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# COMPASS RH<sub>00</sub> ANALYSIS

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April 10th, 2025

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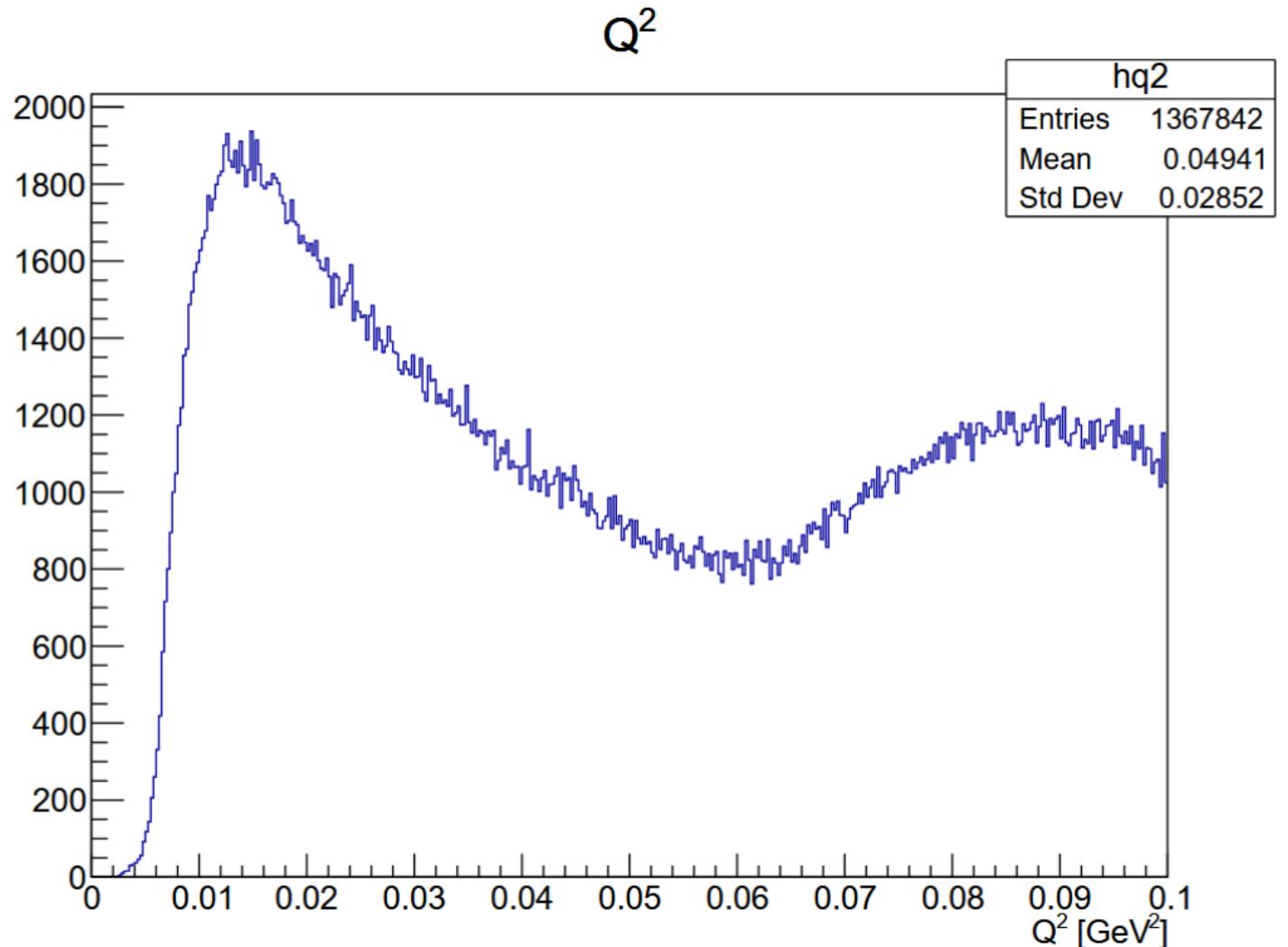
# COMPASS DATA AND MC

- Year 2016, and period 04,05,06,07,09
  - P09 is used for the Monte Carlo comparison and SDME extraction
- COMPASS is using two different Monte Carlo for their 2012 analysis:
  - HepGEN – For the exclusive  $\rho^0$  reaction
  - LEPTO –For the SIDIS Background

# Small $Q^2$ events

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1. Low  $Q^2$  physics
  - o A group at COMPASS who looks at the low  $Q^2$  physics
  - o quasi-real photoproduction
2. Bad reconstruction for small scattering angle
3. Acceptance with the scattered muon trigger
4. For DIS, the kinematic cut of  $Q^2 > 0.8$  GeV $^2$  is typically used ( $Q^2 > 1$  for this analysis)



# Event Selection Muons

Coming from DVCS analysis of 2016 data  
(J. V. Giarra, Deeply Virtual Compton Scattering at COMPASS, PhD thesis, 2022.)

## Incoming muon track ( $\mu$ ):

- first measured before the target ( $Z_{\text{tgt,min.}} = -318.5 \text{ cm}$ )
- track crosses the full target length
- momentum:  $140 \text{ GeV}/c < p_\mu < 180 \text{ GeV}/c$
- momentum error:  $\Delta p_\mu \leq 0.025 \cdot p_\mu$
- meantime:  $-2 \text{ ns} < t_{\text{track}} < 2 \text{ ns}$
- hits in Beam Momentum Station (BMS):  $\geq 3$
- hits in Scintillation Fibre detectors (SCIFI):  $\geq 2$
- hits in Silicon strip detectors (SI):  $\geq 3$

## Outgoing charged track ( $\mu'$ ):

- same charge as incoming muon
- rel. radiation length:  $X / X_0 > 15$
- first measured before and last after SM1:  $Z_{\text{first}} < 350 \text{ cm}$  and  $Z_{\text{last}} > 350 \text{ cm}$
- track extrapolations are in the active hodoscope areas (PaHodoHelper::iMuPrim())

## Vertex requirements:

- in target
  - $-318.5 \text{ cm} < Z_{\text{vtx}} < -78.5 \text{ cm}$
  - $R_{\text{vtx}} < 1.9 \text{ cm}$
  - $Y_{\text{vtx}} < 1.2 \text{ cm}$
- exactly one outgoing charged track

# Event Selection Hadrons

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Coming from 2012 Rho analysis (W. Augustyniak, et al. ,Spin Density Matrix Elements for exclusive  $\rho^0$  meson production using the 2012 COMPASS data,internal note, 2021.)

- Hadrons

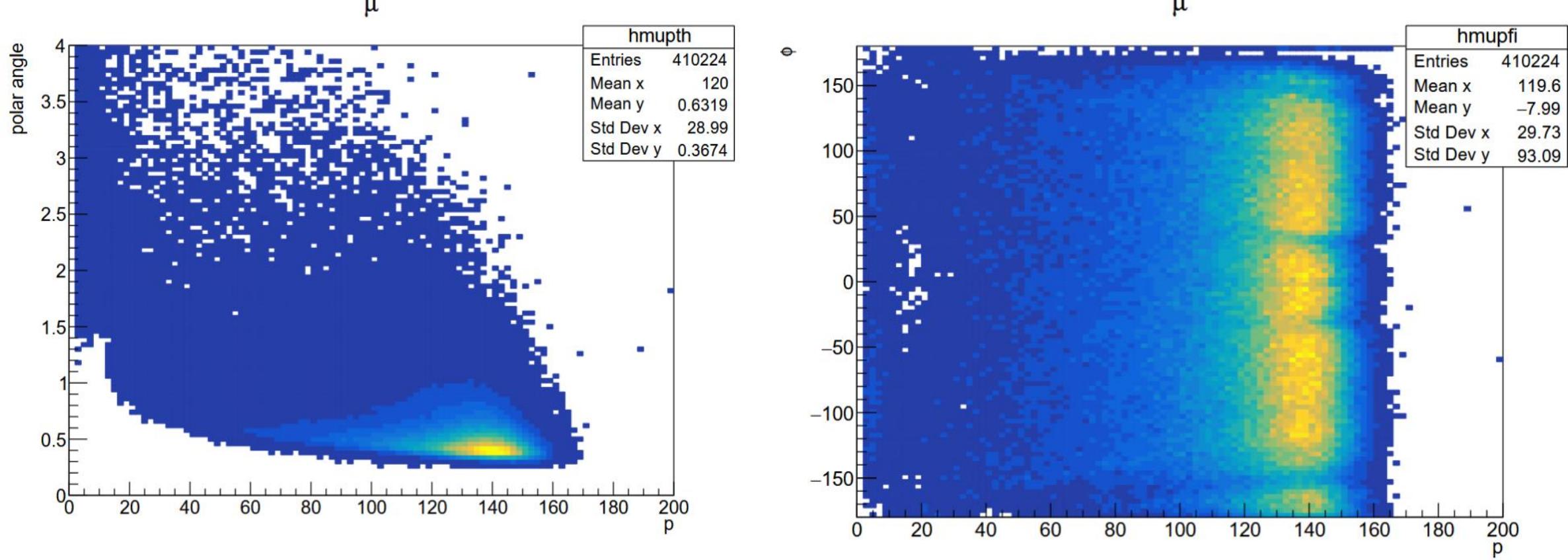
- Good fit quality of scattered hadron ( $\pi^+, \pi^-$  reconstruction, given by reduced  $\chi^2$  is required to be smaller than 10 ( $\chi^2 < 10$ ).  
Track reconstruction quality  $\chi^2 < 10$ .
- Penetration length of hadron track should be smaller than 10 radiation lengths.
- Track starts before SM1, i.e.  $Z_{first} < 350.0$  cm .

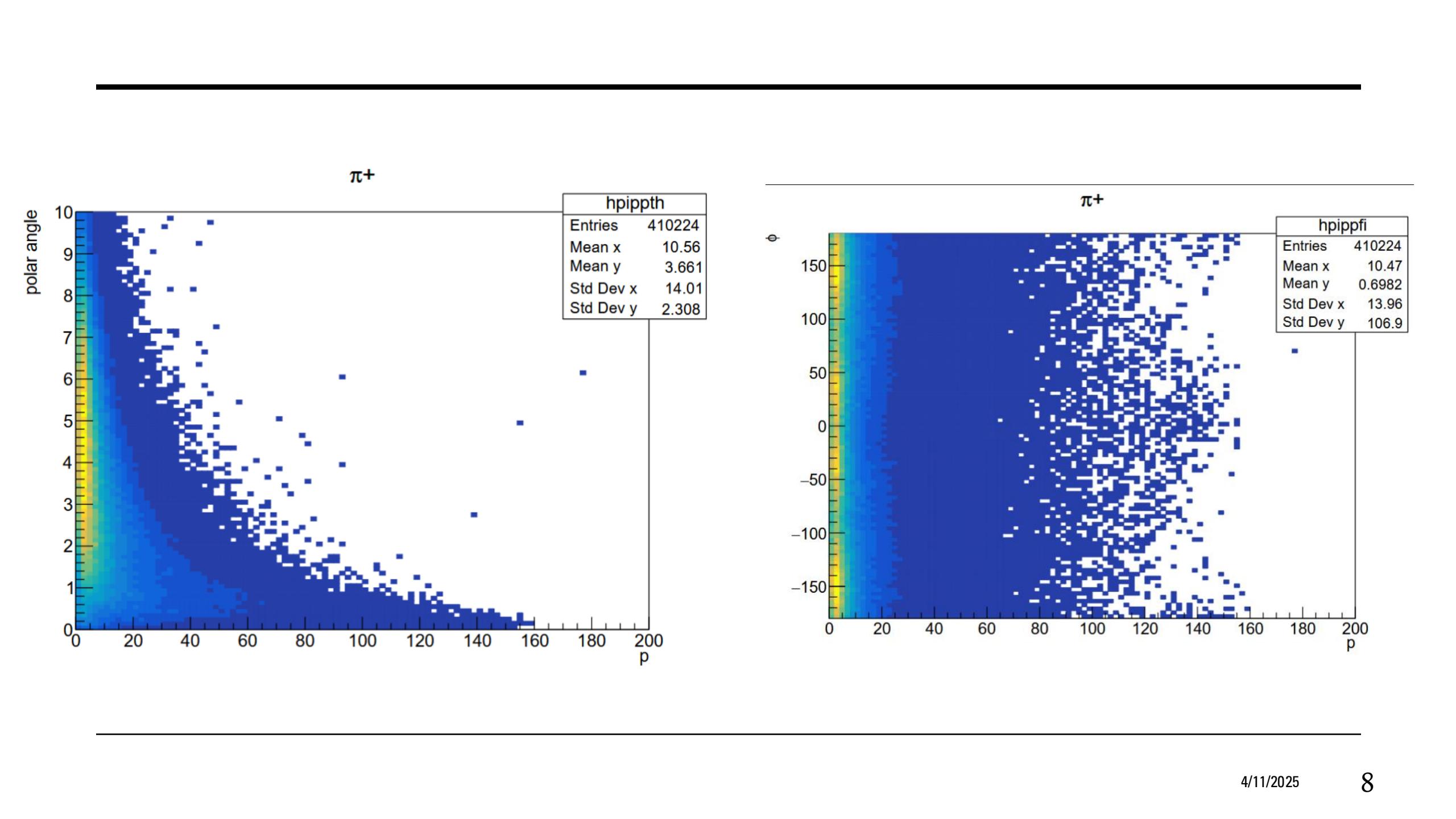
- Fit is on the track of the pions
- Also required both hadrons to have opposite charge
- Proton was identified using Missing Mass (2012 pre-CAMERA)

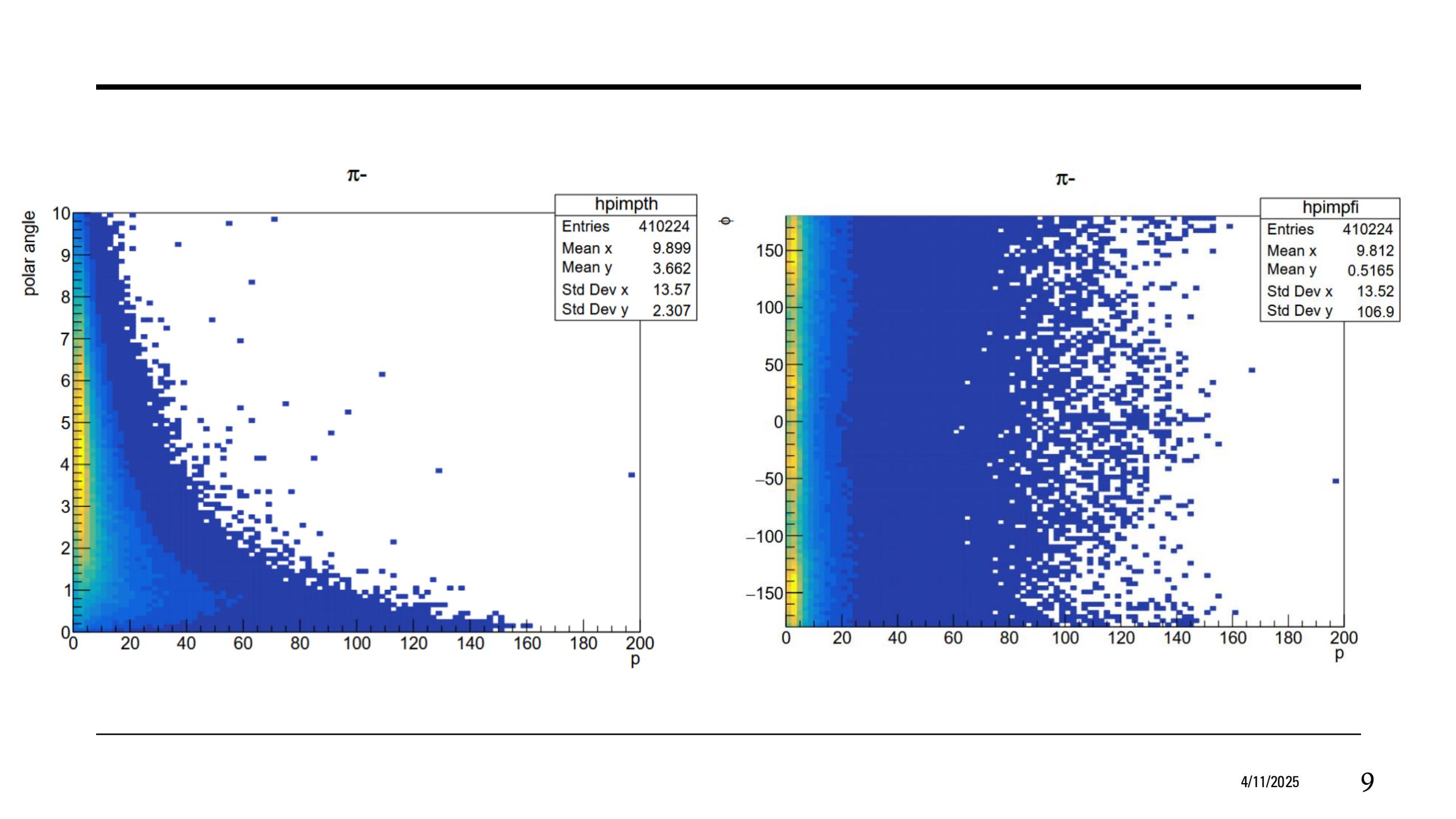
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# **DATA PARTICLE KINEMATICS**

## **NO EXCLUSIVE CUTS ( $Q^2 > 0.8$ GEV $^2$ )**





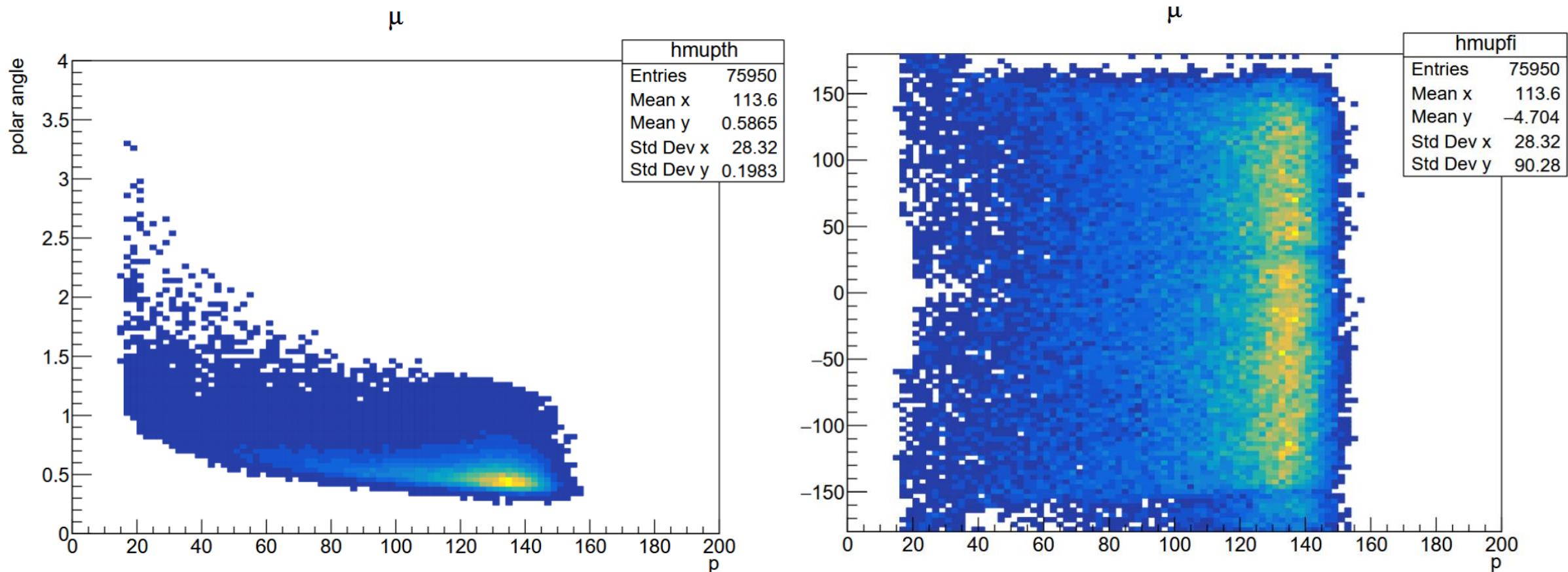


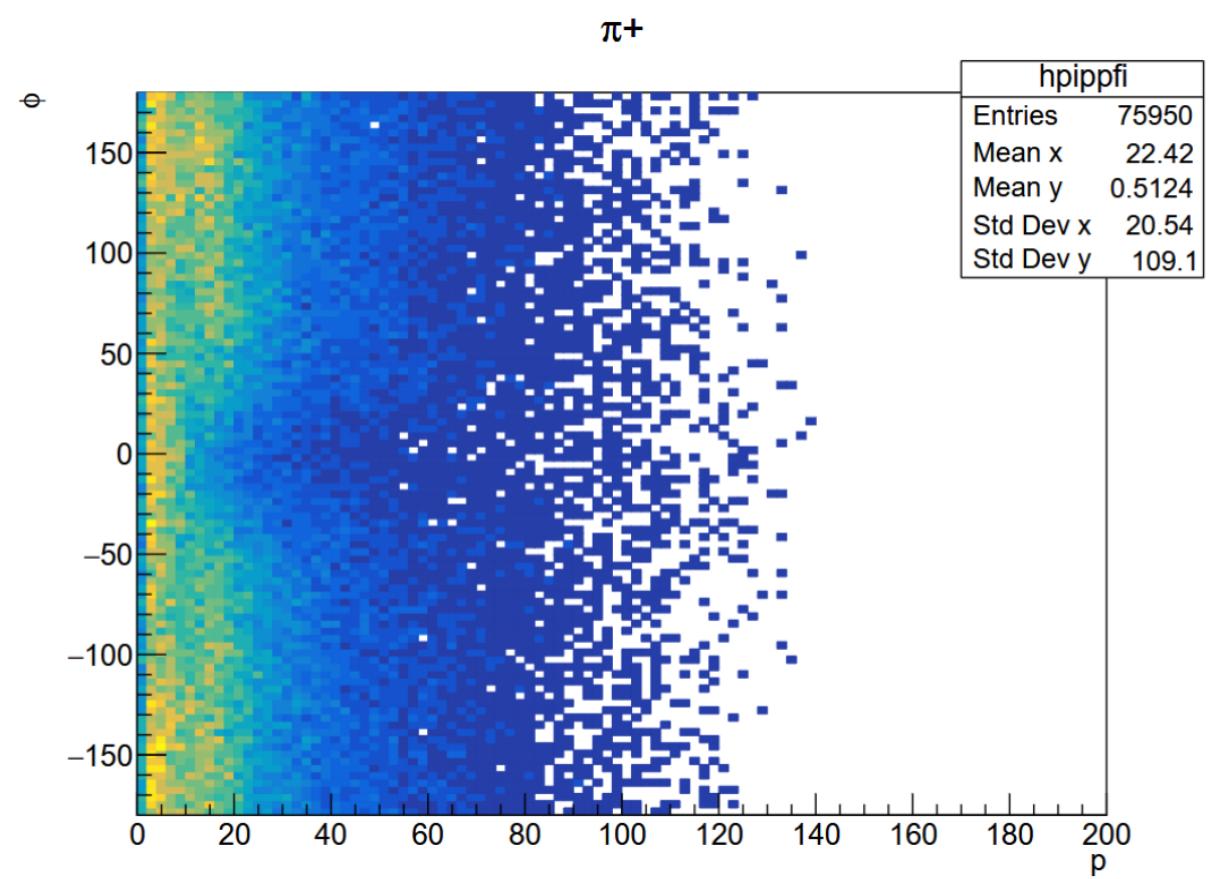
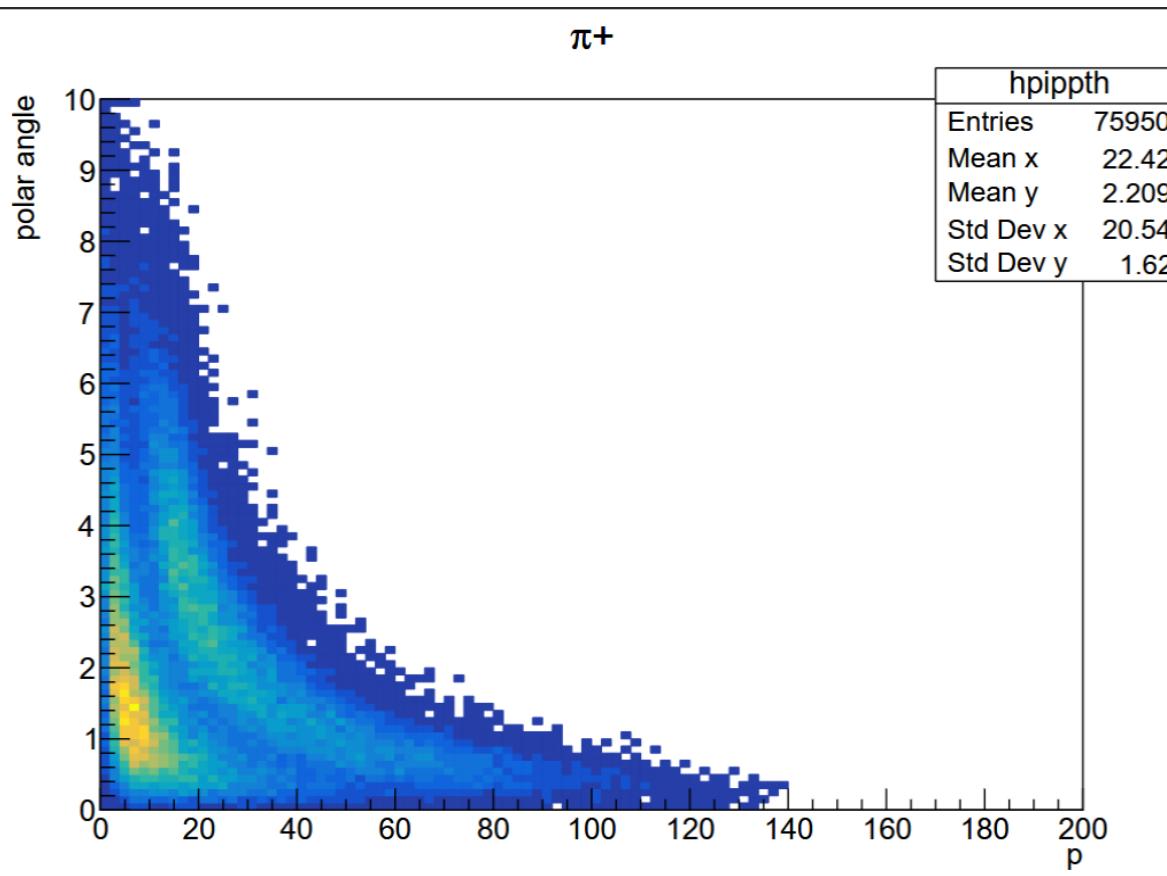
# KINEMATIC CUTS

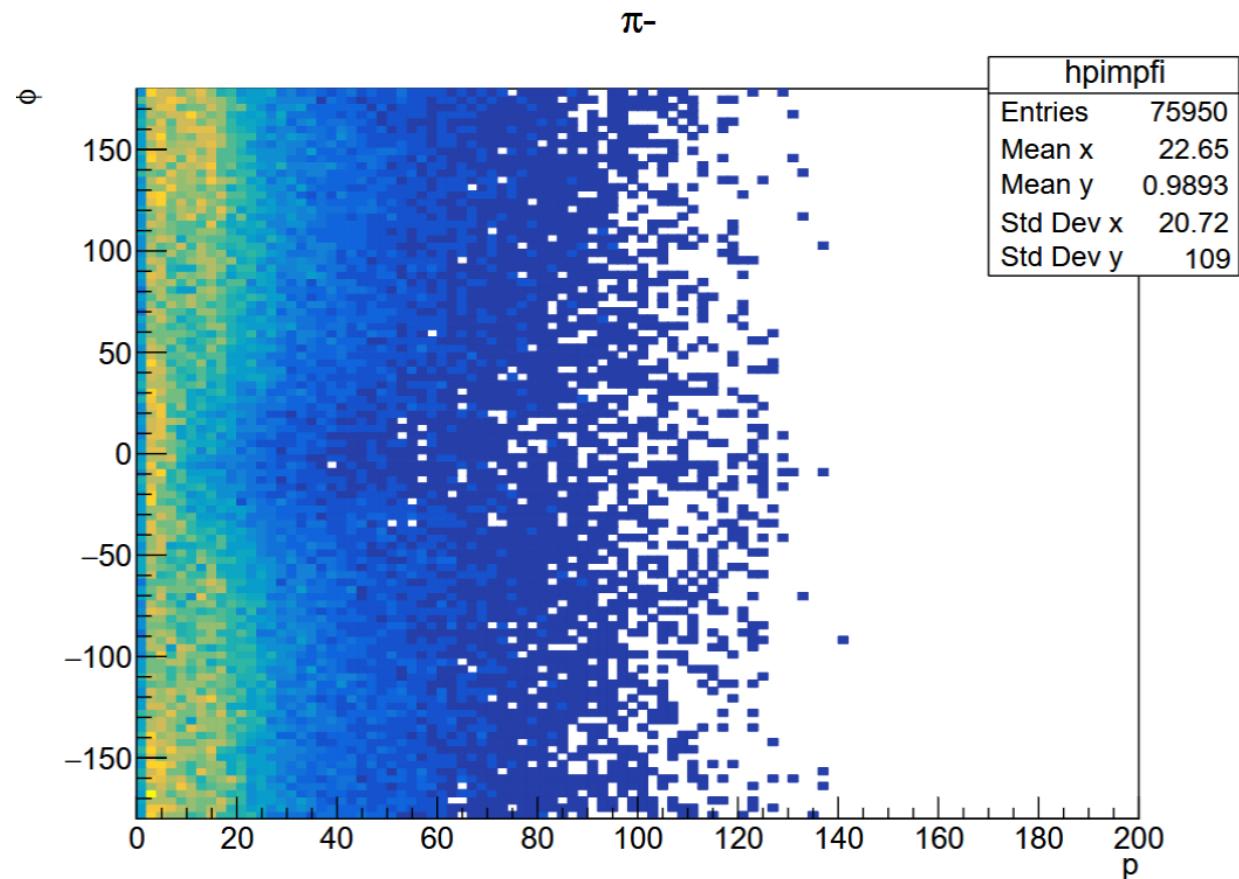
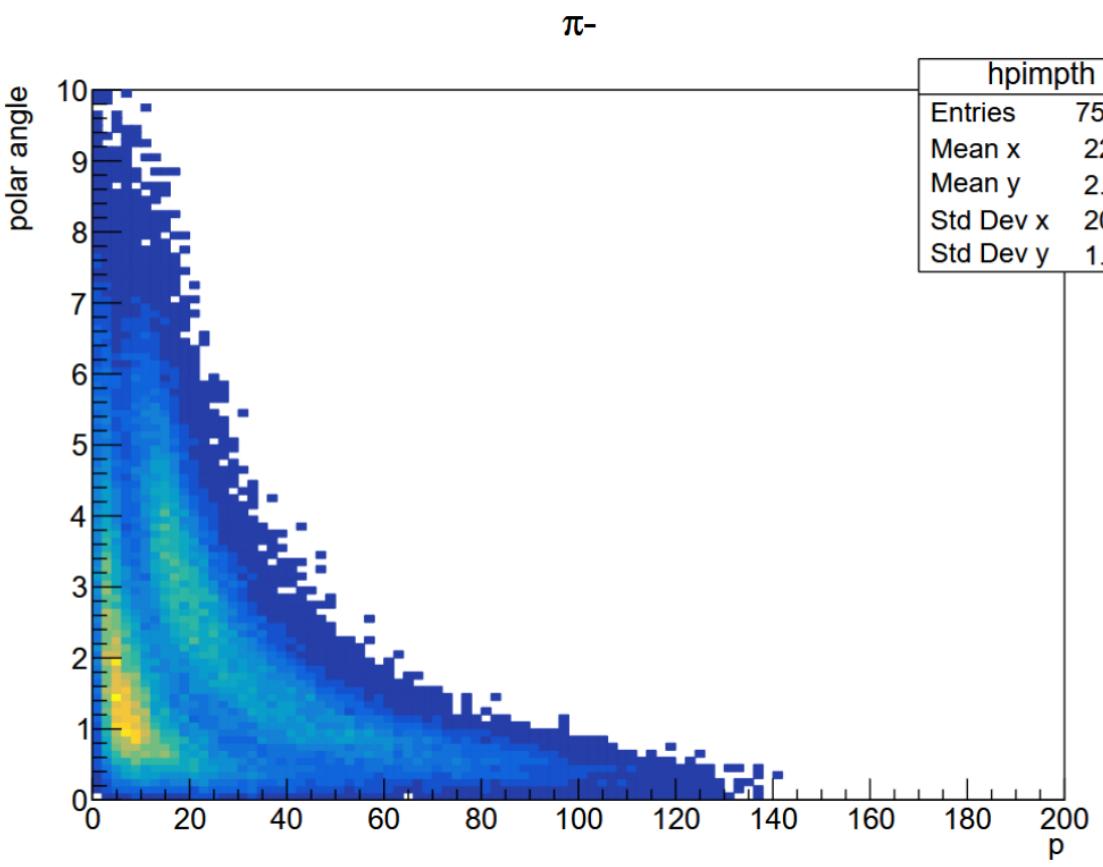
- $W > 5.0$  GeV to remove the kinematic region where the cross section for the semi-inclusive reactions changes rapidly due to a resonances production.
- $0.1 < y < 0.9$ , lower cut suppresses events with a poorly reconstructed kinematics. The upper cut on  $y$  remove events with large radiative corrections.
- $1.0 < Q^2 < 10.0$   $(\text{GeV}/c)^2$ , lower cut on virtuality  $Q^2$  ensures hard processes regime and the upper one suppresses background due to the hadron production in DIS which hereafter is referred to as "SIDIS background".
- $\nu > 16 \text{ GeV}$        $0.1 < y \longrightarrow 160 * 0.1 \longrightarrow 16 < \nu$
- squared transverse momentum of  $\rho^0$  with respect to the virtual photon:  $0.01 < p_T^2 < 0.5$   $(\text{GeV}/c)^2$ .
- $0.5 < M_{\pi^+\pi^-} < 1.1$   $\text{GeV}/c^2$  invariant mass of two pions.
- $-2.5 < E_{miss} < 2.5$  GeV .  $E_{miss} = \frac{M_X^2 - M_p^2}{2M_p}$ , with  $M_p$  the proton mass and  $M_X^2 = (p + q - p_{\pi^+} - p_{\pi^-})^2$  - the missing mass squared, where  $p$ ,  $q$ ,  $p_{\pi^+}$  and  $p_{\pi^-}$  are the four-momenta of target nucleon, virtual photon, and each of the two pions, respectively.
- momentum of  $\rho^0$   $P_{\rho^0} > 15$   $\text{GeV}/c$ . To reduce the semi-inclusive background contribution.

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# **DATA PARTICLE KINEMATICS WITH CUTS**

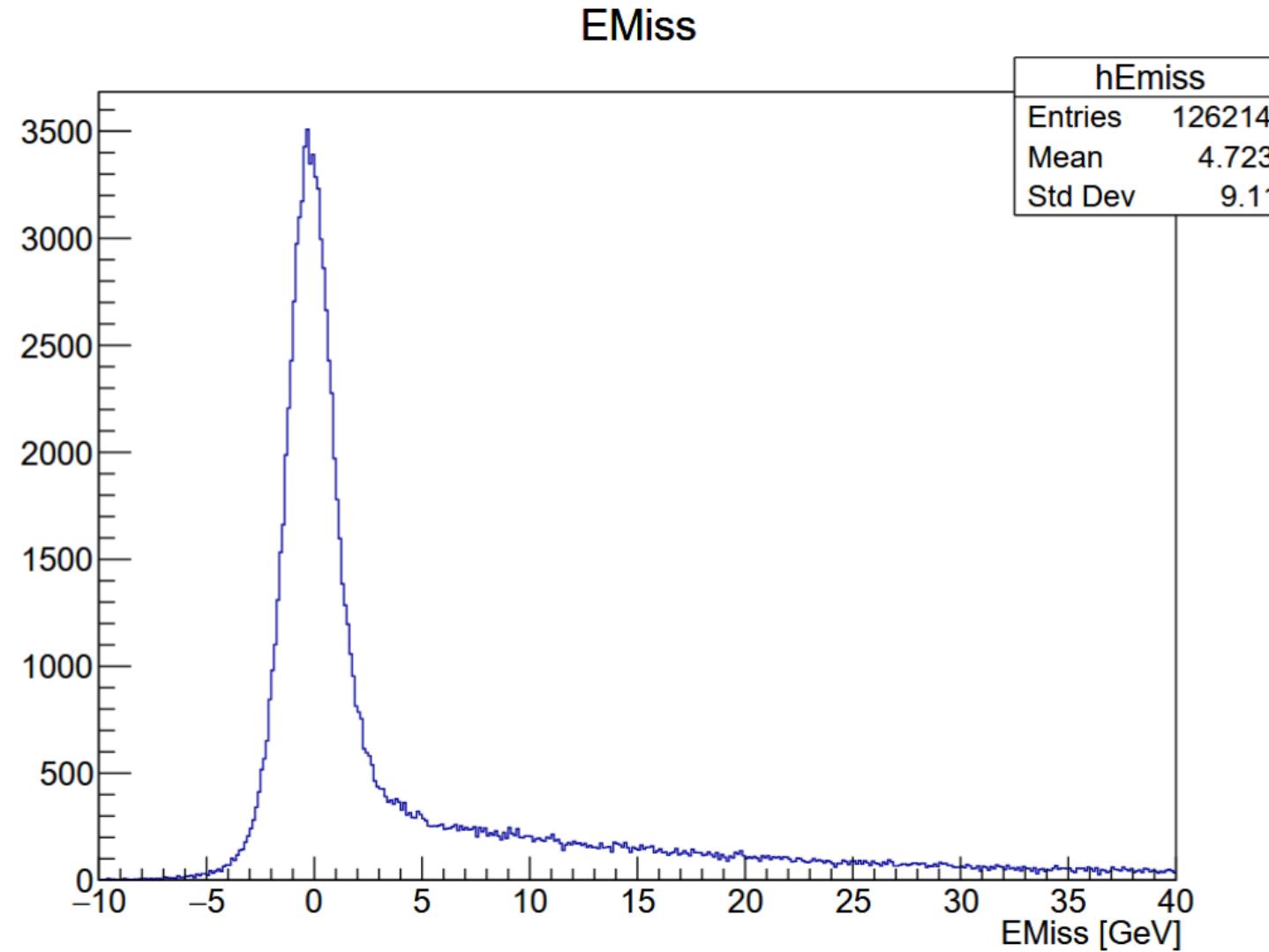






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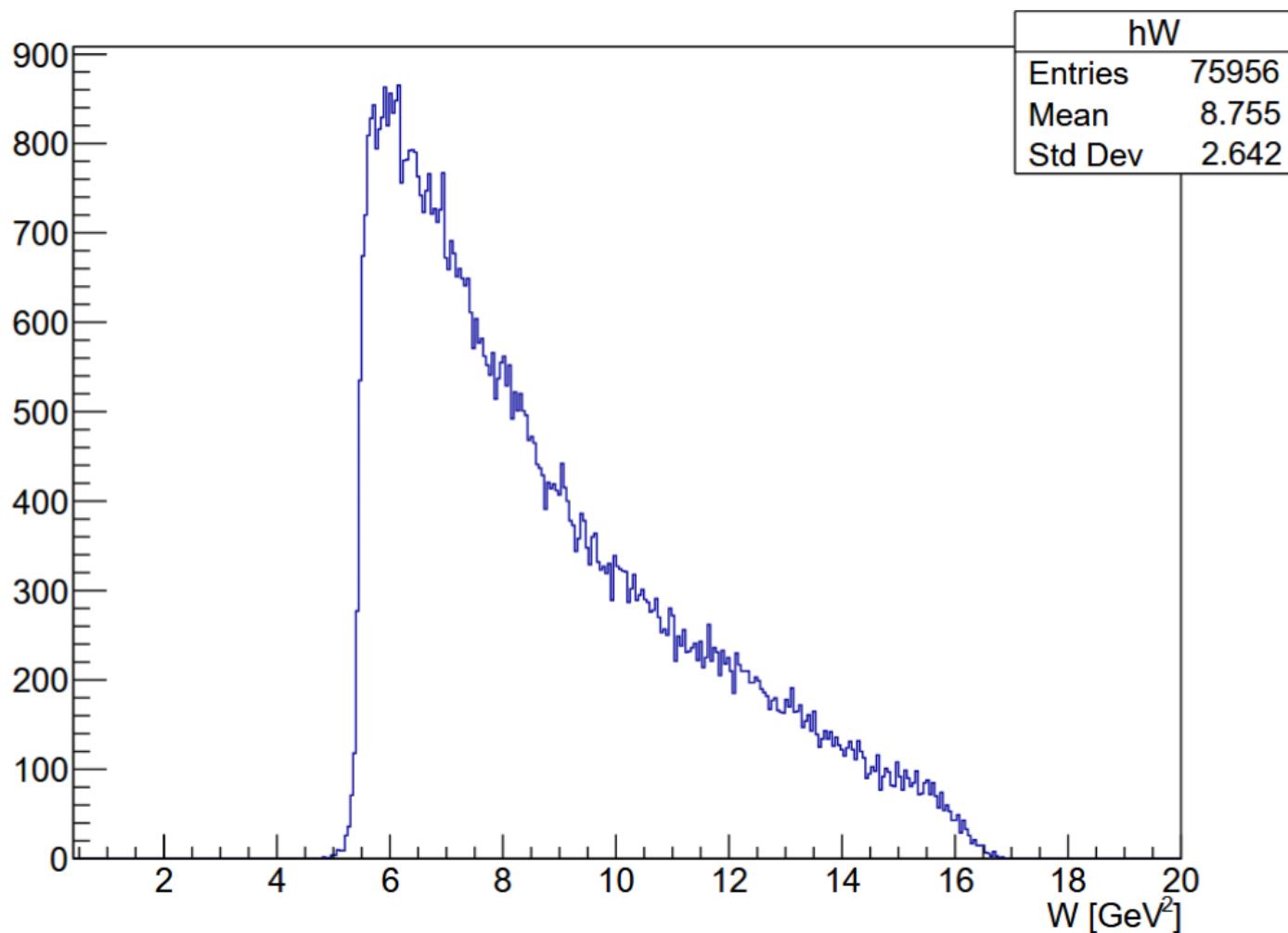
# **DATA EXCLUSIVE KINEMATICS WITH CUTS**



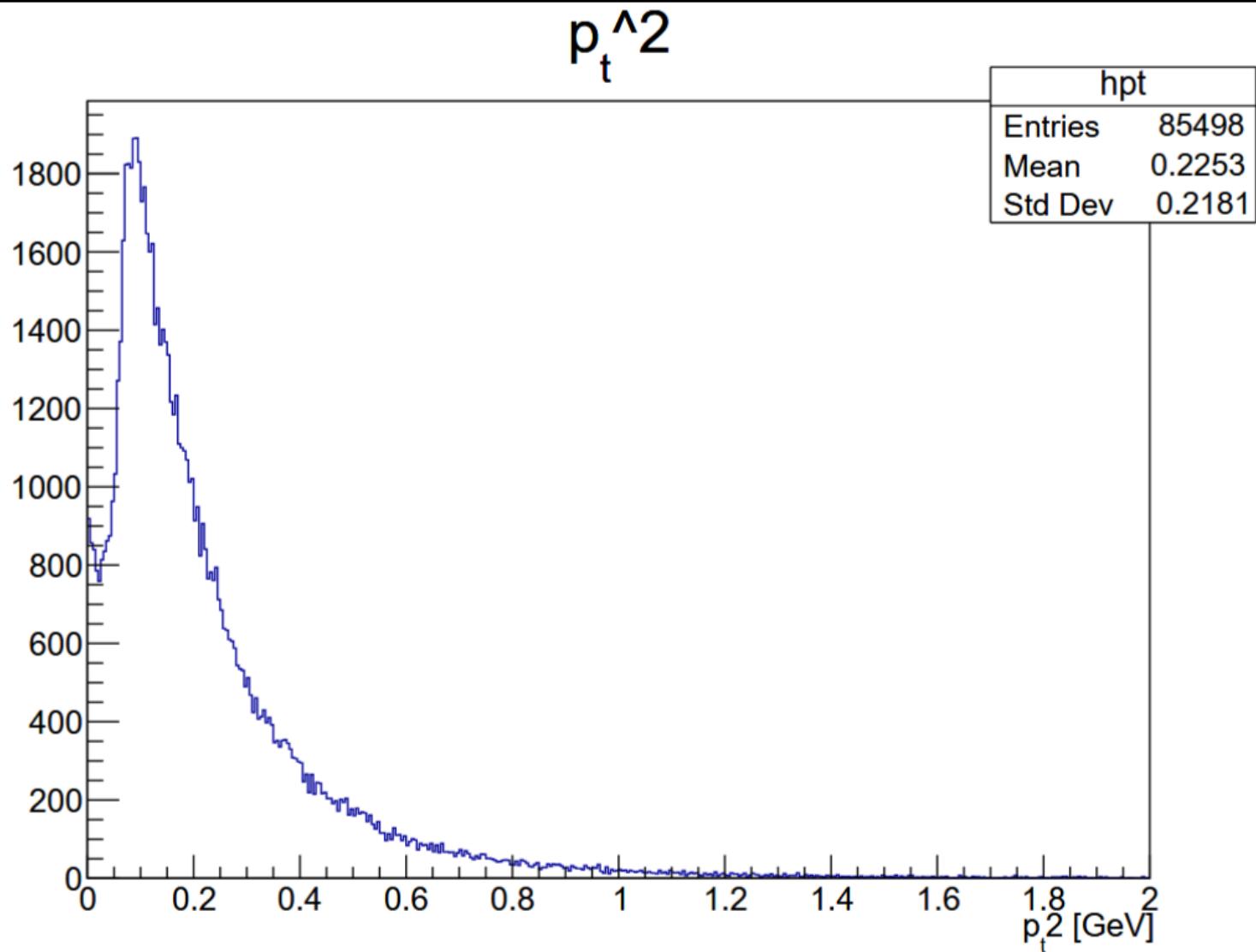
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Cuts:W,y,Q2,nu,Pt2, Invariant Mass,  
Momentum of rho0

W

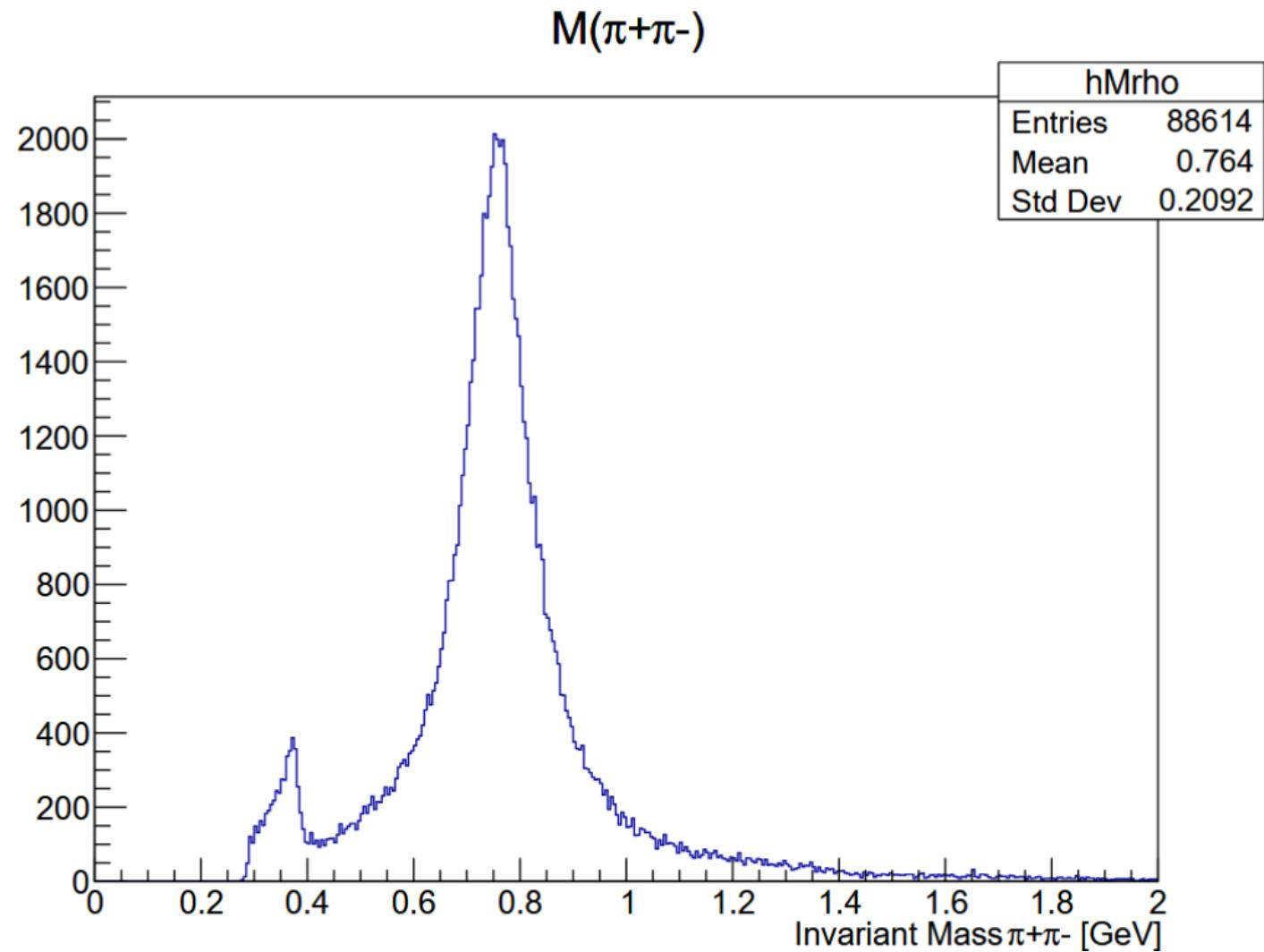


Cuts:y,Q2,nu,Pt2, Invariant Mass  
Missing Energy, Momentum of rho0



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Cuts:W,y,Q2,nu, Invariant Mass  
Missing Energy, Momentum of rho0

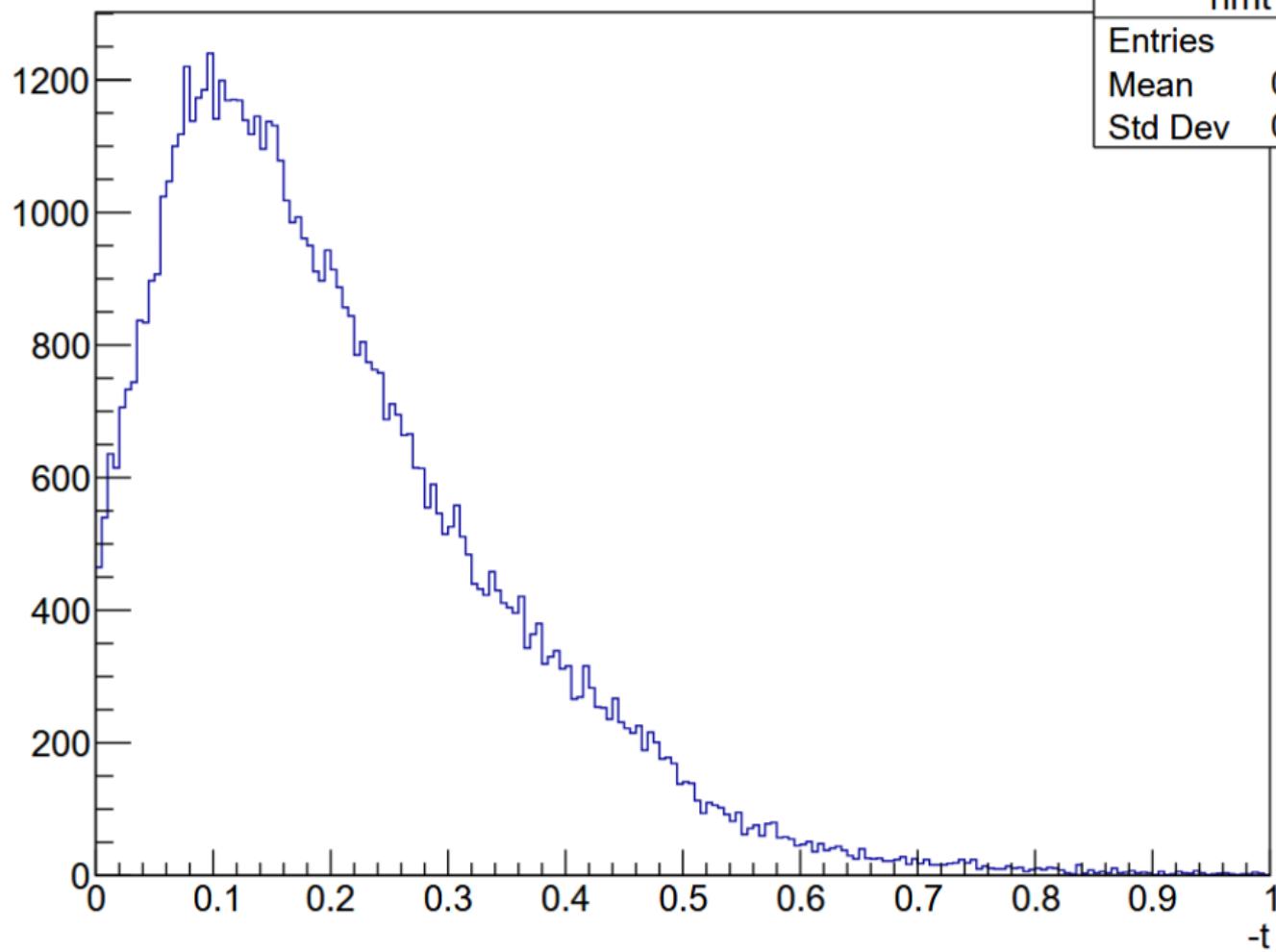


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Cuts:W,y,Q2,nu,Pt2, Missing  
Energy, Momentum of rho0

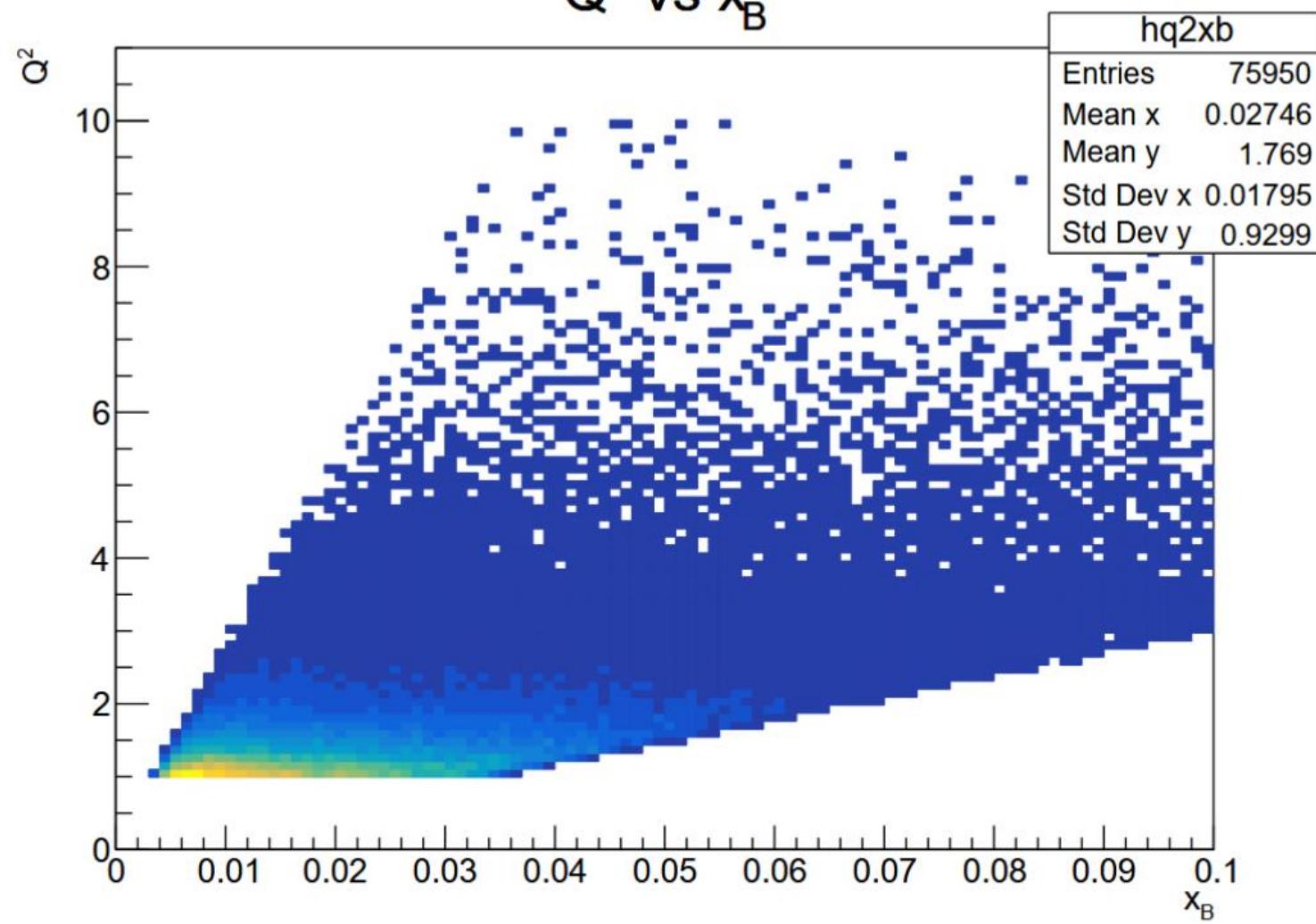
$-t$

hmt	
Entries	75950
Mean	0.2064
Std Dev	0.1454



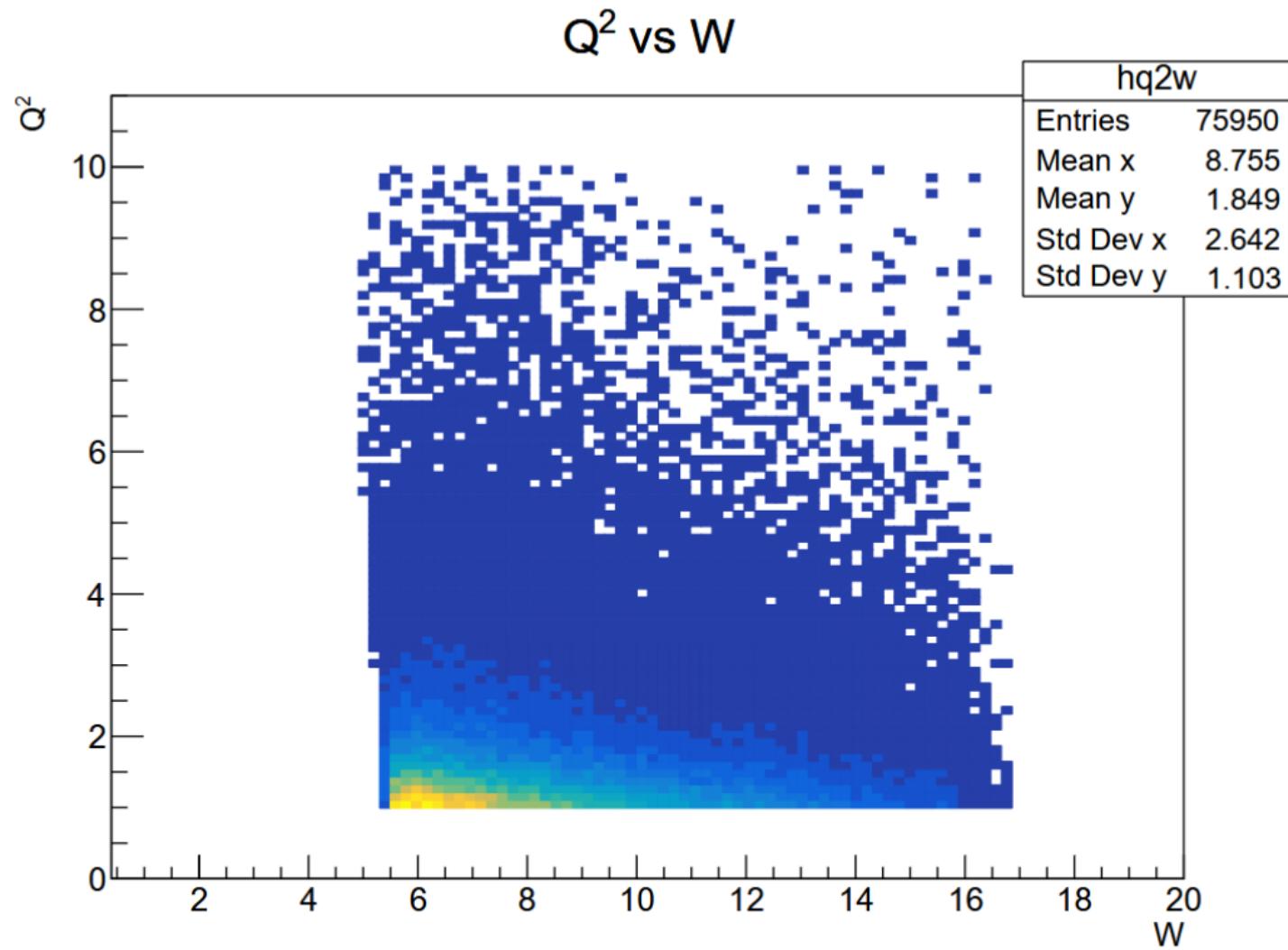
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## $Q^2$ vs $x_B$



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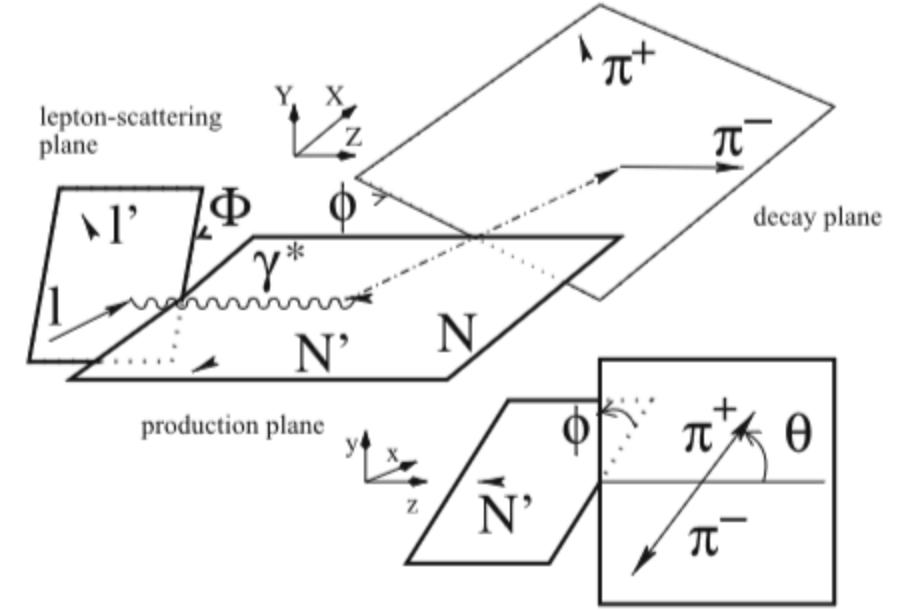
Cuts: W,y,Q2,nu,Pt2, Invariant Mass  
Missing Energy, Momentum of rho0



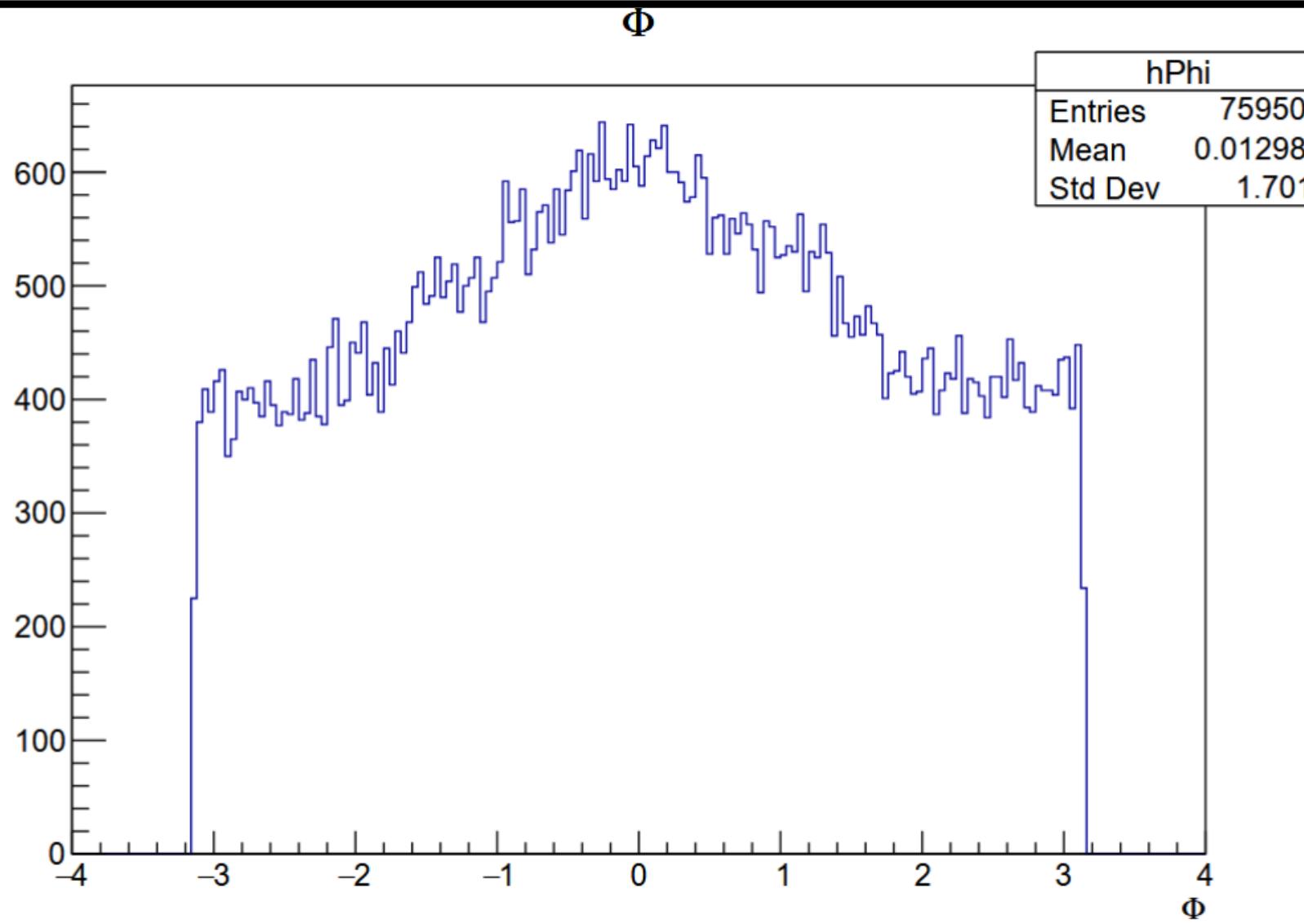
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Cuts: W,y,Q2,nu,Pt2, Invariant Mass  
Missing Energy, Momentum of rho0

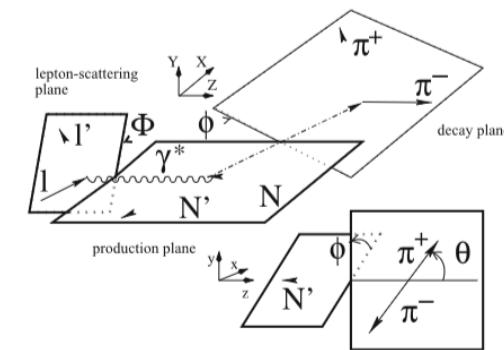
# ANGLES FOR SDME

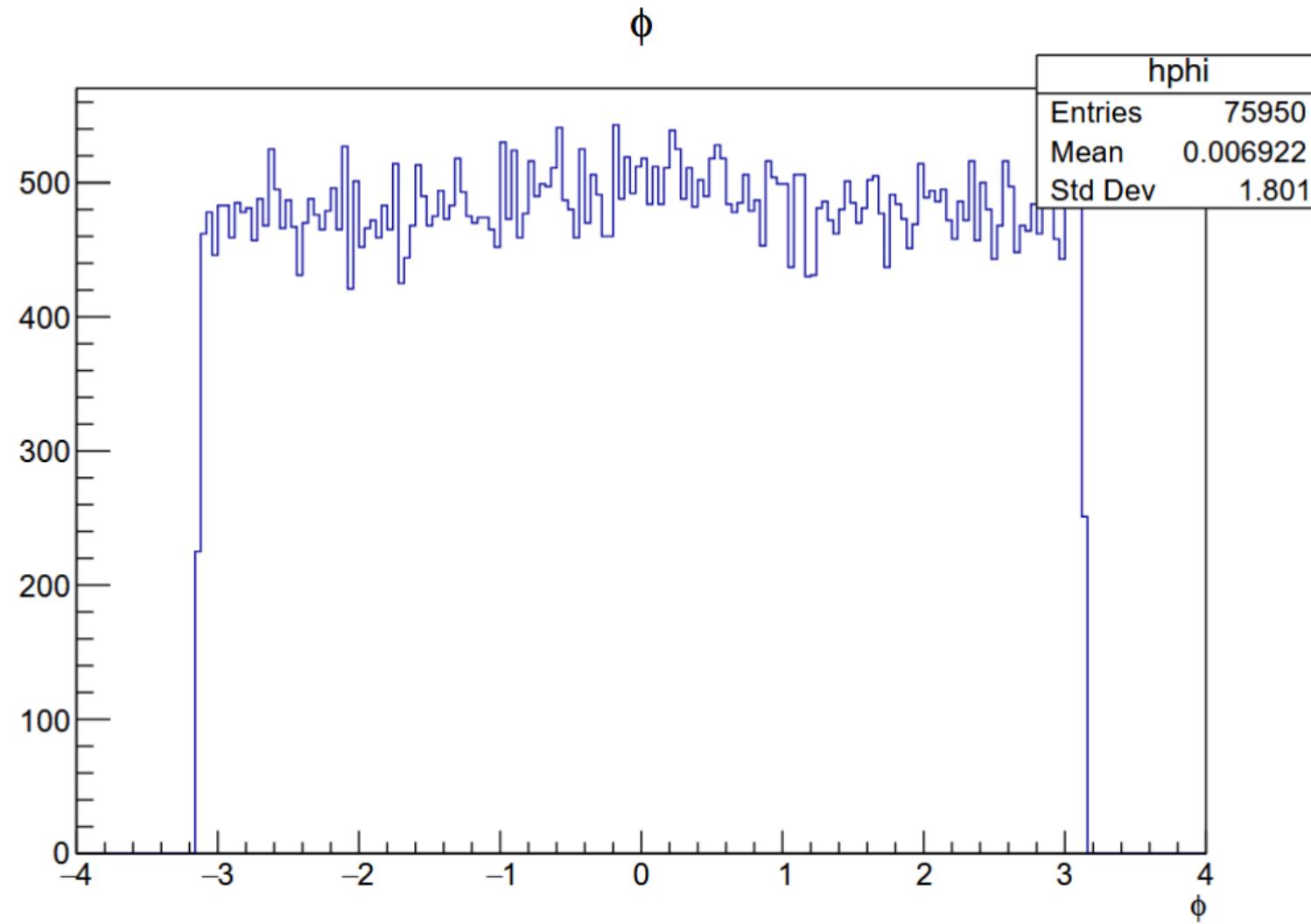


W. Augustyniak, et al. ,Spin Density Matrix Elements for exclusive  $\rho^0$  meson production using the 2012 COMPASS data,internal note, 2021.

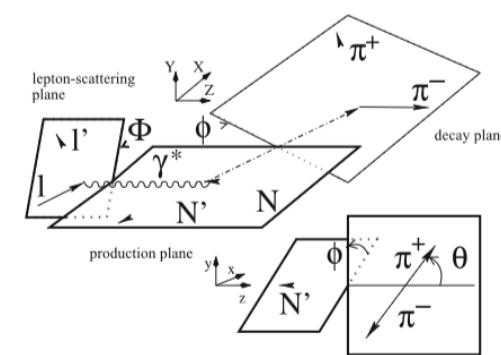


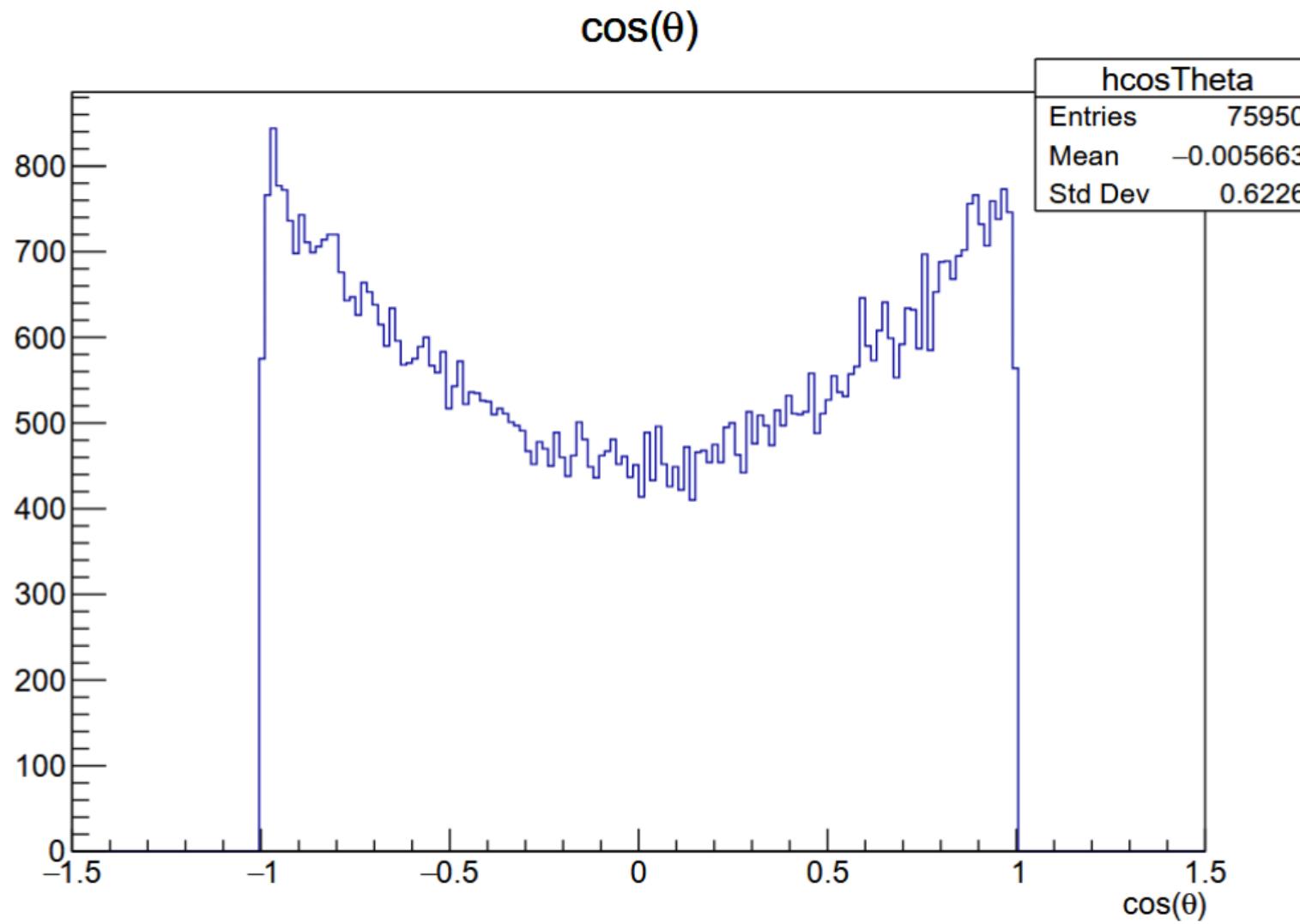
Angle between the  
lepton scattering plane  
and rho production  
plane (phi trento)



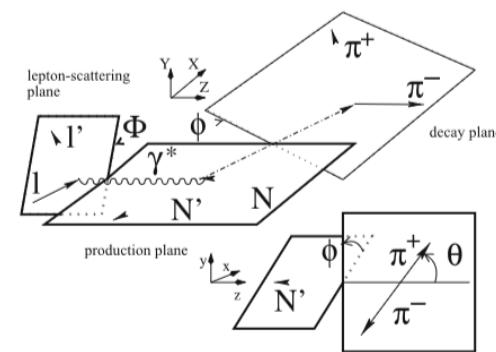


Angle between the rho production plane and the rho decay plane





The polar angle of the  
pi+ in the vector meson  
decay frame



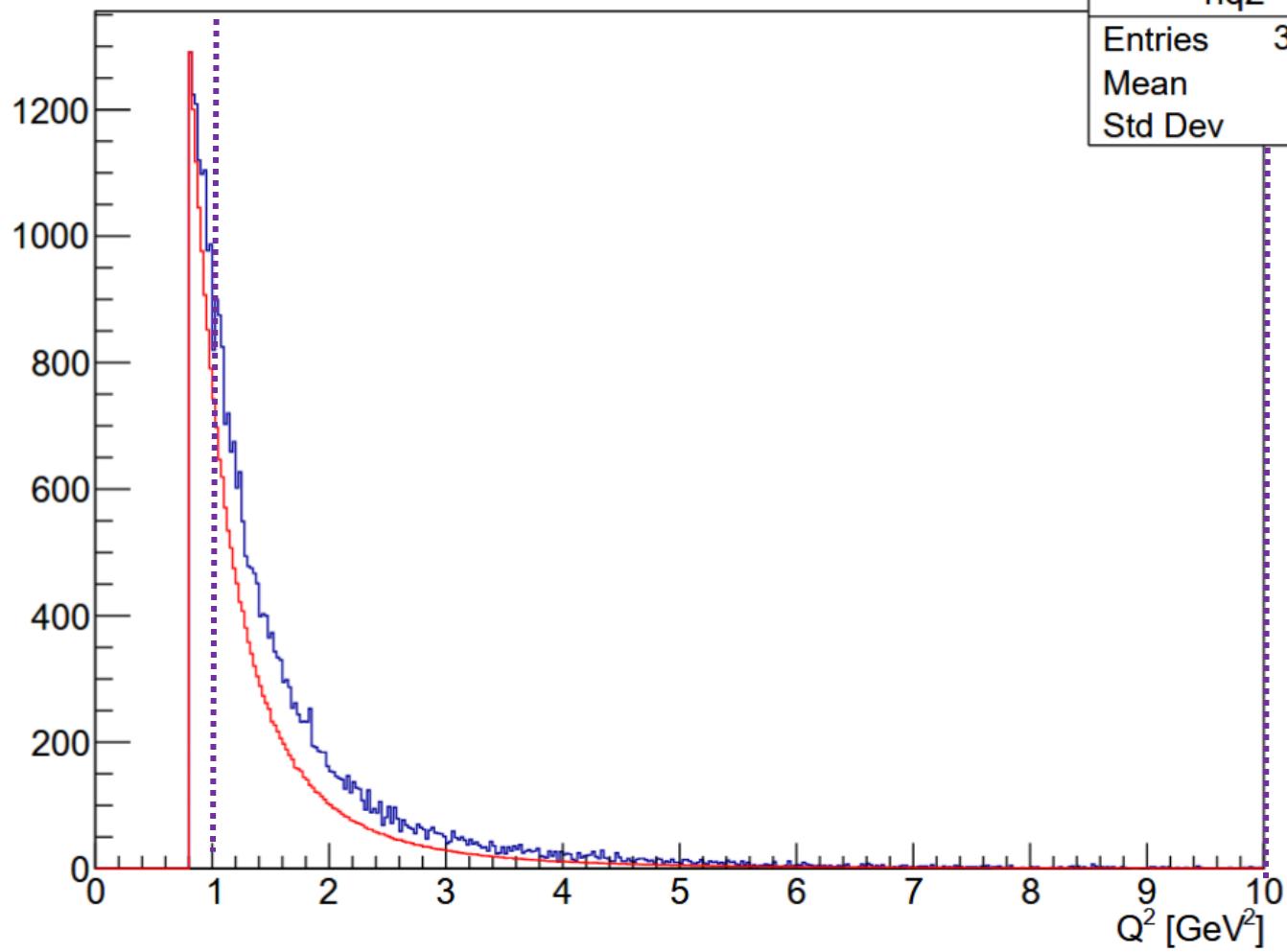
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# DATA VS MONTE CARLO (HEPGEN)

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$Q^2$

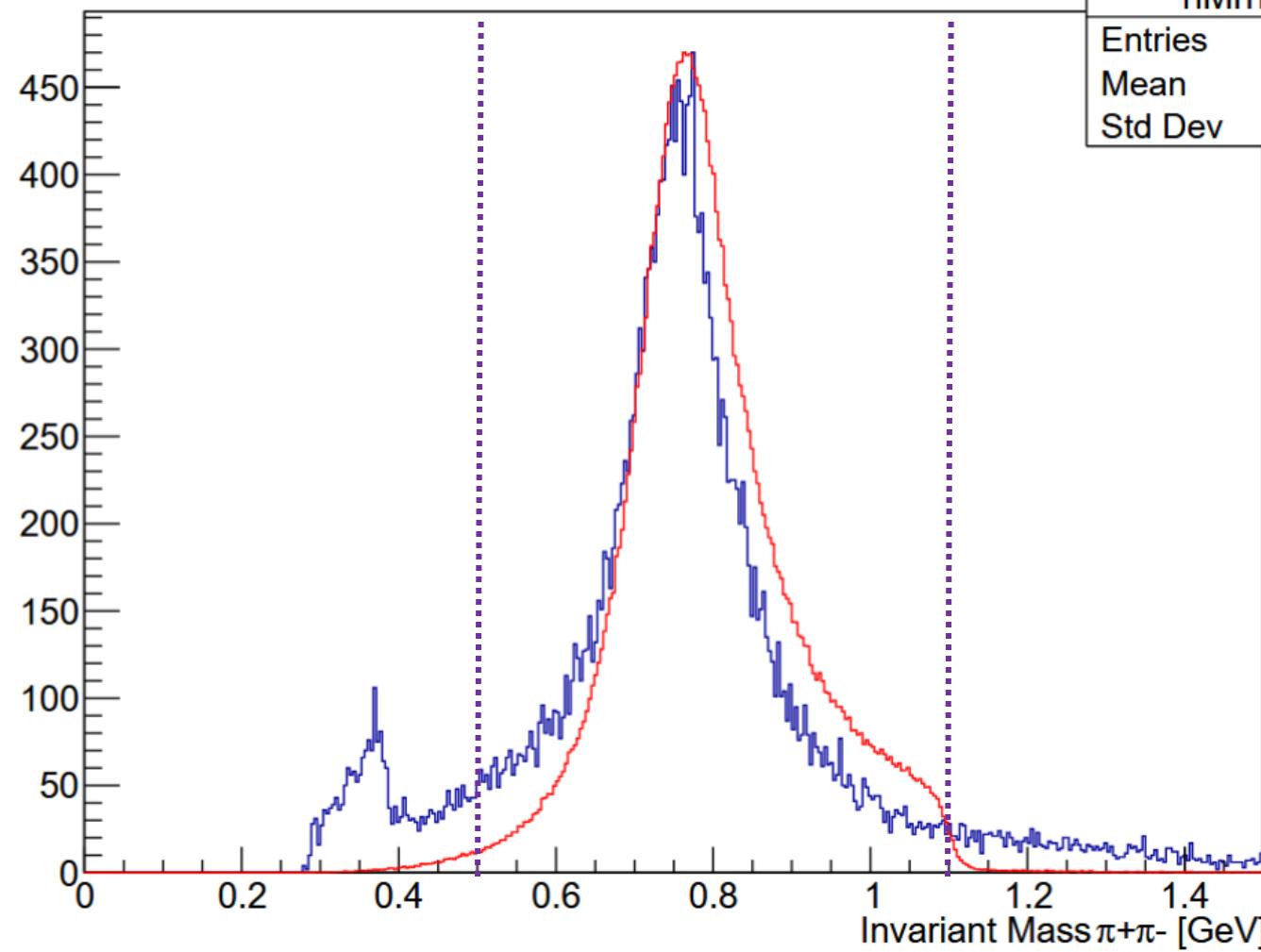
hq2	
Entries	32447
Mean	1.61
Std Dev	1.079



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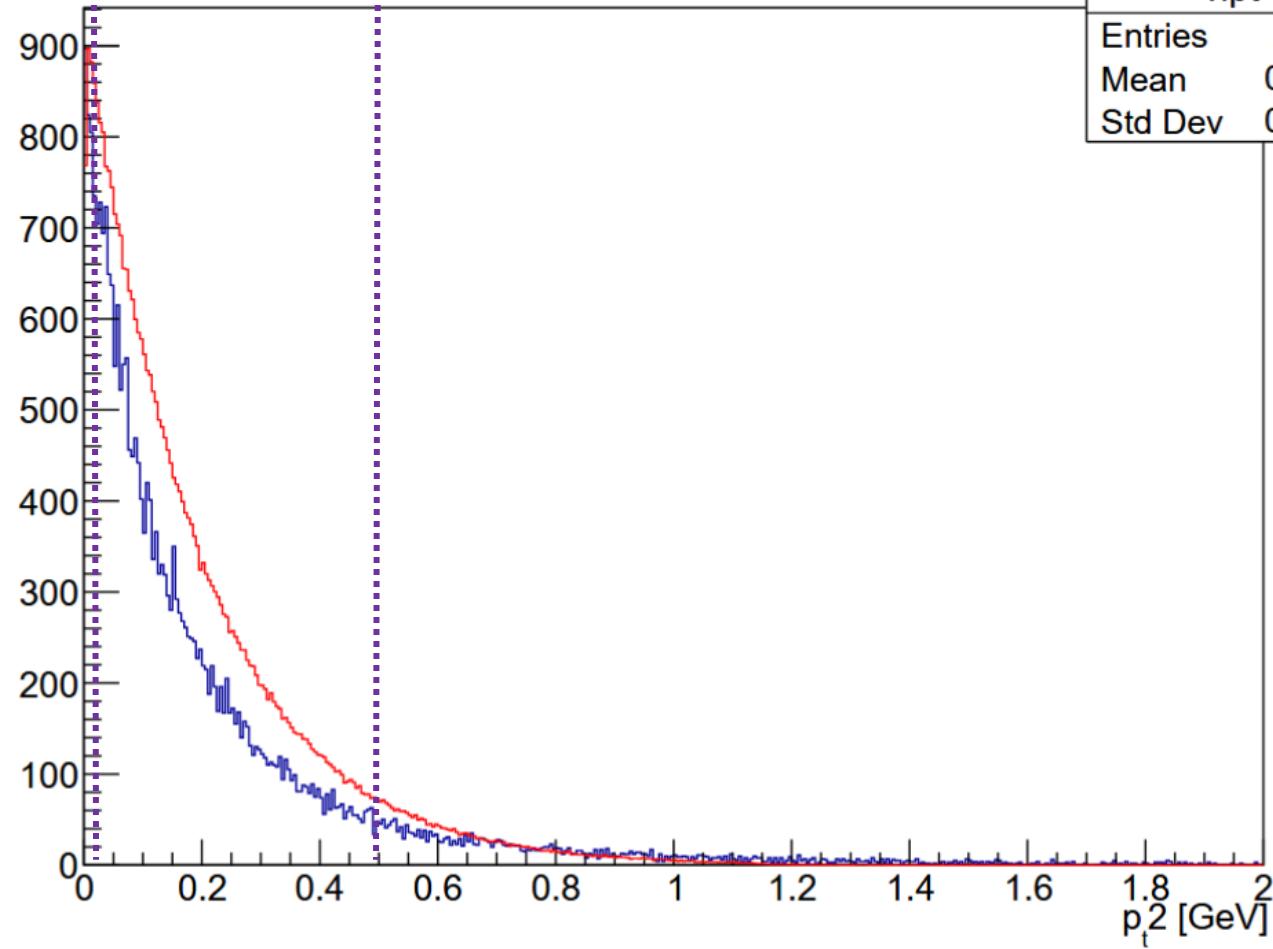
$M(\pi^+\pi^-)$

hMrho	
Entries	28007
Mean	0.7548
Std Dev	0.1928



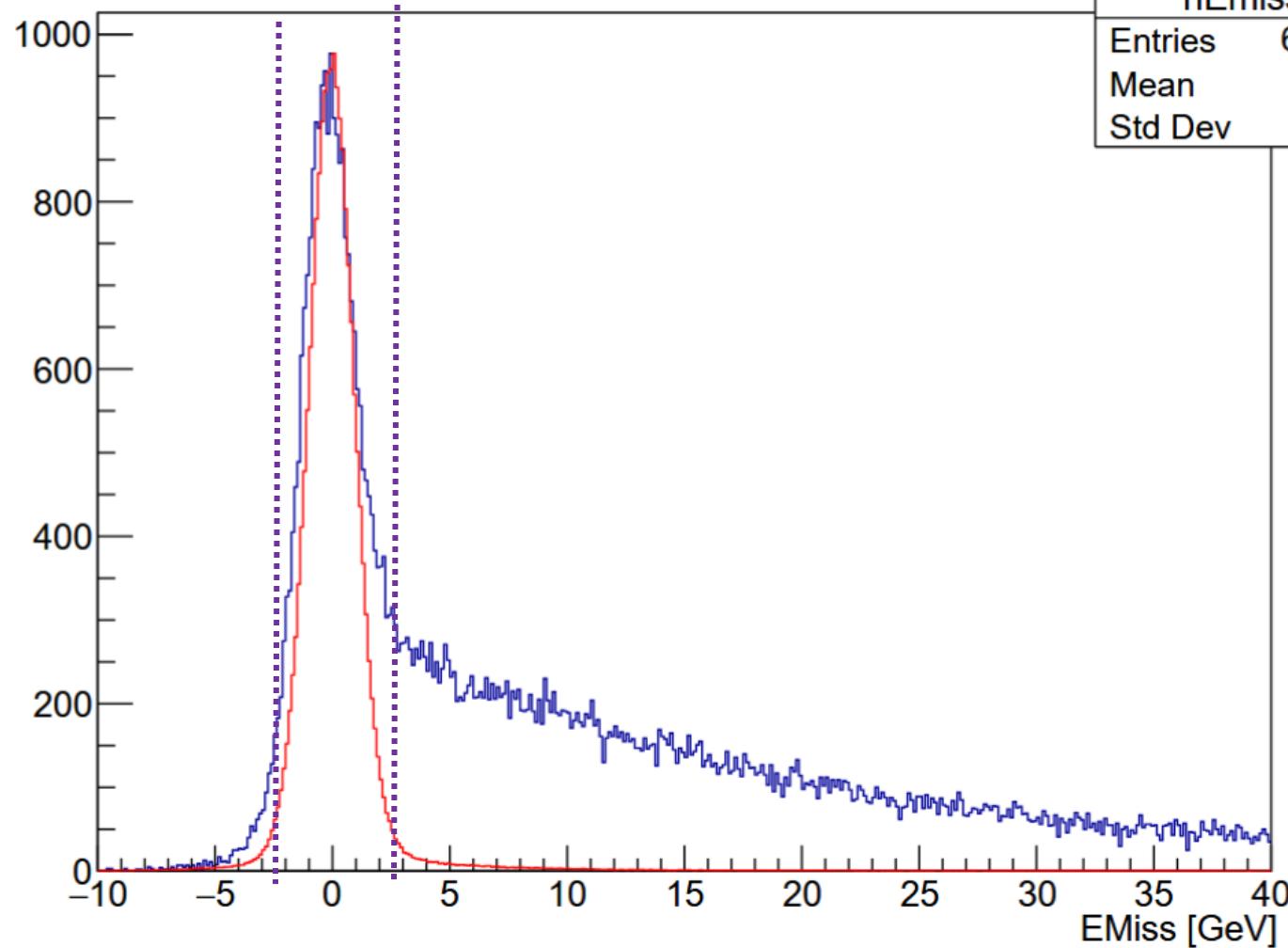
$p_t^2$

hpt	
Entries	28082
Mean	0.2127
Std Dev	0.2674



EMiss

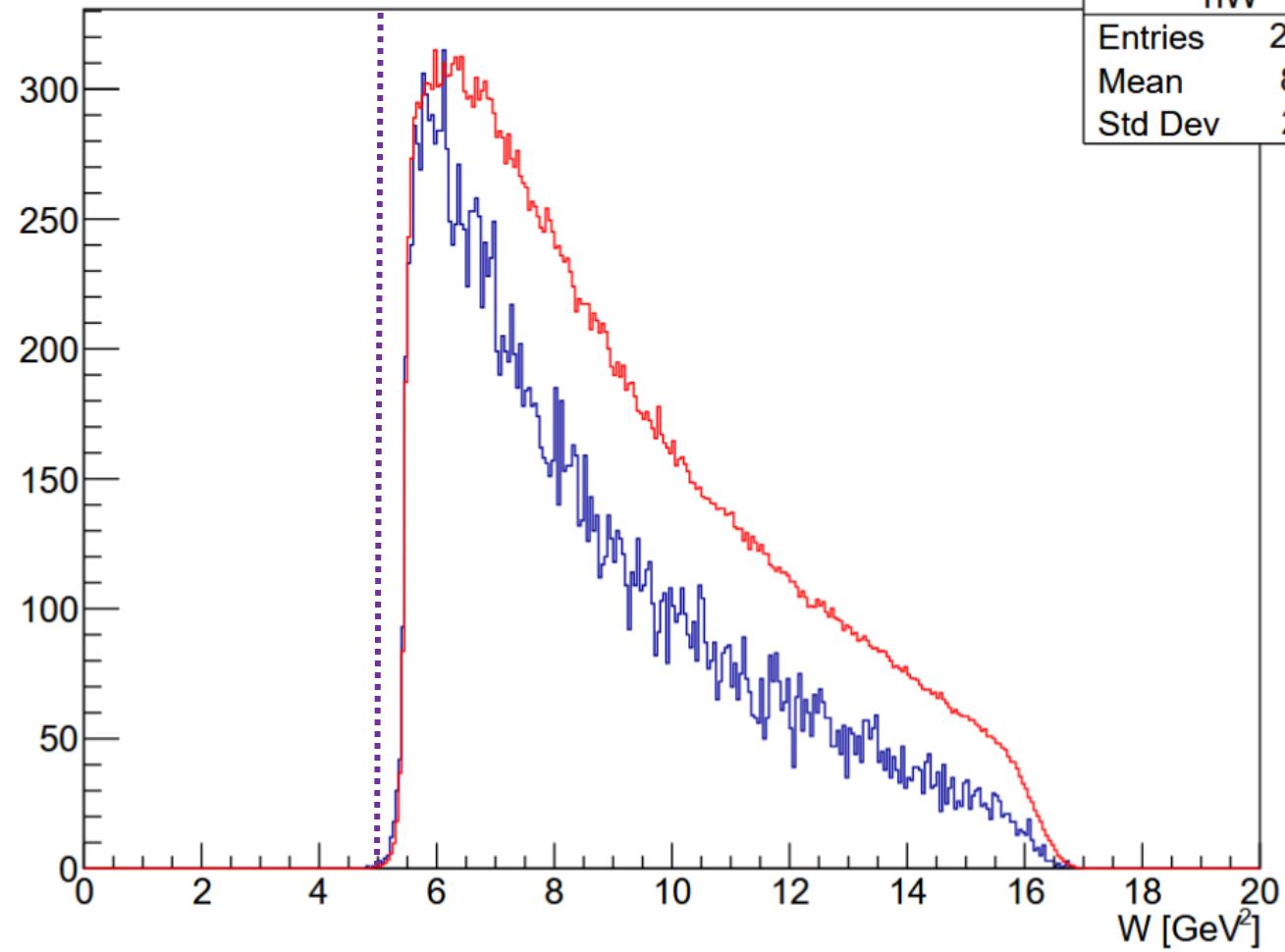
hEMiss	
Entries	67399
Mean	9.149
Std Dev	10.88



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W

hW	
Entries	23337
Mean	8.658
Std Dev	2.643



Some Suggestions:

- Get rid of background with lepto
- Reweight the MC to the data

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# **BACKGROUND SUBTRACTION**

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# BACKGROUND SUBTRACTION USING MISSING ENERGY

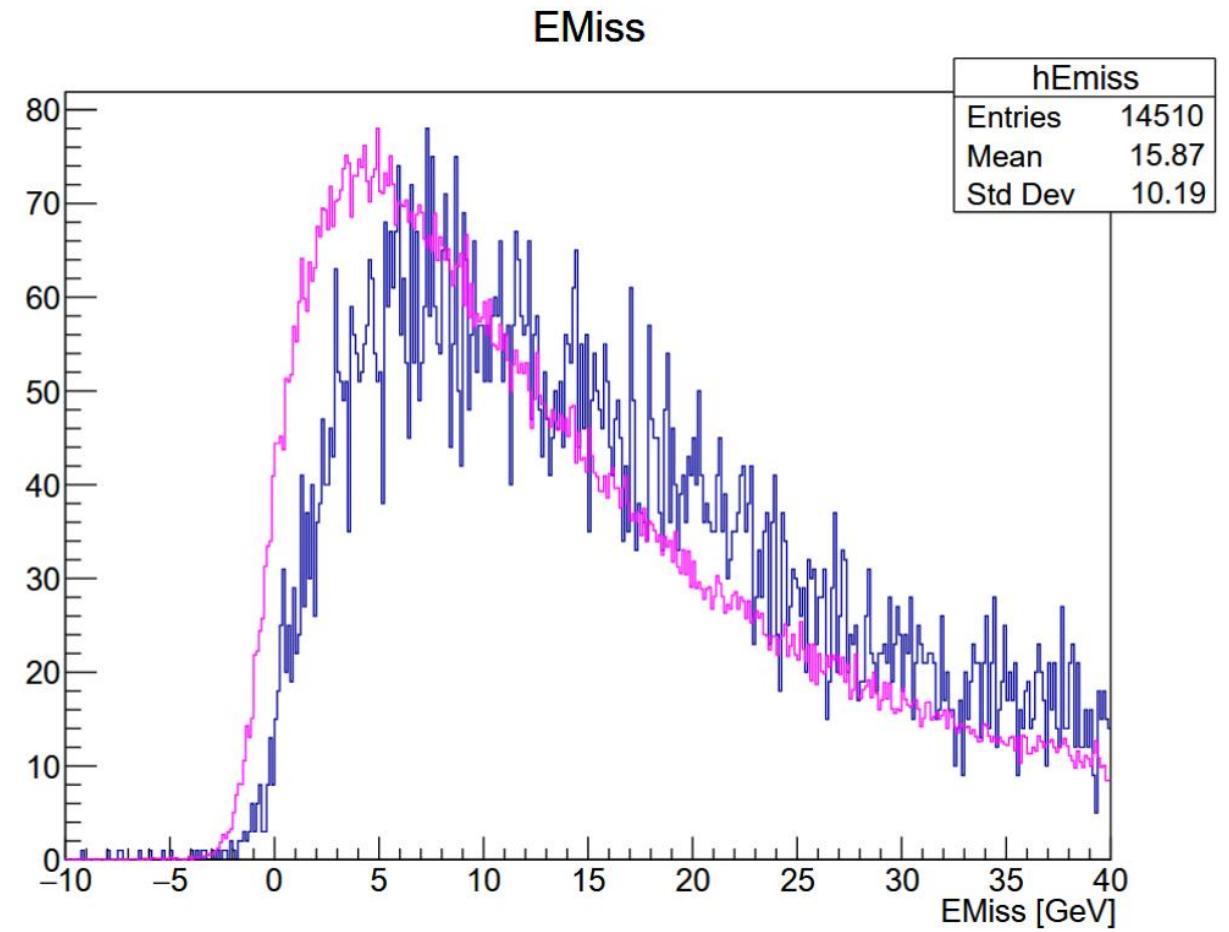
- Missing Energy should be centered around zero so background events should be subtracted
  - weight Monte Carlo to match data so we can subtract those events

$$w(E_{\text{miss}}) = \frac{N_{rd}^{sc}(E_{\text{miss}})}{N_{MC}^{sc}(E_{\text{miss}})}.$$

- Here N is the number of events with same charged pions found in the data (numerator) and the Monte Carlo (denominator)
- The fractional background,  $f_{\text{bkg}}$ , is calculated
  - Find the number of events of the Monte Carlo and data in our missing energy region

- The plots are for events where we have hadron pairs with the same charge
  - $\text{Pi}^+ \text{Pi}^+$
  - $\text{Pi}^- \text{Pi}^-$
- Using all other exclusive cuts
- The weight is determined by finding the number of events in each histogram

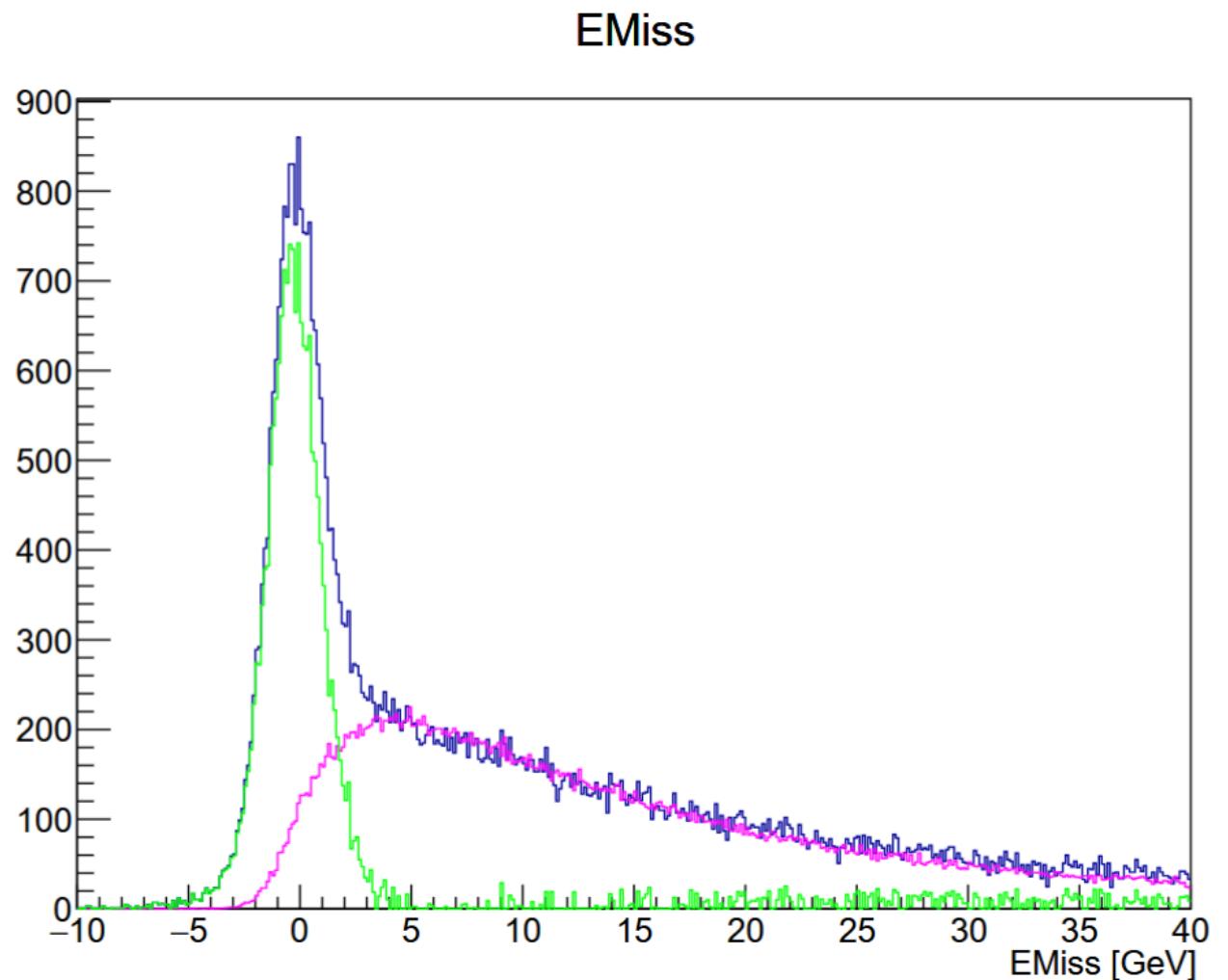
$$w(E_{\text{miss}}) = \frac{N_{rd}^{sc}(E_{\text{miss}})}{N_{MC}^{sc}(E_{\text{miss}})}.$$



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# DATA VS MONTE CARLO (WEIGHTED LEPTO)

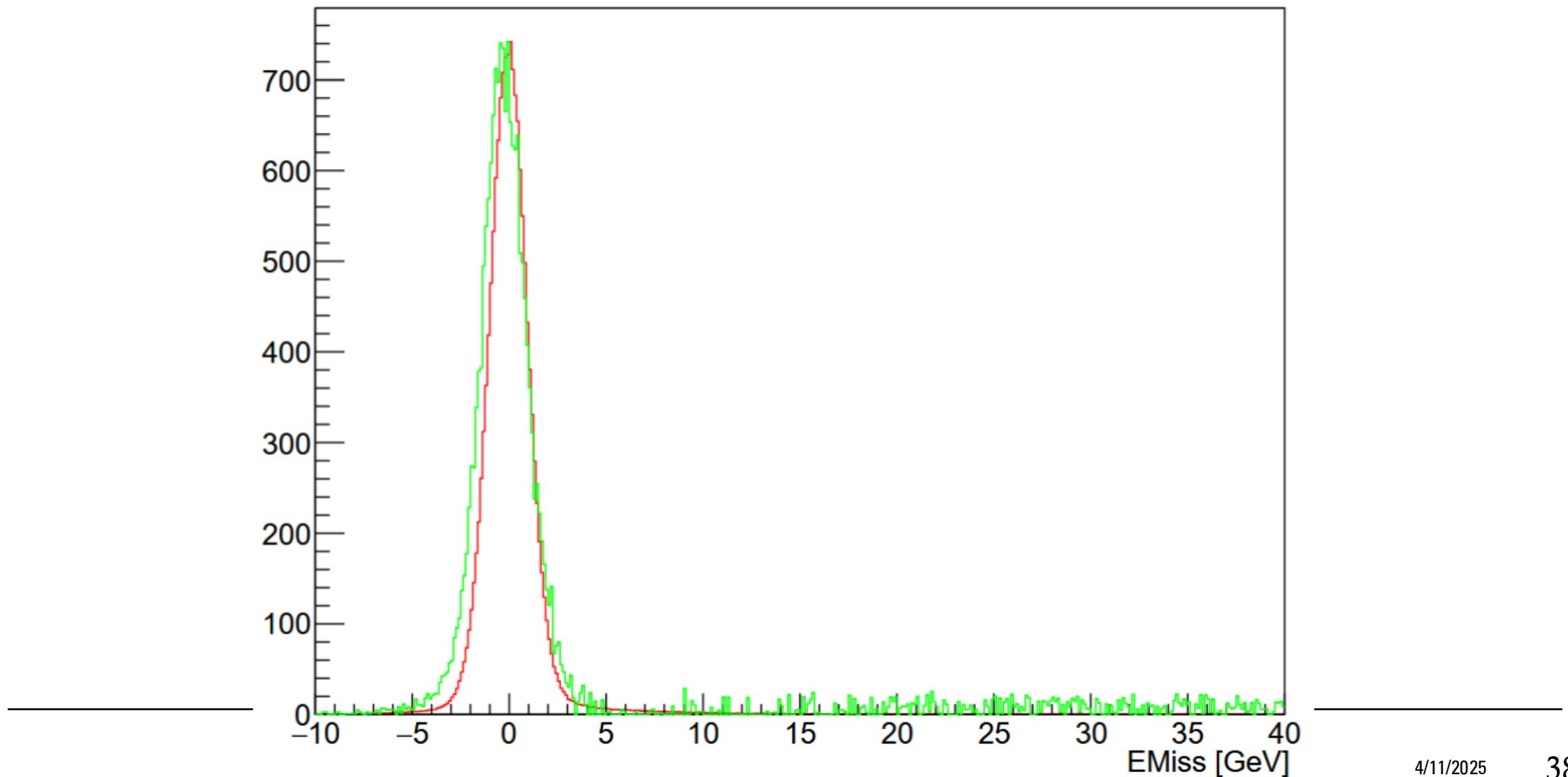
- The Monte Carlo is normalized to the region  $7 < \text{Emiss} < 20$
- The fraction background is calculated in the region of  $-3 < \text{Emiss} < 3$ 
  - $F_{\text{bkg}} = N_{\text{bkg}}/N_{\text{T}}$
  - $F_{\text{bkg}} = 0.1183$



# HEPGEN VS DATA WITH BACKGROUND SUBTRACTED

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EMiss

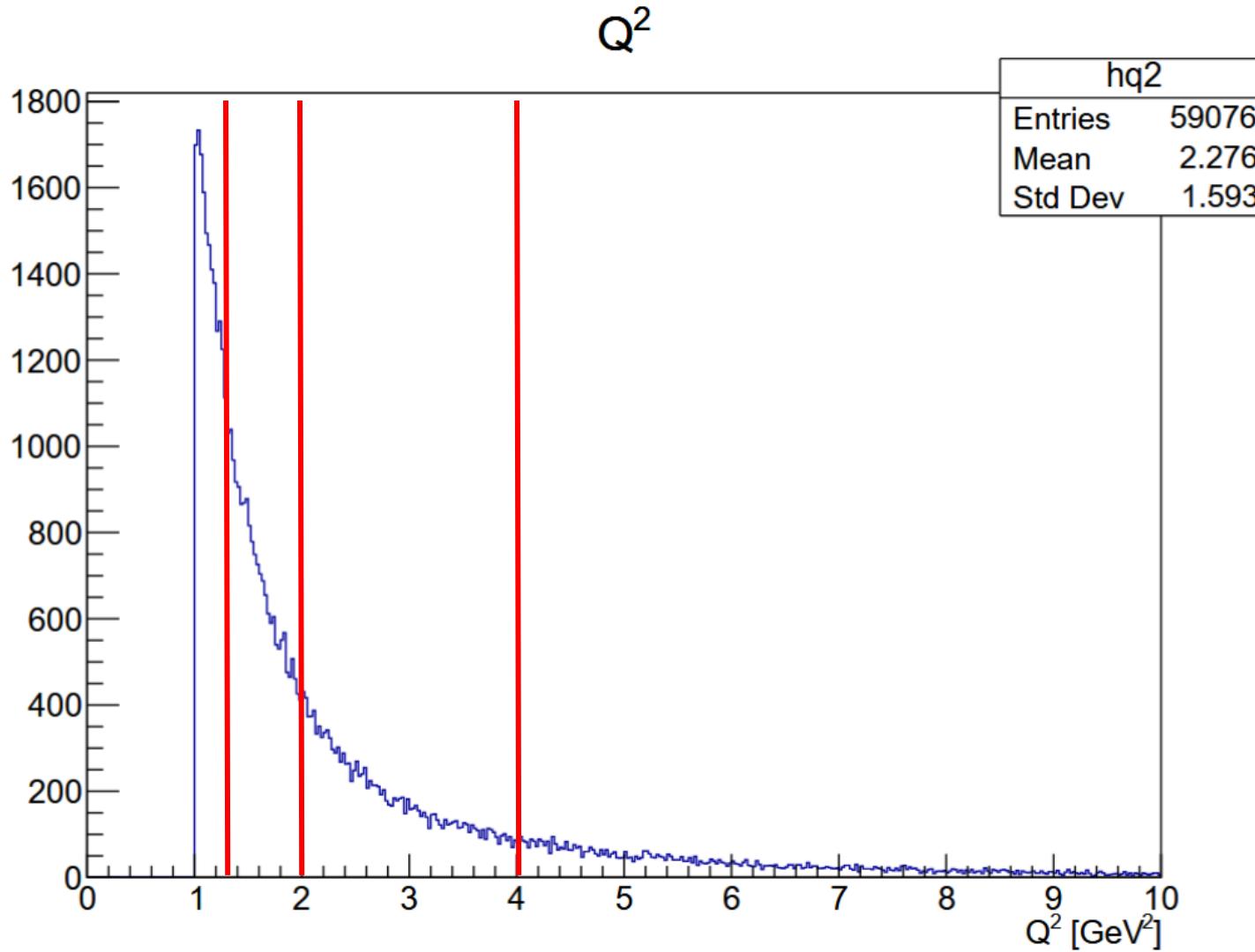


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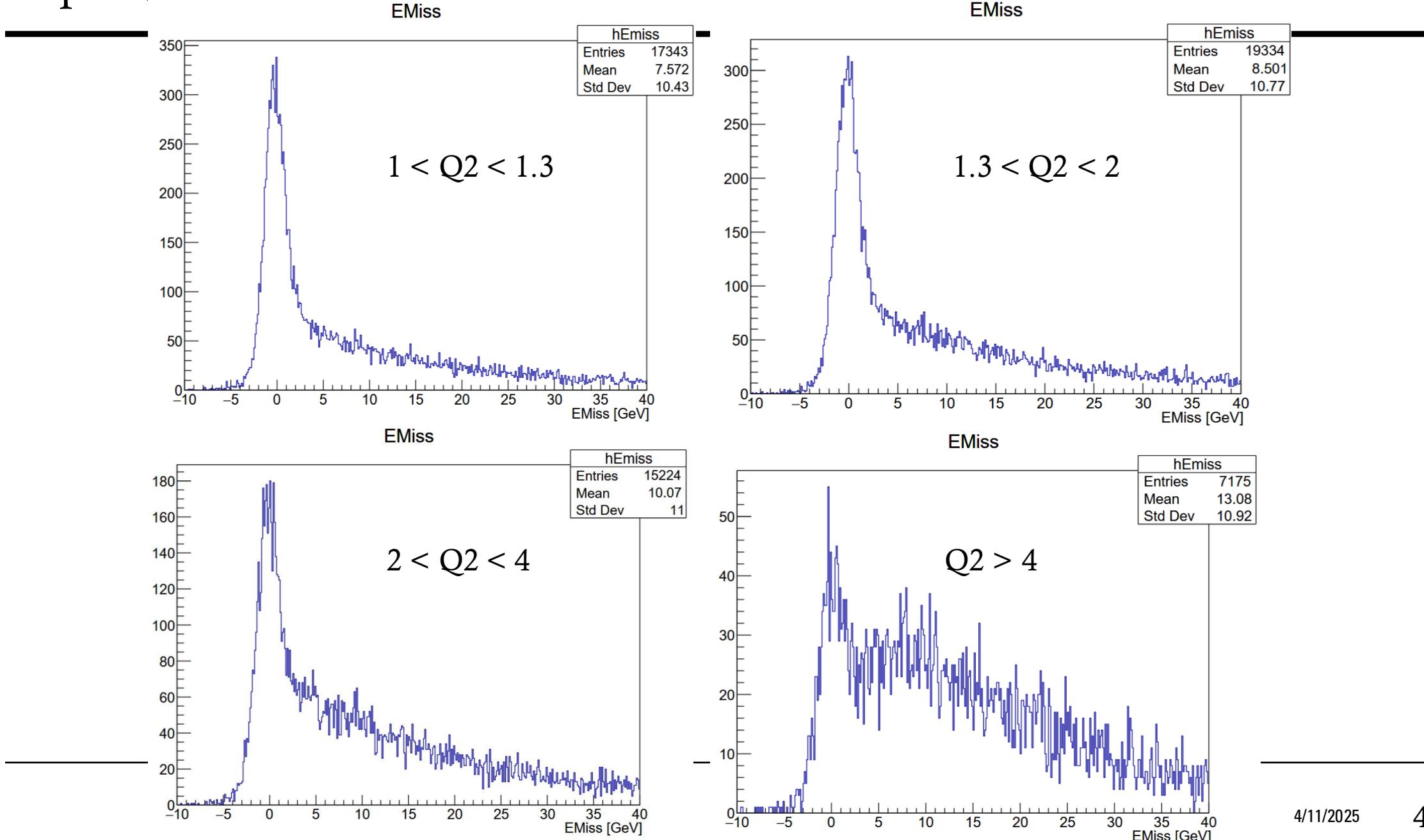
# BINNING SCHEME

# 1D Q2 Binning for Background Subtraction

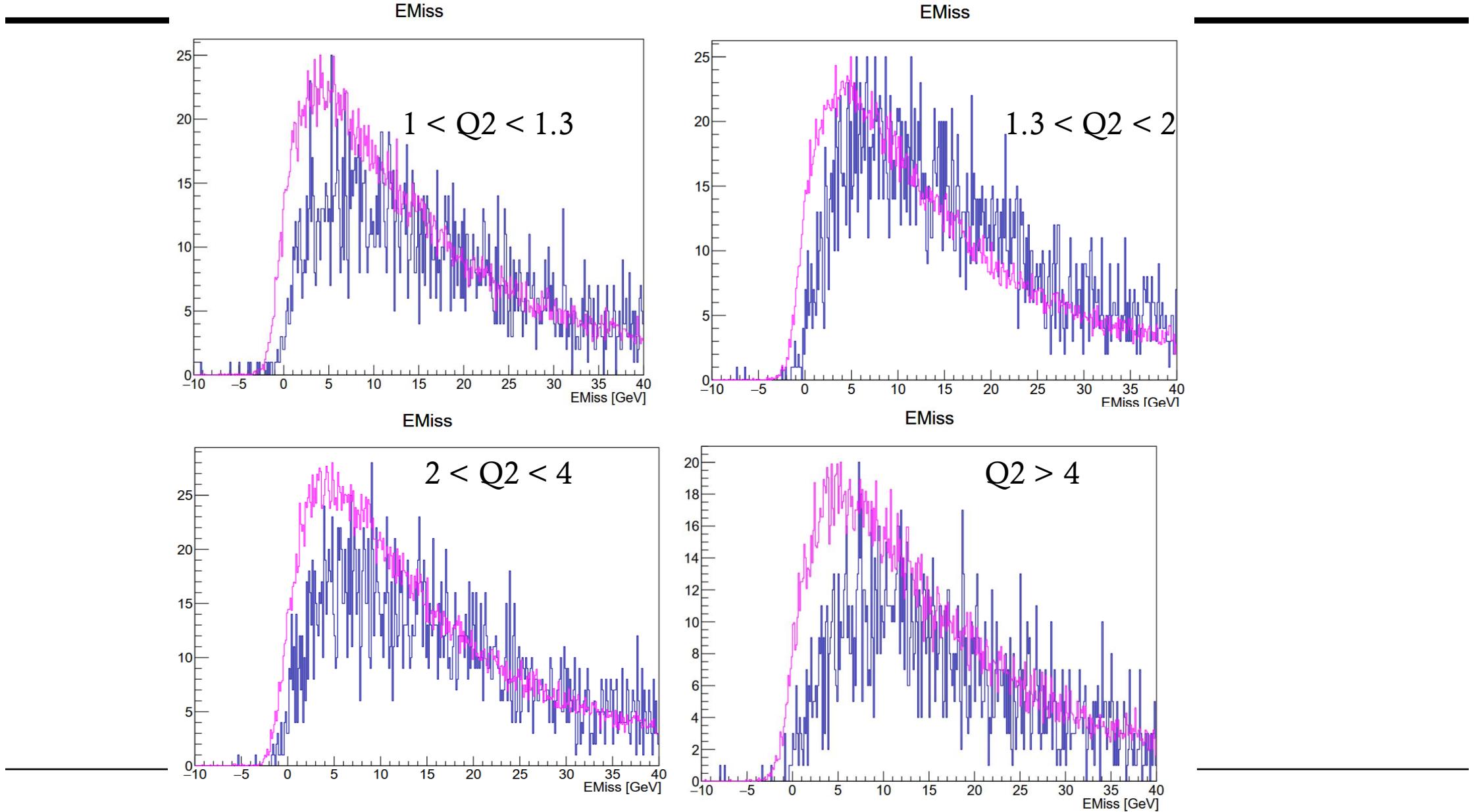
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# EMiss per O2 bin



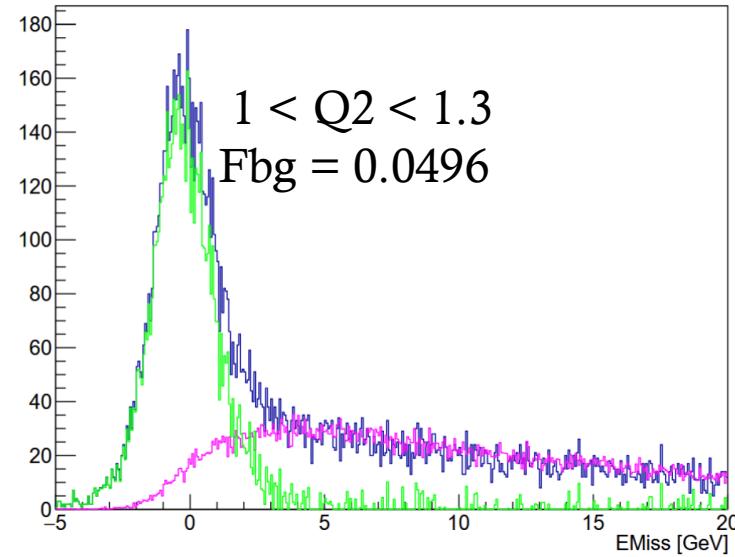
# EMiss per Q2 bin for Events with same charge hadrons



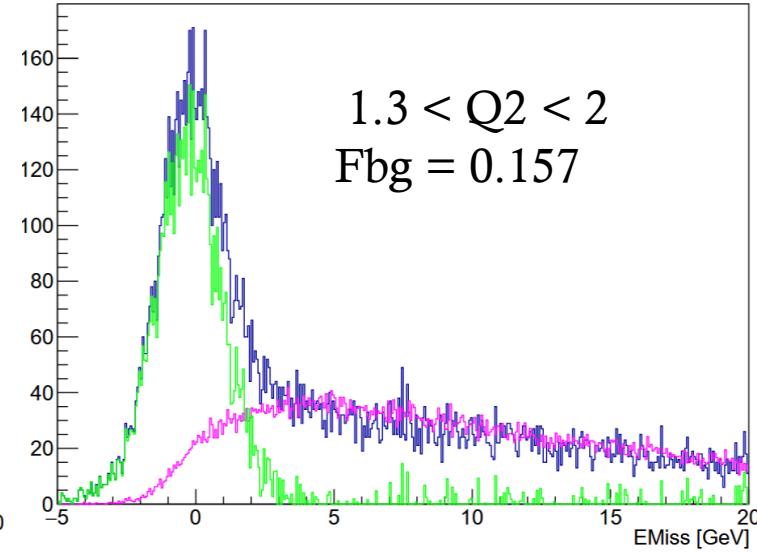
# EMiss per Q2 bin (background subtraction)

Fbg is in the region  
 $-2.5 < \text{Emiss} < 2.5$

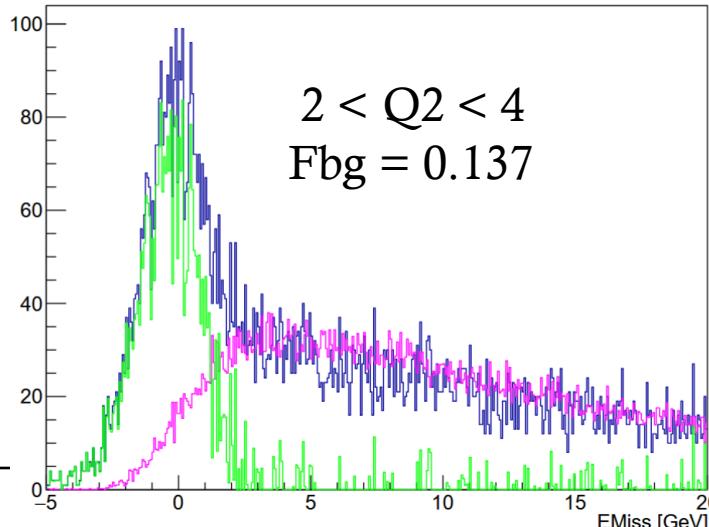
EMiss



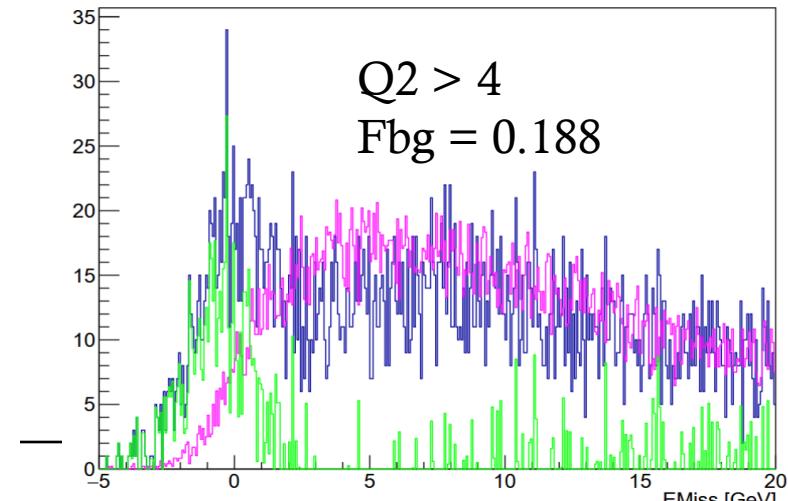
EMiss



EMiss



EMiss



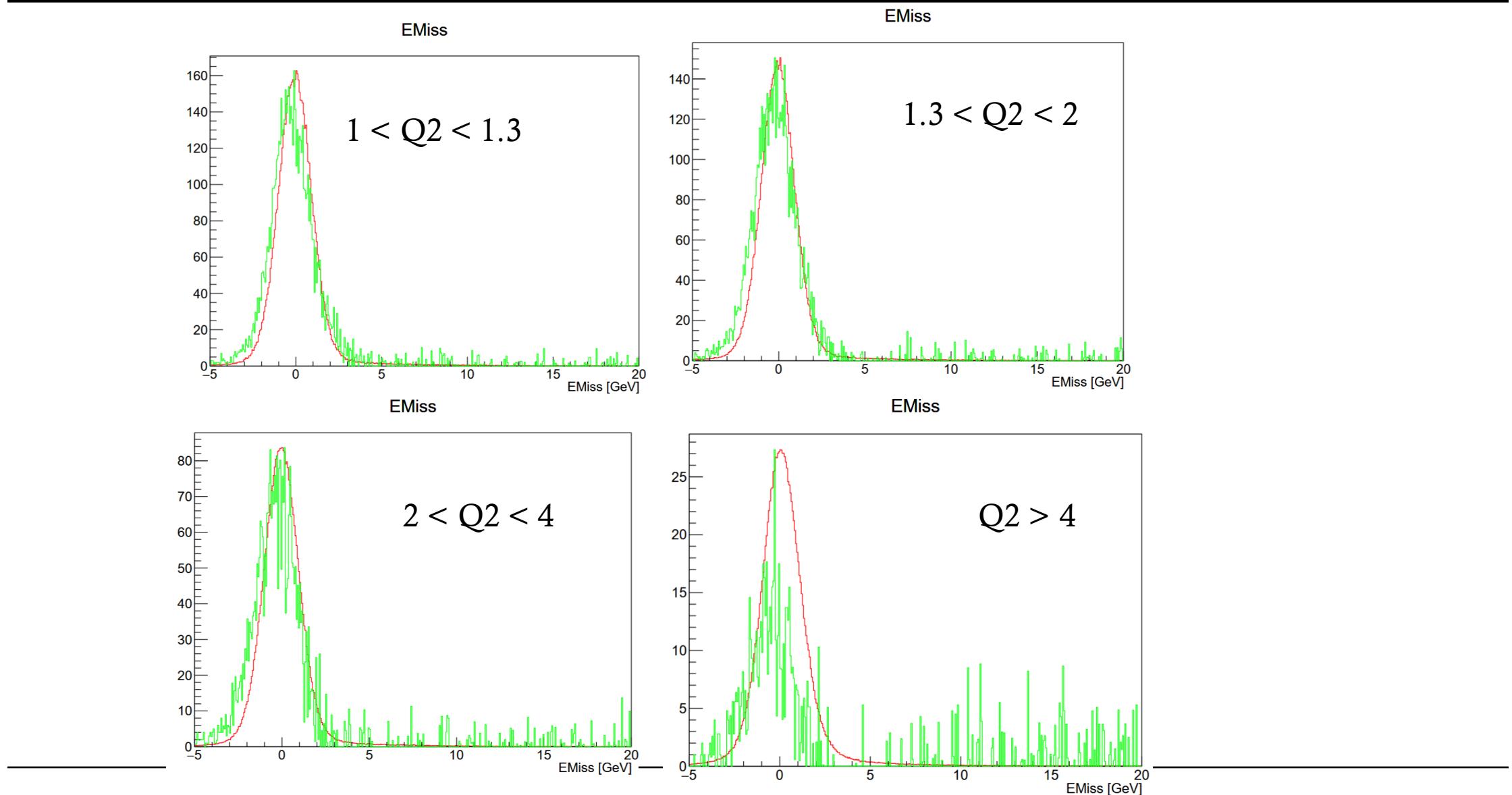
Data

Lepto

Data - Lepto

# EMiss per Q2 bin (Data w/o background vs HepGen)

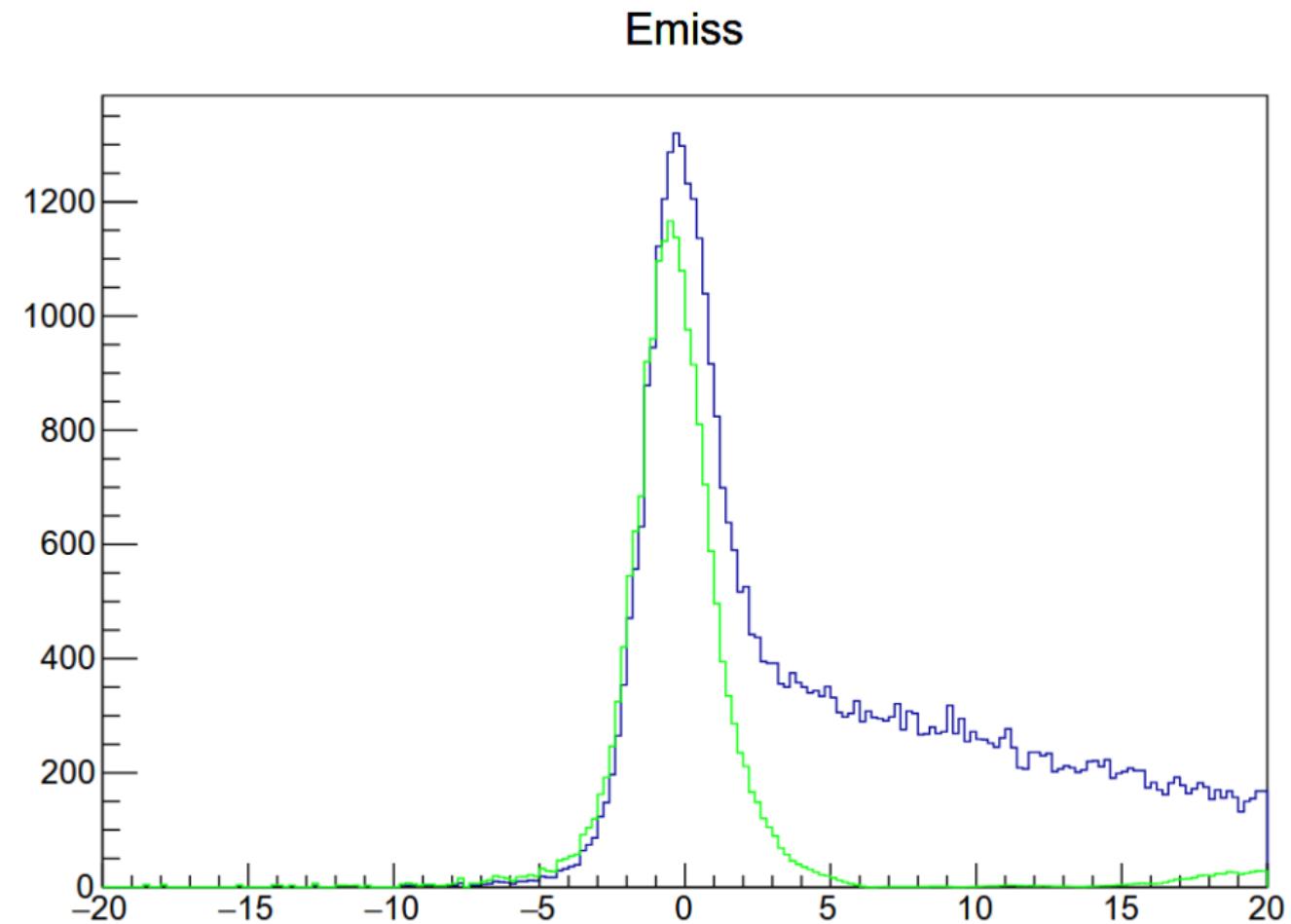
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# EMiss background subtraction with weight

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- Using the four bins in Q2
  - Interpolated the background fraction from 10 bins in EMiss from  $-2.5$  to  $22.5$  GeV
- This allowed me to weight my distribution between 0 and 1 for each event
- Reweight the HepGen to match the data with no background

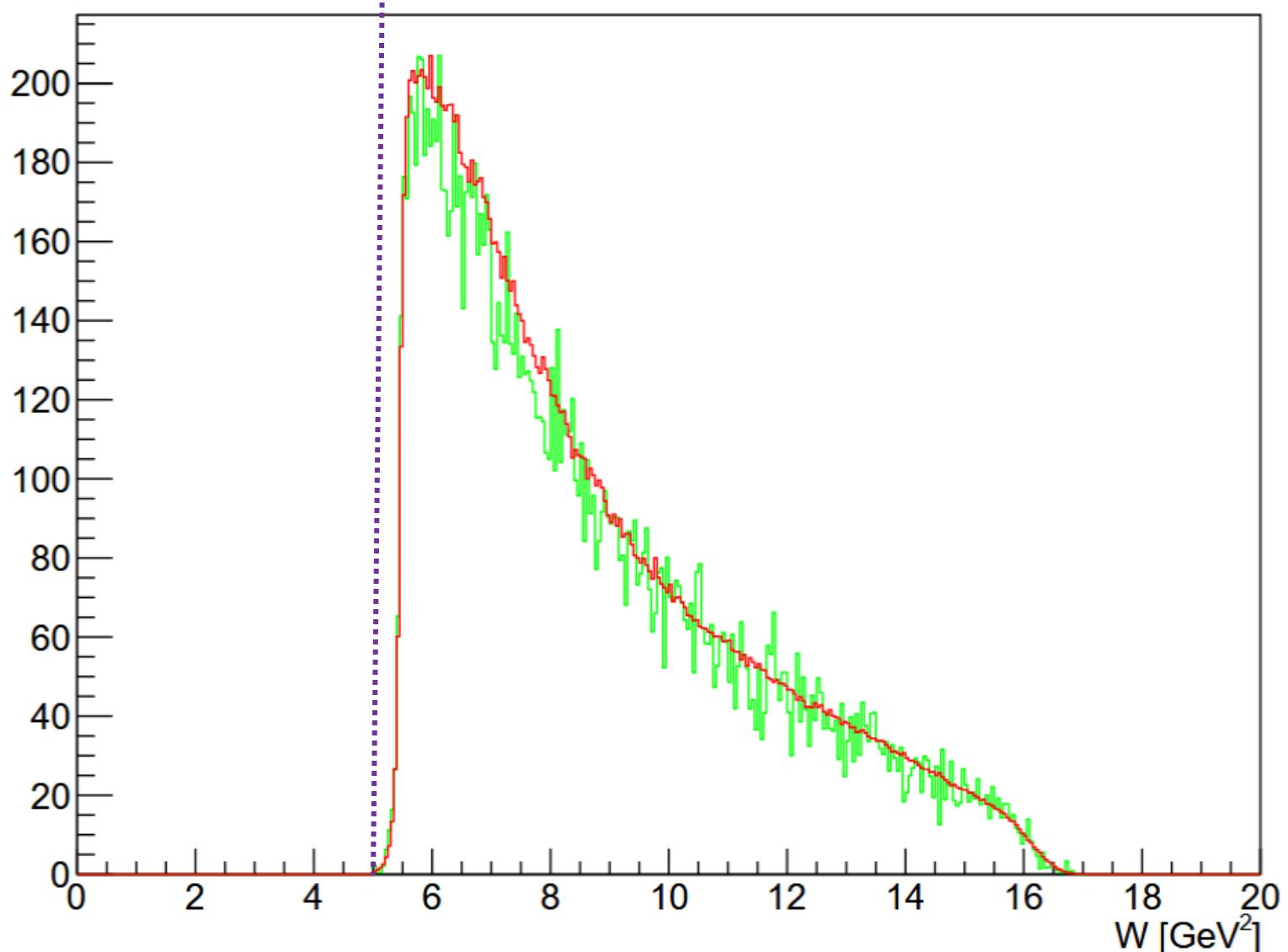


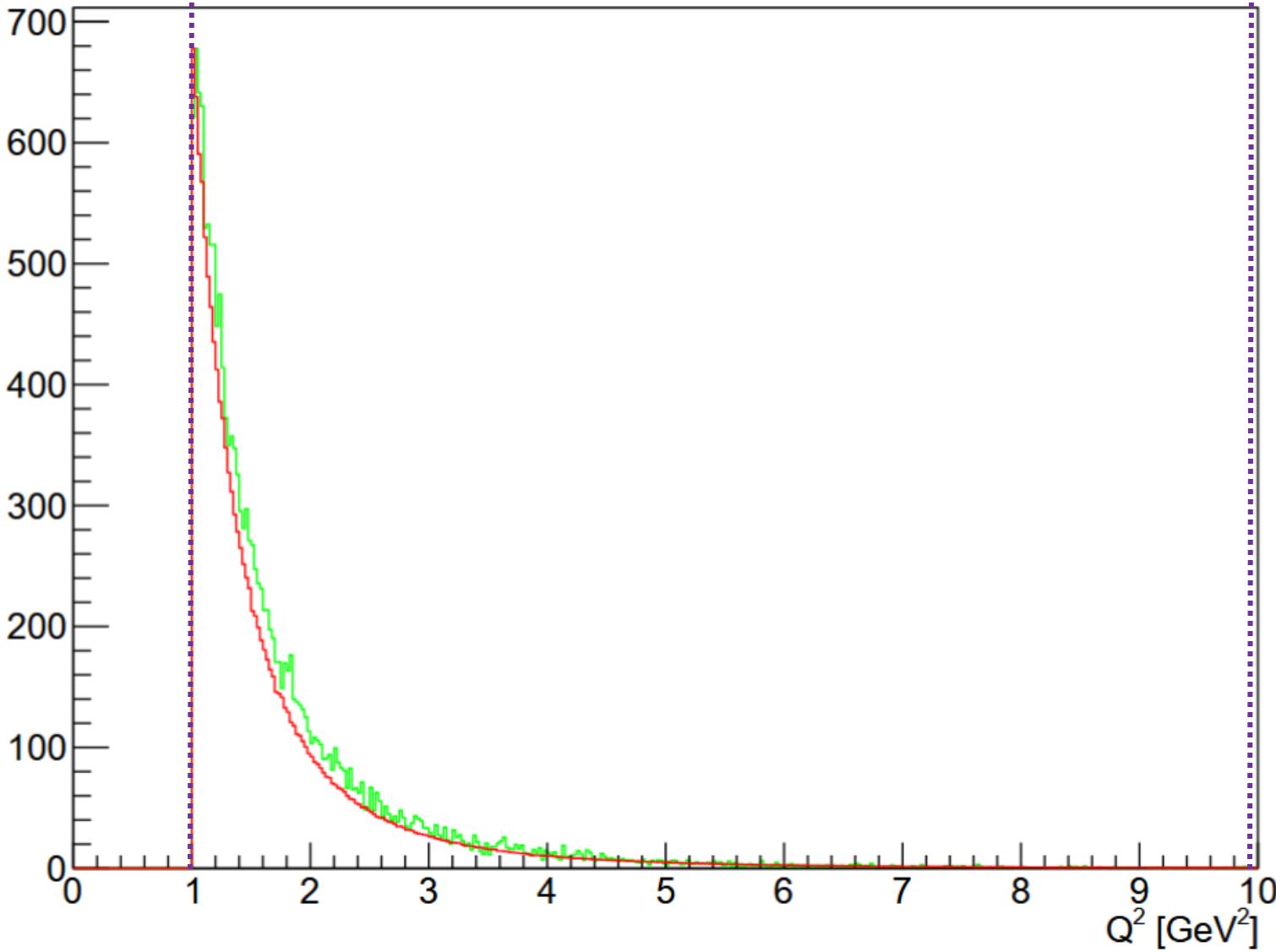
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# DATA VS REWEIGHTED HEPGEN

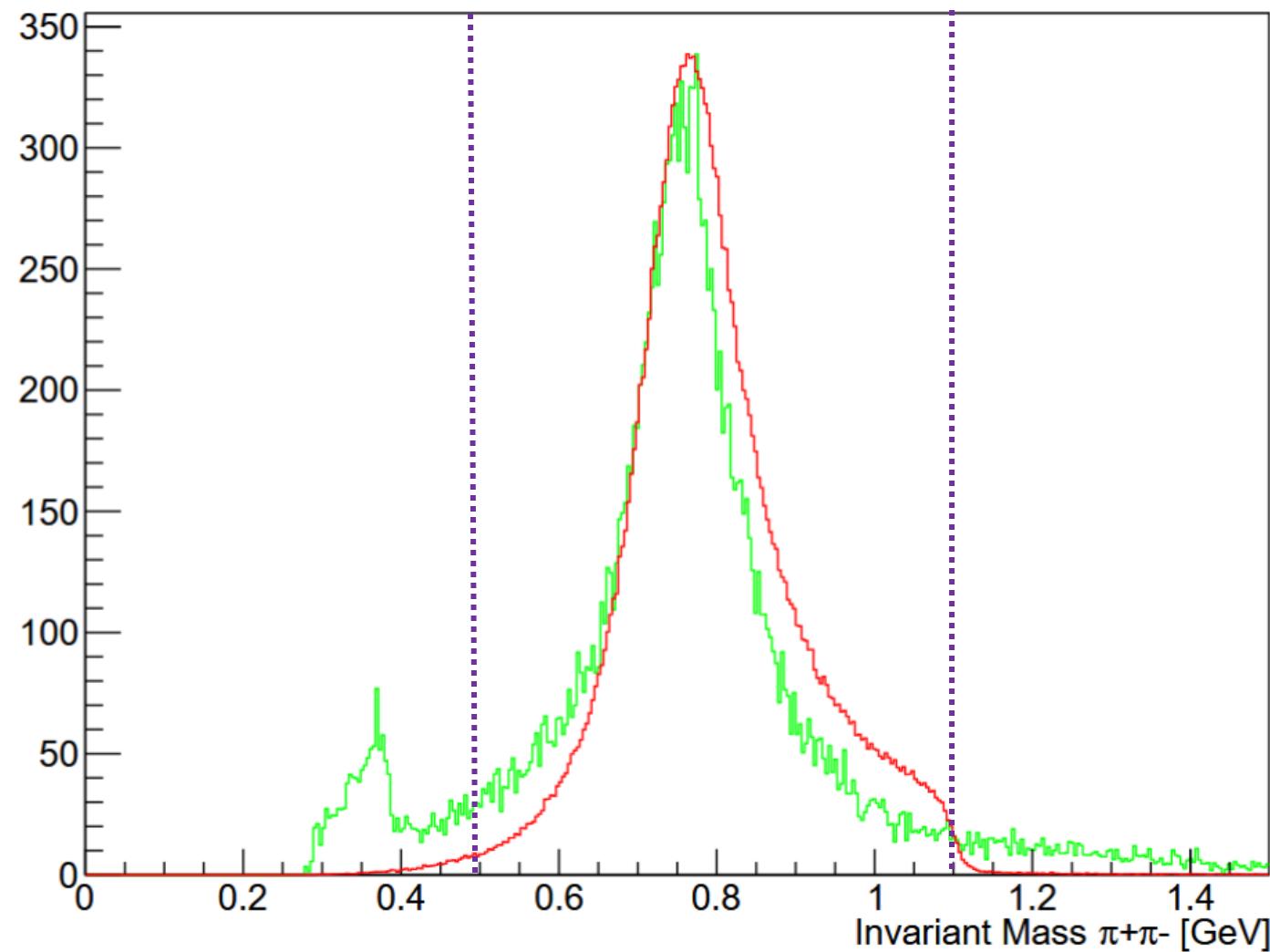
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W

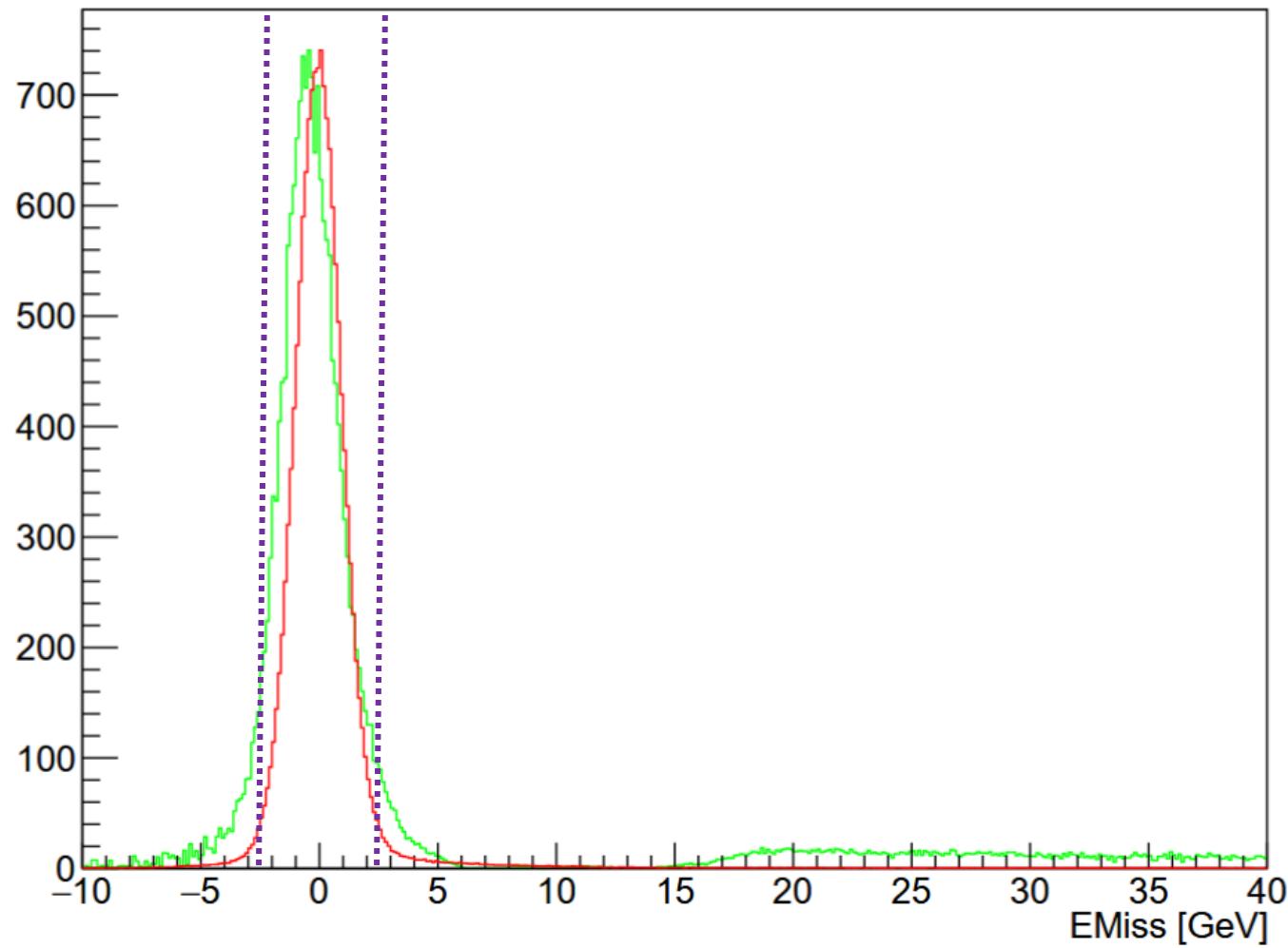


$Q^2$ 

$M(\pi^+\pi^-)$



## EMiss



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# SPIN DENSITY MATRIX ELEMENTS

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# EXTRACTING SDME WITHOUT BACKGROUND

- Introduce 23 more SDME for just the background events:

$$-\ln L(\mathcal{R}) = - \sum_{i=1}^N \ln \left[ \frac{(1 - f_{bg}) * \mathcal{W}^{U+L}(\mathcal{R}; \Phi_i, \phi_i, \cos \Theta_i)}{\tilde{\mathcal{N}}(\mathcal{R}, \mathcal{B})} + \frac{f_{bg} * \mathcal{W}^{U+L}(\mathcal{B}; \Phi_i, \phi_i, \cos \Theta_i)}{\tilde{\mathcal{N}}(\mathcal{R}, \mathcal{B})} \right]$$

$$\tilde{\mathcal{N}}(\mathcal{R}, \mathcal{B}) = \sum_{j=1}^{N_{MC}} [(1 - f_{bg}) * \mathcal{W}^{U+L}(\mathcal{R}; \Phi_j, \phi_j, \cos \Theta_j) + f_{bg} * \mathcal{W}^{U+L}(\mathcal{B}; \Phi_j, \phi_j, \cos \Theta_j)]$$

- Here R is the 23 SDME for the signal, and B is the 23 SDME for the background. MLM has to fit 46 parameters
- Fbg is the fractional background

# SDME CODE

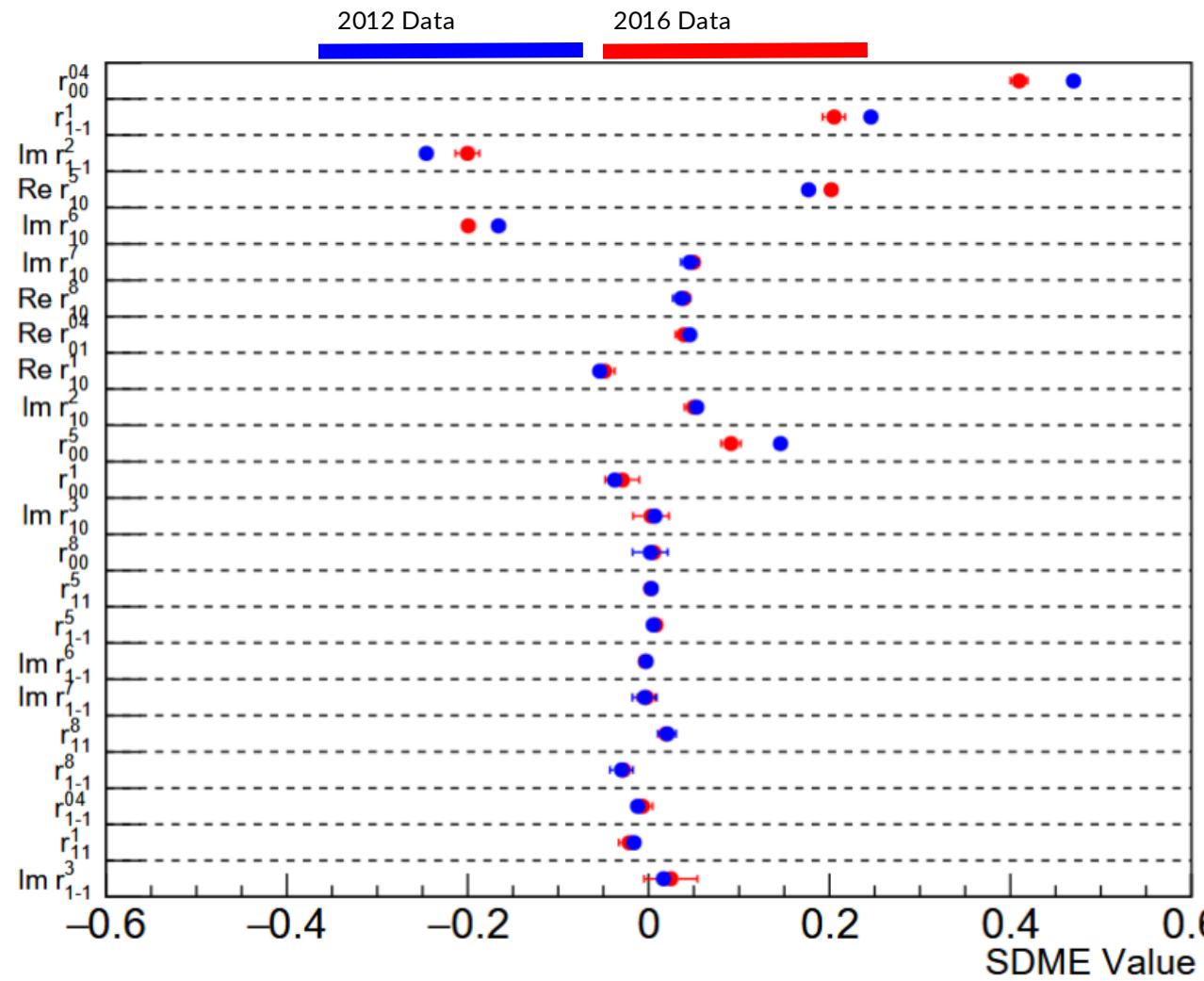
```
import ROOT.Math as rm
import numpy as np
#Log sum function (the one we are minimizing)
class logsum(object):
    def __init__(self, cosTheta, phi, eps, n_Data, cosTheta_sim, phi_sim, eps_sim, n_sim):
        self.cosTheta = cosTheta
        self.phi = phi
        self.Phi = Phi
        self.eps = eps
        self.n_Data = n_Data
        self.cosTheta_sim = cosTheta_sim
        self.phi_sim = phi_sim
        self.Phi_sim = Phi_sim
        self.eps_sim = eps_sim
        self.n_sim = n_sim
    def __call__(self, x):
        N = 0.0
        for i in range(self.n_Data):
            ci = self.cosTheta[i]
            ph = self.phi[i]
            Ph = self.Phi[i]
            sin2Theta = 2 * ci * rm.sqrt(1 - ci * ci)
            sinTheta2 = (1 - ci * ci)
            N_U = (1/2 * (1 - x[0]) + 1/2 * (3 * x[0] - 1) * ci * ci
                   - rm.sqrt(2) * x[1] * sin2Theta * rm.cos(ph)
                   - x[2] * sinTheta2 * rm.cos(2 * ph))
            N_U += (-self.eps[i] * rm.cos(2 * Ph) * (x[3] * sinTheta2 + x[4]) * ci * ci
                   - rm.sqrt(2) * x[5] * sinTheta * rm.cos(ph)
                   - x[6] * sinTheta2 * rm.cos(2 * ph)))
            N_U += (-self.eps[i] * rm.sin(2 * Ph) * (rm.sqrt(2) * x[7] * sin2Theta * rm.sin(ph)
                   + x[8] * sinTheta2 * rm.sin(2 * ph)))
            N_U += (rm.sqrt(2 * self.eps[i] * (1 + self.eps[1])) * rm.cos(Ph) * (x[9] * sinTheta2
                   + x[10] * ci * ci * rm.sqrt(2) * x[11] * sin2Theta * rm.cos(ph)
                   - x[12] * sinTheta2 * rm.cos(2 * ph)))
            N_U += (rm.sqrt(2 * self.eps[i] * (1 + self.eps[1])) * rm.sin(Ph) * (rm.sqrt(2) * x[13] * sin2Theta * rm.sin(ph)
                   + x[14] * sinTheta2 * rm.sin(2 * ph)))
            N_P = (rm.sqrt(1 - self.eps[i] * self.eps[1]) * (rm.sqrt(2) * x[15] * sin2Theta * rm.sin(ph)
                   + x[16] * sinTheta2 * rm.sin(2 * ph)))
            N_P += (rm.sqrt(2 * self.eps[i] * (1 + self.eps[1])) * rm.cos(Ph) * (rm.sqrt(2) * x[17] * sin2Theta * rm.sin(ph)
                   + x[18] * sinTheta2 * rm.sin(2 * ph)))
            N_P += (rm.sqrt(2 * self.eps[i] * (1 + self.eps[1])) * rm.sin(Ph) * (x[19] * sinTheta2
                   + x[20] * ci * ci * rm.sqrt(2) * x[21] * sin2Theta * rm.cos(ph)
                   - x[22] * sinTheta2 * rm.cos(2 * ph)))
            N += 3 / (8 * rm.pi * rm.pi) * (N_U + N_P)
        NF = 0.0
        for i in range(self.n_sim):
            ci = self.cosTheta_sim[i]
            ph = self.phi_sim[i]
            Ph = self.Phi_sim[i]
            sin2Theta = 2 * ci * rm.sqrt(1 - ci * ci)
            sinTheta2 = (1 - ci * ci)
            N_U = (1/2 * (1 - x[0]) + 1/2 * (3 * x[0] - 1) * ci * ci
                   - rm.sqrt(2) * x[1] * sin2Theta * rm.cos(ph)
                   - x[2] * sinTheta2 * rm.cos(2 * ph))
            N_U += (-self.eps_sim[i] * rm.cos(2 * Ph) * (x[3] * sinTheta2 + x[4]) * ci * ci
                   - rm.sqrt(2) * x[5] * sinTheta * rm.cos(ph)
                   - x[6] * sinTheta2 * rm.cos(2 * ph)))
            N_U += (-self.eps_sim[i] * rm.sin(2 * Ph) * (rm.sqrt(2) * x[7] * sin2Theta * rm.sin(ph)
                   + x[8] * sinTheta2 * rm.sin(2 * ph)))
            N_U += (rm.sqrt(2 * self.eps_sim[i] * (1 + self.eps_sim[1])) * rm.cos(Ph) * (x[9] * sinTheta2
                   + x[10] * ci * ci * rm.sqrt(2) * x[11] * sin2Theta * rm.cos(ph)
                   - x[12] * sinTheta2 * rm.cos(2 * ph)))
            N_U += (rm.sqrt(2 * self.eps_sim[i] * (1 + self.eps_sim[1])) * rm.sin(Ph) * (rm.sqrt(2) * x[13] * sin2Theta * rm.sin(ph)
                   + x[14] * sinTheta2 * rm.sin(2 * ph)))
            N_P = (rm.sqrt(1 - self.eps_sim[i] * self.eps_sim[1]) * (rm.sqrt(2) * x[15] * sin2Theta * rm.sin(ph)
                   + x[16] * sinTheta2 * rm.sin(2 * ph)))
            N_P += (rm.sqrt(2 * self.eps_sim[i] * (1 + self.eps_sim[1])) * rm.cos(Ph) * (rm.sqrt(2) * x[17] * sin2Theta * rm.sin(ph)
                   + x[18] * sinTheta2 * rm.sin(2 * ph)))
            N_P += (rm.sqrt(2 * self.eps_sim[i] * (1 + self.eps_sim[1])) * rm.sin(Ph) * (x[19] * sinTheta2
                   + x[20] * ci * ci * rm.sqrt(2) * x[21] * sin2Theta * rm.cos(ph)
                   - x[22] * sinTheta2 * rm.cos(2 * ph)))
            NF += 3 / (8 * rm.pi * rm.pi) * (N_U + N_P)
        tot = ROOT.TMath.Log(N) - ROOT.TMath.Log(NF)
        return -tot
```

- The code for extracting the SDMEs using maximum likelihood method (MLM) has been written
  - Extracts all 23 SDMEs
  - Based on the python code used for sig\_LT'/sig\_0 extraction
  - Minuit2 minimizer used
    - "Minimize" as minimizer

# SDME EXTRACTION

Only 1000 events where ran for 2016

COMPASS 2012



2012 is after background subtraction

2016 still has background

---

# NEXT STEPS

- Create background subtraction MLM to extract SDMEs
  - Look at Lepto for background simulation
- Fix up the errors with this MLM
- Multidimensional binning

---

# **BACKUP SLIDES**

---

# KINEMATIC CUTS

- $W > 5.0 \text{ GeV}$
- $0.1 < y < 0.9$
- $1.0 < Q^2 < 10.0$
- $0.01 < pT^2 < 0.5$
- $0.5 < M_{\pi^+ \pi^-} < 1.1$
- $P_{-\{\rho^0\}} > 15$

\*Each plot is shown without the cut on the variable\*

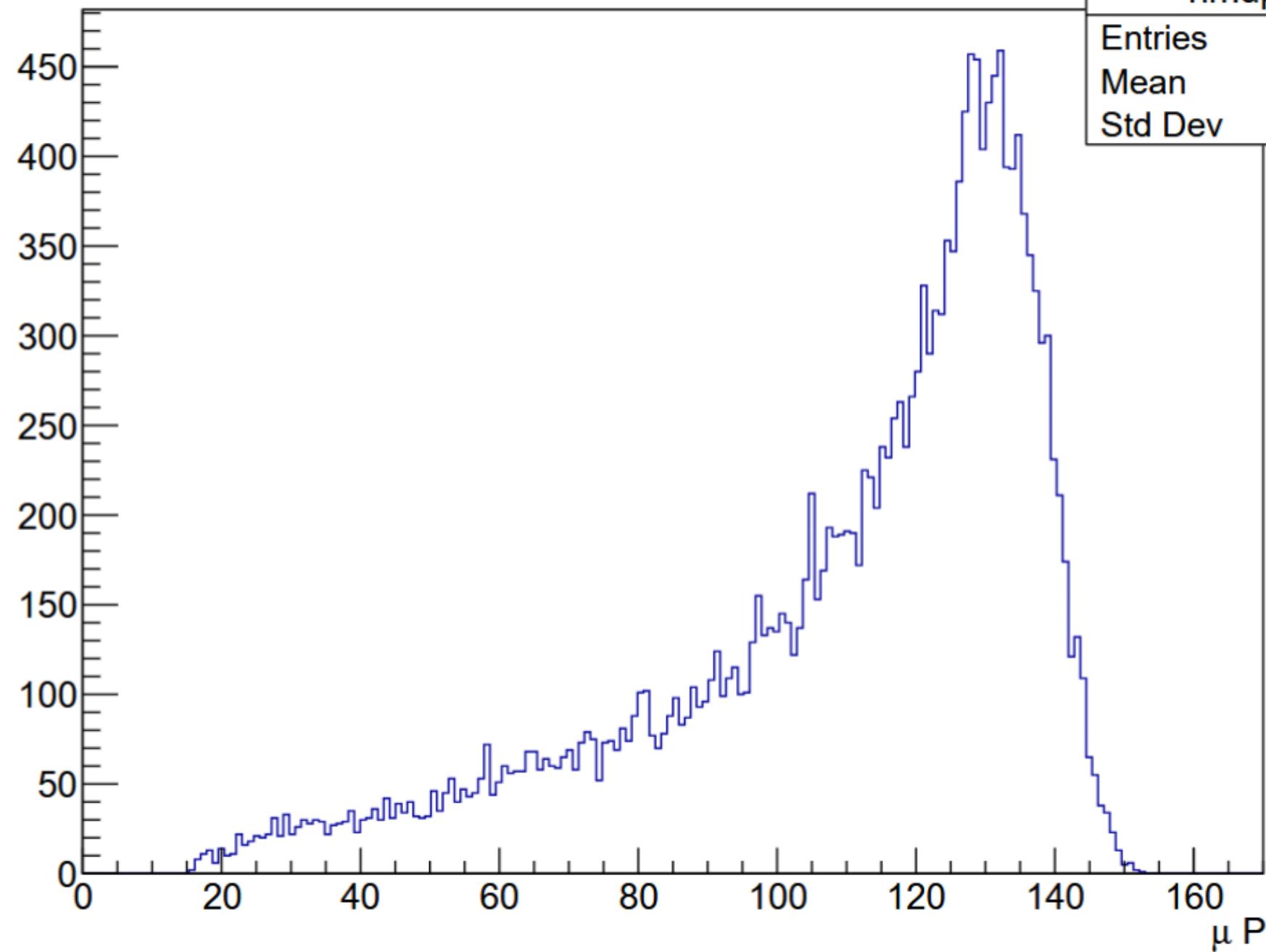
---

# **DATA 1D PARTICLE KINEMATICS WITH CUTS**

$\mu P$ 

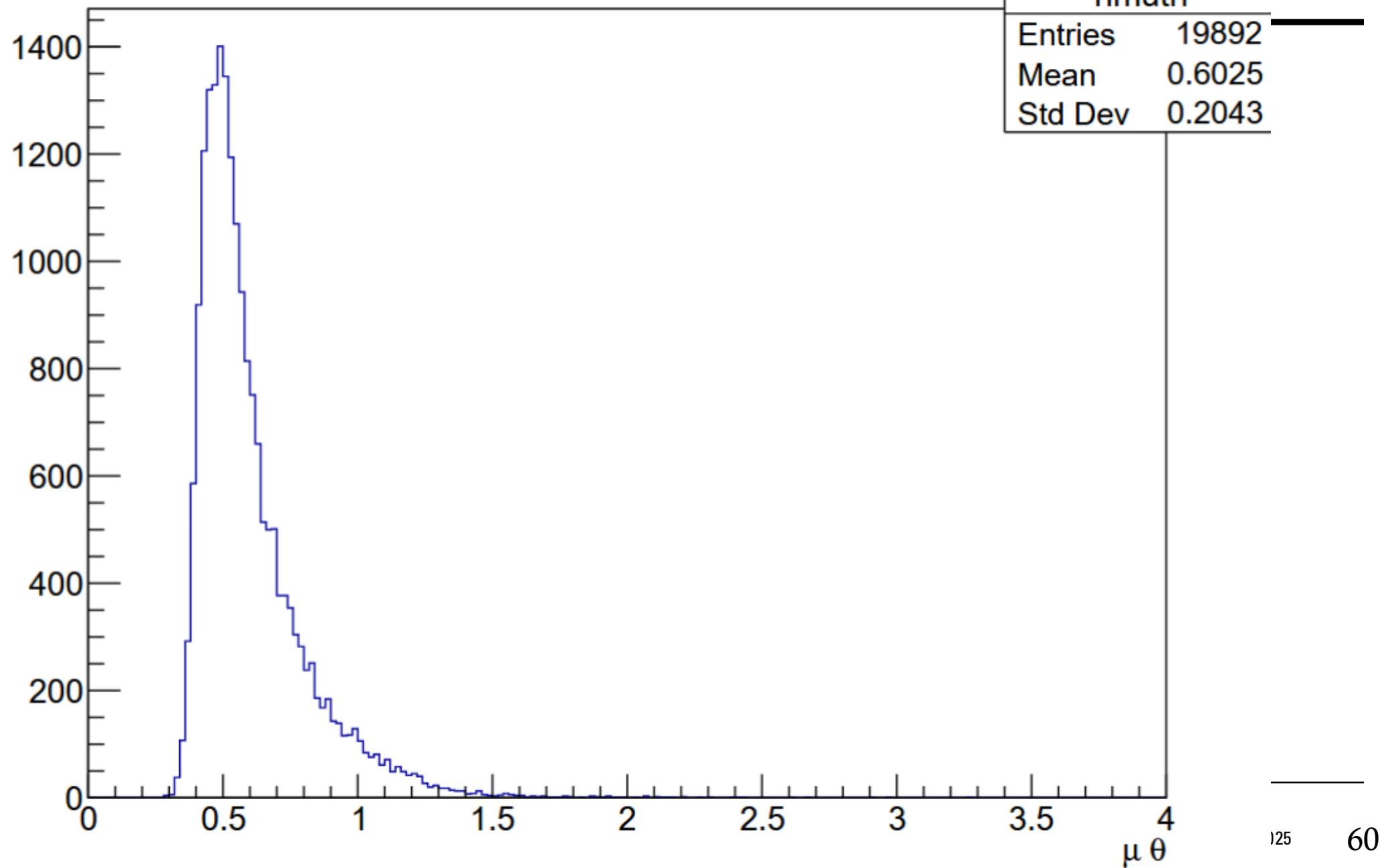
hmup

Entries	19892
Mean	109.9
Std Dev	28.16



$\mu \theta$ 

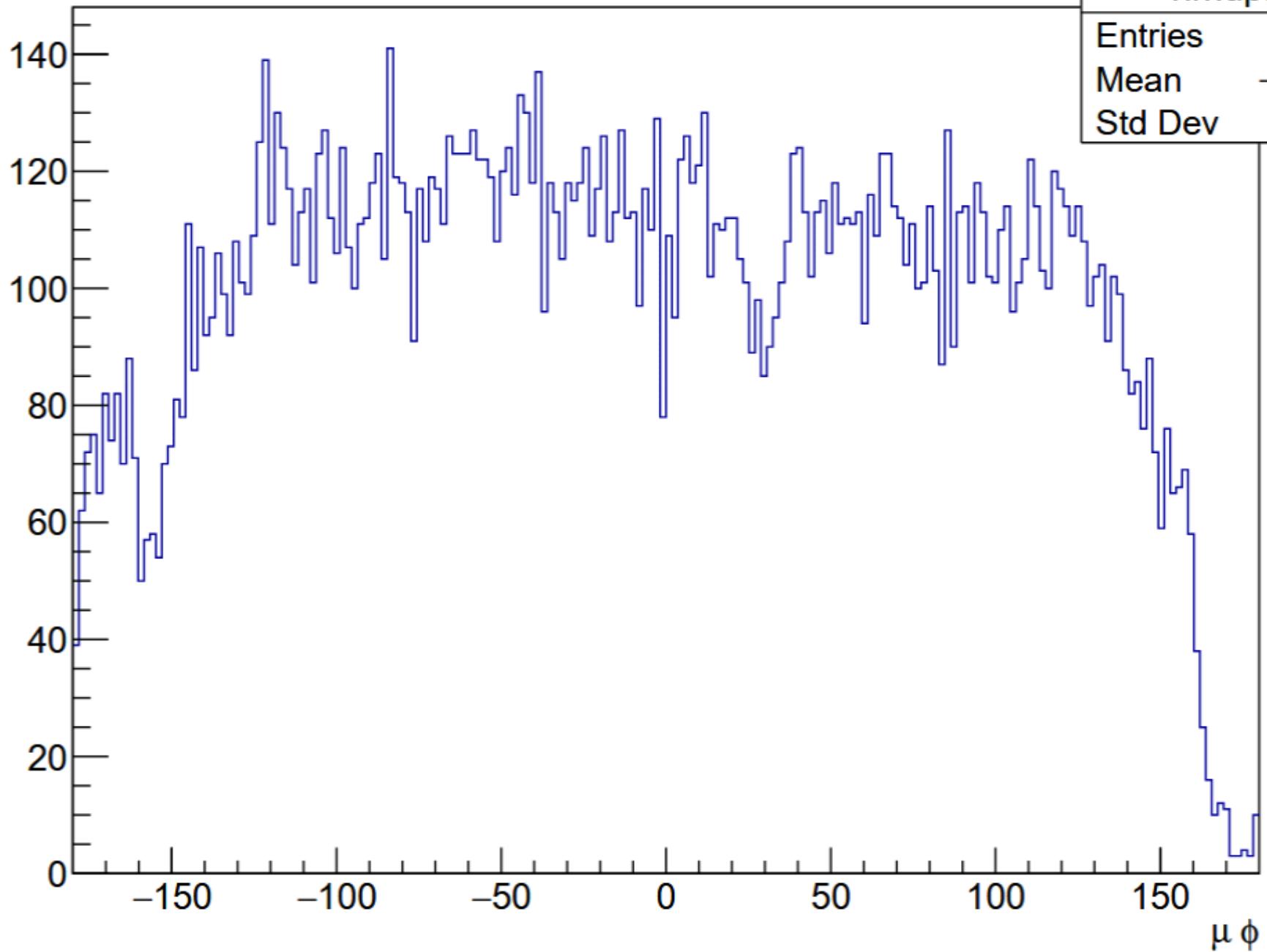
hmuth	
Entries	19892
Mean	0.6025
Std Dev	0.2043



$\mu \phi$ 

hmuphi

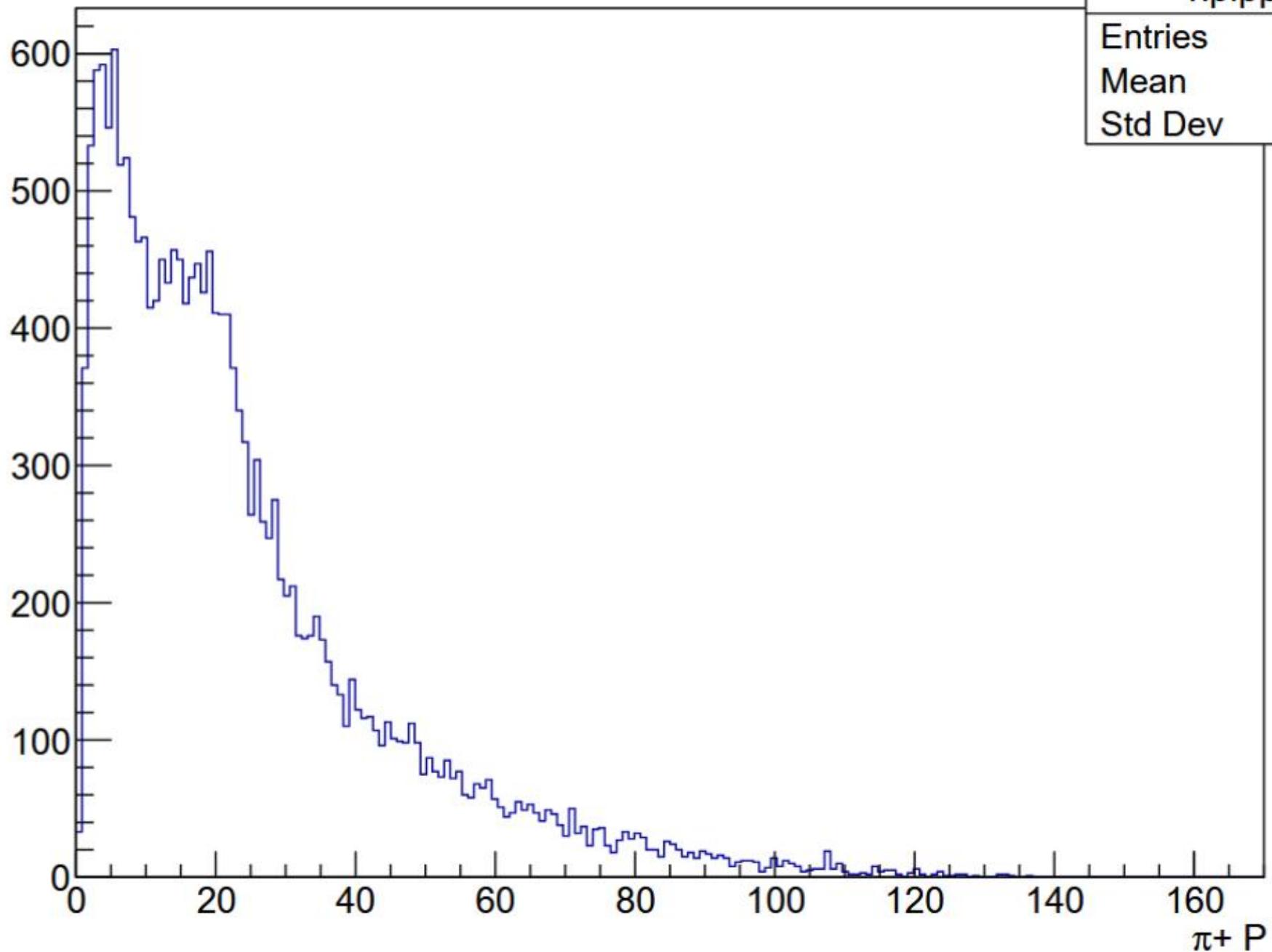
Entries	19892
Mean	-7.524
Std Dev	93.25



$\pi^+ P$ 

hpipp

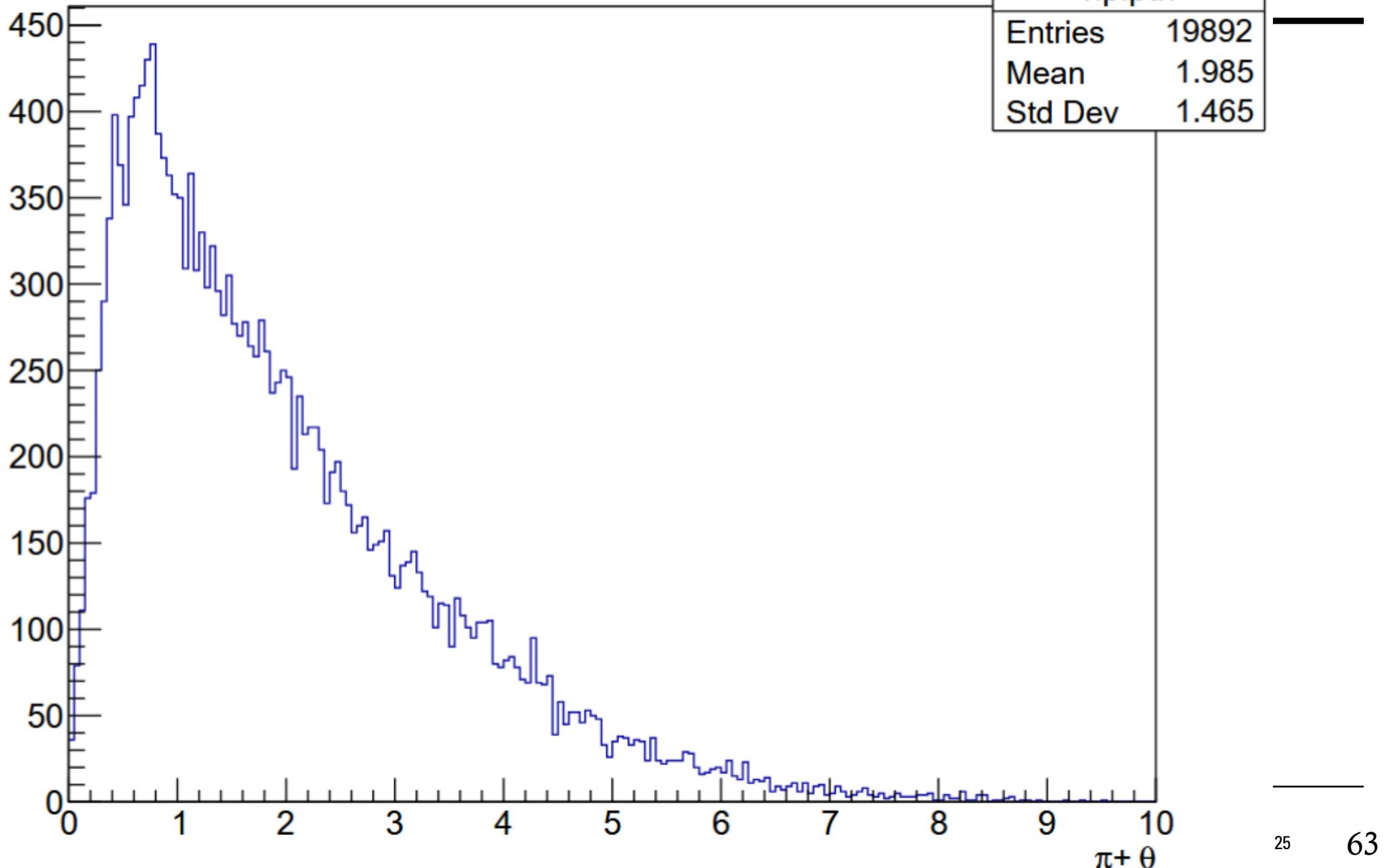
Entries	19892
Mean	24.14
Std Dev	20.98

25  
62

$\pi^+ \theta$ 

hpipth

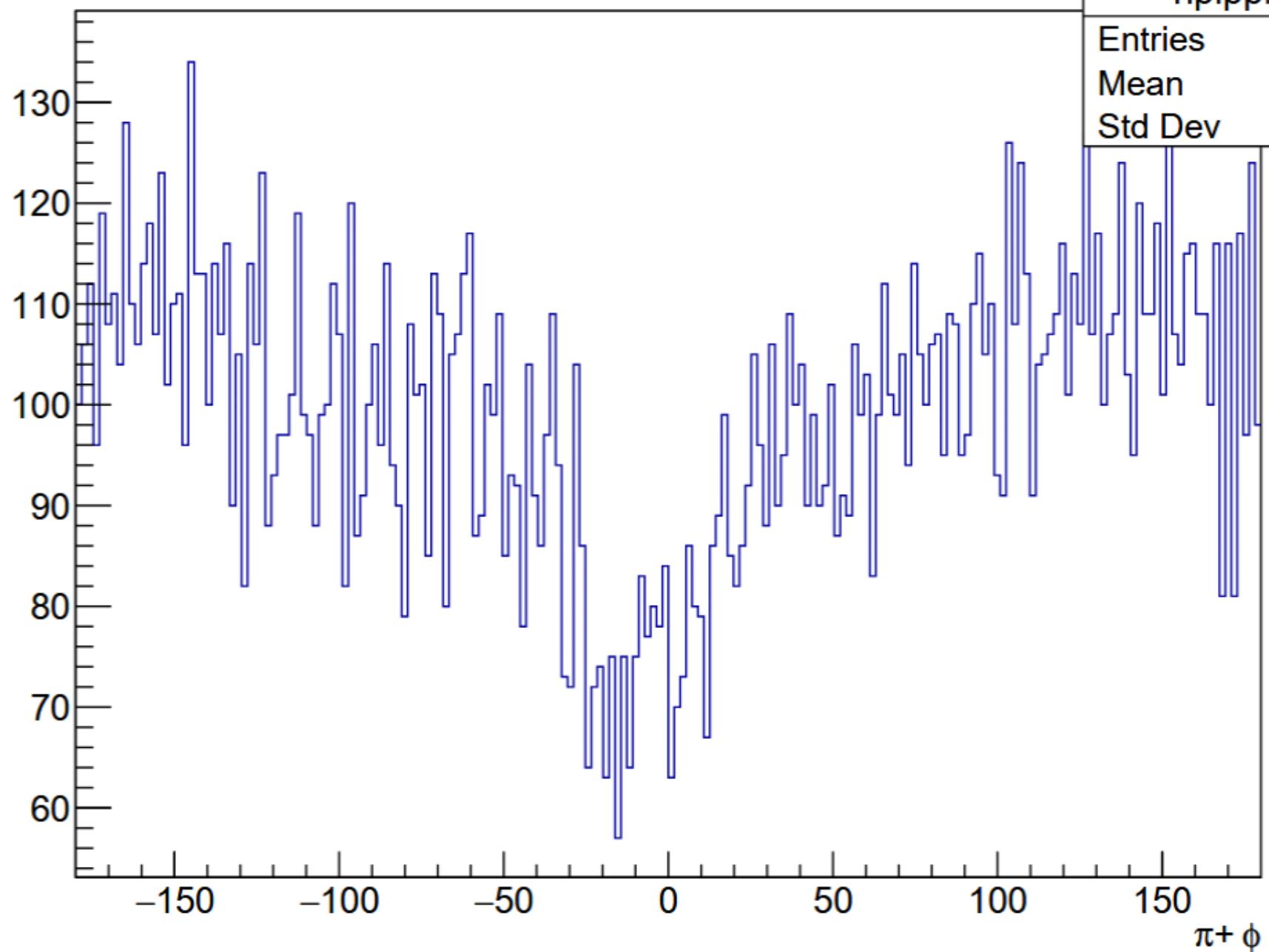
Entries	19892
Mean	1.985
Std Dev	1.465



$\pi^+ \phi$ 

hpiphi

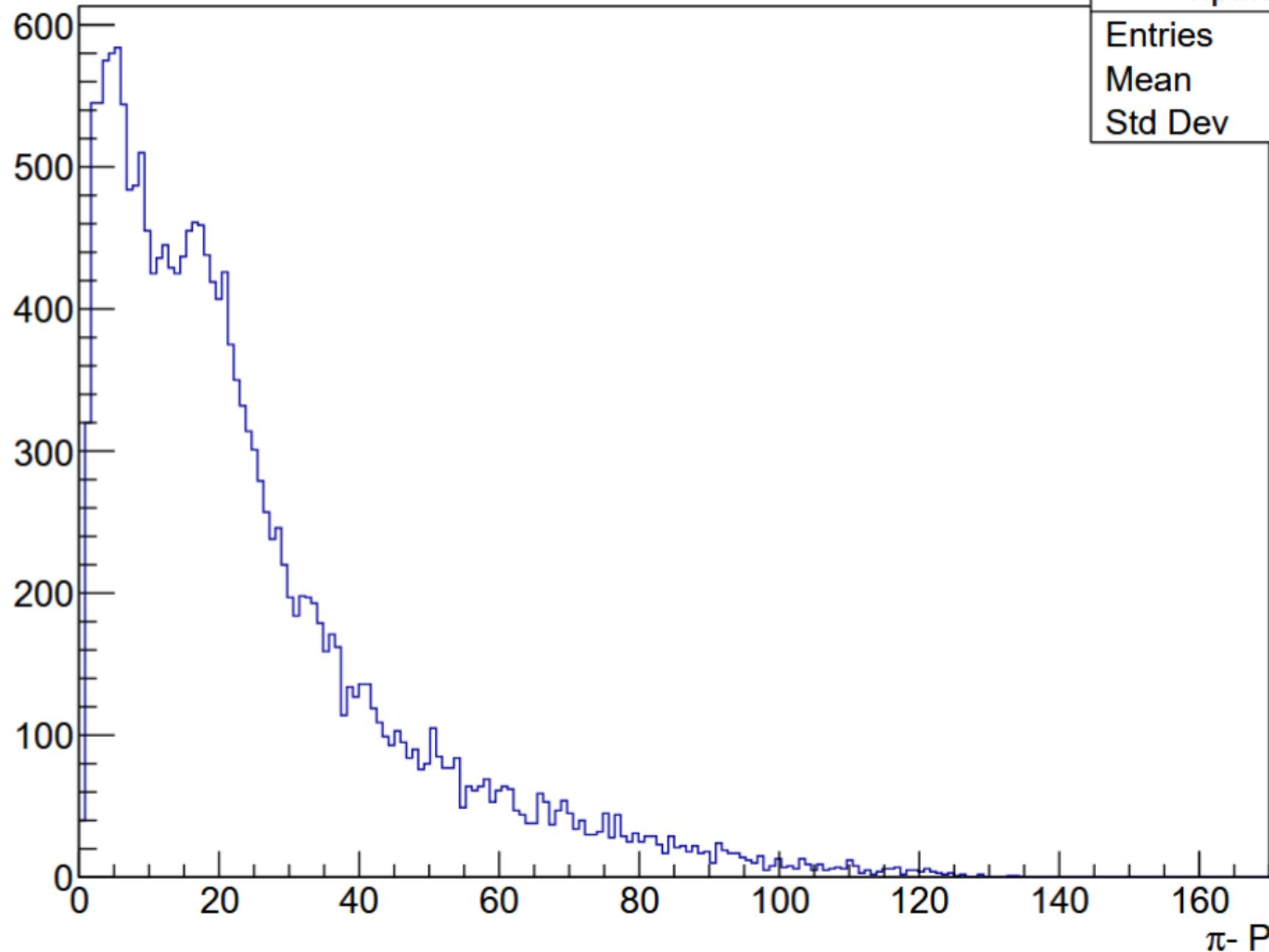
Entries	19892
Mean	1.049
Std Dev	107.6



$\pi^- P$ 

hpimp

Entries	19892
Mean	24.5
Std Dev	21.43

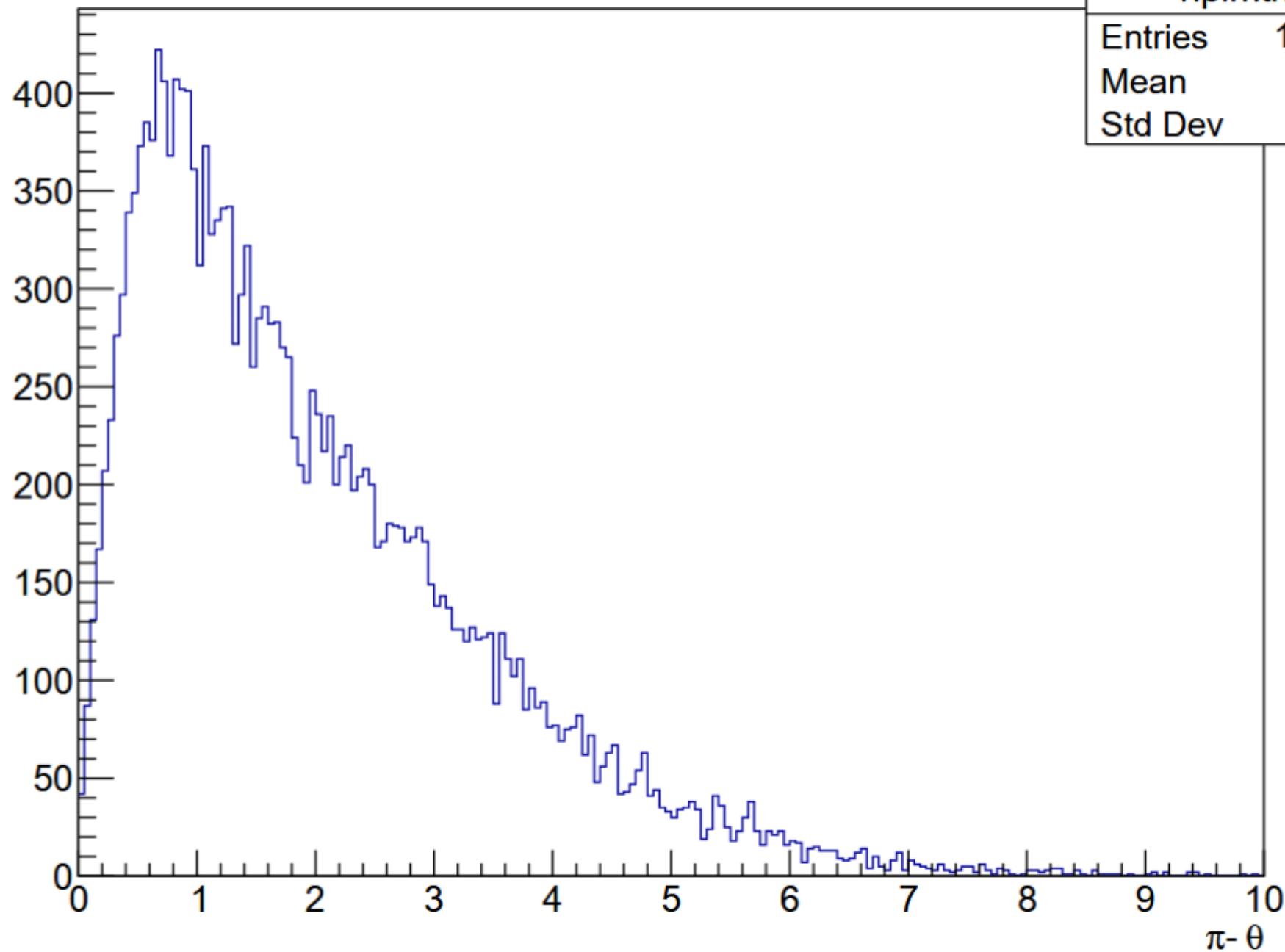


25 65

$\pi - \theta$ 

hpimth

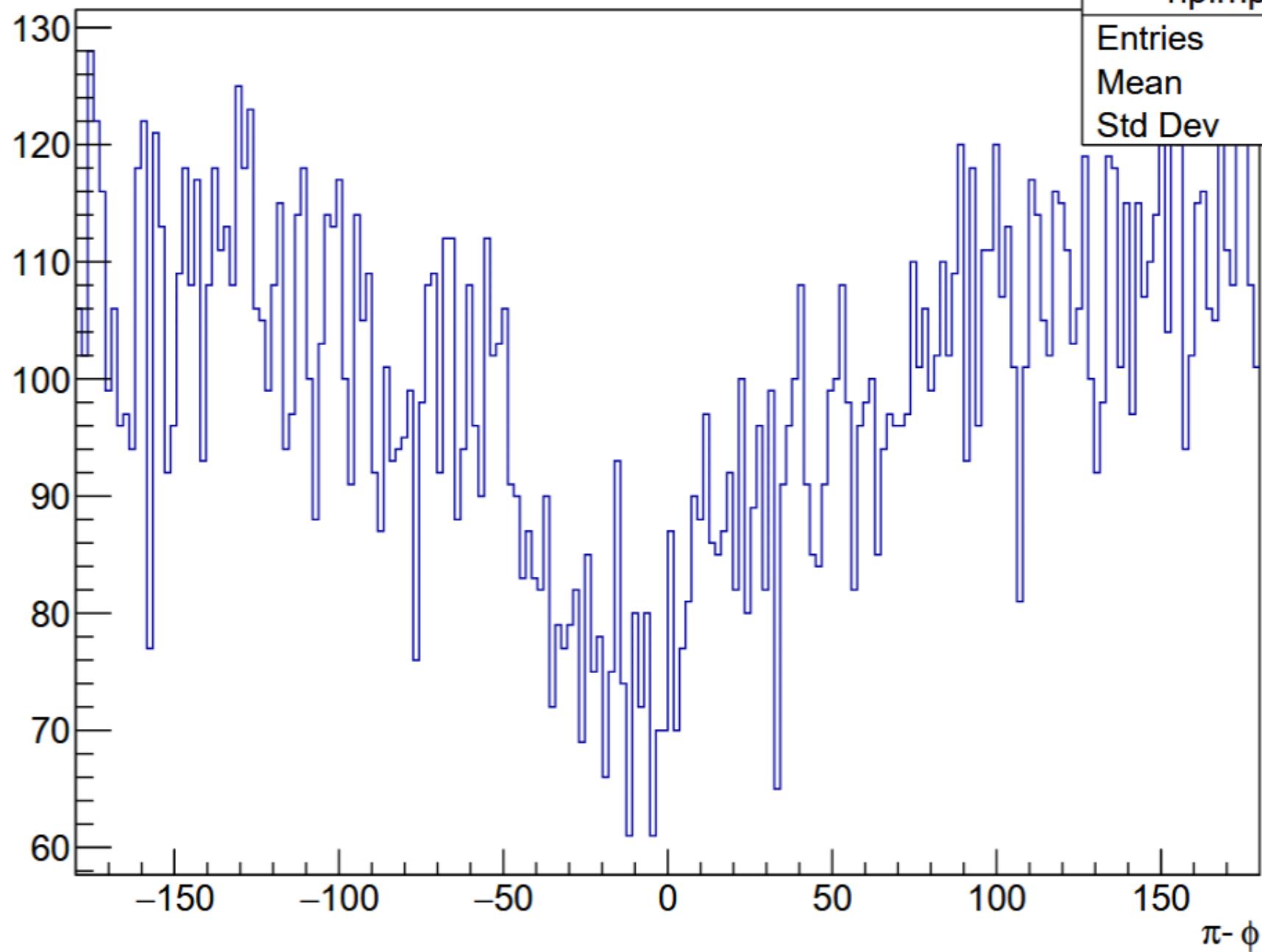
Entries	19892
Mean	1.991
Std Dev	1.454



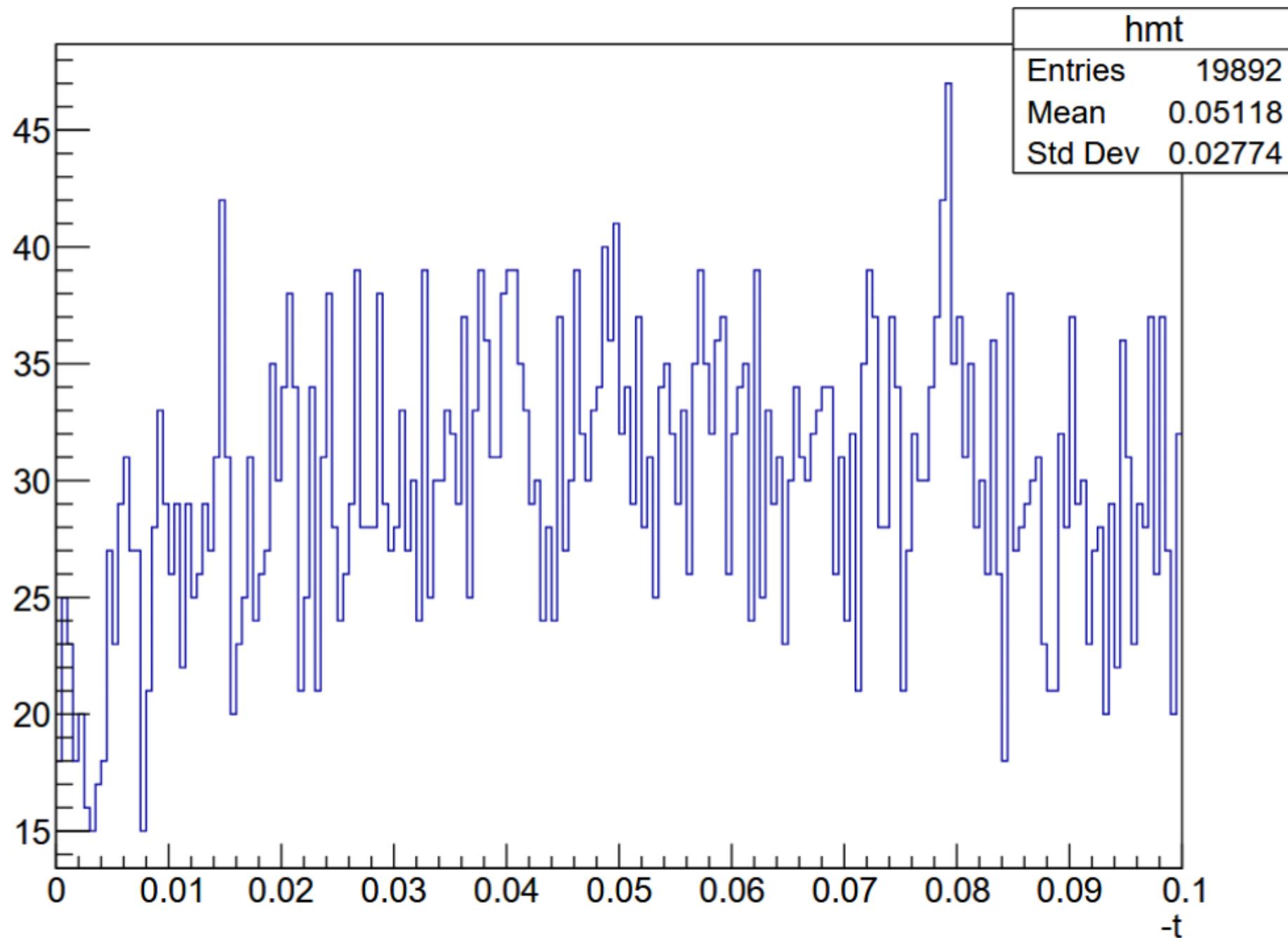
$\pi^- \phi$ 

hpimphi

Entries	19892
Mean	1.107
Std Dev	108



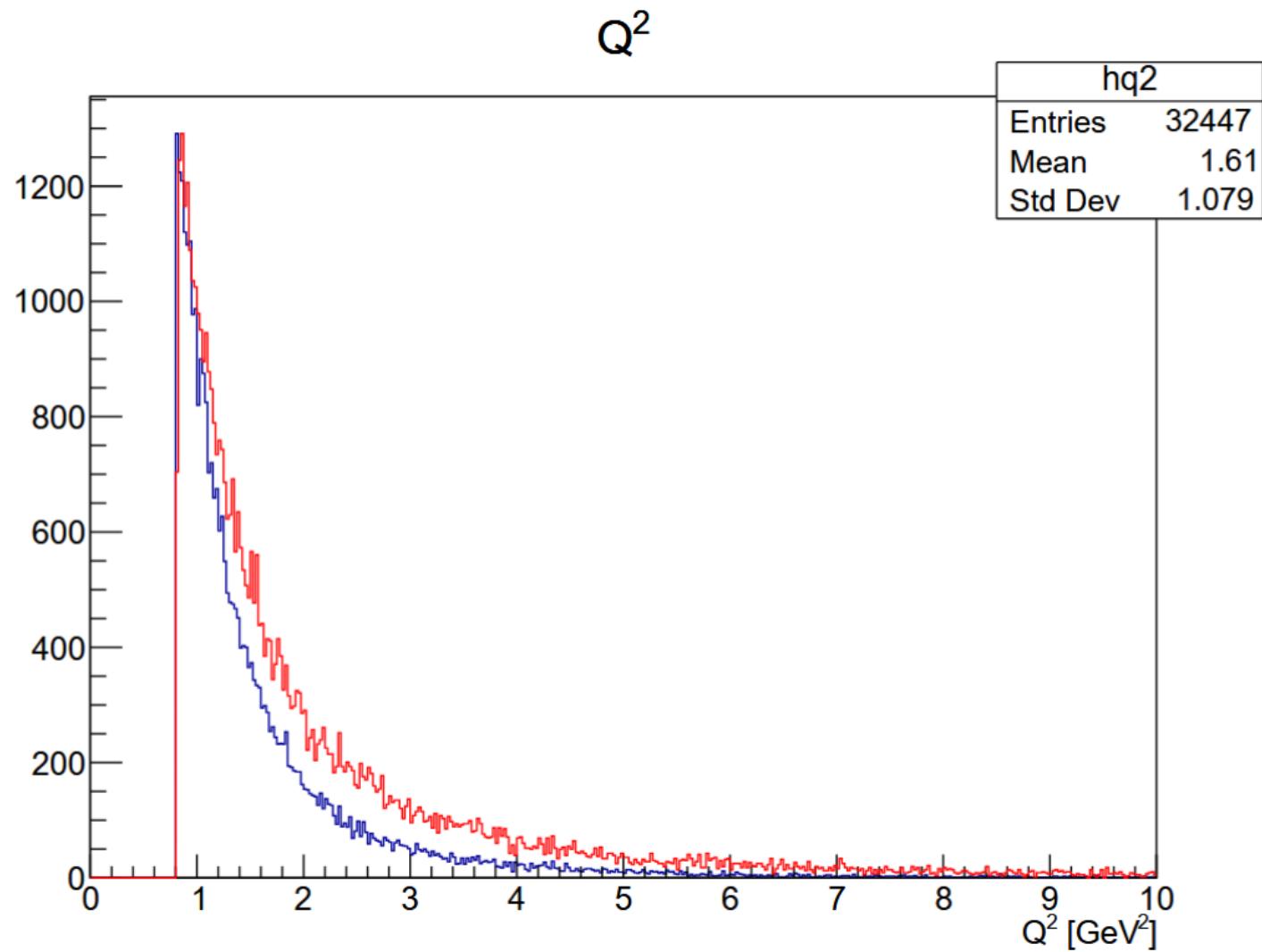
-t



---

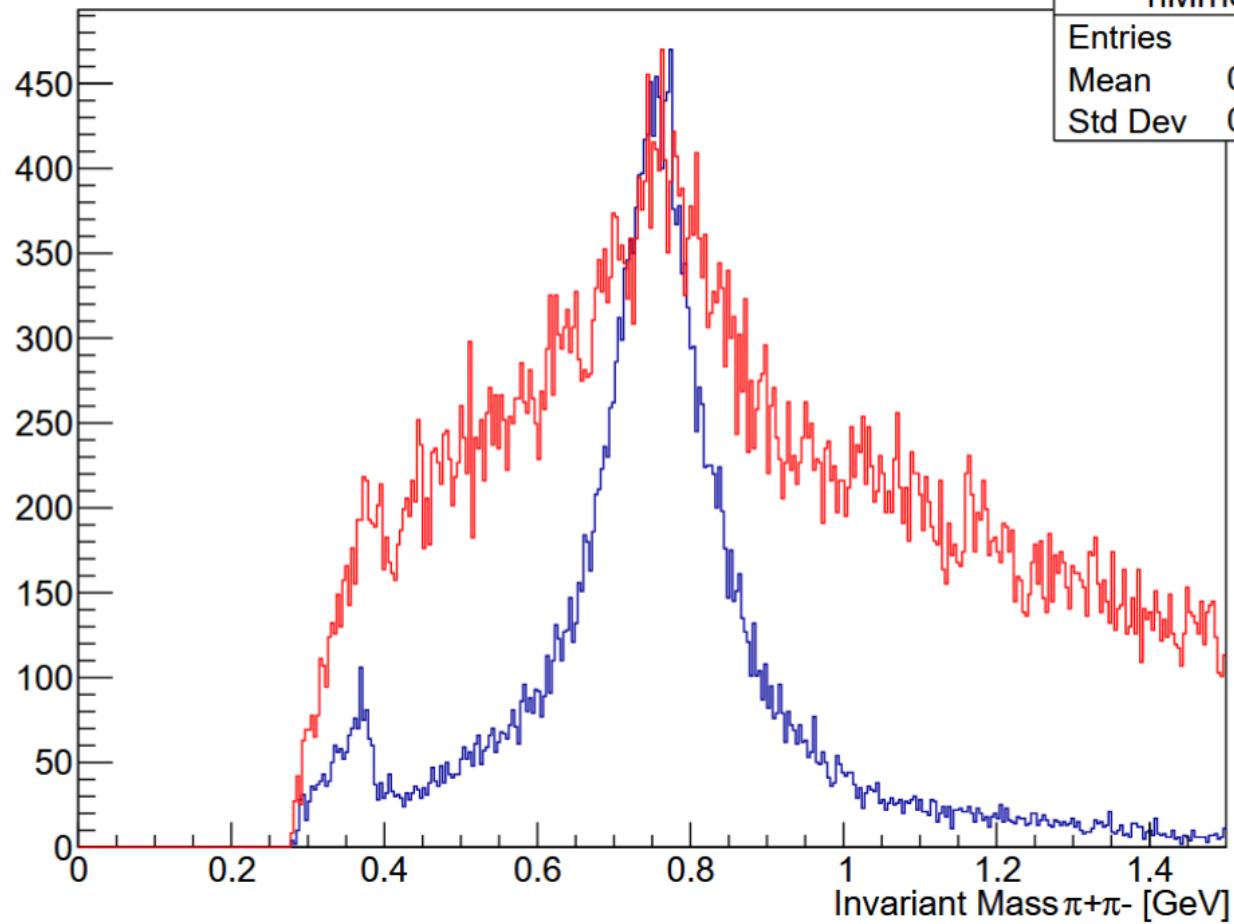
## DATA VS MONTE CARLO ( NONWEIGHTED LEPTO)

---



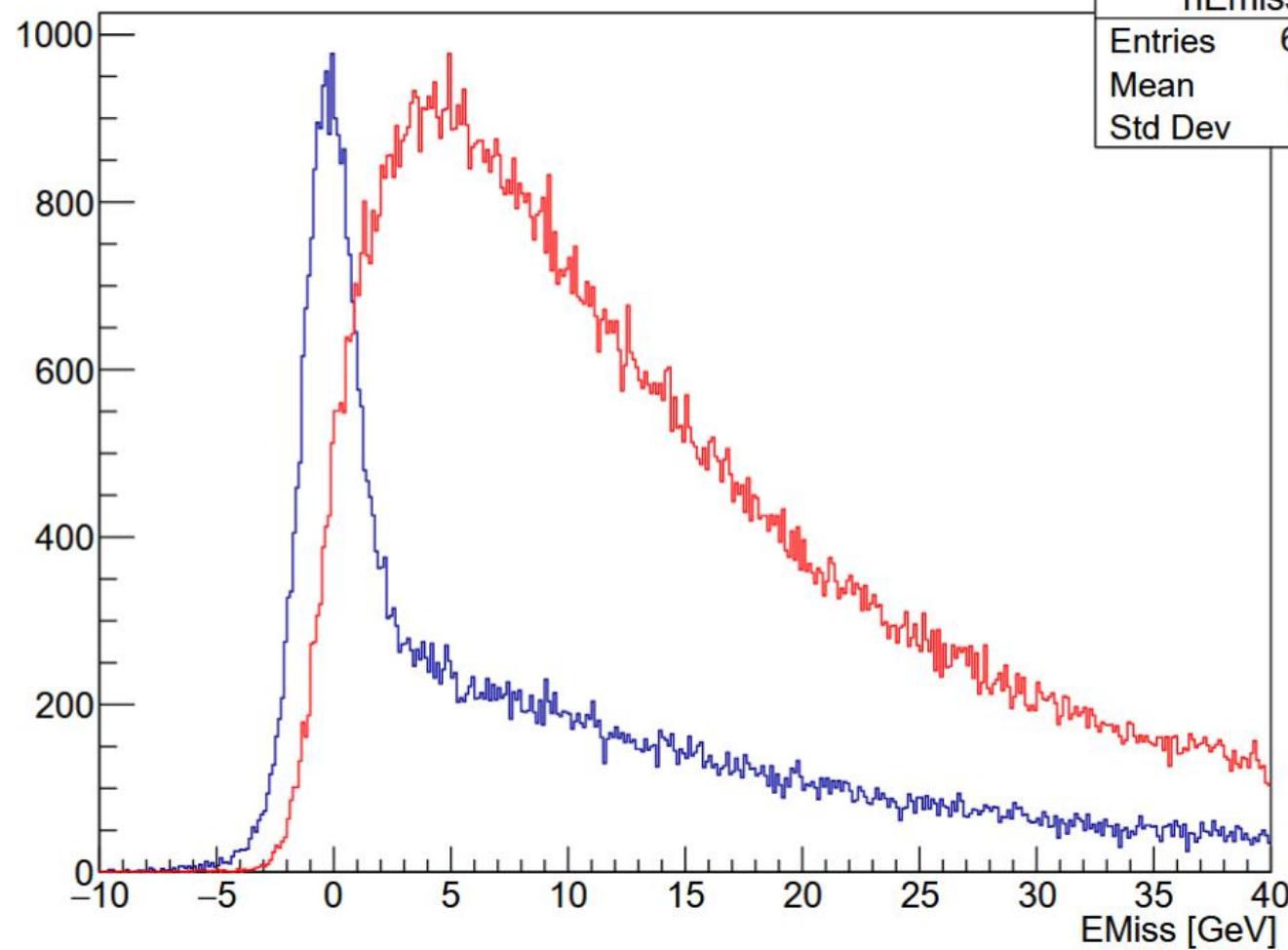
$M(\pi^+\pi^-)$

hMrho	
Entries	28007
Mean	0.7548
Std Dev	0.1928



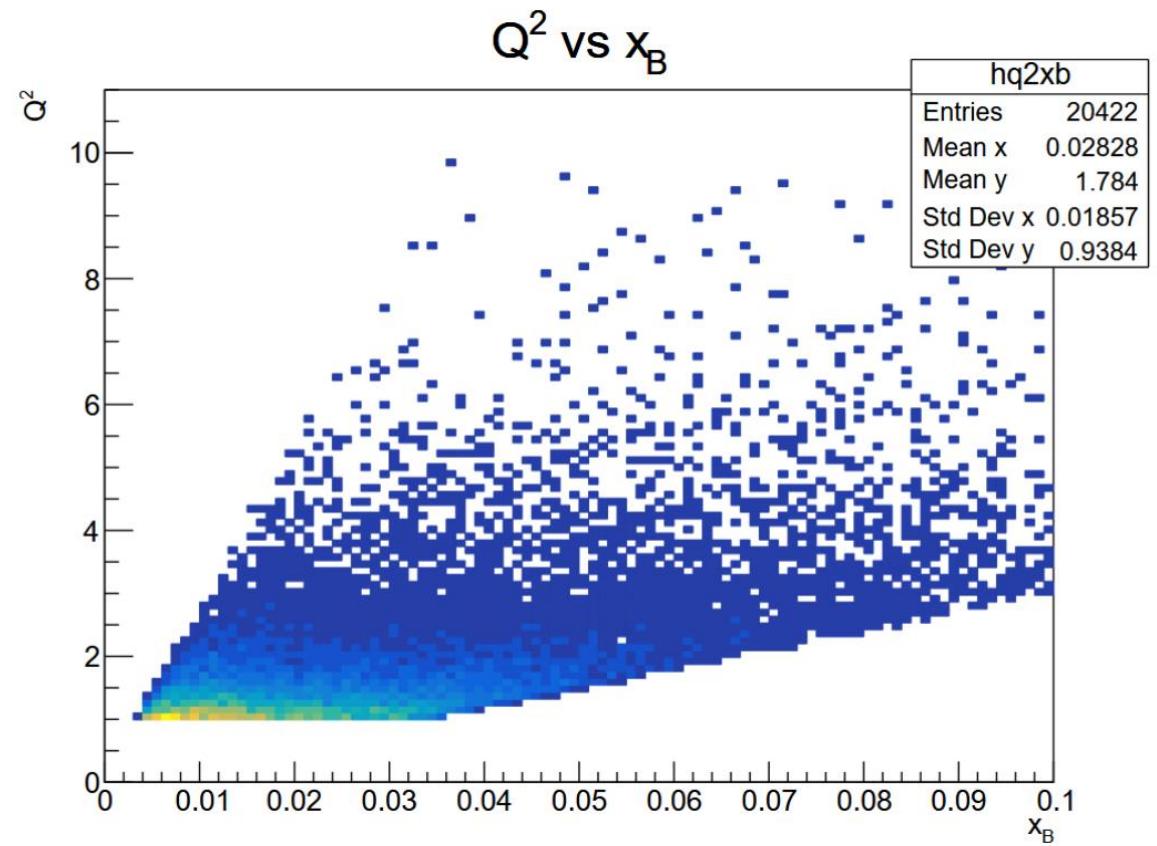
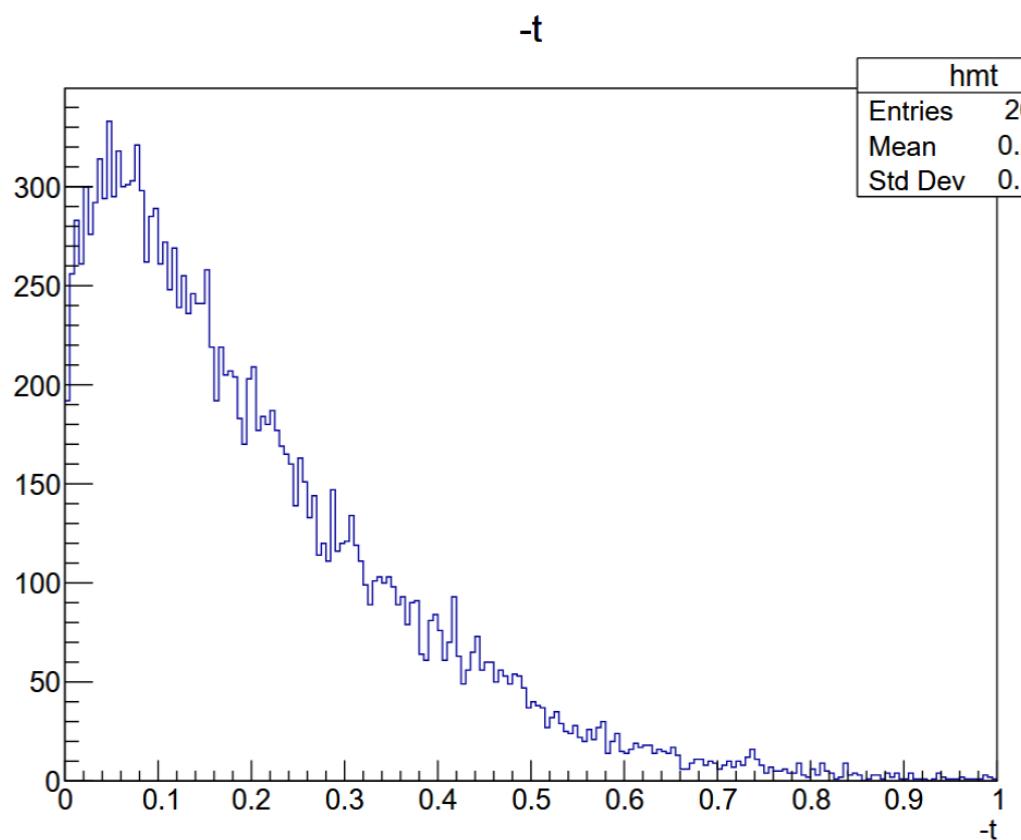
## EMiss

hEmiss	
Entries	67399
Mean	9.149
Std Dev	10.88



## Q2 for just P09

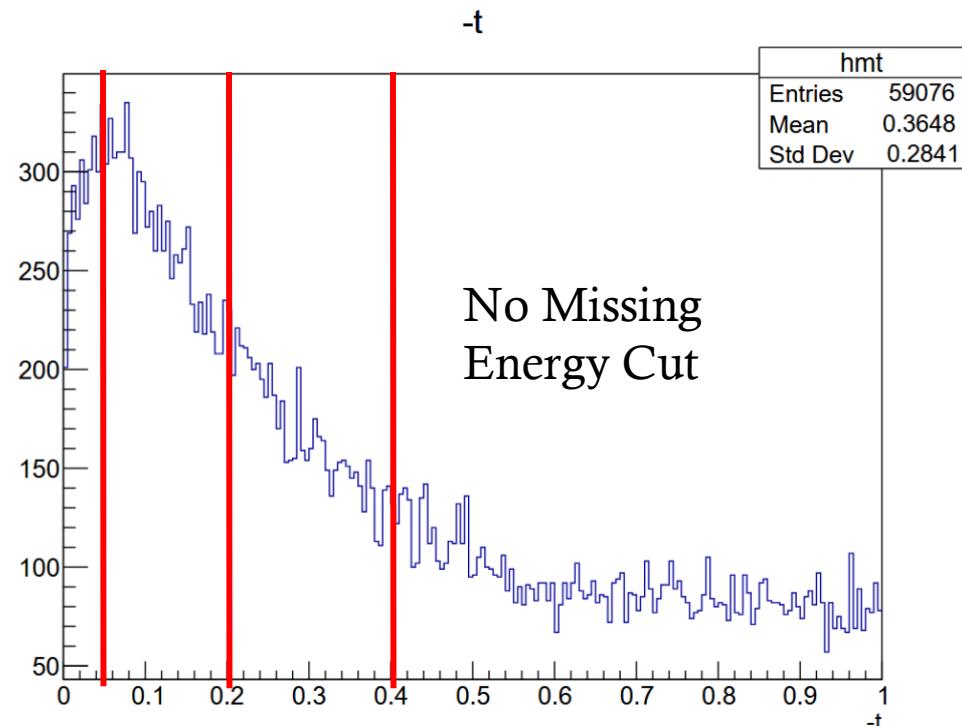
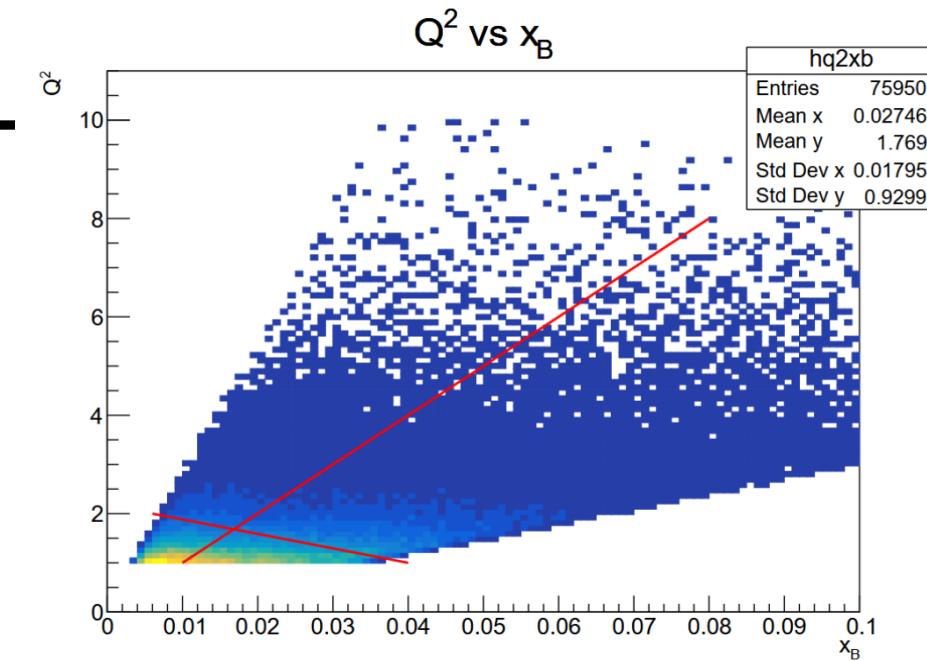
---



# Binning for Background Subtraction

---

1. Overall Goal is 3D binning  $\{Q^2, x_B, -t\}$ 
  - o  $Q^2$   $x_B$  bin not final
2. 1D which can be done with P09 data
  - o Bin in  $-t$
  - o Once this is setup, 3D bin can be done quickly



# EMiss per $-t$ bin

