Preliminary results on J/ψ electroproduction cross-sections at CLAS12

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Vector Quarkonia and Pressure Gauges Mini-Workshop

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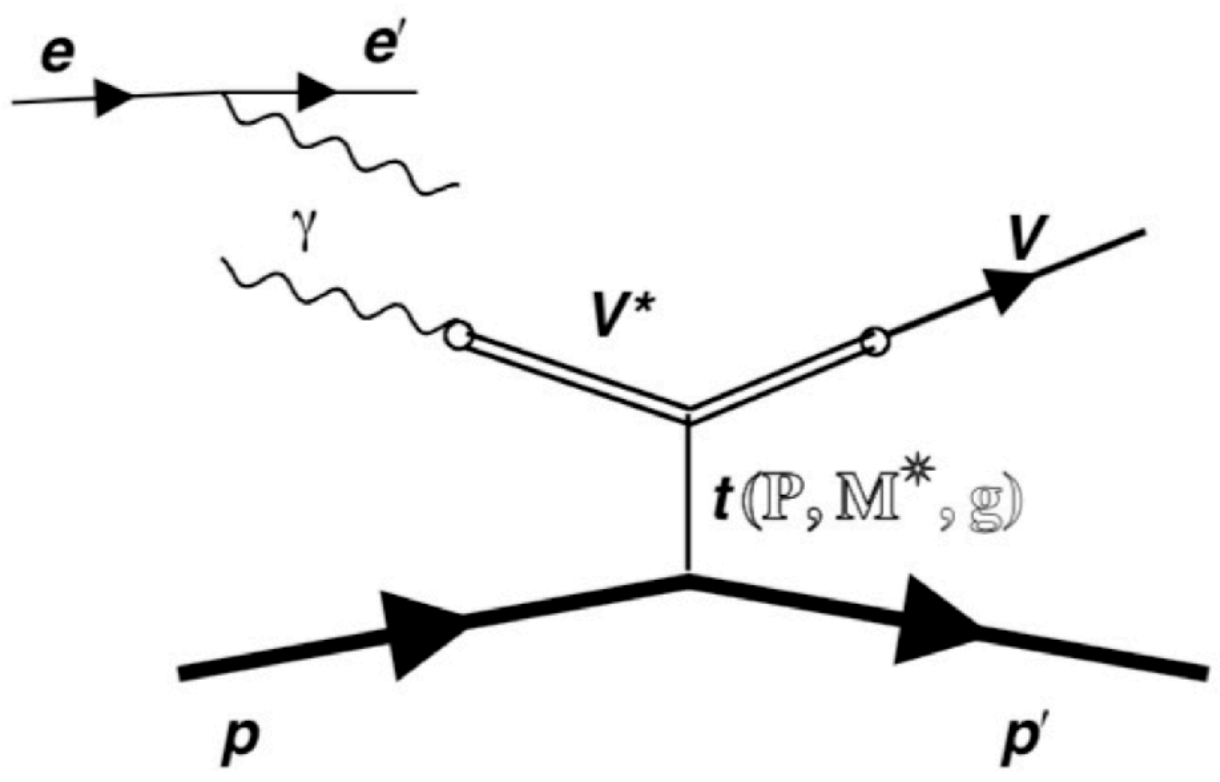
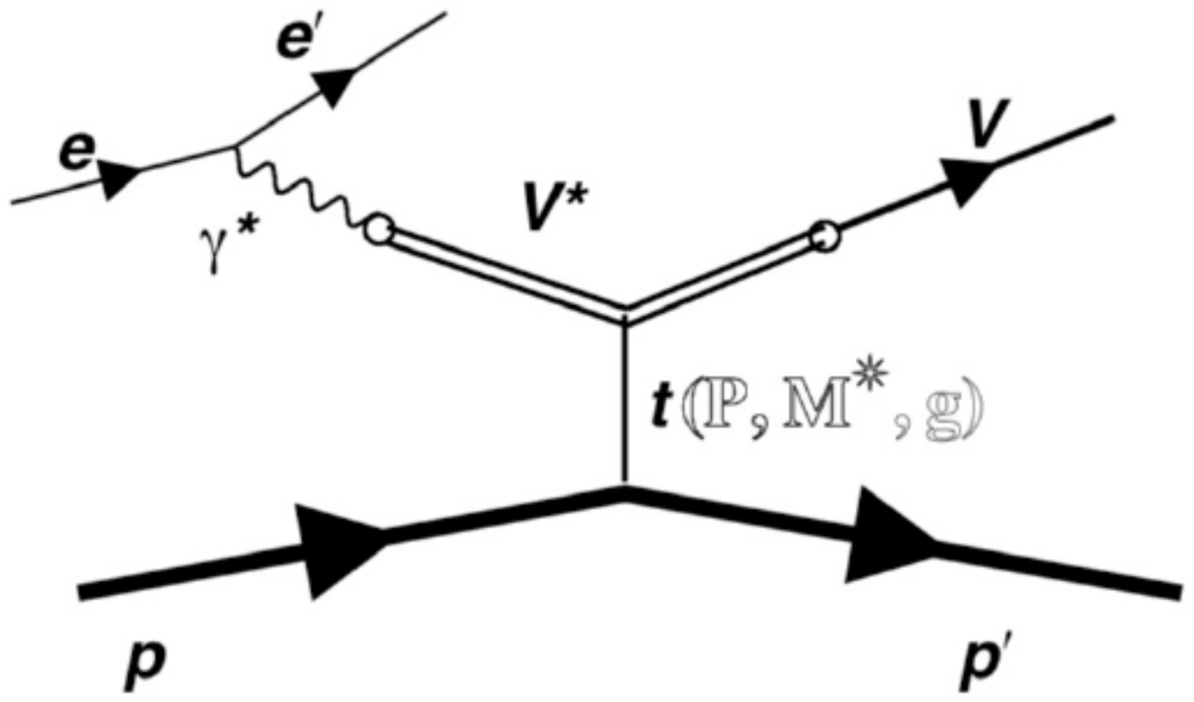
Motivation

- Near-threshold J/ψ production is a uniquely sensitive probe of the gluonic structure of the proton, specifically its gravitational form factors.
- Existing near-threshold J/ψ photoproduction data at JLab: CLAS12, GlueX, J/ψ-007.
- Near-threshold J/ψ electroproduction at low Q^2 allows studies in different final state topologies, where charm pentaquarks, for example, should show up in the W-distributions.



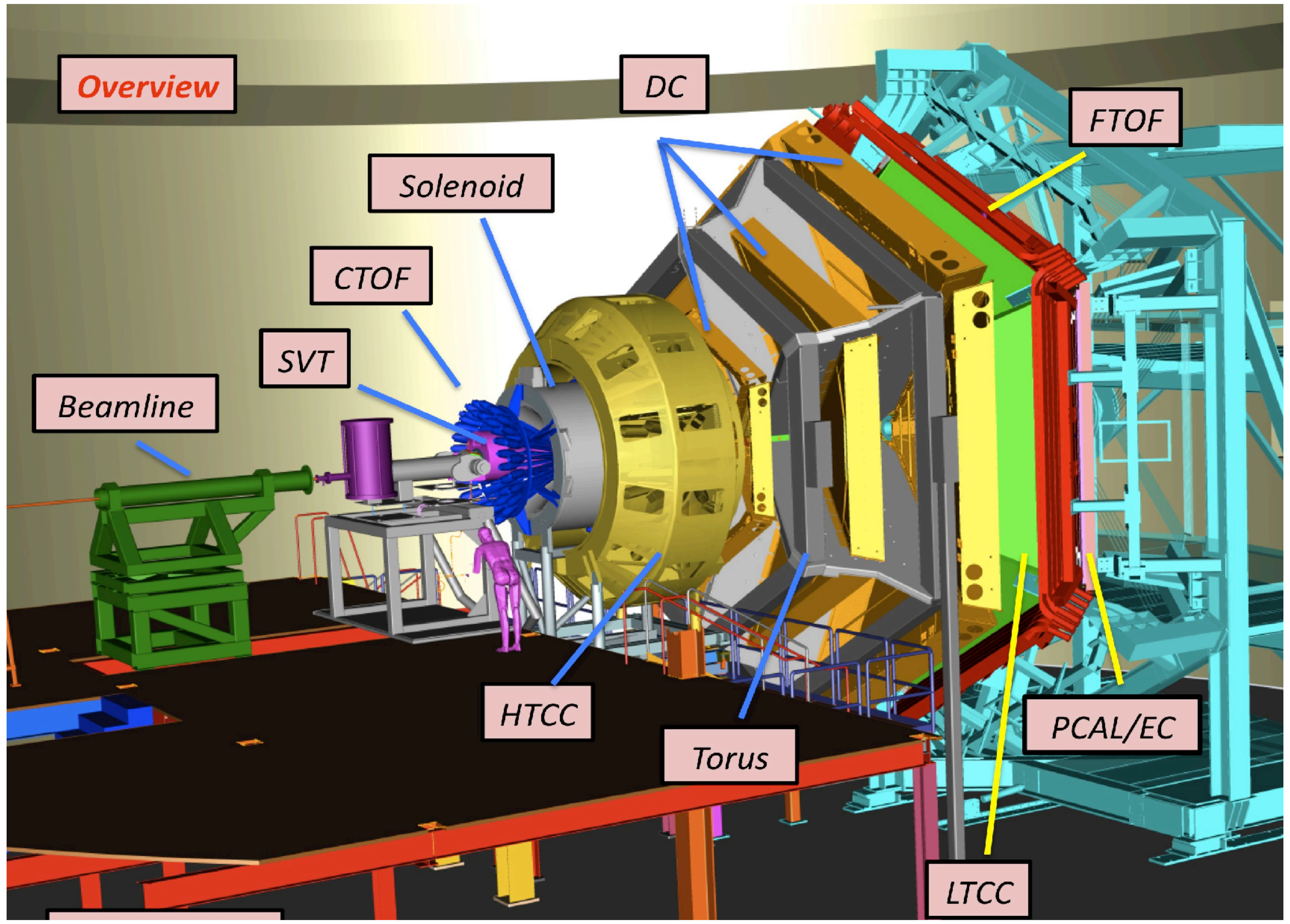


Experimental setup: CLAS12

- 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)



Analysis Framework

- For this analysis, all the available RG-A Pass2 data is used. The target was liquid hidrogen.

Dataset	Accumulated Charge (mC)
Spring 2018 Inbending	69.5511
Spring 2018 Outbending	16.9145
Fall 2018 Inbending	35.0234
Fall 2018 Outbending	32.7332
Spring 2019 Inbending	47.736

10.6 GeV (Spring 2018 Inbending – Fall 2018 Outbending)

10.2 GeV (Spring 2019 Inbending)

Analysis Framework

- The reaction to study is

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

where p, e^+ and e^- are measured in the Forward Detector, e' is measured in the Forward Tagger.

- From here we can explore several final states

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

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

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

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If the proton is not specifically excluded, it includes the 4-particle topology

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

Cleanest in terms of background

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

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

Very challenging background

Analysis Framework

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

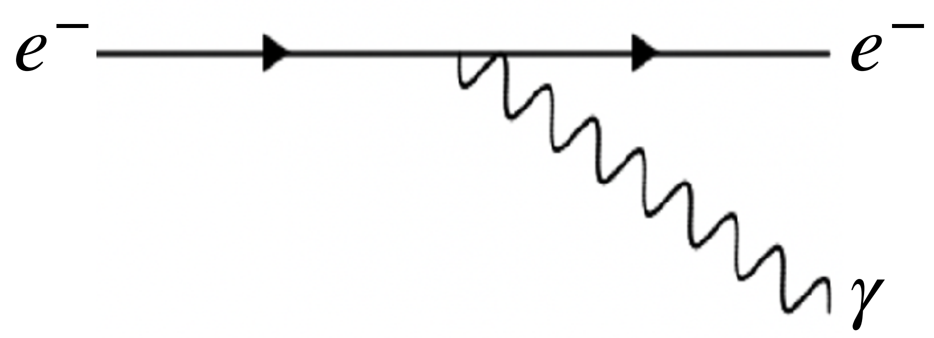
•For e^+ and e^- in FD:

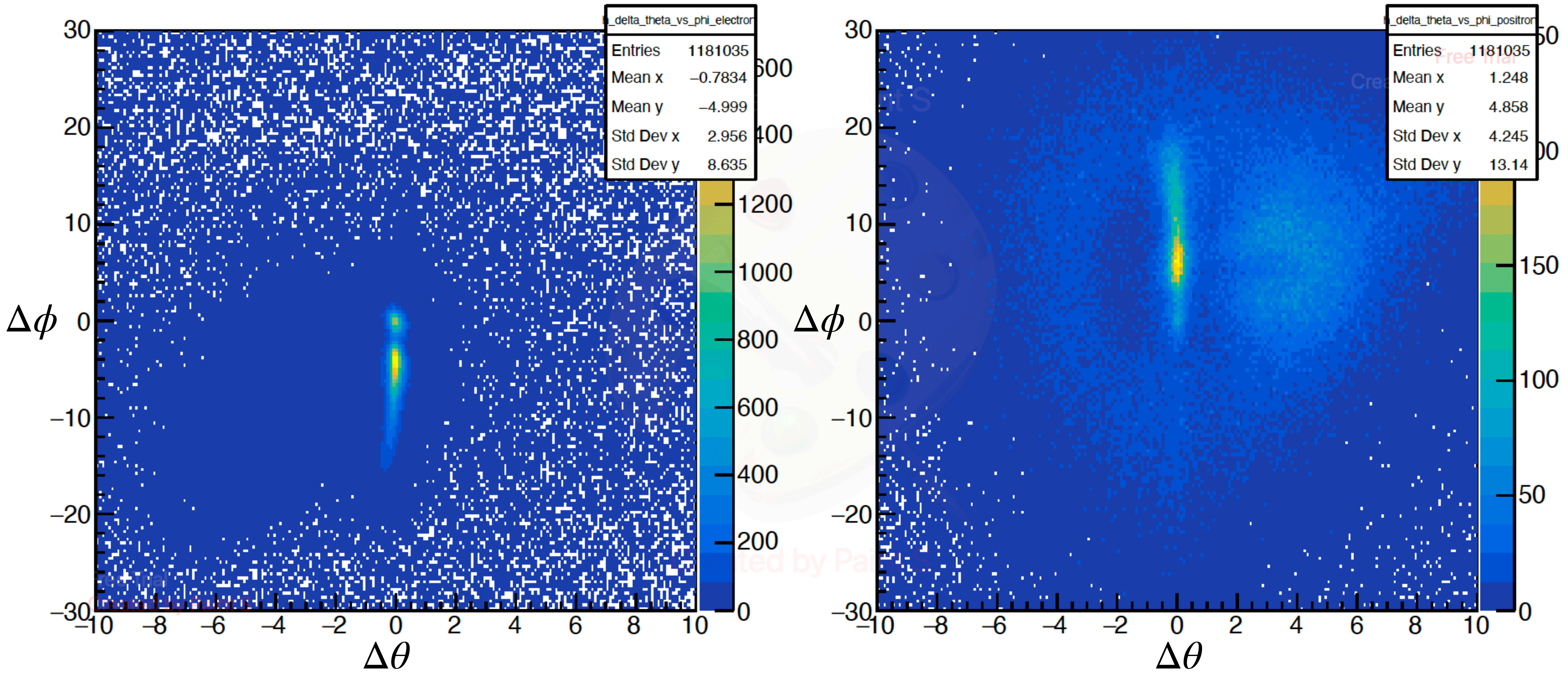
-**Radiative loss correction**

-Vertex time difference $\leq 1ns$

-Lepton momentum corrections are being applied

-Lepton PID based on BDT





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

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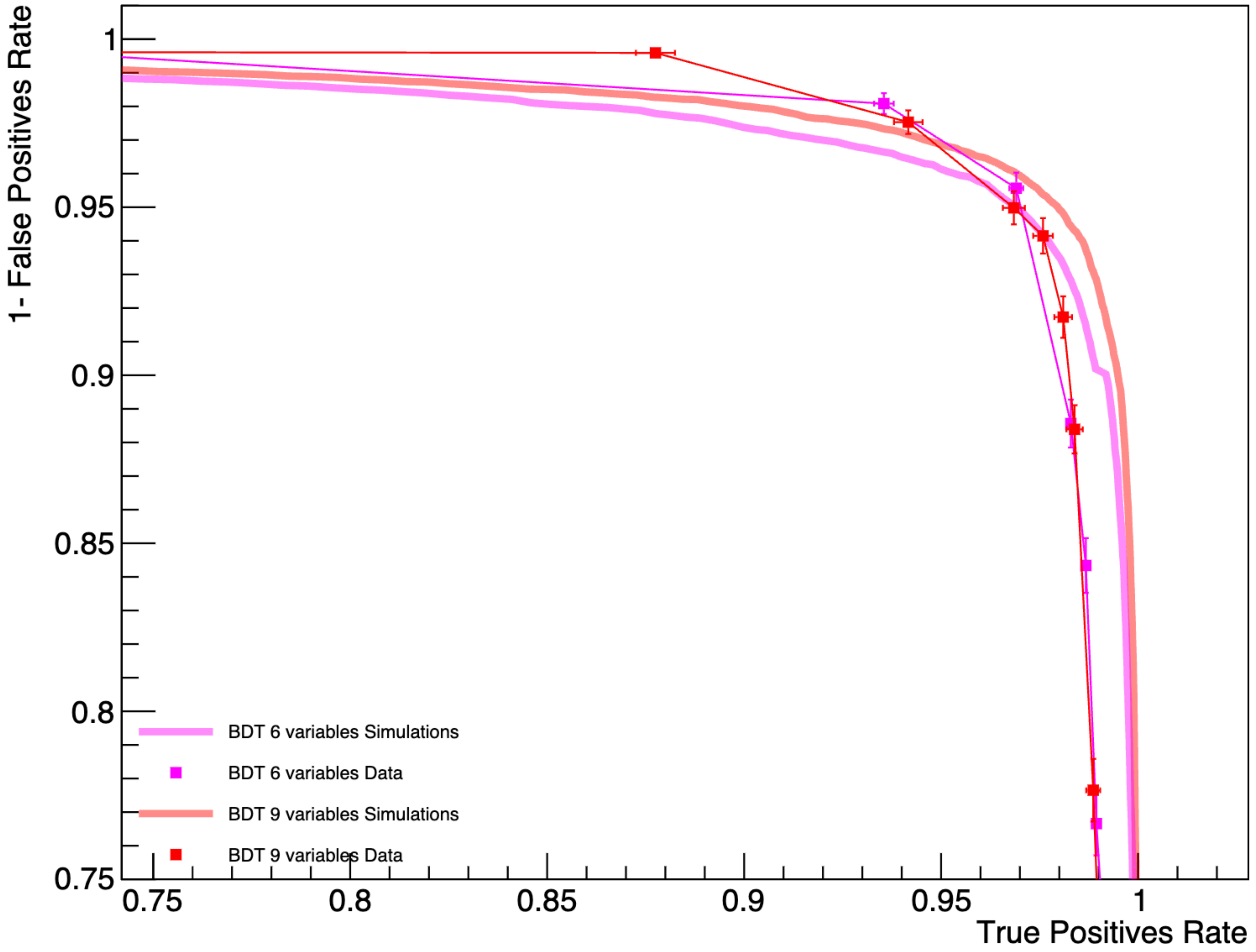
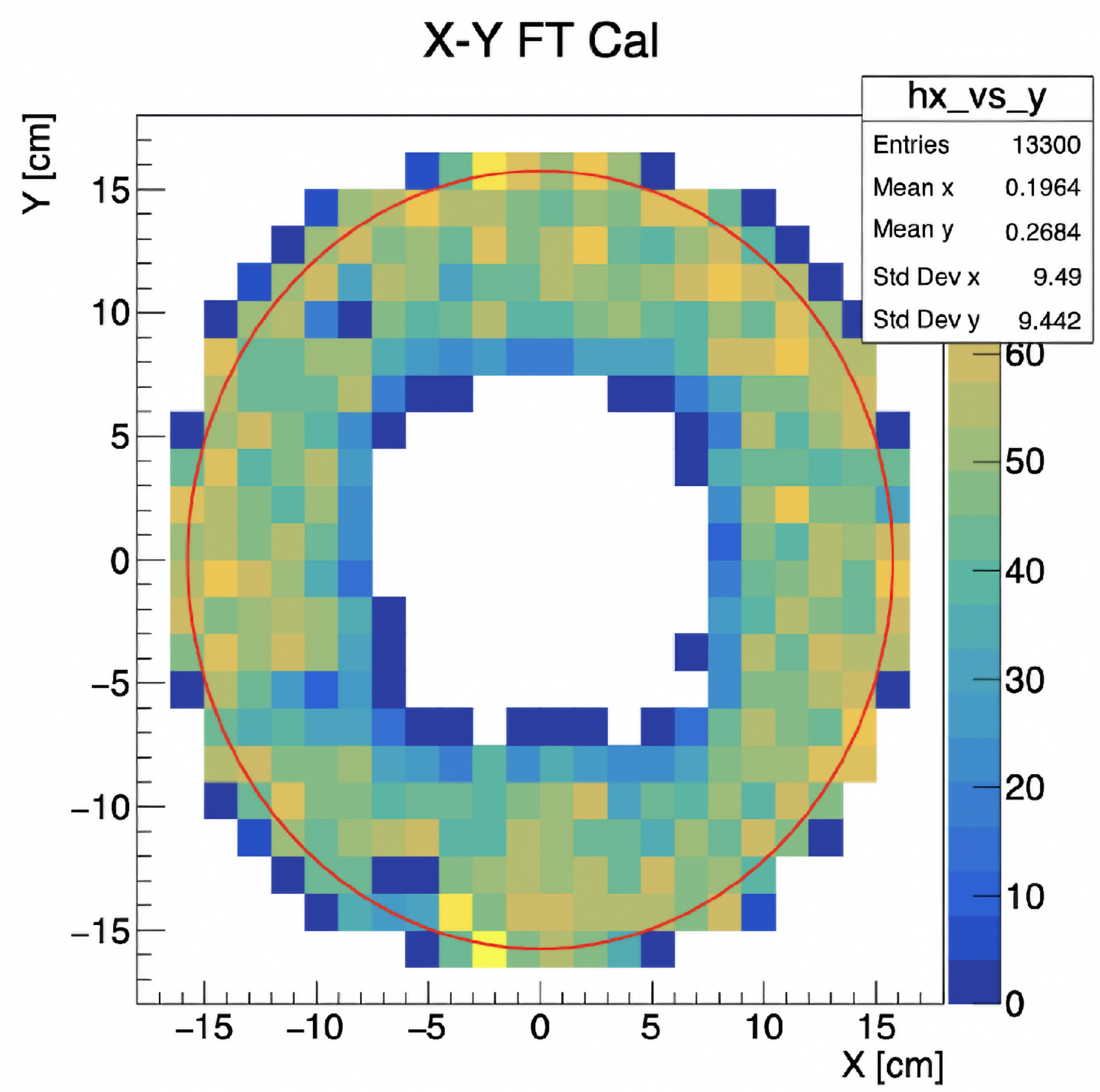
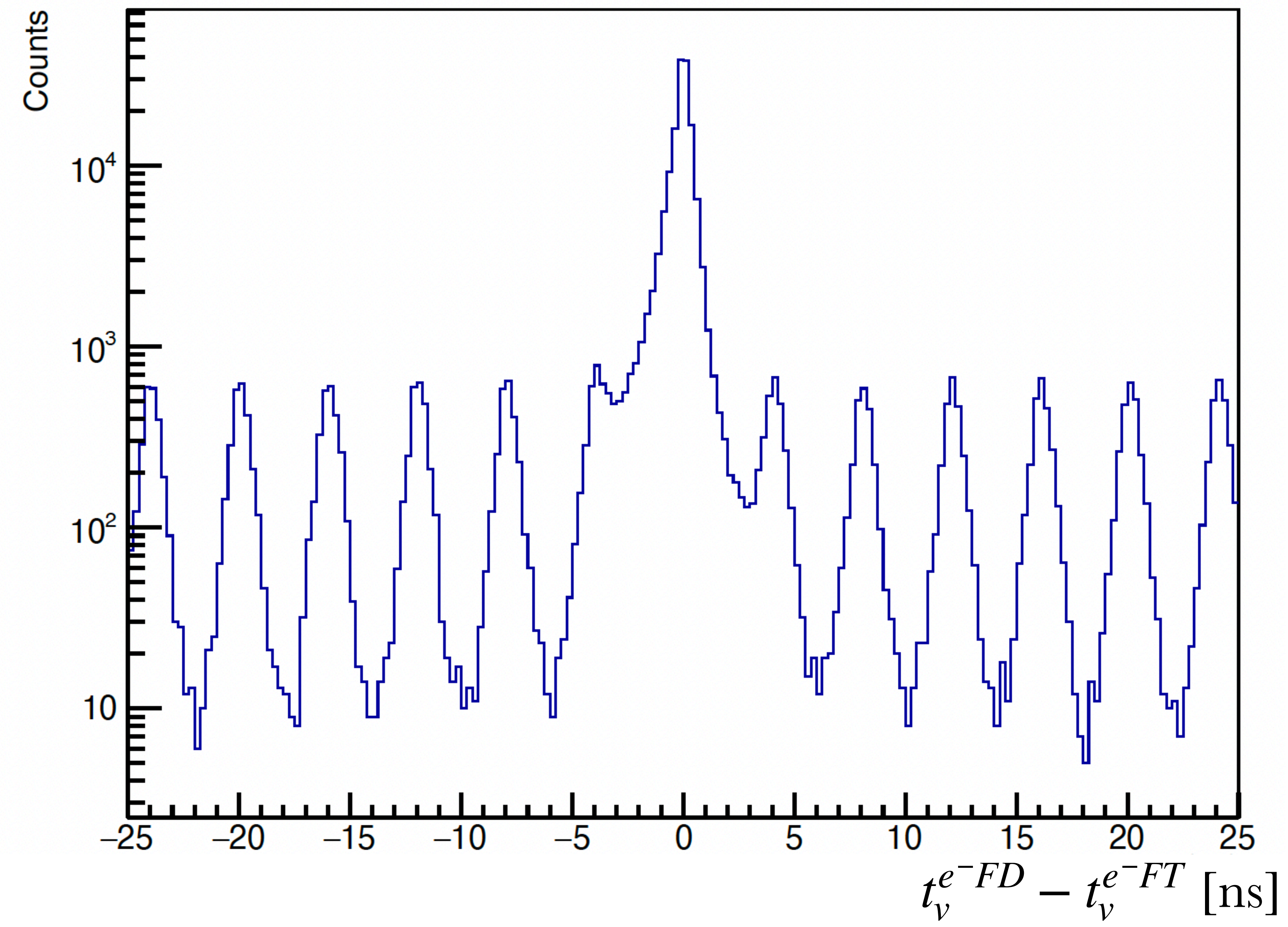


ROC curve for 6 and 9 variable models for F18inbending

Analysis Framework



- Electron e'
  - Forward Tagger
  - $|v_{t_{e-}} - v_{t_{e+}}| \leq 2.5ns$
  - Energy corrections
  - $8 < r < 15.75$ cm, $r = \sqrt{x^2 + y^2}$



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•For e^+ and e^- in FD:
-Radiative loss correction
-Vertex time difference $\leq 1ns$
-Lepton momentum corrections are being applied
-Lepton PID based on BDT

These are the required cuts for studying the final state: $ep \rightarrow e'e^+e^-X$

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

When the proton in considered in the final state we also include the above cuts

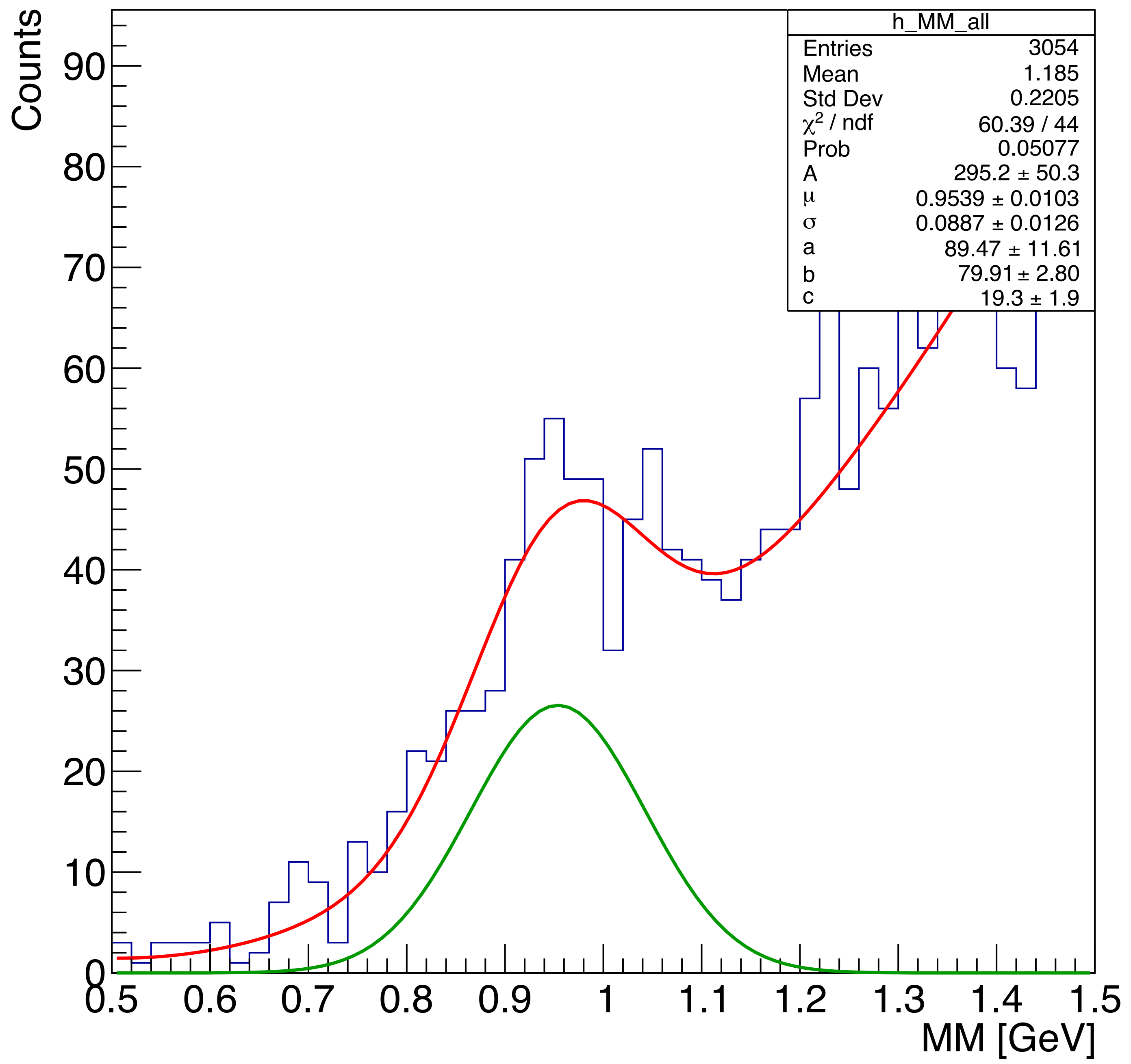
$ep \to e'e^-e^+(p')$

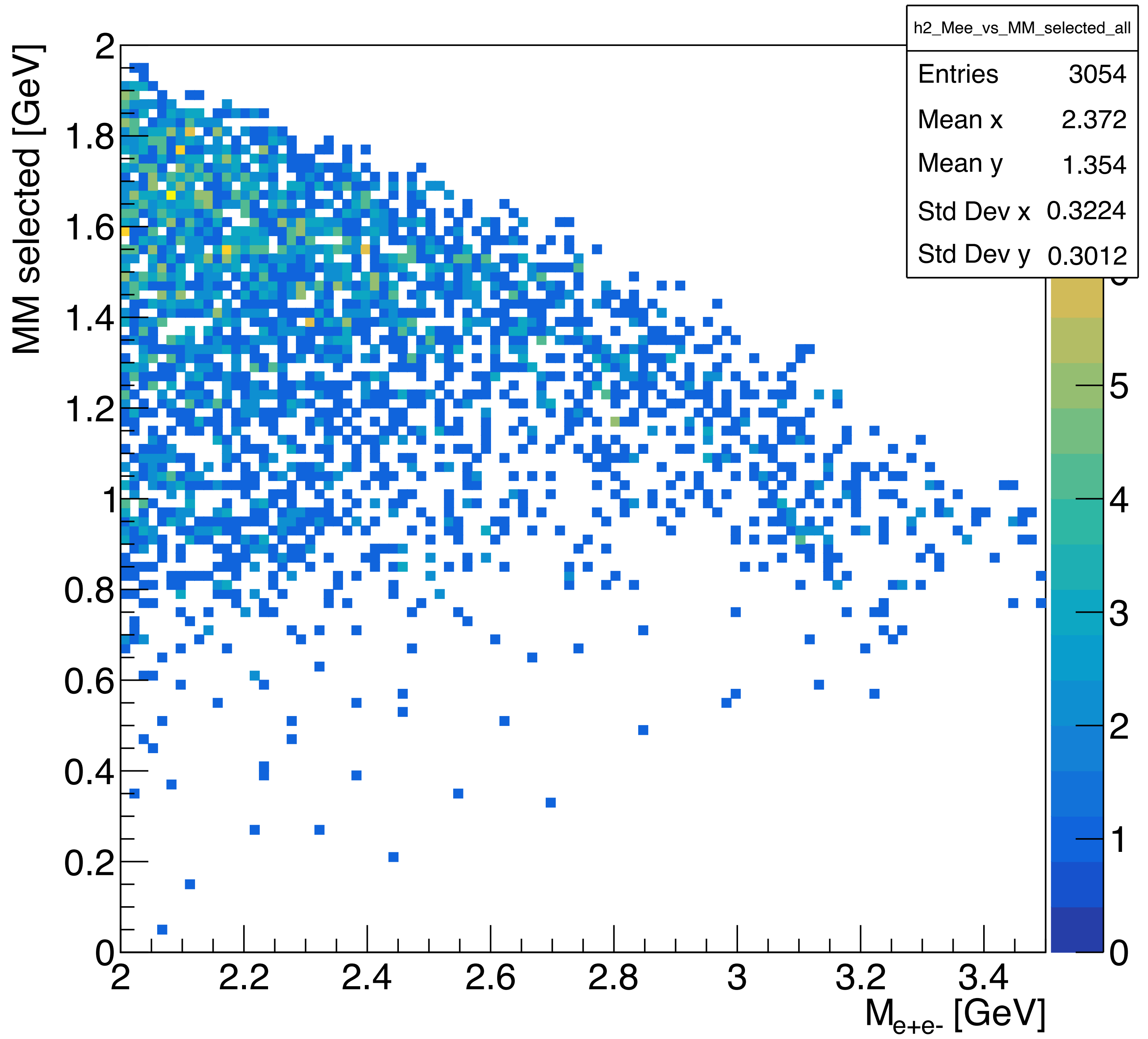
- The missing four-momentum is defined as

$$p_X = p_e + p_p - p_{e^-} - p_{e^+} - p_{e'}$$

- We 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.

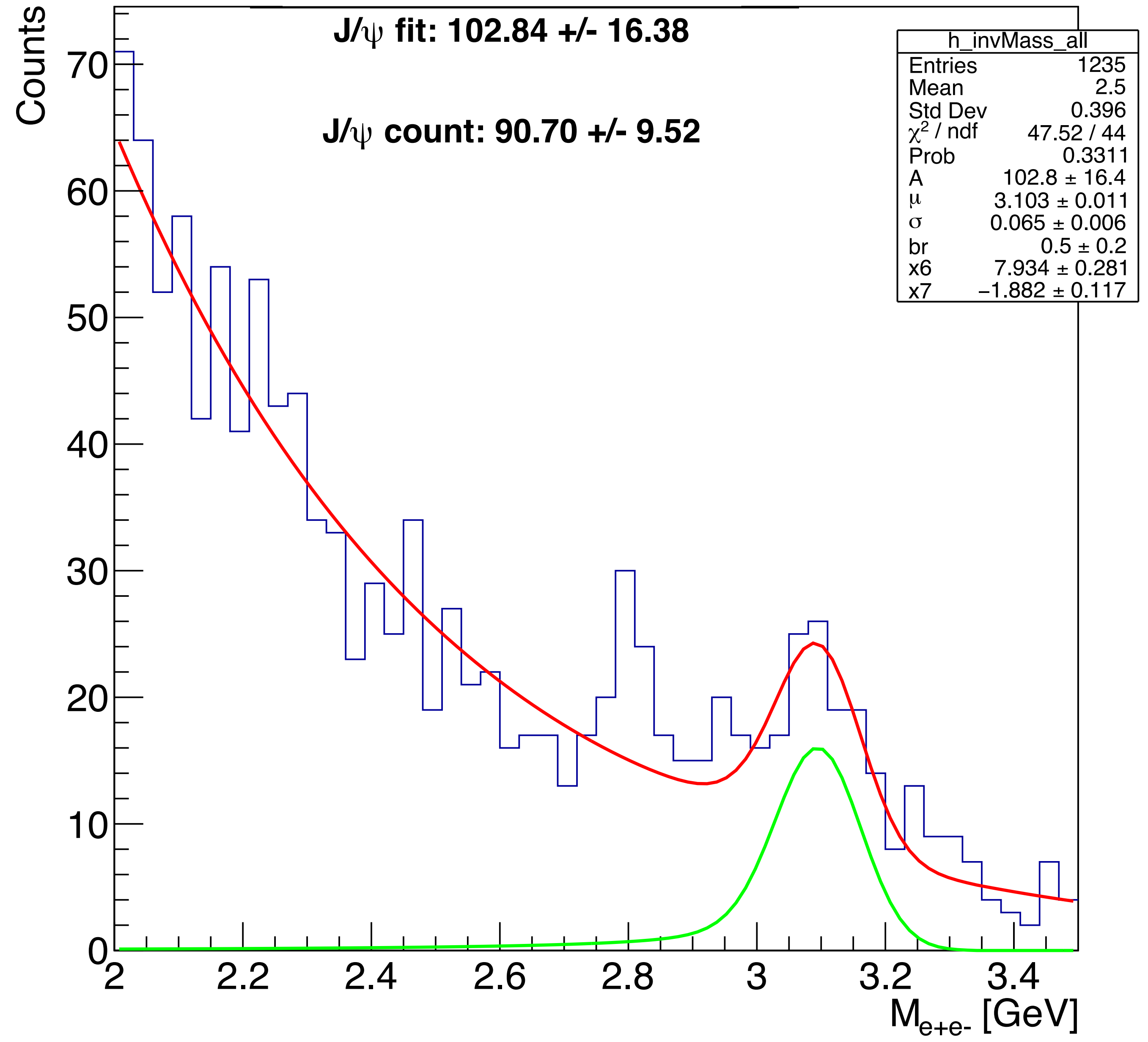
- We look at the invariant mass distribution $M^2(e^-e^+) = (p_{e^-} + p_{e^+})^2$ in the 2.0 GeV to 3.5 GeV region.





- $E_{\text{beam}} - E_{e'} > 8.1$GeV
- $M_{e^+e^-} > 2.0$ GeV

We are explicitly excluding any events that contain one proton in FD



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

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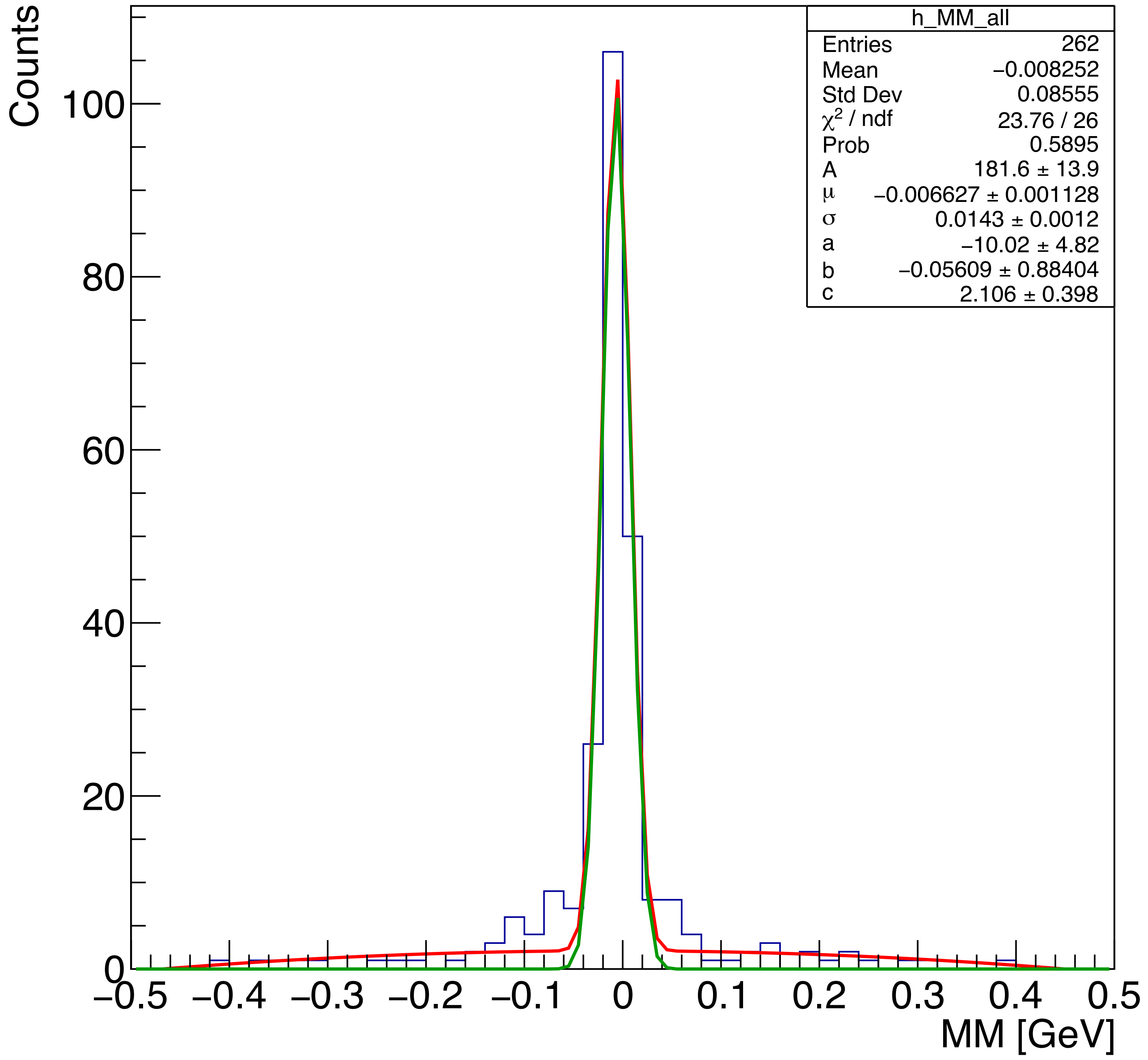
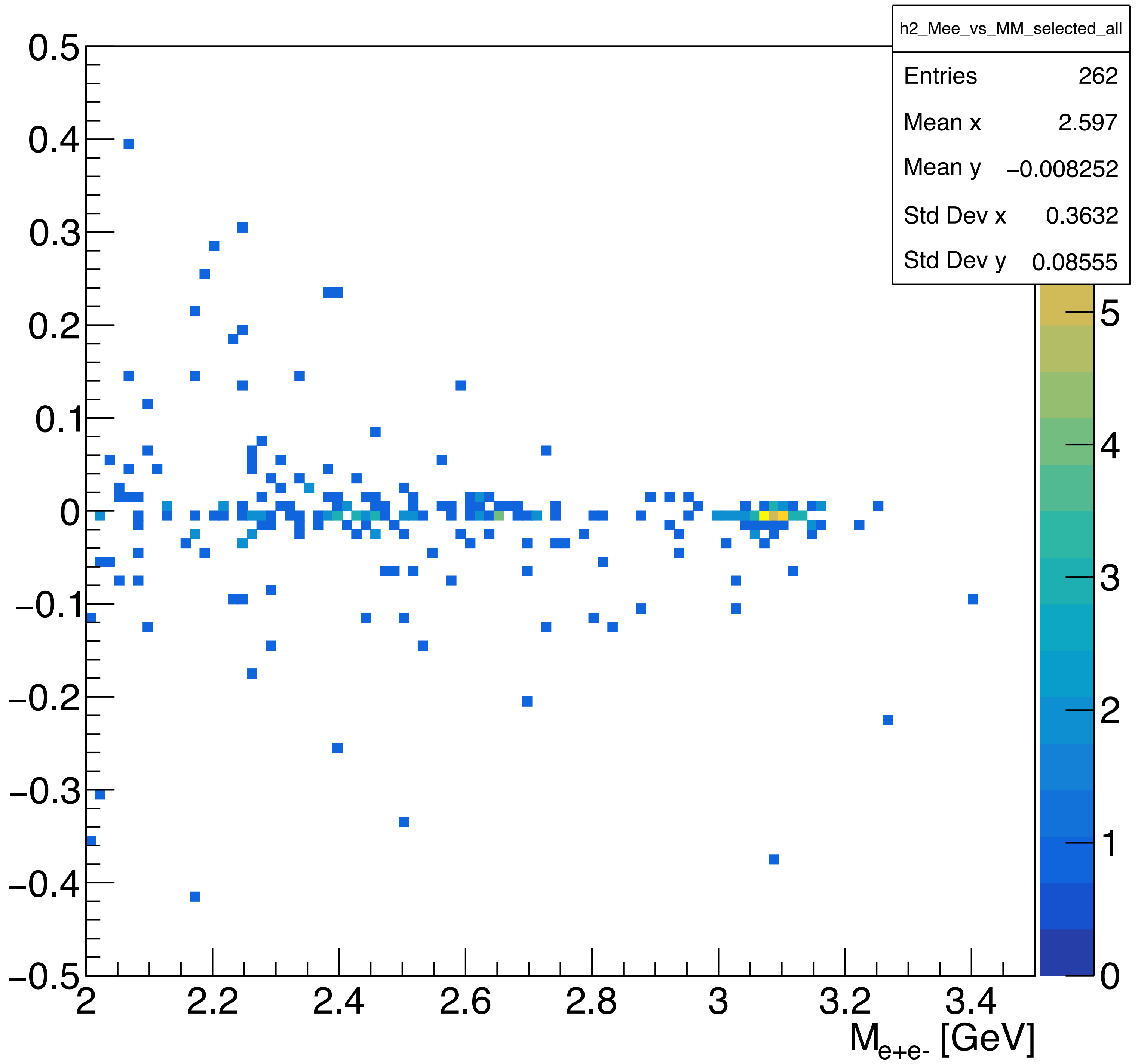
$$p_X = p_e + p_p - p_{e^-} - p_{e^+} - p_{e'} - p_{p'}$$

- We calculate the missing mass as $M_X^2 = p_X^2$, expecting to peak at zero.

- 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.

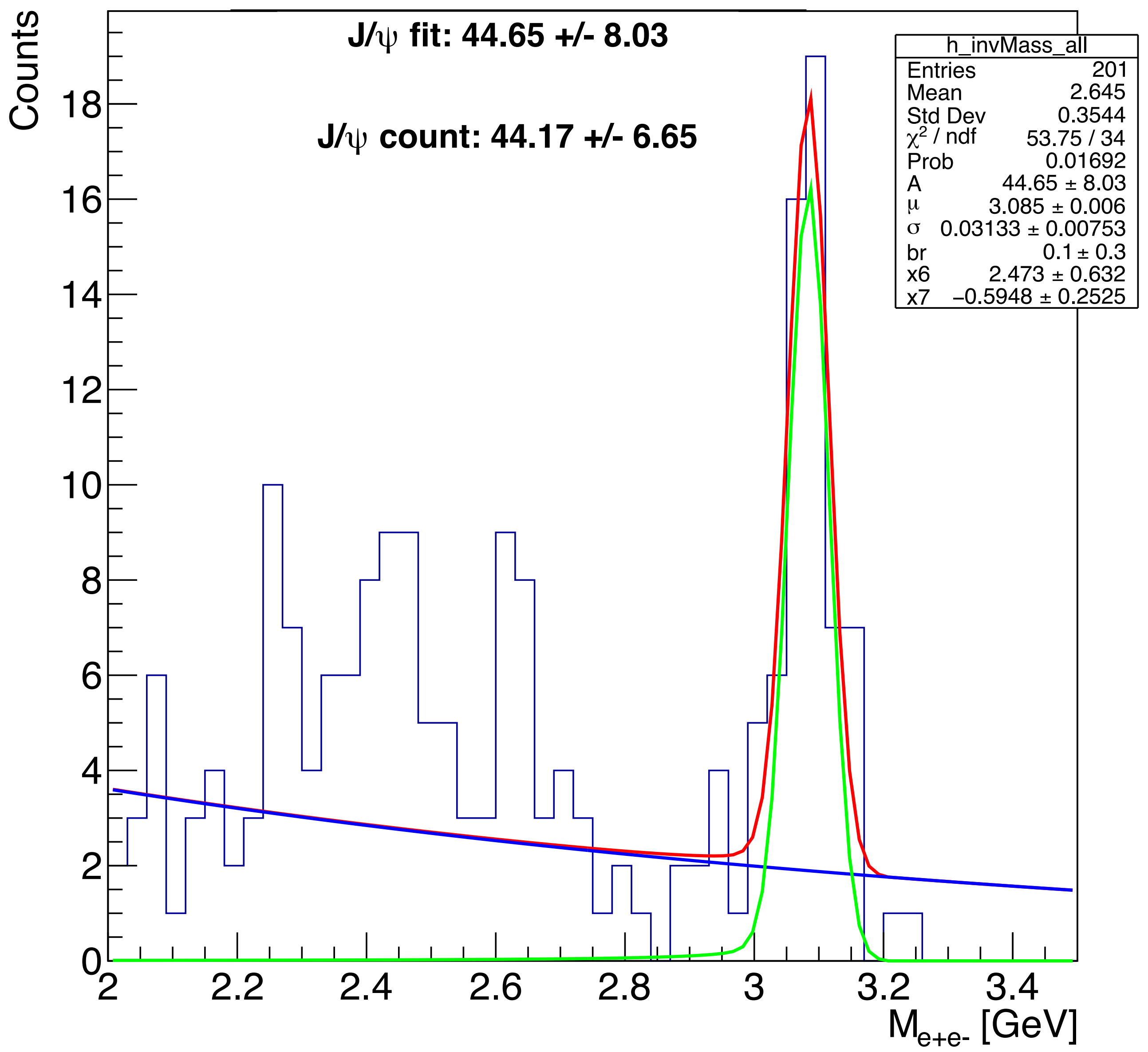
- In addition to the invariant mass, we can look at the missing mass $M_X(e'p') = e + p - e' - p'$.





- $E_{beam} - E_{e'} > 8.1\text{GeV}$
- $M_{e^+e^-} > 2.0$ GeV

This is the cleanest topology in terms of background, but also limited by the requirement of 4 particles in the final state



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

- The missing four-momentum is defined as

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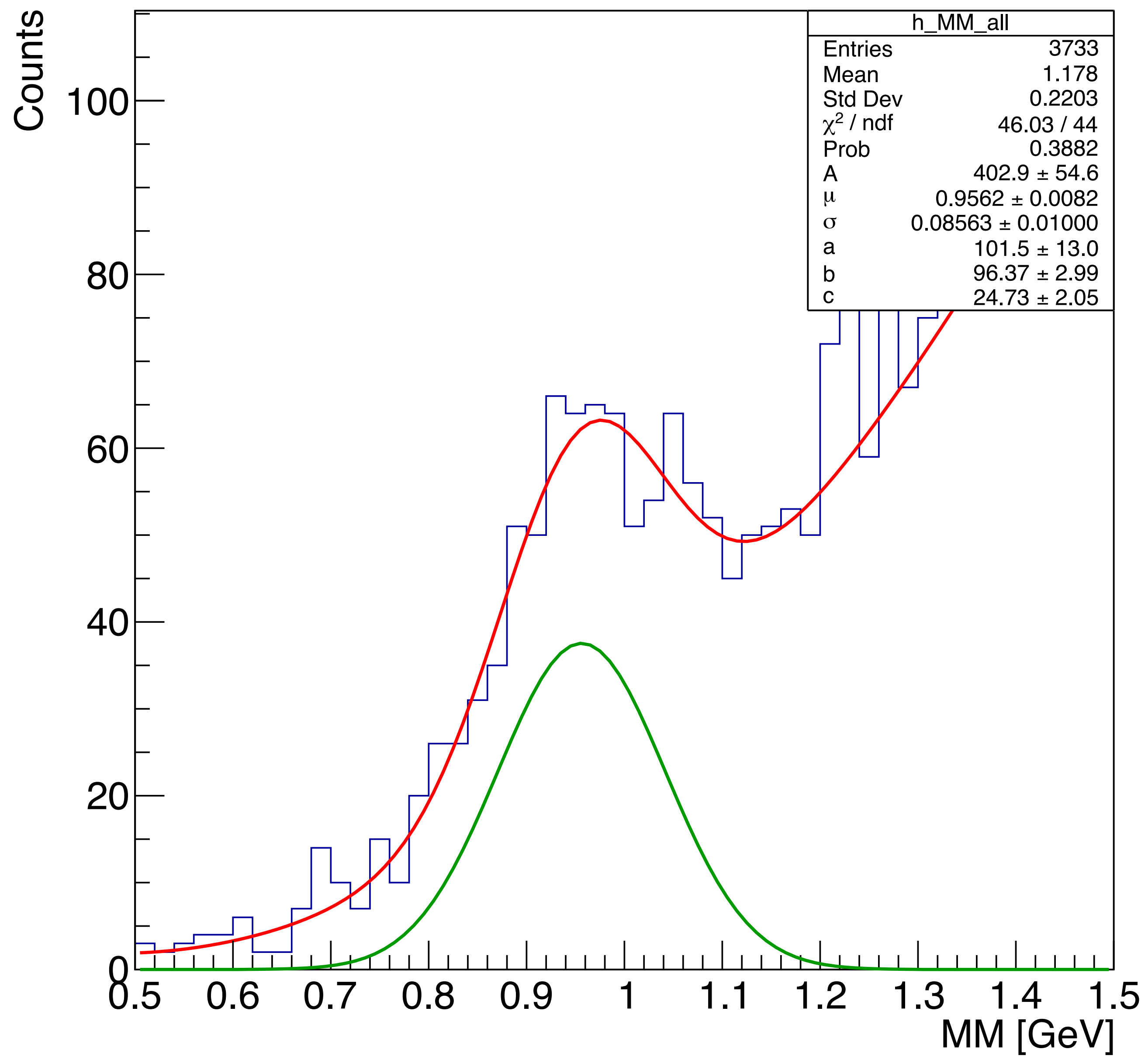
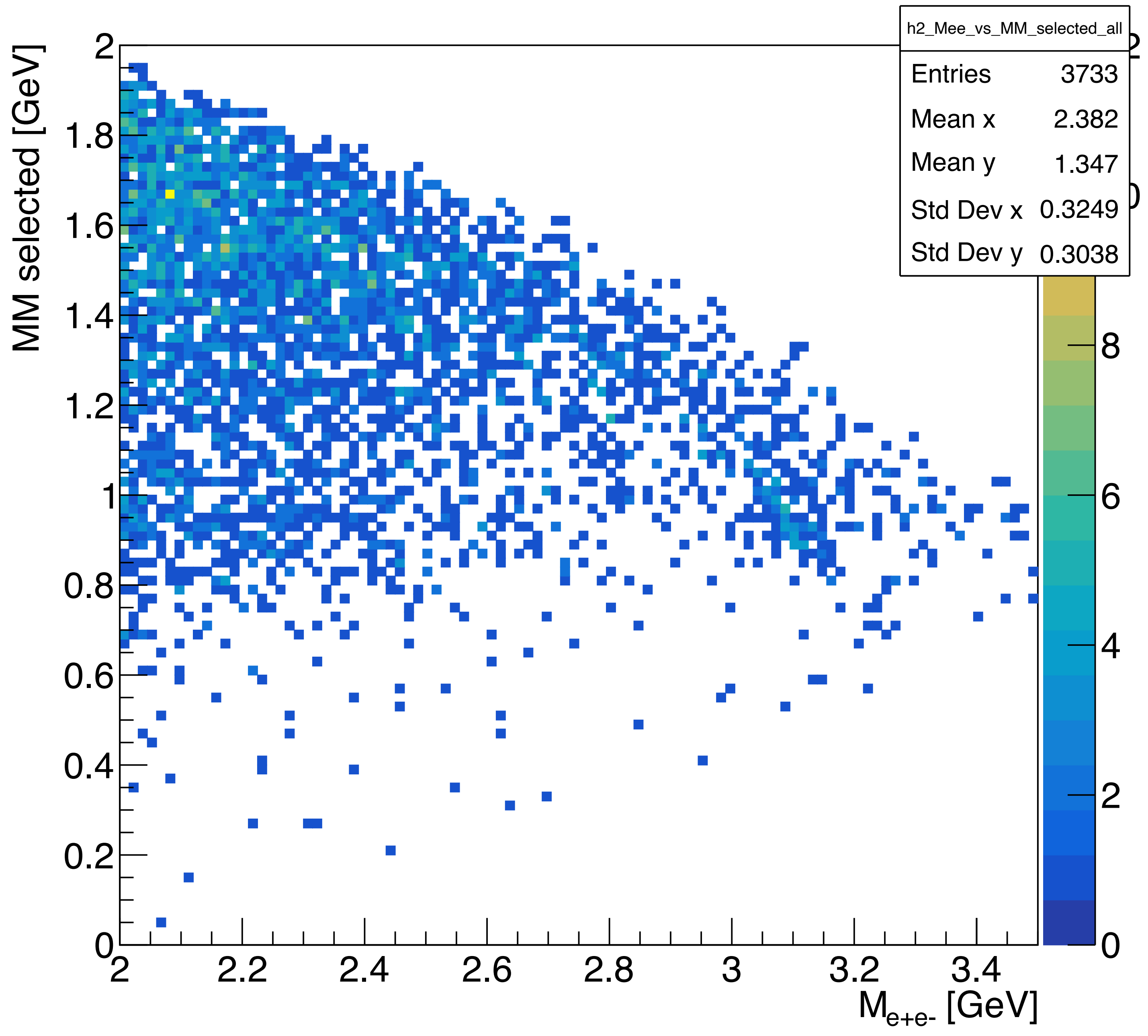
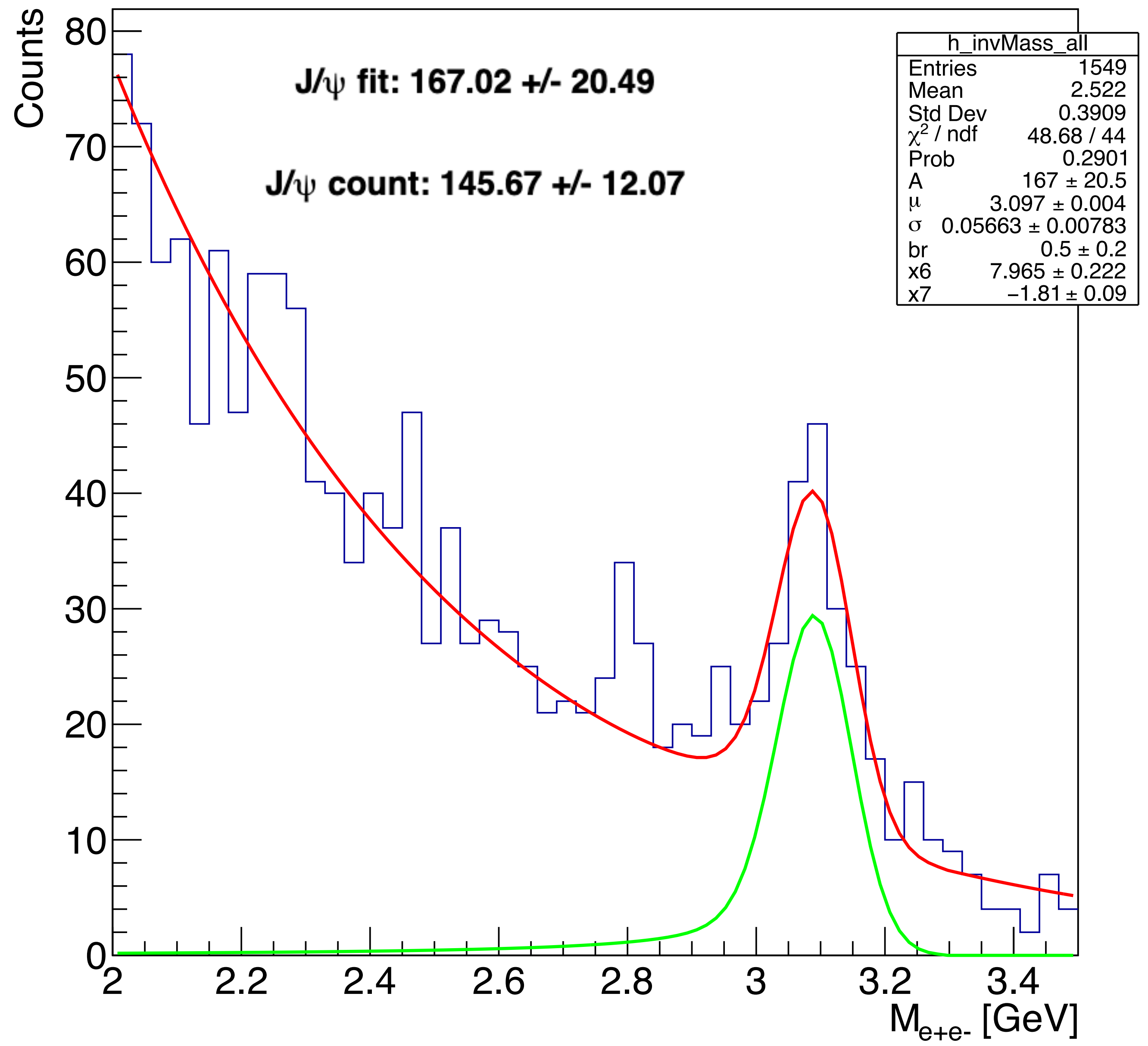




- $E_{\mathrm{beam}} - E_{e'} > 8.1\mathrm{GeV}$
- $M_{e^+e^-} > 2.0$ GeV

In this case we are not specifically excluding the proton, so the 4-particle final state is included here



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

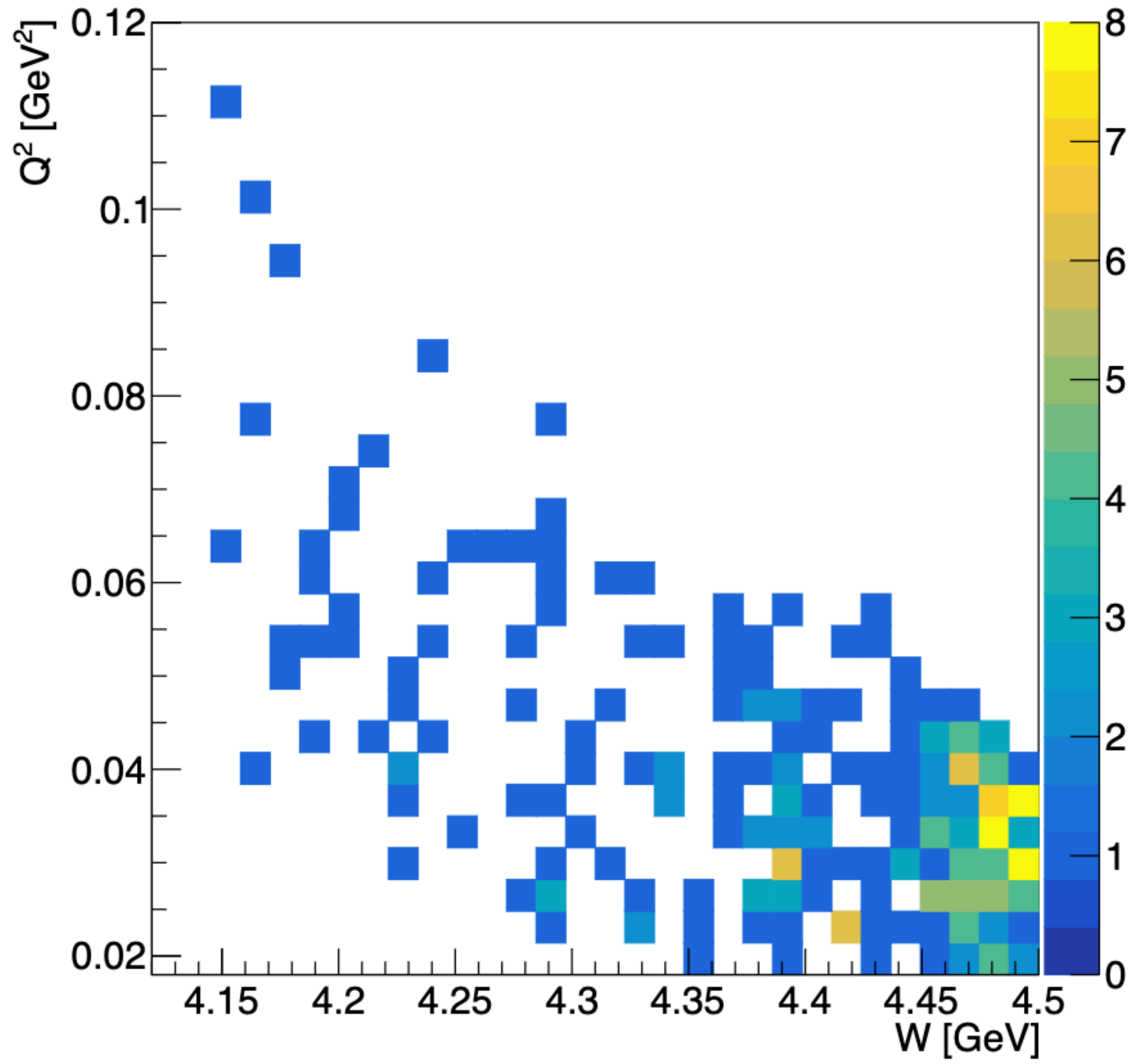
- Once we got our distribution, we can look at events under the peak.

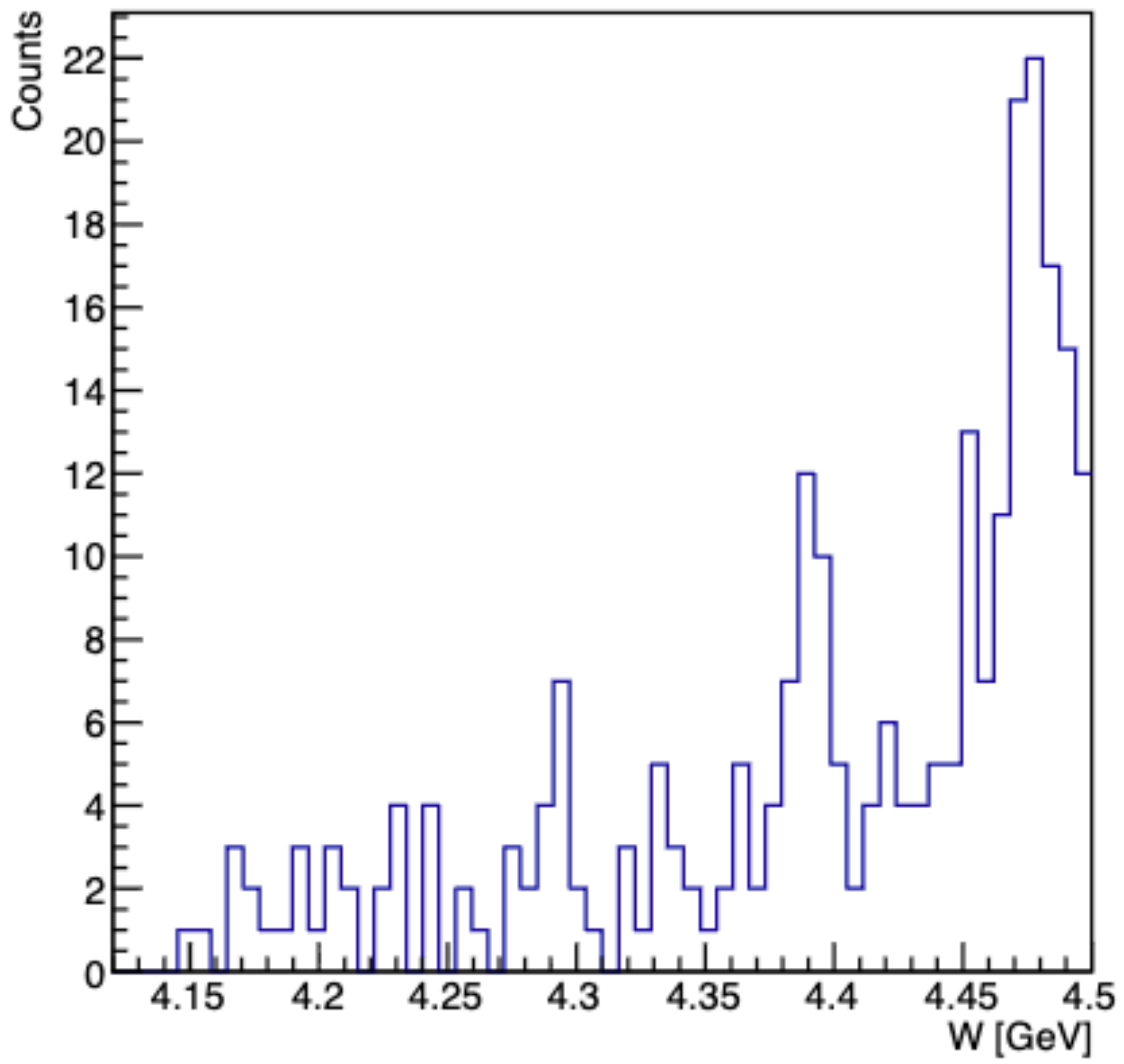
$$W = \sqrt{m_p^2 + 2m_pE_\gamma - Q^2}$$

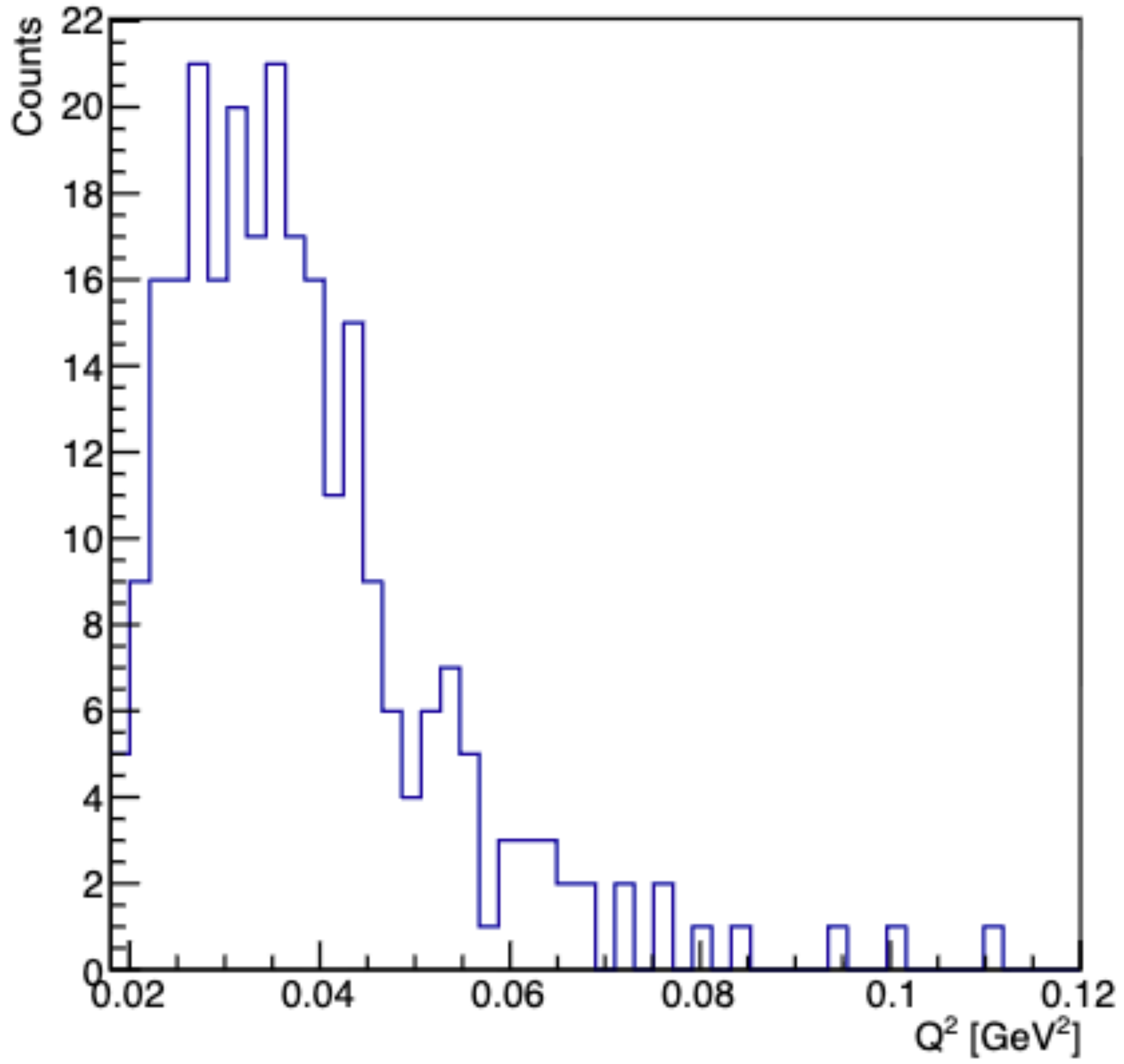
where $E_\gamma = E_{beam} - E_{e'}$ and

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

- $E_{\text{beam}} - E_{e'} > 8.1\text{GeV}$
- $M_{e^+e^-} > 2.0$ GeV
- $2.95 < M(e^+e^-) < 3.2$ GeV







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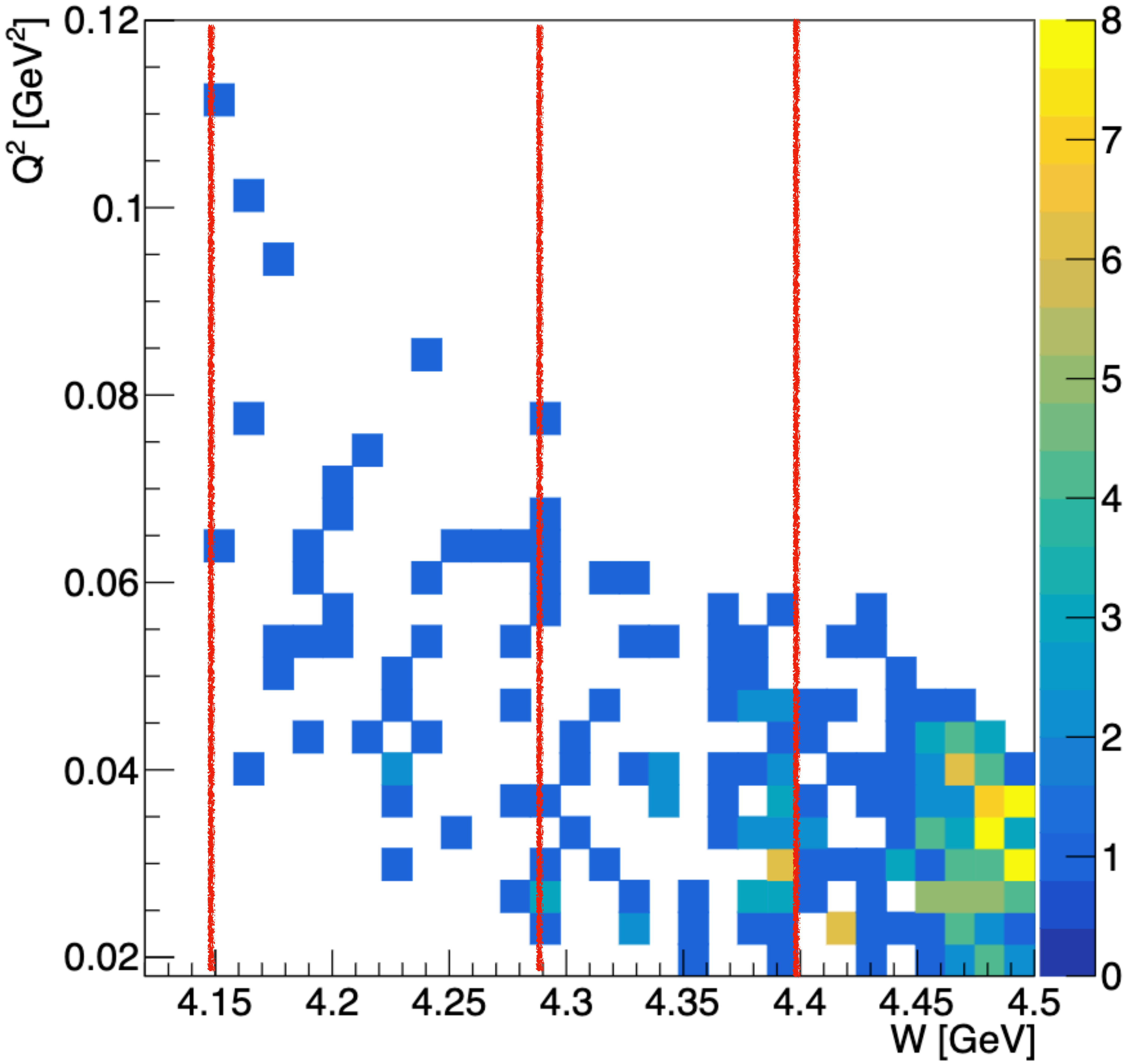
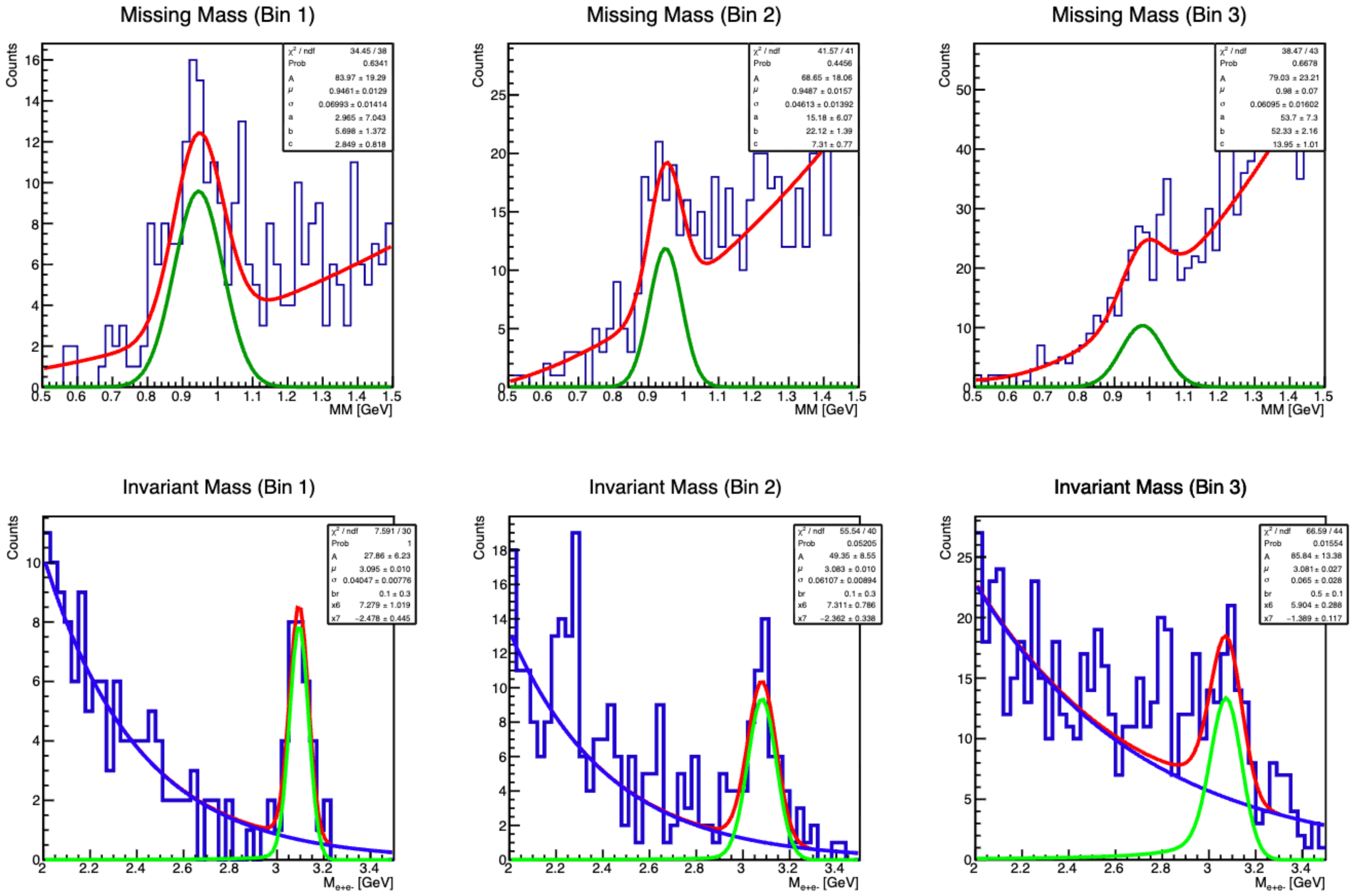
Bin 1: W [4.15, 4.29]
Bin 2: W[4.29, 4.40]
Bin 3: W [4.40, 4.50]





Cross-Sections

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

$$\frac{d\sigma_{ep}}{dWdQ^2} = \frac{\mathscr{Y}}{L \cdot Br} \frac{1}{\Delta W \Delta Q^2}$$

Where $L = N_e \cdot N_p$ and $Br = 0.06$.

- 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.

$$\sigma_{\gamma^*} = \frac{1}{\Phi_{\gamma^*}} \sigma_{ep}$$

At low Q^2 $\quad \sigma_\gamma \approx \sigma_{\gamma^*}$

$$\Phi_{\gamma^*} = \int_{\Delta Q^2} \int_{\Delta W} \Gamma(W, Q^2)\, dW\, dQ^2$$

$$Br = 0.06$$

$$\frac{d\sigma_{ep}}{dWdQ^2} = \frac{\mathcal{Y}}{L \cdot Br} \frac{1}{\Delta W \Delta Q^2}$$

$N_e = \frac{Q}{e}$ $\quad$ $N_p = \frac{\rho \cdot l \cdot N_A}{A} = 2.0909 \times 10^{23} \text{cm}^{-2}$

$$L = N_p * N_e = 1.3052 \times 10^{42}\ \text{cm}{-2} \times Q$$
$$= 1305226\ \text{nb}^{-1}\text{mC} \times Q$$

ρ: target density $0.07\ \text{g/cm}^3$ for liquid hydrogen

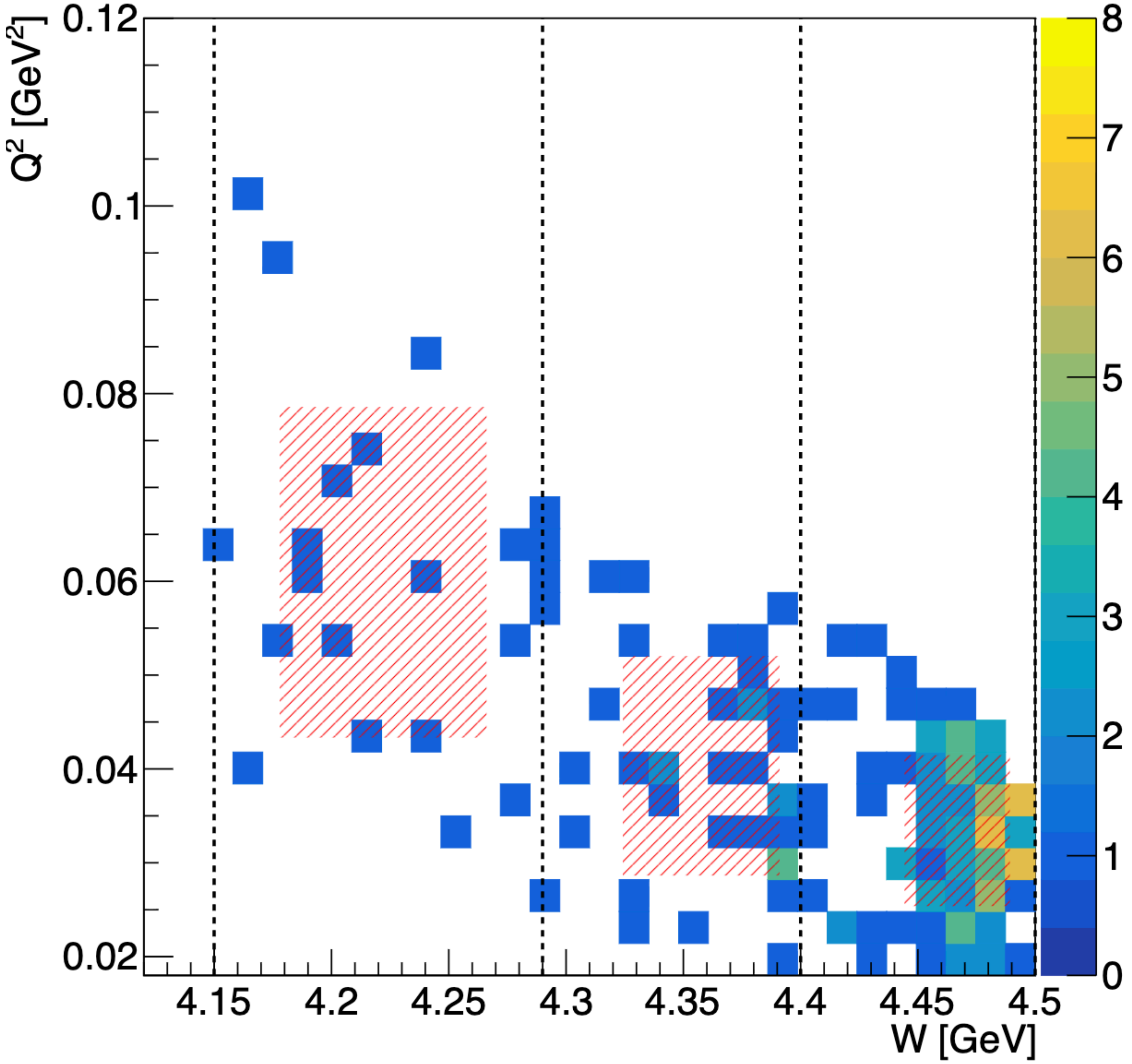
l: target length 5 cm

N_A: Avogadro's number $\approx 6.022 \times 10^{23}\ \text{mol}^{-1}$

A: Atomic mass of hydrogen $1.008\ \text{g mol}^{-1}$

e: electron charge 1.602×10^{-19} C

$\Delta W \Delta Q^2$



$$\frac{d\sigma_{ep}}{dWdQ^2} = \frac{\mathcal{Y}}{L \cdot Br} \frac{1}{\Delta W \Delta Q^2}$$

Yield calculation

- There are 2 ways that we can extract the efficiency corrected yield: Using an event based efficiency and using average bin efficiency. Both methods have been tested and have been found to yield to similar results.

$$\mathcal{Y}_1 = \frac{N_{J/\psi}}{N_s} \times \sum_{i=1}^{N_s} \frac{1}{\eta_i}$$

Event-based

$$\mathcal{Y}_{2a} = \frac{N_{J/\psi}}{\bar{\eta}_a}$$

Average-based

$$\eta = \frac{N^R}{N^G}$$

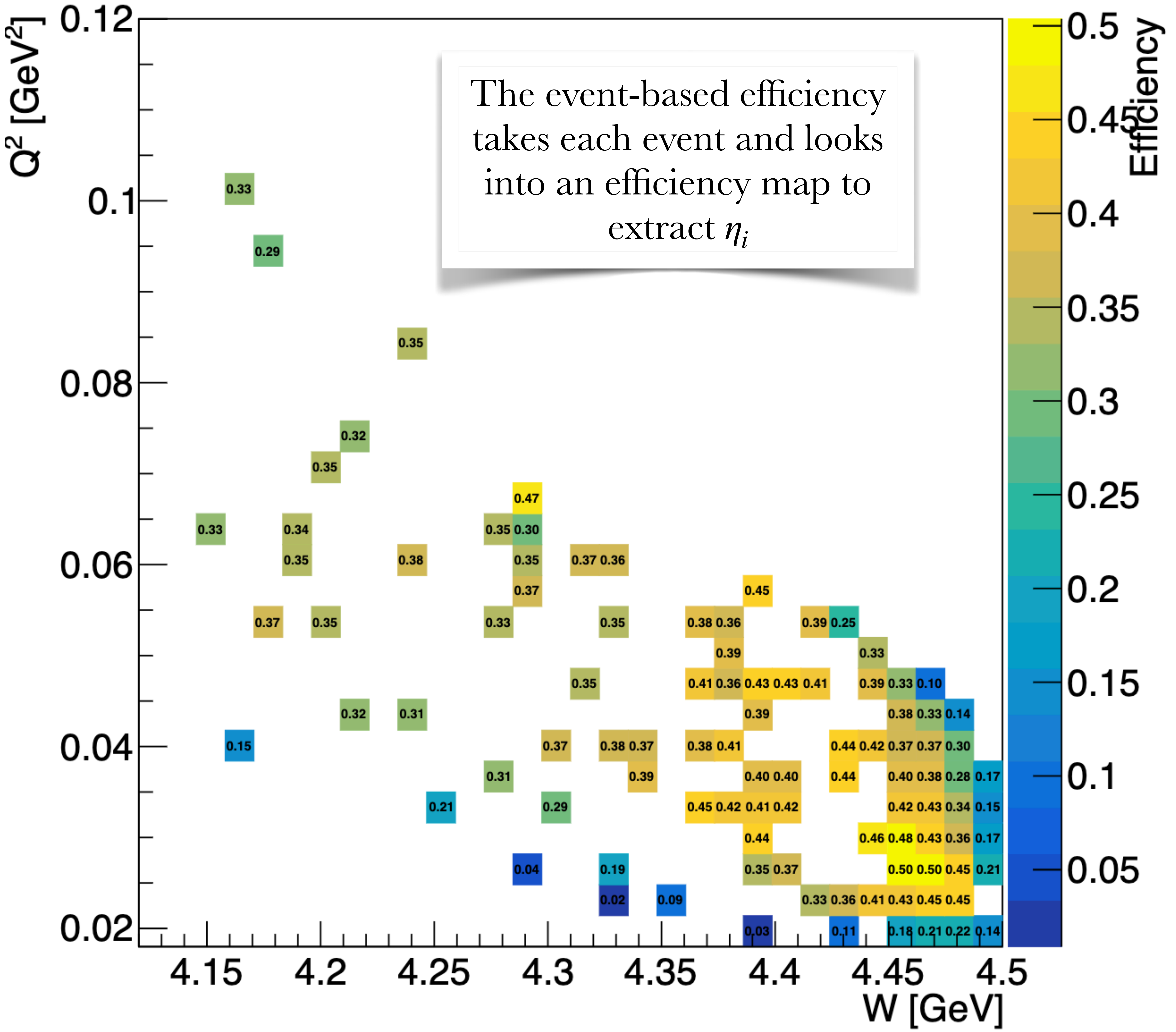
The event-based efficiency takes each event and looks into an efficiency map to extract η_i

The average based takes the average efficiency in the bin.

Simulations

$$\eta = \frac{N^R}{N^G}$$

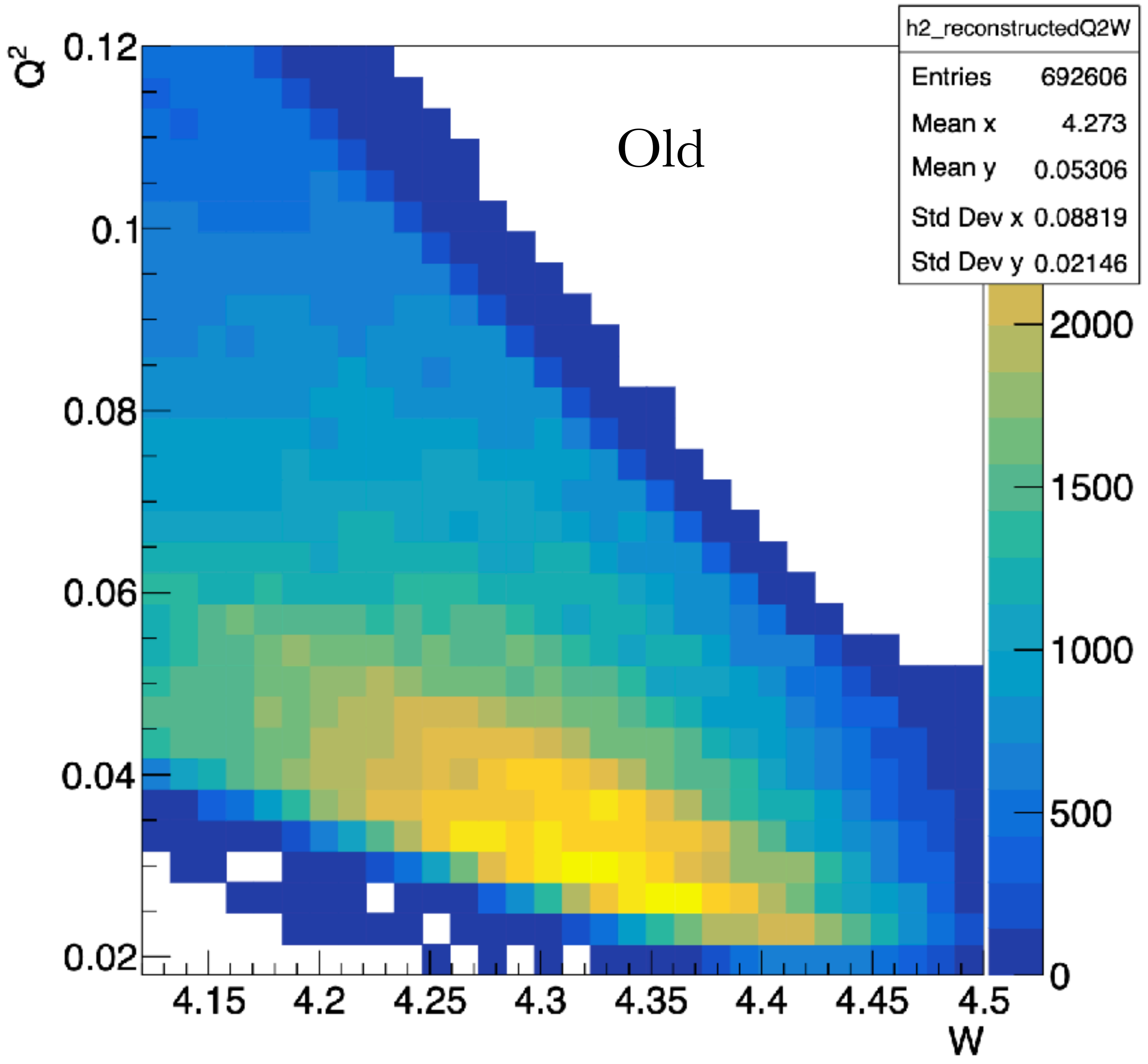
Dataset	Beam Current (nA)	Fraction	Files Used	Events Generated
Fall 2018 Inbending	45	0.74	1847	9.24 M
	50	0.10	250	1.25 M
	55	0.16	399	2.00 M
Fall 2018 Outbending	40	0.64	1597	7.99 M
	50	0.36	899	4.50 M
Spring 2018 Inbending	35	0.08	200	1.0 M
	50	0.92	2296	11.48 M
Spring 2018 Outbending	45	1.00	2496	12.48 M
Spring 2019 Inbending	50	1.00	2496	12.48 M

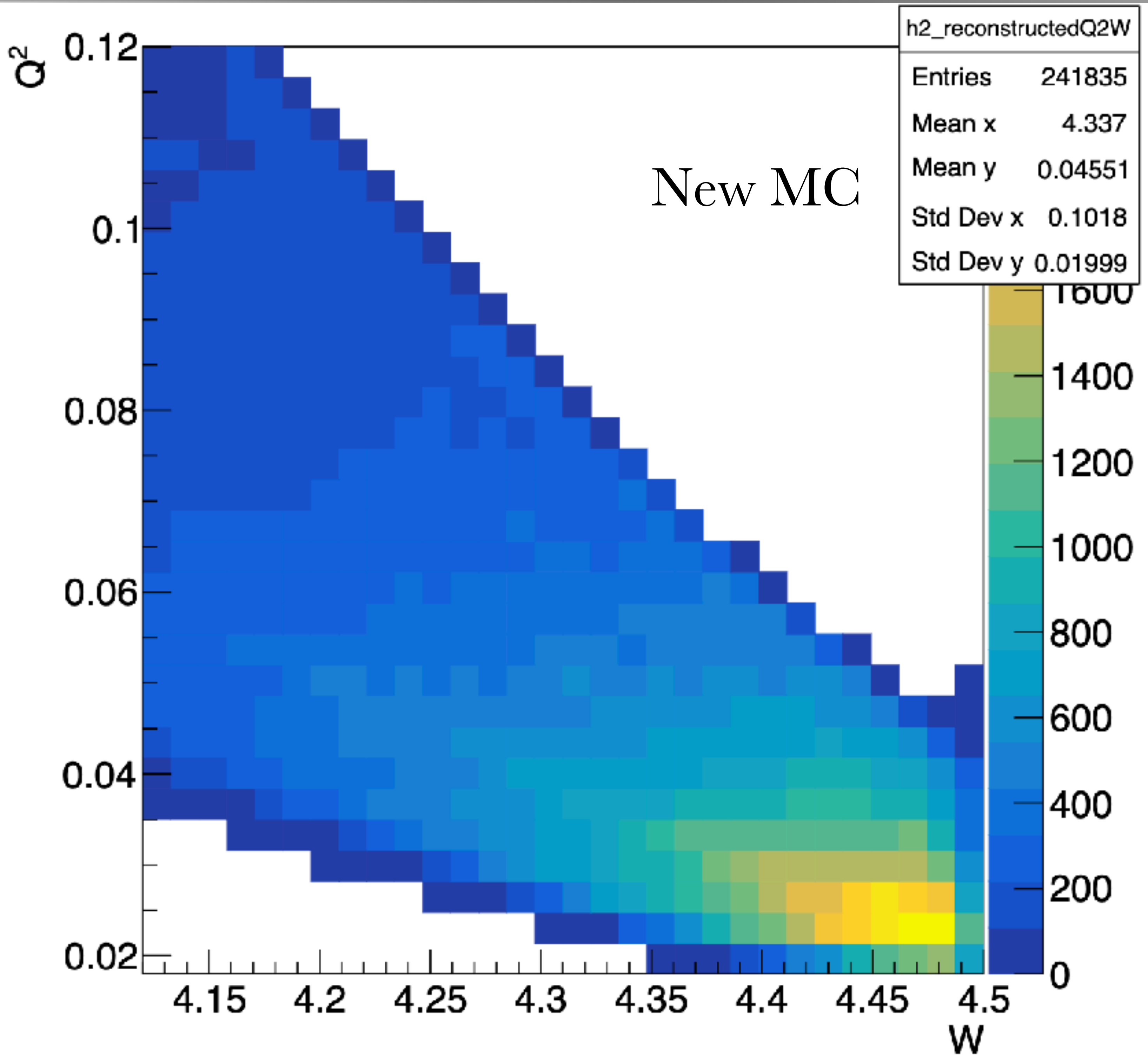


A couple bugs have been found in the MC in the last few weeks:

One was related to the photons detected in the ECAL, which were not being detected, and affected the radiative loss correction for the e^+ and e^- in the FD.

The second one was related to the reconstruction of the e' in the FT. There was a discrepancy between reconstruction in MC and in data that was preventing low energy -high angles e' to reach the last steps of reconstruction in MC





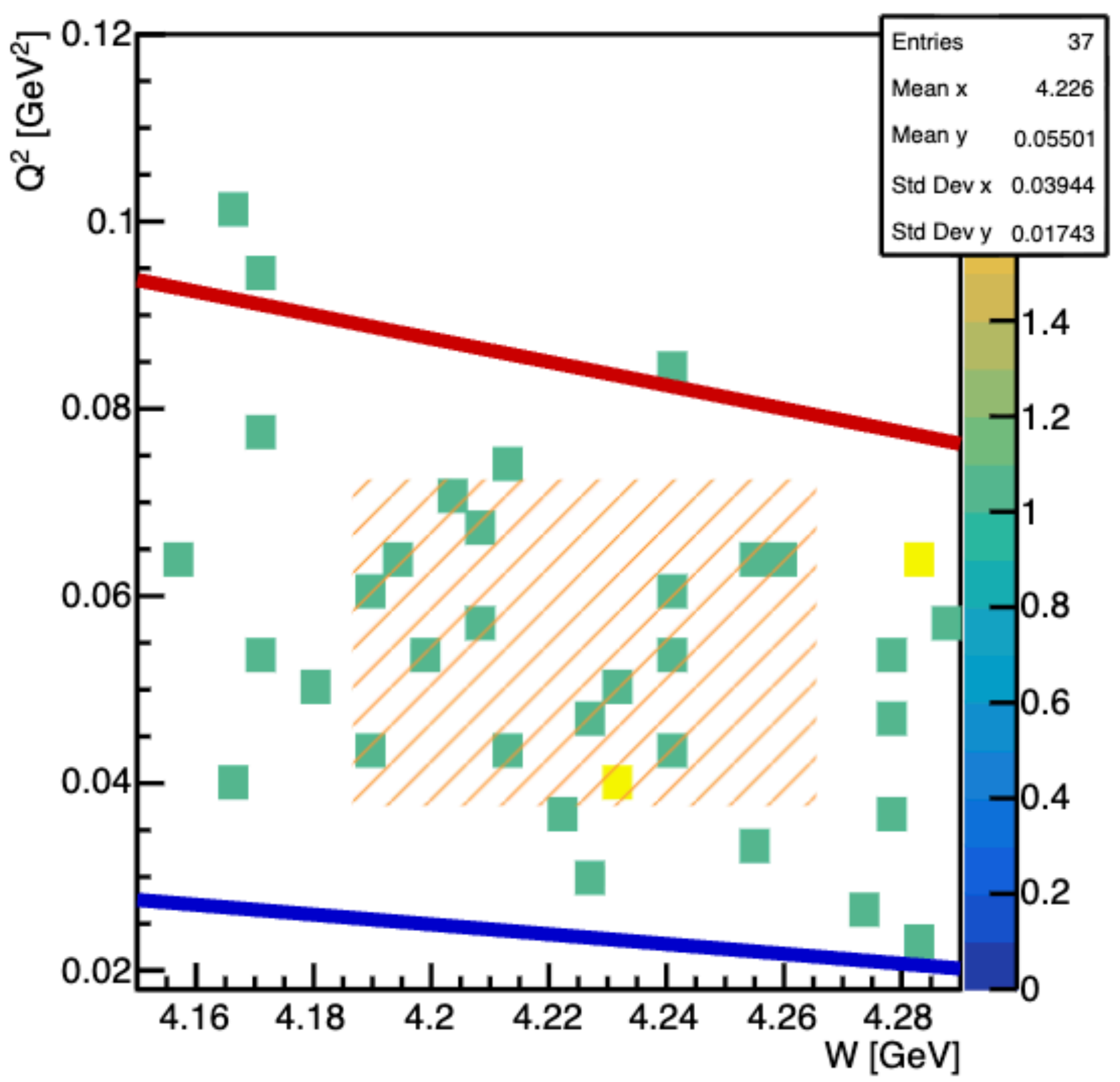
Photon Flux

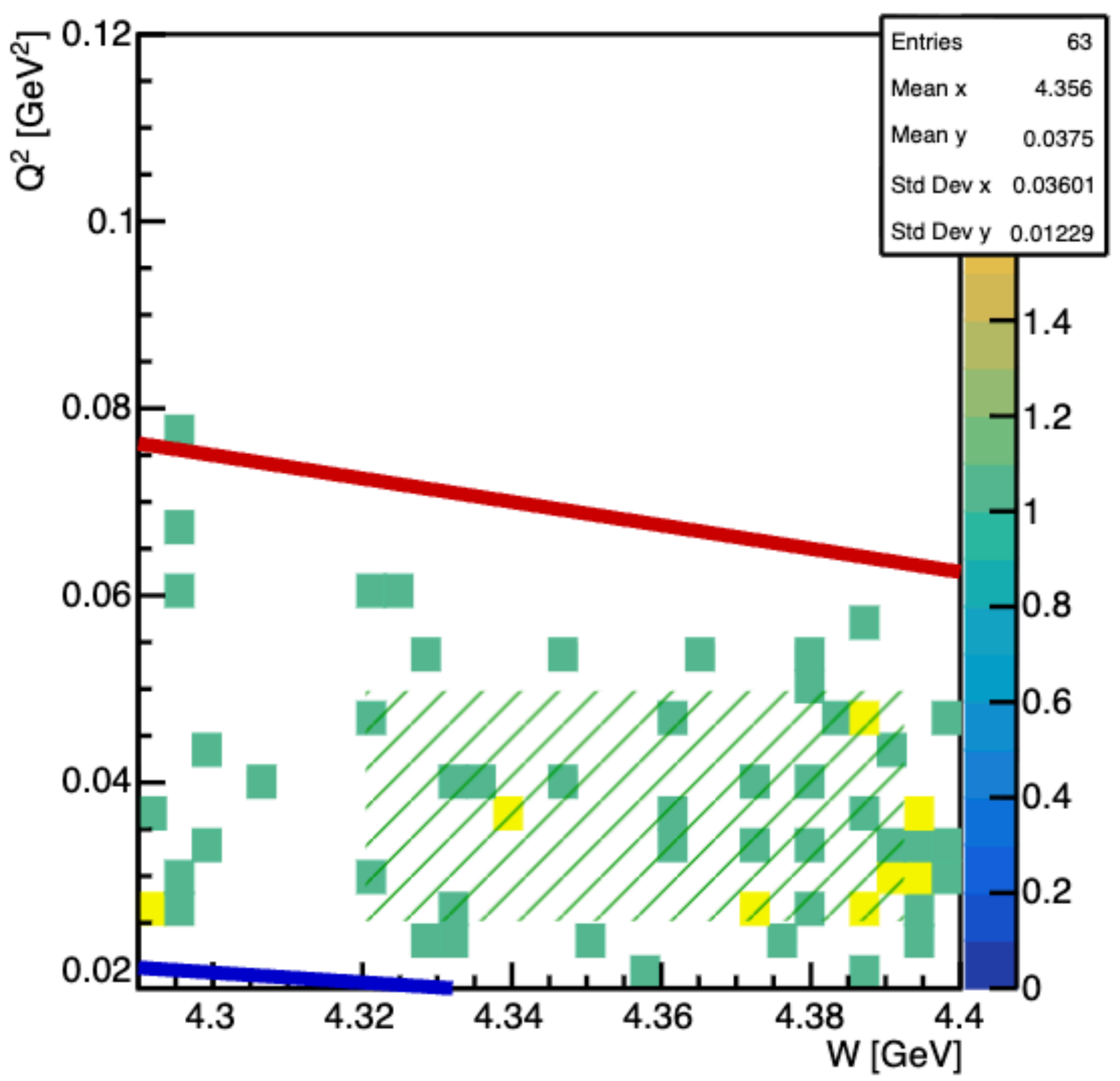
$$\Phi_{\gamma^*} = \int_{\Delta Q^2} \int_{\Delta W} \Gamma(W, Q^2)\, dW\, dQ^2$$

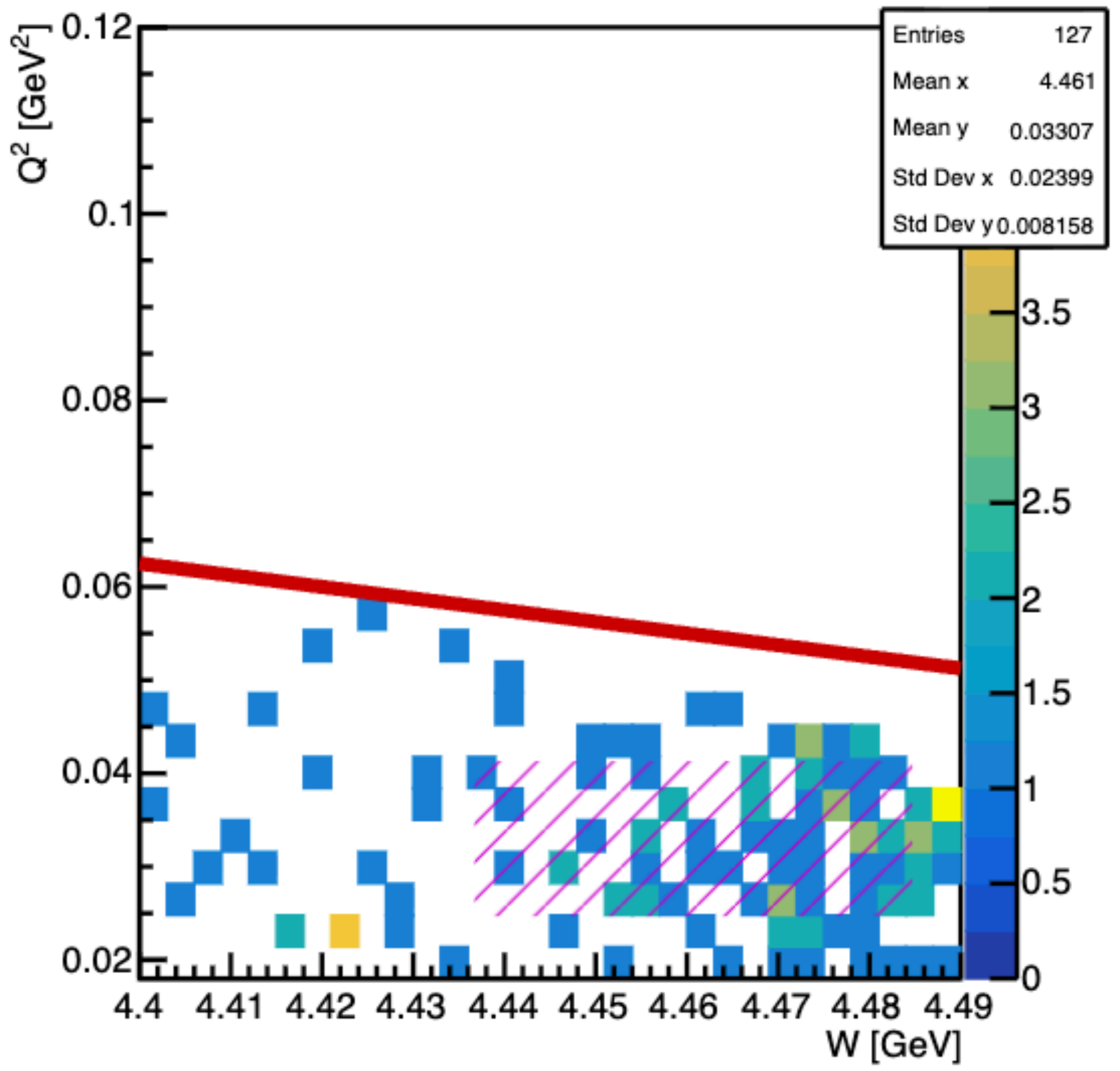
Where Γ is given as:

$$\Gamma = \frac{\alpha}{4\pi} \cdot \frac{W^2 - M_p^2}{M_p^2 E^2} \cdot \frac{W}{Q^2(1-\varepsilon)}$$

$\alpha = \frac{1}{137}$ is the fine-structure constant,
$M_p = 0.938\,\text{GeV}$ is the proton mass,
E is the incoming electron energy, and E' the scattered energy,
ε is the transverse polarization of the virtual photon, given by: $\varepsilon = \dfrac{1}{1 + \frac{2(Q^2+\nu^2)}{4EE' - Q^2}}$







Preliminary Results

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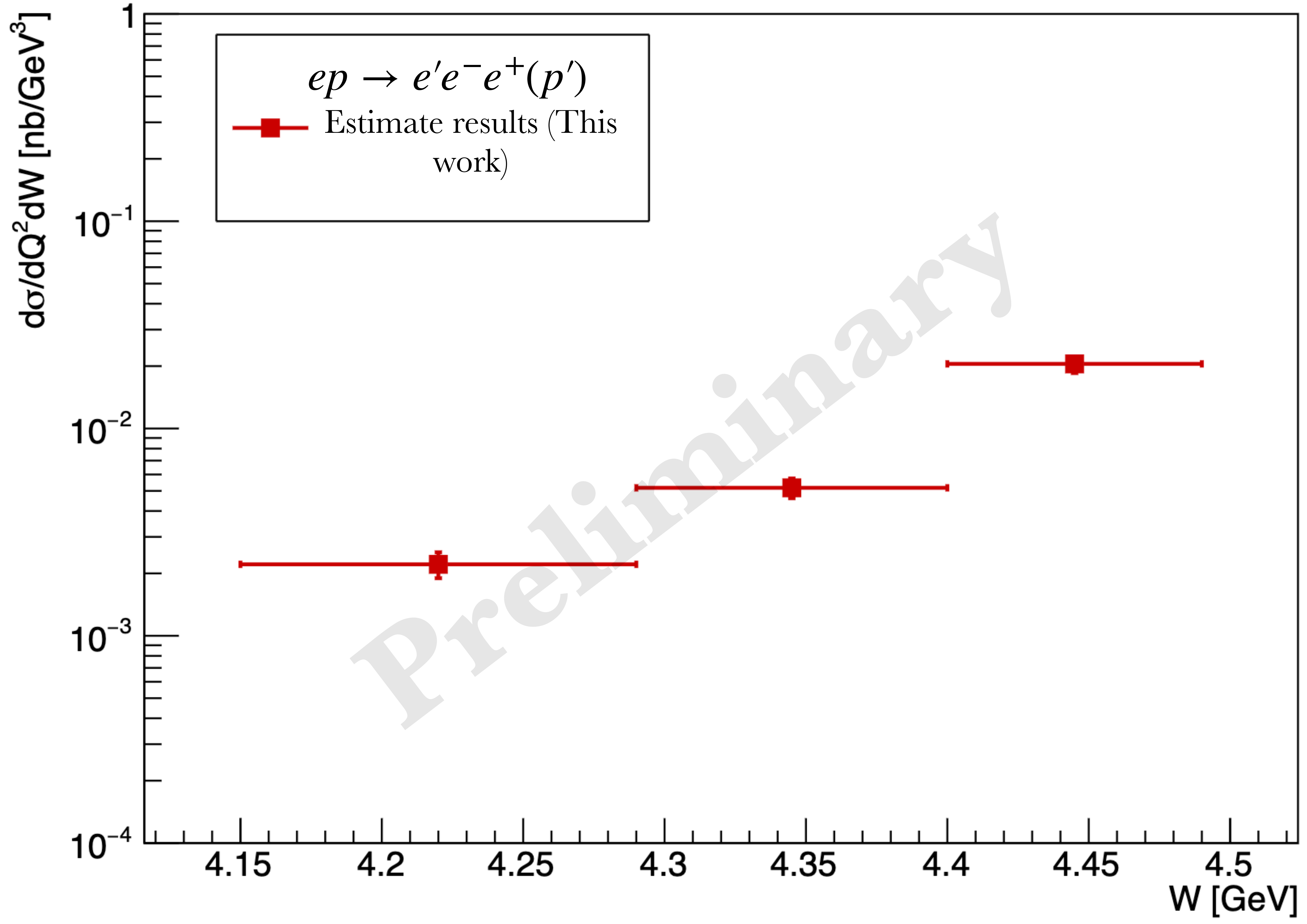

$$\frac{d\sigma_{ep}}{dWdQ^2} = \frac{\mathscr{Y}}{L \cdot Br} \frac{1}{\Delta W \Delta Q^2}$$

This is only an estimate so far, we have all the chain ready to run as soon as we get the correct and full MC

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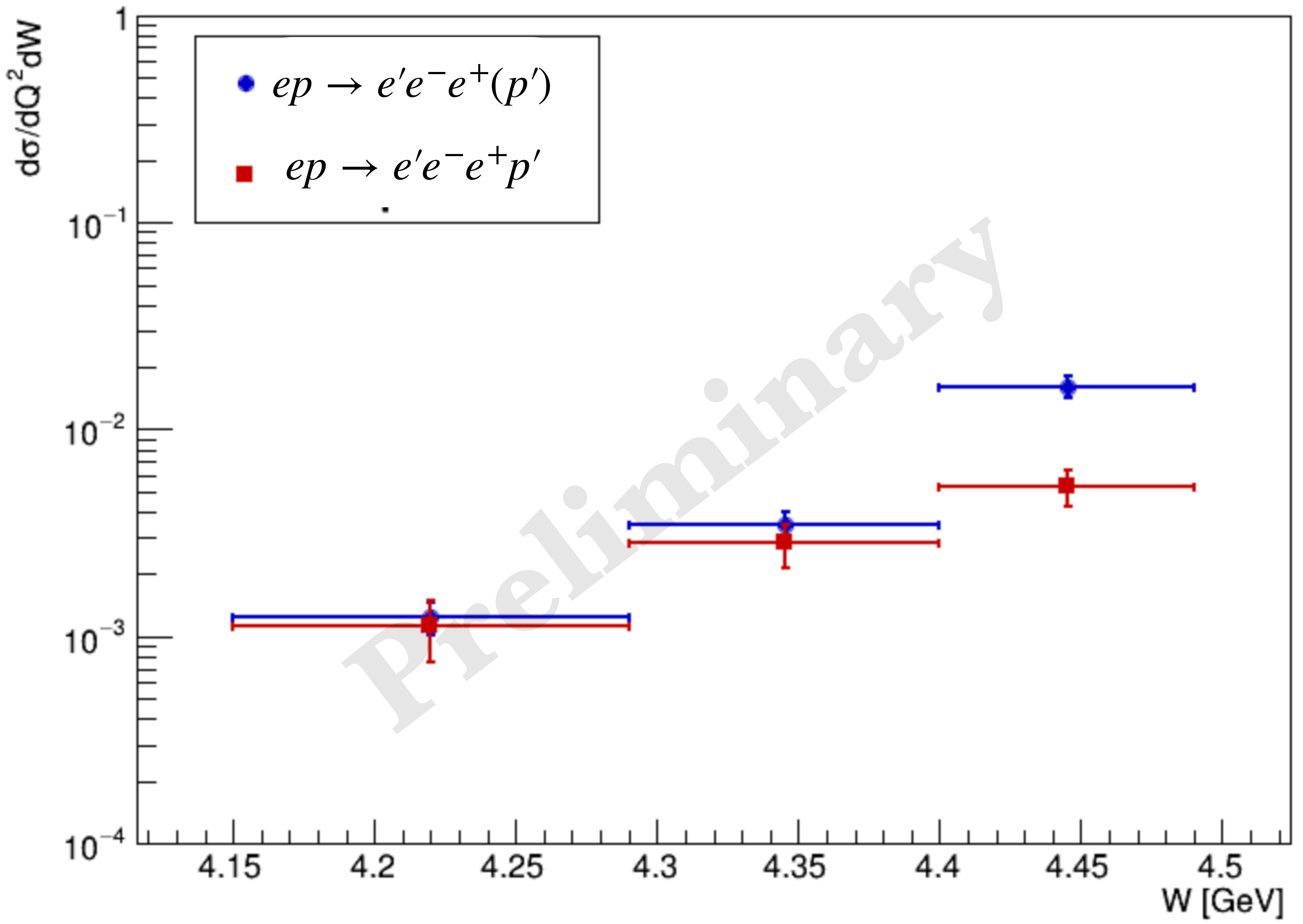

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We are explicitly excluding any events that contain one proton in FD for $ep \to e'e^-e^+(p')$

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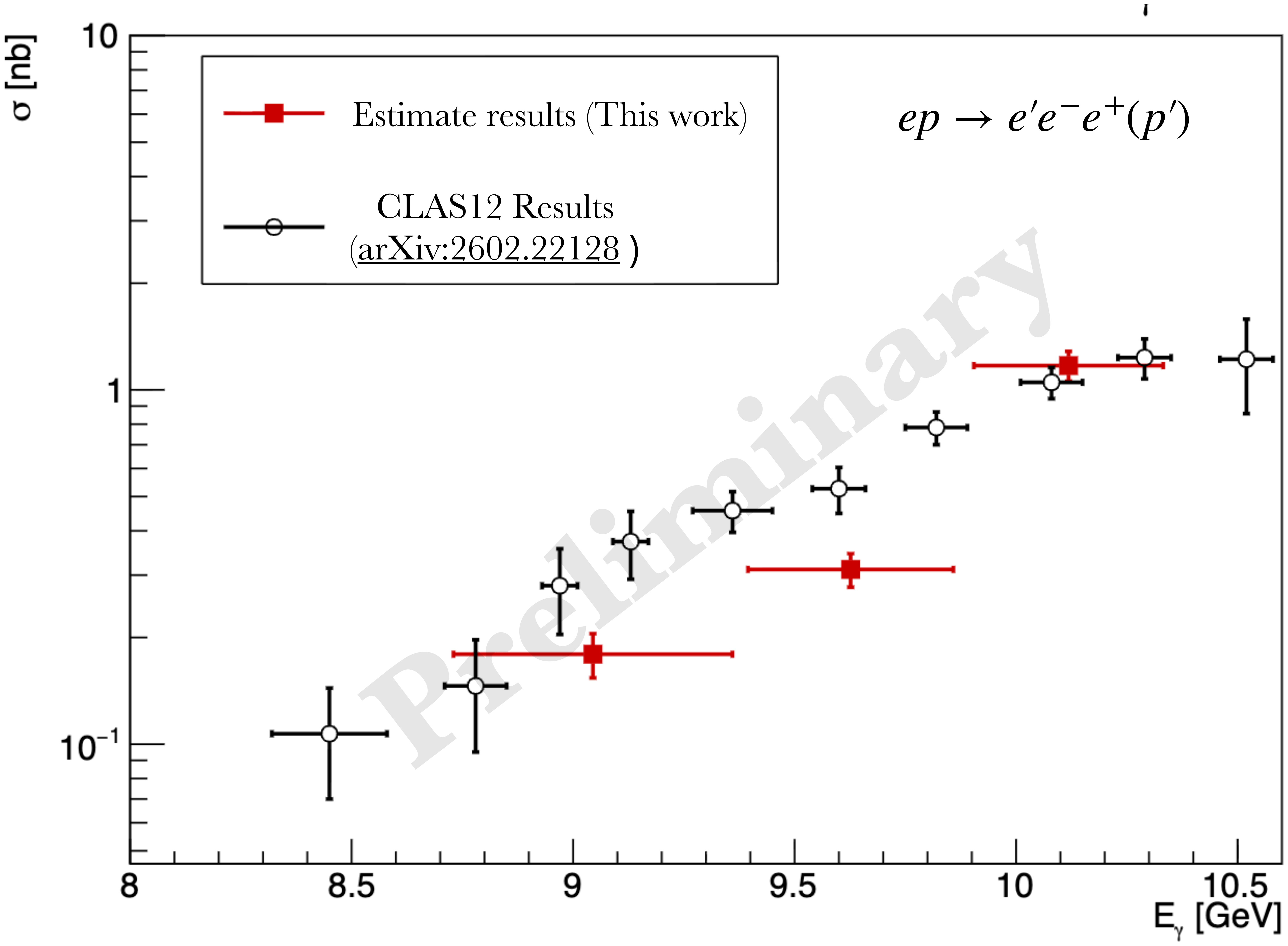

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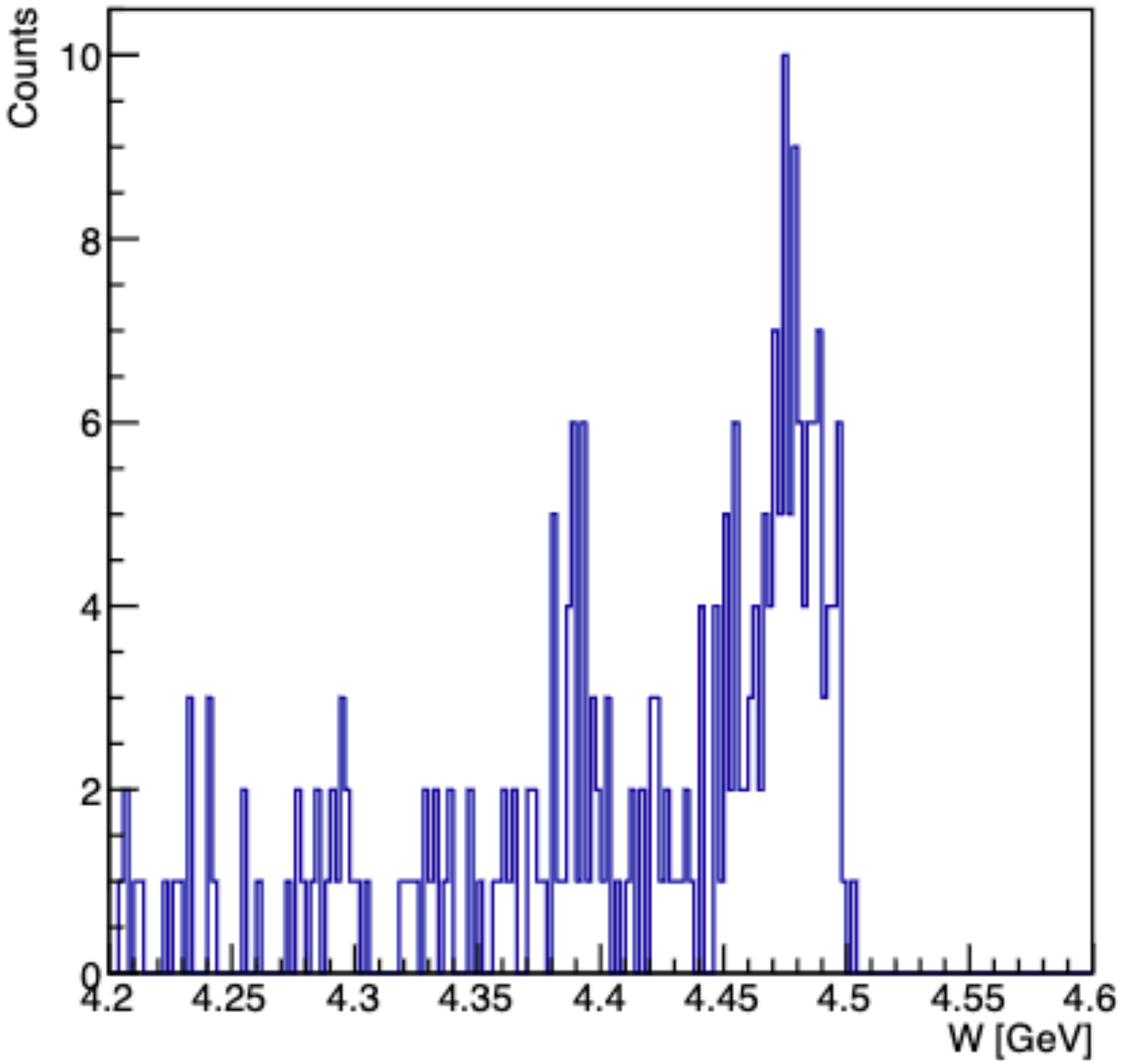
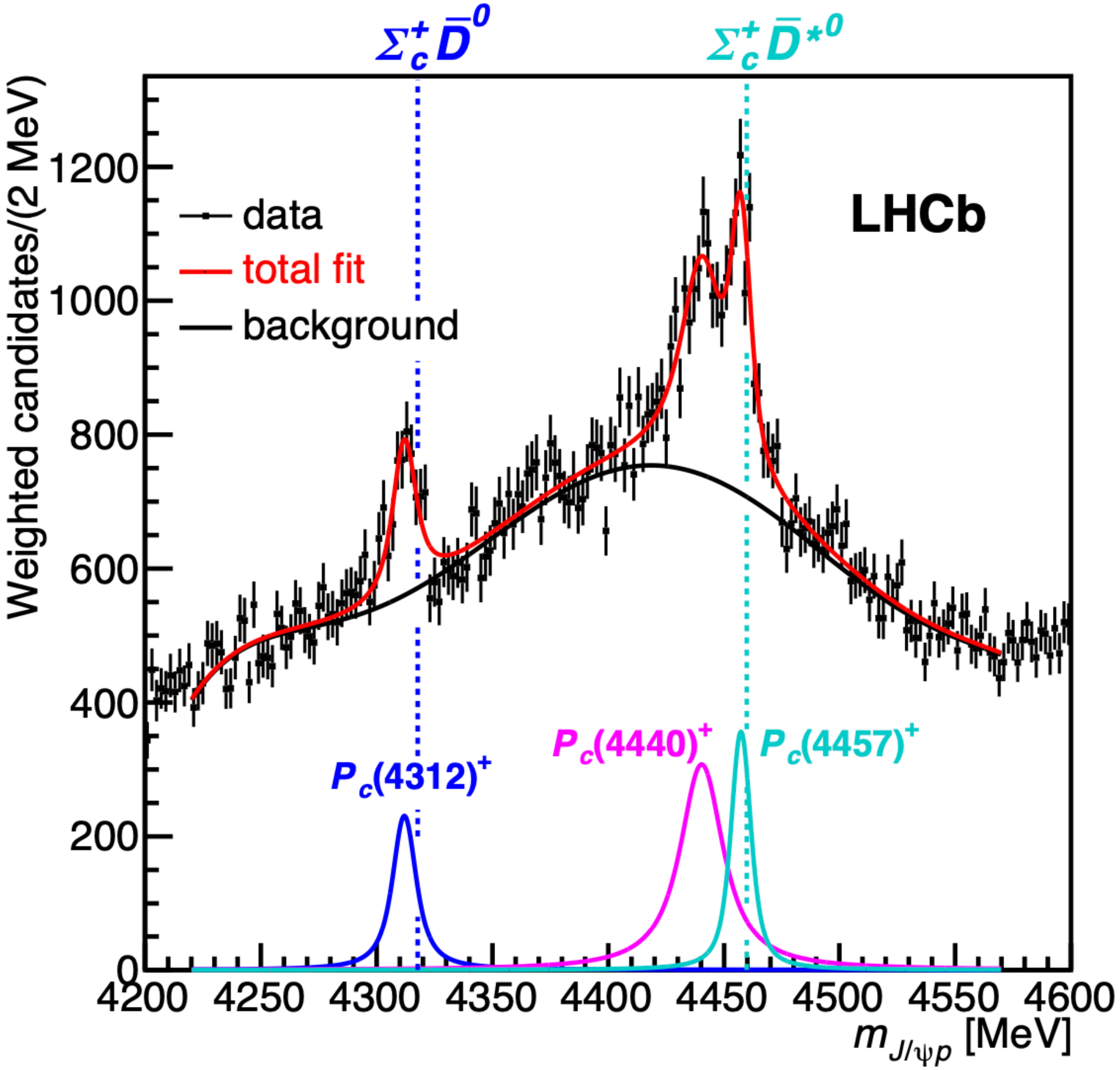
What about the P_c states?

Still low statistics, but some side bin studies are being done to do a fair assesment





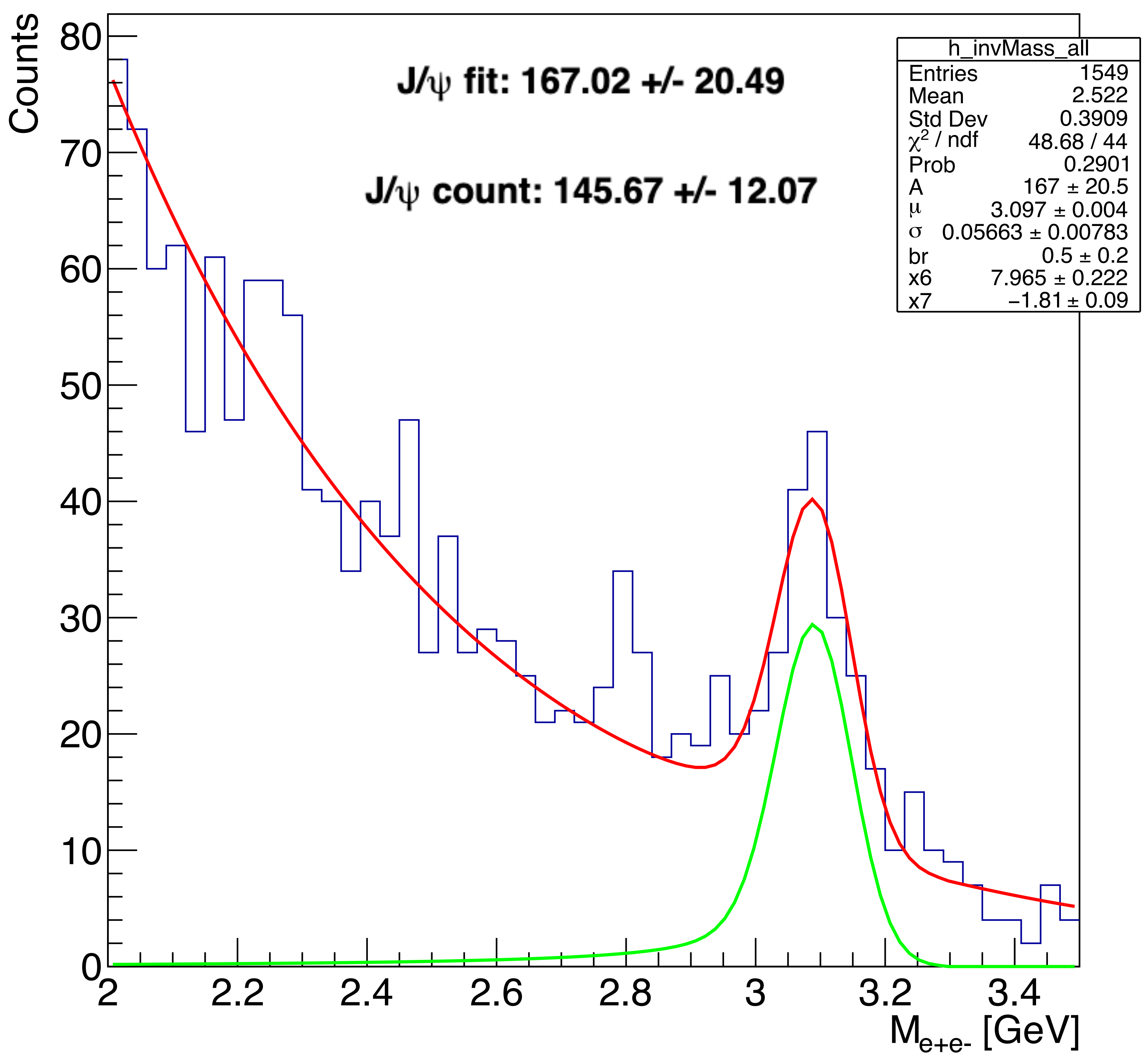
Conclusion

- First measurement of near-threshold J/ψ electroproduction cross-sections at CLAS12 using full RGA Pass2 data (W = 4.15–4.50 GeV, Q^2 = 0.02–0.12 GeV^2)
- The $ep \to e'e^-e^+(p')$ topology provides the cleanest signal extraction, but the other topologies provide a useful cross-check.
- Efficiency-corrected yields with MC are in progress, and final results will be coming in the next few weeks.
- Two other topologies are also possible with this framework $ep \to e'p'e^+(e^-)$ and $ep \to e'p'e^-(e^+)$

Back-up

- $E_{\text{beam}} - E_{e'} > 8.1\text{GeV}$
- $M_{e^+e^-} > 2.0$ GeV

Signal Extraction



There are two ways to extract the signal:

1) From the fit
2) From background substraction.

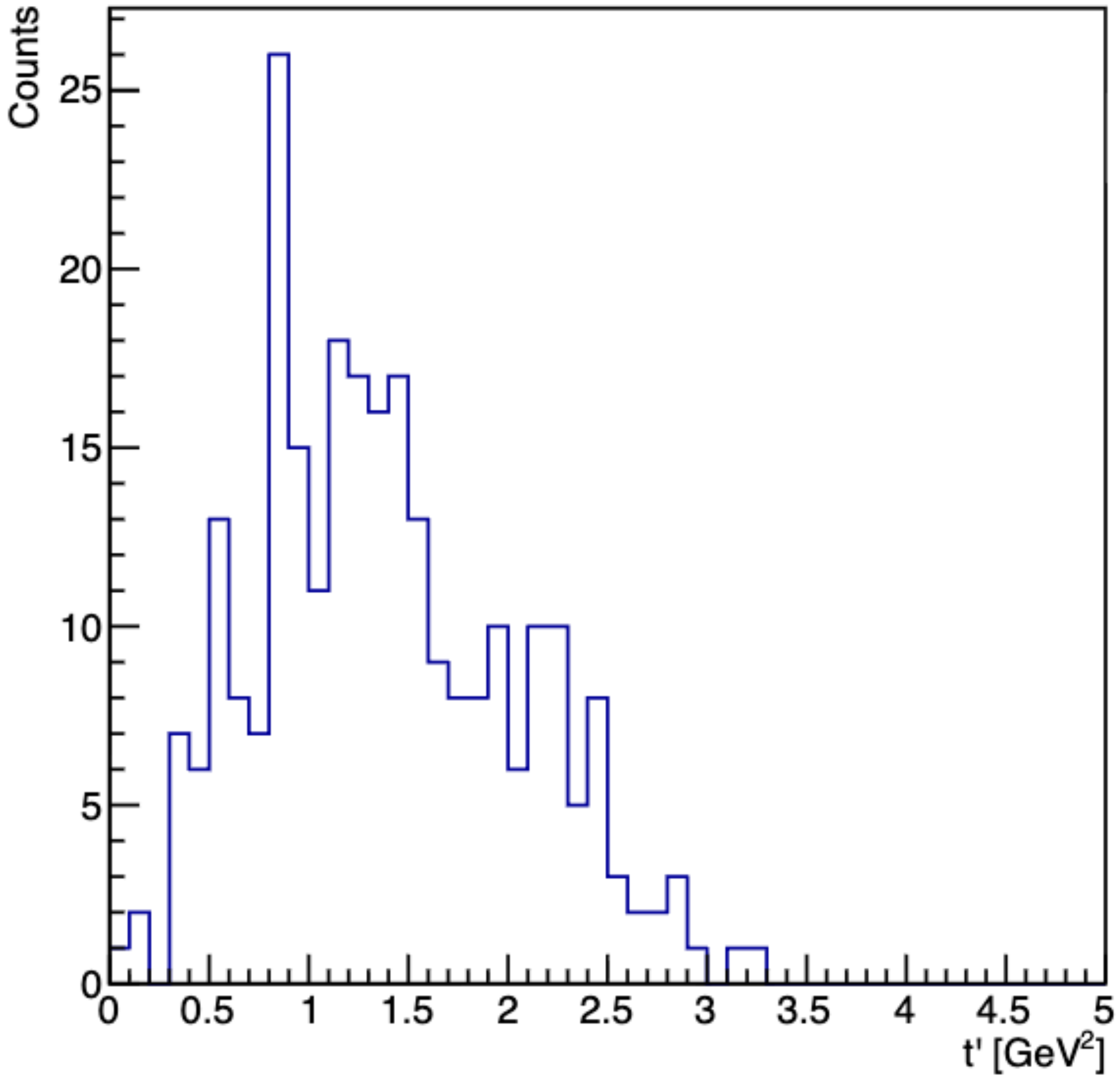
1) The fit is physically motivated signal function that incorporates the QED radiative decay tail, together with an exponential background component.

2) The total number of counts inside the mass window is added, and the fitted background contribution is subtracted:

$$N^{\text{count}}_{J/\psi} = \sum N_{\text{peak}} - \int_{2.946}^{3.246} BG_{\text{fit}}(M)\, dM$$

This one is prefered when statistics is low

t' distribution for data under the peak

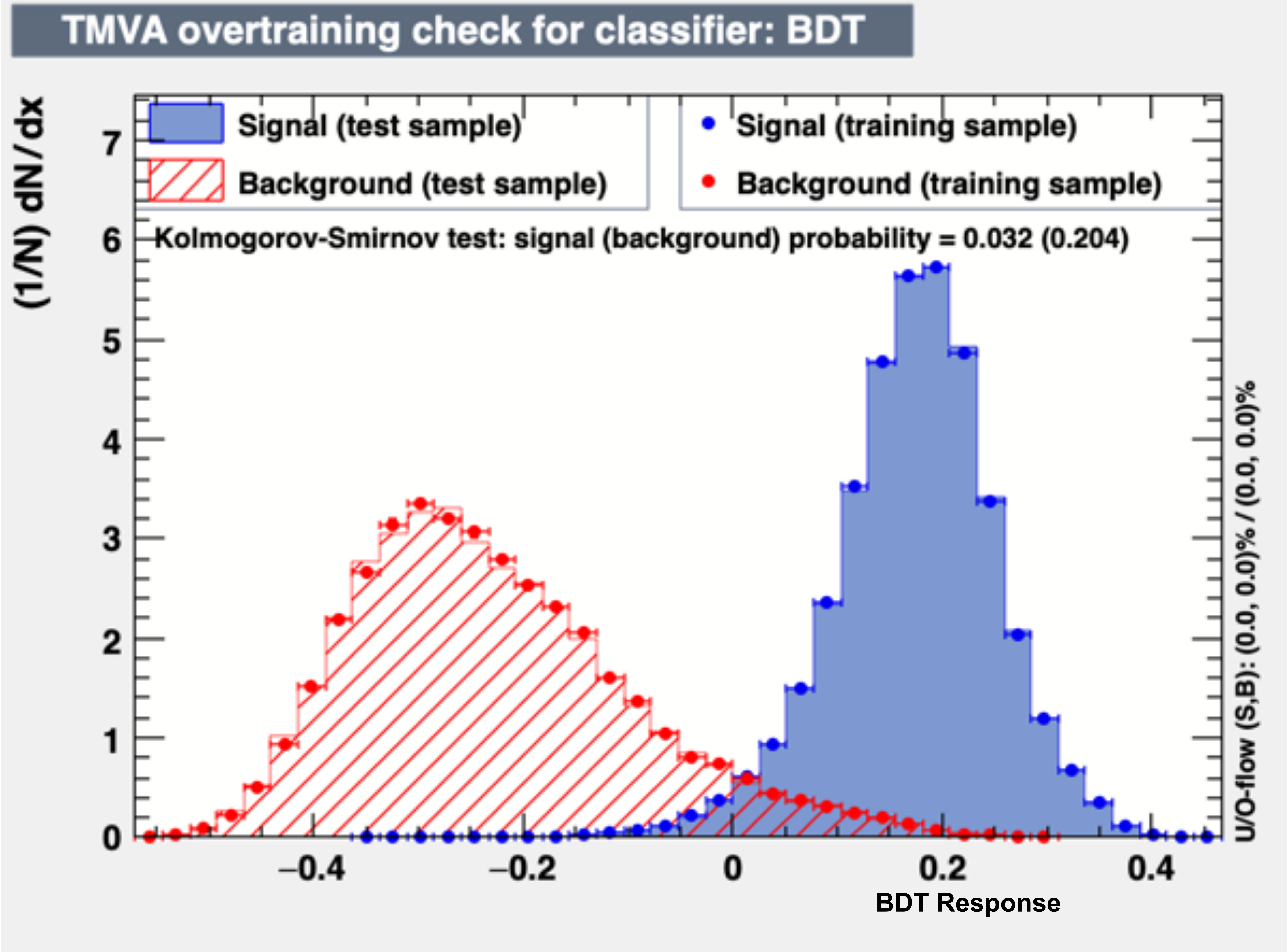


$$t = (p_p - p_{p'})^2$$

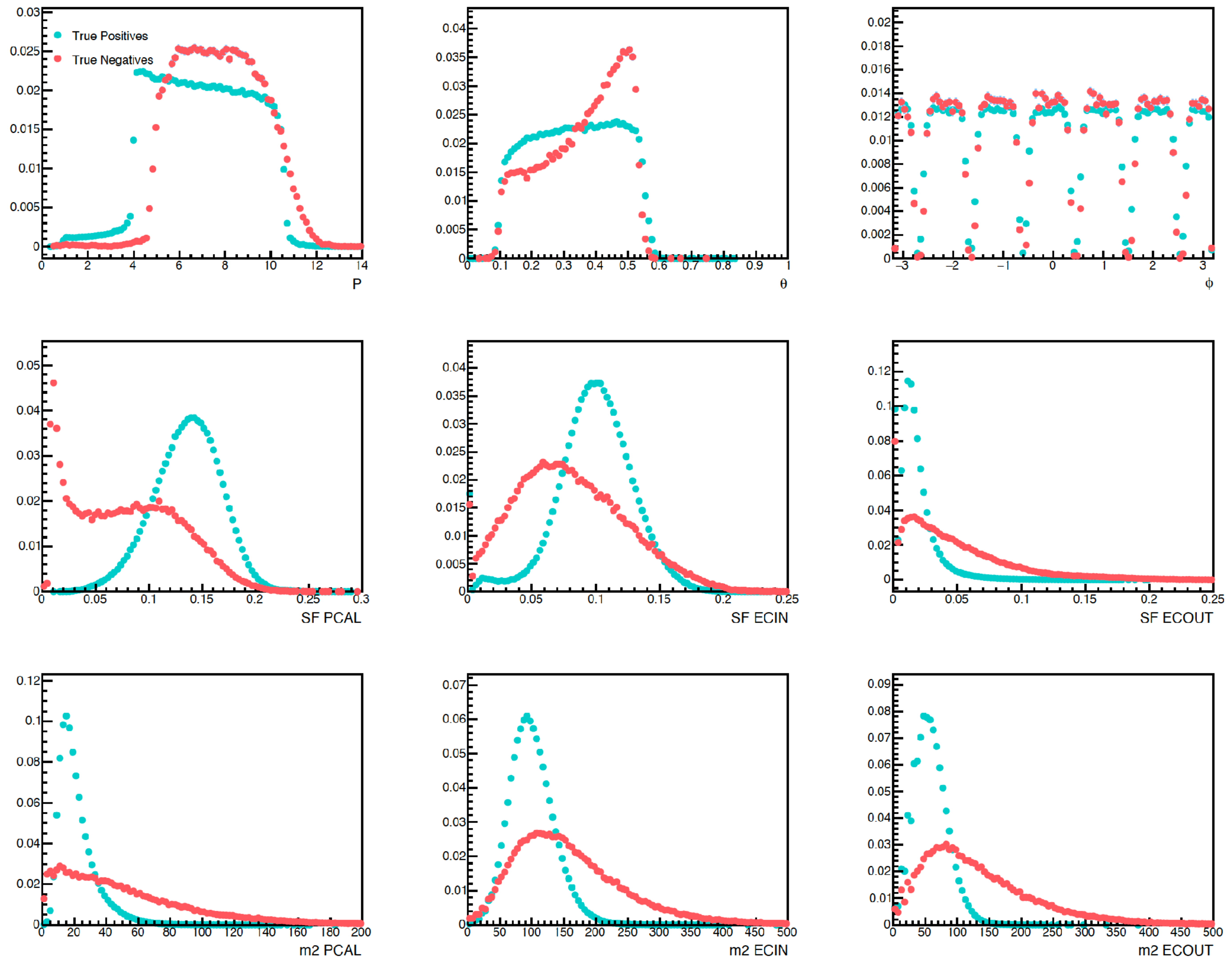
$$t' = -(t - t_{\min})$$

$$t_{\min} = -\frac{(M_{J/\psi}^2 - m_p^2)^2}{4\nu^2 m_p^2}$$

Training



Distributions of signal and background events as a function of the classifier response.

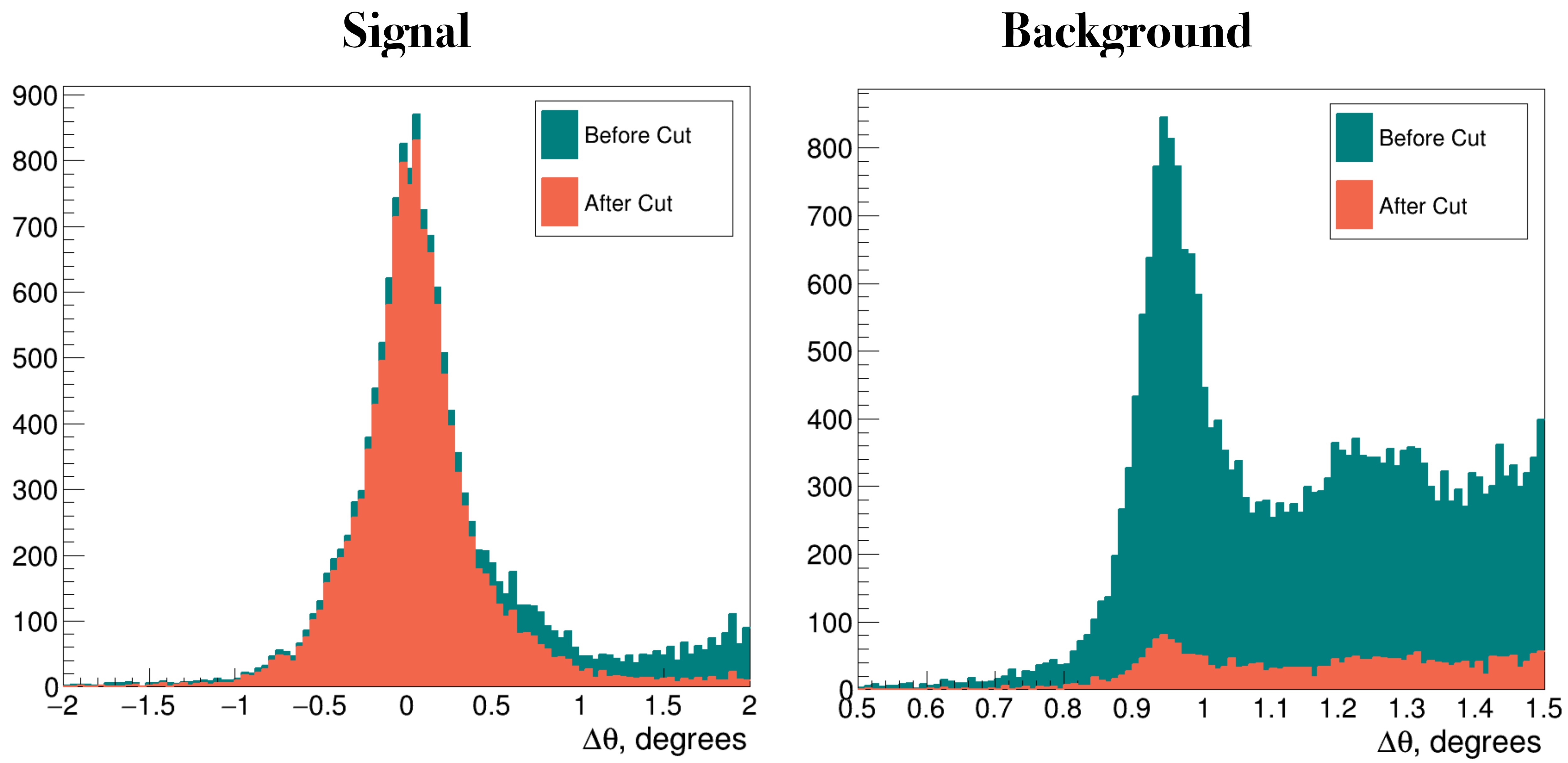


Model Validation

- For Signal: A clean lepton sample is obtained using radiated photons detected in the ECAL. The number of true leptons is extracted by fitting the peak at zero in $\Delta\theta_{e\gamma}$.

- For Background: The reaction $ep \rightarrow e^-\pi^+_{PID=-11}(X)$ is used, where π^+ was identified as positron. Background yields are extracted by fitting the missing neutron mass peak.

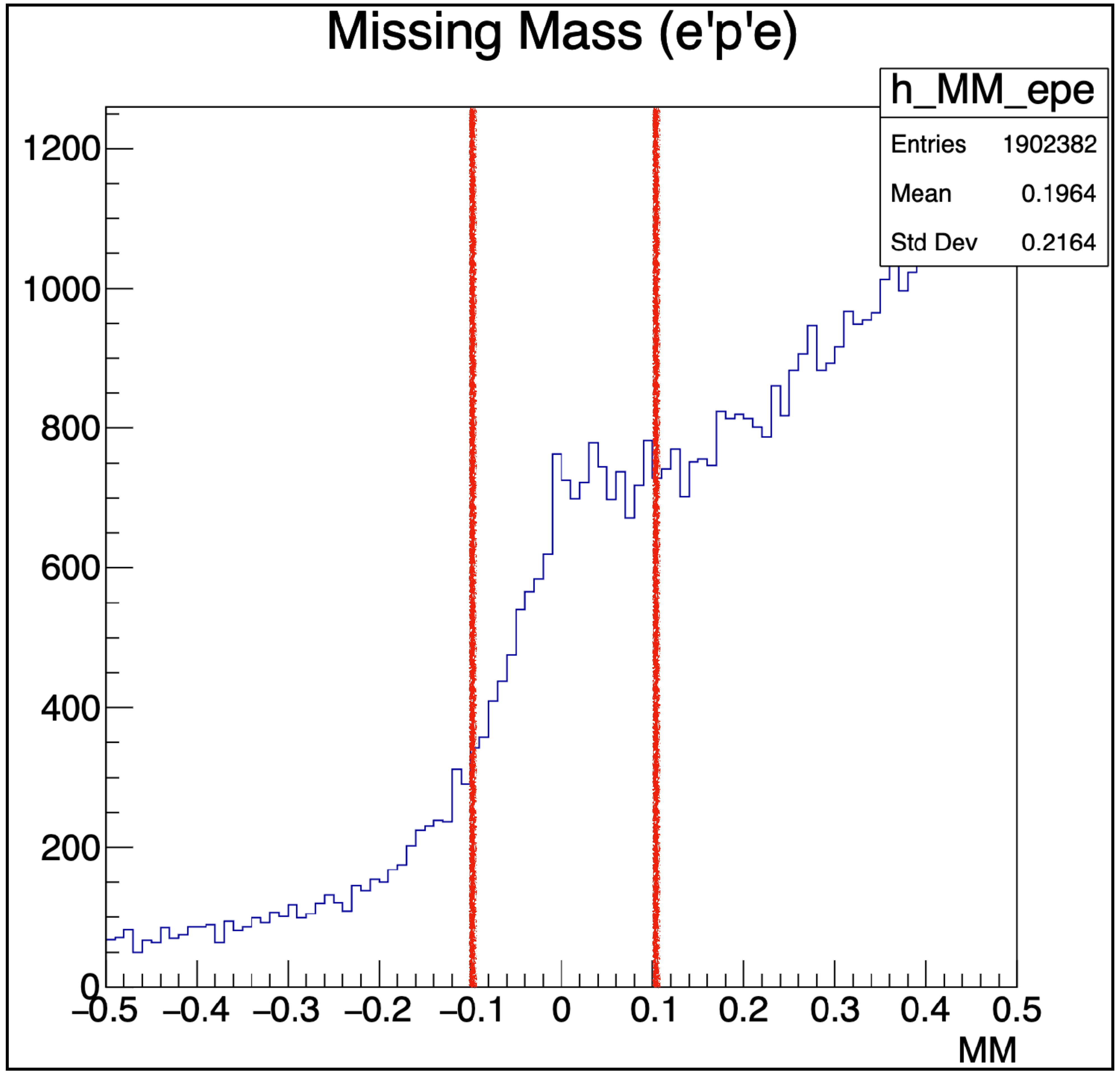
- All samples are restricted to $P > 4.5 GeV$.



The models successfully cut background by a factor of 10, while preserving around 90% of the leptons.

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

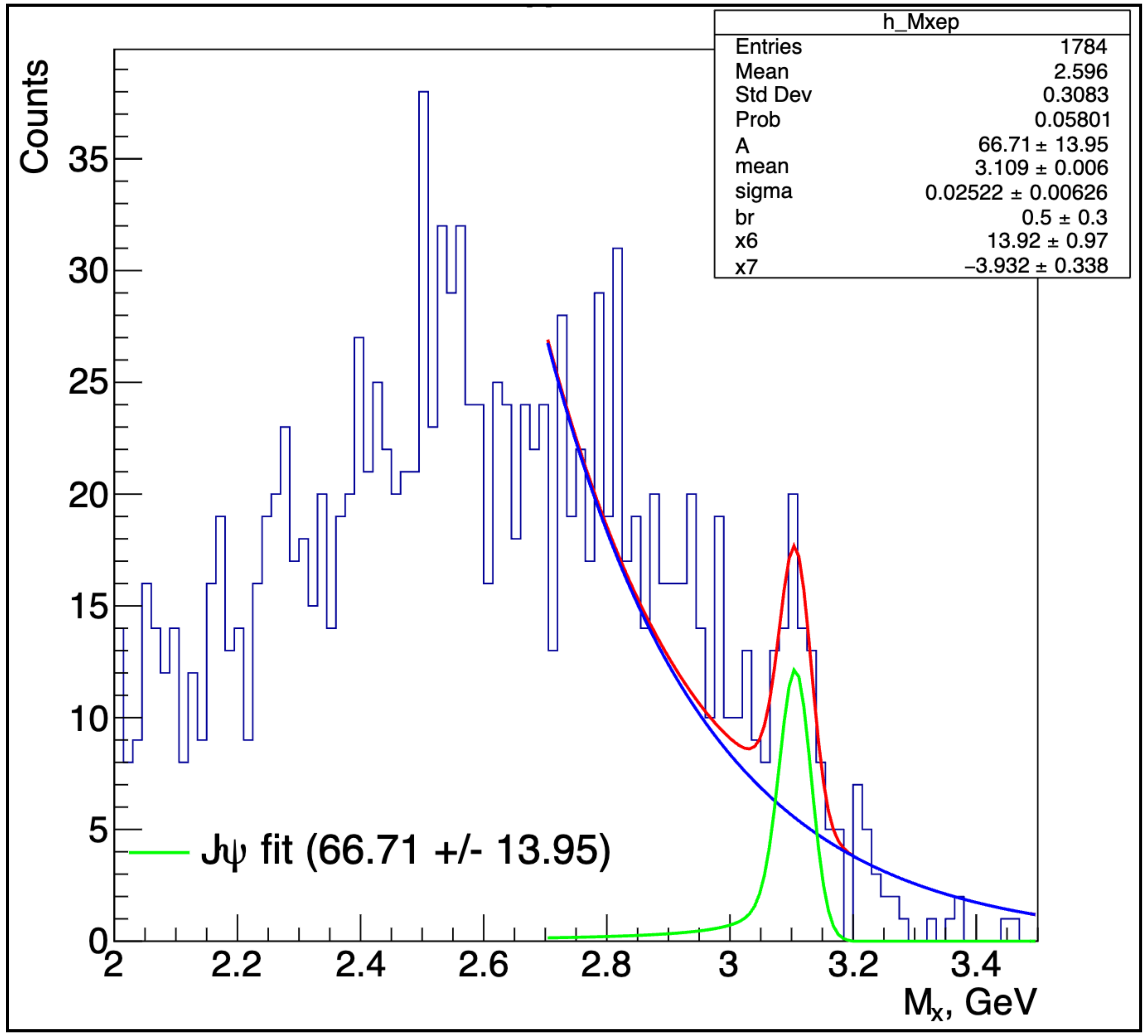
- For the reaction $ep \to e'p'e^+(e^-)$
- We select one electron in FT, one positron in FD and one proton in FD.
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^+} - p_{e'} - p_{p'}$
- We keep events with $E_\gamma > 8.1\,\mathrm{GeV}$ where $E_\gamma = E_{beam} - E_{e'}$
- The peak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



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

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

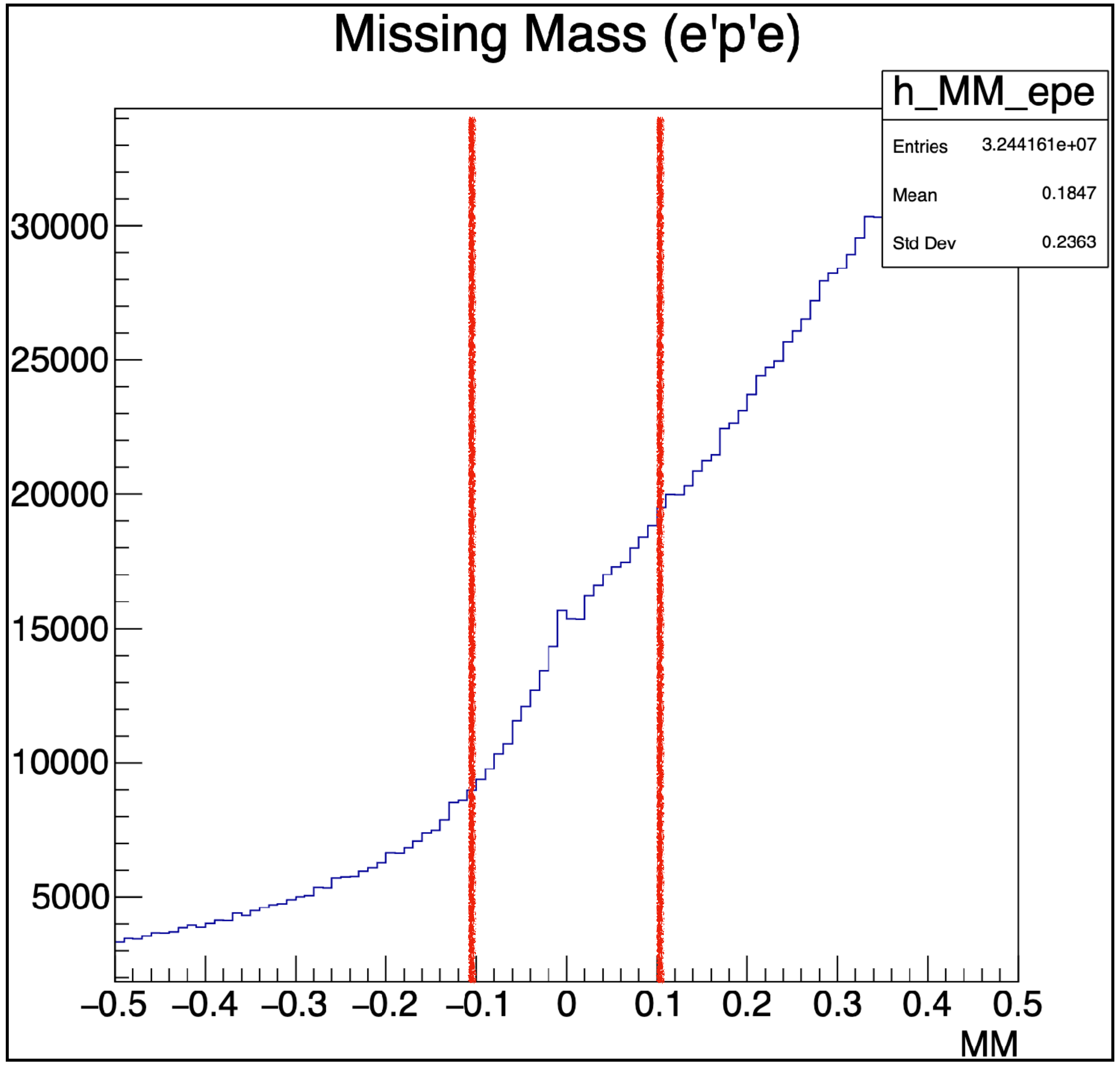
- For the reaction $ep \to e'p'e^+(e^-)$
- We select one electron in FT, one positron in FD and one proton in FD.
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^+} - p_{e'} - p_{p'}$
- We keep events with $E_\gamma > 8.1\,\mathrm{GeV}$ where $E_\gamma = E_{beam} - E_{e'}$
- The peak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



$M_X(e'p')$

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

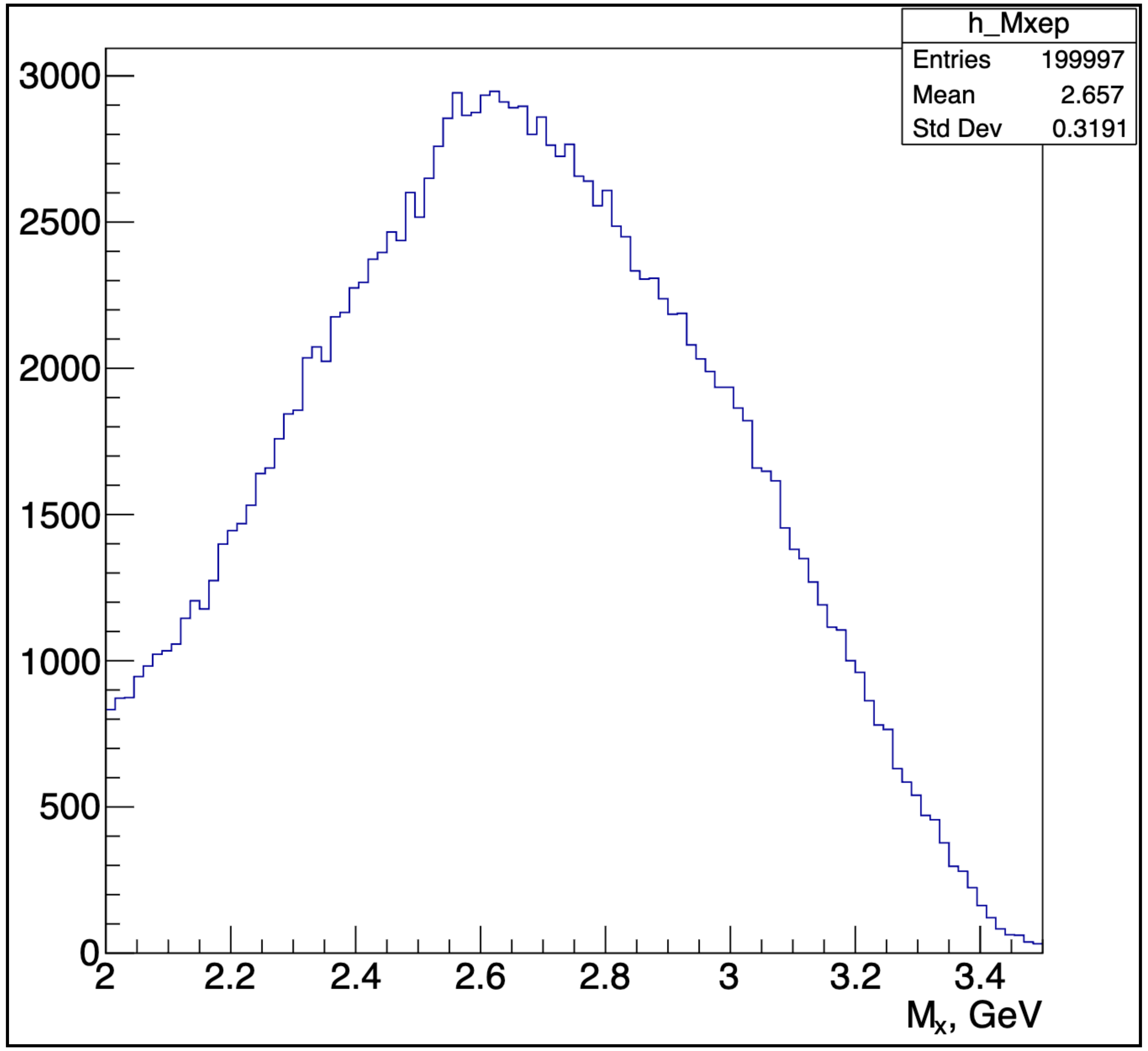
- For the reaction $ep \to e'p'e^-(e^+)$
- We select one electron in FT, one positron in FD and one proton in FD.
- The missing four-momentum is defined as $p_X = p_e + p_p - p_{e^-} - p_{e'} - p_{p'}$
- The peak on the distribution should be around the mass of the missing lepton.
- We keep events with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



$M_X(e'p')$