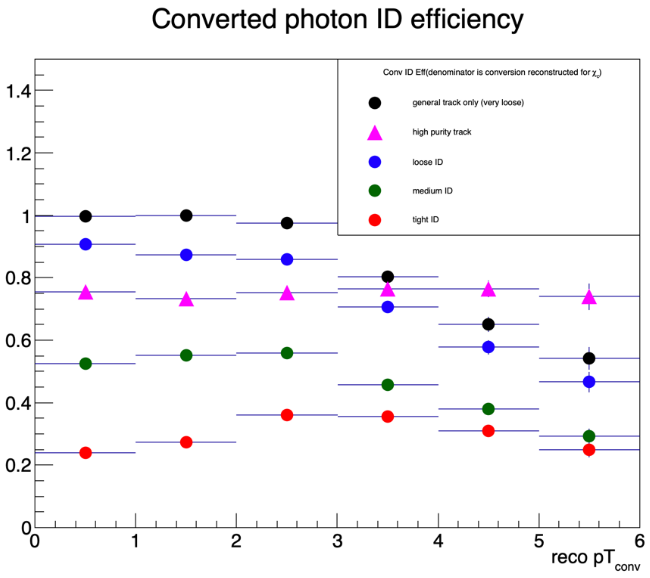


Systematic Uncertainties – Conversion Selection TnP

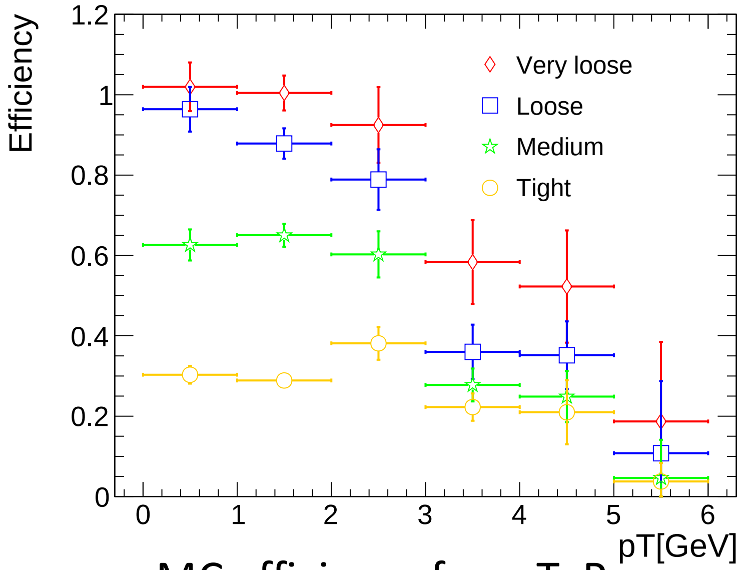
Using the TnP data-driven method, we can assess the conversion efficiency directly from π_0 candidates. ($\pi_0 \rightarrow \gamma\gamma$)

Calculate the π_0 conversion efficiency for both MC and Data to determine if MC is consistent with Data.

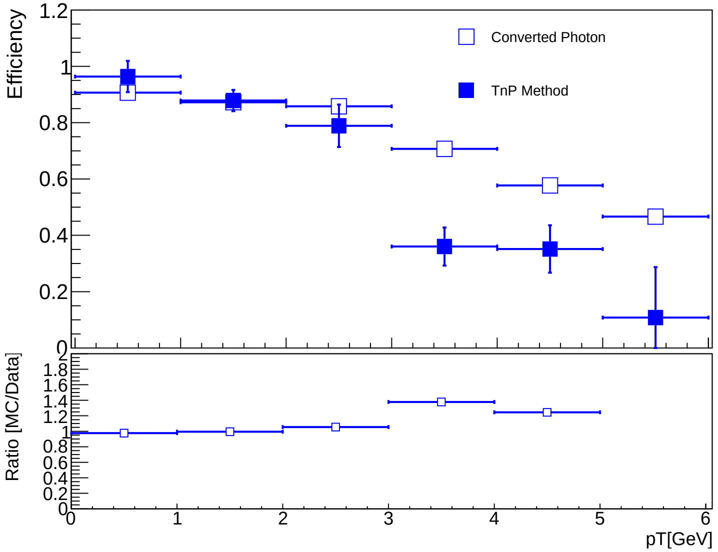
Verify MC conversions directly from χ_c to crosscheck the results.
->The trends are quite similar at low pT. Since there are not much candidates at high pT, we consider this discrepancy to be negligible.



MC efficiency from χ_c



MC efficiency from TnP



Comparison

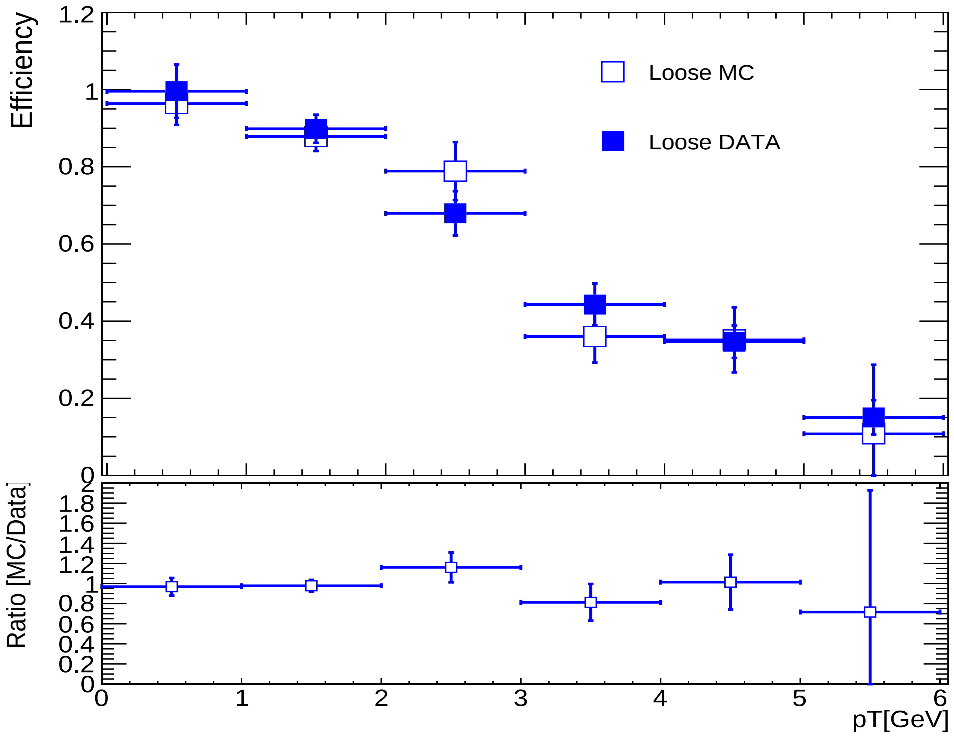
Systematic Uncertainties – Conversion Selection TnP

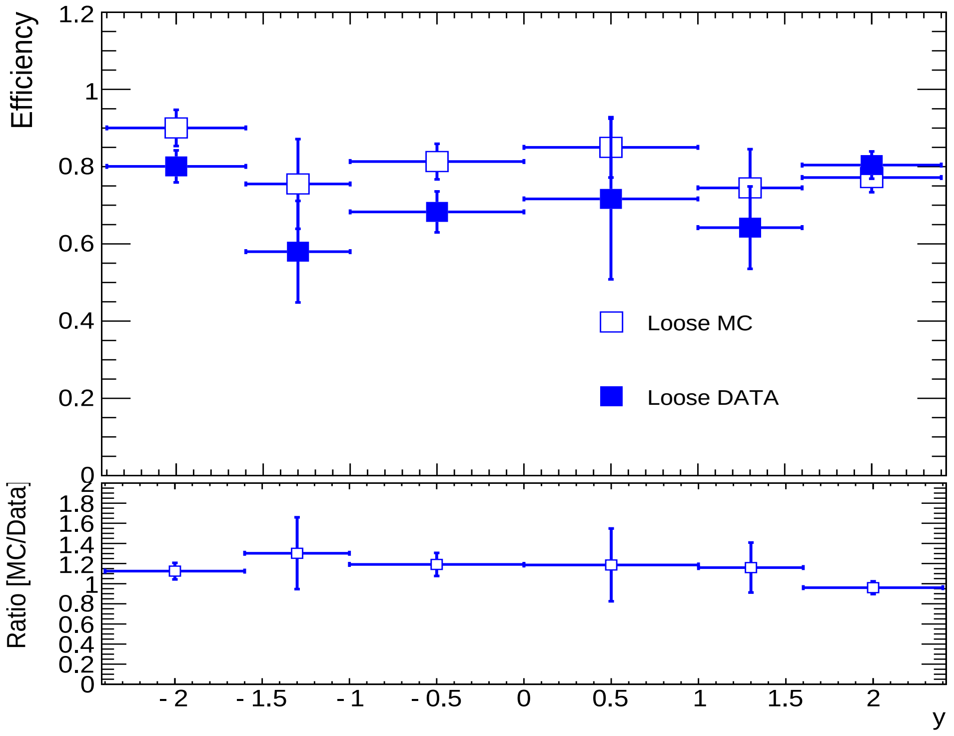
Comparation of data vs MC

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

Given the strong correlation at low pT (low candidate) , 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 will be added as the difference between MC and data.





Systematic Uncertainties – MC settings

MC distributions primarily affect the photon acceptance and kinematic distributions

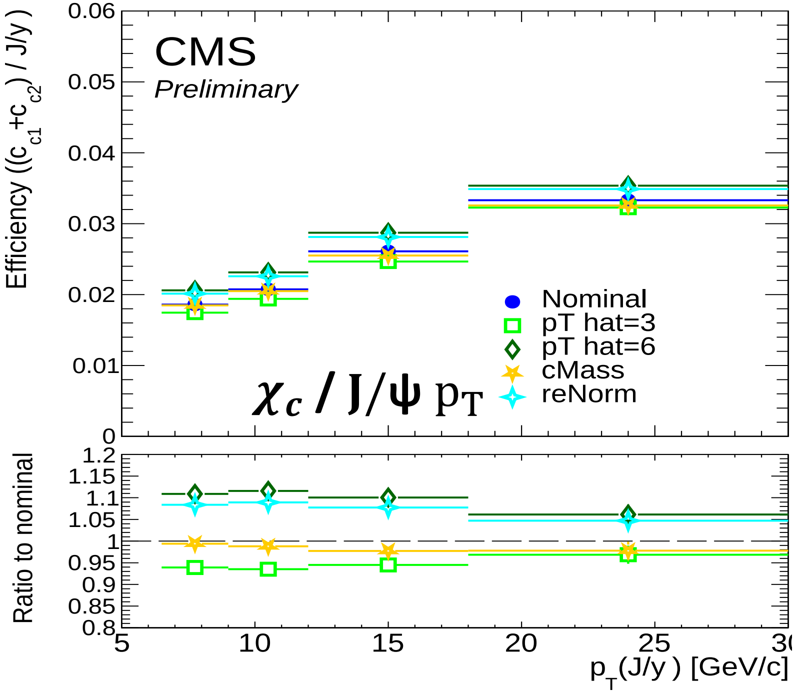
Approach: Vary the parameters of Pythia simulation

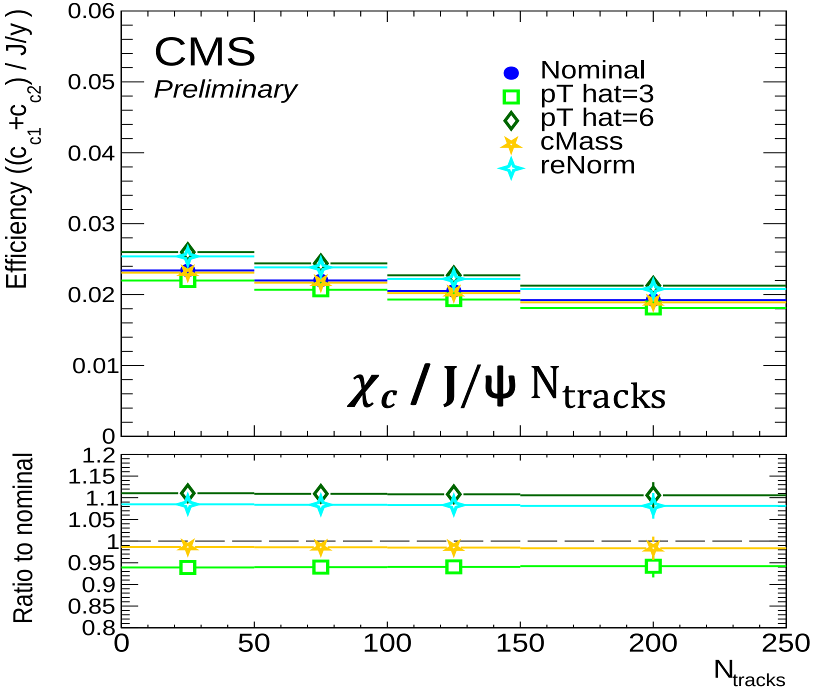
- pThat , c mass, renormalization and factorization

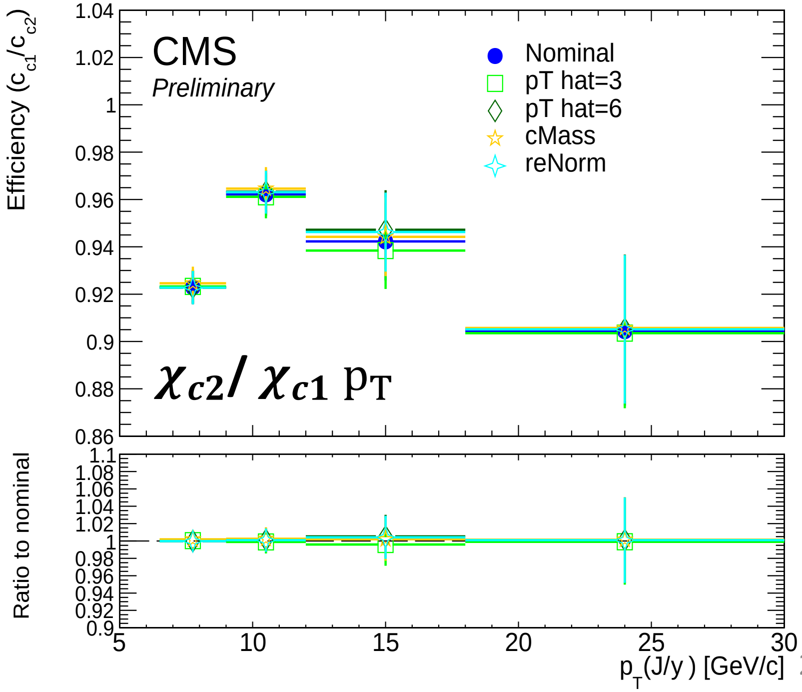
- Using small private MC sample derived from the official MC

- Sample reweighted to match the data p_T distribution

Relevant for χ_c / J/ψ
Negligible for χ_{c2}/ χ_{c1}



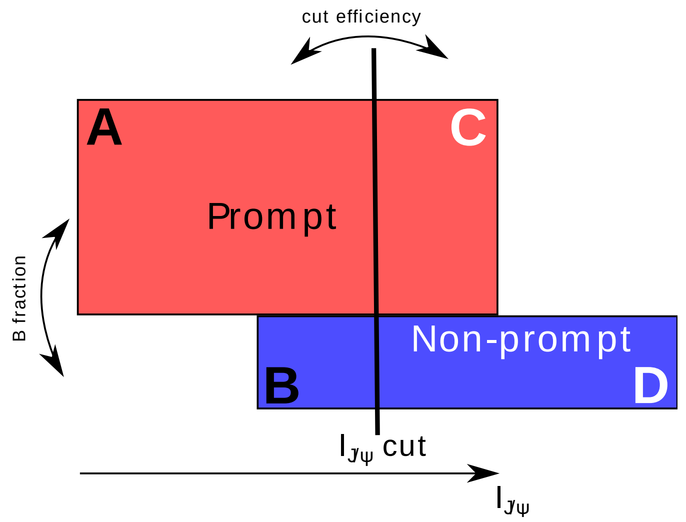




Systematic Uncertainties – Non-Prompt Rejection

Non-prompt production can't be neglected at LHC energy

-> It is important to estimate how much our selected dataset is contaminated by non-prompt contribution



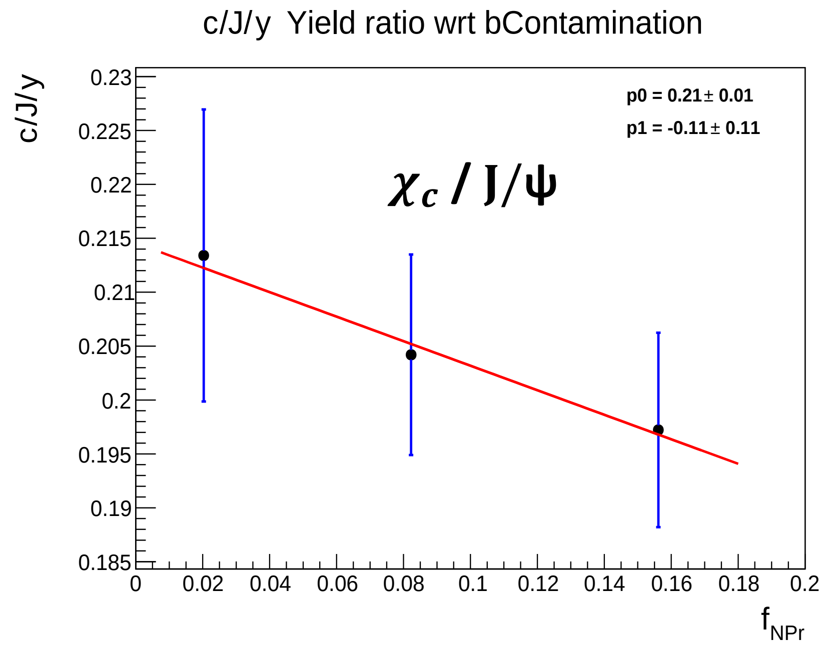
Prompt J/ψ and non-prompt J/ψ embedded in EPOS samples were used for this study

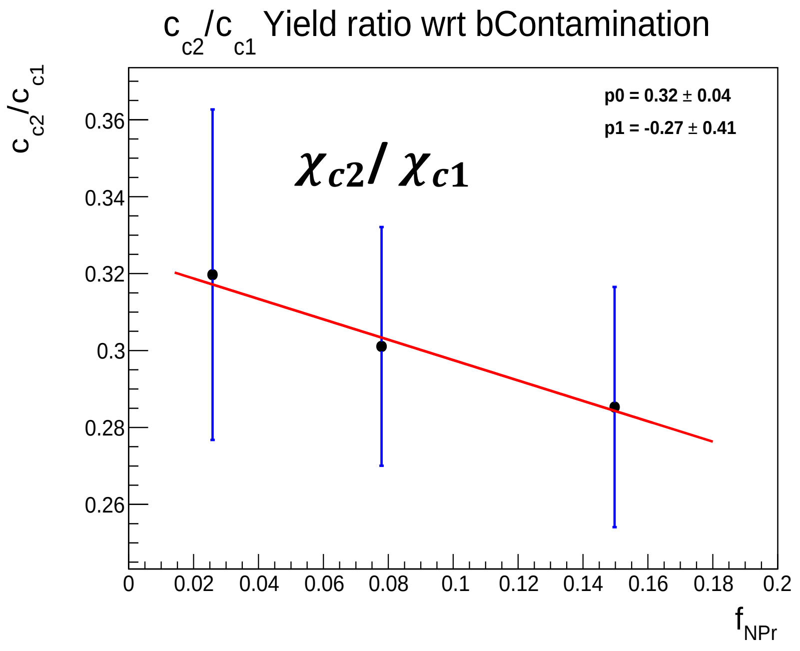
Varied cuts to plot trend lines, then compared the differences between the original point and the point where contamination reaches zero.

Overall uncertainties

5% for χ_c / J/ψ

8 % for $\chi_{c2}/\ \chi_{c1}$





Polarization

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Summary

Polarization

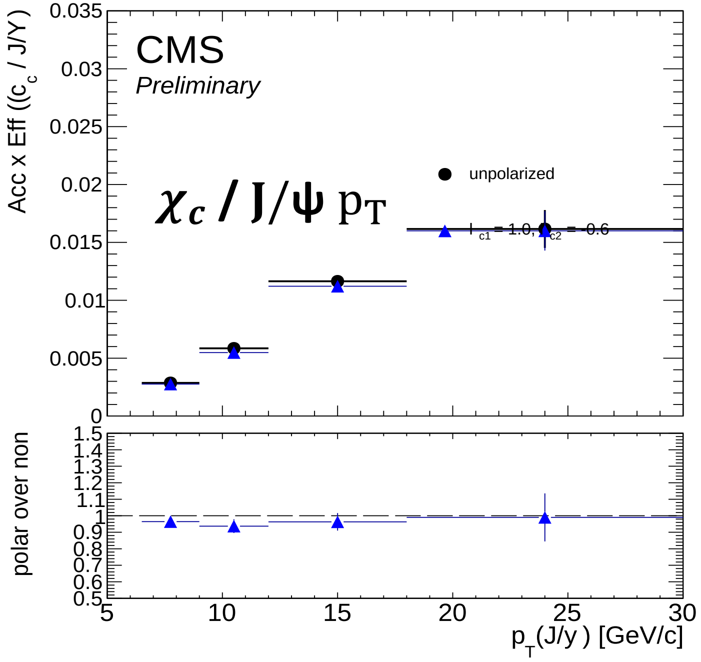
A different polarization scenario can vary the kinematics of muons and photon
-> can change the p_T distribution

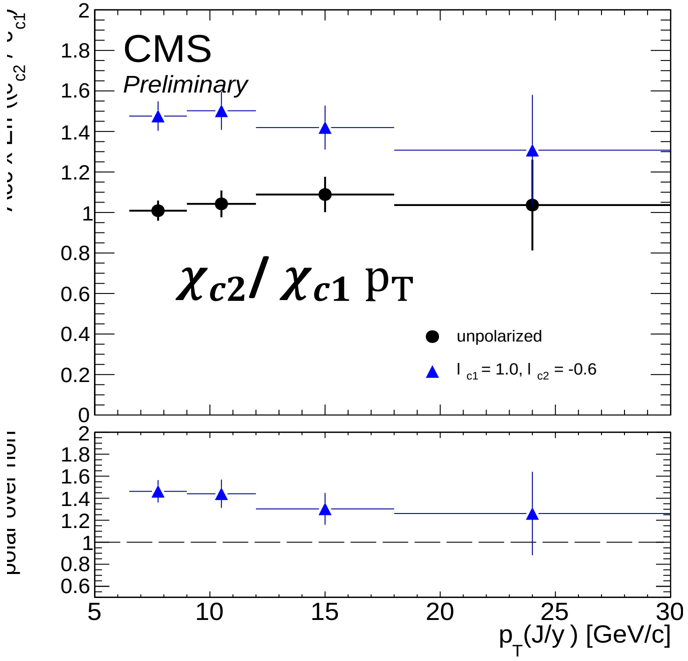
Studying the effects of the most likey polarization scenario (BPH-13-001)

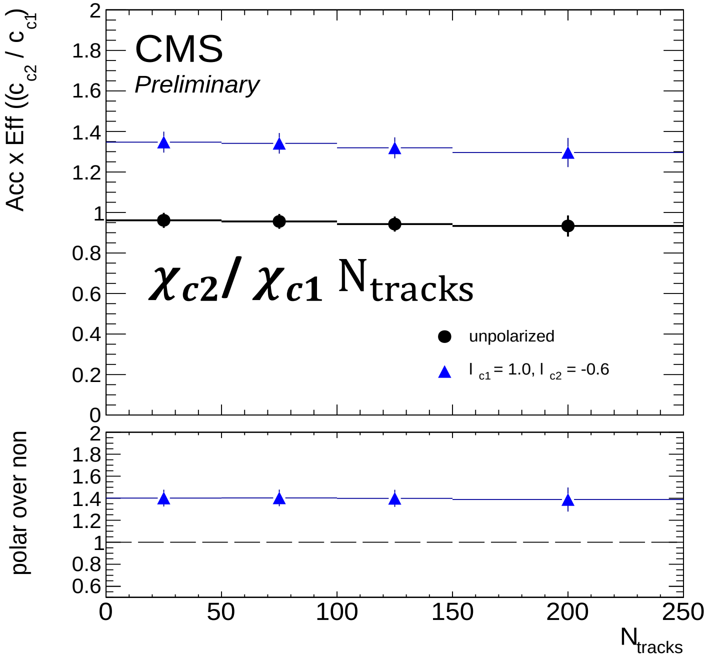
- Use reweighting factor $\mathbf{1+\ \lambda_\theta cos^2\theta}$ ($\boldsymbol{\theta}$ is the polar angle of the positive muon direction in the J/ψ frame)
- Weighting the MC to match polarized case ($\lambda_{\theta 1} = 1.0, \lambda_{\theta 2} = -0.6$ which is $J_{z1} = 0, J_{z2} = 0$)

This results is not added to systematics We can just modify final results

Larger effect
$\boldsymbol{\chi_{c2}/\ \chi_{c1}}$







Results

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Results

Analysis is still on-going (pre-approval) Results might be changed.

Target conference : QM

Both ratios are flat

- χ_c modified vs multiplicity similarly to J/ψ

- Different from what is seen for ψ(2S)

Results – pp comparisons

χ_c / J/ψ is consisted with pp results

- Left : Different rapidity region
- Right : Similar rapidity region

No relative suppression of χ_c compared to J/ψ in pPb

Summary

- **Measured χ_c / J/ψ and χ_{c2}/χ_{c1} in pPb 8.16 TeV**
- **No modification of ratios on particle multiplicty was observed, which means the cold nuclear matter effect is very small for P-state quarkonia**
- **Consistent with existing pp data**
- **Analysis is still on-going (pre-approval)**
- **The result is under approval procedure in CMS and will be published for the QM this April**

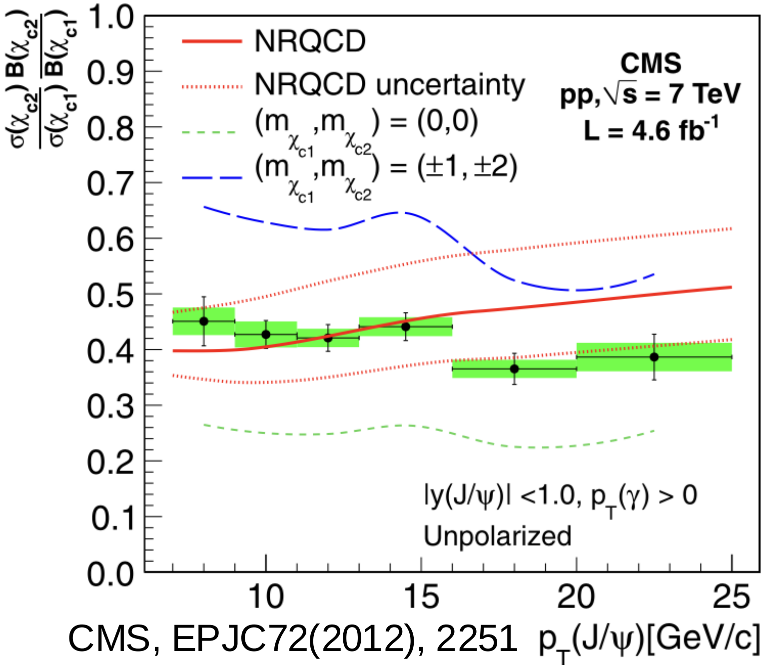
Backup

Existing results for excited charmonium at LHC

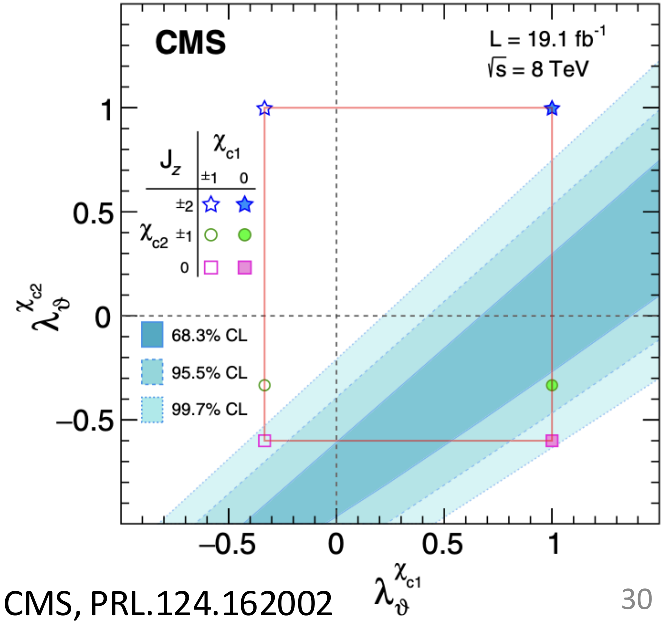
pp

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

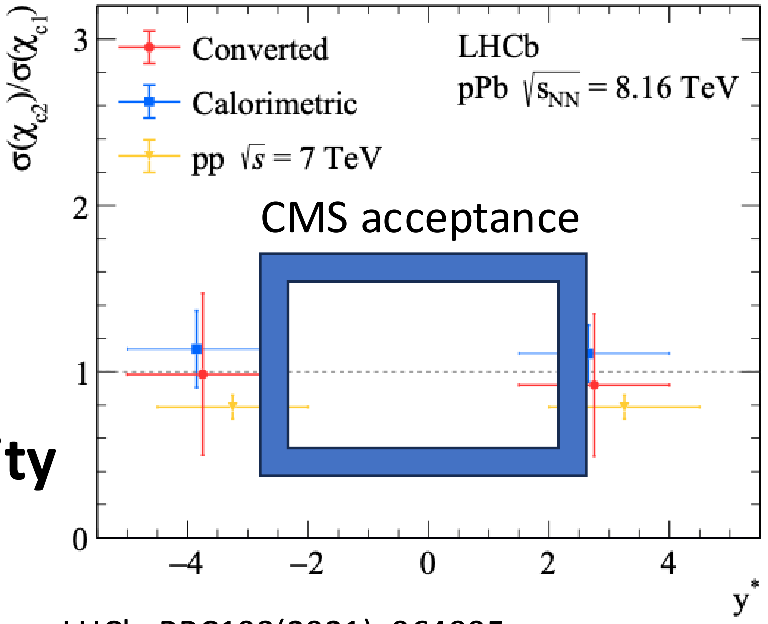
pPb

LHCb

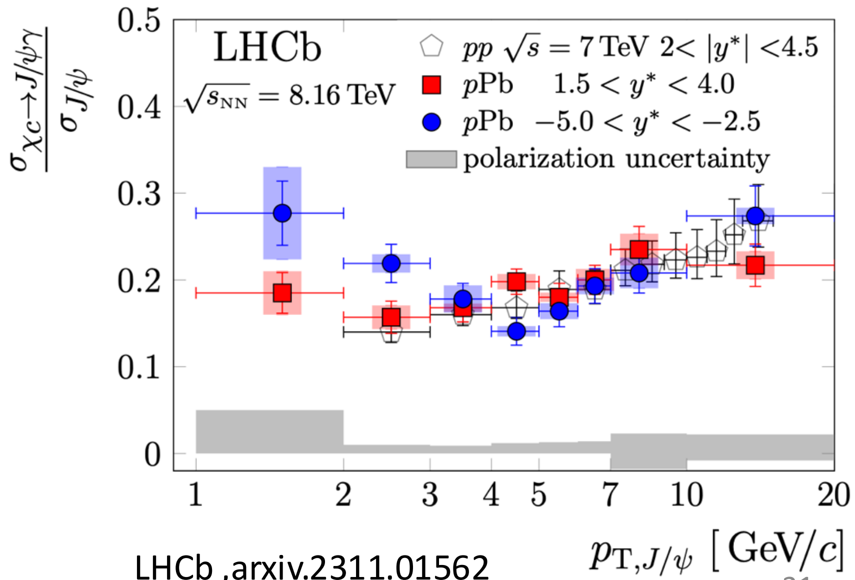
- First measurement of χ_{c2}/χ_{c1} and χ_c / J/ψ in pPb with rapidity
  1.5 < $y*$ < 4.0
  −5.0< $y*$ <−2.5

- 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

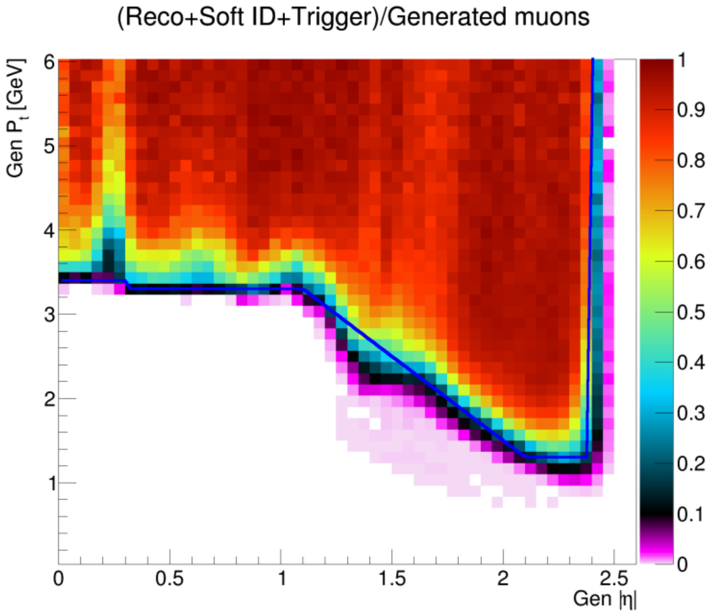


LHCb ,arxiv.2311.01562

Muon and J/ψ Selection

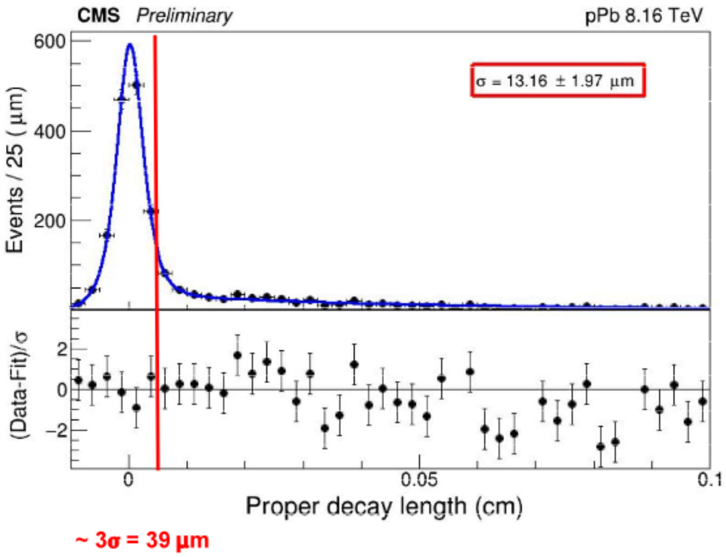
Muon

- **Selection**
  - Soft ID
  - Trigger (HLT_PAL1DoubleMuOpen_v1)
- **Acceptance**
  - Recommended acceptance region for Soft ID + trigger



J/ψ

- **Opposite sign muons**
- **Common vertex probability > 1%**
- **Removing non-prompt J/ψ : $(c\tau)/\sigma(c\tau) < 3$**
- **$|y| < 2.4$, $6.5 < p_T < 30$ GeV**
- **To be considered candidate for χ_c: 2.9 < m(J/ψ) < 3.25 GeV**



Data and MC Samples

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)

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 the data
  - pPb/Pbp luminosity
  - Ntrack distribution (associated with the dimuon PV, to account for pile-up)
  - p_T distribution

χ_c Charmonium P-states

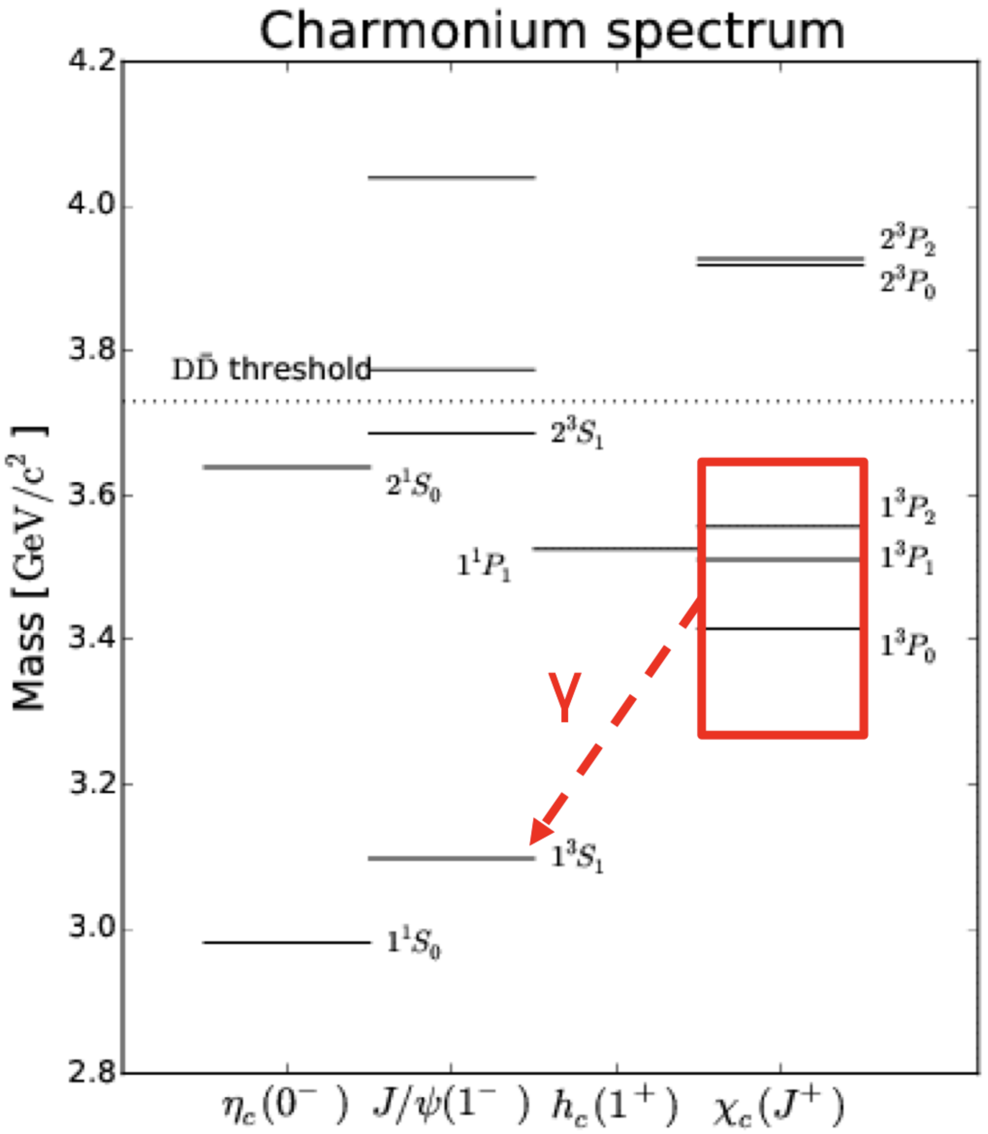
P states

- 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**



MC Phytia Settings

pTHatMin **: Minimum invariant p_T used for the generating parton interaction.**

- Varied from nominal (4.5) down to 3.0 up to 6.0

C-mass : Mass of c-quark used in the generator

- Nominal 1.5 alternative 1.43 (Used in similar study)

reNorm: Geometric mean of the squared transverse masses of the two outgoing particles

- Used Pythia 6 Setting

	Nominal	**Alternative 1** pThat3	**Alternative 2** pThat6	**Alternative 3** c-mass	**Alternative 4** 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

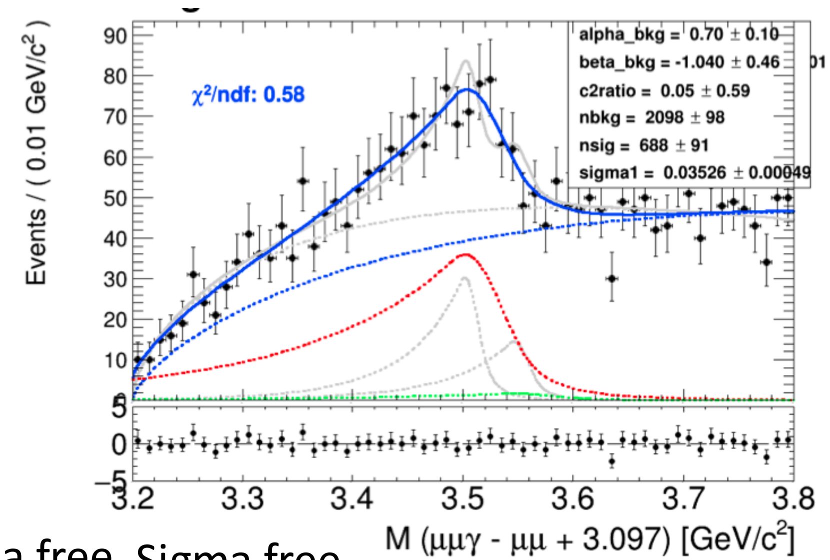
χ_c Systematics –Free parameter

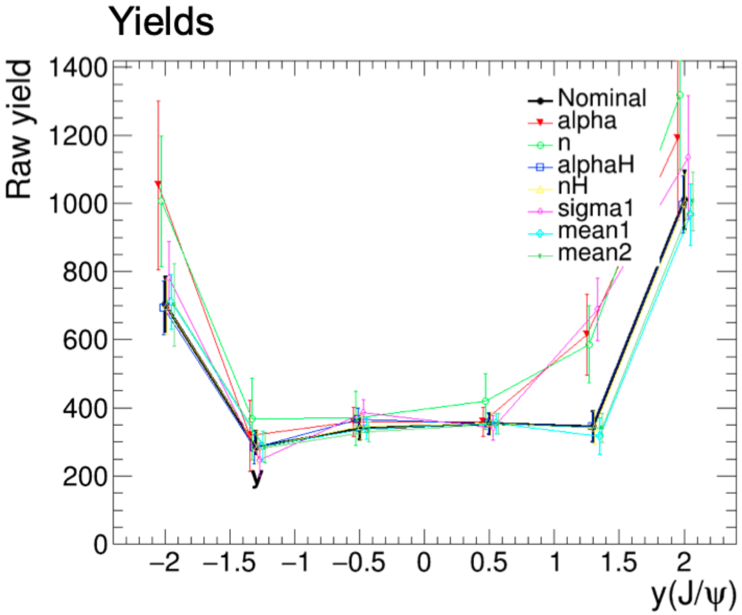
Previous Method

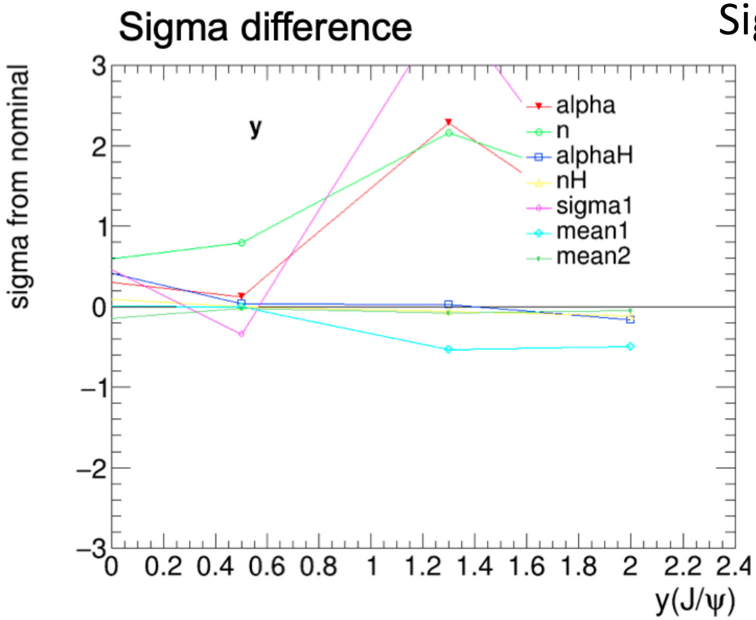
Each parameter was released one at a time, and compared the results

- The fitting shape was collapse and showed unphysical results
- We couldn't compare the yields of each parameter with this results.
- Alternatively apply Gaussian constrain and release parameter at once not one by one.

n free







Sigma free Sigma free