Multiplicity dependence of J/ψ polarization measurement in pp collisions at $\sqrt{s}$ = 13.6 TeV with ALICE at the LHC

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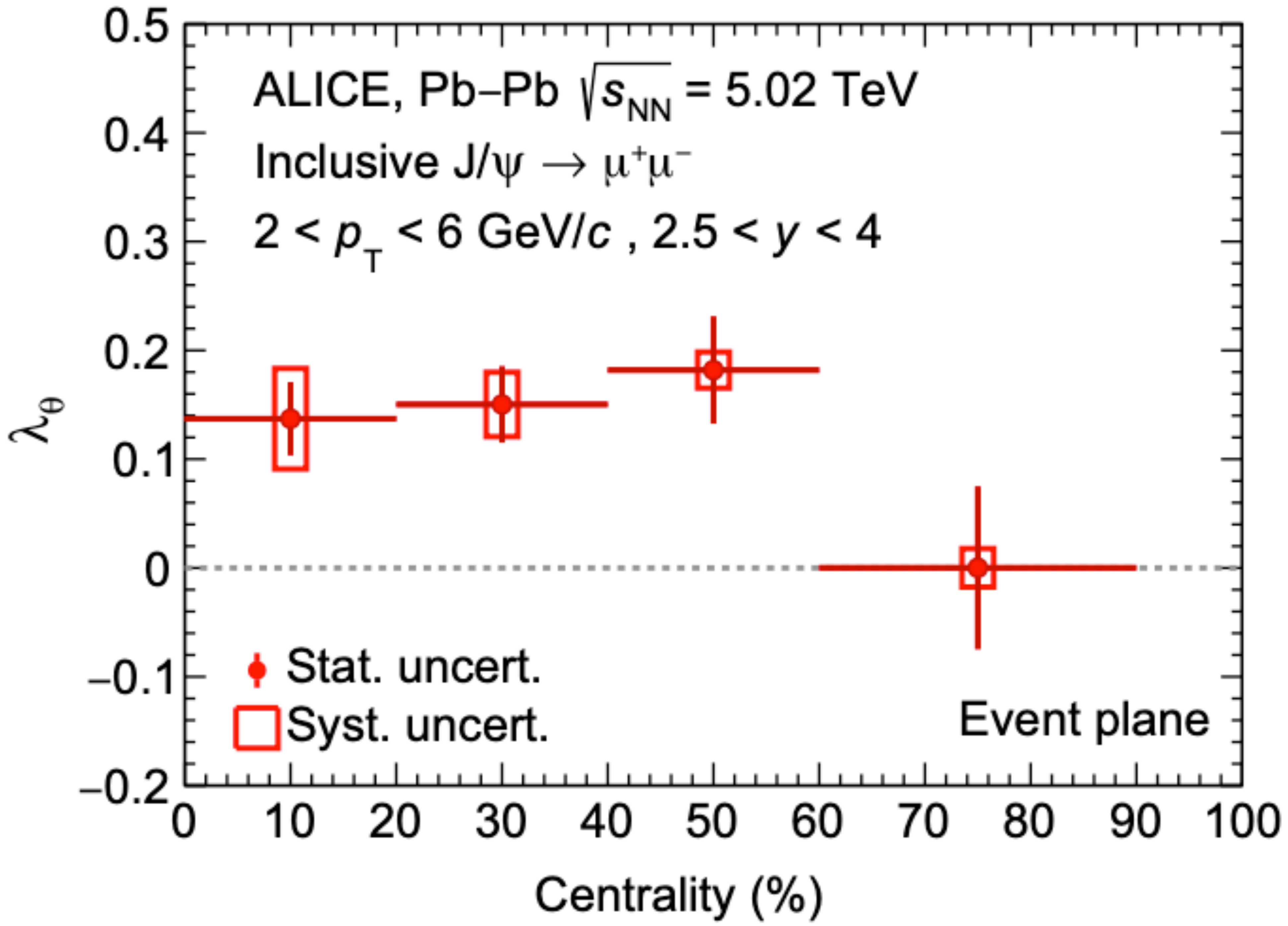
Outlines

- Motivation of the study
- Introduction
- Dataset and track selection cuts
- Signal extraction method
- Results
- Summary and Outlook

Motivation of the Study

- A hint of finite polarization of J/ψ in most and mid central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- First measurement of J/ψ polarization parameter is obtained with respect to the Event Plane method at forward rapidity



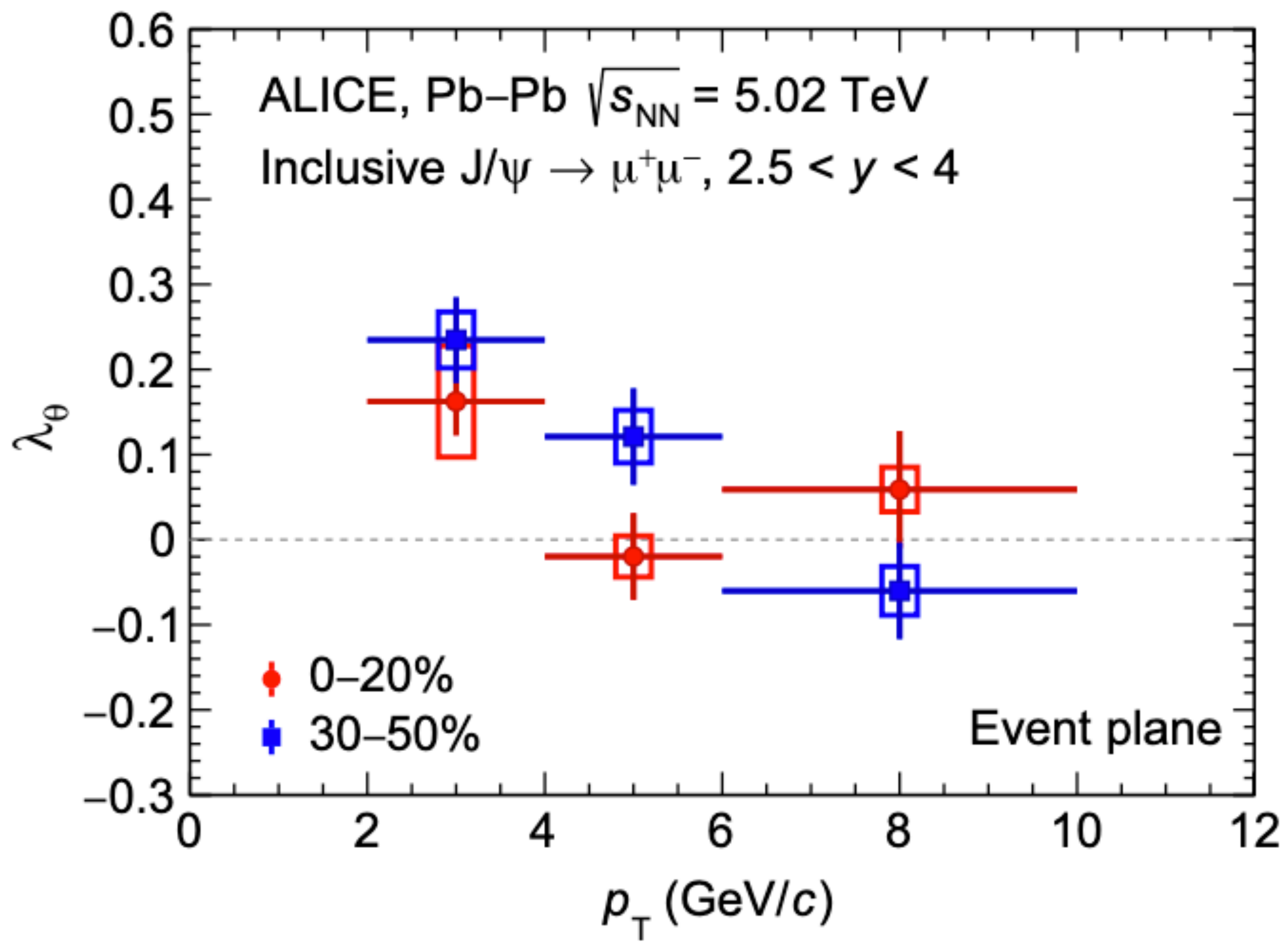
PHYSICAL REVIEW LETTERS **131,** 042303 (2023)

Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC

S. Acharya *et al.**
(ALICE Collaboration)

Motivation of the Study

- Further, a hint of finite polarization of J/ψ is observed at low p_T for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
- Significant deviation (3.9σ) is observed for (30-50)% at low transverse momentum ($2 < p_T < 4$ GeV/c)



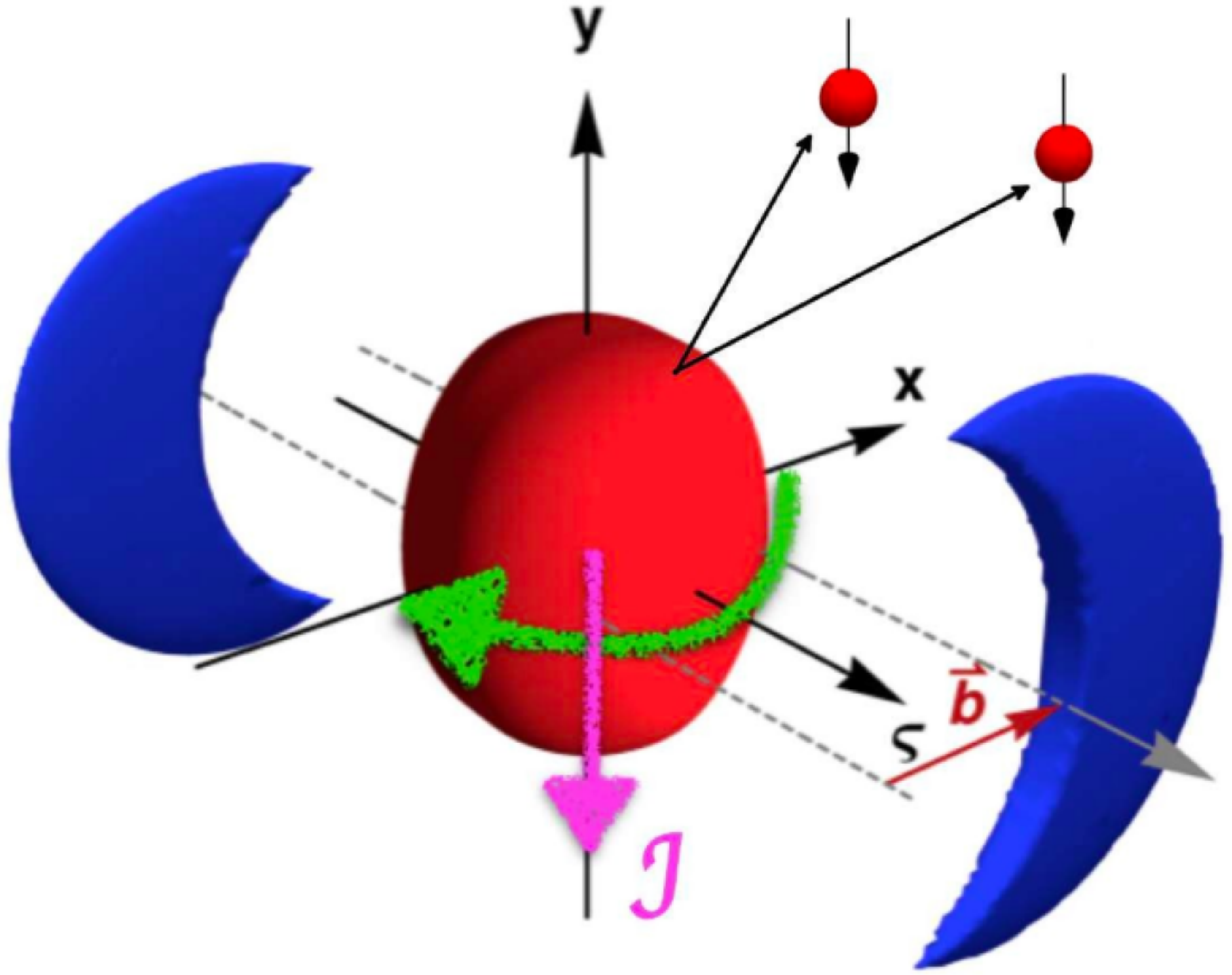
PHYSICAL REVIEW LETTERS **131,** 042303 (2023)

Measurement of the *J/ψ* Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC

S. Acharya *et al.*[*]
(ALICE Collaboration)

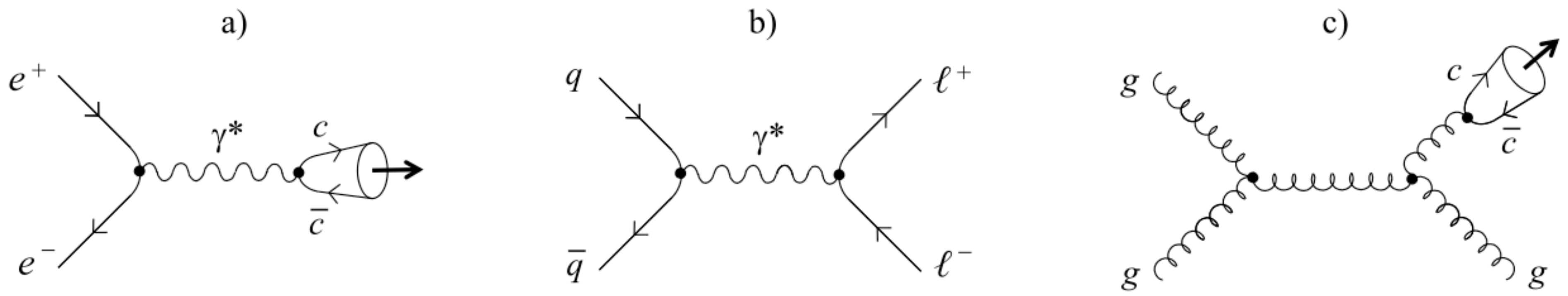
Sources of J/ψ polarization

- What could be the possible sources of J/ψ polarization?
    - Vorticity field?
    - Electromagnetic field?
    - Vector meson force field?
    - Anisotropic flow?
    - Production mechanism?
- Does medium has any role on J/ψ polarization?
- Need to be investigated
- What about pp collisions?
    - Basic Conservation Laws
        - Helicity Conservation
        - Rotational covariance of angular momentum eigenstates
        - Parity conservation



$$L_0 = \frac{Ab\sqrt{s_{NN}}}{2}$$

Prog. Nucl. Phys, **108**, 103709 (2019)

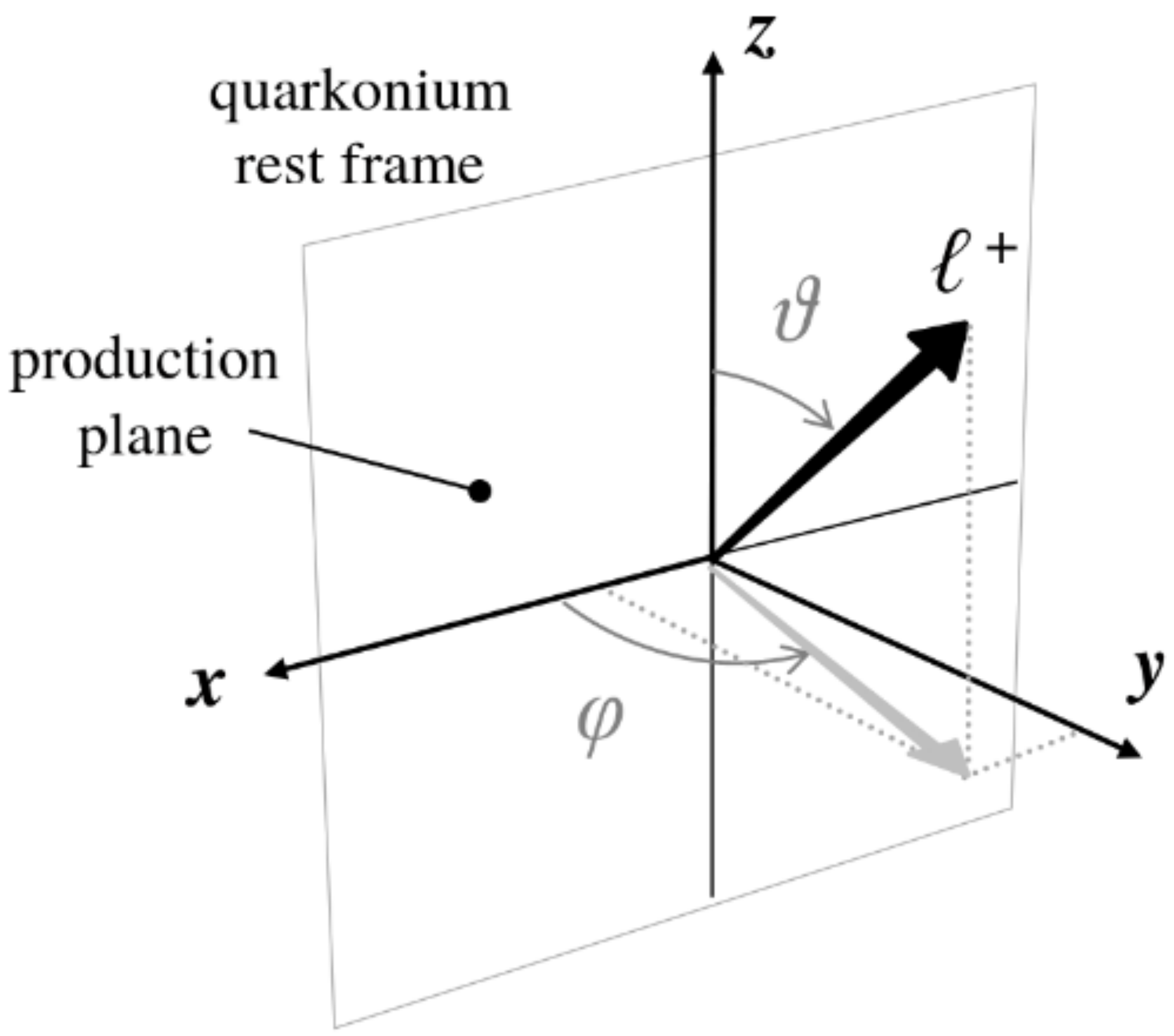


Faccioli et. al, EPJC **69**, 657 (2010).

Quarkonium Polarization: an Introduction

- What is polarization?
  - It is an observable which measures the alignment of particle spin with respect to a chosen quantisation axis
- How do we measure it in experiment?
  - For a vector meson (**V**) the total angular momentum ($\boldsymbol{J}, \boldsymbol{J_z}$) state can be expressed as

J/ψ, ψ(2S), Υ(1S), Υ(2S), Υ(3S), etc. [$J^{PC} = 1^{--}$]



Faccioli et. al, EPJC **69**, 657 (2010).

$$|V : J, J_z\rangle = \mathbf{b}_{-1}|1,-1\rangle + \mathbf{b}_0|1,0\rangle + \mathbf{b}_{+1}|1,+1\rangle$$

Spin alignment⇔Decay daughter's angular distribution

Dilepton decay angular distribution

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

$(\lambda_\theta,\ \lambda_\phi,\ \lambda_{\theta\phi}) = (1,0,0) \rightarrow$ Pure transverse polarization

$(\lambda_\theta,\ \lambda_\phi,\ \lambda_{\theta\phi}) = (-1,0,0) \rightarrow$ Pure longitudinal polarization

$(\lambda_\theta,\ \lambda_\phi,\ \lambda_{\theta\phi}) = (0,0,0) \rightarrow$ zero polarization

Polarization Frames

- Polarization parameters $\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}$ are frame dependent
- Conventionally, three polarization frames are defined
- Polarization frames are decided on the definition of quantization axis (say, z axis)

- **Helicity Frame (HF)**

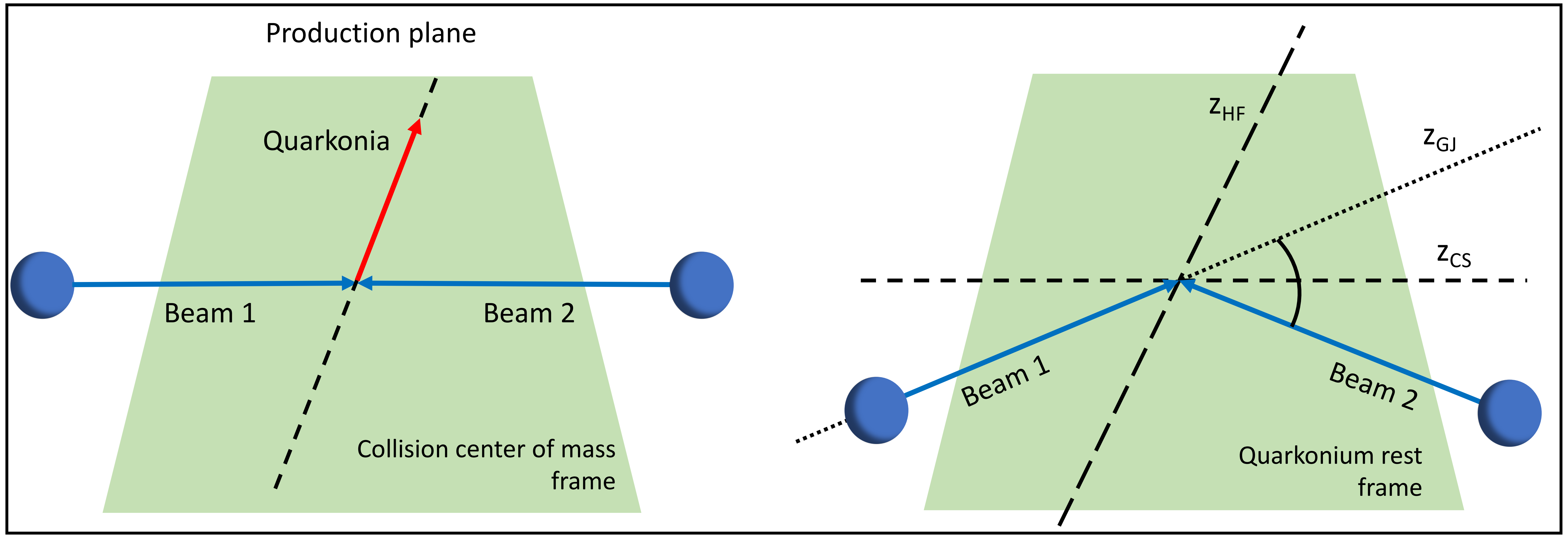
  In the direction of quarkonia momentum in the center of the mass frame of the colliding beams

- **Collins-Soper Frame (CS)**

  The bisector of the angle between the momentum of one beam and the opposite of the other beam

- **GottFried-Jackson Frame (GJ)**

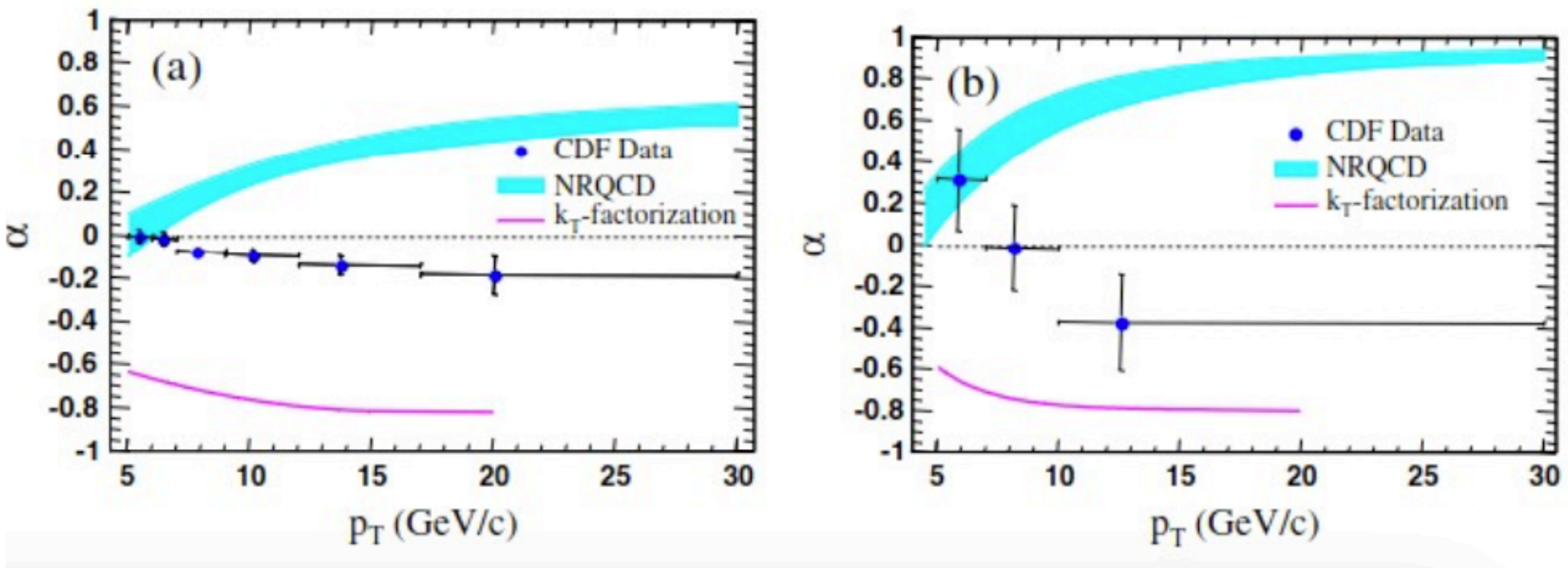
  The direction of the momentum of one of the colliding beams



B. Sahoo et. al, Phys.Rev.C 109 (2024) 3, 034910

J/ψ polarization puzzle

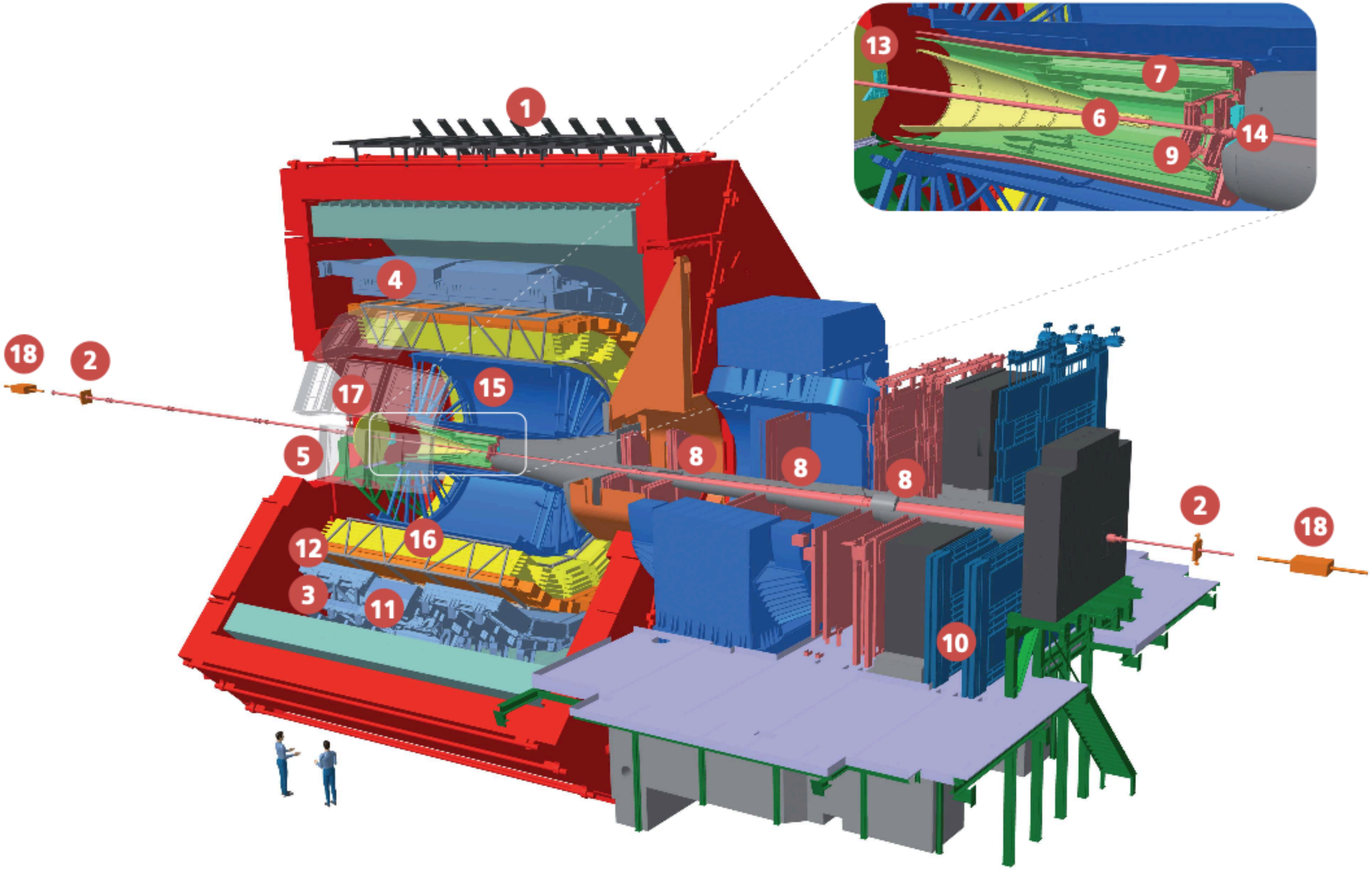
- Polarization measurement constrain quarkonium production mechanism
- J/ψ and ψ(2S) polarization measured by the CDF collaboration as a function of p_T in the Helicity frame for pp collisions $\sqrt{s}$ = 1.96 TeV (|y| < 0.6)



- PRL **99**, 132001 (2007).

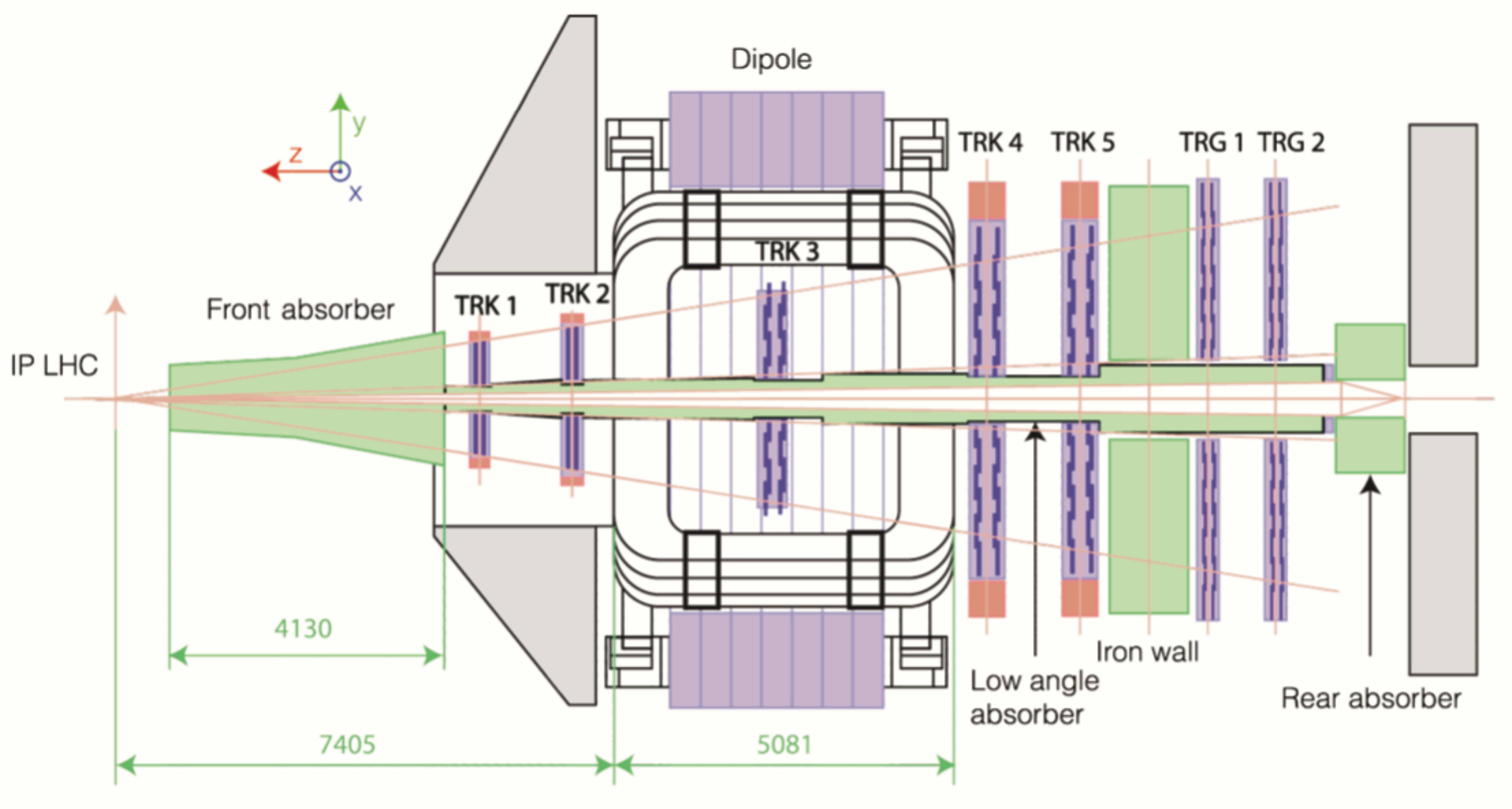
- NRQCD → Strong transverse polarization
- k_T-Factorization → Strong longitudinal polarization
- CDF Run 2 Data → Very weak longitudinal polarization
- So called "J/ψ polarization puzzle"

ALICE Detector: Run 3 Configuration



1. **ACORDE** | ALICE Cosmic Rays Detector
2. **AD** | ALICE Diffractive Detector
3. **DCal** | Di-jet Calorimeter
4. **EMCal** | Electromagnetic Calorimeter
5. **HMPID** | High Momentum Particle Identification Detector
6. **ITS-IB** | Inner Tracking System - Inner Barrel
7. **ITS-OB** | Inner Tracking System - Outer Barrel
8. **MCH** | Muon Tracking Chambers
9. **MFT** | Muon Forward Tracker
10. **MID** | Muon Identifier
11. **PHOS / CPV** | Photon Spectrometer
12. **TOF** | Time Of Flight
13. **T0+A** | Tzero + A
14. **T0+C** | Tzero + C
15. **TPC** | Time Projection Chamber
16. **TRD** | Transition Radiation Detector
17. **V0+** | Vzero + Detector
18. **ZDC** | Zero Degree Calorimeter

Muon Spectrometer



Dataset Selection

- **Dataset**: LHC22o_pass6_minBias_medium
- **Run Periods:** 526641, 526964, 527041, 527240
- Package Tag: daily-20240513-0200-1
- Train Number: 212423
- JIRA Tickets: JIRA : PWGDQ-84
- Analyser Name : bhsahoo
- Analysis Name: Multiplicity dependence of Jpsi polarization in pp collisions
- Path to hyperloop: https://alimonitor.cern.ch/hyperloop/view-analysis/50643
- Wagon Name: tablemaker-run3-association-test2, tablereader-run3-association-test2

Analysis Cuts: Event and Track Selection Cuts

1. table-maker: (Analysis Task: tableMaker.cxx)

Event Cuts: eventStandardNoINT7

Muon Cuts: muonQualityCuts

- $-4 < \eta_{\mu} < -2.5$
- $17.6 < R_{Abs} < 89.5$ cm
- pDCA cut
- $\chi^2_{\mu} > 0$
- $\chi^2_{MCH-MID} > 0$

processAssociatedMuonOnlyWithCovAndMults: " true"
cfgMuonLowPt: 0
cfgPropMuon: "true"

Dependencies: fwdtrack-collision-association, EventSelection_Run3_pp, FwdTrackExtension, Multiplicity_Run3_pp, TimestampCreator

Wagon Name: tablemaker-run3-association-test2

2. table-reader: (Analysis Task: tableReader.cxx)

Event Cuts: eventStandardNoINT7

Muon Cuts: matchedMchMid, muonLowPt10SigmaPDCA, muonLowPt210SigmaPDCA, muonLowPt510SigmaPDCA

MCH-MID (Track Type 3)
- $-4 < \eta < -2.5$
- $17.6 < R_{Abs} < 89.5$ cm

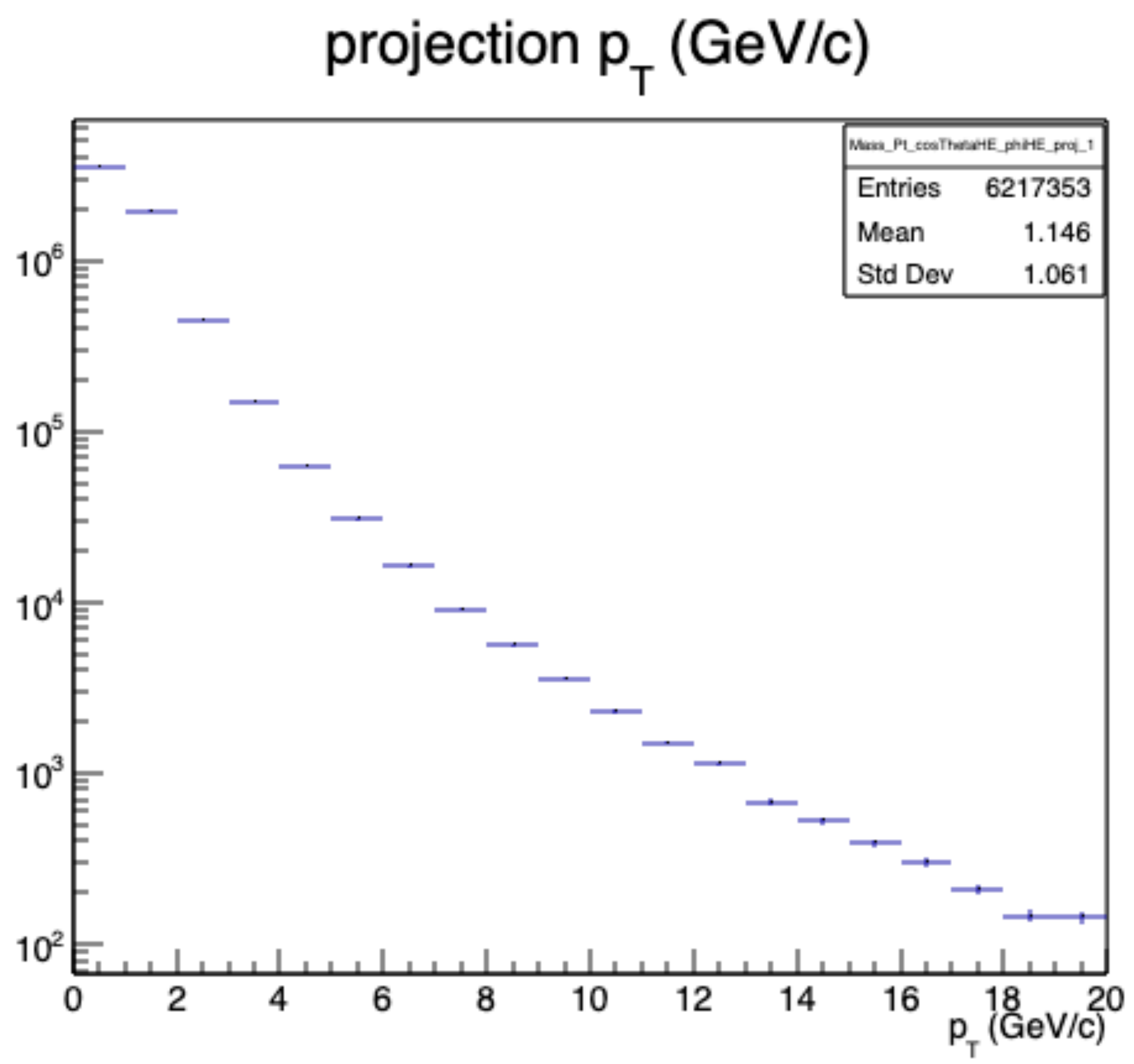
processDecayToMuMuSkimmed: "true"
cfgAddSEPHistogram: "dimuon-polarization-he,dimuon-polarization-cs"

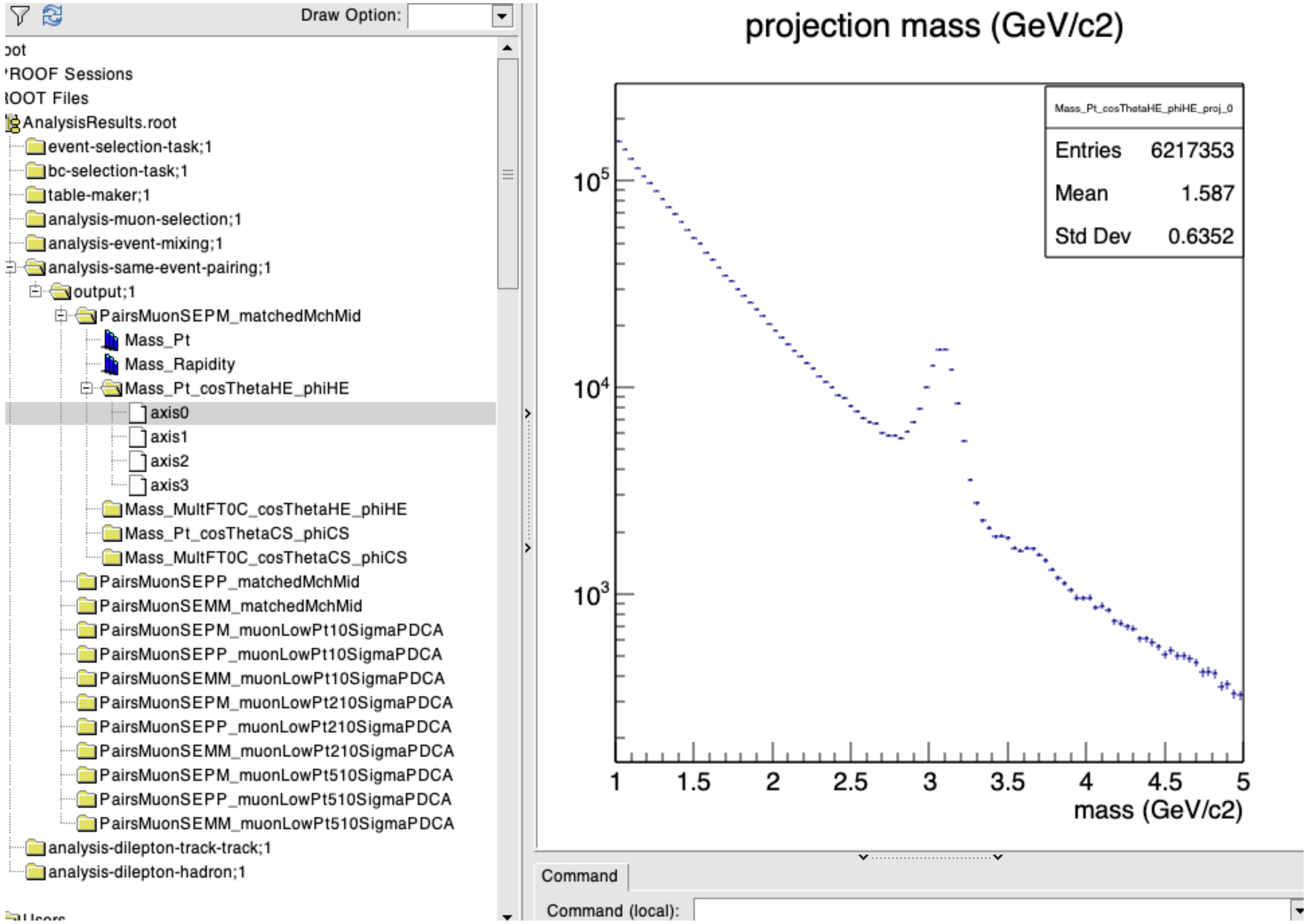
Dependencies: tablemaker-run3-association-test2

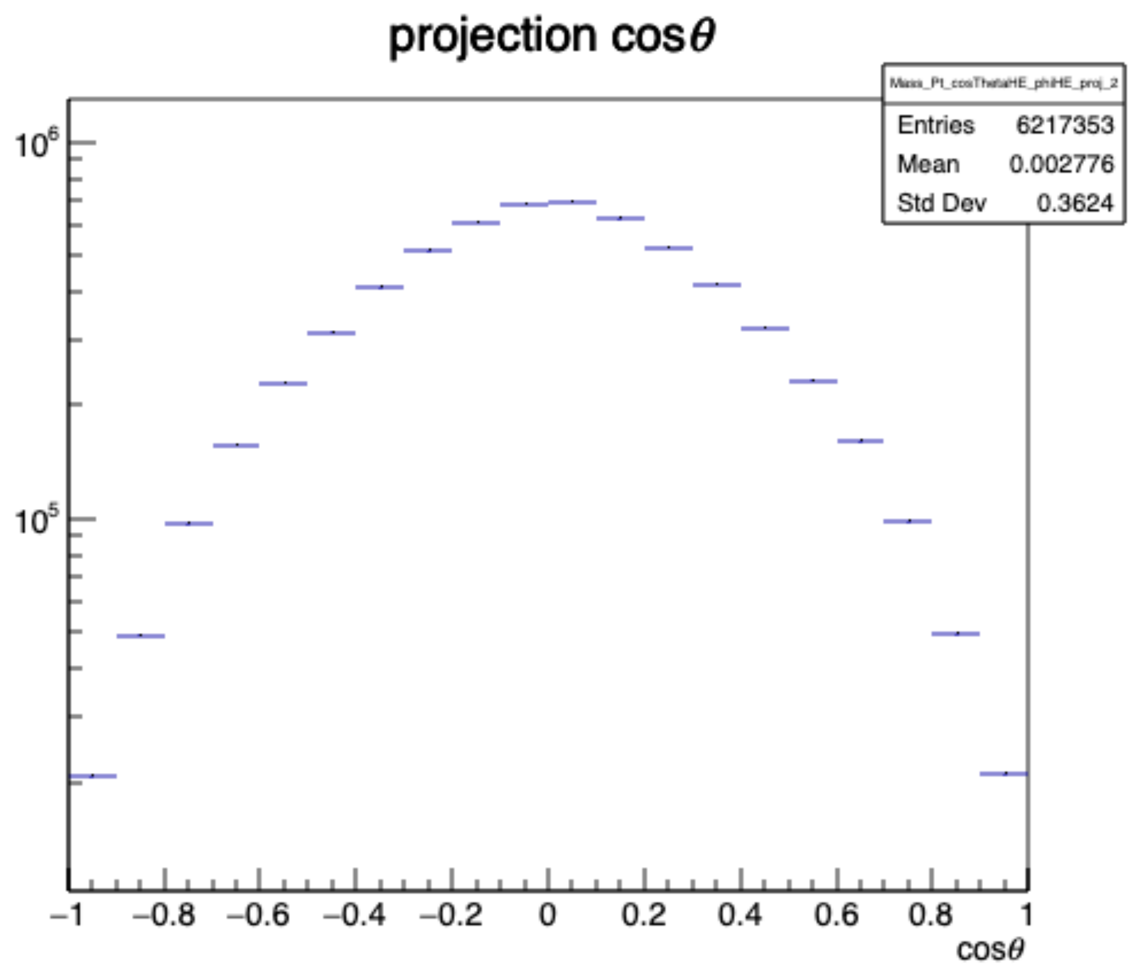
Wagon Name: tablereader-run3-association-test2

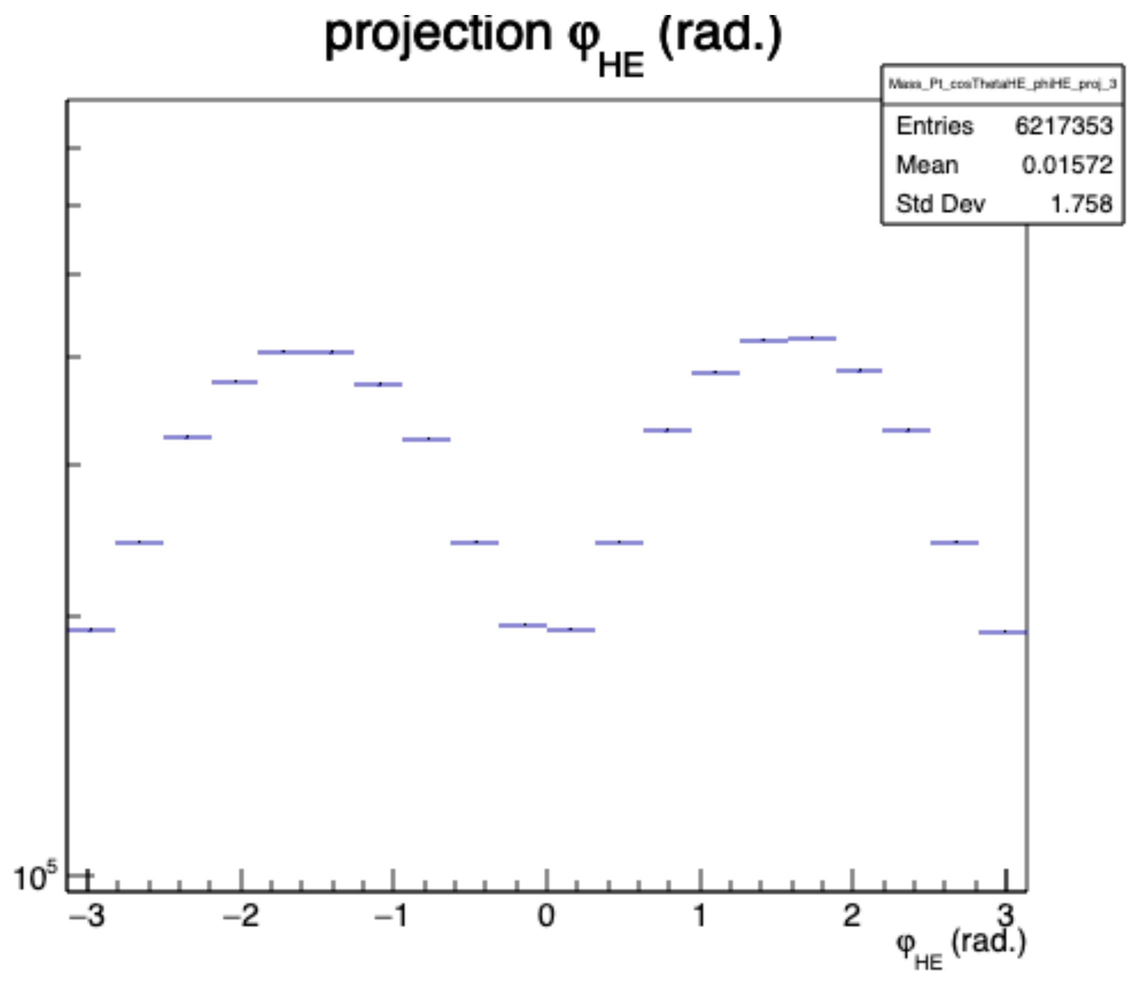
Output of the TableReader Task

- Mass, p_T, ϕ, and $\cos\theta$ are filled in two four dimensional histogram for helicity and Collins-Soper frame using THnSparse
- Mass, multiplicity, ϕ, and $\cos\theta$ are filled in two four dimensional histogram for helicity and Collins-Soper frame using THnSparse









Fitting Function

– signal shape: double Crystal Ball function (CB2) :

$$f(x;N,\bar{x},\sigma,t_1,t_2,p_1,p_2) = N \cdot \begin{cases} A\cdot(B-t)^{-p_1} & ,t \leq t_1 \\ \exp\left(-\frac{1}{2}t^2\right) & ,t_1 < t < t_2 \\ C\cdot(D+t)^{-p_2} & ,t \geq t_2 \end{cases}$$

where

$$t = \frac{x-\bar{x}}{\sigma}$$

$$A = \left(\frac{p_1}{|t_1|}\right)^{p_1} \cdot \exp\left(-\frac{|t_1|^2}{2}\right)$$

$$B = \frac{p_1}{|t_1|} - |t_1|$$

$$C = \left(\frac{p_2}{|t_2|}\right)^{p_2} \cdot \exp\left(-\frac{|t_2|^2}{2}\right)$$

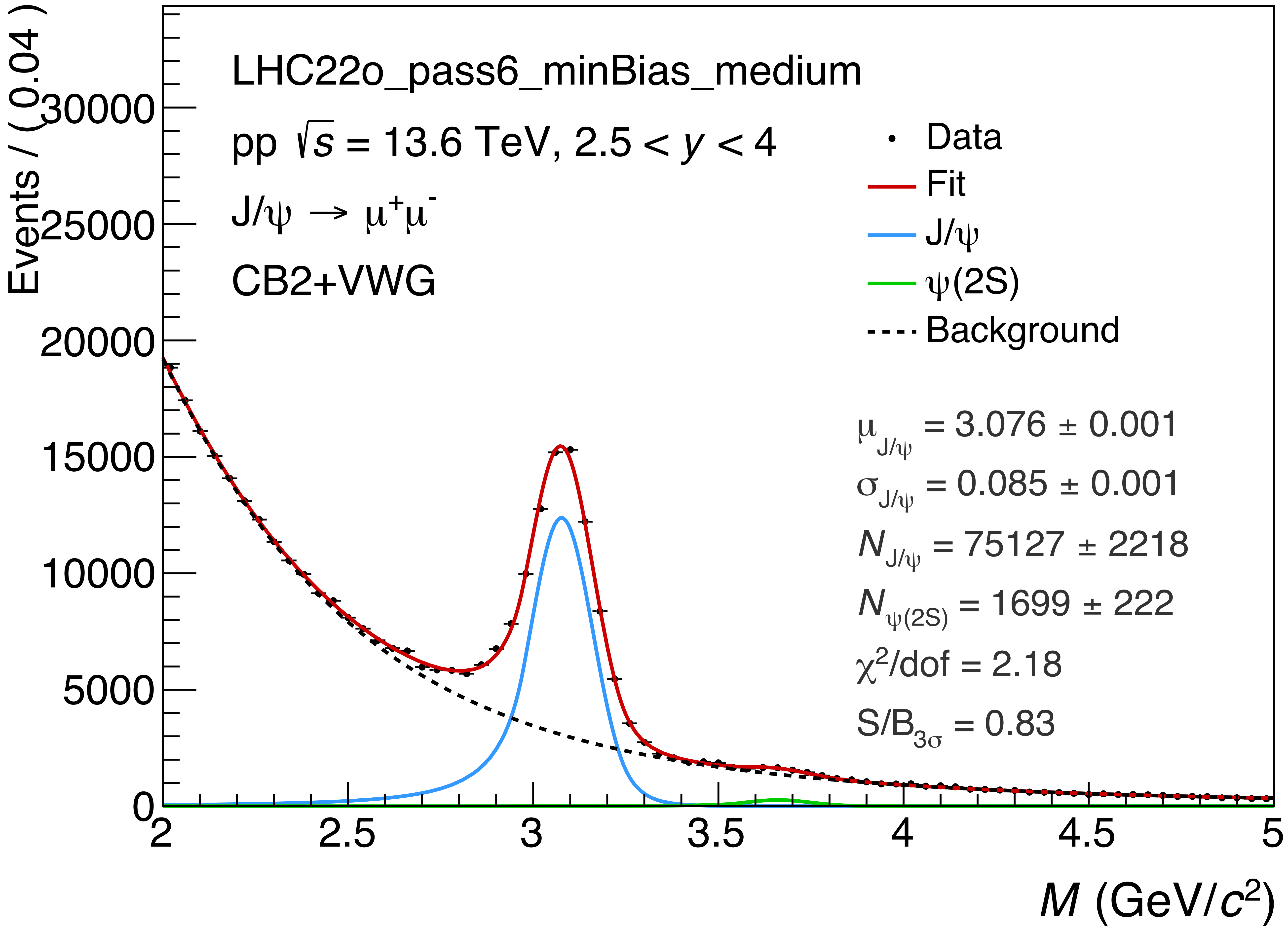
$$D = \frac{p_2}{|t_2|} - |t_2|$$

– background shapes: variable Width Gaussian (VWG) :

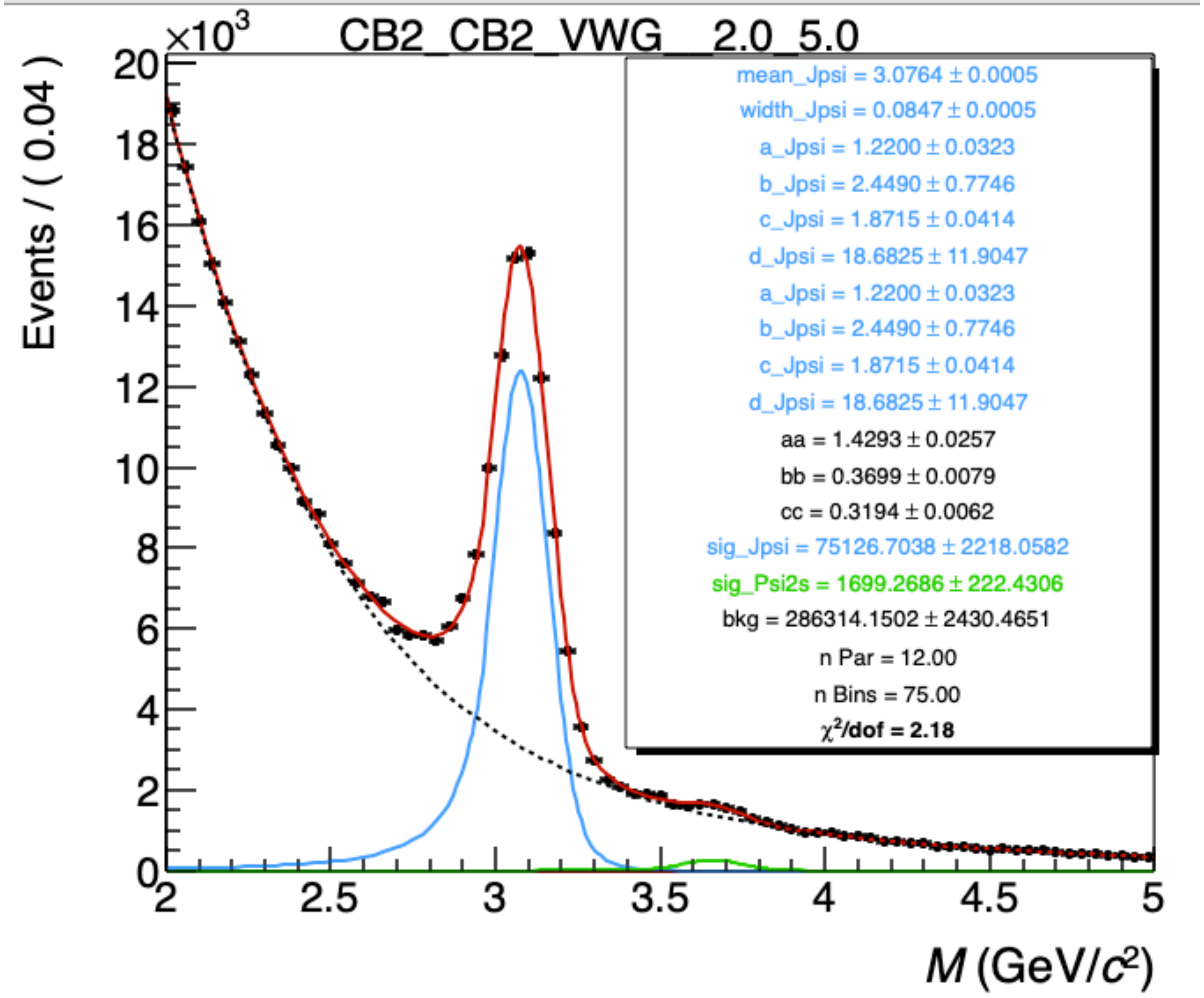
$$f(x;N,\bar{x},A,B) = N \cdot \exp\left(-\frac{(x-\bar{x}^2}{2\sigma_{VWG}^2}\right)$$

where

$$\sigma_{VWG} = A + B \cdot \frac{x-\bar{x}}{\bar{x}}$$



J/ψ and ψ(2S) Tail Parameters



Fitting Procedure

- Fitting is done through **DQ Fit Library**
- The tail parameters are kept free
- Once the MC data is available the tail parameter will change accordingly
- All other parameters are free
- The mass and width of ψ(2S) are fixed using the formula

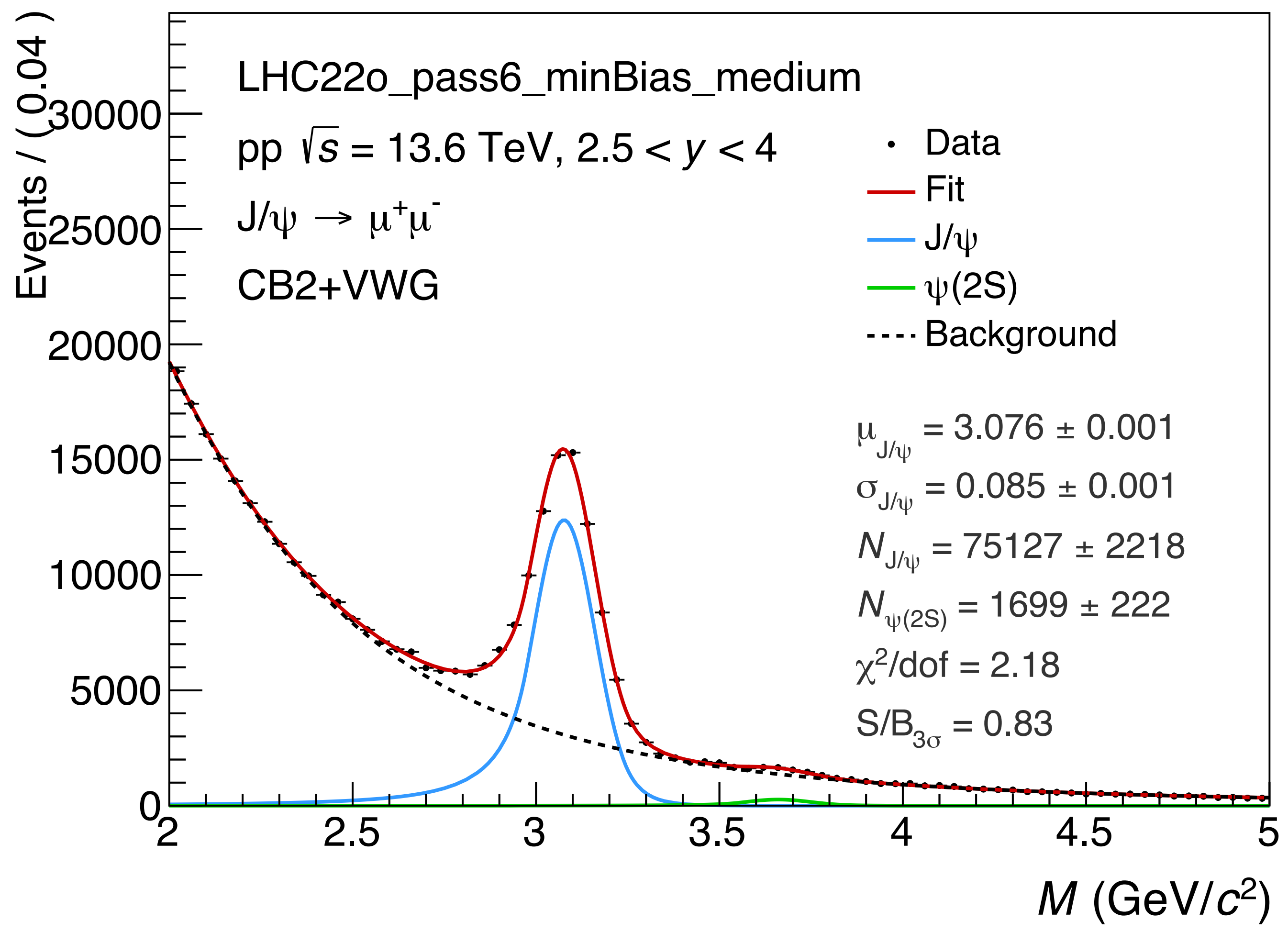
$$m_{\psi(2S)} = m_{J/\psi}^{FIT} + \Delta m^{PDG},$$

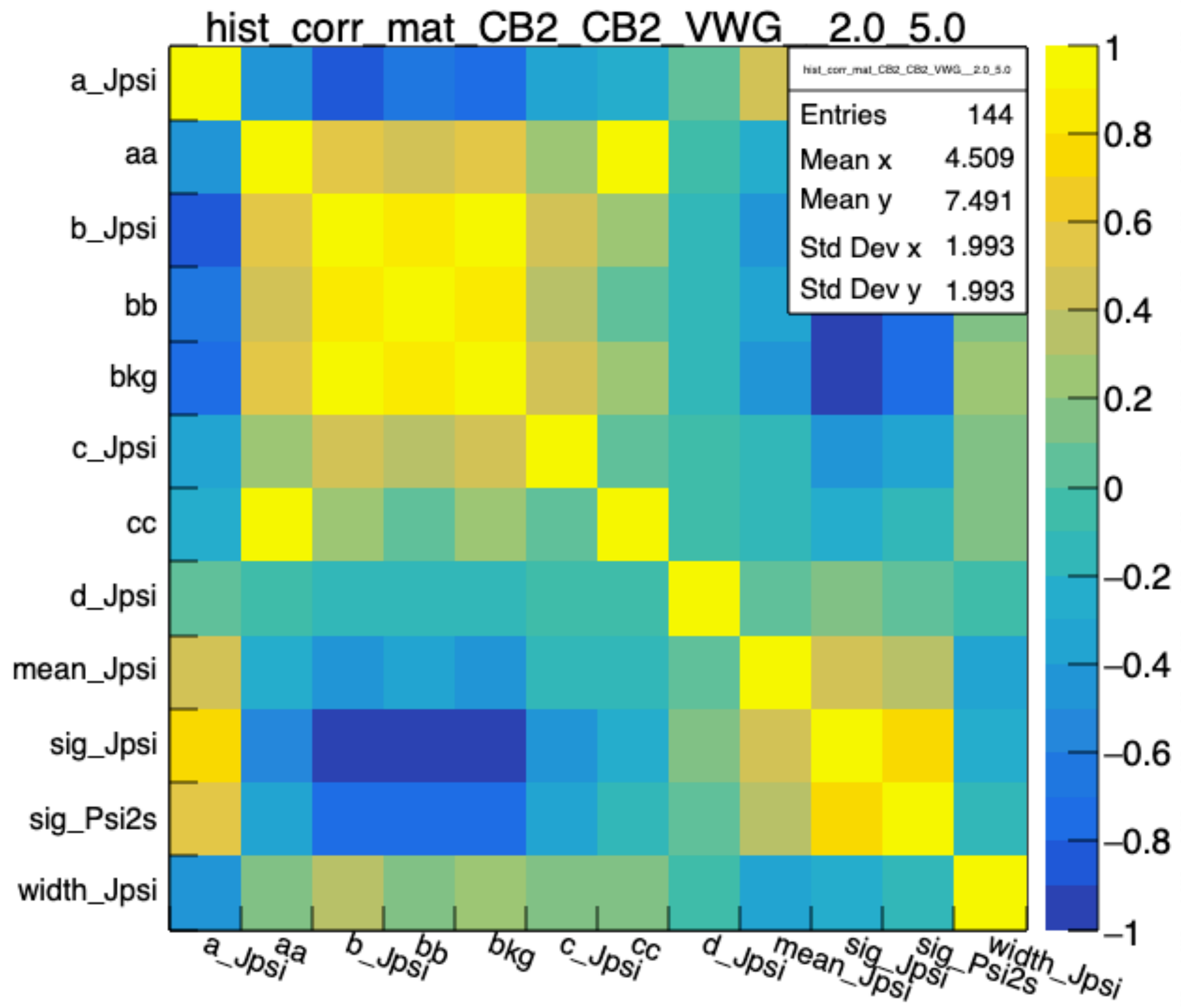
$$\Delta m^{PDG} = m_{\psi(2S)}^{PDG} - m_{J/\psi}^{PDG}$$

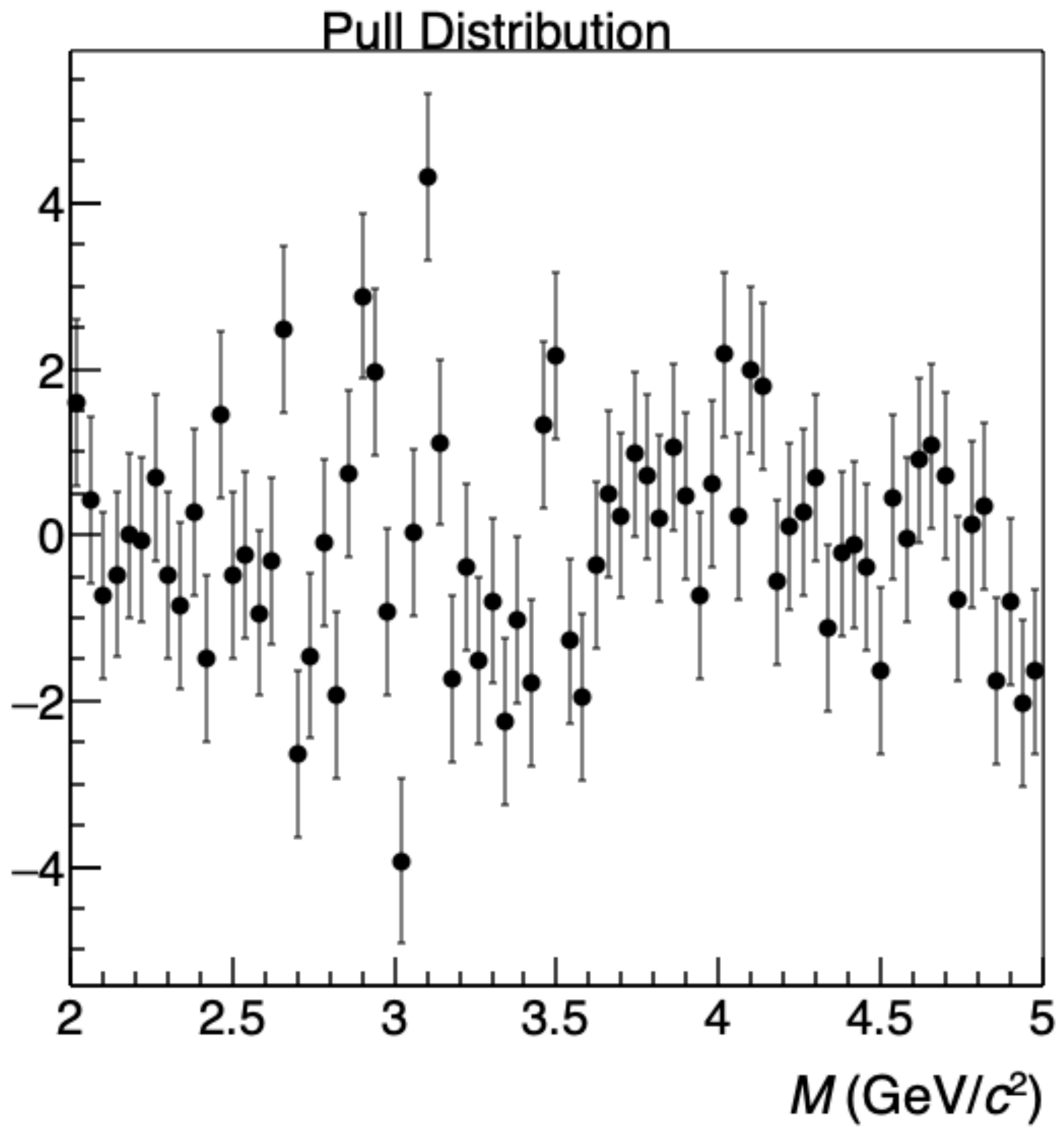
$$\sigma_{\psi(2S)} = \sigma_{J/\psi}^{FIT} \times \frac{\sigma_{\psi(2S)}^{MC}}{\sigma_{J/\psi}^{MC}}$$

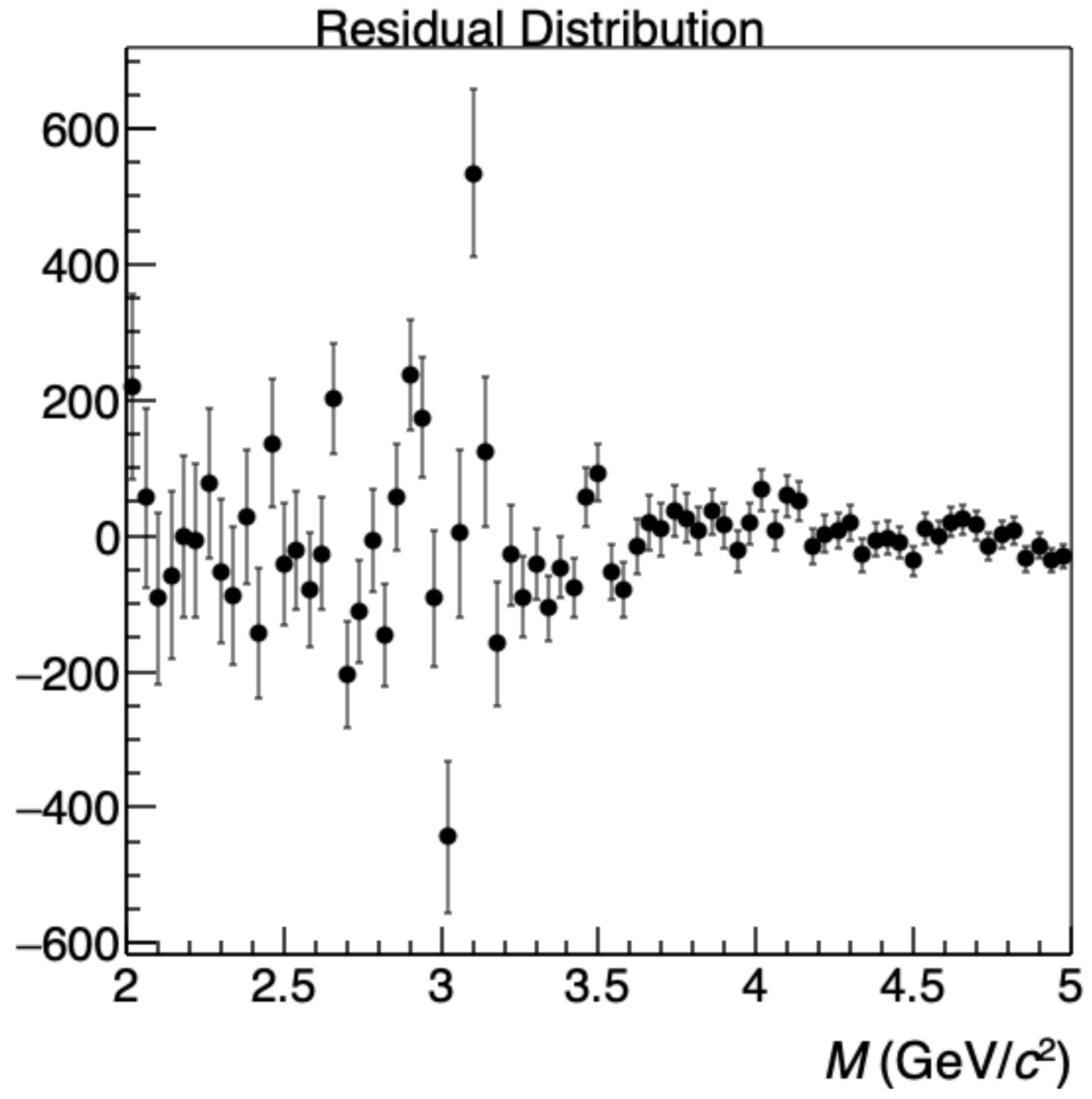
- Fitting is done through the Log Liikelyhood method
- Fit is assumed to be a good fit once the Covariance matrix calcualted successfully and the fit is converged with a message “covariance matrix quality: Full, accurate covariance matrix”

Quality of Fit: Correlation Matrix, Residual and Pull Distribution



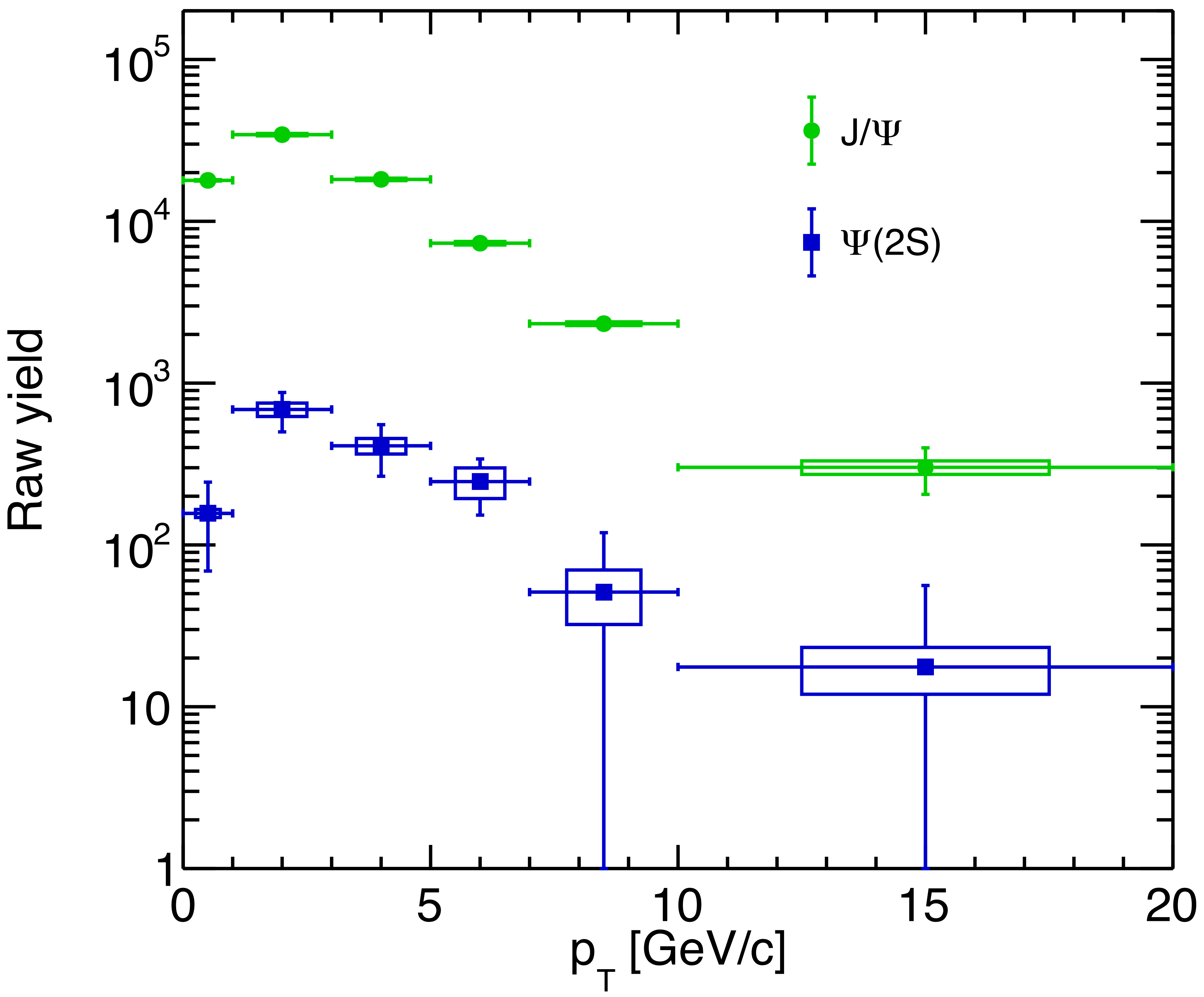


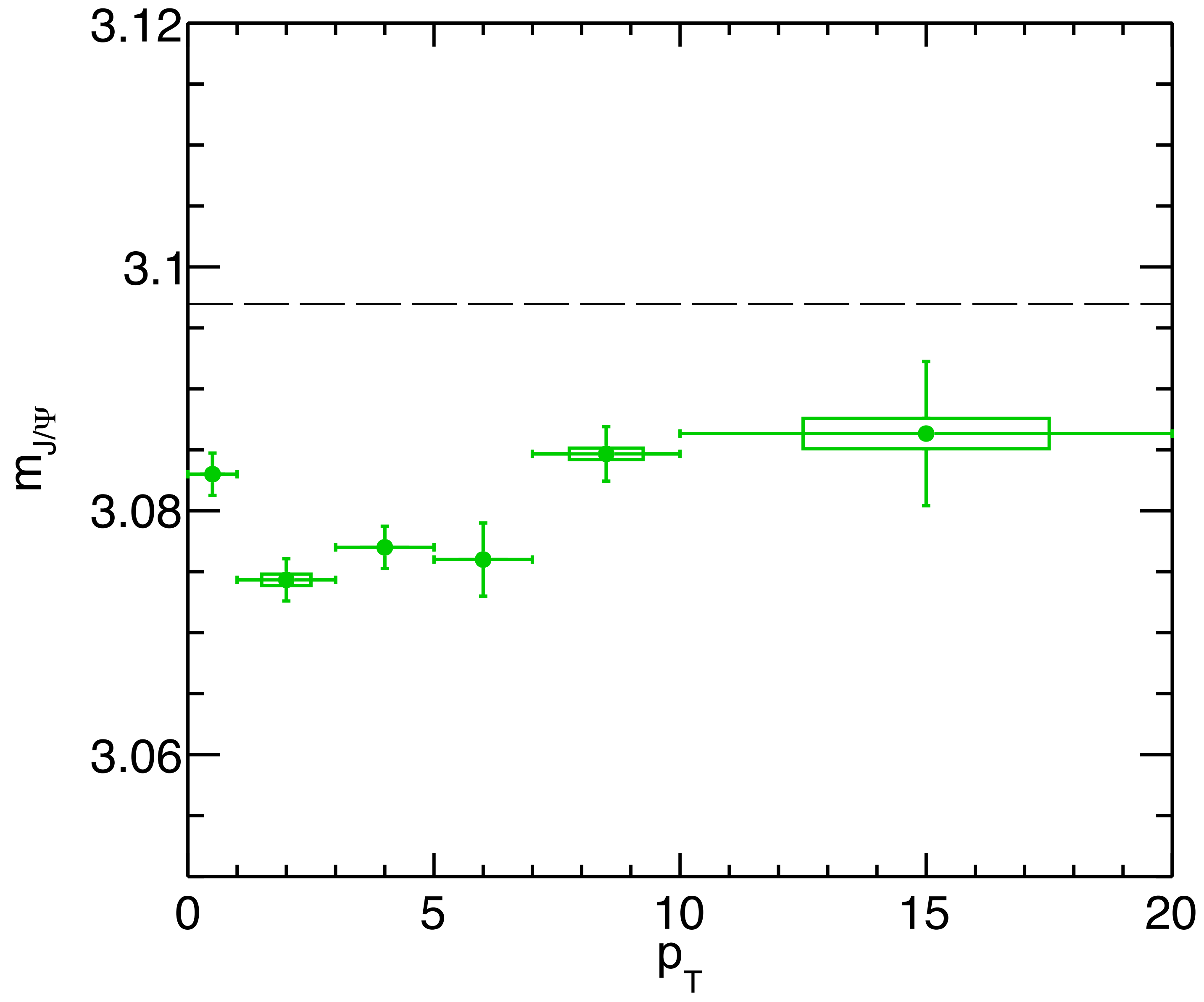


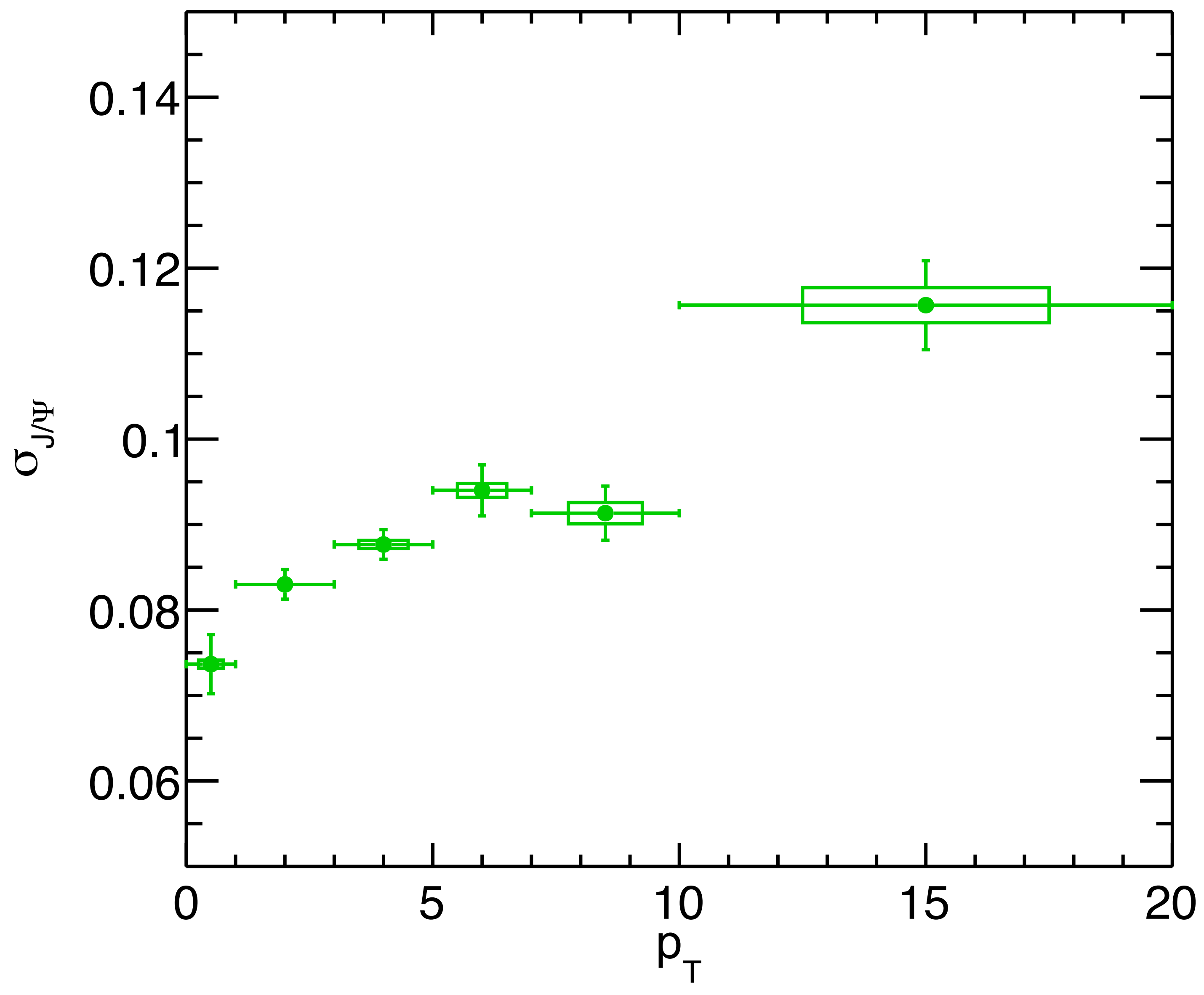


- The correlation matrix suggest the diagonal elements are 100% correlated
- Residual Distribution
  - Differences between the observed and predicted values
- Pull distribution:
  - Normalized residuals that account the uncertainties of the observations
  - Used to describe the quality of fits

J/ψ and ψ(2S): p_T spectra







- J/ψ and ψ(2S) raw yield is obtained by analysing the p_T differential dimuon mass spectrum
- The J/ψ mass and resolution are compatible with the Run 3 Preliminary results
- Here, the systematic uncertainty is only due to different fitting ranges.
- The open box represent systematic and solid line represent the statistical uncertainty.

Fit Ranges

2.0 - 5.0 GeV/c²

2.2 - 4.8 GeV/c²

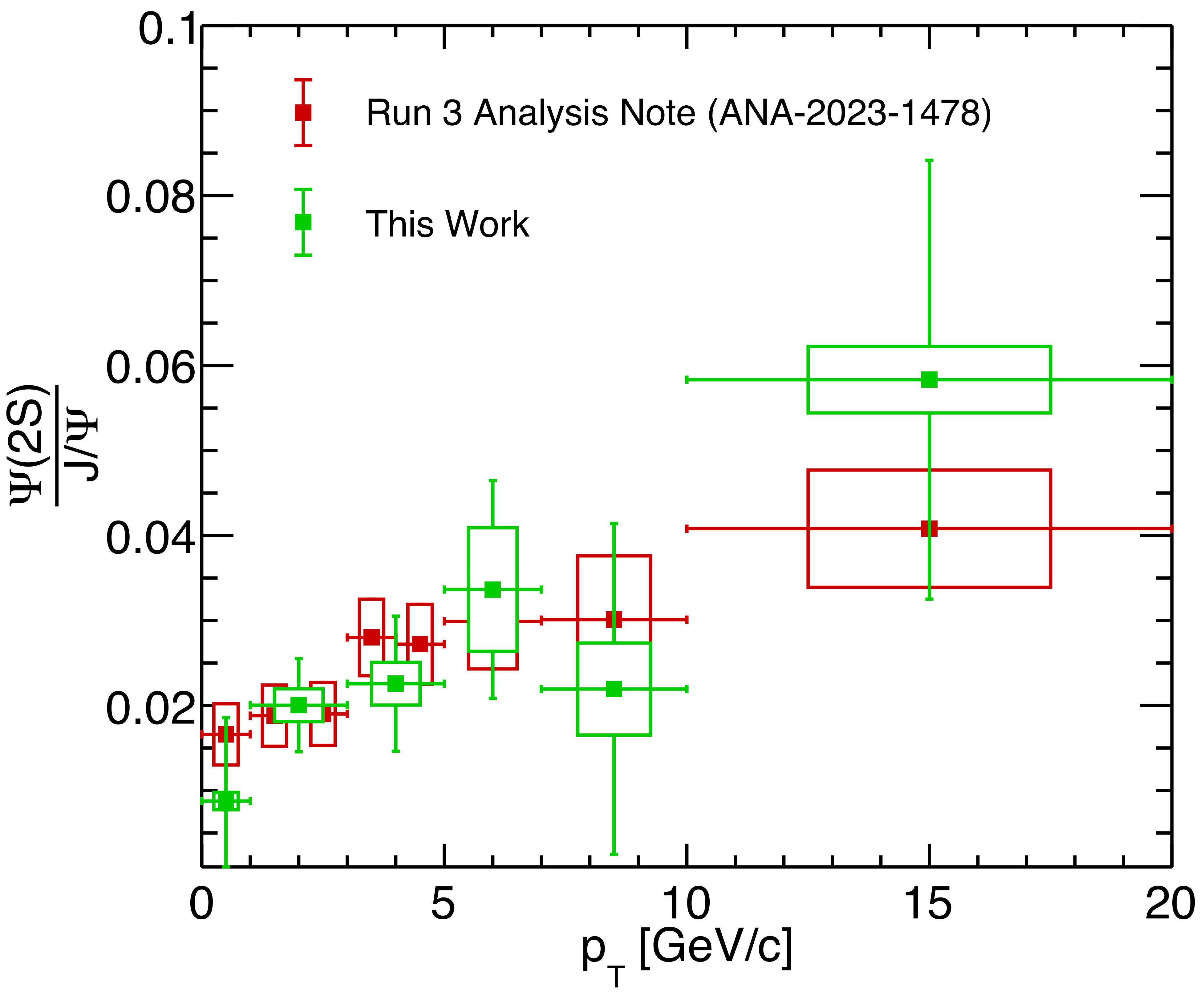
2.4 - 4.6 GeV/c²

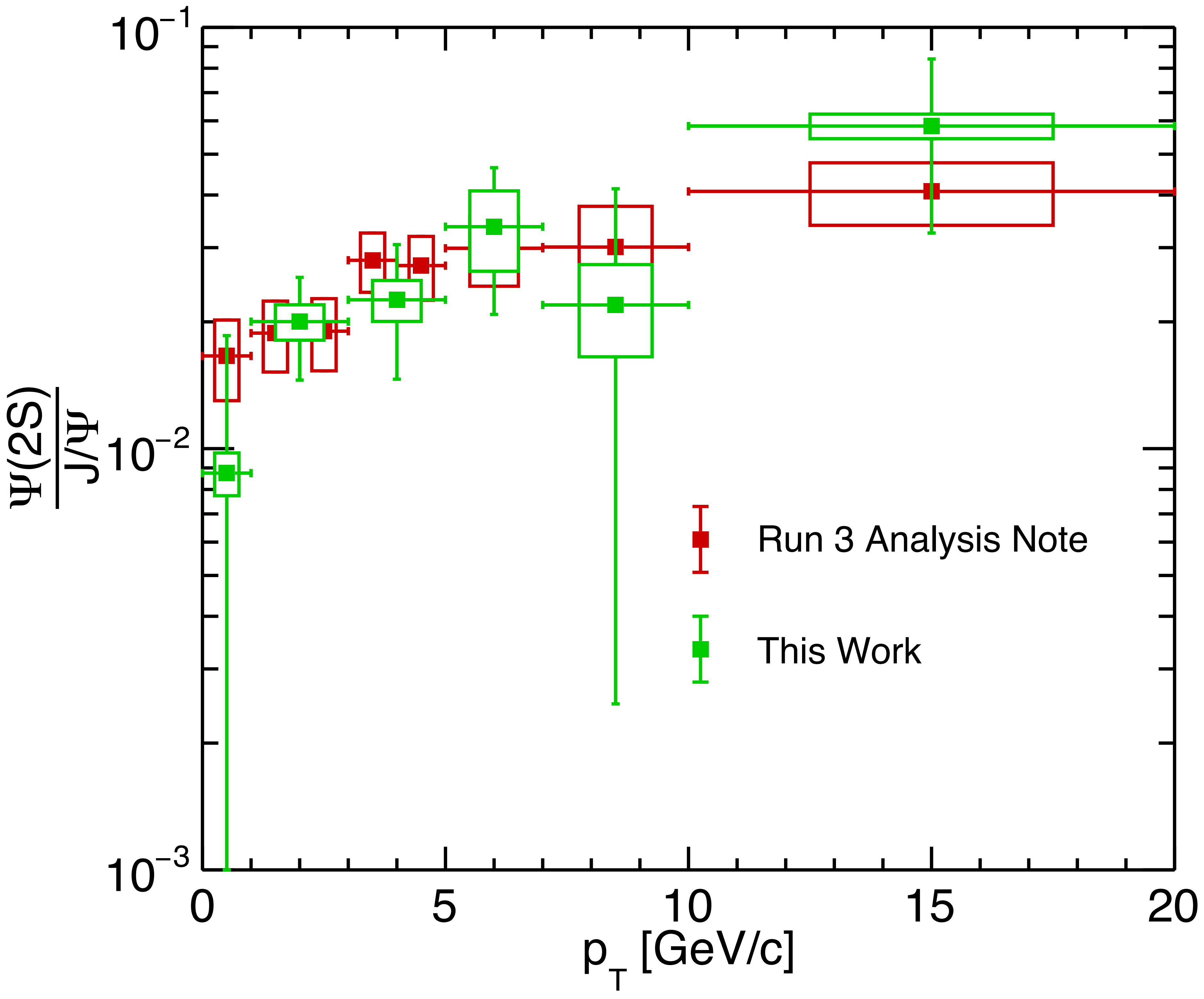
$$\bar{\lambda} = \frac{\Sigma_j \lambda^j}{N}$$

$$\sigma_{\bar{\lambda}}^{stat} = \frac{\Sigma_j \sigma_{\lambda}^j}{N}$$

$$\sigma_{\bar{\lambda}}^{syst} = \sqrt{\frac{\Sigma_j [\lambda^j - \bar{\lambda}]^2}{N}}$$

ψ(2S)/J/ψ ratios





- ψ(2S)/J/ψ ratios is almost compatible with the preliminary results within statistical uncertainties.
- Small discrepancy could be due to less statistics

p_T differential raw yield

- **p_T differential raw yield**

$p_T (GeV/c)$	$N_{J/\psi}$	$N_{\psi(2S)}$
0.00 - 1.00	8953 $\pm$291 $\pm$ 172	79 $\pm$87 $\pm$ 9
1.00 - 3.00	34326 $\pm$556 $\pm$ 578	688 $\pm$188 $\pm$ 65
3.00 - 5.00	18158 $\pm$389 $\pm$ 320	410 $\pm$144 $\pm$ 45
5.00 - 7.00	7323 $\pm$224 $\pm$ 181	246 $\pm$93 $\pm$ 53
7.00 - 10.00	3495 $\pm$150 $\pm$ 61	77 $\pm$68 $\pm$ 19
10.00 - 20.00	1509 $\pm$96 $\pm$ 29	88 $\pm$38 $\pm$ 6
Sum	73764 $\pm$6841	1588

- **p_T integrated raw yield**

$p_T (GeV/c)$	$N_{J/\psi}$	$N_{\psi(2S)}$
0.00 - 20.00	73795 $\pm$3950	1526 $\pm$330

Fit Ranges

2.0 - 5.0 GeV/c^2

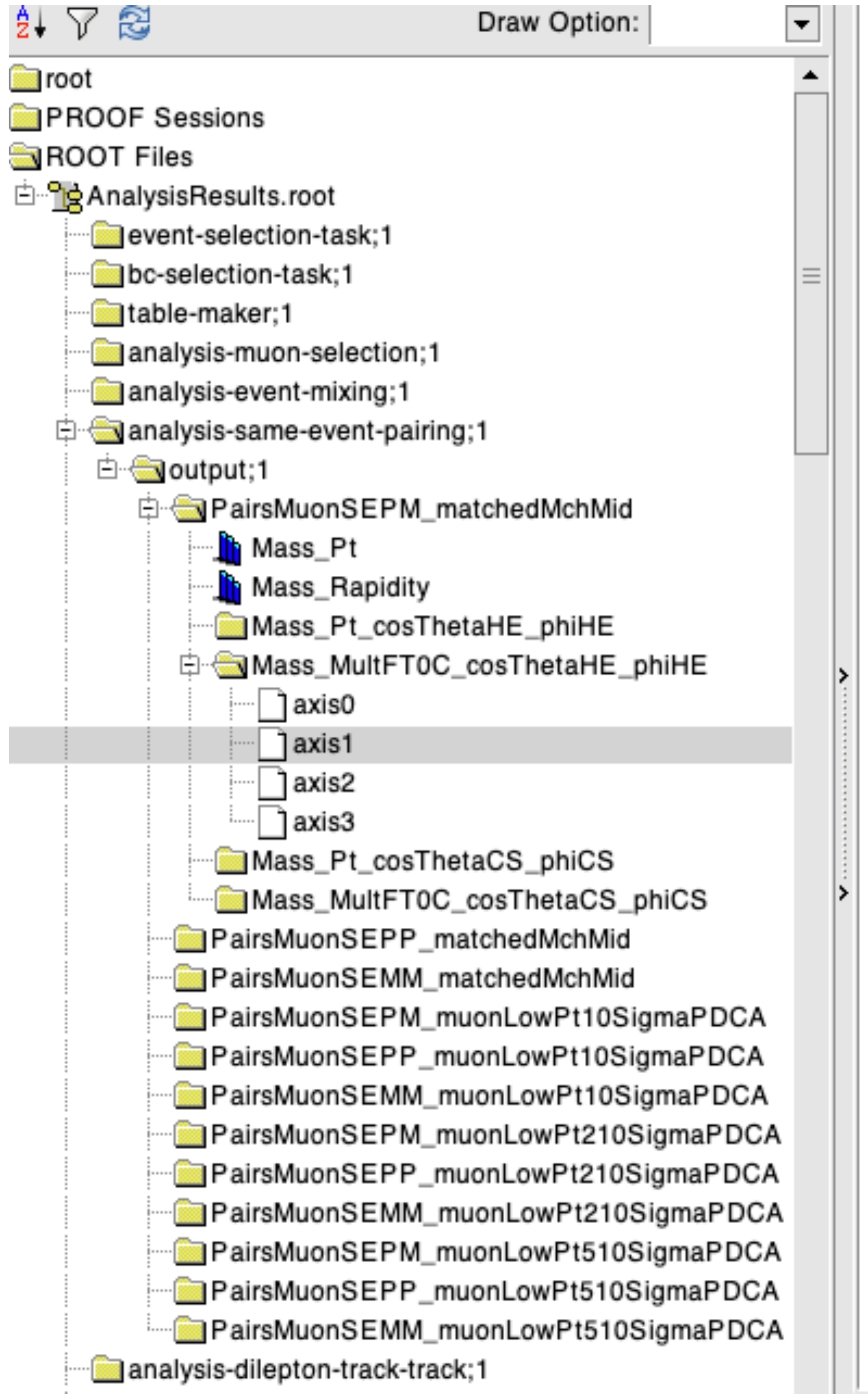
2.2 - 4.8 GeV/c^2

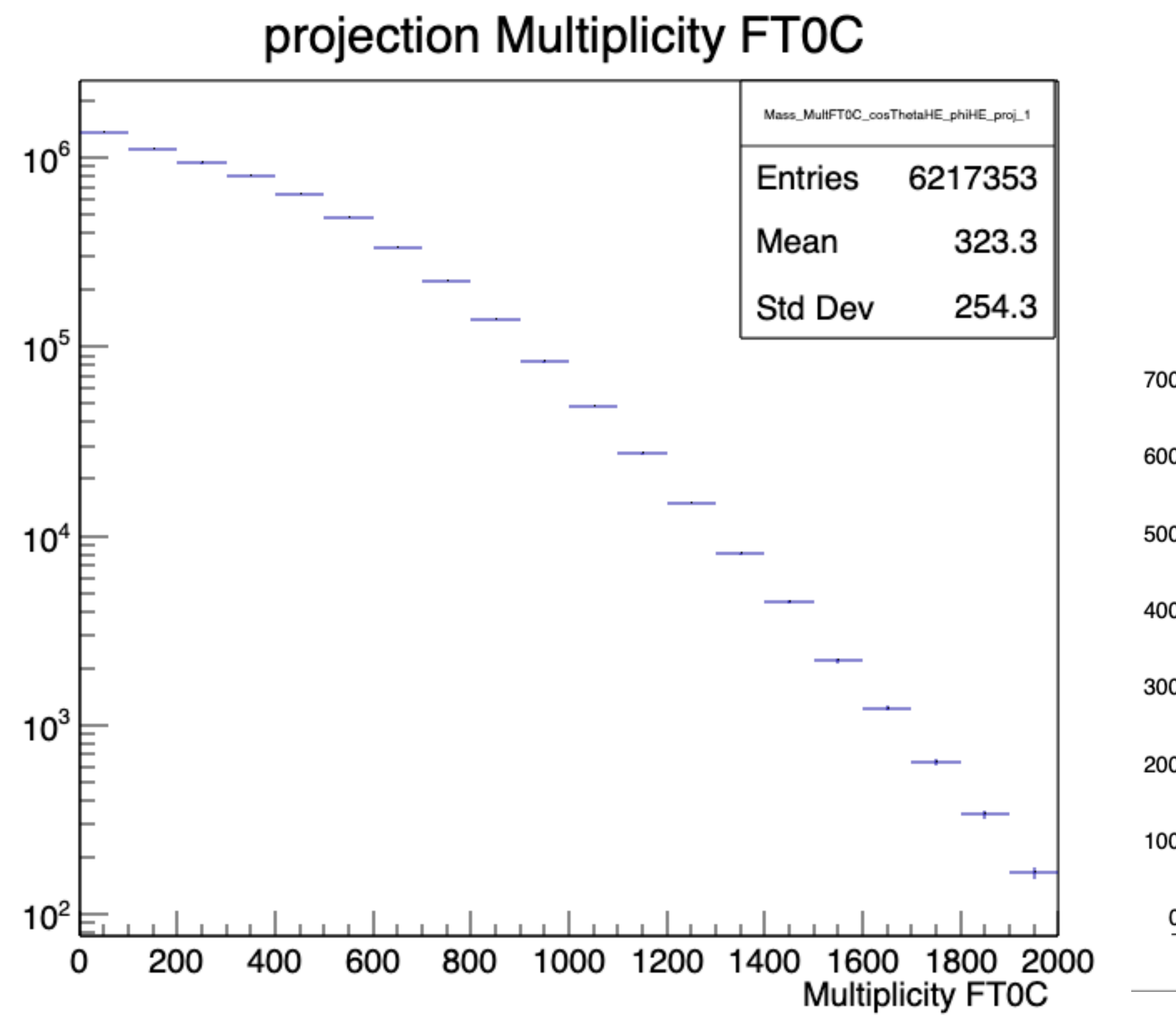
2.4 - 4.6 GeV/c^2

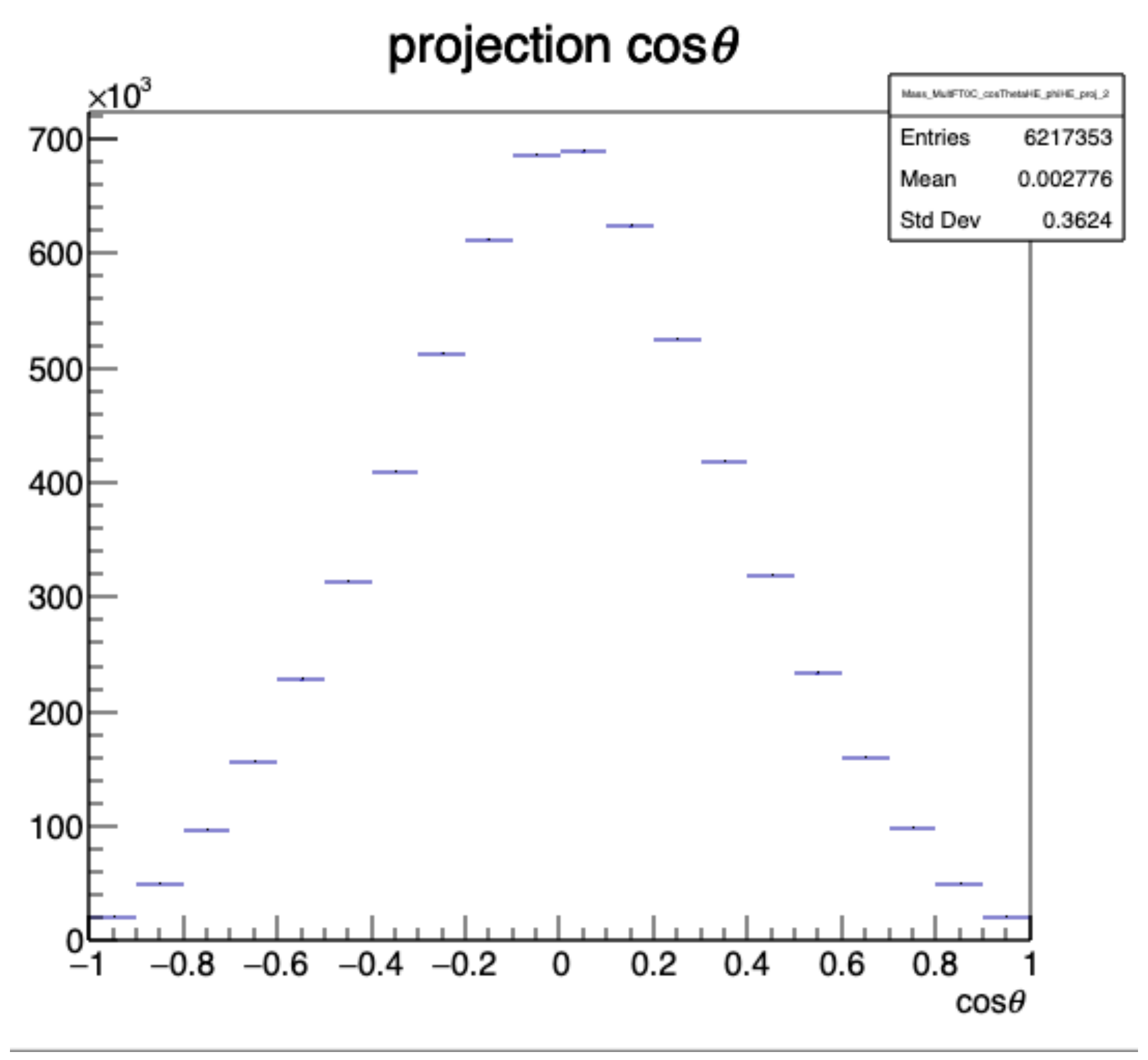
- The first uncertainty is statistical, the second is the systematics associated to the signal extraction
- The p_T differential raw yield is obtained by averaging the yield from three different fit ranges
- The sum of p_T differential raw yield agrees with the integrated one within uncertainty

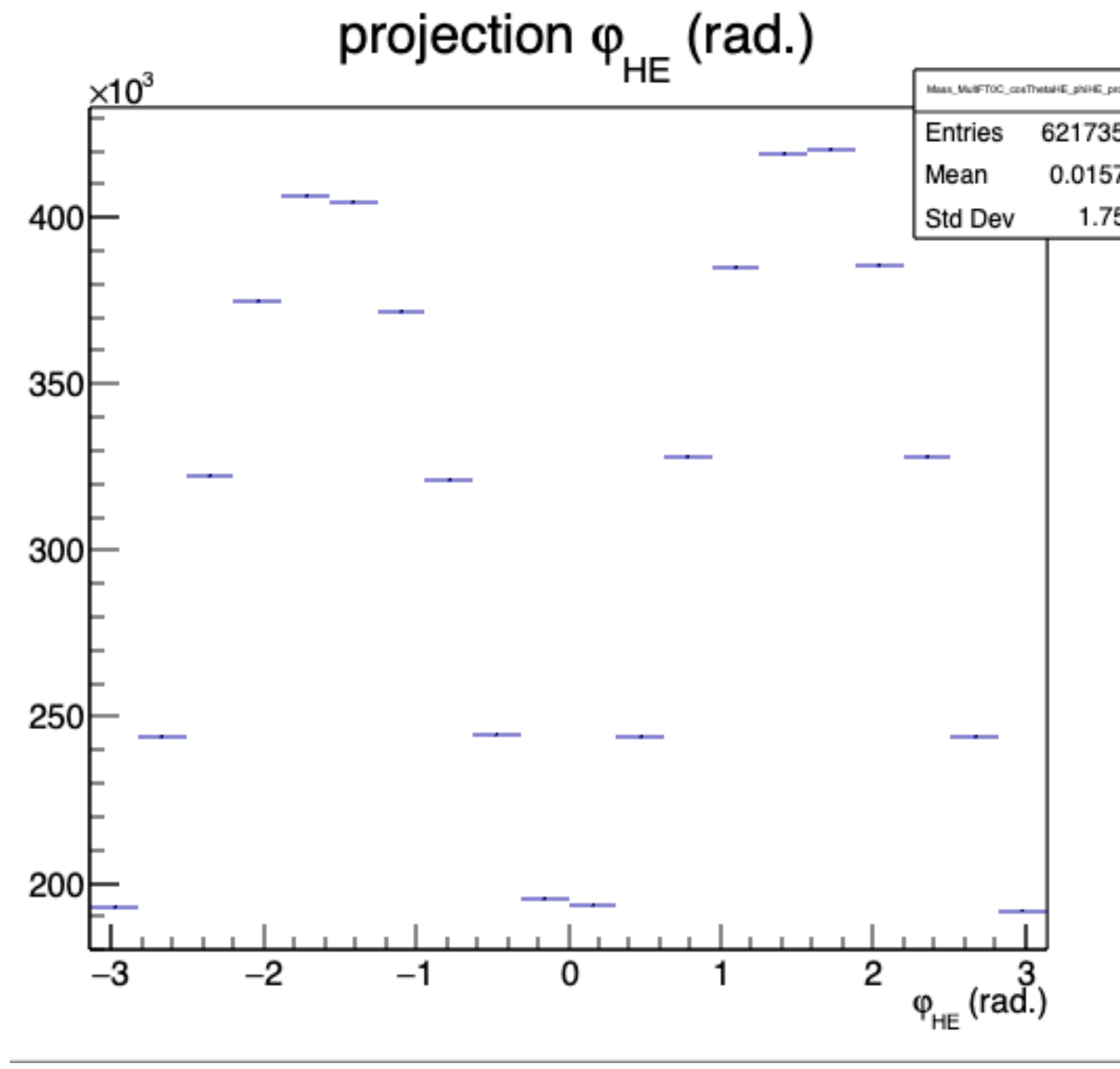
Multiplicity Distribution (Run 3 Configuration)

- The global detector FIT is used to determine collision centrality, collision time and particle multiplicity in Run 3 configuration
- FIT consists of FT0, FV0, FDD ranging from -19.5m to 17m from the interaction point (IP)
- Currently, FT0C detector of FT0 is used for centrality and multiplicity estimation in Pb-Pb and pp, respectively
- In this study, we used the FT0C multiplicity for our analysis

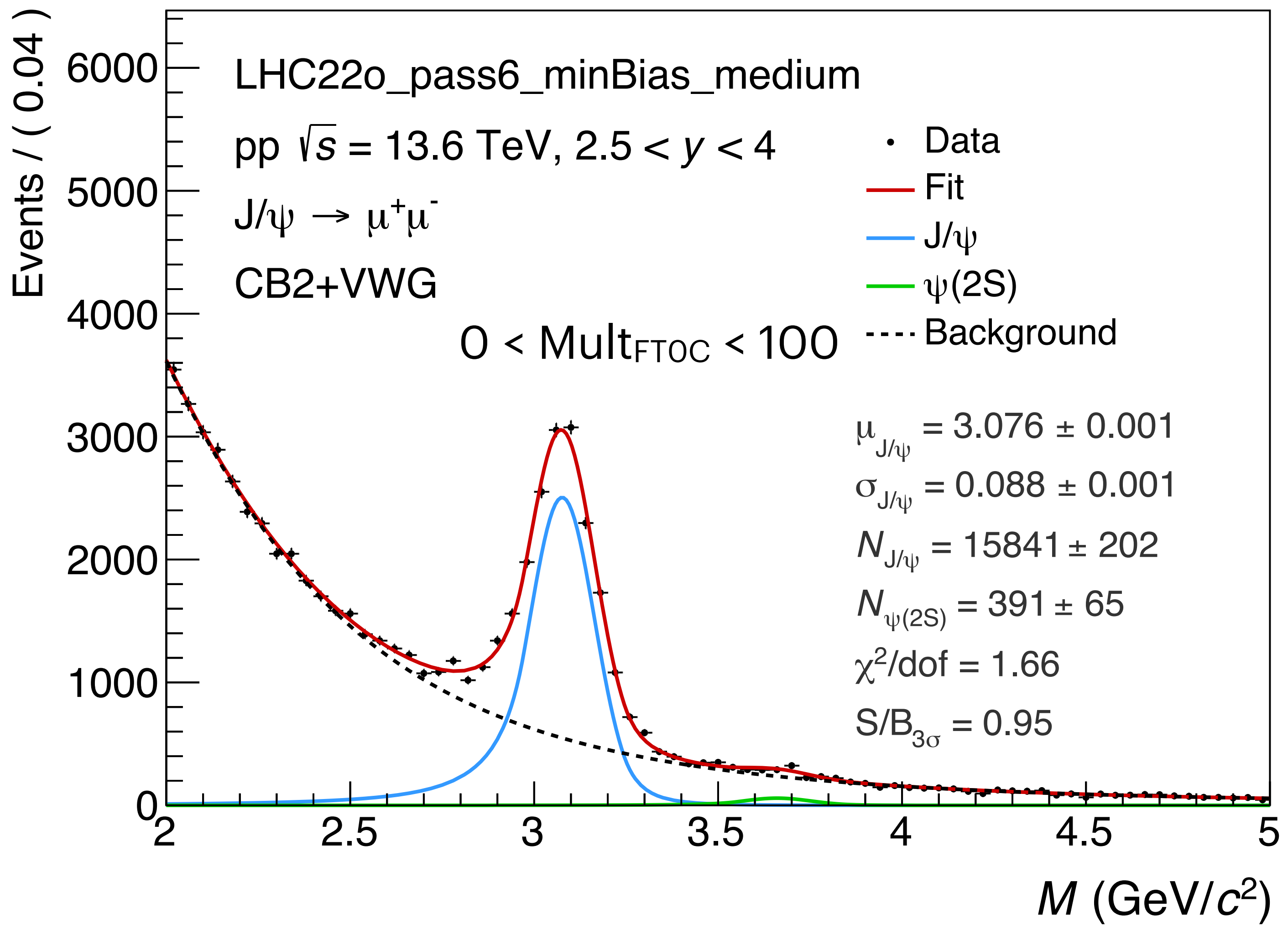


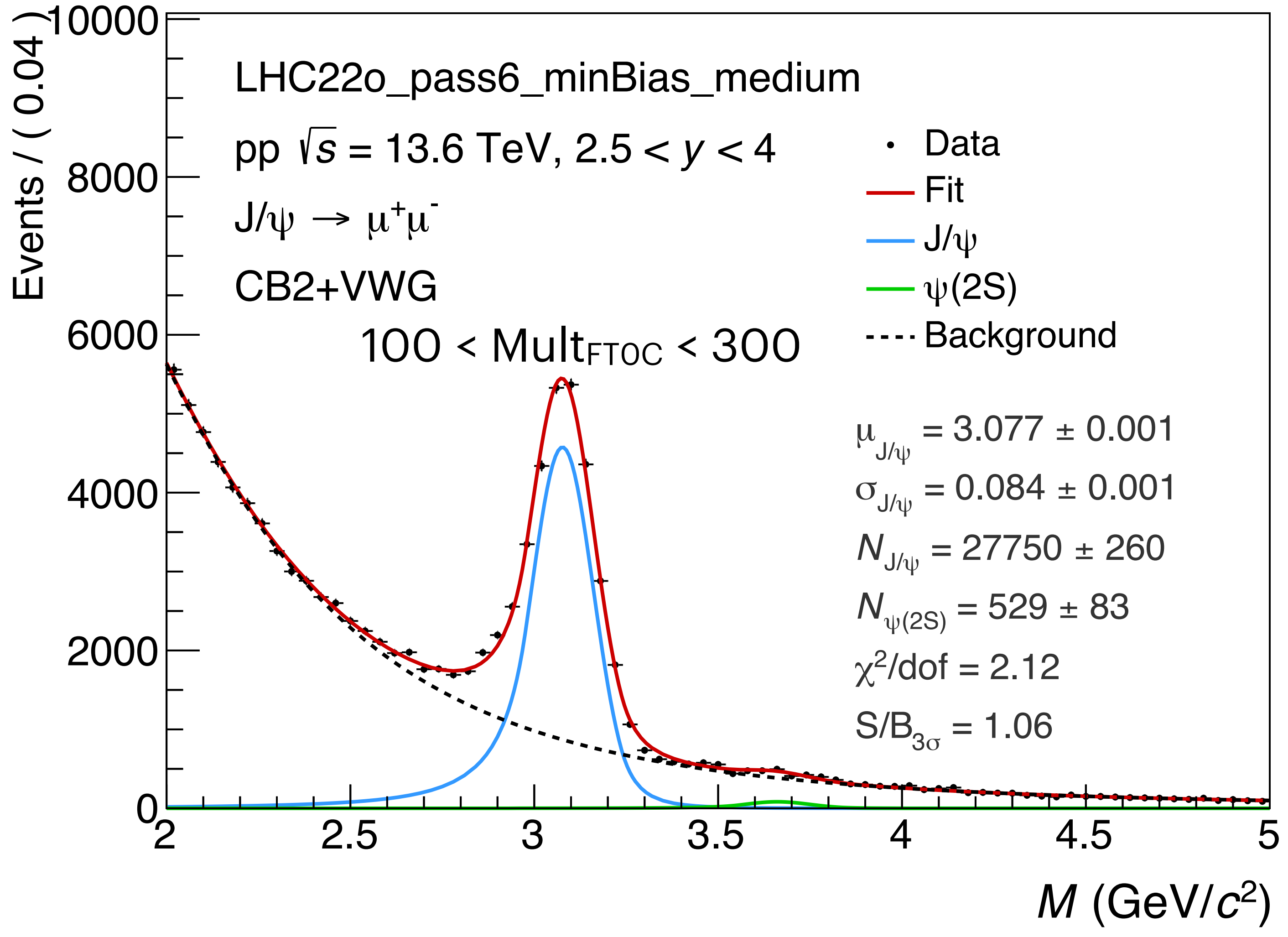


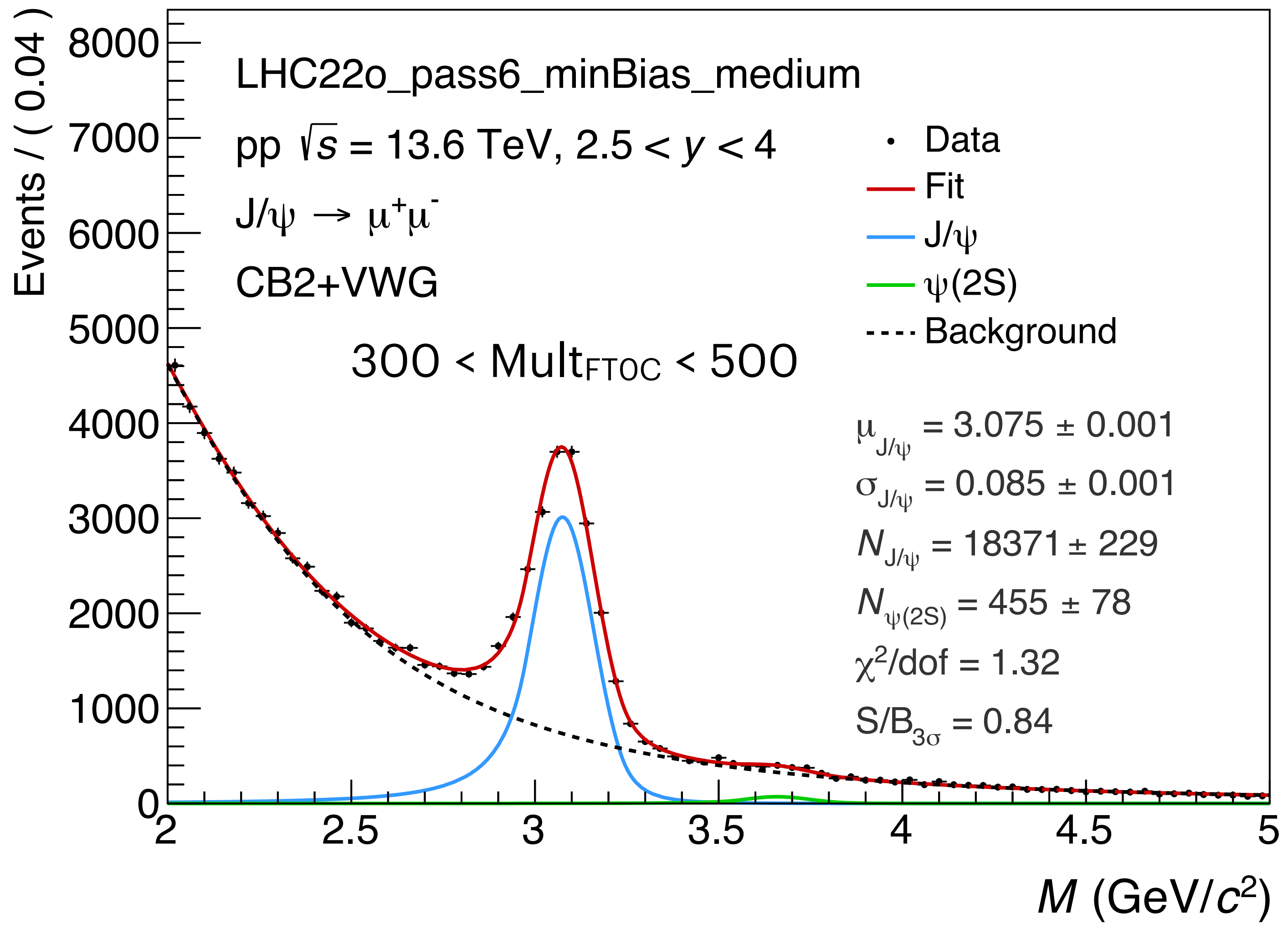


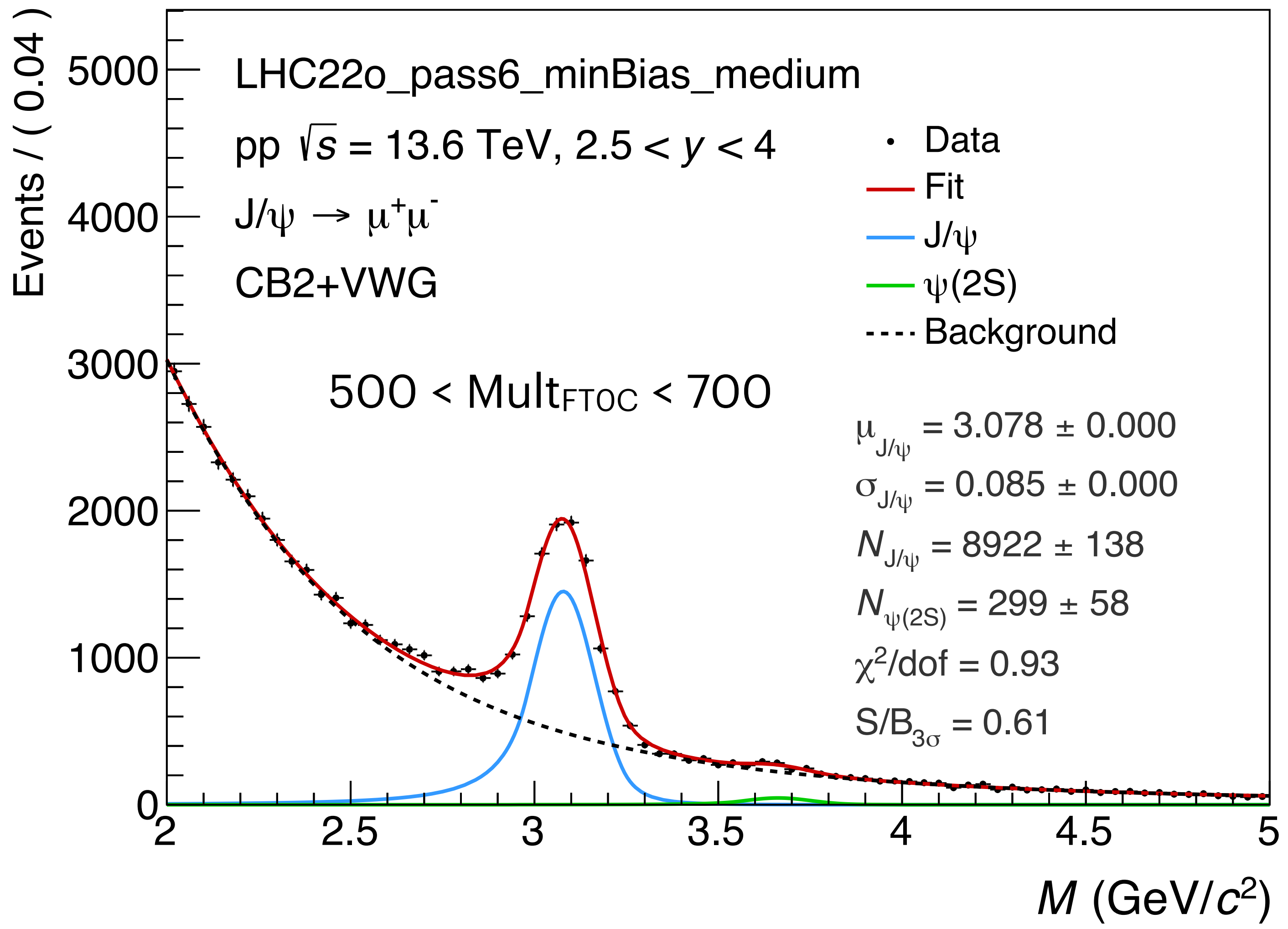


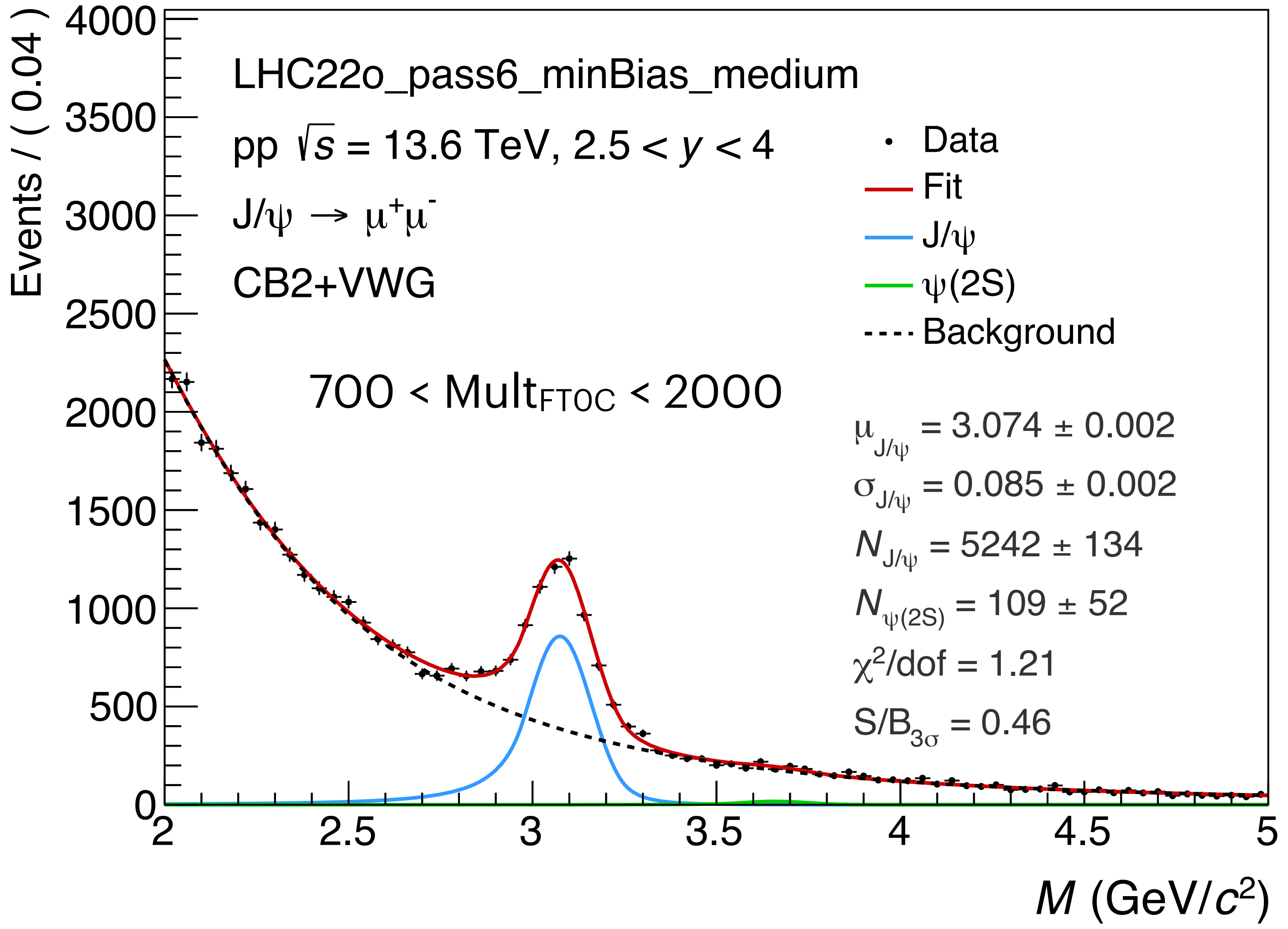
Signal Extraction: Multiplicity differential (Fit range: 2.0 - 5.0 GeV/c²)











- **Multiplicity differential raw yield**

Mult_{FT0C}	$\text{N}_{J/\psi}$	$\text{N}_{\psi(2S)}$
0 - 100	15841 $\pm$202	391 $\pm$65
100 - 300	27750 $\pm$260	529 $\pm$83
300 - 500	18371 $\pm$229	455 $\pm$78
500 - 700	8922 $\pm$138	299 $\pm$58
700 - 2000	5242 $\pm$134	109 $\pm$52
Sum	76126 $\pm$2743	1783 $\pm$1050

- **Multiplicity integrated raw yield**

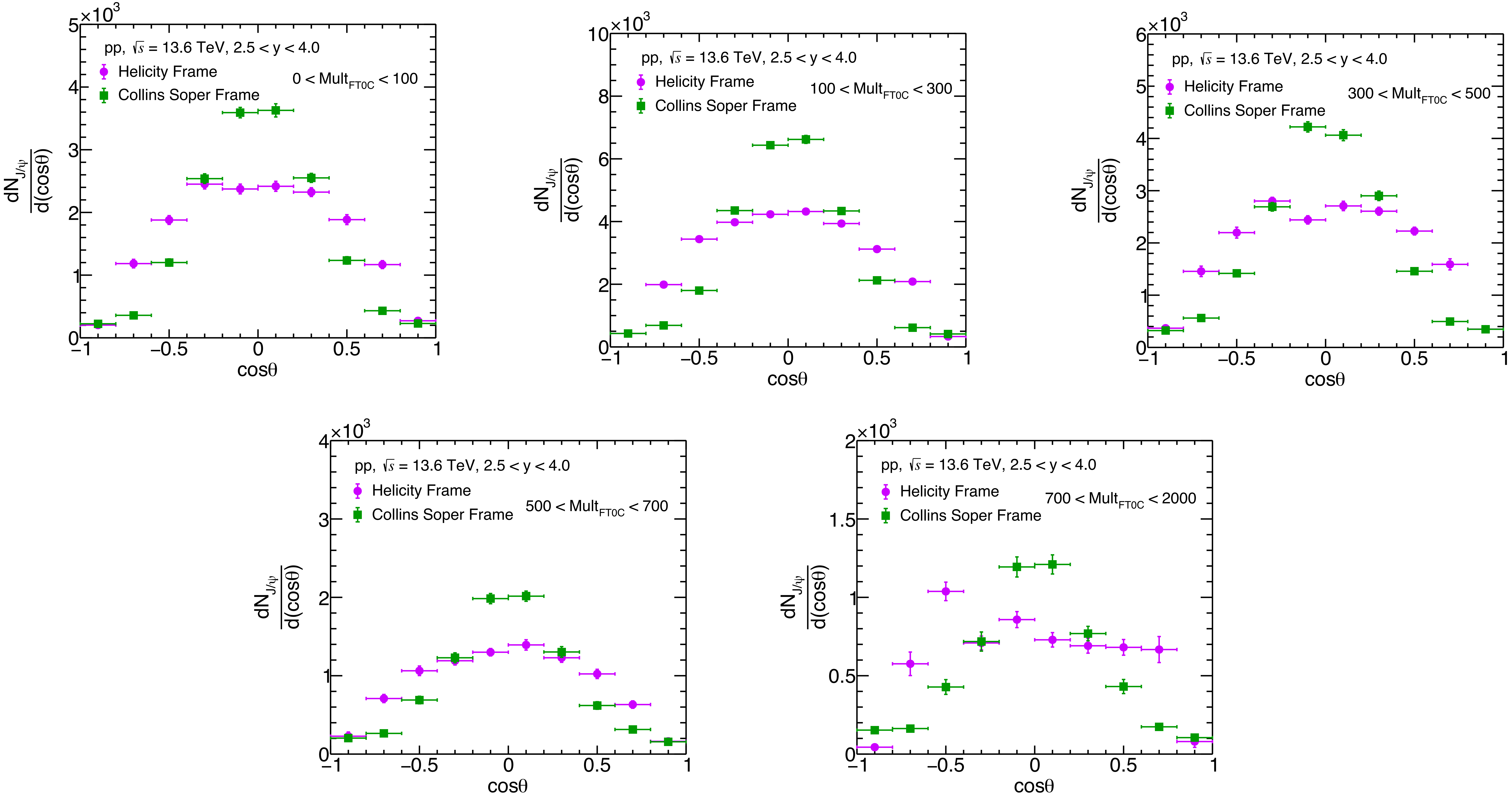
Mult_{FT0C}	$\text{N}_{J/\psi}$	$\text{N}_{\psi(2S)}$
0 - 2000	76168 $\pm$1473	1838 $\pm$177

Fit Ranges

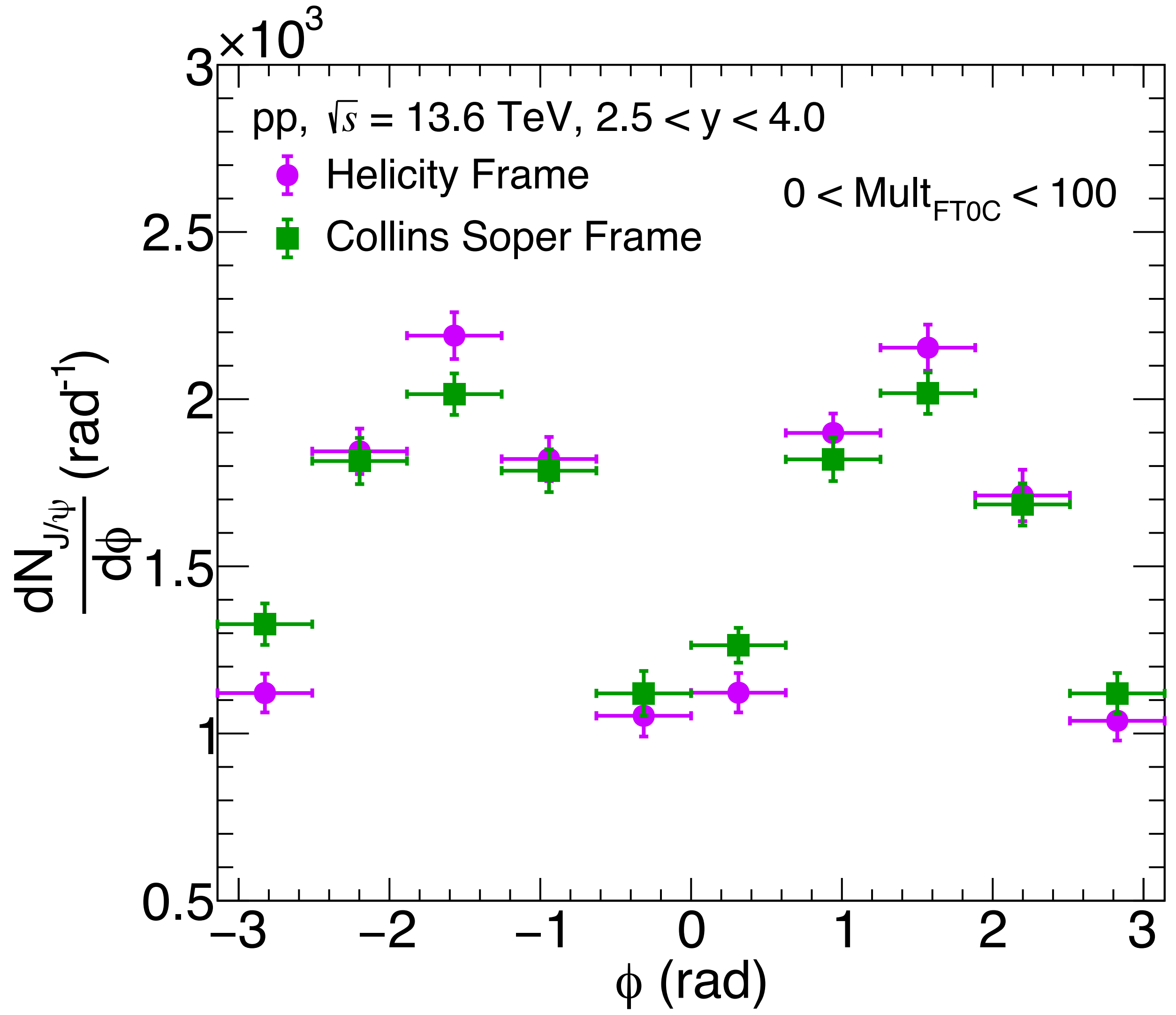
2.0 - 5.0 GeV/c^2

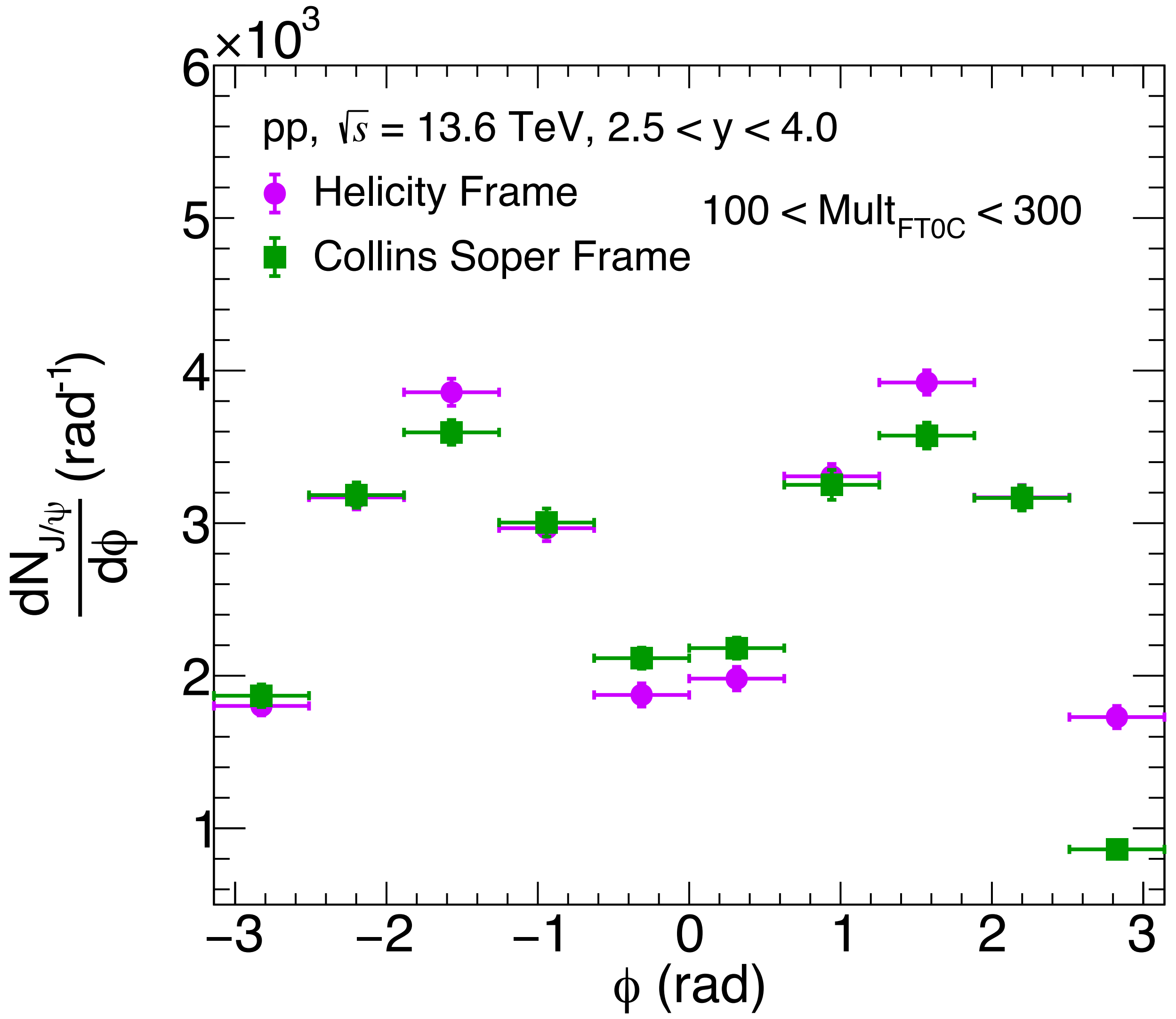
- The first uncertainty is statistical, the second is the systematics associated to the signal extraction
- The multiplicity differential raw yield is obtained for fit range (2.0 - 5.0) GeV/c^2
- The sum of multiplicity differential raw yield agrees with the integrated one within uncertainty

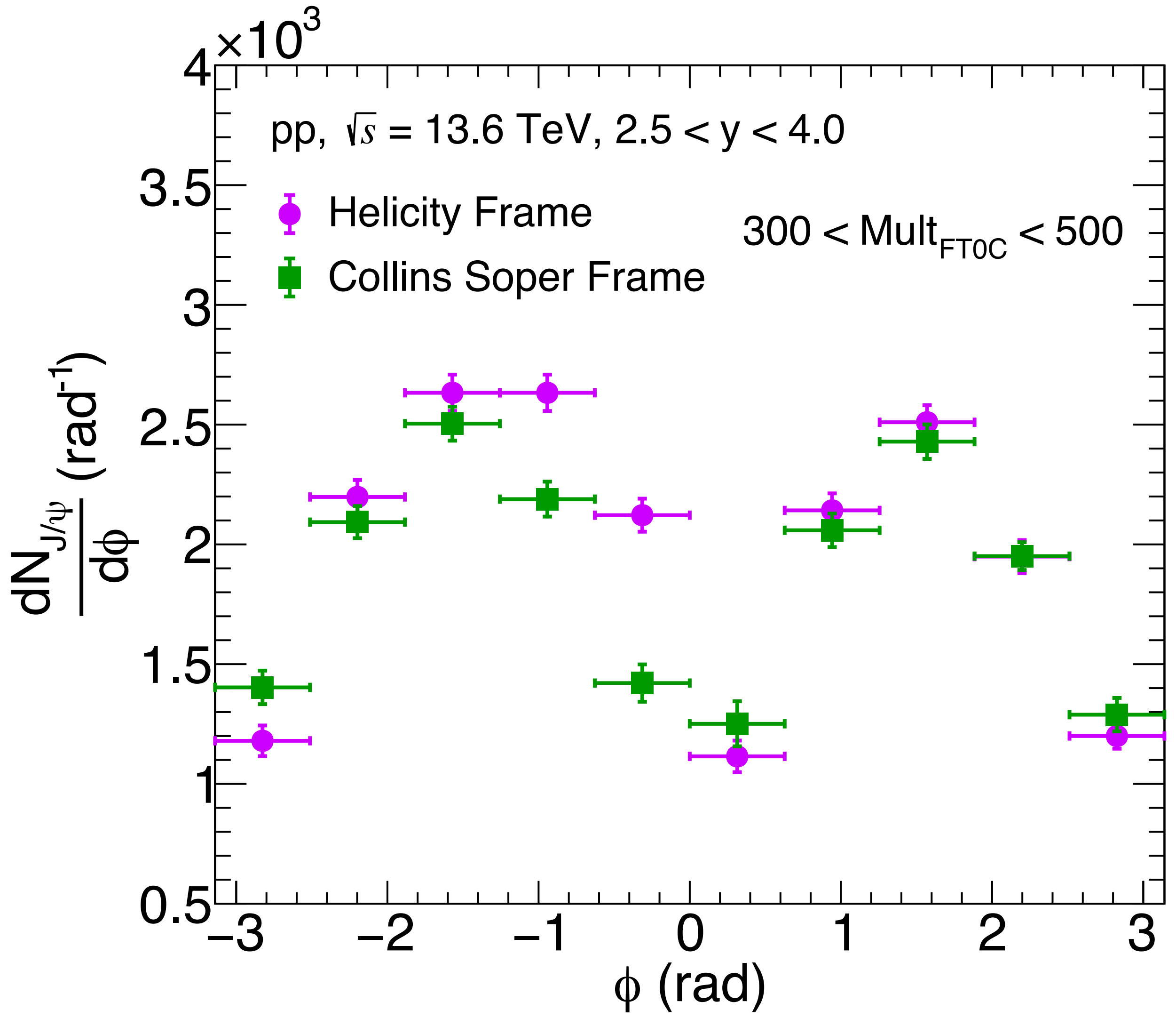
J/ψ angular distribution: Multiplicity dependent cosθ raw distribution

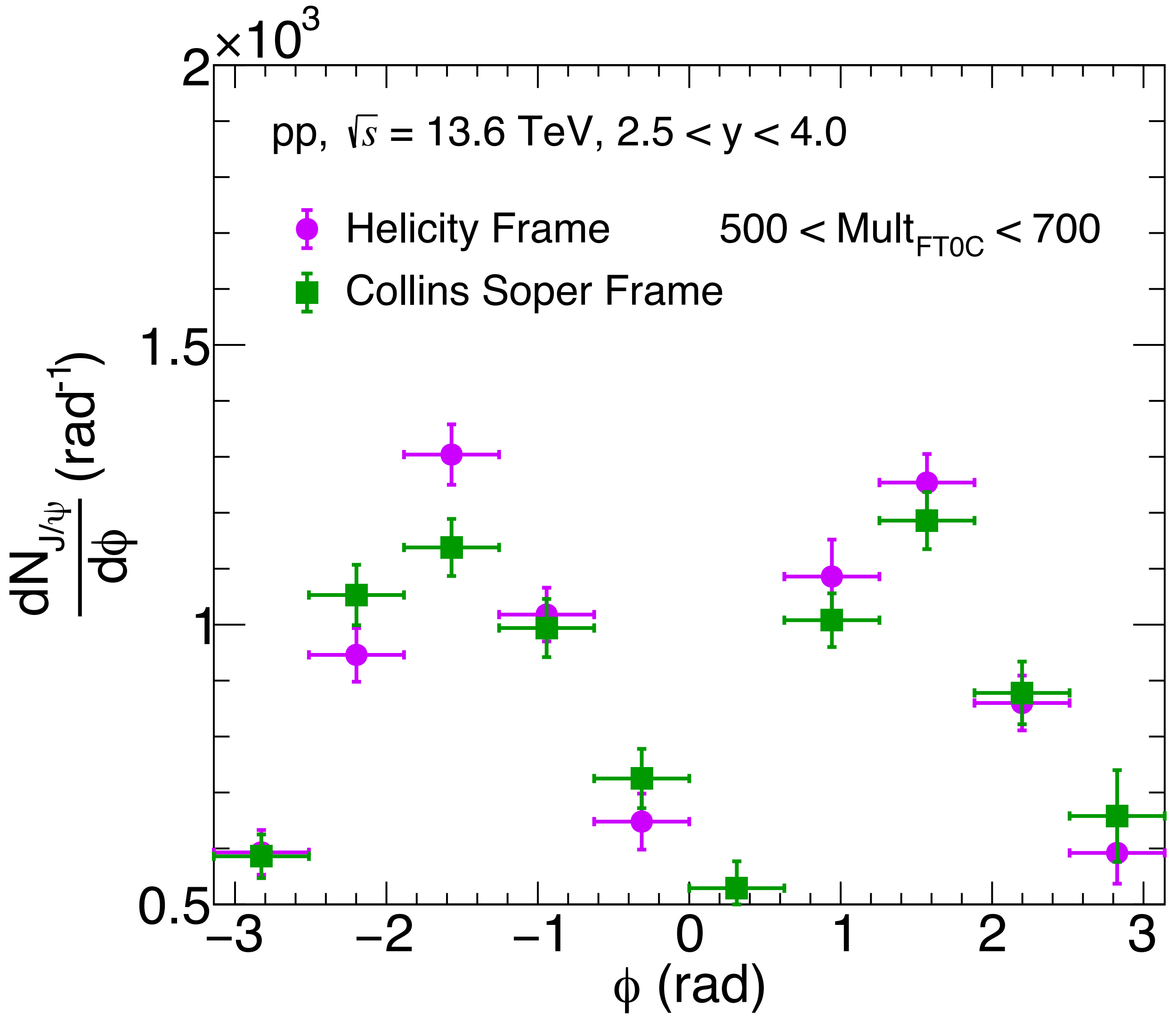


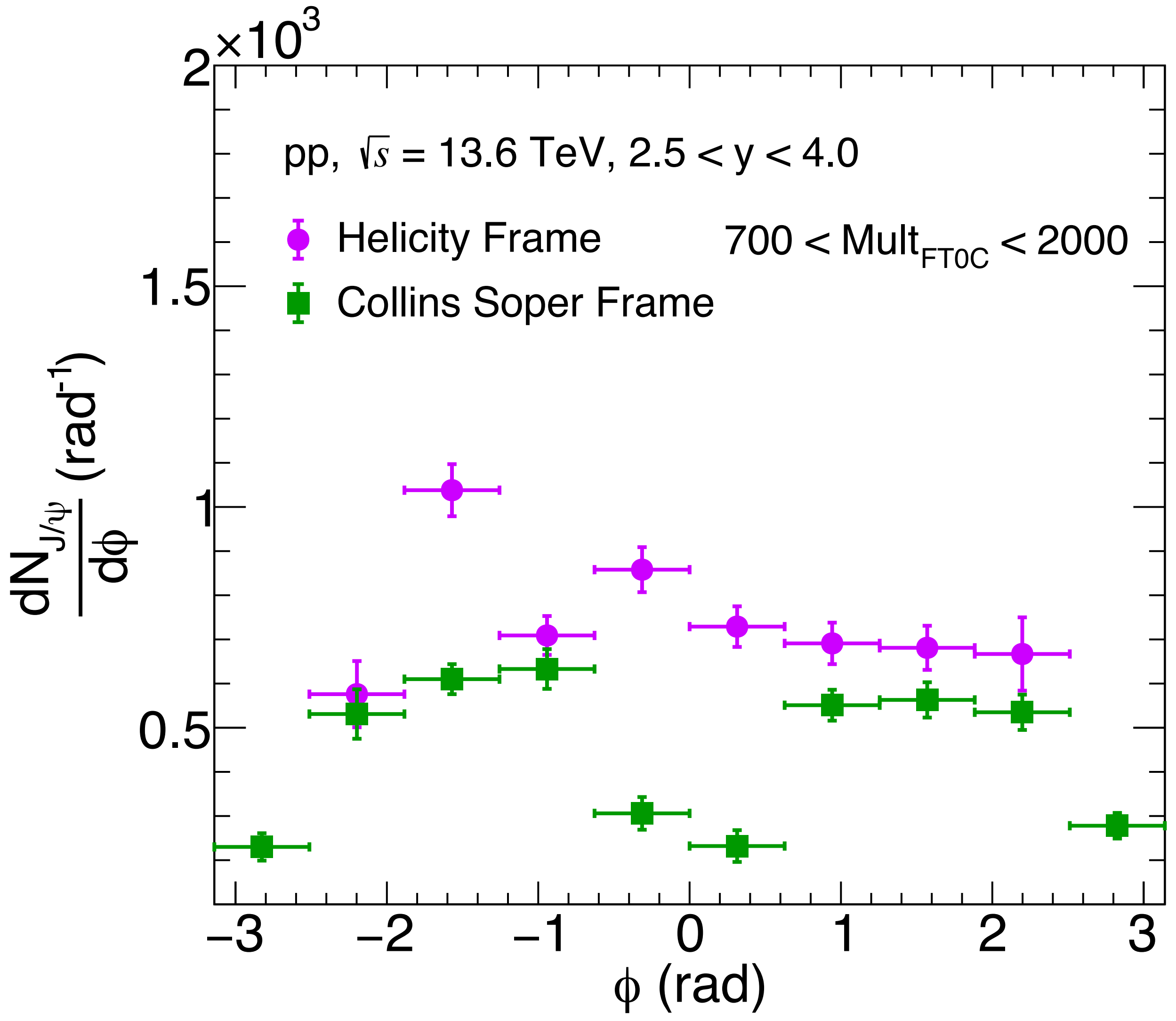
J/ψ angular distribution: Multiplicity dependent ϕ raw distribution



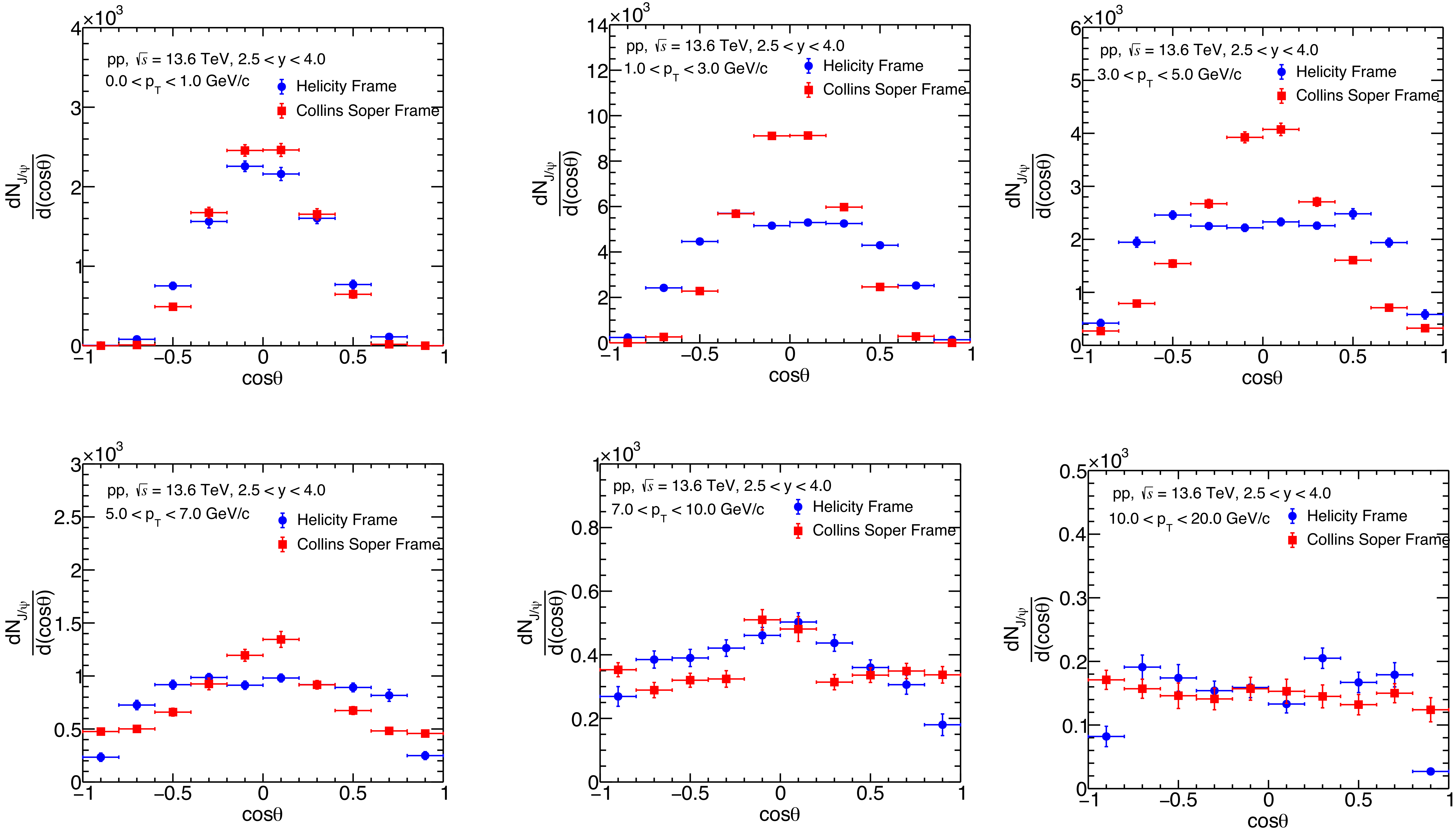




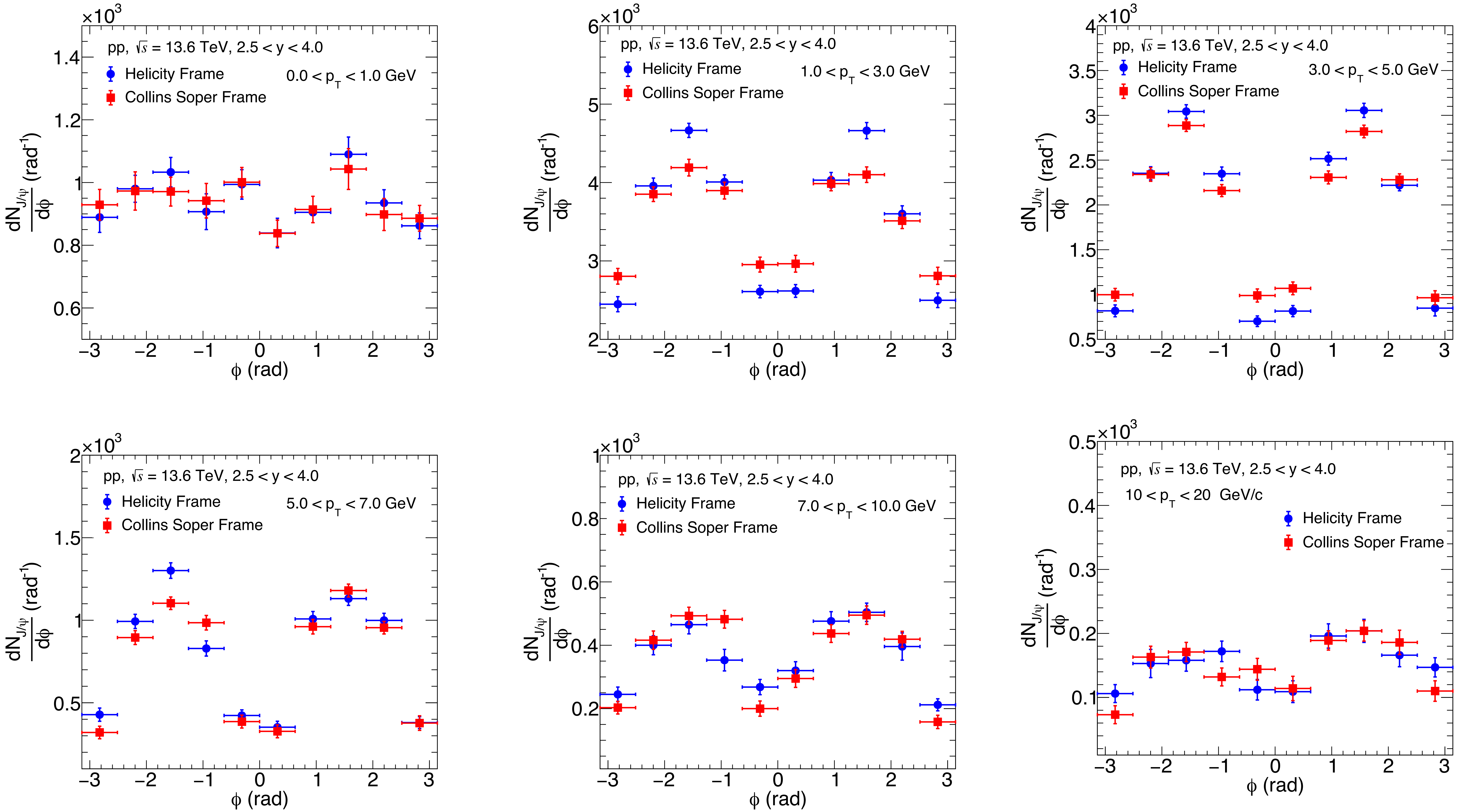




J/ψ angular distribution: p_T dependent cosθ raw distribution



J/ψ angular distribution: p_T dependent φ raw distribution



Summary and Outlook

Summary

- Preliminary results are obtained to study the multiplicity dependence of J/ψ polarization parameters in pp collisions at $\sqrt{s}$ = 13.6 TeV using a small statistics Run 3 data sample
- The J/ψ and ψ(2S) raw yield, ψ(2S)/J/ψ ratios, mass and resolution of J/ψ is obtained as a function of transverse momentum
- The FT0C multiplicity dependence raw angular distribution is obtained for both helicity and Collins-Soper frames
- The p_T differential raw angular distributions are obtained along with the multiplicity dependence to compare with Run 2 result

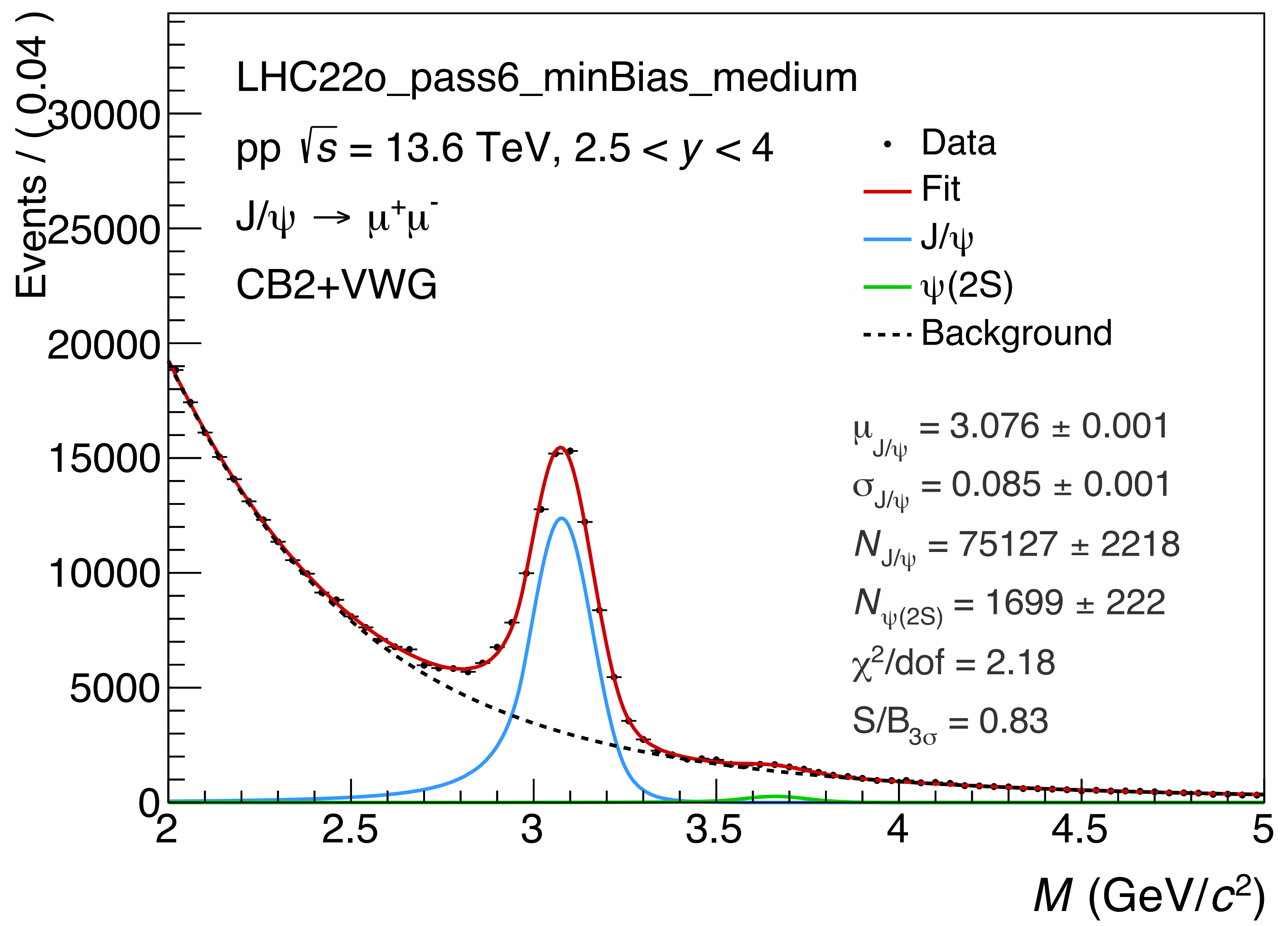
Outlook

- The raw angular distribution will be obtained with large statistics data sample (LHC 22o, LHC22m, LHC22r, LHC22q, LHC22t and LHC23 datasets)
- Waiting for the approval of Long Train Request
- The raw angular distribution will be corrected with the Acceptance x Efficiency to obtain the corrected angular distribution
- Waiting for ideal MC simulation
- The precise measurement of transverse momentum and rapidity dependence polarization parameters can be explored in this analysis with high statistics Run 3 data

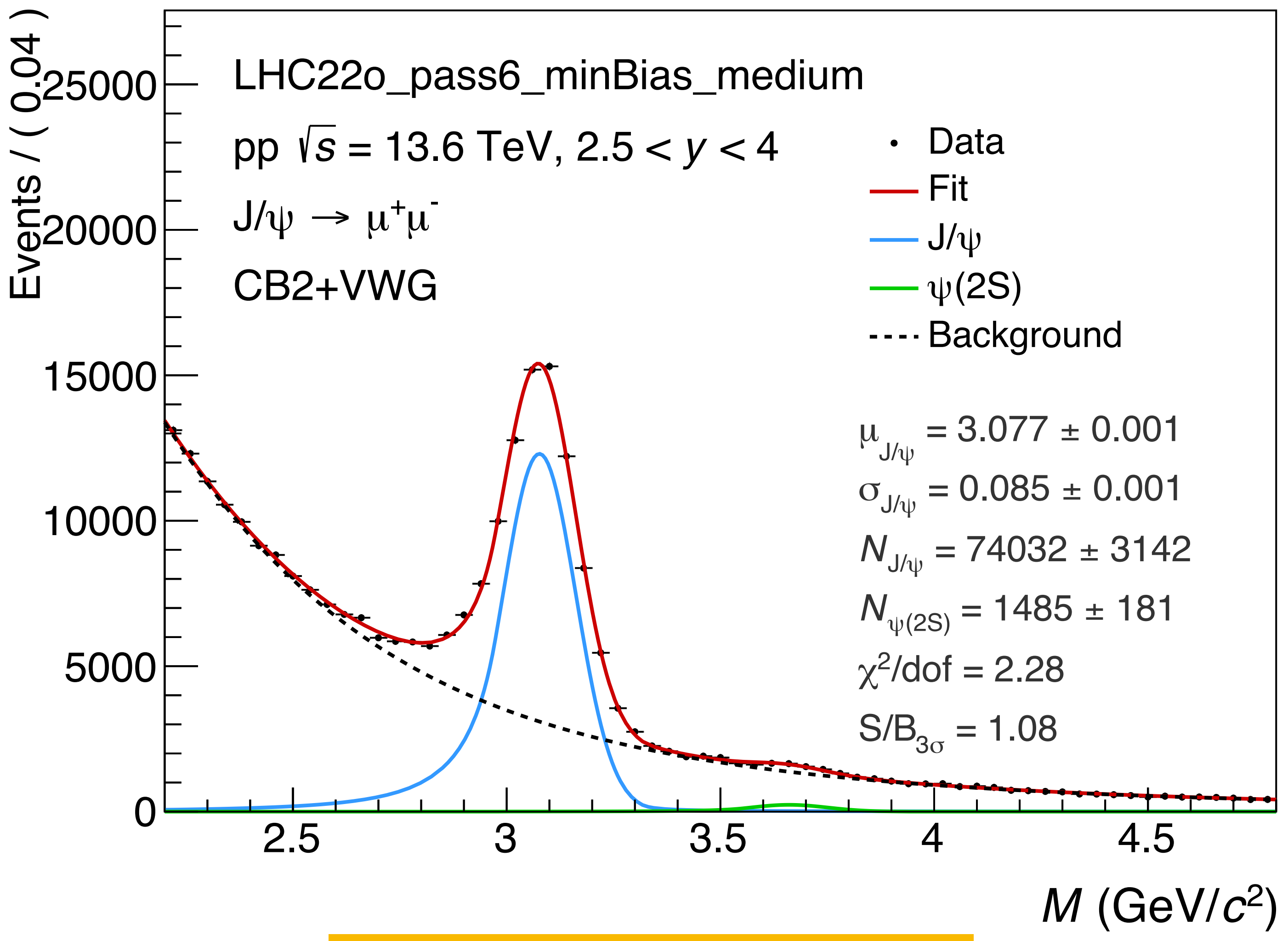
Thank You very much !!

Backup

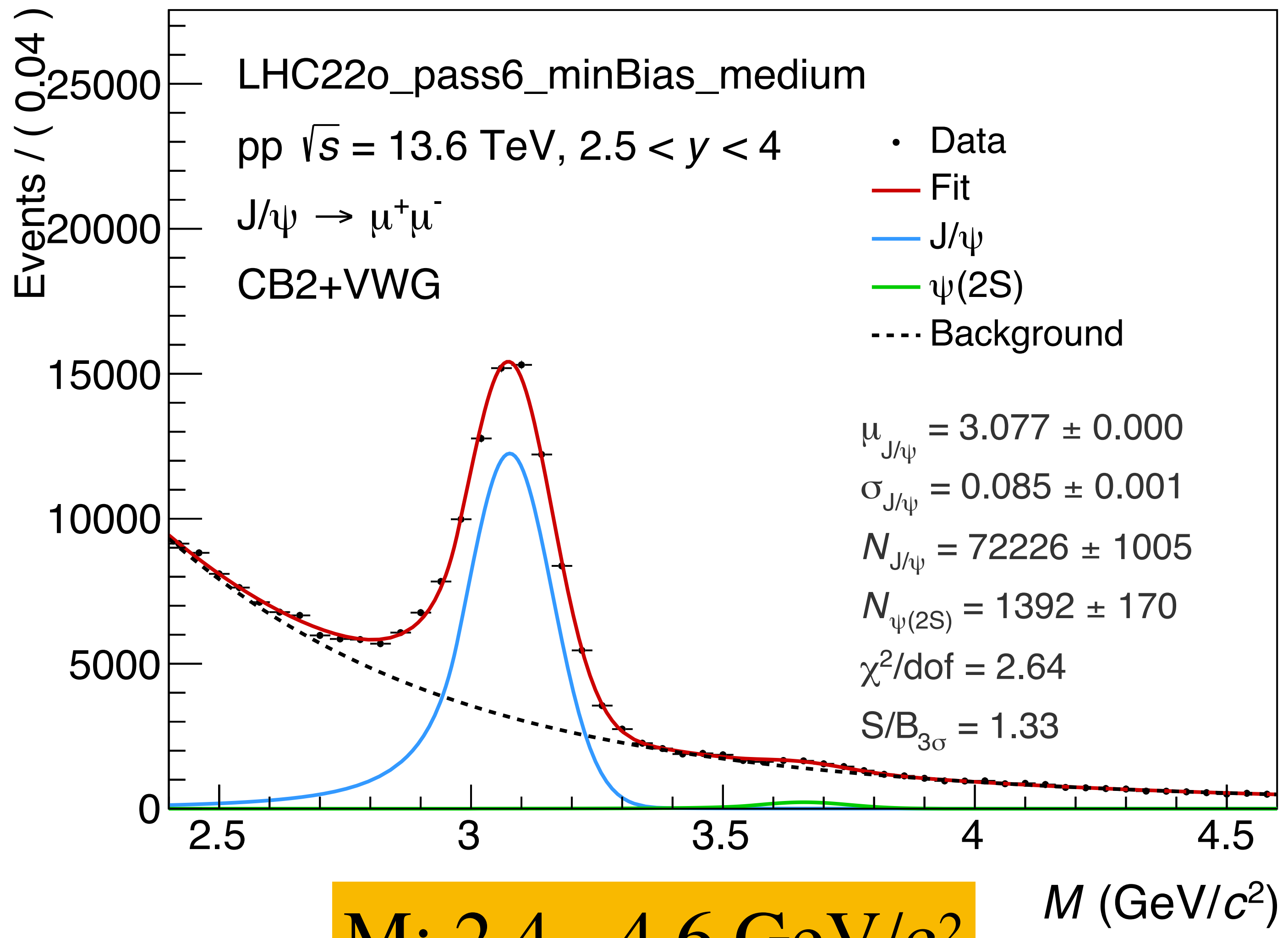
Signal Extraction: Three different fit ranges (Integrated p_T)



M: 2 - 5 GeV/c^2



M: 2.2 - 4.8 GeV/c^2



M: 2.4 - 4.6 GeV/c^2

- The mass and resolution are found to be consistent in each fit ranges
- The tail parameters are free in these fits

pass6

type	t_1	p_1	t_2	p_2
Data	1.22 ±0.0323	2.449 ±0.7746	1.8715 ±0.0414	18.6825 ±11.9047

CB2 tail parameters (Fit ranges: 2.0 - 5.0 GeV/c^2)

type	t_1	p_1	t_2	p_2
Data	1.2134 ±0.0197	2.8672 ±0.5979	2.7864 ±0.1699	1.0 ±11.3356

CB2 tail parameters (Fit ranges: 2.2 - 4.8 GeV/c^2)

type	t_1	p_1	t_2	p_2
Data	1.2288 ±0.0186	2.7731 ±0.4509	3.2787 ±0.0696	1.0 ±2.8396

CB2 tail parameters (Fit ranges: 2.4 - 4.6 GeV/c^2)

Comparison of Tail parameters with Run 3 Analysis Note

pass4

type	t_1	p_1	t_2	p_2
Data	1.061	23.725	3.183	21.144
MC	1.137	2.371	1.871	5.032

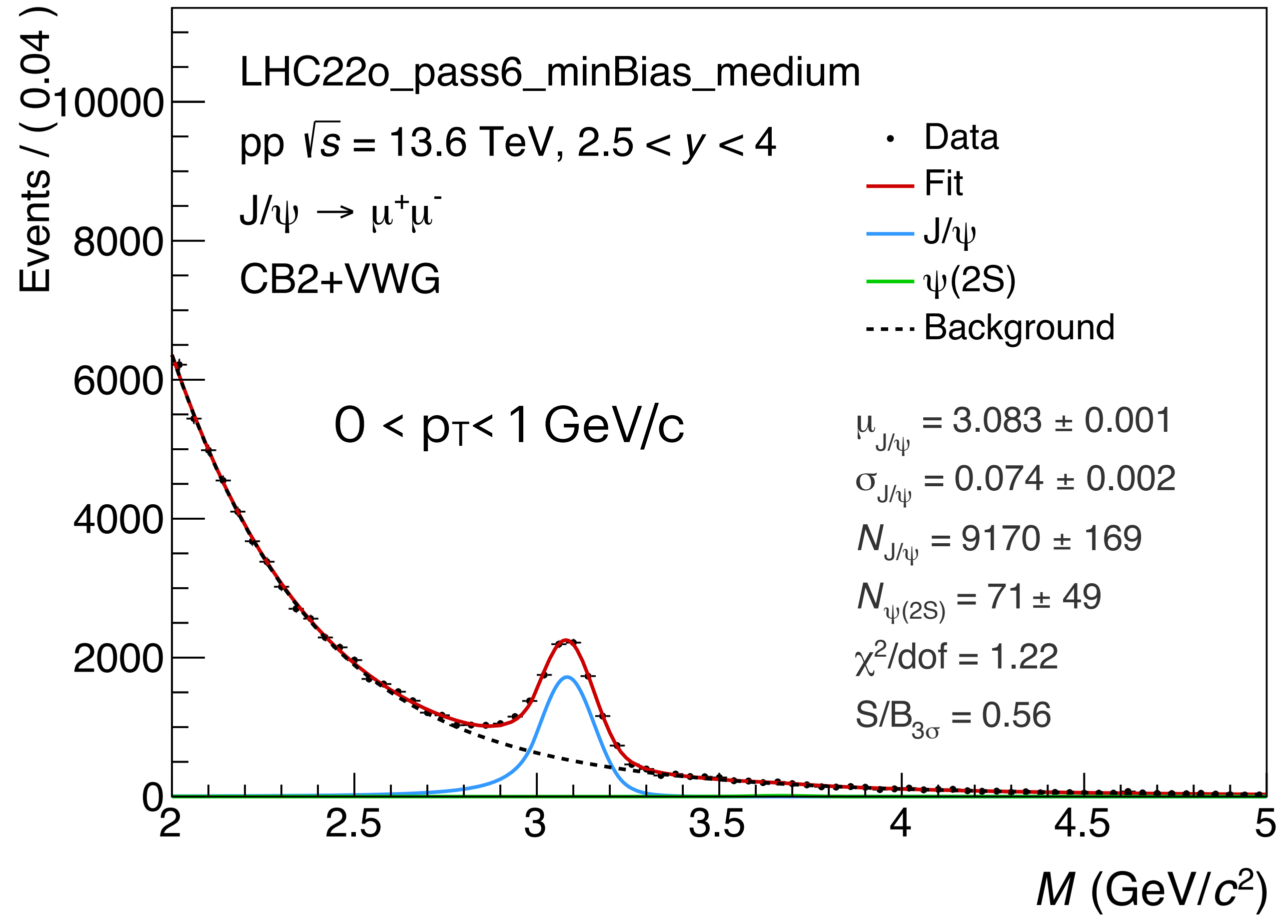
Table 1: CB2 tail parameters

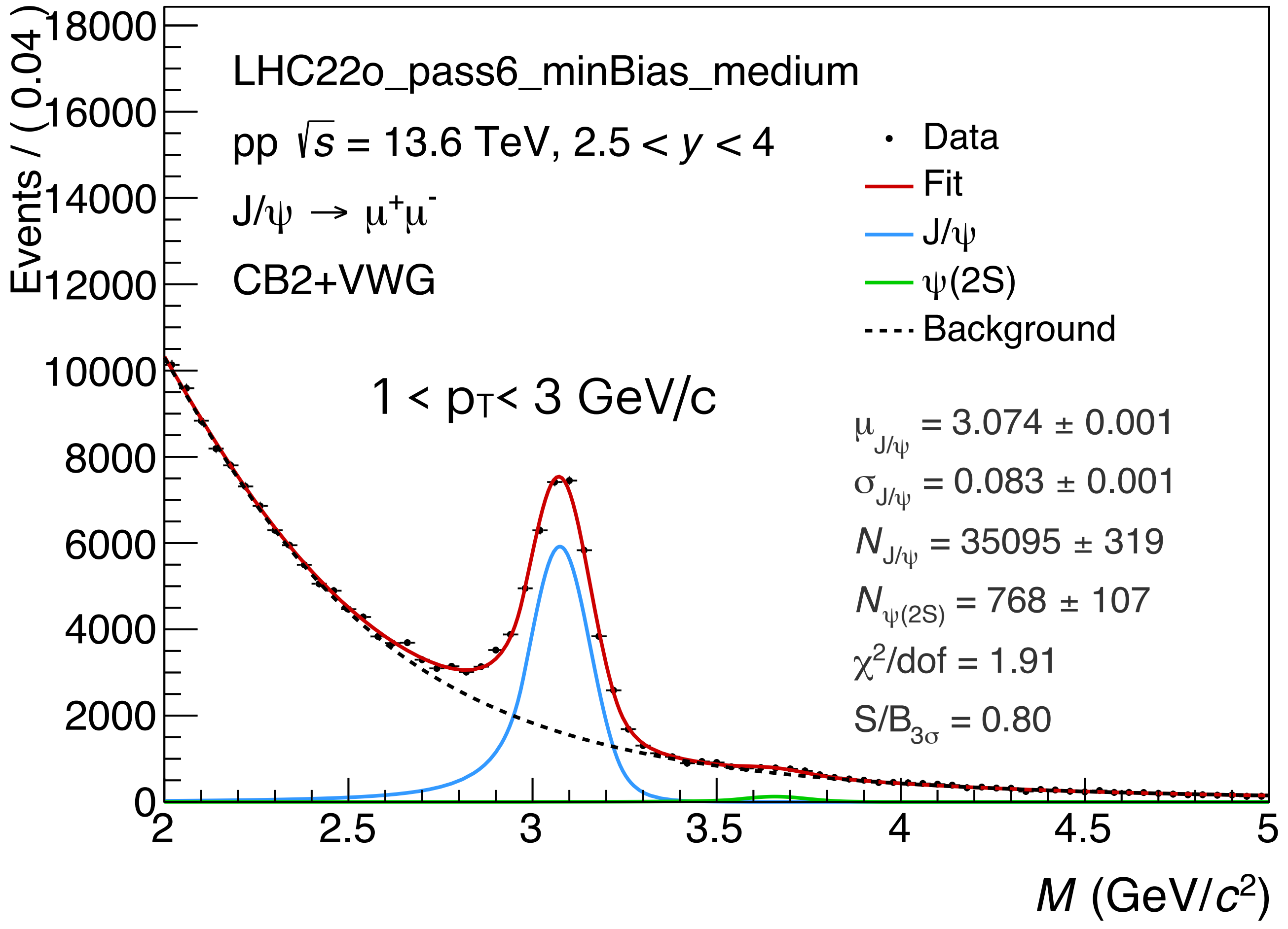
pass5

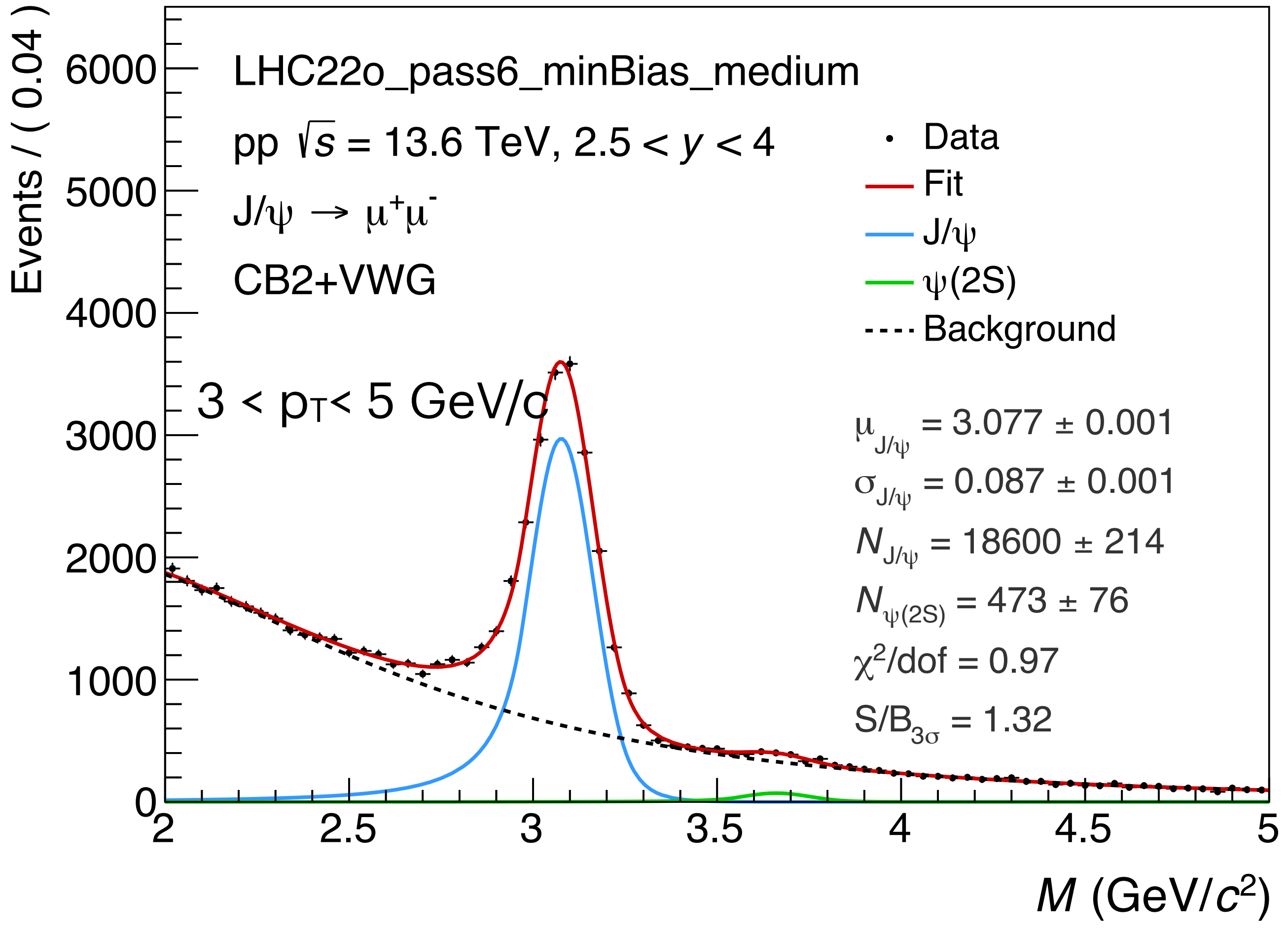
type	t_1	p_1	t_2	p_2
Data	1.003	4.311	2.232	6.246
MC	1.150	2.211	2.577	2.826

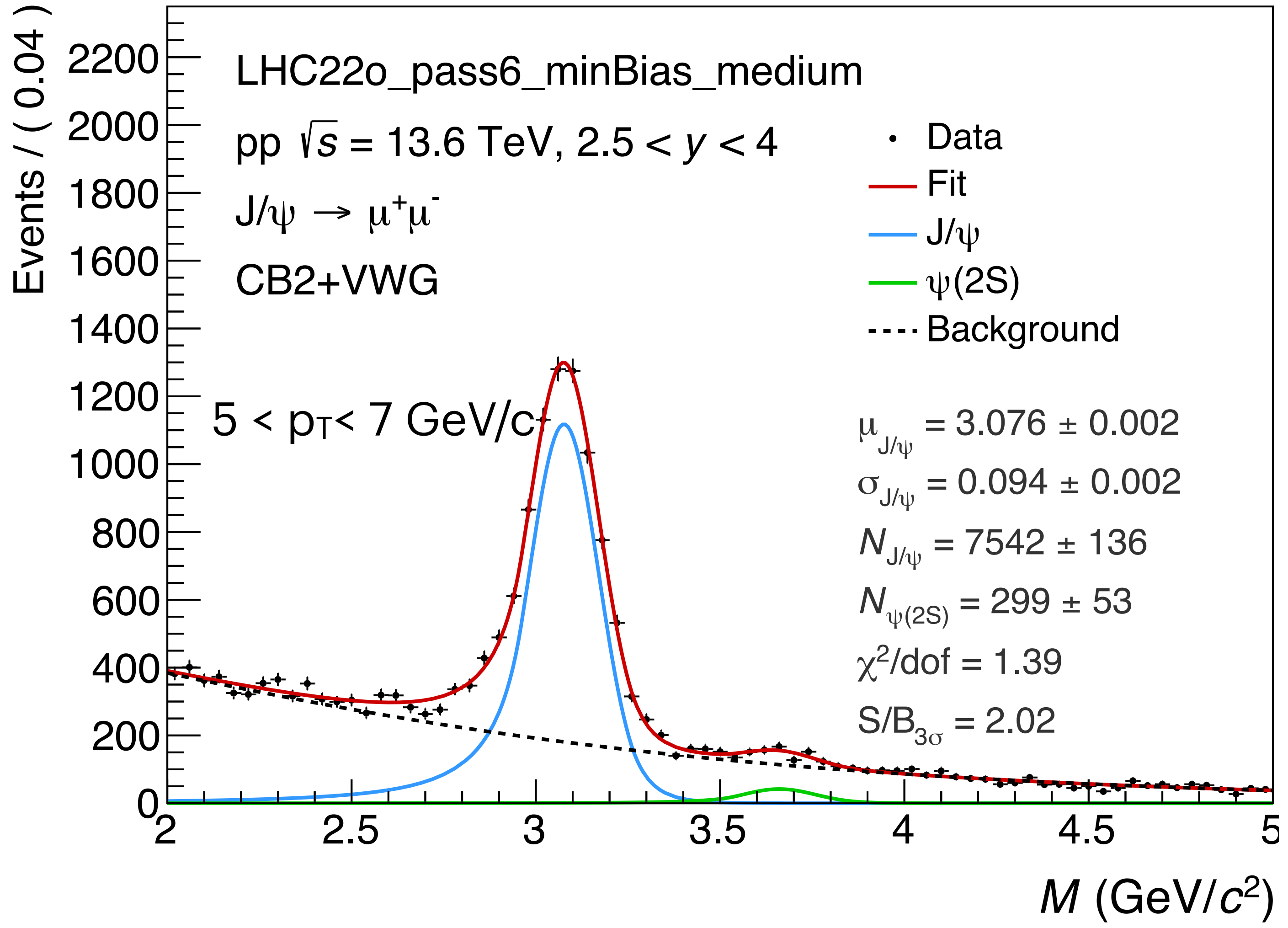
Table 15: CB2 tail parameters

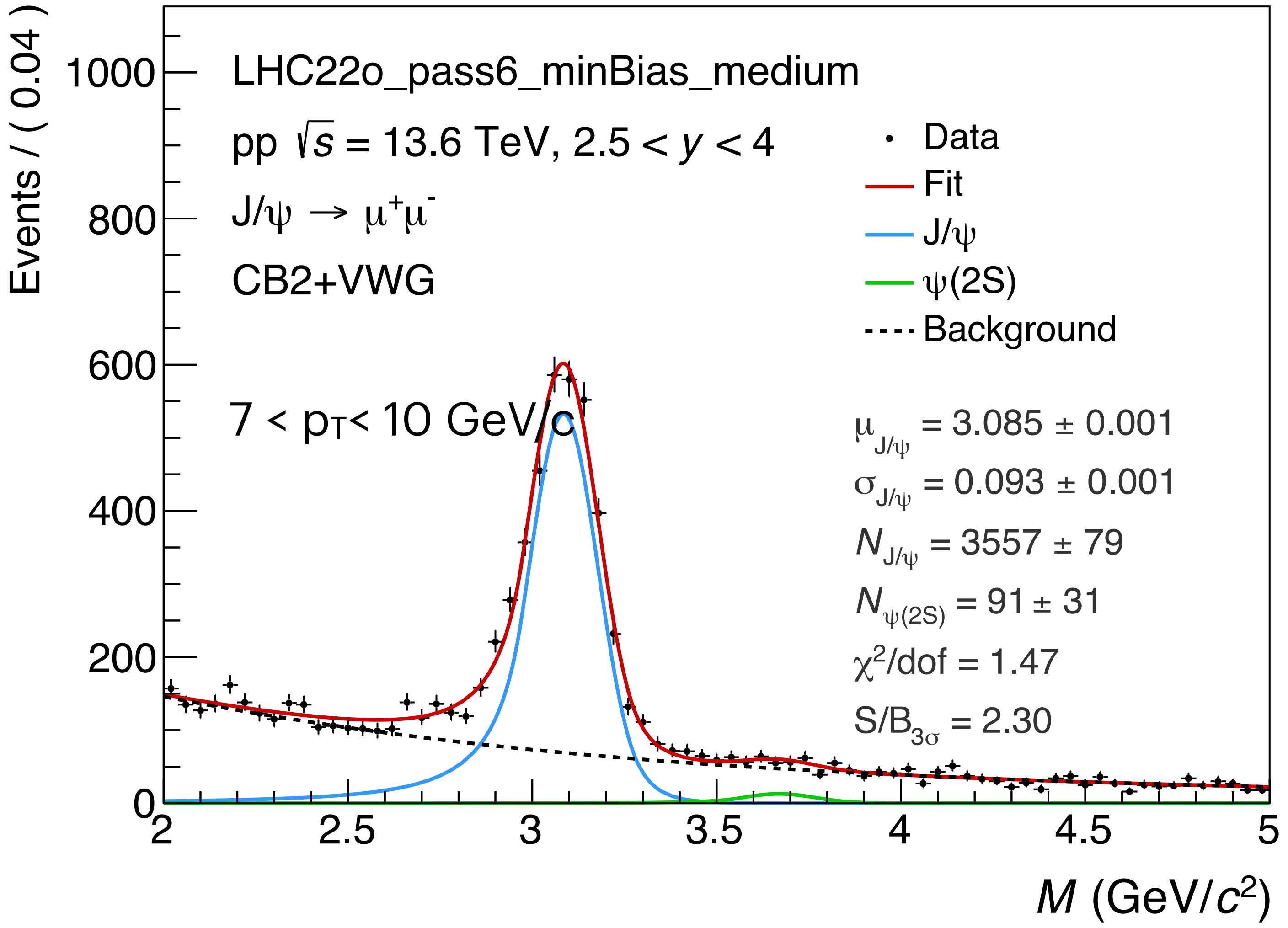
Signal Extraction: p_T differential (Fit range: 2.0 - 5.0 GeV/c^2)

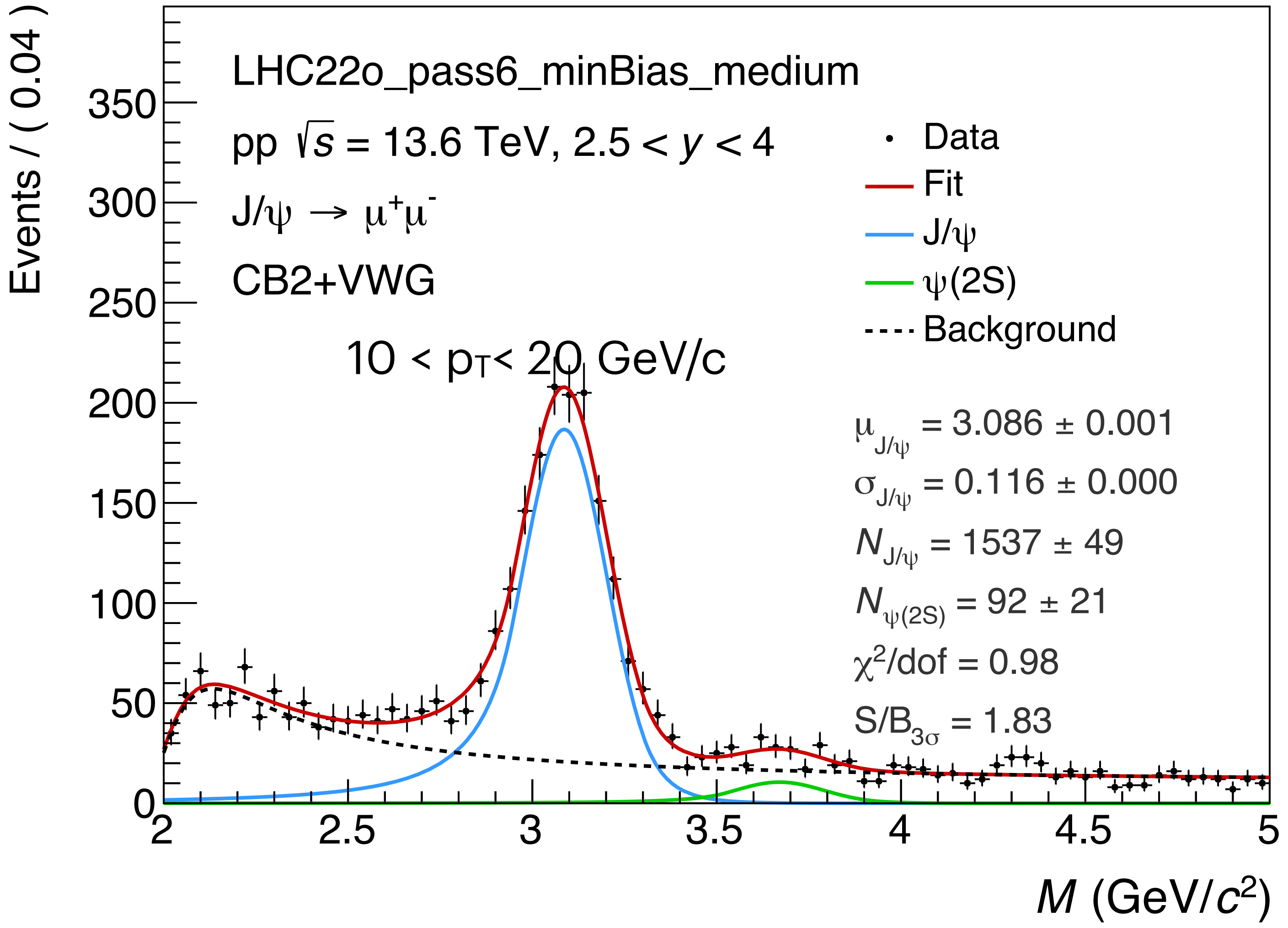




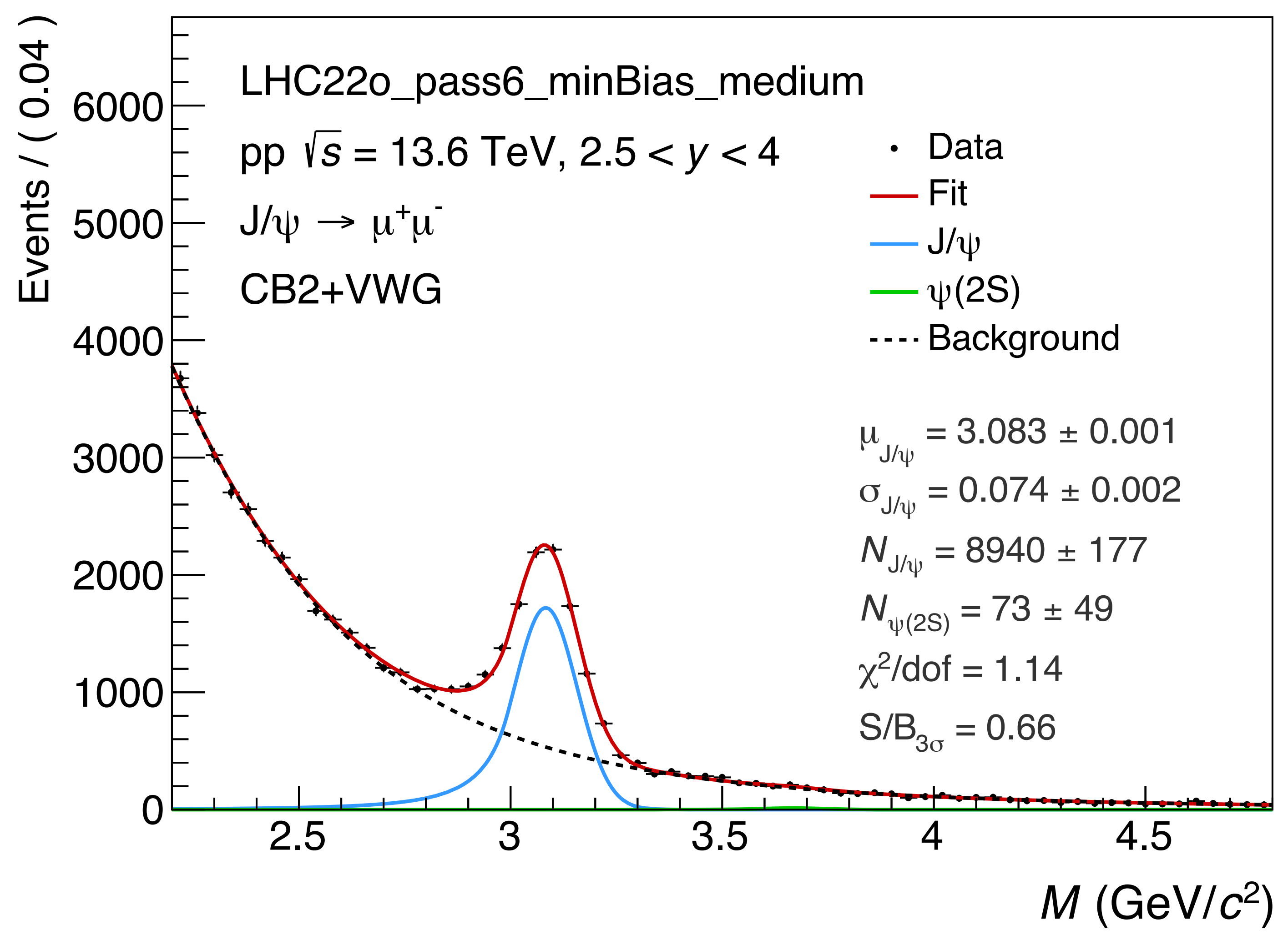


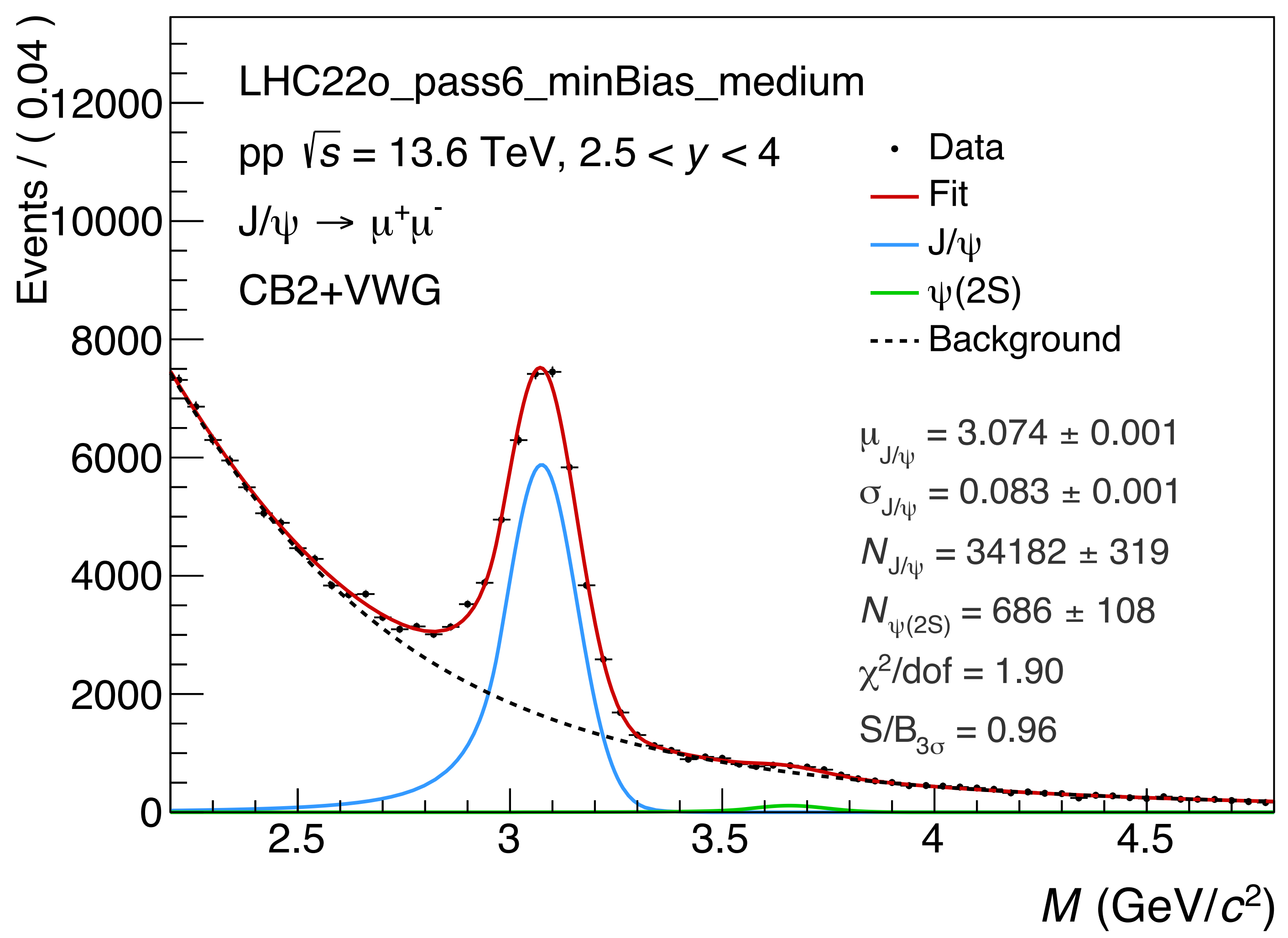


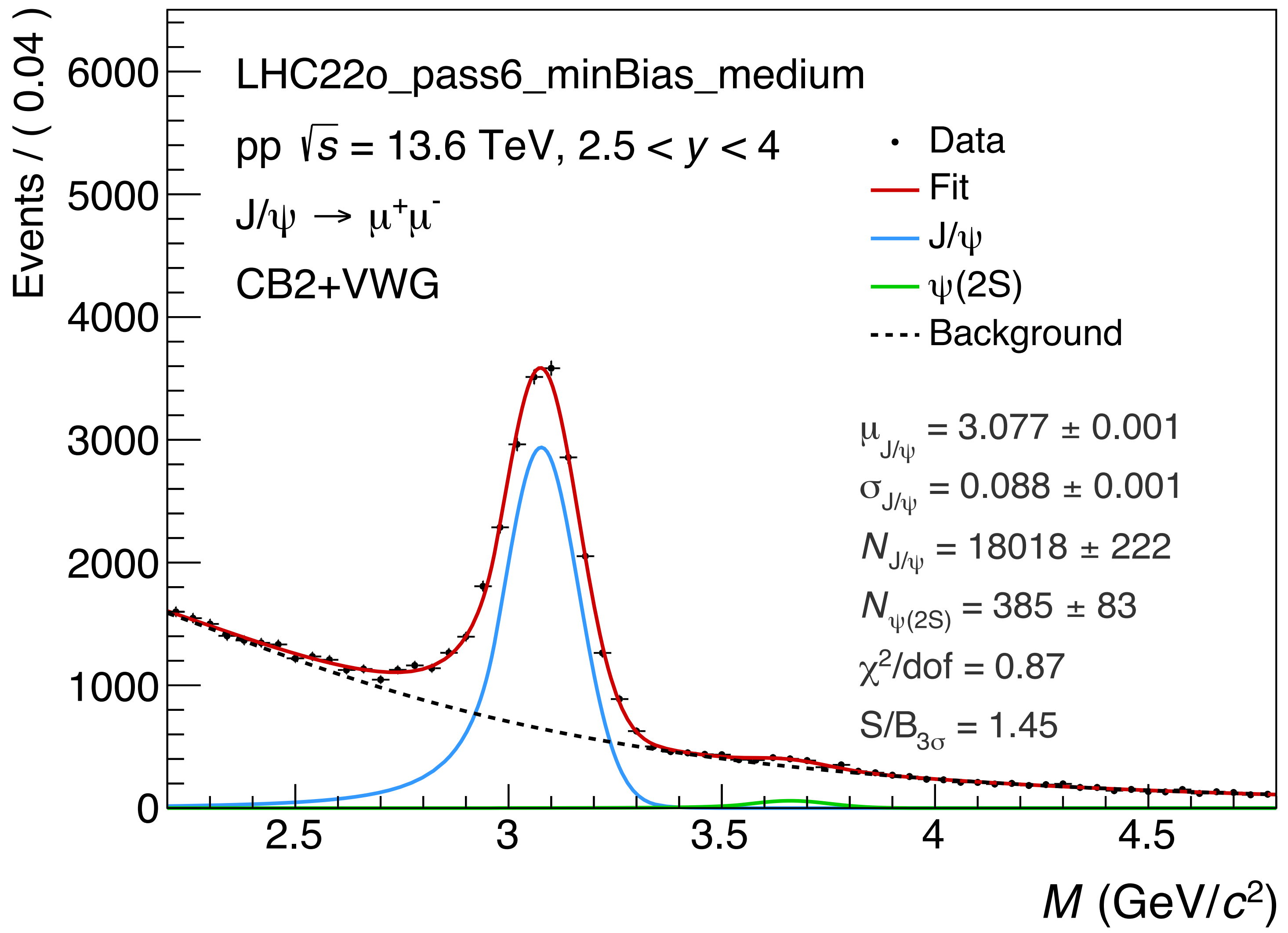


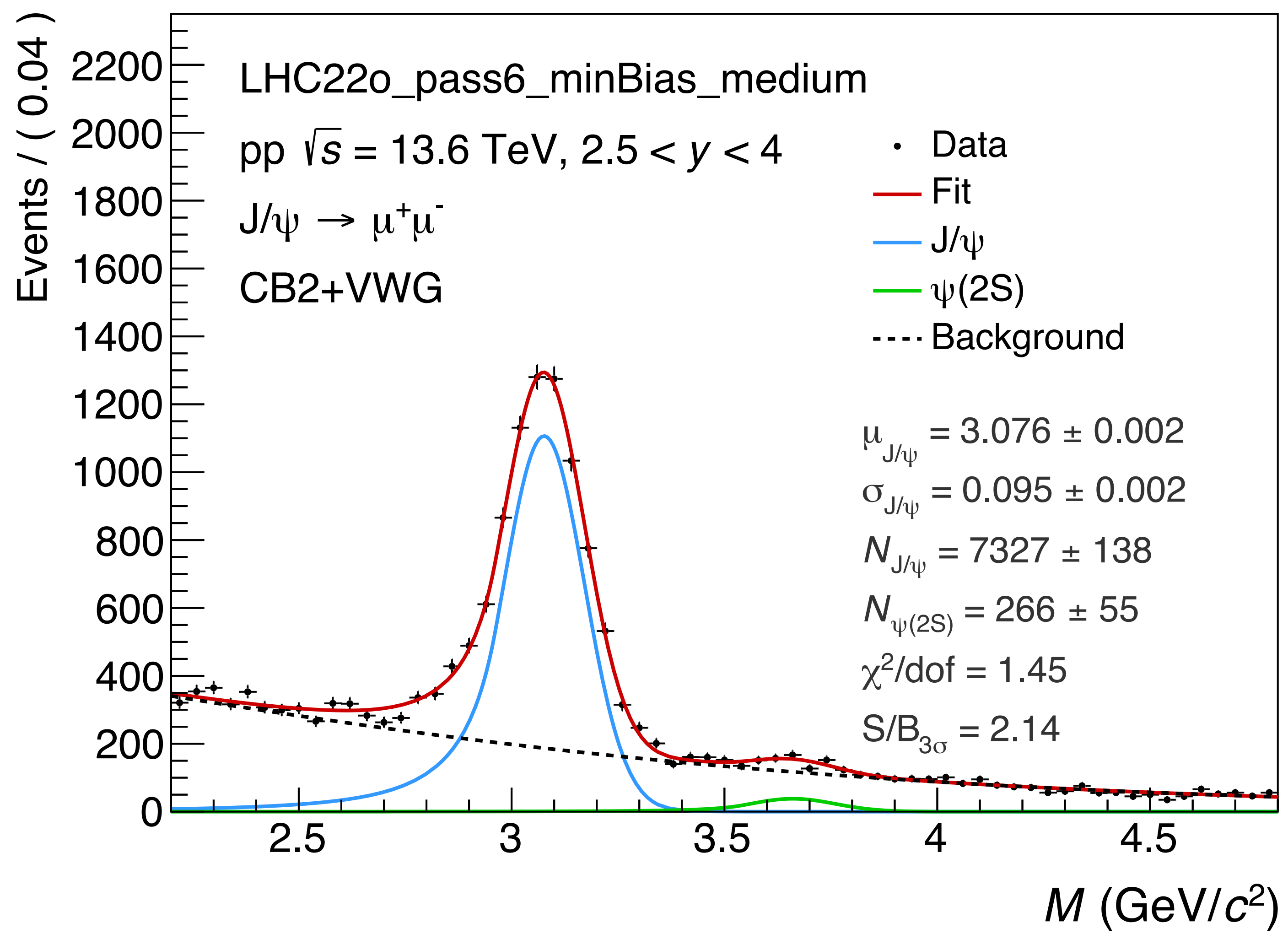


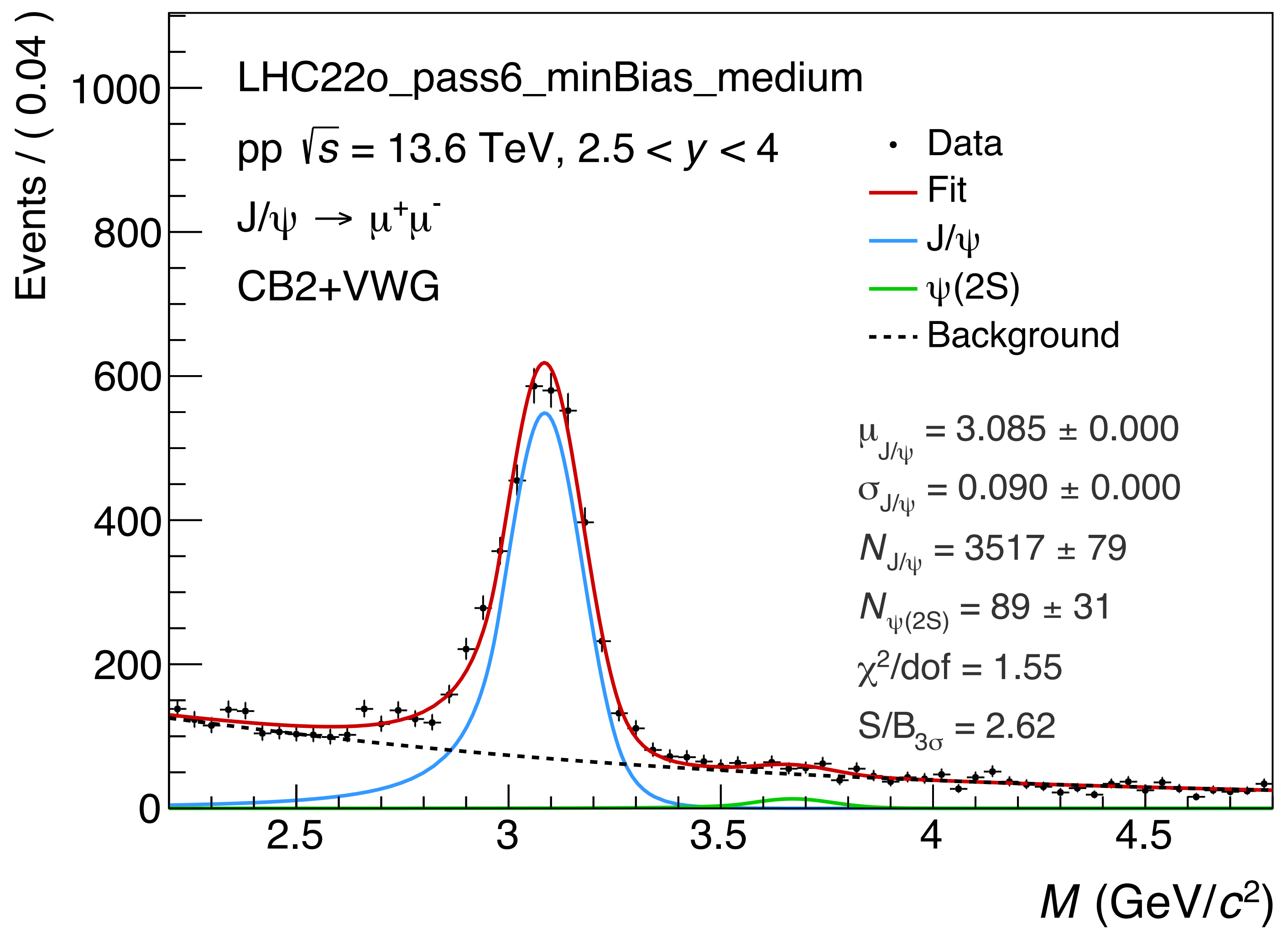
Signal Extraction: p_T differential (Fit range: 2.2 - 4.8 GeV/c^2)

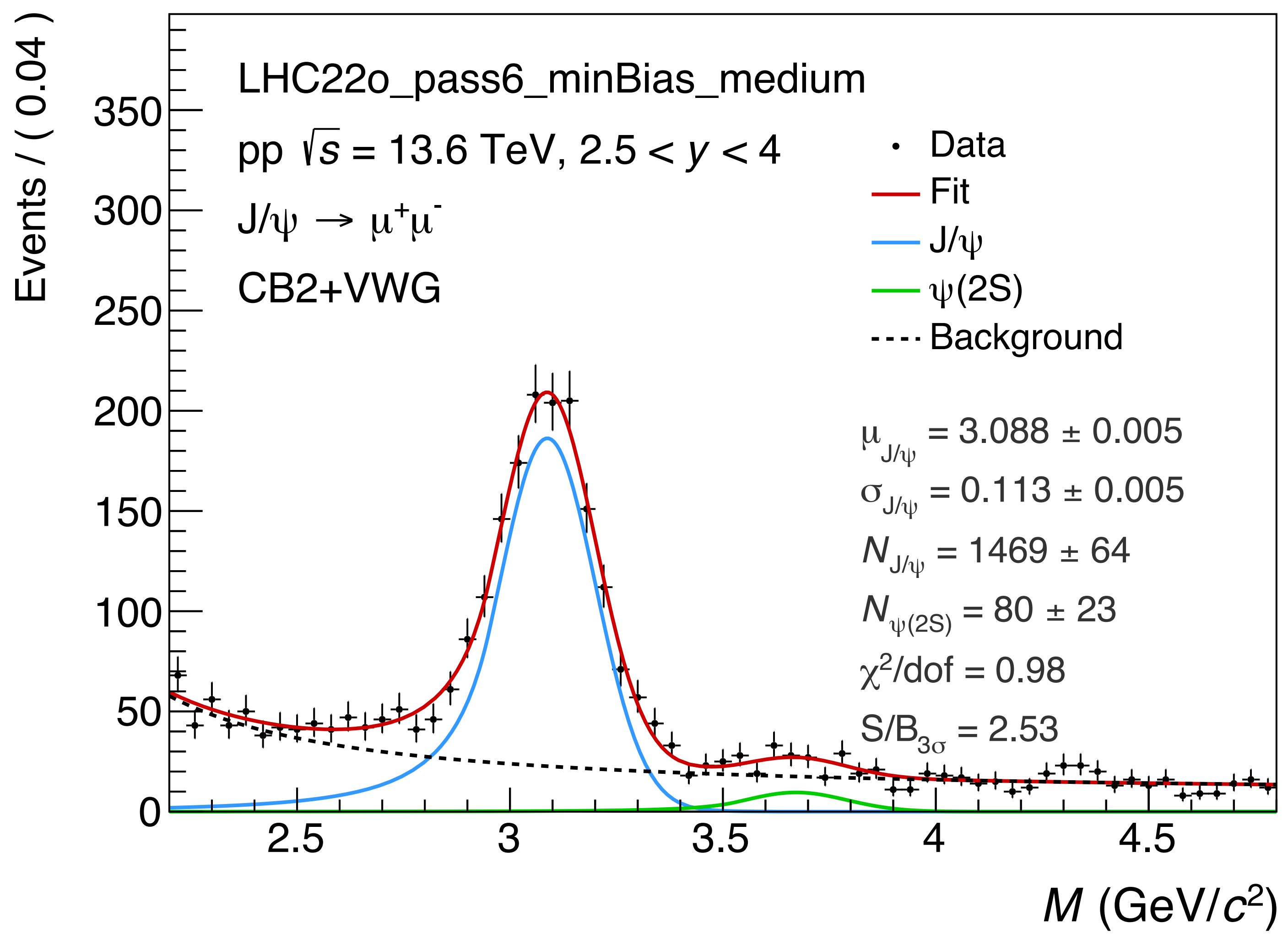




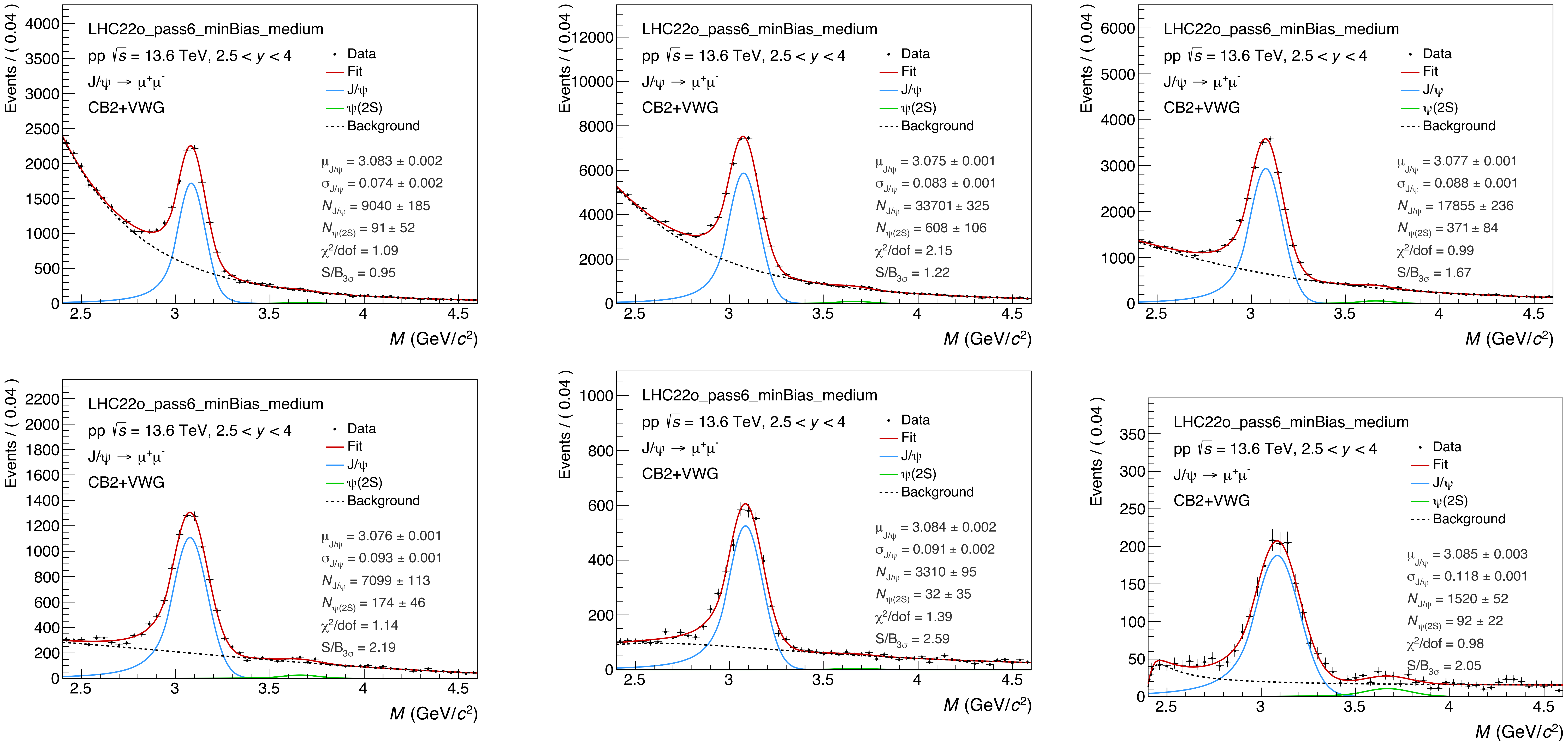




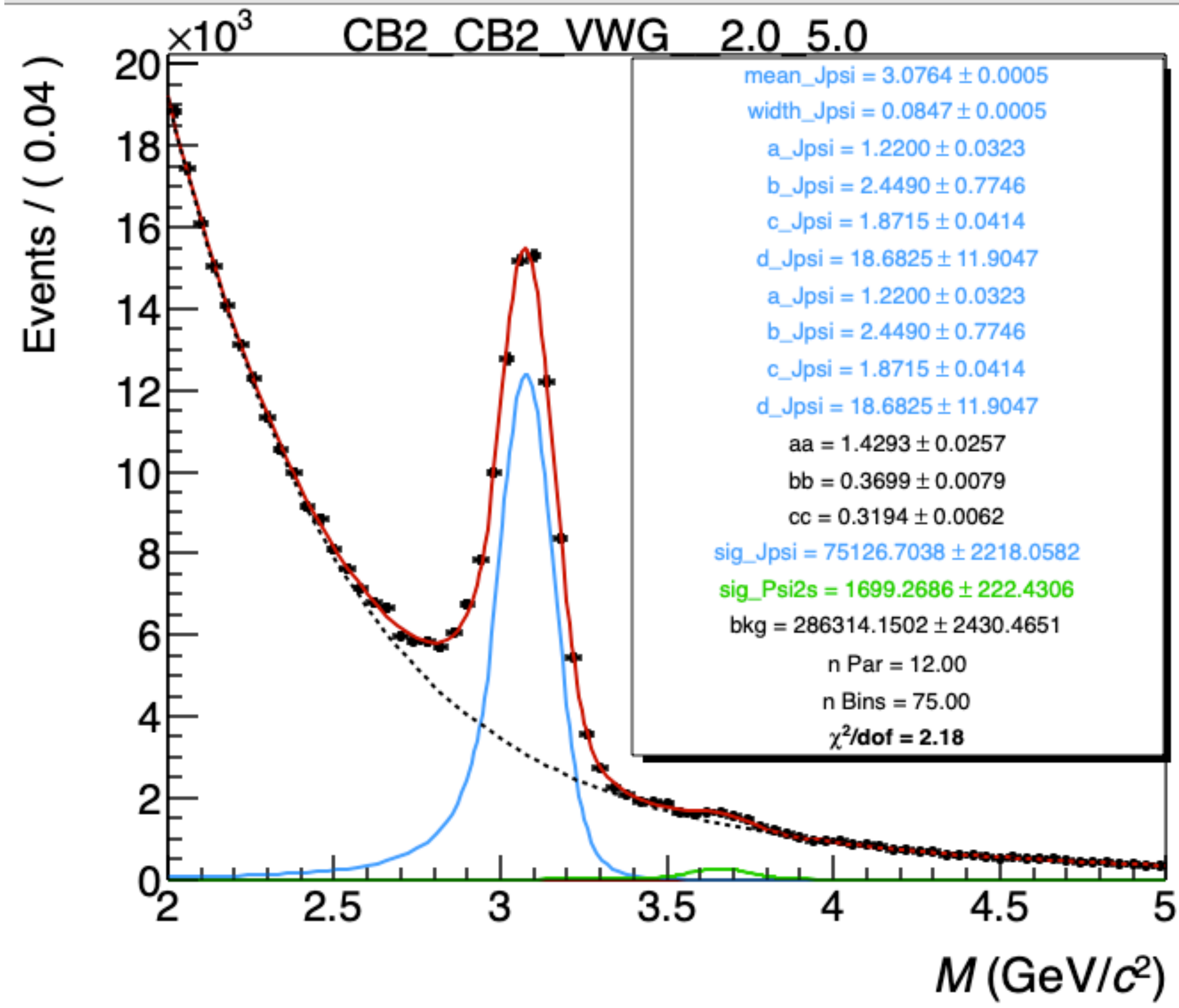




Signal Extraction: p_T differential (Fit range: 2.4 - 4.6 GeV/c^2)



J/ψ and $\psi(2S)$ Tail Parameters



Notation in according to fitting function

mean_Jpsi ($\mu_{J/\psi}$) = $\tilde{x}$

width_Jpsi ($\sigma_{J/\psi}$) = σ

a_Jpsi = t1

b_Jpsi = p1

c_Jpsi = t2

d_Jpsi = p2

aa = $\tilde{x}$

bb = A

cc = B

sig_Jpsi = $N_{J/\psi}$

sig_Psi2s = $N_{\psi(2S)}$

bkg = N_{bkg}

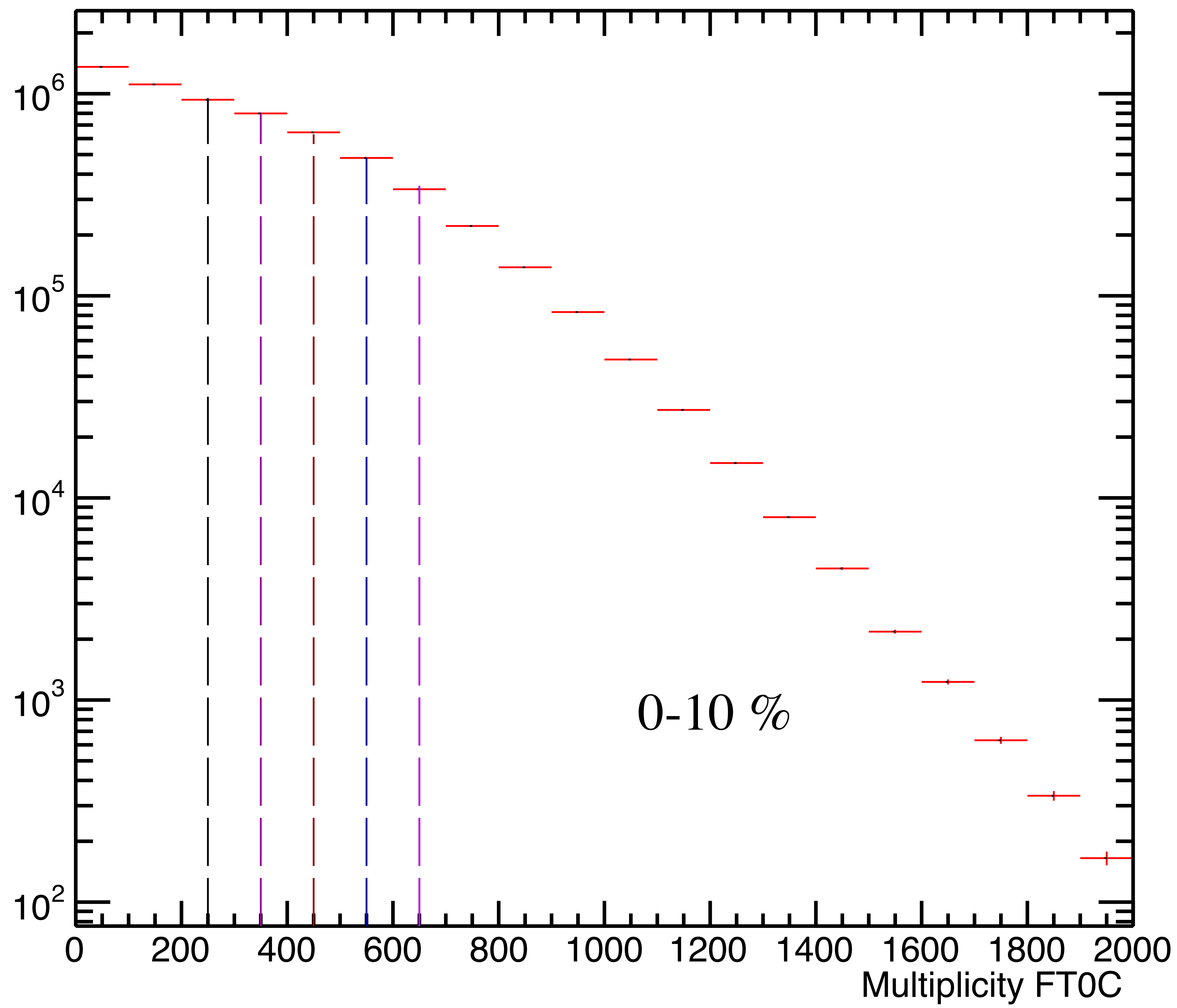
Issues with multiplicity class selections

- The multiplicity class selection is usually done by slicing the the multiplicity distribution on equal number of events (say 10 %)
- However, due to less number of multiplicity bins, getting the exact BinCenter is difficult.
- More fine binning is required
- However, Increasing the number of bins leads to crash of analysis task due to large output size

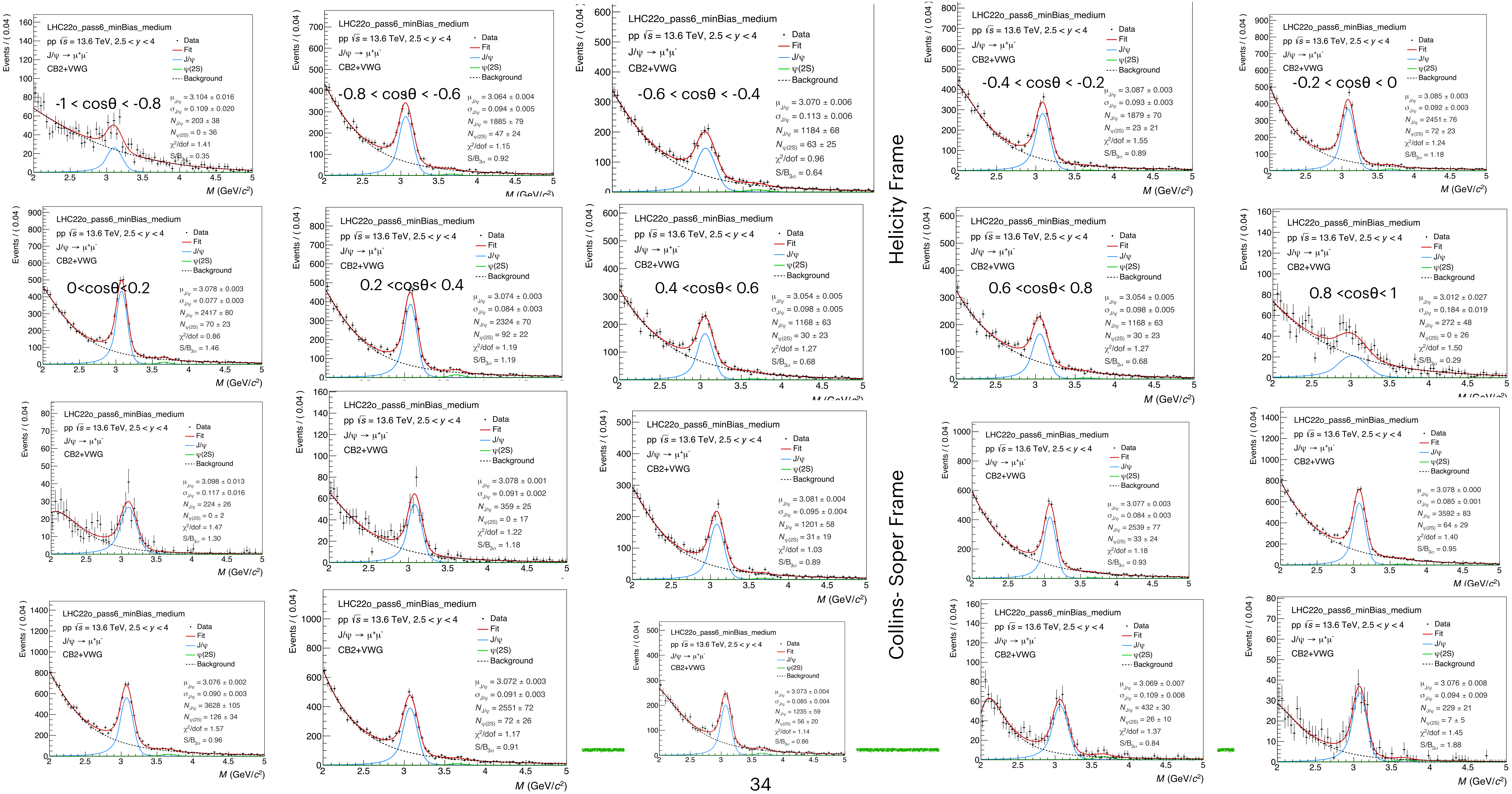
Possible Solution:

- Choose the low multiplicity classes with a narrower bin and wider bin for highest multiplicity classes to accommodate more particles.
- Similar multiplicity selection criterion is adopted in PWG-DQ Jpsi2e using TPC multiplicity.
- Presented in PWG DQ meeting - QM approval [performance-approval]

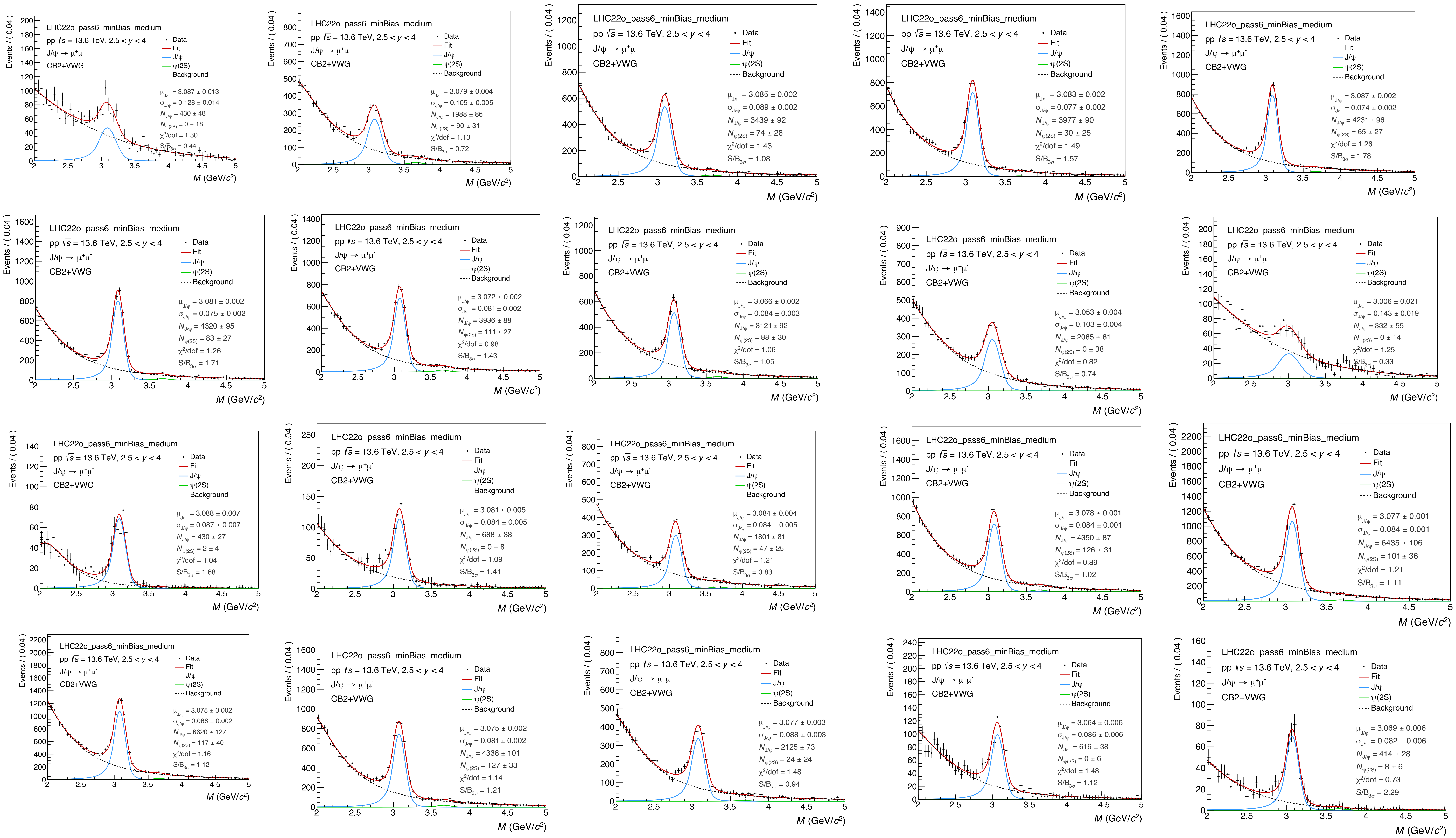
https://indico.cern.ch/event/1309455/#6-performance-approval-jpsi-po



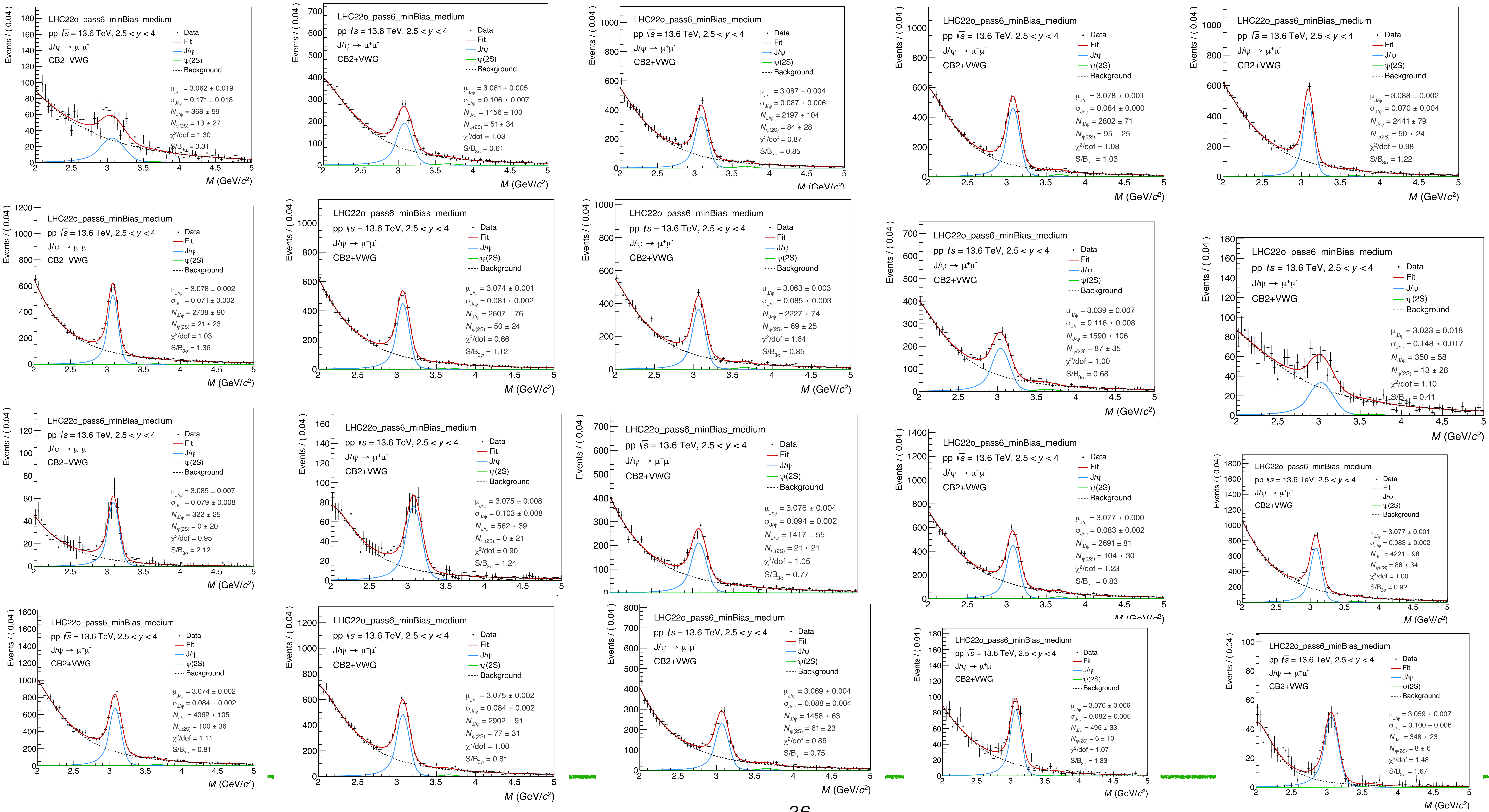
Signal Extraction: FT0C multiplicity and cosθ differential (0 < $Mult_{FT0C}$ < 100)



Signal Extraction: FT0C multiplicity and cosθ differential ($100 < \mathrm{Mult_{FT0C}} < 300$)

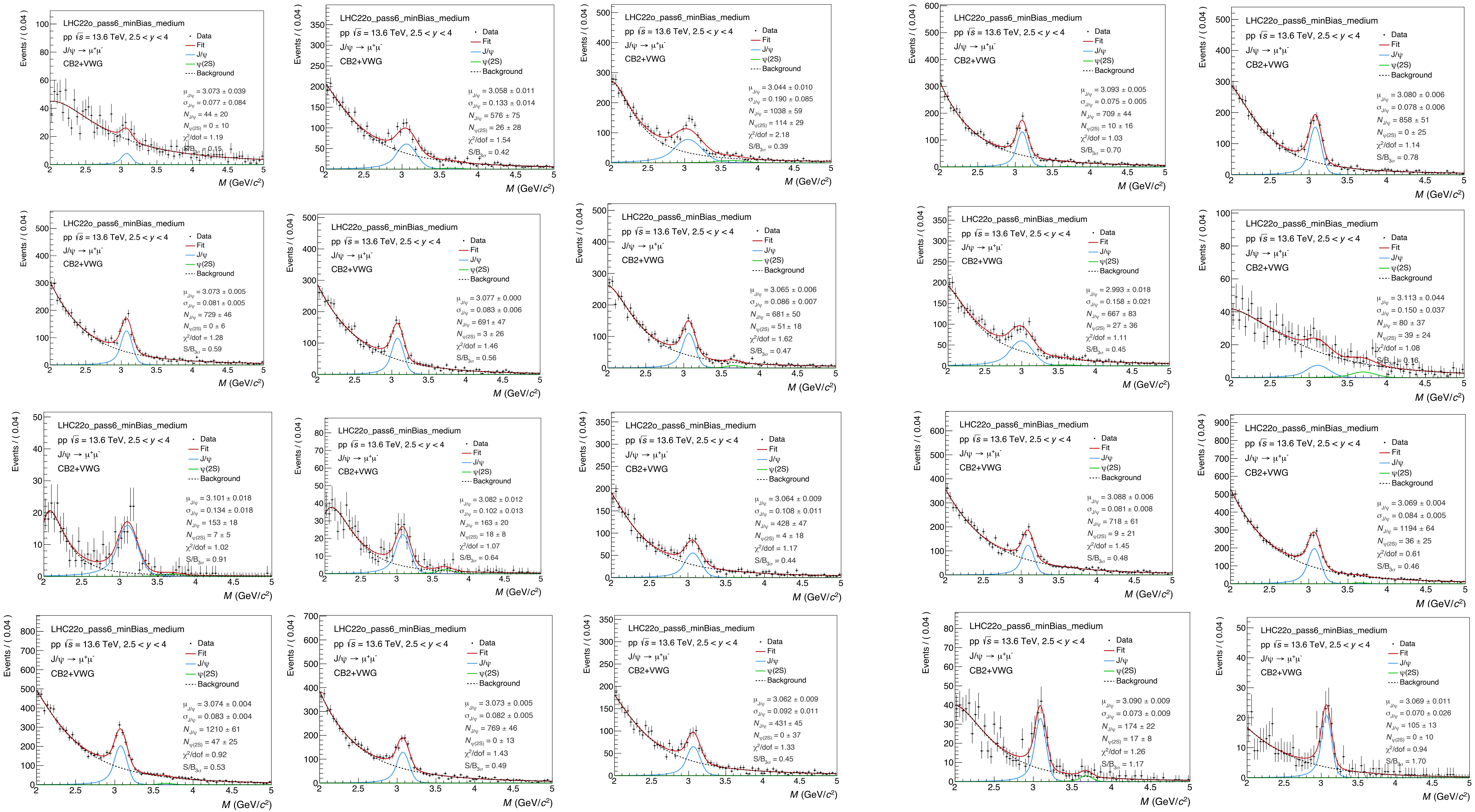


Signal Extraction: FT0C multiplicity and cosθ differential (300 < $Mult_{FT0C}$ < 500)

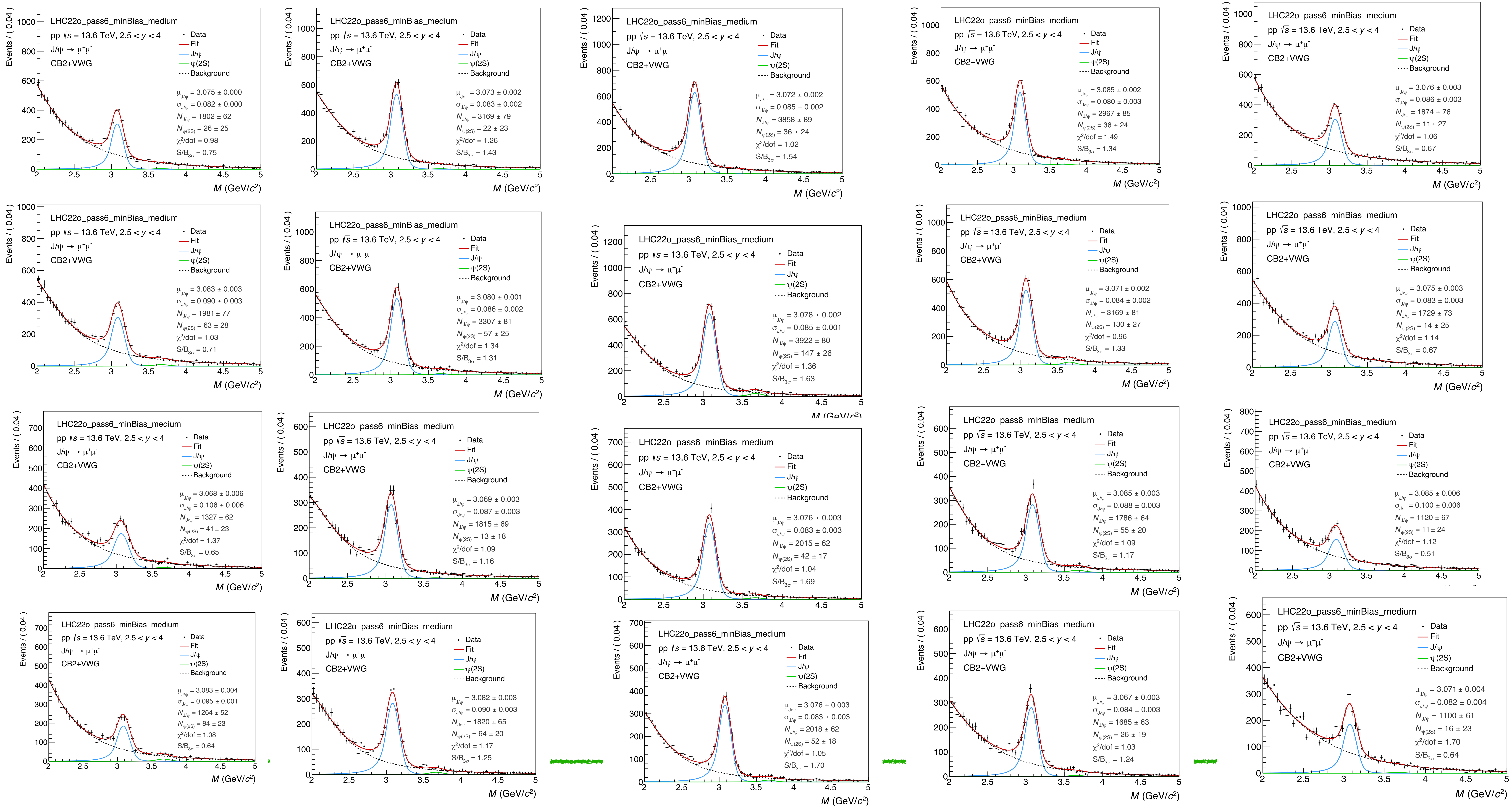


Signal Extraction: FT0C multiplicity and cosθ differential (500 < $Mult_{FT0C}$ < 700)

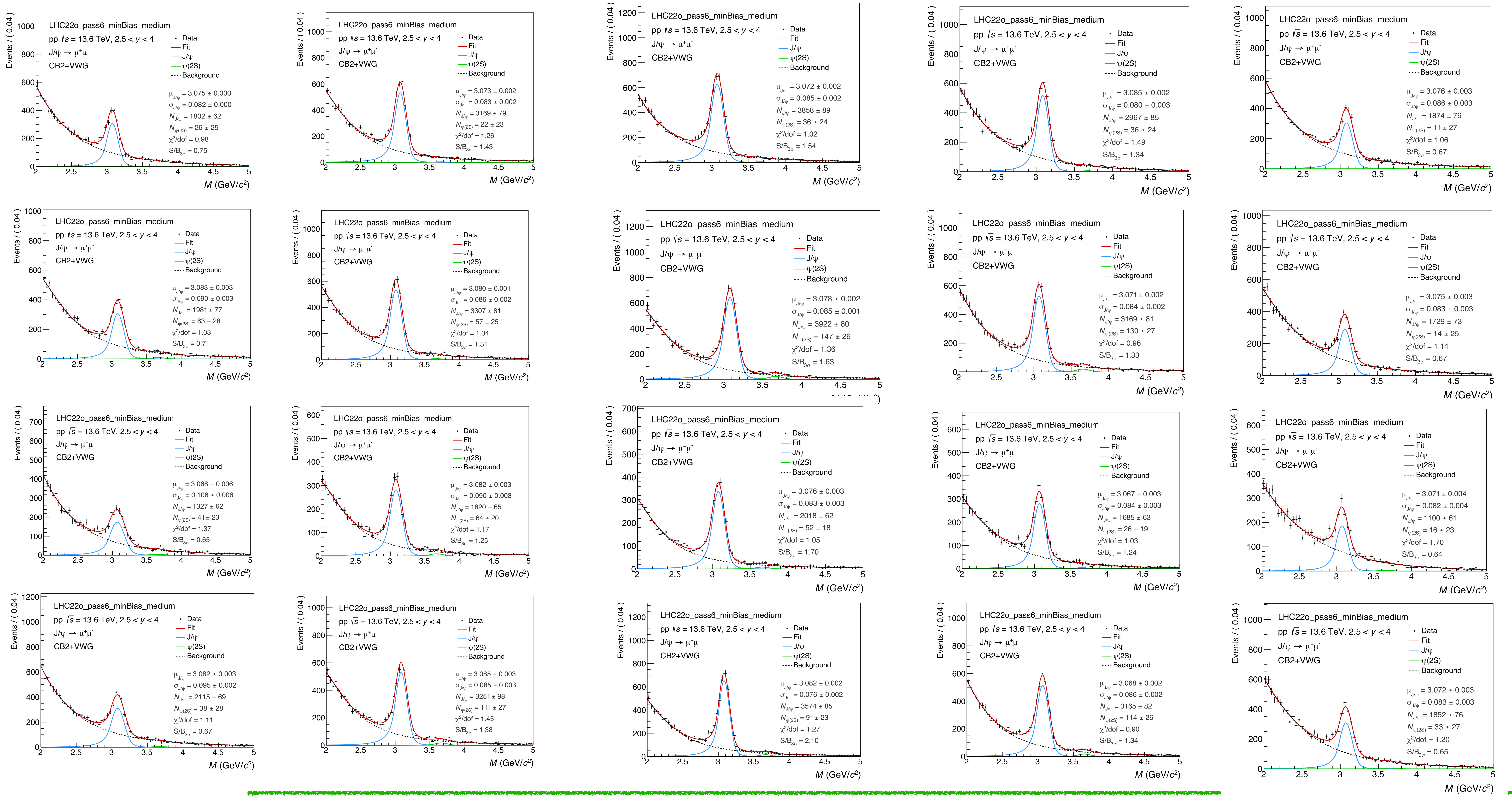
Signal Extraction: FT0C multiplicity and coss differential (700 < $Mult_{FT0C}$ < 2000)



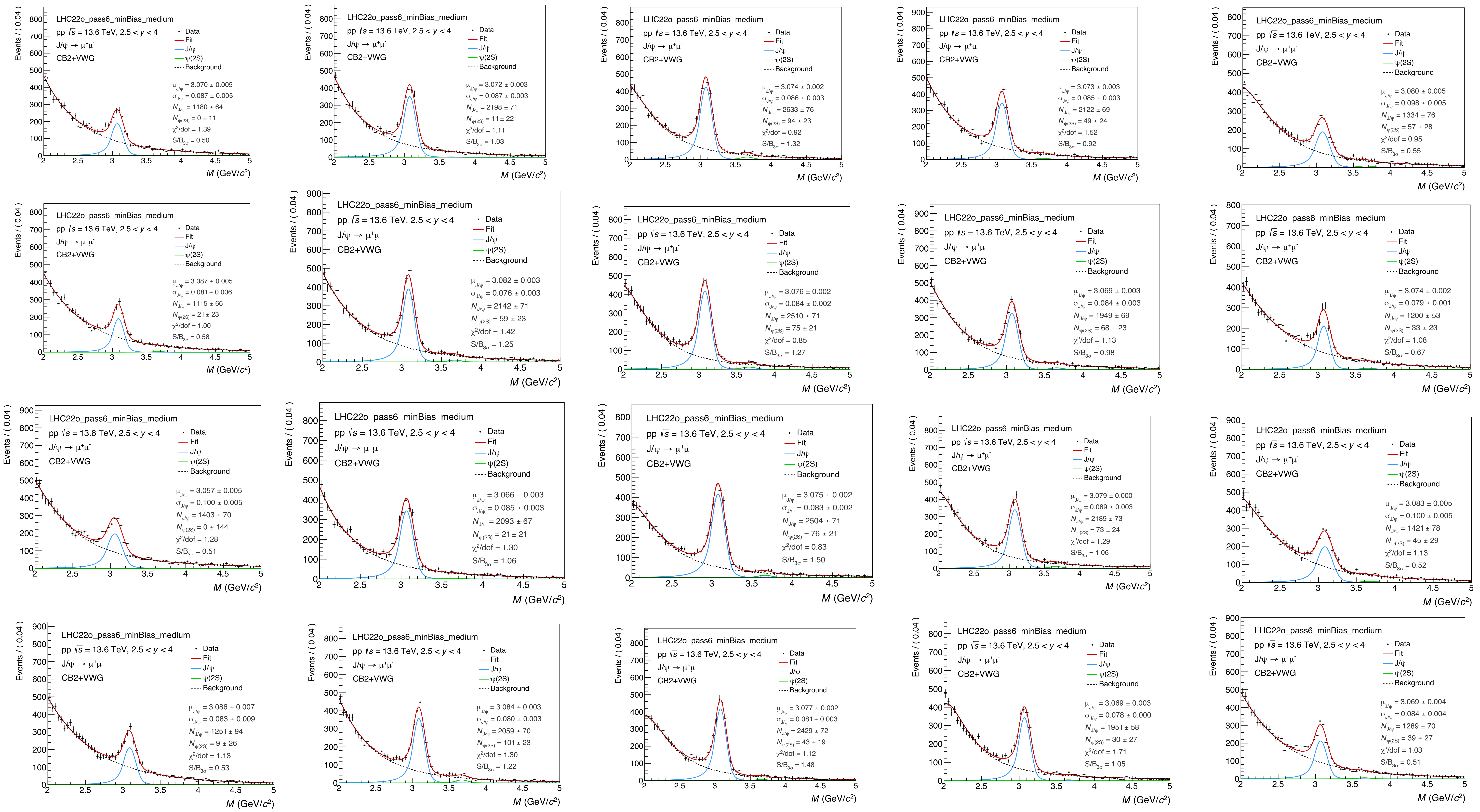
Signal Extraction: FT0C multiplicity and ϕ differential ($0 < Mult_{FT0C} < 100$)



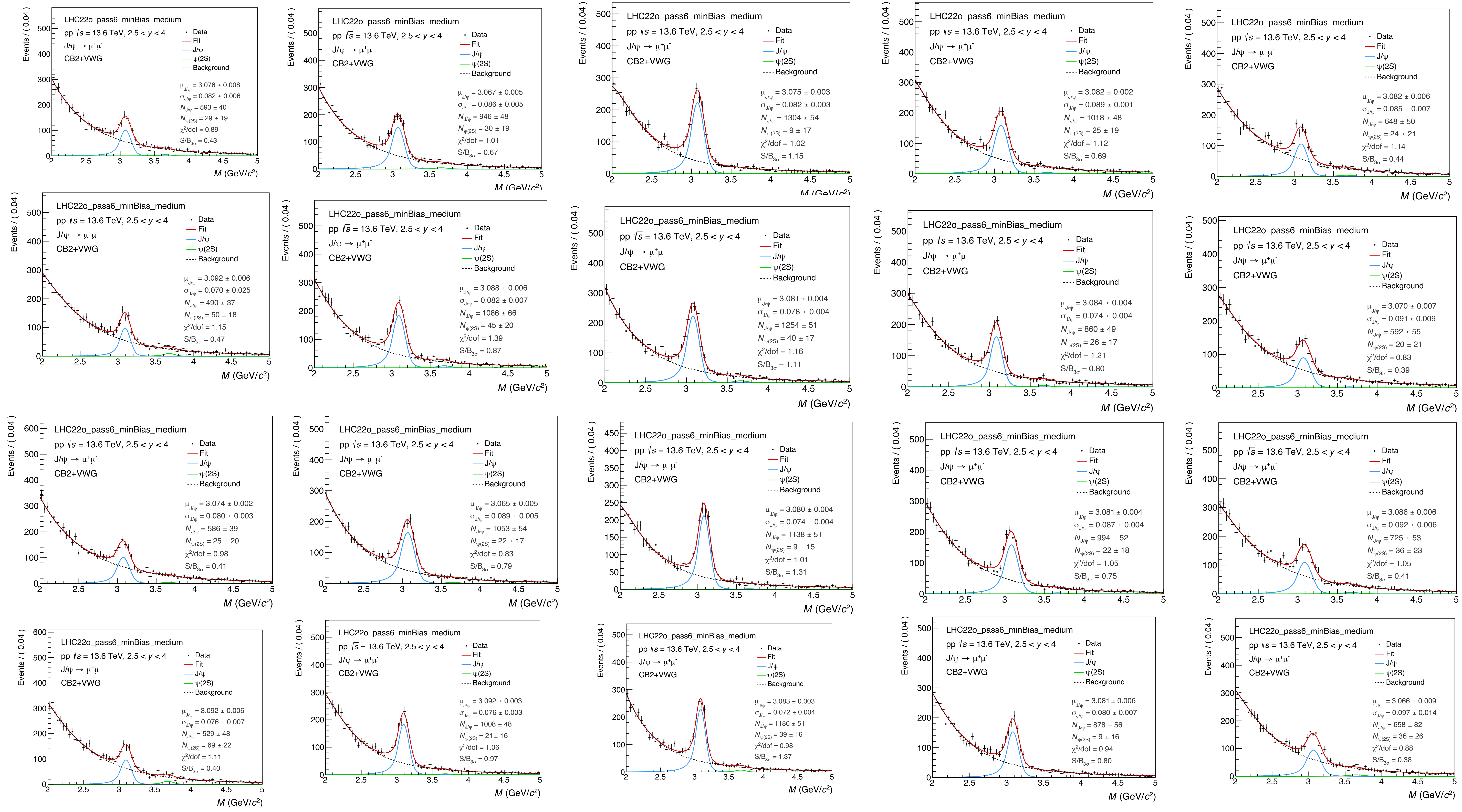
Signal Extraction: FT0C multiplicity and ϕ differential ($100 < \mathrm{Mult}_{\mathrm{FT0C}} < 300$)



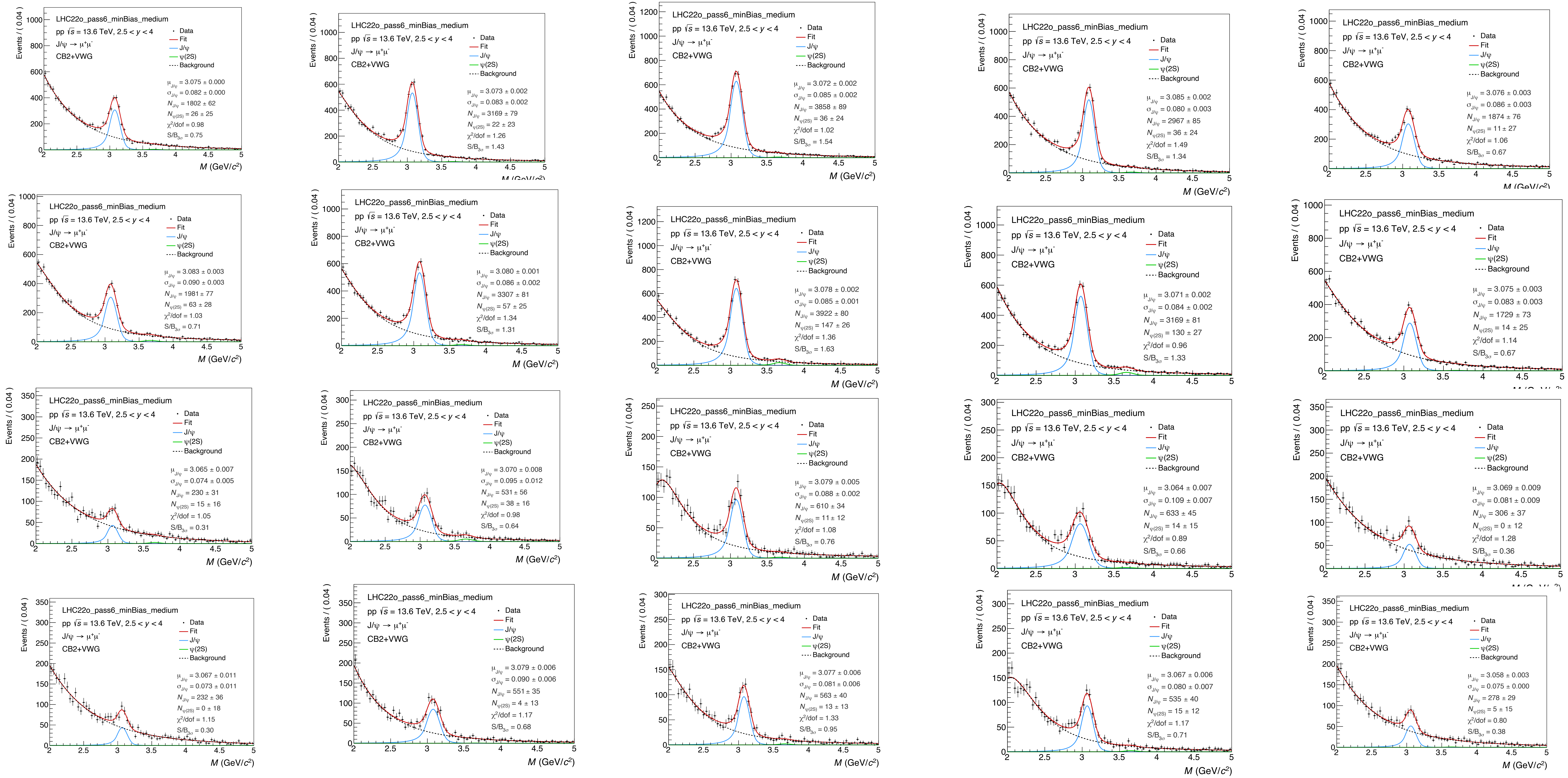
Signal Extraction: FT0C multiplicity and ϕ differential ($300 < Mult_{FT0C} < 500$)

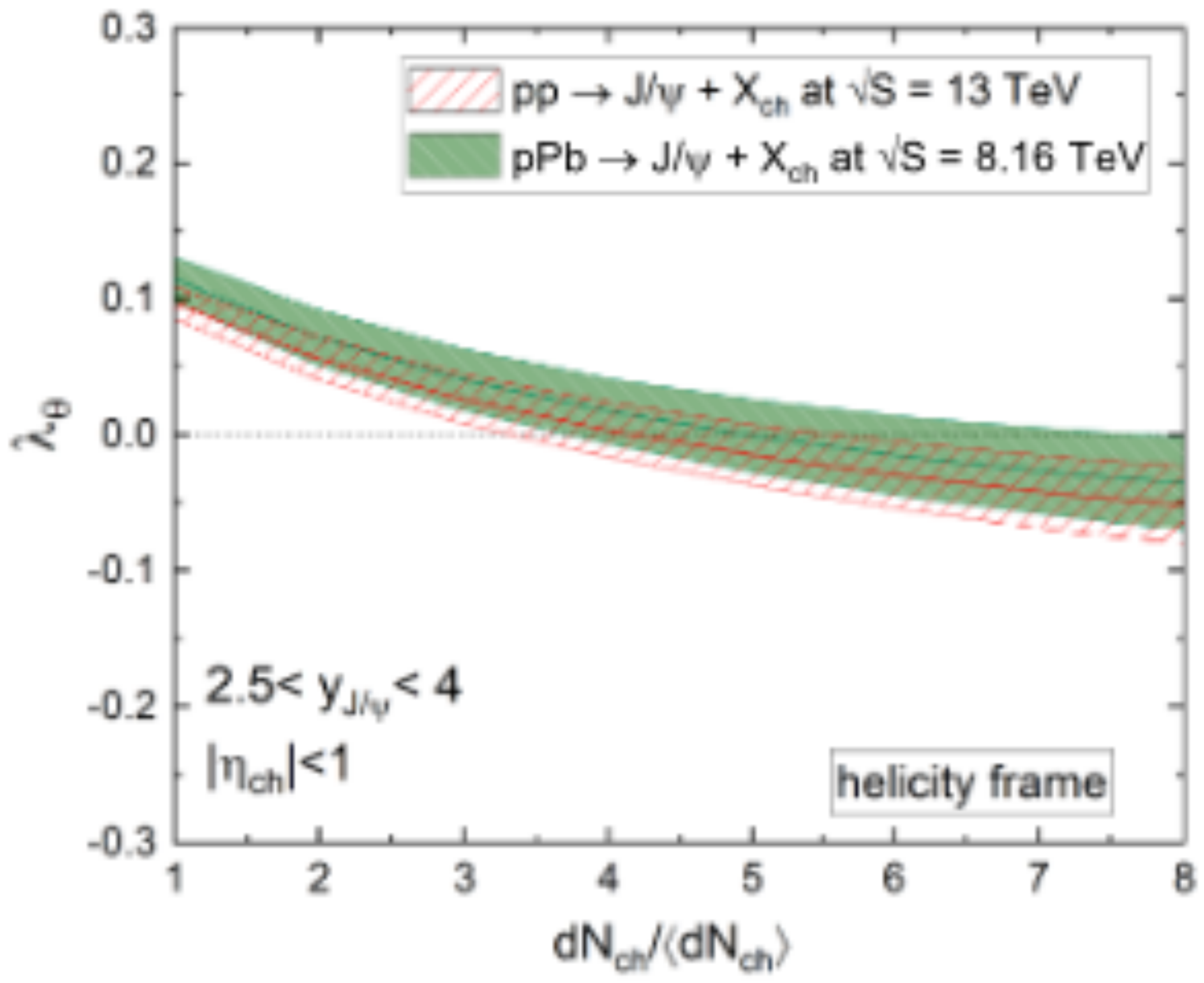


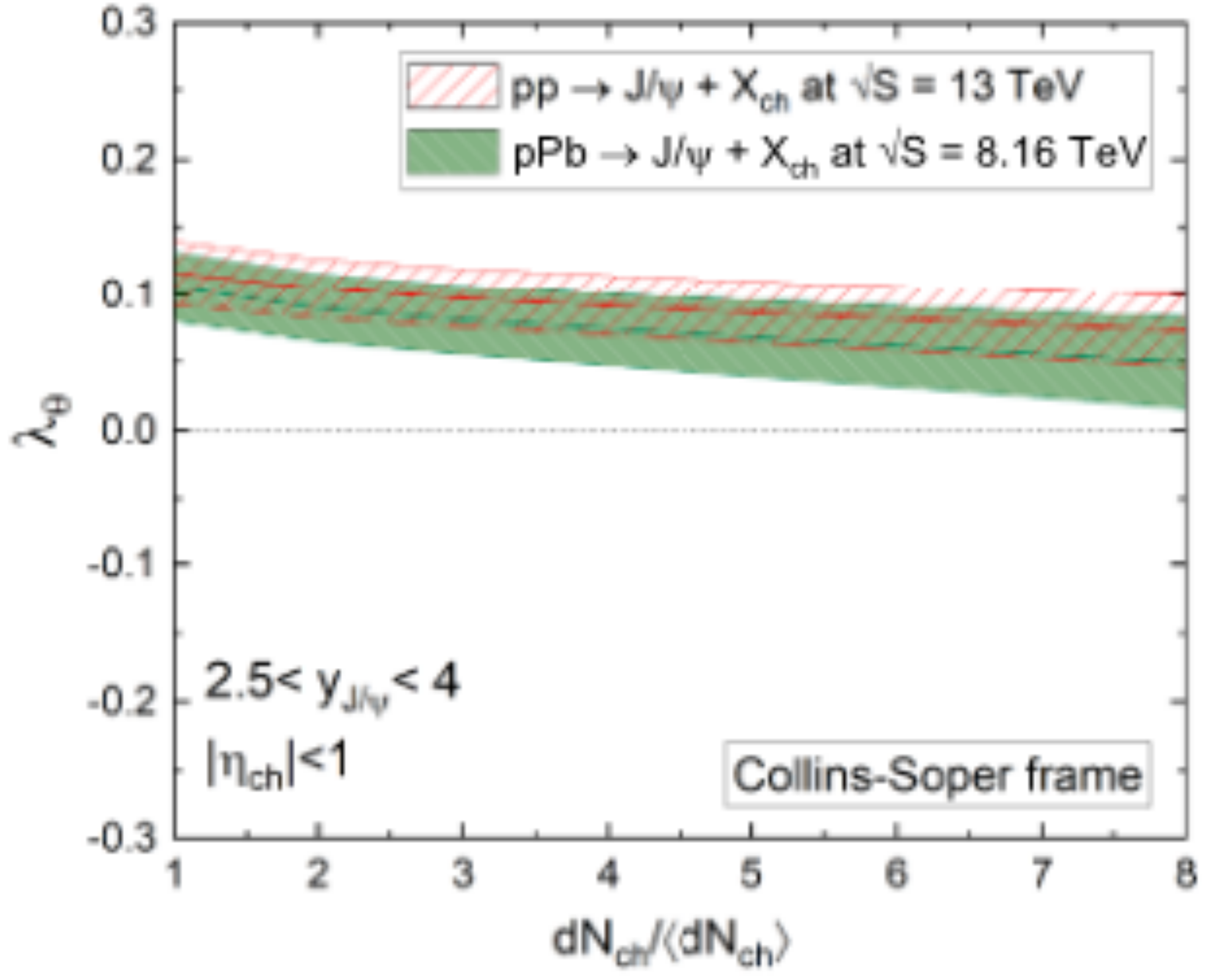
Signal Extraction: FT0C multiplicity and ϕ differential ($500 < \mathrm{Mult_{FT0C}} < 700$)



Signal Extraction: FT0C multiplicity and φ differential (700 < $Mult_{FT0C}$ < 2000)







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