Measuring CLAS12 D(e,e’π) Cross Sections for e4ν Update

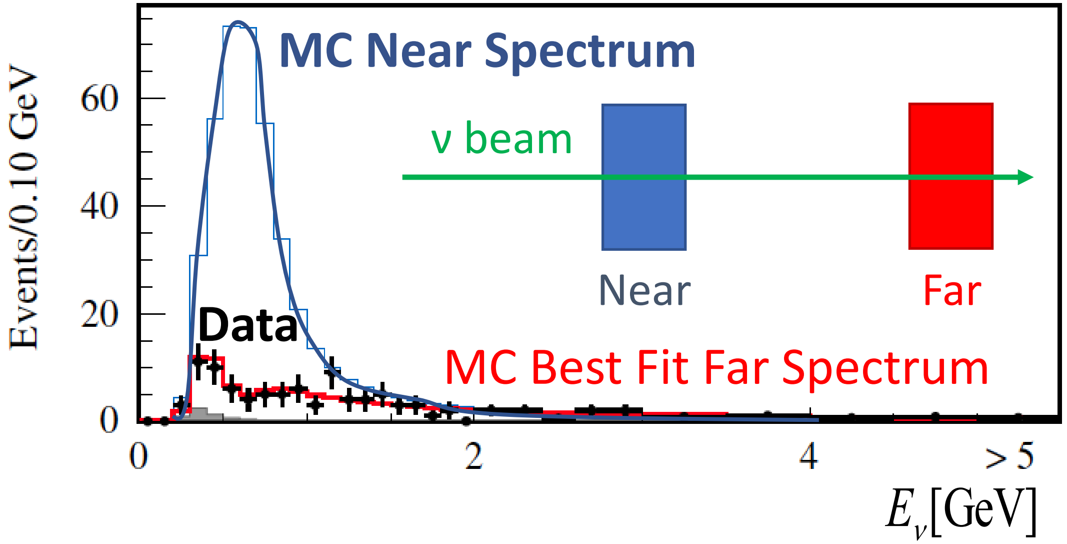
Caleb Fogler for the CLAS Collaboration

Neutrino Experiments and Validating GENIE

Neutrino experiments are difficult

- Large beam energy spread
- Small cross sections

PRD 91, 072010 (2015)



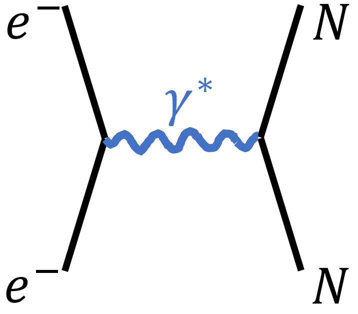
$$N_\alpha(E_{rec}, L) = \int \Phi_\alpha(E, L)\sigma(E) f_\sigma(E, E_{rec}) dE$$

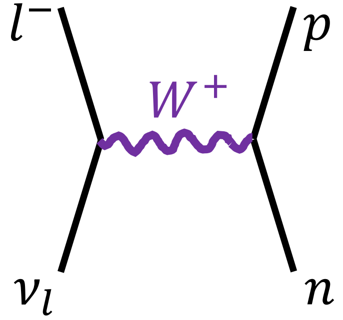
Measured Flux Simulated

Need GENIE to extract the neutrino flux from data

Use electrons to validate GENIE models:

- Monoenergetic
- Larger cross sections
- Similar interactions





EM Current:

$$j^\mu_{em} = \bar{u}\gamma^\mu u$$

Vector

Charge-Coupling Weak Current:

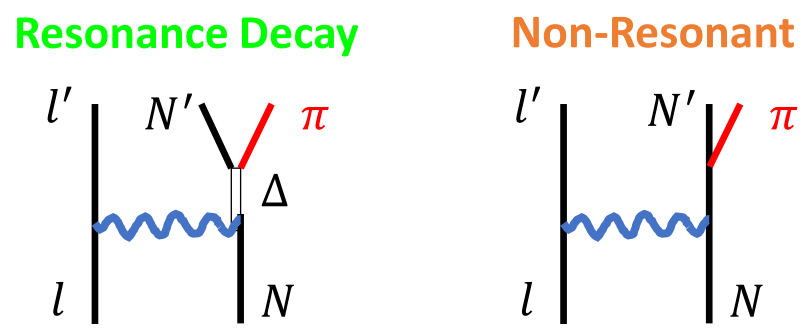
$$j^\mu_\pm = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$$

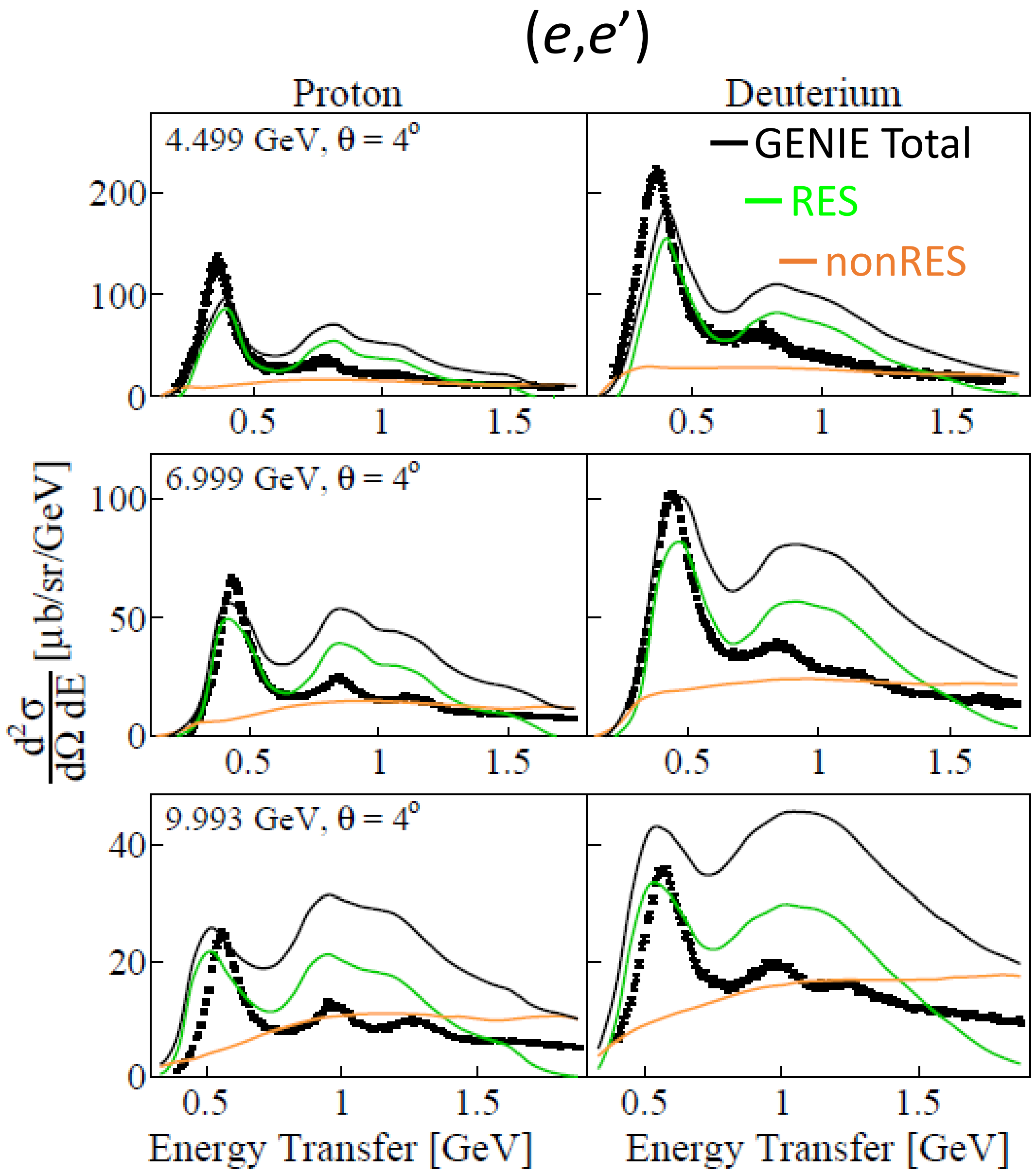
Vector Axial

If GENIE can describe neutrinos, it can describe electrons

Motivation

- GENIE badly describes inclusive *p*(*e*,*e*') and *d*(*e*,*e*') scattering in pion production region
  - GENIE parameters are being tuned to better describe the data
- I measured 4.2 GeV RG-B *d*(*e*,*e*'π) Forward Detector cross sections to test and improve GENIE





PRD 103, 113003 (2021)

GENIE and onepigen Pion Production Models

Onepigen

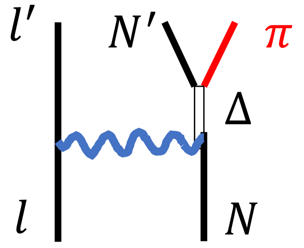
Nucl.Phys. A645 (1999) 145-174

arXiv:nucl-th/9807001v2

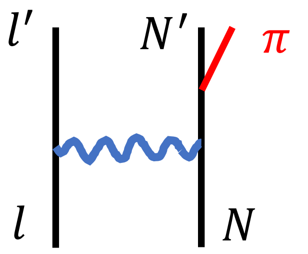
- Single pion event generator
- MAID2007 unitary isobar model

Eur. Phys. J. A**34**, (2007) 69-97

Resonant Production



Non-Resonant Production



GENIE

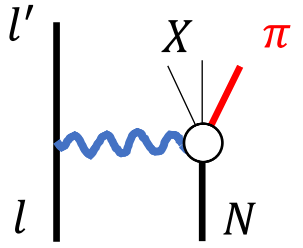
- Phenomenological semi-classical event generator
  - Quasi-elastic scattering

    PRD 103 (2021) 113003
  - Baryon resonance production (Berger-Sehgal)

    PRD 76 (2007) 113004
  - DIS and non resonant production (Bodek-Yang)

    J. Phys. G: Nucl. Part. Phys. 29 (2003) 1899–1905

DIS Production



Cuts, Corrections, and Uncertainties

Electron Cuts:

- Electron PID
- DC fiducial cuts
- ECAL fiducial cuts
- Vertex cuts

Pion Cuts:

- Pion PID
- DC fiducial cuts
- Vertex cuts

Applied corrections and uncertainties

- Radiative corrections (GENIE) THANKS JULIA!!!
  - Replaces limited radiative corrections from onepigen
- Acceptance corrections (GENIE)
- Cut variance uncertainties
- Systematic uncertainties
- 10% normalization uncertainty (not shown)

GENIE Acceptance and Radiative Corrections

Acceptance corrections

- Calculate correction bin-by-bin by dividing generated with detected

$$AC = G_{Born}^{GEN} / G_{Born}^{det_\pi}$$

- Uncertainty 10% of pion acceptance correction

$$\delta AC = 0.1 * \left(G_{Born}^{det_e} / G_{Rad}^{det_\pi} - 1 \right)$$

Radiative corrections

(See March CLAS talk)

- Calculate correction bin-by-bin by dividing nonradiative with radiative

$$RC = G_{Born}^{det} / G_{Rad}^{det}$$

- Uncertainty 10% of correction

$$\delta RC = 0.1 * (RC - 1)$$

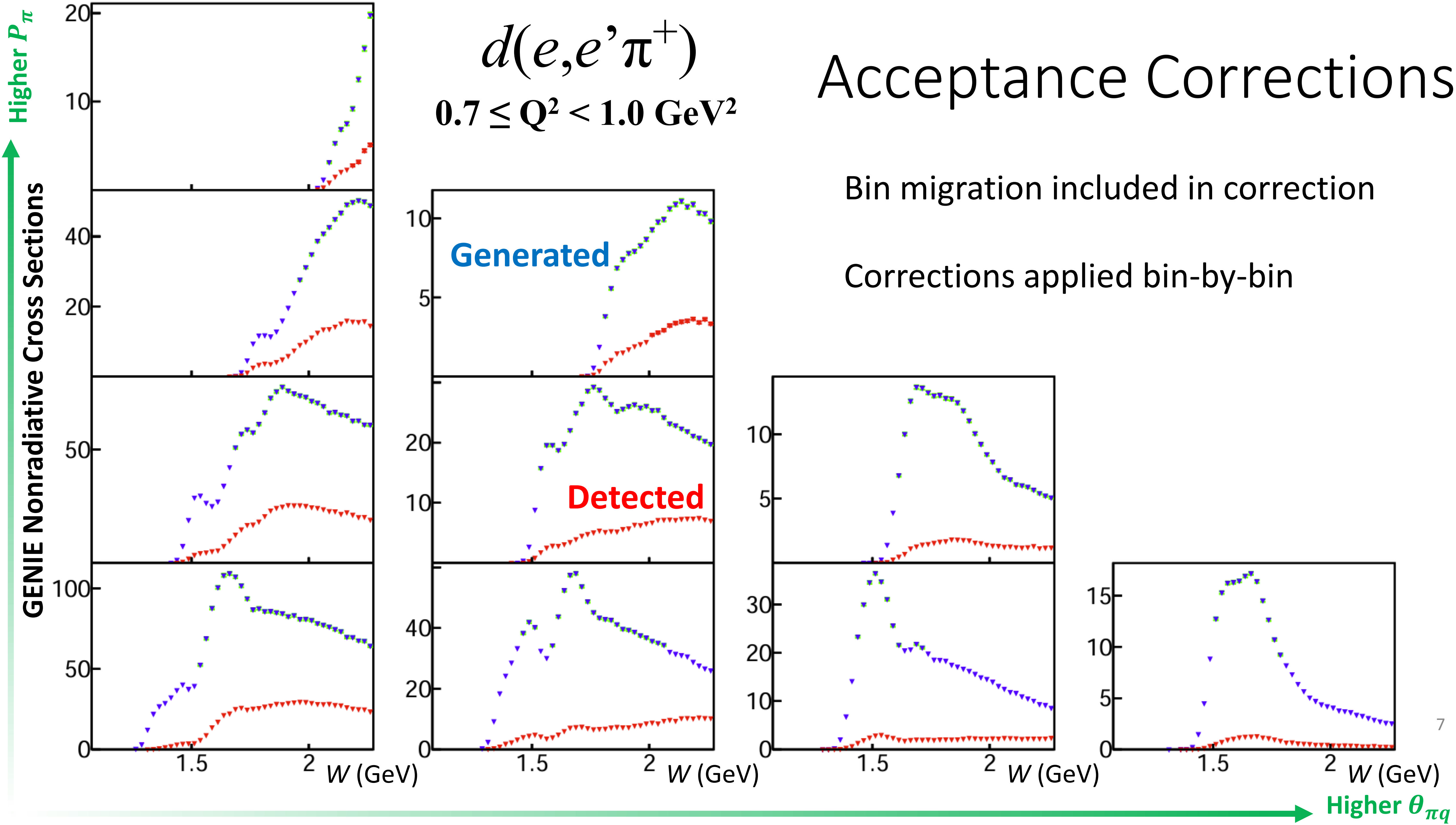
Acceptance Corrections

$d(e,e'\pi^+)$

$0.7 \leq Q^2 < 1.0$ GeV^2

Bin migration included in correction

Corrections applied bin-by-bin

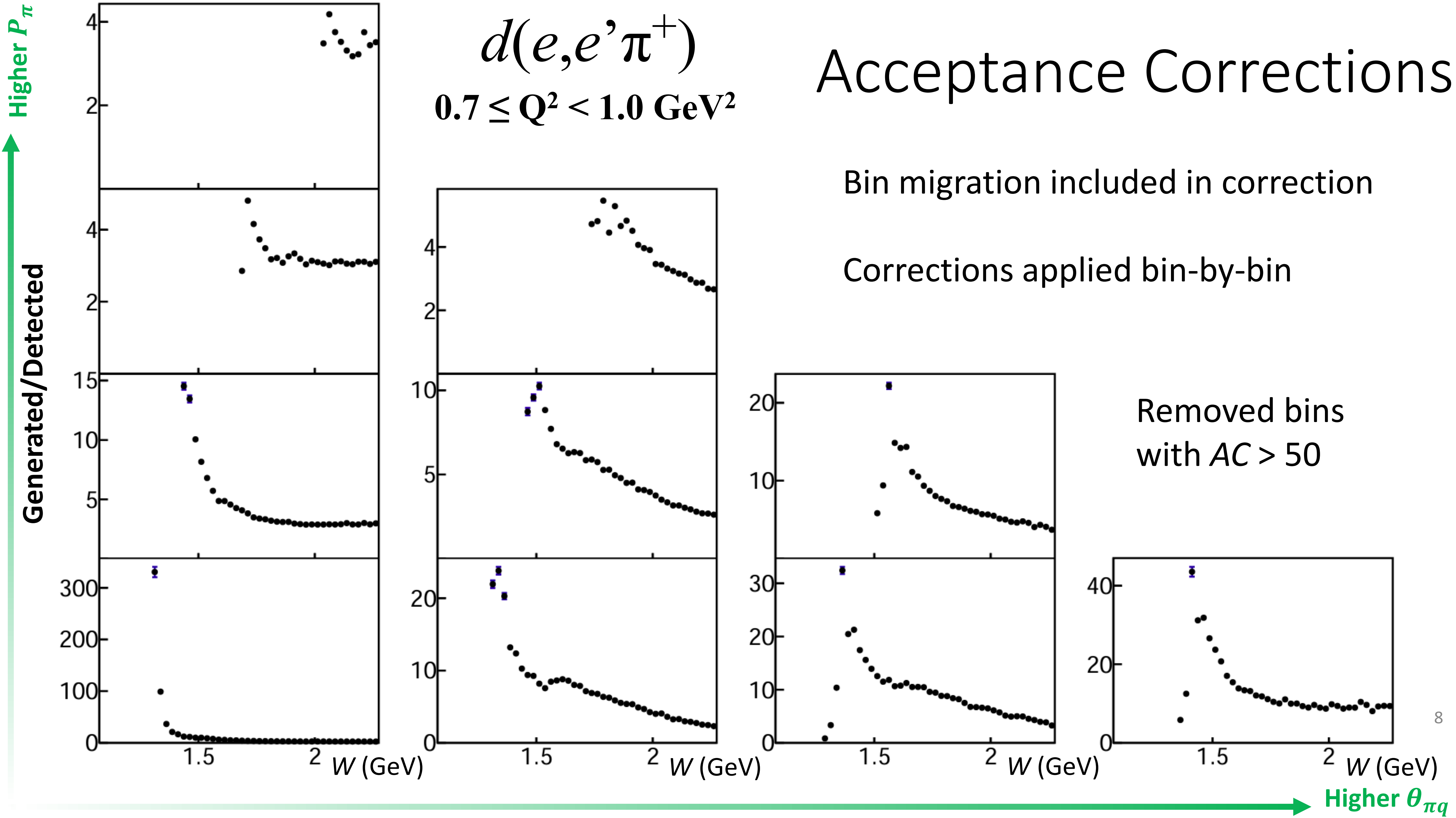


Acceptance Corrections

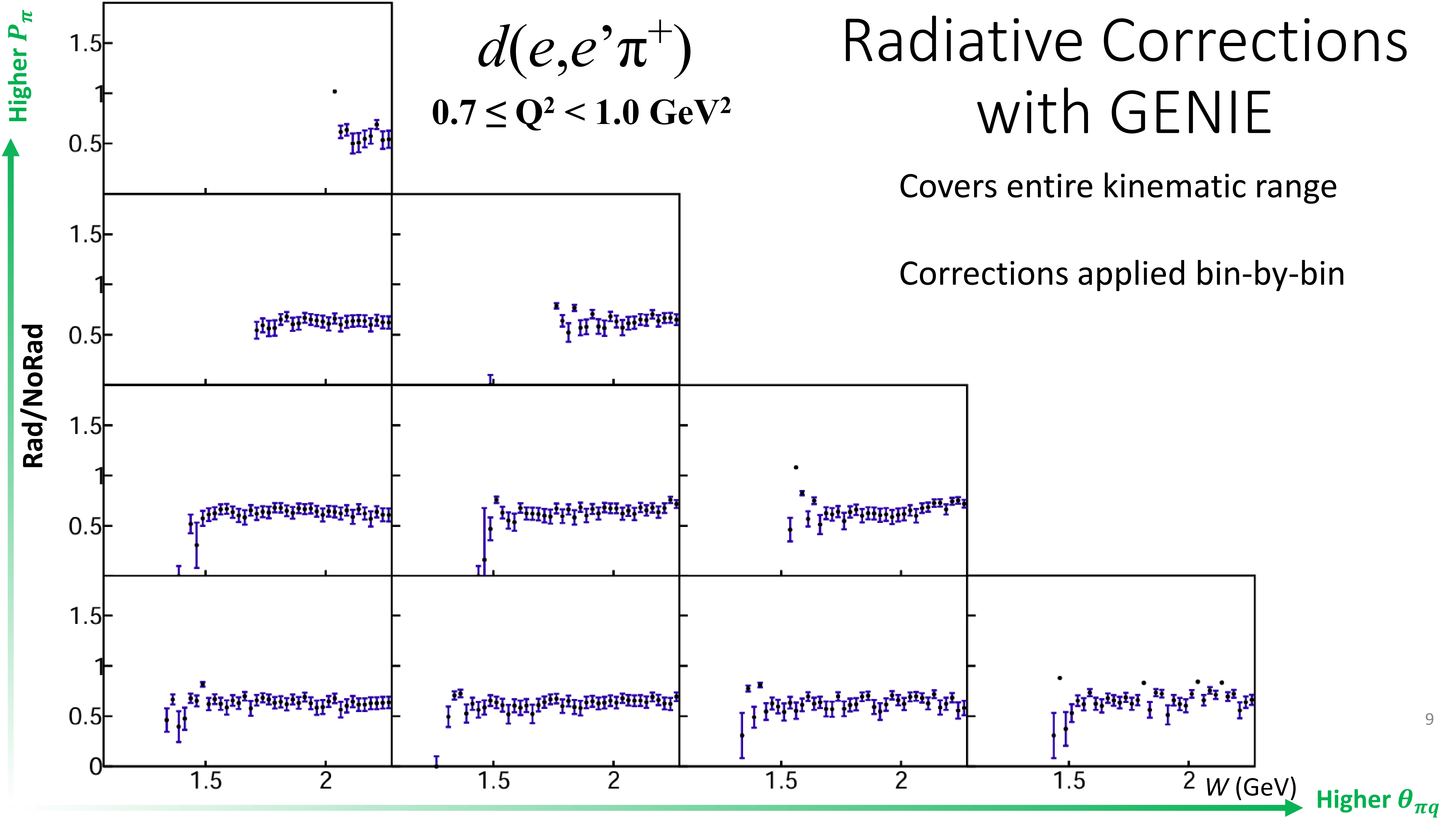
Bin migration included in correction

Corrections applied bin-by-bin

Removed bins with $AC > 50$



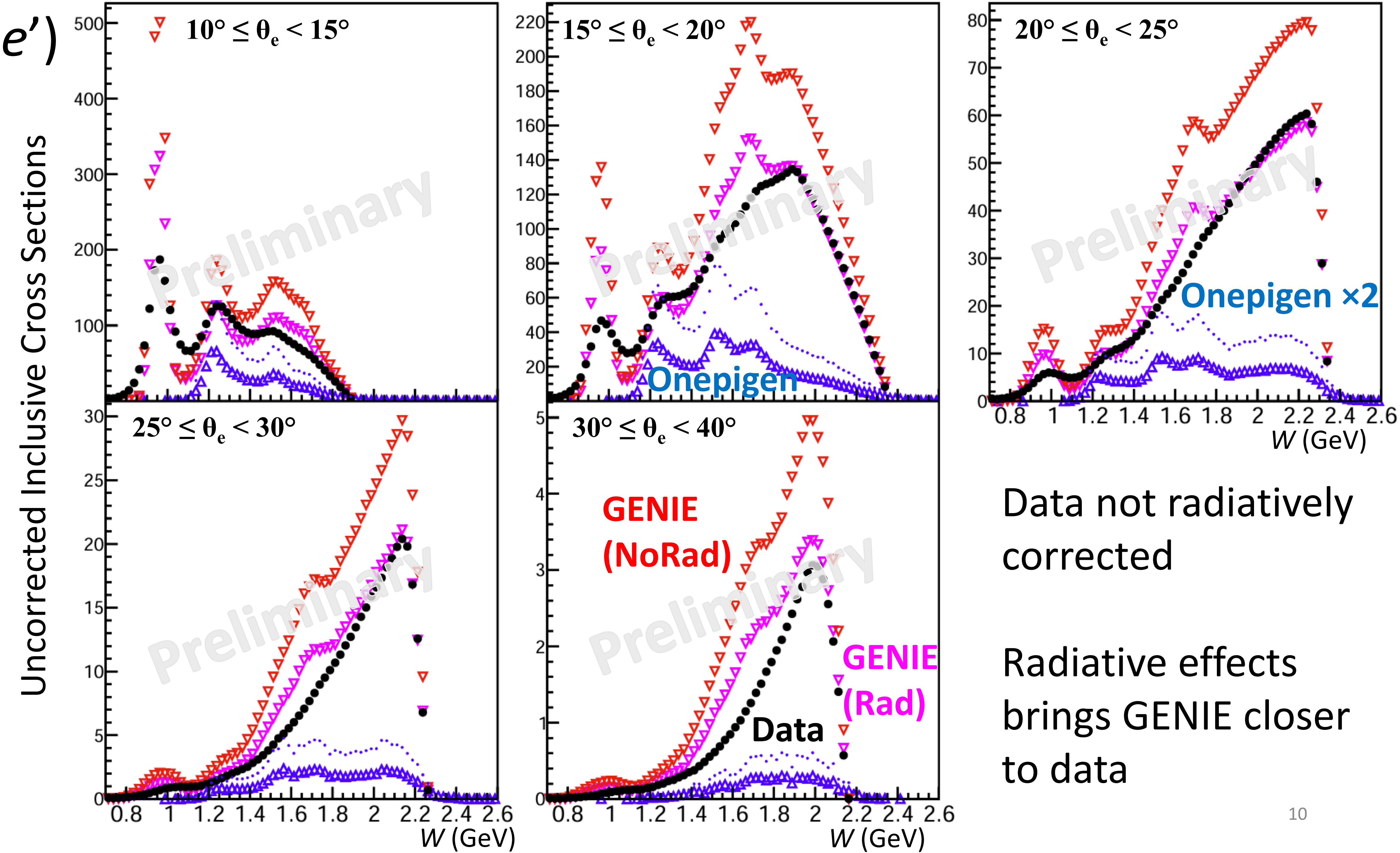
Radiative Corrections with GENIE



Covers entire kinematic range

Corrections applied bin-by-bin

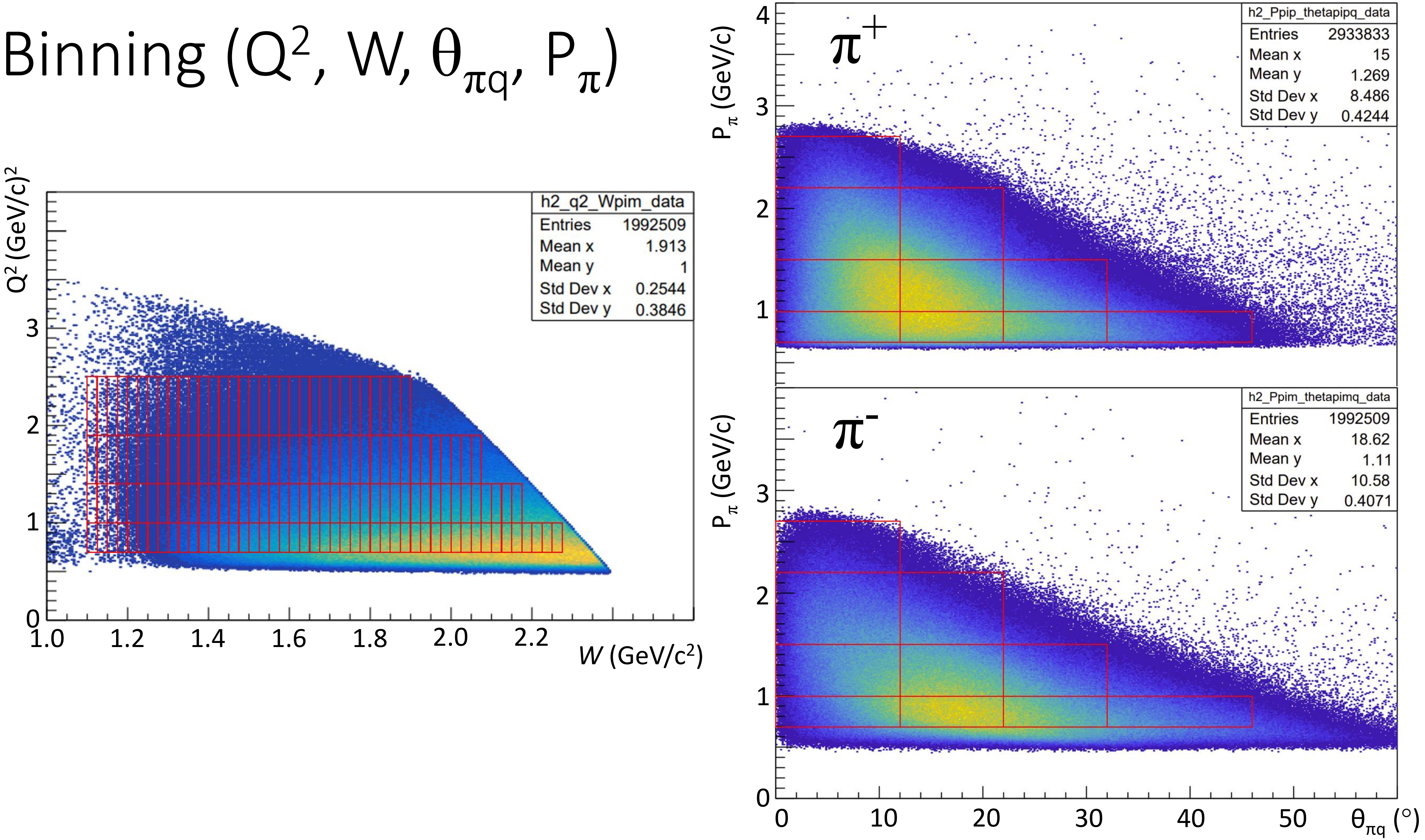
$d(e,e')$



Data not radiatively corrected

Radiative effects brings GENIE closer to data

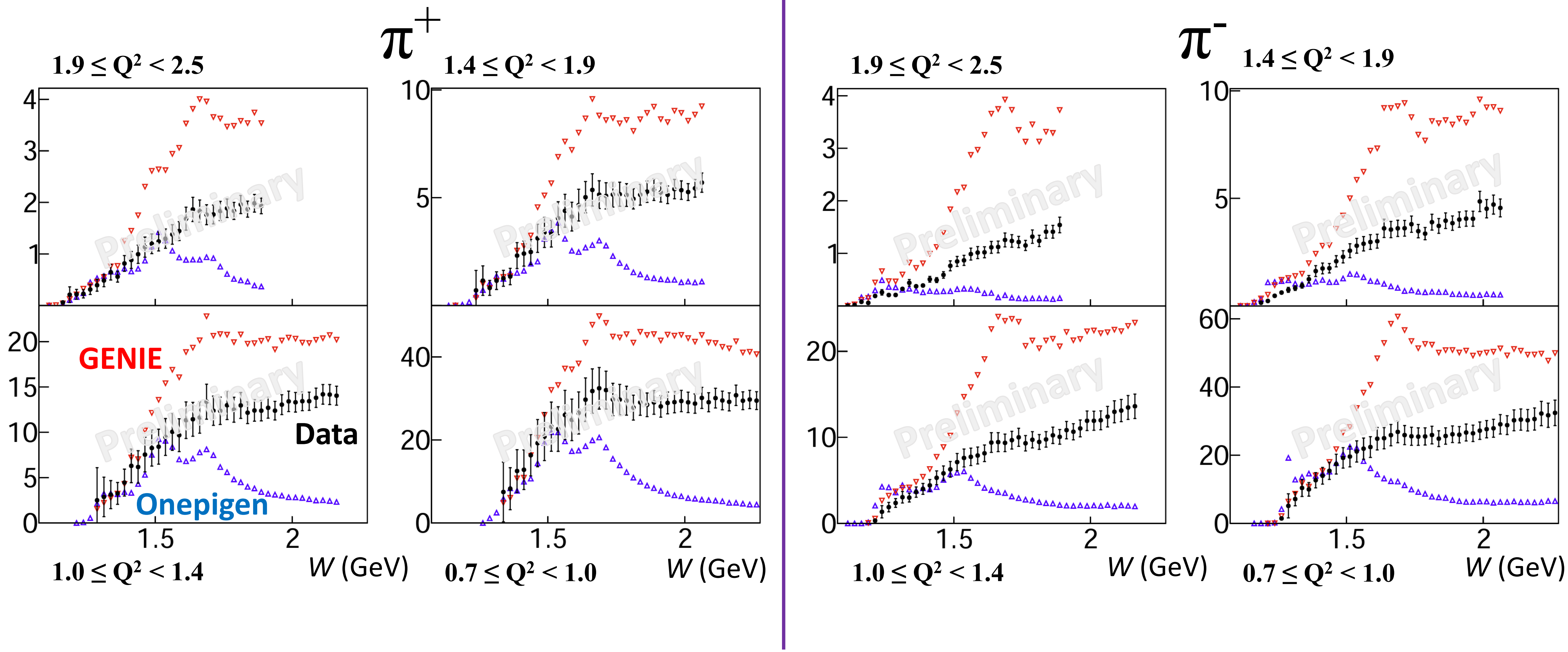
Binning (Q^2, W, $\theta_{\pi q}$, P_π)



Cross Sections

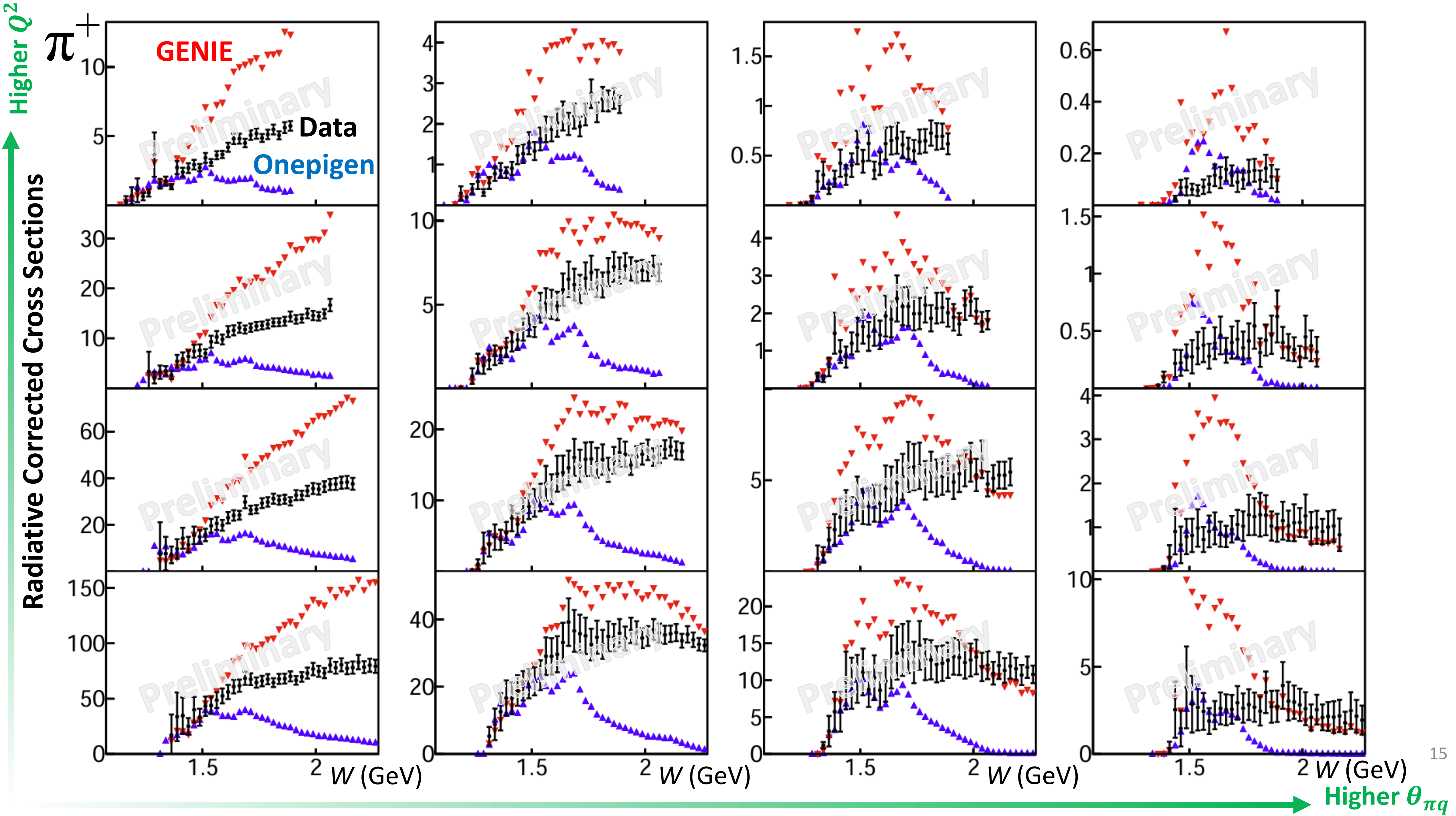
- Includes radiative corrections, acceptance corrections, statistical uncertainties, and systematic uncertainties
- Binning
  - **Q^2**
  - Q^2 and $\theta_{\pi q}$
  - Q^2 and P_π
  - Q^2, $\theta_{\pi q}$, and P_π

D(e,e'π) Cross Sections vs W binned in Q^2

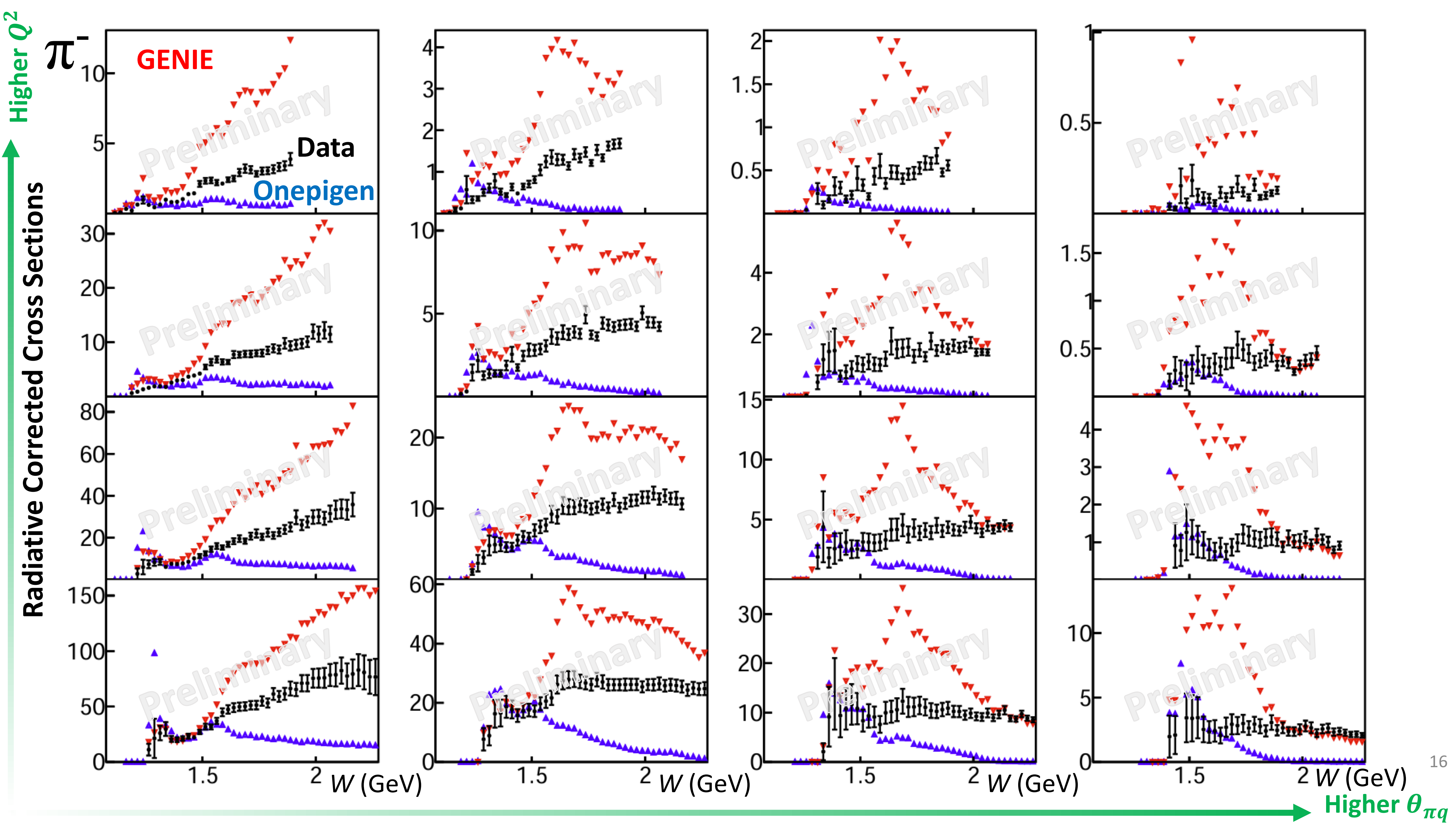


Cross Sections

- Includes radiative corrections, acceptance corrections, statistical uncertainties, and systematic uncertainties
- Binning
  - Q^2
  - **Q^2 and $\theta_{\pi q}$**
    - **Four Q^2 bins: 0.7 – 2.5 GeV^2**
    - **Four $\theta_{\pi q}$ bins: 0° – 46°**
  - Q^2 and P_π
  - Q^2, $\theta_{\pi q}$, and P_π



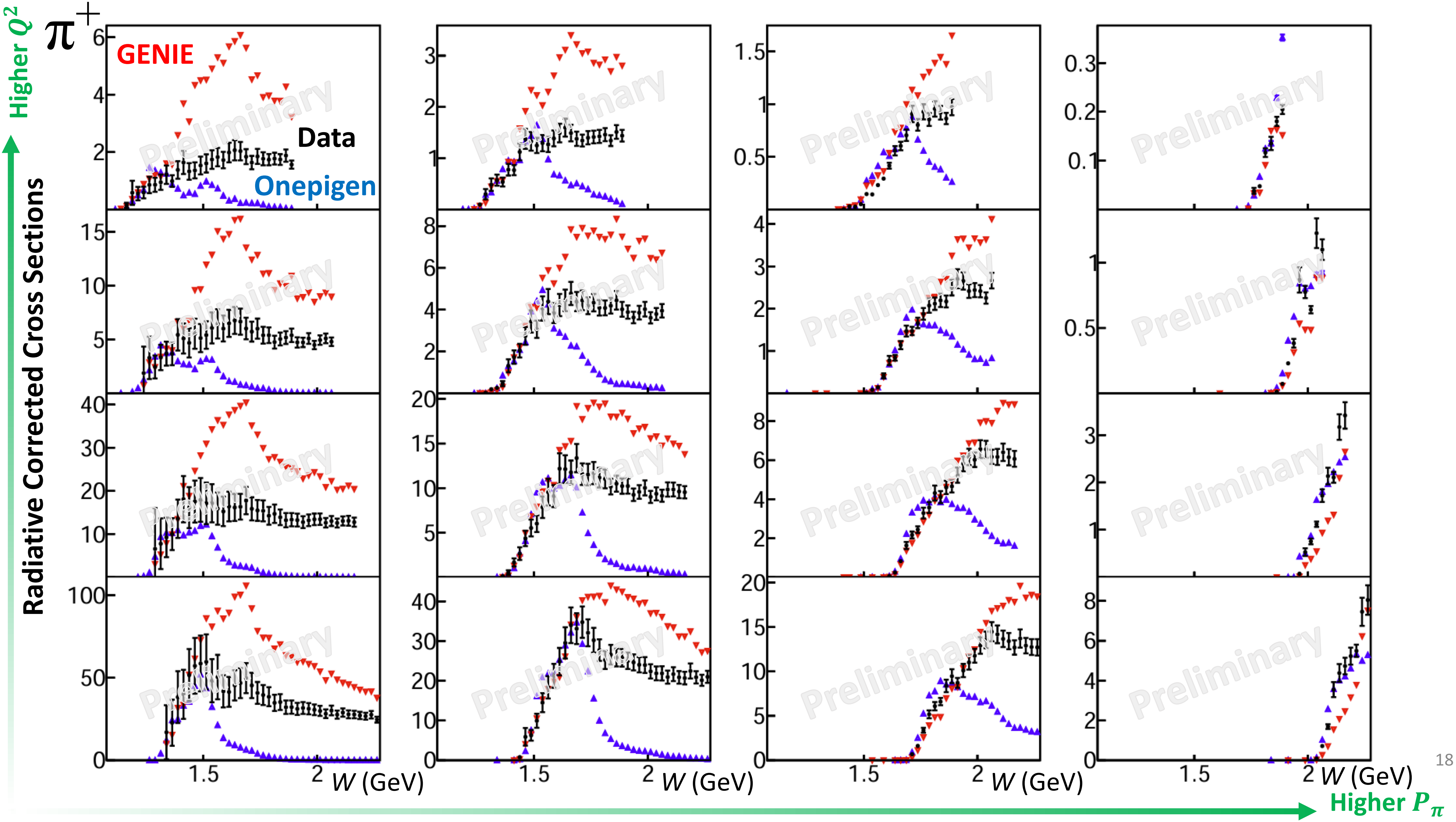
Higher Q^2
π^+
GENIE
Data
Onepigen
Preliminary
Radiative Corrected Cross Sections
W (GeV)
Higher $\theta_{\pi q}$



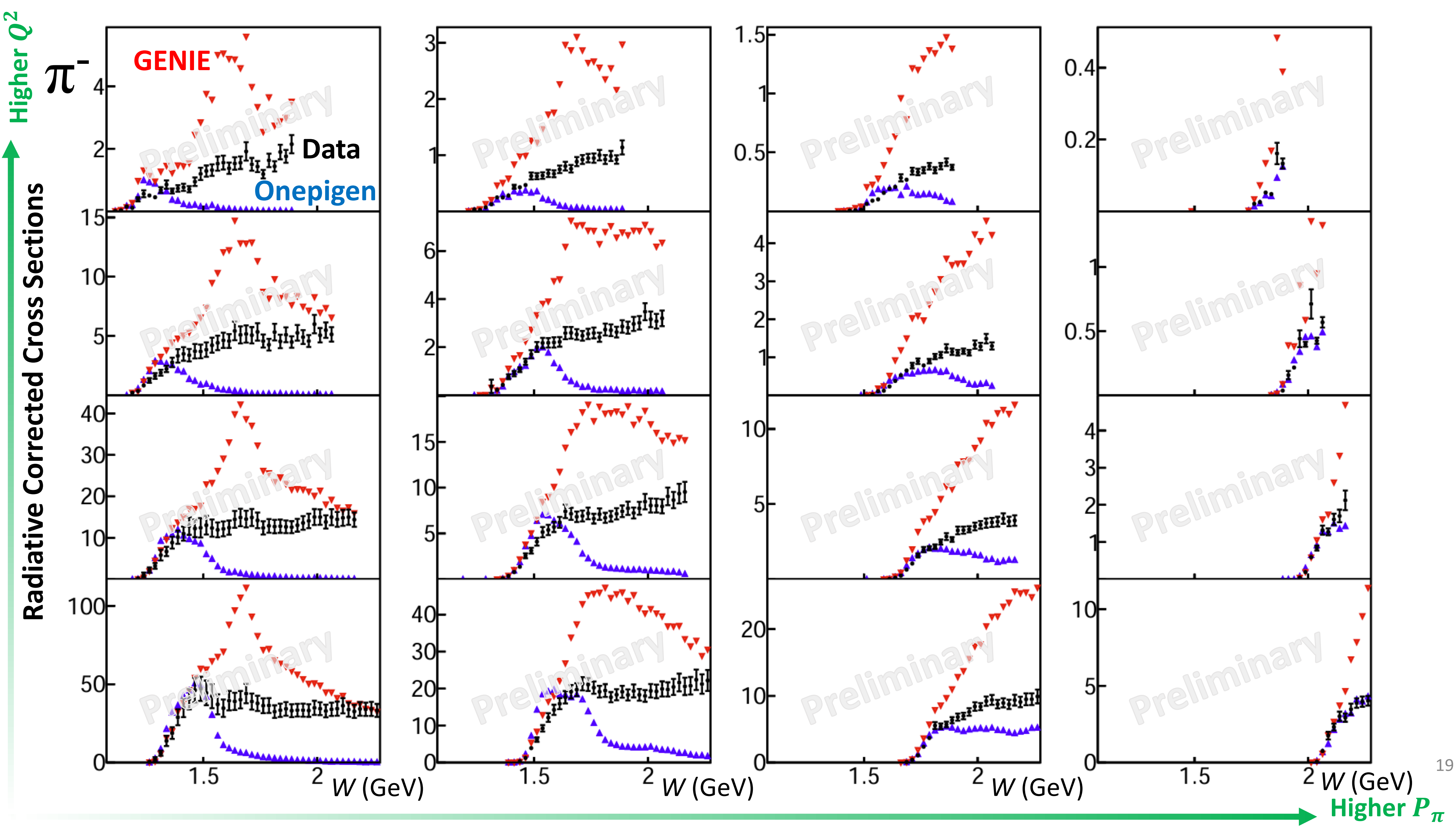
π^-
GENIE
Data
Onepigen
Preliminary
Radiative Corrected Cross Sections
Higher Q^2
Higher $\theta_{\pi q}$
W (GeV)

Cross Sections

- Includes radiative corrections, acceptance corrections, statistical uncertainties, and systematic uncertainties
- Binning
  - Q^2
  - Q^2 and $\theta_{\pi q}$
  - **Q^2 and P_π**
    - **Four Q^2 bins: 0.7 – 2.5 GeV^2**
    - **Four P_π bins: 0.7 – 2.7 GeV/c**
  - Q^2, $\theta_{\pi q}$, and P_π



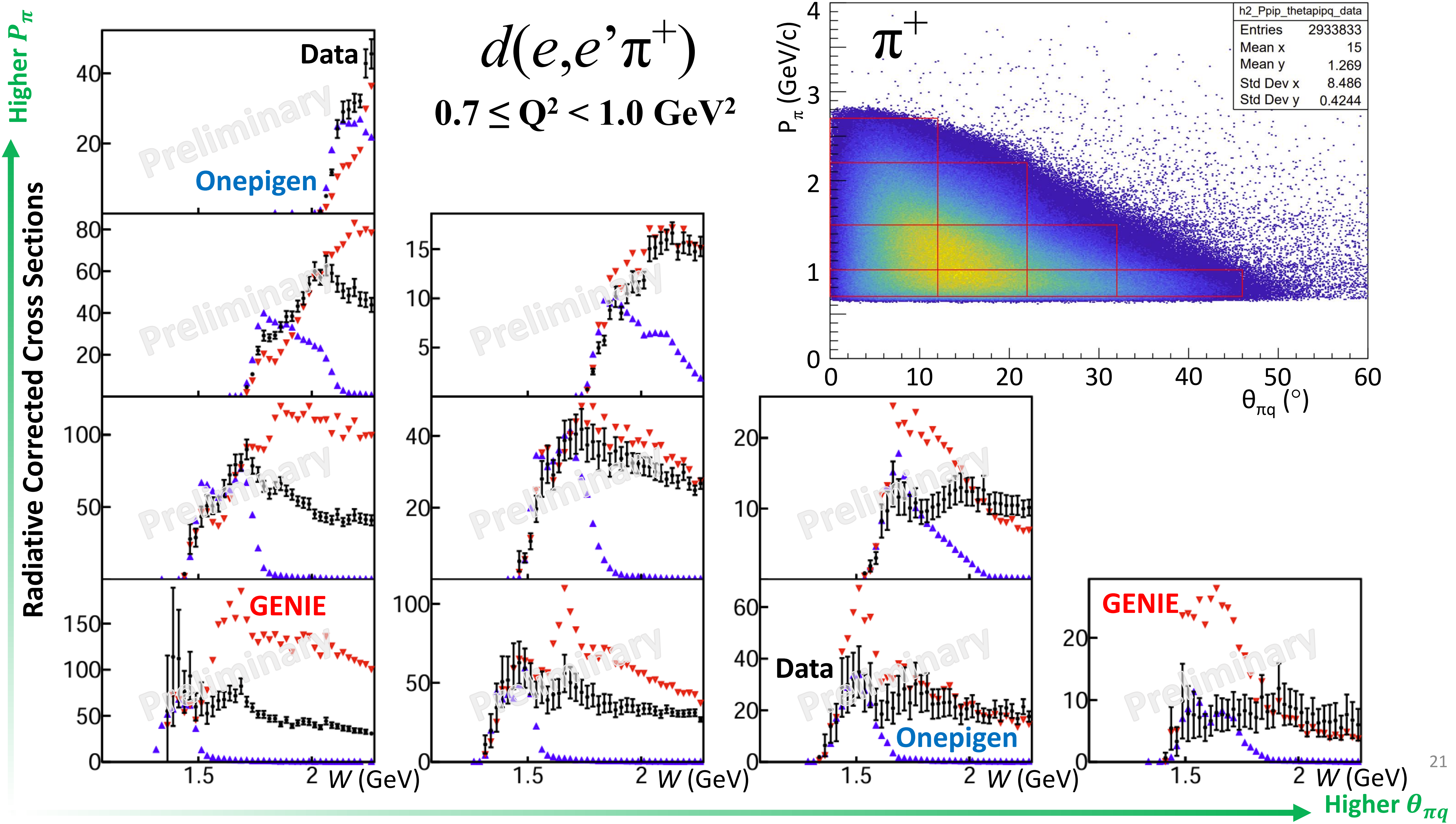
Higher Q^2
π^+
GENIE
Data
Onepigen
Preliminary
Radiative Corrected Cross Sections
W (GeV)
Higher P_π



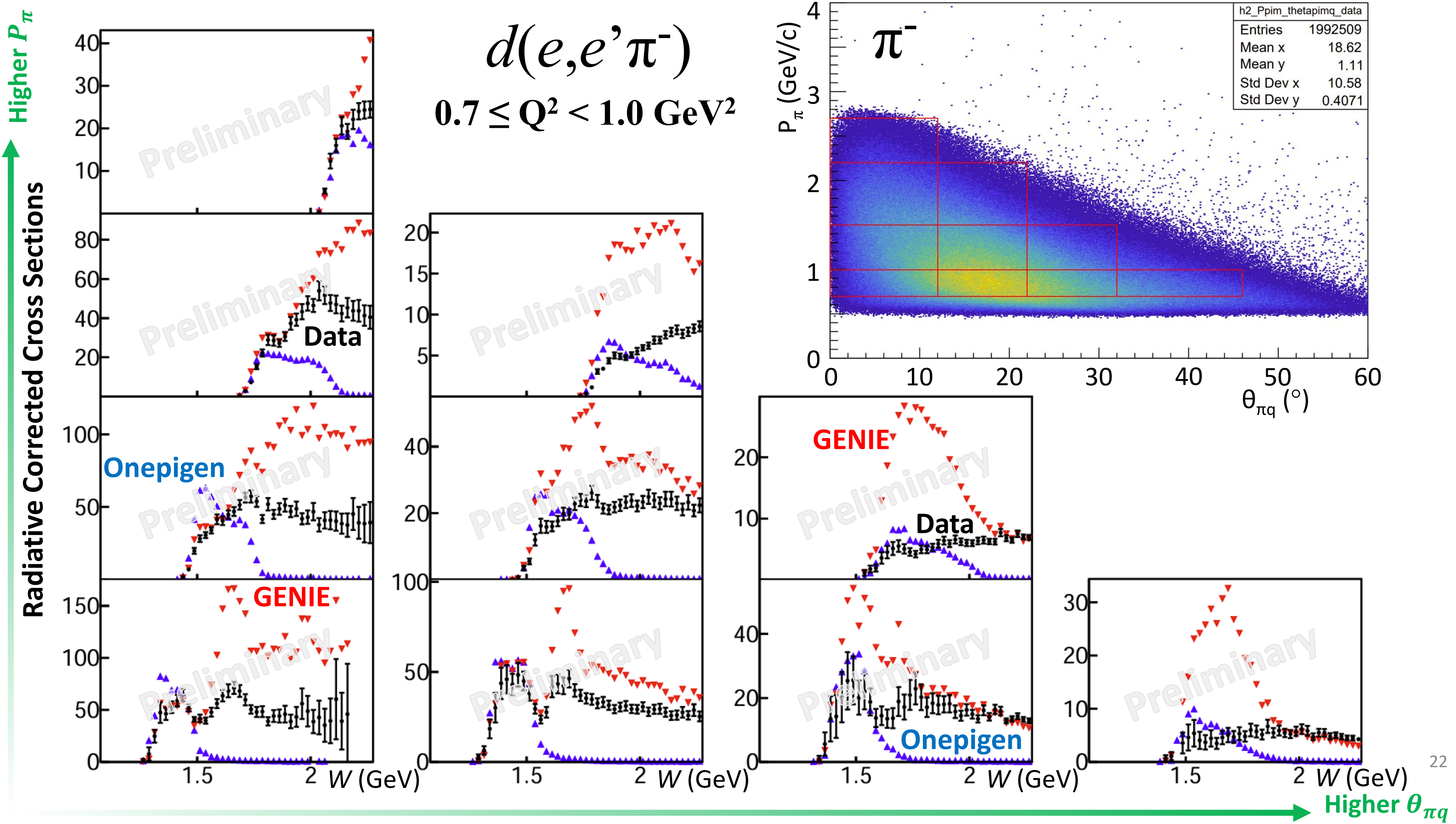
Higher Q^2
π^-
GENIE
Data
Onepigen
Preliminary
Radiative Corrected Cross Sections
W (GeV)
Higher P_π

Cross Sections

- Includes radiative corrections, acceptance corrections, statistical uncertainties, and systematic uncertainties
- Binning
  - Q^2
  - Q^2 and $\theta_{\pi q}$
  - Q^2 and P_π
  - **Q^2, $\theta_{\pi q}$, and P_π**
    - **Four Q^2 bins: 0.7 – 2.5 GeV^2**
    - **Four $\theta_{\pi q}$ bins: 0° – 46°**
    - **Four P_π bins: 0.7 – 2.7 GeV/c**



$d(e,e'\pi^+)$
$0.7 \leq Q^2 < 1.0$ GeV^2
Higher P_π
Radiative Corrected Cross Sections
Higher $\theta_{\pi q}$
Data
Onepigen
GENIE
Preliminary
W (GeV)
π^+
h2_Ppip_thetapipq_data
Entries 2933833
Mean x 15
Mean y 1.269
Std Dev x 8.486
Std Dev y 0.4244
P_π (GeV/c)
$\theta_{\pi q}$ (°)

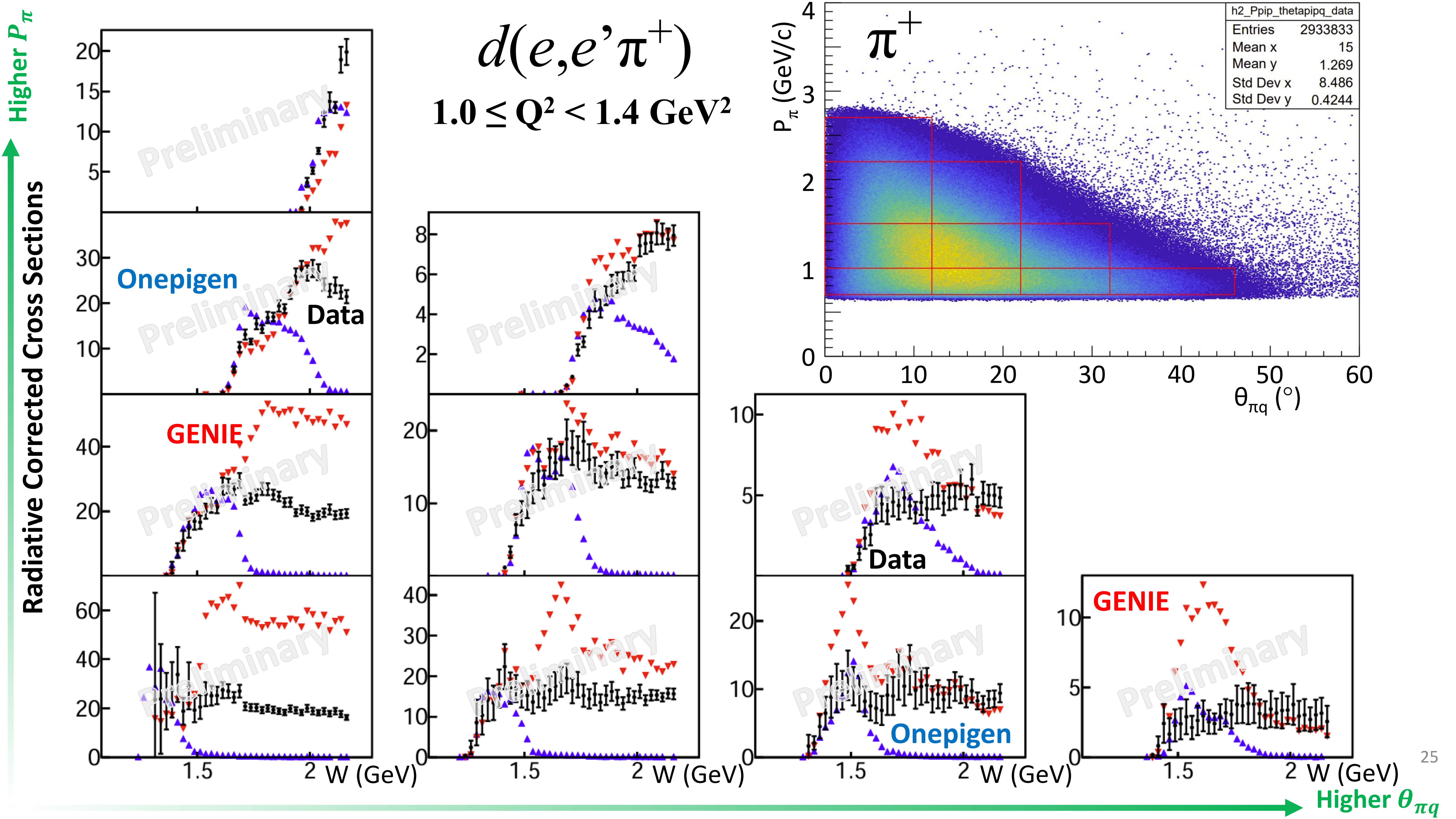


$d(e,e'\pi^-)$
$0.7 \leq Q^2 < 1.0$ GeV^2
Higher P_π
Radiative Corrected Cross Sections
Higher $\theta_{\pi q}$
Data
Onepigen
GENIE
Preliminary
W (GeV)
h2_Ppim_thetapimq_data
Entries 1992509
Mean x 18.62
Mean y 1.11
Std Dev x 10.58
Std Dev y 0.4071
π^-
P_π (GeV/c)
$\theta_{\pi q}$ (°)

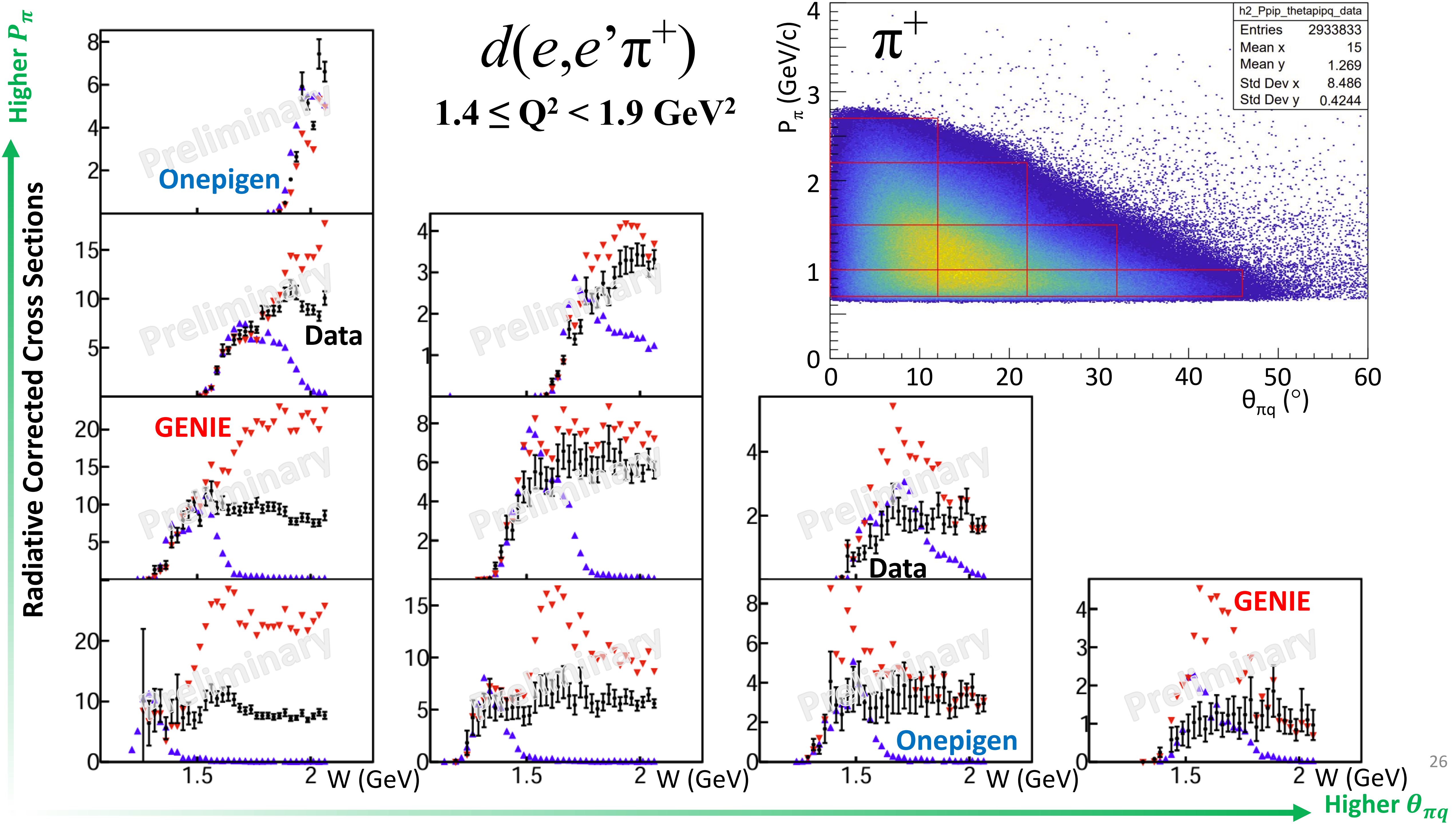
Conclusions

- Physics
    - GENIE and onepigen describe data well for $W < 1.5$ GeV
    - Significant discrepancies for $W > 1.5$ GeV
    - 4D binning shows specific areas to improve GENIE
- Request preliminary approval for data
- Analysis note in progress

Backup Slides



d(e,e'π+)
1.0 ≤ Q2 < 1.4 GeV2
π+
h2_Ppip_thetapipq_data
Entries 2933833
Mean x 15
Mean y 1.269
Std Dev x 8.486
Std Dev y 0.4244
Pπ (GeV/c)
θπq (°)
Higher Pπ
Radiative Corrected Cross Sections
Higher θπq
Onepigen
Data
GENIE
Preliminary
W (GeV)



$d(e,e'\pi^+)$
$1.4 \le Q^2 < 1.9$ GeV^2
Higher P_π
Radiative Corrected Cross Sections
Higher $\theta_{\pi q}$
Onepigen
Data
GENIE
Preliminary
W (GeV)
π^+
h2_Ppip_thetapipq_data
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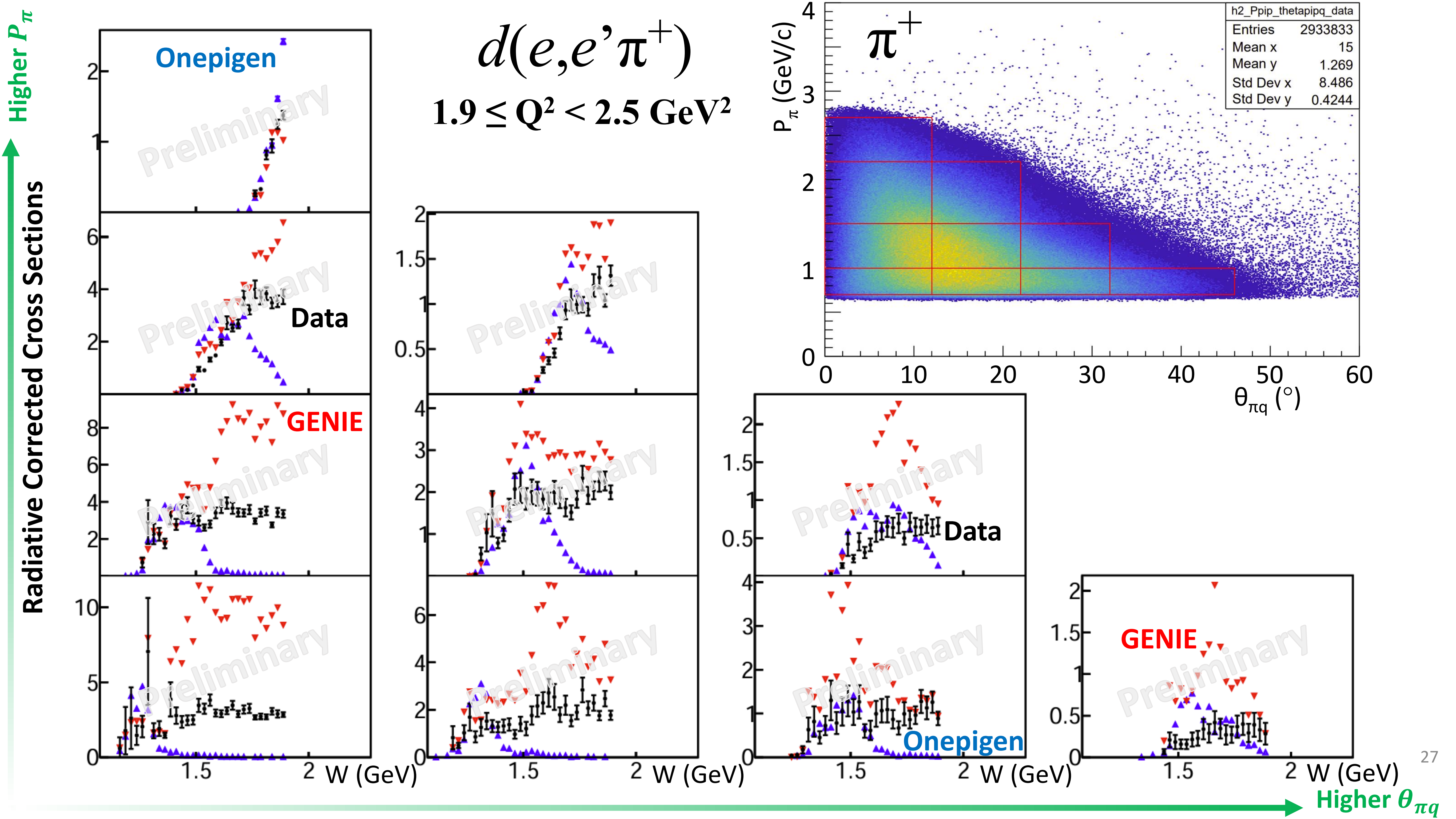
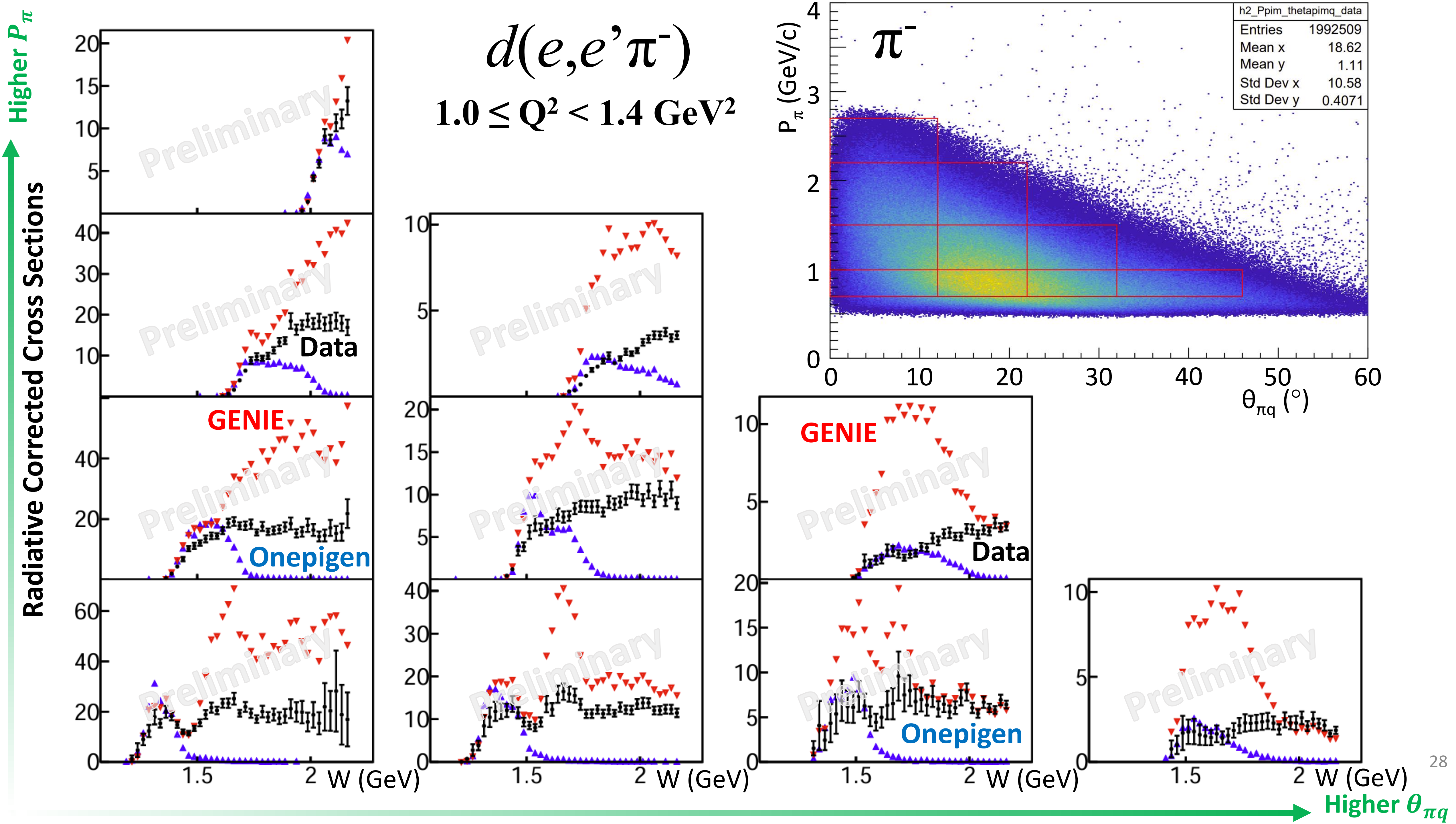
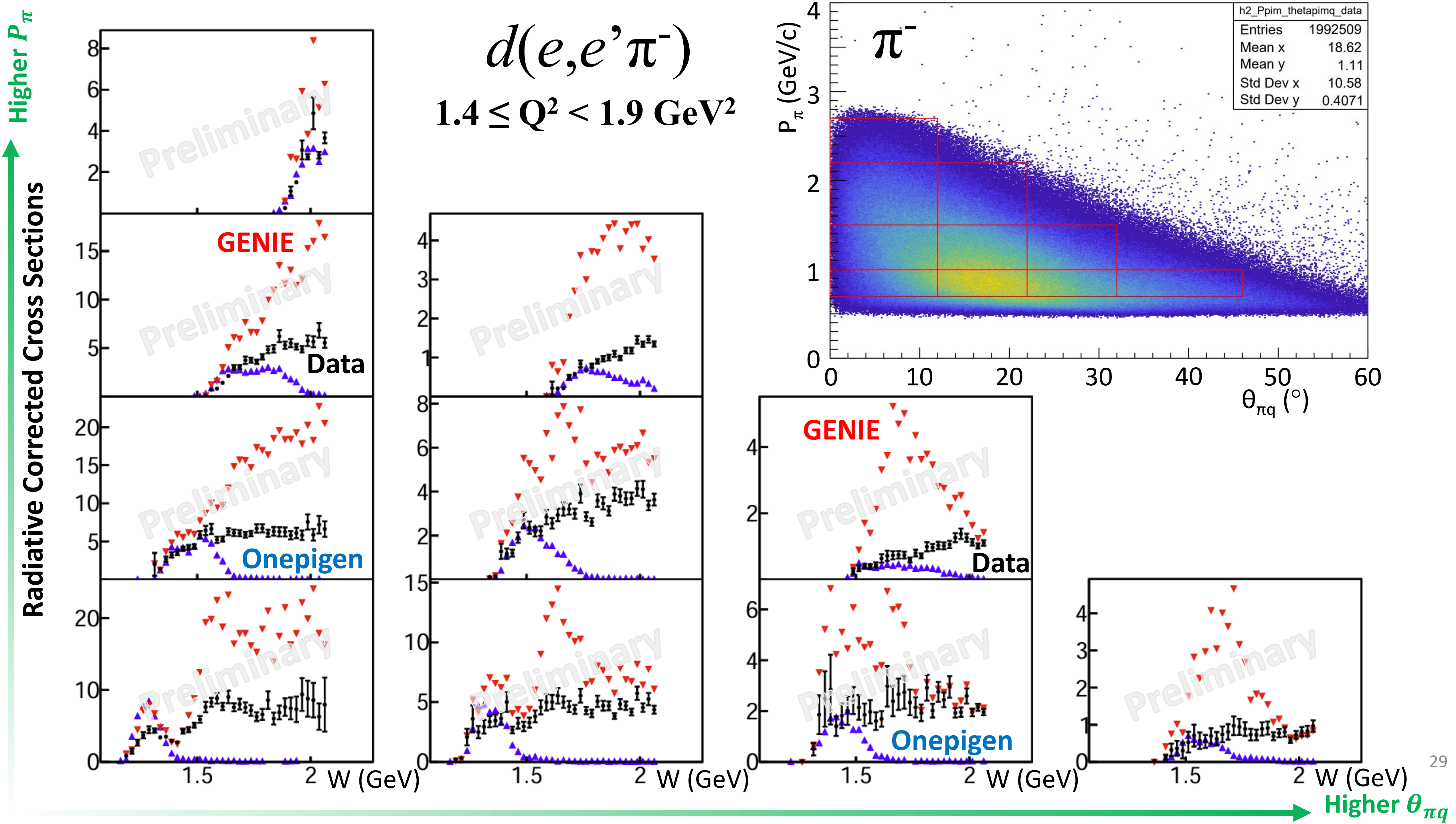
Mean x 15
Mean y 1.269
Std Dev x 8.486
Std Dev y 0.4244
P_π (GeV/c)
$\theta_{\pi q}$ (°)



$d(e,e'\pi^+)$
$1.9 \leq Q^2 < 2.5$ GeV^2
π^+
h2_Ppip_thetapipq_data
Entries 2933833
Mean x 15
Mean y 1.269
Std Dev x 8.486
Std Dev y 0.4244
P_π (GeV/c)
$\theta_{\pi q}$ (°)
Onepigen
Data
GENIE
Preliminary
W (GeV)
Radiative Corrected Cross Sections
Higher P_π
Higher $\theta_{\pi q}$



$d(e,e'\pi^-)$
$1.0 \leq Q^2 < 1.4$ GeV^2
π^-
h2_Ppim_thetapimq_data
Entries 1992509
Mean x 18.62
Mean y 1.11
Std Dev x 10.58
Std Dev y 0.4071
P_π (GeV/c)
$\theta_{\pi q}$ (°)
Higher P_π
Higher $\theta_{\pi q}$
Radiative Corrected Cross Sections
Preliminary
Data
GENIE
Onepigen
W (GeV)



Higher P_π
Radiative Corrected Cross Sections
$d(e,e'\pi^-)$
$1.4 \leq Q^2 < 1.9$ GeV^2
π^-
h2_Ppim_thetapimq_data
Entries 1992509
Mean x 18.62
Mean y 1.11
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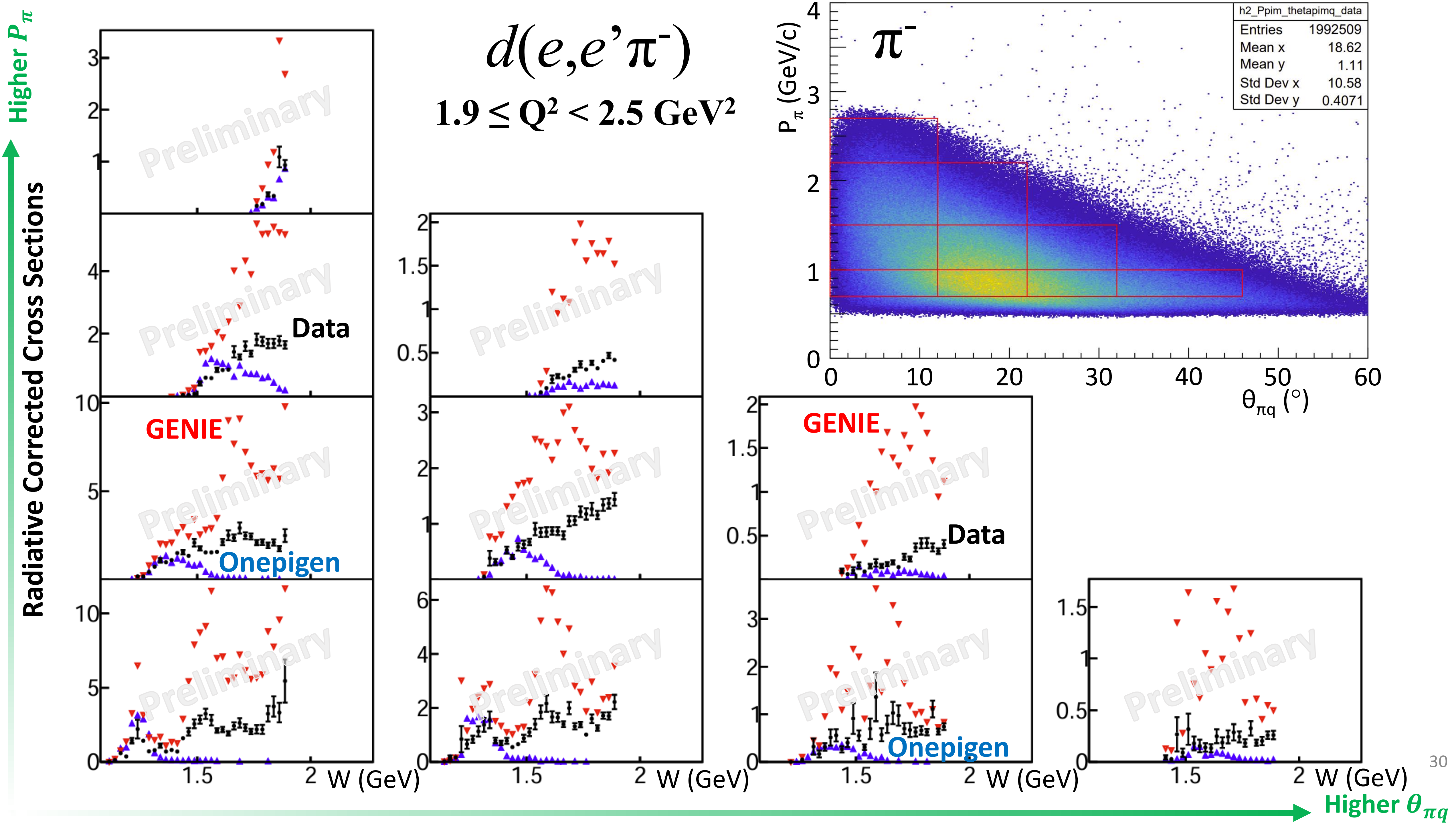
P_π (GeV/c)
$\theta_{\pi q}$ (°)
GENIE
Data
Onepigen
Preliminary
W (GeV)
Higher $\theta_{\pi q}$



$d(e,e'\pi^-)$
$1.9 \leq Q^2 < 2.5$ GeV^2
π^-
h2_Ppim_thetapimq_data
Entries 1992509
Mean x 18.62
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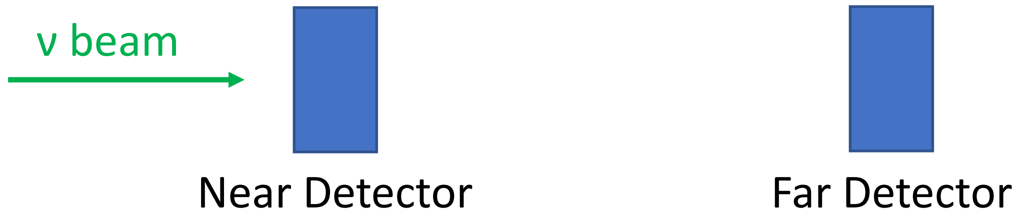
P_π (GeV/c)
$\theta_{\pi q}$ (°)
Higher P_π
Higher $\theta_{\pi q}$
Radiative Corrected Cross Sections
Data
GENIE
Onepigen
Preliminary
W (GeV)

Neutrino Experiments



Neutrino Flux:

$$\Phi_\alpha(E,L) = \left[1 - P_{\nu_\alpha \to \nu_\beta}(E,L)\right] \Phi_\alpha(E,0)$$

Far Near

$$N_\alpha(E_{rec},L) = \int \Phi_\alpha(E,L)\sigma(E) f_\sigma(E,E_{rec})dE$$

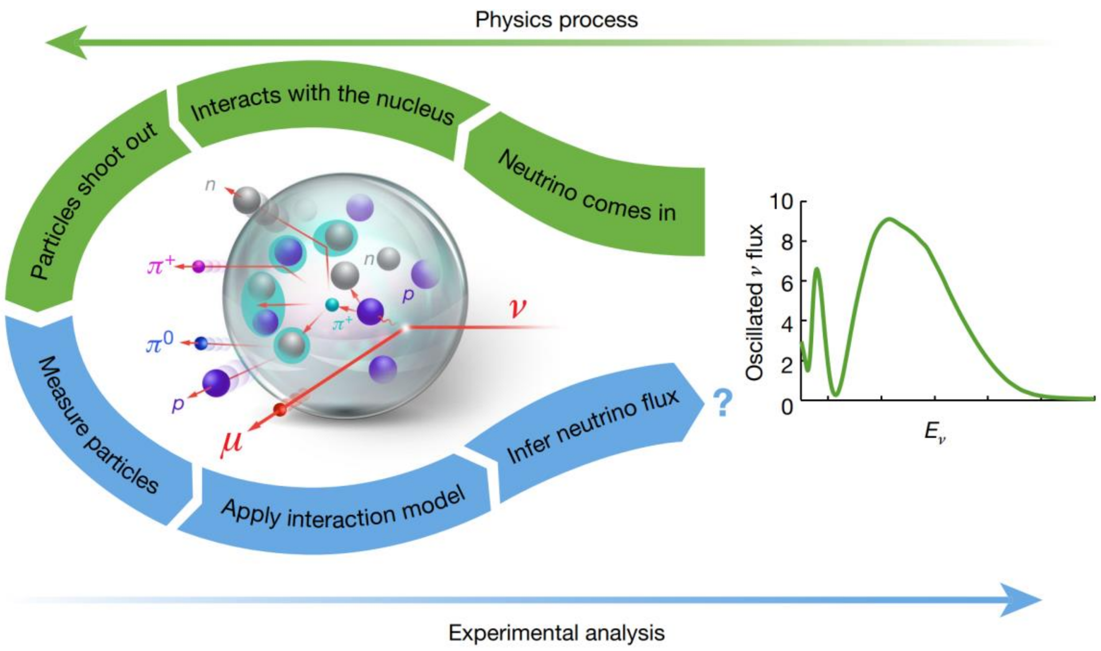
Measured Flux Simulated

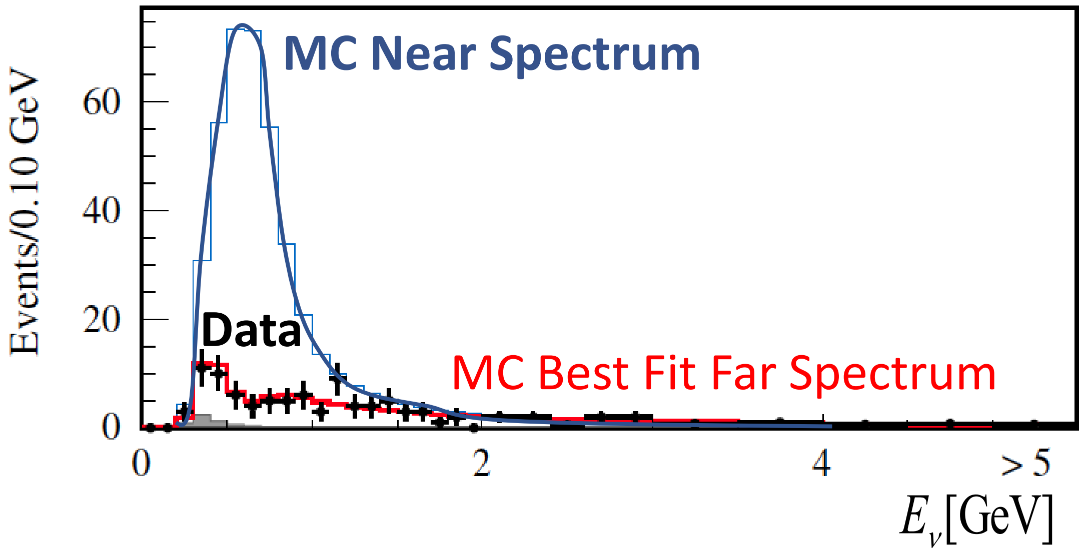
Neutrino experiments are difficult

- Large beam energy spread
- Small cross sections

Need GENIE to extract the neutrino flux from data

How to validate GENIE?

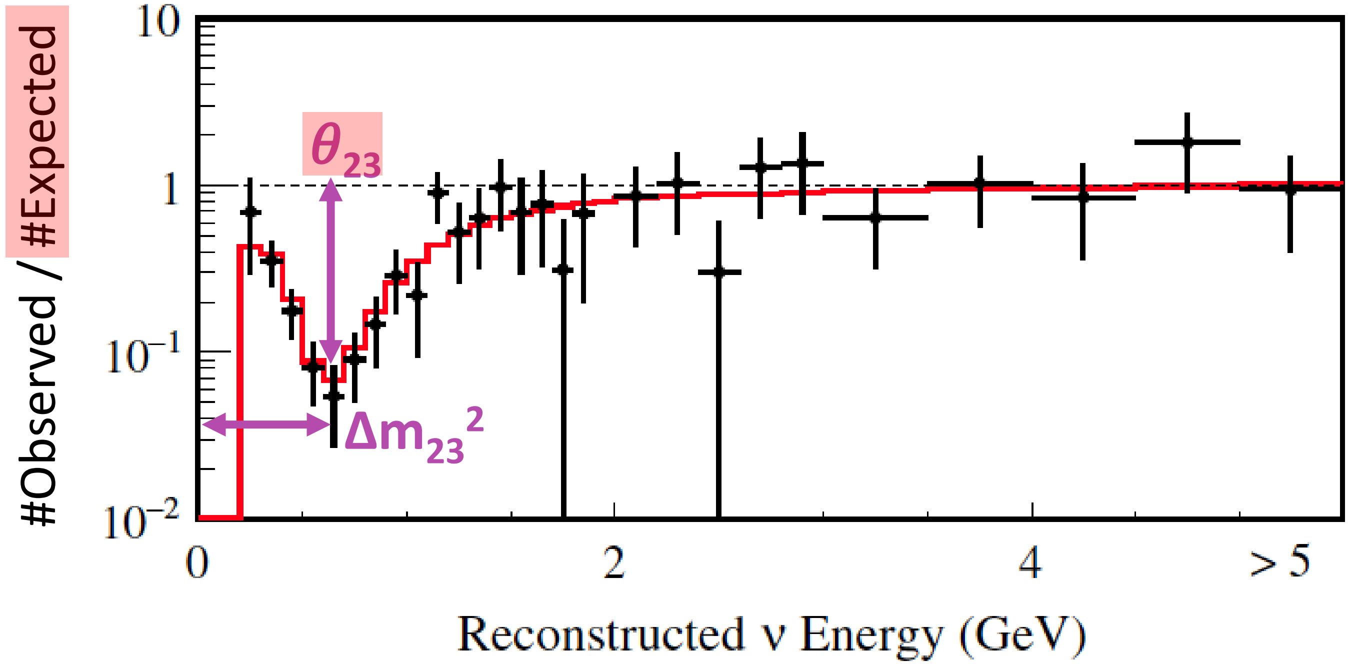




PRD 91, 072010 (2015)

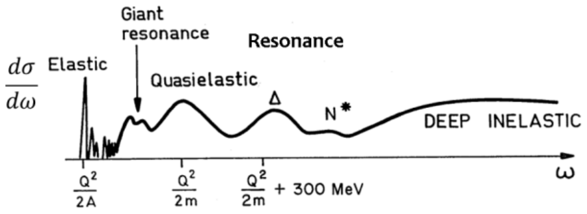
Oscillation Probability

$$P(\nu_\mu \to \nu_\mu) = \sin^2(2\theta_{23}) \times \sin^2\left(\frac{\Delta m_{32}{}^2 L}{4E_\nu}\right)$$

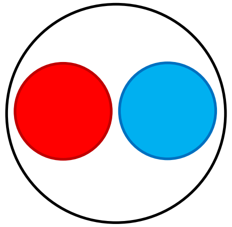


T2K PRD (2015)

Pion Physics



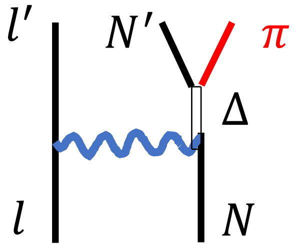
- Mesons consisting of combinations of u and d quarks and antiquarks
- Commonly produced in scattering experiments



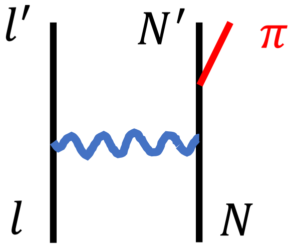
$$e + p \to e' + n + \pi^+ \qquad e + n \to e' + p + \pi^-$$

$$e + p \to e' + p + \pi^0 \qquad e + n \to e' + n + \pi^0$$

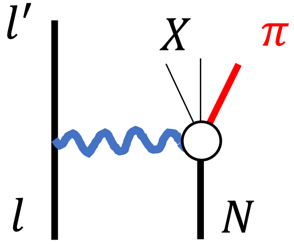
Resonance Decay Production

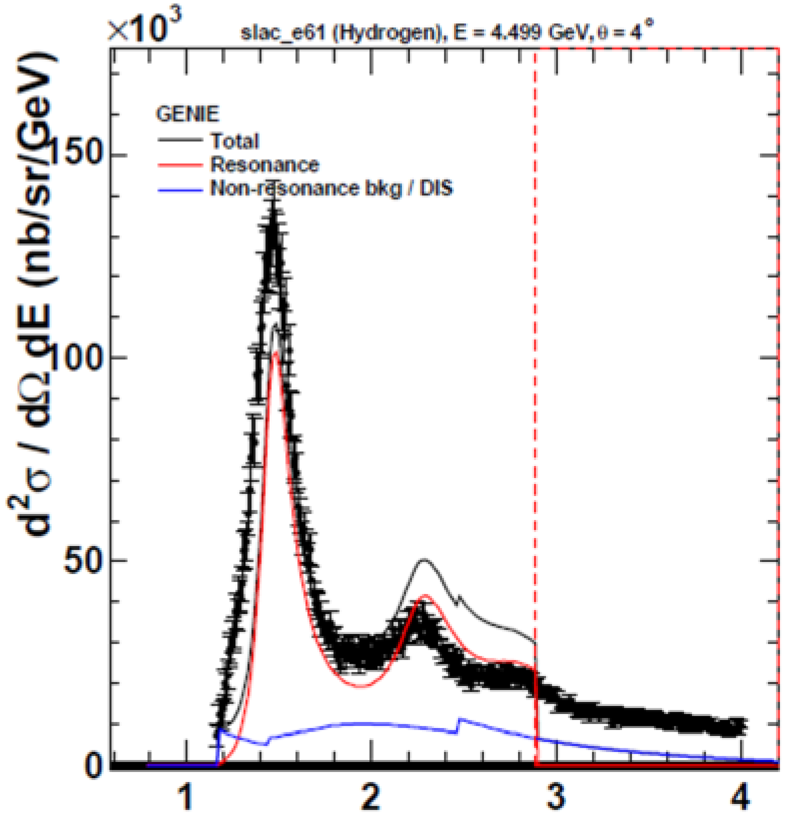


Non-Resonant Production



DIS Production

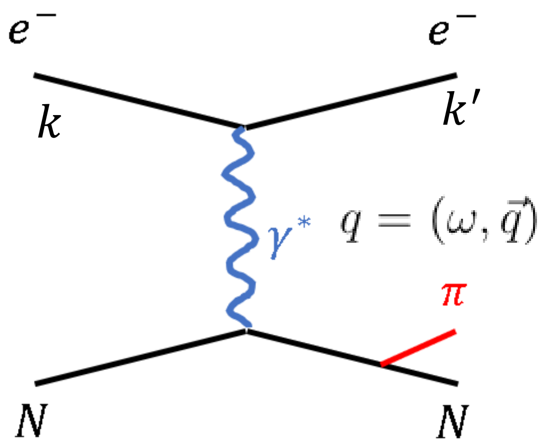




Steve Dytman (Univ. of Pittsburgh)
FUNFACT at JLab
May 15, 2015

$$Q^2 = -q^2 = (k - k')^2$$

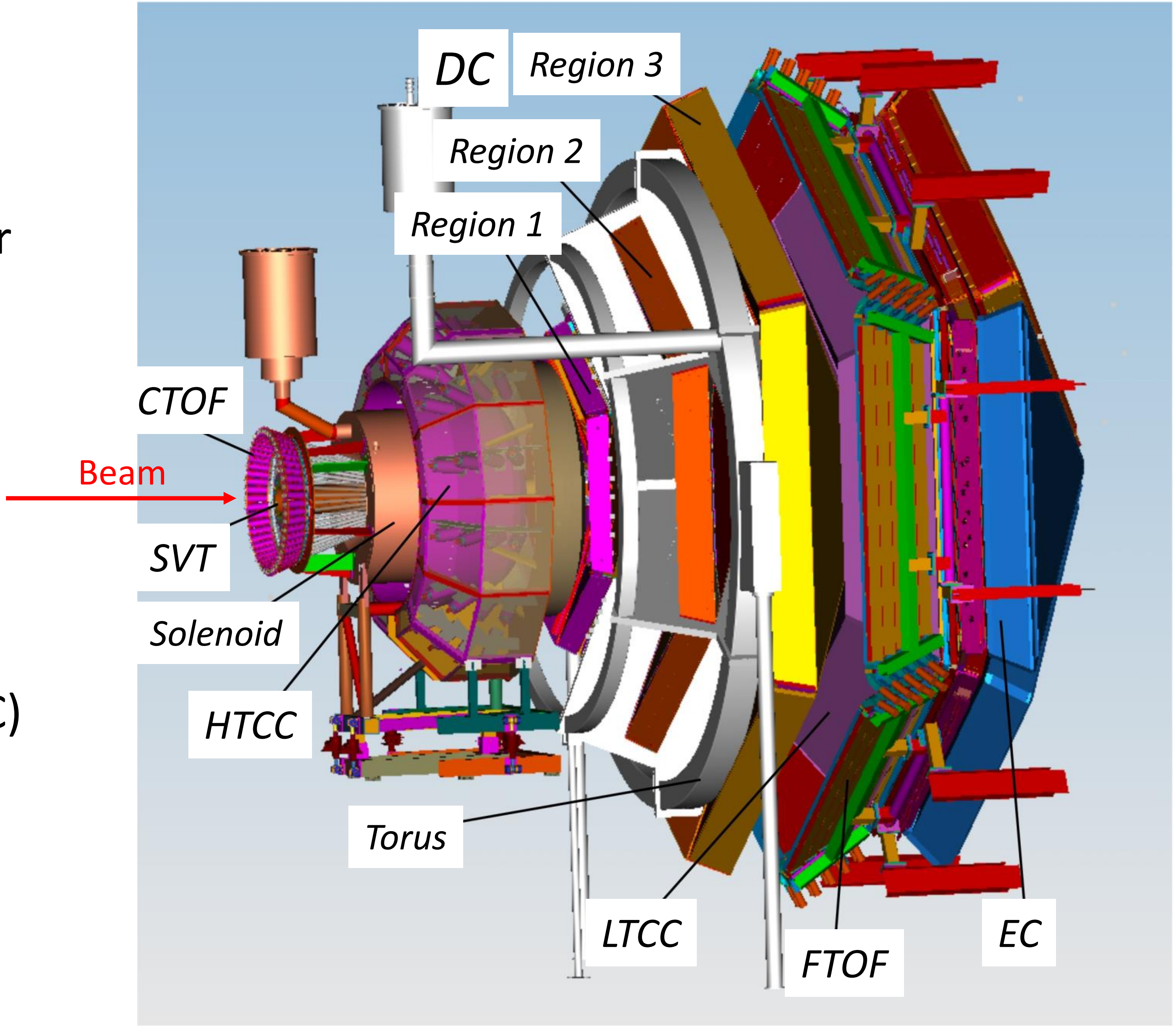
$$W = \sqrt{M_N^2 + 2M_N\omega - Q^2}$$



CLAS12

- Forward Detector:
  - High Threshold Cerenkov Counter (HTCC) identifies scattered electrons
  - Drift Chambers (DC) measure charged particle momenta
  - Forward Time-of-Flight (FTOF) measures time-of-flight of charged particles
  - Electromagnetic Calorimeters (EC) identifies scattered electrons
    - Includes Pre-shower Calorimeter (PCAL)
- Central Detector:

  Not used in this analysis

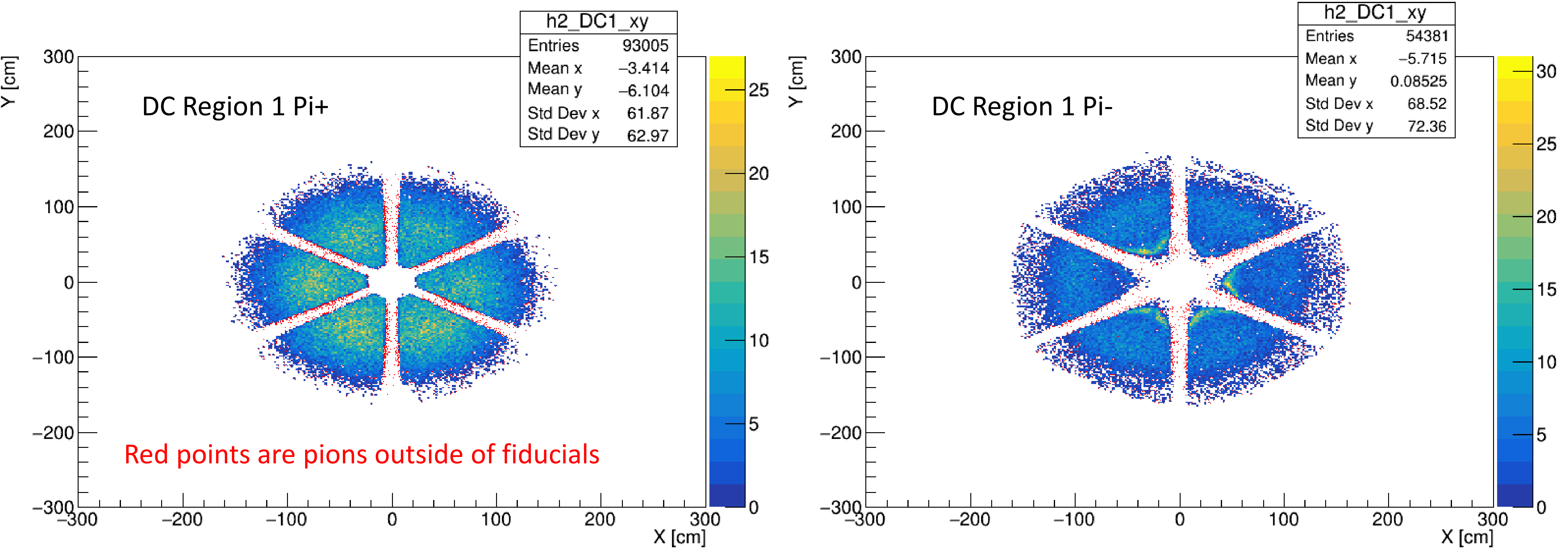


FTOF Best Fit

$$\Delta t = t_{start\ time} - \left[t_{FTOF} - \frac{L}{\beta_h(p)} \right]; \beta_h(p) = \frac{p}{\sqrt{p^2 + m^2}}$$

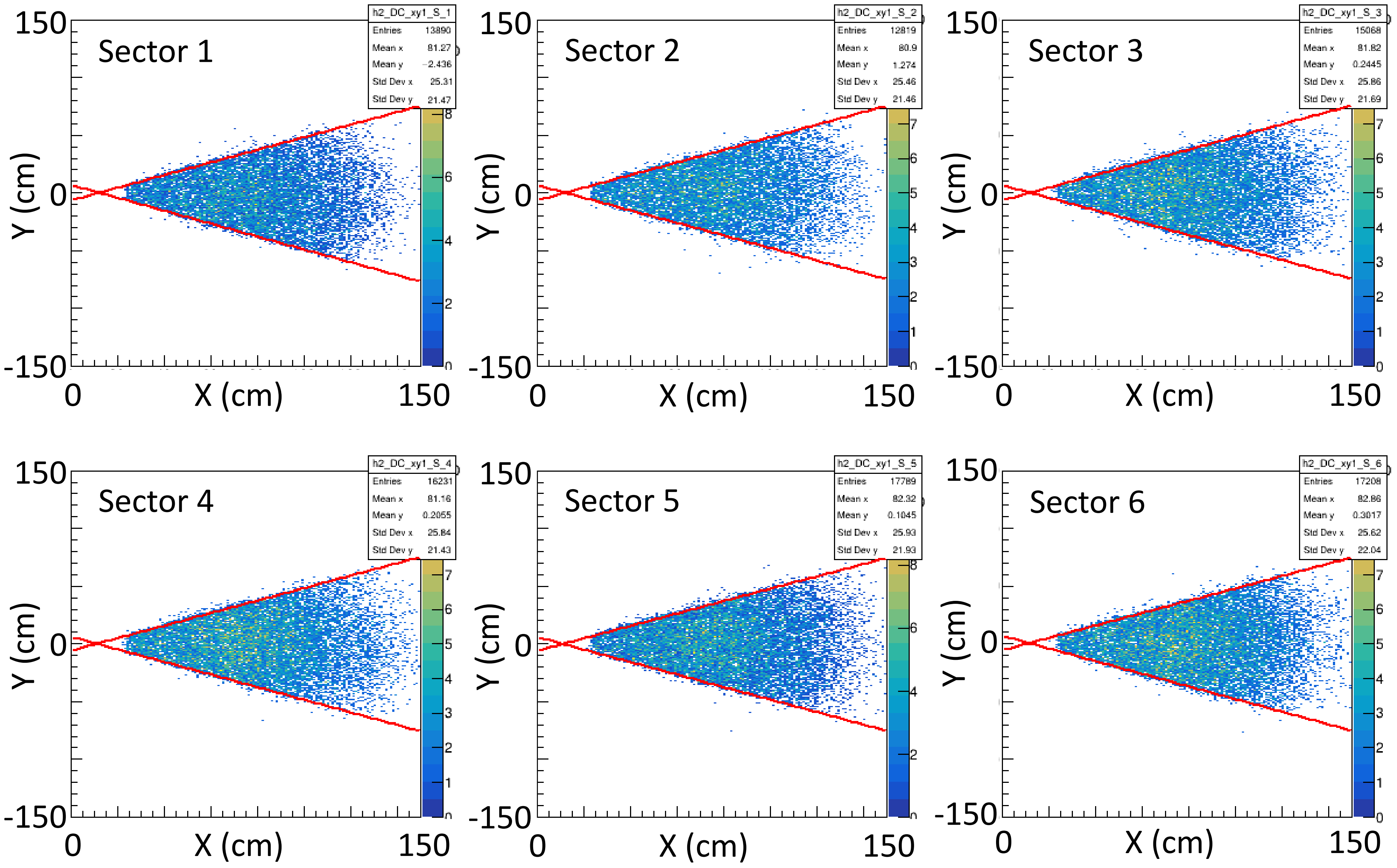
DC Fiducial Cuts

- Fiducial cuts select hits (or tracks) with near 100% efficiency



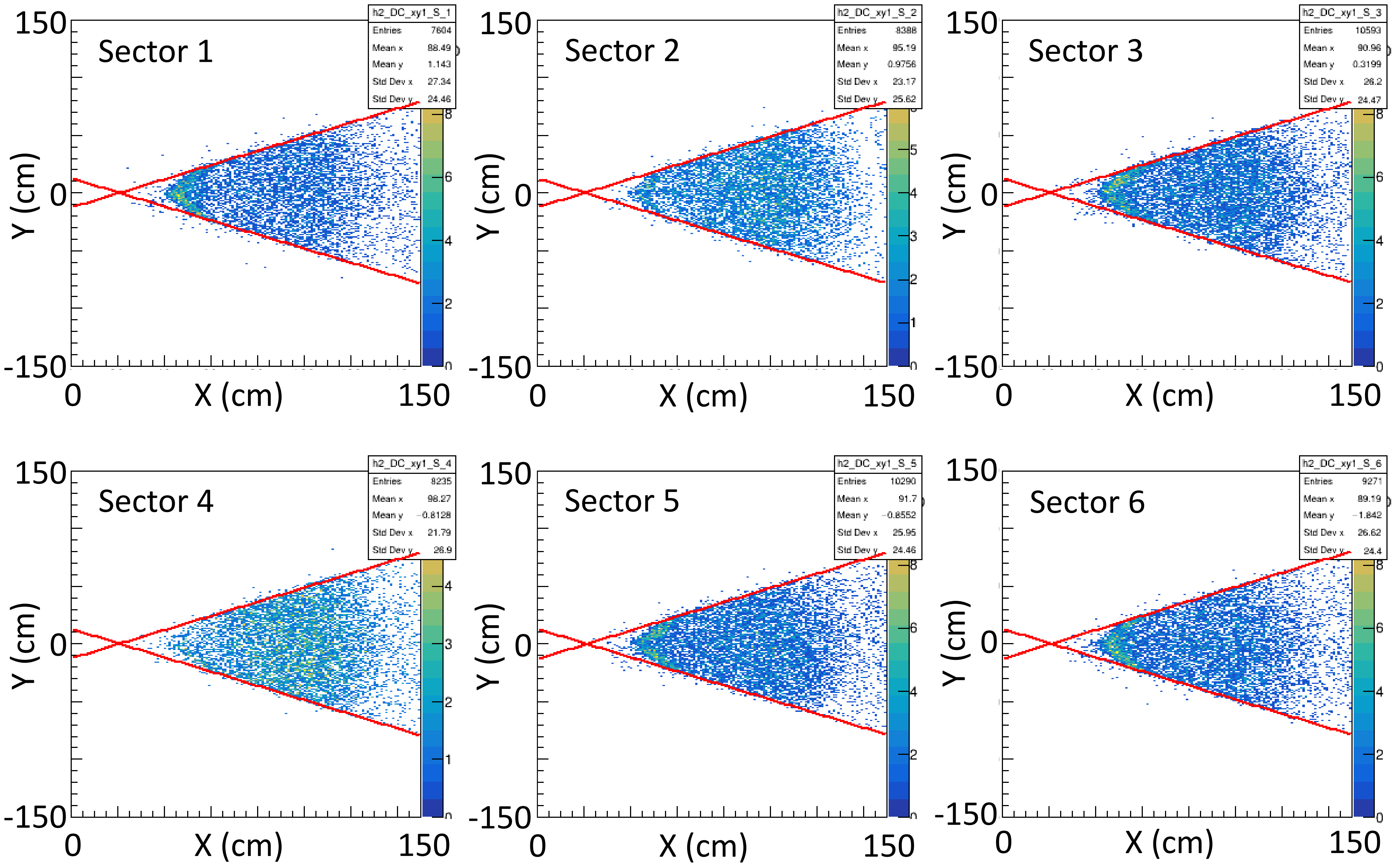
DC Fiducial Cuts

Region 1 (Pi+)

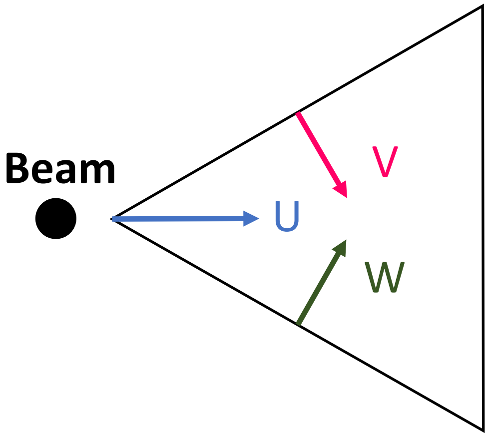


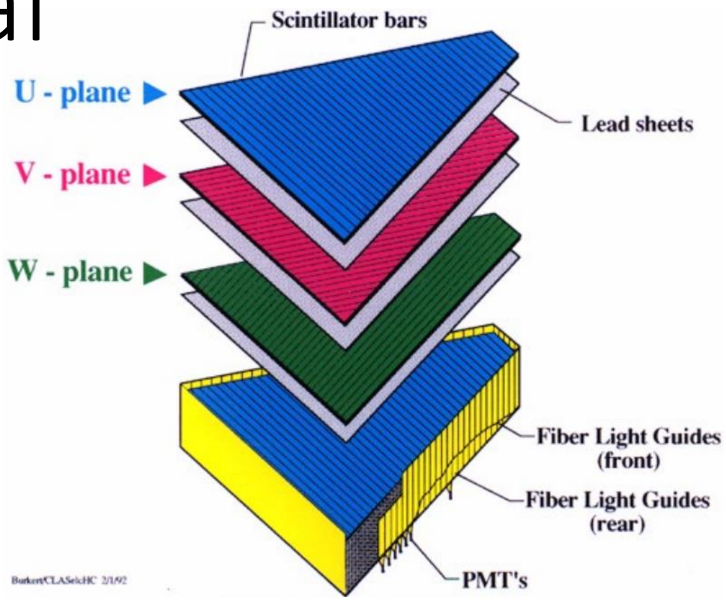
DC Fiducial Cuts

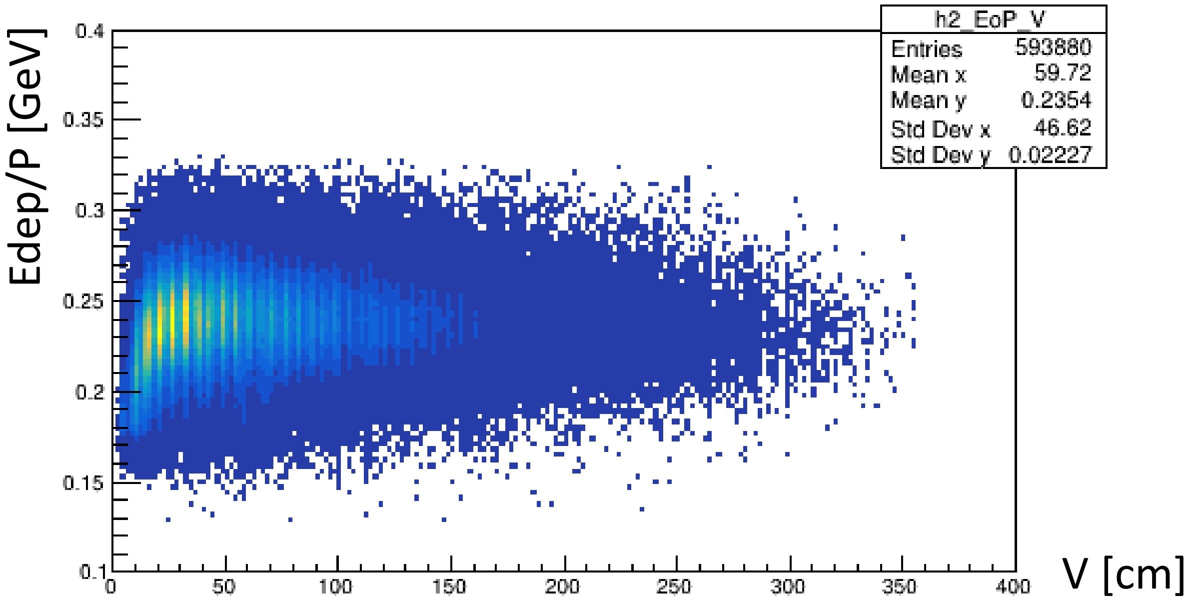
Region 1 (Pi-)

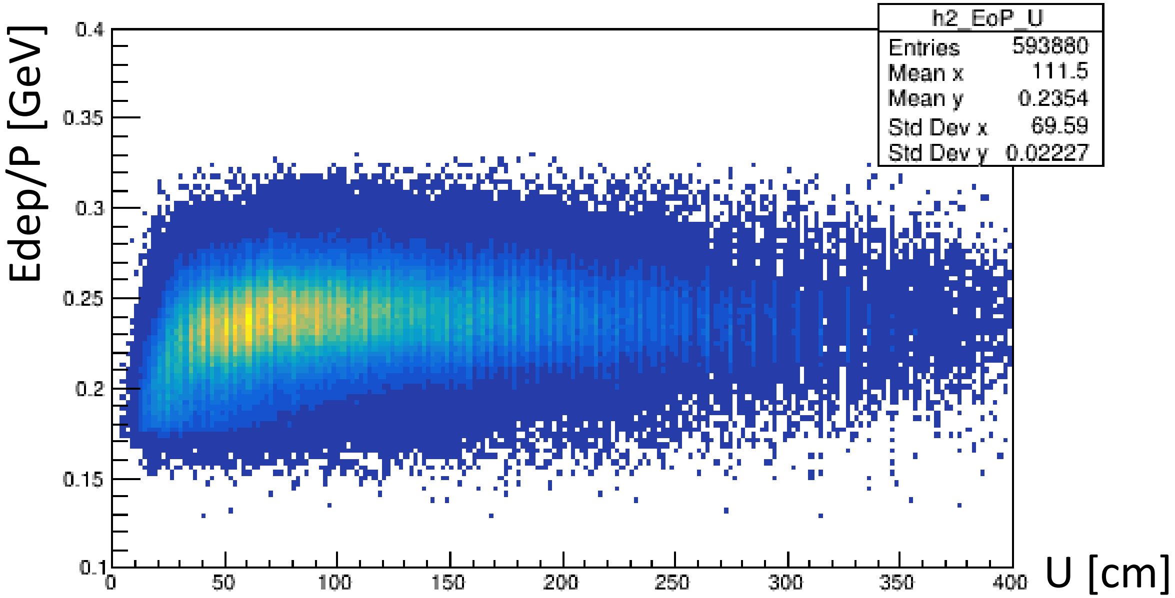


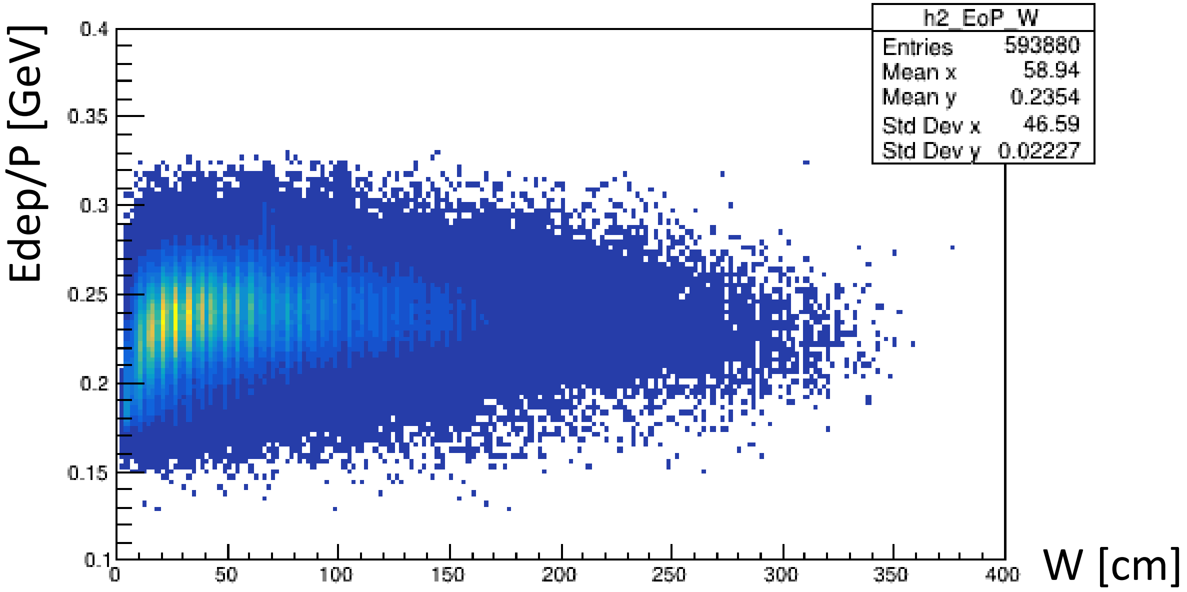
EC Fiducial Cuts





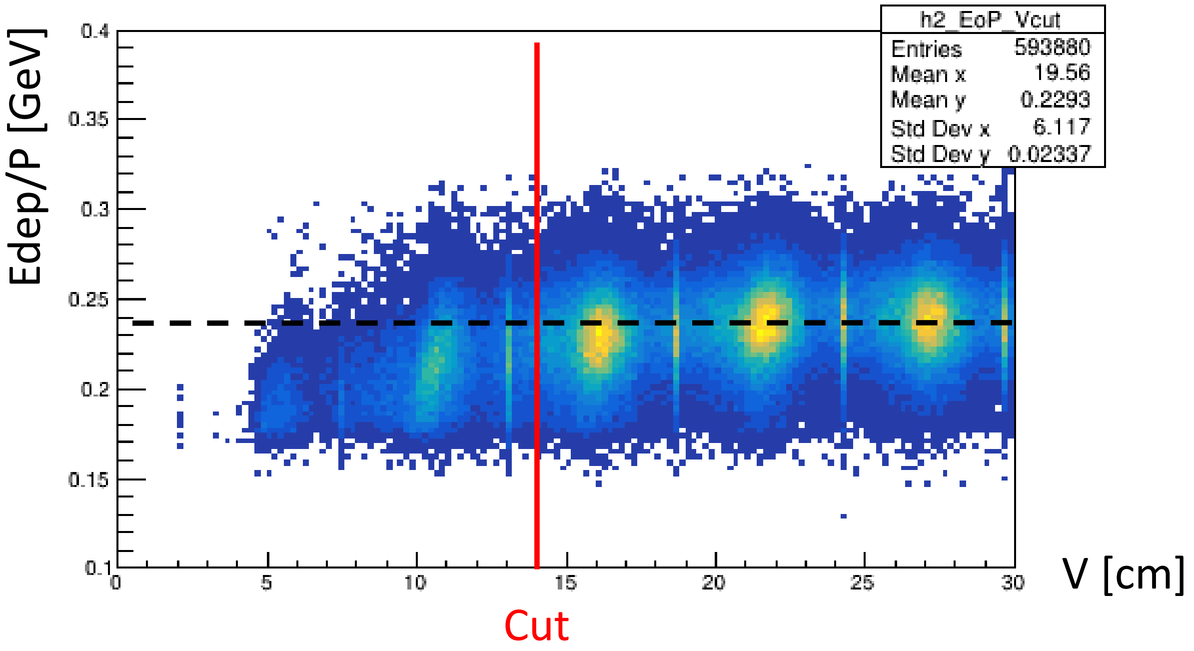


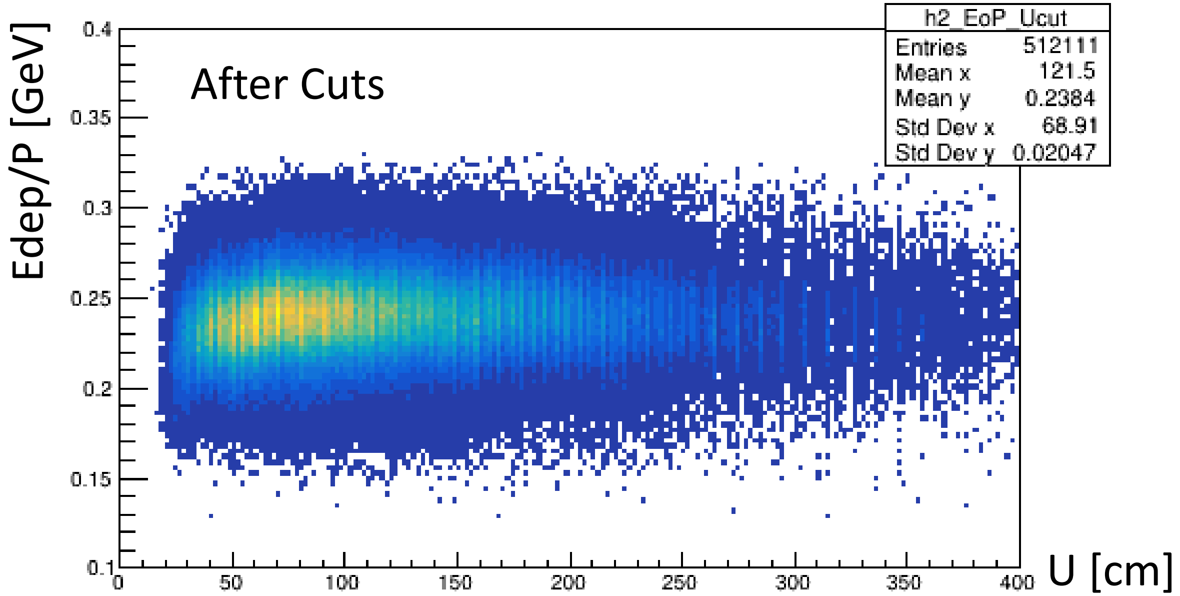


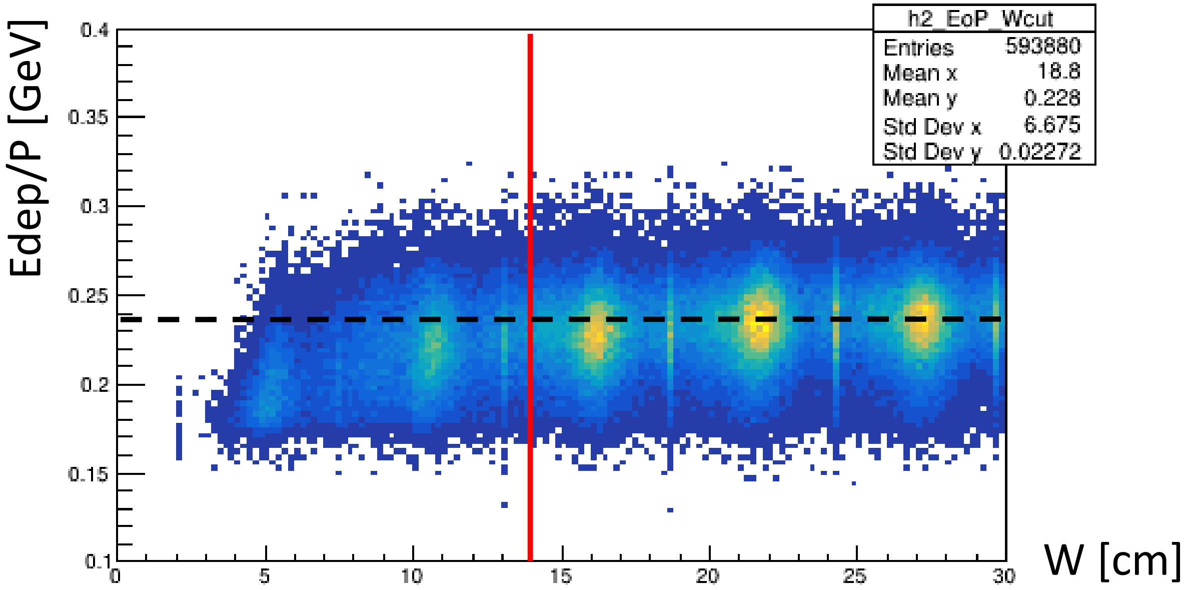


EC Fiducial Cuts

Required V, W > 14 cm (removed outer 2 bars)

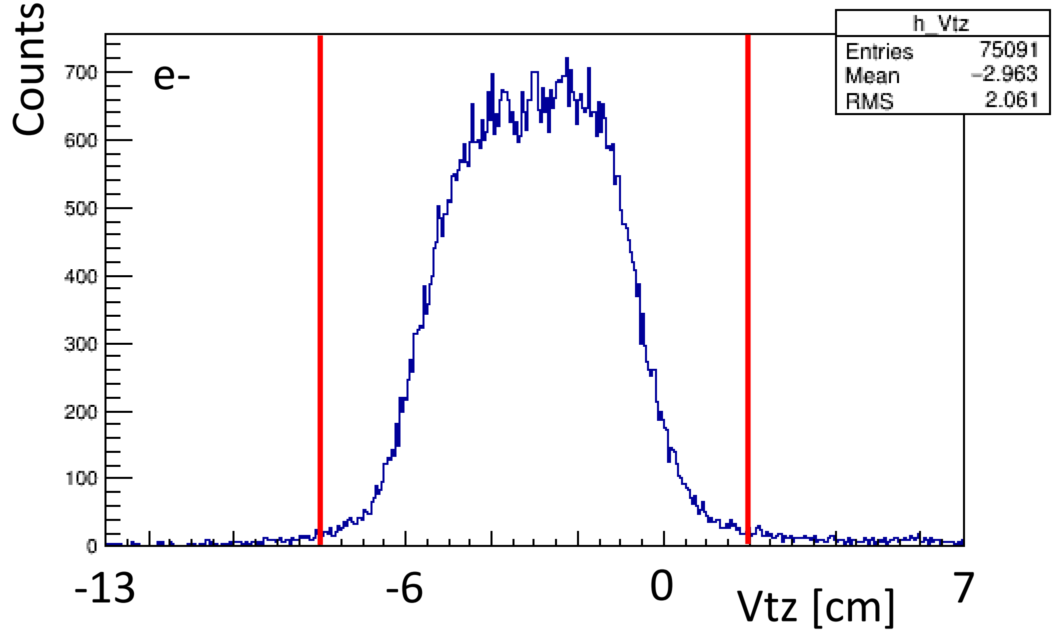


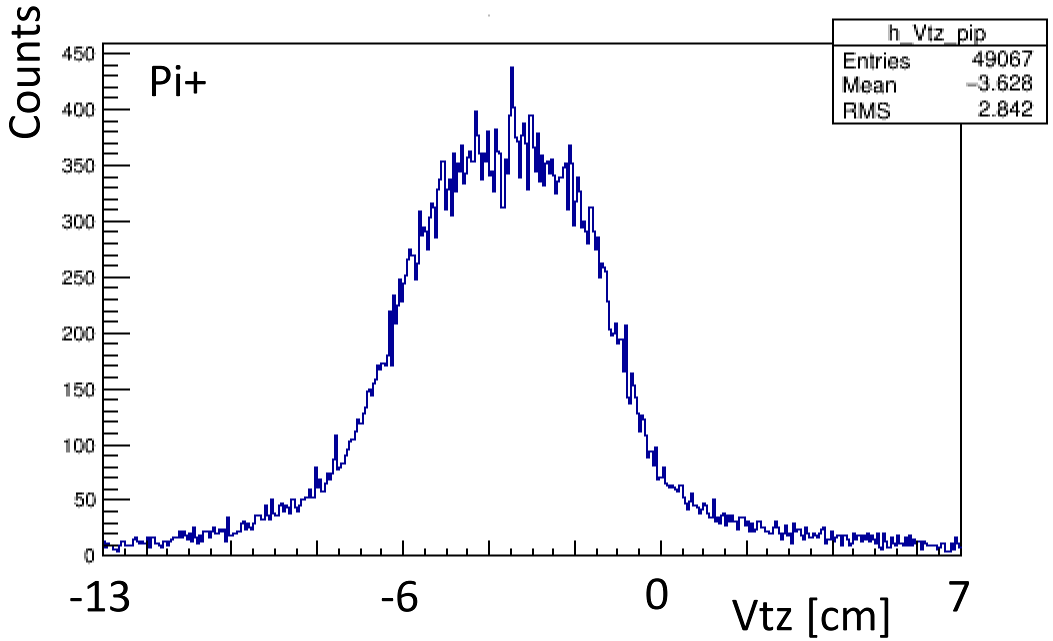


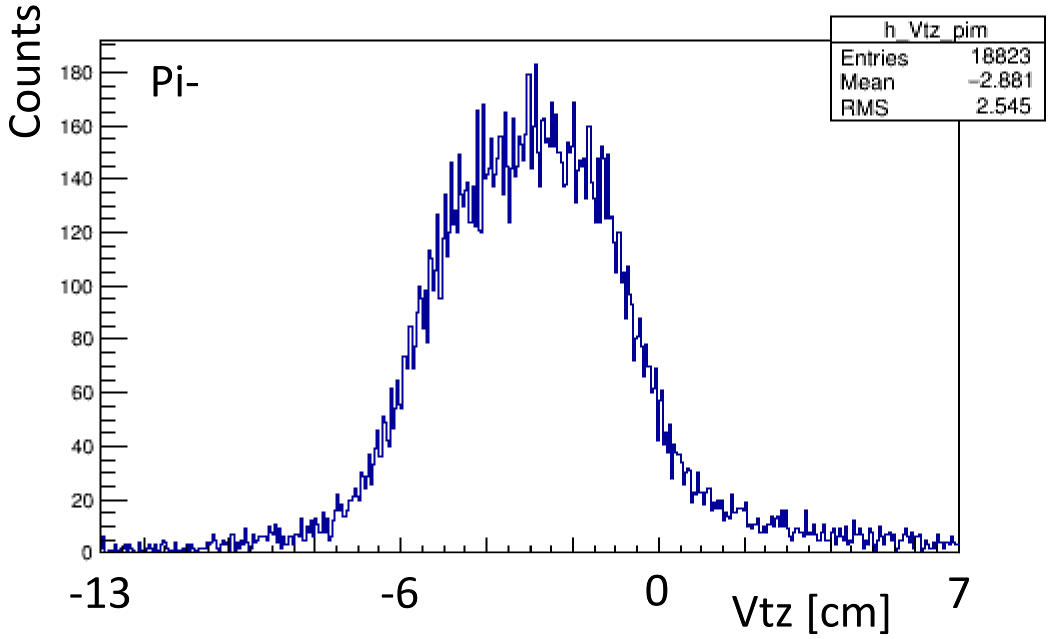


Electron and Pion z Vertices

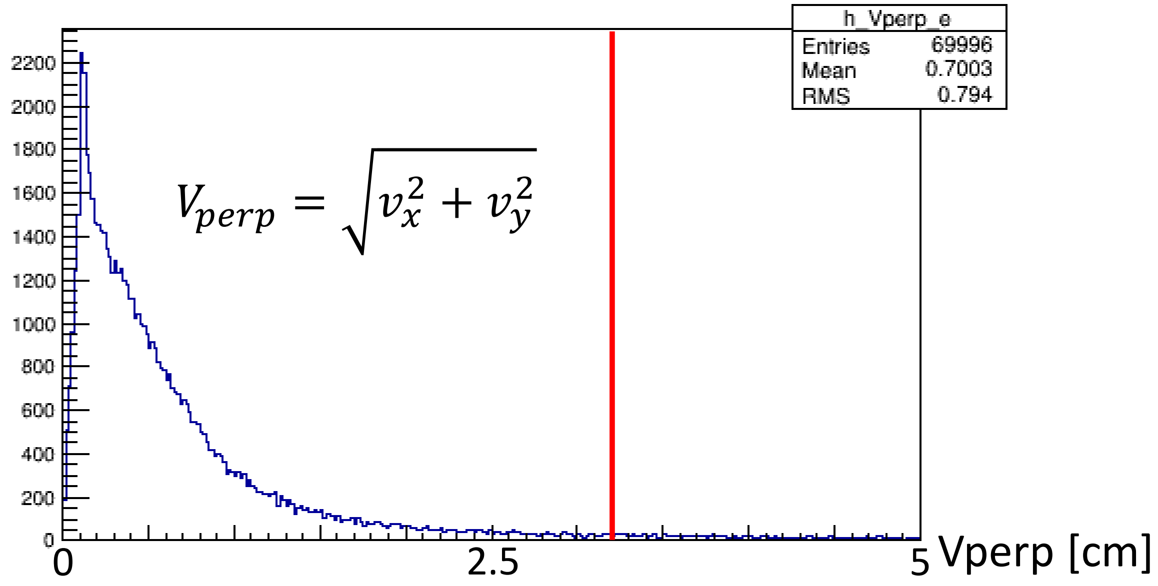
-8 cm < Vtz_e < 2 cm

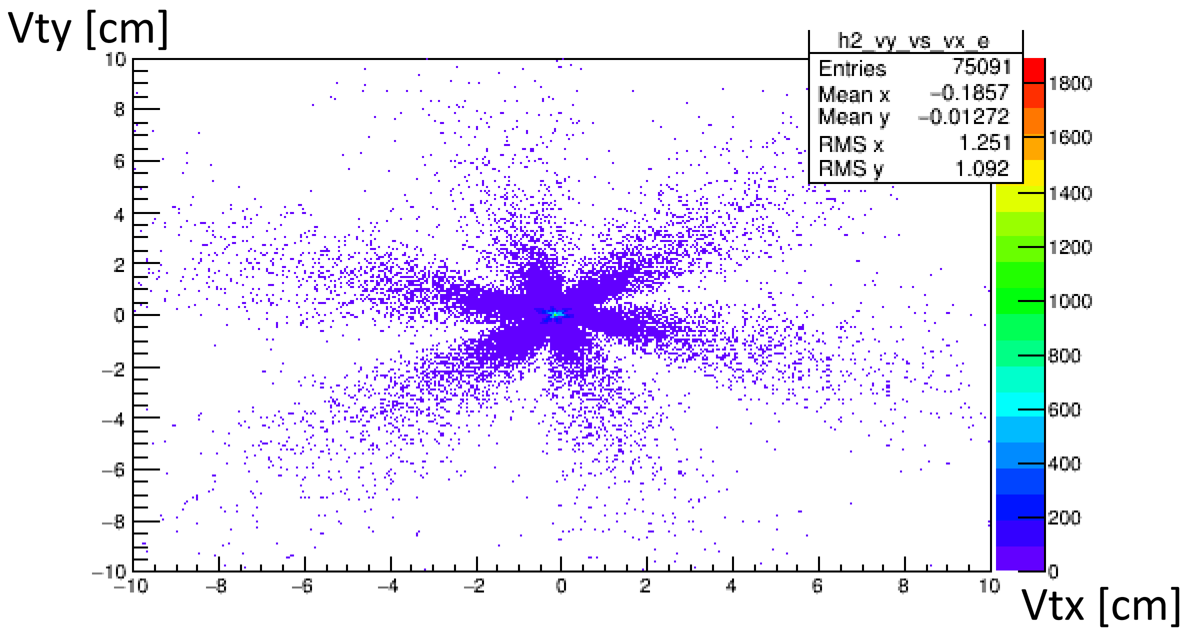


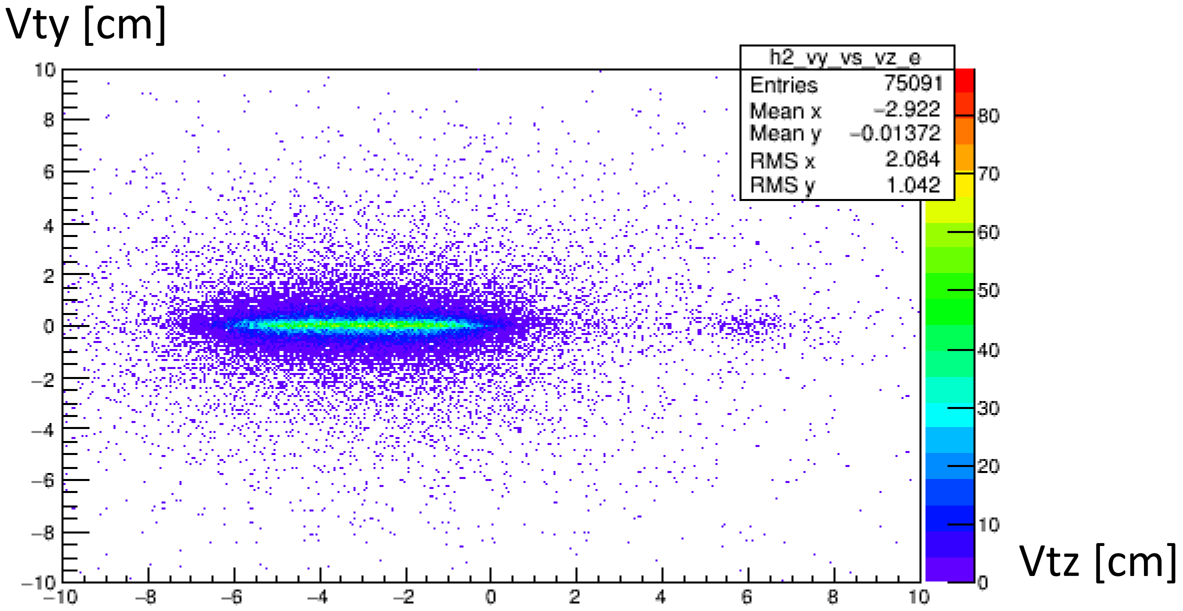


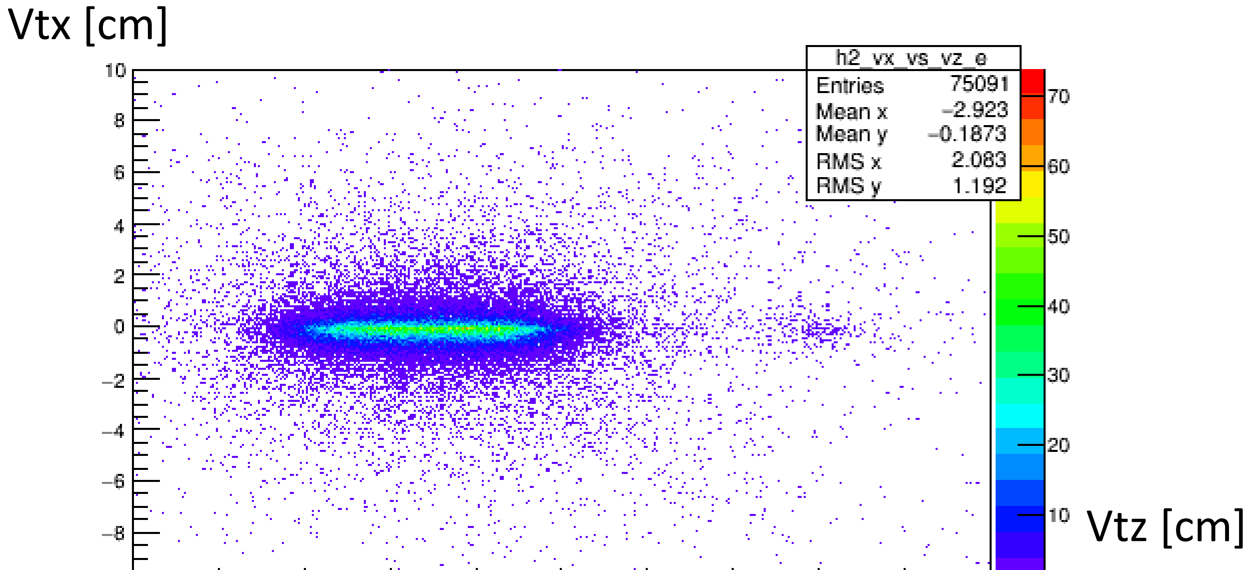


Electron Perpendicular Vertices

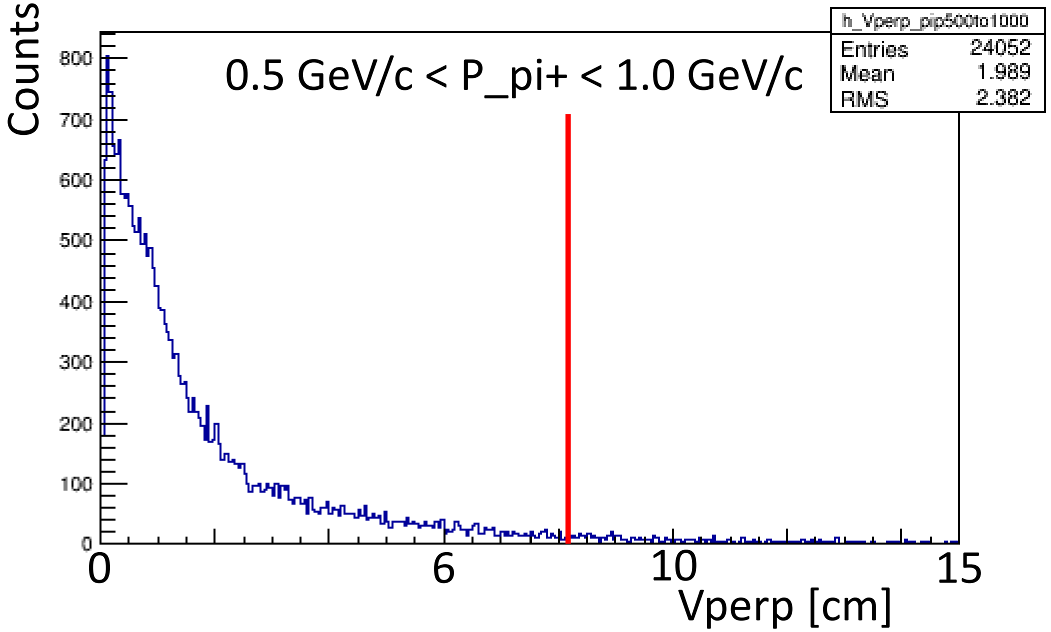


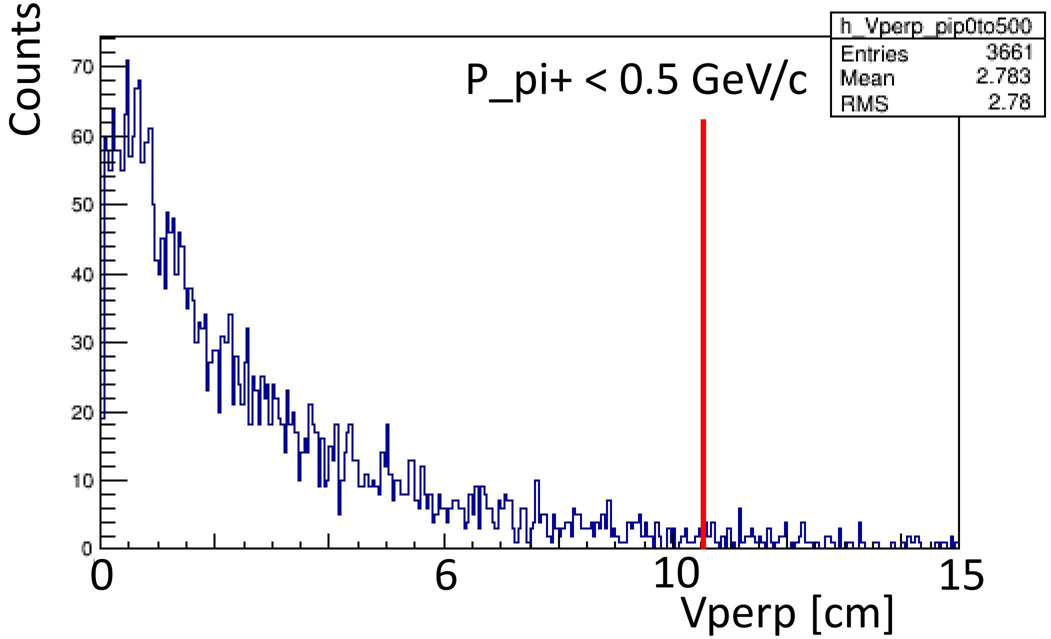


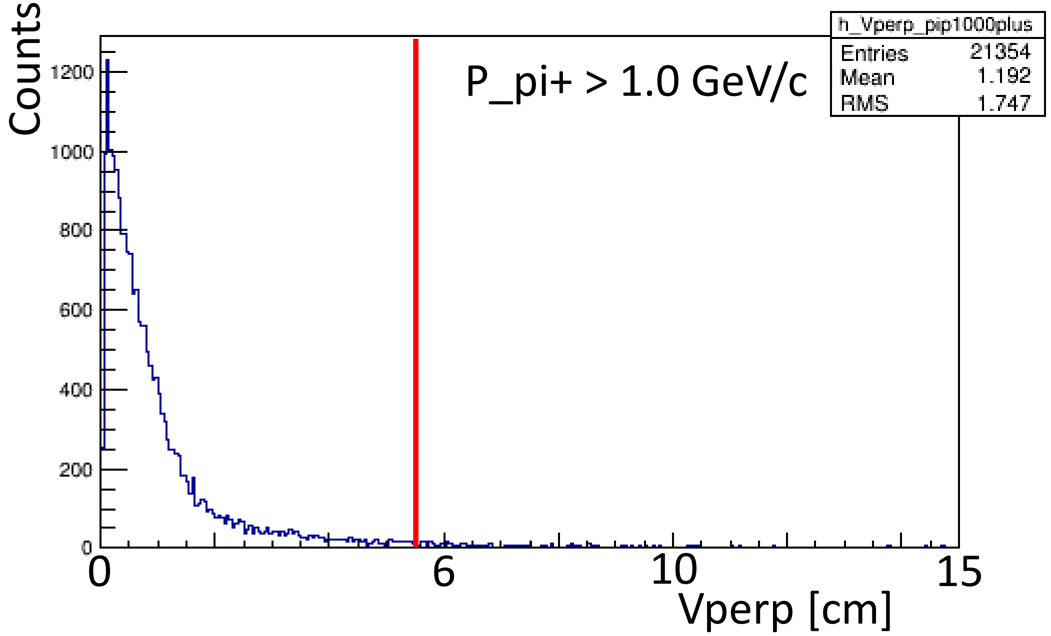




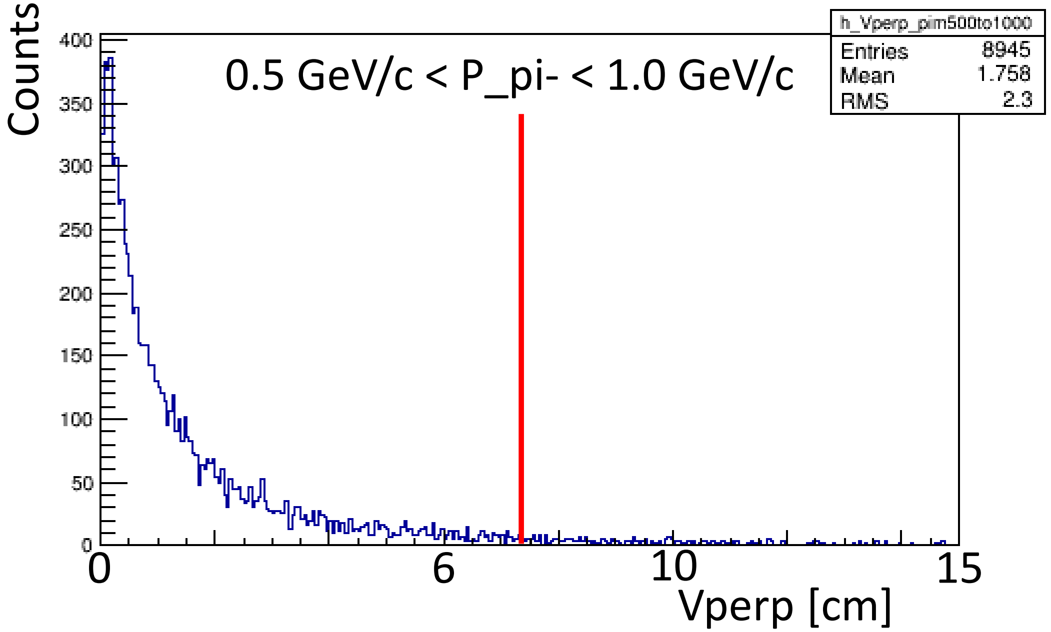
Pi+ Perpendicular Vertices

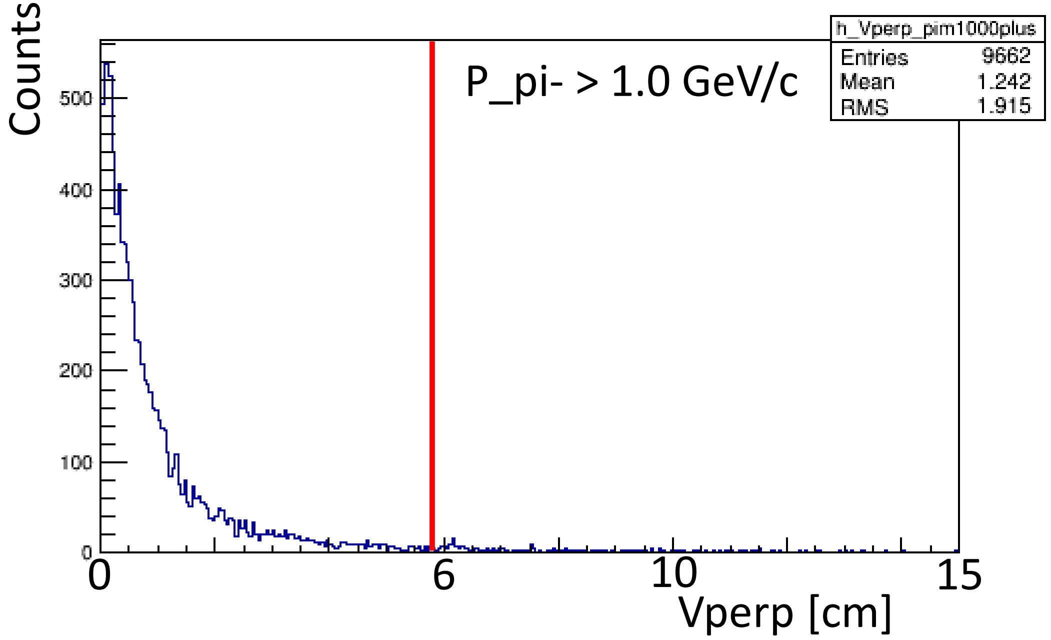






Pi- Perpendicular Vertices

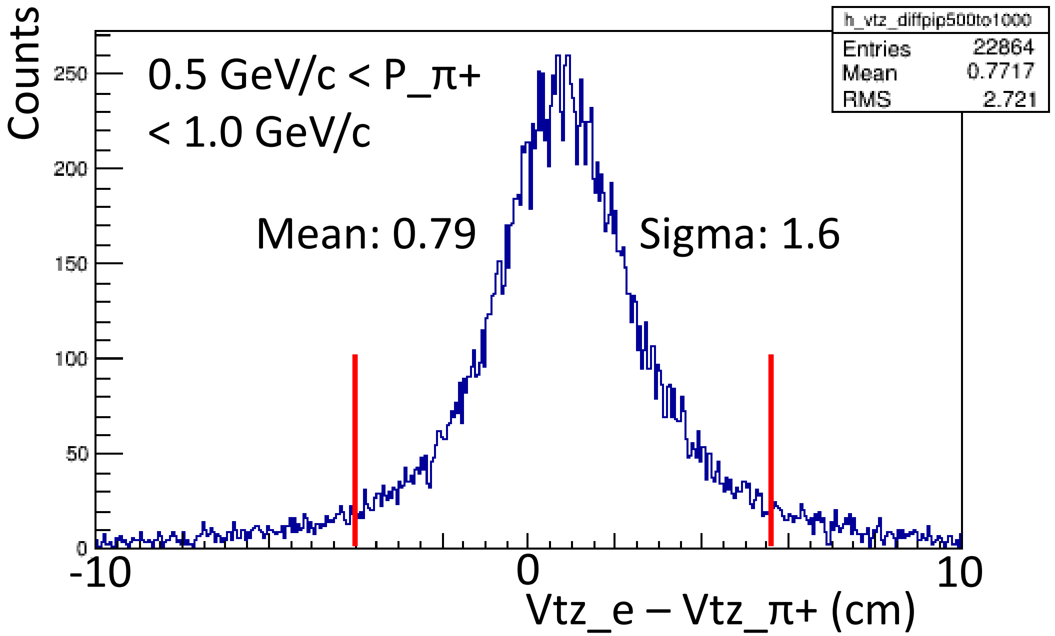


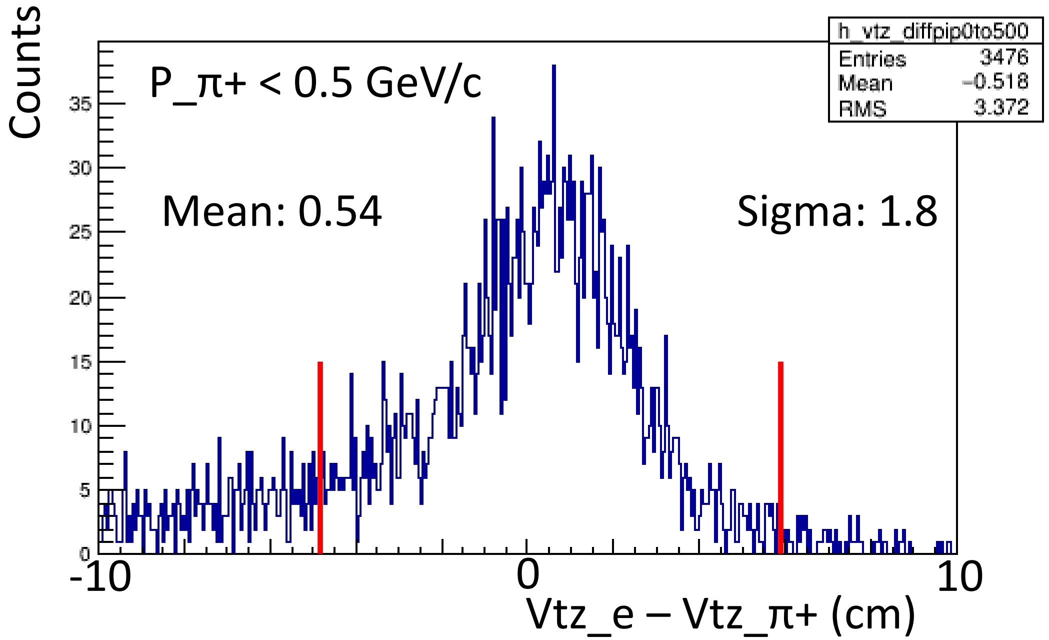


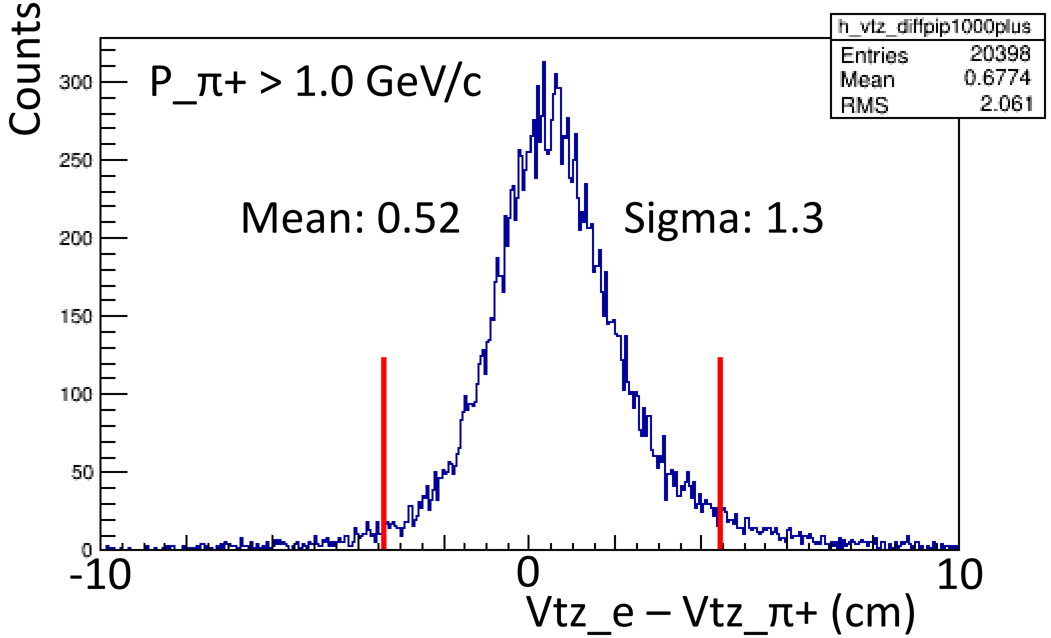
Vertex Z Difference (Electron – Pi+)

Fitted with gaussian

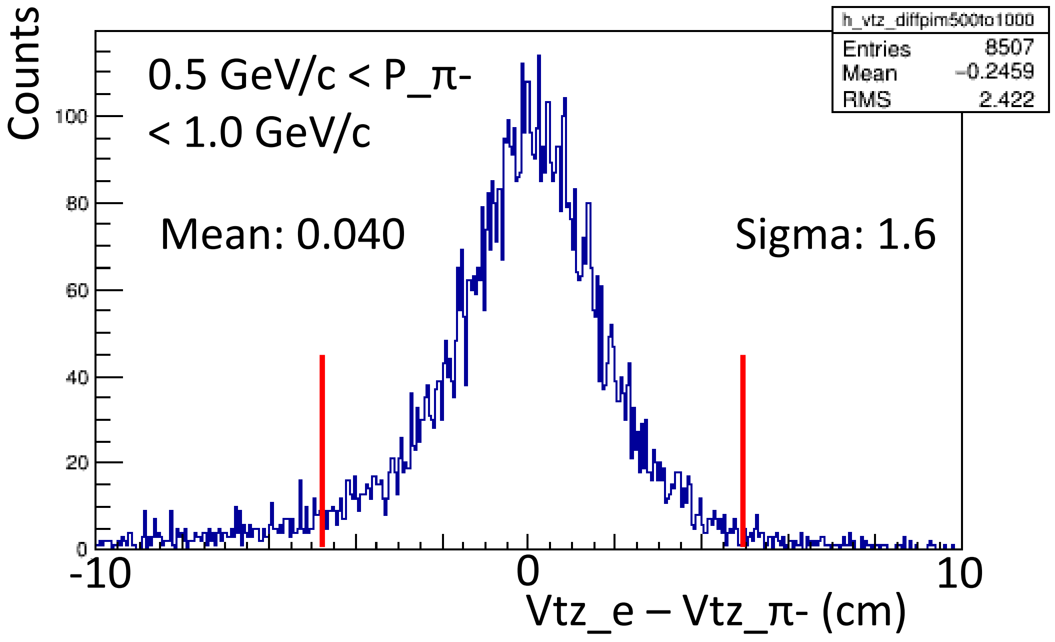
Cut = mean ± 3 * σ

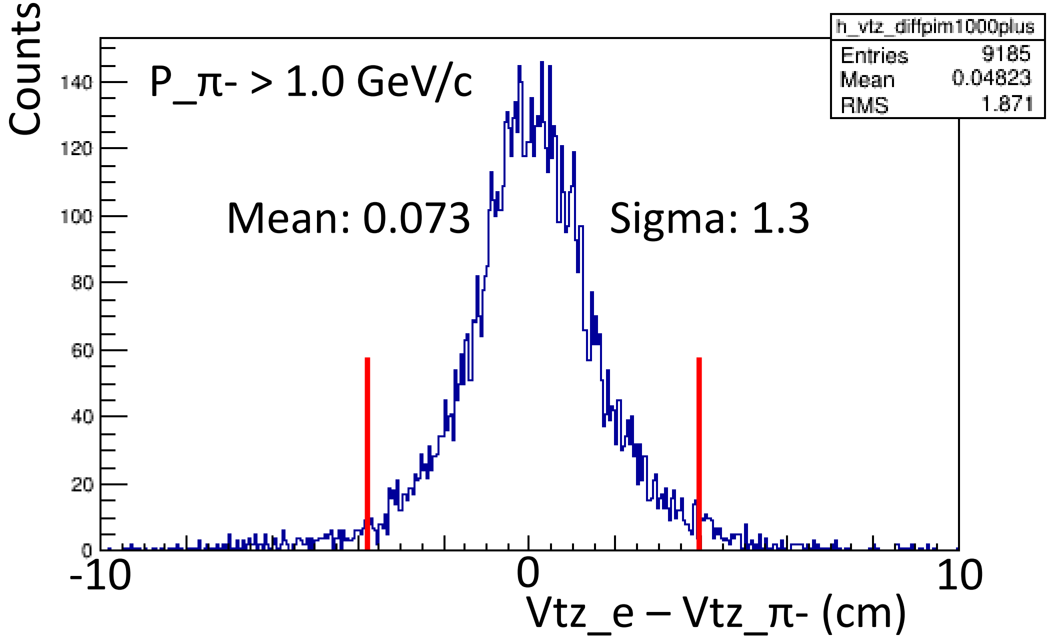






Vertex Z Difference (Electron – Pi-)

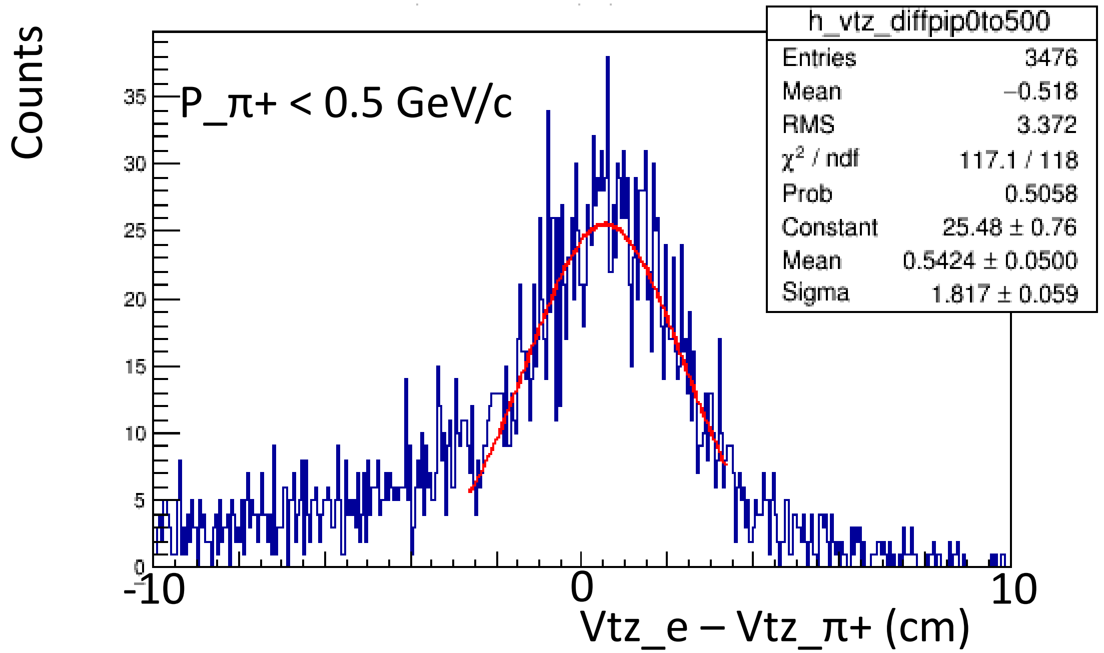


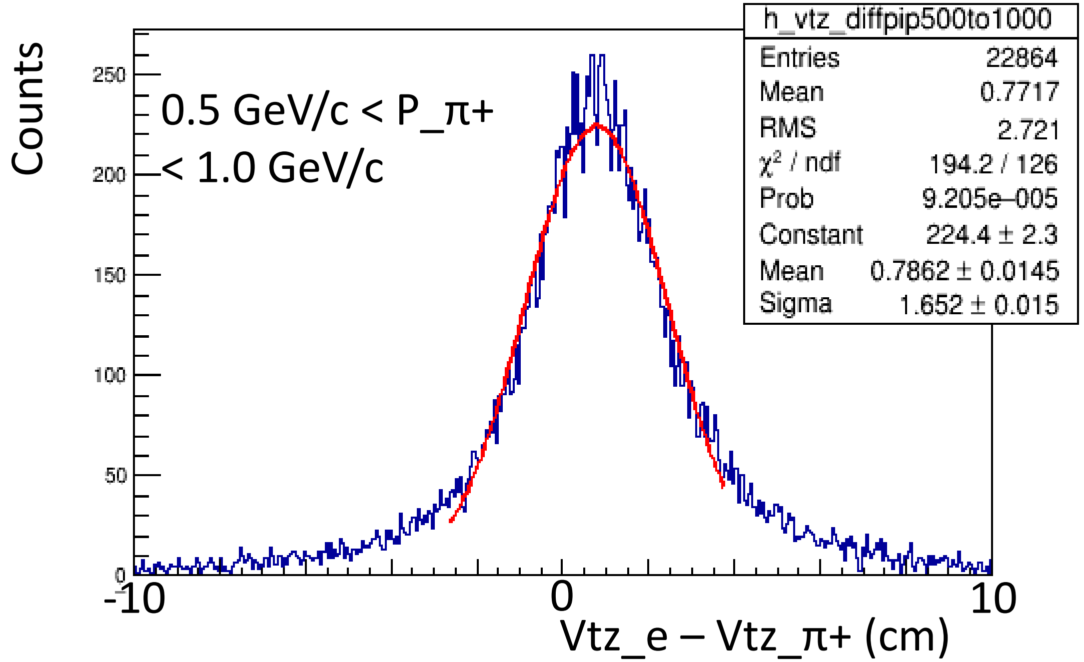


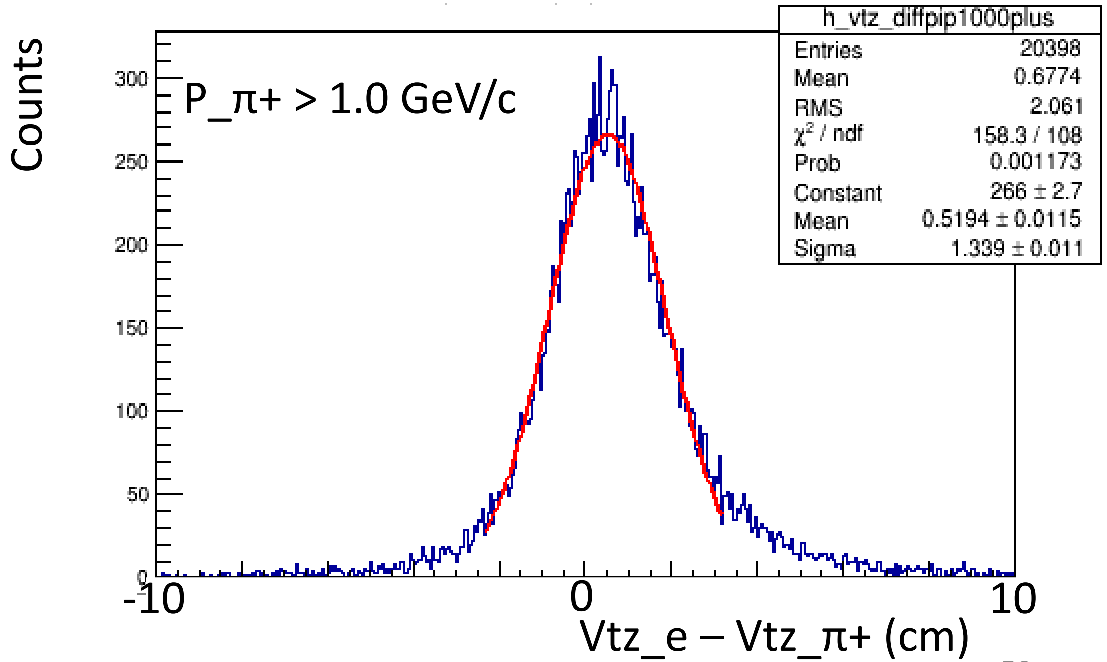
Vertex Z Difference (Electron – Pi+)

Fitted with gaussian

Cut = mean ± 3 * σ



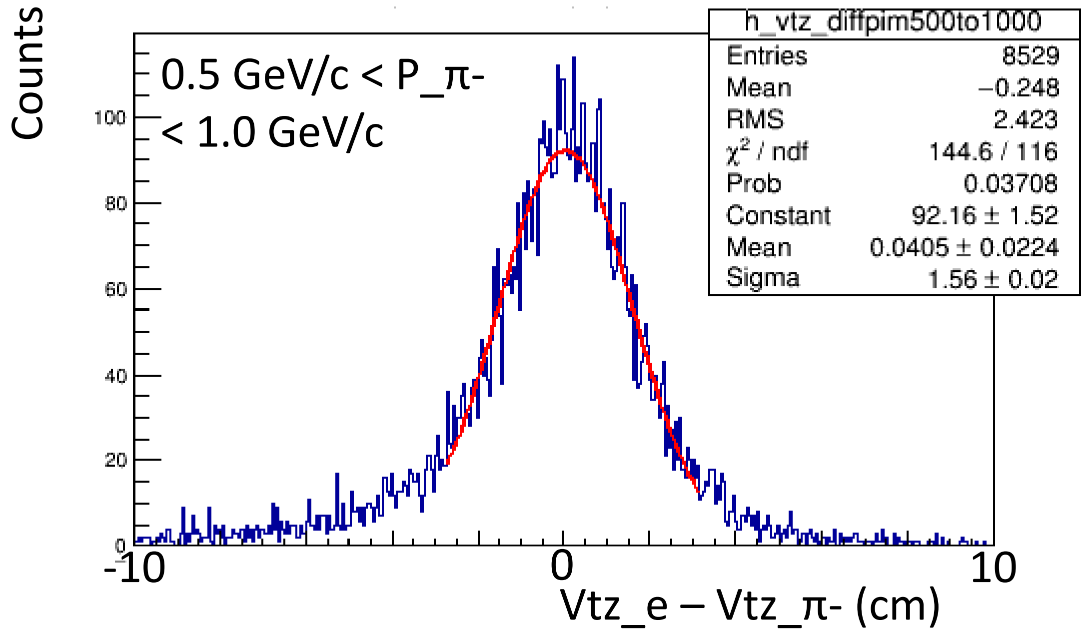


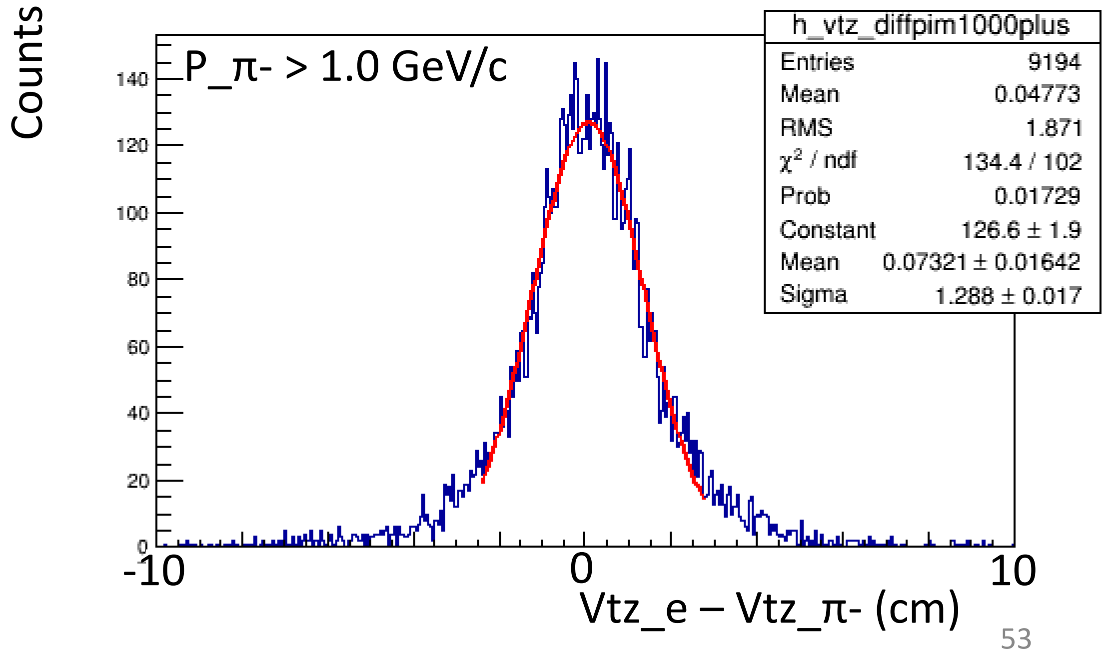


Vertex Z Difference (Electron – Pi-)

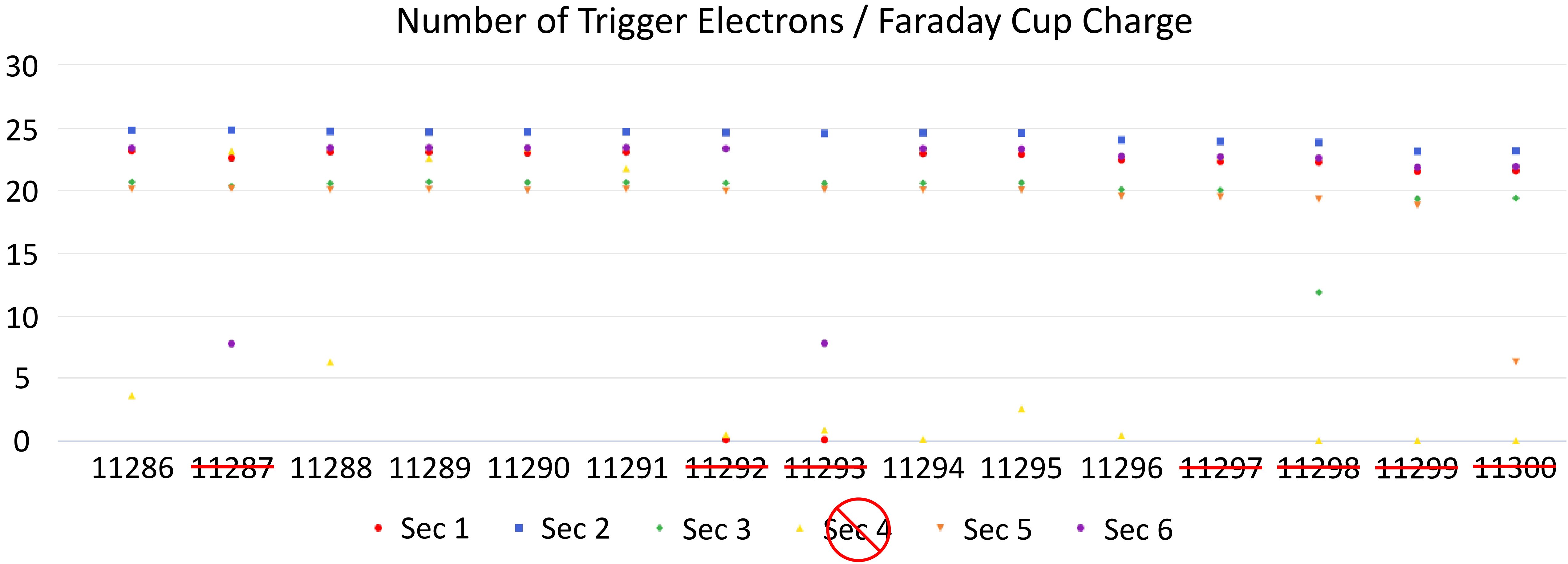
Fitted with gaussian

Cut = mean ± 3 * σ





Run Selection



Sector d(e,e’$\pi^{\pm}$) cross section issues after cuts

About 5 M d(e,e’$\pi^{\pm}$) events after cuts

D(e,e'pi) Cross Sections

$$N_{events} = \boxed{\frac{d^6\sigma}{d\Omega_E d\Omega_\pi dE' dT_\pi}} \Delta\Omega_E \Delta\Omega_\pi \Delta E' \Delta T_\pi * N_e t_{tgt} * correction\ factors$$

What we want

$$N_{events} = \frac{d^2\sigma}{dW dT_\pi} \Delta W \Delta T_\pi * N_e t_{tgt} * correction\ factors$$

$$\boxed{\frac{d^2\sigma}{d\omega dT_\pi} = \frac{N_{events}}{\Delta W \Delta T_\pi L} * corr.factors}$$

Our formula

$$L = N_e * t_{tgt} \qquad N_e = \frac{Q_{tot}}{q_e} \qquad t_{tgt} = \frac{\rho_{tgt} l_{tgt} N_A}{mol_{tgt}}$$

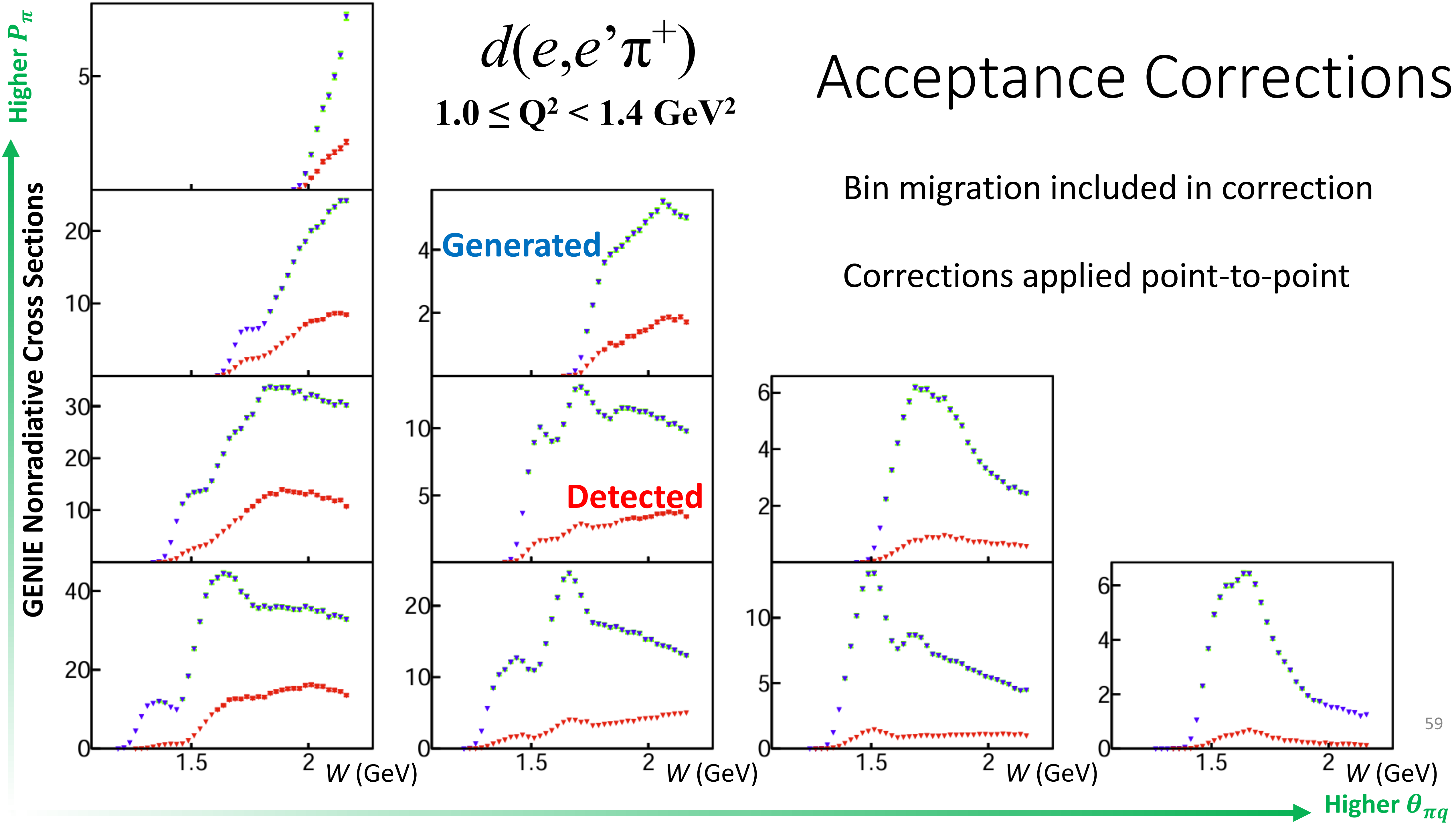
Acceptance Corrections

$d(e,e'\pi^+)$

$1.0 \leq Q^2 < 1.4$ GeV^2

Bin migration included in correction

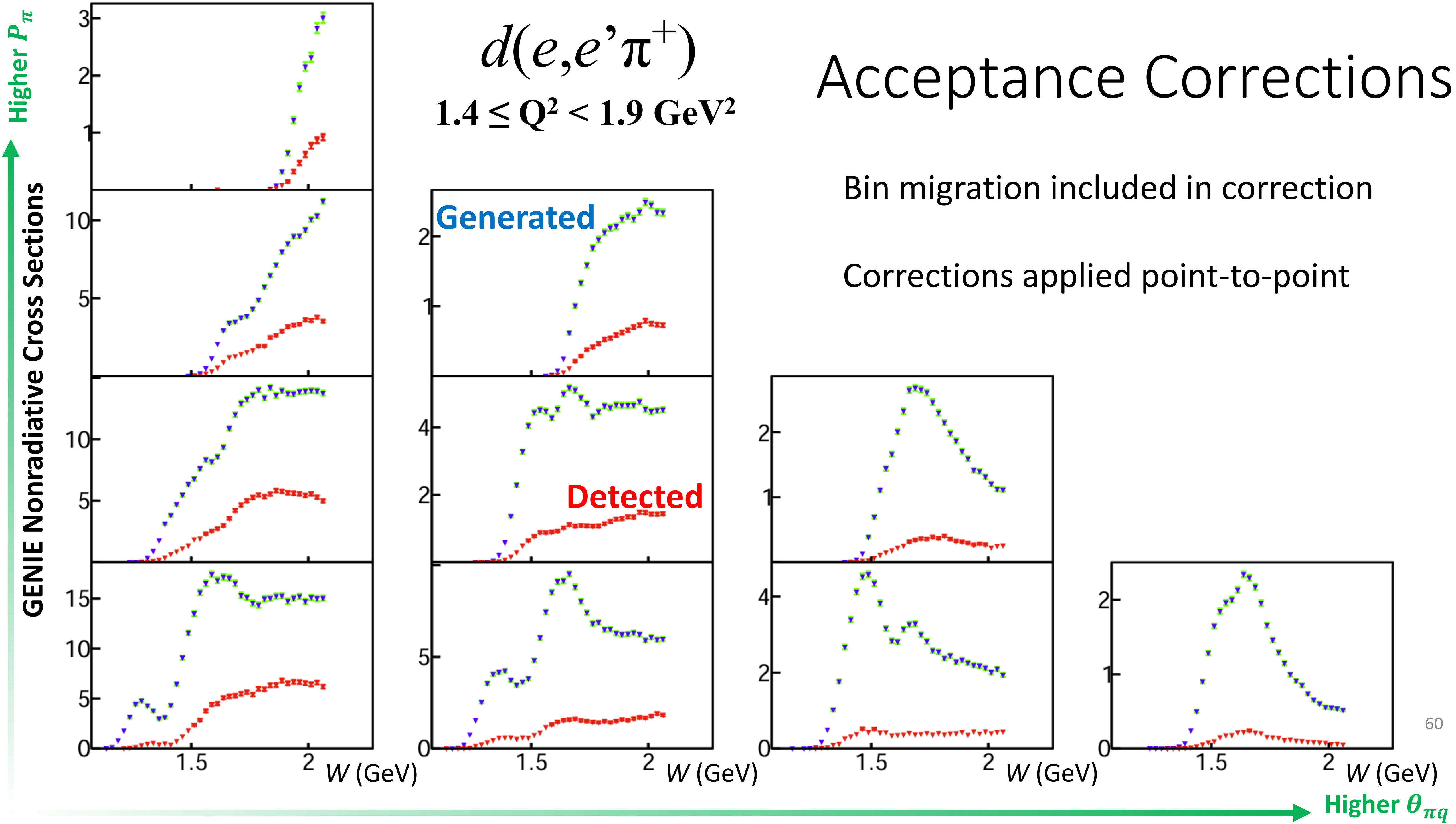
Corrections applied point-to-point



Acceptance Corrections

Bin migration included in correction

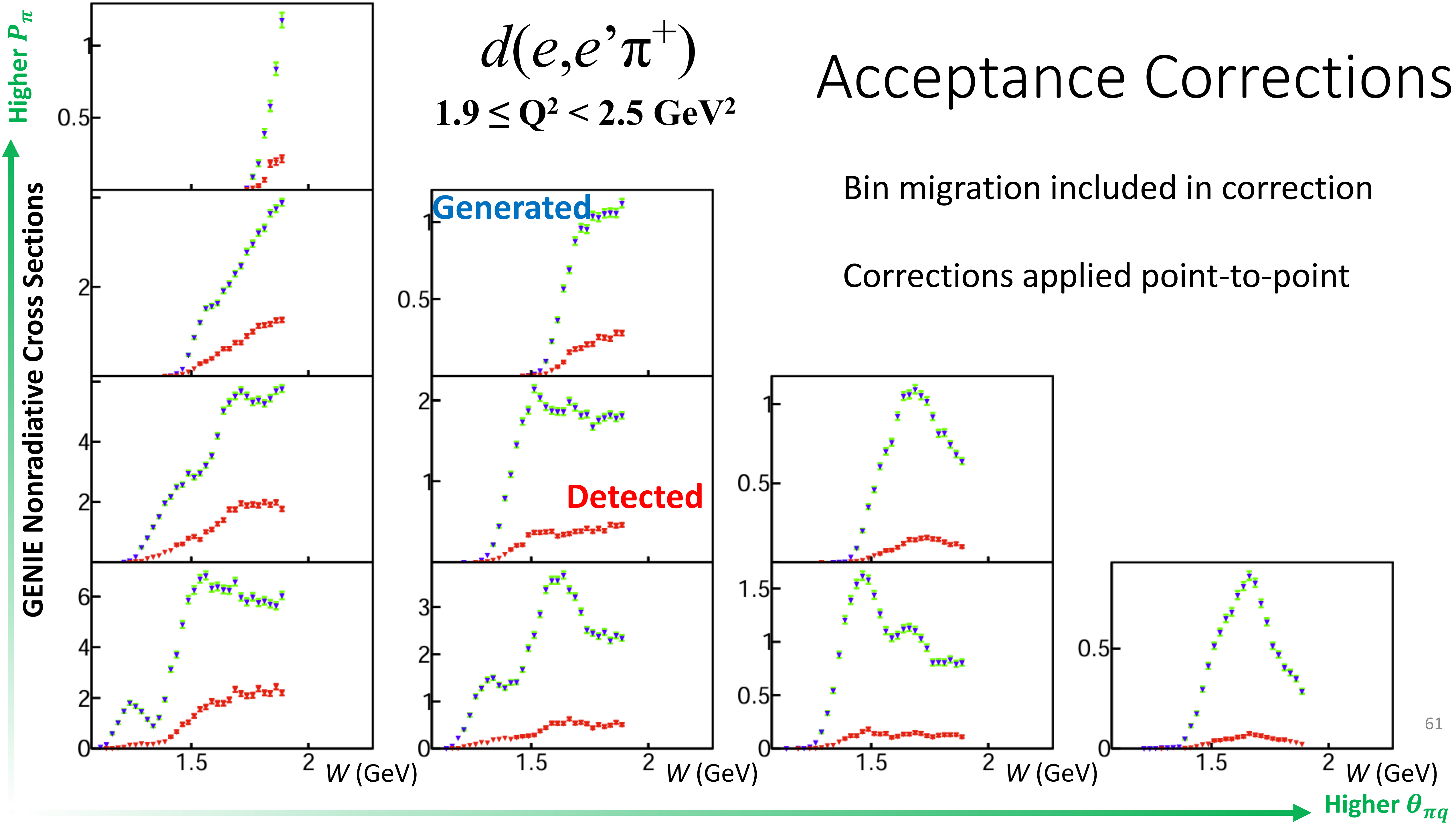
Corrections applied point-to-point



Acceptance Corrections

$d(e,e'\pi^+)$

$1.9 \leq Q^2 < 2.5$ GeV^2



Bin migration included in correction

Corrections applied point-to-point

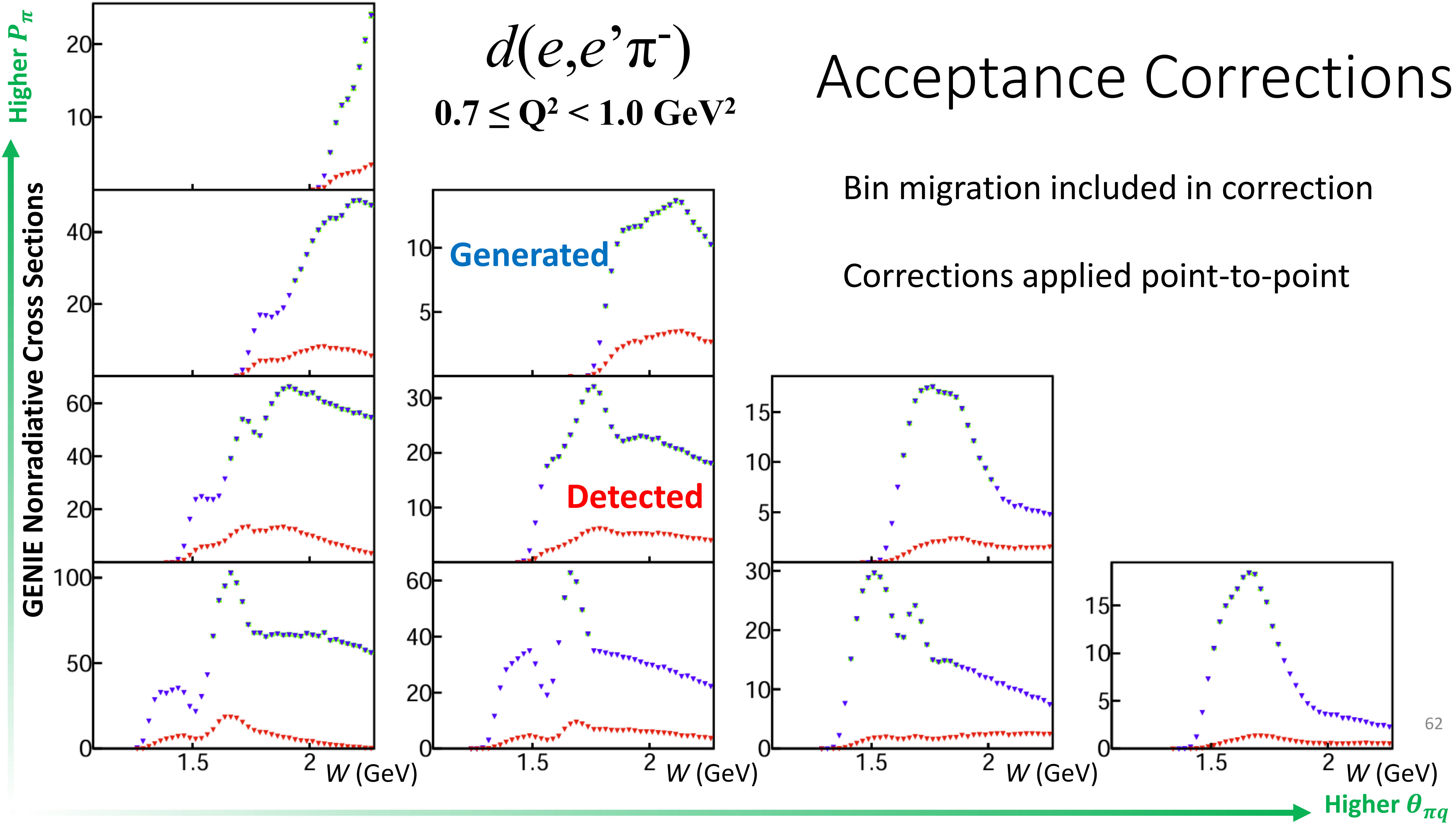
Acceptance Corrections

$d(e,e'\pi^-)$

$0.7 \leq Q^2 < 1.0$ GeV^2

Bin migration included in correction

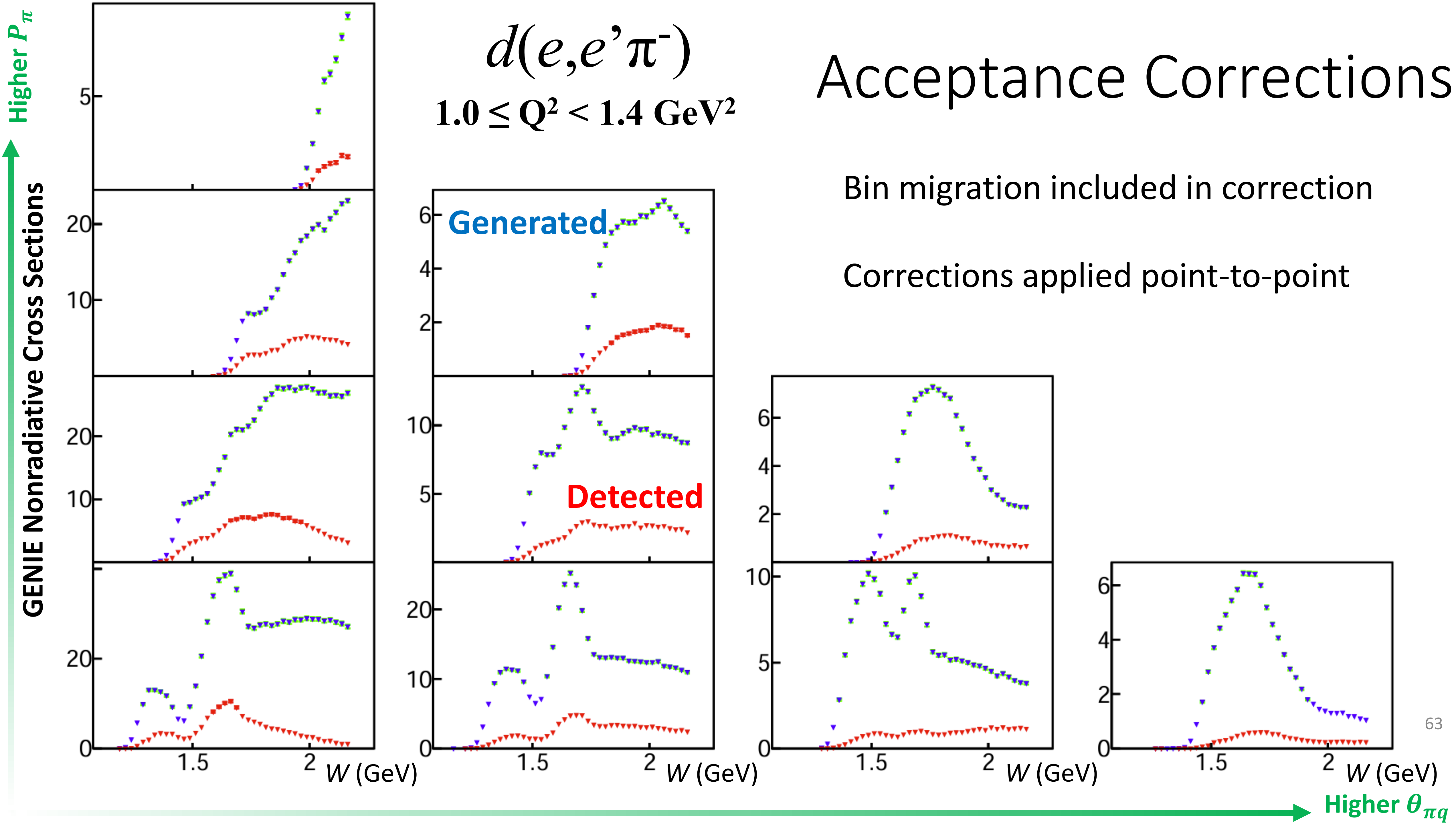
Corrections applied point-to-point



Acceptance Corrections

Bin migration included in correction

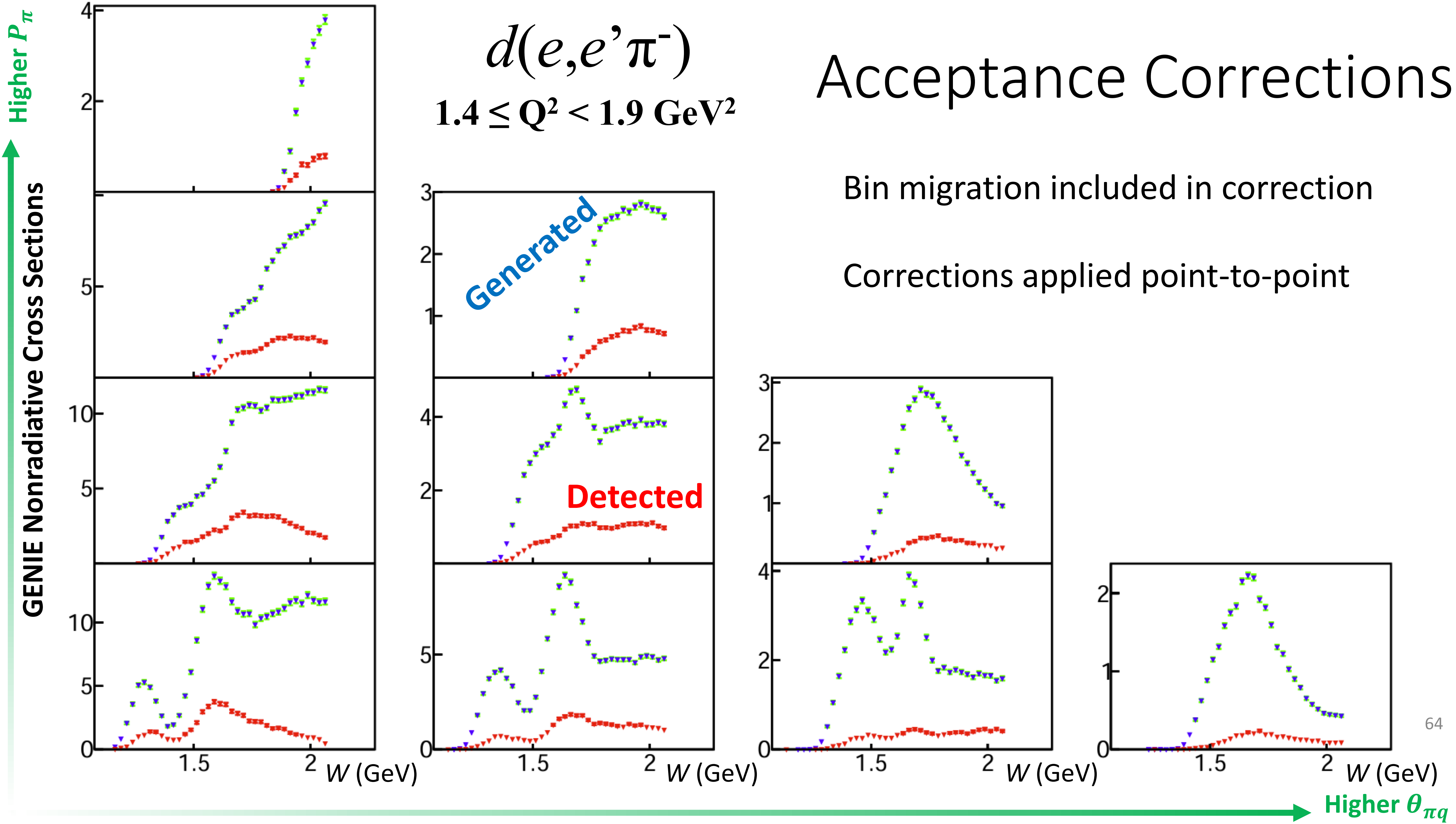
Corrections applied point-to-point



Acceptance Corrections

Bin migration included in correction

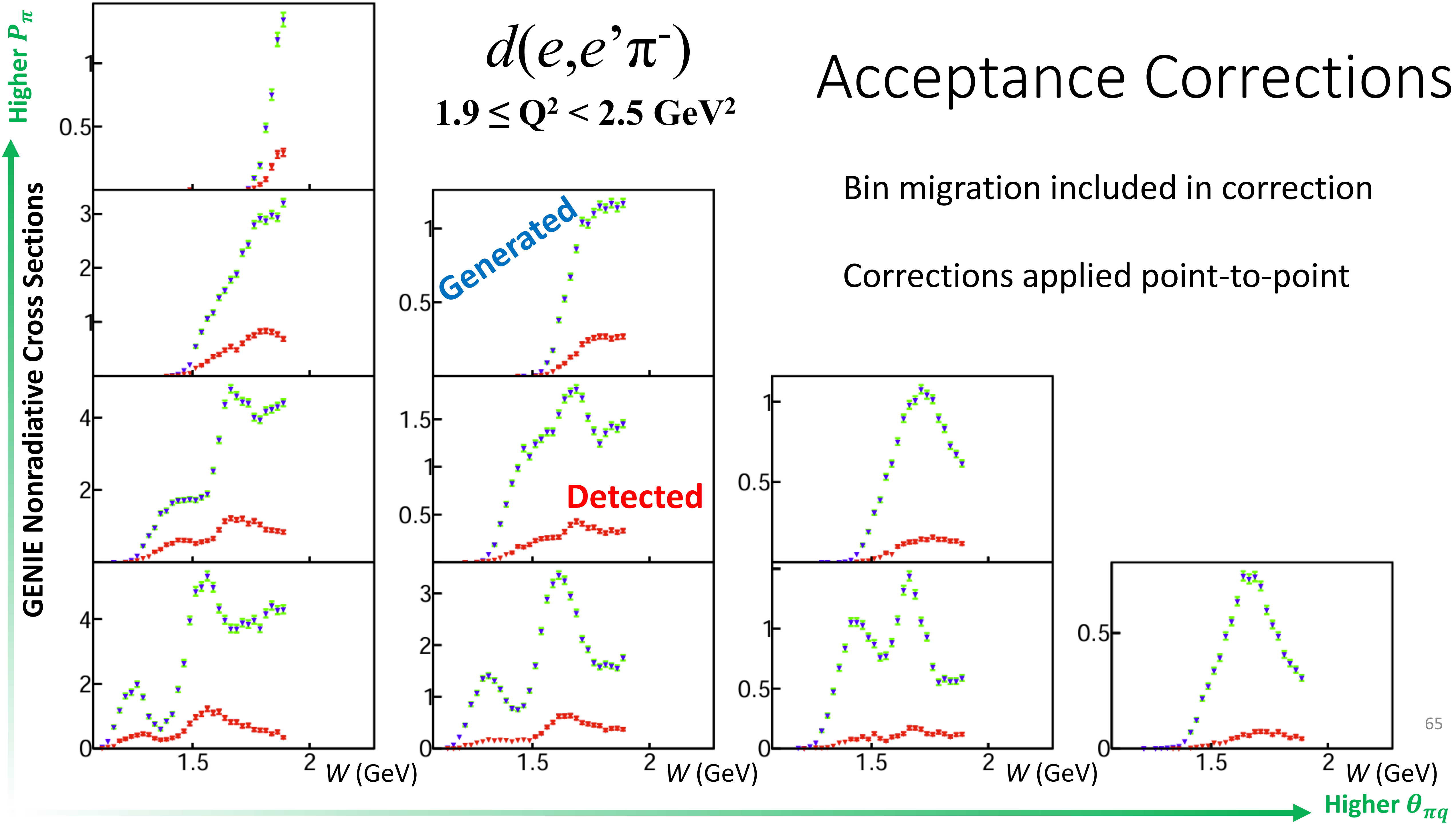
Corrections applied point-to-point



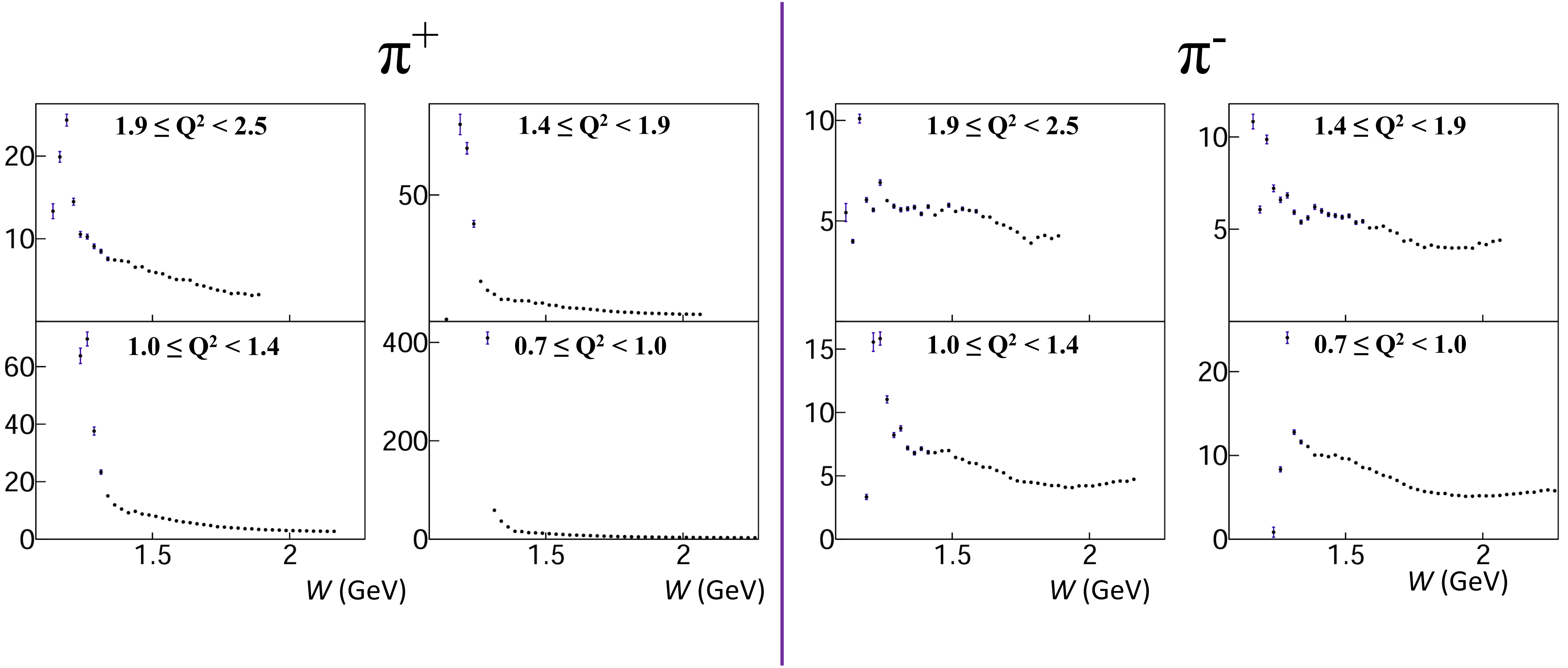
Acceptance Corrections

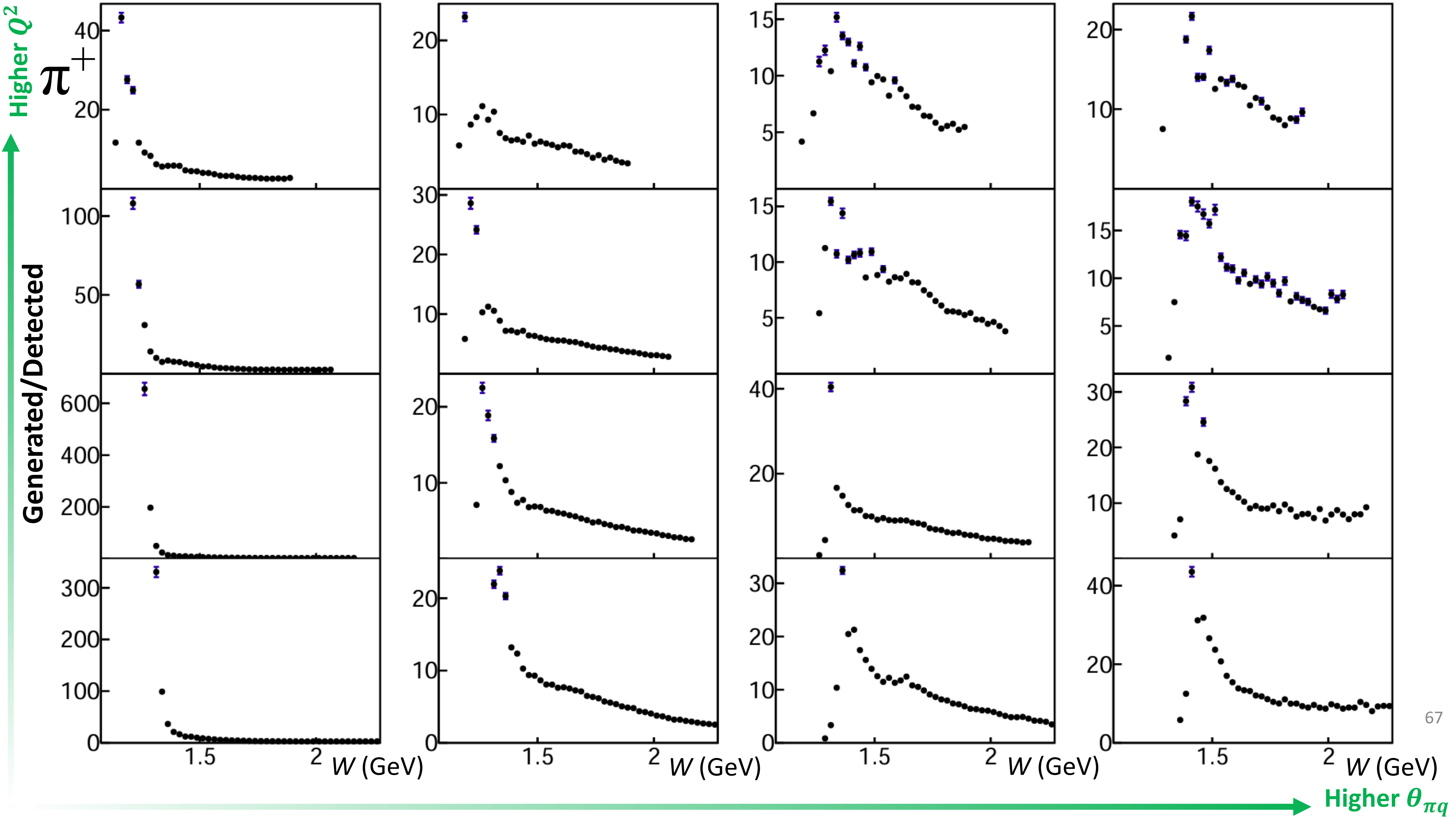
Bin migration included in correction

Corrections applied point-to-point

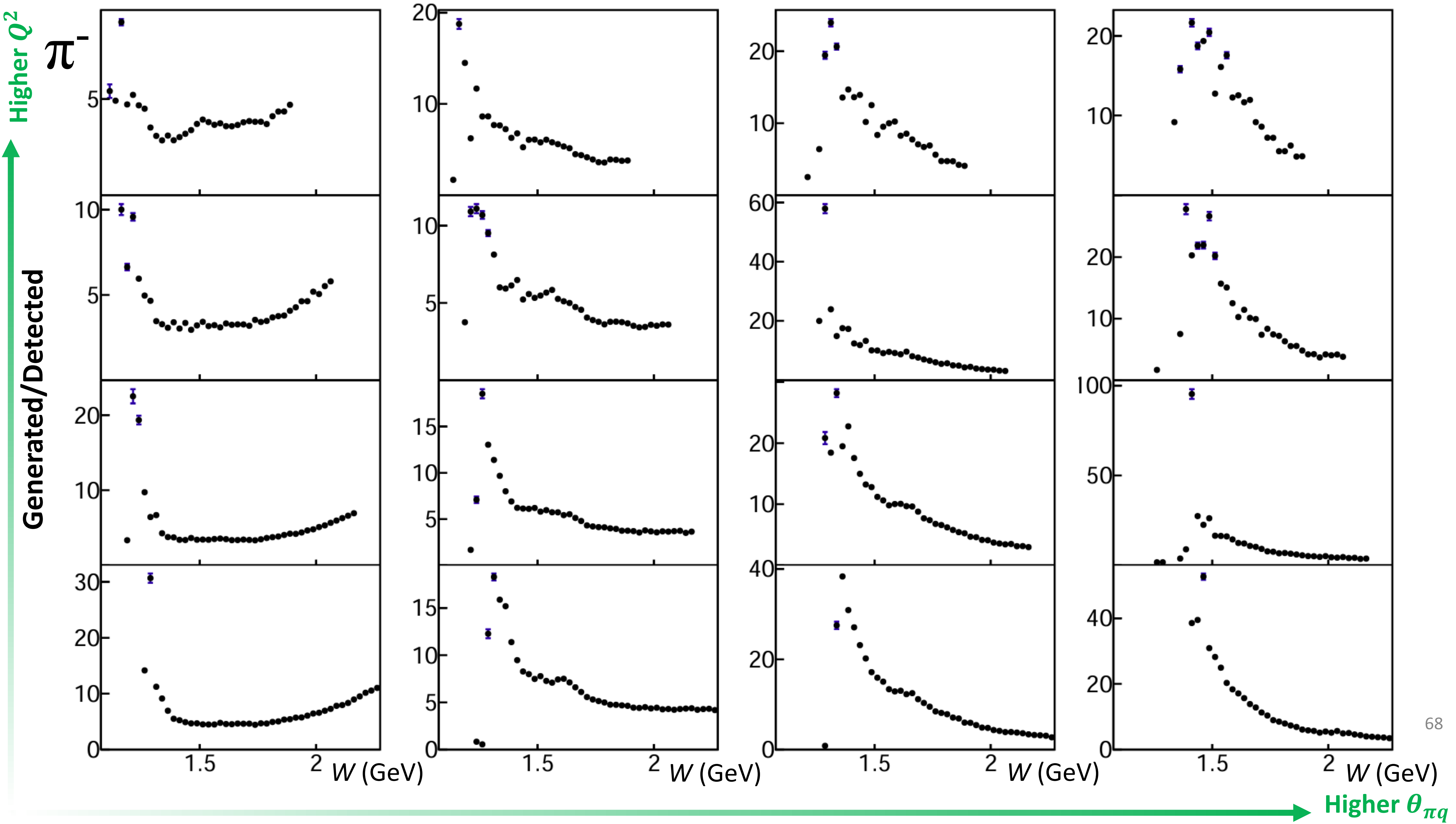


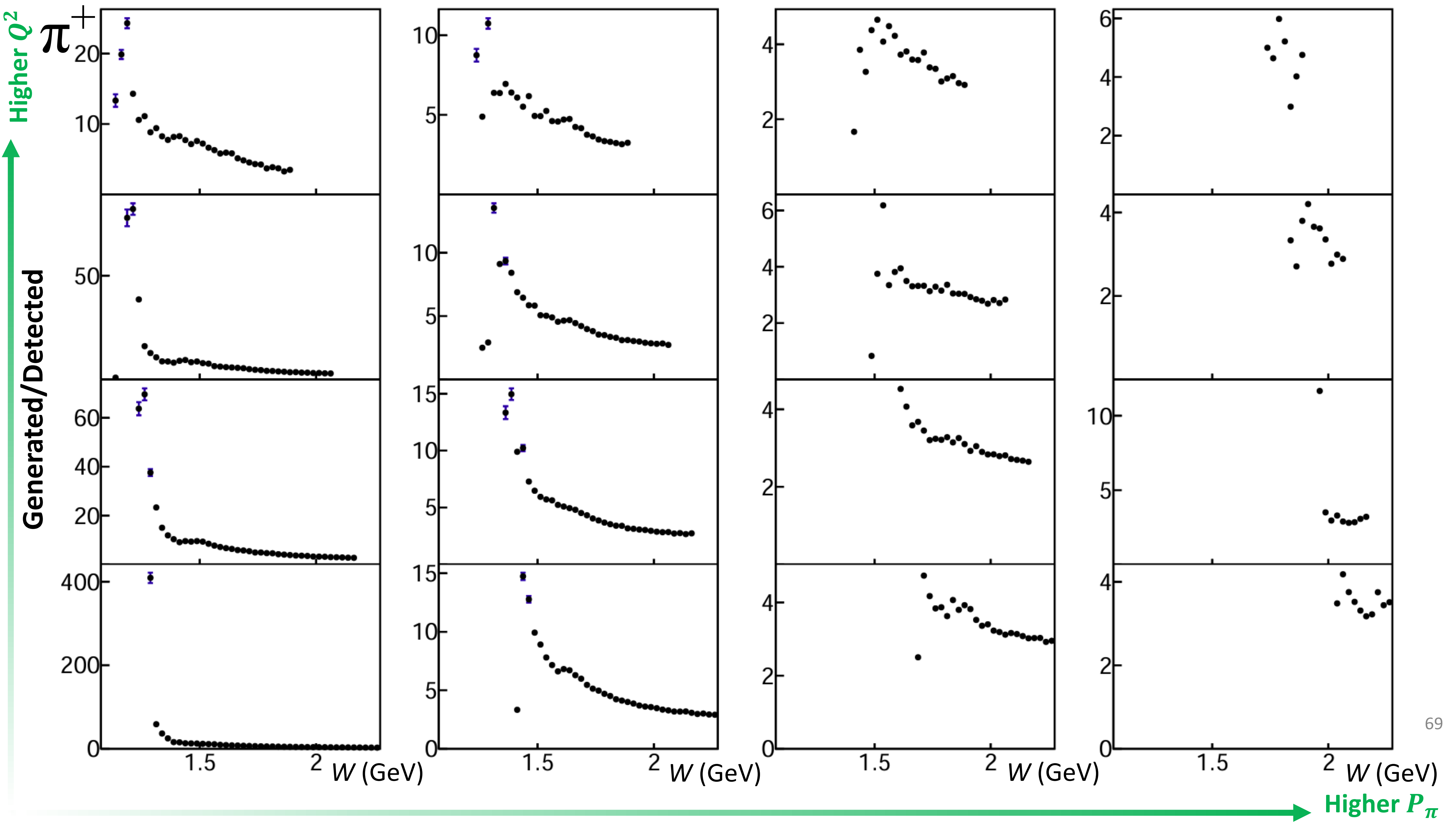
D(e,e’π) Acceptance Corrections vs W binned in Q^2



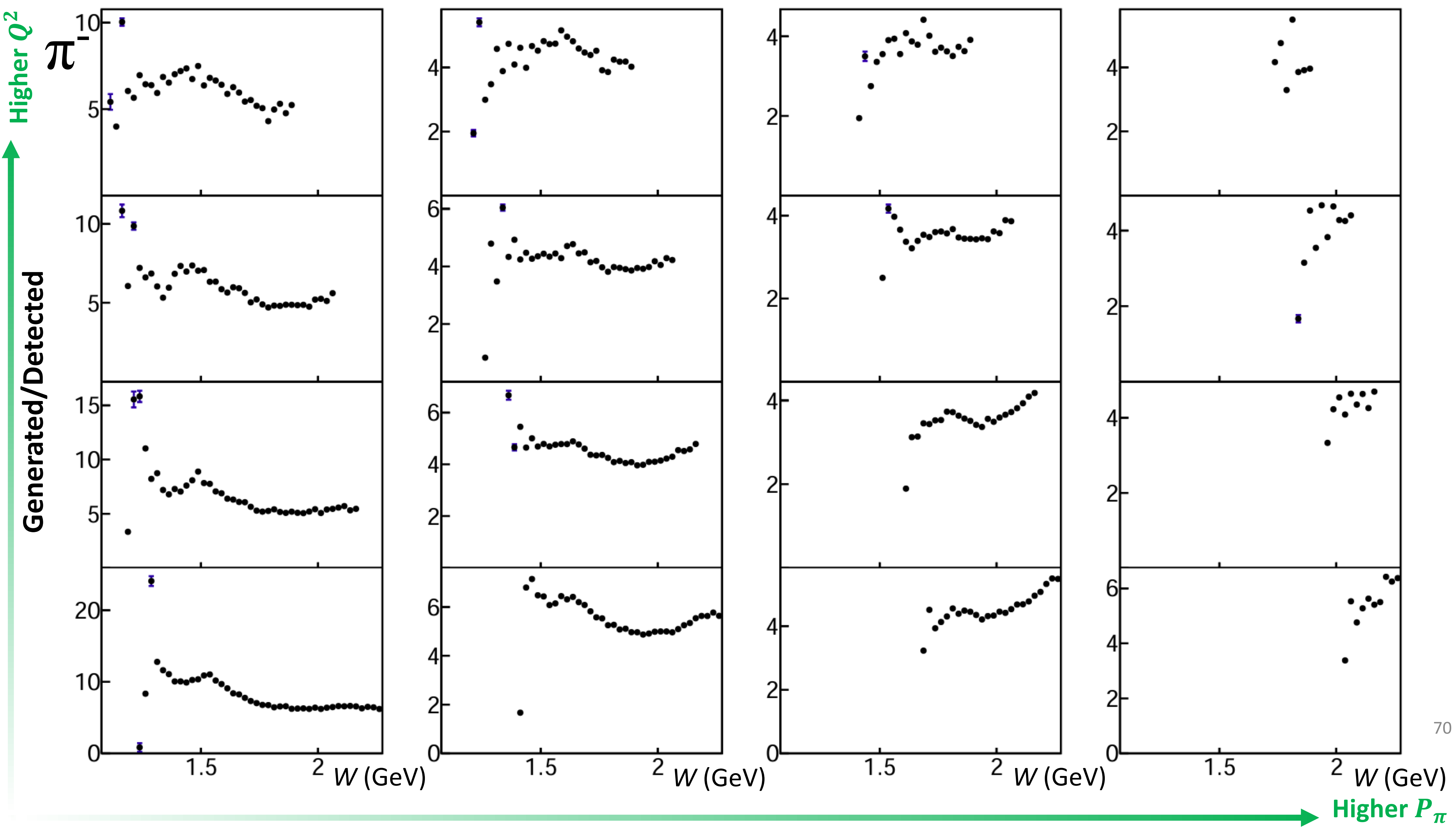


Higher Q^2
π^+
Generated/Detected
W (GeV)
W (GeV)
W (GeV)
W (GeV)
Higher $\theta_{\pi q}$


π-
Higher Q^2
Generated/Detected
W (GeV)
Higher $\theta_{\pi q}$



π^+
Higher Q^2
Generated/Detected
Higher P_π
W (GeV)
W (GeV)
W (GeV)
W (GeV)



π⁻
Higher Q^2
Generated/Detected
Higher P_π
W (GeV)
W (GeV)
W (GeV)
W (GeV)

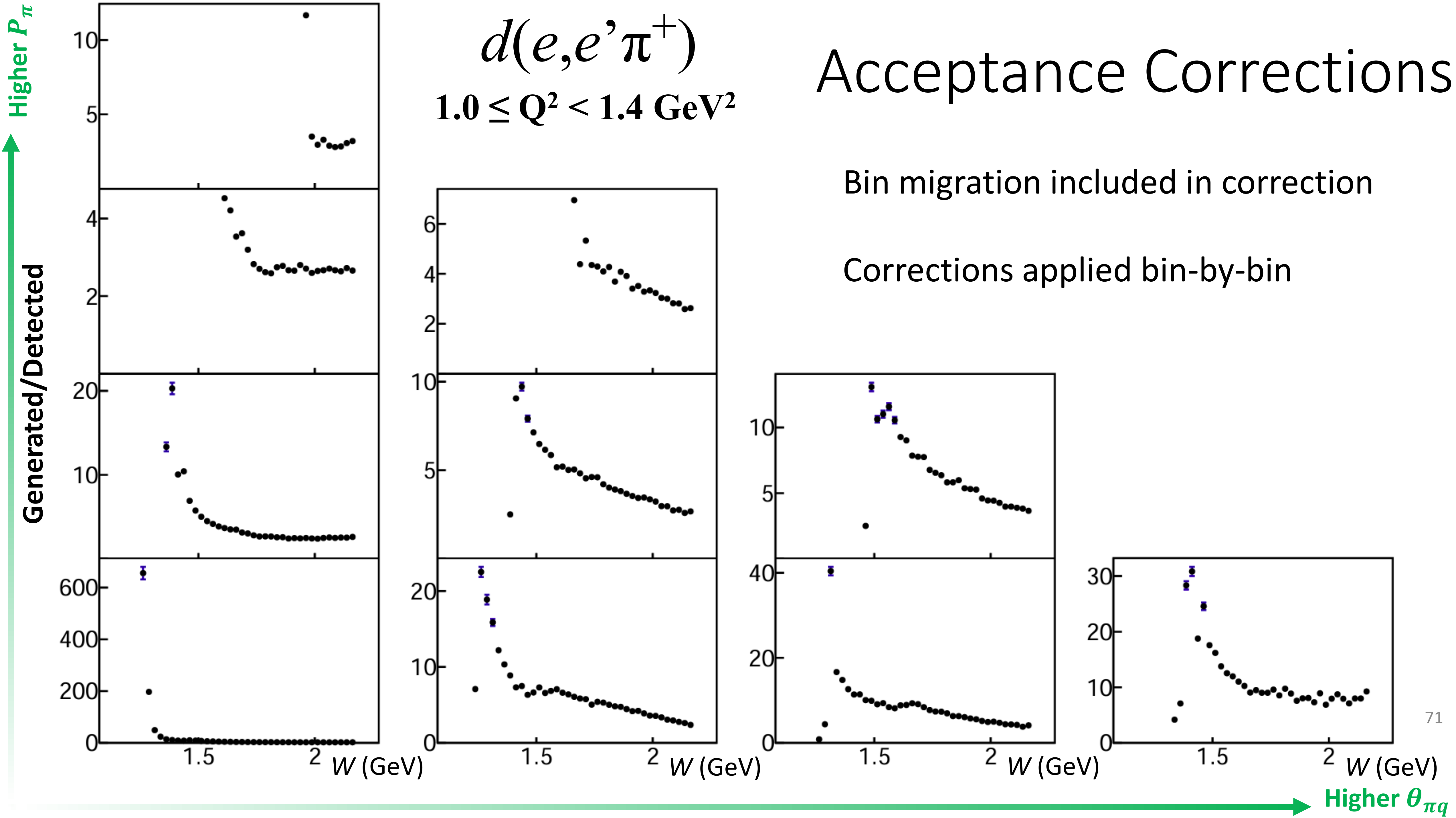
Acceptance Corrections

$d(e,e'\pi^+)$

$1.0 \leq Q^2 < 1.4$ GeV^2

Bin migration included in correction

Corrections applied bin-by-bin



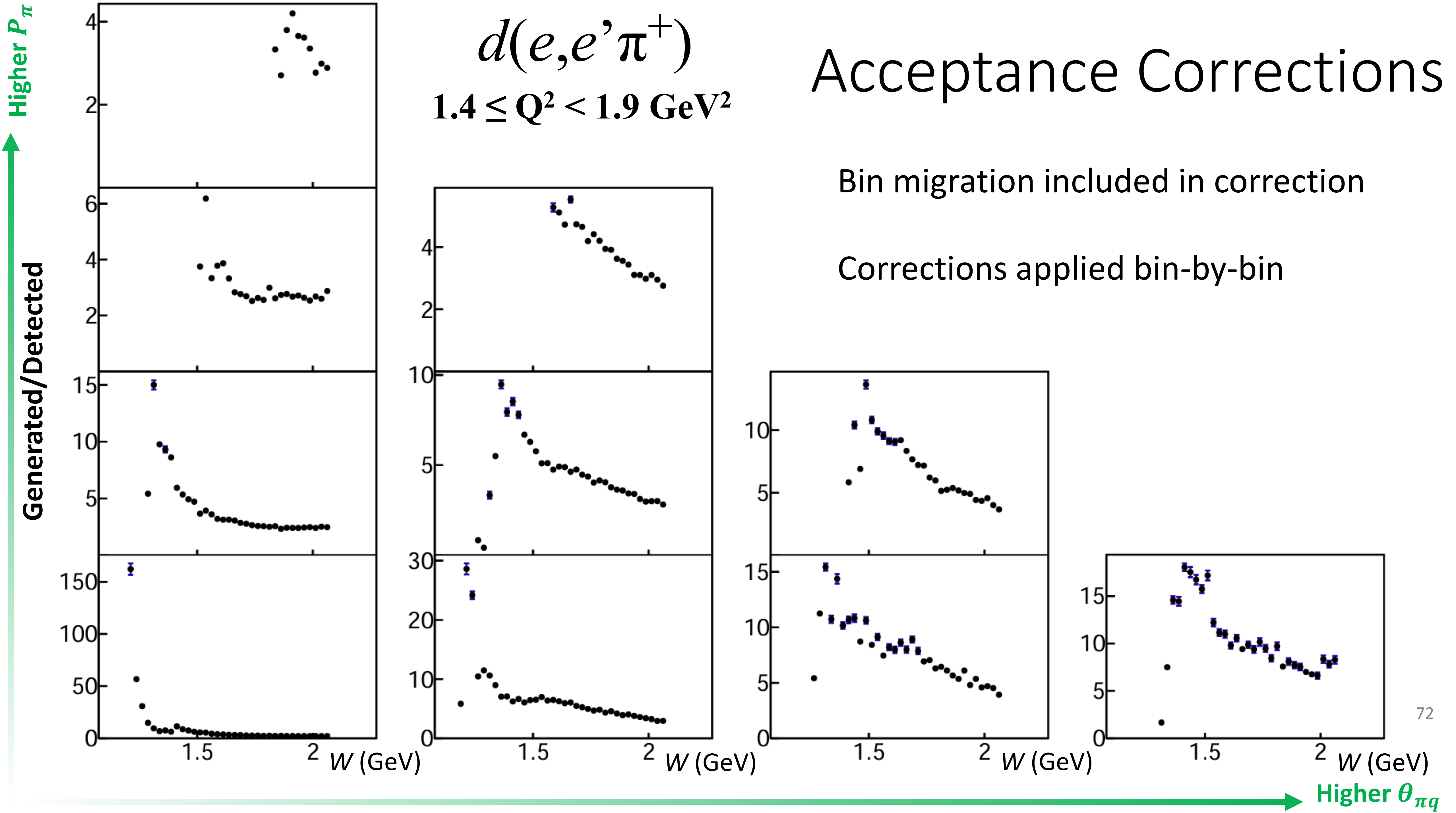
Acceptance Corrections

$d(e,e'\pi^+)$

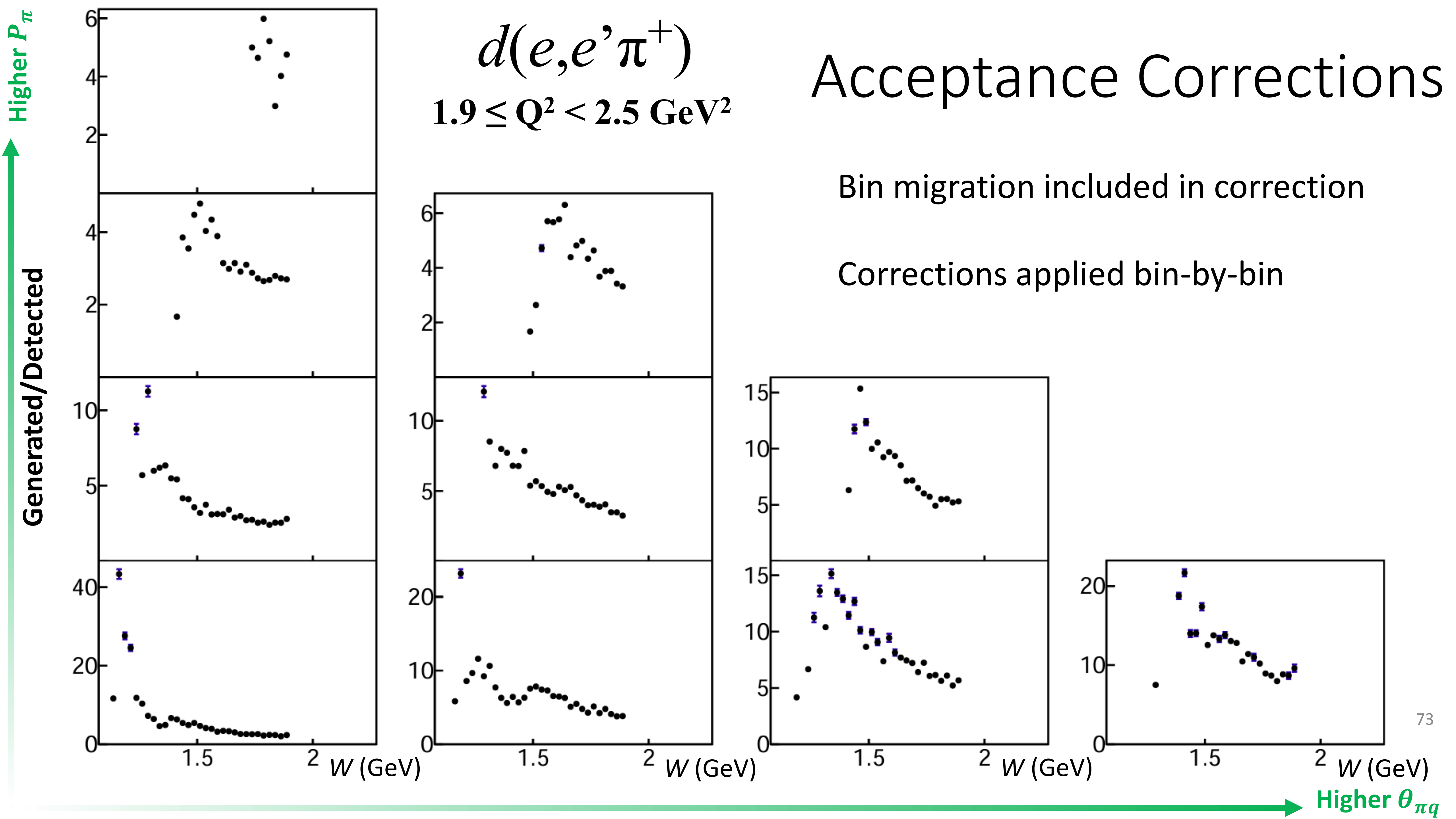
$1.4 \leq Q^2 < 1.9$ GeV^2

Bin migration included in correction

Corrections applied bin-by-bin



Acceptance Corrections



Bin migration included in correction

Corrections applied bin-by-bin

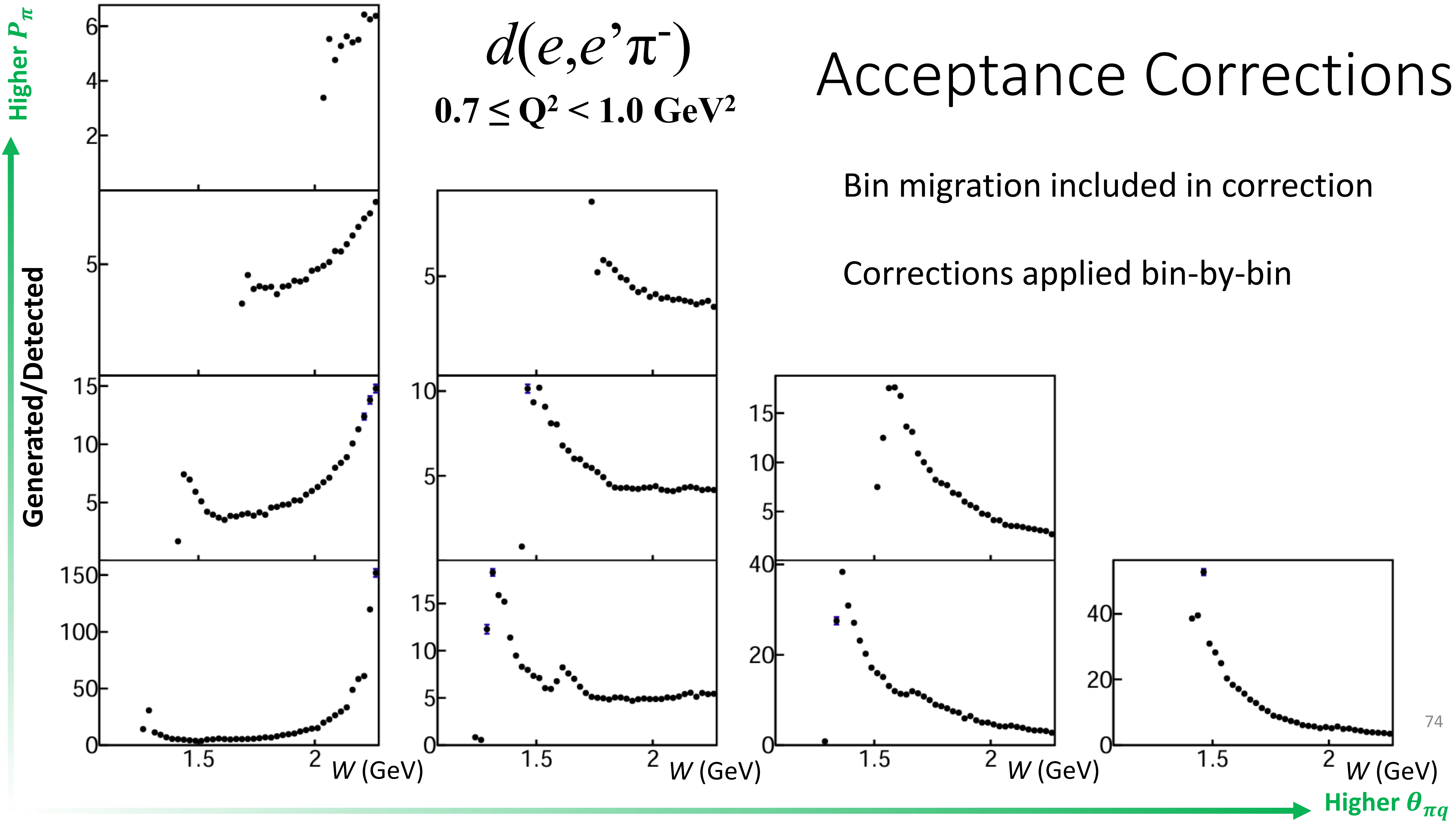
Acceptance Corrections

$d(e,e'\pi^-)$

$0.7 \le Q^2 < 1.0$ GeV^2

Bin migration included in correction

Corrections applied bin-by-bin

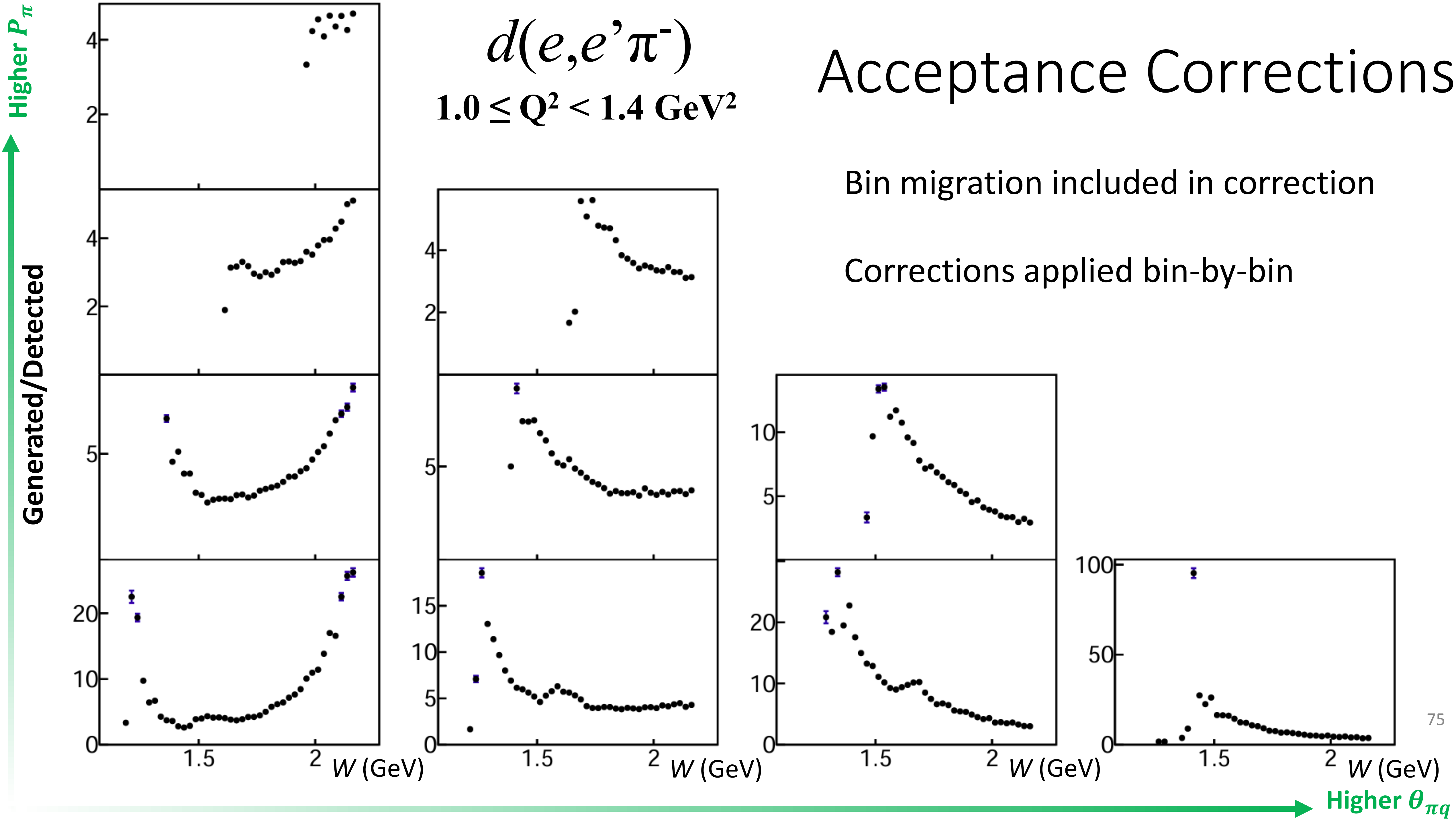


Acceptance Corrections

$d(e,e'\pi^-)$
$1.0 \le Q^2 < 1.4$ GeV^2

Bin migration included in correction

Corrections applied bin-by-bin



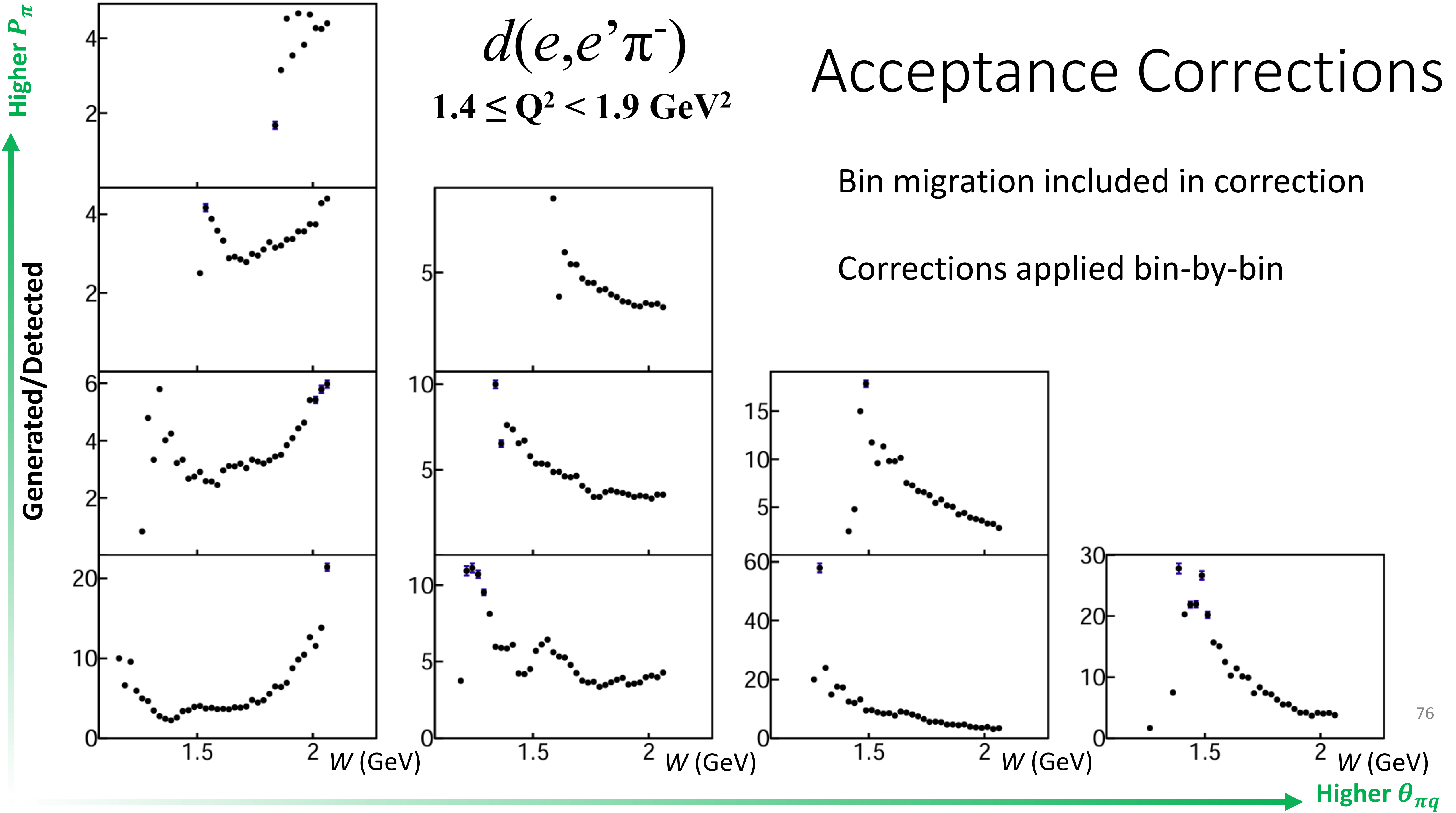
Acceptance Corrections

$d(e,e'\pi^-)$

$1.4 \leq Q^2 < 1.9$ GeV^2

Bin migration included in correction

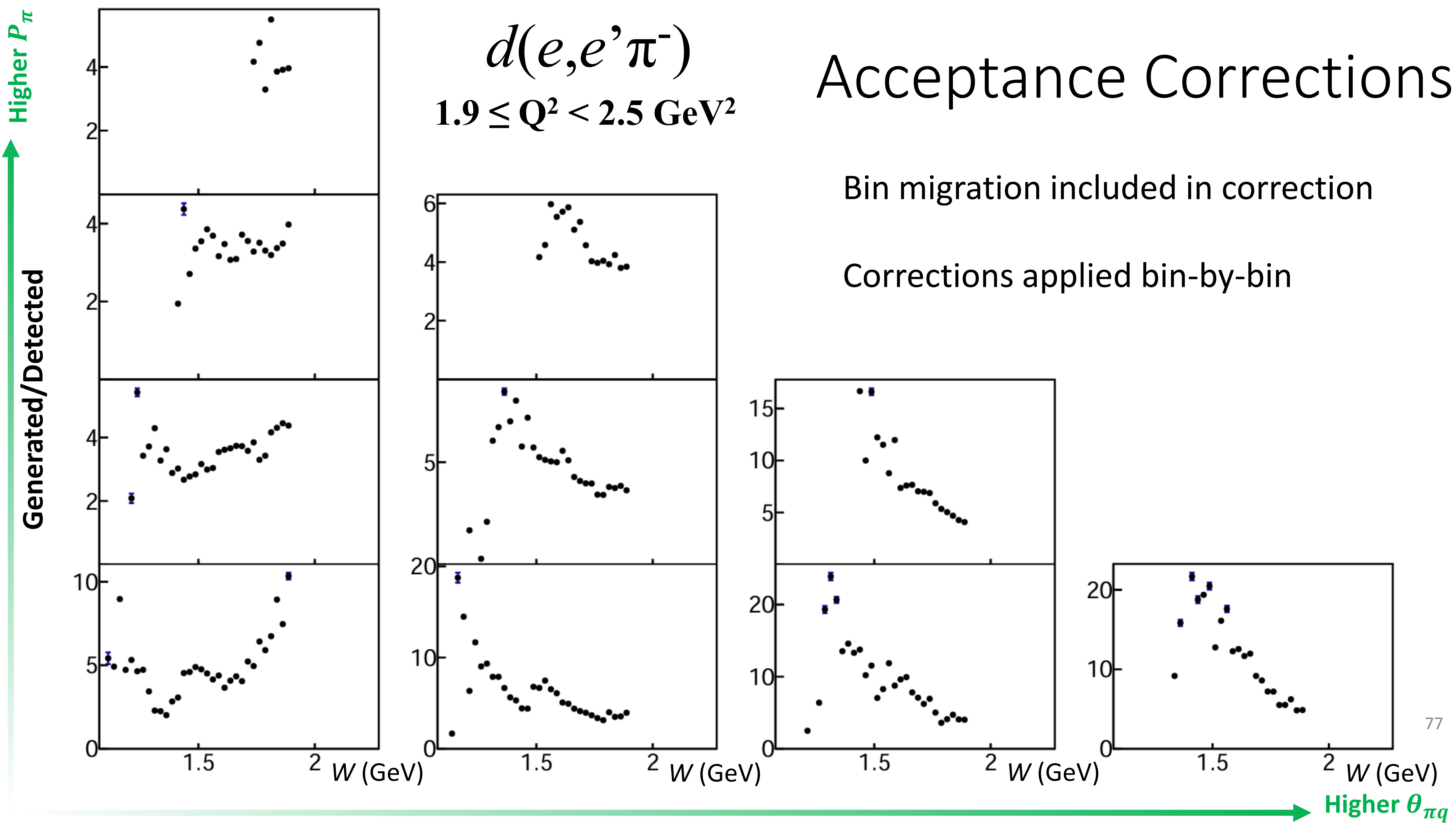
Corrections applied bin-by-bin



Acceptance Corrections

Bin migration included in correction

Corrections applied bin-by-bin

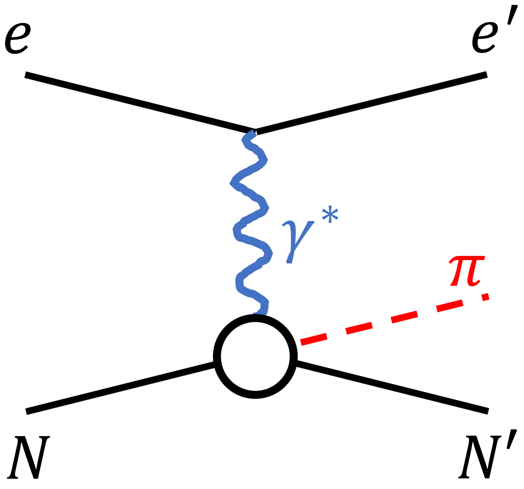


Radiative Correction

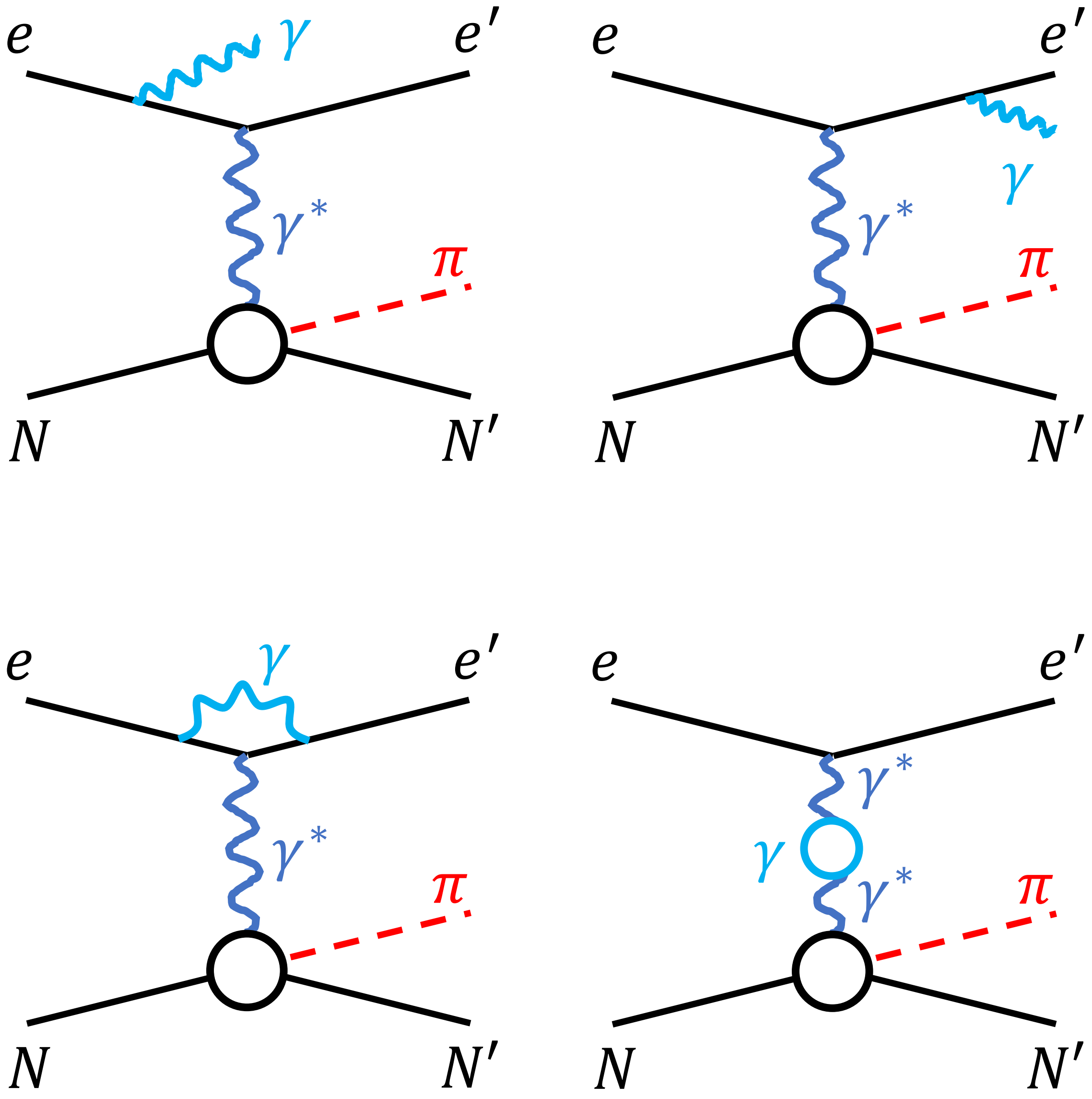
- with GENIE

$$\frac{1}{RC} = \frac{CS_{rad}^{GENIE}}{CS_{norad}^{GENIE}}$$

$$CS_{norad}^{data} = CS_{rad}^{data} * RC$$

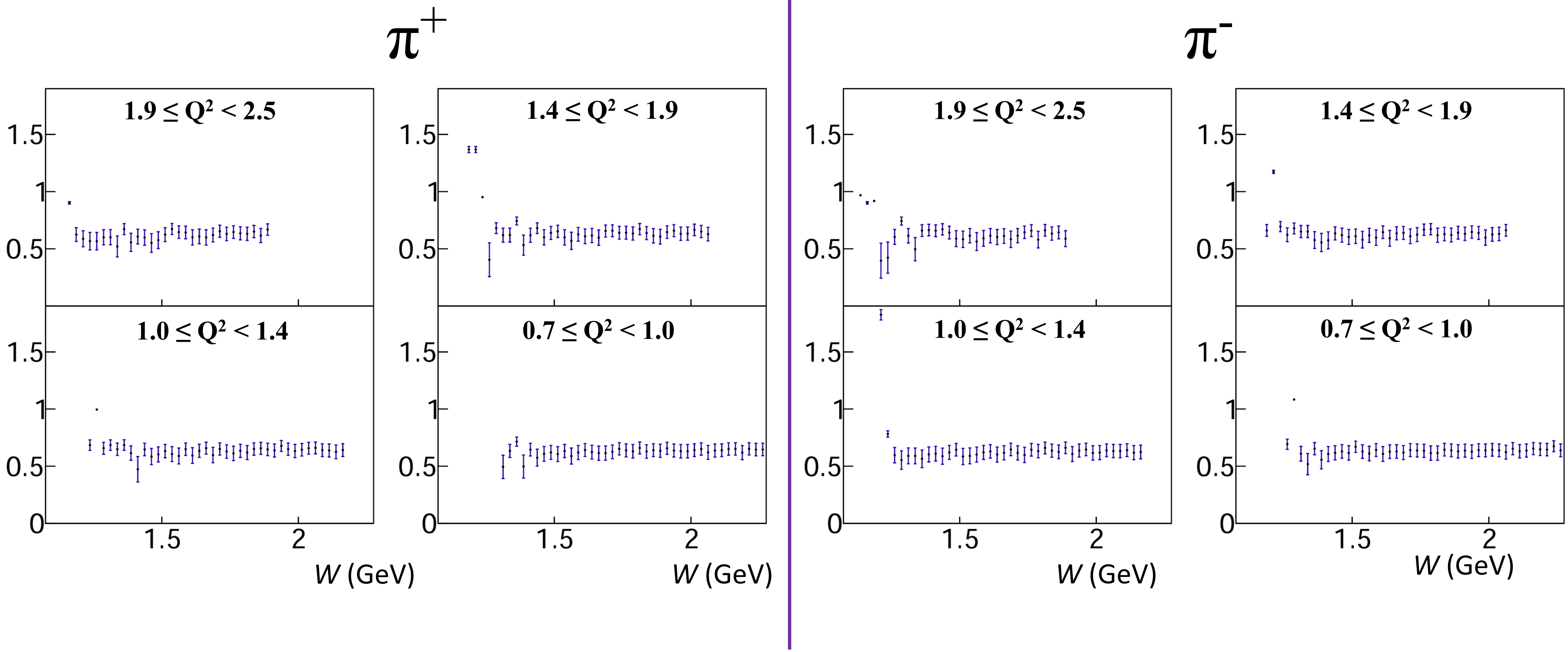


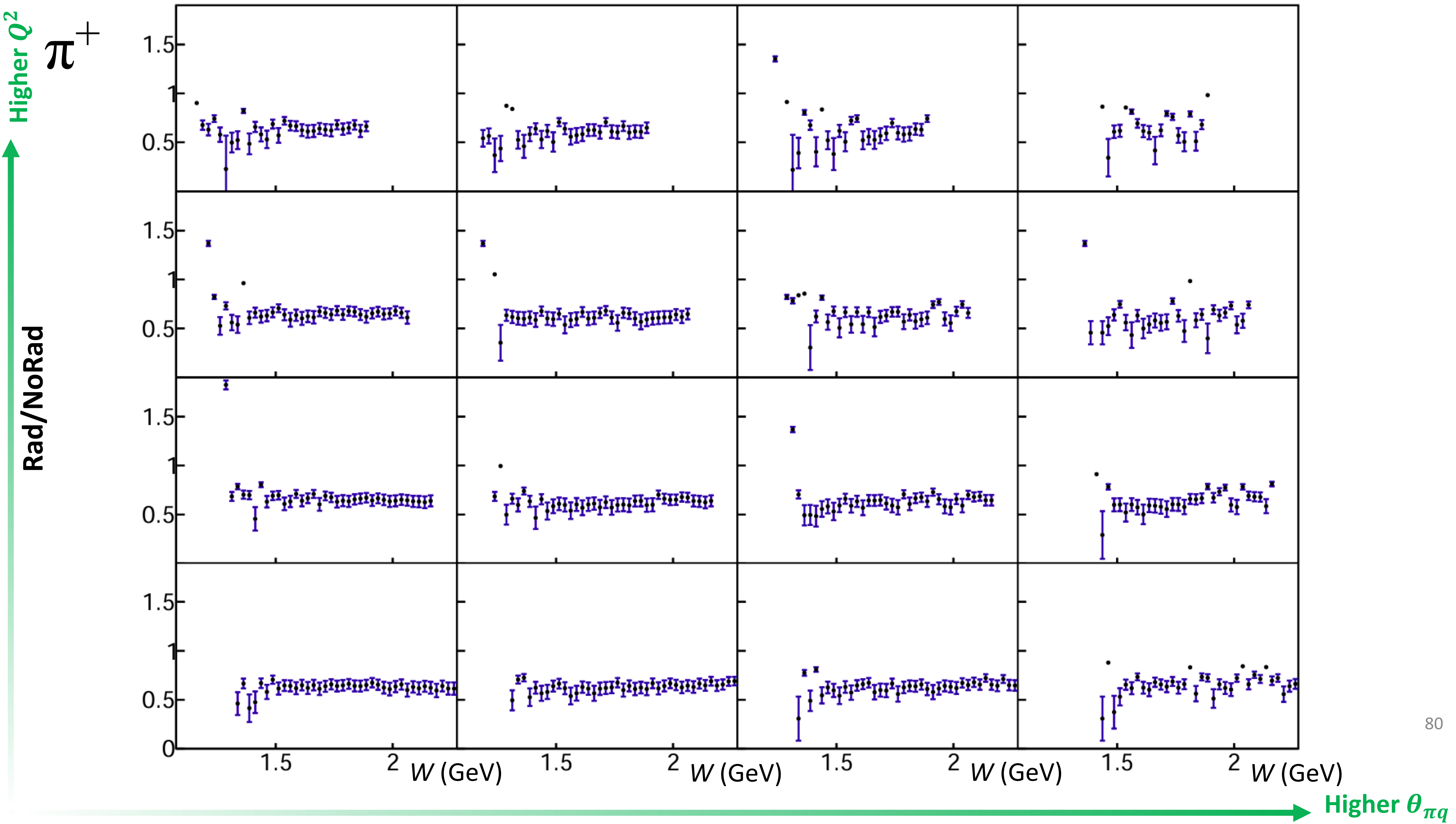
Non-radiative

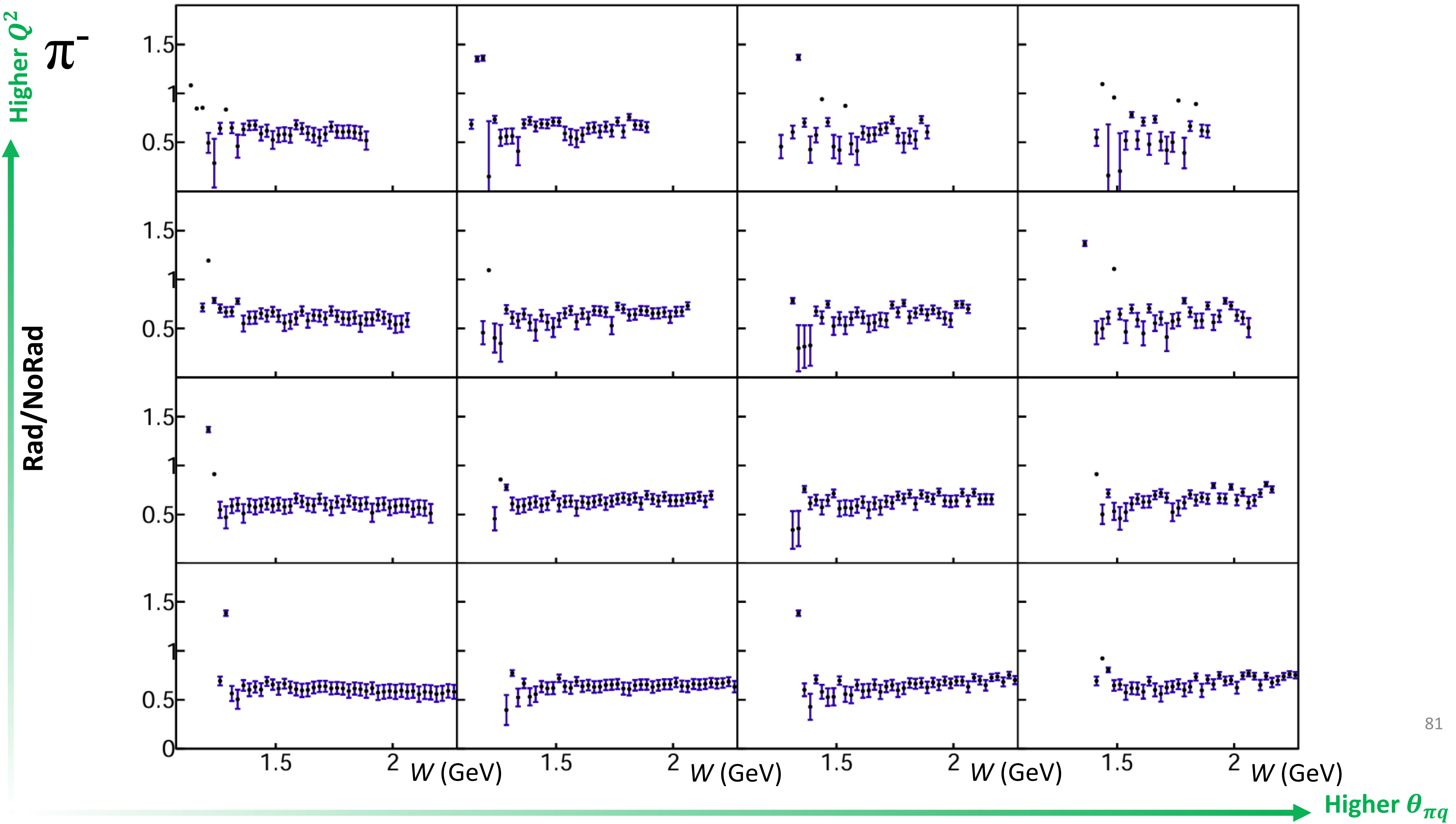


Radiative

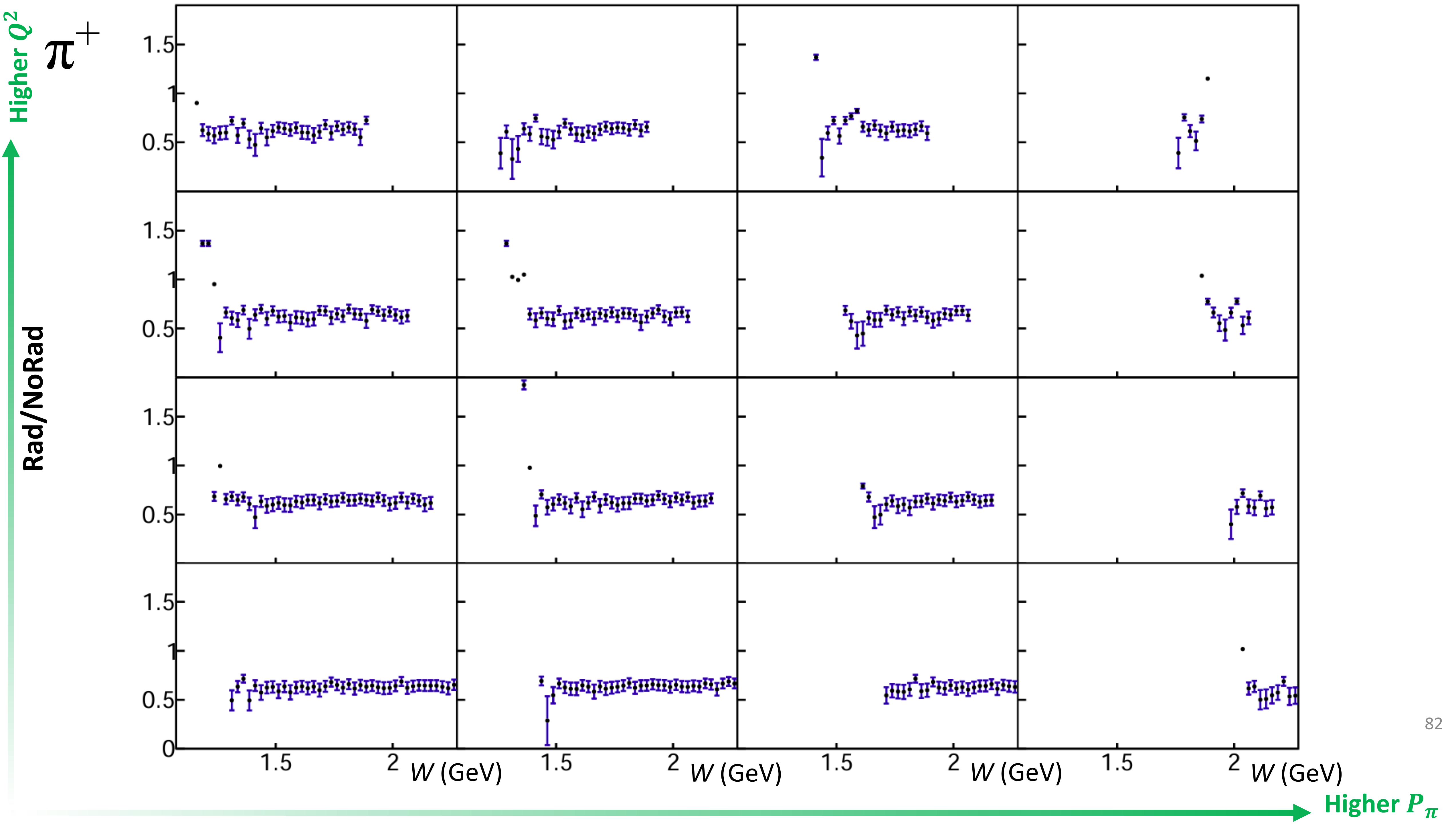
D(e,e'π) Radiative Corrections vs W binned in Q^2



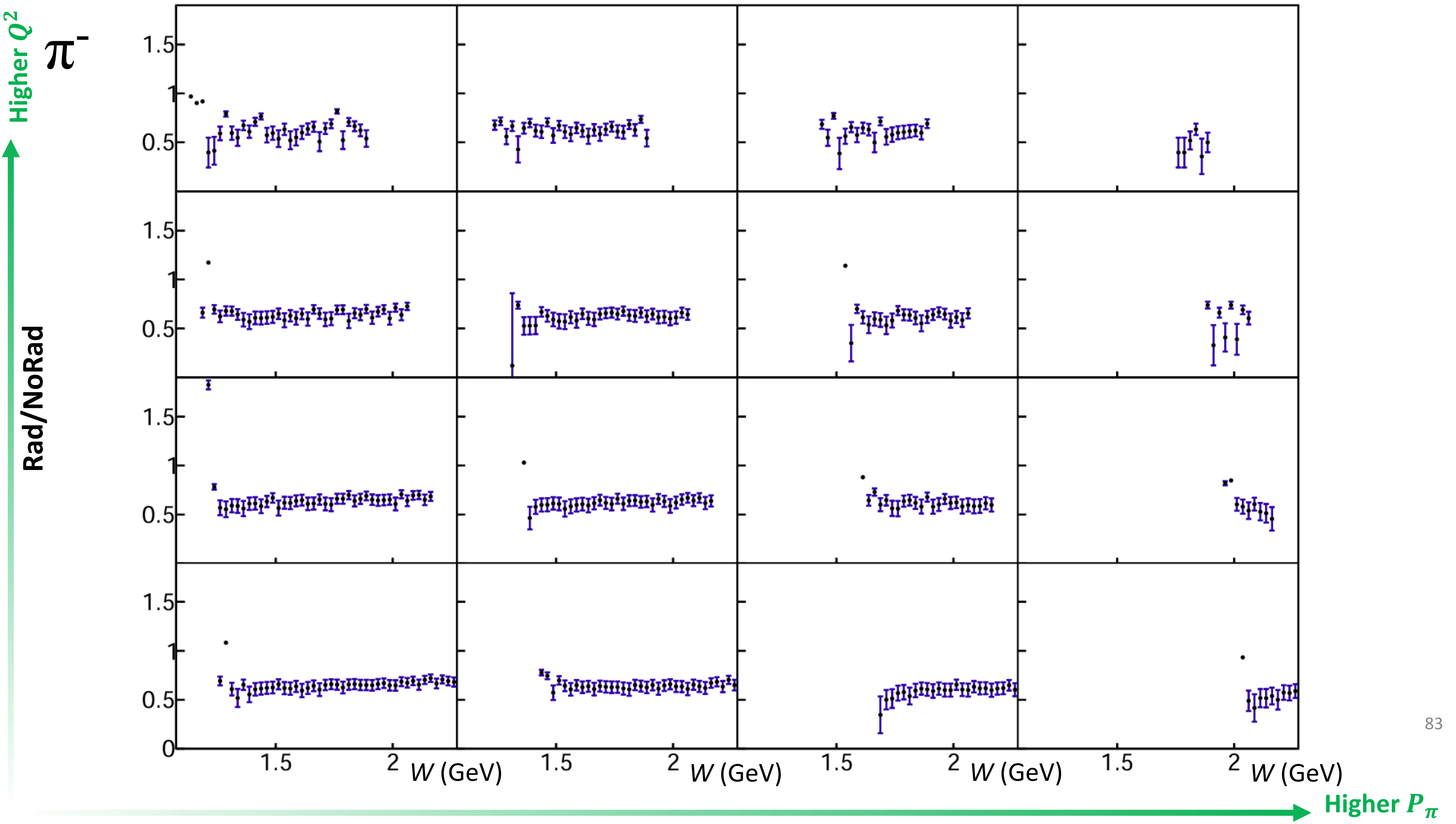

π+
Higher Q^2
Rad/NoRad
1.5
1
0.5
0
1.5
2
W (GeV)
Higher $\theta_{\pi q}$



Higher Q^2
π^-
Rad/NoRad
1.5
1
0.5
0
1.5
2
W (GeV)
Higher $\theta_{\pi q}$



Higher Q^2
π^+
Rad/NoRad
1.5
1
0.5
0
1.5
2
W (GeV)
Higher P_π

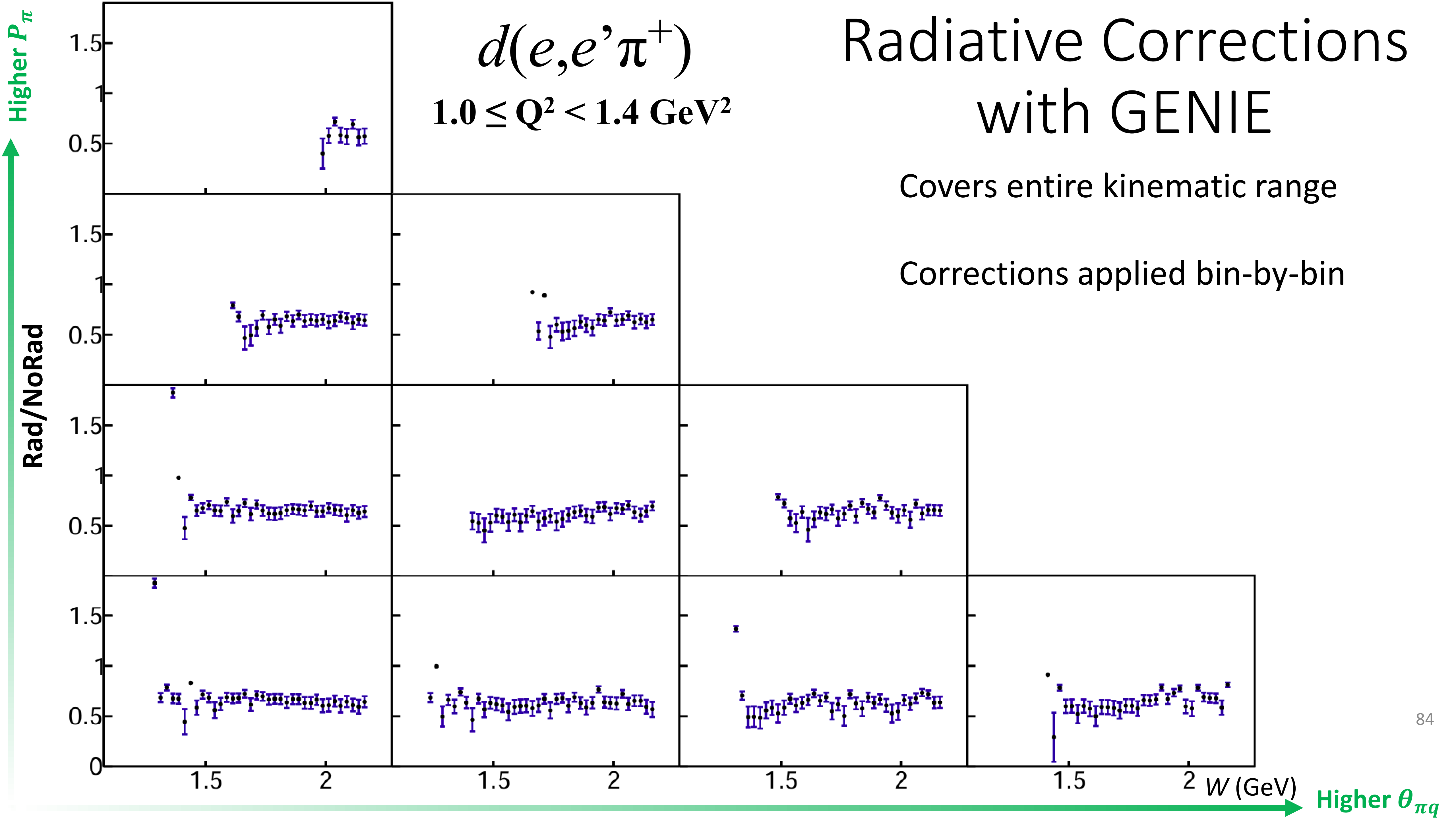


Higher Q^2
π^-
Rad/NoRad
1.5
1
0.5
0
1.5
2
W (GeV)
Higher P_π

Radiative Corrections with GENIE

Covers entire kinematic range

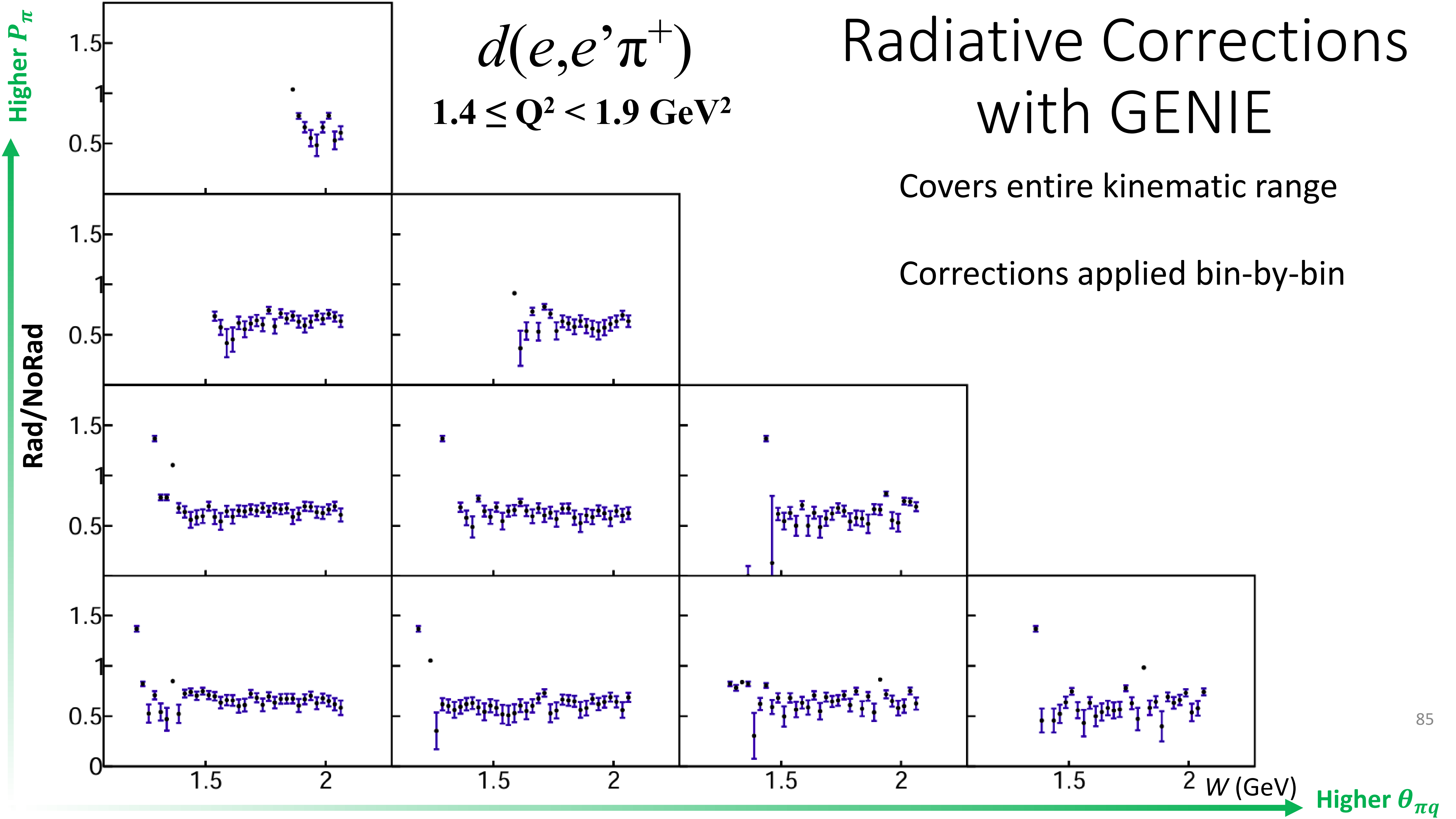
Corrections applied bin-by-bin



Radiative Corrections with GENIE

Covers entire kinematic range

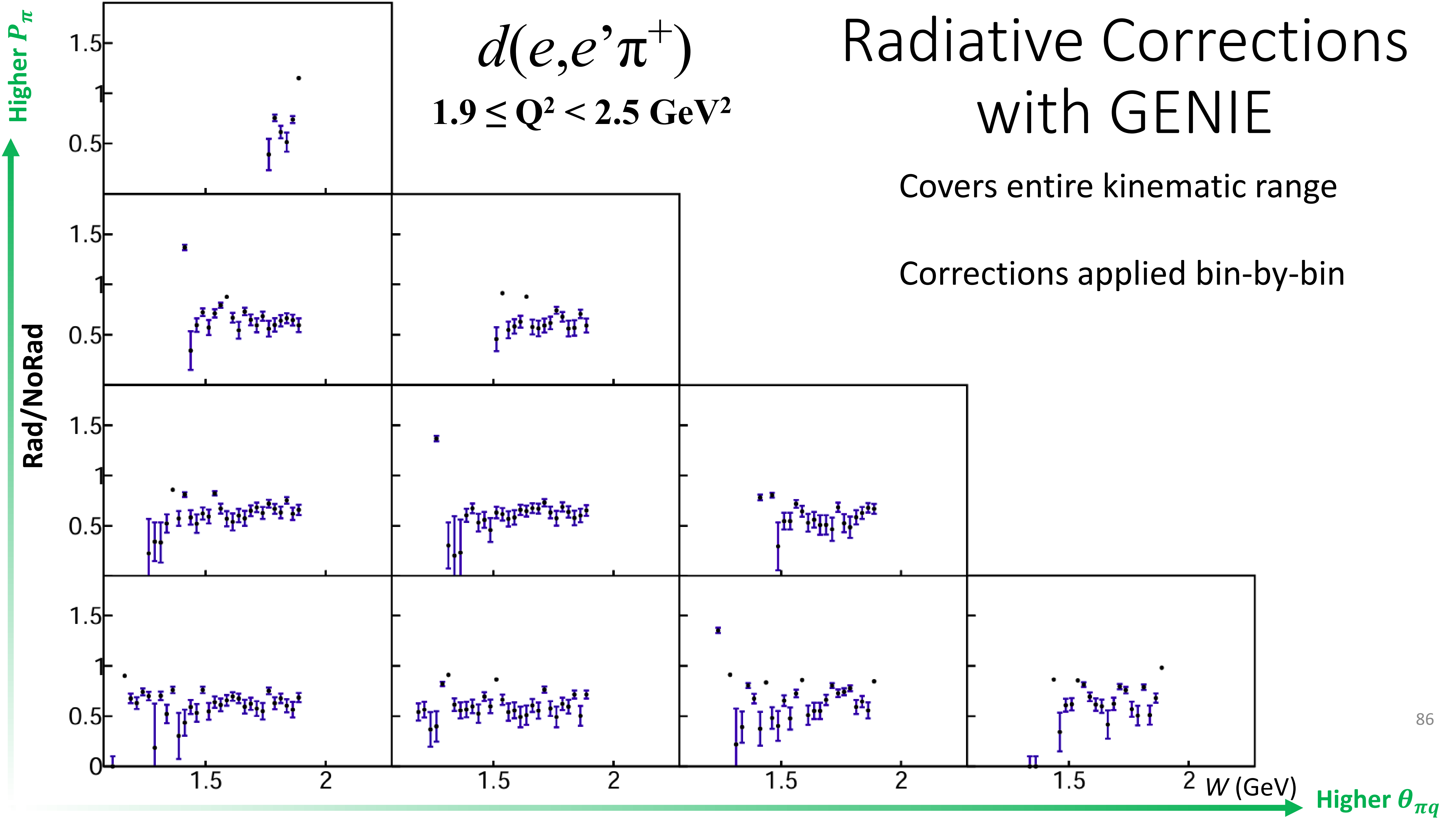
Corrections applied bin-by-bin



Radiative Corrections with GENIE

$d(e,e'\pi^+)$

$1.9 \leq Q^2 < 2.5$ GeV^2



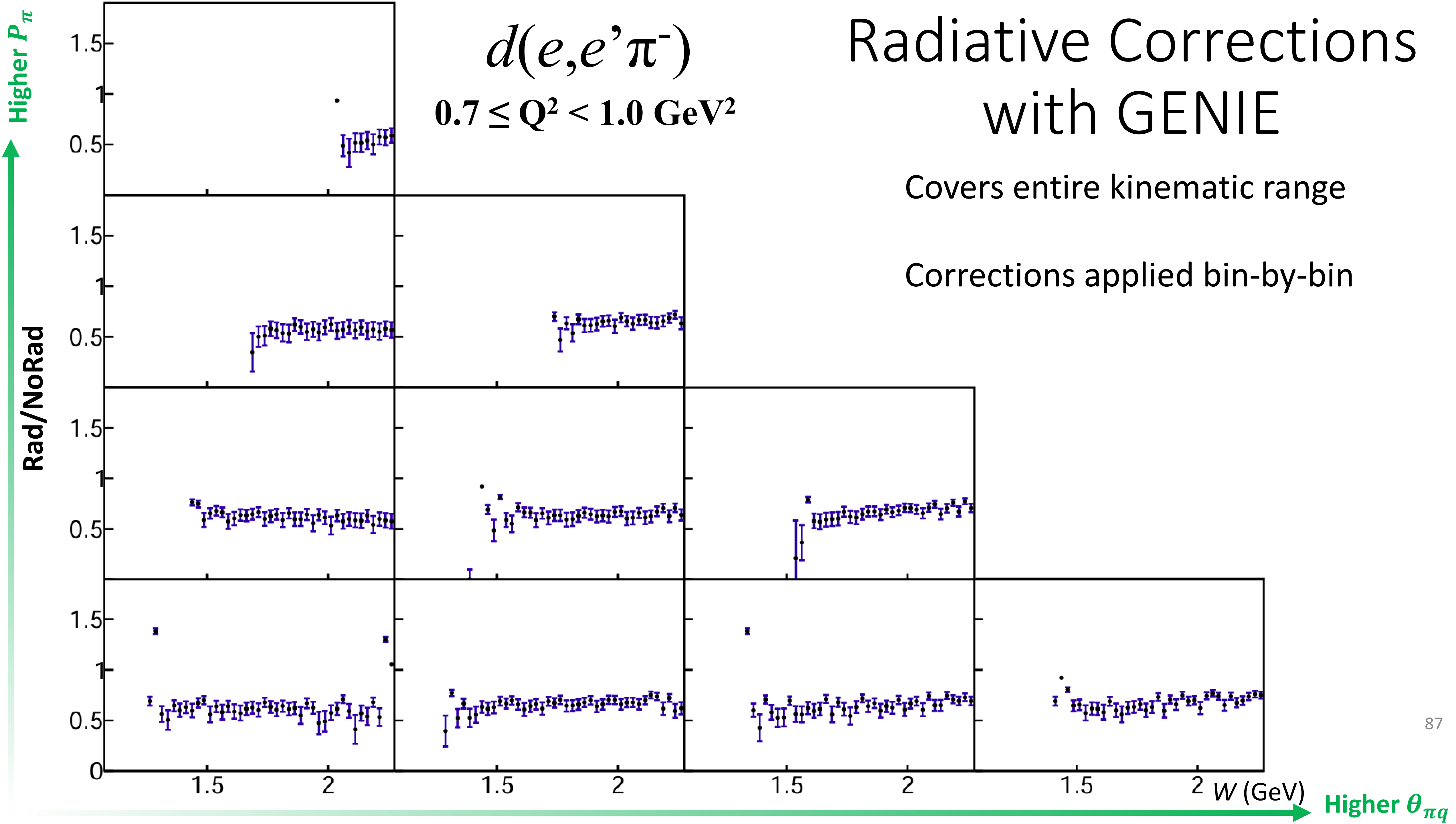
Covers entire kinematic range

Corrections applied bin-by-bin

Radiative Corrections with GENIE

Covers entire kinematic range

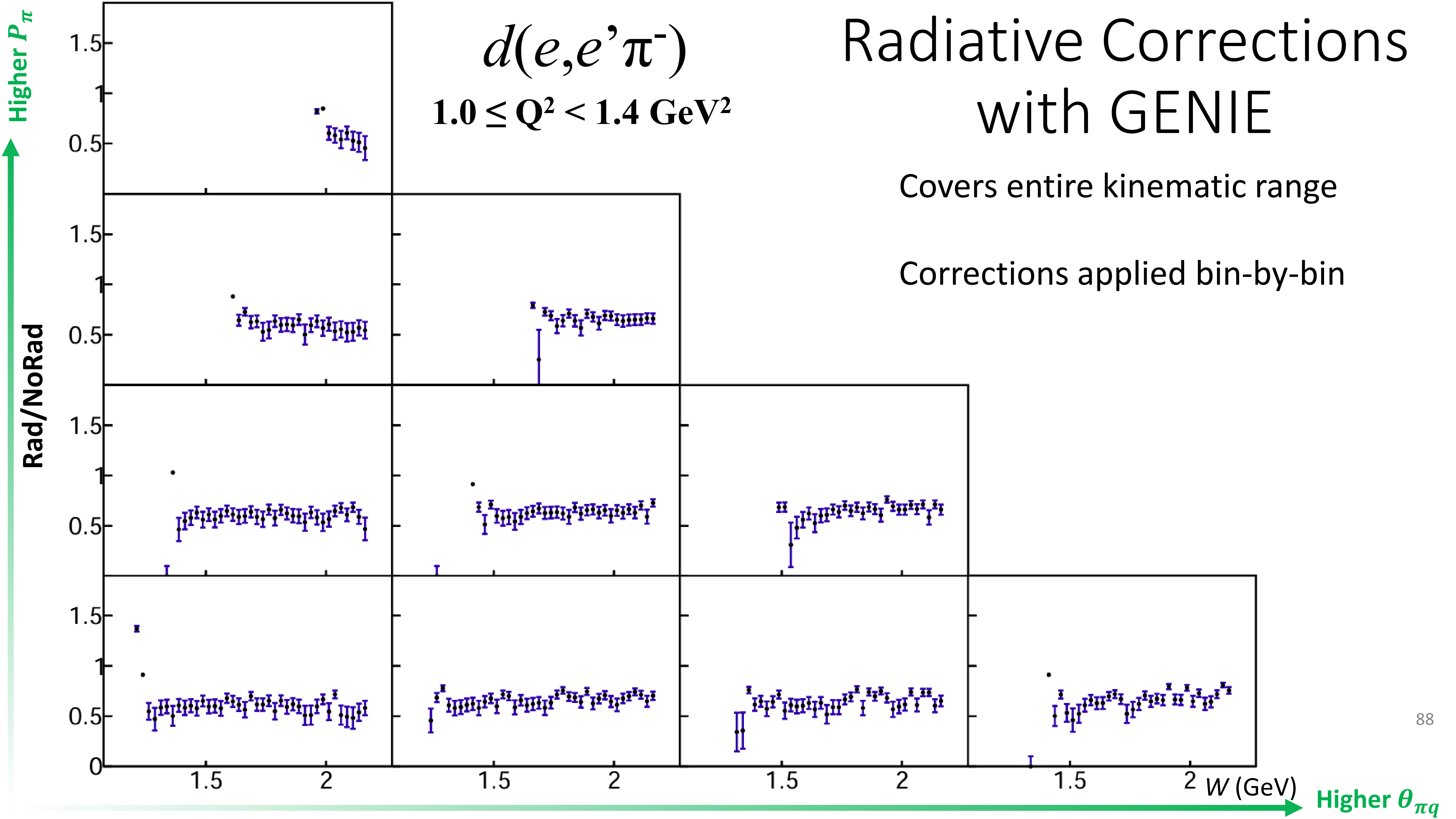
Corrections applied bin-by-bin



Radiative Corrections with GENIE

Covers entire kinematic range

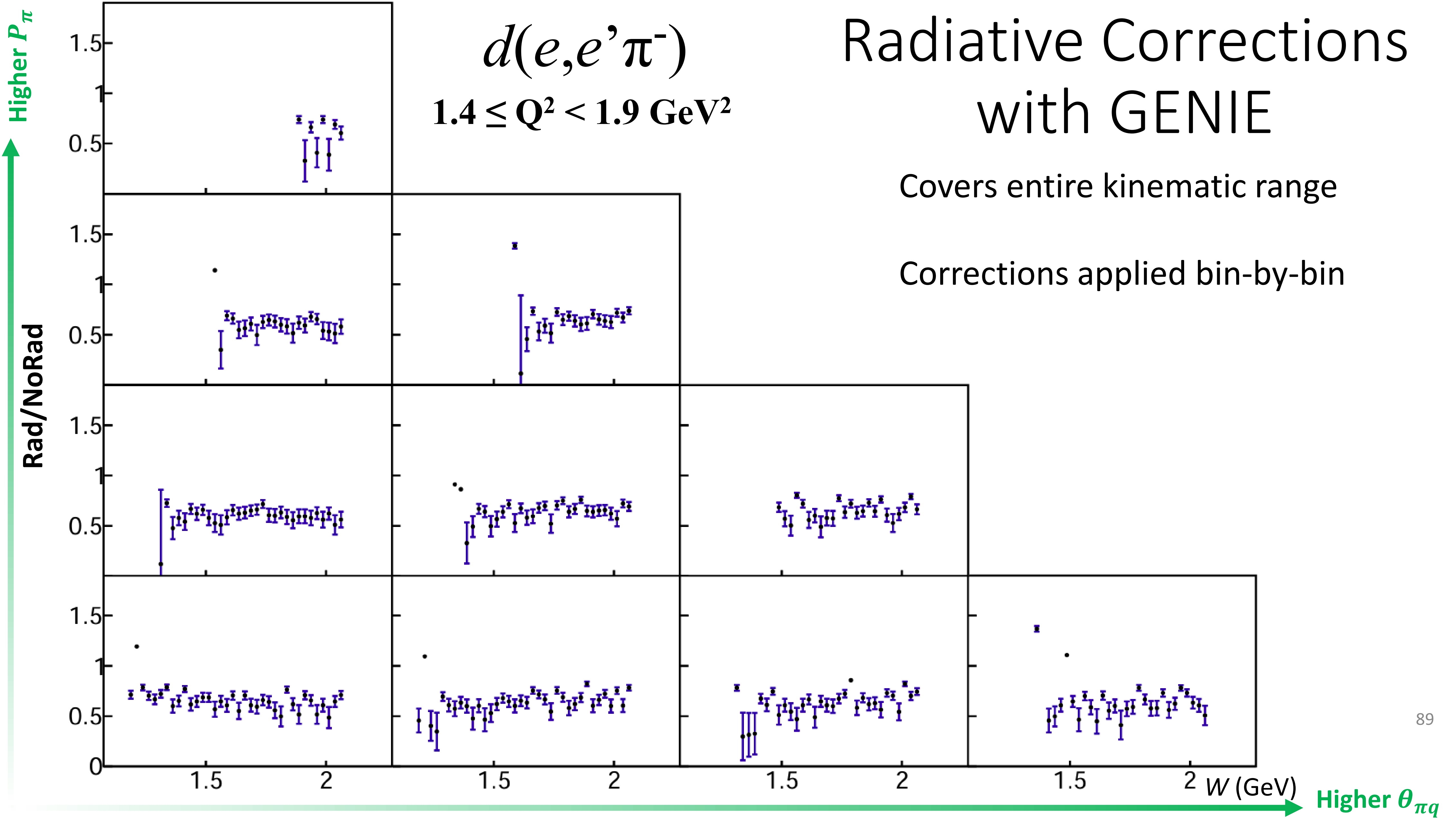
Corrections applied bin-by-bin



Radiative Corrections with GENIE

$d(e,e'\pi^-)$

$1.4 \leq Q^2 < 1.9$ GeV^2



Covers entire kinematic range

Corrections applied bin-by-bin

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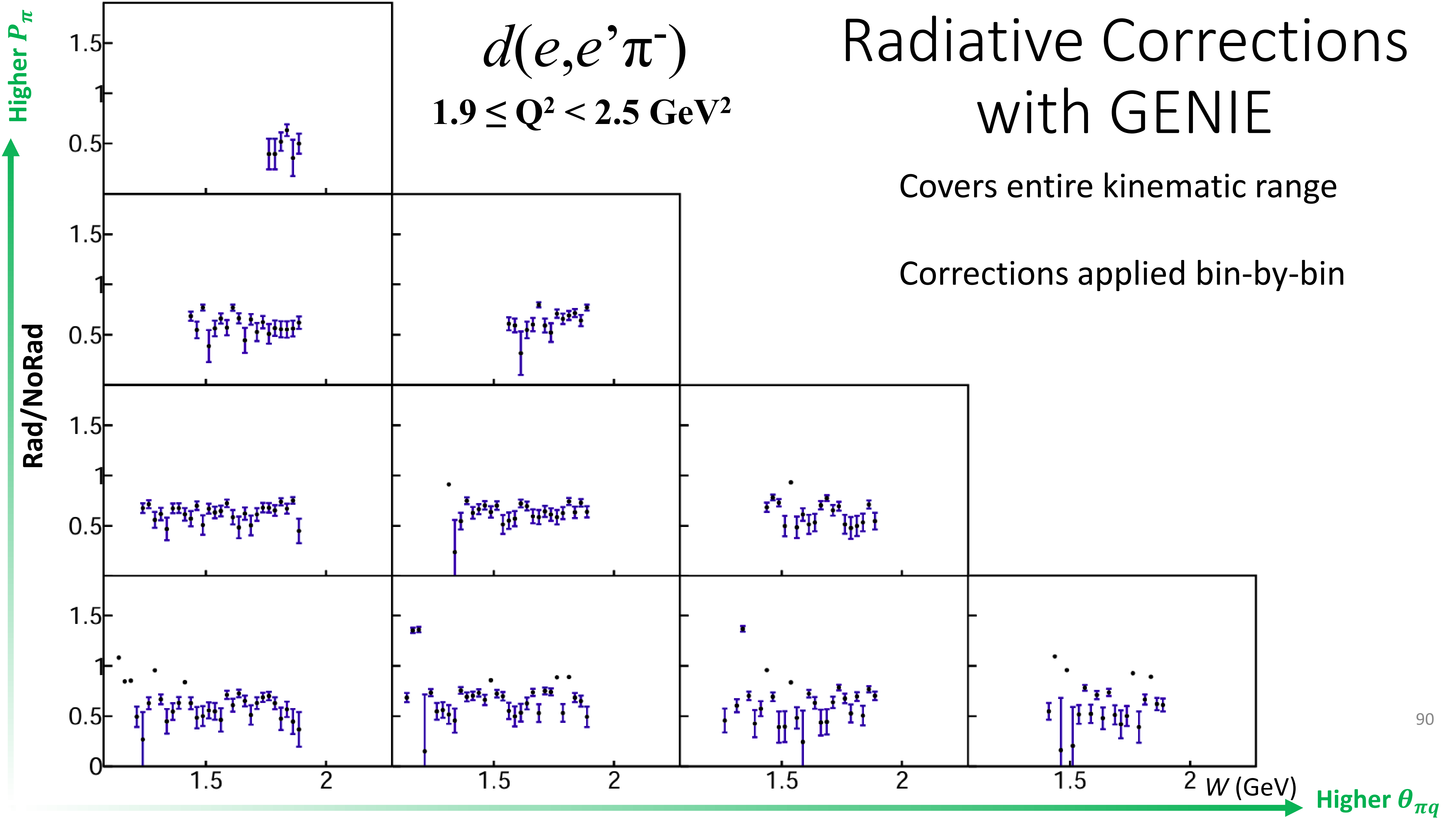
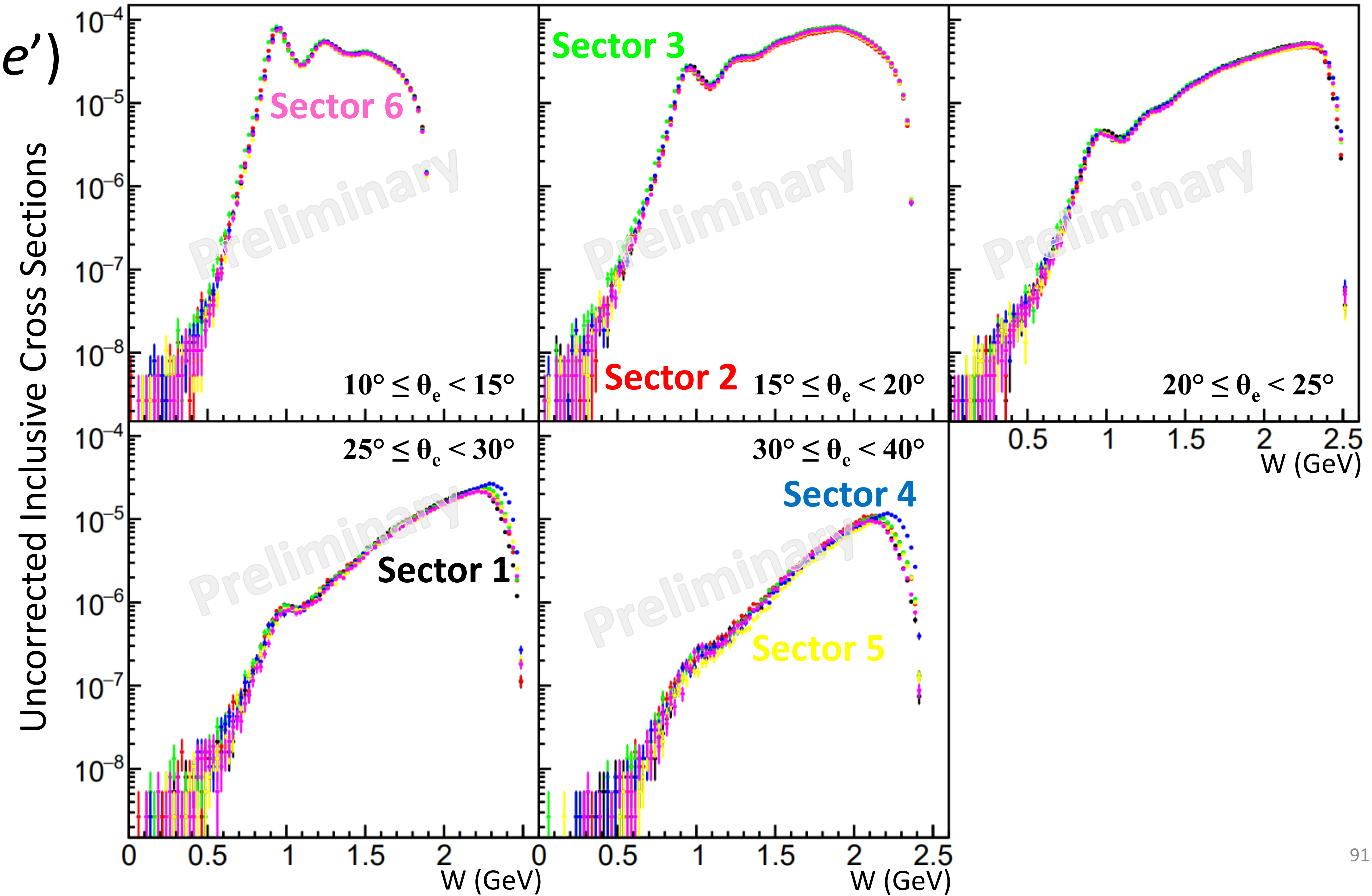
Covers entire kinematic range

Corrections applied bin-by-bin



d(e,e')


Uncorrected Inclusive Cross Sections
Sector 6
Sector 3
Sector 2
Sector 1
Sector 4
Sector 5
10° ≤ θe < 15°
15° ≤ θe < 20°
20° ≤ θe < 25°
25° ≤ θe < 30°
30° ≤ θe < 40°
Preliminary
W (GeV)

Systematic Uncertainty

- Inclusive sector

$$SysUnc_{sec} = \sqrt{var}$$

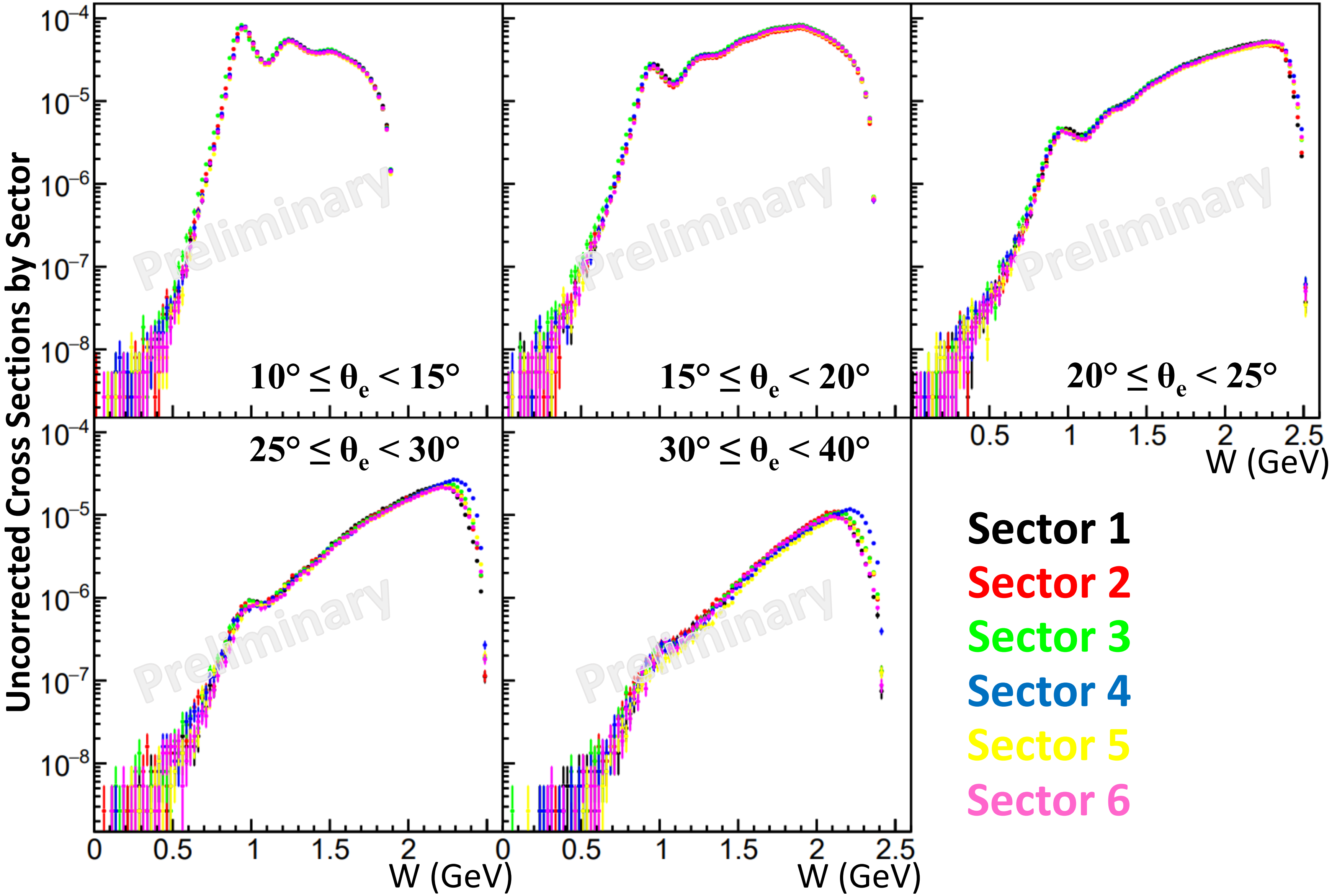
$$var = \frac{1}{5}\sum_{i}^{sec}(y_i - \bar{y})^2 - \frac{1}{6}\sum_{i}^{sec}\sigma_i^2$$

$y_i = data\ point\ for\ sector\ i$

$$\bar{y} = \frac{1}{6}\sum_{i}^{sec} y_i = ave.\ for\ all\ sectors$$

$\sigma_i = statistical\ uncertainty\ of\ y_i$

$d(e,e')$



Used similar procedure for semi-inc. cross sections

All sectors divided by Sector 1

$$SysUnc_{sec} = \sqrt{var}$$

$$var = \frac{1}{5}\sum_{i}^{sec}(y_i - \bar{y})^2 - \frac{1}{6}\sum_{i}^{sec}\sigma_i^2$$

$y_i = data\ point\ for\ sector\ i$

$\bar{y} = \frac{1}{6}\sum_{i}^{sec} y_i = ave.\ for\ all\ sectors$

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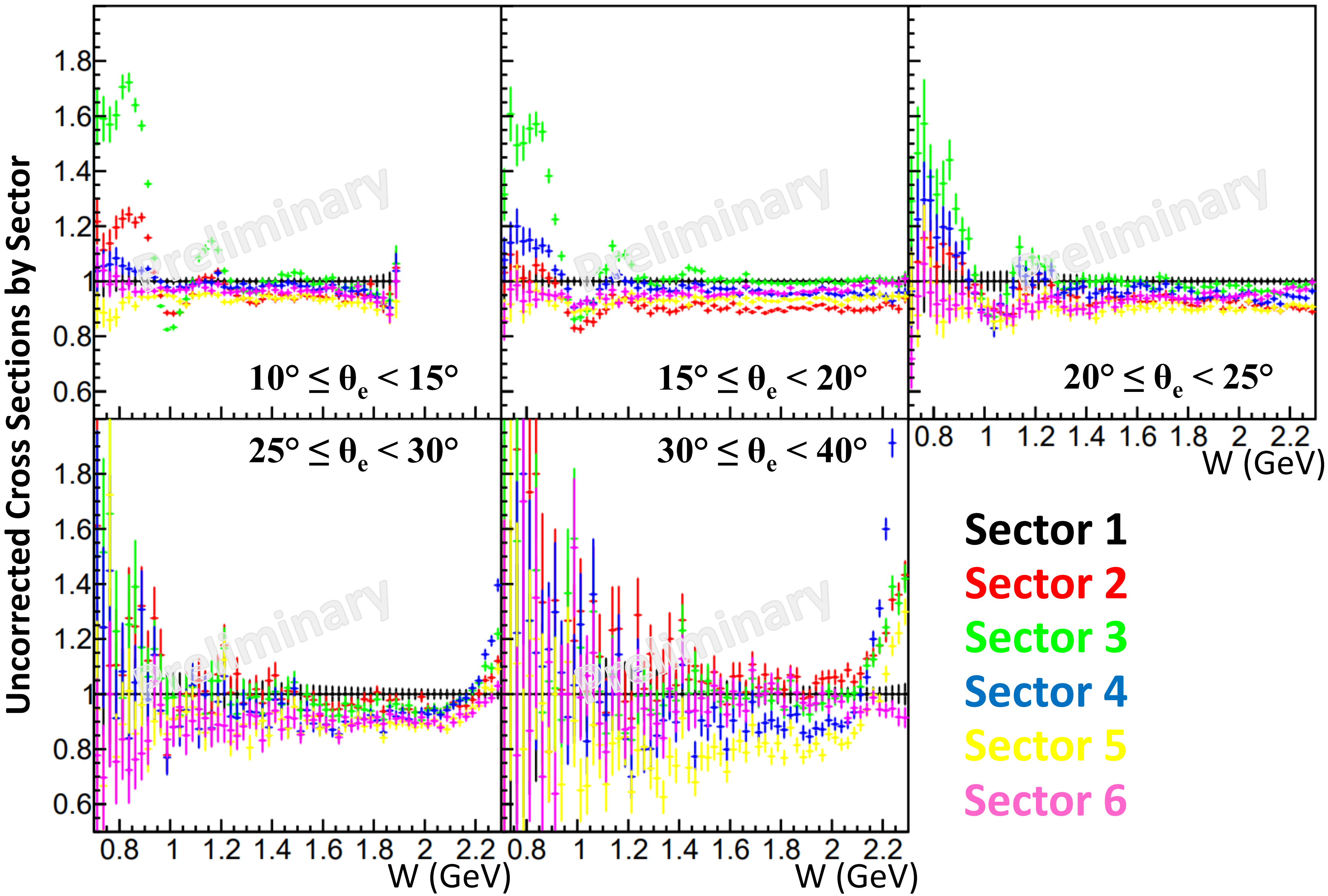
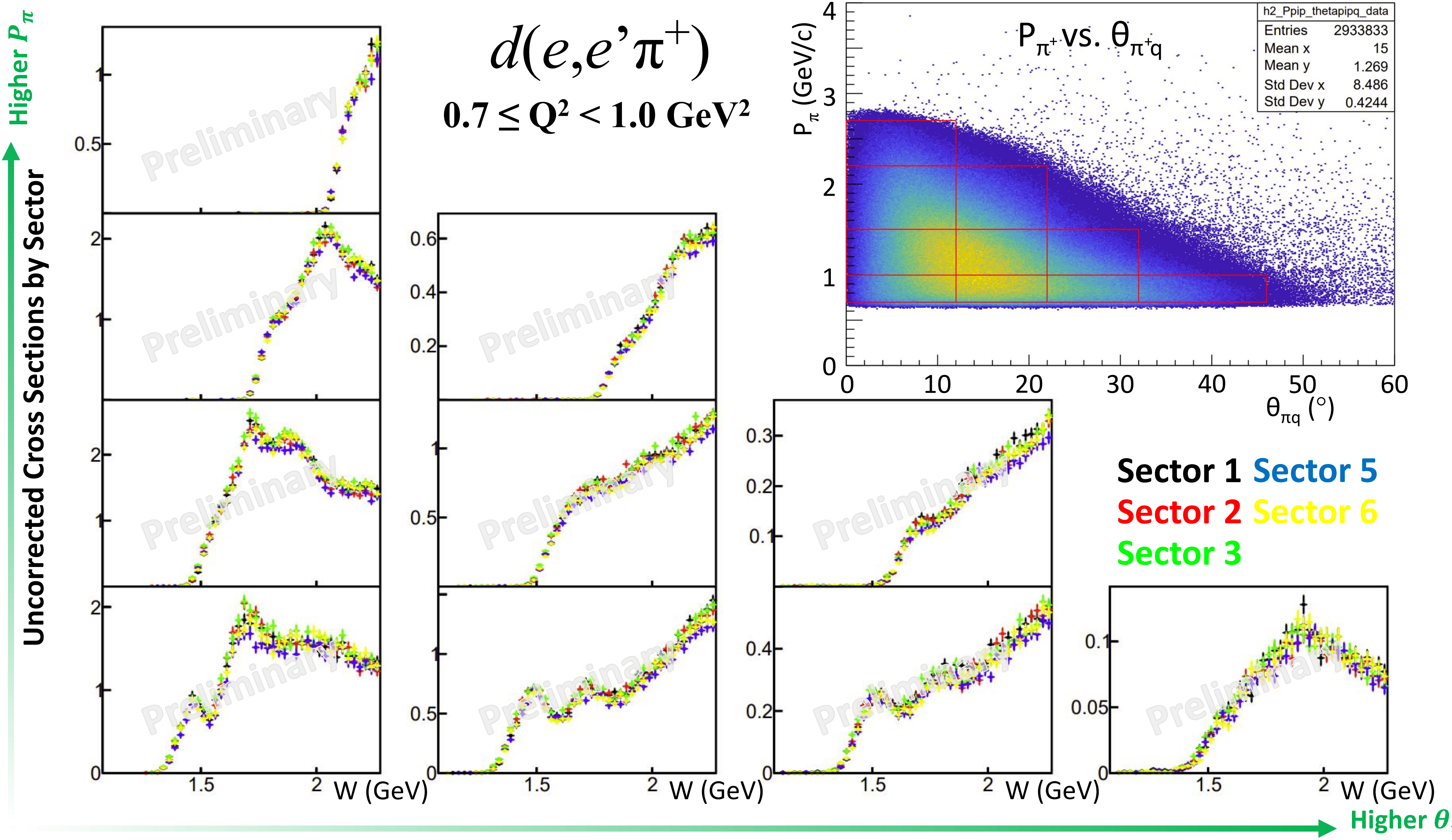
d(e,e')



Used similar procedure for semi-inc. cross sections



d(e,e'π+)
0.7 ≤ Q² < 1.0 GeV²
Higher Pπ
Uncorrected Cross Sections by Sector
Higher θπq
Pπ+ vs. θπ+q
h2_Ppip_thetapipq_data
Entries 2933833
Mean x 15
Mean y 1.269
Std Dev x 8.486
Std Dev y 0.4244
Pπ (GeV/c)
θπq (°)
Sector 1
Sector 5
Sector 2
Sector 6
Sector 3
W (GeV)
Preliminary