J/ψ polarization in p-p collision at 13 TeV using ALICE detector

Deekshit Kumar
Supervisor: Dr. Partha Pratim Bhaduri

Variable Energy Cyclotron Centre(VECC), Kolkata

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Outline

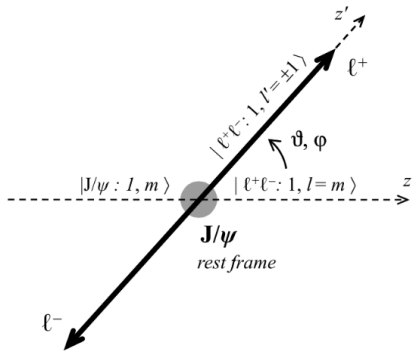
- Motivation of study of particle polarizations.
- How we can measure J/ψ polarizations?
- Analysis strategy & plan of J/ψ polarizations measurement.
- Results
- Summary

J/ψ as a useful probe in hadronic collisions

- Non-relativistic bound state of charm quark(c) and charm antiquark($\bar{c}$).
- In hadronic collisions, J/ψ production is believed to be a factorizable two step process:
  - $c\bar{c}$ pair production (calculable within pQCD)
  - $c\bar{c}$ pair hadronization (formation of physical resonance)
- Different models for color neutralization.
- Different predictions from different models on transverse spectra and angular distributions.
- No model can simulatneously explain measured J/ψ p_T spectra and polarization parameters.
- Need precise experimental measurements over a large kinematic domain, to constrain the theoretical model estimations of production cross section and polarization

J/ψ Polarization

- Polarization is defined as the alignment of particle spin in a given direction.
- It can be measured through the angular distribution of decay products because of very small lifetime of quarkonia.



- Angular Distribution of Decay products is parameterised as:

$$W(cos\theta, \varphi) \propto \frac{1}{(3+\lambda_\theta)} \left(1 + \lambda_\theta \, cos^2\theta + \lambda_{\theta\varphi} \, sin2\theta cos\varphi + \lambda_\varphi \, sin^2\theta cos2\varphi \right)$$

where, $(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (1,0,0) \rightarrow$ Transverse polarization

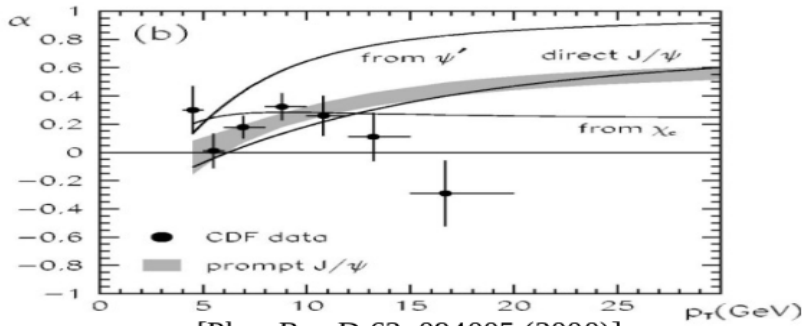
$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (-1,0,0) \rightarrow$ Longitudinal Polarization

$(\lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi}) = (0,0,0) \rightarrow$ Unpolarized State

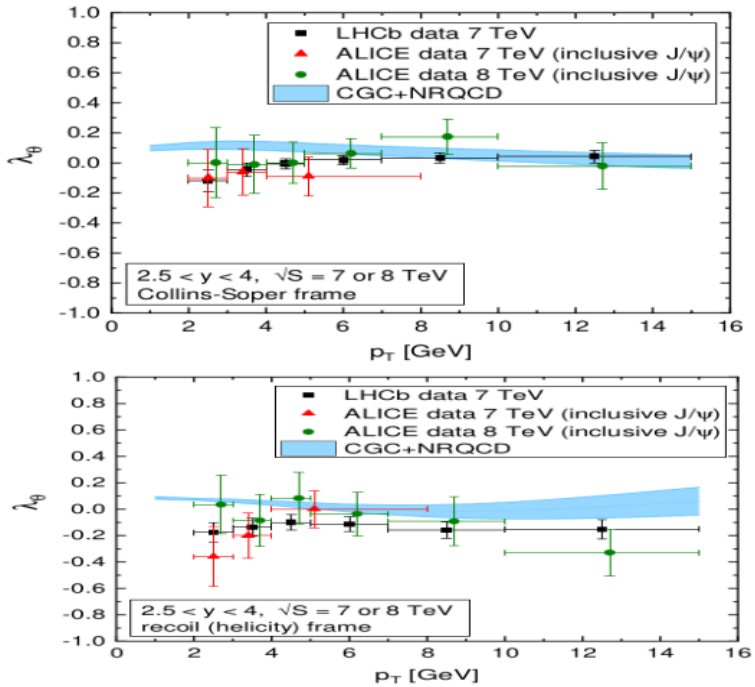
J/ψ polarization puzzle ?

- Experimental measurement of polarization parameters from Tevatron, RHIC and LHC show almost no J/ψ polarization in hadronic collisions.

- Theoretical predictions based on NRQCD model suggested substantially non-zero polarization at high p_T [https://arxiv.org/pdf/1201.1872.p



[Phys.Rev.D 62, 094005 (2000)]

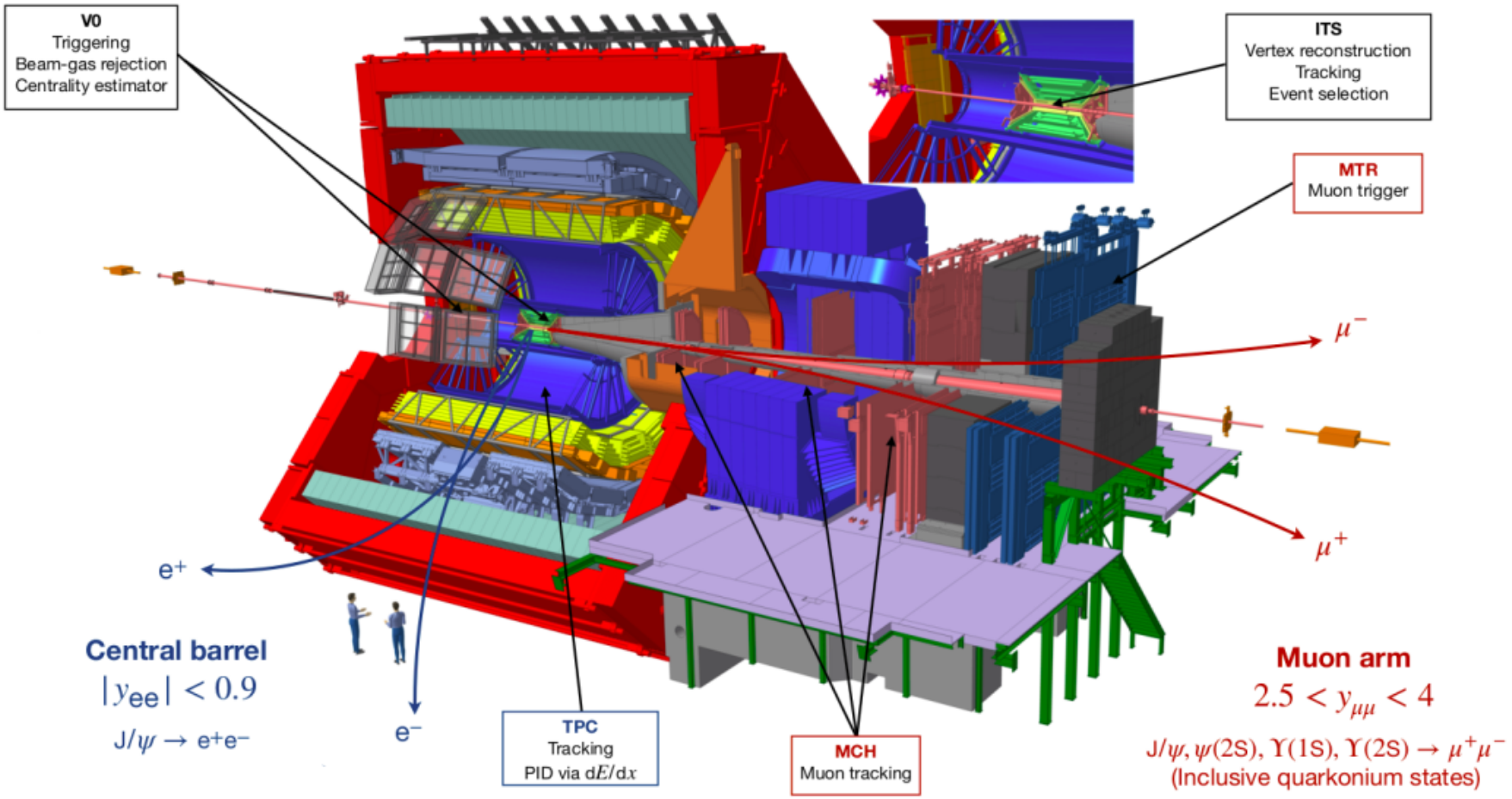


https://doi.org/10.1007/JHEP12(2018)057

Motivations for J/ψ polarization studies in pp collisions at $\sqrt{s} = 13$ TeV

- No measurement so far in ALICE at this energy, possibility to have first results and study energy dependence of polarization parameters.
- Largest dataset (from Run2) in pp collisions are available at $\sqrt{s}$ =13 TeV, allows one to measure J/ψ polarization with unprecedented precision and p_T up to 15 GeV/c.
- Possibility of comparing the results with the ones obtained by ALICE (Pb-Pb at $\sqrt{s} = 5.02$ TeV, pp at $\sqrt{s} = 8$ TeV) and LHCb (pp at $\sqrt{s} = 7$ TeV)
- Higher p_T reach, more stringent tests to QCD models.

ALICE Detector



Data Set And Analysis Goal

- Data sets:
  2016: LHC16f, g, h, i, j, k, o, p
  2017: LHC17h, i, k, l, m, o, r
  2018: LHC18b, c, d, e, f, g, h, i, j, l, m, o, p
- All the good runs in these periods have the same low-p_T trigger threshold (0.5 GeV/c) .
- Files: AliAOD.Muons.root
- Muon trigger: CMUL7-B-NOPF-MUFAST
- CMUL7 trigger event analyzed = 596.43 M
- Analysis goal: Studying J/ψ polarization both in helicity reference frame (HE) and Collins-Soper reference frame (CS) and extraction of polarization parameters.

Reference frames

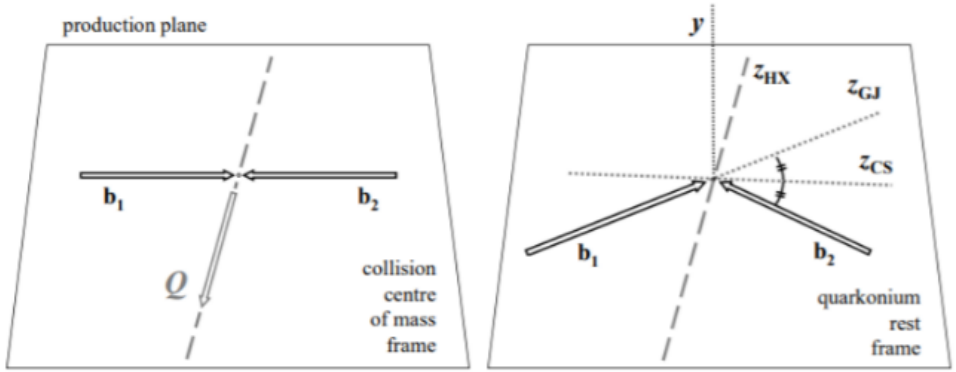


Figure: Reference frames

- **Helicity reference frame:** the z axis is defined as the quarkonium momentum direction in the collision reference frame.
- **Collins-Soper reference frame:** the z axis is defined as the bisector of the angle between the momentum of the first colliding object (the incoming proton) and the opposite of the momentum of the second colliding object as seen from the quarkonium rest frame.

Selection criteria:

- **Selection of muon track candidates:**
  - The track pseudo-rapidity must be in the range corresponding to the muon spectrometer acceptance,
    $$\textbf{-4.0} < \eta < \textbf{-2.5}$$
  - Transverse radius coordinate of the tracks at the end of the hadron absorber, must be in the range,
    $$\textbf{17.6} < R_{abs} < \textbf{89.5 (cm)} \quad \text{or} \quad \textbf{2.0} < \theta_{abs} < \textbf{10.0 (Degree)}$$
  - Each track reconstructed in the muon tracking system must match a track in the trigger system and additionally must pass the low- p_T trigger condition.
  - pDCA cut applied for each track.
- **Selection of di-muon track candidates:**
  - Opposite sign muon pair **(charge1 + charge2 = 0)**.
  - Each unlike-sign di-muon pair is required to be in the absolute rapidity range, $\textbf{2.5} < |y| < \textbf{4}$

Signal extraction:

- 2 signal functions: double CB (crystal ball) for J/ψ and ψ'(2S).
- VWG (variable width gaussian), for background.

- **Details of fit procedure:**
  Fixed parameters:
  - Tail parameters(n_L ,α_L ,n_R and α_R) of J/ψ and ψ'(2S) are same and fixed from MC data .
  - Mean(mass) and Sigma(width) of ψ'(2S) signal are fixed by,
    $M_{\psi(2S)} = M_{J/\psi} + (\ M_{\psi(2S)}\text{(PDG)} - M_{J/\psi}\text{(PDG)}\ )$
    $\sigma_{\psi(2S)} = \sigma_{J/\psi} \times (\frac{\sigma^{MC}_{\psi(2S)}}{\sigma^{MC}_{J/\psi}})$

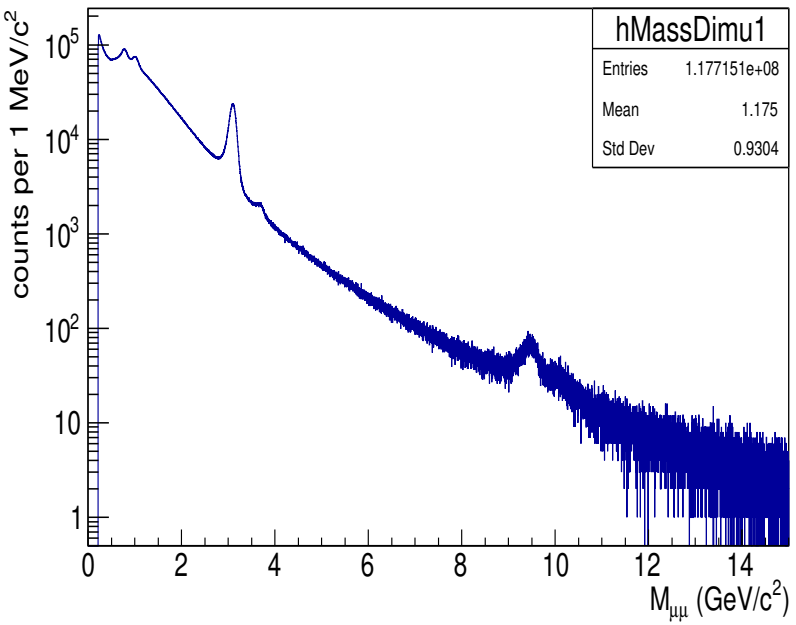
  Free parameters:
  - Mean and Sigma of J/ψ signal are free.
  - Normalization constants are free for both J/ψ and ψ(2S).
  - Parameters of background function are also free.

Signal extraction from inclusive invariant mass spectra:

Fitting function:

- **Signal:** CB2
- **Background:** VWG
- **Fitting Range:** [2.0, 5.0]

- **Bin width of invariant mass =** $1\ MeV/c^2$



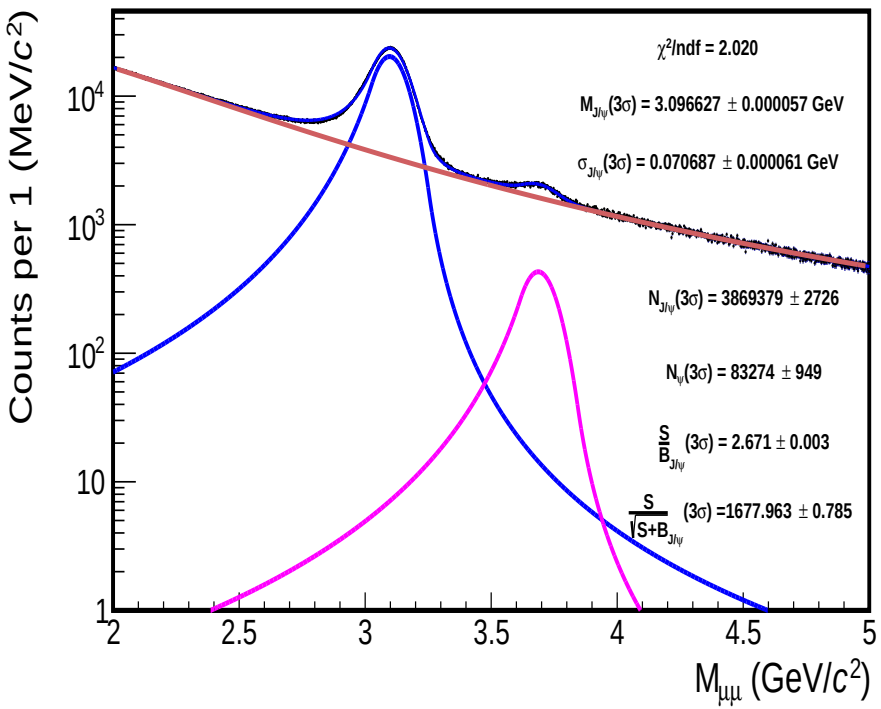


Figure: Invariant mass spectra

Differential analysis in p_T bins:

Splitting data in dimuon p_T bins: twelve bins between 0 GeV/c and 15 GeV/c with variable width (1 GeV/c, from 0 GeV/c up to 10 GeV/c, then 2.5 GeV/c up to 15 GeV/c).

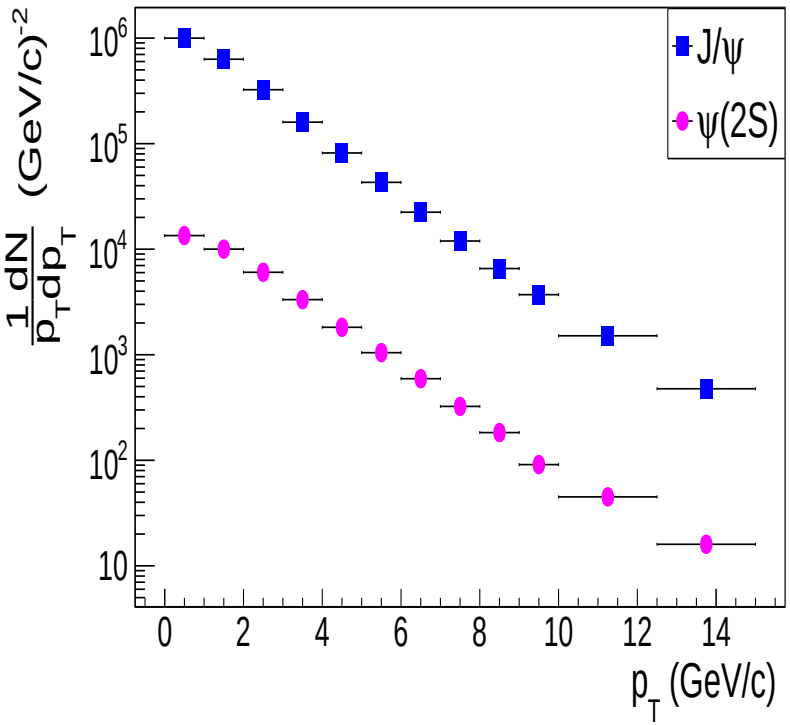


Figure: Uncorrected p_T spectra:

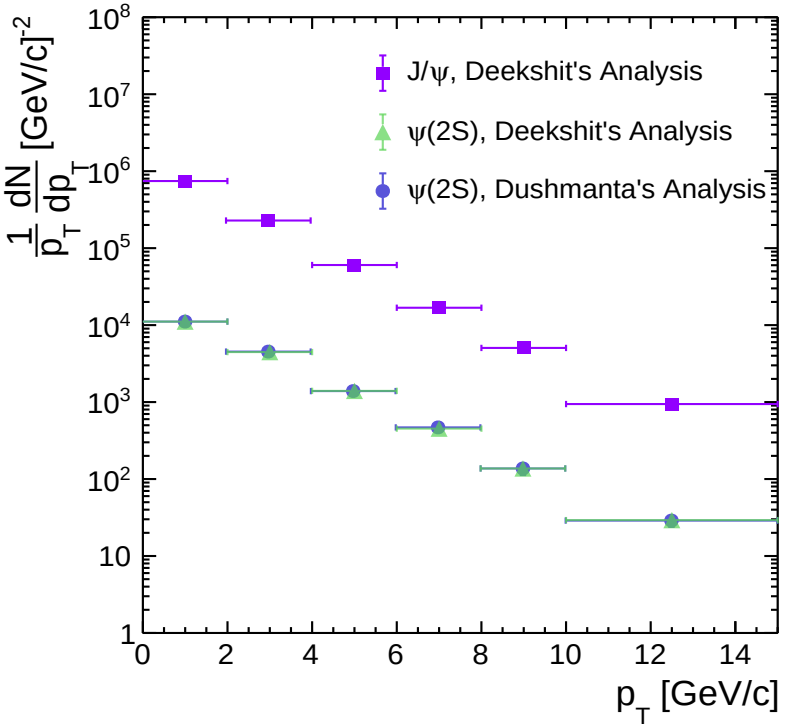


Figure: Comparision spectra:

- Plots are accepted in PAG-DQ Quarkonium2mumu Group

MC- p_T differential analysis: A x ϵ correction

$$\text{A x } \epsilon = \frac{N^{Rec}_{J/\psi}}{N^{Gen}_{J/\psi}}$$

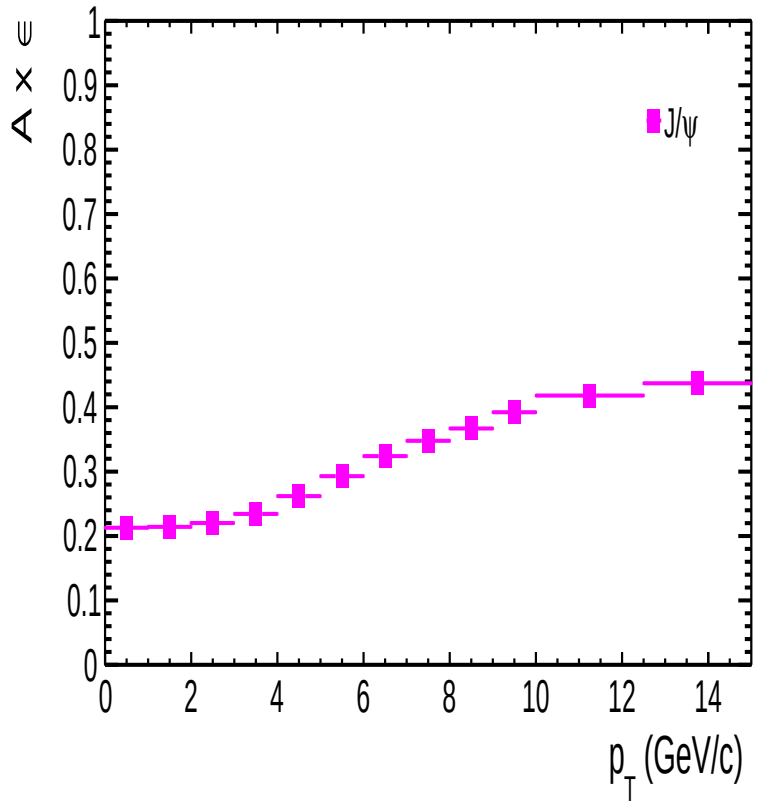


Figure: A x ϵ correction

$$N^{Corr}_{J/\psi} = \frac{N^{Raw}_{J/\psi}}{Ax\epsilon}$$

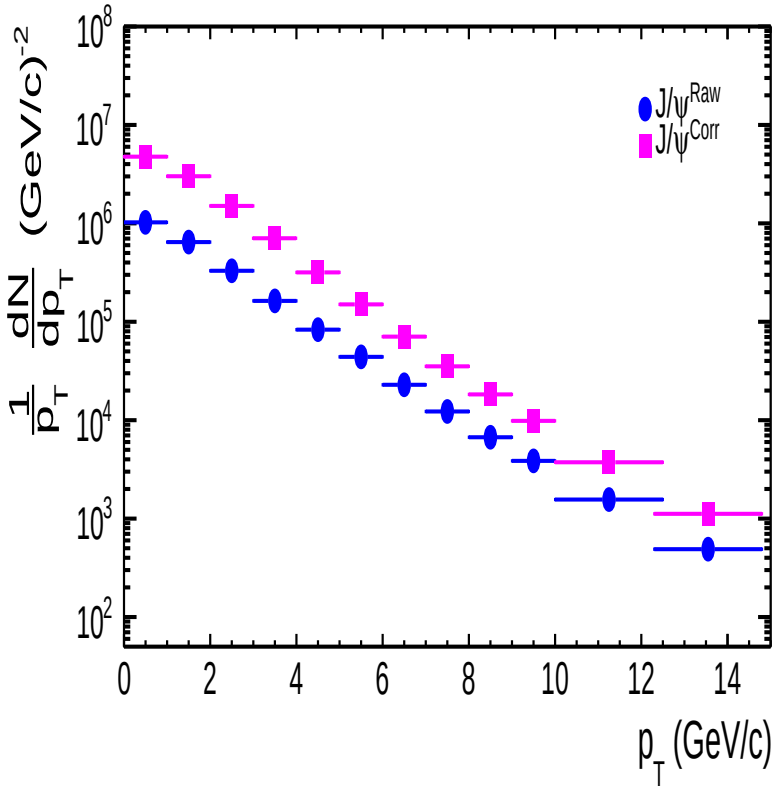
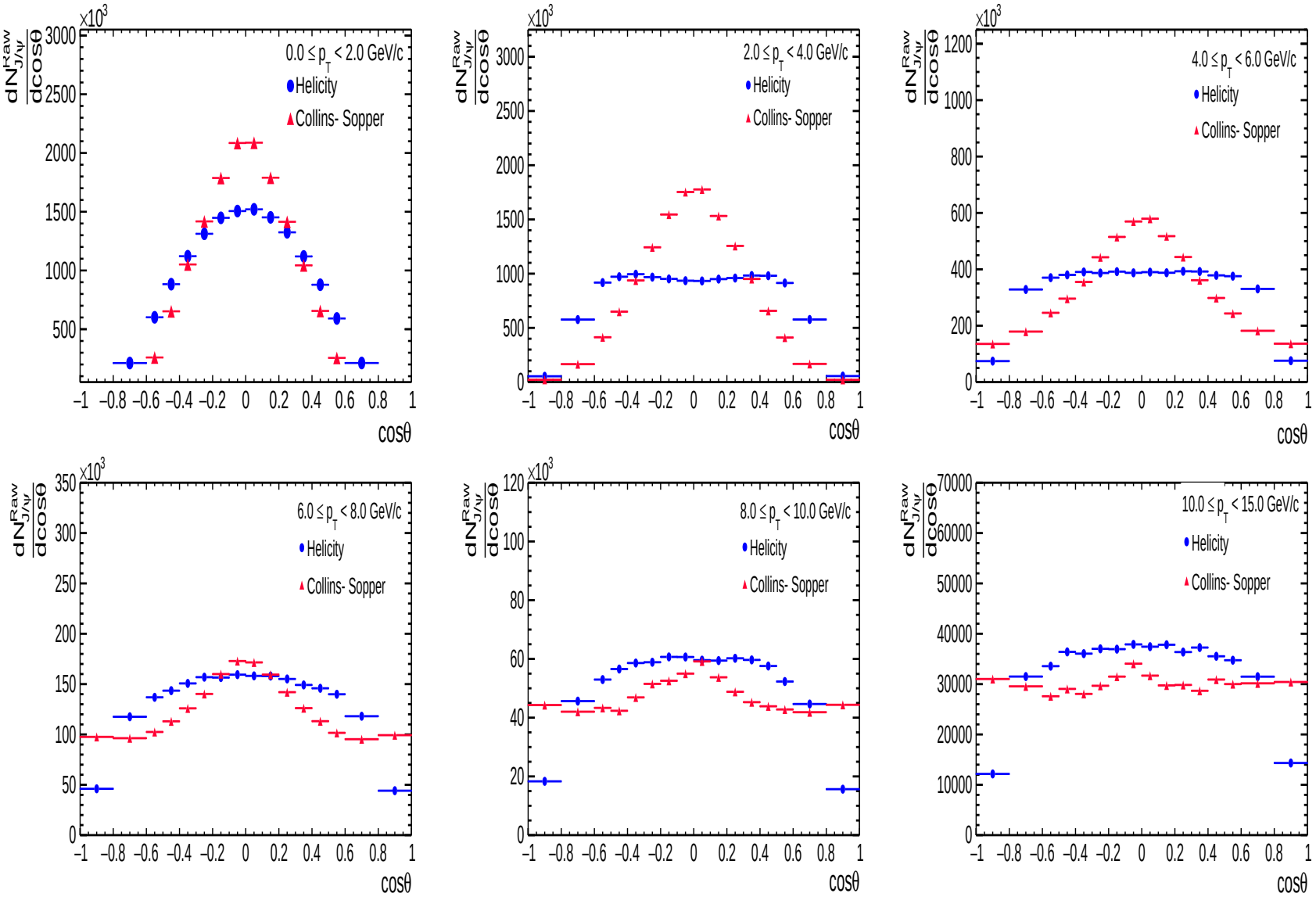
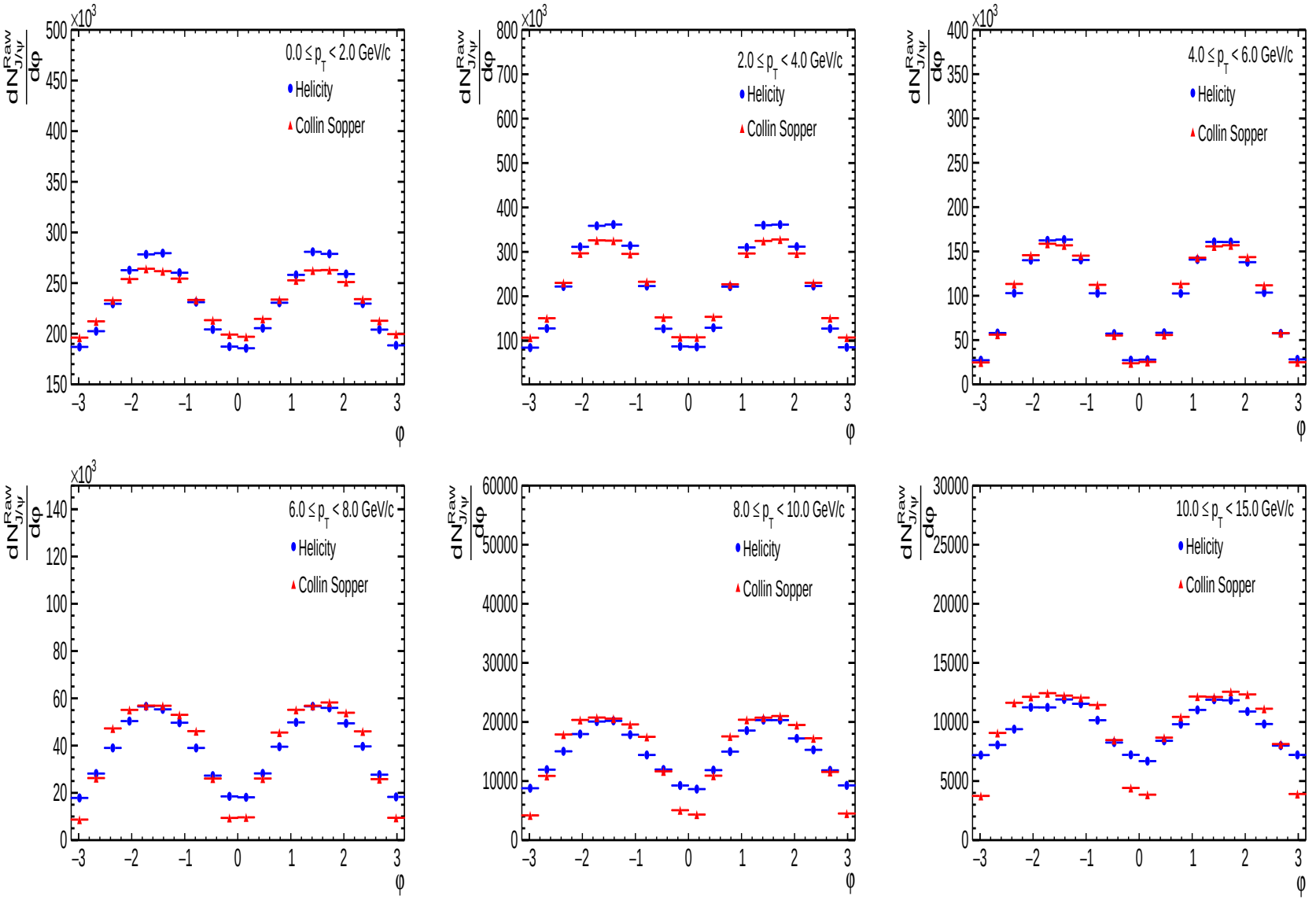


Figure: Corrected p_T Spectra

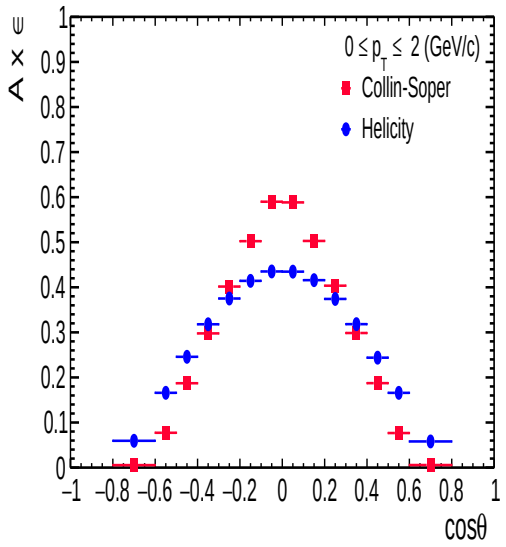
Differential $cos\theta$ analysis: Raw yield extraction

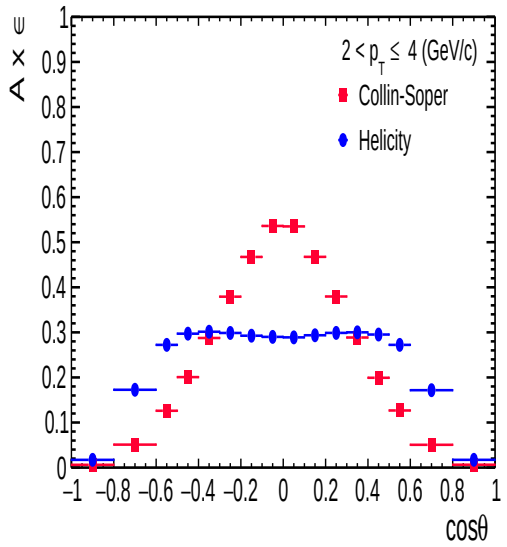


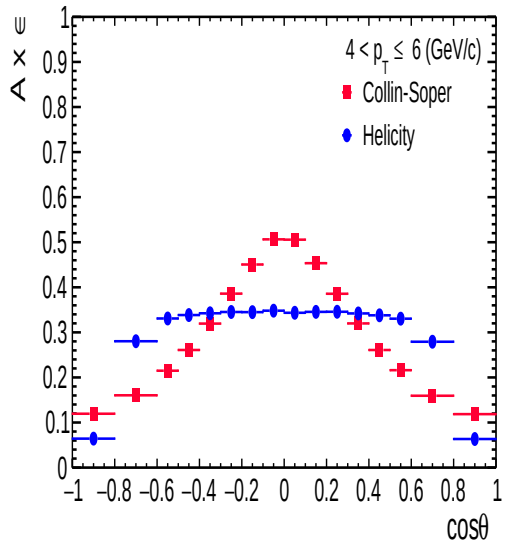
Differential φ analysis: Raw yield extraction

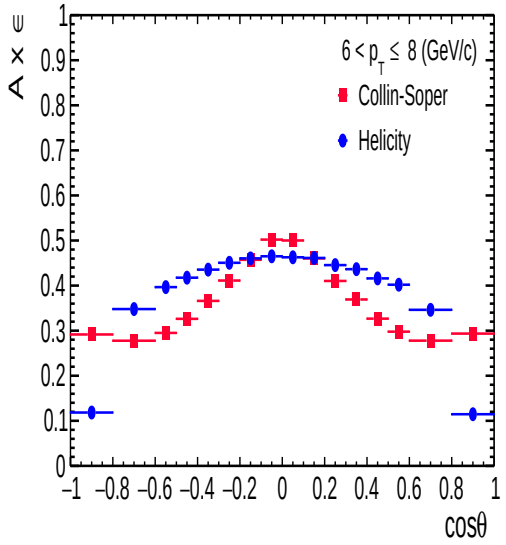


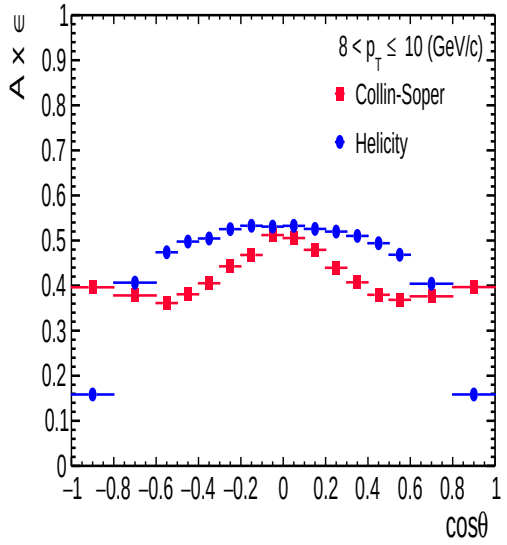
A x ϵ as a function of cosθ

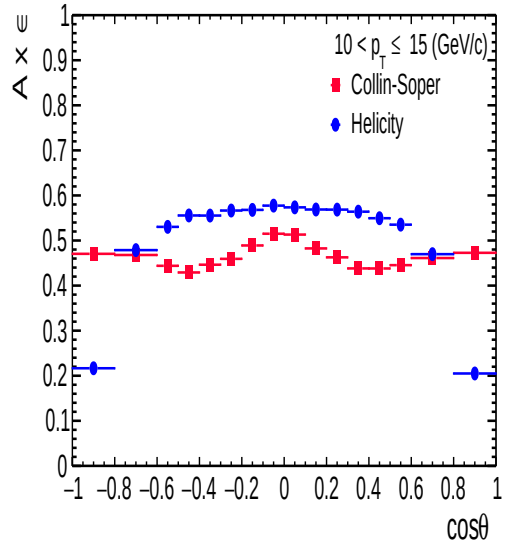




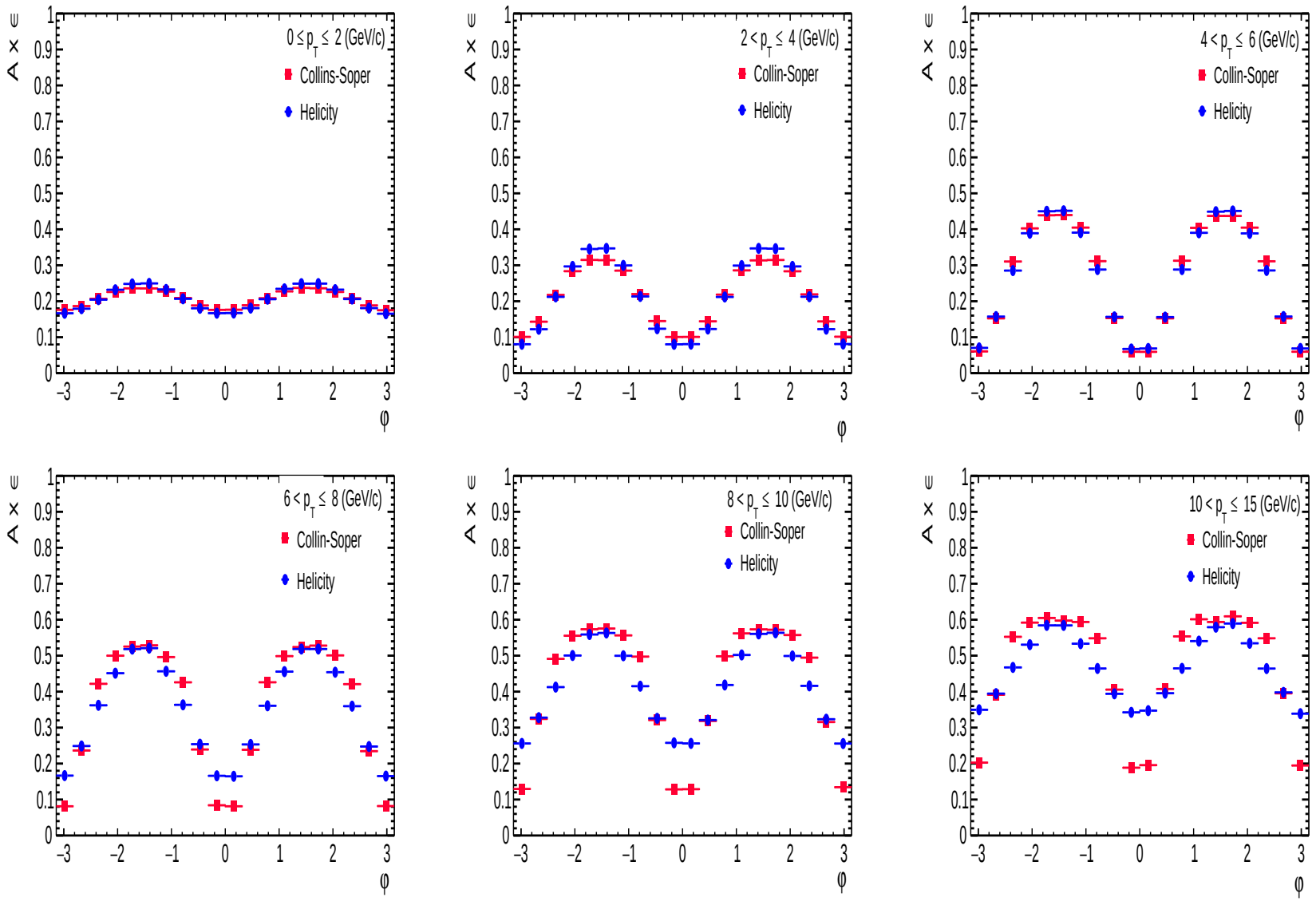




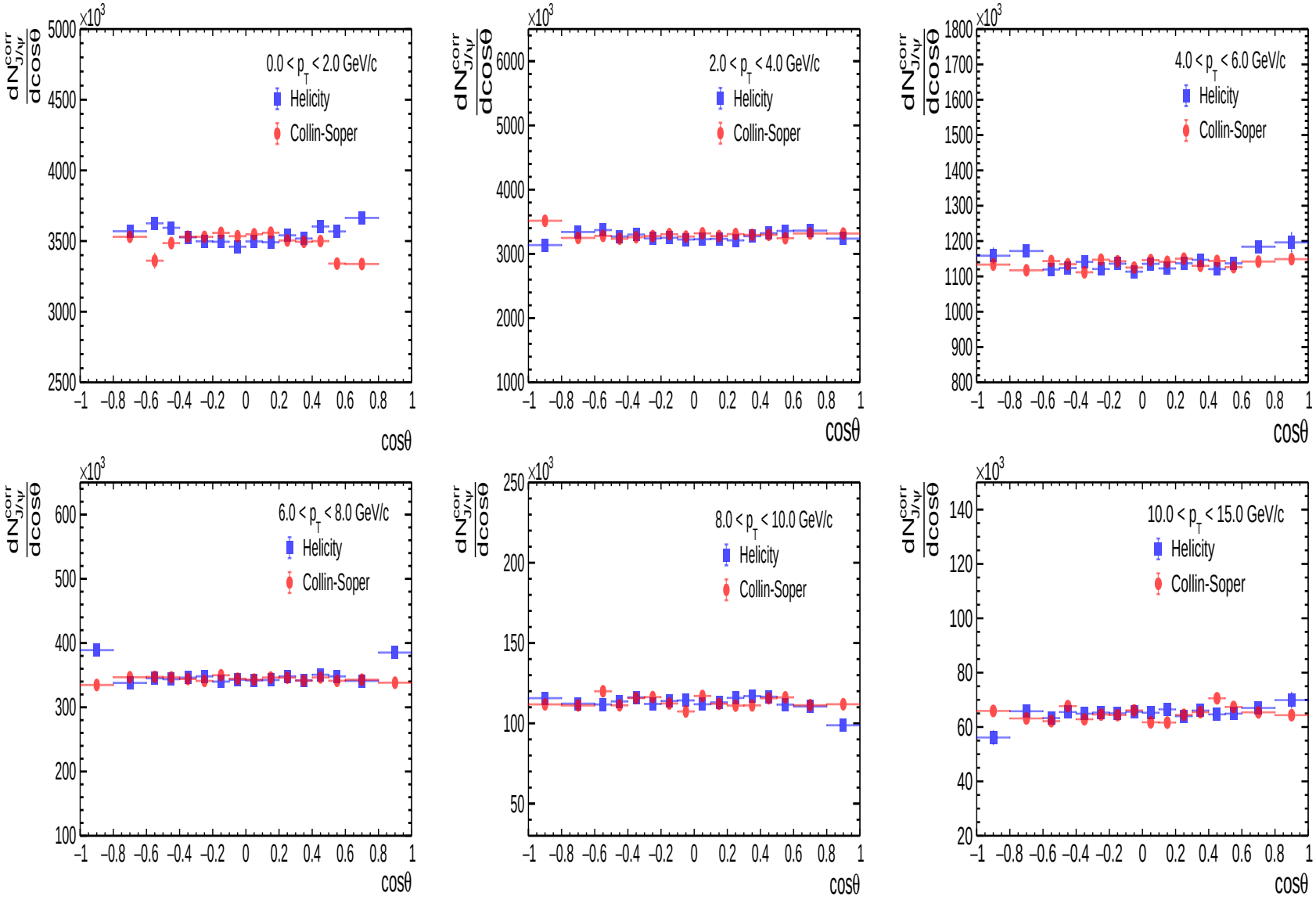




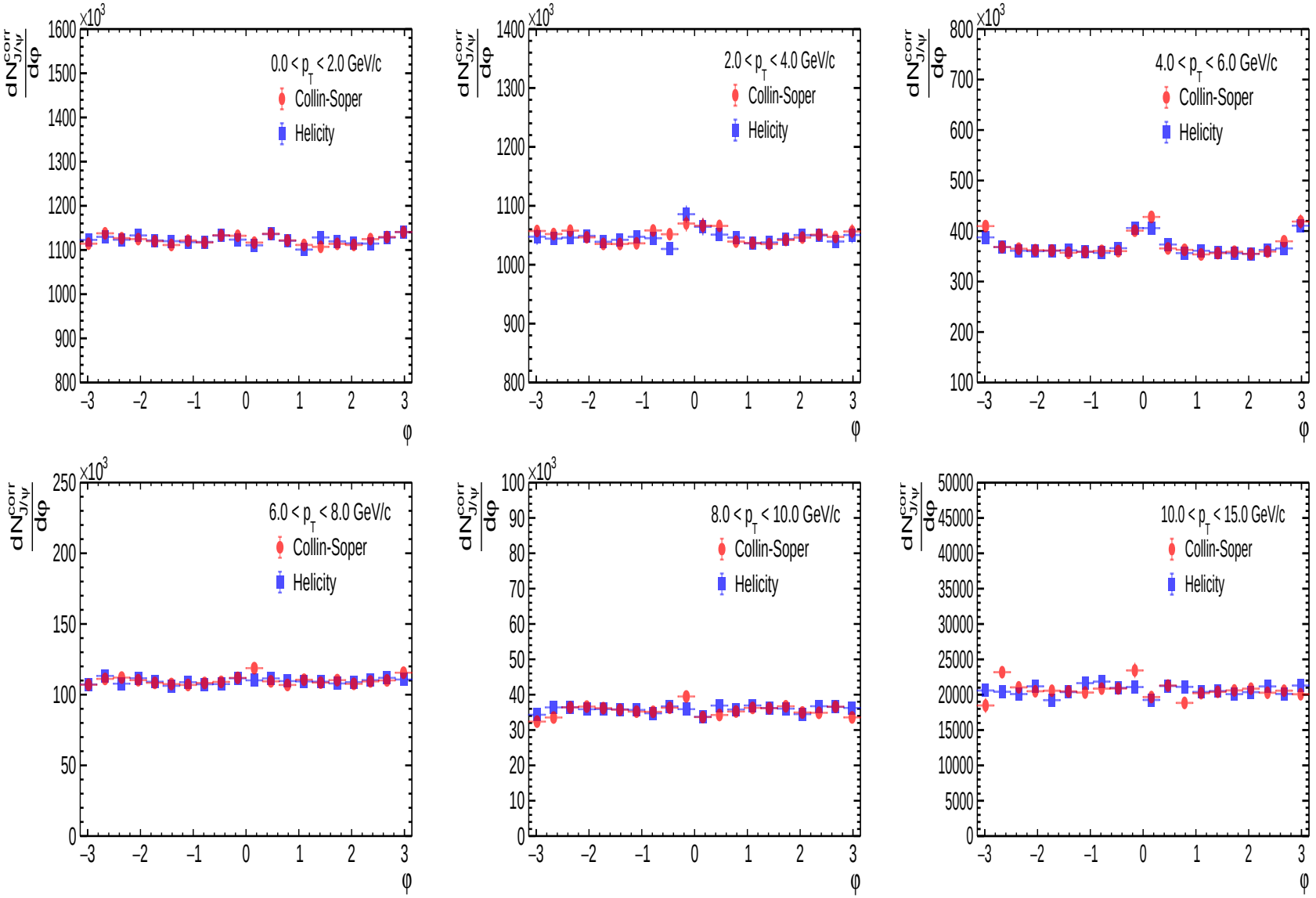
A x ϵ as a function of φ



Corrected J/ψ as a function of cosθ



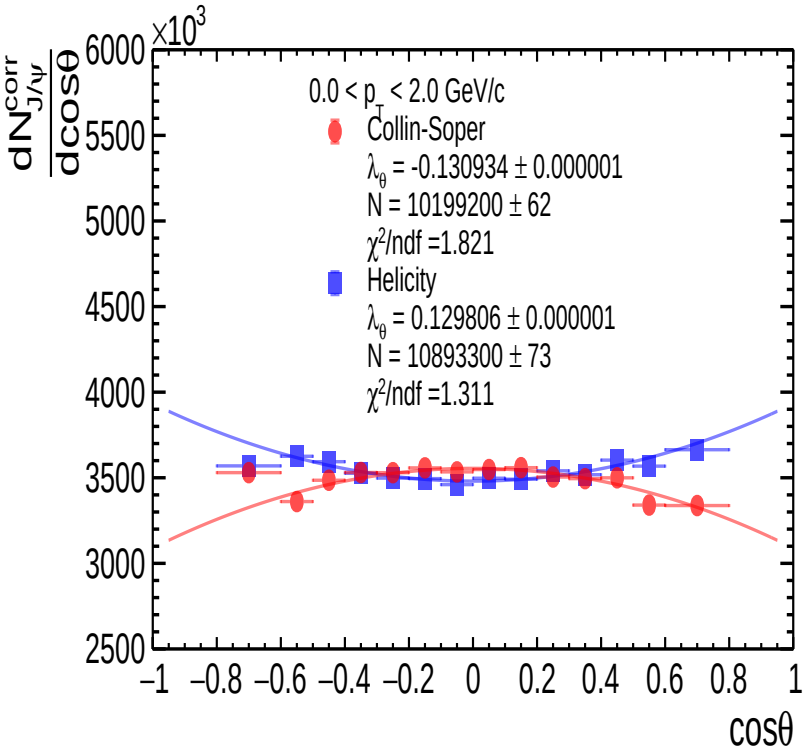
Corrected J/ψ as a function of φ

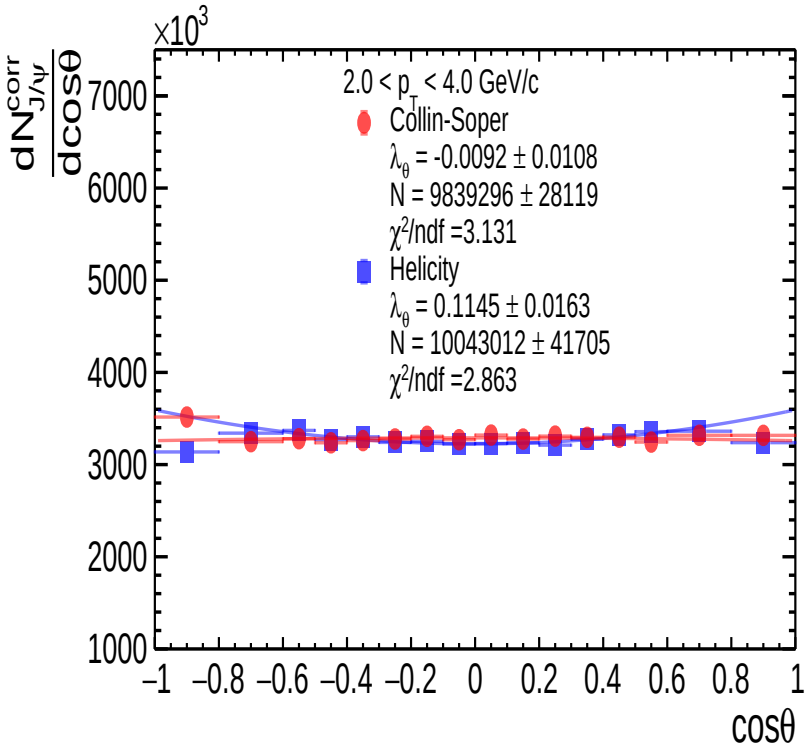


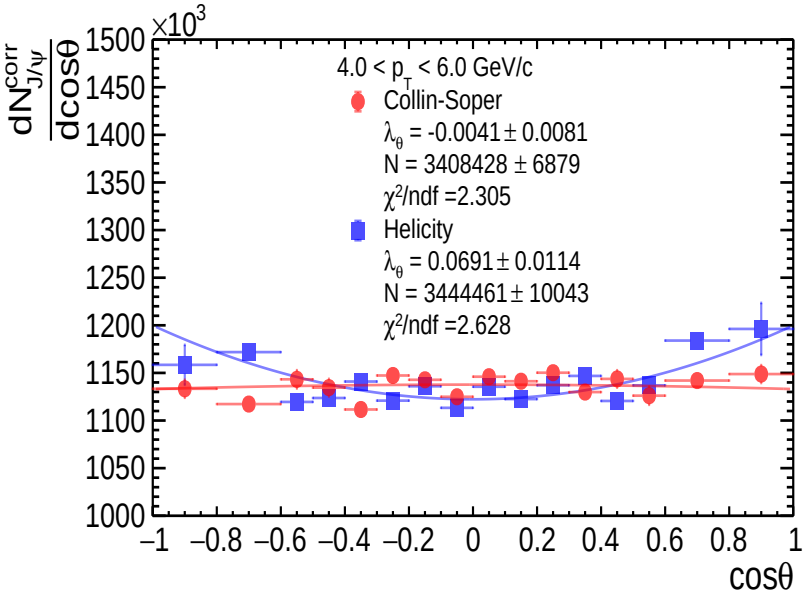
Fit as a function of cosθ

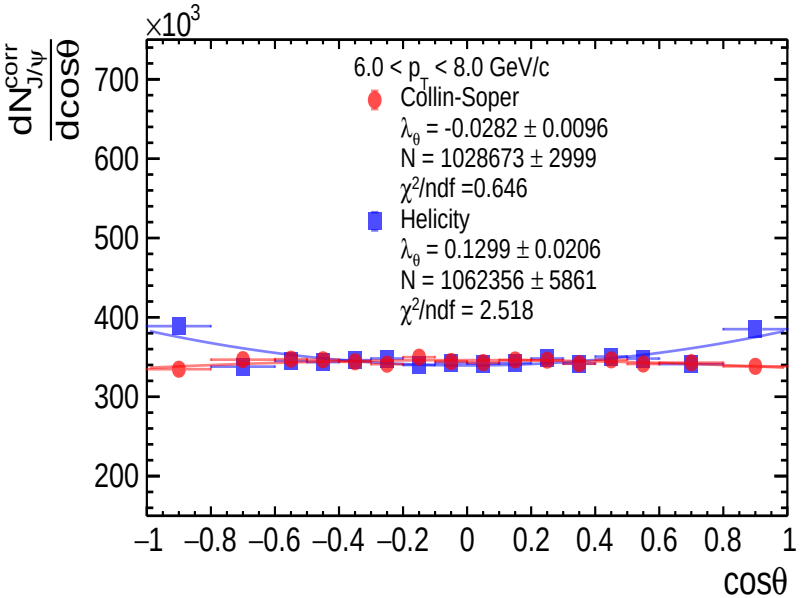
- 1D fit to the cosθ distribution:

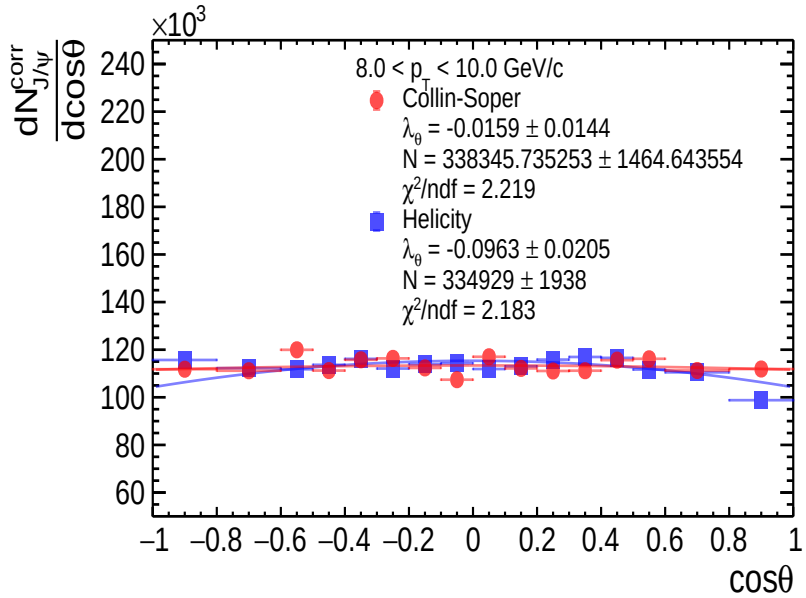
$$W(cos\theta|\lambda_\theta) = \frac{N}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta)$$

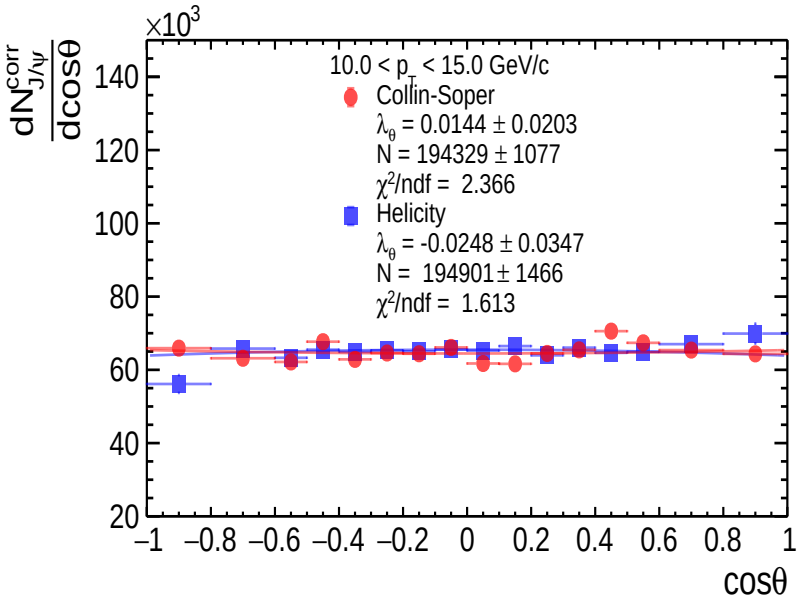




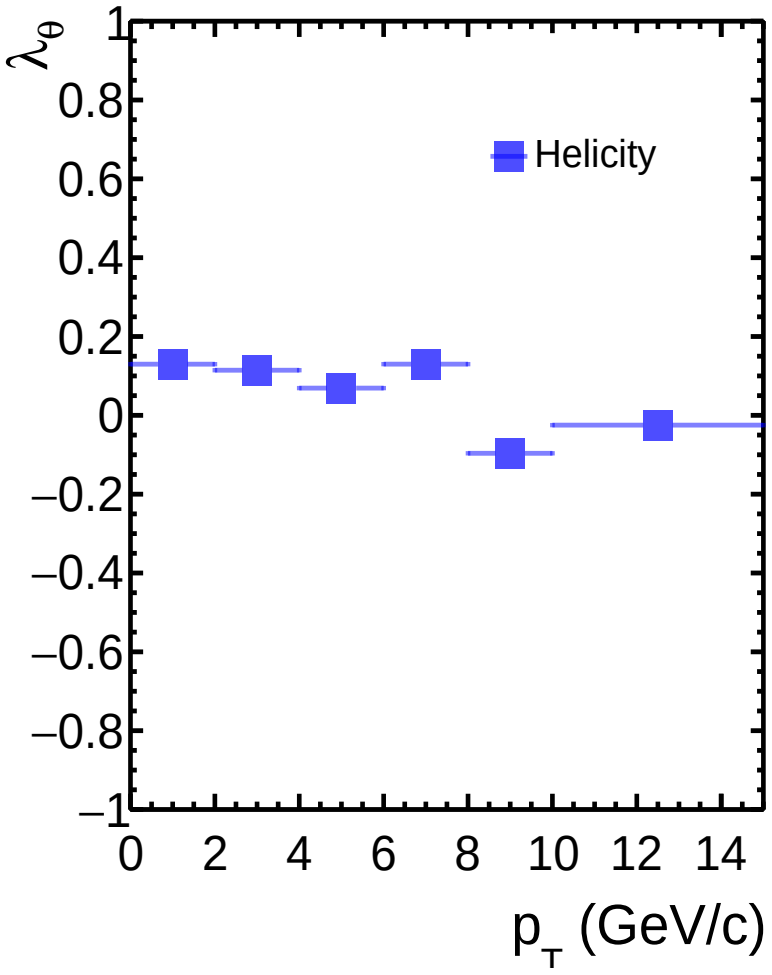

$\frac{dN^{corr}_{J/\psi}}{d\cos\theta}$
×10^3
4.0 < p_T < 6.0 GeV/c
Collin-Soper
λ_θ = -0.0041 ± 0.0081
N = 3408428 ± 6879
χ²/ndf =2.305
Helicity
λ_θ = 0.0691 ± 0.0114
N = 3444461 ± 10043
χ²/ndf =2.628
cosθ

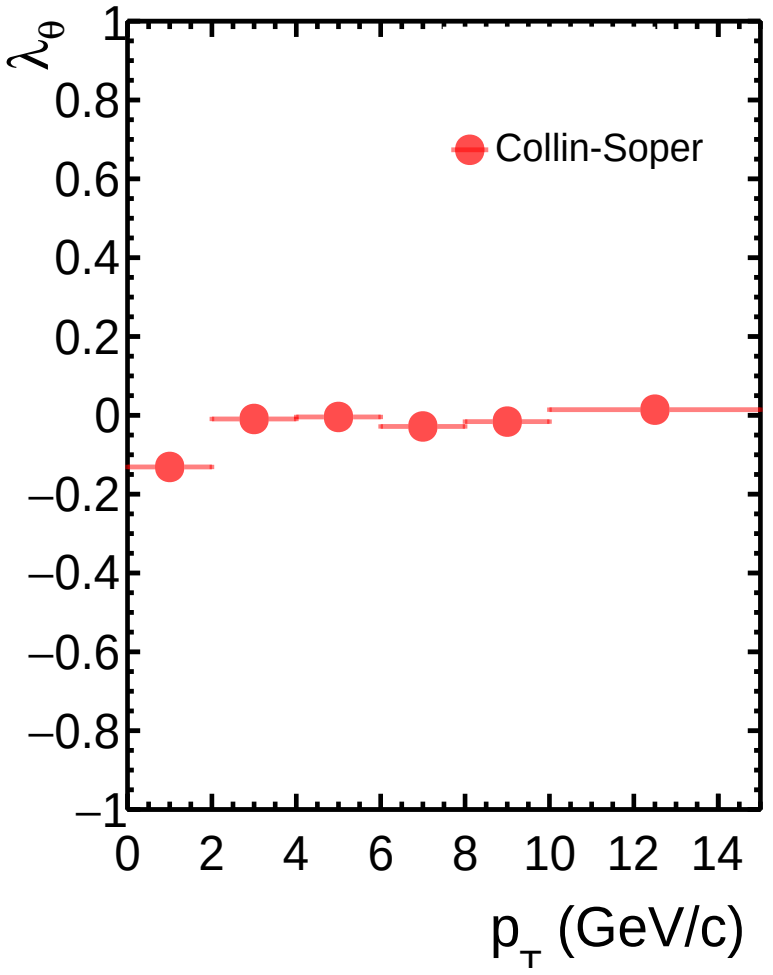

$\frac{dN^{corr}_{J/\psi}}{d\cos\theta}$
×10^3
6.0 < p_T < 8.0 GeV/c
Collin-Soper
λ_θ = -0.0282 ± 0.0096
N = 1028673 ± 2999
χ²/ndf =0.646
Helicity
λ_θ = 0.1299 ± 0.0206
N = 1062356 ± 5861
χ²/ndf = 2.518
cosθ


$\frac{dN^{corr}_{J/\psi}}{d\cos\theta}$
×10^3
8.0 < p_T < 10.0 GeV/c
Collin-Soper
λ_θ = -0.0159 ± 0.0144
N = 338345.735253 ± 1464.643554
χ²/ndf = 2.219
Helicity
λ_θ = -0.0963 ± 0.0205
N = 334929 ± 1938
χ²/ndf = 2.183
cosθ


$\frac{dN^{corr}_{J/\psi}}{d\cos\theta}$
×10^3
10.0 < p_T < 15.0 GeV/c
Collin-Soper
λ_θ = 0.0144 ± 0.0203
N = 194329 ± 1077
χ²/ndf = 2.366
Helicity
λ_θ = -0.0248 ± 0.0347
N = 194901 ± 1466
χ²/ndf = 1.613
cosθ

λ_θ as a function of p_T





Summary and Outlook:

- Raw yields extraction have been done in differential p_T and angular bin
- MC Analysis have been performed for correcting the J/ψ raw yield in differential p_T and angular bin
- Perform the fit to extract the polarization parameters (λ_θ)
- Analysis note submitted in ALICE repository

Future analysis plan:

- Perform the simultaneously fit to extract the other polarization parameters
- Study polarization parameters as a function of transverse momentum
- Other systematics evaluation

Thank you

To fit the signal:

The standard signal (J/ψ) function is a double Crystal Ball (CB2) defined as

$$f_{J/\psi}(x; N_{J/\psi}, \mu, \sigma, \alpha_L, n_L, \alpha_R, n_R) = N_{J/\psi} \begin{cases} \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right] & \text{for} \quad -\alpha_L < \frac{x-\mu}{\sigma} < \alpha_R \\ A\left(B - \frac{x-\mu}{\sigma}\right)^{-n_L} & \text{for} \quad \frac{x-\mu}{\sigma} \leq -\alpha_L \\ C\left(D + \frac{x-\mu}{\sigma}\right)^{-n_R} & \text{for} \quad \frac{x-\mu}{\sigma} \geq \alpha_R \end{cases}$$

$$\begin{aligned} \text{with} \quad A &= \left(\frac{n_L}{|\alpha_L|}\right)^{n_L} \exp\left(-\frac{|\alpha_L|^2}{2}\right) \\ B &= \frac{n_L}{|\alpha_L|} - |\alpha_L| \\ C &= \left(\frac{n_R}{|\alpha_R|}\right)^{n_R} \exp\left(-\frac{|\alpha_R|^2}{2}\right) \\ D &= \frac{n_R}{|\alpha_R|} - |\alpha_R| \end{aligned}$$

To fit the background:

$$f_{\text{bkg}}(x; N_B, \alpha, \beta, \gamma) = N_B \exp\left[-\frac{1}{2}\left(\frac{x-\alpha}{\sigma}\right)^2\right] \quad \text{with} \quad \sigma = \beta + \gamma\frac{x-\alpha}{\alpha}.$$

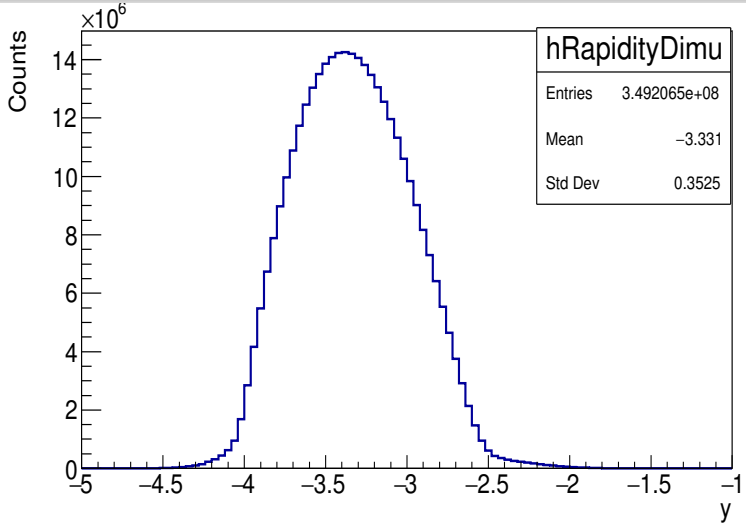


Figure: Rapidity distribution

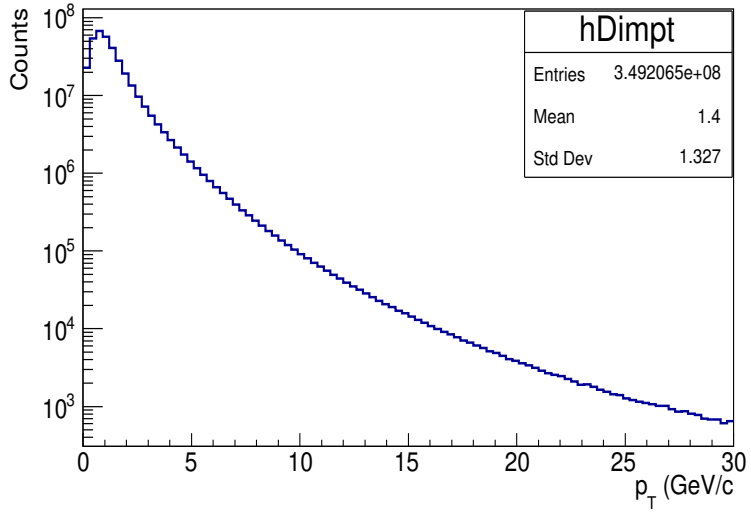


Figure: p_T distribution

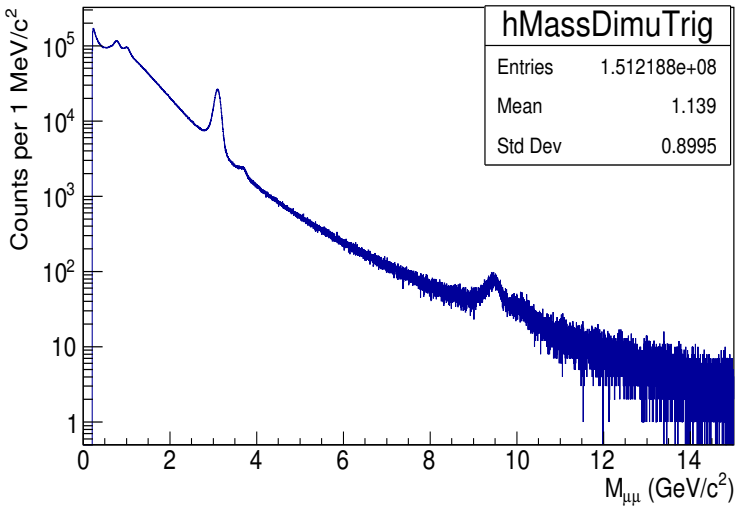


Figure: Without physics selecton

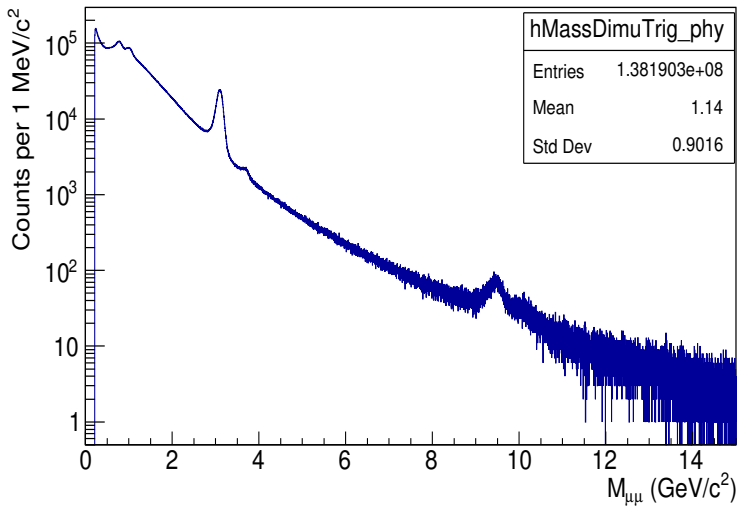


Figure: With physics selecton

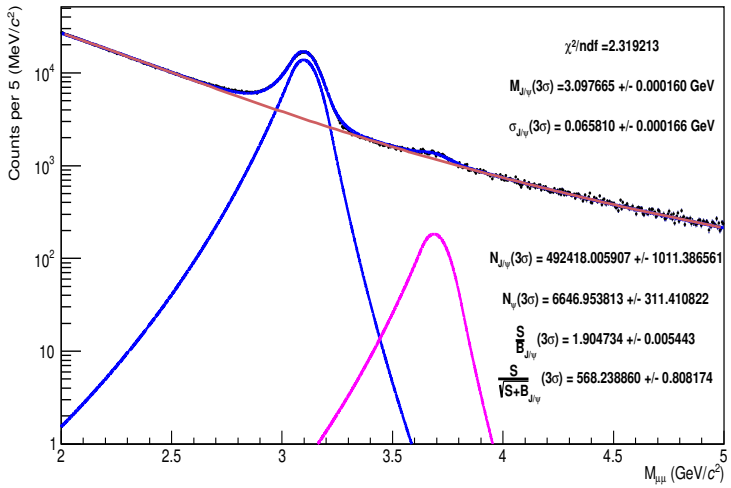


Figure: $0 < p_T < 1$ (GeV/c)

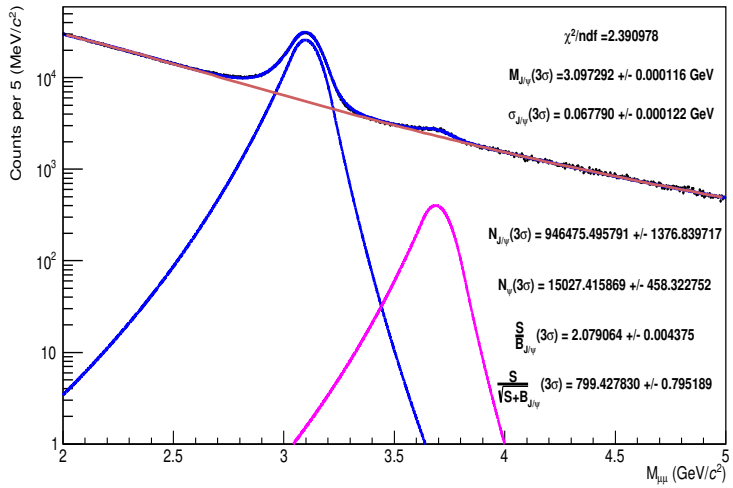


Figure: $1 < p_T < 2$ (GeV/c)

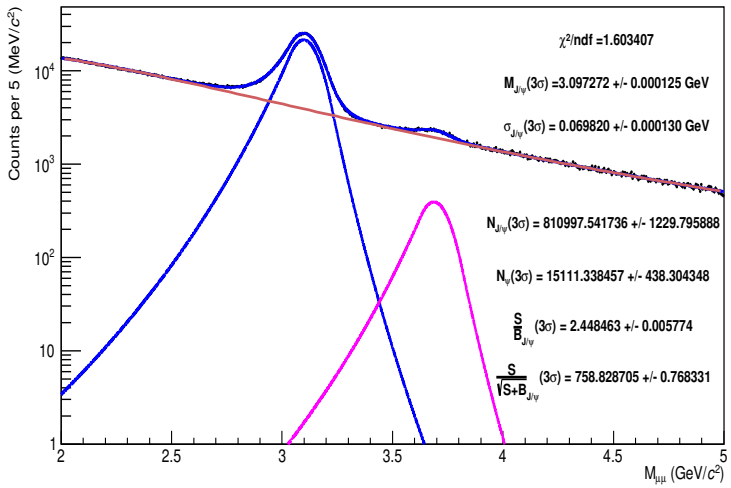


Figure: $2 < p_T < 3$ (GeV/c)

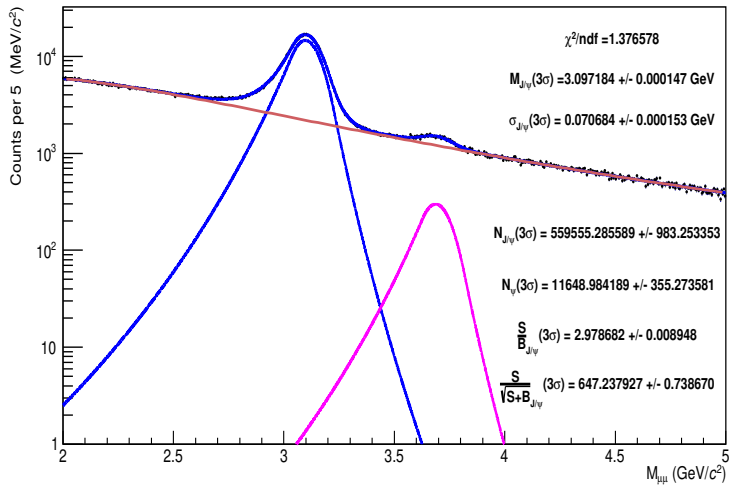


Figure: $3 < p_T < 4$ (GeV/c)

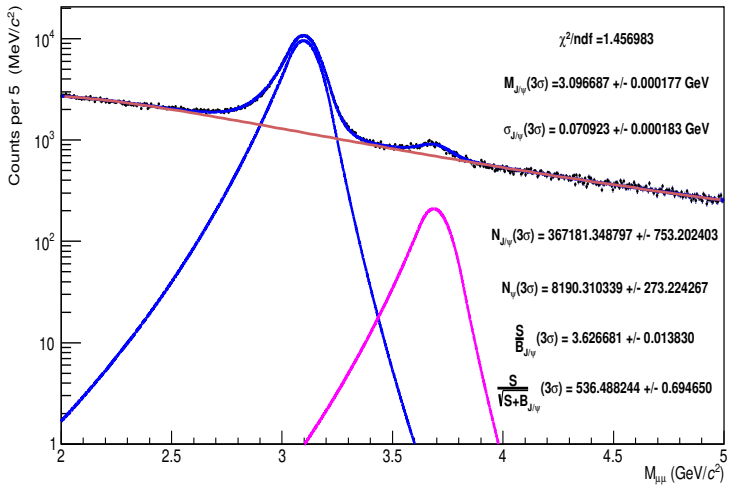


Figure: $4 < p_T < 5$ (GeV/c)

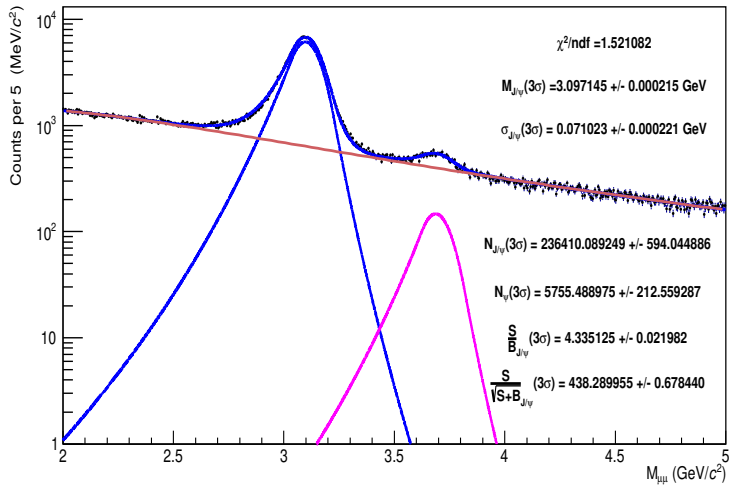


Figure: $5 < p_T < 6$ (GeV/c)

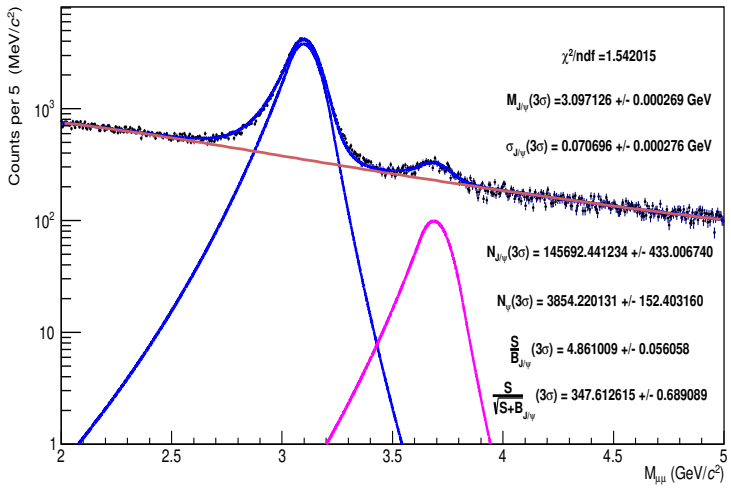


Figure: $6 < p_T < 7$ (GeV/c)

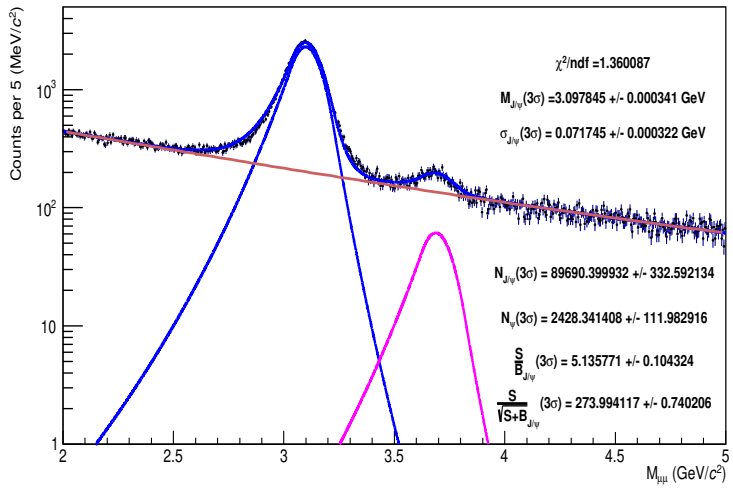


Figure: $7 < p_T < 8$ (GeV/c)

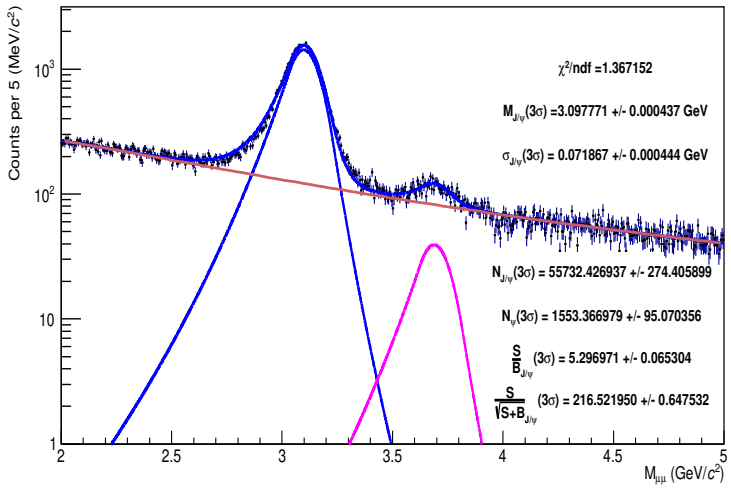


Figure: $8 < p_T < 9$ (GeV/c)

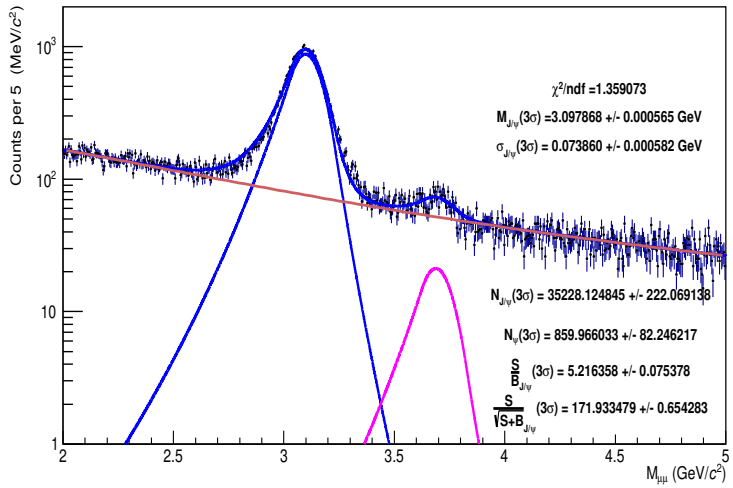


Figure: $9 < p_T < 10$ (GeV/c)

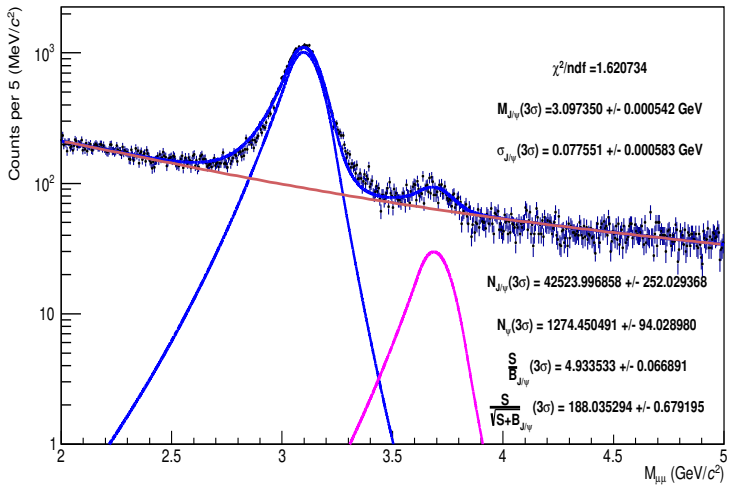


Figure: $10 < p_T < 12.5$ (GeV/c)

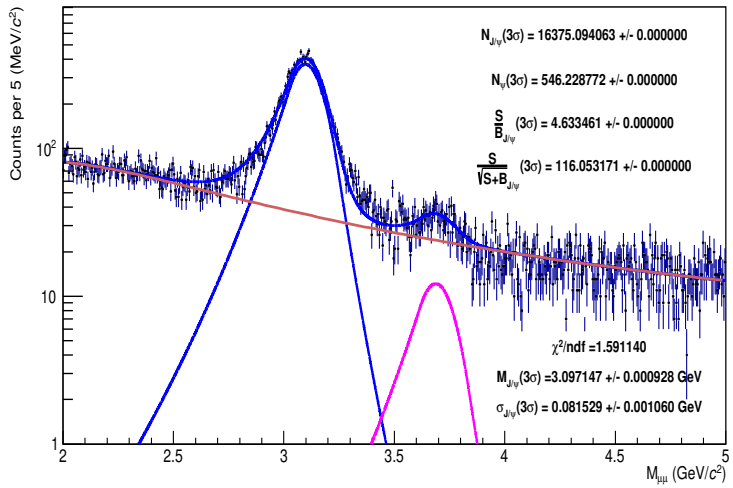


Figure: $12.5 < p_T < 15$ (GeV/c)

Table of differential analysis in different p_T (GeV/c) bins

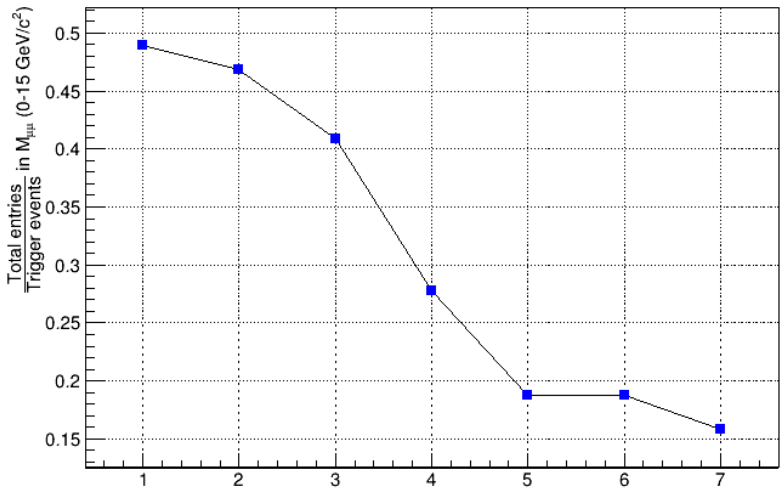
p_T bin (GeV/c)	No.of J/ψ	No.of ψ	χ^2/NDF
$0 < p_T < 1$	492418 $\pm$ 1011	6647 $\pm$ 311	2.31
$1 < p_T < 2$	946475 $\pm$ 1377	15027 $\pm$ 458	2.39
$2 < p_T < 3$	810998 $\pm$ 1230	15111 $\pm$ 438	1.60
$3 < p_T < 4$	559555 $\pm$ 938	11649 $\pm$ 355	1.38
$4 < p_T < 5$	367181 $\pm$ 753	8190 $\pm$ 273	1.45
$5 < p_T < 6$	236410 $\pm$ 594	5755 $\pm$ 213	1.52
$6 < p_T < 7$	145692 $\pm$ 433	3854 $\pm$ 152	1.54
$7 < p_T < 8$	89690 $\pm$ 333	2428 $\pm$ 112	1.36
$8 < p_T < 9$	55732 $\pm$ 274	1553 $\pm$ 95	1.37
$9 < p_T < 10$	35228 $\pm$ 222	860 $\pm$ 82	1.35
$10 < p_T < 12.5$	42524 $\pm$ 252	1274 $\pm$ 94	1.62
$12.5 < p_T < 15$	16375 $\pm$ 163	546$\pm$ 58	1.62
	3798278 $\pm$ 7580	72894 $\pm$ 2641	

Table of differential analysis in different p_T (GeV/c) bins

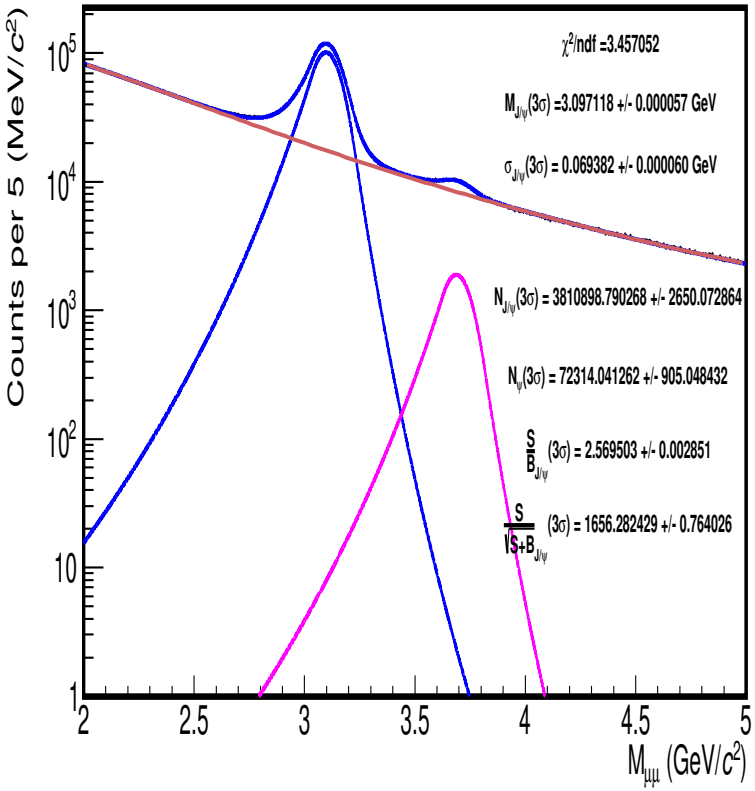
p_T bin (GeV/c)	No.of J/ψ	No.of ψ
$0 \leq p_T < 2$	1438550 ± 1714	21712 ± 558
$2 \leq p_T < 4$	1370800 ± 1573	26775 ± 565
$4 \leq p_T < 6$	603614 ± 965	13979 ± 346
$6 \leq p_T < 8$	235384 ± 579	6327 ± 208
$8 \leq p_T < 10$	90942 ± 355	2416 ± 120
$10 \leq p_T \leq 15$	58908 ± 290	1830 ± 101
	3798198	73039

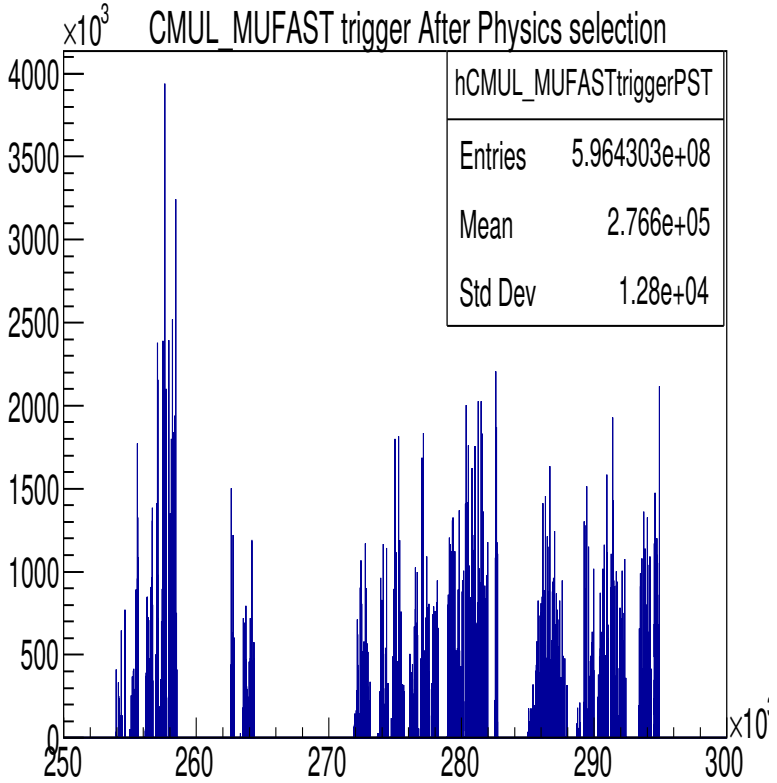
Sensitivity of different cuts on di-muon invariant mass spectra for LHC16h period:

- C_1: pDCA cut
- C_2: $17.6 < R_{abs} < 89.5$ (cm).
- C_3: -4.0 $< \eta <$ -2.5
- C_4: charge1 + charge2 =0
- C_5: Trigger+Physics selection cut.
- C_6: $2.5 < |y| < 4.0$.
- C_7: Match trigger track and low p_T threshold codition.



	Applied cuts	Total entries/Trigger event in $M_{\mu\mu}$(0-15 GeV/c^2)
1	C_1	0.4893
2	C_1+C_2	0.4685
3	$C_1+C_2+C_3$	0.4041
4	$C_1+C_2+C_3+C_4$	0.2772
5	$C_1+C_2+C_3+C_4+C_5$	0.1880
6	$C_1+C_2+C_3+C_4+C_5+C_6$	0.1879
7	$C_1+C_2+C_3+C_4+C_5+C_6+C_7$	0.1583





- Integrated J/ψ yield = 3810899 $\pm$ 2650
- CMUL7 trigger event with physics selection =596.43 M
- Relative fraction of $N_{J/\psi}$ / Number of CMUL7 events = 0.006389

Differential analysis in p_T bins:

Splitting data in dimuon p_T bins: twelve bins between 0 GeV/c and 15 GeV/c with variable width (1 GeV/c, from 0 GeV/c up to 10 GeV/c, then 2.5 GeV/c up to 15 GeV/c).

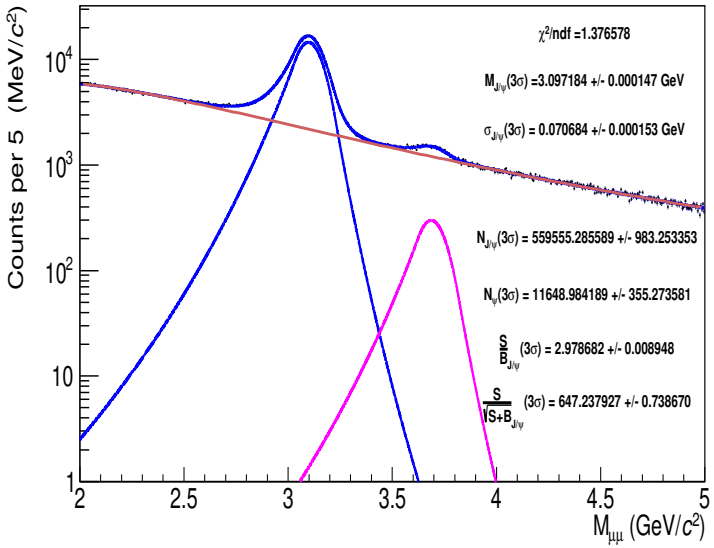


Figure: $3 < p_T < 4$ (GeV/c)

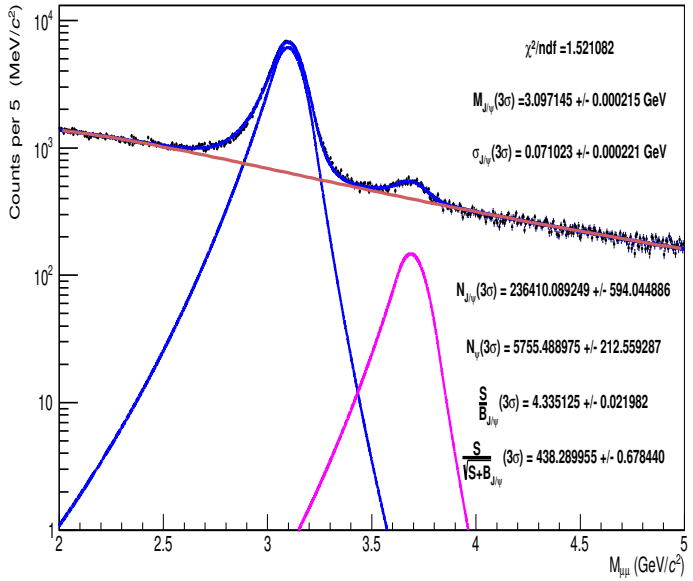


Figure: $5 < p_T < 6$ (GeV/c)

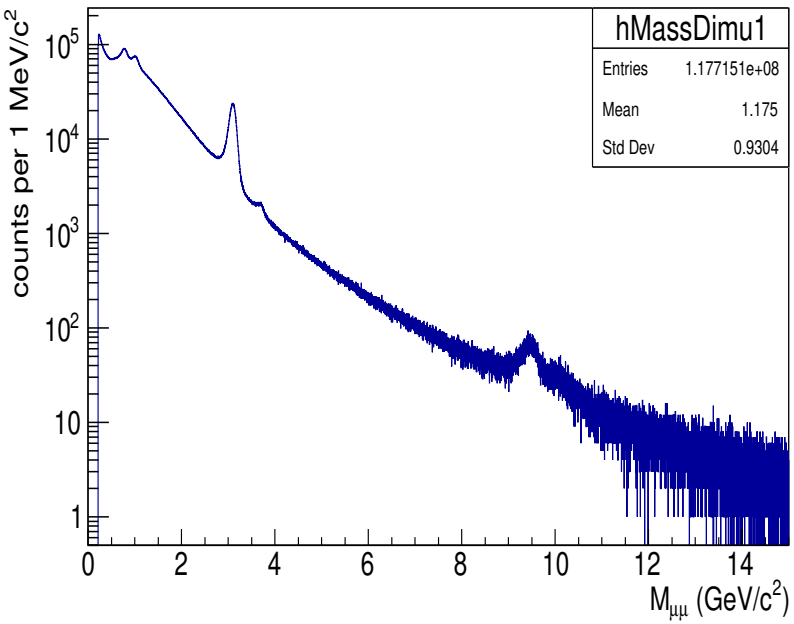
- Fitting status converged in all p_T bin.
- Bin width of invariant mass $= 5\ MeV/c^2$

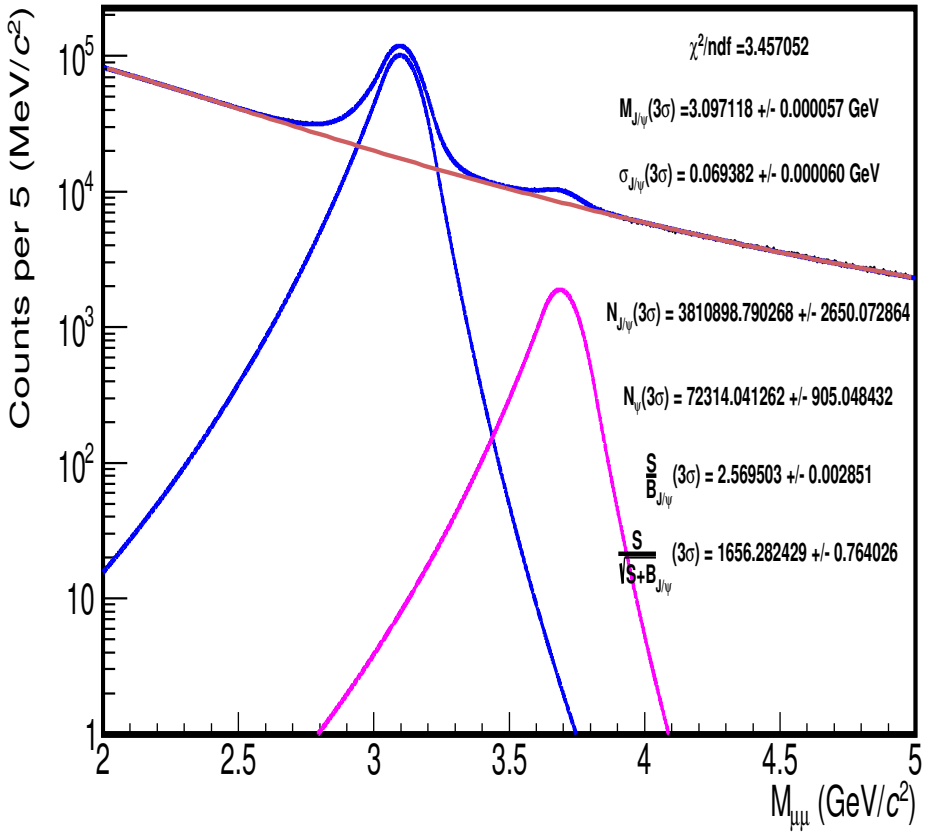
Signal extraction from inclusive invariant mass spectra:

Fitting function:

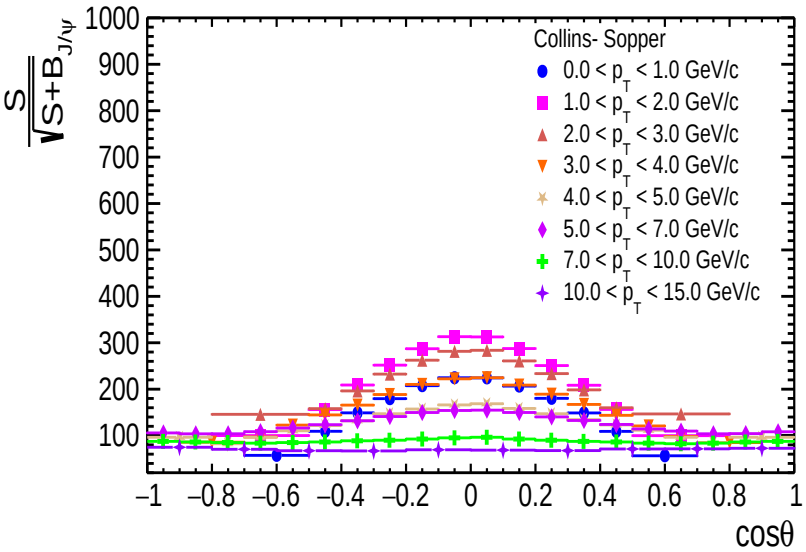
- **Signal:** CB2
- **Background:** VWG
- **Fitting Range:** [2.0,5.0]

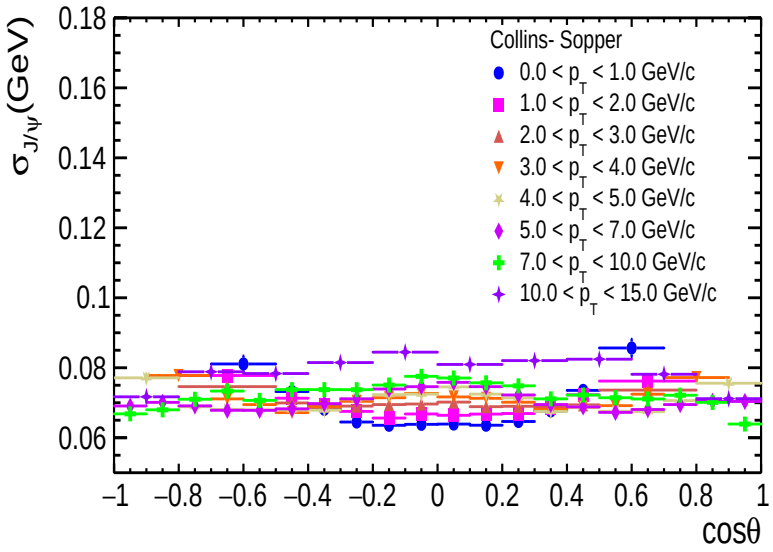
- **Bin width of invariant mass =** 5 MeV/c^2

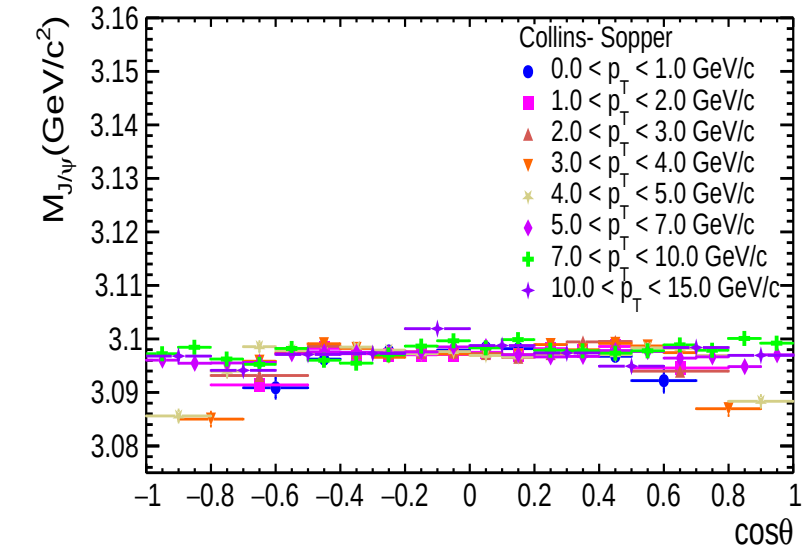


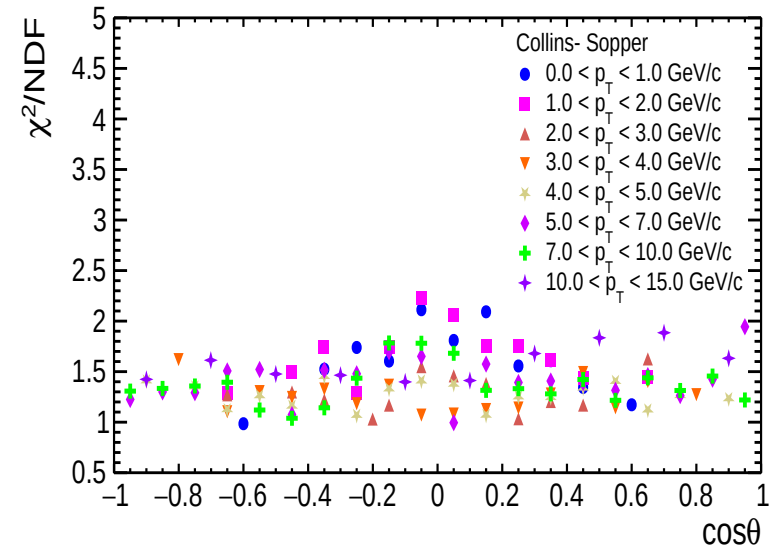


Differential analysis of J/ψ in cosθ bin in CS frame

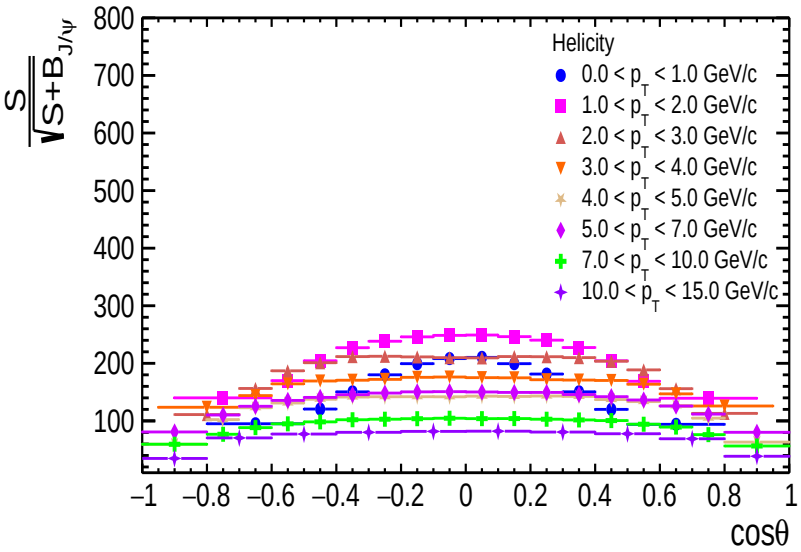


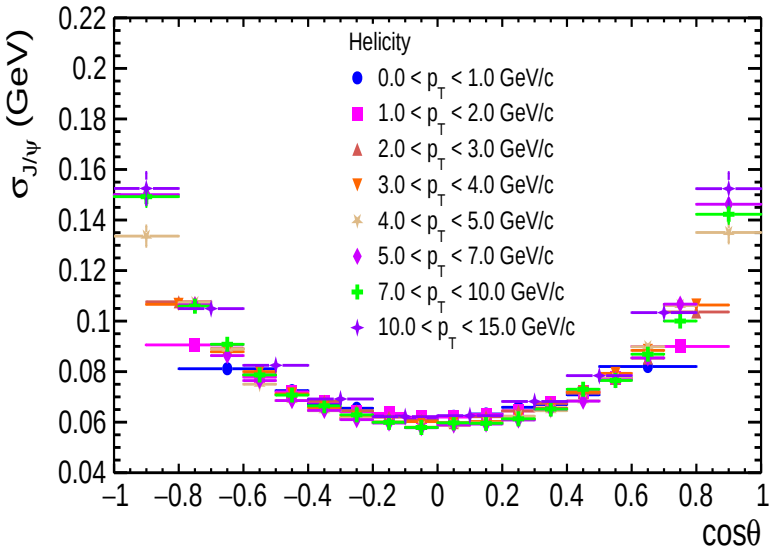


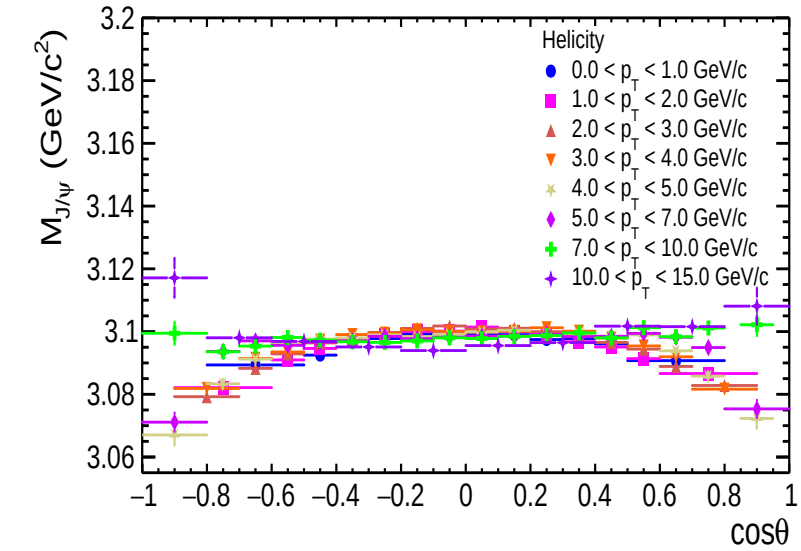


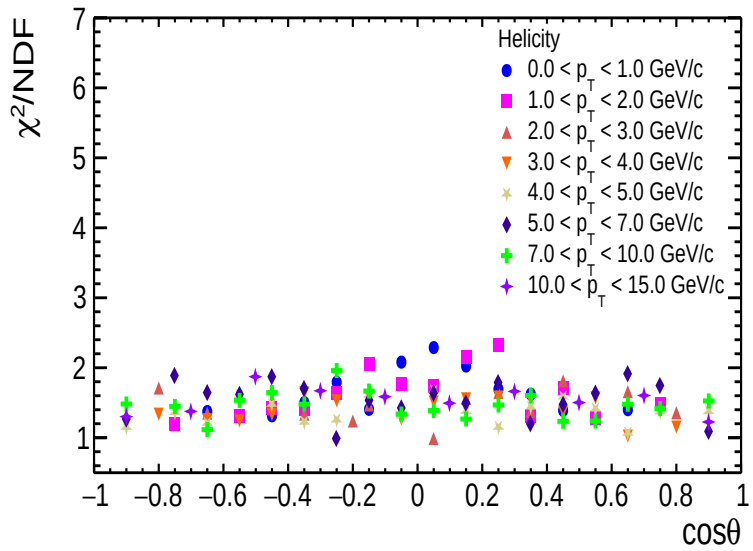


Differential analysis of J/ψ in cosθ bin in HE frame

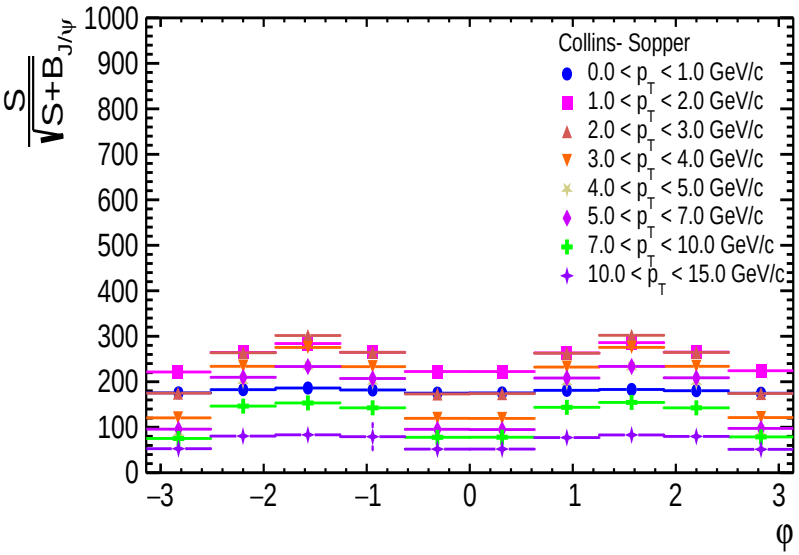


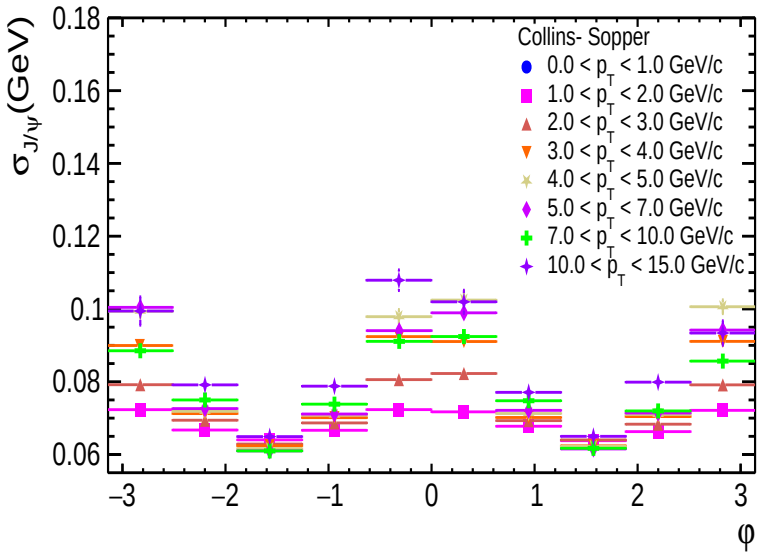


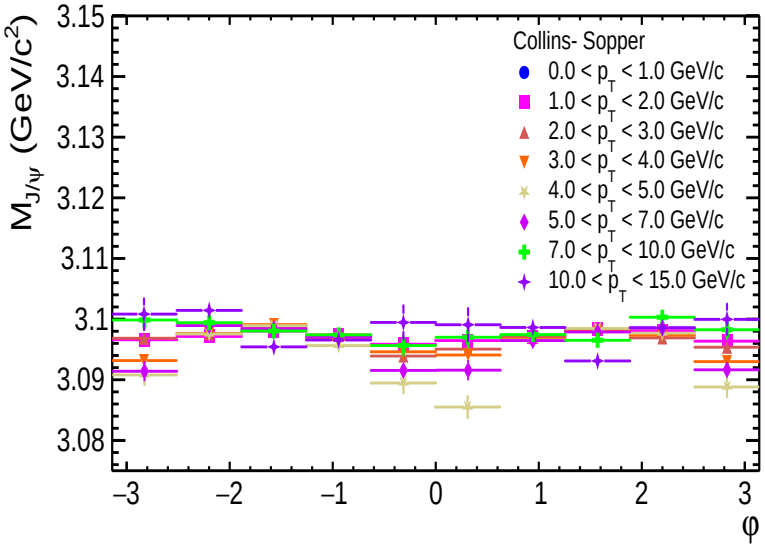


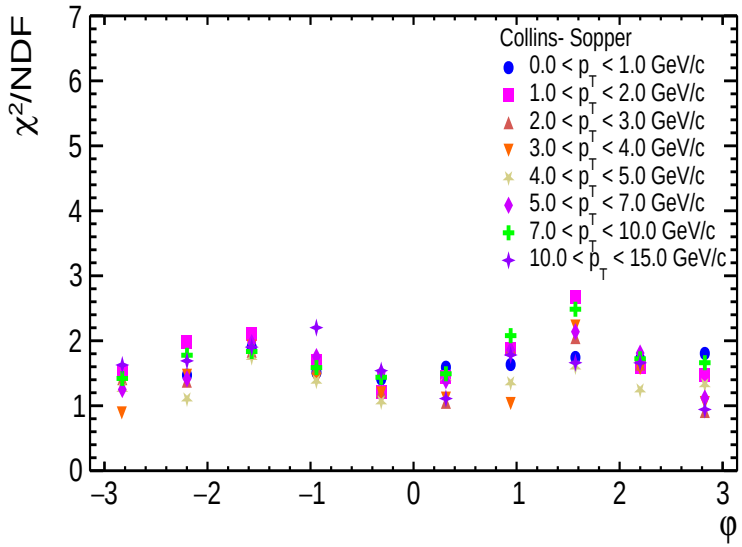


Differential analysis of J/ψ in φ bin in CS frame

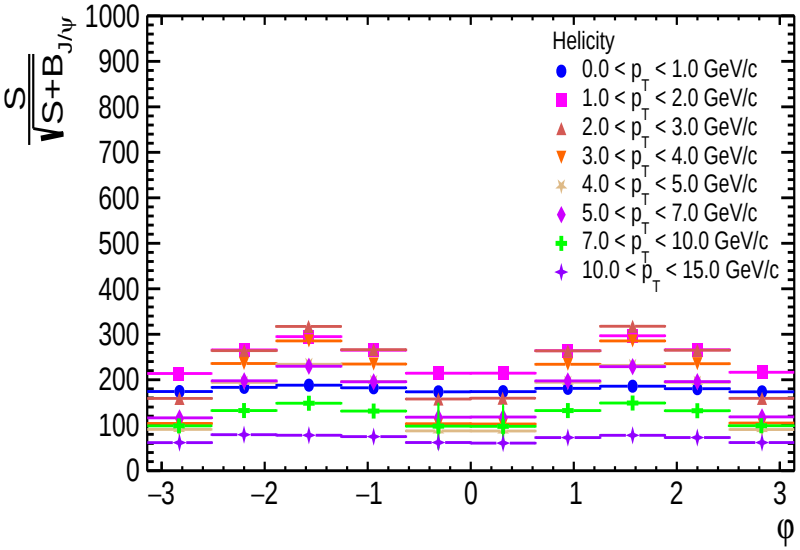


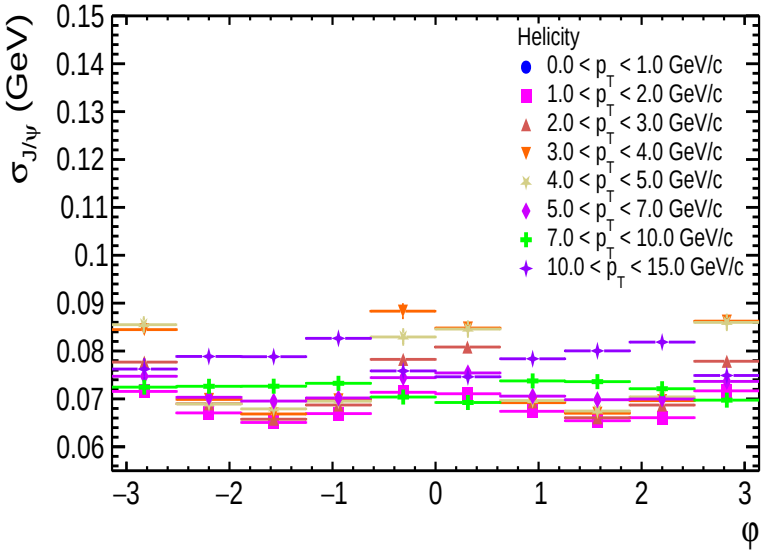


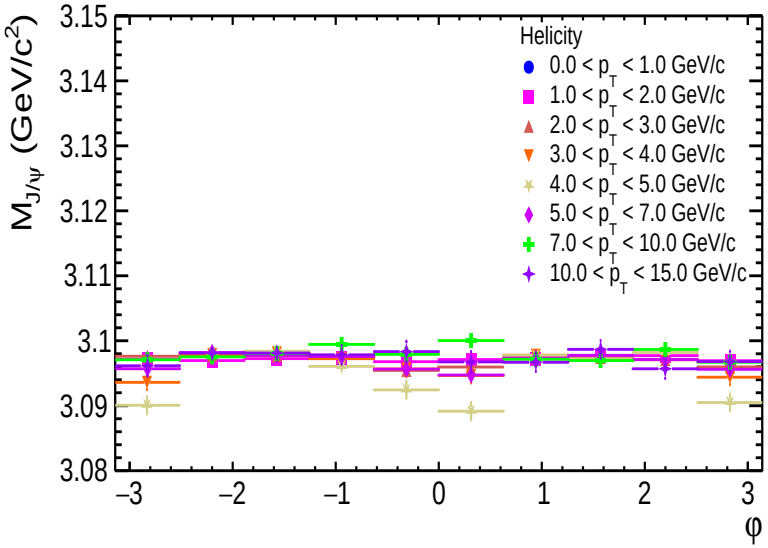


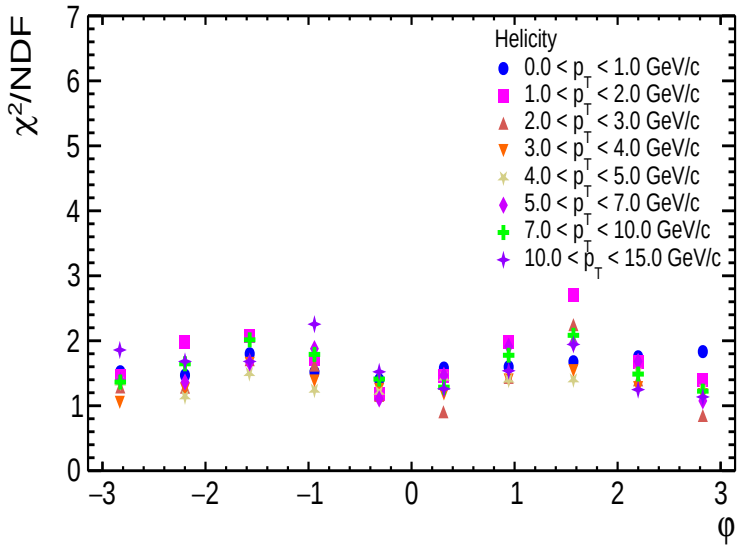


Differential analysis of J/ψ in φ bin in HE frame







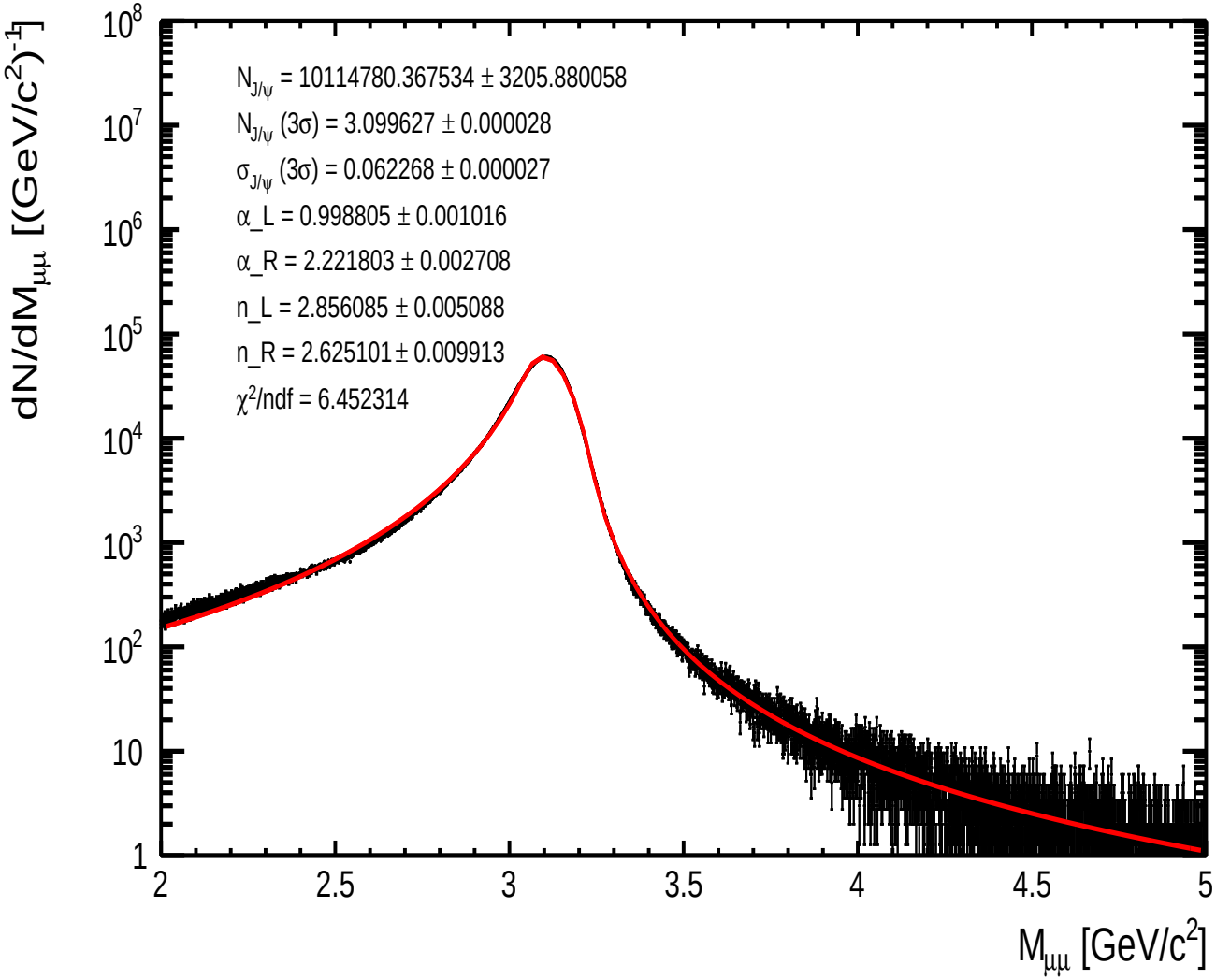


MC production detail

- JIRA ticket: https://alice.its.cern.ch/jira/browse/ALIROOT-8846?filter=-2
- MC production for $\psi(2S)$ in pp collisions at 13TeV
- p_T and the rapidity distributions are tuned according to Eur. Phys. J. C 77, 392 (2017)
- MC refers to the 2016, 2017 and 2018 data-taking periods
- Generated tag: LHC23e7 (1880 run numbers)

MC Analysis: Reconstructed invariant mass spectra

- **For all(1880) MC run numbers**



MC- p_T differential analysis