J/ψ production Tagged analysis

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Motivation

- The production process of the J/ψ is sensitive to Gravitational Form Factors (GFF) which provide information about the mechanical properties of the nucleon. We can relate the gluon GFF to the J/ψ photoproduction differential cross section.

- The LHCb collaboration reported that the $P_c(4450)^+$ structure in the decay channel $P_c^+ \to J/\psi p$, consist on two narrow overlapping peaks $P_c(4440)^+$ and $P_c(4457)^+$ at 4440 and 4457 MeV respectively.

- The calculation of the yield of this process will be useful for detailed studies of the production of pentaquark resonances.

$$\sigma(\gamma + p \to P_c \to J/\psi + p) = \frac{2J+1}{4} Br(P_c \to \gamma + p) Br(P_c \to J/\psi + p) 1.1 \times 10^{-27} \text{cm}^2$$

- This study focus on the tagged photoproduction, where we use the Forward Tagged (FT) to detect the scattered electron.

V. Kubarovsky and M. B. Voloshin, Phys. Rev. D ., 92, 031502,R , (2015).

Extraction of cross-section

- The cross-section depends on the total center of mass energy, W, the exchange photon virtuality Q^2 and the transfered momentum squared, t

$$\frac{d\sigma}{dWdQ^2dt} = \frac{N_{J/\psi}(W,Q^2,t)}{L \cdot Br \cdot \eta}\frac{1}{\Delta W \Delta Q^2 \Delta t}$$

Where $L = N_e \cdot N_p$, $Br = 0.06$ and η is the detector efficiency.

- When we have low statistics, the width of the kinematic variables $(\Delta W, \Delta Q^2, \Delta t)$ is large and the dependencies are limited to one variable by integrating over the others.

$$\frac{d\sigma_i}{dW} = \frac{Y_i}{L \cdot Br}\frac{1}{\Delta W} \qquad Y_i = \sum_{j=1}^{N^i_{J/\psi}} \frac{1}{\eta_j}$$

- At $Q^2 < 0.2\text{GeV}^2$ the electroproduction cross-section can be expressed as

$$\frac{d\sigma_{ep\to e'J/\psi p'}}{dQ^2dWdt} = \Gamma_T \frac{d\sigma_\gamma}{dt}$$

Where Γ_T is the flux of transverse virtual photons and $\frac{d\sigma_\gamma}{dt}$ is the photoproduction cross section

Tagged Analysis Framework

- For this analysis the RG-A Fall 2018 and Spring 2019 Pass2 data is presented.
  - Fall 2018: Inbending and Outbending configurations, 10.6 GeV
  - Spring 2019: Inbending configuration, 10.2 GeV

- The reaction to study is

$$ep \to e'J/\psi\ p' \to e'e^+e^-X$$

- Where e^+ and e^- are measured in the Forward Detector, e' is measured in the Forward Tagger and X corresponds to the recoil proton and will be identified in the missing momentum analysis.

- In addition, we have other three topologies that are exploring:

$$ep \to e'p'e^+e^-$$
$$ep \to e'p'e^-X$$
$$ep \to e'p'e^+X$$

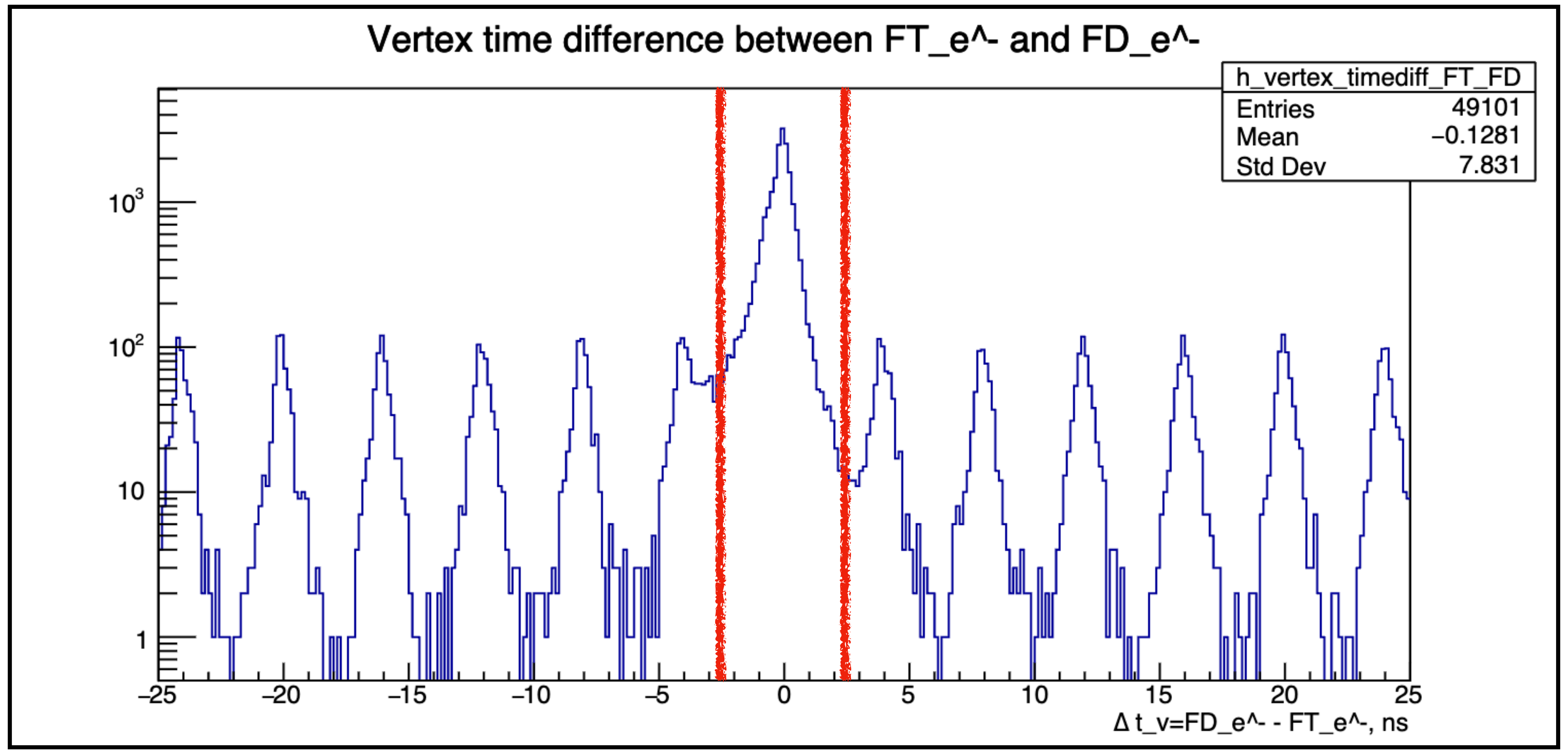
Event selection $ep \to e'p'J/\psi \to e'e^+e^-(p')$

- We select one electron in the Forward Tagger. In addition we select exactly one electron and one positron in the forward detector.

- Electron e^-
  - Forward Tagger
  - $|v_{t_{e^-}} - v_{t_{e^+}}| \leq 2ns$

- Electron e^-
  - Forward Detector
  - $p > 1.95$ GeV/c
  - $E_{PCAL} > 0.07$ GeV
  - $V_{PCAL} > 9$ cm
  - $W_{PCAL} > 9$ cm
  - $-8 < V_z < 4$ cm

- Positron e^+
  - Forward Detector
  - $p > 1.95$ GeV/c
  - $E_{PCAL} > 0.07$ GeV
  - $V_{PCAL} > 9$ cm
  - $W_{PCAL} > 9$ cm
  - $|\chi^2_{PID}| < 5$
  - $SF_{EC} \geq (0.195 - SF_{PCAL})$

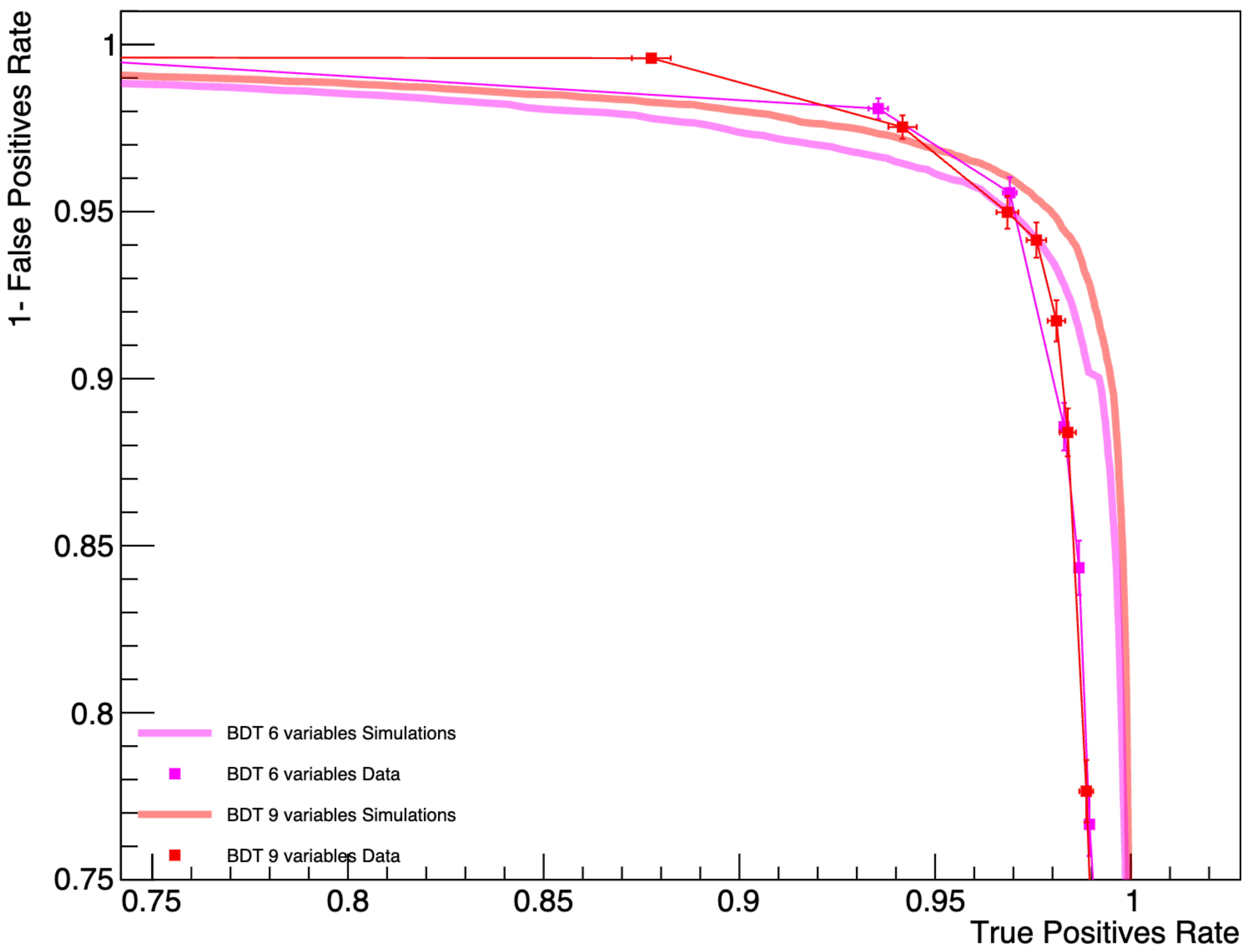


Vertex time difference between the electron in the FD and the electron in the FT

Lepton ID at high momenta

- We apply BDT to identify leptons at high momenta, $p > 4.5$ GeV.
- We have 6 classifiers: e^+ and e^- identification on each Pass2 RGA configuration.
- We use as variables $e^{\pm}(P, \theta, \phi)$ and SF and m2 of PCAL, ECIN and ECOUT
- All models were trained using MC, and validated on data and simulations.

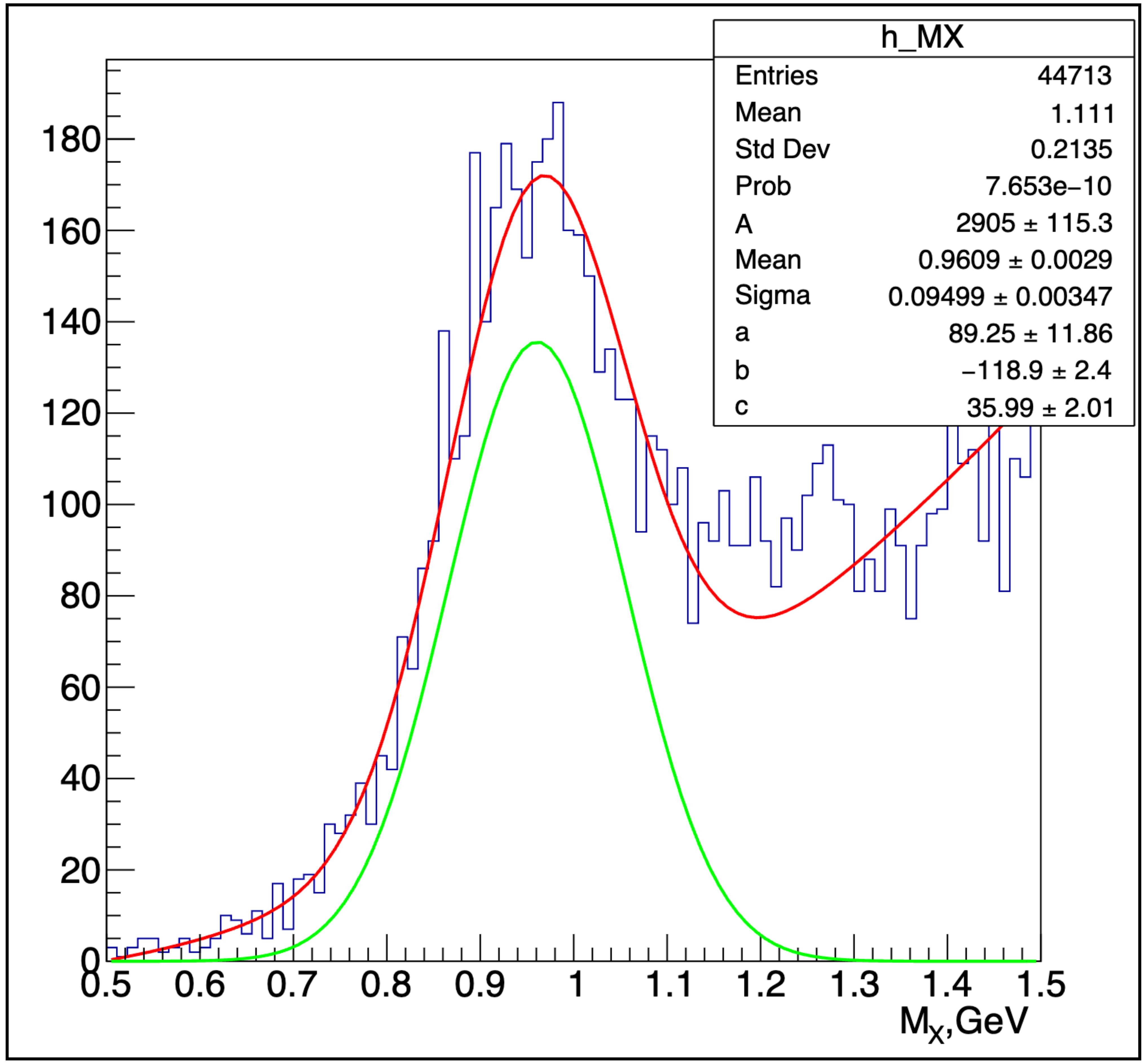
CLAS12 Note 2024-005



ROC curve for 6 and 9 variable models for F18inbending

$ep \rightarrow e'p'J/\psi \rightarrow e'e^+e^-(p')$

- For the reaction $ep \rightarrow e'e^+e^-(p')$
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e^+} - p_{e'}$
- The peak on the distribution should be around the mass of the missing proton.
- We keep events with $E_\gamma > 8.1$ GeV where $E_\gamma = E_{beam} - E_{e'}$
- Invariant mass $M^2(e^-e^+) = (p_{e^-} + p_{e^+})^2$ should be in the 2.0 GeV to 3.5 GeV region
- We also apply a cut in the missing mass as $|M_X = 0.9609| < 3\sigma$



Missing mass distribution for the final state $e'e^+e^-$.The peak correspond to the missing mass of the proton.

$ep \to e'p'J/\psi \to e'e^+e^-(p')$

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- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e^+} - p_{e'}$
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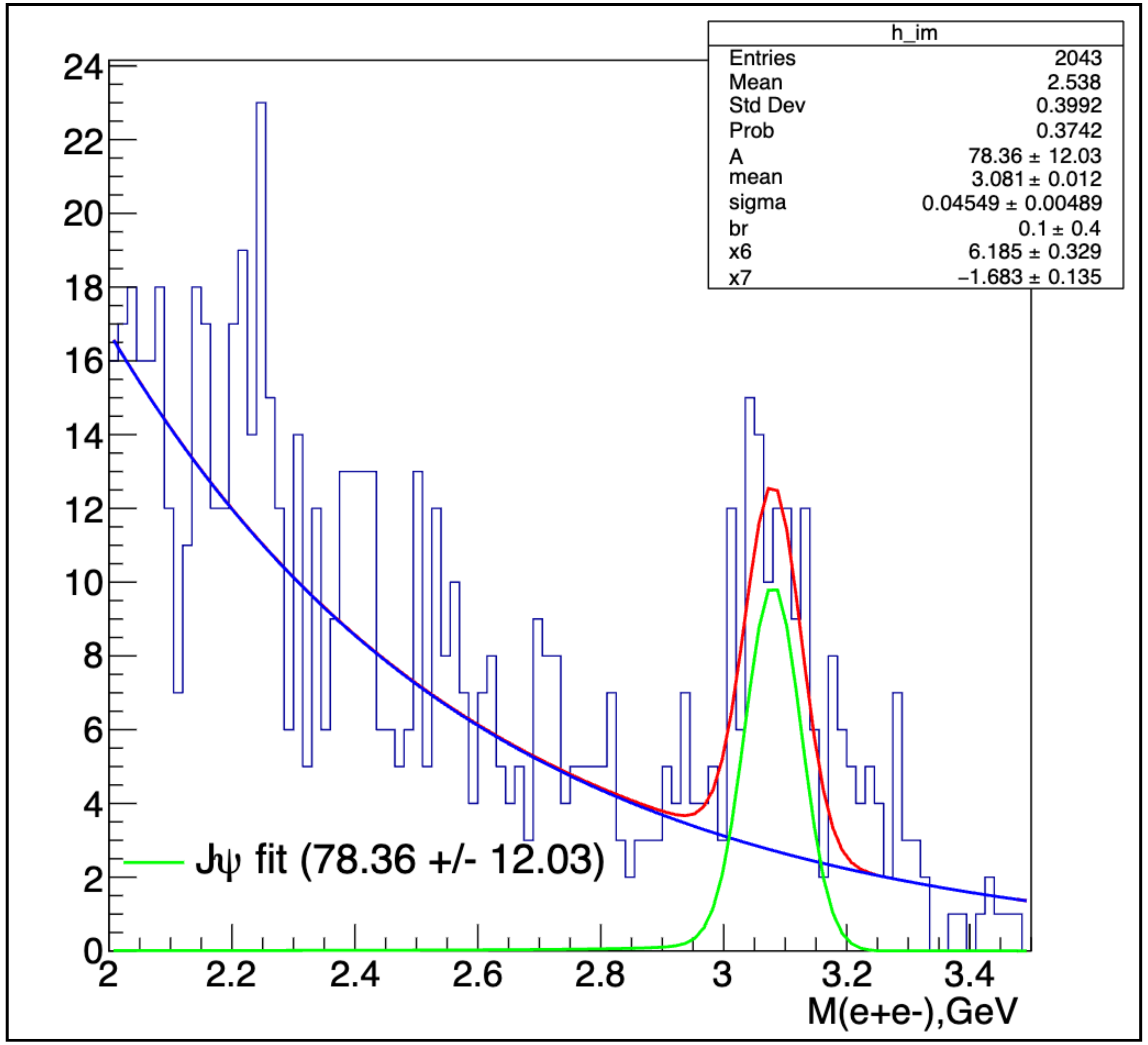
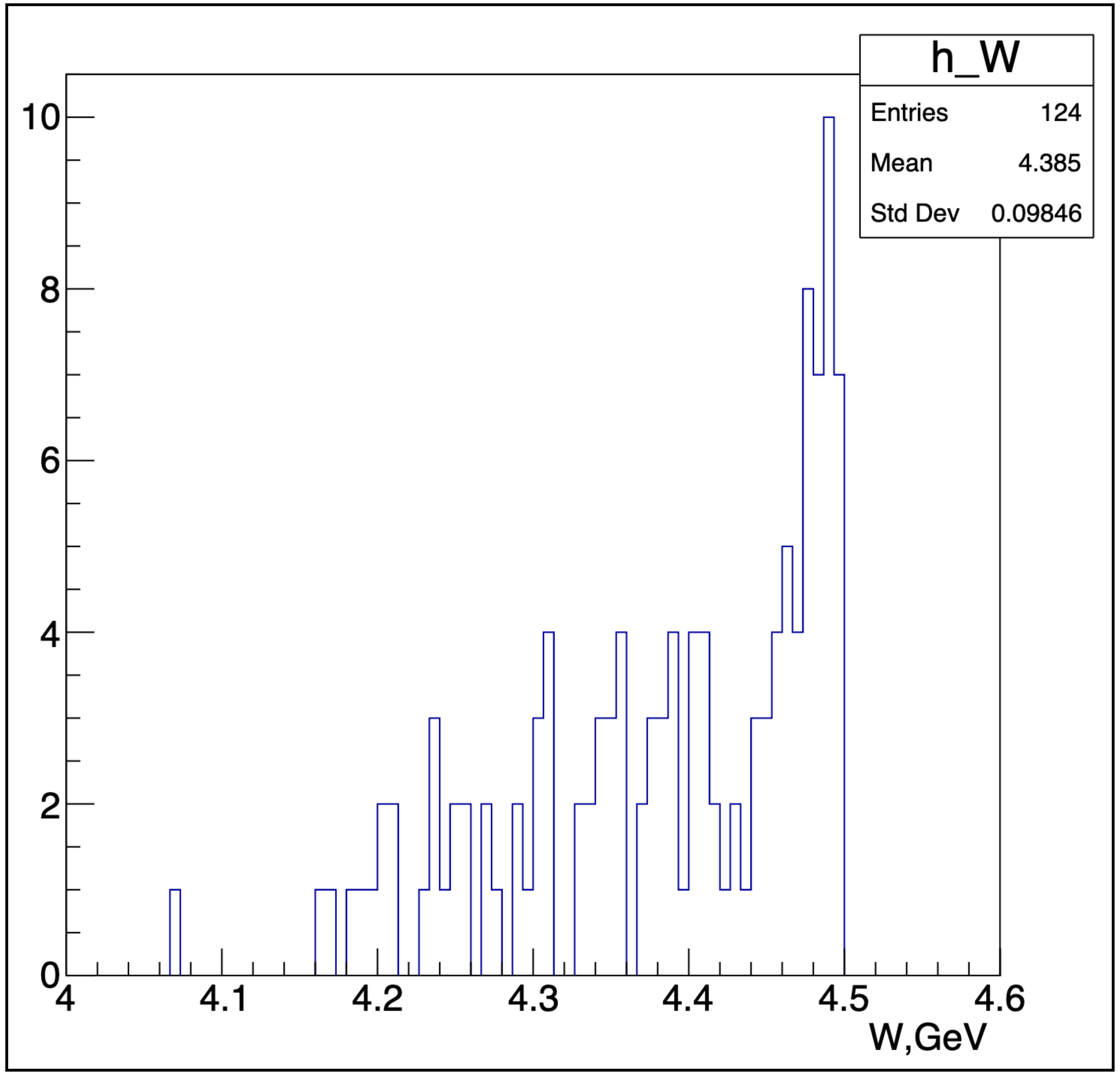


Invariant Mass

Hadronic Mass $ep \to e'p'J/\psi \to e'e^+e^-(p')$



Hadronic mass. Topology: $ep \to e'e^+e^-(p')$

- For this distribution, we consider events that fall into the mass range $3.0 < M(e^+e^-) < 3.2$ GeV
- The hadronic mass corresponds to the mass of the pentaquark P_c . We expect to see their existence in this distribution.

$$W = \sqrt{m_p^2 + 2m_pE_\gamma - Q^2}$$

$$E_\gamma = E_{beam} - E_{e'}$$

$$Q^2 = 2E_{beam}E_{e'}(1 - \cos(\theta_{e'}))$$

Event selection $ep \rightarrow e'p'J/\psi \rightarrow e'e^+e^-p'$

- We select one electron in the Forward Tagger. In addition we select exactly one electron, one positron and one proton in the forward detector.

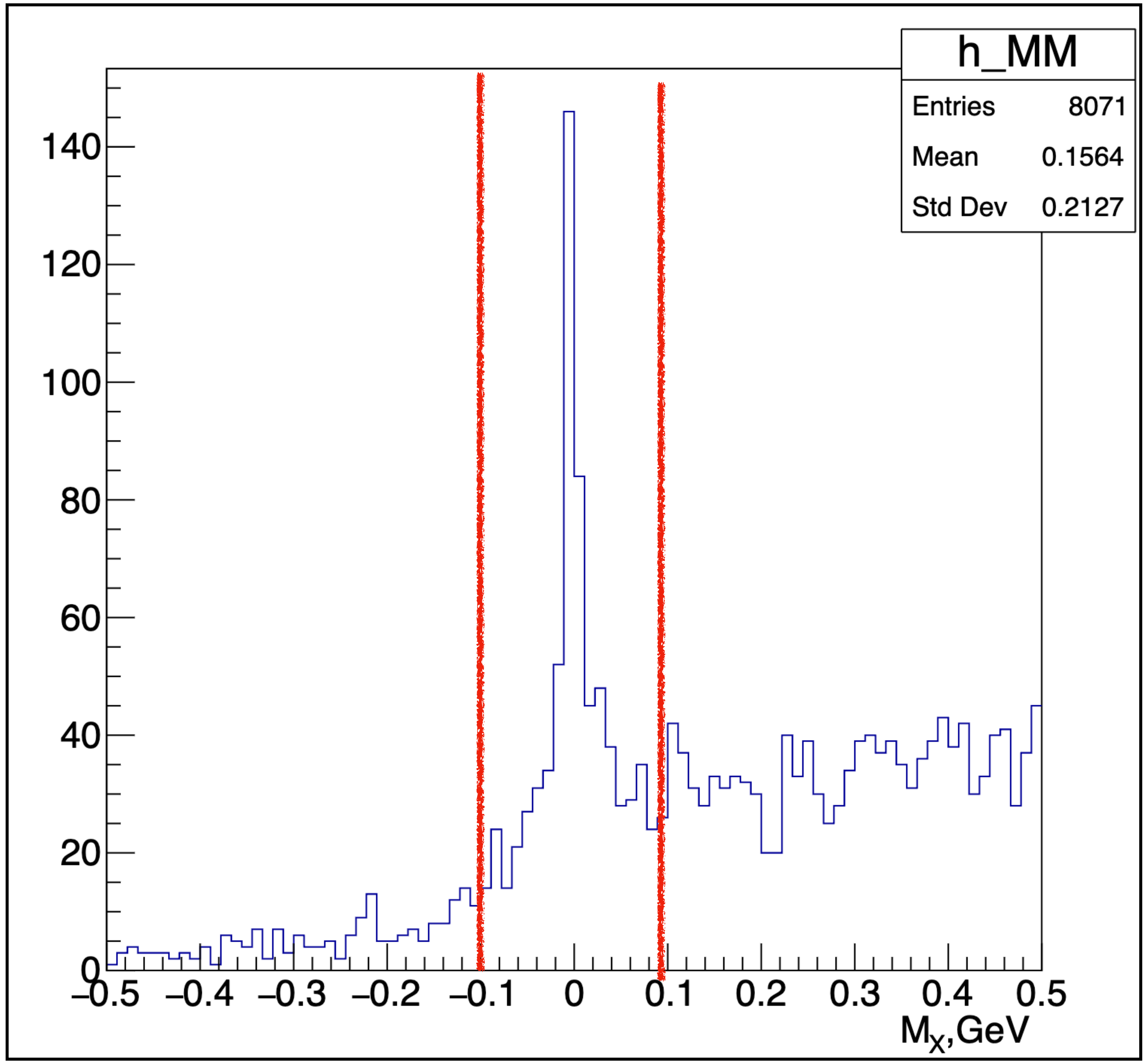
- Electron e^-
  - Forward Tagger
  - $|v_{t_{e^-}} - v_{t_{e^+}}| \leq 2ns$
- Proton p
  - Forward Detector
  - $p >$ 0.4 GeV/c
  - $\beta >$ 0.1
  - $|\chi^2_{PID}|$<10

- Electron e^-
  - Forward Detector
  - $p > 1.95$ GeV/c
  - $E_{PCAL} > 0.07$ GeV
  - $V_{PCAL} > 9$ cm
  - $W_{PCAL} > 9$ cm
  - $-8 < V_z < 4$ cm

- Positron e^+
  - Forward Detector
  - $p > 1.95$ GeV/c
  - $E_{PCAL} > 0.07$ GeV
  - $V_{PCAL} > 9$ cm
  - $W_{PCAL} > 9$ cm
  - $|\chi^2_{PID}| < 5$
  - $SF_{EC} \geq (0.195 - SF_{PCAL})$

$ep \to e'p'J/\psi \to e'e^+e^-p'$

- For the reaction $ep \to e'e^+e^-p'$
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e^+} - p_{e'} - p_{p'}$
- We looked at the missing mass of the reaction, expecting it to peak at zero.
- We keep events with $E_\gamma > 8.1$ GeV where $E_\gamma = E_{beam} - E_{e'}$
- Invariant mass $M^2(e^-e^+) = (p_{e^-} + p_{e^+})^2$ should be in the 2.0 GeV to 3.5 GeV region
- We also apply a cut in the missing mass as $|M_X| < 0.1$



Missing mass distribution for the final state $e'e^+e^-p'$.

$ep \rightarrow e'p'J/\psi \rightarrow e'e^+e^-p'$

- For the reaction $ep \rightarrow e'e^+e^-p'$
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e^+} - p_{e'} - p_{p'}$
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- Invariant mass $M^2(e^-e^+) = (p_{e^-} + p_{e^+})^2$ should be in the 2.0 GeV to 3.5 GeV region
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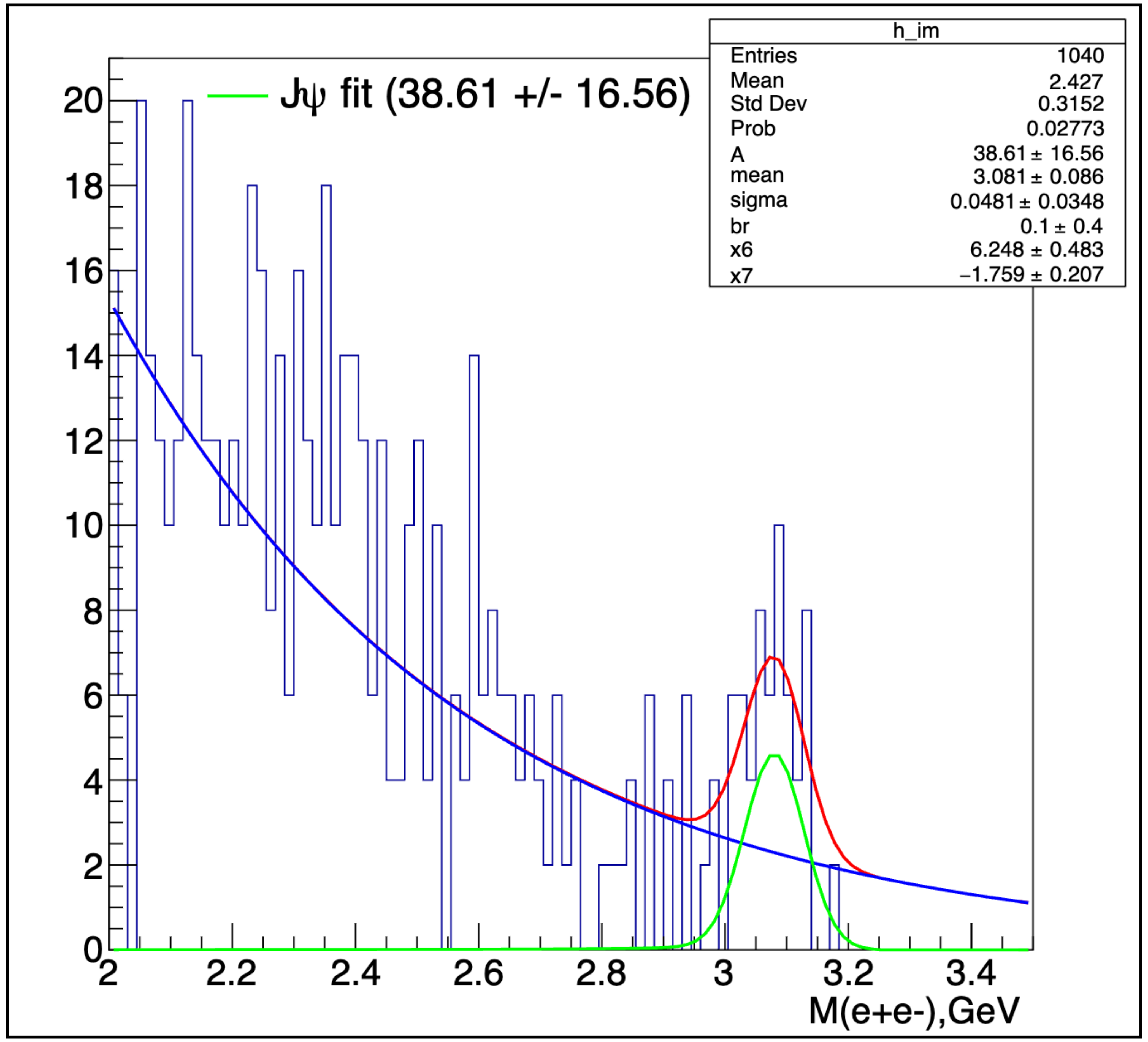
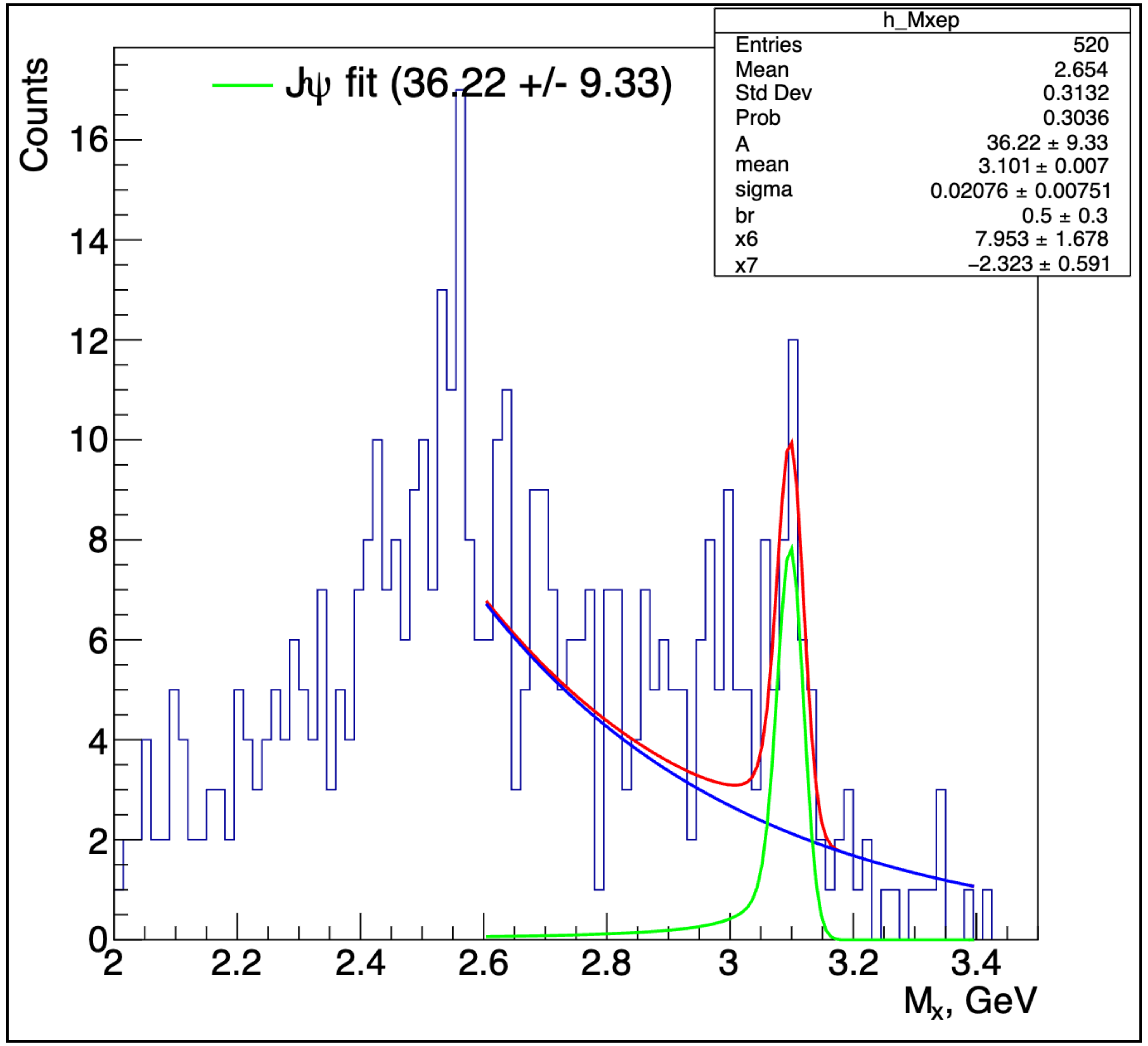


Invariant Mass

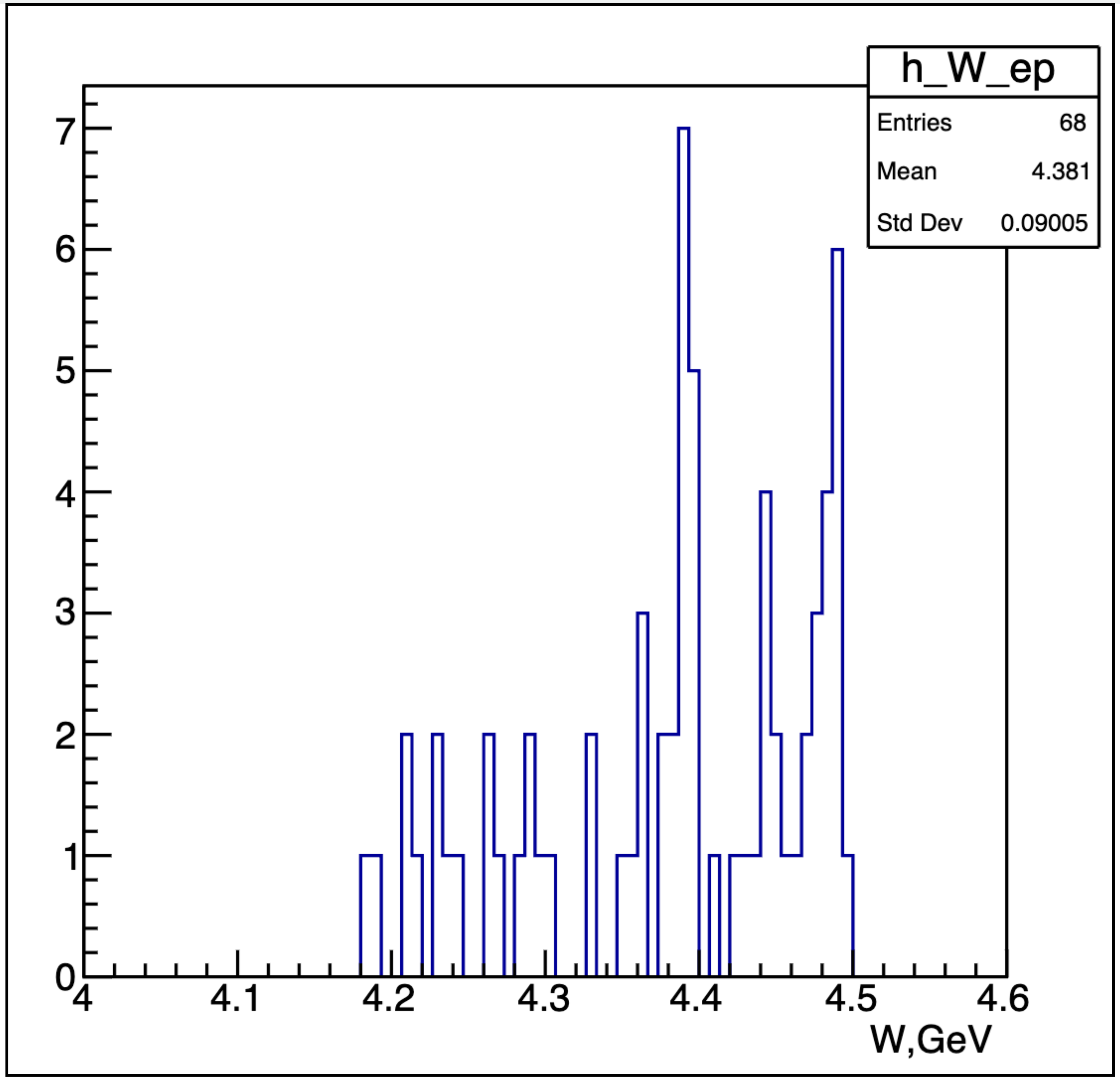
$ep \to e'p'J/\psi \to e'e^+e^-p'$

- For the reaction $ep \to e'e^+e^-p'$
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e^+} - p_{e'} - p_{p'}$
- We looked at the missing mass of the reaction, expecting it to peak at zero.
- We keep events with $E_\gamma > 8.1$ GeV where $E_\gamma = E_{beam} - E_{e'}$
- Invariant mass $M^2(e^-e^+) = (p_{e^-} + p_{e^+})^2$ should be in the > 2.0 GeV region
- We also apply a cut in the missing mass as $|M_X| < 0.1$
- In addition to the invariant mass, we can look at the missing mass $M_X(e'p') = e + p - e' - p'$



$M_X(e'p')$

Hadronic Mass $ep \to e'p'J/\psi \to e'e^+e^-p'$



Hadronic mass. Topology: $ep \to e'e^+e^-p'$

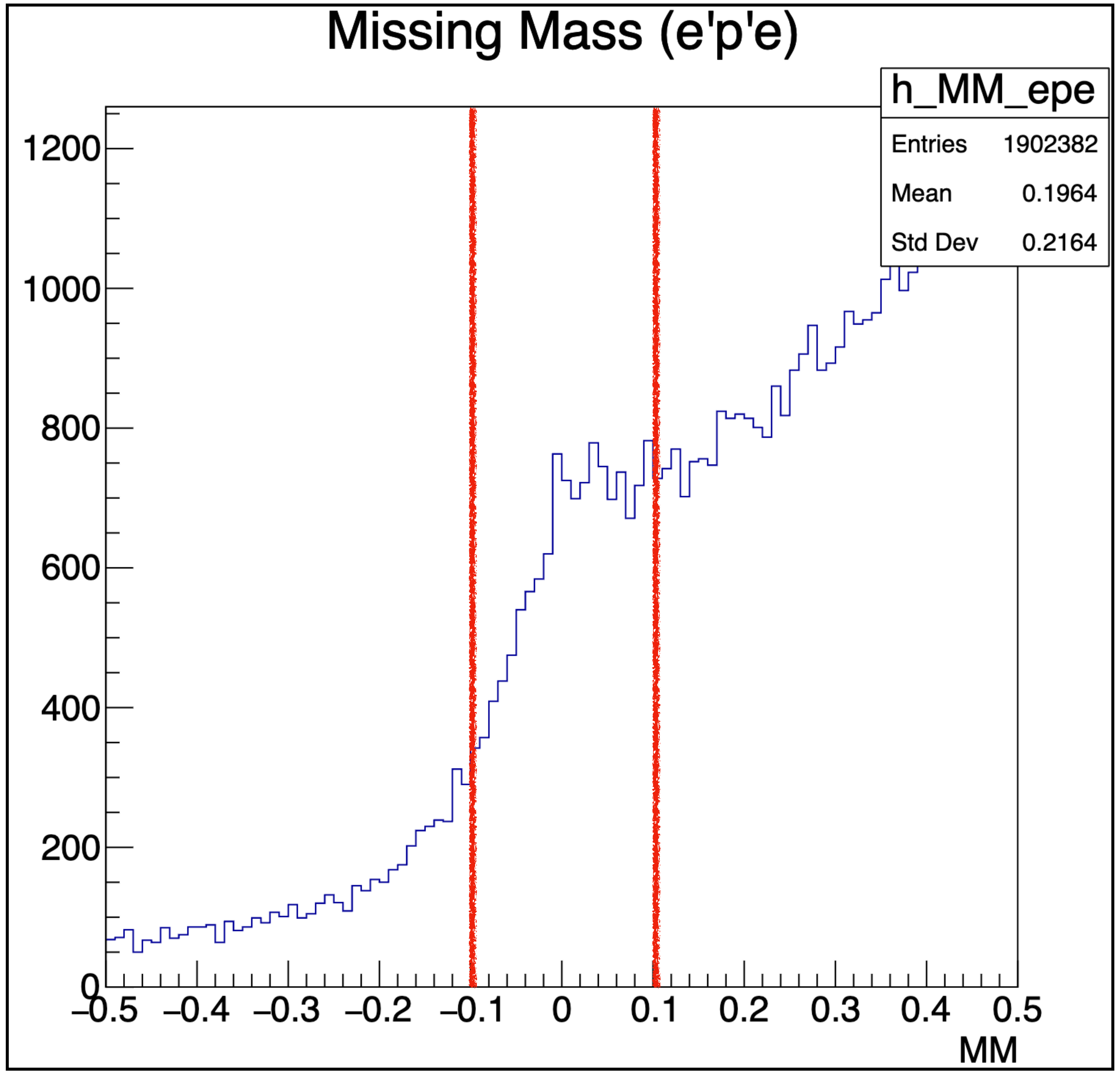
$$W = \sqrt{m_p^2 + 2m_pE_\gamma - Q^2}$$

$$E_\gamma = E_{beam} - E_{e'}$$

$$Q^2 = 2E_{beam}E_{e'}(1 - \cos(\theta_{e'}))$$

$ep \to e'p'J/\psi \to e'e^+p'(e^-)$

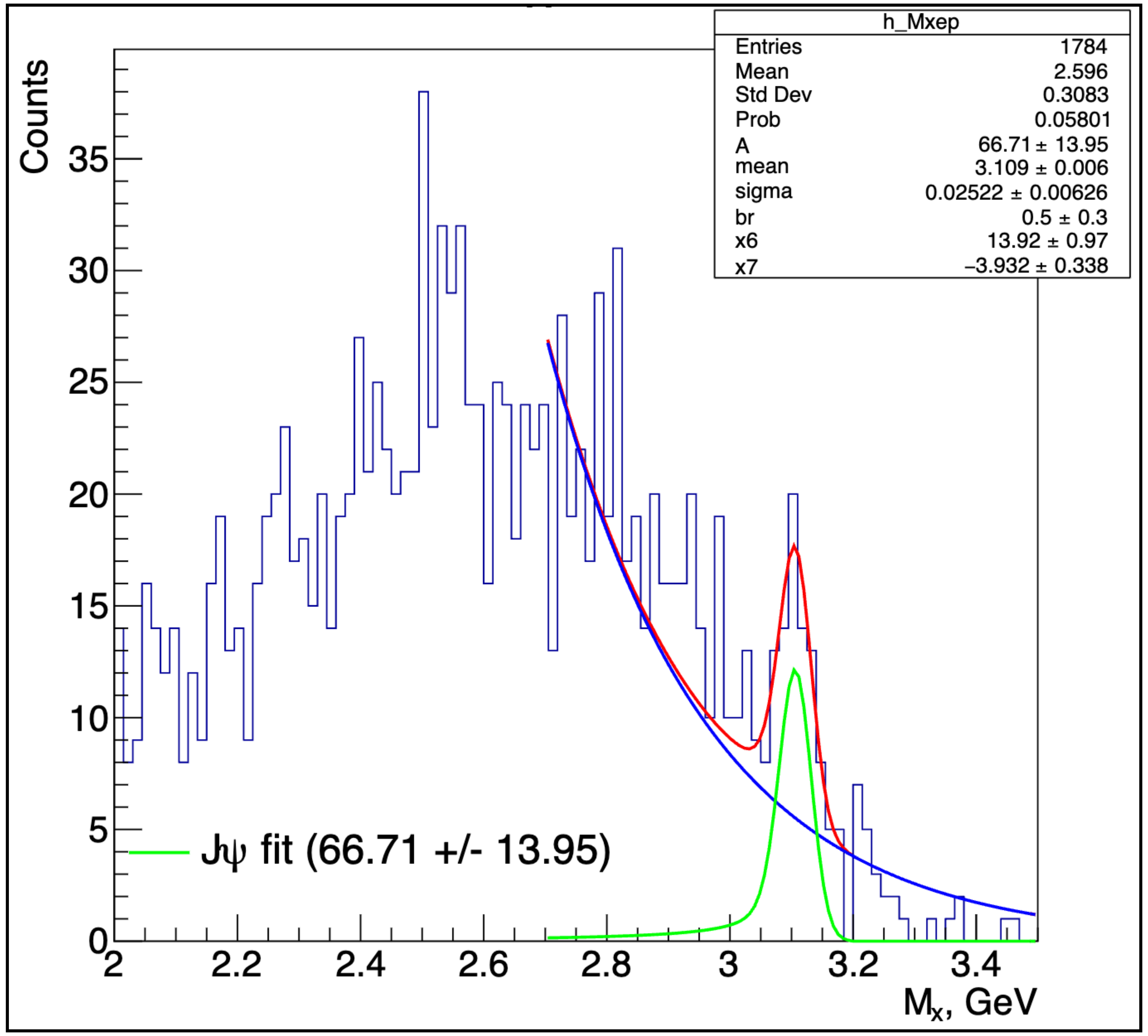
- For the reaction $ep \to e'p'e^+(e^-)$
- We select one electron in FT, one positron in FD and one proton in FD.
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^+} - p_{e'} - p_{p'}$
- The peak on the distribution should be around the mass of the missing lepton.
- We keep events with $E_\gamma > 8.1\,\mathrm{GeV}$ where $E_\gamma = E_{beam} - E_{e'}$
- We apply a cut in the missing mass as $|M_X| < 0.1$
- To get the number of J/ψ, we can look at the missing mass $M_X(e'p') = e + p - e' - p'$



Missing mass distribution for the final state $e'e^+p'$.

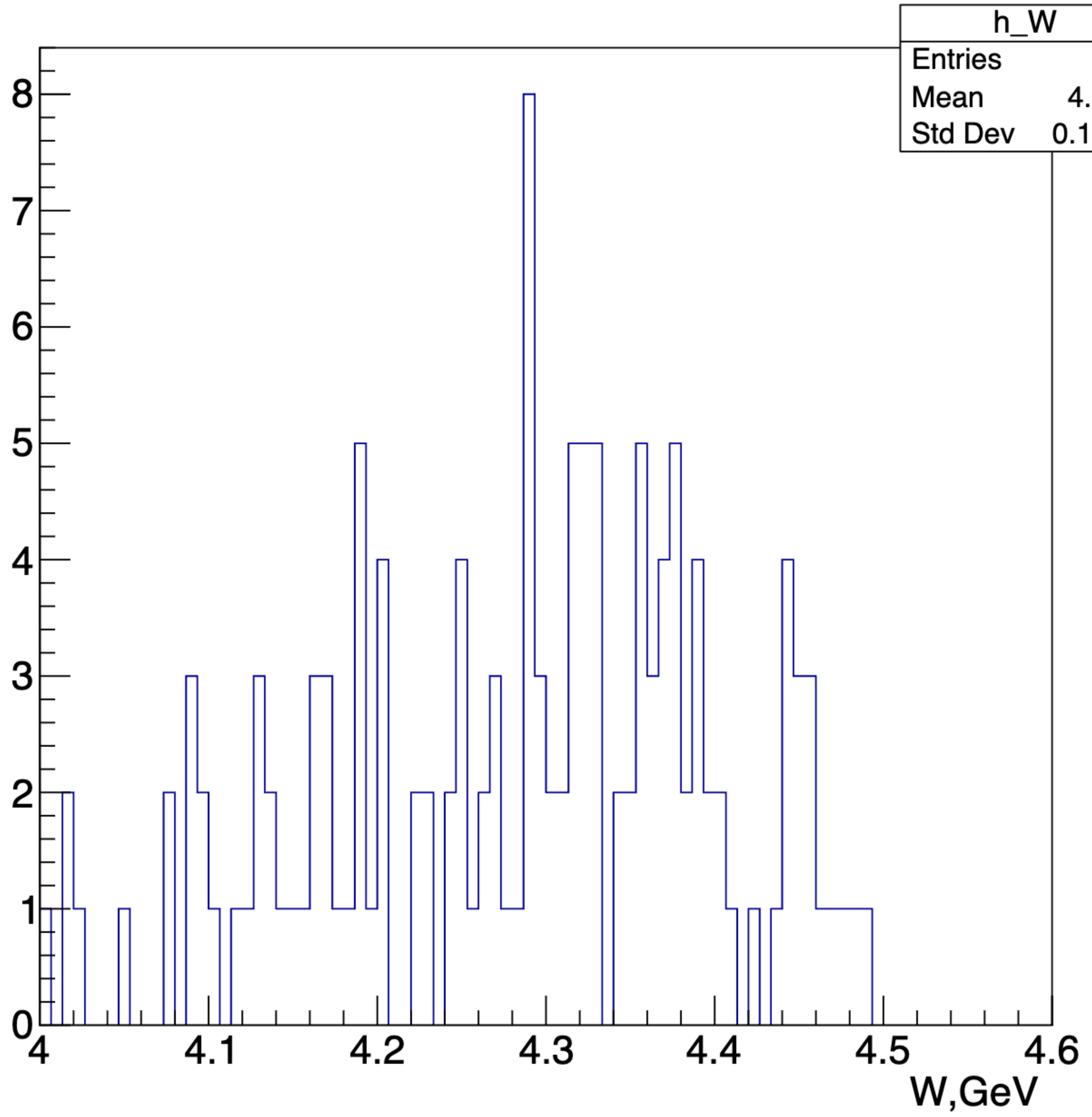
$ep \rightarrow e'p'J/\psi \rightarrow e'e^+p'(e^-)$

- For the reaction $ep \rightarrow e'p'e^+(e^-)$
- We select one electron in FT, one positron in FD and one proton in FD.
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^+} - p_{e'} - p_{p'}$
- The peak on the distribution should be around the mass of the missing lepton.
- We keep events with $E_\gamma > 8.1\,\mathrm{GeV}$ where $E_\gamma = E_{beam} - E_{e'}$
- We apply a cut in the missing mass as $|M_X| < 0.1$
- To get the number of J/ψ, we can look at the missing mass $M_X(e'p') = e + p - e' - p'$



$M_X(e'p')$

Hadronic Mass $ep \to e'p'J/\psi \to e'e^+(e^-)p'$



Hadronic mass. Topology: $ep \to e'e^+(e^-)p'$

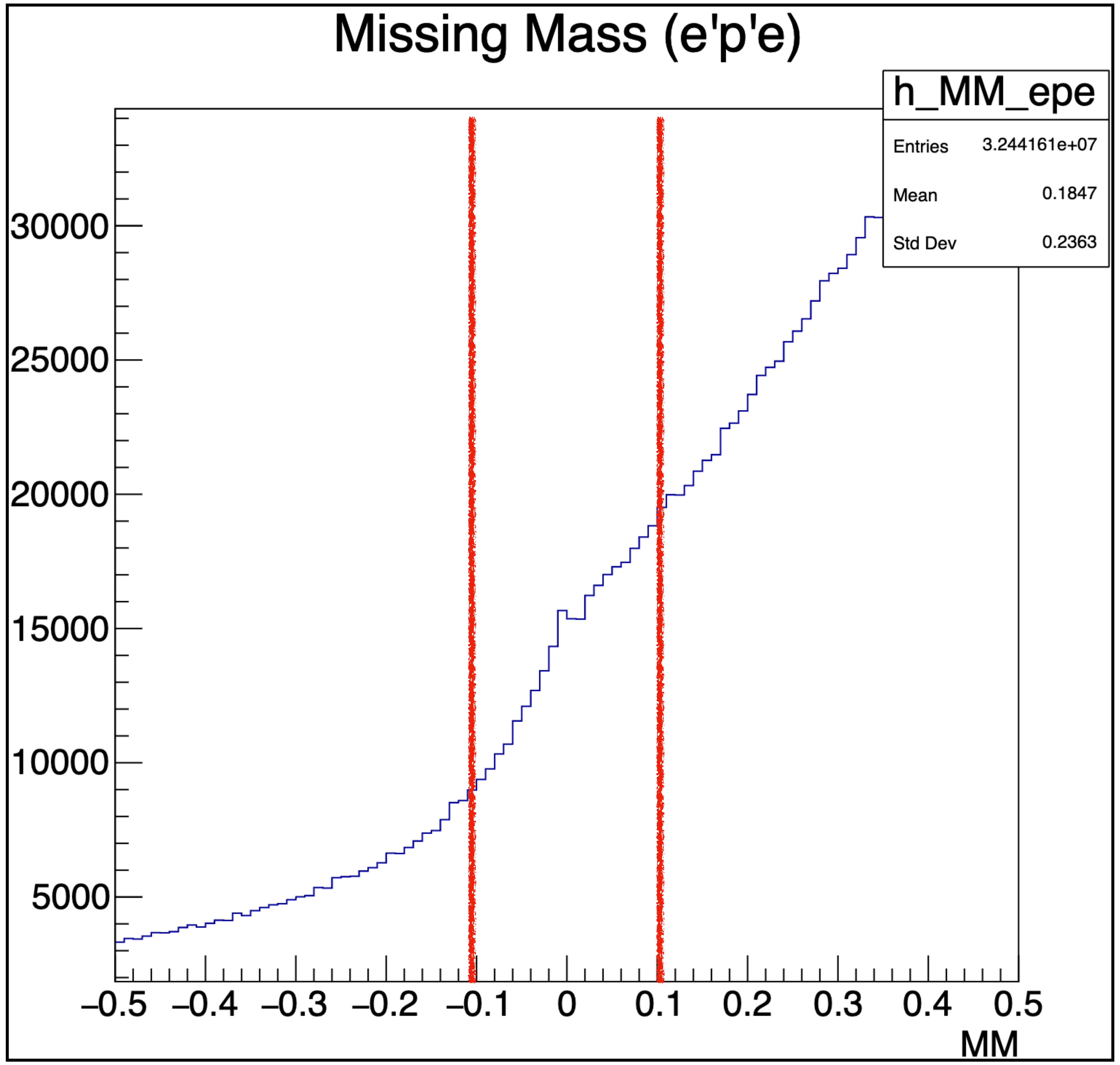
$$W = \sqrt{m_p^2 + 2m_pE_\gamma - Q^2}$$

$$E_\gamma = E_{beam} - E_{e'}$$

$$Q^2 = 2E_{beam}E_{e'}(1 - \cos(\theta_{e'}))$$

$ep \to e'p'J/\psi \to e'e^-p'(e^+)$

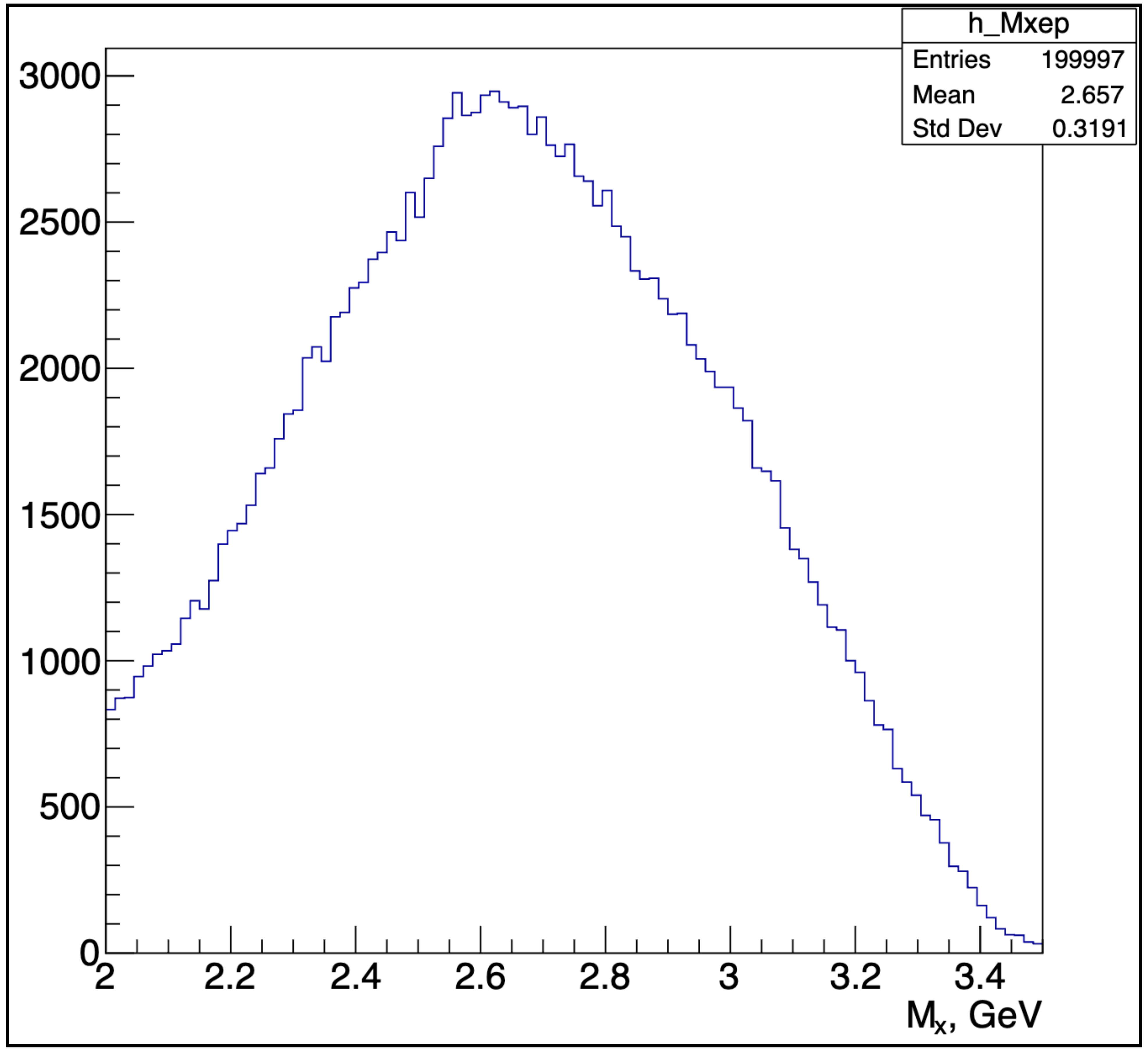
- For the reaction $ep \to e'p'e^-(e^+)$
- We select one electron in FT, one positron in FD and one proton in FD.
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e'} - p_{p'}$
- The peak on the distribution should be around the mass of the missing lepton.
- We keep events with $E_\gamma > 8.1$ GeV where $E_\gamma = E_{beam} - E_{e'}$
- We apply a cut in the missing mass as $|M_X| < 0.1$
- To get the number of J/ψ, wee can look at the missing mass $M_X(e'p') = e + p - e' - p'$



Missing mass distribution for the final state $e'e^-p'$.

$ep \to e'p'J/\psi \to e'e^-p'(e^+)$

- For the reaction $ep \to e'p'e^-(e^+)$
- We select one electron in FT, one positron in FD and one proton in FD.
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e'} - p_{p'}$
- The peak on the distribution should be around the mass of the missing lepton.
- However, upon reaching this stage, we observe a significant amount of background. Even with ore rigorous cuts, the background remains substantial and is not significantly reduced. How to solve this?



$M_X(e'p')$

Using machine learning…

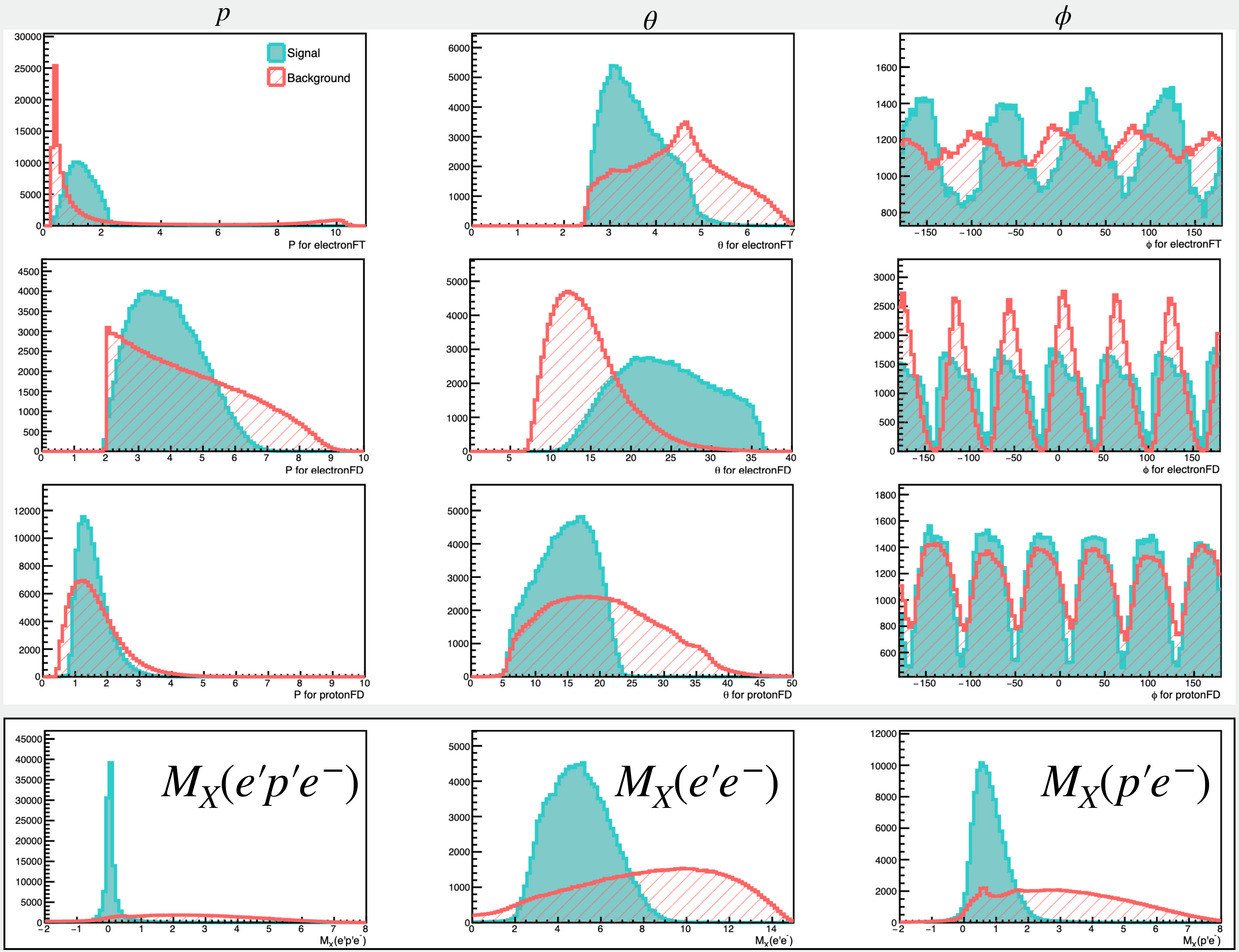
- Signal - MC
- Background - Data: We select events where I have in the final state $e'p'e^-\pi^+$ or $e'p'e^-\pi^-$ or $e'p'e^-\gamma$
- We use as input variables $e'(P,\theta,\phi)$, $p'(P,\theta,\phi)$, $e^-(P,\theta,\phi)$ and $M_X(e'p'e^-)$ $M_X(e'e^-)$ and $M_X(p'e^-)$ (12 variables)
- We are doing test on BDT, MLP and BDTG models
- Preliminary results are promising, but further investigation is ongoing.

Forward Tagger e'

Forward Detector e^-

Forward Detector p'

Missing mass variables



Conclusion

- Measured number of J/ψ events using various reaction topologies, leveraging tagged analysis with both inbending and outbending configurations

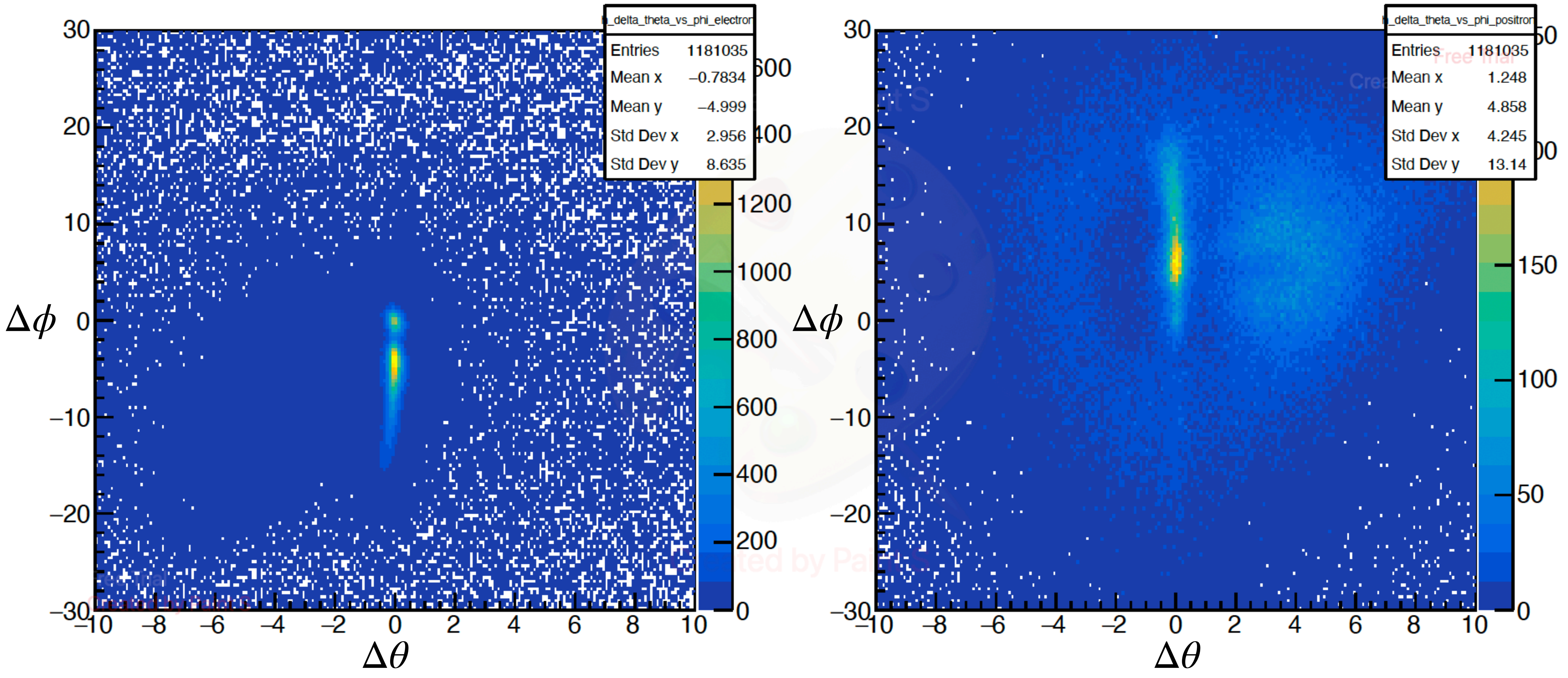
- Ongoing work focuses on optimizing cuts, improving machine learning models, and cross-section extractions.

Topology	Number J/ψ in $M(e^+e^-)$ distribution	Mean [GeV]	Sigma	Number J/ψ in $M_X(e'p')$ distribution	Mean [GeV]	Sigma
$ep \to e'p'J/\psi \to e'e^+e^-(p')$	78 +/- 12	3.081 +/- 0.012	0.0454 +/- 0.0048	-	-	-
$ep \to e'p'J/\psi \to e'e^+e^-p'$	37 +/- 17	3.081 +/- 0.086	0.0481 +/- 0.0348	36 +/- 9	3.101 +/- 0.007	0.02076 +/- 0.00751
$ep \to e'p'J/\psi \to e'p'e^+(e^-)$	-	-	-	67 +/- 14	3.109 +/- 0.006	0.02522 +/- 0.00626
$ep \to e'p'J/\psi \to e'p'e^-(e^+)$	-	-	-	Working on it		

Thank you!

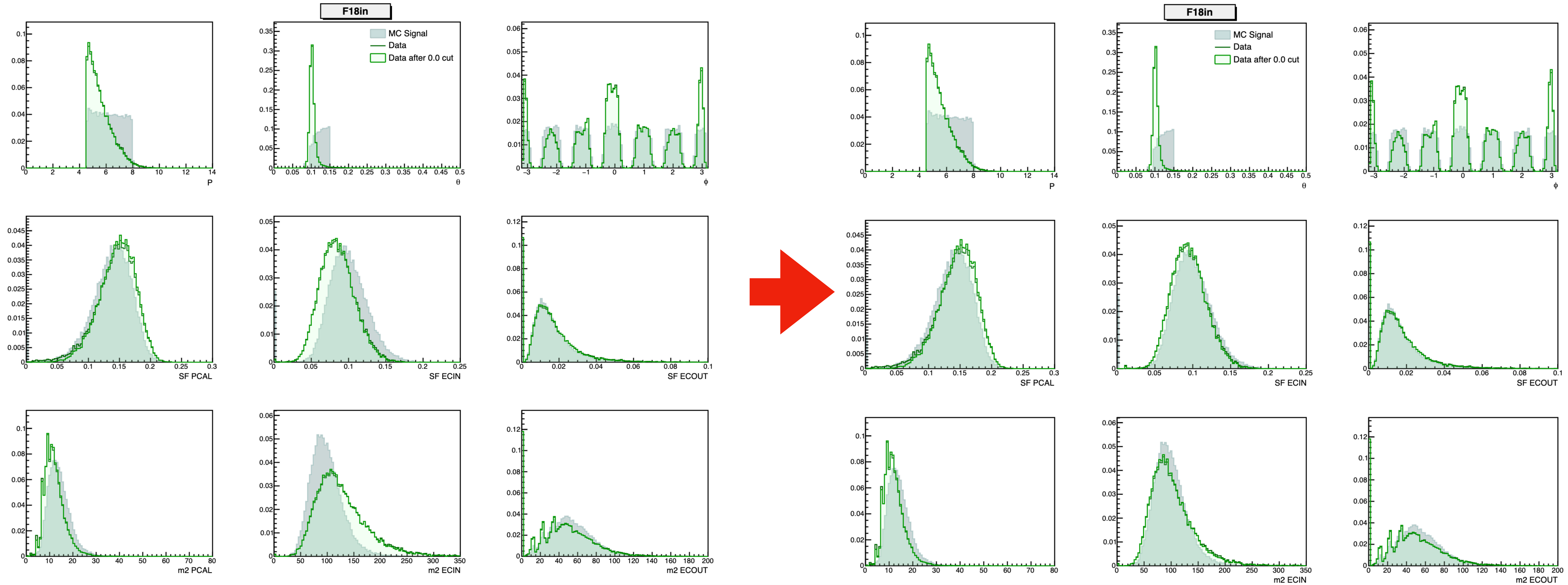
Event Selection

- First, a selection of events is done using the CLAS12 QADB tool is done
- Radiative photons with θ coincidence with $|\Delta\theta| < 0.7$ for energy loss correction
- Energy corrections for proton and energy correction for eFT



$\Delta\phi$ vs $\Delta\theta$ distributions for electrons (left) and positrons (right). Spring 2019 Pass2 data set

Corrections to SF and m2 ECAL



Configuration	Fall 2018 Inbending		Fall 2018 Outbending		Spring 2019	
Variable	SF	m^2	SF	m^2	SF	m^2
Correction e^+	+0.01	$*0.8$	+0.03	$*1.0$	+0.01	$*0.8$
Correction e^-	+0.02	$*0.8$	+0.05	$*1.1$	+0.03	$*0.8$