CLAS12 Charged Two-Pion Electroproduction Off the Proton

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Overview

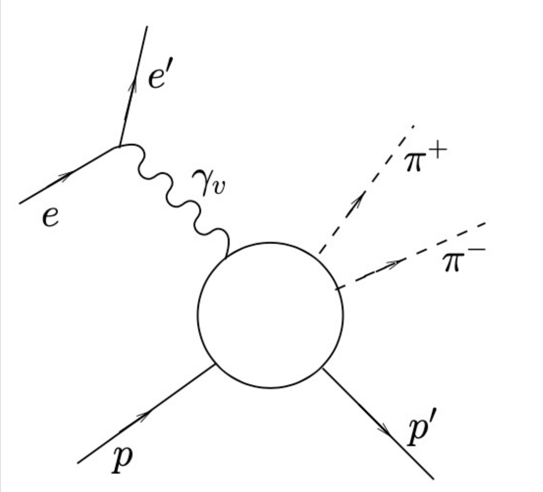
- **Goal :** Exclusive two-pion channel electroproduction cross-sections extraction in resonance region with Q^2 range (1.5-10.5) $(GeV/c)^2$
- **Data :**

  EXP: Run Group A, Fall2018 data with inbending configuration (using FD and CD particles)

  Sim: TWOPEG event generator is used (available on Jlab's OSG portal**)**
- **Physics Analysis and Methods**
- **Preliminary Results**
- **Conclusions**

Physics Analysis: Two-Pion Channel Cross-Section

- **Particle Identification:**
  - Electron pid cuts ✅
  - Hadron pid cuts ✅
- **Event Selection** ✅
- **Cross-Section Calculations** (In progress)
- **Corrections**
  - **-** Energy loss, Momentum, ΔP ✅
  - Detector Efficiency from Experimental Data ☑️
  - Smearing of MC Data ☑️
- **Holes Filling** ✅
- **Background Subtraction** ✅
- Bin Centering Corrections, Error Analysis (Systematic Uncertainties) ❌
- Pass2 Data Analysis ☒



ep-->e'p' $\pi^+\pi^-$

Exp. Data: - Using Run Group A, Fall2018 data with inbending configuration (pass1), runs same as ongoing Inclusive analysis

- The beam energy is 10.6041 GeV
- 1.3 GeV/c < W< 2.5 GeV/c & 1.5 $GeV^2/c^2 < Q^2 < 10.5\ GeV^2/c^2$

Simulations: - TWOPEG event generator is used (gemc 4.4.2, coatjava 6.5.6.1) (pass1)

Particle Identification

Electron pid cuts:

- Electron must have negative charge -1
- Event-builder electron pid cut
- Momentum of electron > 1.5 GeV
- The electron is detected in forward detector
- Chi-square pid cut
- EC outer vs EC inner Cut
- CC Number of Photoelectron Cut
- Z component of the vertex position cut around target
- 3.5 sigma cut on Sampling Fraction
- Preshower calorimeter fiducial cuts:

  (triangular and inner circular)
- Drift chambers fiducial cuts:

  (triangular and inner circular)
- 1.3 GeV < W < 2.5 GeV
- 1.5 GeV^2 < Q^2 < 10.5 GeV^2

Hadron pid cuts:

- Event-builder pid cuts for proton, π^+ and π^-
- Delta t cuts for proton, pip and pim

$$\Delta t = \frac{l_{SC}}{\beta . c} - t_{SC} + vertex\ time$$

where, $\beta = \sqrt{\frac{p^2}{m^2+p^2}}$,

$vertex\ time = t^e_{SC} - \frac{l^e_{SC}}{c}$,

l_{SC}, l^e_{SC} are length of path from vertex to SC for hadron, electron,

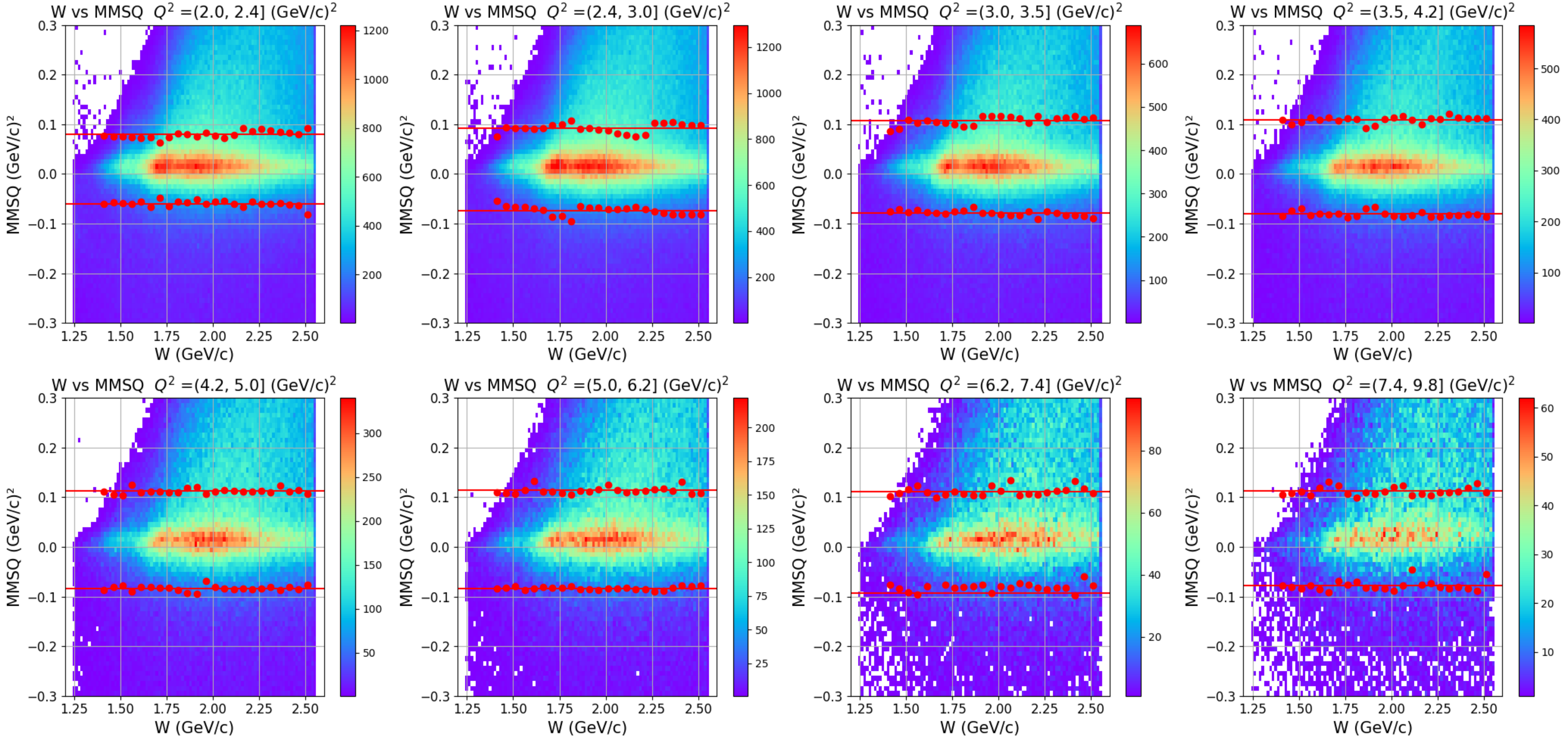
t_{SC}, t^e_{SC} are time measured by SC for hadron, electron,

c is the speed of light.

- Momentum of FTOF particle > 0.4 GeV
- Momentum of CTOF particle > 0.2 GeV
- Chi-Square pid cuts
- Difference between vertex position of hadron and electron cut
- DC Fiducial cuts

Two-Pion Events Selection: MMSQ Cuts on Experimental Data

We use Missing Pim topology out of 4 different topologies in this reaction Channel: e(p,p′π⁺X)e′ (Missing π⁻):



Two-Pion Events Selection: MMSQ Cuts on MC Data

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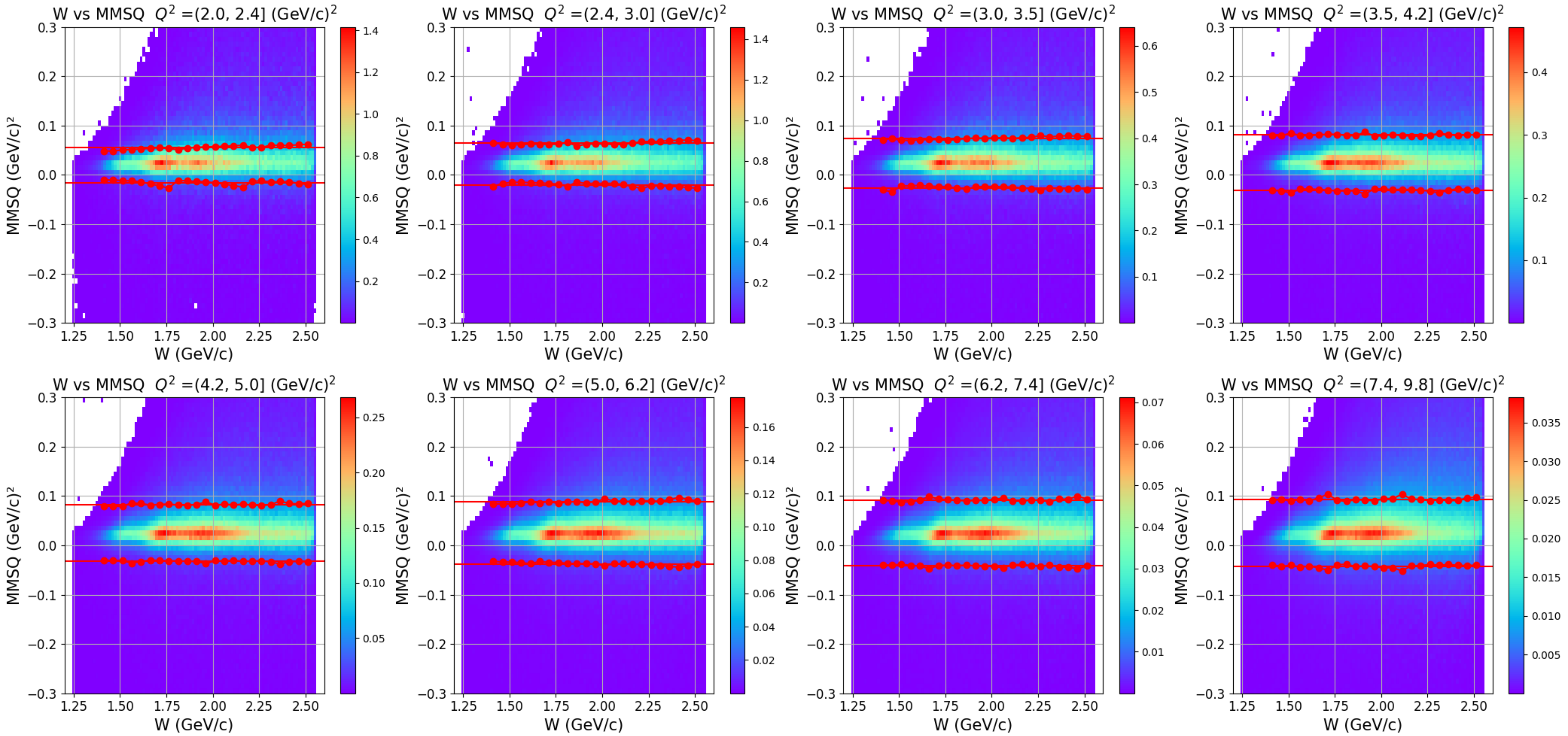
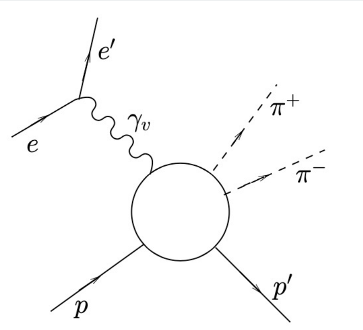


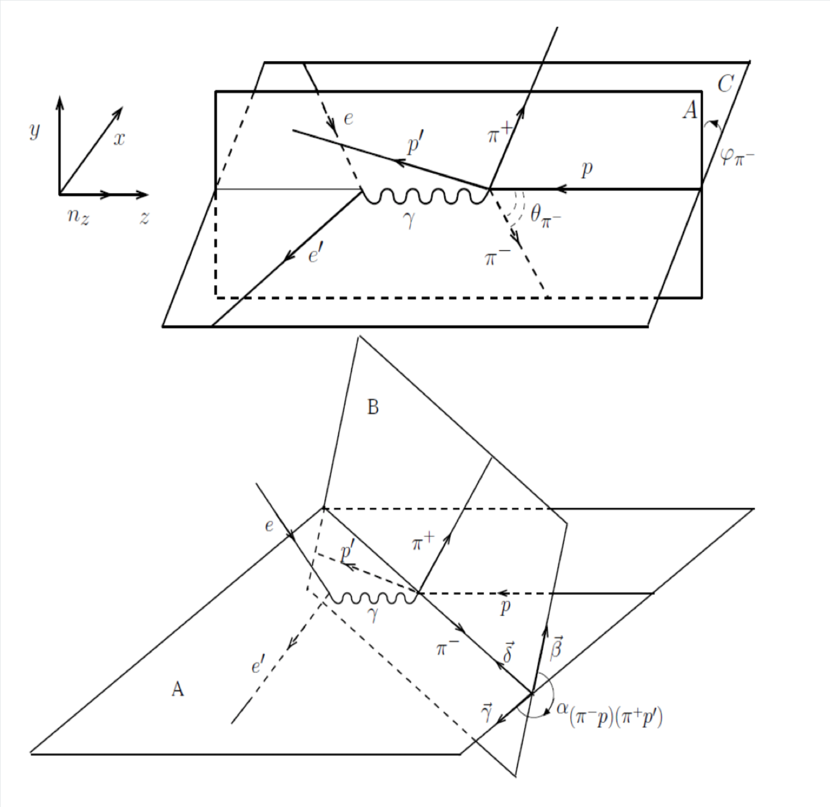
Two-Pion Channel Cross-Section Extraction

Electron scattering Cross-Section:

$$\frac{d^7\sigma}{dW\,dQ^2\,dM_{P\pi+}\,dM_{\pi+\pi-}\,d\Omega\,d\alpha_{\pi-}} = \frac{1}{A.E.R}\,\frac{\left(\frac{\Delta N_{full}}{Q_{full}} - \frac{\Delta N_{empty}}{Q_{empty}}\right)}{\Delta W\,\Delta Q^2\,\Delta\tau\,L}$$

Where:
ΔN, Q are no of two-pion events inside 7-differential bin and charge on faraday cup with full an empty target, A, E, R are correction factors, ΔW, ΔQ^2 are kinematical bins, L is luminosity,
$\Delta\tau = \Delta M_{p\pi+}\Delta M_{\pi+\pi-}\Delta(-\cos(\theta_{\pi-}))\Delta\varphi_{\pi-}\Delta\alpha_{\pi-}$ is an element of the hadronic 5-dimensional phase space





1) $M_{\pi-\pi+}$, $M_{\pi+p'}$, $\theta_{\pi-}$, $\varphi_{\pi-}$ and $\alpha_{(p\pi-)(p'\pi+)}$ (ie. $\alpha_{\pi-}$) [π−, π+, p′]

2) $M_{p'\pi+}$, $M_{\pi+\pi-}$, $\theta_{p'}$, $\varphi_{p'}$ and $\alpha_{(pp')(\pi+\pi-)}$ (ie. $\alpha_{p'}$) [p′, π−, π+]

3) $M_{\pi+\pi-}$, $M_{\pi-p'}$, $\theta_{\pi+}$, $\varphi_{\pi+}$ and $\alpha_{(p\pi+)(p'\pi-)}$ (ie. $\alpha_{\pi+}$) [π−, π+, p′]

Binning:
- 24 W bins
- 8 Q^2 bins
- 6 invariant mass bins
- 10 θ bins
- 6 φ bins
- 8 α bins
- Total: 24 * 8 * 6 * 6 * 10 * 6 * 8 = 3,317,760

Two-Pion Channel Cross-Section Extraction

Electron Scattering Cross-Section:

$$\frac{d^7\sigma_e}{dW\,dQ^2\,dM_{P\pi+}\,dM_{\pi+\pi-}\,d\Omega\,d\alpha_{\pi-}} = \frac{1}{A.E.R}\,\frac{\left(\frac{\Delta N_{full}}{Q_{full}} - \frac{\Delta N_{empty}}{Q_{empty}}\right)}{\Delta W\,\Delta Q^2\,\Delta\tau\,L}$$

Hadronic Cross-Section:

$$\frac{d^5\sigma_v}{dM_{P\pi+}\,dM_{\pi+\pi-}\,d\Omega\,d\alpha_{\pi-}} = \frac{1}{\Gamma_v}\,\frac{d^7\sigma_e}{dW\,dQ^2\,d^5\tau}$$

$Q^2 = -q^\mu q_\mu$

Single Differential Cross-Section:

$$\frac{d\sigma_v}{dM_{\pi+\pi-}} = \int \frac{d^5\sigma_v}{dM_{P\pi+}\,dM_{\pi+\pi-}\,d\Omega\,d\alpha_{\pi-}}\,dM_{P\pi+}\,d\Omega\,d\alpha_{\pi-}$$

Q_{full}= 0.0251 C , Q_{empty}= 0.0024075 C

ΔW = 0.0025 GeV

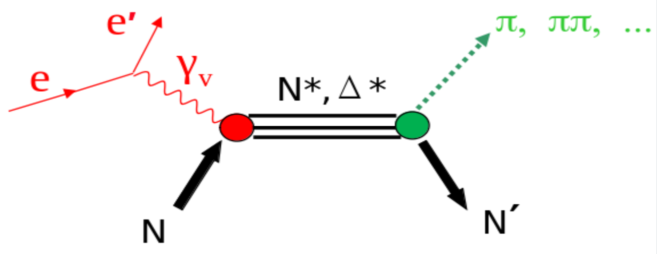
ΔQ^2 = 0.5 GeV^2 for bin 3.0-3.5 GeV^2

1/L =1/($\frac{l\,\rho\,NA}{q_e\,MH}$) = 0.755314965e−12 µb C

R = Radiative Correction Factor

Γ_v = Virtual Photon Flux

A = Acceptance from Simulated data



In Progress

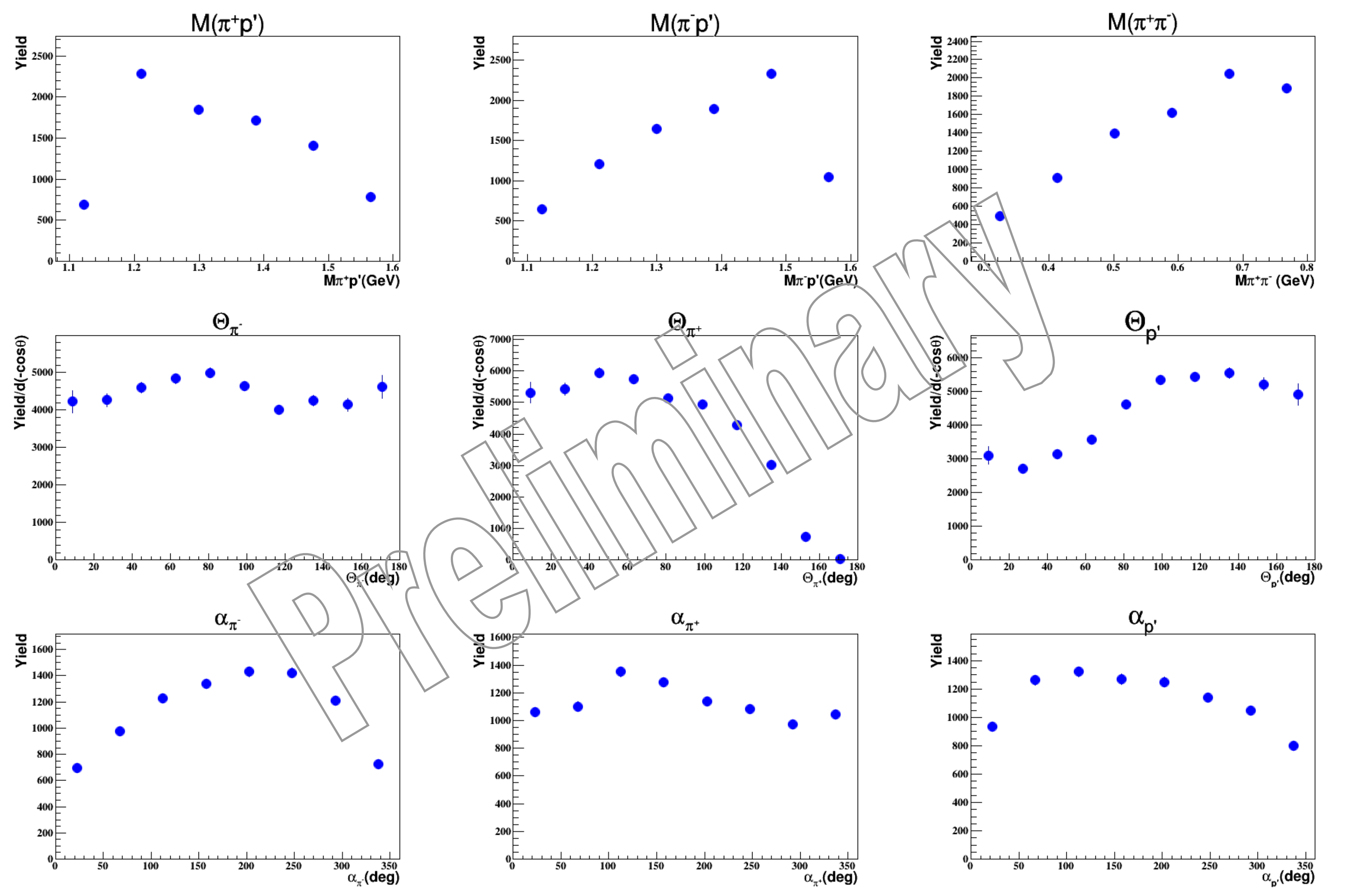
Corrections: Energy loss, Momentum, Background (Implemented)

E = Single Particle Efficiency Correction Factors (In progress)

In Future: Bin centering corrections, Error Analysis, Pass2..

Nine 1-Differential Experimental Yields

Using four vectors of the particles survived after all the cuts and event selection process



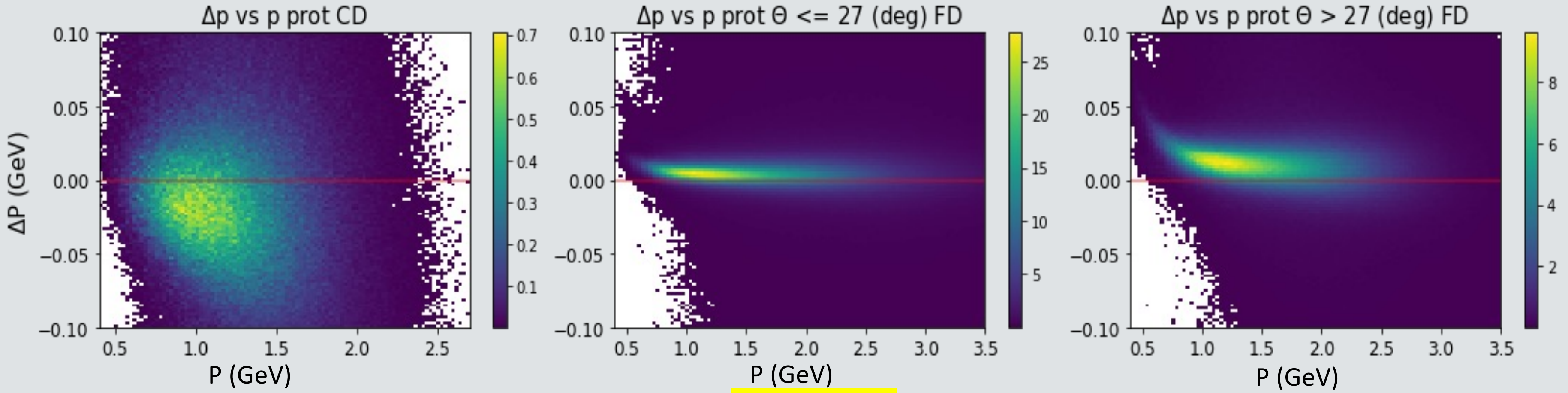
These 9 are most useful variables for extraction of reaction amplitudes in JM Model developed by V.I. Mokeev

W-Q^2 bin for these yields: 1.75 GeV < W < 1.80 GeV, 4.2 GeV^2 < Q^2 < 5.0 GeV^2

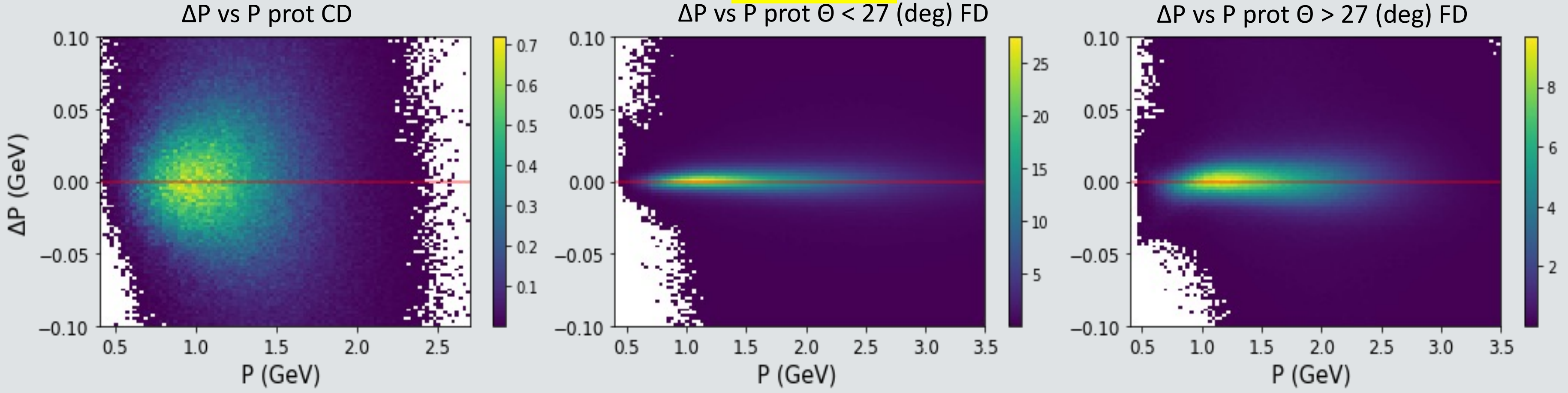
Corrections

Energy loss correction for proton : Using MC data: separate for FD/CD and binning in theta and momentum, polynomial fit in both momentum and theta

Uncorrected



Corrected



- Energy loss corrections are applied for pip and pim as well
- Energy loss corrections are up to 5.80%

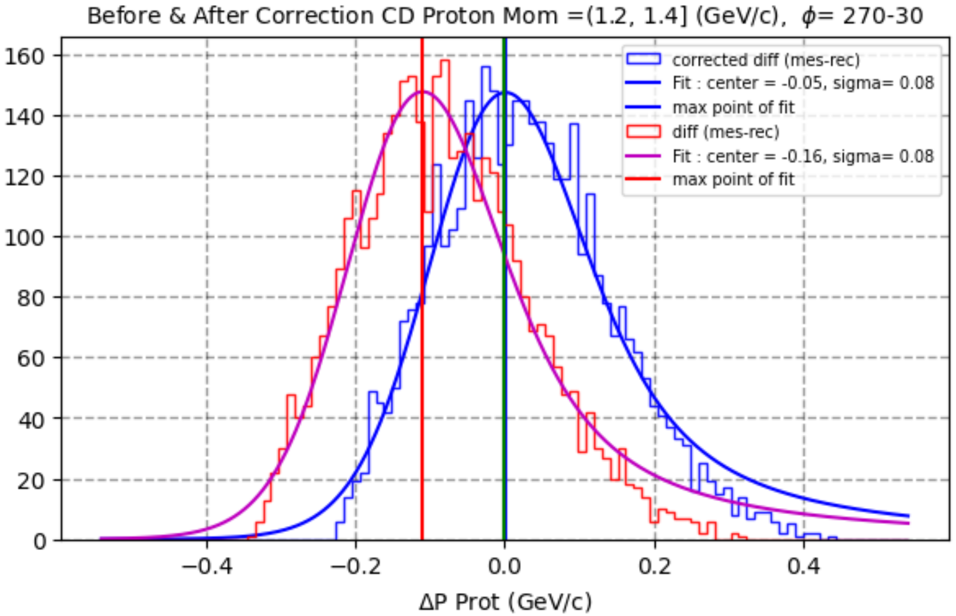
We apply the momentum corrections provided by the momentum correction task force : https://clasweb.jlab.org/wiki/index.php/CLAS12_Momentum_Corrections#tab=Correction_Code

ΔP corrections: CD Proton

Procedure:

- We take TwoPion events with background subtracted

- We calculate ΔP the difference between reconstructed (measured) and reconstructed (missing) particle momentum in different bins based on momentum , phi and FD/CD



Note: Similar corrections are applied for all three hadrons (FD/CD)

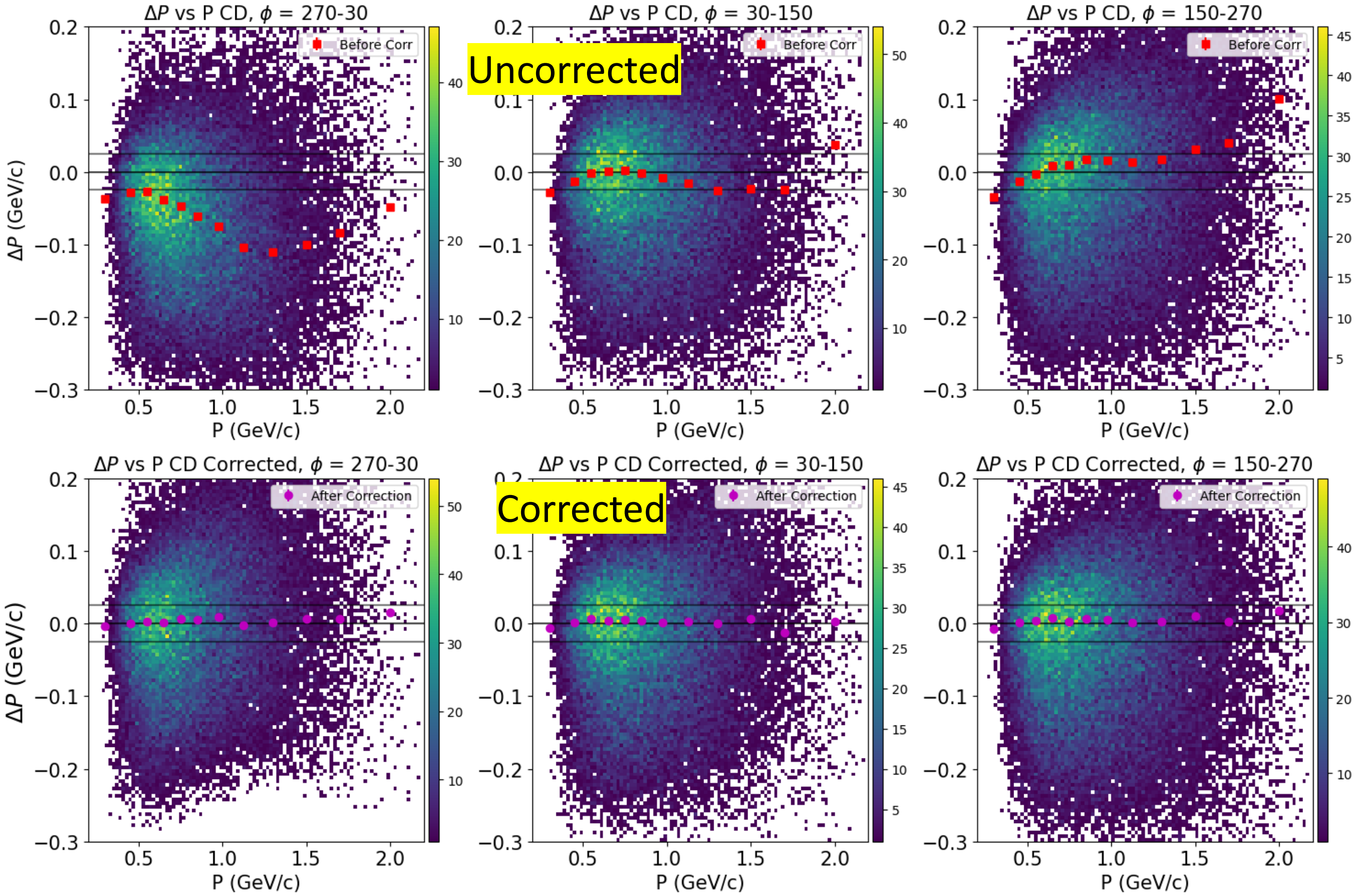
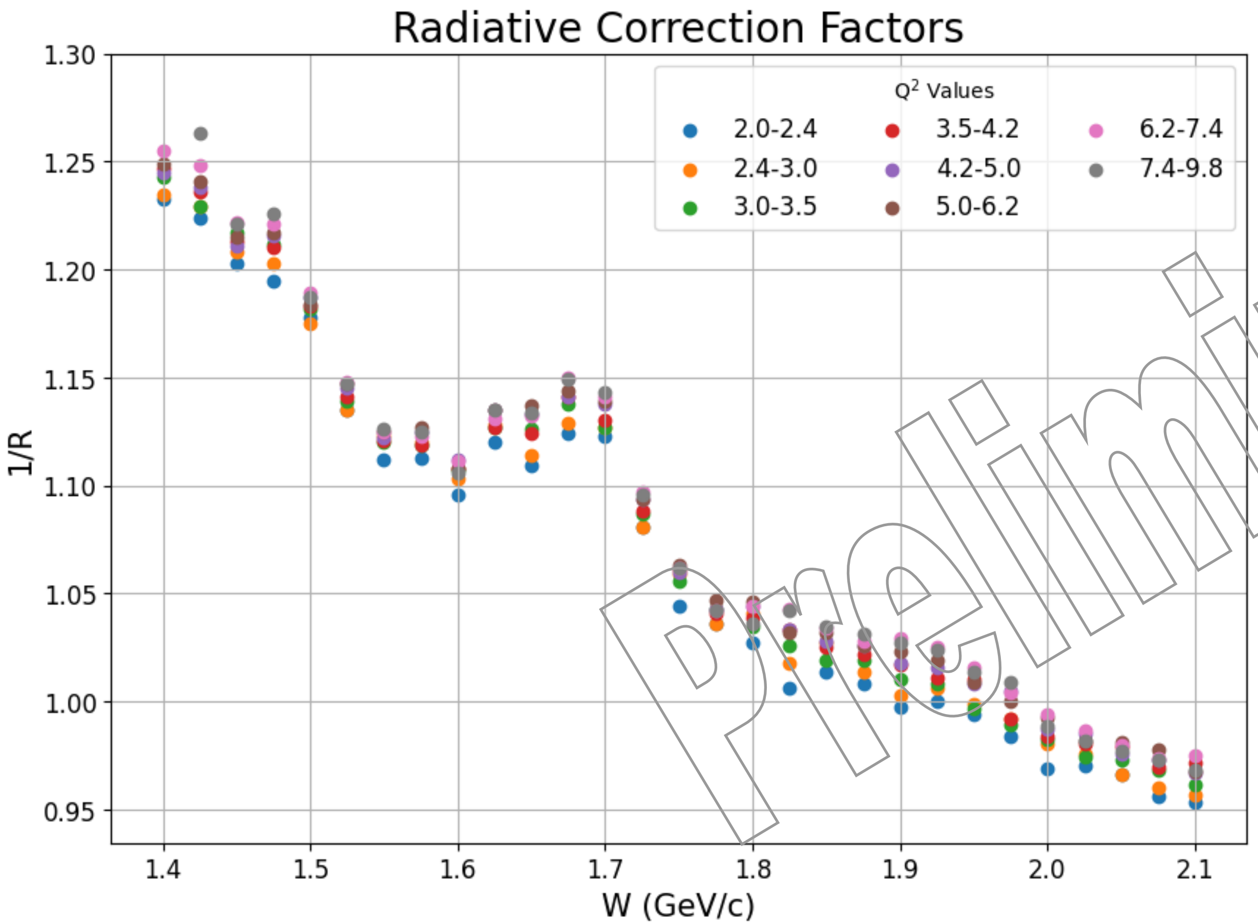
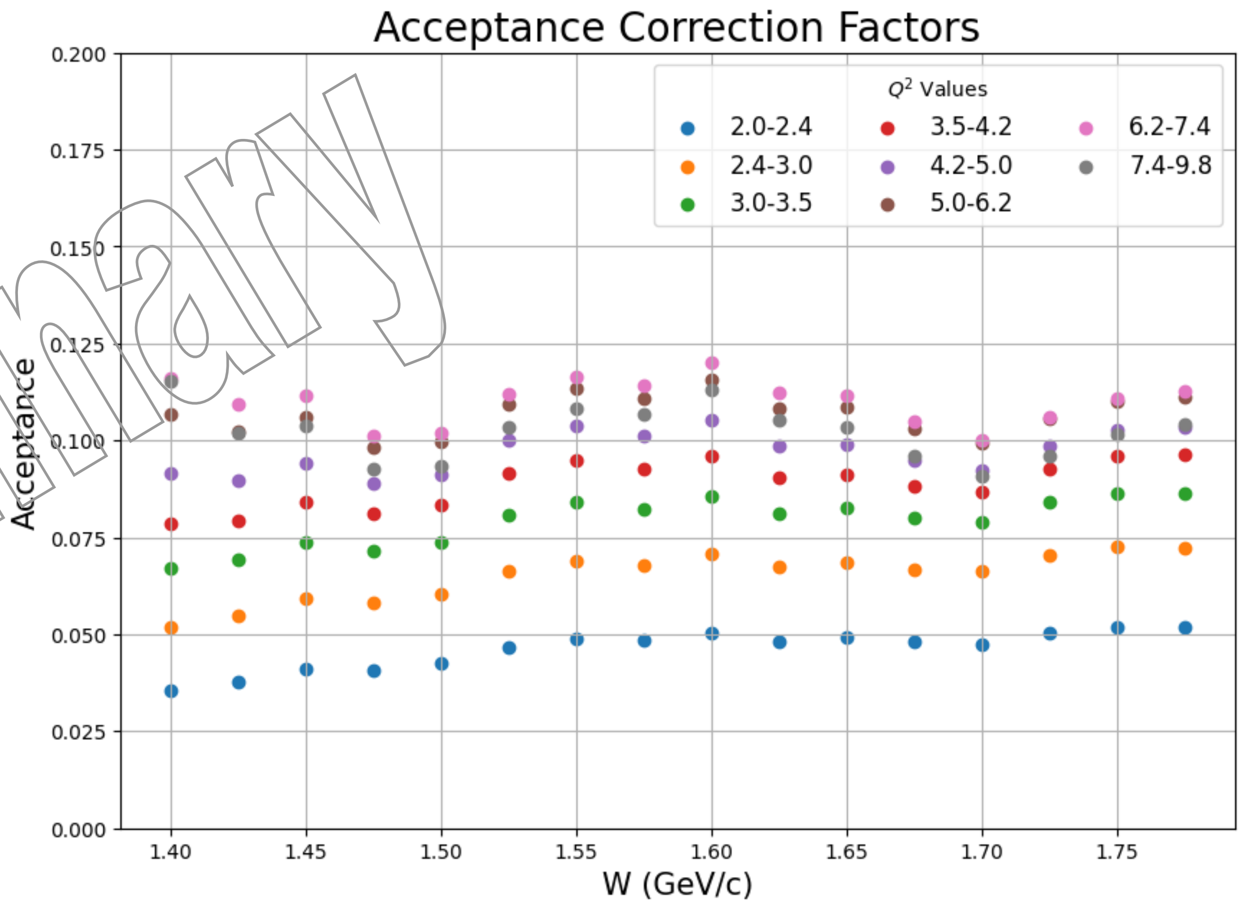


Fig: ΔP vs P for CD protons

Radiative and Acceptance Correction Factors from MC Data



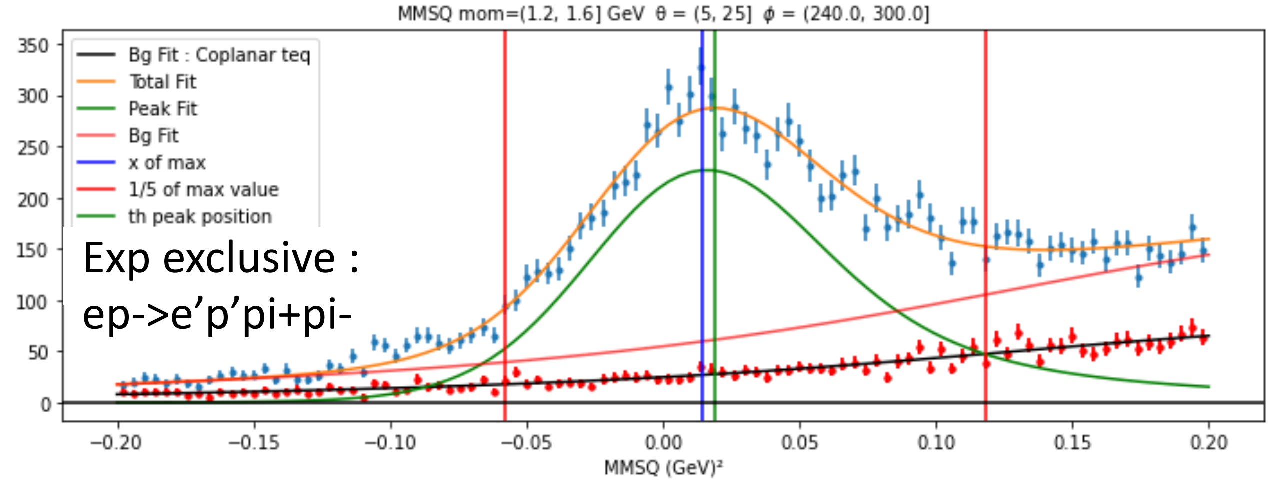


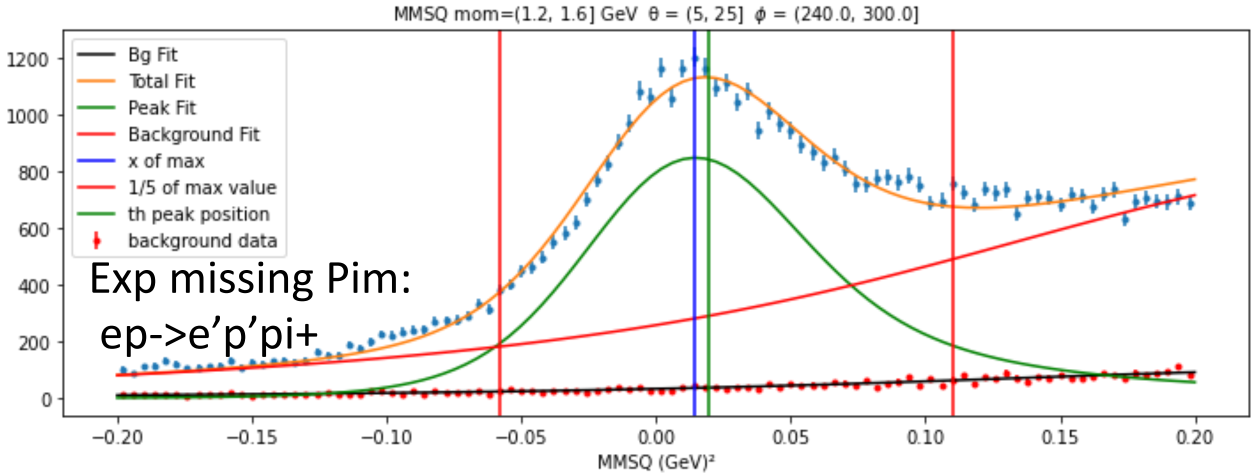
Single Particle Efficiency Correction Factors: Pim

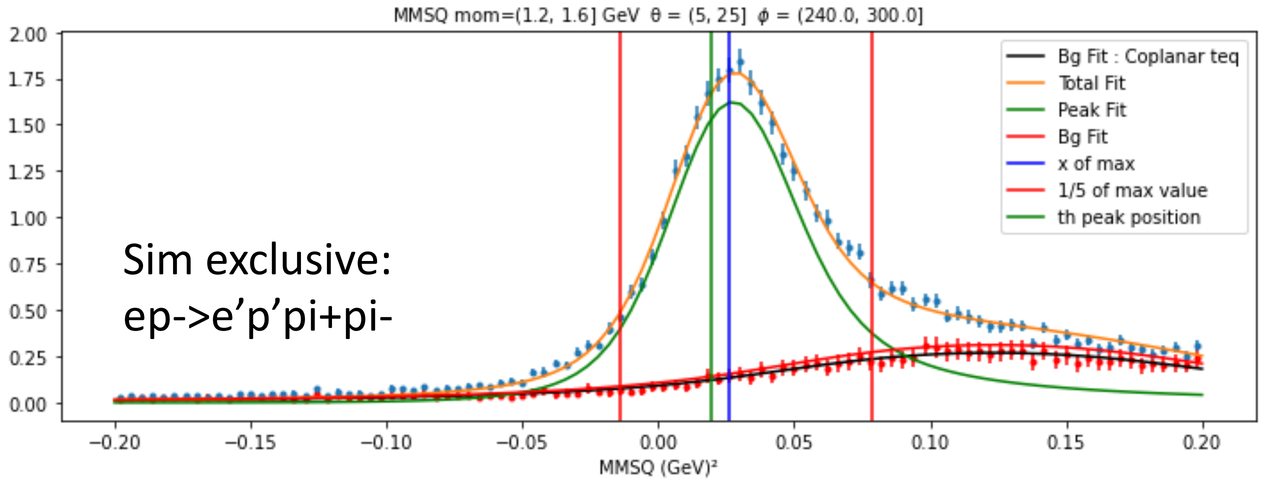
For each 3-D (momentum, theta, phi) bins, we take integral of background subtracted signals and take:

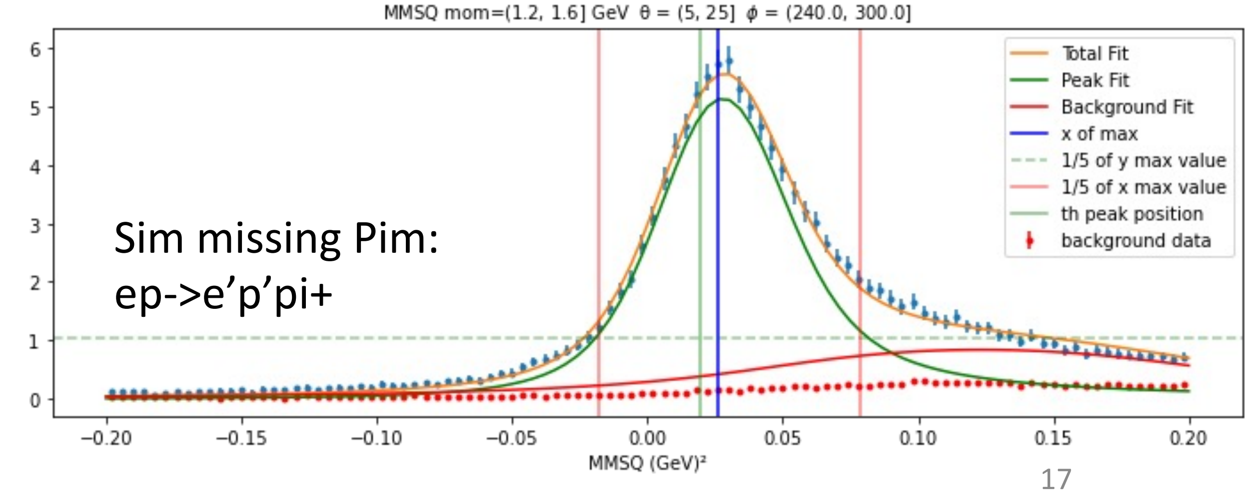
Theta: [5-25]
Mom: [0.6, 1.2, 1.6, 1.9, 2.2, 2.5, 3.0 , 5.0]
Phi : [0, 60, 120, 180, 240, 300, 360]

$$ratio = \frac{exclusive\ pim}{missing\ pim} \quad \Rightarrow \quad efficiency\ \ factor = \frac{sim\_ratio}{exp\_ratio}$$

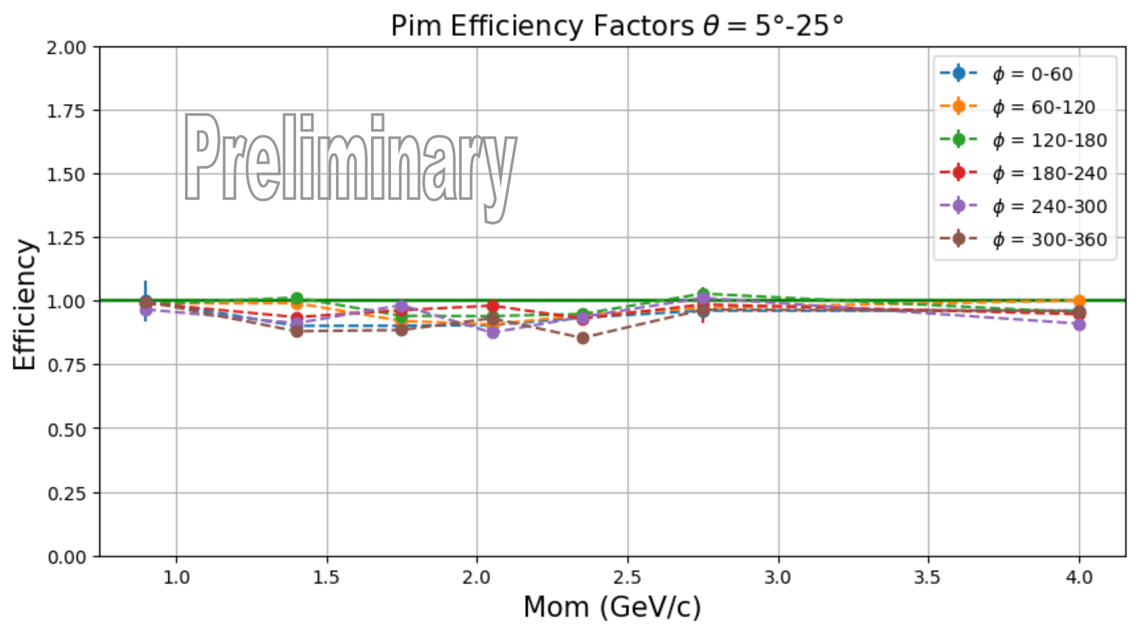


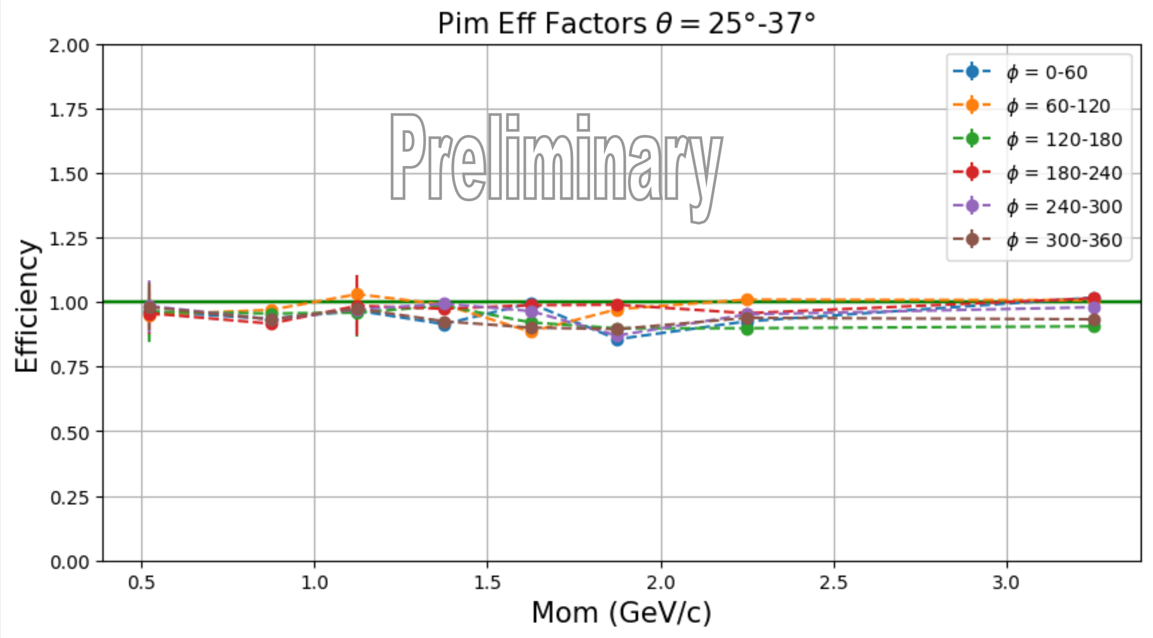


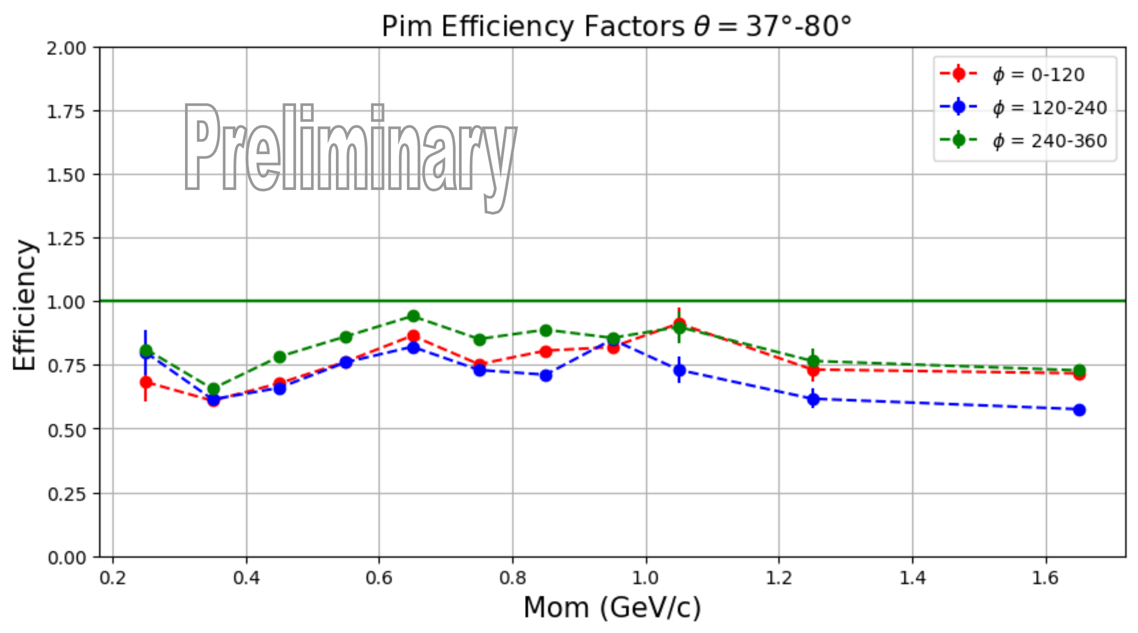


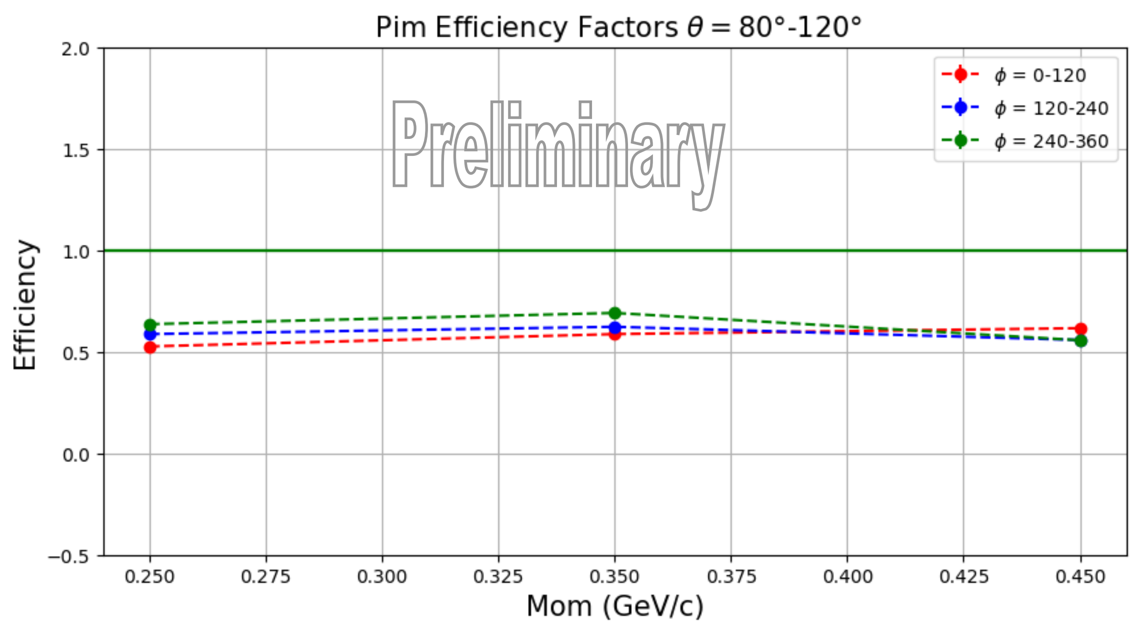


Single Particle Efficiency Correction Factors : Pim









Smearing MC Data to Match Resolutions

6.2 Matching the experimental resolution

Realistic resolutions have been implemented for the momentum, θ and ϕ of the reconstructed electrons and pions to match the experimental resolutions. The applied resolution functions, which were provided by F.X. Girod based on p, θ and ϕ of any charged particle are given by:

$$p_{S1} = 0.0184291 - 0.0110083 \cdot \theta + 0.00227667 \cdot \theta^2 - 0.000140152 \cdot \theta^3 + 3.07424 \cdot 10^{-6} \cdot \theta^4$$

$$p_R = 0.02 * \sqrt{(p_{S1} \cdot p)^2 + (0.02 \cdot \theta)^2}$$

$$\theta_R = 2.5 \cdot \sqrt{((0.004 \cdot \theta + 0.1) \cdot (p^2 + 0.13957 \cdot 0.13957)/(p^2))^2)}$$

$$\phi_{S1} = 0.85 - 0.015 \cdot \theta, \quad \phi_{S2} = 0.17 - 0.003 \cdot \theta$$

$$\phi_R = 3.5 \cdot \sqrt{(\phi_{S1} \cdot \sqrt{p^2 + 0.13957 \cdot 0.13957/(p^2)})^2 + \phi_{S2}^2}$$

$$\phi_{new} = \phi + \phi_R \cdot gRandom \rightarrow Gaus(0,1)$$

$$\theta_{new} = \theta + \theta_R \cdot gRandom \rightarrow Gaus(0,1)$$

$$p_{new} = p + p_R \cdot gRandom \rightarrow Gaus(0,1) \cdot p$$

The functions are valid for the in-bending and out-bending torus field.

https://www.jlab.org/HallB/shifts/admin/paper_reviews/2022/pip_gpd_analysis_note_v3-7074513-2022-03-10-v7.pdf

Smearing MC Data to Match Resolutions

Proton Momentum:

FD : [0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 4.0, 5.0]

CD : [0.4, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.6, 2.2]

Pip Momentum:

FD : [0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 4.0, 5.0]

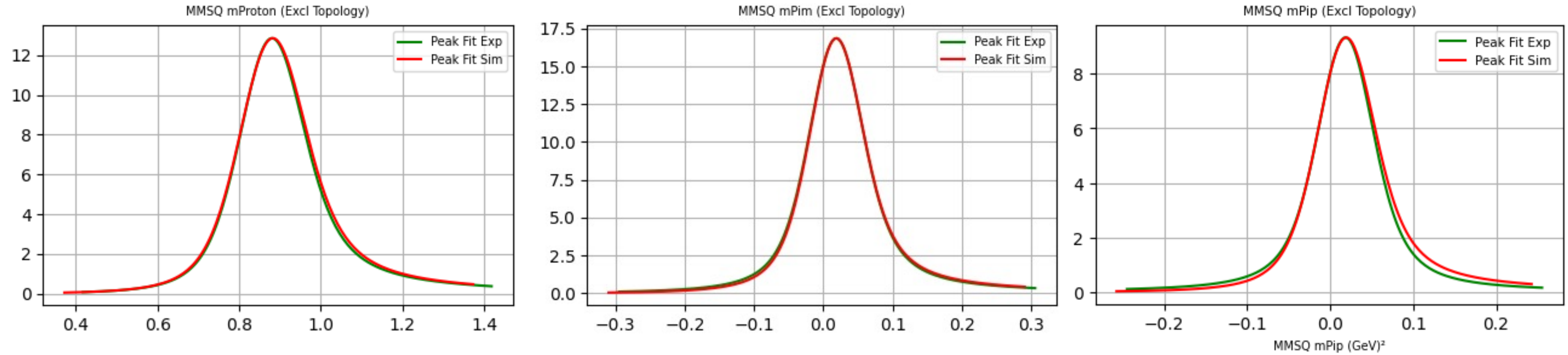
CD : [0.2 , 0.3, 0.4 , 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.7]

Pim Momentum :

FD : [0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 4.0, 5.0]

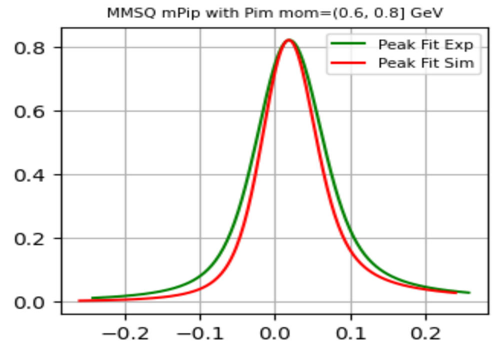
CD : [0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.4, 1.9]

Electron: factor = 0.4 applied (First try was 0.75* FX's function for all 4 particles)



MMSQ Background Subtracted Signal Fits

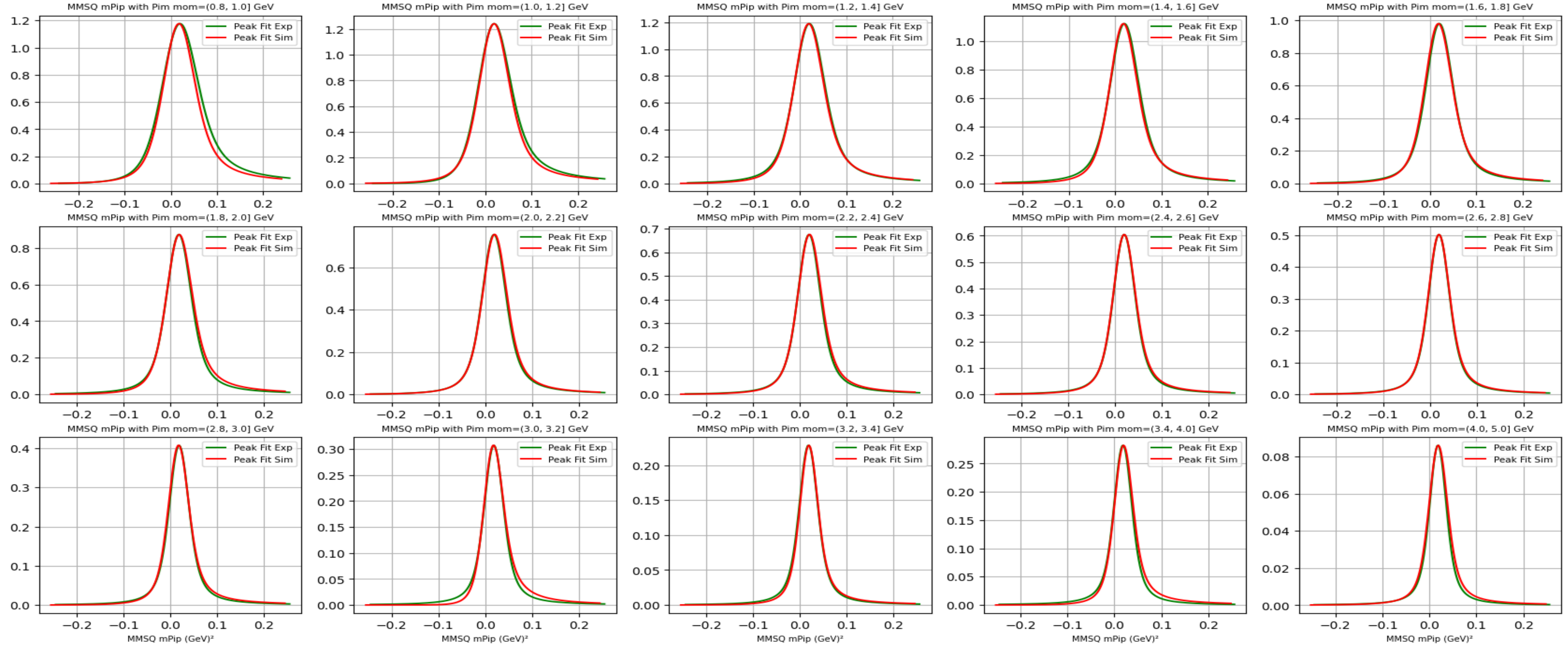
Smearing MC Data to Match Resolutions



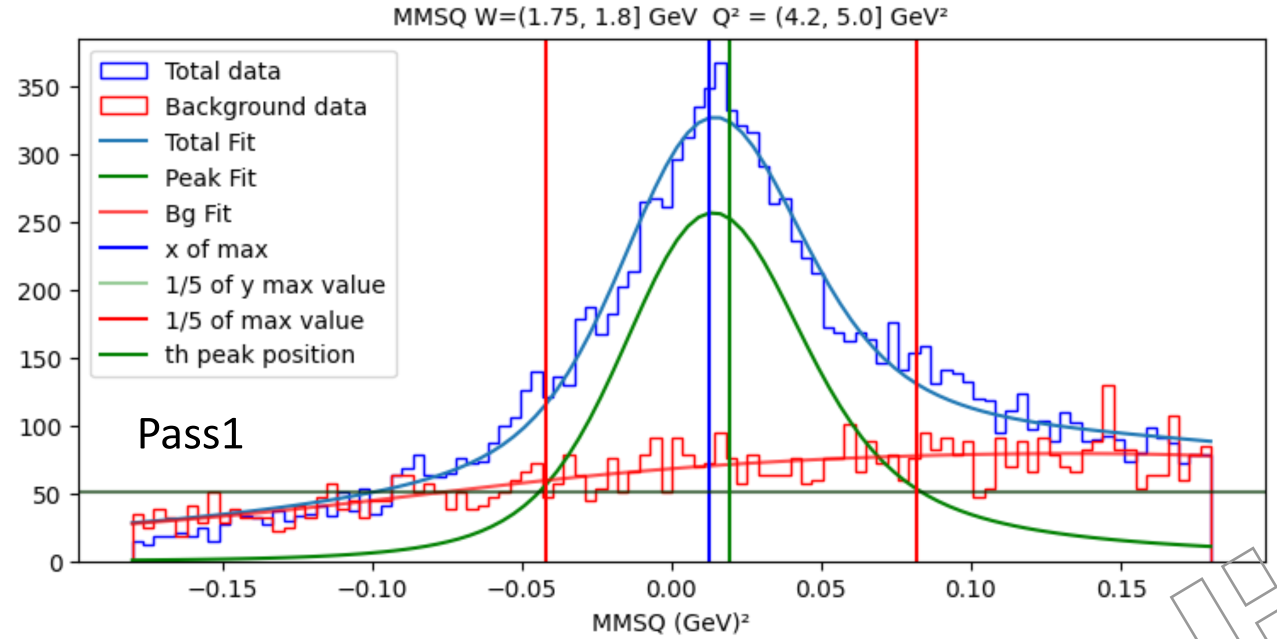
FD Pim (excl topo): mPip MMSQ Background Subtracted Signal Fits

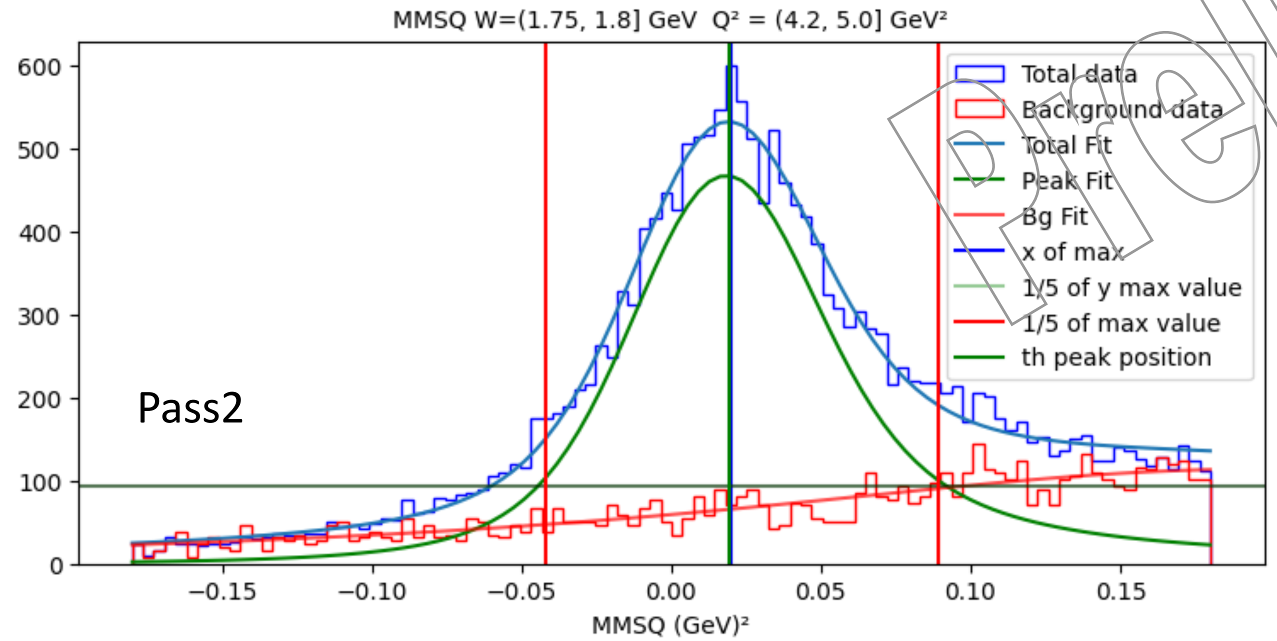
Momentum bins:

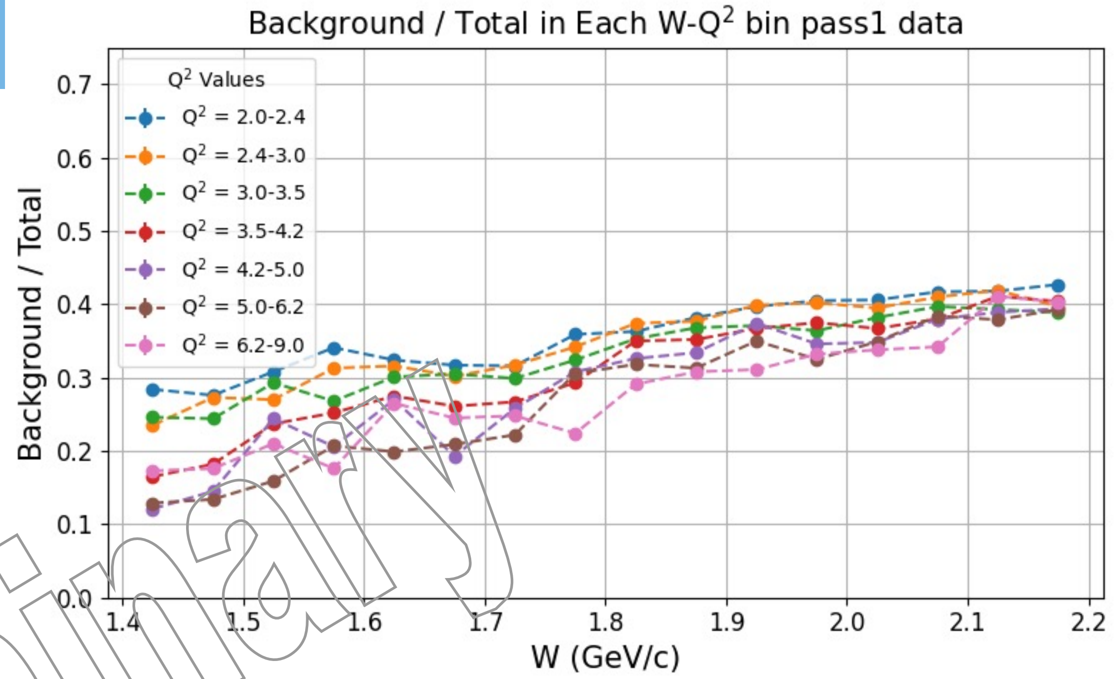
[0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 4.0, 5.0]

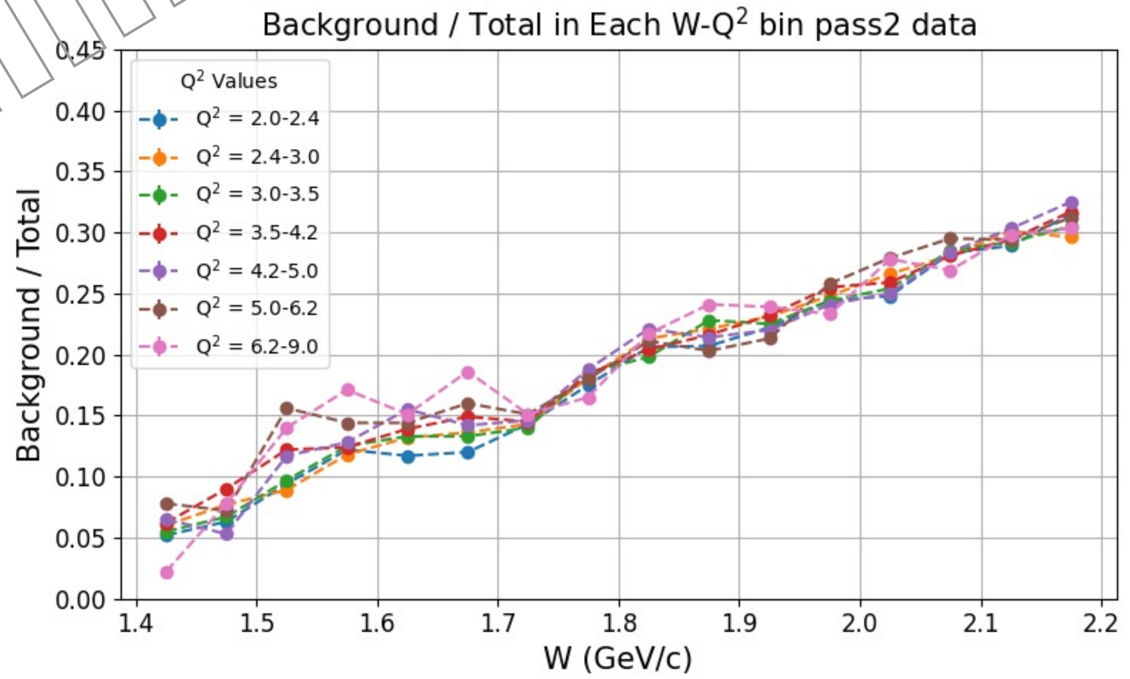


Background Subtraction

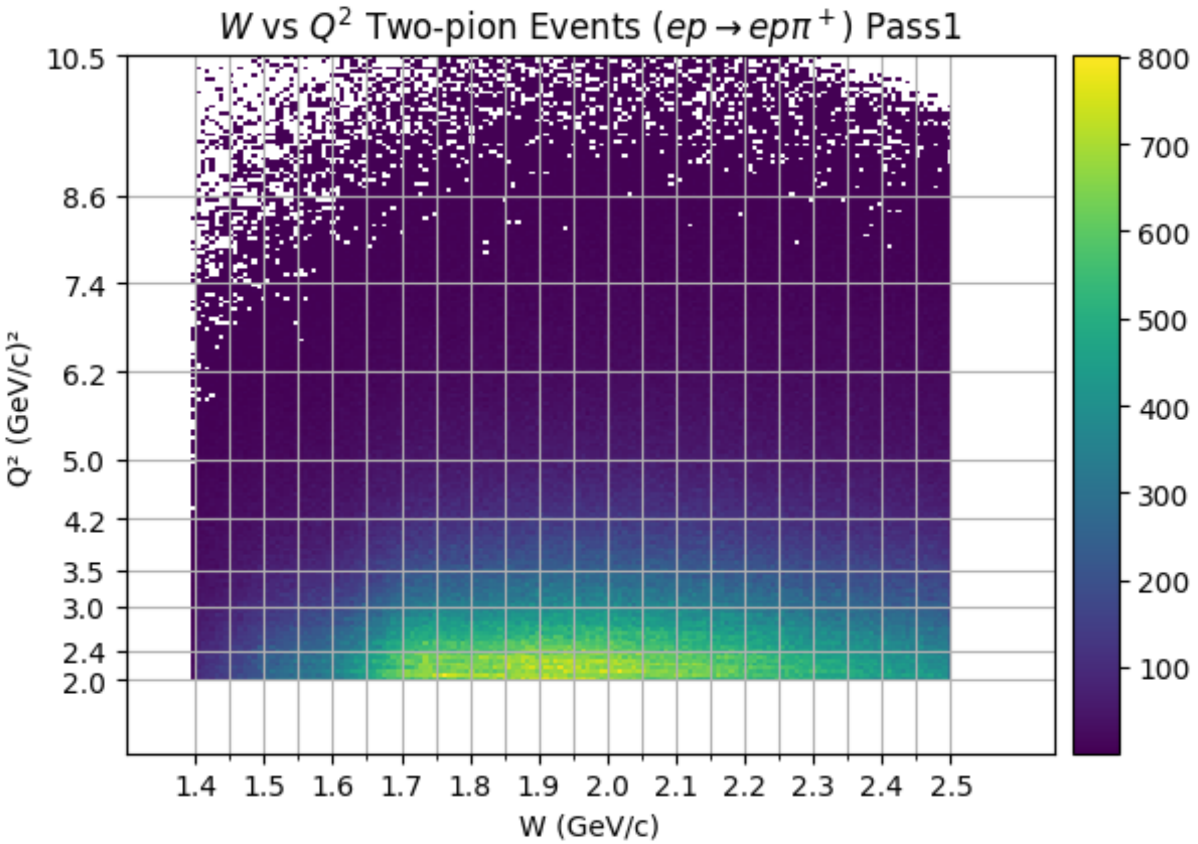


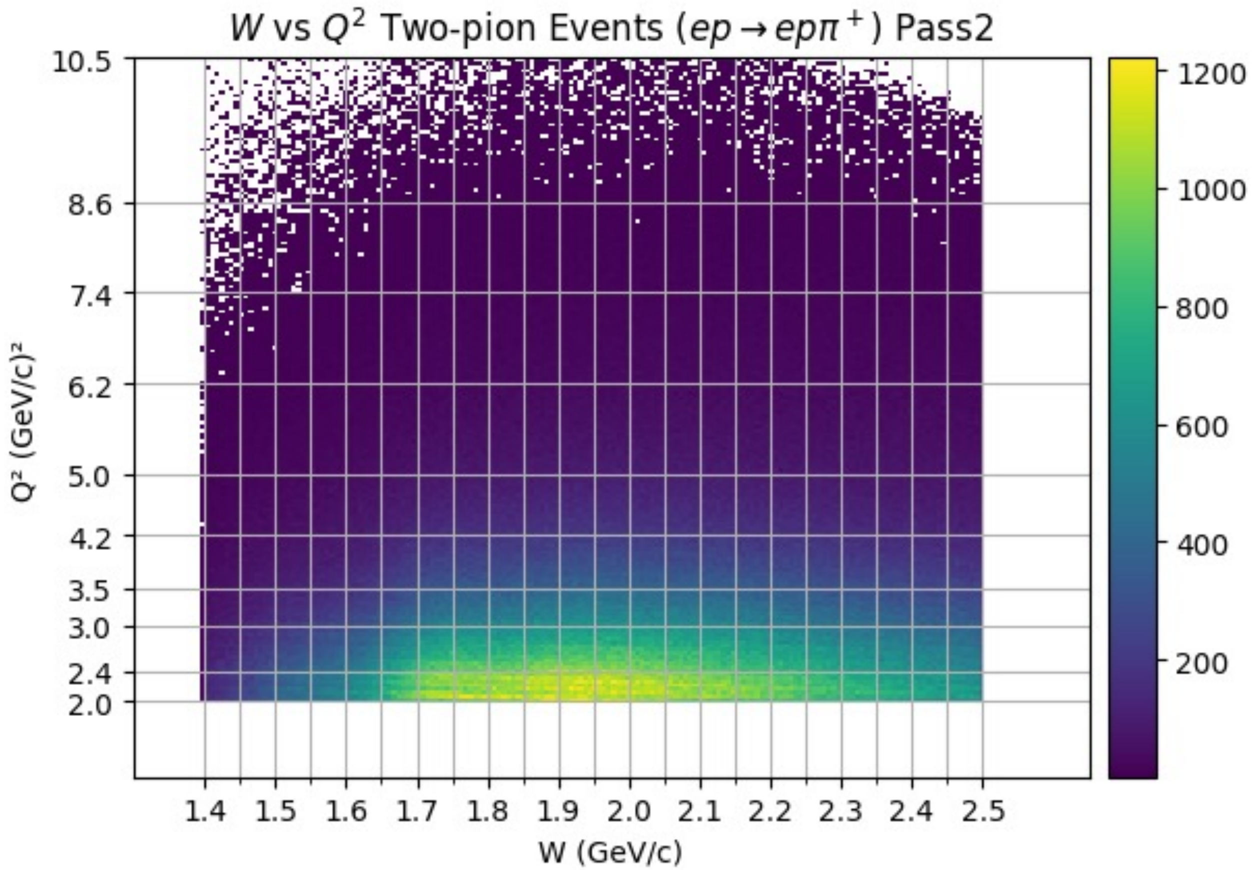






Exp Data: W-Q^2 Distributions for ep->e'p'pi+ Events



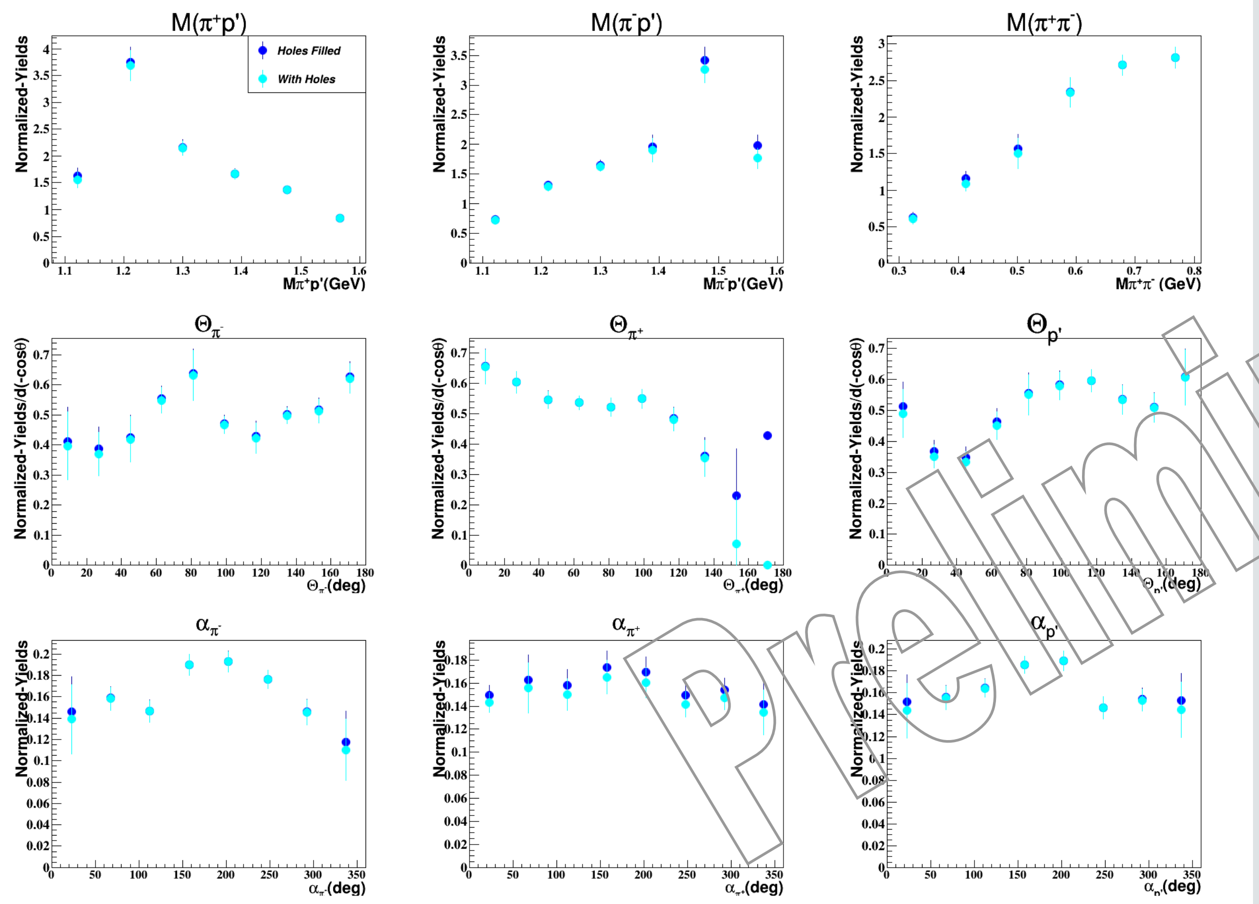


Nine 1-Dfifferential Normalized Yields : Pass1 and Pass2

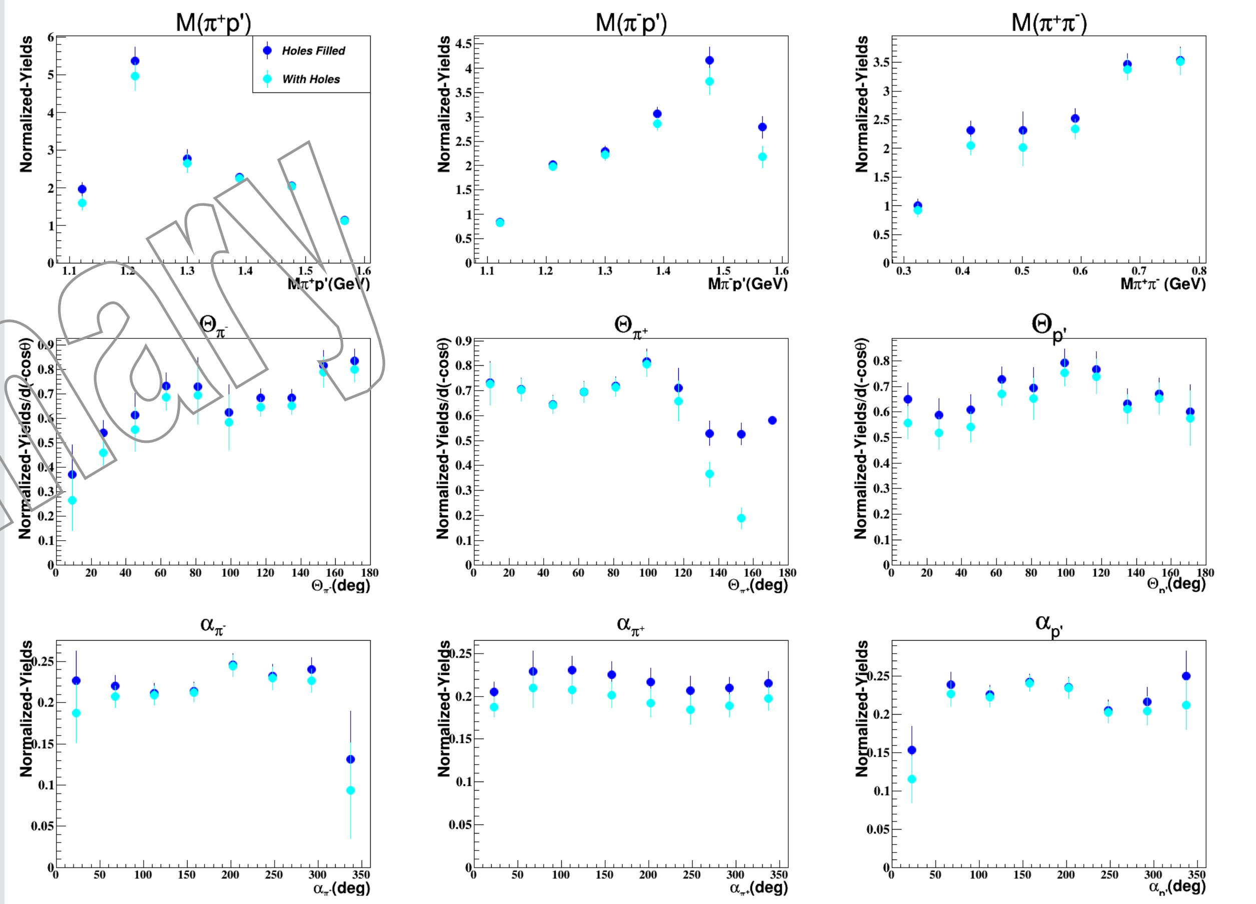
Holes Filling:

- CLAS12 detector does not fully cover 4π angular area
- The acceptance factor on those holes is zero
- Design constraint of detector system leads to some physical gaps called holes
- We need to fill those holes by using scaled generated yields

Pass1



Pass2



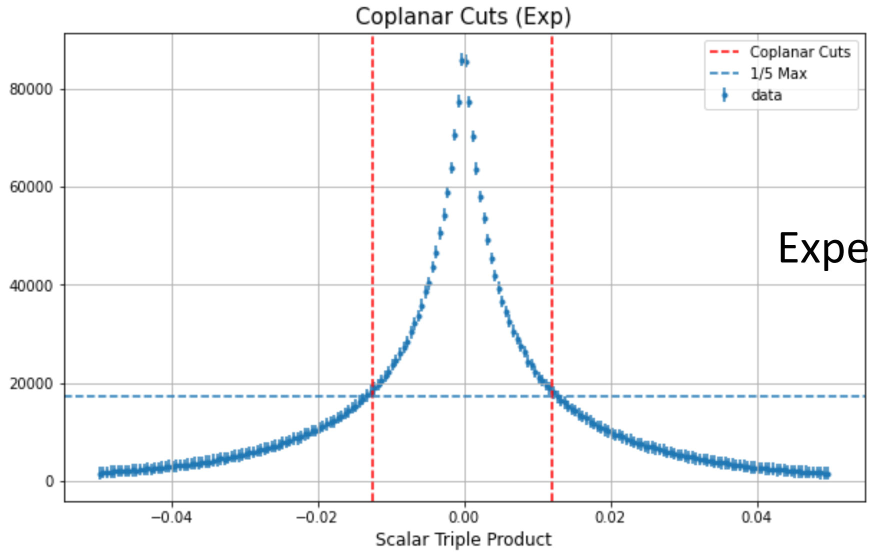
W-Q^2 bin for these Normalized Yields: 1.75 GeV < W < 1.80 GeV, 4.2 GeV^2 < Q^2 < 5.0 GeV^2

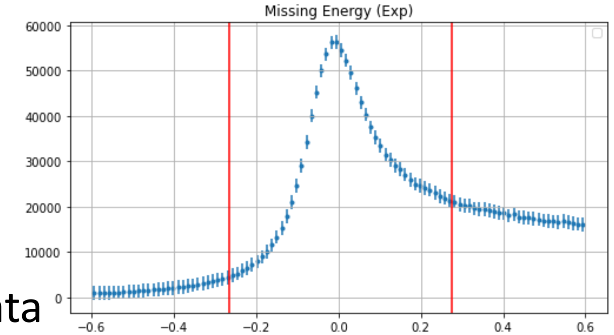
Conclusions

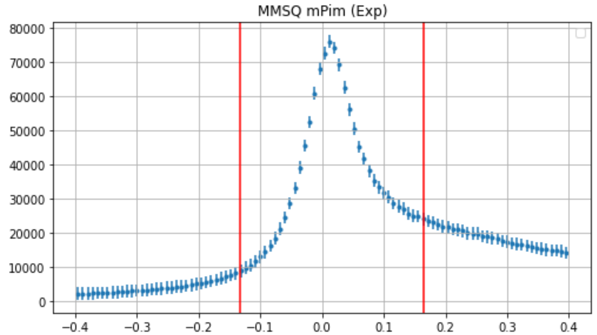
- Particle identification cuts have been implemented, refinement and adjustments will be made as needed
- Based on missing π^- topology, two-pion events are selected, and experimental yields are extracted
- Using TWOPEG event generator, acceptance correction factor are applied, and remaining holes are filled
- Energy/momentum corrections, radiative effect corrections, background subtractions are applied
- Smearing MC data, Detector efficiency studies are in progress, bin centering/migration corrections are next in line
- Systematic studies are needed to quantify uncertainties and **extract precise Cross-Sections**
- Very preliminary evaluations of Pass 2 data indicate promising results, this needs further systematic checks and refinements to conclude

Thank You!

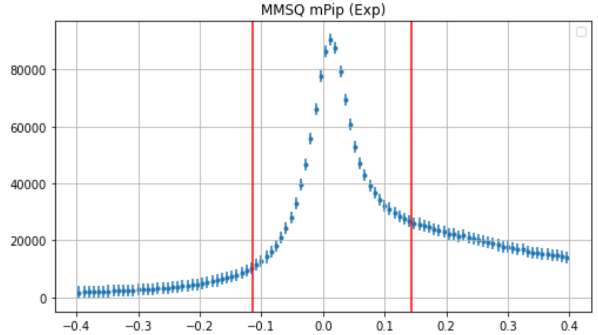
Background Selection

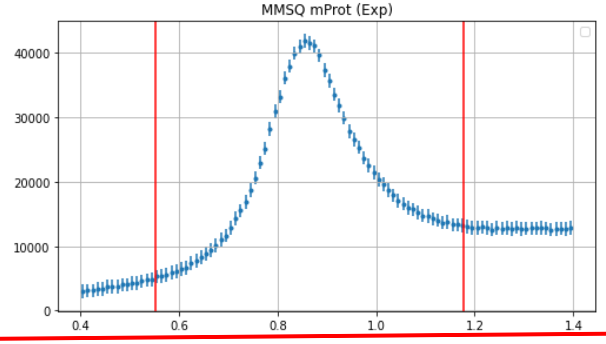




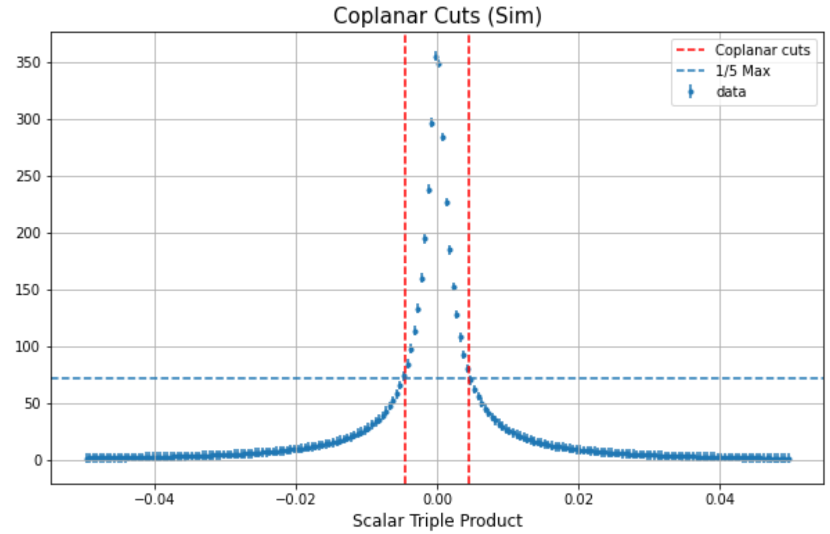


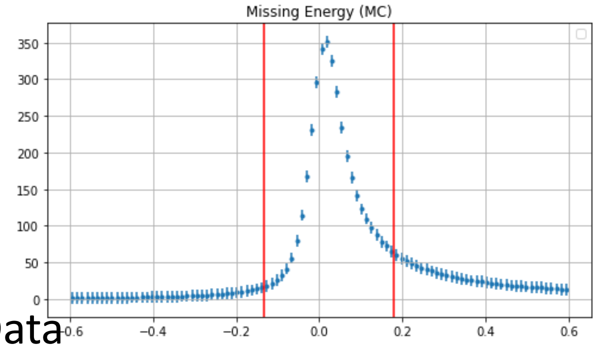
Experimental Data

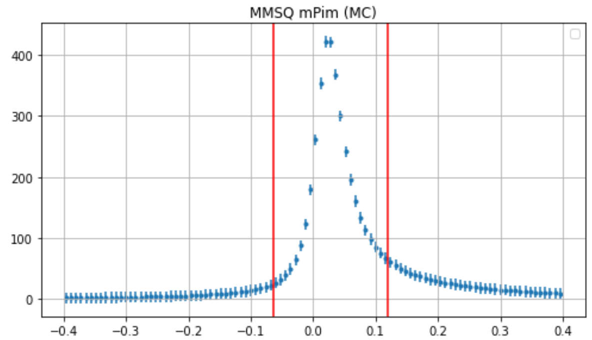




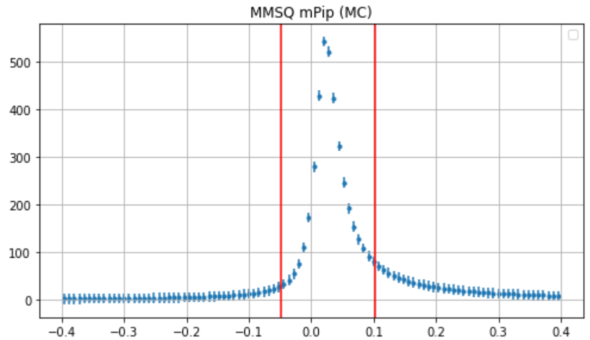
ep → e’p’pi+pi-

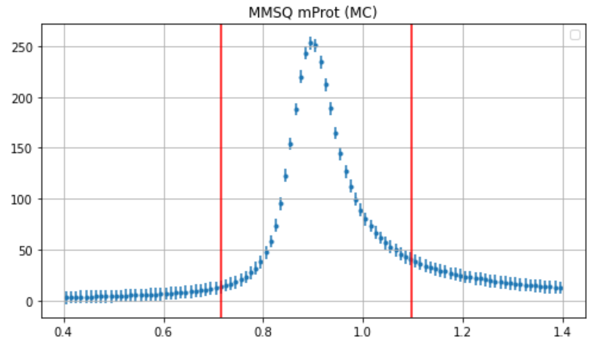






Simulated Data

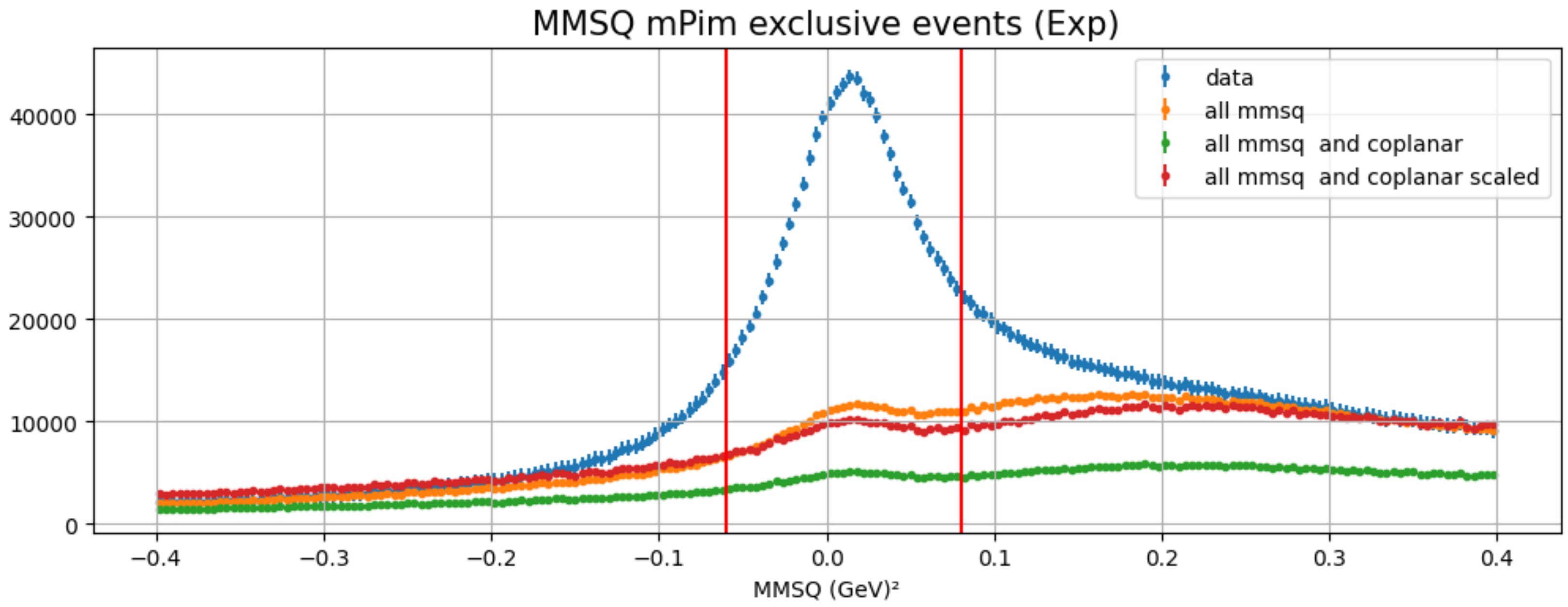


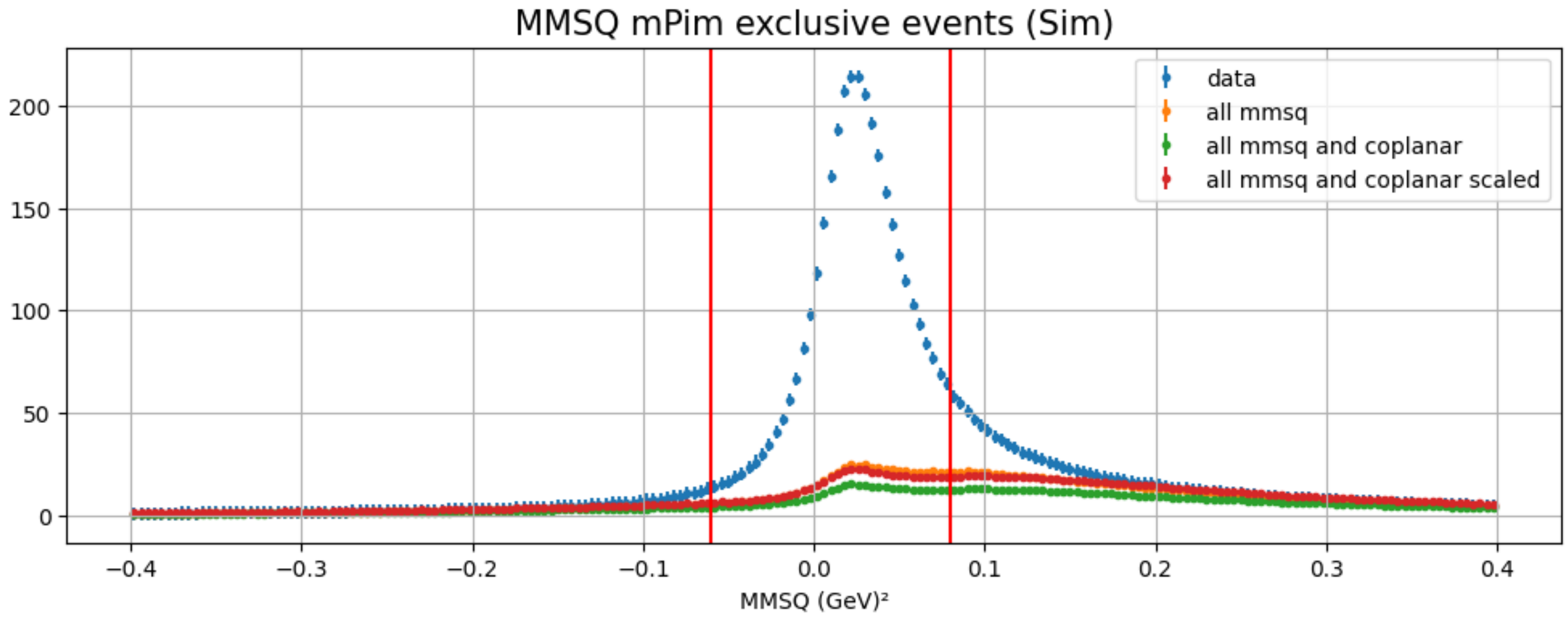


CM System

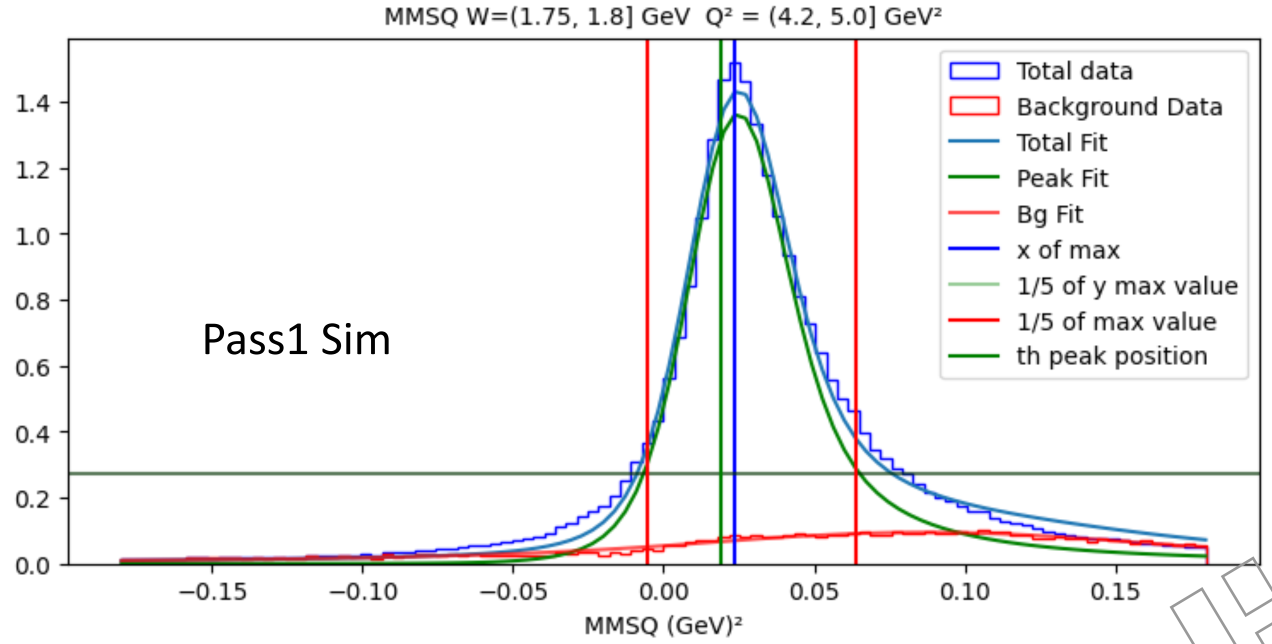
```
return (_prot_Vect3.Dot(_pip_Vect3.Cross(_pim_Vect3)));
```

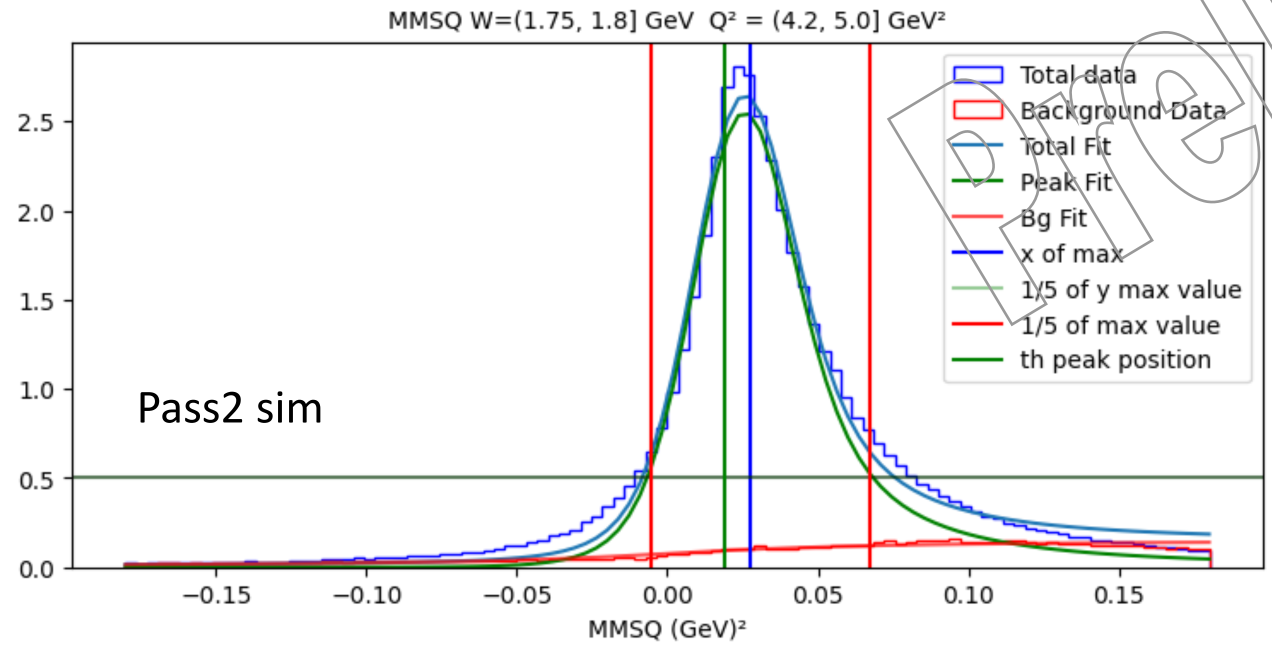
Background Selection

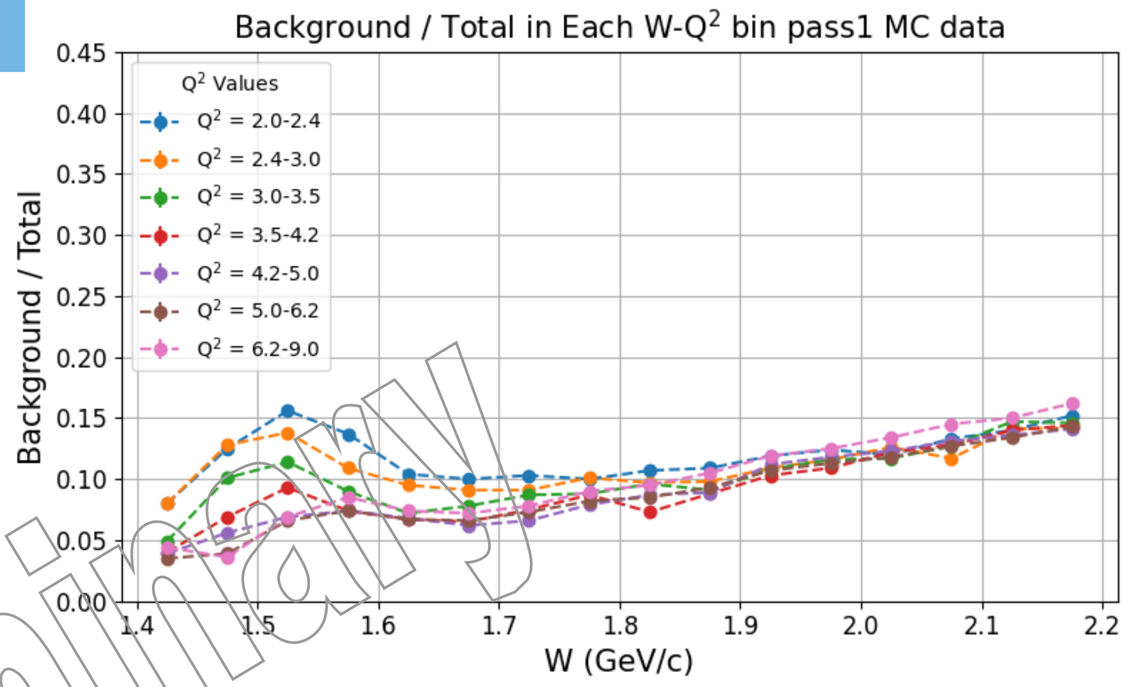


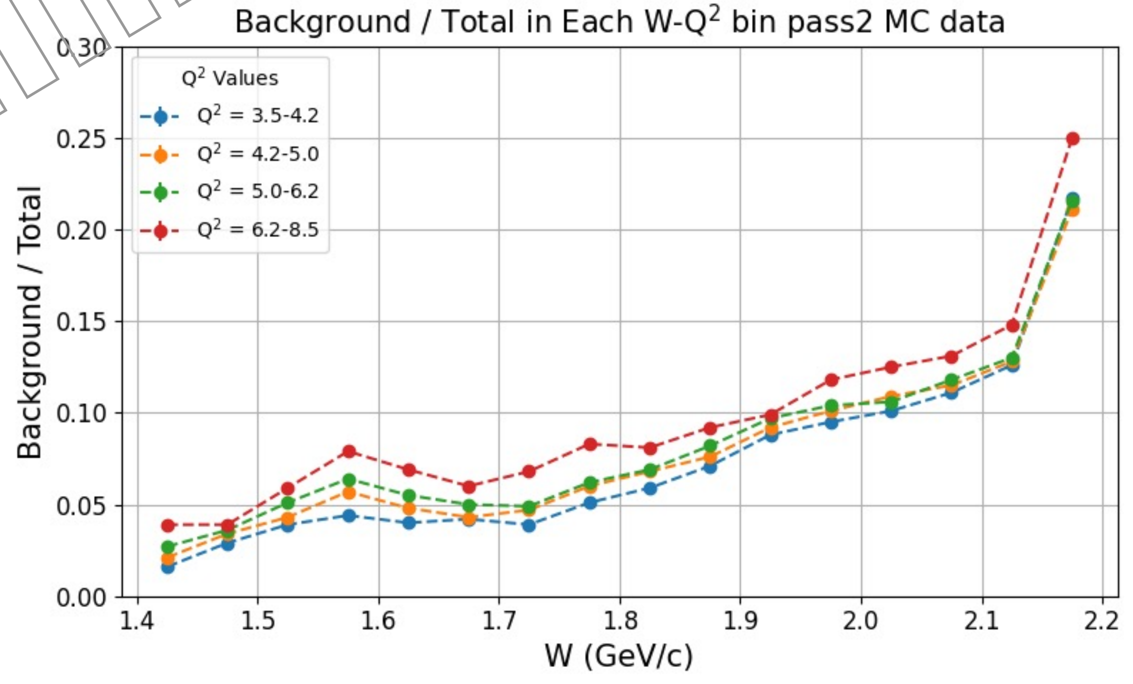


Background Subtraction









Back up Slide: Virtual Photon Flux

$$\frac{d^5\sigma_v}{d^5\tau} = \frac{1}{\Gamma_v}\frac{d^7\sigma_e}{dW\,dQ^2 d^5\tau} ,$$

where Γ_v is the virtual photon flux given by

$$\Gamma_v(W, Q^2) = \frac{\alpha}{4\pi}\frac{1}{E_{beam}^2 m_p^2}\frac{W(W^2 - m_p^2)}{(1-\varepsilon_T)Q^2}$$

Here α is the fine structure constant (1/137), m_p the proton mass, $E_{beam} =$ 10.6 GeV the laboratory energy of the incoming electron beam, and ε_T the virtual photon transverse polarization given by

$$\varepsilon_T = \left(1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\tan^2\left(\frac{\theta_{e'}}{2}\right)\right)^{-1} ,$$

where $\nu = E_{beam} - E_{e'}$ is the virtual photon energy, while $E_{e'}$ and $\theta_{e'}$ are the energy and the polar angle of the scattered electron in the lab frame, respectively.

e + p(uud) → Δ^{++}(uuu) + π^-(dū) + e' → p(uud)+ π^+(u d̄)+ π^-(dū) + e'
e + p(uud) → Δ^0(udd) + π^+(u d̄) + e' → p(uud)+ π^+(u d̄)+ π^-(dū) + e'
e + p(uud) → ρ^0((u d̄ + dū)/√2)+p(uud) + e' → p(uud)+ π^+(u d̄)+ π^-(dū) + e'

Backup Slide : Hole Filling Process

- In simulation:

  1. h5-ST = Thrown yield
  2. h5-SR = Thrown yield reconstructed in simulated detector.
  3. h5-SA = Acceptance (h5-SA=h5-SR/h5-ST)
  4. h5-SC = Acceptance corrected yield. (h5-SC=h5-SR/h5-SA)
  5. h5-SH = Hole yield (h5-SH=h5-ST-h5-SC)
  6. h5-SF = Yield in full (PS) (h5-SF=h5-SC+h5-SH)

- In experiment:

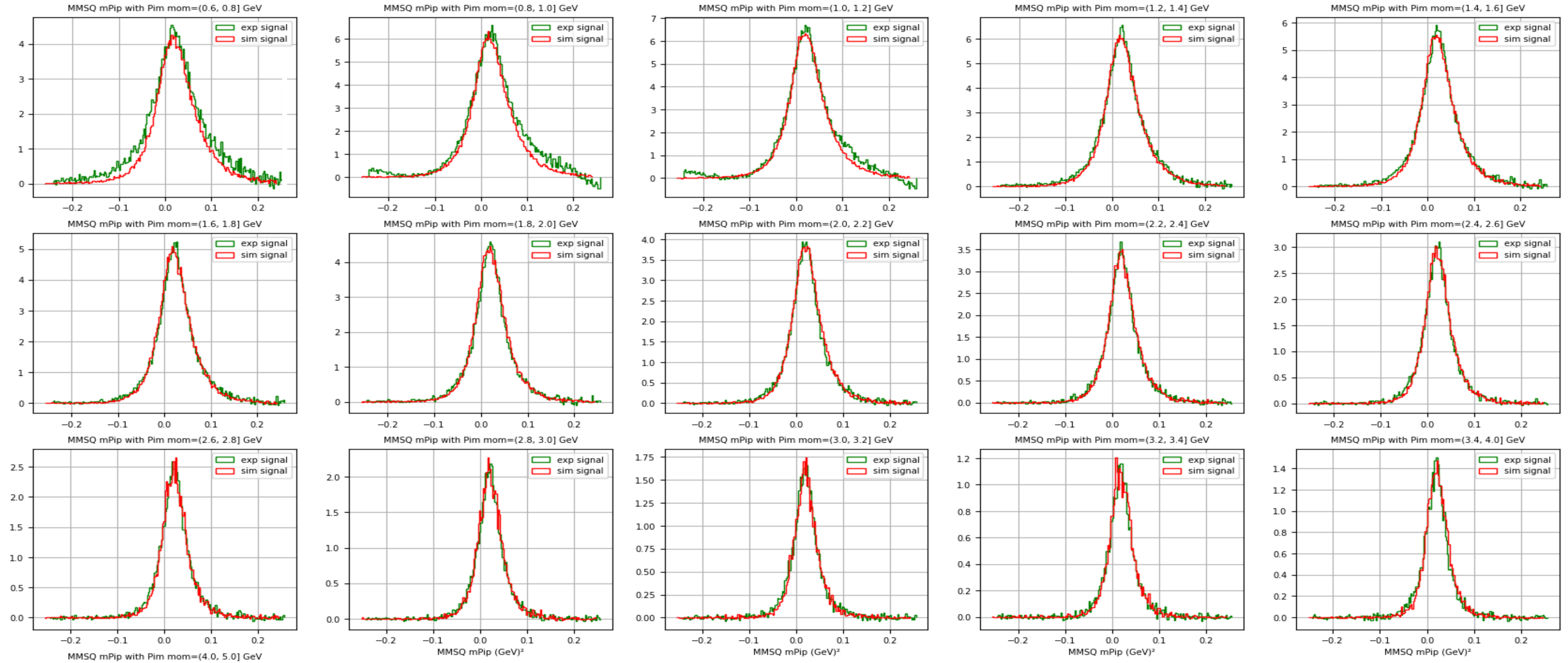
  1. h5-ER = Natural yield reconstructed in actual detector.
  2. h5-EC = Acceptance corrected yield (h5-EC=h5-ER/h5-SA)
  3. h5-EH = Hole yield. (h5-EH='sf'xh5-SH)
  4. h5-EF = Yield in full (PS) (h5-EF=h5-EC+h5-EH)

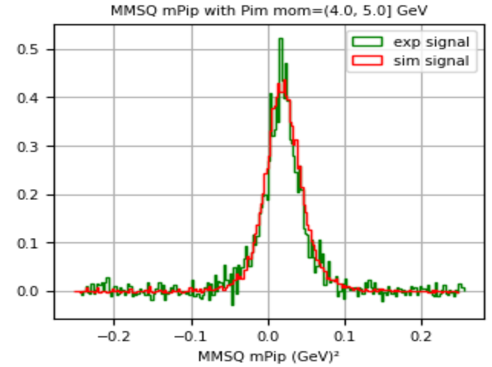
Obtain 'sf' as the ratio of total yield in h5-EC and total yield in h5-SC. Note that for both, the total yield is integrated over h5-SC's PS bins that are *filled* (i.e. their bin content > 0).

$$\text{sf} = \frac{\sum_{i=1}^{N} \text{h5-EC}_i}{\sum_{i=1}^{N} \text{h5-SC}_i}$$

where i=1,...,N are the *filled* PS bins filled in h5-SC.

Source: Arjun Trivedi (PhD Thesis) Measurement of New Observables from the $\pi^+\pi^-$ Electroproduction off the Proton





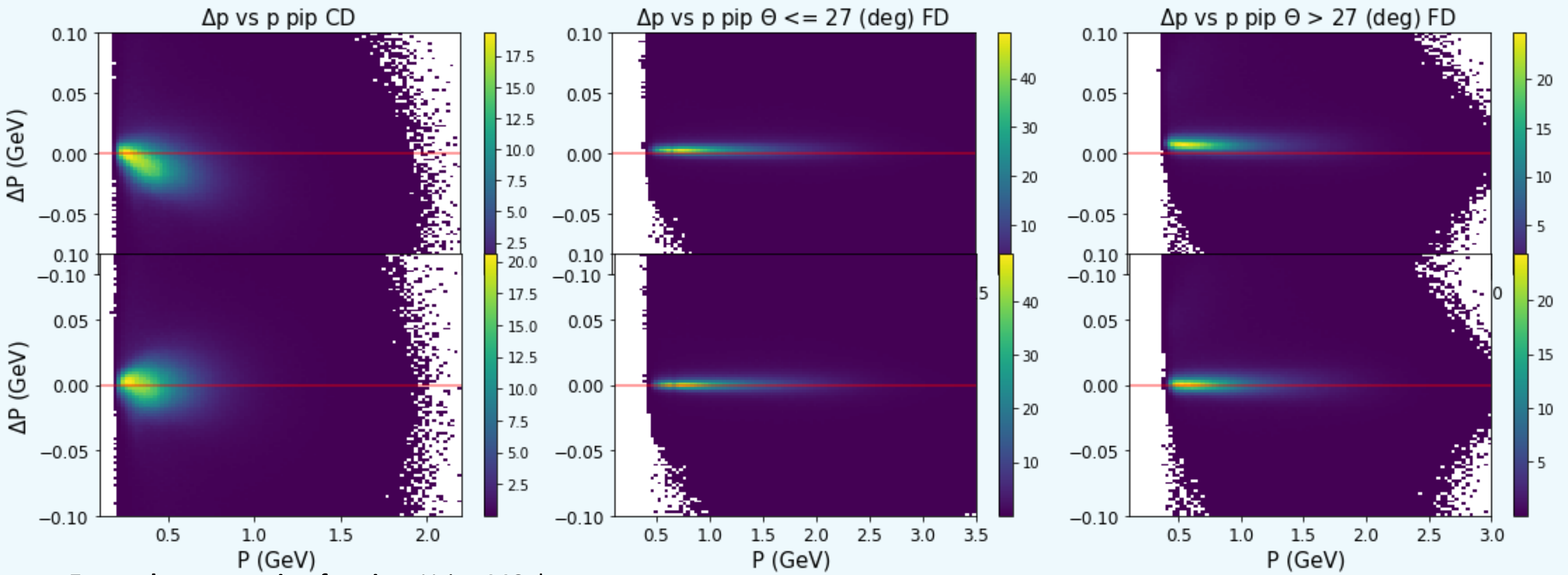
FD Pim (excl topology): mPip MMSQ , Background Subtracted Data

Momentum bins:

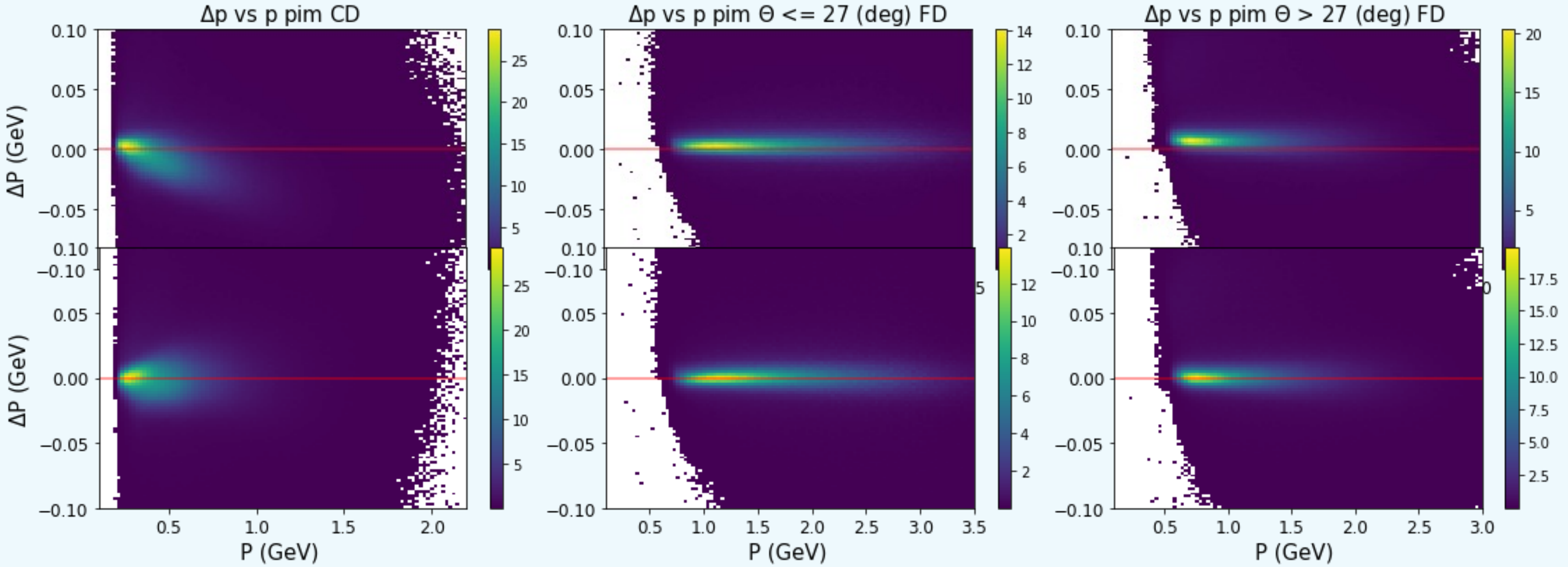
[0.3, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.2, 2.4, 2.6, 2.8, 3.0, 3.2, 3.4, 4.0, 5.0]

Back up Slide: Corrections

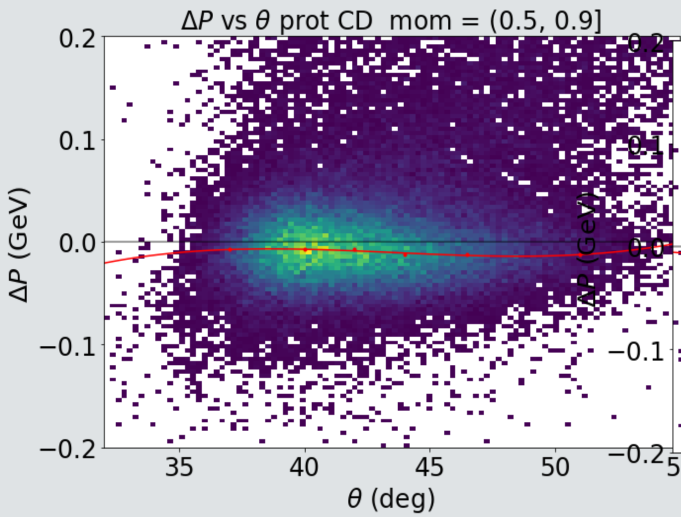
Energy loss correction for pip : Using MC data

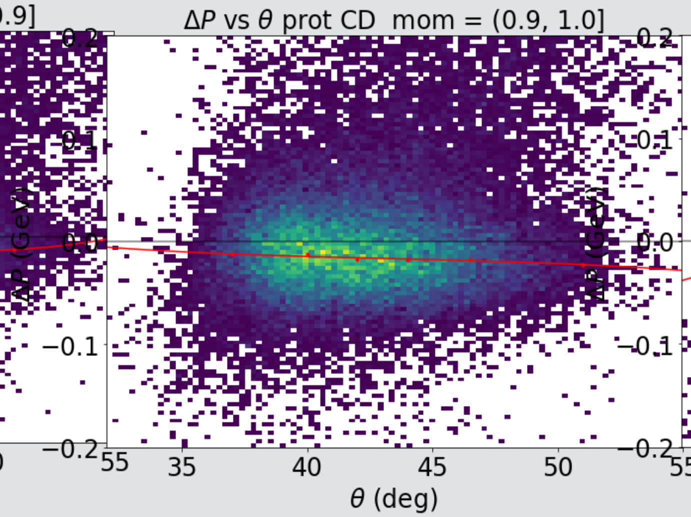


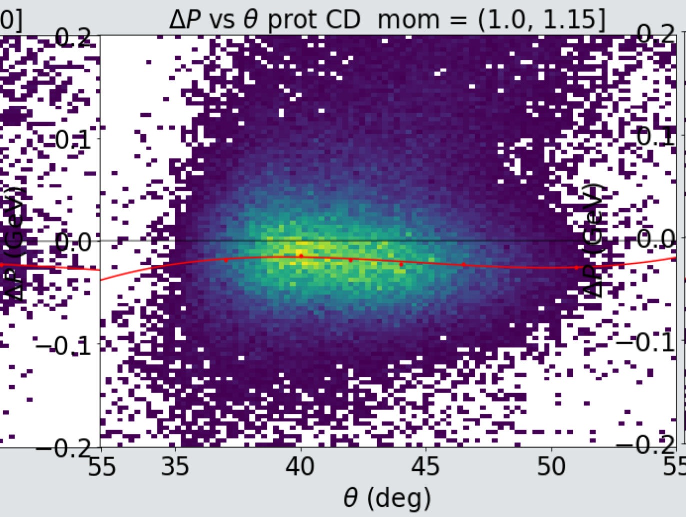
Energy loss correction for pim : Using MC data

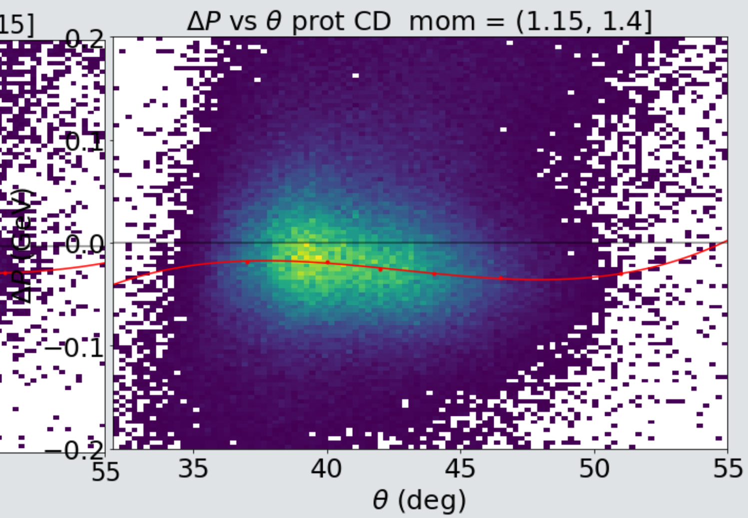


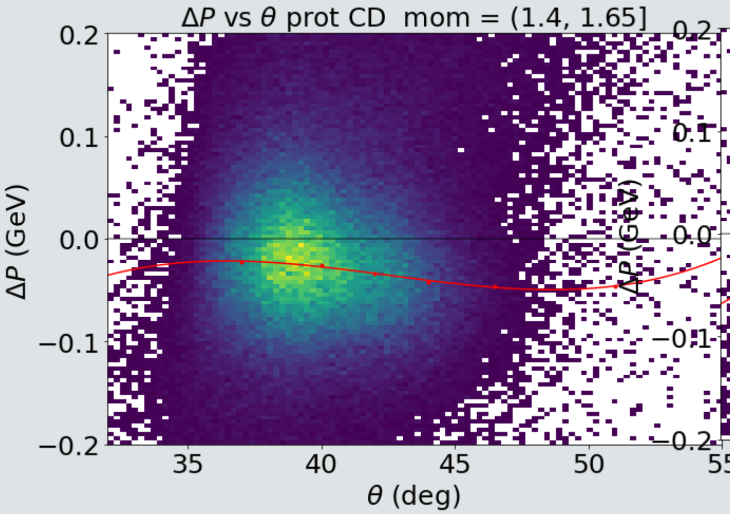
Energy Loss Corrections: CD Proton

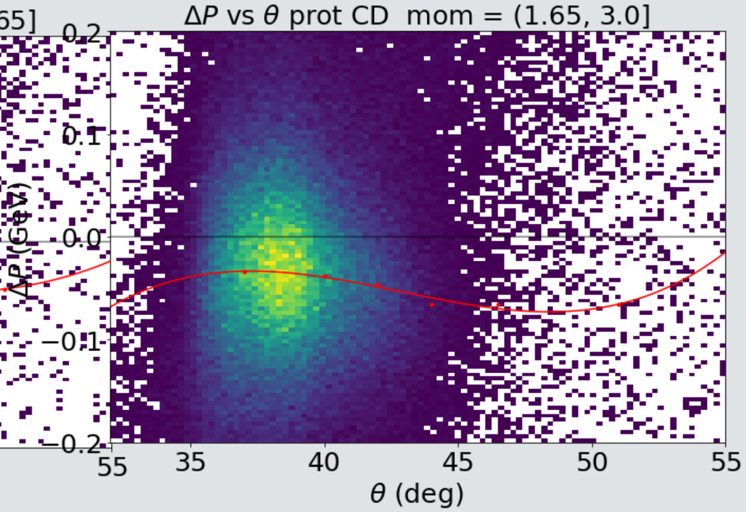


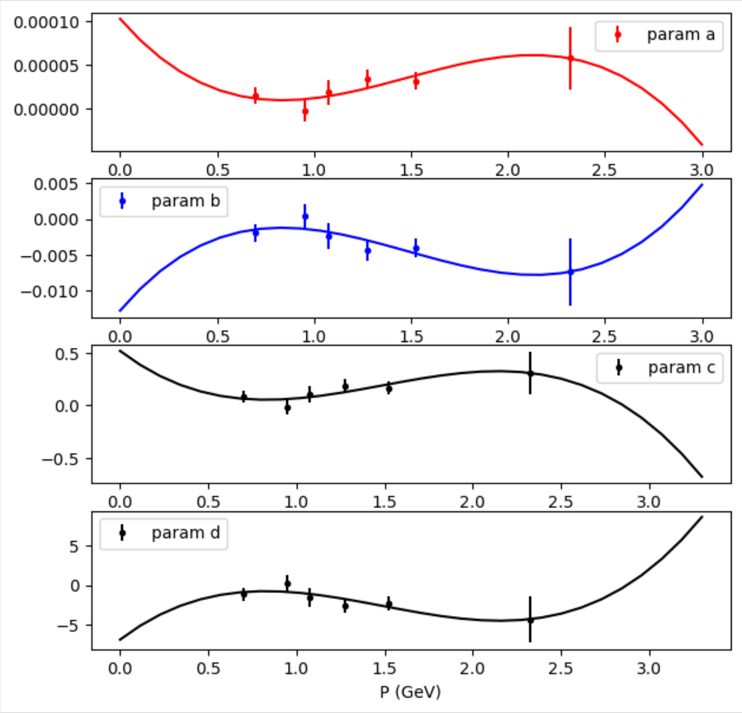












mom_bin_ranges = [0.5, 0.9, 1.0, 1.15, 1.4, 1.65, 3.0]

theta_bin_ranges = [35, 39, 41, 43, 45, 48, 54]

ΔP = prot_mom_gen - prot_mom_mes