J/psi photoproduction near threshold in CLAS12

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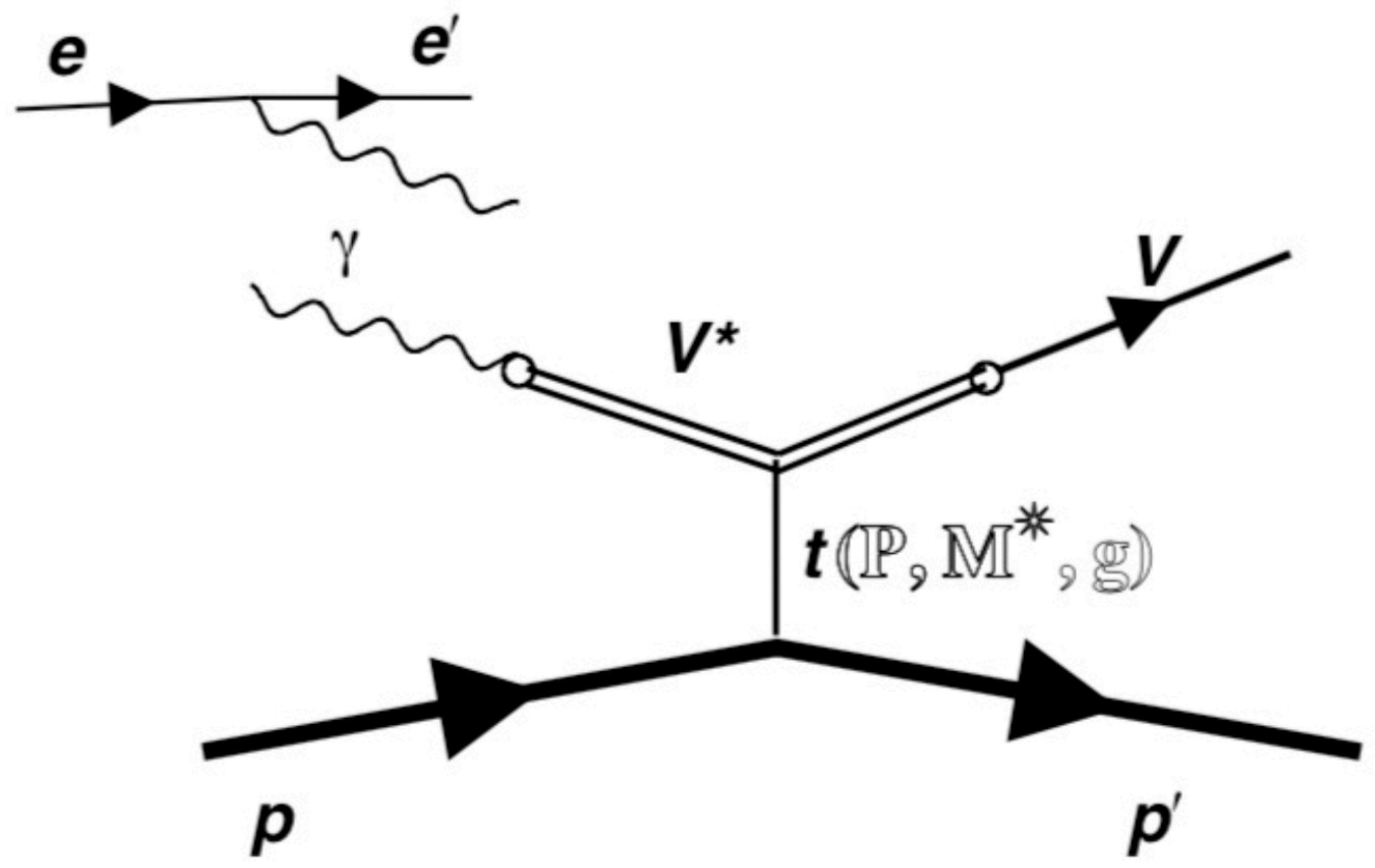
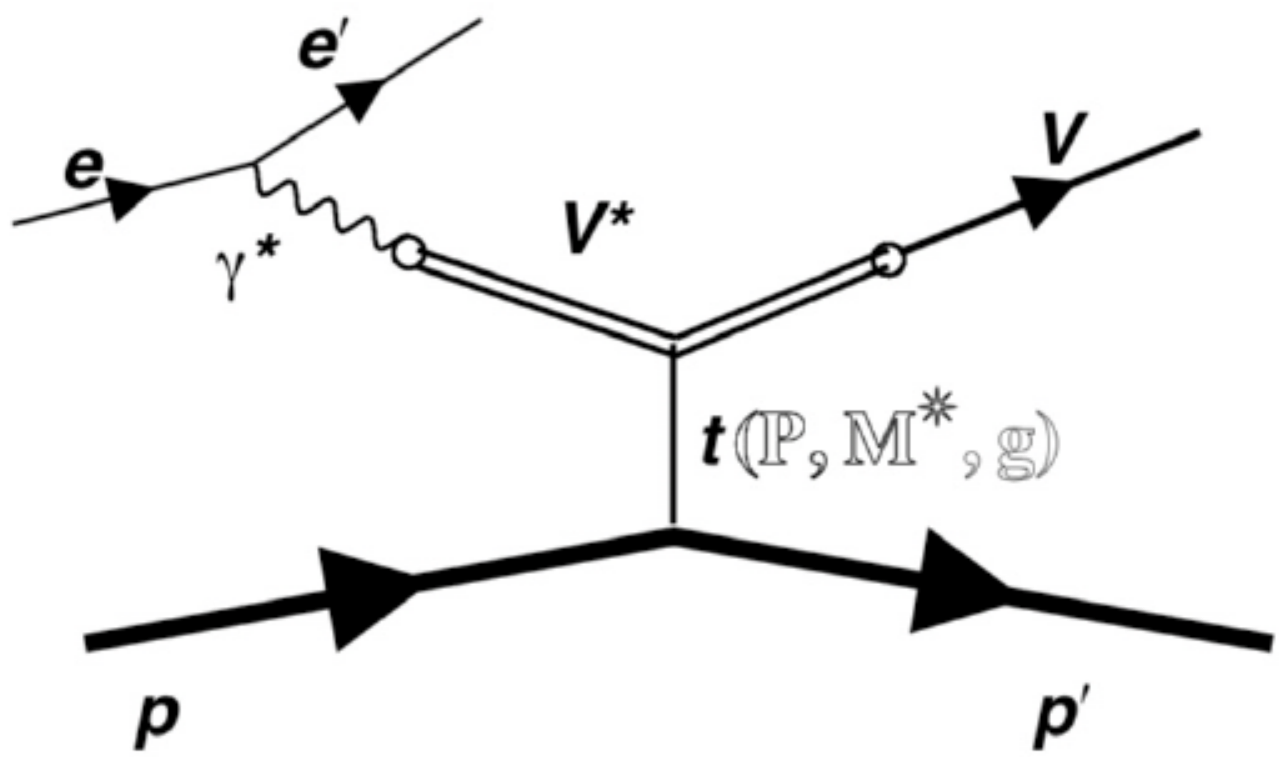
Motivation

- The production process of the J/ψ meson serves as a unique probe of the structure of the nucleon.

- The production of a vector meson such as the J/ψ in an scattered electron experiment can be described as $ep \rightarrow e'J/\psi p'$.

- For the measurement of J/ψ production near threshold, two mechanisms contribute to the process: pure photoproduction and electroproduction.





Motivation

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

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

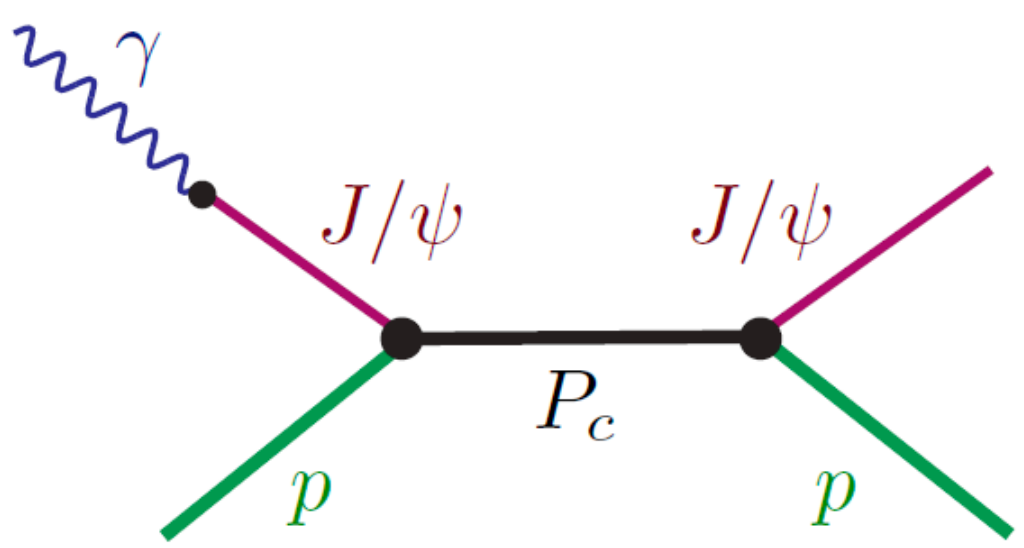
Where $L = N_e \cdot N_p$, $Br = 0.06$ and η is the detector efficiency.

- The electroproduction cross section can be compared to photoproduction by integrating over Q^2 and W accounting for the virtual photon flux factor Γ_T, which relates the virtual photon-induced process to the equivalent real-photon cross section.

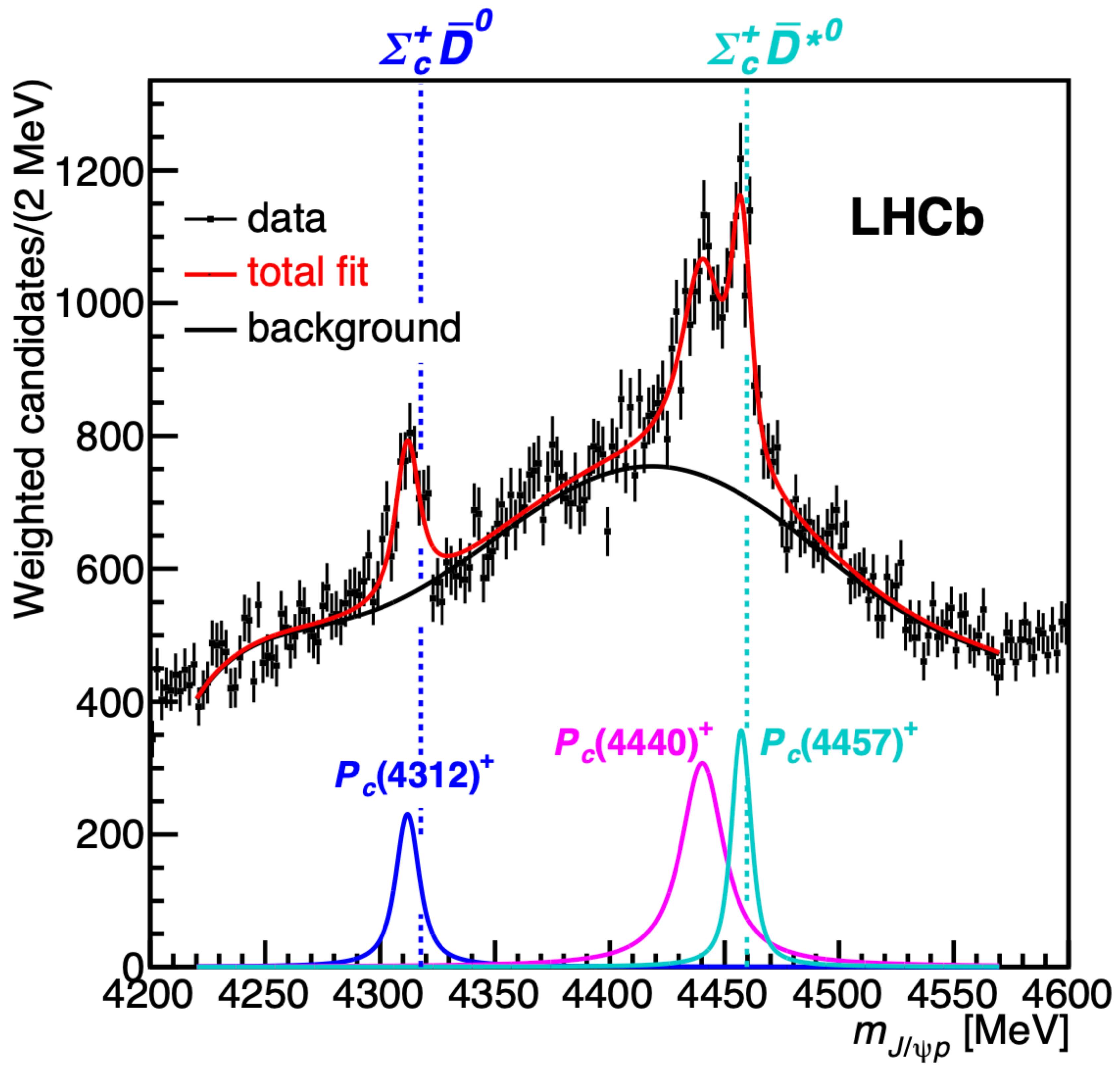
$$\frac{d\sigma}{dt} = \Gamma_T \frac{d\sigma_\gamma}{dt}$$

Motivation

- The LHCb collaboration reported that the P_c structures of the decay channel $P_c^+ \to J/\psi p$ consisted on $P_c(4312)^+$, $P_c(4440)^+$ and $P_c(4457)^+$.



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



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

R. Aaij et al. Phys. Rev. Lett., 122,22, (2019).
V. Kubarovsky and M. B. Voloshin, Phys. Rev. D ., 92, 031502,R , (2015).

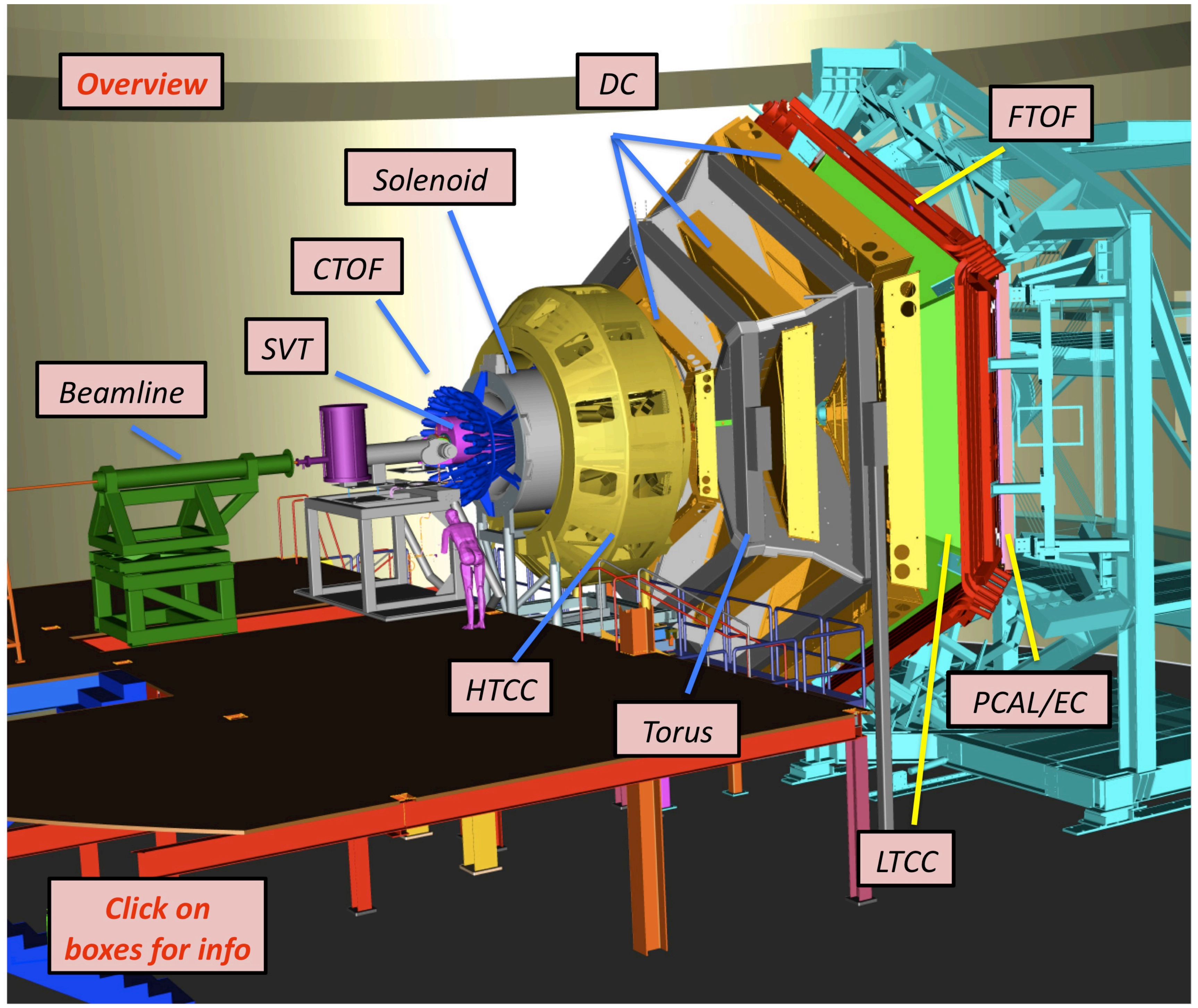
Experimental setup: CLAS12

- The Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab (JLab) accelerates and recirculates electrons at up to 12 GeV. After the beam reaches its maximum energy, this is redirected to Hall B, where the CEBAF Large Acceptance Spectrometer (CLAS12) detector is located.

- The particles on the CLAS12 detector can be detected and identified by measuring their momenta, time in vertex, the number of photons produced in threshold Cherenkov counters, and energy losses in the calorimeters and scintillator counters.

- Forward Detector (FD):
  - High-Threshold Cherenkov Counter (HTCC)
  - Low-Threshold Cherenkov Counter (LTCC)
  - Electromagnetic Calorimeter (ECAL)
  - Forward Time-Of-Flight (FTOF)
  - Drift Chambers (DC)

- Forward Tagger (FT)



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

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

- 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 topologies that are exploring:

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

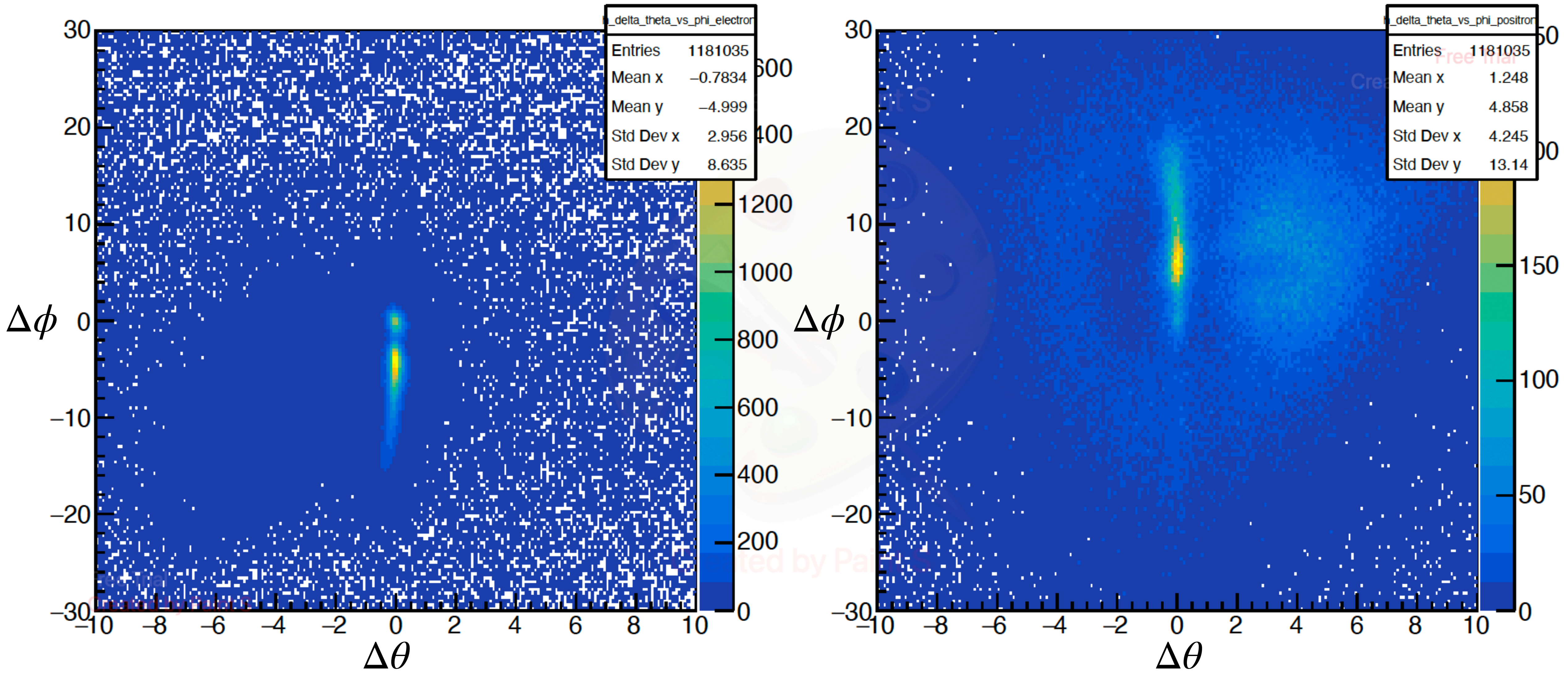
Event Selection

- First, a selection of events is done using the CLAS12 QADB tool.

- **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
  - $|\chi^2_{PID}| < 5$
  - $SF_{EC} \geq (0.195 - SF_{PCAL})$

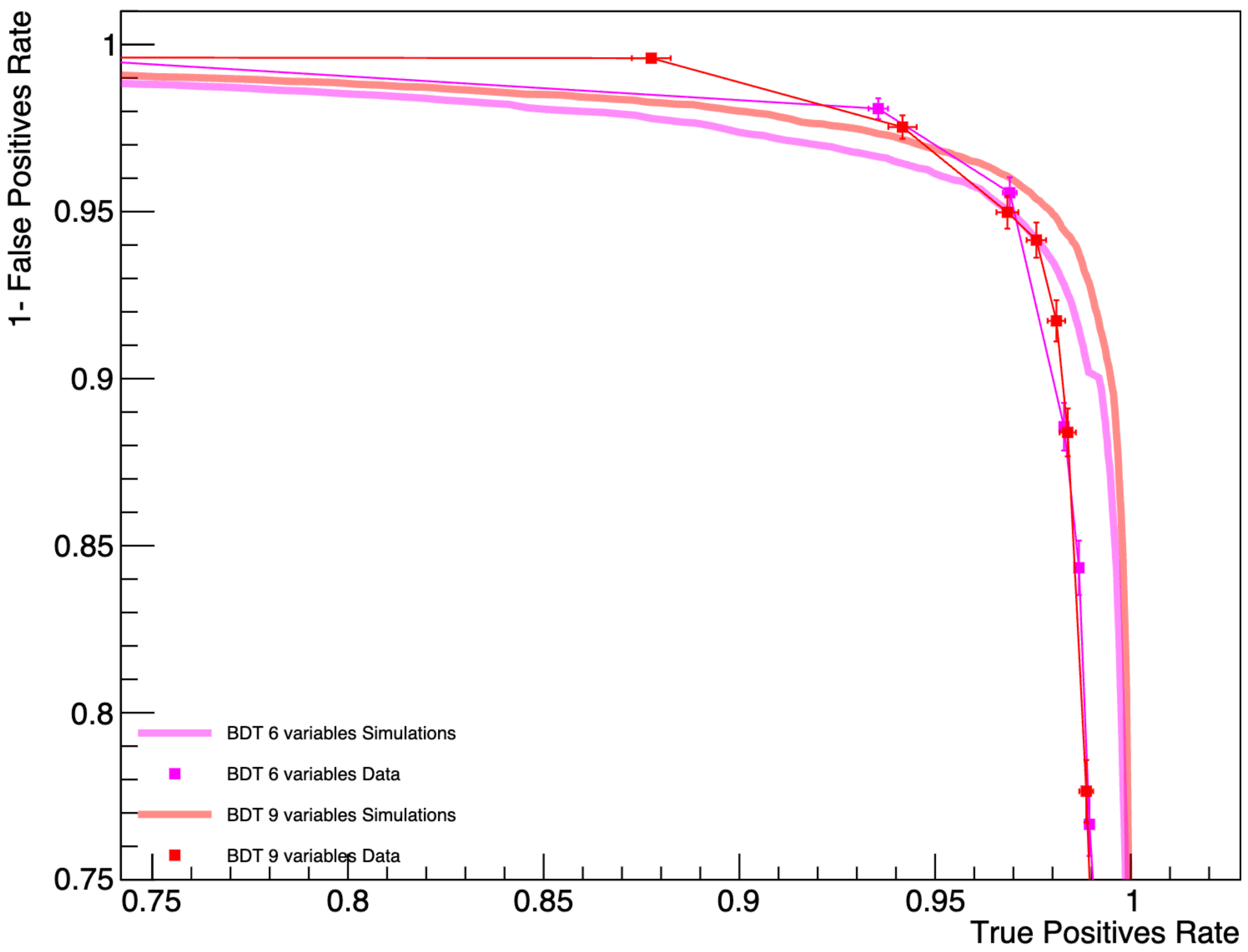
- Radiative photons detected at ECAL with θ coincidence $|\Delta\theta| < 0.7$ are detected for energy loss correction.



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

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.



ROC curve for 6 and 9 variable models for F18inbending

CLAS12 Note 2024-005

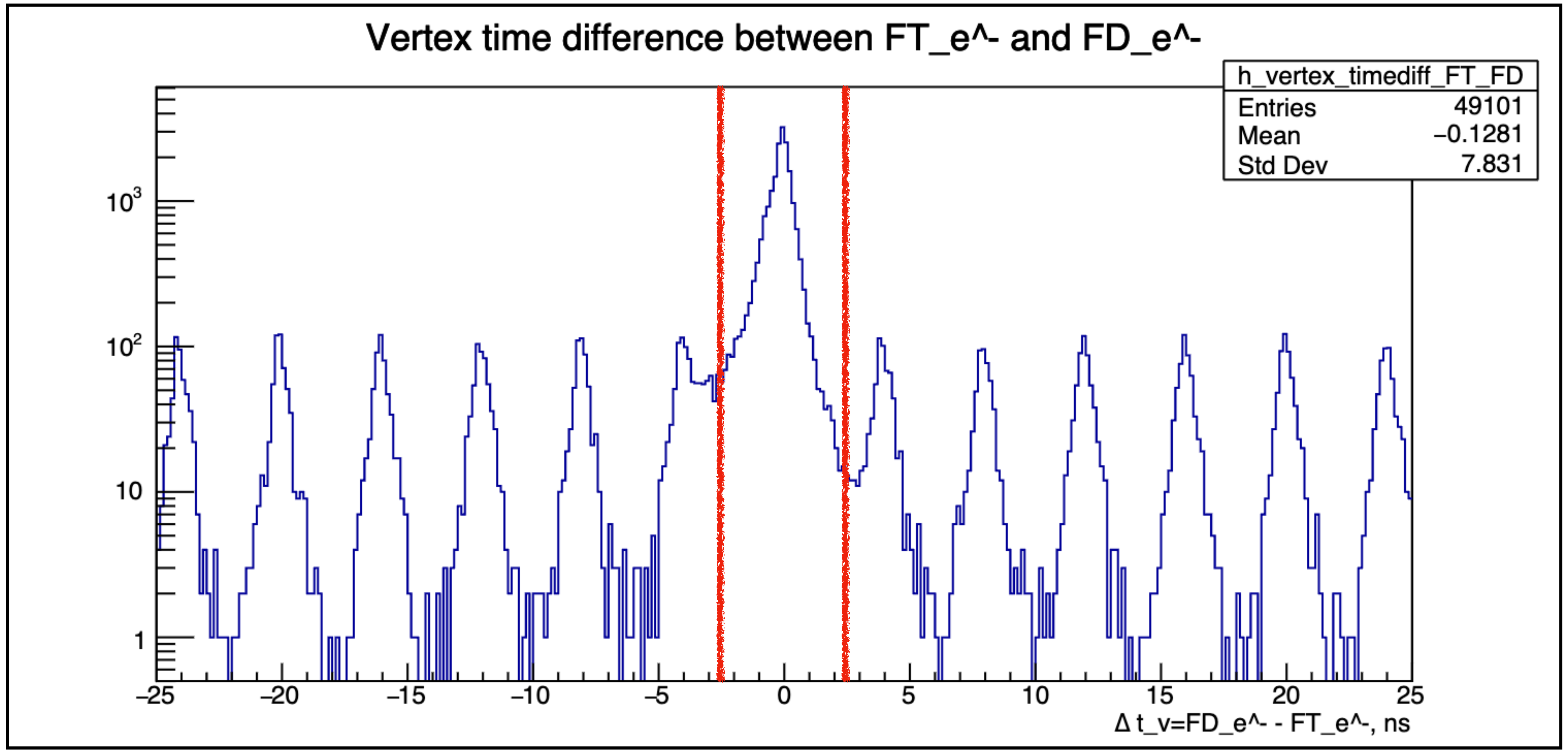
Event selection

- We select one electron in the Forward Tagger. We apply an energy correction for this electron.

- **Electron e^-**

  - Forward Tagger

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

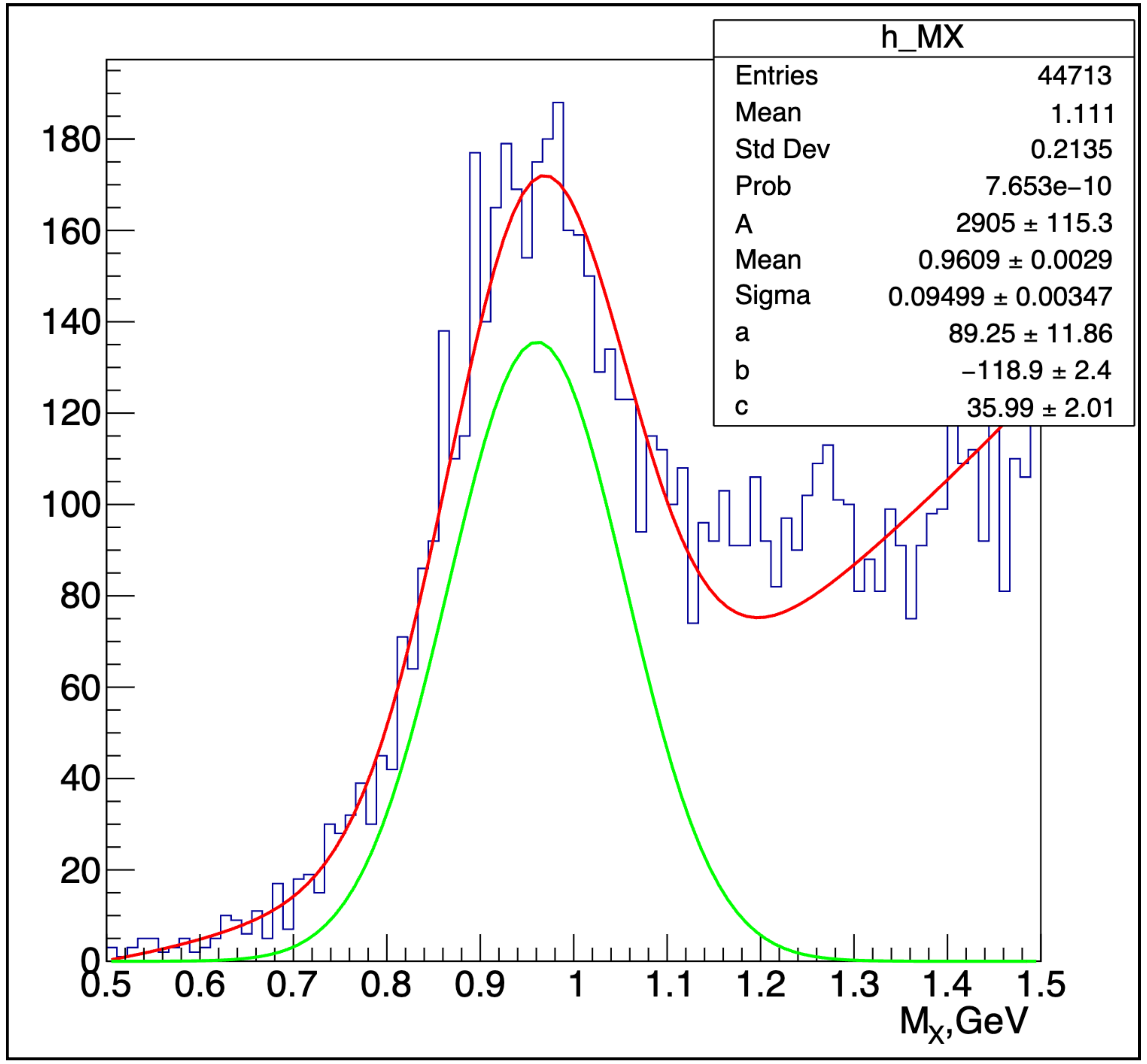


Vertex time difference between the electron in the FD and the electron in the FT

- The central peak shows well-matched events where both particles come from the same interaction vertex, while events outside this area are accidental coincidences. The 4ns spacing between peaks is due to the timing structure of the beam.

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

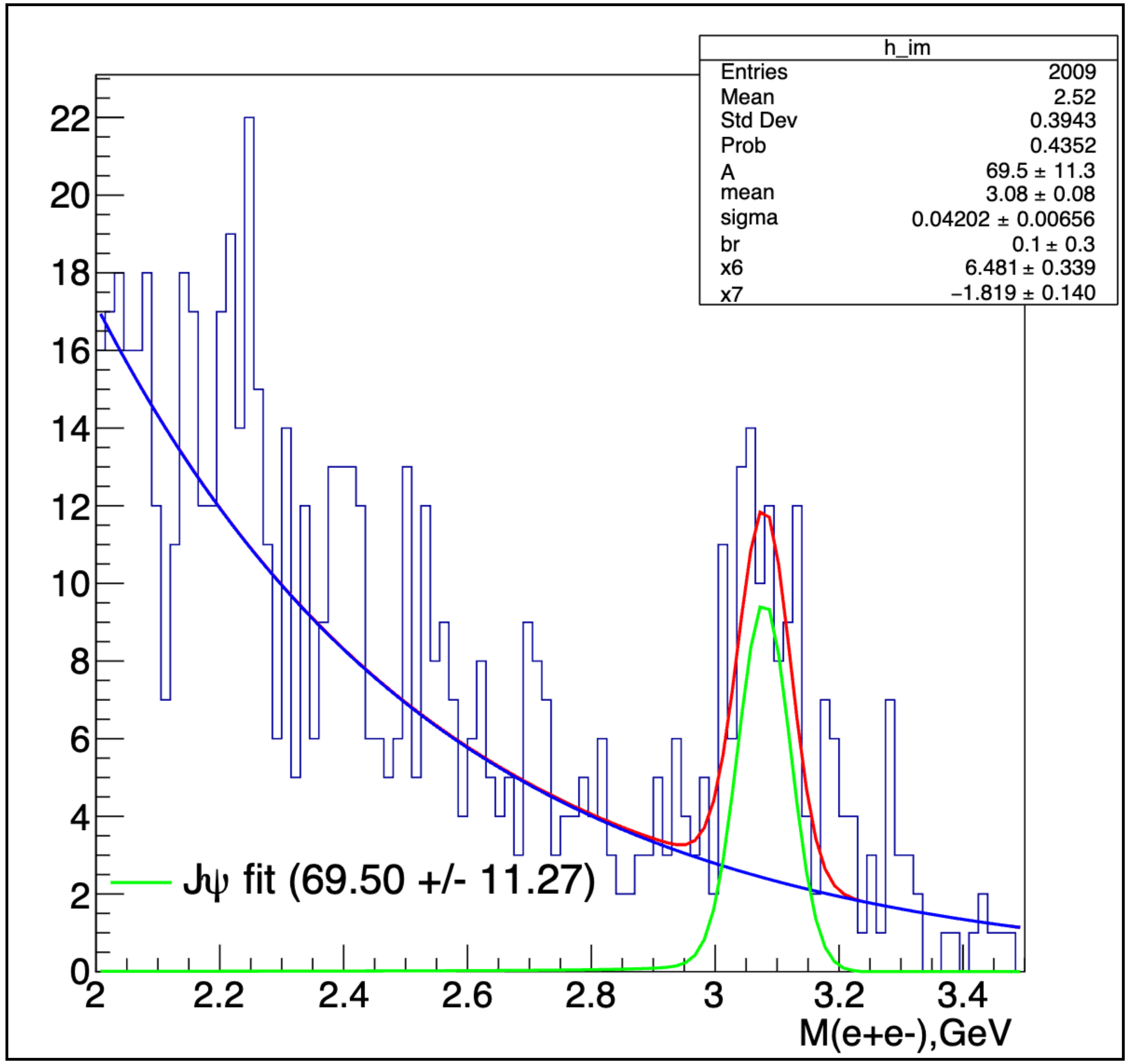
- For the reaction $ep \to e'e^+e^-(p')$
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e^+} - p_{e'}$
- We keep events with $E_\gamma > 8.1$ GeV where $E_\gamma = E_{beam} - E_{e'}$
- We calculate the missing mass as $M_X = \sqrt{p_X^2}$, where the peak on the distribution should be around the mass of the missing proton



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

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

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



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, one positron and one proton in the forward detector.

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

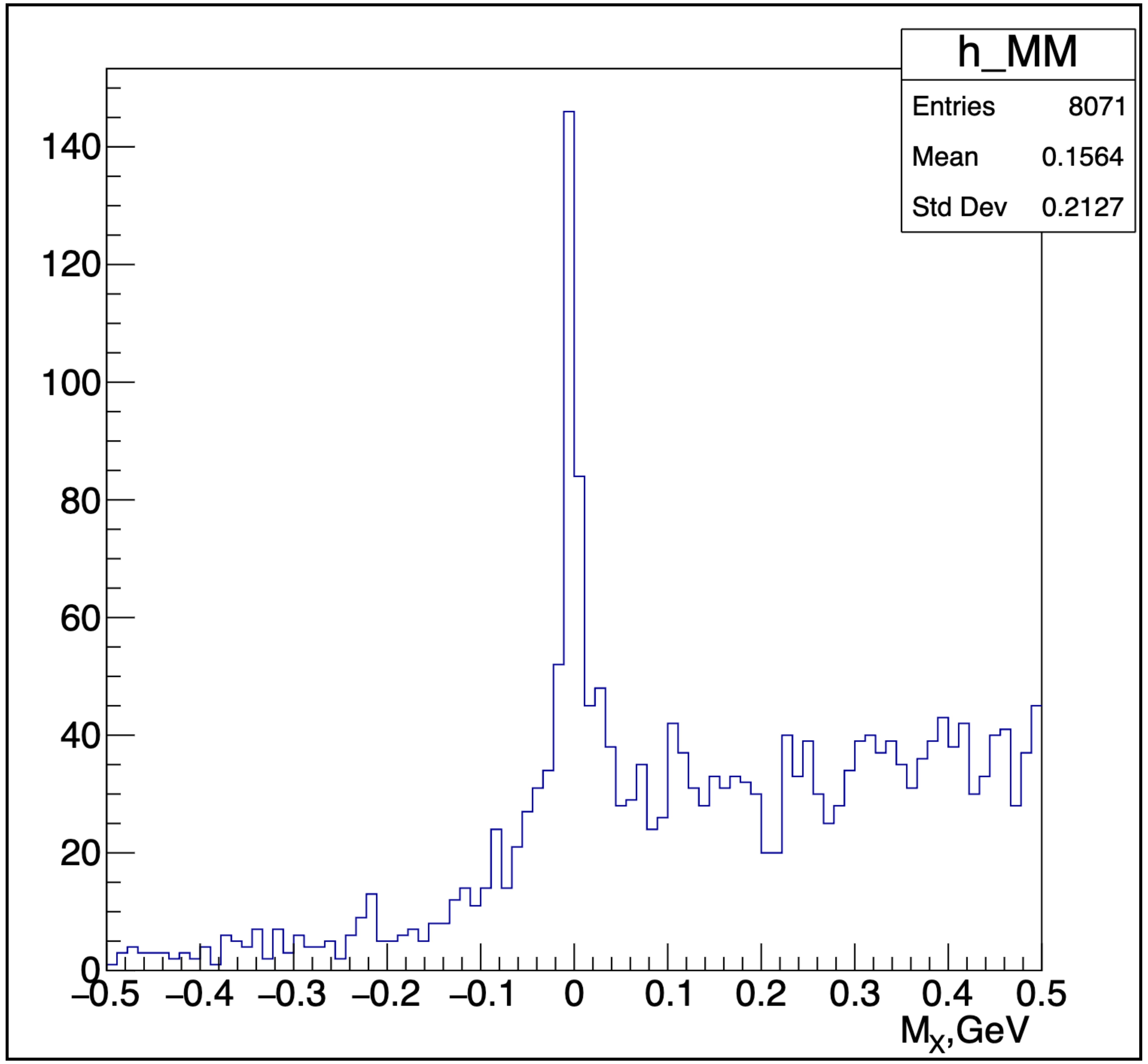
- Proton p
  - Forward Detector
  - $p >$ 0.4 GeV/c
  - $\beta >$ 0.1
  - $|\chi^2_{PID}|$<10

- 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
  - $|\chi^2_{PID}| < 5$
  - $SF_{EC} \geq (0.195 - SF_{PCAL})$

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

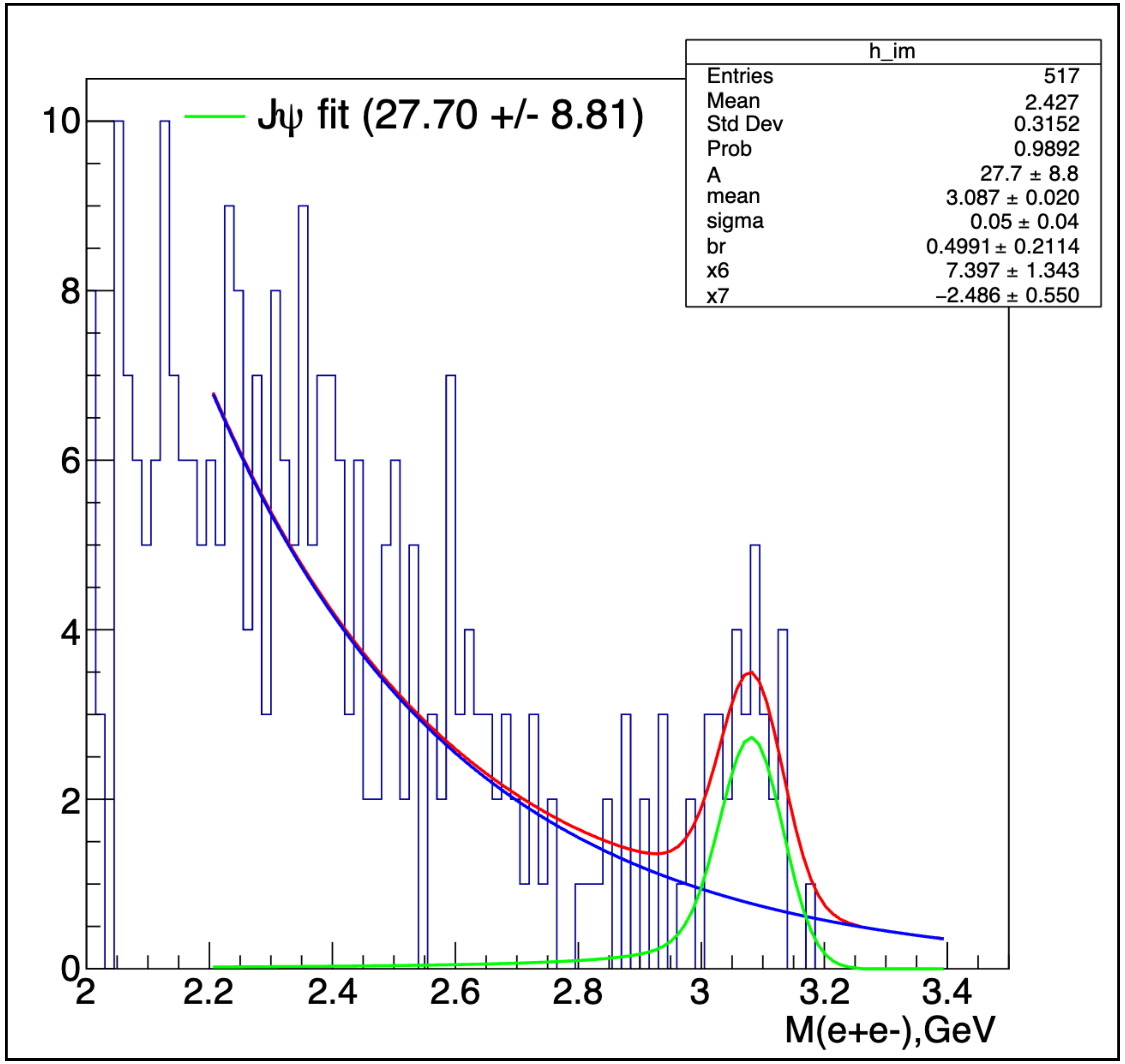
- For the reaction $ep \rightarrow e'e^+e^-p'$
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e^+} - p_{e'} - p_{p'}$
- We keep events with $E_\gamma > 8.1$ GeV where $E_\gamma = E_{beam} - E_{e'}$
- We looked at the missing mass of the reaction, $M_X^2 = p_X^2$ expecting it to peak at zero.



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

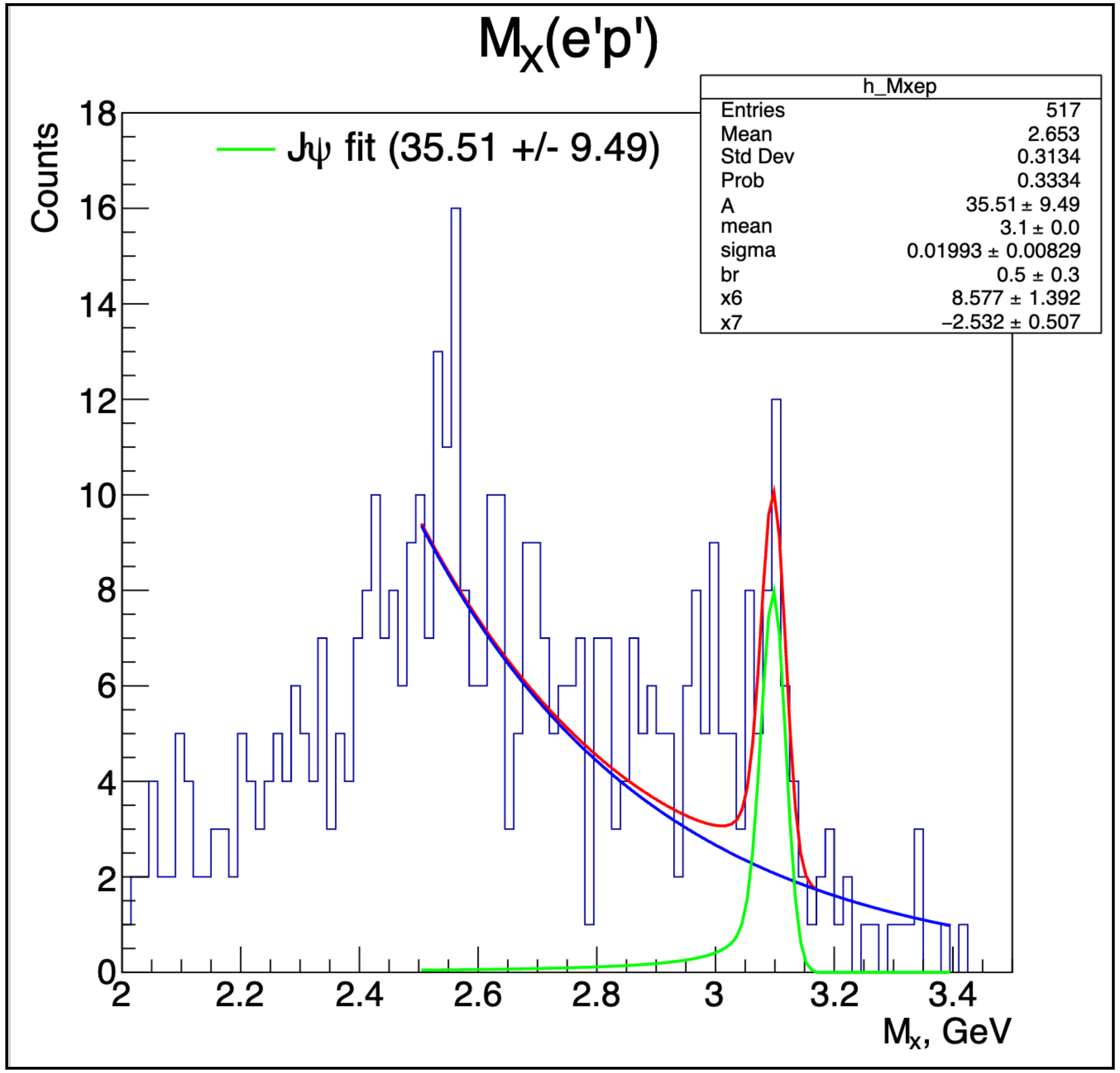
$ep \to e'p'J/\psi \to e'e^+e^-p'$

- 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 keep events with $E_\gamma > 8.1$ GeV where $E_\gamma = E_{beam} - E_{e'}$
- We looked at the missing mass of the reaction, $M_X^2 = p_X^2$ expecting it to peak at zero.
- We also apply a cut in the missing mass as $|M_X| < 0.1$
- We look at the Invariant mass distribution $M^2(e^-e^+) = (p_{e^-} + p_{e^+})^2$ in the 2.0 GeV to 3.5 GeV region



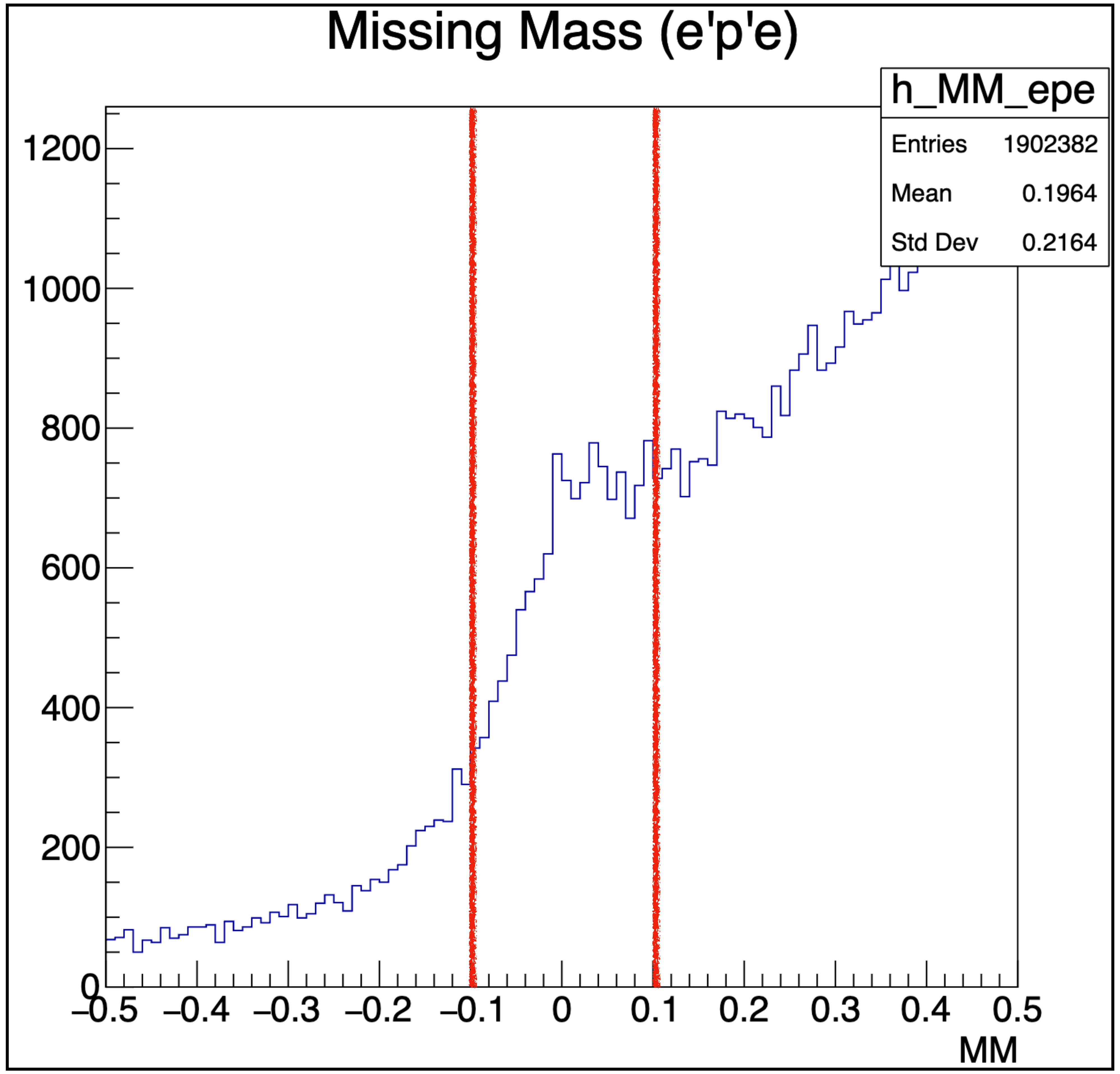
$ep \to e'p'J/\psi \to e'e^+e^-p'$

- 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 keep events with $E_\gamma > 8.1\,\mathrm{GeV}$ where $E_\gamma = E_{beam} - E_{e'}$
- We looked at the missing mass of the reaction, $M_X^2 = p_X^2$ expecting it to peak at zero.
- 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 $M_X(e'p') = e + p - e' - p'$



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

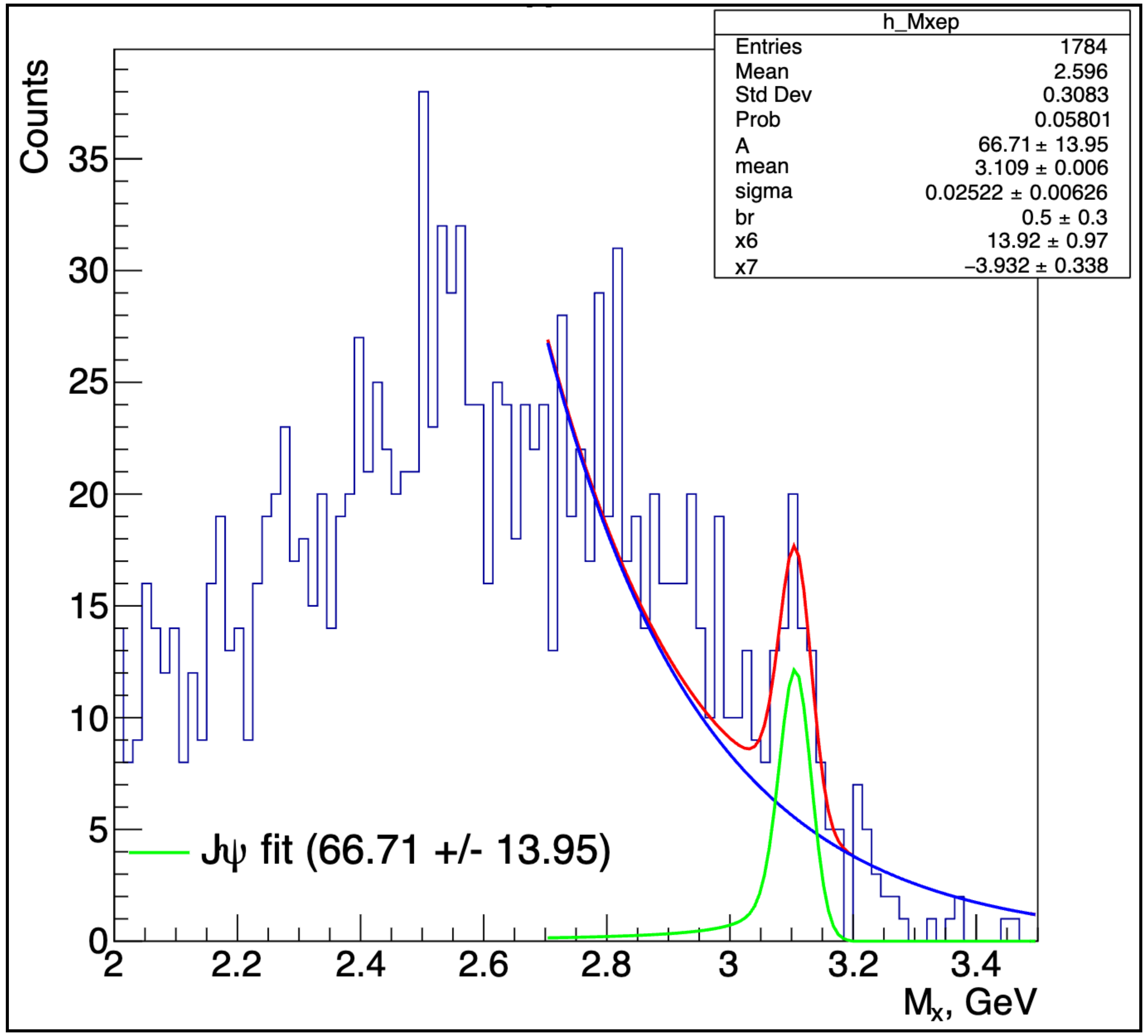
- For the reaction $ep \to e'p'e^+(e^-)$
- We select one electron in FT, one positron in FD and one proton in FD.
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^+} - p_{e'} - p_{p'}$
- We keep events with $E_\gamma > 8.1\,\text{GeV}$ where $E_\gamma = E_{beam} - E_{e'}$
- The peak on the distribution should be around the mass of the missing lepton.



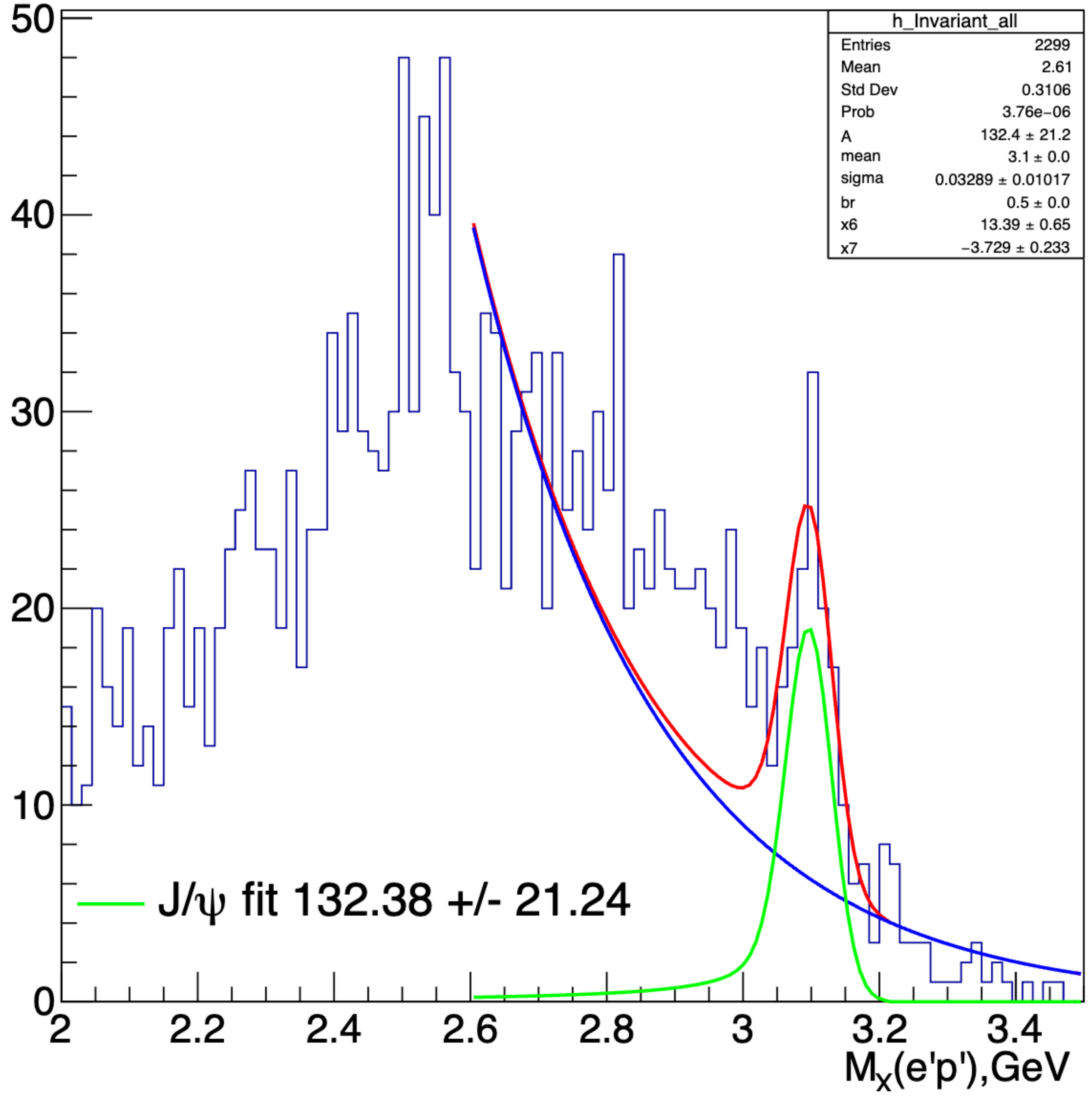
Missing mass distribution for the final state $e'e^+p'$.

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

- 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 $p_X = p_e + p_p - p_{e^+} - p_{e'} - p_{p'}$
- We keep events with $E_\gamma > 8.1$ GeV where $E_\gamma = E_{beam} - E_{e'}$
- The peak on the distribution should be around the mass of the missing lepton.
- 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 $M_X(e'p') = e + p - e' - p'$

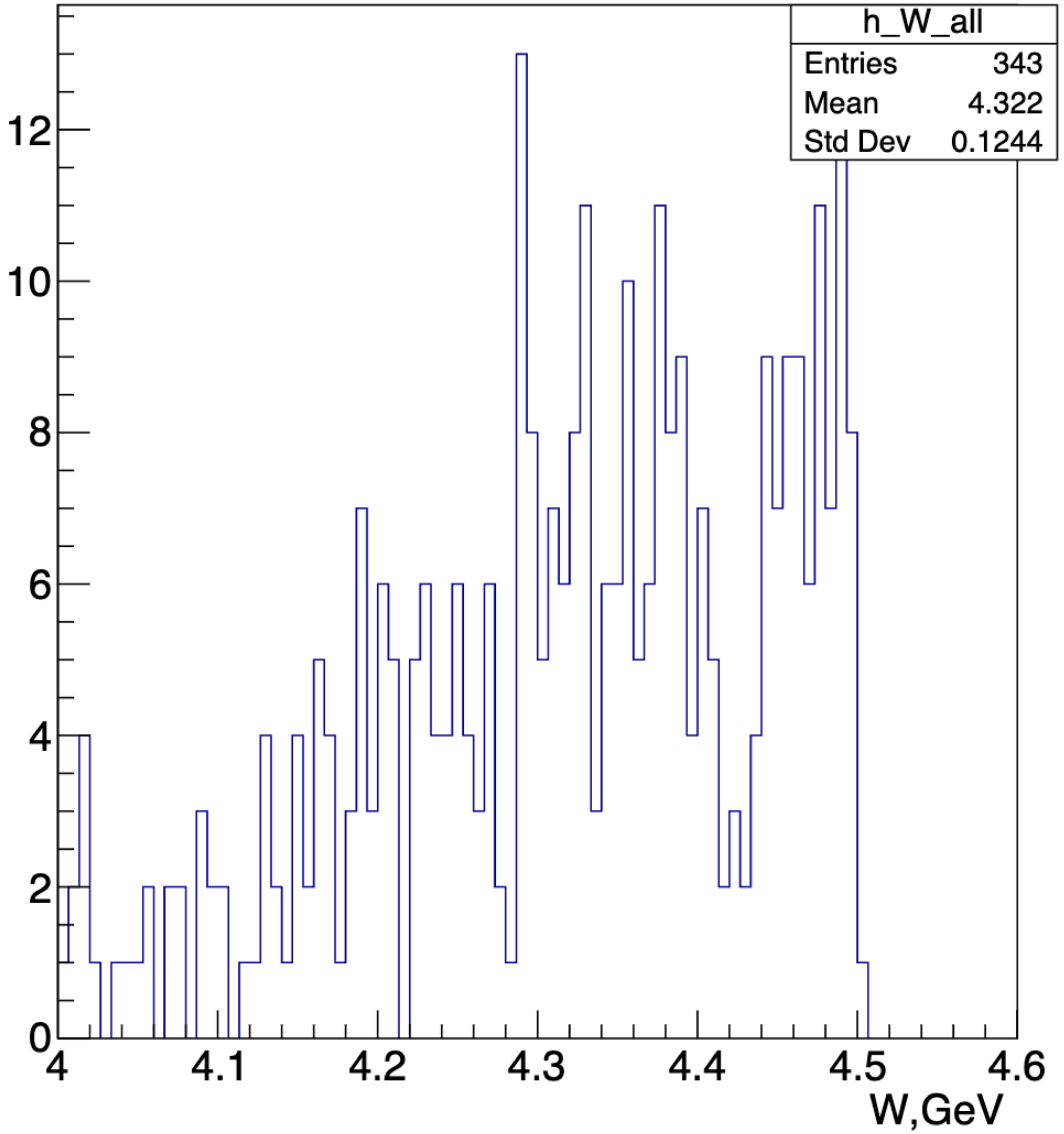


$M_X(e'p')$



Topology	N(J/psi) $M(e^+e^-)$	Mean [GeV]	Sigma	N(J/psi) $M_X(e'p')$	Mean [GeV]	Sigma
$ep \rightarrow e'p'J/\psi \rightarrow e'e^+e^-(p')$	69+/- 12	3.081 +/- 0.012	0.0454 +/- 0.0048	-	-	-
$ep \rightarrow e'p'J/\psi \rightarrow e'e^+e^-p'$	27 +/- 17	3.081 +/- 0.086	0.0481 +/- 0.0348	**36 +/- 9**	3.101 +/- 0.007	0.02076 +/- 0.00751
$ep \rightarrow e'p'J/\psi \rightarrow e'p'e^+(e^-)$	-	-	-	**67 +/- 14**	3.109 +/- 0.006	0.02522 +/- 0.00626

Hadronic Mass



- For this distribution, we consider events that fall into the mass range $2.95 < M(e^+e^-) < 3.2$ GeV
- The hadronic mass corresponds to the mass of the pentaquark P_c . We expect to see their existence in this distribution.

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

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

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

Summary

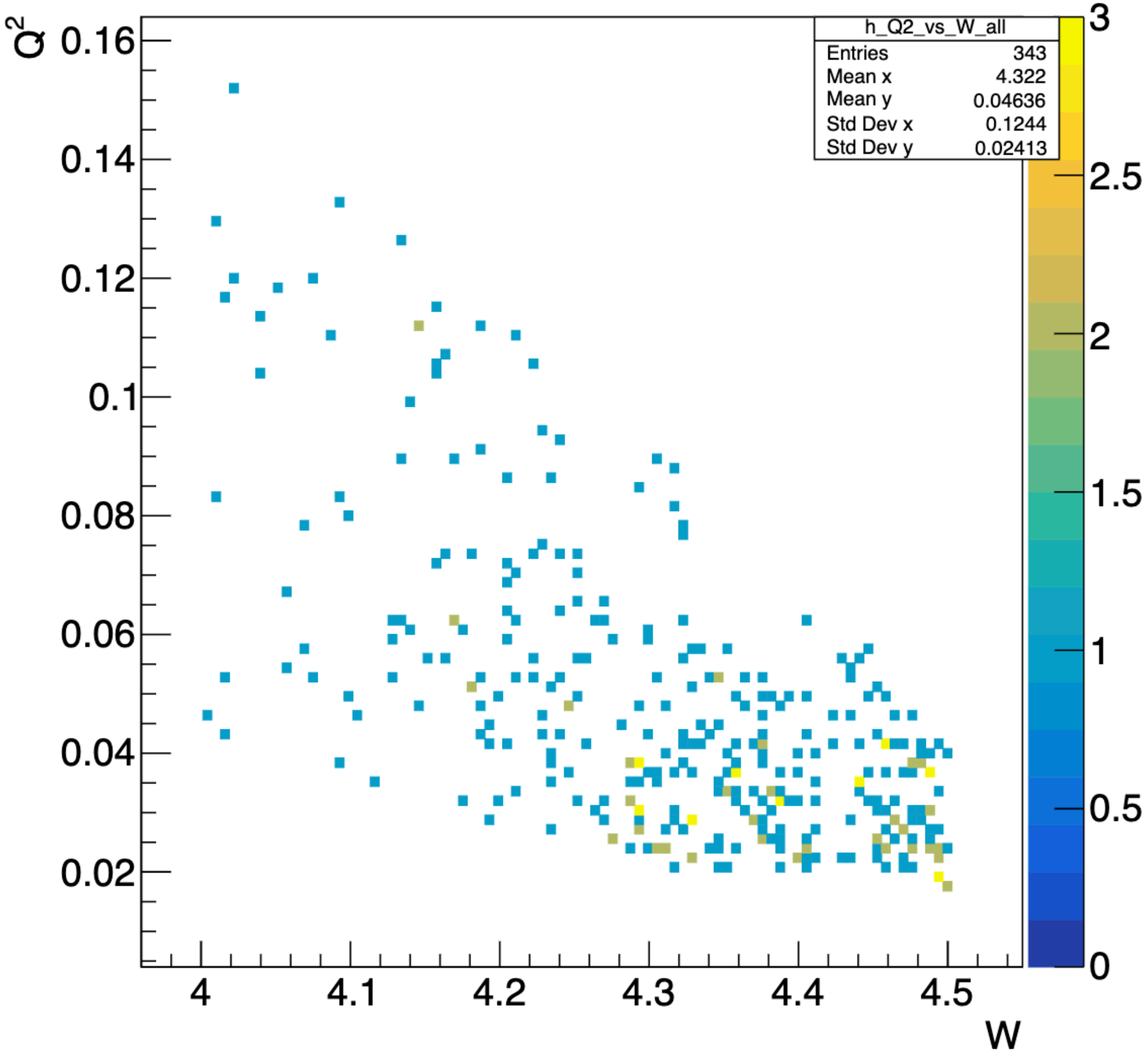
- The selection of events was carefully performed, and the number of J/ψ events was measured across various reaction topologies.

- Cross section calculations are being done at the moment!

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

Thank you!

Q^2 and W distribution

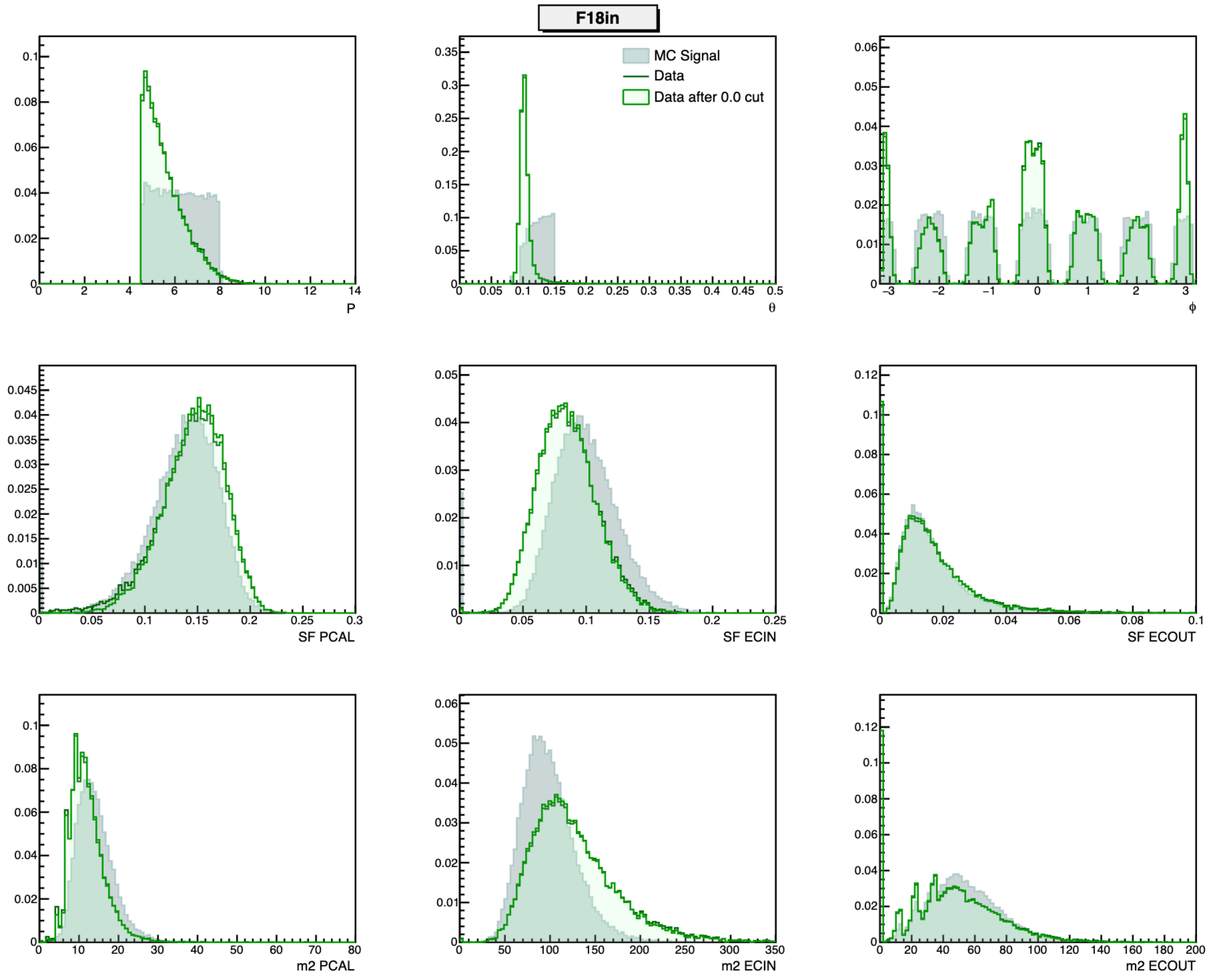


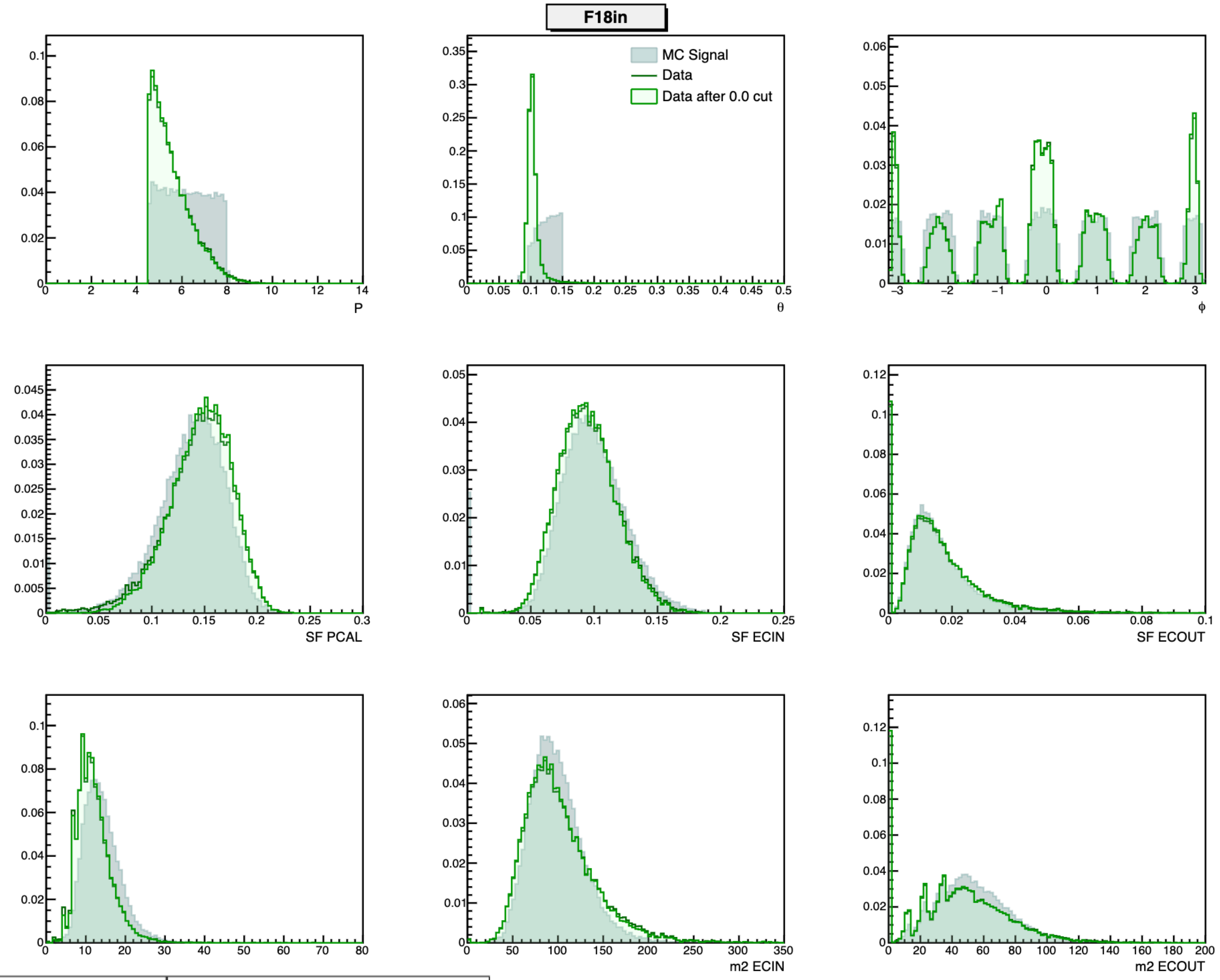
$$W = \sqrt{m_p^2 + 2m_pE_\gamma - Q^2}$$

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

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

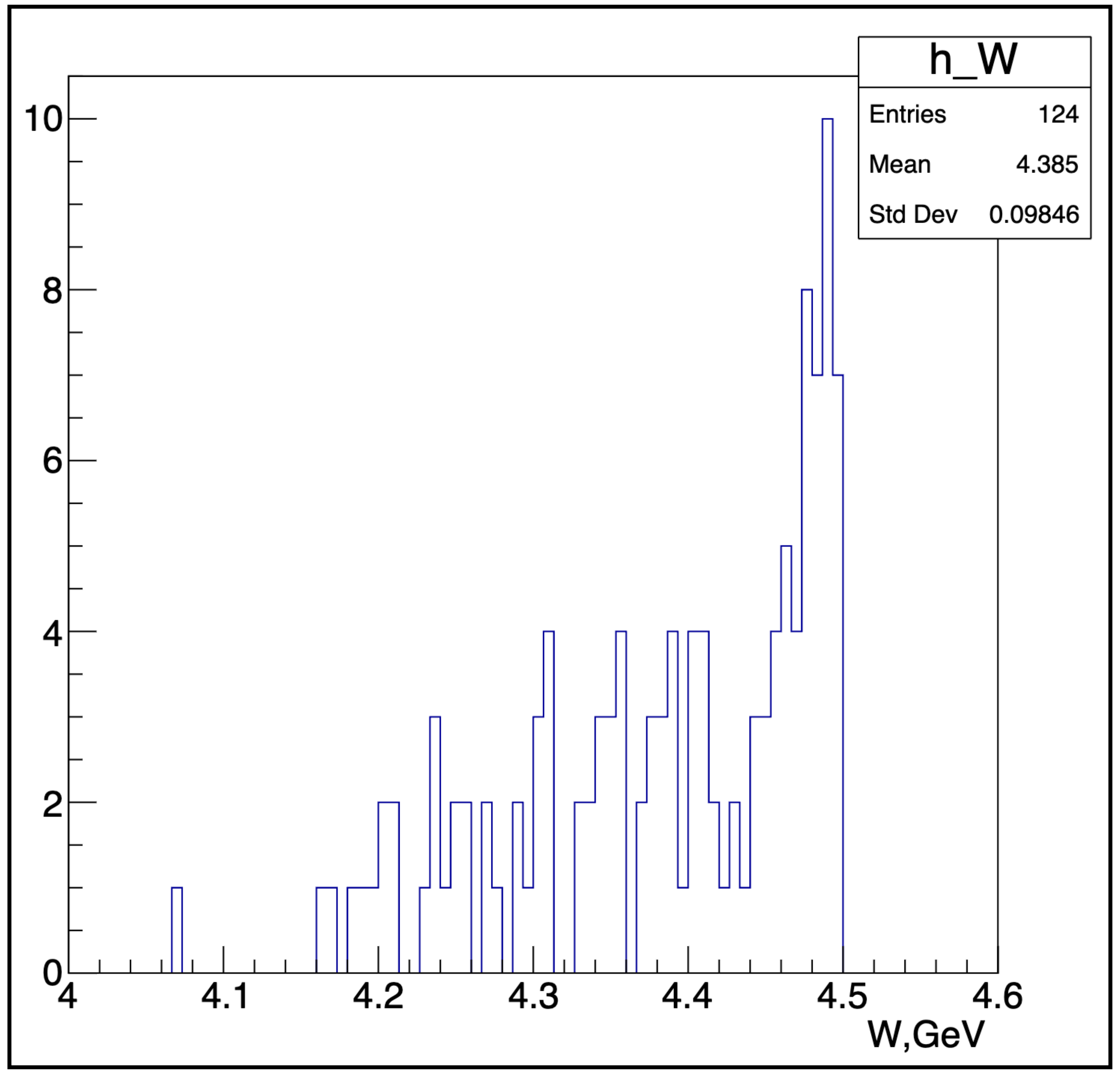
Corrections to SF and m2 ECAL



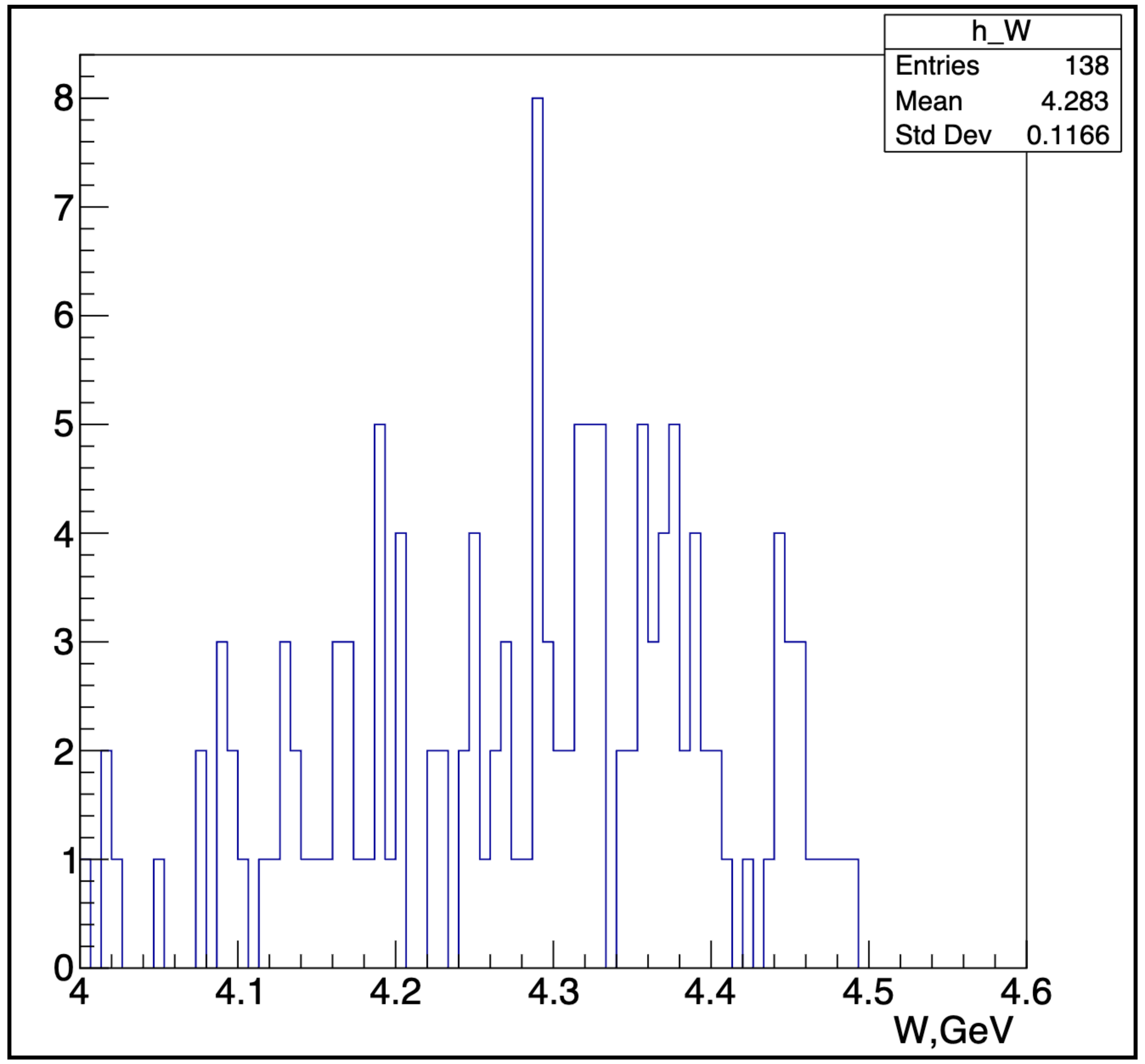


Configuration	Fall 2018 Inbending		Fall 2018 Outbending		Spring 2019	
Variable	SF	m^2	SF	m^2	SF	m^2
Correction e^+	$+0.01$	$*0.8$	$+0.03$	$*1.0$	$+0.01$	$*0.8$
Correction e^-	$+0.02$	$*0.8$	$+0.05$	$*1.1$	$+0.03$	$*0.8$

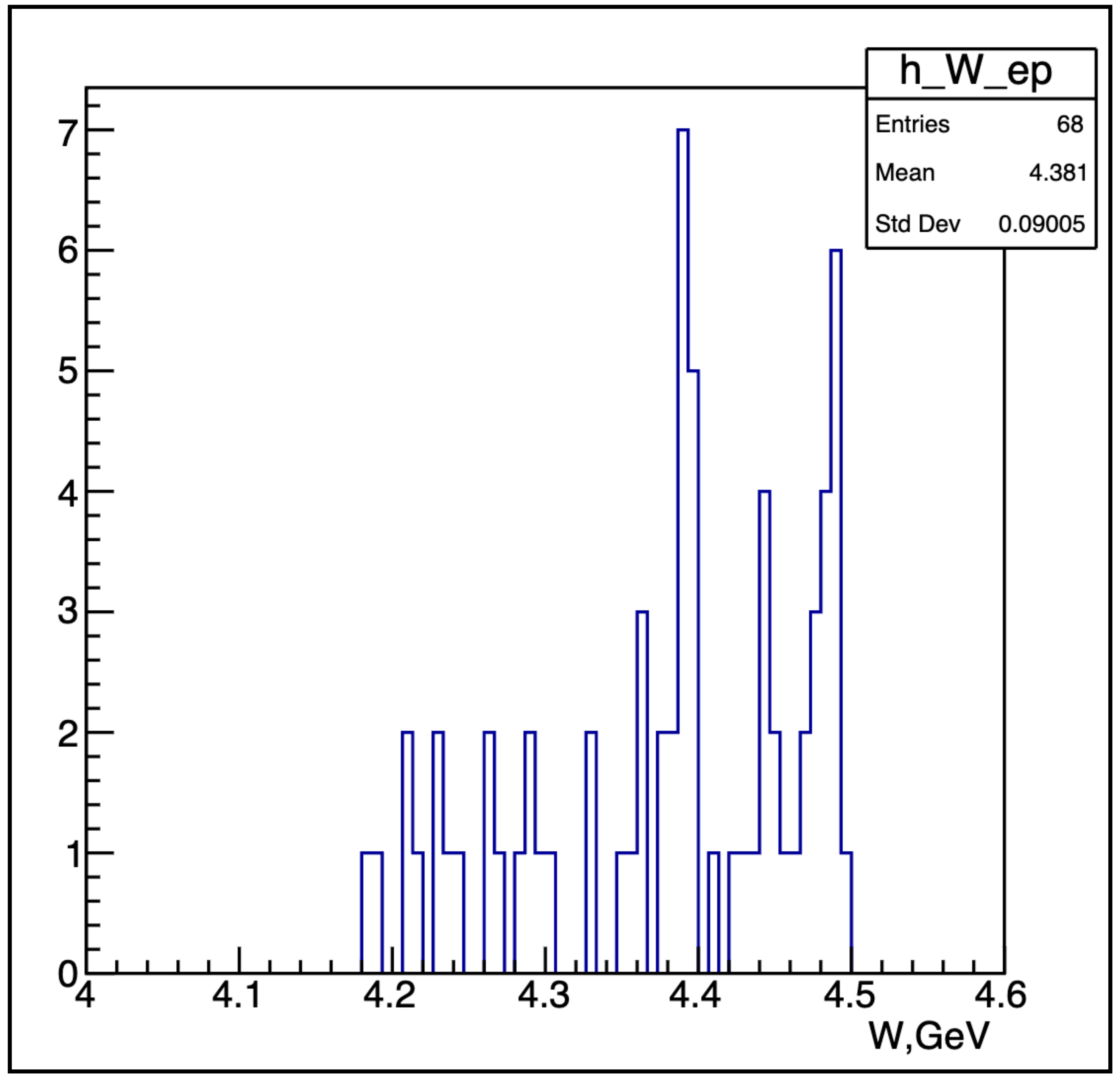
Hadronic Mass $ep \to e'p'J/\psi \to e'e^+e^-(p')$



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



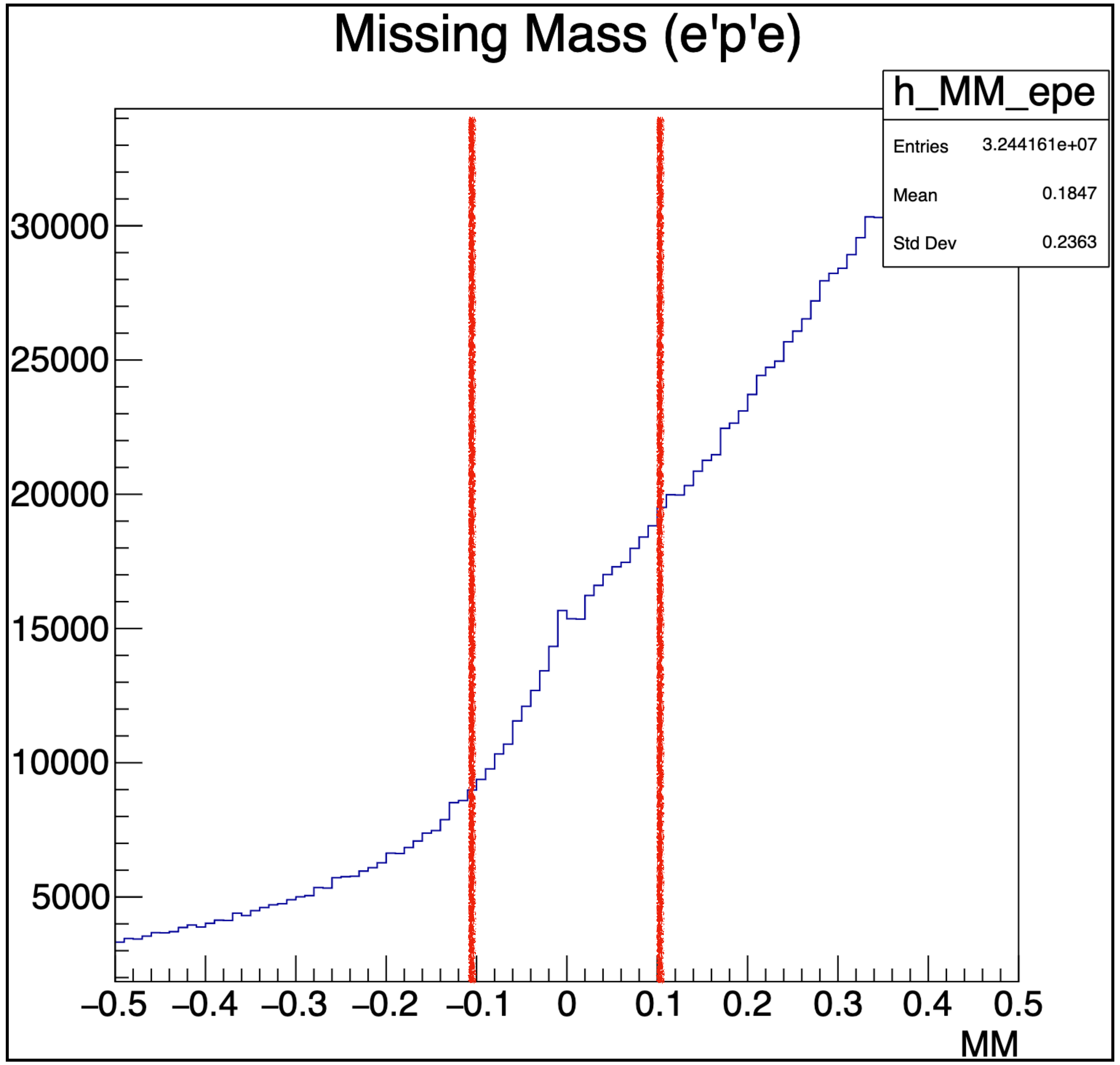
Hadronic mass. Topology: $ep \to e'e^+(e^-)p'$



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

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

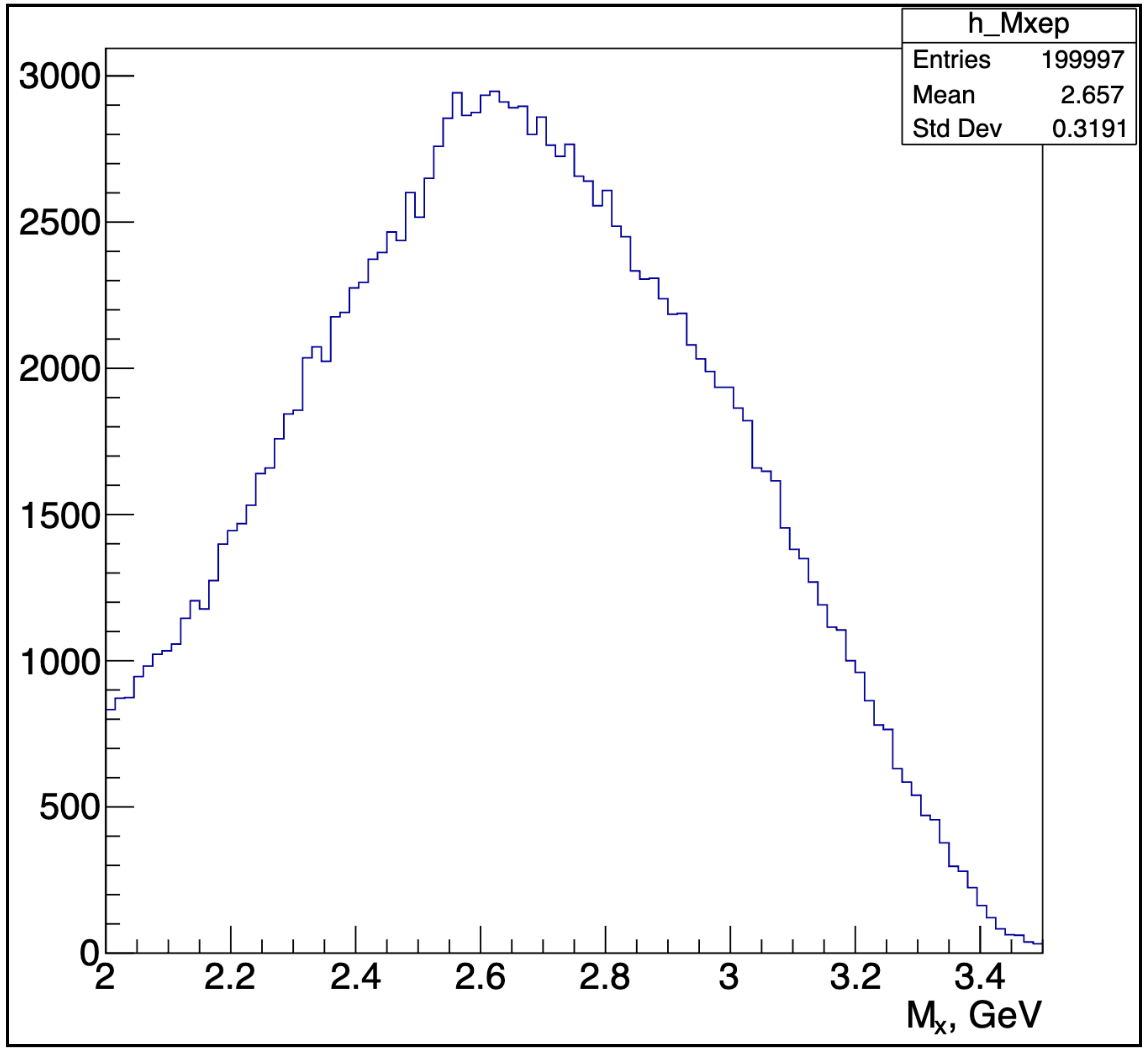
- For the reaction $ep \to e'p'e^-(e^+)$
- We select one electron in FT, one positron in FD and one proton in FD.
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e'} - p_{p'}$
- The peak on the distribution should be around the mass of the missing lepton.
- We keep events with $E_\gamma > 8.1\,\mathrm{GeV}$ 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 $e'e^-p'$.

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

- 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.



$M_X(e'p')$