

Feasibility Study of $Z_{cs}(3985)$ in $\bar{p}p$ with the PANDA Detector

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Outline

- Zcs(3985)
 - Event Generation
 - Reconstruction & Analysis
 - Background
- Summary

Intro

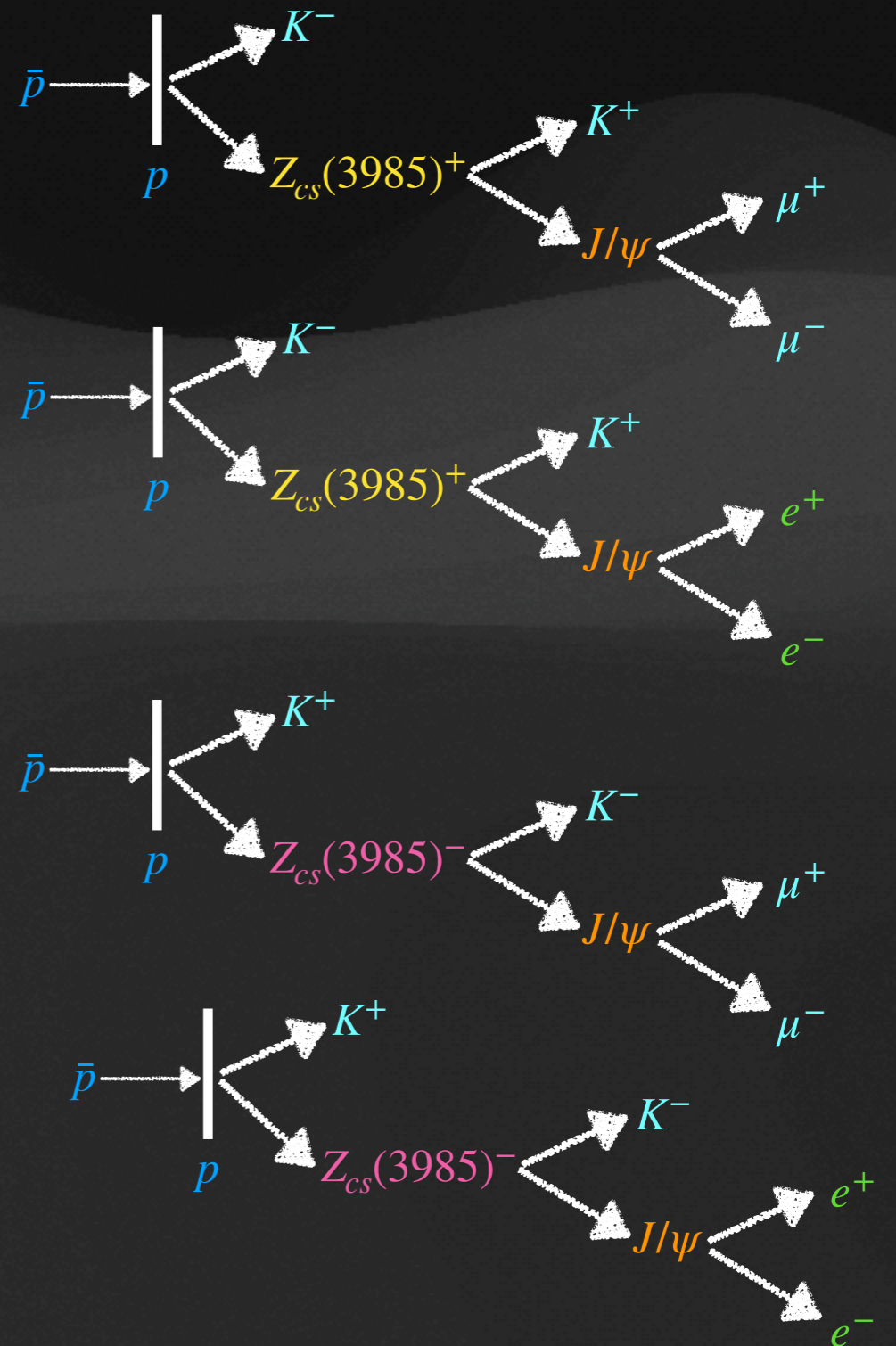
- The $Z_{cs}(3985)^-$ was observed in $\pi^- J/\psi$ invariant mass distribution in the study of $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ at BESIII and Belle experiments [M. Ablikim et al., C. Z. Yuan et al.].

[1] M. Ablikim et al. (BESIII Collaboration), *Phys. Rev. Lett.* 126, 102001 (2021)

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Event Generation

- 1.99 million events at each
- $P_{\bar{p}} = 15 \text{ GeV}/c$ (at max of PANDA)
- assuming the branching ratio of 100% for $Z_{cs}(3985) \rightarrow K + J/\psi$
- Mass of $Z_{cs}(3985)^\pm$: $m_{Z_{cs}(3985)} = 3982.5 \pm 2.3 \text{ [Mev}/c^2]$
- Width: $\Gamma = 12.8 \pm 3.0 \text{ [Mev}/c^2]$



Reconstruction

Production and Reco:

- Simulation of transport through the detector
 - **Production & Reco:** Using PandaRoot dev: / FairSoft jun19p2 / FairRoot v18.2.1
 - **Analysis:** Using PandaRoot dev: / FairSoft apr22 / FairRoot v18.6.8
- Transport and reconstruction of particles is done with the PandaRoot framework
- Follow the decay tree
- Best PID algorithm is used (MuonBestPlus for μ^+ ,...)

Analysis

Reconst. Final States efficiencies

- Used decay pattern recognition and “best” particle identification (PID)
- Reconstructed FS: μ^+ , μ^- , K^+ , K^-
- Reconstruction efficiency for final state particles:

Parçacık türü ε [%]

μ^+ 99.84

μ^- 94.12

K^+ 77.2

K^- 79.39

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

Parçacık türü ε [%]

e^+ 90.8

e^- 82.36

K^+ 76.95

K^- 79.16

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow e^+ e^-)$

Parçacık türü ε [%]

μ^+ 94.91

μ^- 94.15

K^+ 80.86

K^- 75.61

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

Parçacık türü ε [%]

e^+ 82.74

e^- 82.43

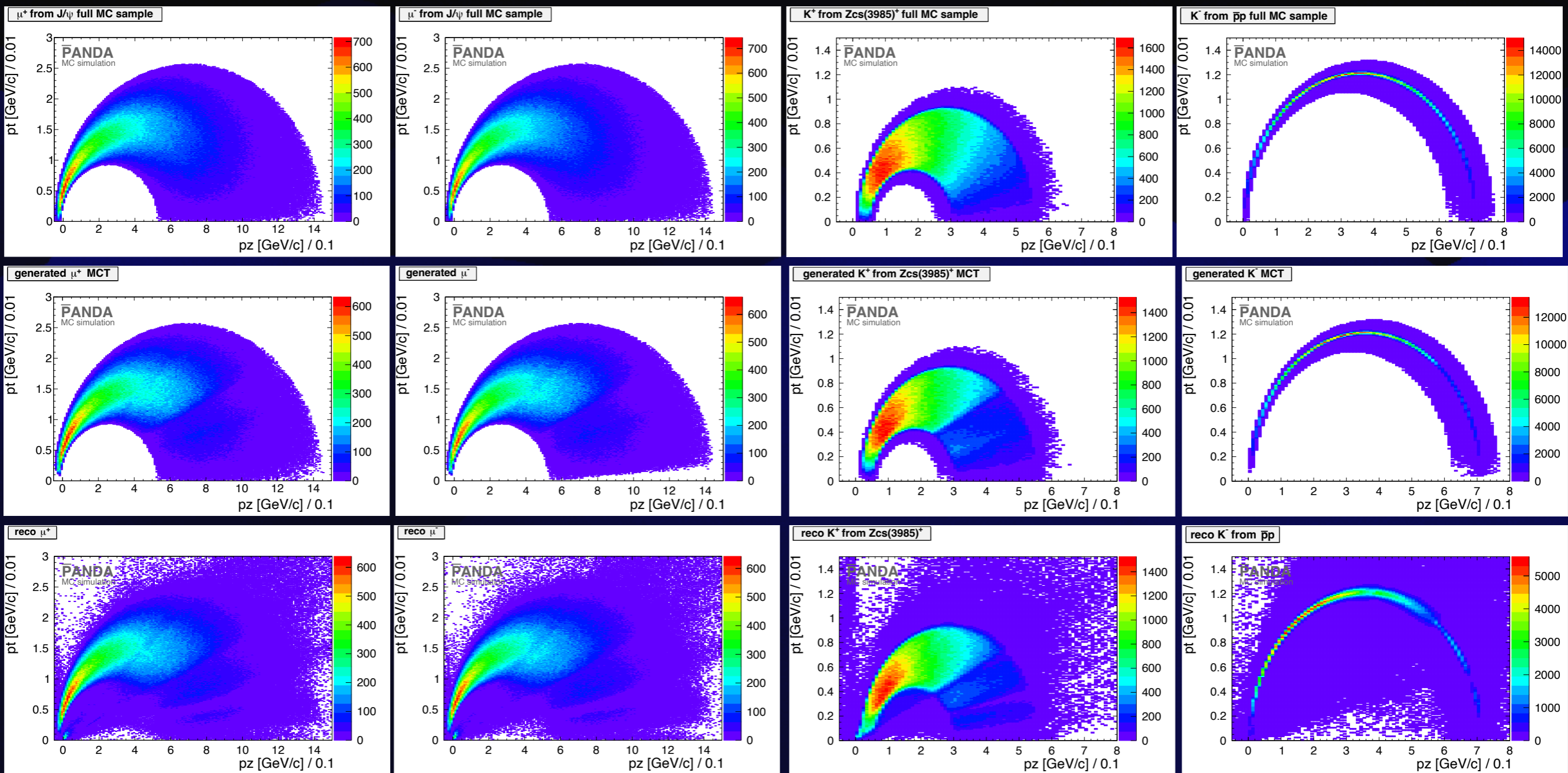
K^+ 80.78

K^- 75.4

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow e^+ e^-)$

Analysis

Reconstruction of FS: transverse vs. longitudinal Momentum Distributions

 μ^+ μ^- K^+ K^- 

Analysis

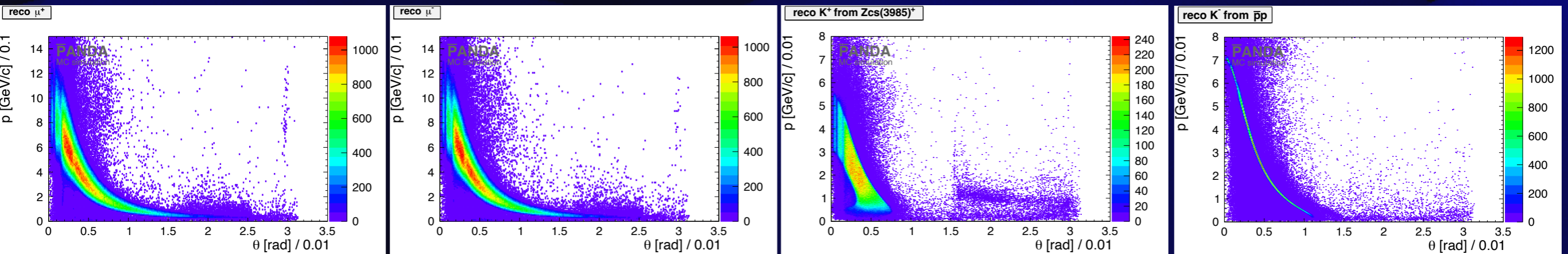
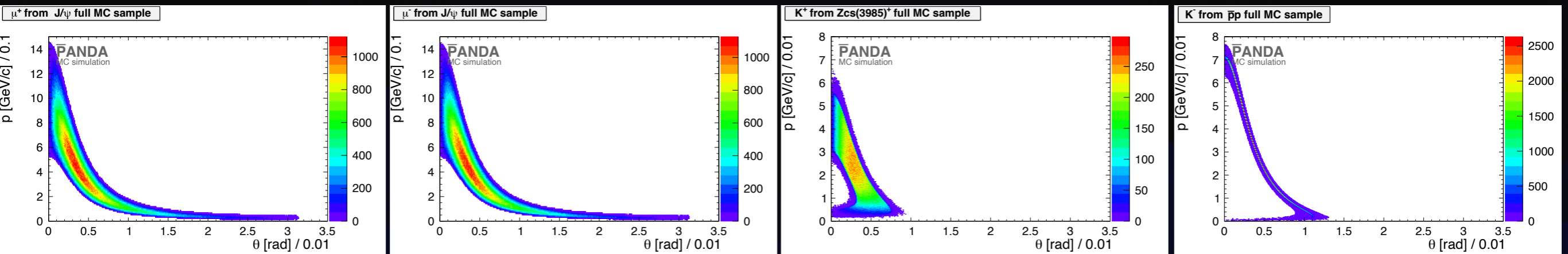
Reconstruction of FS: total momentum vs. Θ angle Distributions

μ^+

μ^-

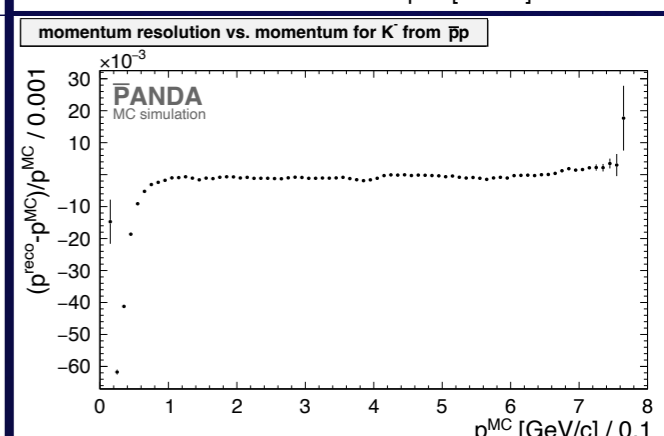
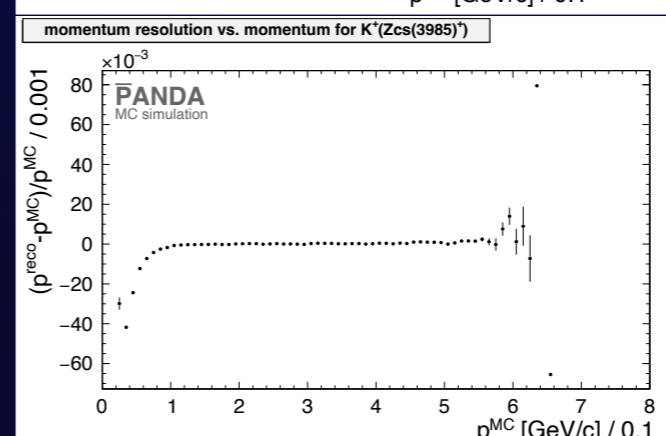
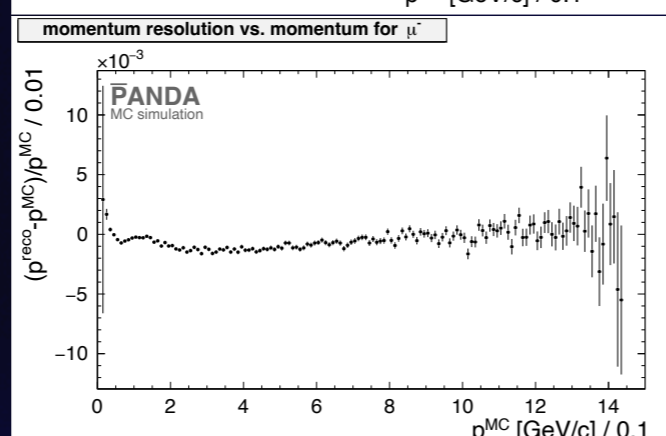
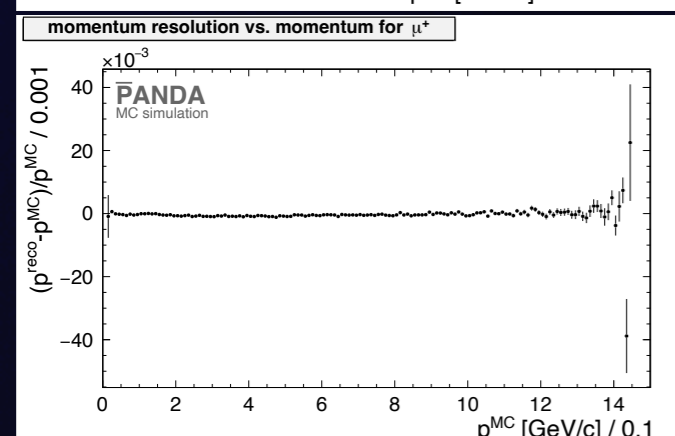
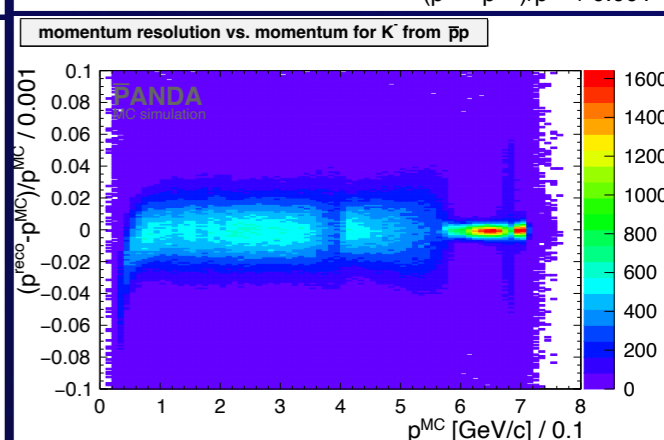
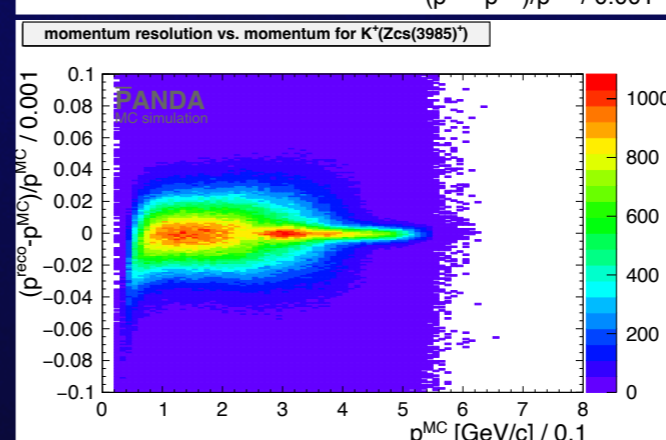
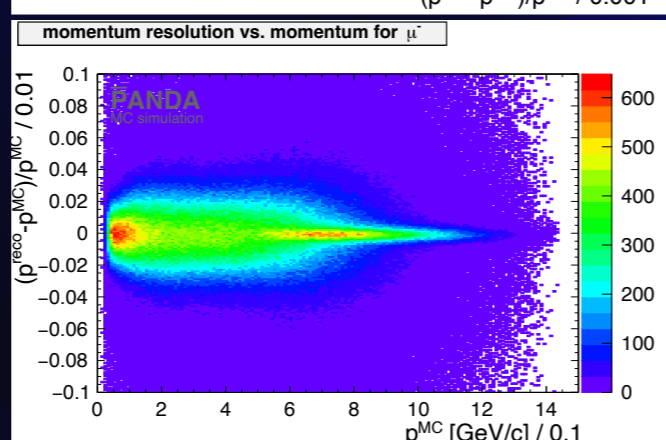
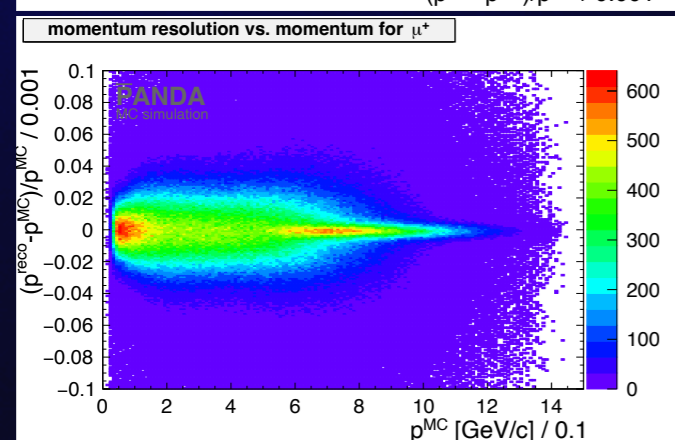
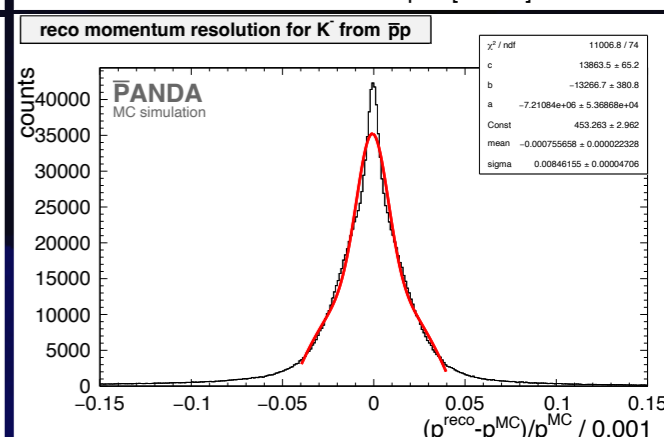
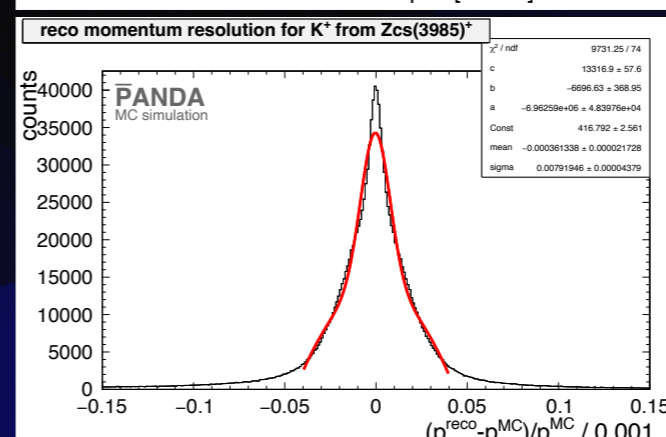
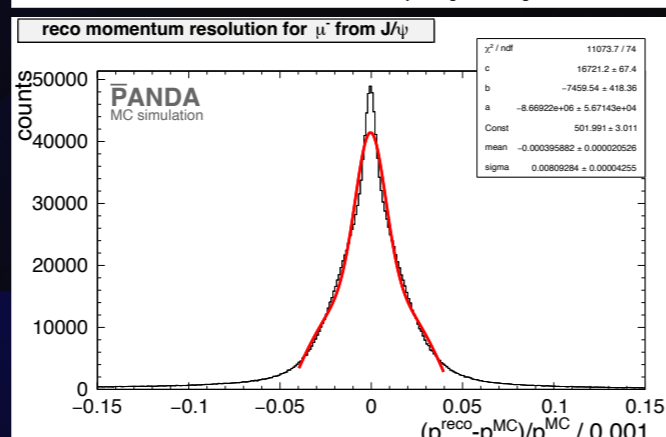
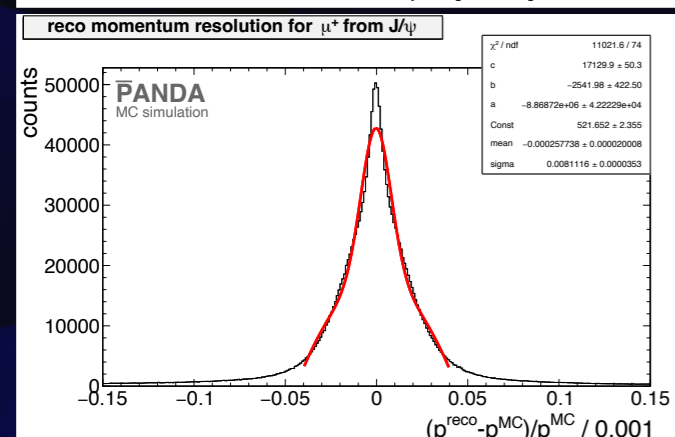
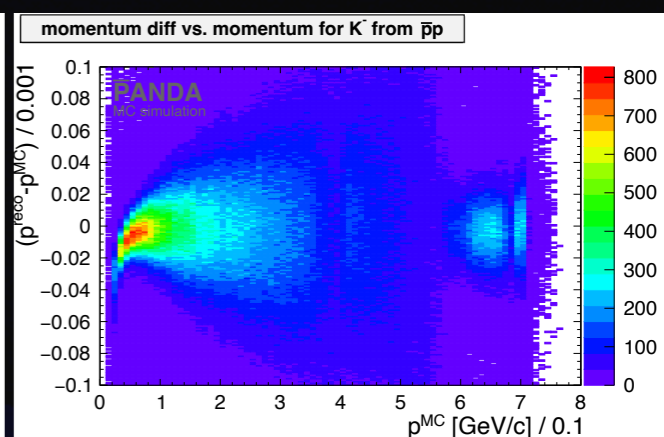
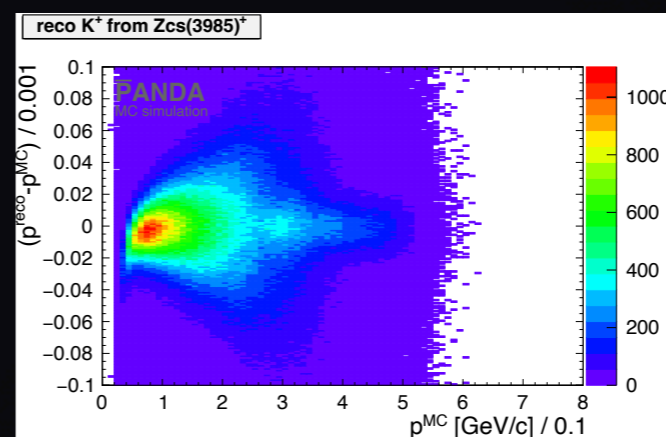
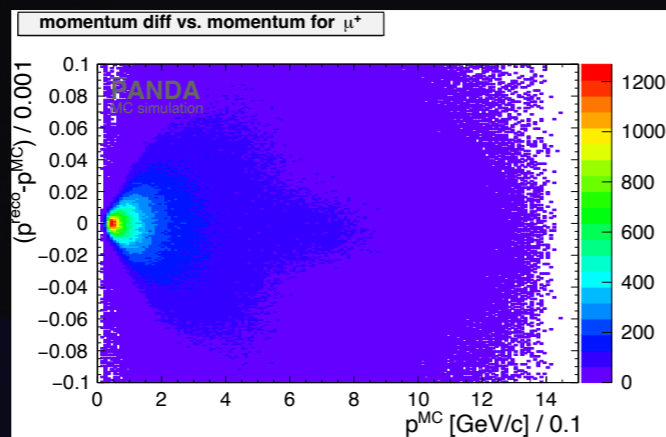
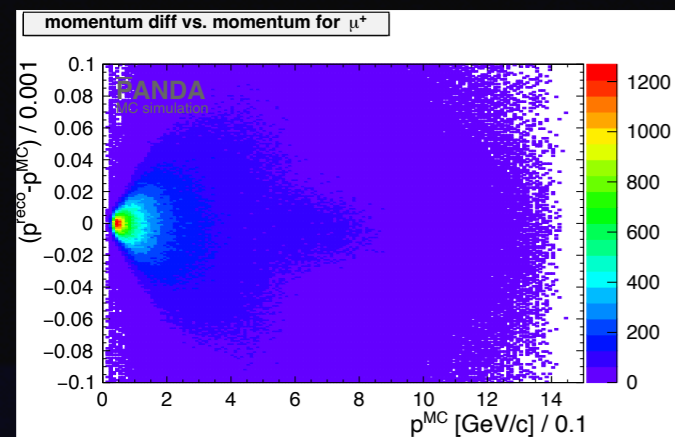
K^+

K^-



Analysis

Reconstruction of FS: Momentum Resolution

 μ^+ μ^- K^+ K^- 

Analysis

Reconstructed FS: μ^- , μ^+ , π^- , π^+

- Momentum Resolutions

| Parçacık türü | dp/p [%] |
|---------------|----------|
| μ^+ | 0.8109 |
| μ^- | 0.8095 |
| K^+ | 0.7916 |
| K^- | 0.8464 |

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

| Parçacık türü | dp/p [%] |
|---------------|----------|
| e^+ | 0.6003 |
| e^- | 0.482 |
| K^+ | 0.4194 |
| K^- | 0.3626 |

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow e^+ e^-)$

| Parçacık türü | dp/p [%] |
|---------------|----------|
| μ^+ | 0.8257 |
| μ^- | 0.7994 |
| K^+ | 0.8447 |
| K^- | 0.783 |

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

| Parçacık türü | dp/p [%] |
|---------------|----------|
| e^+ | 1.209 |
| e^- | 1.223 |
| K^+ | 0.8424 |
| K^- | 0.7857 |

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow e^+ e^-)$

Analysis

Reconstruction of Resonance State : J/ψ

- Invariant mass cut on $\mu^+\mu^-$ (e^+e^-) to select J/ψ cands $m_{J/\psi}$:
(3.0969 \pm 1.55) GeV/c²
- Perform RhoDecayTreeFitter fit
- Select candidate with DecayTree fit prob > 0.01

Analysis

Resonance States: J/ψ

- Reconstructed: efficiency

Parçacık türü ϵ [%]

J/ψ 67.37

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

Parçacık türü ϵ [%]

J/ψ 67.24

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

Parçacık türü ϵ [%]

J/ψ 27.97

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow e^+ e^-)$

Parçacık türü ϵ [%]

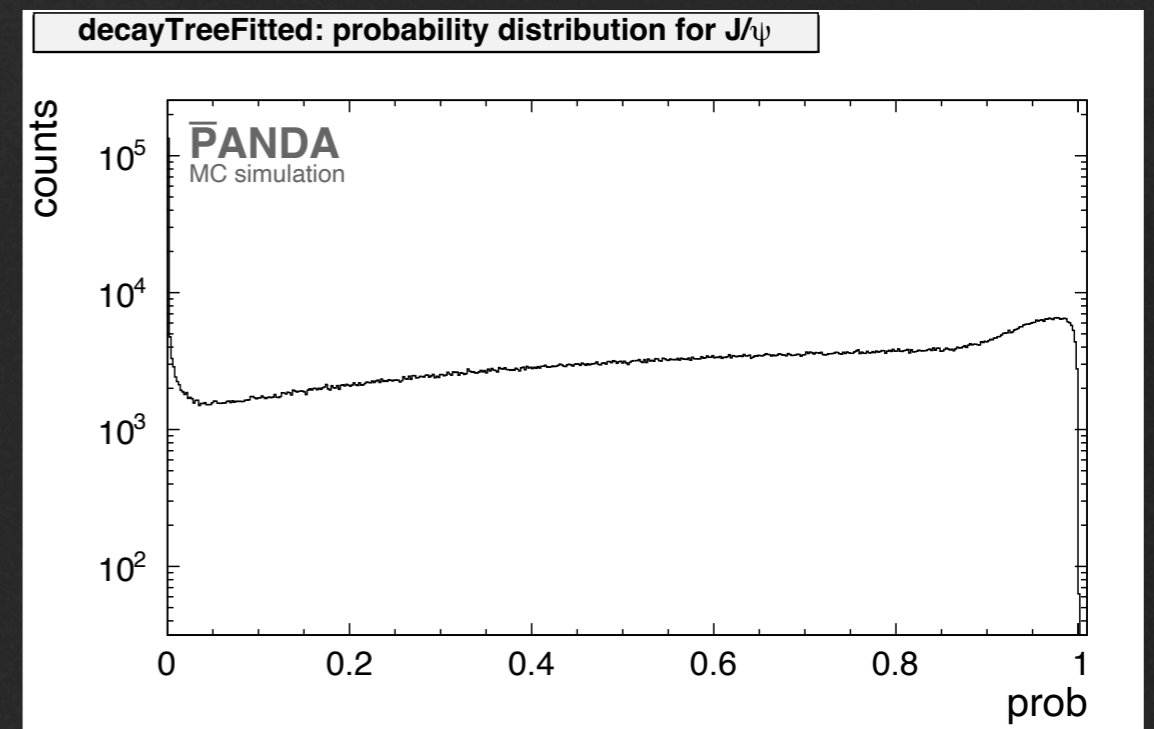
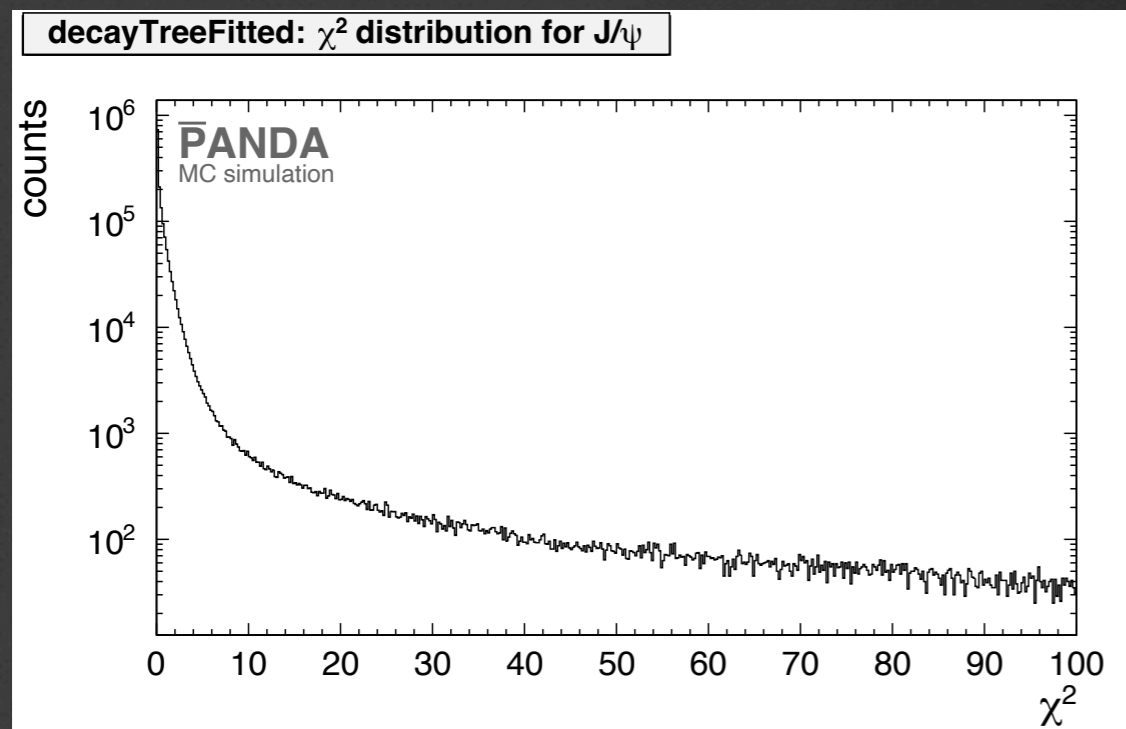
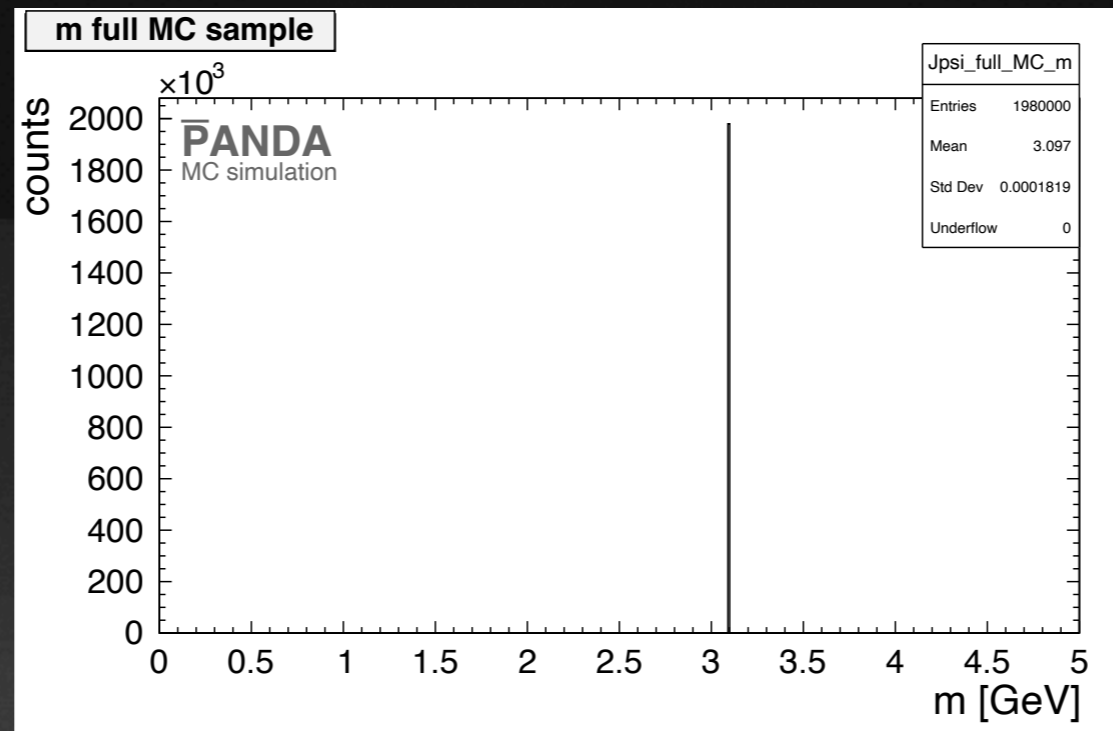
J/ψ 27.94

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow e^+ e^-)$

Analysis

Resonance States: J/ψ

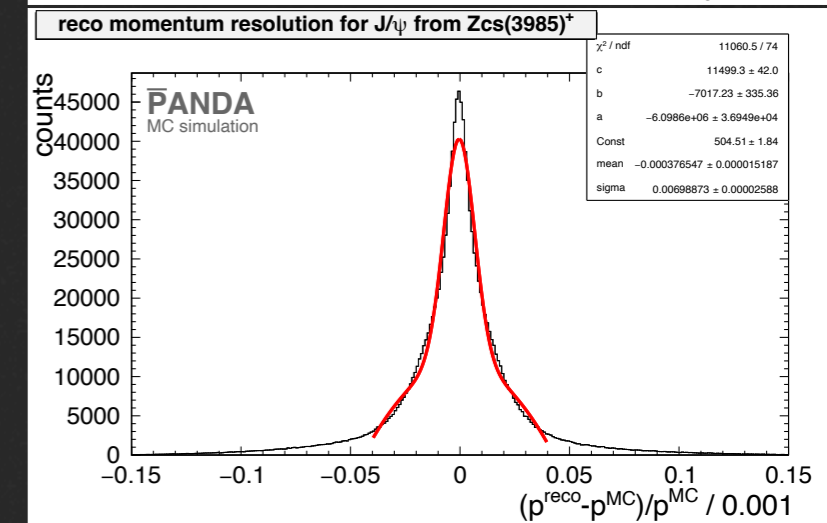
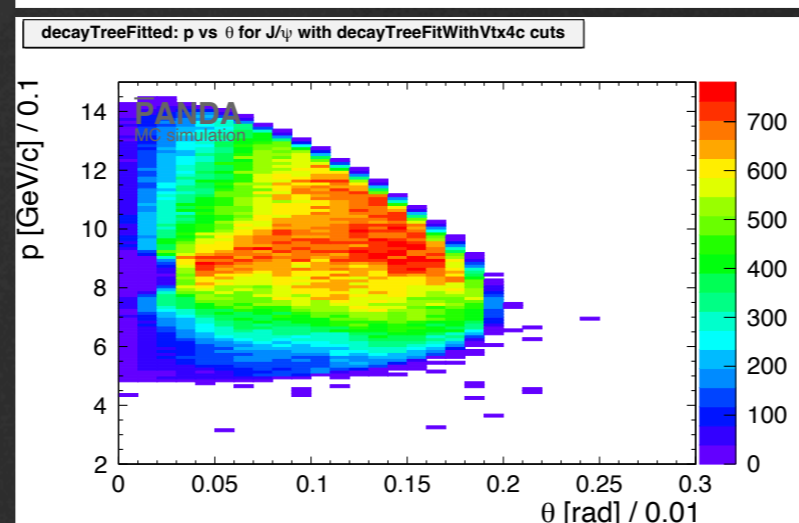
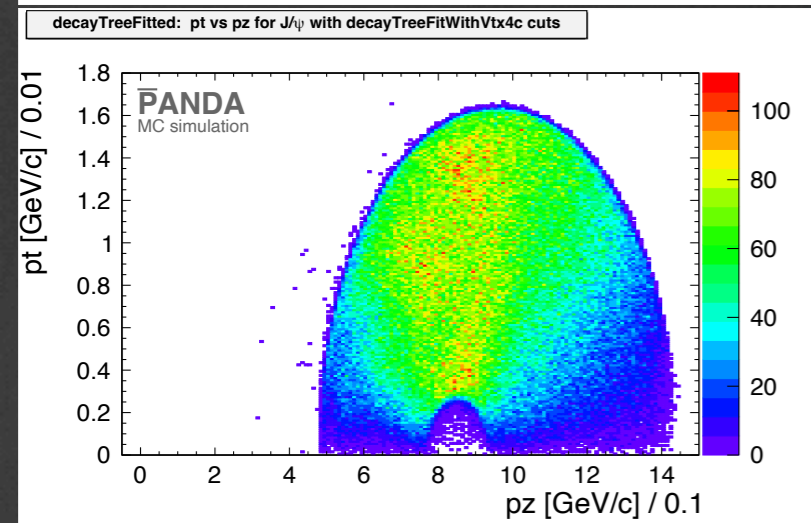
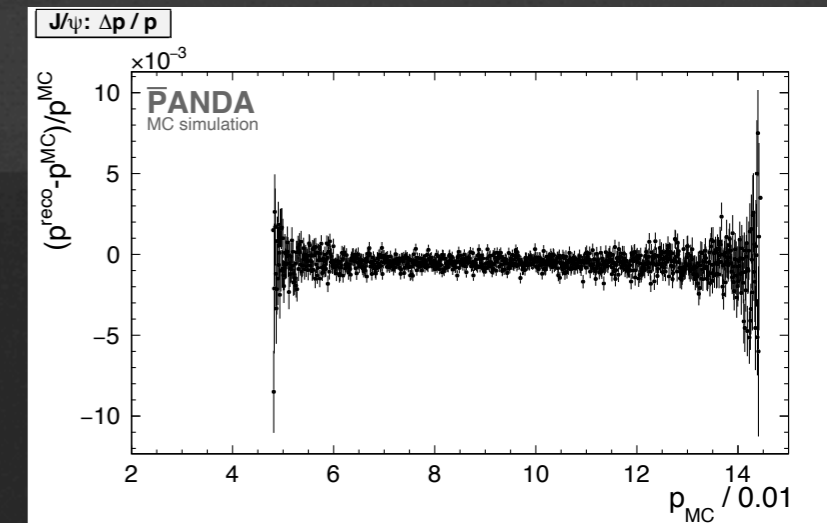
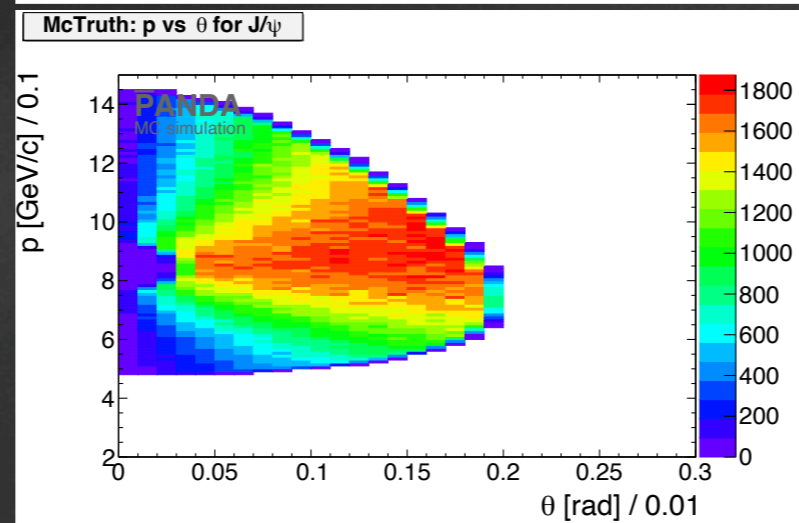
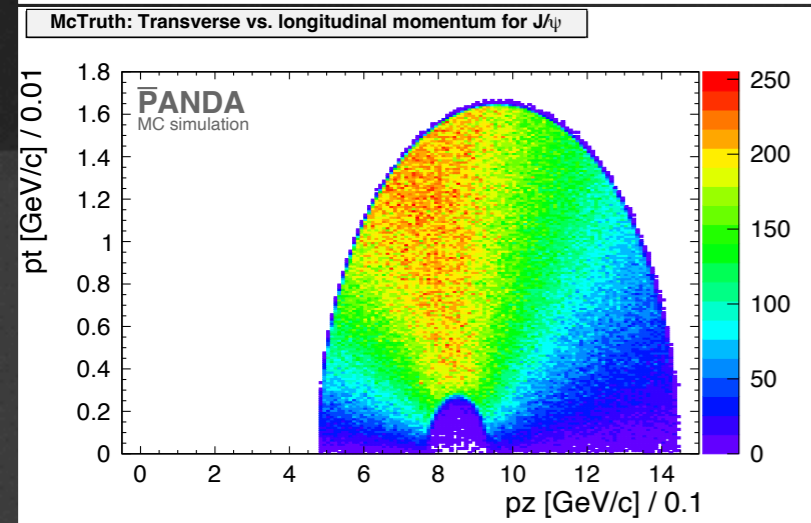
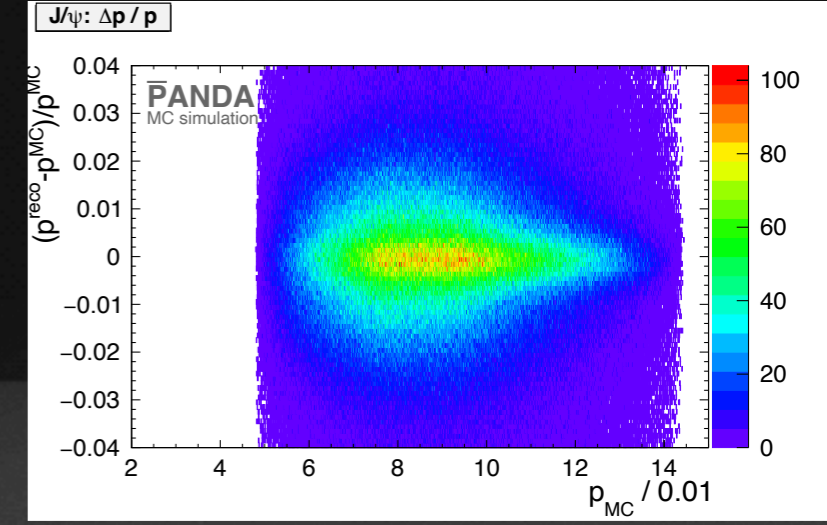
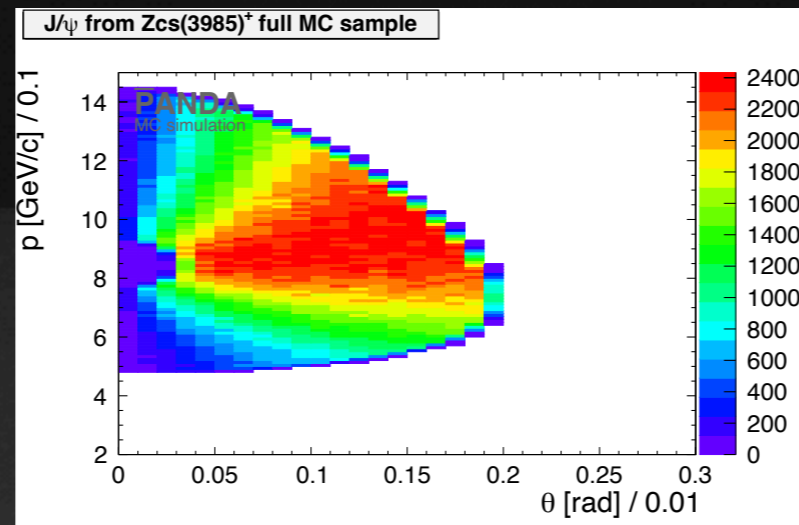
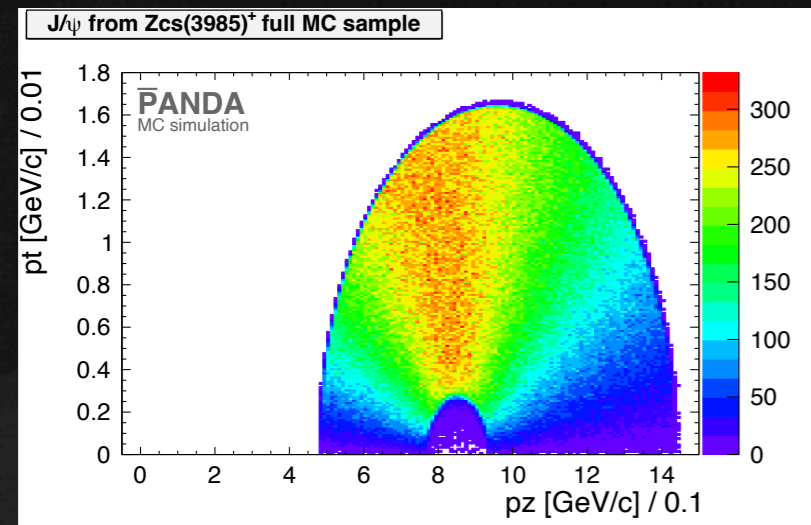
- Reconstructed: m, chi2, prob



Analysis

Resonance States: Momentum Distributions

- Reconstructed: J/ψ



Analysis

Reconst. Resonance States: J/ψ

- Reconstructed: Momentum Resolution

Parçacık türü dp/p [%]

J/ψ 0.6985

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

Parçacık türü dp/p [%]

J/ψ 0.6956

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

Parçacık türü dp/p [%]

J/ψ 1.145

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow e^+ e^-)$

Parçacık türü dp/p [%]

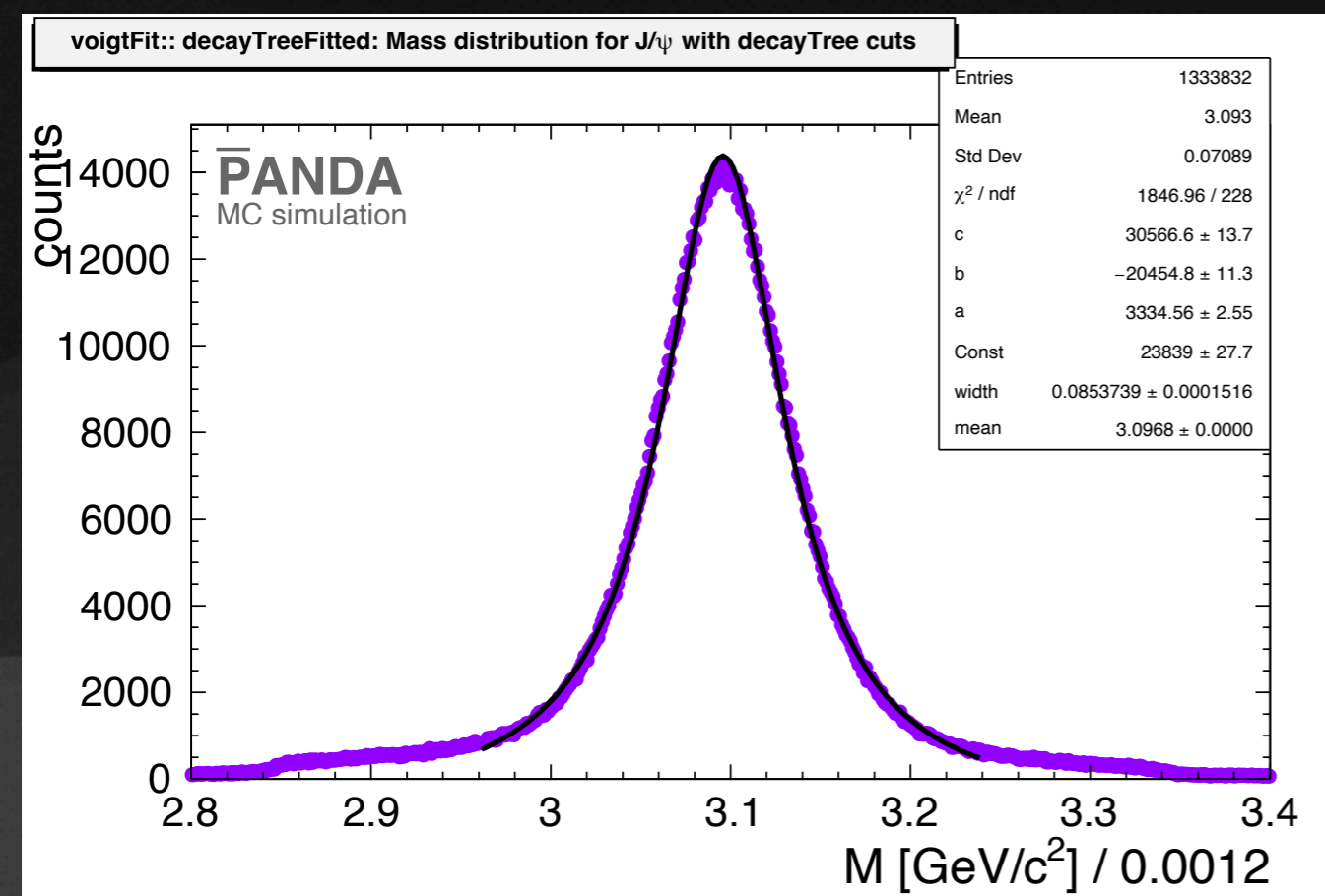
J/ψ 1.126

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow e^+ e^-)$

Analysis

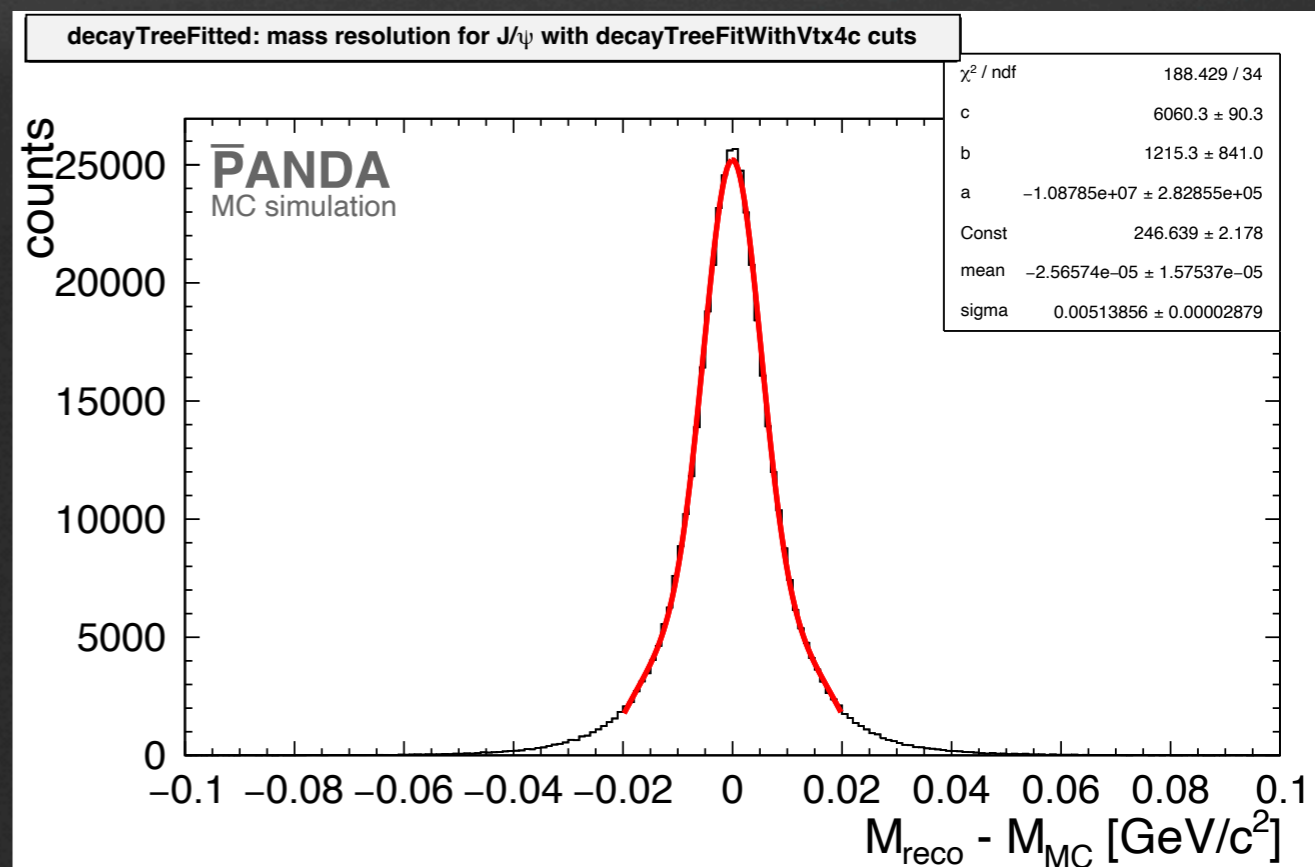
Reconst. Resonance States: J/ψ

- Reconstructed: m , $m\text{Diff}$



$$M_{J/\psi}^{\text{evt.pdl}} : 3.09690 \text{ GeV}/c^2$$

$$M_{J/\psi}^{\text{reco}} : 3.0968 \text{ GeV}/c^2$$



Analysis

Reconst. Resonance States : $Z_{cs}(3985)$

- Combine J/ψ and π
- Mass cut with window $m_{Z_{cs}(3985)} : [3.8872 \pm 1.94] \text{ GeV}/c^2$
- Perform RhoDecayTreeFitter fit
- Select candidate with DecayTree fit prob > 0.01

Analysis

Reconst. Resonance States: $Z_{cs}(3985)$

- Reconstructed: efficiency

Parçacık türü ϵ [%]

$Z_{cs}(3985)$ 45.44

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

Parçacık türü ϵ [%]

$Z_{cs}(3985)$ 44.31

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

Parçacık türü ϵ [%]

$Z_{cs}(3985)$ 18.31

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow e^+ e^-)$

Parçacık türü ϵ [%]

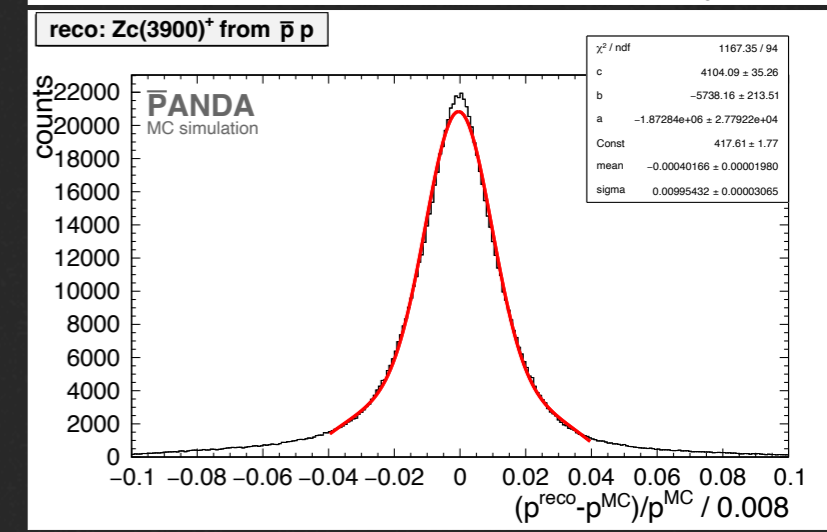
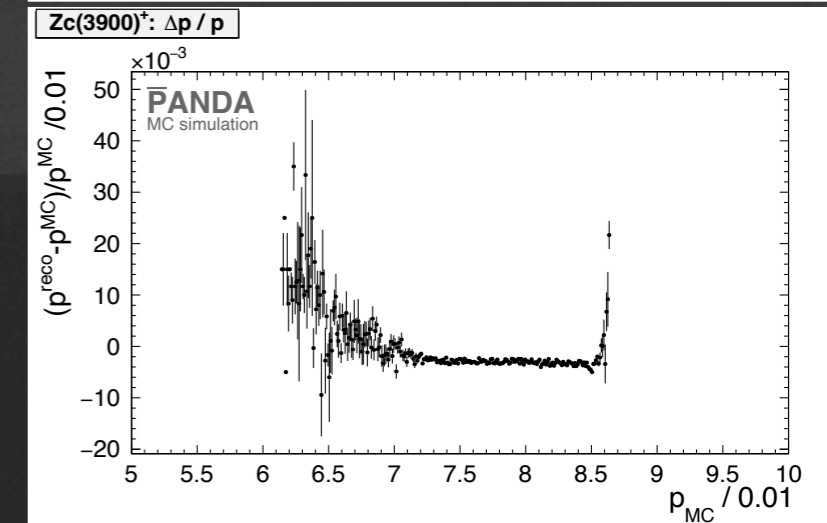
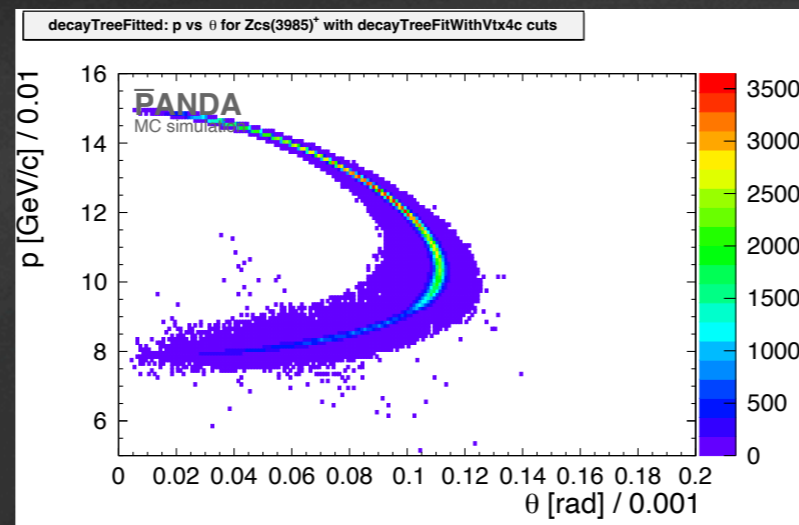
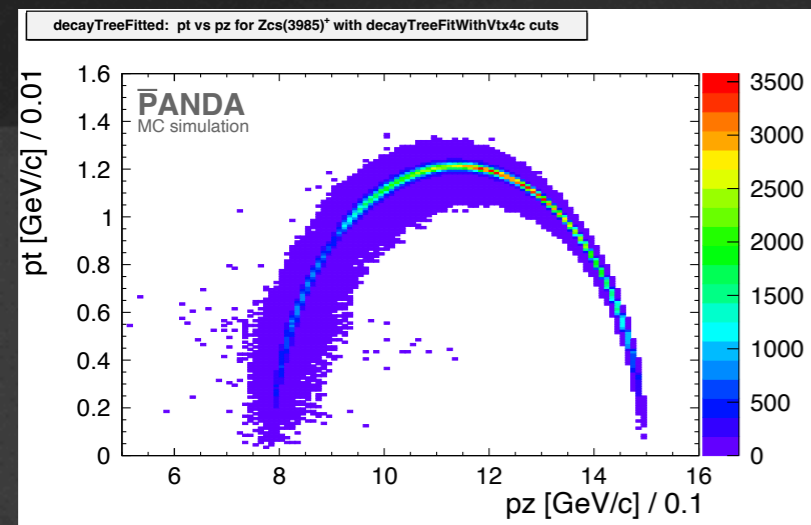
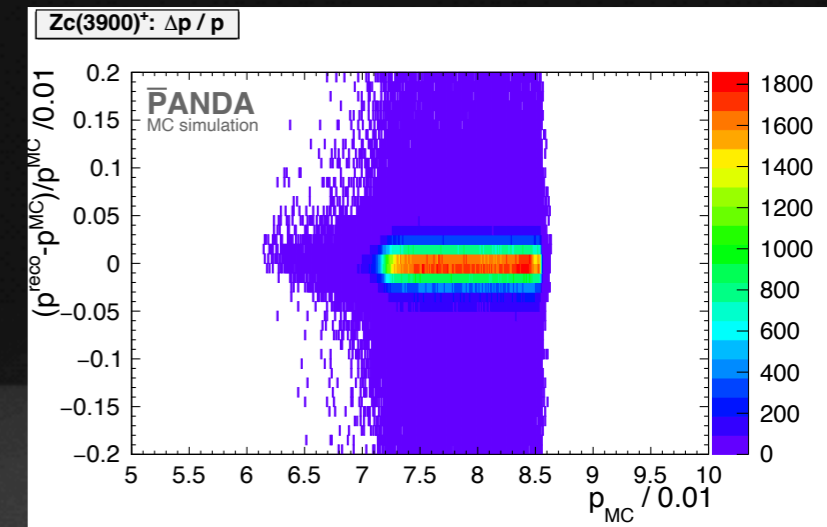
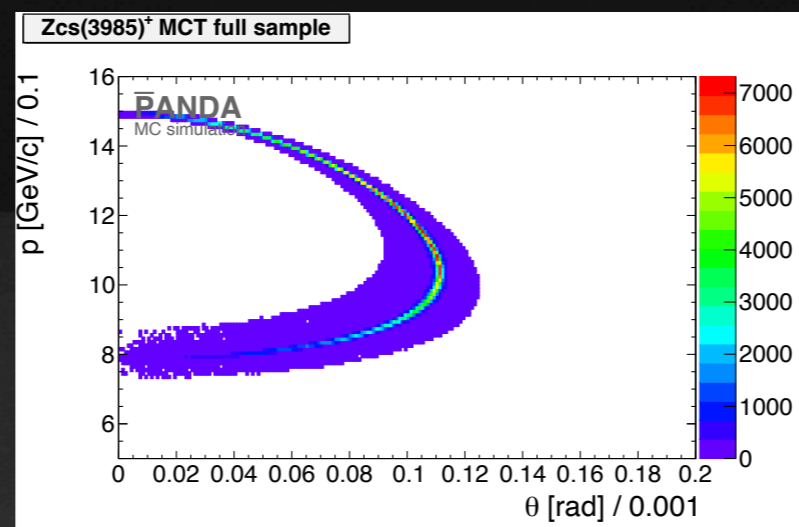
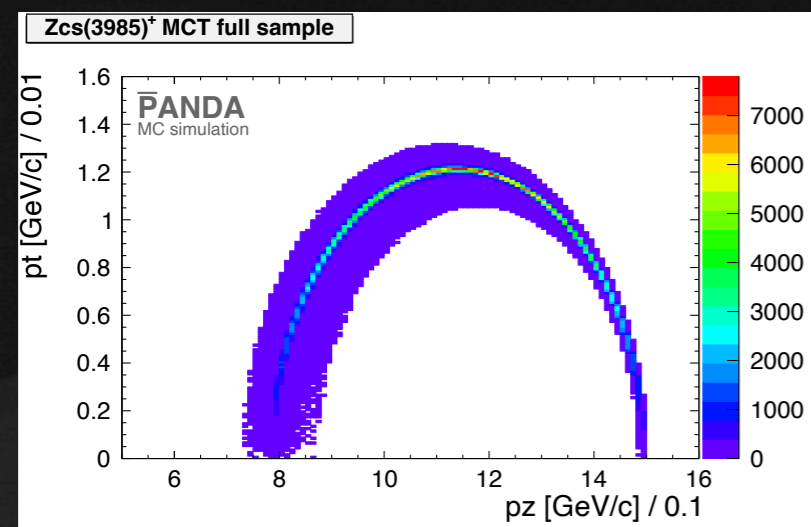
$Z_{cs}(3985)$ 17.88

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow e^+ e^-)$

Analysis

Reconst. Resonance States: $Z_{cs}(3985)$

- Reconstructed: momentum distributions



Analysis

Reconst. Resonance States: $Z_{cs}(3985)$

- Reconstructed: momentum resolutions

| Parçacık türü | dp/p [%] |
|---------------|----------|
|---------------|----------|

| | |
|----------------|--------|
| $Z_{cs}(3985)$ | 0.7922 |
|----------------|--------|

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

| Parçacık türü | dp/p [%] |
|---------------|----------|
|---------------|----------|

| | |
|----------------|--------|
| $Z_{cs}(3985)$ | 0.7892 |
|----------------|--------|

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow \mu^+ \mu^-)$

| Parçacık türü | dp/p [%] |
|---------------|----------|
|---------------|----------|

| | |
|----------------|-------|
| $Z_{cs}(3985)$ | 1.174 |
|----------------|-------|

$\bar{p}p \rightarrow K^- Z_{cs}(3985)^+, (Z_{cs}(3985)^+ \rightarrow K^+ J/\psi), (J/\psi \rightarrow e^+ e^-)$

| Parçacık türü | dp/p [%] |
|---------------|----------|
|---------------|----------|

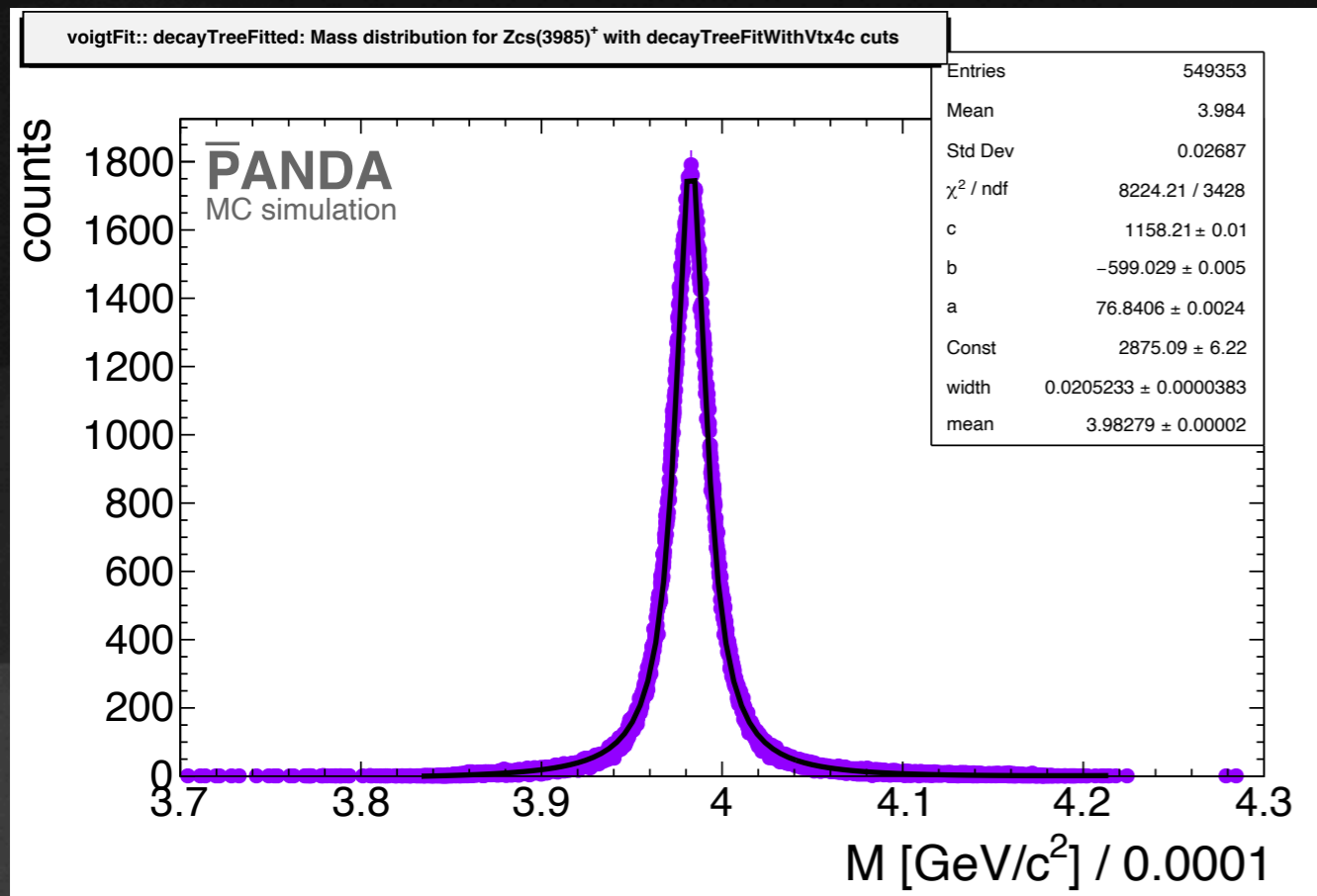
| | |
|----------------|-------|
| $Z_{cs}(3985)$ | 1.177 |
|----------------|-------|

$\bar{p}p \rightarrow K^+ Z_{cs}(3985)^-, (Z_{cs}(3985)^- \rightarrow K^- J/\psi), (J/\psi \rightarrow e^+ e^-)$

Analysis

Reconst. Resonance States: $Z_{cs}(3985)$

- Reconstructed: m , $m\text{Diff}$

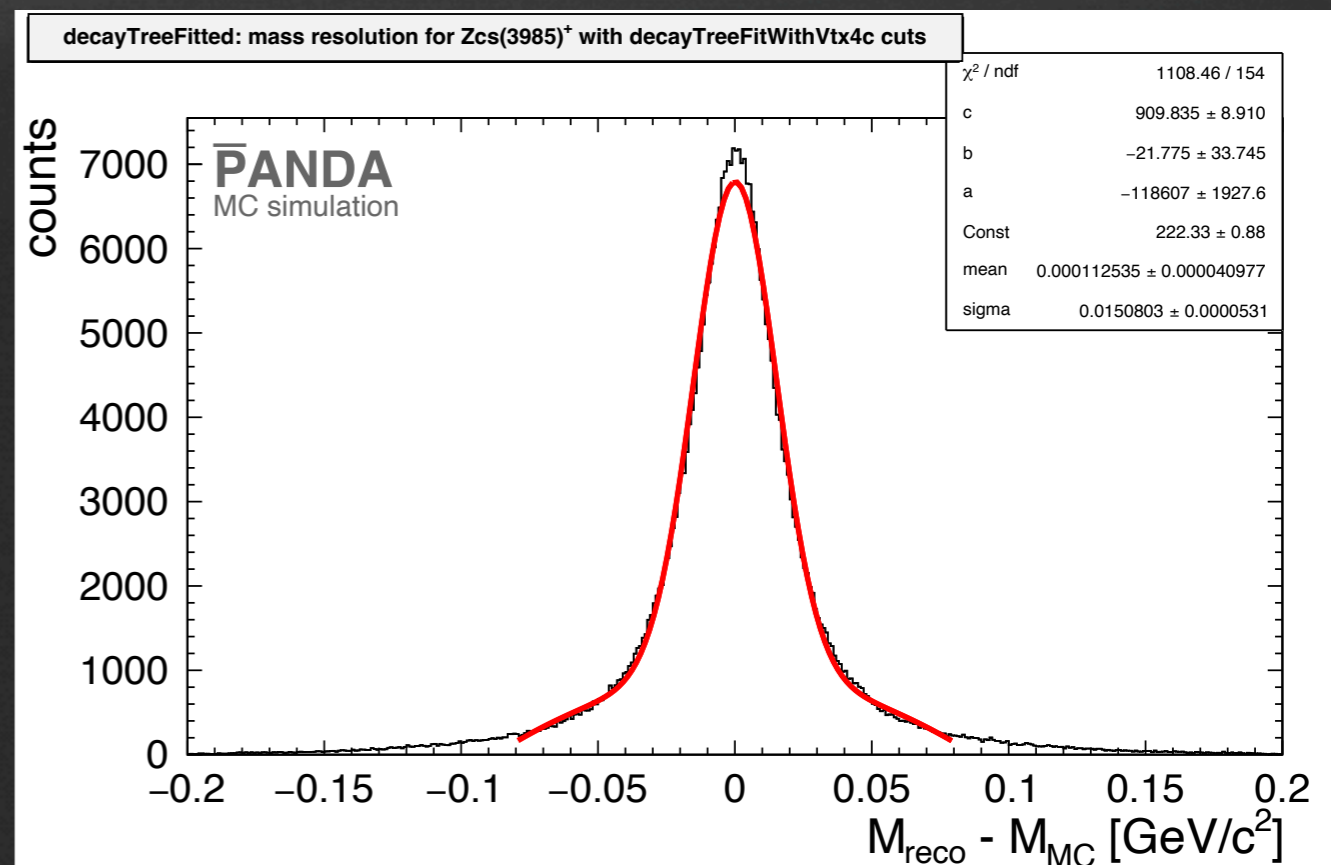


$$M_{Z_{cs}(3985)_{evt.pdl}} : [3.9825] \text{ GeV}/c^2$$

$$\Gamma_{Z_{cs}(3985)_{evt.pdl}} : [0.0128] \text{ GeV}/c^2$$

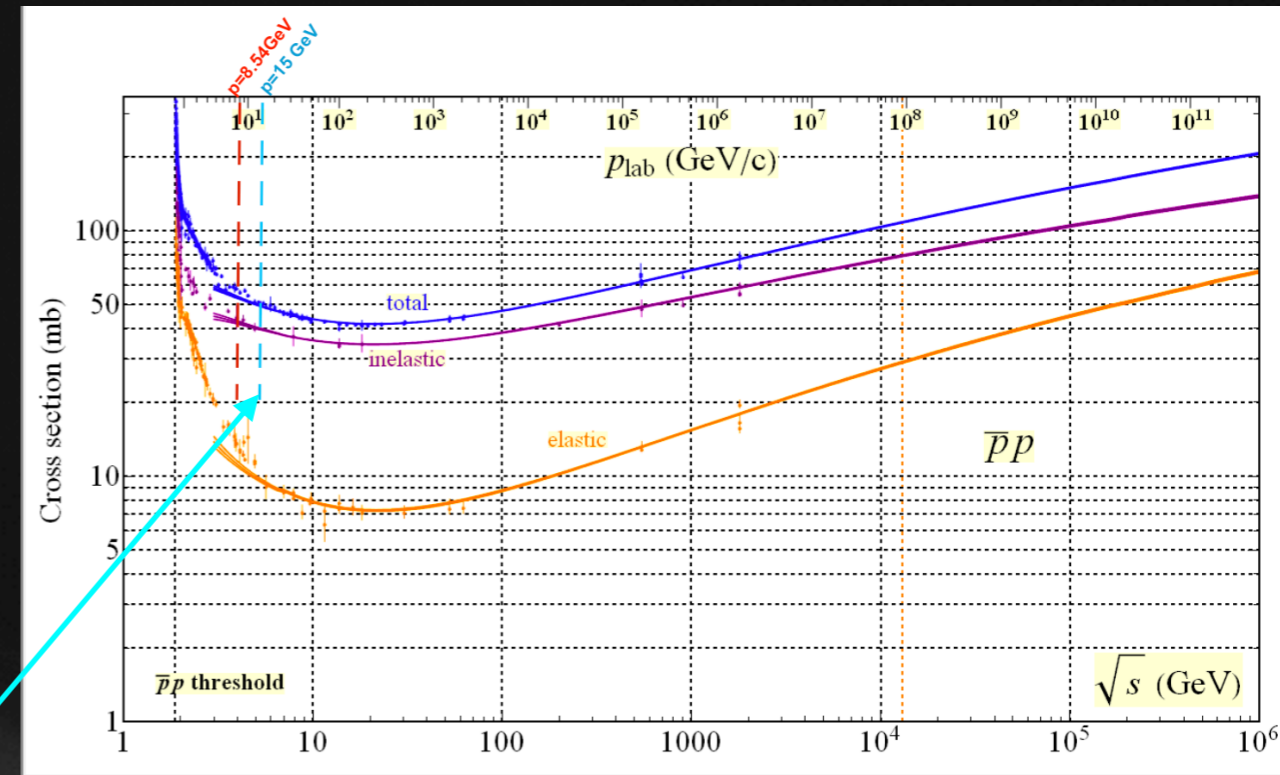
$$M_{Z_{cs}(3985)_{reco}} : [3.98279 \pm 0.00002] \text{ GeV}/c^2$$

$$\Gamma_{Z_{cs}(3985)_{reco}} : [0.0205 \pm 0.00004] \text{ GeV}/c^2$$



Analysis Background

- 30 million events were generated with Dual Parton Model (DPM)
- Same analysis strategy applied to background events
 - no event out of 30 million survived after the applied cuts.
 - The non-observation of any background events corresponds to a 90% confidence upper limit of 2.3 events. (means reco eff, $\epsilon_{bkg} = 2.3 \cdot 10^{-8}$)
 - $\sigma_{sig} = [4.4 \pm 1.4] \text{ pb}$ from Ref.[1] @ $\sqrt{s} = 4.681 \text{ GeV}$
 - at a beam momentum of 15 GeV/c, the inelastic cross section is $\sigma_{bkg} = 40 \text{ mb}$ Ref.[2].
 - The branching ratio of J/psi is set to 100% during event generation. To correct this value for the following calculations, the branching ratio $Br_{sig} = Br_{J/\psi} = 5.961$ for the J/psi decay in the decay tree is taken into account.



Signal-to-Background ratio is defined as

$$\frac{S}{B} = \frac{\sigma_{sig} \cdot \epsilon_{sig} \cdot Br_{sig}}{\sigma_{bkg} \cdot \epsilon_{bkg}}$$

Signal significance is defined as

$$S_{sig} = \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg} \cdot F_{bkg}}}$$

Scaling factor is

$$F_{bkg} = \frac{N_{sig}^{gen} \cdot \sigma_{bkg}}{N_{bkg}^{gen} \cdot \sigma_{sig} \cdot Br_{sig}}$$

[1] M. Ablikim et al. (BESIII Collaboration), Phys. Rev. Lett. 126, 102001 (2021)

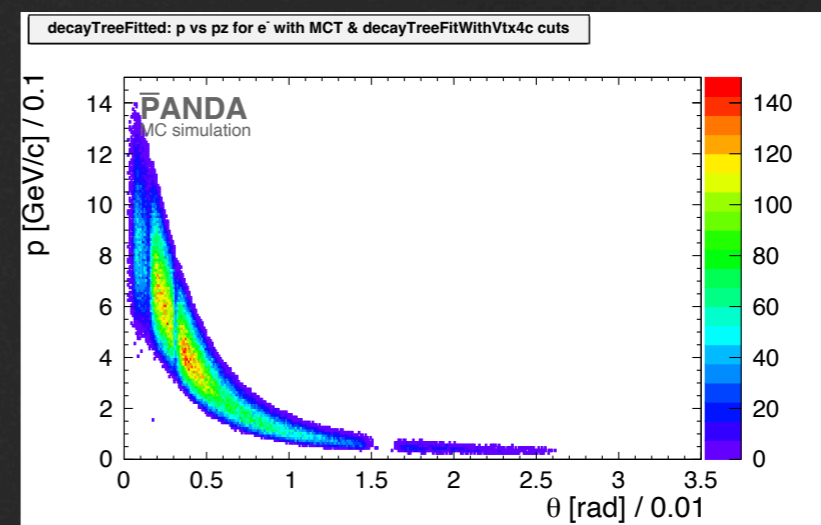
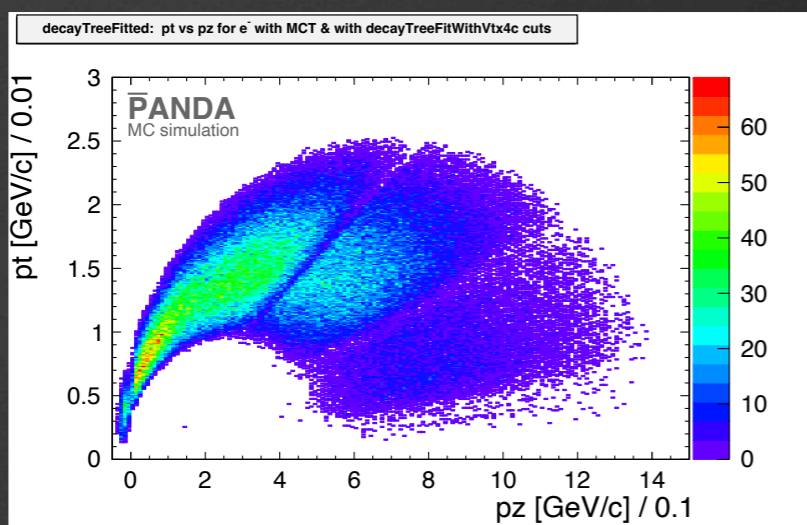
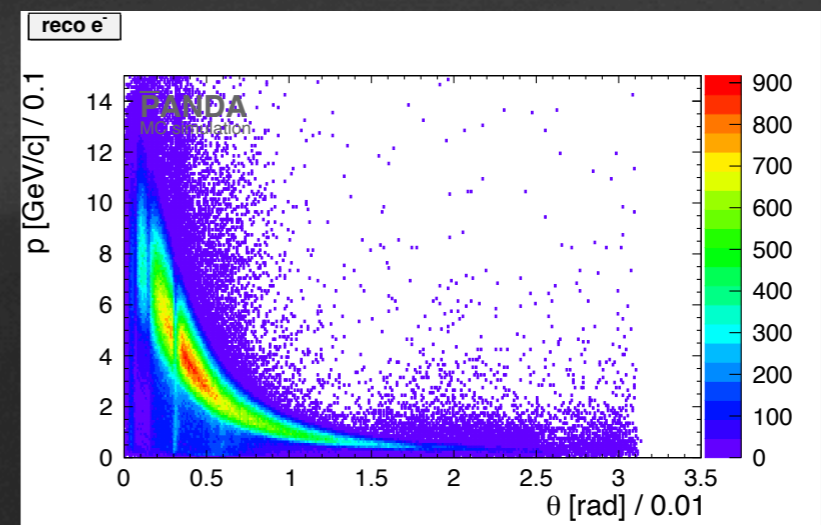
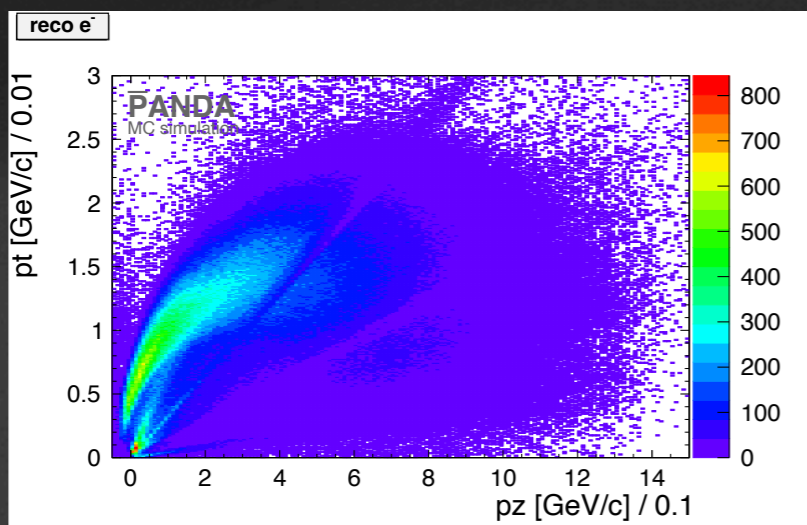
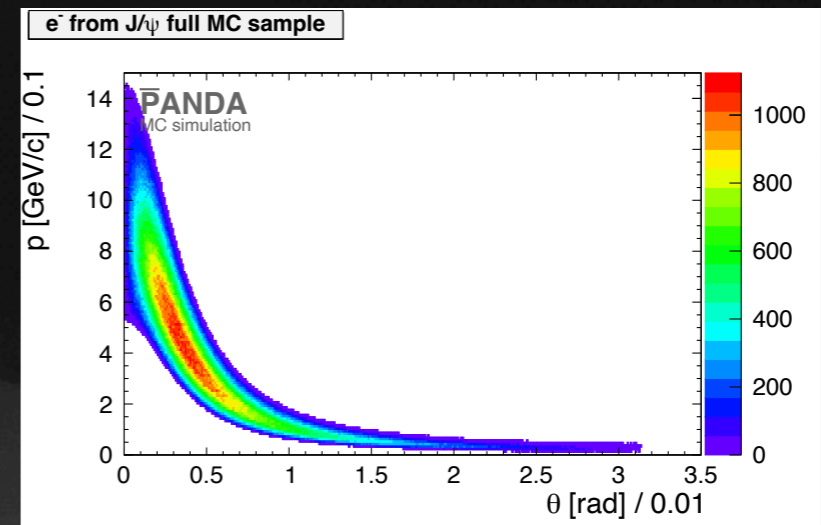
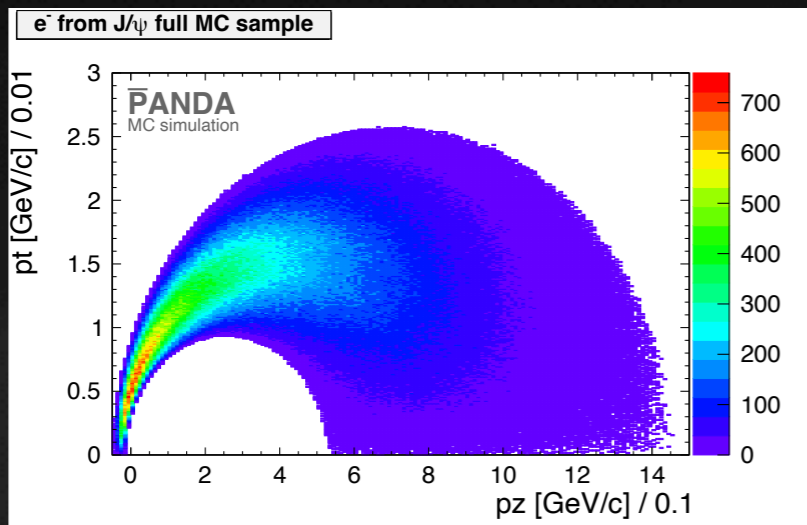
[2] <https://pdg.lbl.gov/2022/hadronic-xsections/>

Summary

| Particle type | ϵ_{reco} [%] | S / B | S _{sig} |
|--|------------------------------|-----------------------|------------------|
| $Z_{cs}(3985)^+$ (from $\mu^+ \mu^-$) | 45.44 | 0.00013 | 5.4617* |
| $Z_{cs}(3985)^+$ (from $e^+ e^-$) | 18.31 | 5.23×10^{-5} | 1.6705* |
| $Z_{cs}(3985)^-$ (from $\mu^+ \mu^-$) | 44.31 | 0.00013 | 5.4446* |
| $Z_{cs}(3985)^-$ (from $e^+ e^-$) | 17.88 | 5.11×10^{-5} | 1.6705* |
| * assuming at least 1 background event | | | |

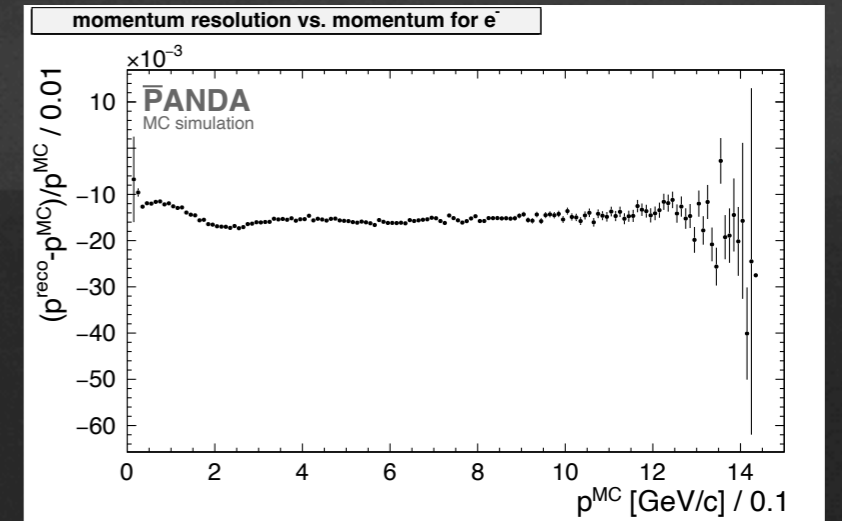
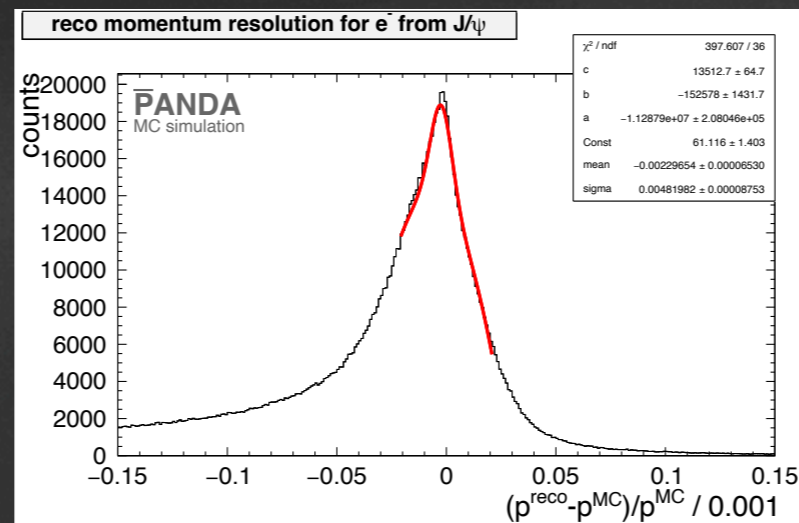
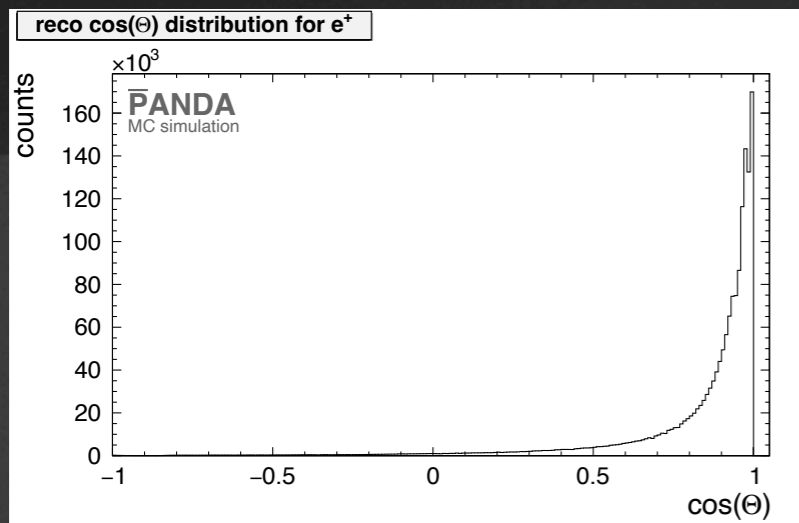
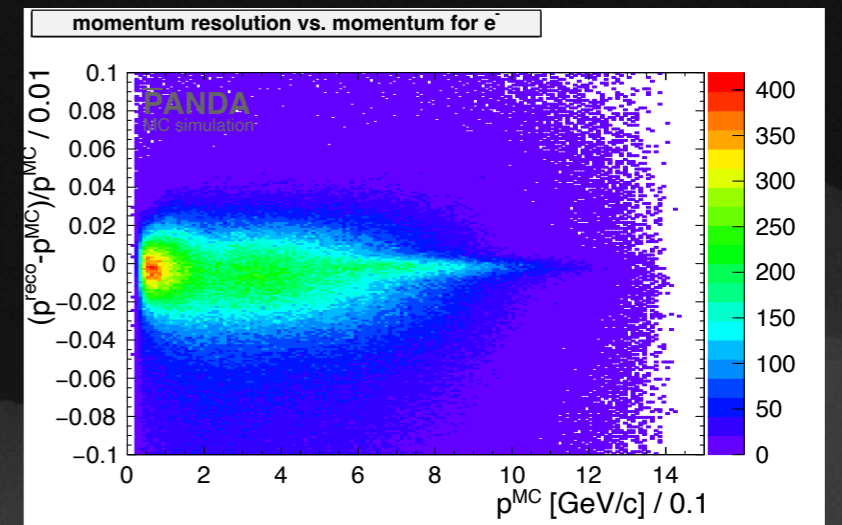
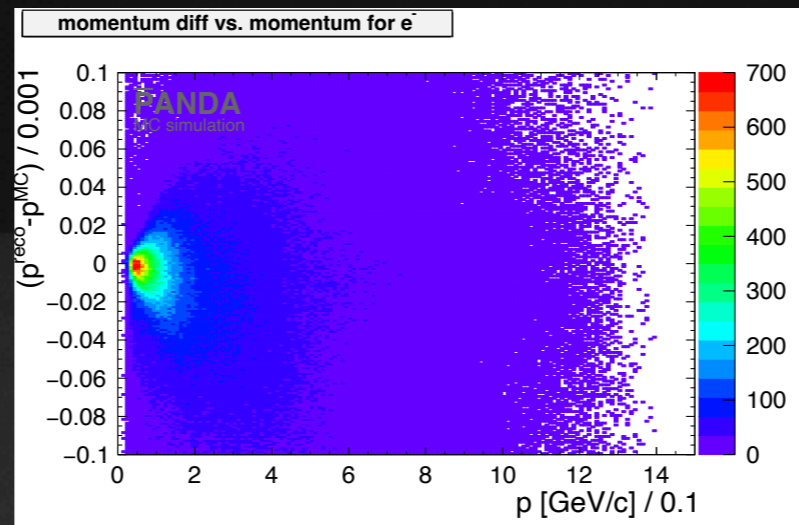
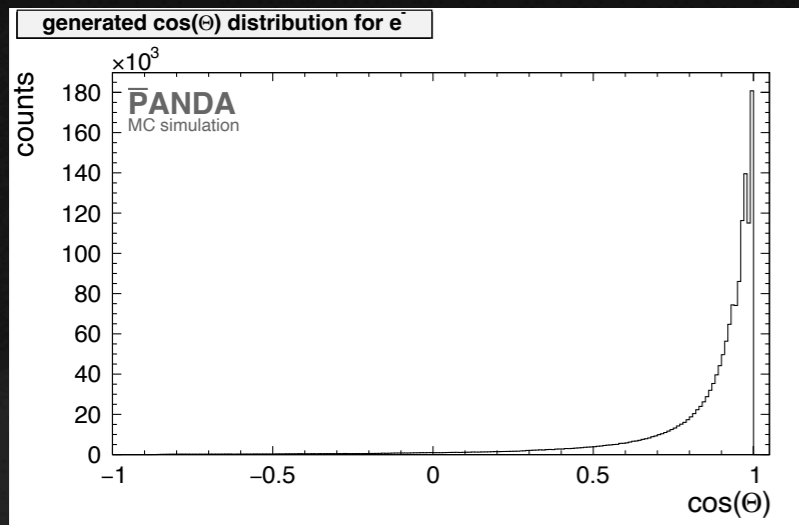
Backups

Electron channel : e^-



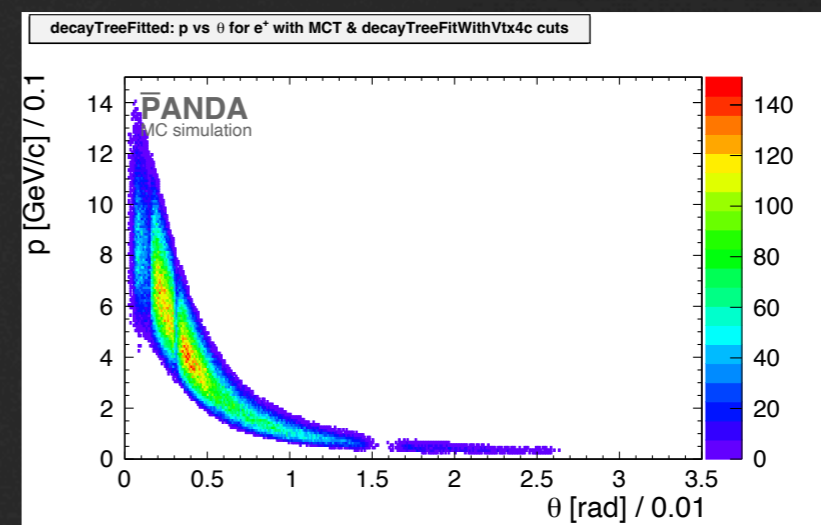
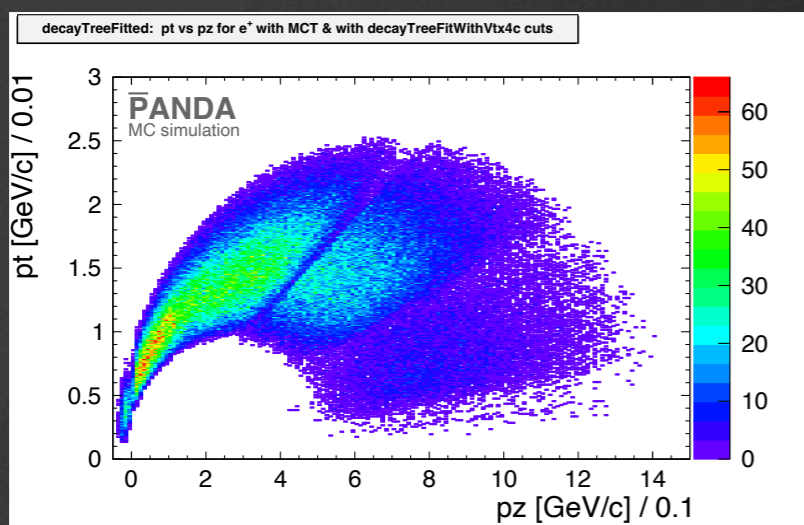
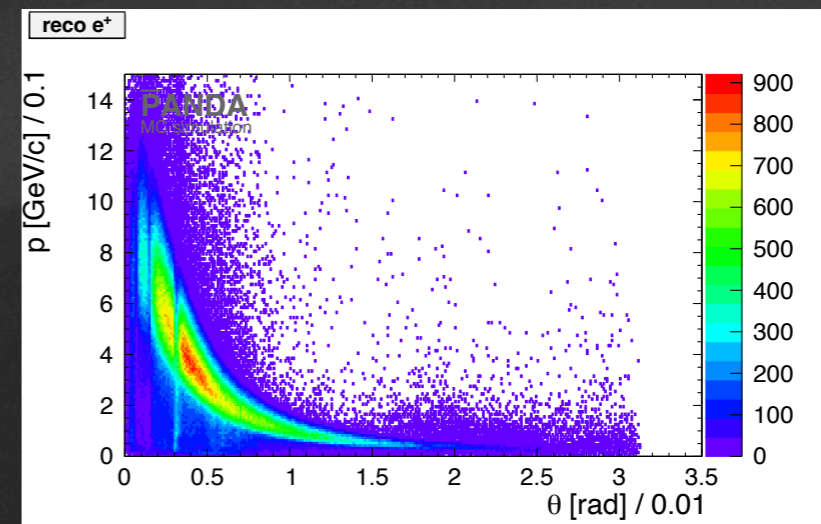
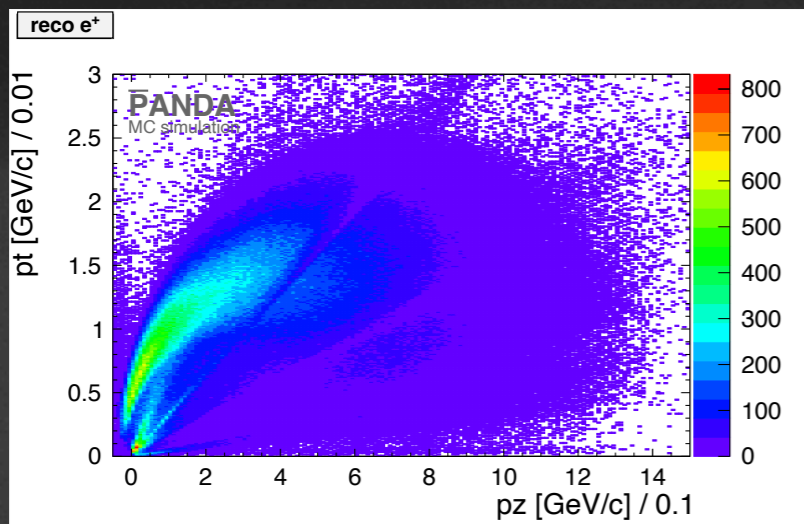
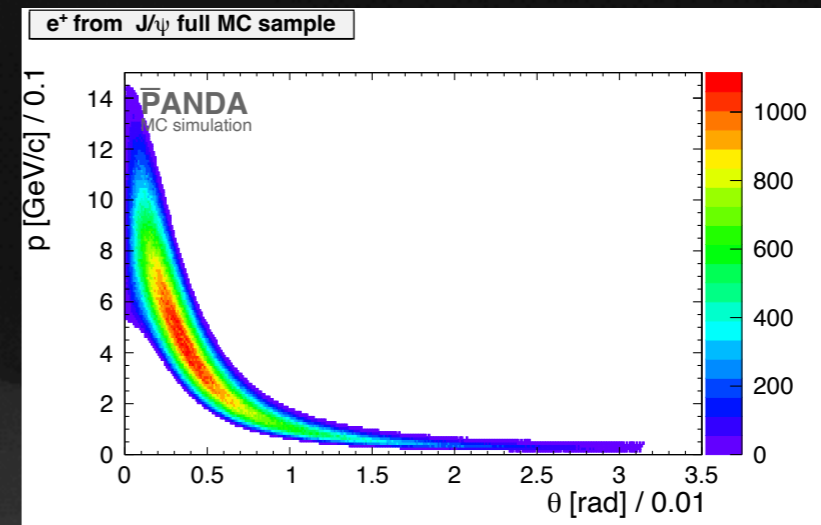
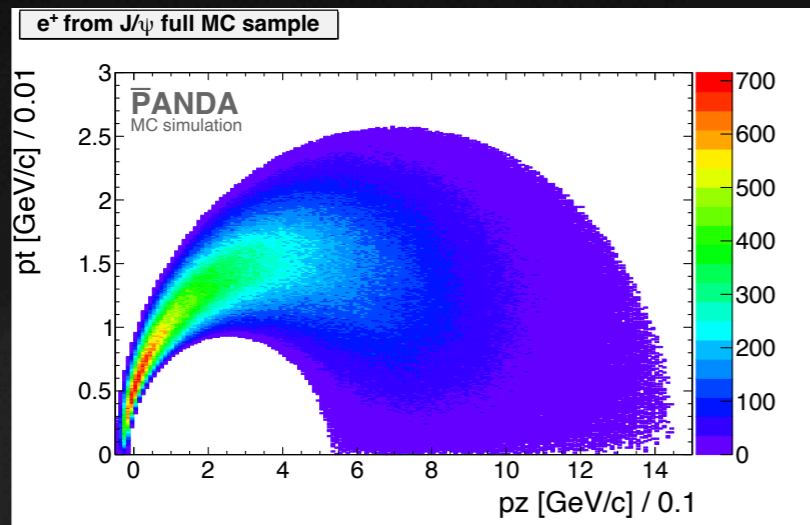
Backups

Electron channel : e^-



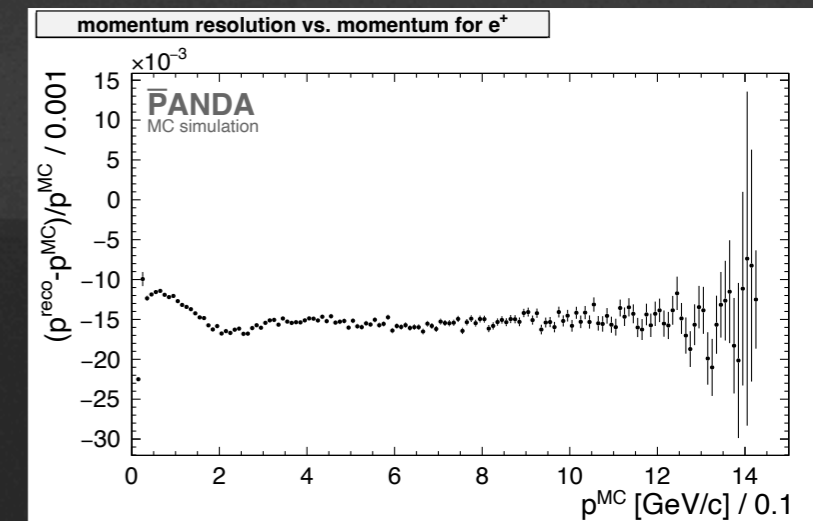
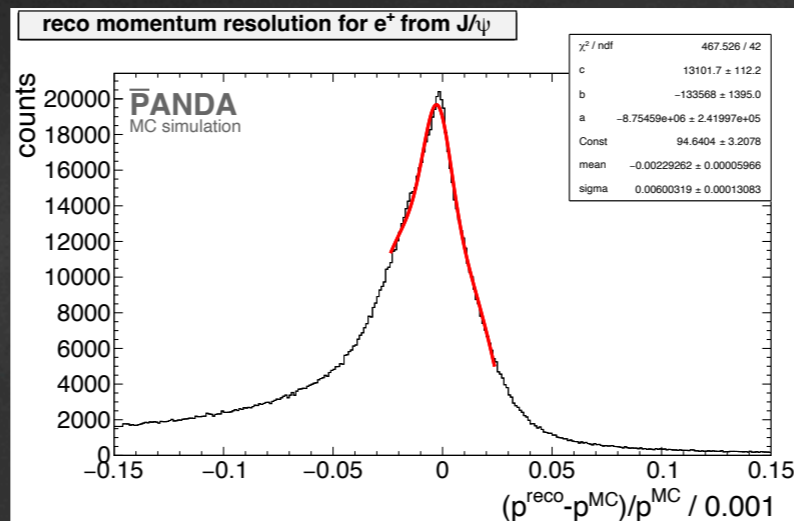
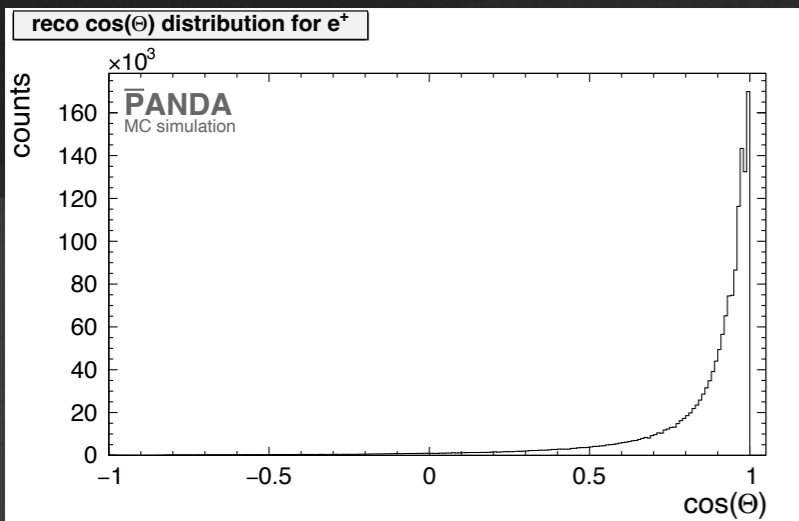
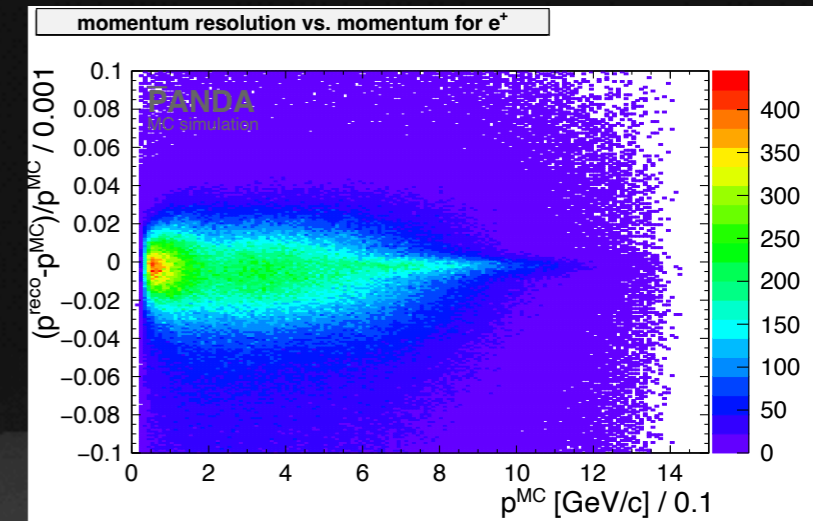
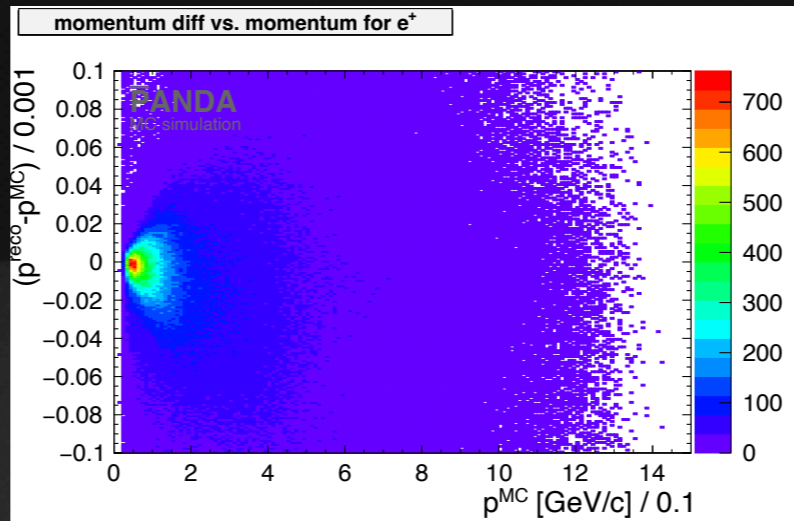
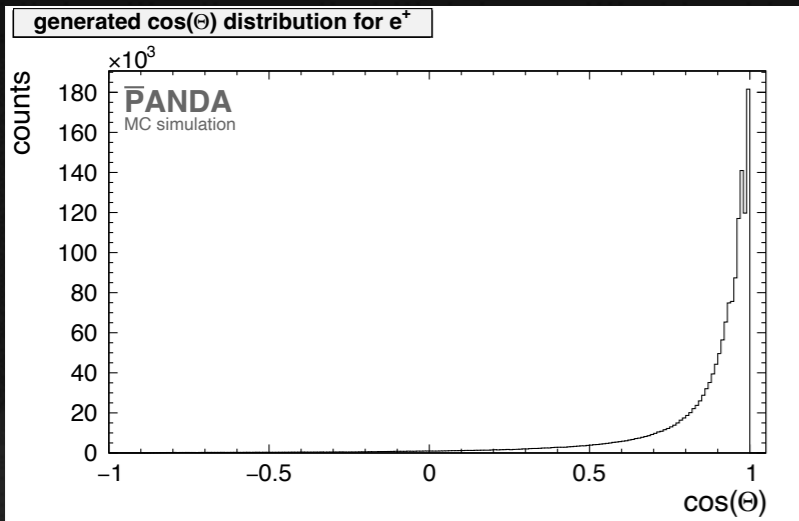
Backups

Electron channel : e^+



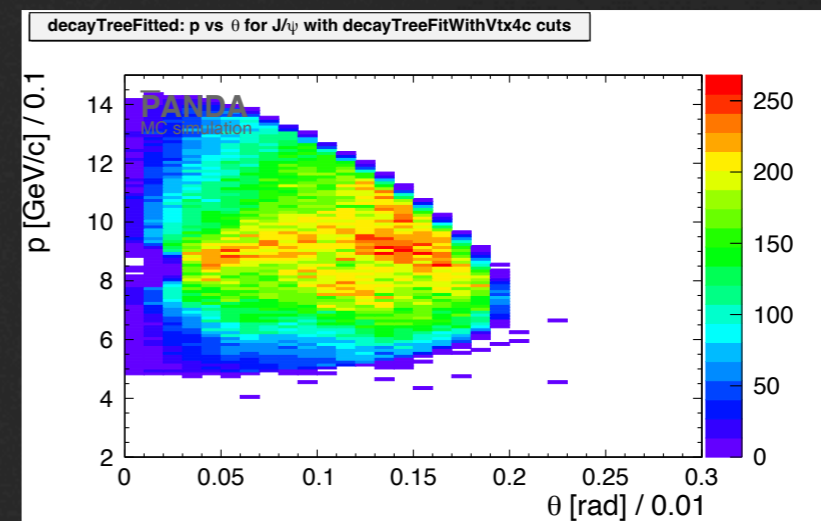
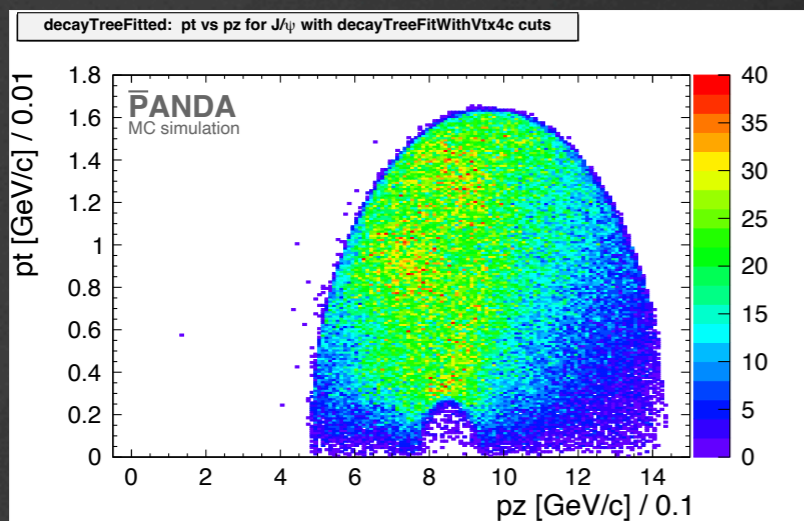
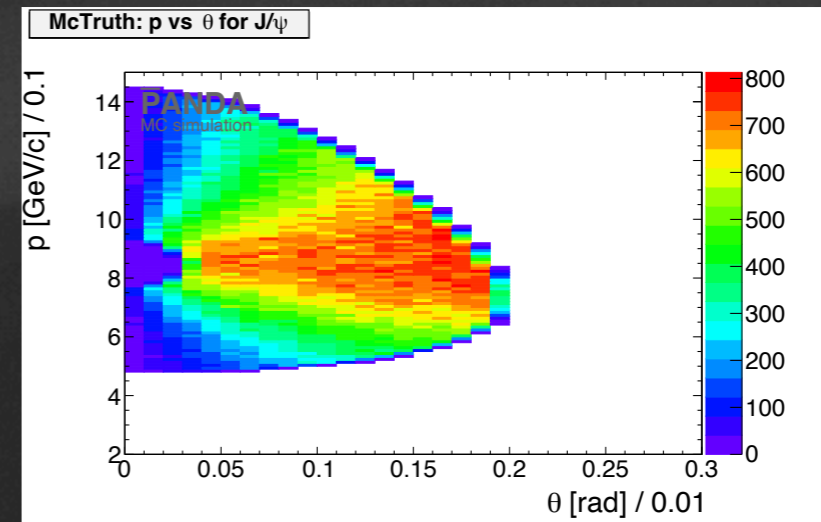
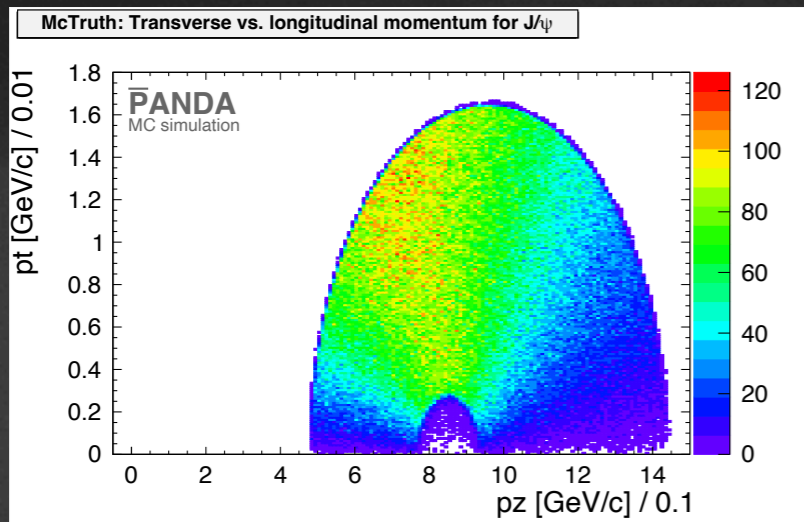
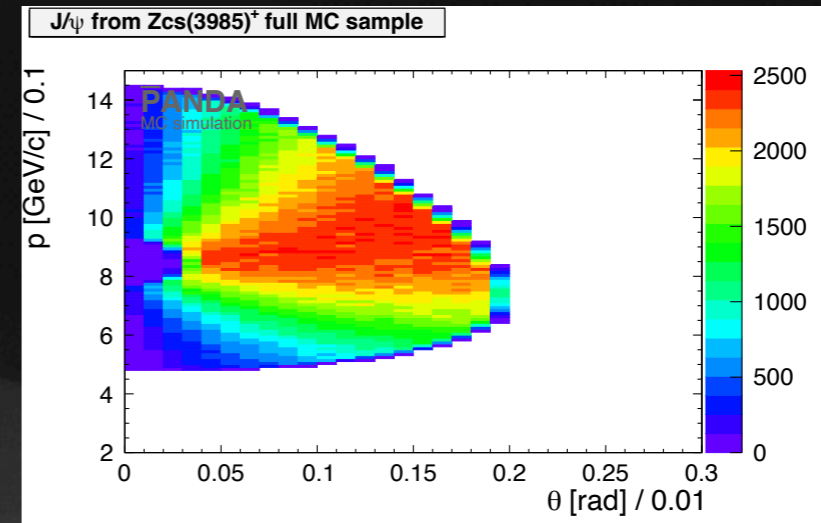
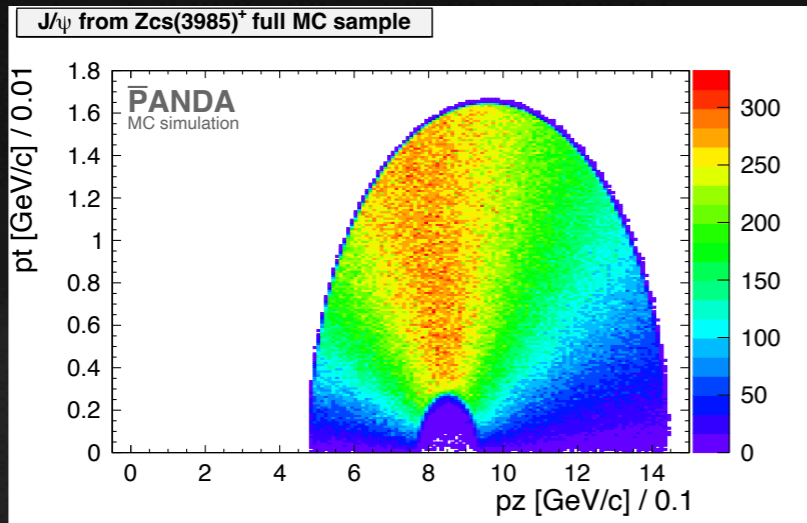
Backups

Electron channel : e^+



Backups

Electron channel : J/ψ



Backups

Electron channel : J/ψ

