

CLAS12 Double-Pion ($N \pi\pi$) Electroproduction Analysis

K. Neupane, R.W. Gothe, V.I. Mokeev, D.S. Carman

CLAS Collaboration Meeting, March 10-13, 2026



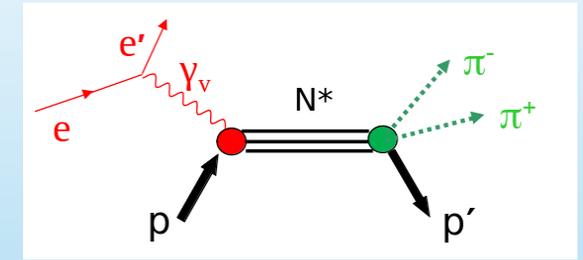
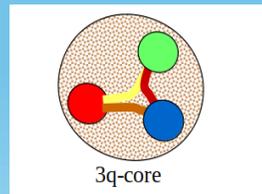
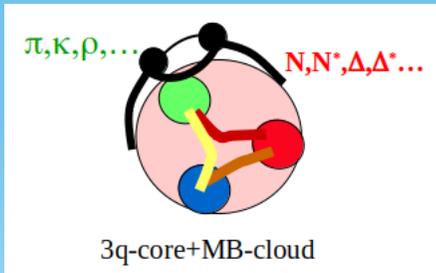
UNIVERSITY OF
South Carolina



Physics motivation

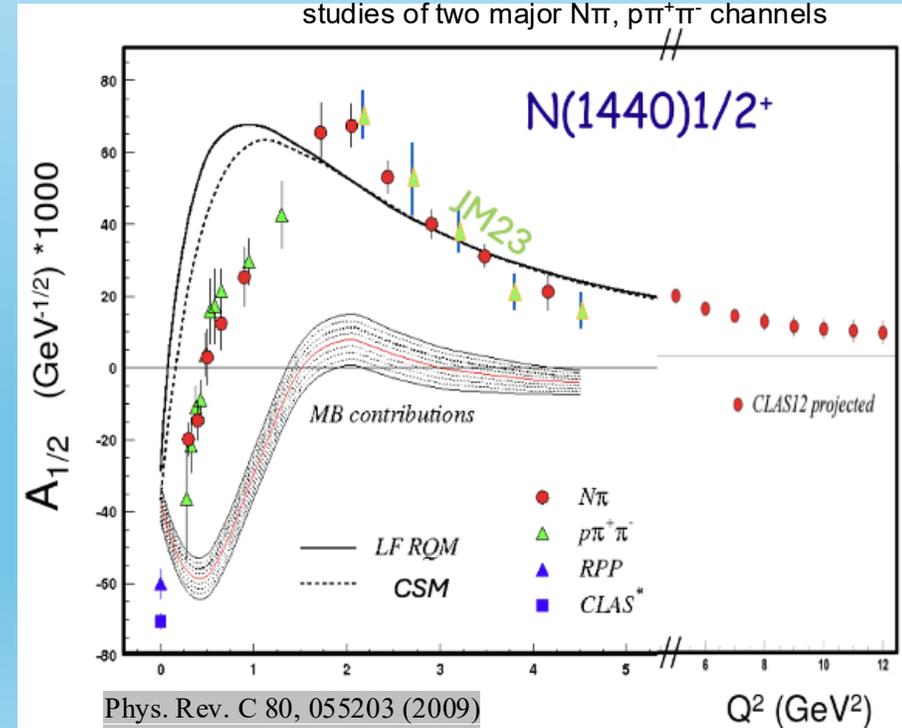
- N^* studies provides key insight into the **internal structure of hadrons** and the **strong interaction dynamics** responsible for nucleon resonance formation.
- This analysis extracts **differential cross sections for charged double-pion electroproduction** using CLAS12 RGA data.
- These cross sections will be used as input to the data-driven **JM model** to **extract resonance electrocouplings** across still not explored range of $Q^2=[5.0-8.0] \text{ GeV}^2$
- The evolution of resonance electrocouplings across this Q^2 range probes the distance scales where the transition from **non-perturbative to perturbative QCD** is expected and provides insight into **hadron mass generation**.

Low Q^2 -----> High Q^2



$$ep \rightarrow N^* \rightarrow e'p'\pi^+\pi^-$$

Helicity transition amplitudes of $N(1440)1/2^+$ electrocouplings from the different models/studies of two major $N\pi$, $p\pi^+\pi^-$ channels



Phys. Rev. C 80, 055203 (2009)

Phys. Rev. C 86, 035203 (2012)

Phys. Rev. C 108, 025204 (2023)

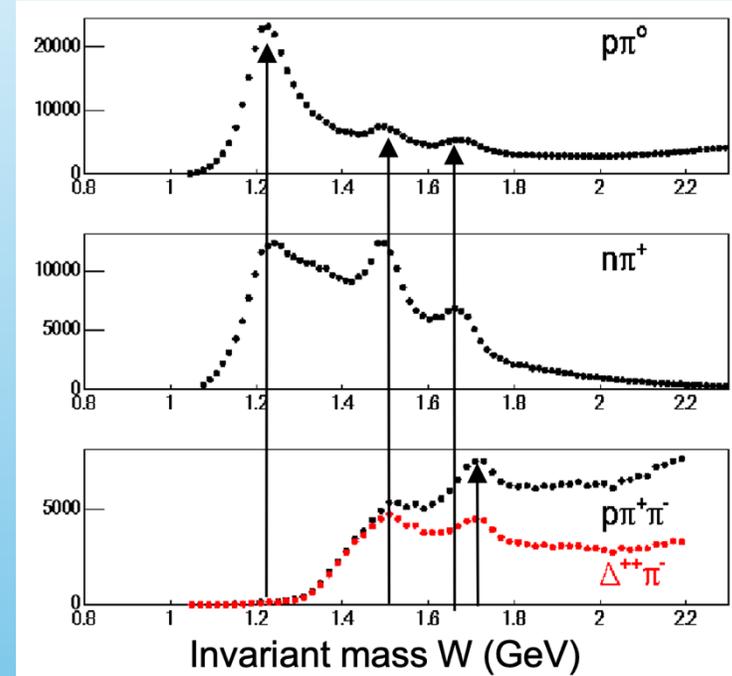
Physics motivation

The double-pion channel is the major contributor to the information in the higher invariant mass $W > 1.6$ GeV range. The N^* studies from the measurements of $N\pi$ and $\pi^+\pi^-p$ electroproduction channels are critical for evaluation of the extracted electrocoupling uncertainties.

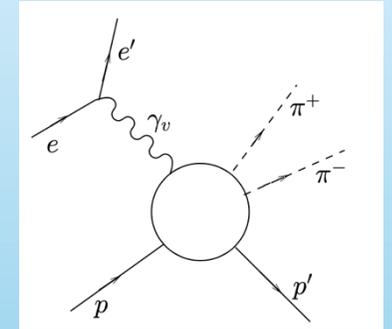
Resonance	Mass (MeV)	J^P	$N\pi$ (%)	$N\pi\pi$ (%)
$\Delta(1232)$	1232	$3/2^+$	≈ 100	< 1
$N(1440)$	1440	$1/2^+$	55-75	17-50
$N(1520)$	1520	$3/2^-$	55-65	25-35
$N(1535)$	1535	$1/2^-$	32-52	4-31
$\Delta(1600)$	1600	$3/2^+$	10-25	75-90
$\Delta(1620)$	1600	$1/2^-$	20-30	70-80
$N(1650)$	1650	$1/2^-$	50-70	20-58
$N(1675)$	1675	$5/2^-$	38-42	25-45
$N(1680)$	1680	$5/2^+$	60-70	28-53
$N(1700)$	1700	$3/2^-$	7-17	> 89
$\Delta(1700)$	1700	$3/2^-$	10-20	80-90
$N(1700)$	1710	$1/2^+$	5-20	14-48
$N(1720)$	1720	$3/2^+$	8-14	> 50
$N(1720)$	1895	$1/2^-$	2-18	17-74
$N(1720)$	1900	$3/2^+$	1-20	> 56
$\Delta(1905)$	1905	$5/2^+$	9-15	85-95
$\Delta(1950)$	1950	$7/2^+$	35-45	20-30

Table 1: Resonances contributing to single and double pion decay channels, including their spin-parity values J^P .

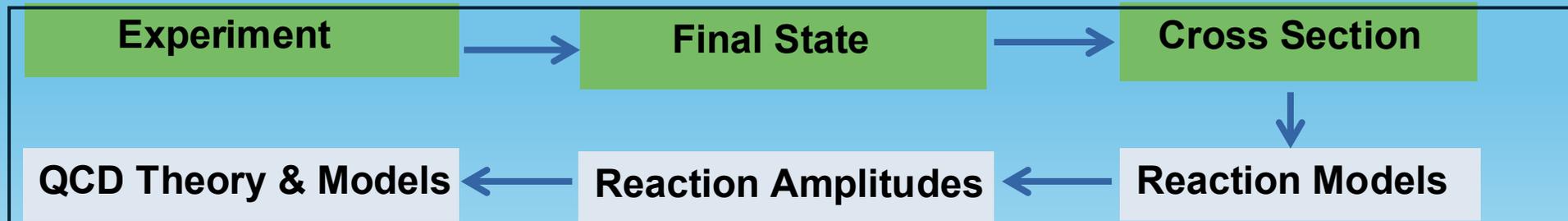
<https://pdg.lbl.gov/2022/tables/rpp2022-sum-baryons.pdf>



N^* with CLAS12, Proposal submitted to JLab PAC34



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



Physics Analysis: Outline

Exp. data: - Using Run Group A, Fall 2018 data with inbending configuration (pass2, Coatjava: 10.0.7)

Simulations: - TWOPEG event generator is used (gemc 5.10, Coatjava: 10.0.7) (pass2), JLab's osg portal

Kinematic range: - $1.4 \text{ GeV} < W < 2.10 \text{ GeV}$ - $2.0 \text{ GeV}^2 < Q^2 < 9.0 \text{ GeV}^2$

Topology:- Missing pim topology

☞ Particle Identification:

- Electron pid cuts
- Hadron pid cuts
- Detector Inefficiency Cuts

☞ Energy loss Corrections

☞ Momentum Corrections

☞ Smearing of MC data

☞ Event Selection

☞ Cross Sections Extraction

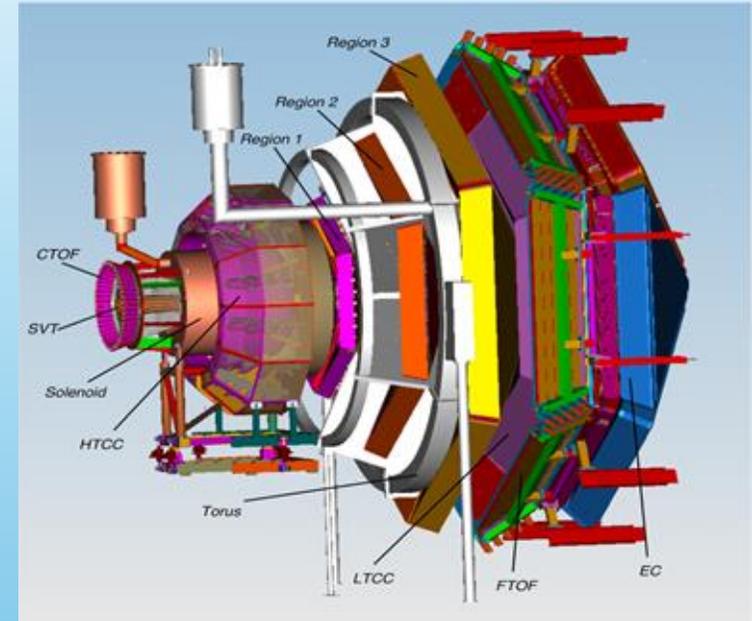
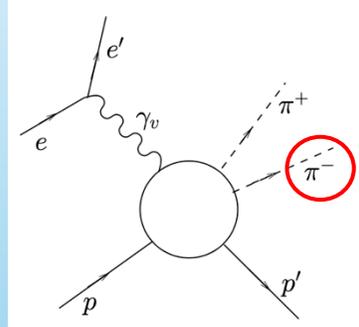
☞ Corrections

☞ Results: Cross Sections

☞ Systematic Uncertainties

☞ Conclusion and Publication Plan

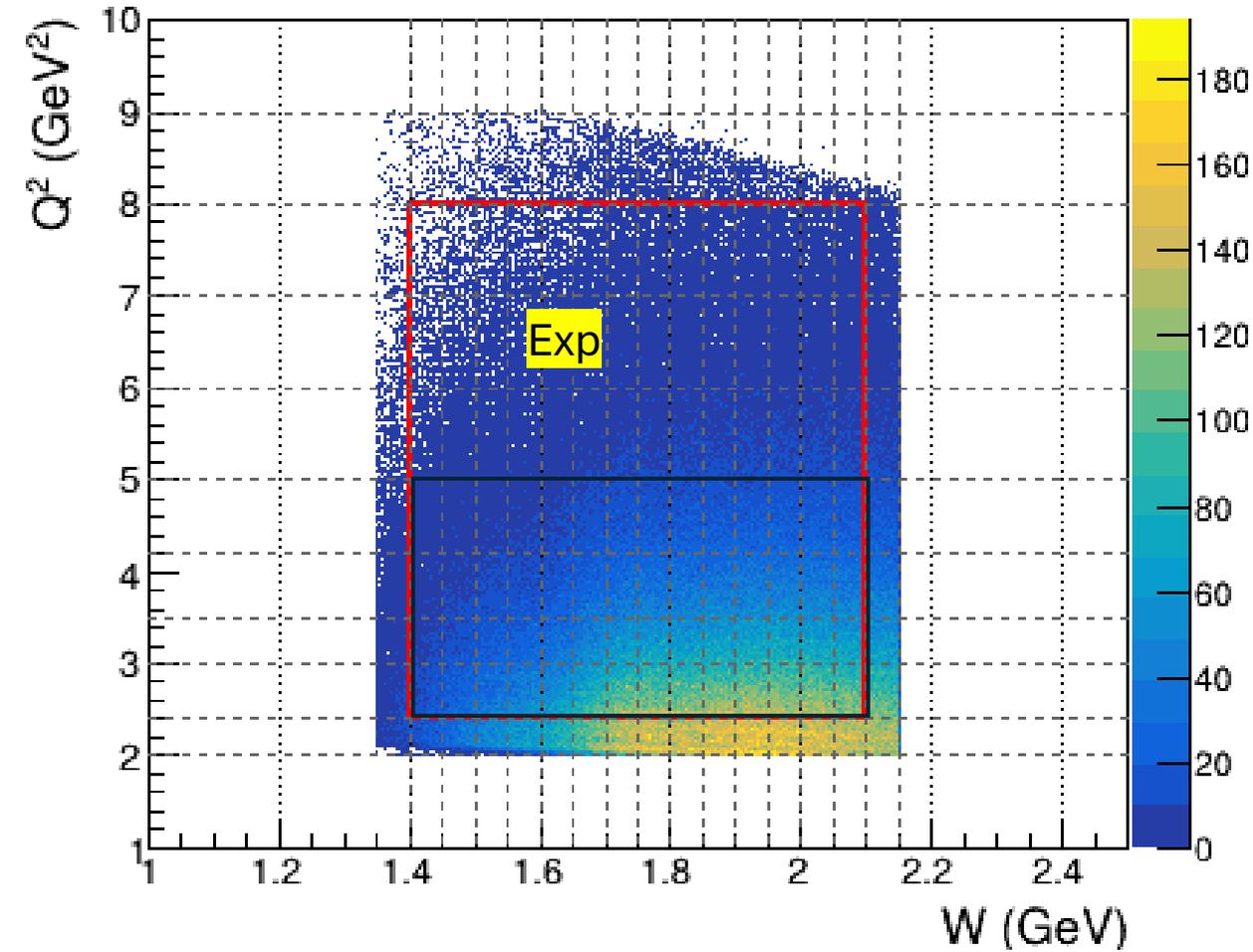
★ CLAS12 Double pion Analysis [review](#)



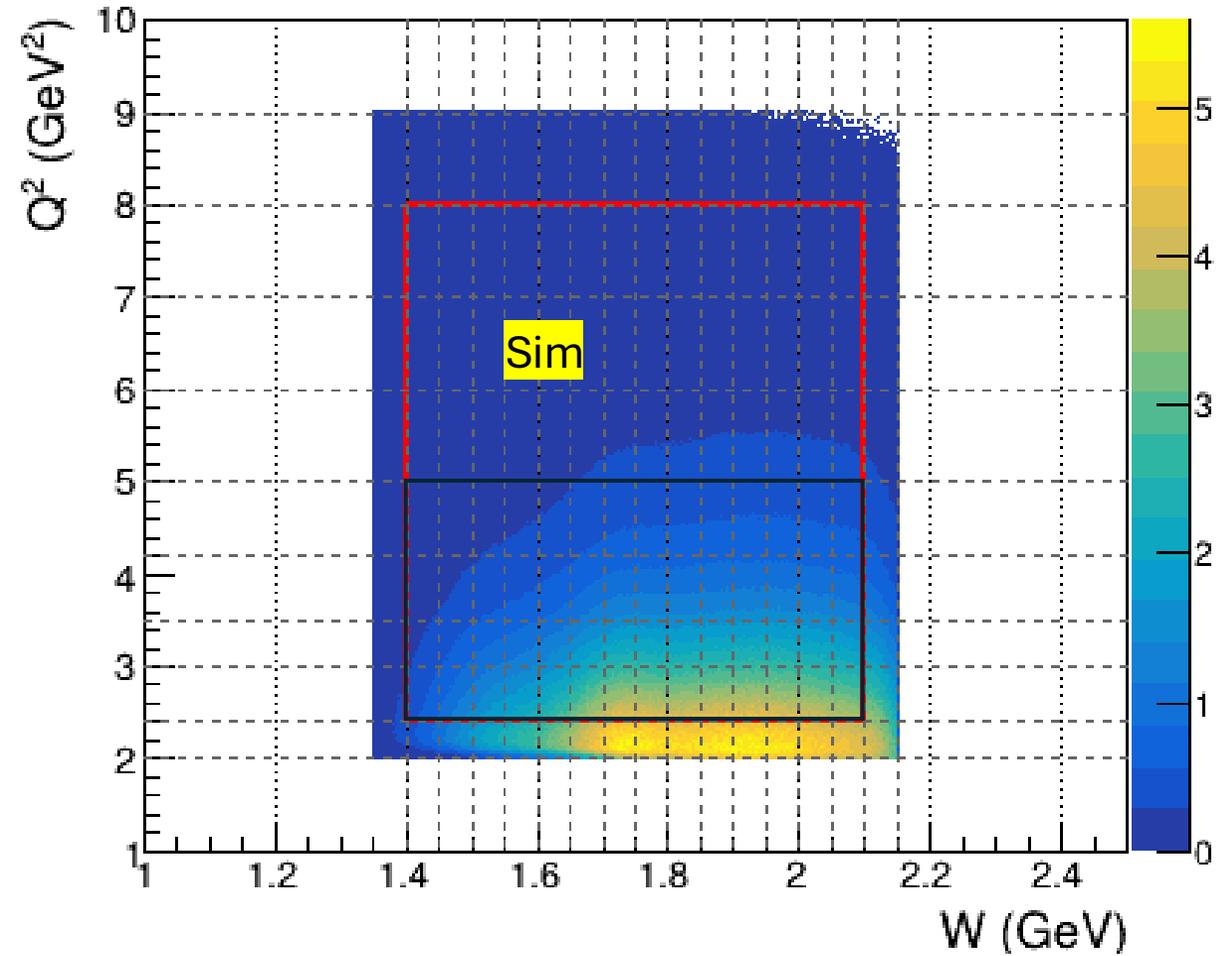
Acceptance Correction
Detector Efficiency from Experimental Data
Radiative Effects
Bin centering Corrections
Background subtraction
Acceptance and Holes

Event selection: Kinematic coverage

W versus Q^2 Distribution Exp. data

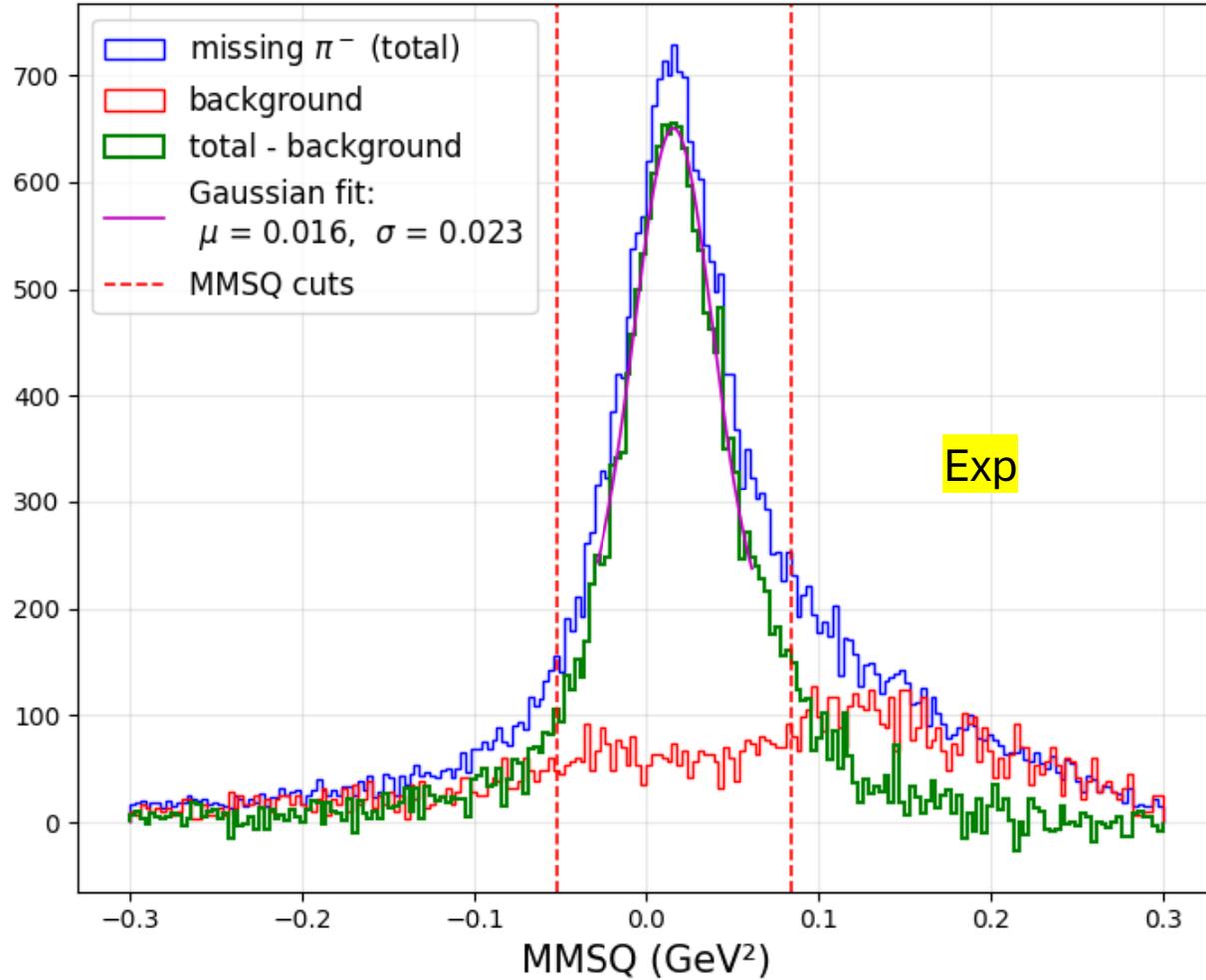


W versus Q^2 Distribution MC data

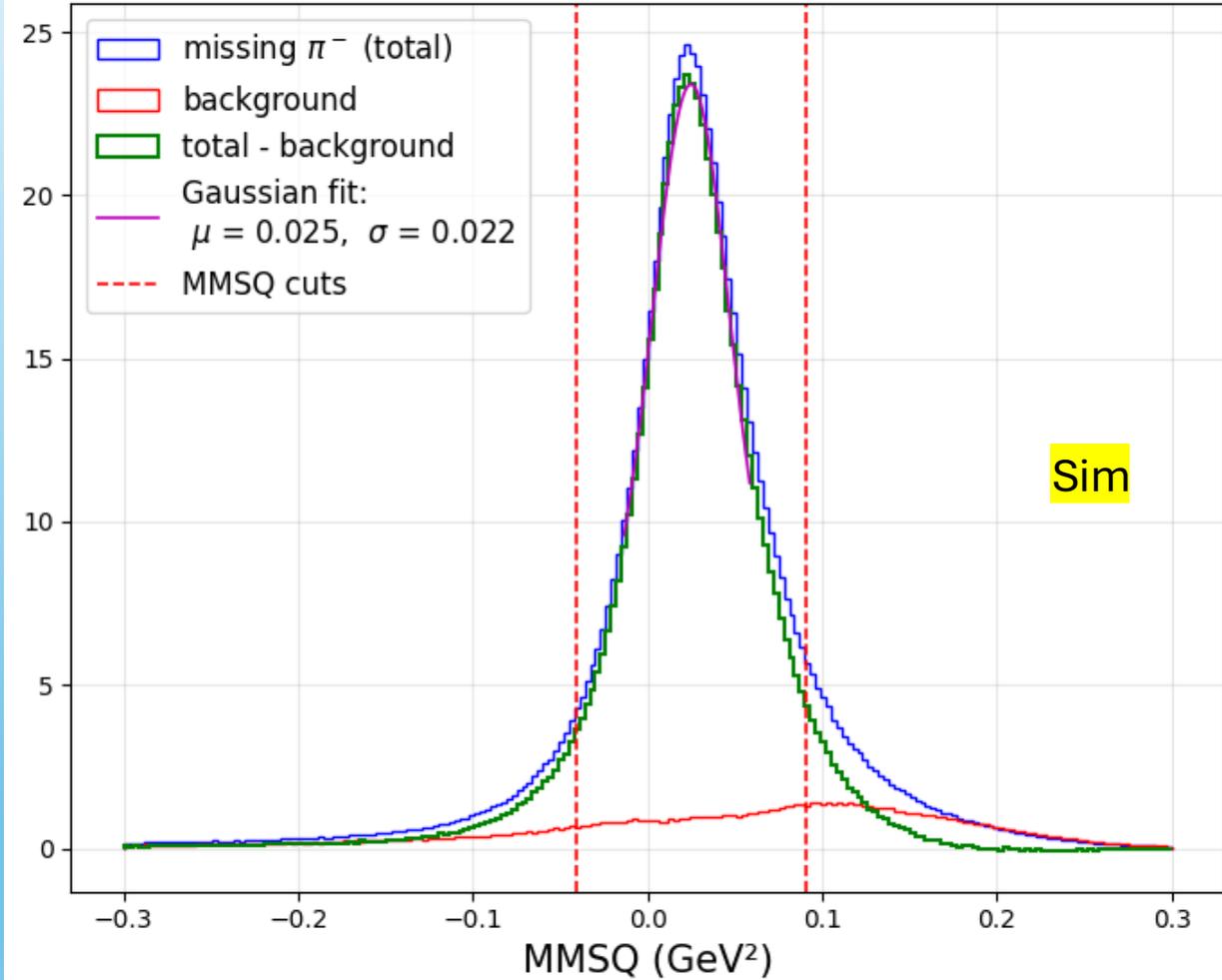


Event selection: MMSQ Cuts

MMSQ for $3.5 \leq Q^2 < 4.2 \text{ GeV}^2$, $1.700 \leq W < 1.750 \text{ GeV}$



MMSQ for $3.5 \leq Q^2 < 4.2 \text{ GeV}^2$, $1.700 \leq W < 1.750 \text{ GeV}$



Double-pion channel cross section

$$Q_{\text{full}} = 0.2878 \text{ C} \quad \text{QADB}$$

$$Q_{\text{empty}} = 0.0022 \text{ C}$$

$$\frac{1}{L} = \left(\frac{l p N_A}{q_e M H} \right)$$

$$= 0.755314965^{-12} \mu b \text{ C}$$

Phys Rev C, 80
VI Mokeev, et.al.
2009

Electron scattering 7D cross sections:

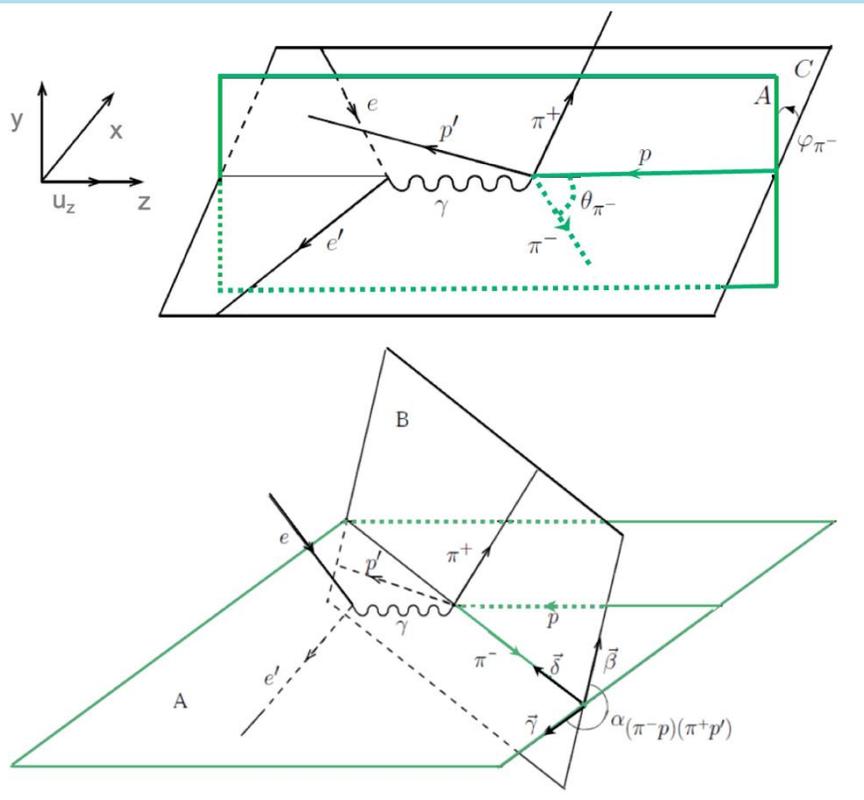
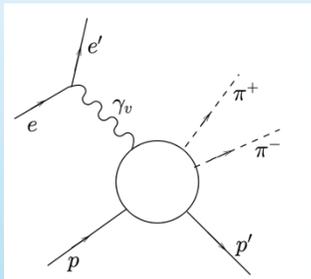
$$\frac{d^7\sigma}{dW dQ^2 dM_{h_1 h_2} dM_{h_2 h_3} d\Omega_{h_1} d\alpha_{h_1}} = \frac{1}{A \cdot E_C \cdot R} \left(\frac{\Delta N_{\text{full}}}{Q_{\text{full}}} - \frac{\Delta N_{\text{empty}}}{Q_{\text{empty}}} \right) \frac{1}{\Delta W \Delta Q^2 \Delta^5 \tau L}$$

Virtual photoproduction 5D cross sections:

$$\frac{d^5\sigma}{dM_{h_1 h_2} dM_{h_2 h_3} d\Omega_{h_1} d\alpha_{h_1}} = \frac{1}{\Gamma_\nu} \frac{d^7\sigma}{dW dQ^2 dM_{h_1 h_2} dM_{h_2 h_3} d\Omega_{h_1} d\alpha_{h_1}}$$

One-fold differential cross sections:

$$\frac{d\sigma}{dM_{h_1 h_2}} = \int \frac{d^5\sigma}{d^5\tau} dM_{h_2 h_3} d\Omega_{h_1} d\alpha_{h_1}$$



- 1) $M_{\pi-\pi^+}$, $M_{\pi^+p'}$, θ_{π^-} , φ_{π^-} and $\alpha_{(p\pi^-)(p'\pi^+)}$ (ie. α_{π^-}) [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) $M_{\pi^+\pi^-}$, $M_{\pi^-p'}$, θ_{π^+} , φ_{π^+} and $\alpha_{(p\pi^+)(p'\pi^-)}$ (ie. α_{π^+}) [π^-, π^+, p']

Binning:

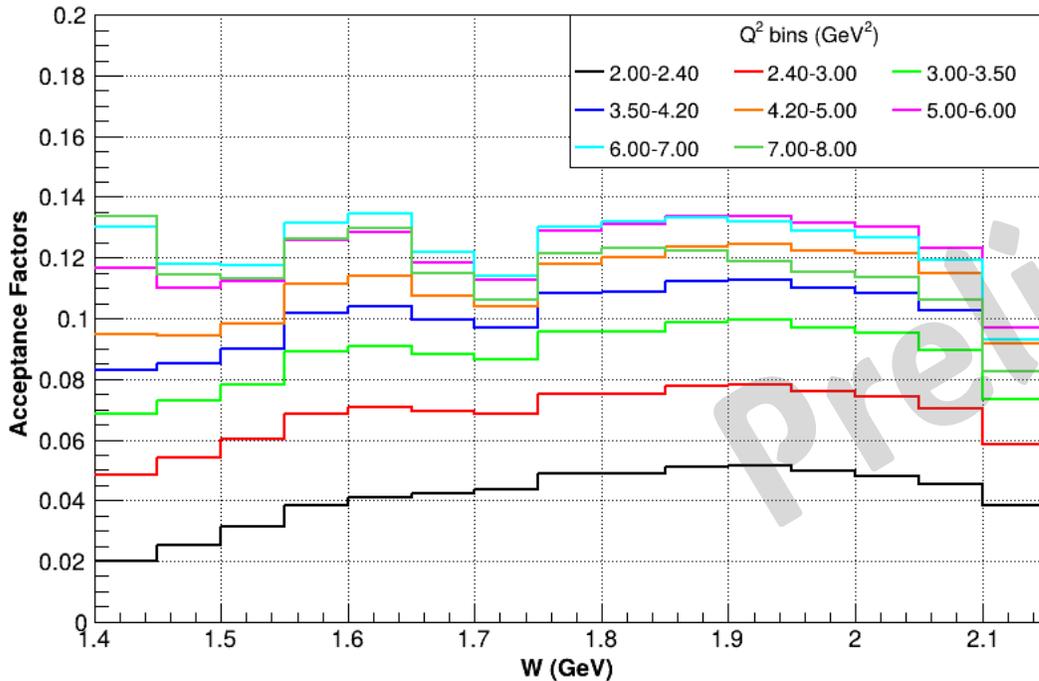
- 15 W bins ($1.4 < W \leq 2.15 \text{ GeV}$)
- 8 Q^2 bins ($2.0 < Q^2 \leq 8.0 \text{ GeV}^2$)
- 14 bins for invariant masses
- 10 bins for θ
- 6 bins for φ
- 10 bins for α

Acceptance Correction Factor A

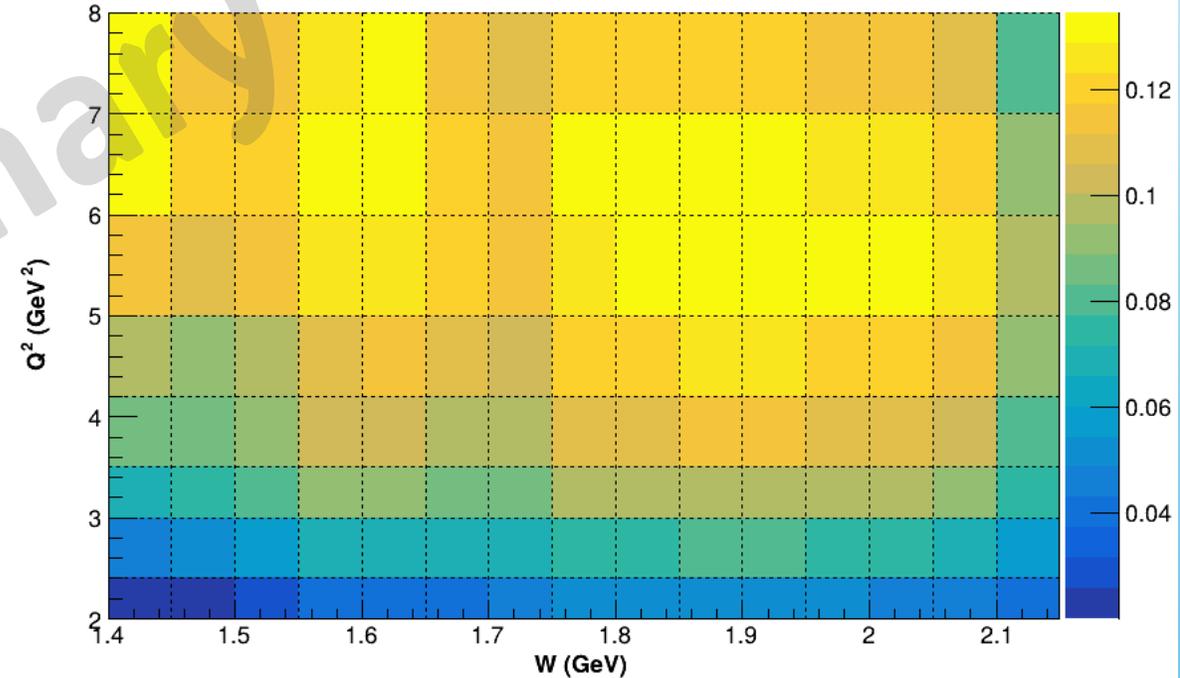
$$A(\Delta W, \Delta Q^2, \Delta^5 \tau) = \frac{N_{\text{rec}}}{N_{\text{gen}}}$$

$$\frac{d^7 \sigma}{dW dQ^2 dM_{h_1 h_2} dM_{h_2 h_3} d\Omega_{h_1} d\alpha_{h_1}} = \frac{1}{A \cdot E_C \cdot R} \left(\frac{\Delta N_{\text{full}}}{Q_{\text{full}}} - \frac{\Delta N_{\text{empty}}}{Q_{\text{empty}}} \right) \frac{1}{\Delta W \Delta Q^2 \Delta^5 \tau \tilde{L}}$$

Acceptance correction factors for various Q^2 bins



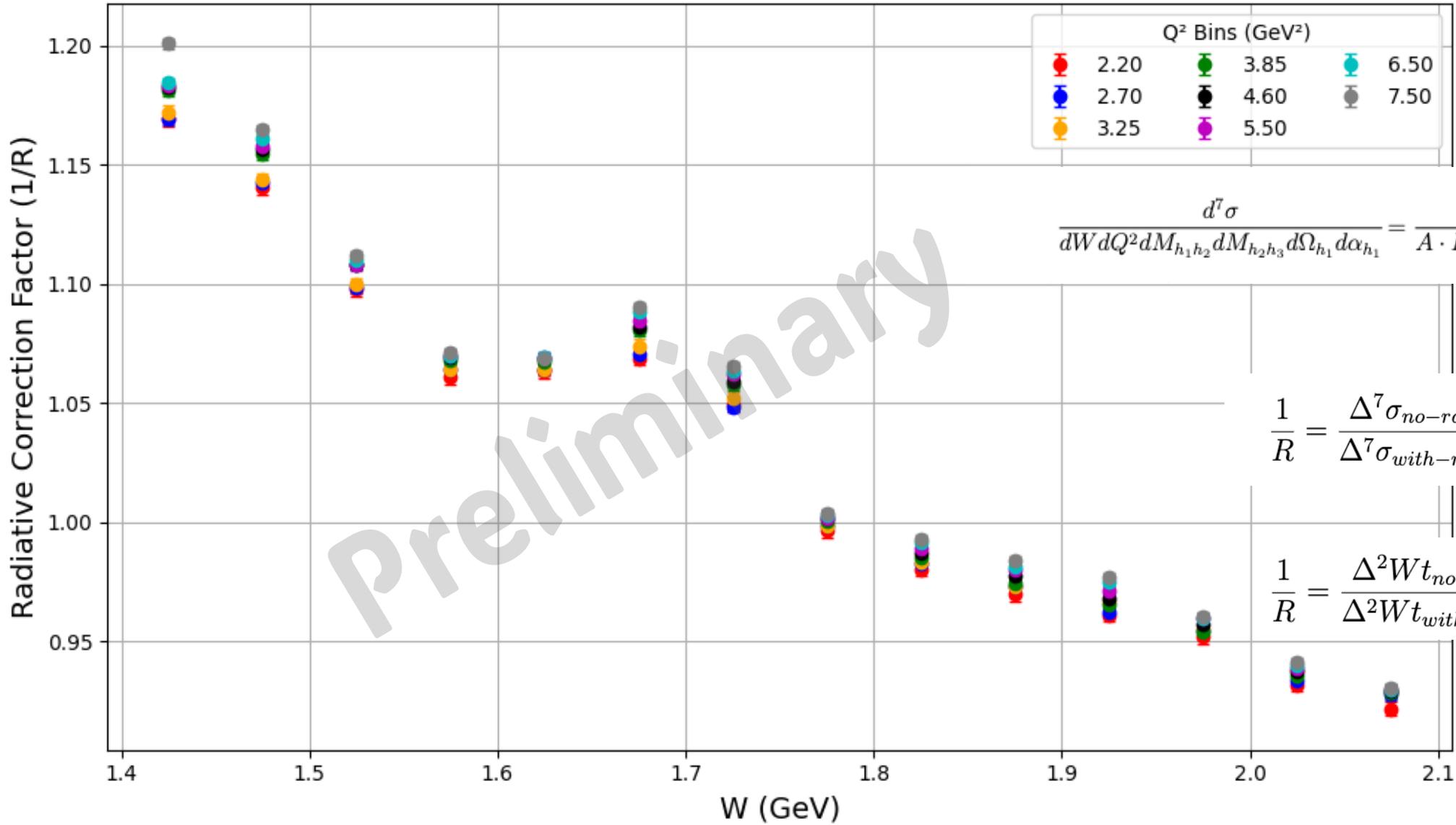
Acceptance correction factors for all W- Q^2 bins



$$A[\Delta W, \Delta Q^2, \Delta^5 \tau] = (\text{THnSparseD}^*) \text{acceptance_7D_hist}[\Delta W, \Delta Q^2, \Delta^5 \tau] =$$

$$(\text{THnSparseD}^*) \text{h_sim_rec_7D_hist}[\Delta W, \Delta Q^2, \Delta^5 \tau] / (\text{THnSparseD}^*) \text{h_thrown_7D}[\Delta W, \Delta Q^2, \Delta^5 \tau]$$

Radiative Effects Correction Factors



The systematics error for this effect is taken 5%, as it was the case for previous double-pion channel analysis.

Reconstruction efficiency correction factor

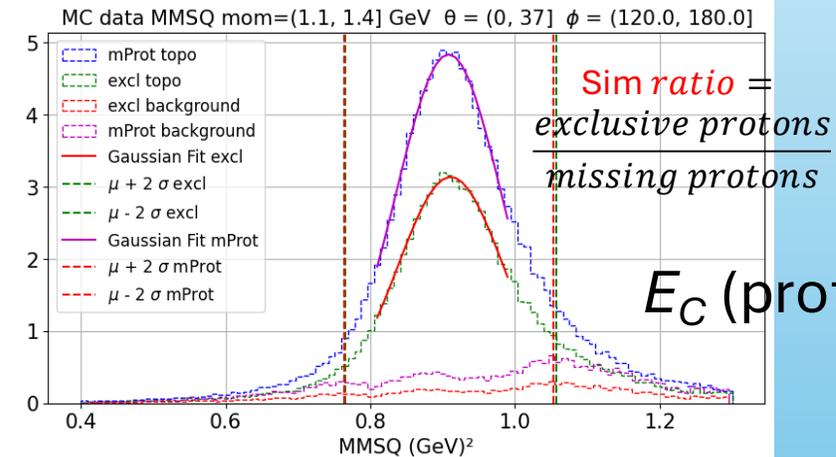
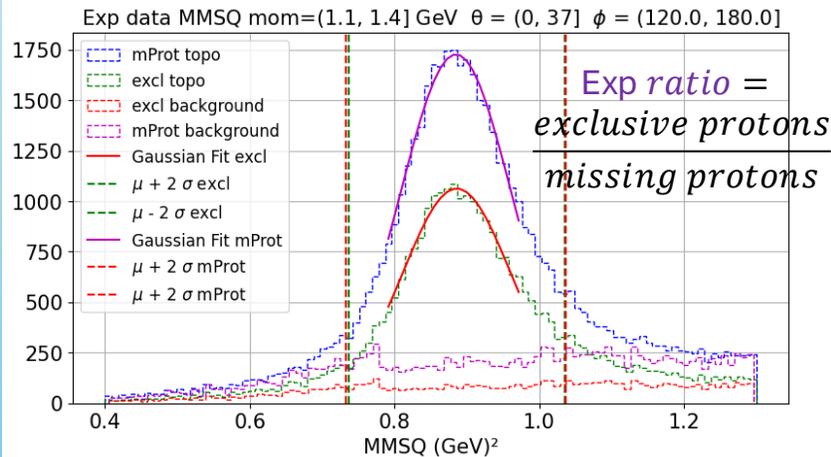
7.3.1 EFFICIENCY CORRECTION FACTOR FOR PROTONS

Table 7.1 Binning for proton efficiency factor

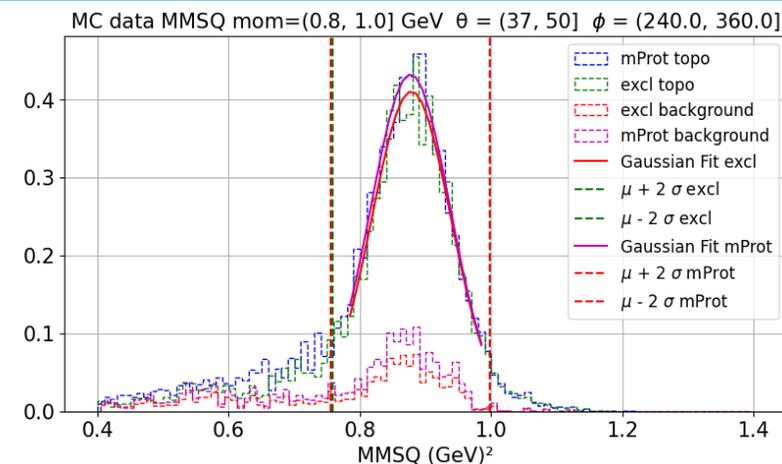
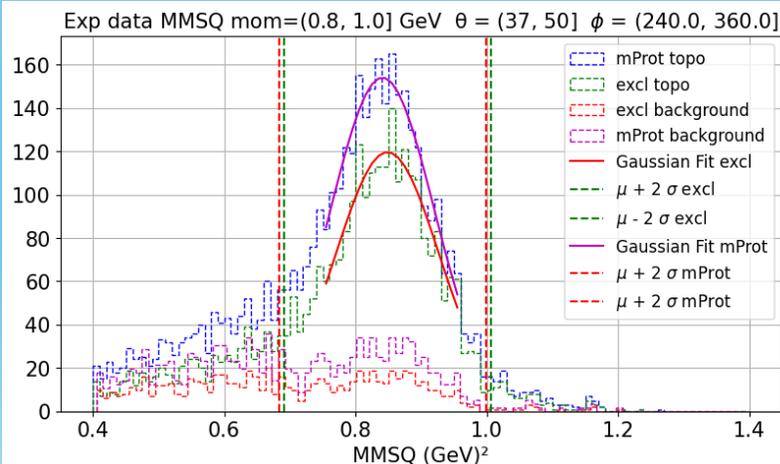
θ (degree)	Momentum (GeV)	ϕ (degree)
0-37	0.4, 0.8, 1.1, 1.4, 1.7, 2.0, 2.5, 3.0, 4.0	0, 60, 120, 180, 240, 300, 360
37-50	0.5, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.2	0, 120, 240, 360

$$\frac{d^7\sigma}{dW dQ^2 dM_{h_1 h_2} dM_{h_2 h_3} d\Omega_{h_1} d\alpha_{h_1}} = \frac{1}{A E_C R} \left(\frac{\Delta N_{\text{full}}}{Q_{\text{full}}} - \frac{\Delta N_{\text{empty}}}{Q_{\text{empty}}} \right) \Delta W \Delta Q^2 \Delta^5 \tau \tilde{L}$$

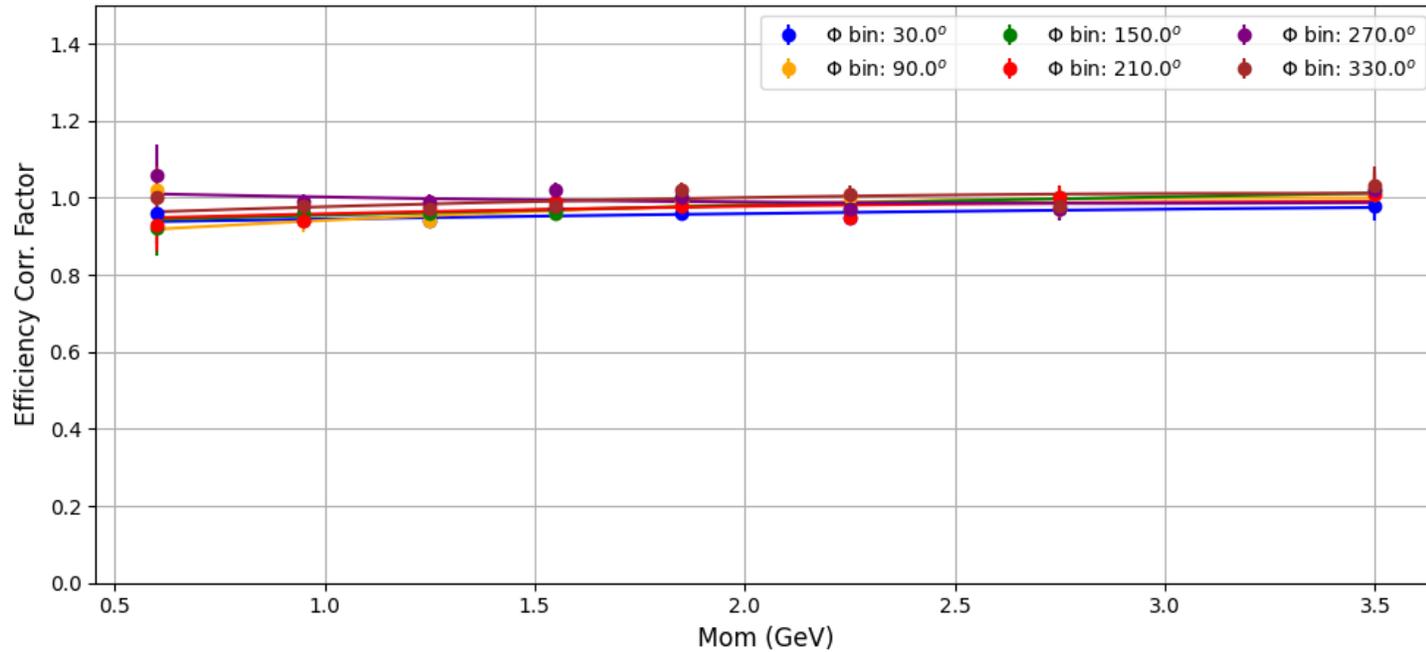
$$E_C = E_C(\text{proton}) \times E_C(\text{pip})$$



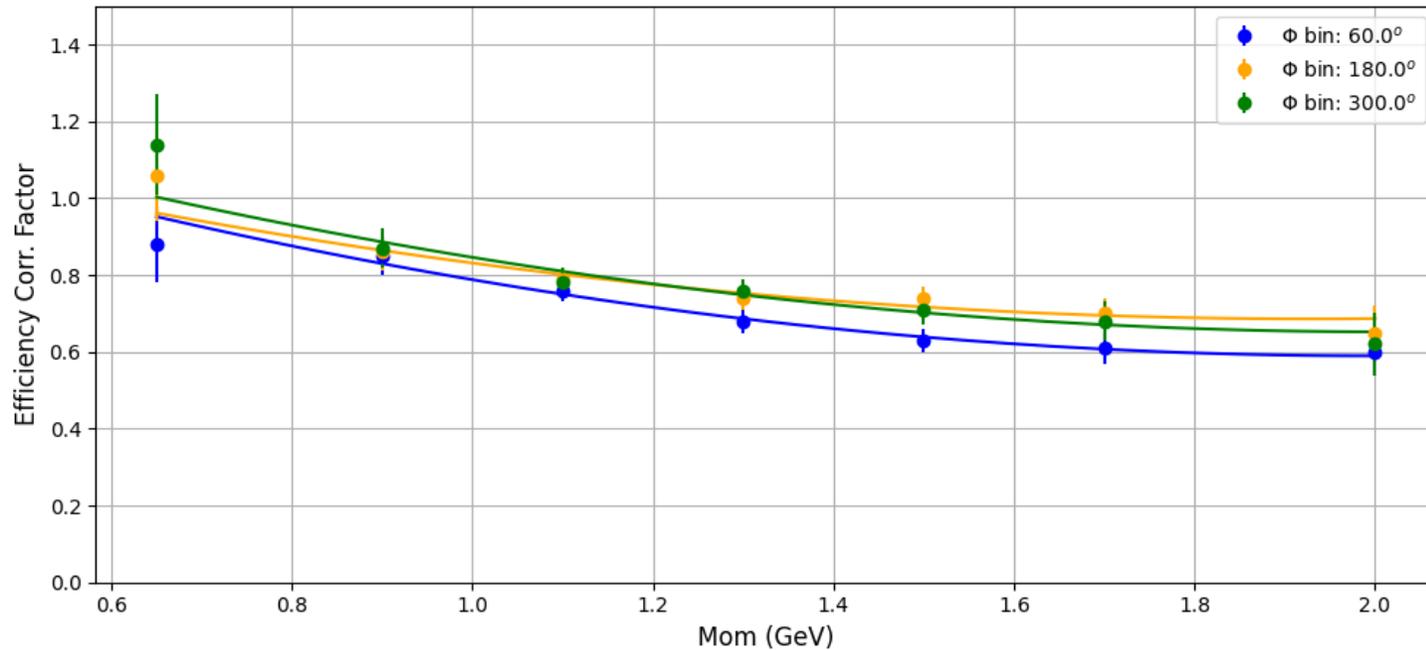
$$E_C(\text{proton}) = \frac{\text{Exp ratio}}{\text{Sim ratio}}$$



Efficiency factors for protons with $\theta = (0^\circ - 37^\circ)$



Efficiency factors for protons with $\theta = (37^\circ - 50^\circ)$



$$\frac{d^7\sigma}{dW dQ^2 dM_{h_1 h_2} dM_{h_2 h_3} d\Omega_{h_1} d\alpha_{h_1}} = \frac{1}{A E_C R} \frac{\left(\frac{\Delta N_{\text{full}}}{Q_{\text{full}}} - \frac{\Delta N_{\text{empty}}}{Q_{\text{empty}}}\right)}{\Delta W \Delta Q^2 \Delta^5 \tau \tilde{L}}$$

This shows the experimental measurement and simulation reconstruction are equally efficient.

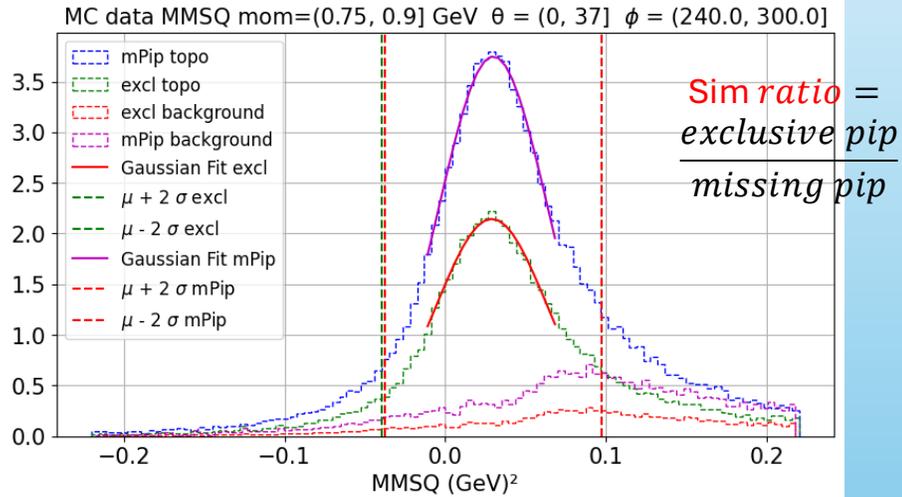
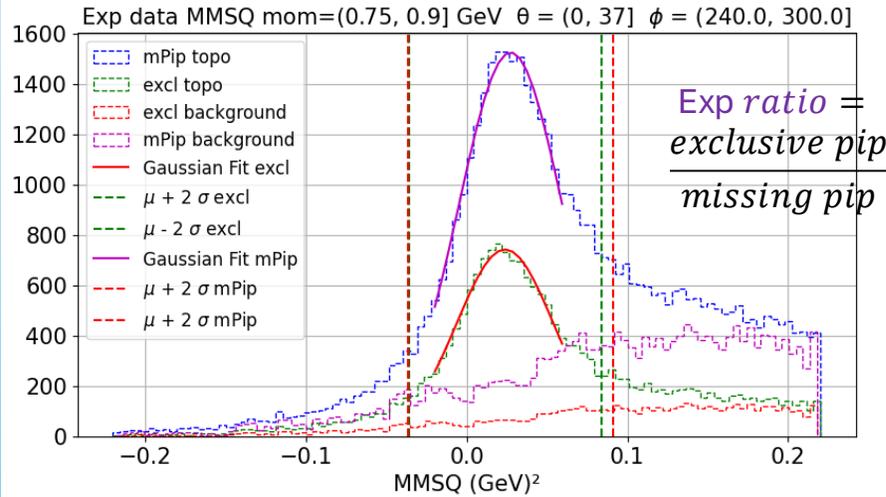
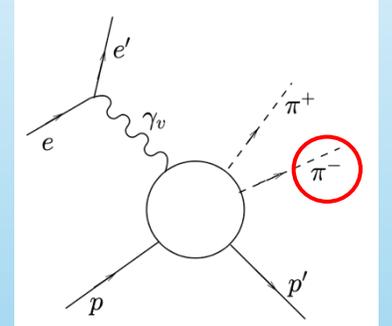
This shows the experimental measurement is less efficient than reconstruction in simulations.

Table 7.2 Binning for π^+ efficiency factor

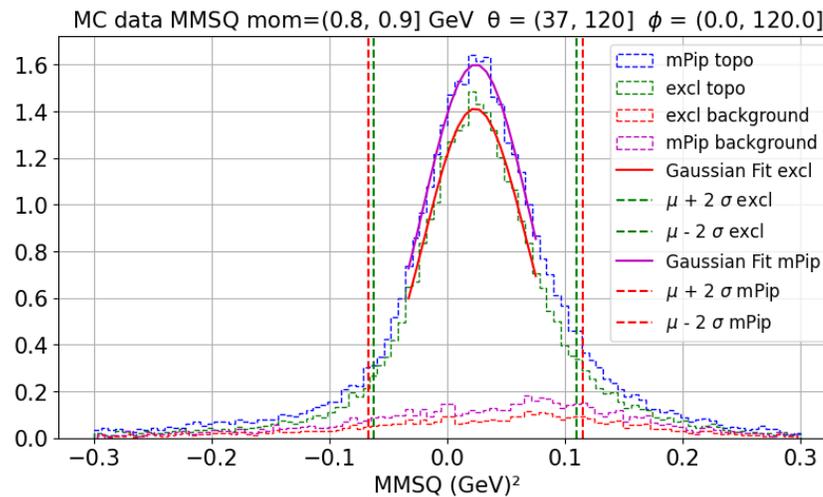
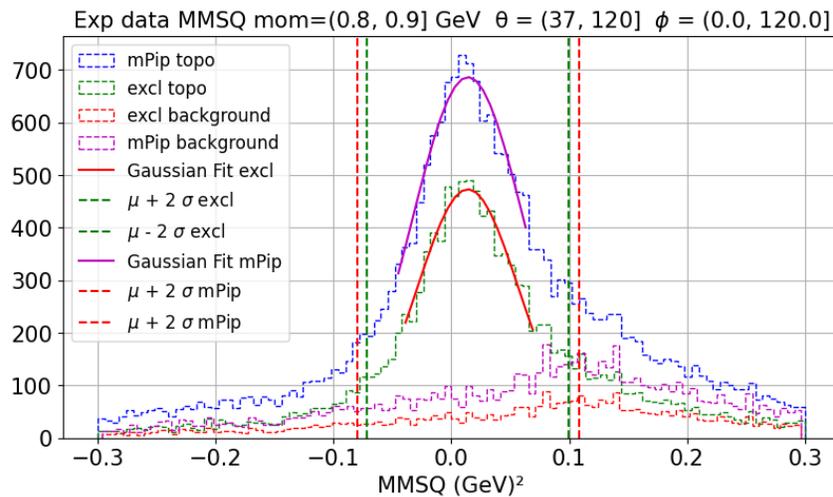
θ (degree)	Momentum (GeV)	ϕ (degree)
0-37	0.4, 0.6, 0.75, 0.9, 1.1, 1.3, 1.5, 1.7, 2.3, 3.50	0, 60, 120, 180, 240, 300, 360
37-120	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.7	0, 120, 240, 360

$$\frac{d^7\sigma}{dW dQ^2 dM_{h_1 h_2} dM_{h_2 h_3} d\Omega_{h_1} d\alpha_{h_1}} = \frac{1}{A E_C R} \left(\frac{\Delta N_{\text{full}}}{Q_{\text{full}}} - \frac{\Delta N_{\text{empty}}}{Q_{\text{empty}}} \right) \frac{1}{\Delta W \Delta Q^2 \Delta^5 \tau \tilde{L}}$$

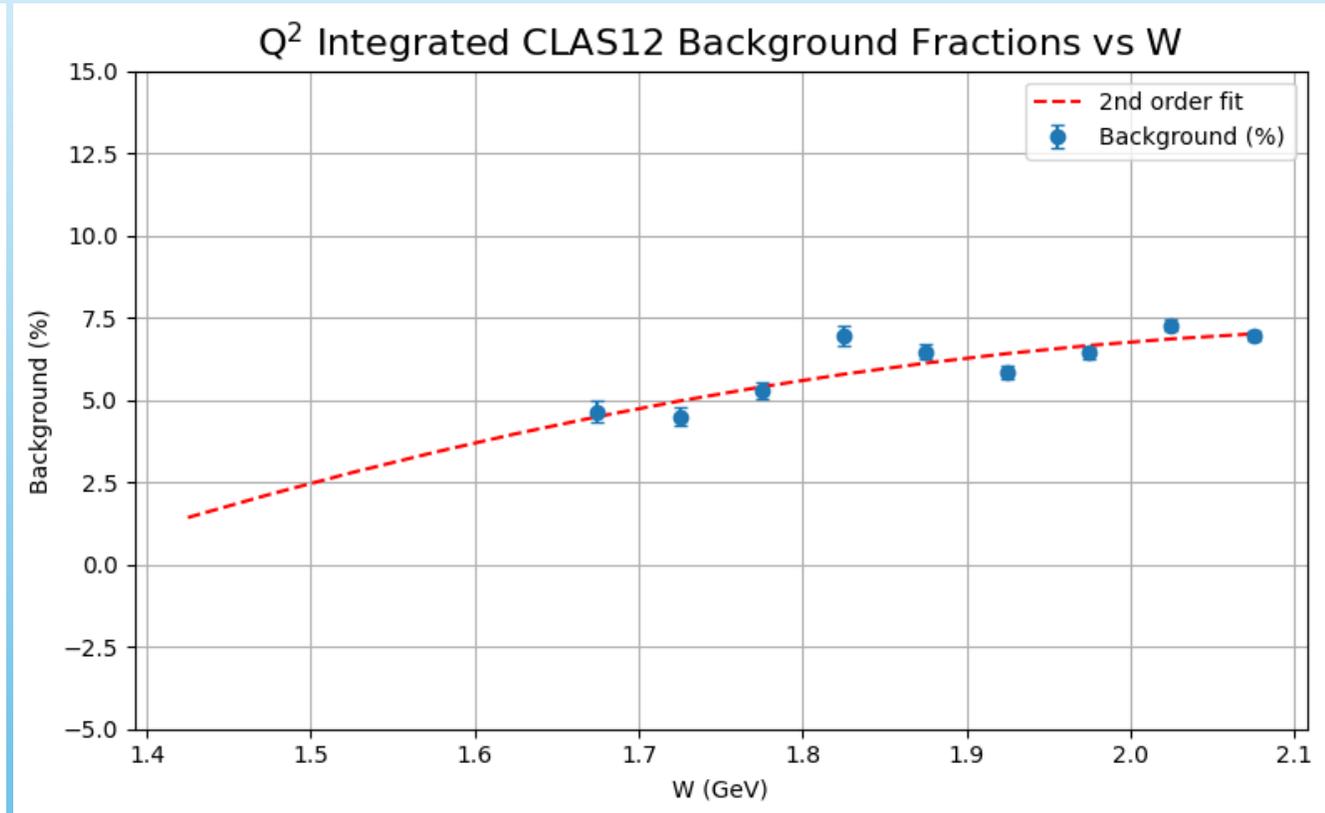
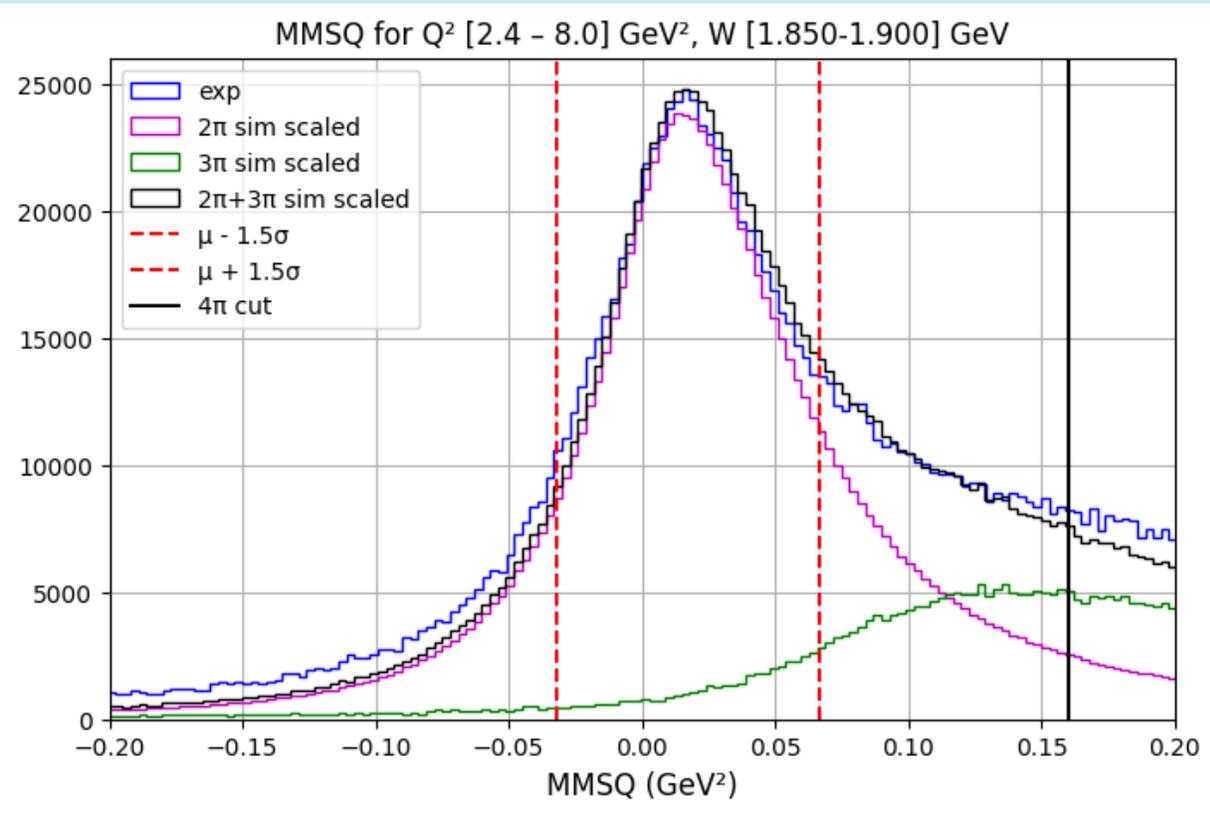
$$E_C = E_C(\text{proton}) \times E_C(\text{pip})$$



$$E_C(\text{pip}) = \frac{\text{Exp ratio}}{\text{Sim ratio}}$$



Background subtraction



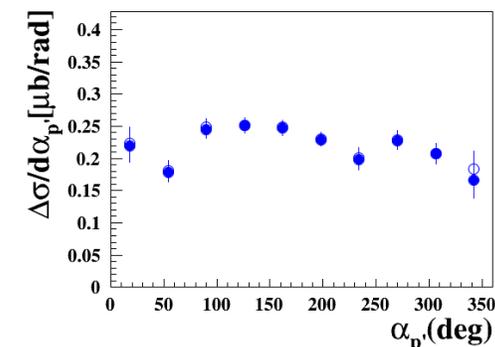
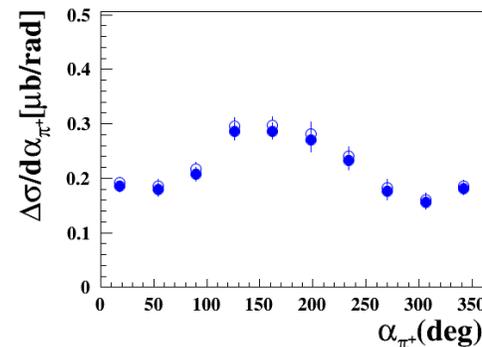
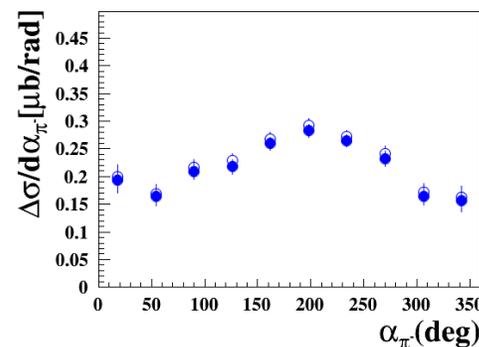
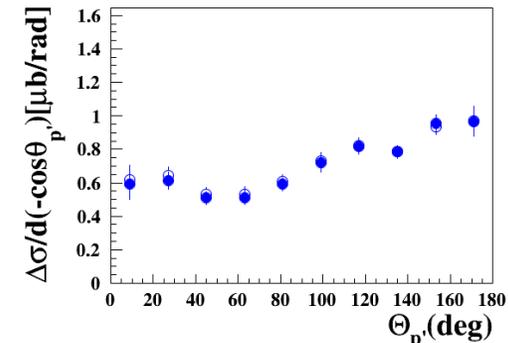
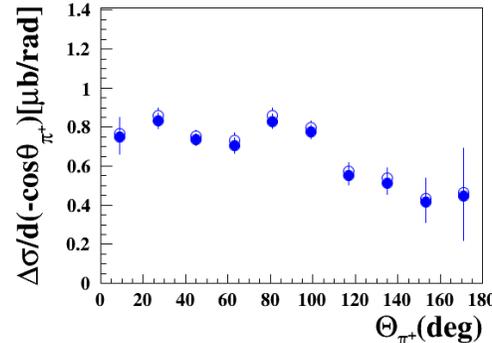
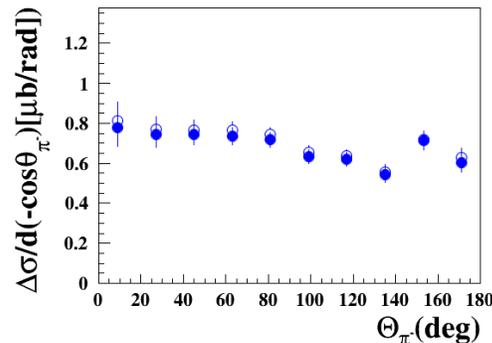
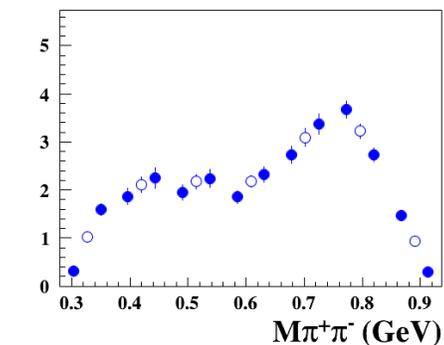
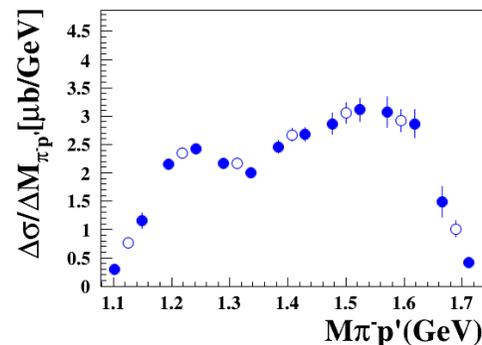
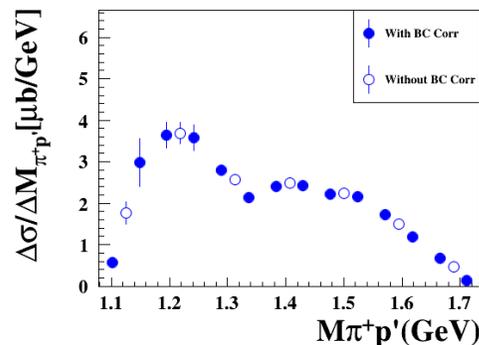
Bin centering corrections

The extracted cross sections are reported at the central value of each bin. However, these reported values represent the average cross section across the entire bin.

$$BC(W) = \frac{Yield(mid)}{Yield(average)}$$

$$BC_{corr} = BC(W) \times BC(Q^2) \times BC(H)$$

$$\sigma_{corr} = BC_{corr} \times \sigma_{uncorr}$$

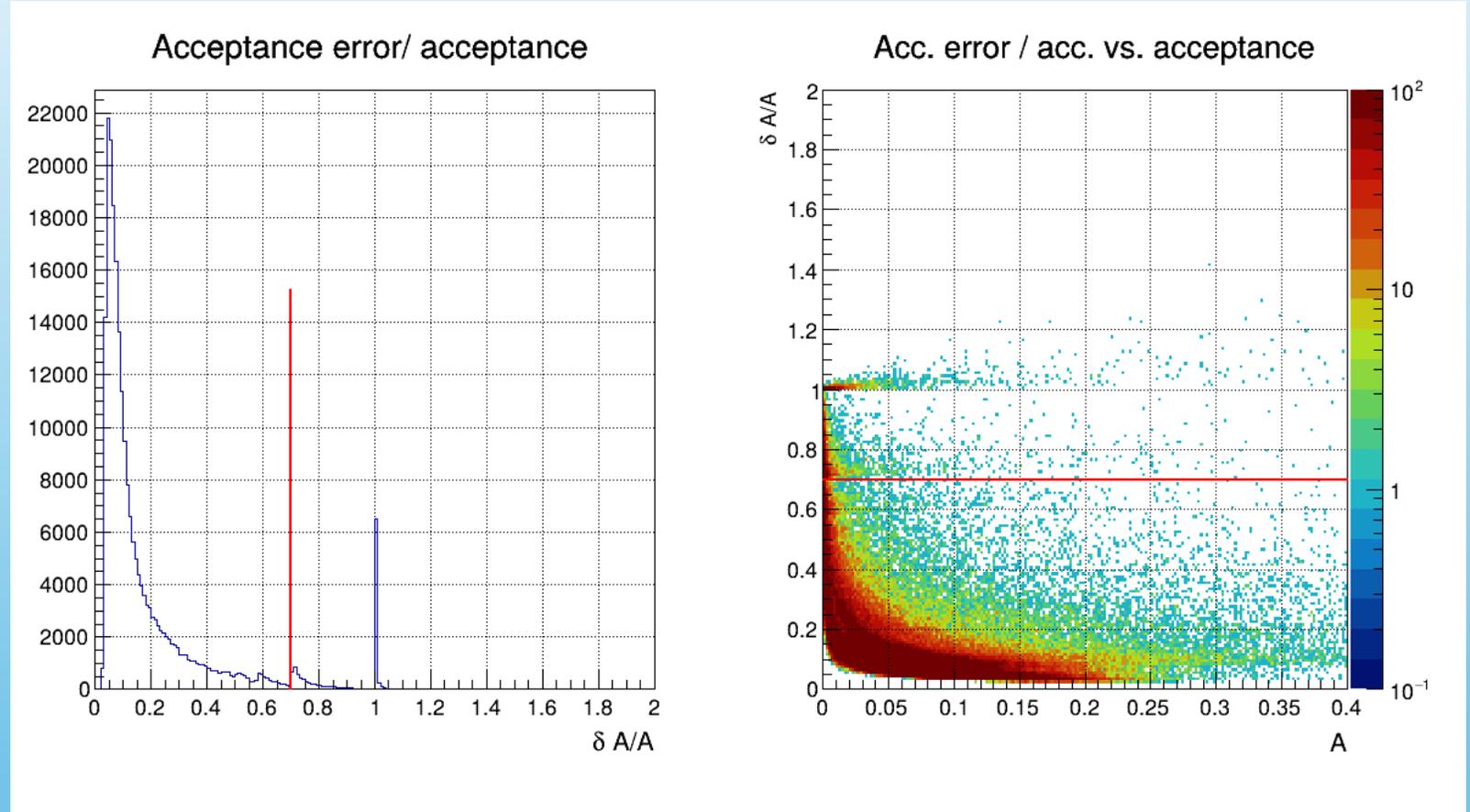


Relative acceptance errors ($\delta A/A$) cut

$$A(\Delta W, \Delta Q^2, \Delta^5 \tau) = \frac{N_{\text{rec}}}{N_{\text{gen}}}$$

1. Sufficient simulations in each 5D bins is crucial to get the proper acceptance factors
2. Low filled 5D bins can leads to the higher acceptance errors

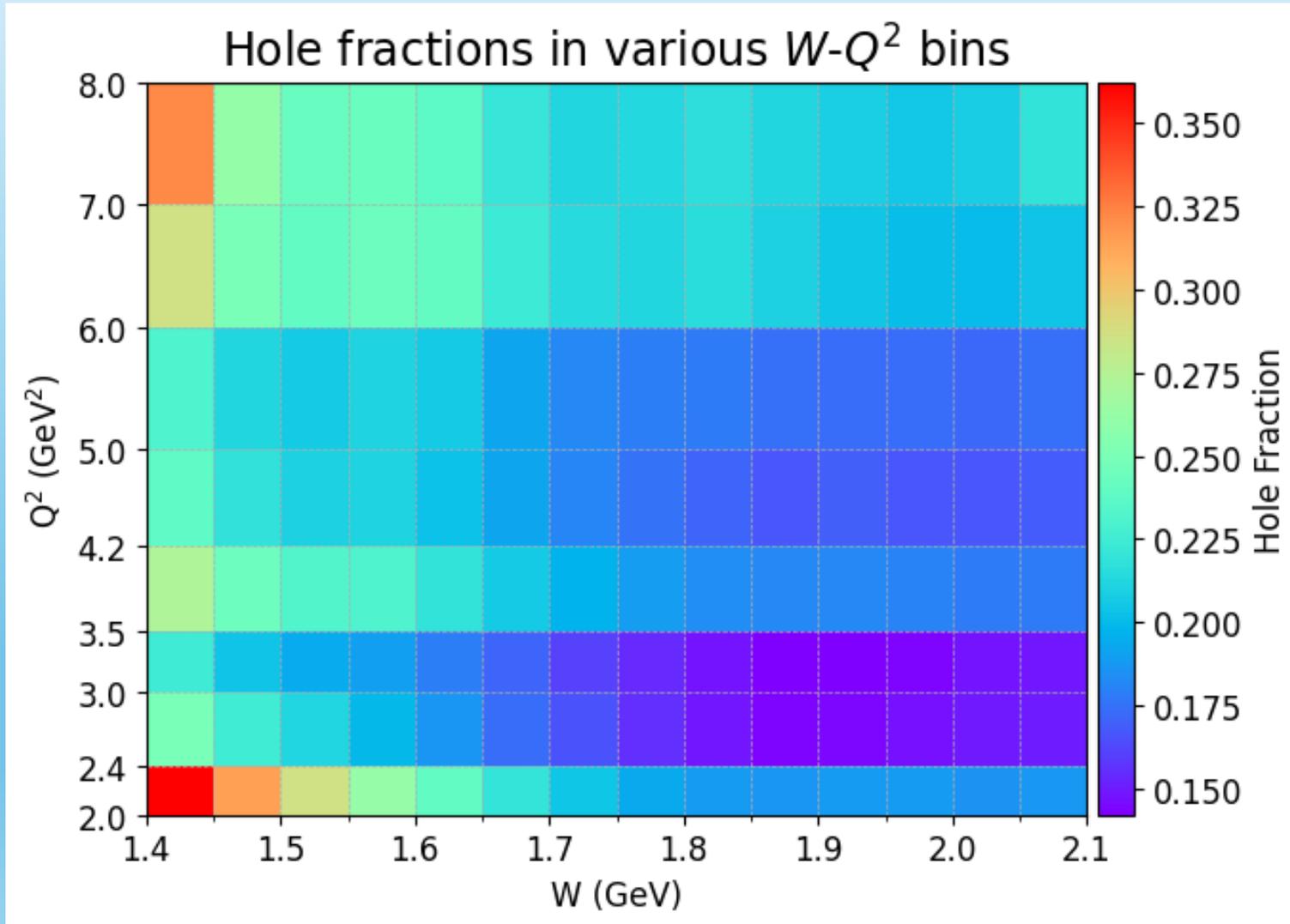
$$\delta A = A \sqrt{\left(\frac{\delta A_{\text{rec}}}{N_{\text{rec}}}\right)^2 + \left(\frac{\delta A_{\text{gen}}}{N_{\text{gen}}}\right)^2}$$



1.80-W-1.85 GeV, 2.4-Q²-3.0 GeV²

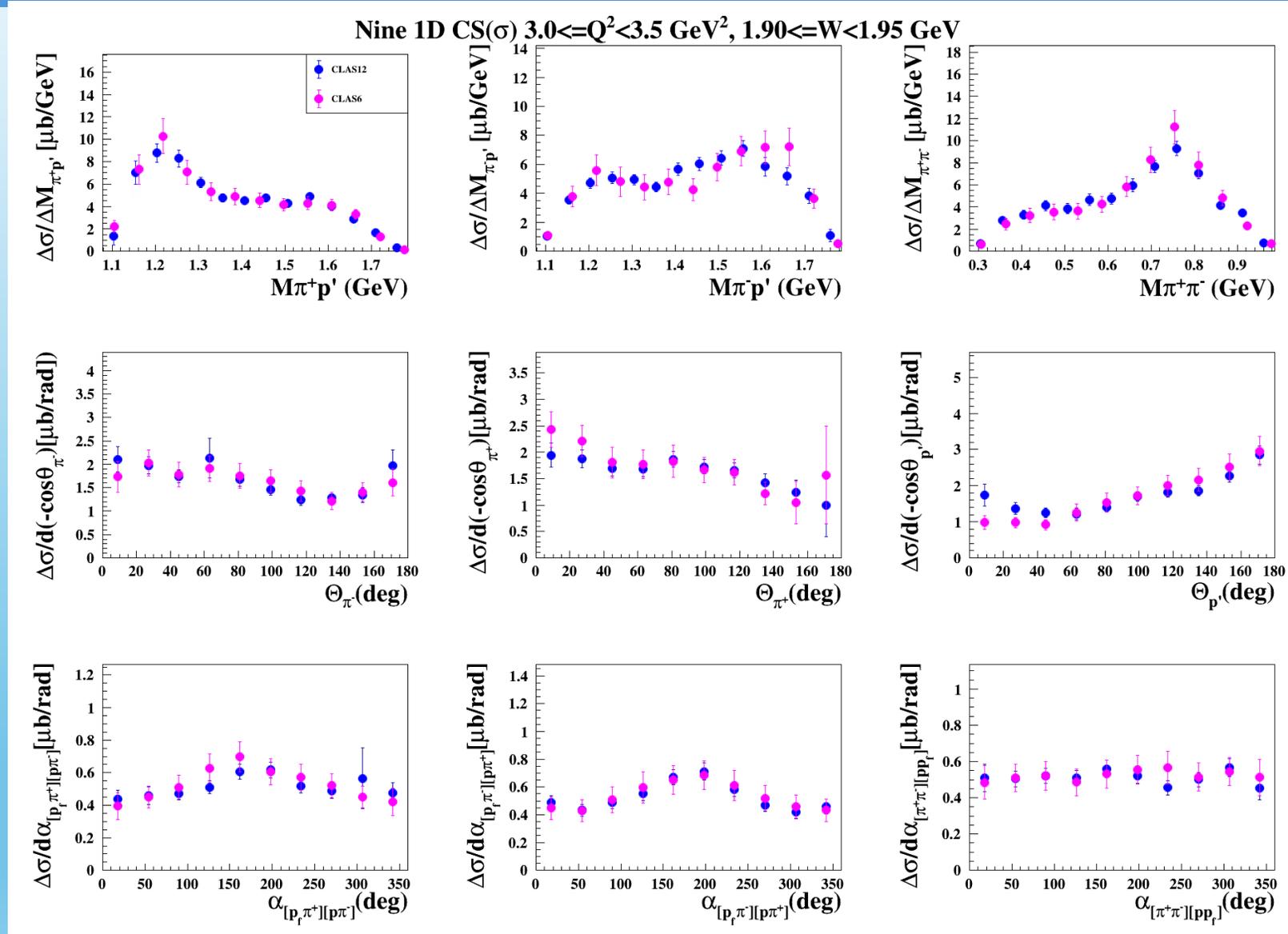
Hole fractions (A=0) in simulations

- CLAS12 detector does not fully cover 4π angular area - Design constraint of detector leads to some physical gaps called holes
- Insufficient simulations, and the acceptance error cuts also increases (artificial) holes
- We need to fill those holes by using scaled generated yields



As hole filling is model dependent its systematics is 50 % of the total hole contribution, for integrated cross sections it is estimated to be 4.55 %

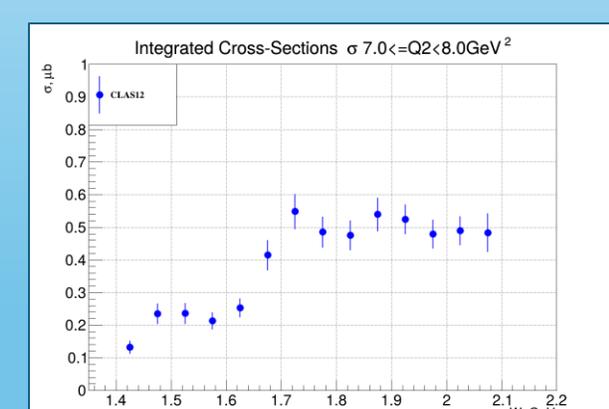
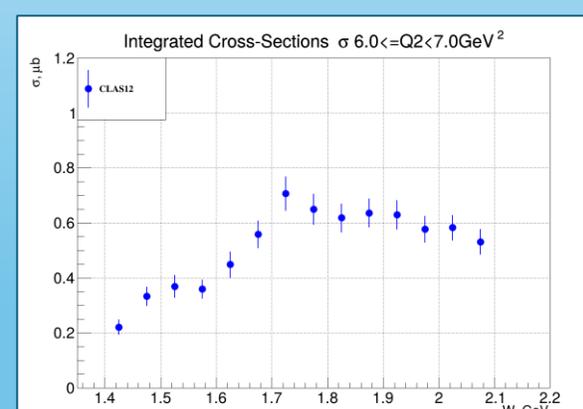
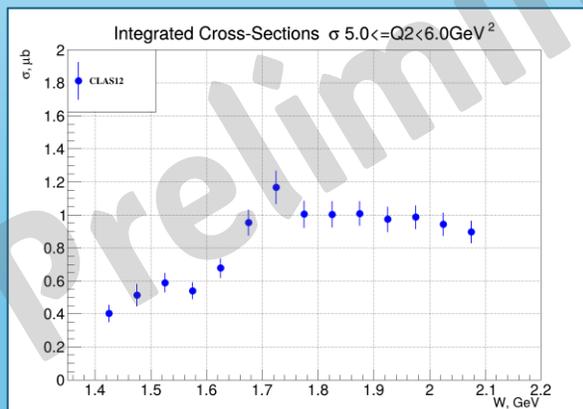
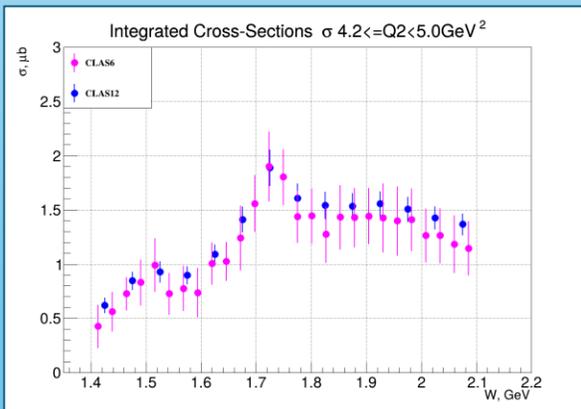
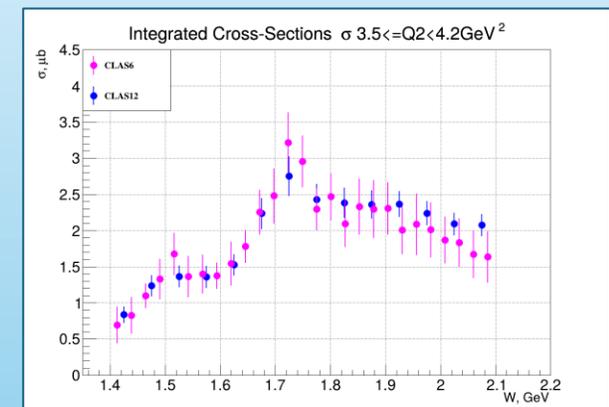
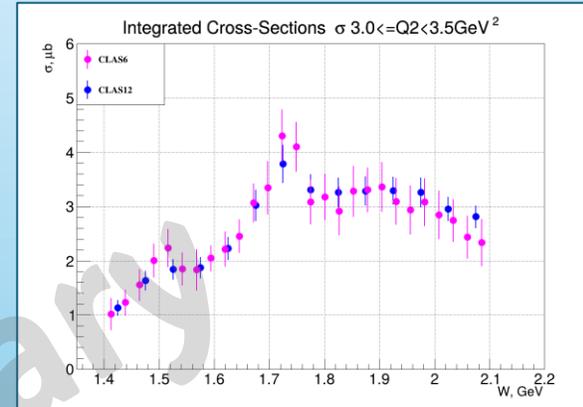
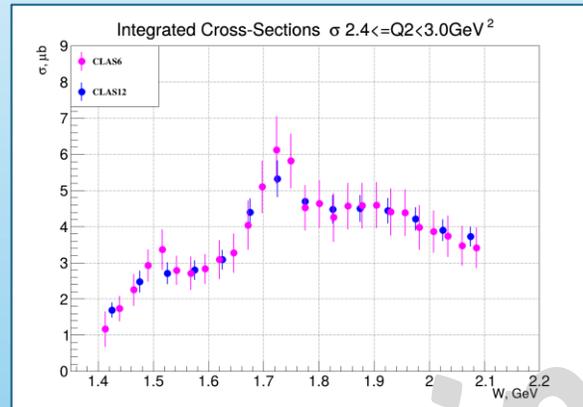
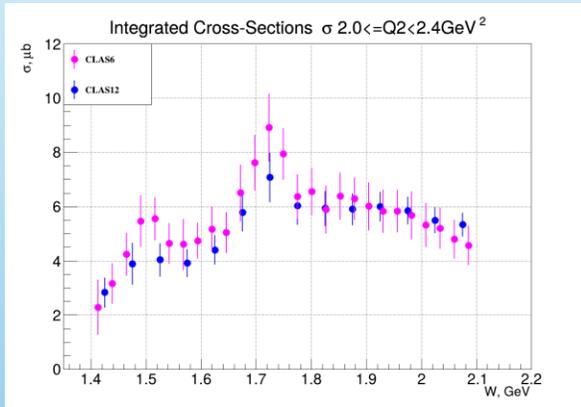
Results: Nine single-differential cross sections



Differential cross sections from the measurements with CLAS and CLAS12 in overlapping (W, Q^2) areas are consistent.

These 1-D cross sections will be fitted with JM Model to extract the N^* resonance electrocouplings

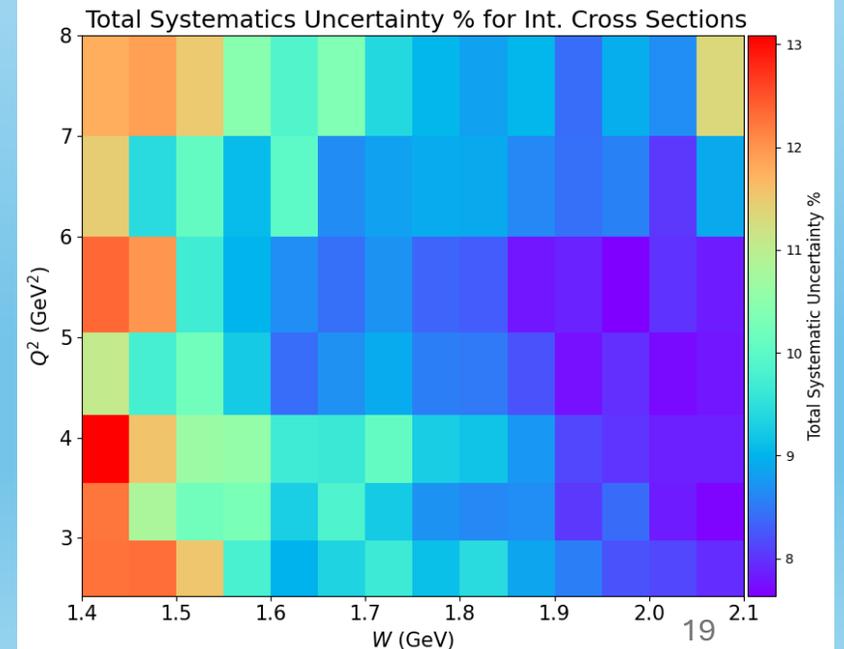
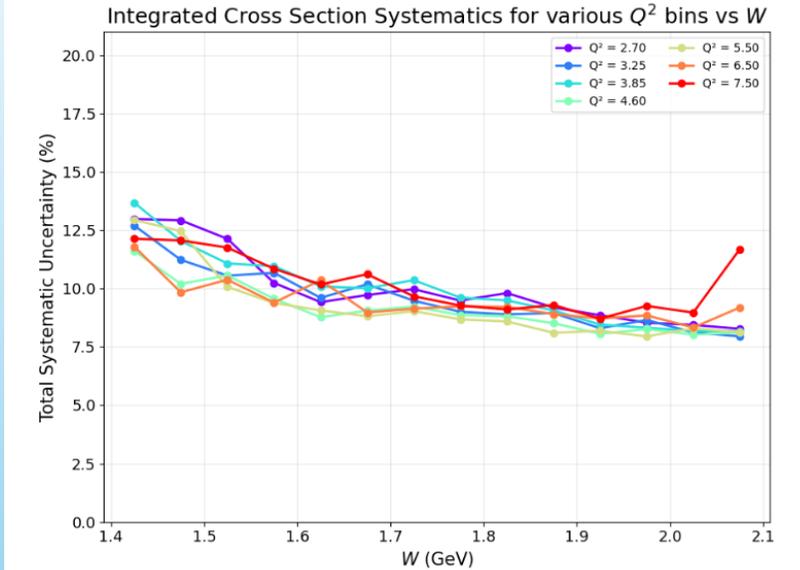
Results: Integrated Cross Sections



Systematic Uncertainties

Table 8.3: List of estimated systematic uncertainties.

Item	Source	Uncertainty (%)
1	PID, fiducial volume, MMSQ cuts (all particles)	2.04
2	Momentum corrections	0.79
3	Particle efficiency corrections	2.83
4	Smearing MC data	1.42
5	Target length	1.00
6	HTCC Efficiency	2.00
7	Accumulated FC Charge	1.20
8	Background merging	3.00
9	Radiative effects	5.00
10	Model dependence	1.39
11	Bin centering	0.53
12	Variable set dependence	1.60
13	Acceptance uncertainty cut	0.47
14	Background subtraction	0.07
15	Kinematic hole filling	4.55
16	Total uncertainty	9.00



Conclusions and Publication Plan

- 1. The cross sections of an exclusive double-pion channel have been extracted using the CLAS12 RGA Fall 2018 dataset.**
- 2. Q^2 coverage of 1D cross sections has been extended from 5 GeV^2 up to 8 GeV^2 for the first time, which will be crucial for the JM model to extend its kinematic coverage.**
- 3. Extracted integrated/differential cross sections are consistent with previous CLAS results for overlapping bins, showing agreement within error bars.**
- 4. Systematic uncertainties have been estimated for both 1D and total cross sections, it is averaged about 9.0 % for total integrated cross sections.**
- 5. Analysis note is completed and submitted to analysis review committee.**
- 6. Plan to publish the final cross sections after approval, paper draft is almost ready.**

Acknowledgements



UNIVERSITY OF
South Carolina



Our Team



R.W. Gothe



V.I. Mokeev



D.S. Carman



K. Neupane

Back up slide: 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
- Vertex position cut around target
- 3.5 sigma cut on sampling fraction
- PCAL fiducial cuts:
- DC fiducial cuts:
- Cuts on V and W planes of the PCAL
- PCAL inefficient region cuts
- $1.4 \text{ GeV} < W < 2.15 \text{ GeV}$
- $2.0 \text{ GeV}^2 < Q^2 < 9.0 \text{ GeV}^2$

Hadron pid cuts:

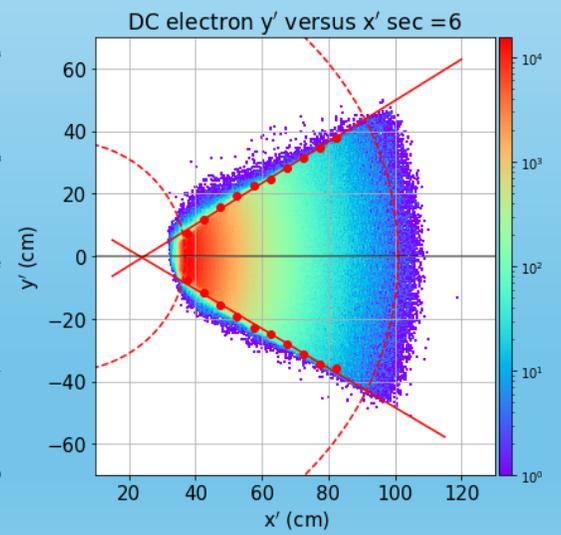
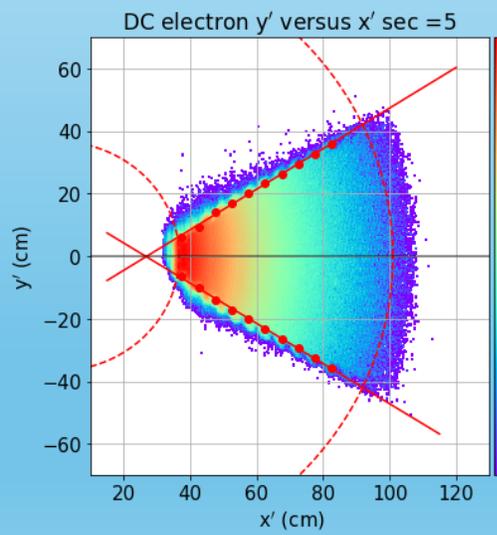
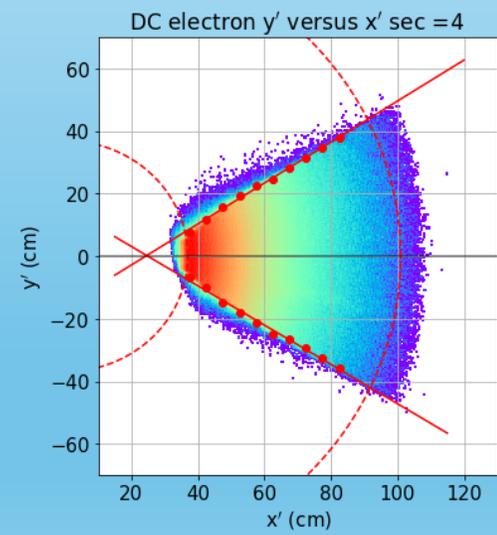
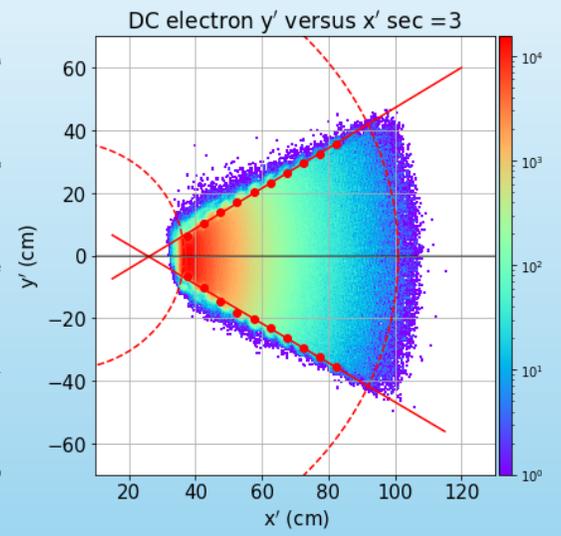
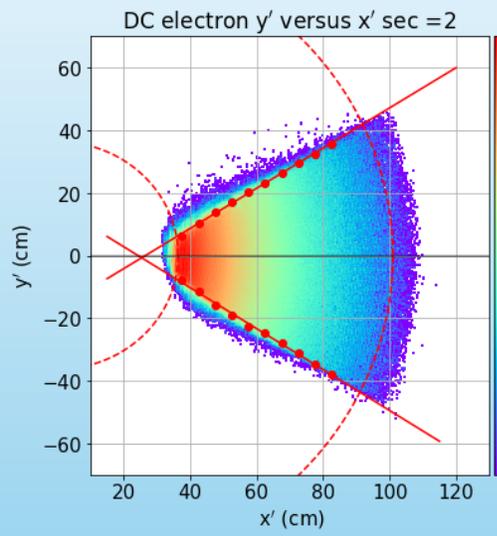
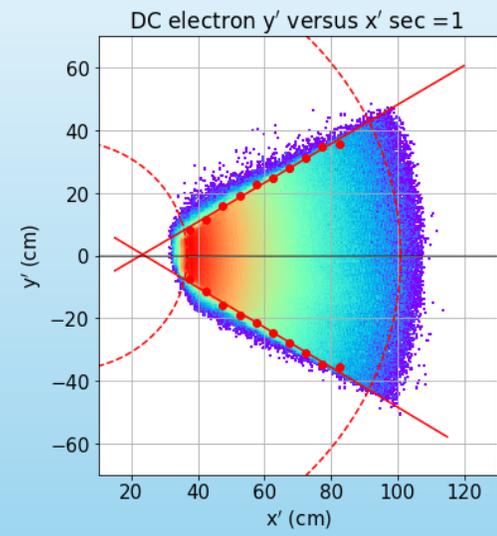
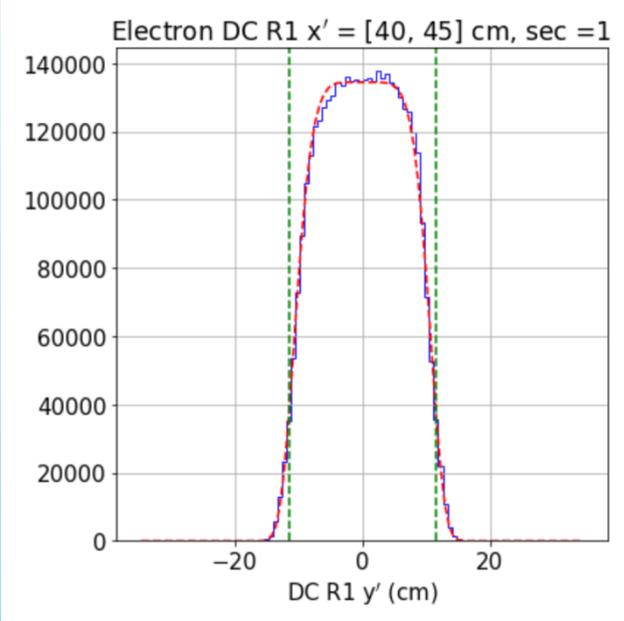
- Event-builder pid cuts for proton, π^+ and π^-
- Charge cut
- Status Cuts
- Δt cut: 3 sigma cuts for all hadrons
- Momentum of FTOF particles > 0.5 GeV
- Momentum of CTOF particle > 0.2 GeV
- Chi-Square pid cuts
- Difference between vertex position of hadron and electron cut
- DC fiducial cuts for FD hadrons
- Transverse momentum versus phi cuts for CD positive hadrons
- DC inefficient regions cuts
- Removal of CD-FD tracks

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

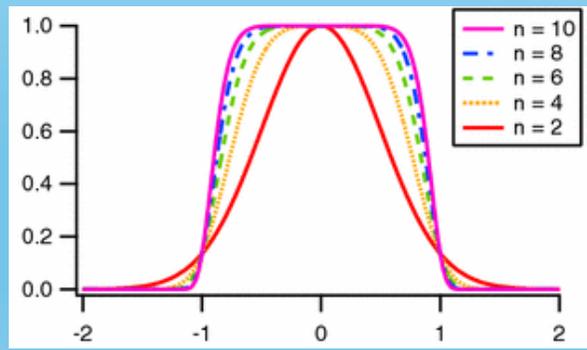
where l_{SC} , t_{SC} are path length and time from vertex to SC,
vertex time = $l_{SC}^e - \frac{t_{SC}^e}{c}$, for electrons

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

Back up slide: Electron DCR1 fiducial cuts

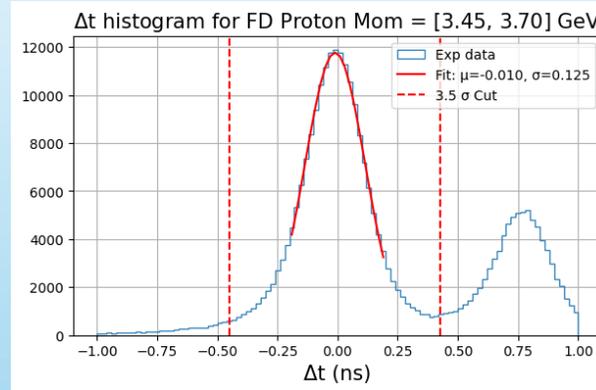
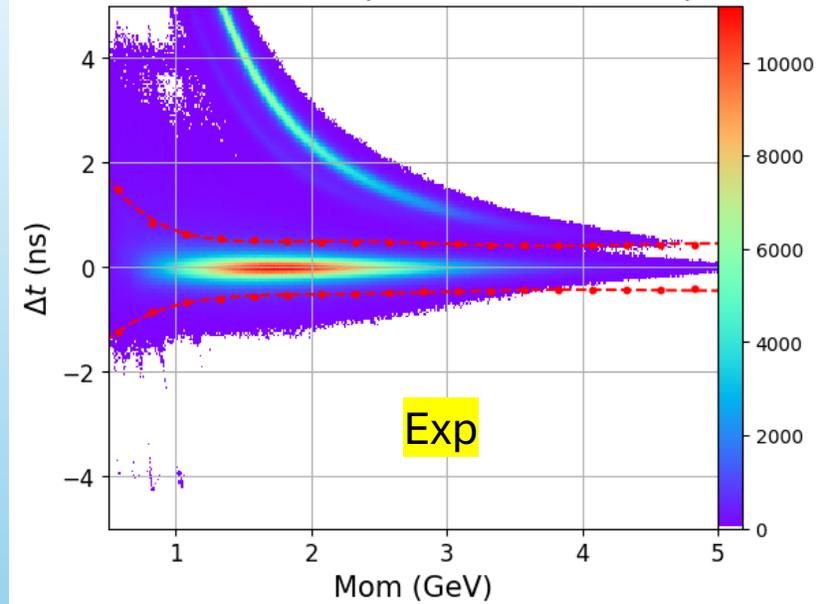


$$f(x) = Ae^{-0.5\left(\frac{x-\mu}{\sigma}\right)^n}$$



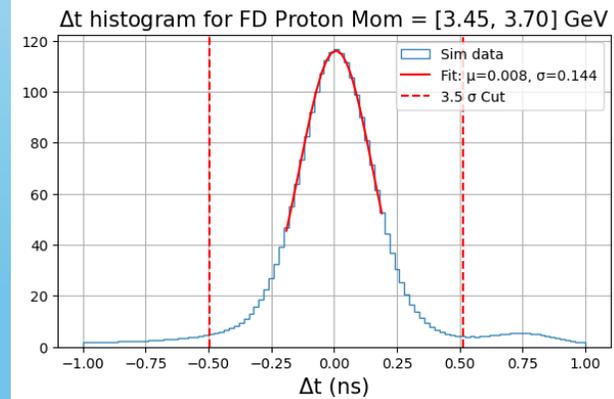
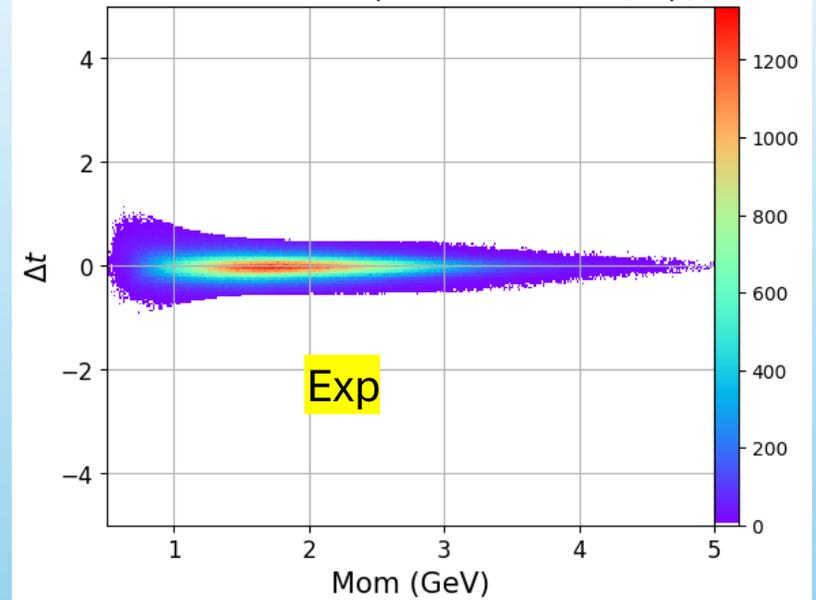
Back up slide: Δt versus Momentum cuts : FTOF

Δt versus P FTOF proton before cuts (exp)

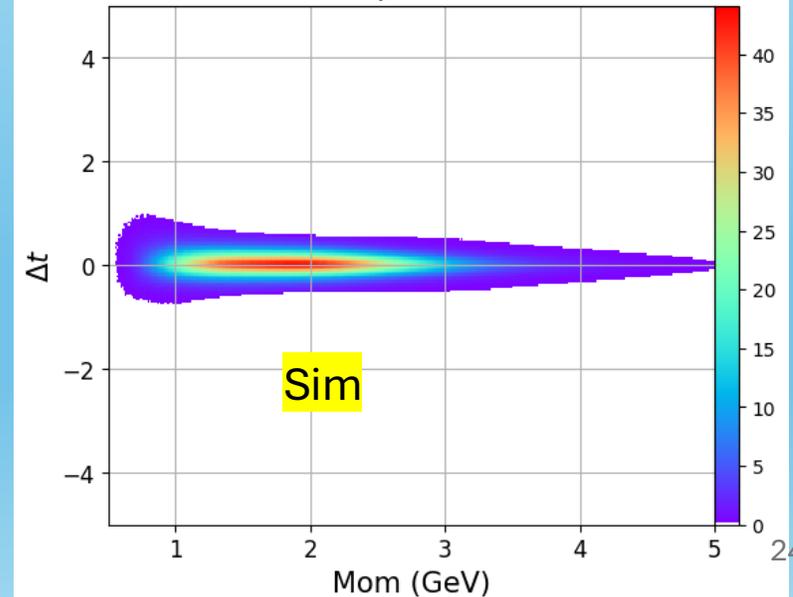


$$\Delta t = \frac{l_{sc}}{\beta c} - tS_C + \text{vertex time,}$$

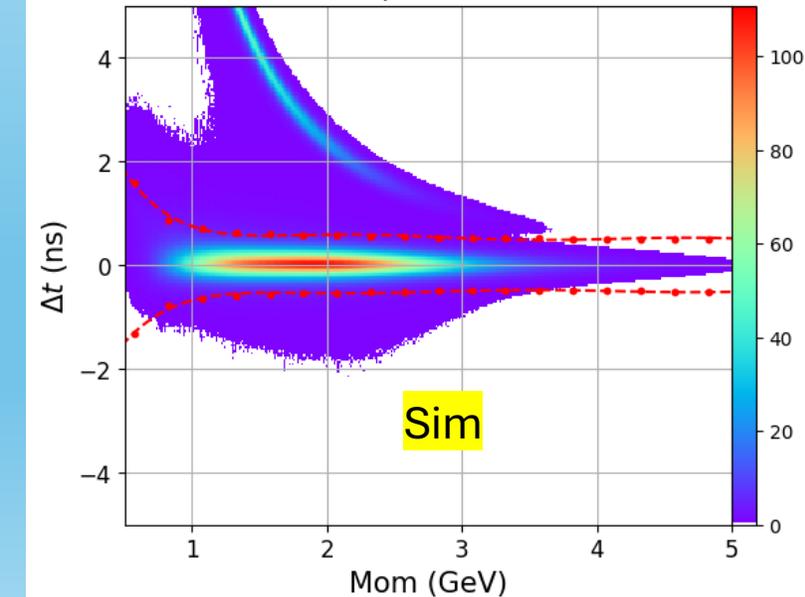
Δt versus P FTOF proton after cuts (exp)



Δt versus P FTOF proton after cuts (sim)

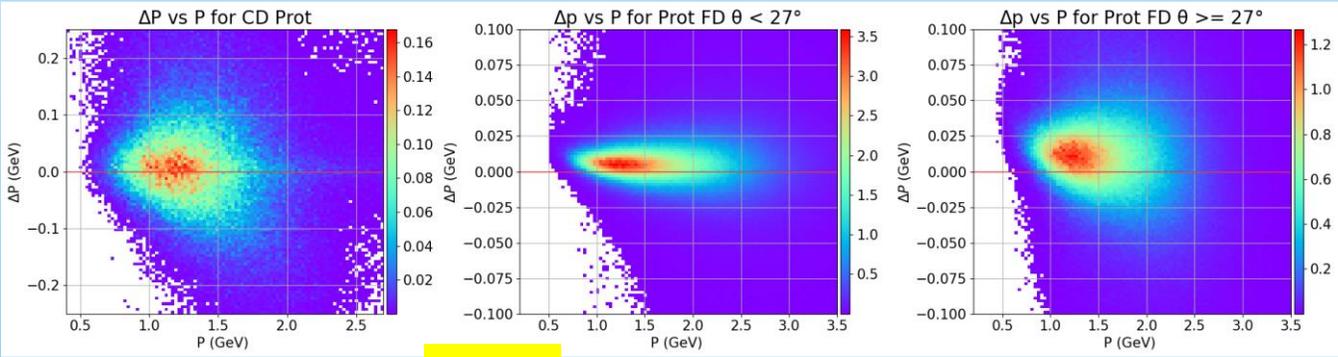
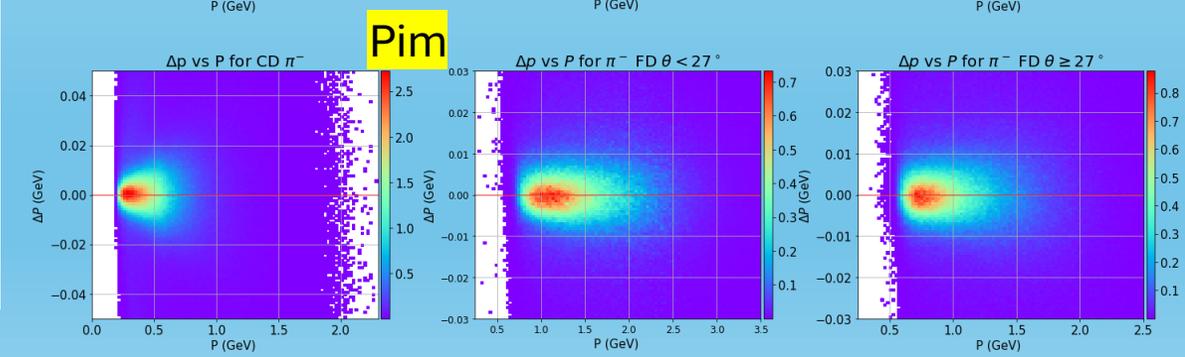
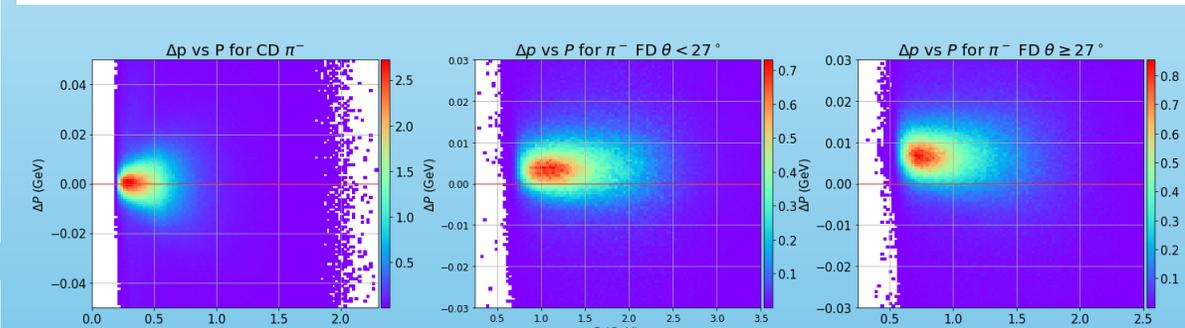
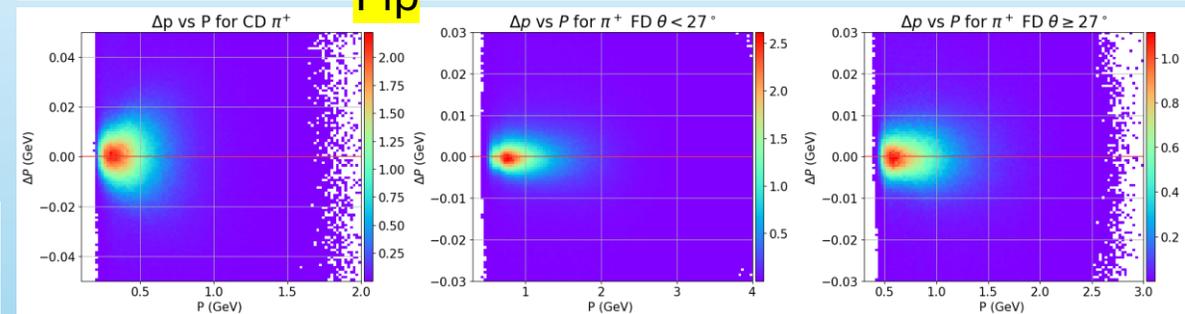
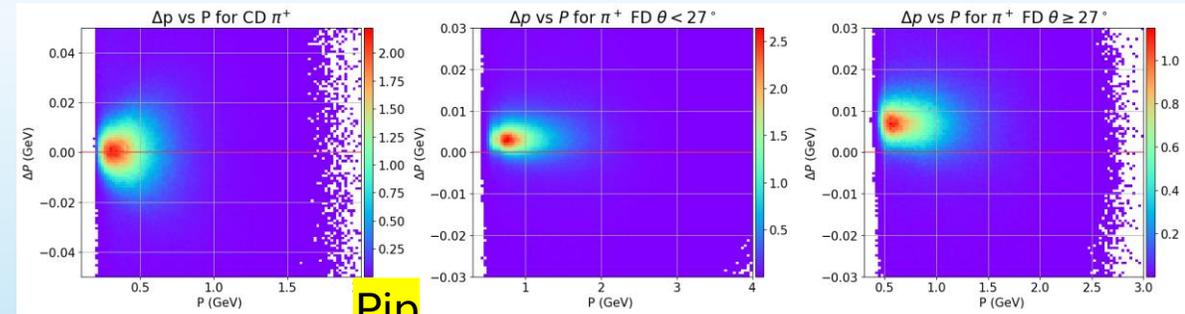


Δt versus P FTOF proton before cuts (sim)

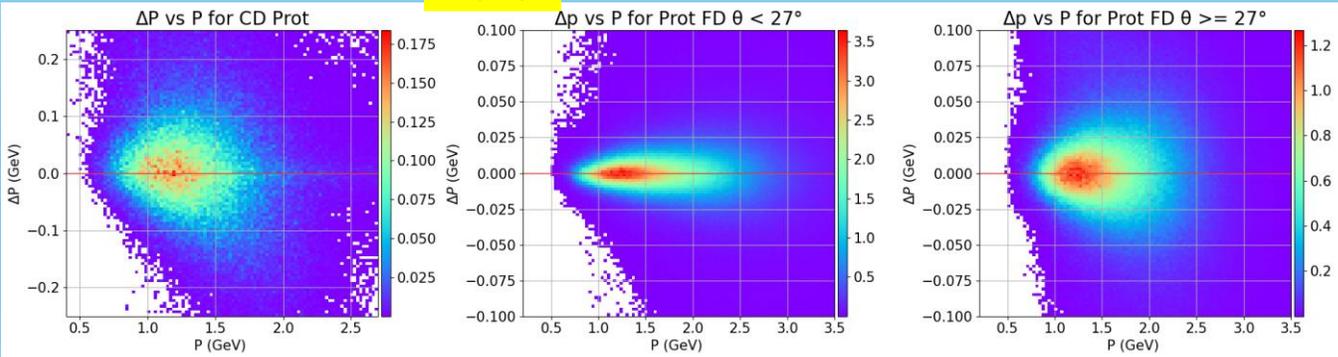


Back up slide: Energy Loss Corrections

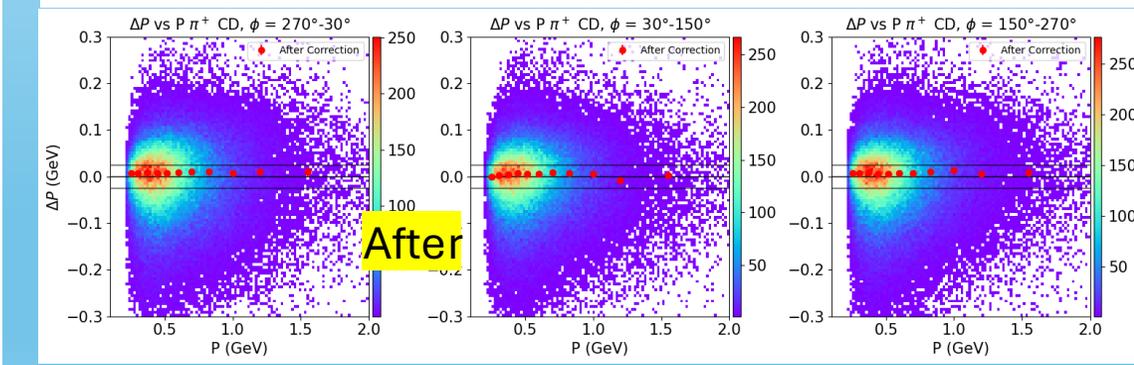
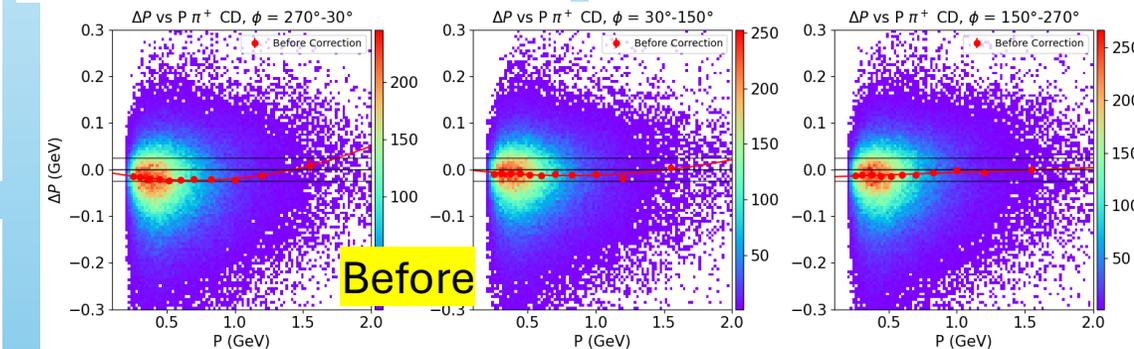
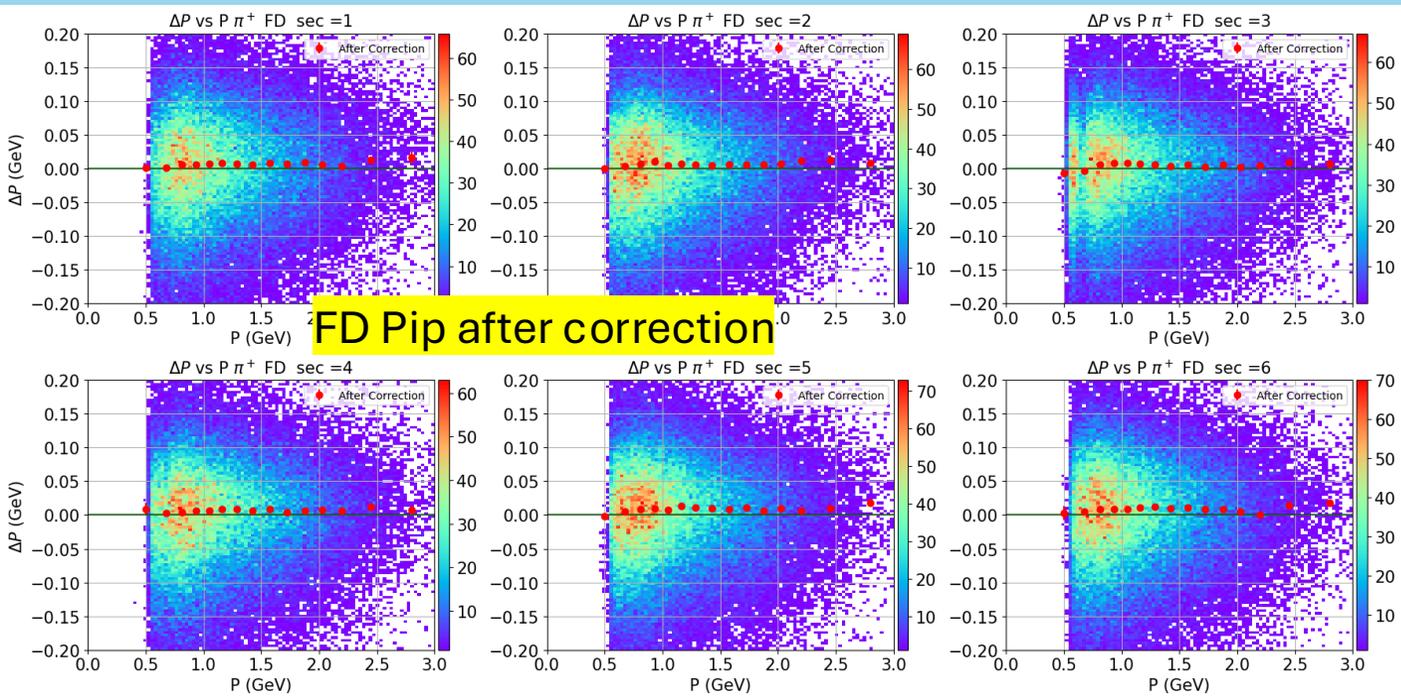
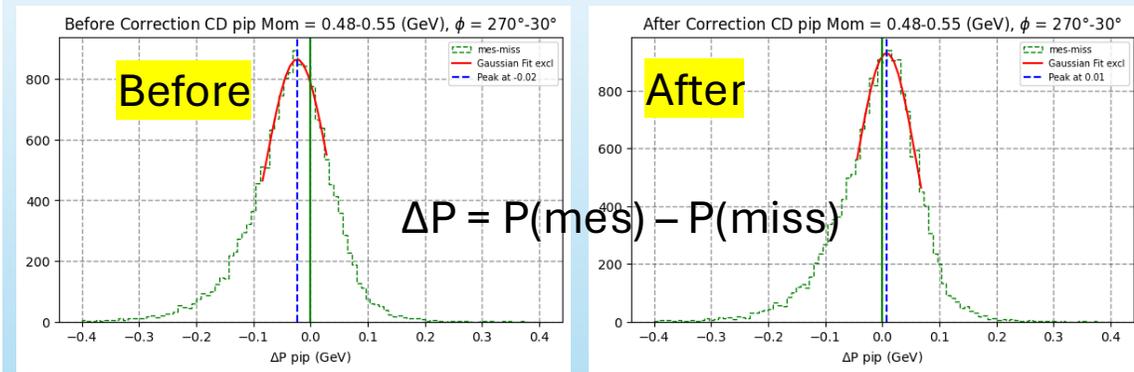
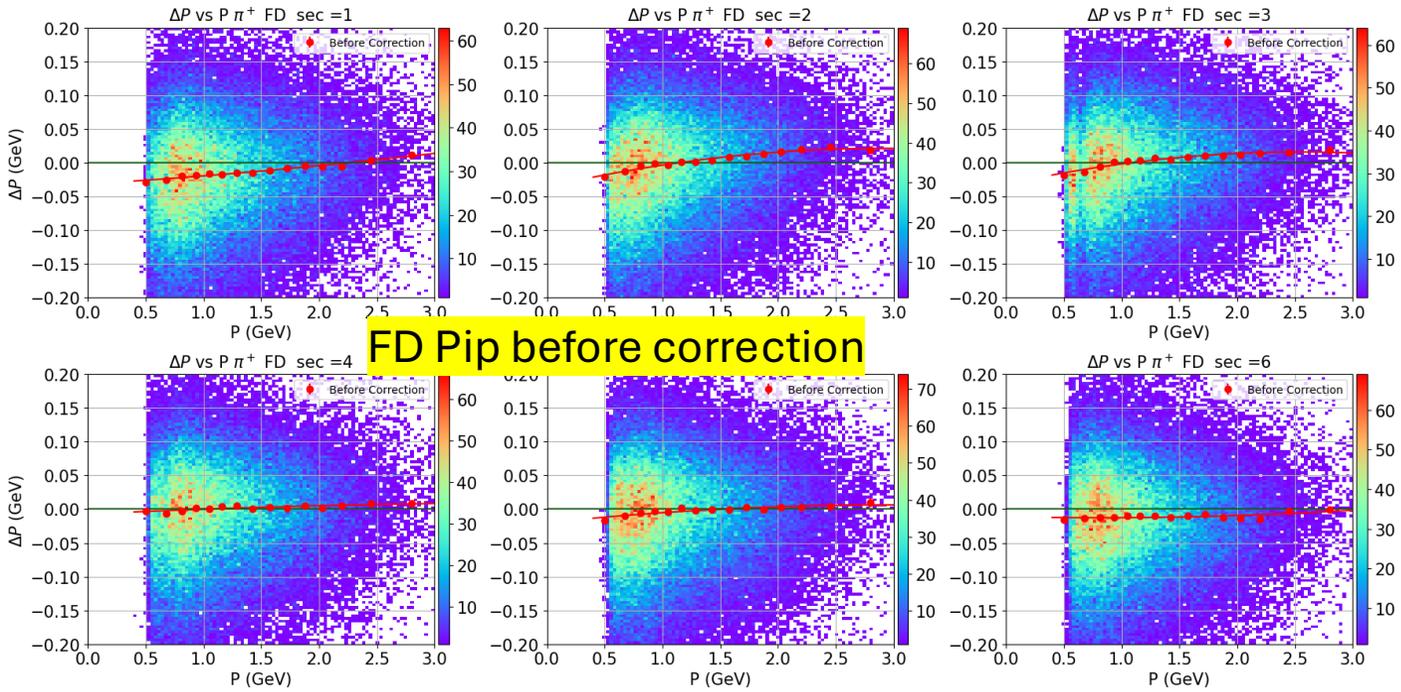
$$\Delta P = P(\text{gen}) - P(\text{rec})$$

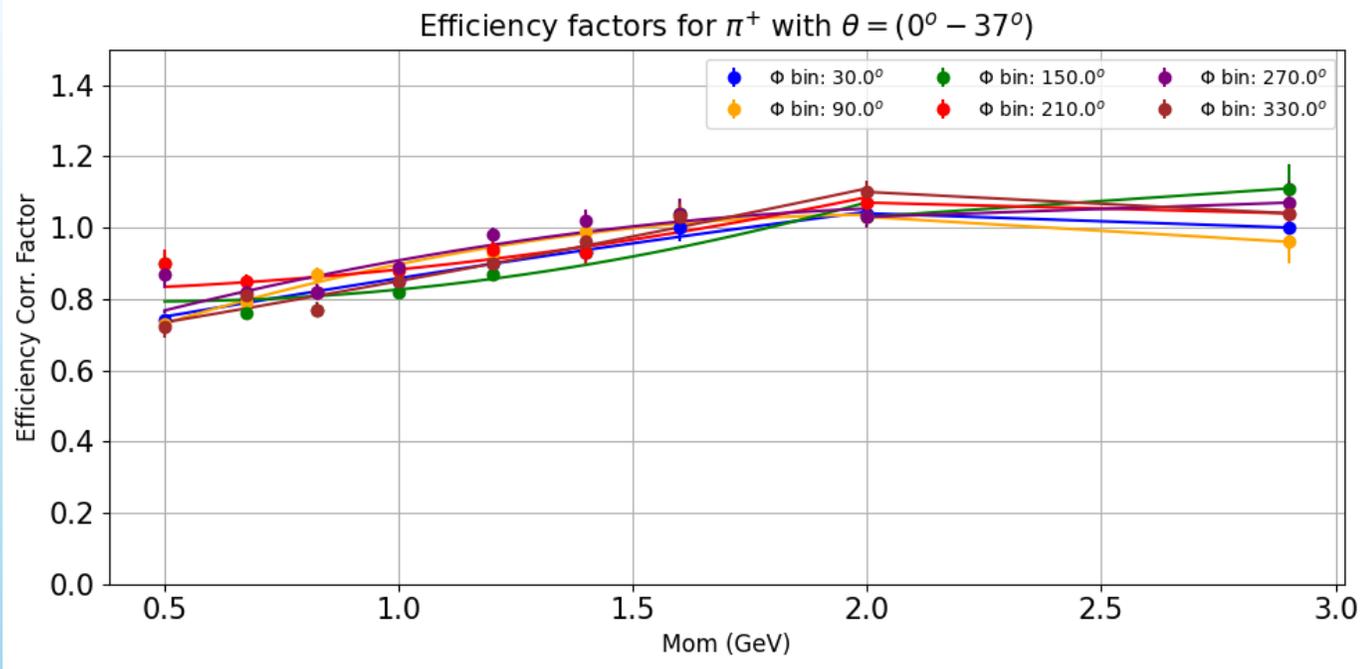


Proton



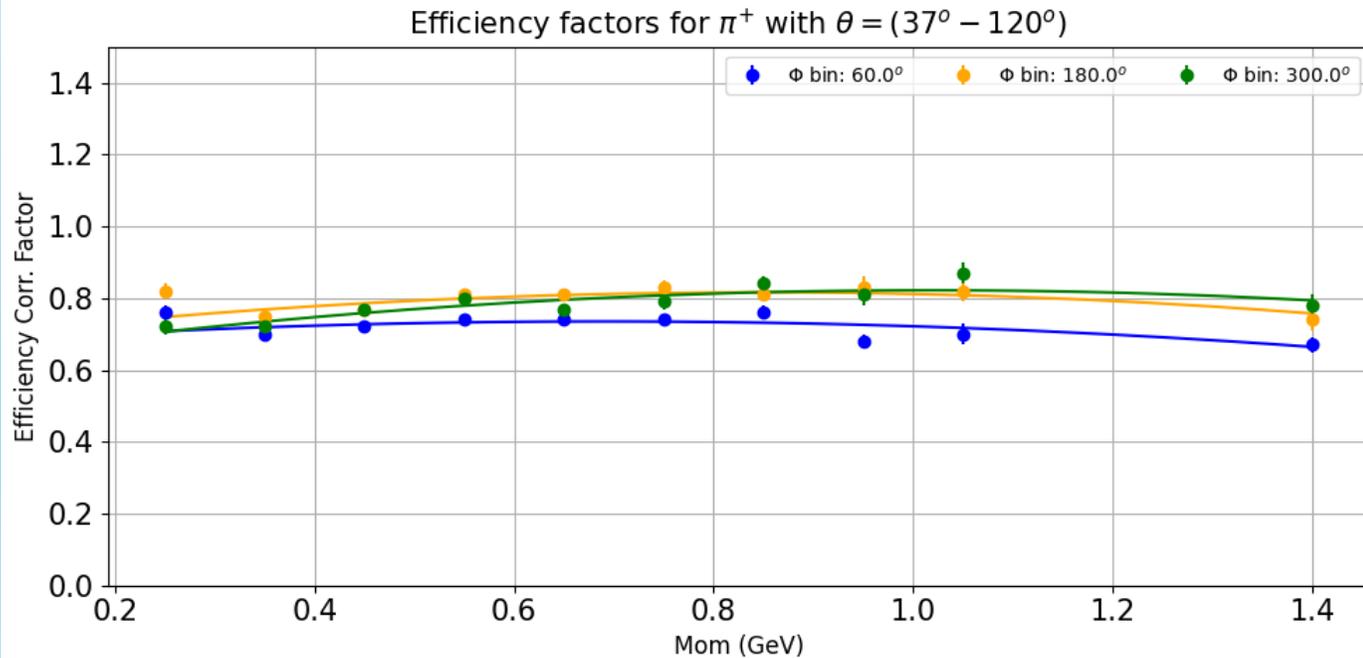
Back up slide Pip Momentum Corrections





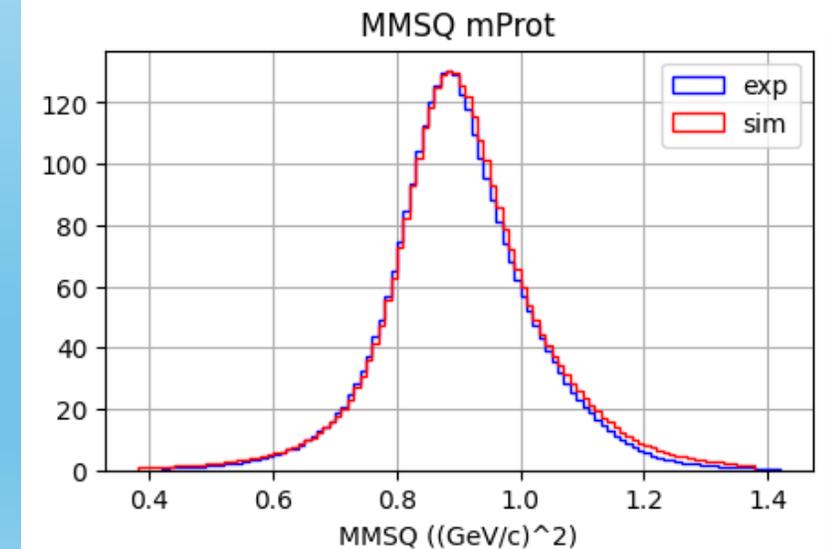
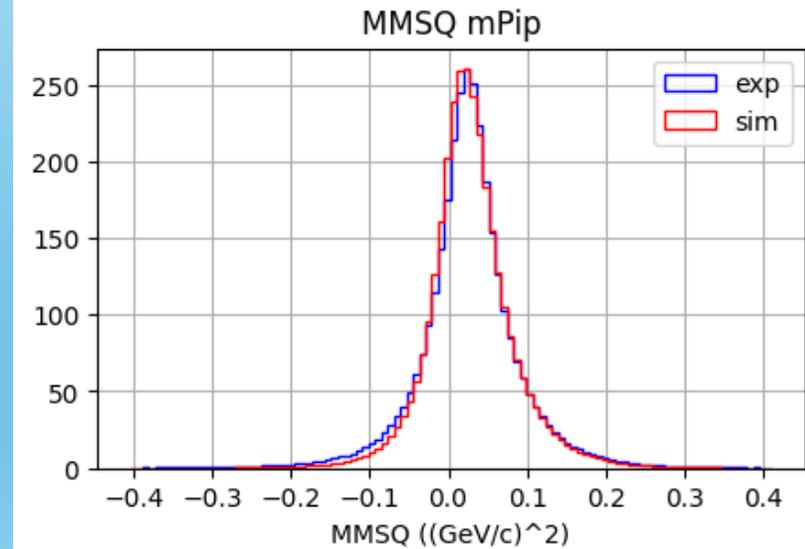
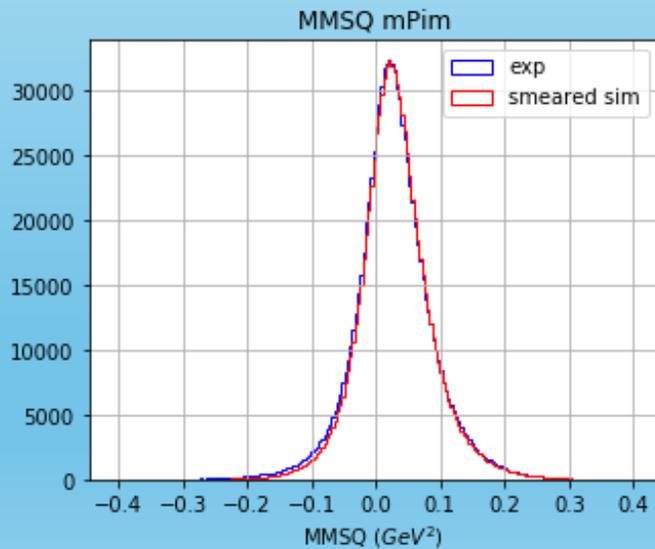
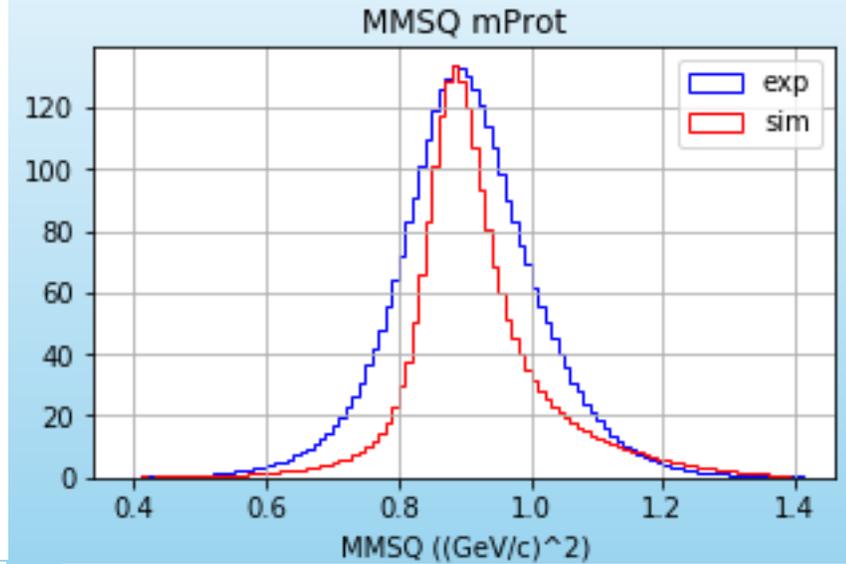
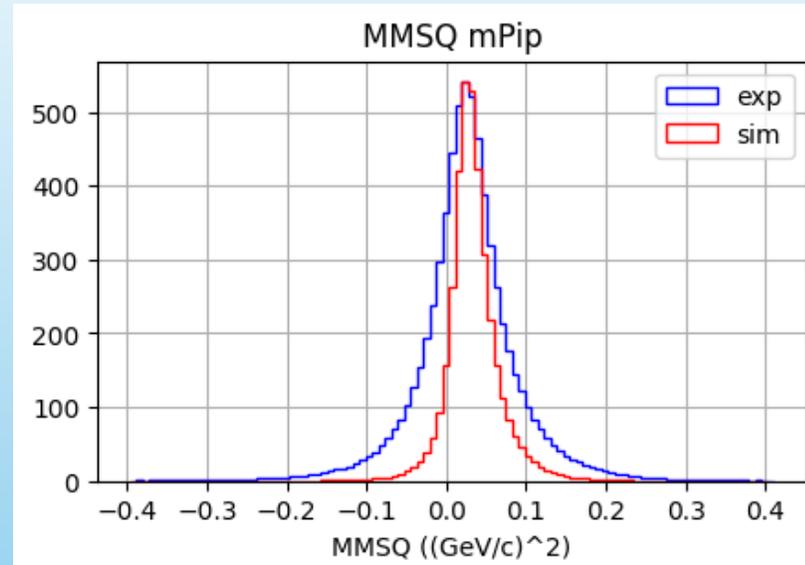
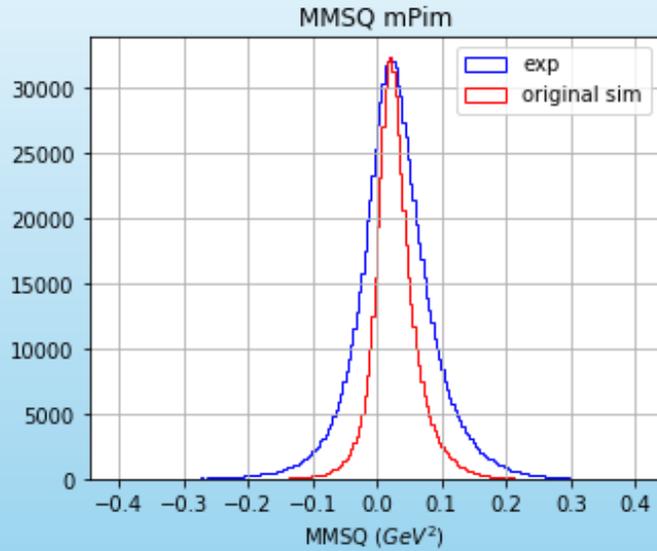
$$\frac{d^7\sigma}{dW dQ^2 dM_{h_1 h_2} dM_{h_2 h_3} d\Omega_{h_1} d\alpha_{h_1}} = \frac{1}{A E_C R} \frac{(\frac{\Delta N_{\text{full}}}{Q_{\text{full}}} - \frac{\Delta N_{\text{empty}}}{Q_{\text{empty}}})}{\Delta W \Delta Q^2 \Delta^5 \tau \tilde{L}}$$

This shows the experimental measurement for low momentum pips is less efficient than reconstruction in simulations



This shows the experimental measurement is less efficient than reconstruction in simulations.

Back up slide: Smearing using exclusive topology



For the systematics 10% variation in the smearing term, it is estimated to be 1.42%

Back up slide: Virtual Photon Flux

In single-photon exchange approximation, the 5-D hadronic cross-section is related to the 7-D electron scattering cross-section by

$$\frac{d^5\sigma}{dM_{p\pi^+}dM_{\pi^+\pi^-}d\Omega d\alpha_{\pi^-}} = \frac{1}{\Gamma_v} \frac{d^7\sigma}{dW dQ^2 dM_{p\pi^+}dM_{\pi^+\pi^-}d\Omega d\alpha_{\pi^-}}, \quad (5.11)$$

where virtual photon flux,

$$\Gamma_v = \frac{\alpha}{4\pi} \frac{1}{E_{beam}^2 M_p^2} \frac{W(W^2 - M_p^2)}{(1 - \varepsilon)Q^2}, \quad (5.12)$$

with α is the fine structure constant (1/137), M_p is the proton mass, and ε is the polarization of the virtual photon, which itself given by

$$\varepsilon = \left(1 + 2 \left(1 + \frac{\omega^2}{Q^2}\right) \tan^2\left(\frac{\theta_{e'}}{2}\right)\right)^{-1}, \quad (5.13)$$

where $\theta_{e'}$ is the angle of scattering electron in the lab frame and ω is the difference between the energy of the initial beam and the final scattered electron.

Backup Slide : Hole Filling Process

$$1. \quad 5D-AC = \frac{5D-SR}{5D-TH},$$

$$2. \quad 5D-AcorrMC = \frac{5D-SR}{5D-AC},$$

$$3. \quad 5D-HS = 5D-TH - 5D-AcorrMC,$$

$$4. \quad 5D-AcorrExp = \frac{5D-ER}{5D-AC},$$

$$5. \quad ScF = \frac{\sum_{i=1}^N 5D-AcorrExp_i}{\sum_{i=1}^N 5D-AcorrMC_i},$$

$$6. \quad 5D-Exp = 5D-ER + (ScF \times 5D-HS \times AF), \quad (6.8)$$

where, i runs from the first bin to the last filled bin (N) in 5D-AcorrMC.