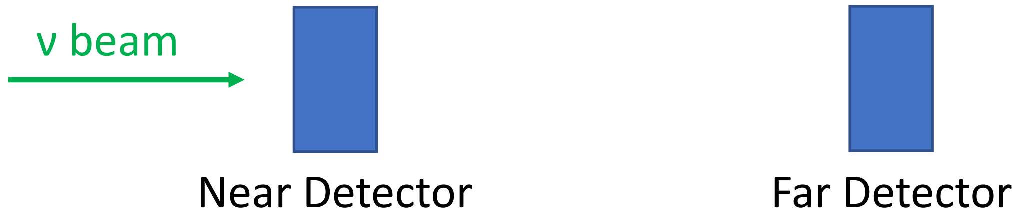
Measuring CLAS12 D(e,e′π) Cross Sections for e4ν

Caleb Fogler for the CLAS Collaboration

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

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

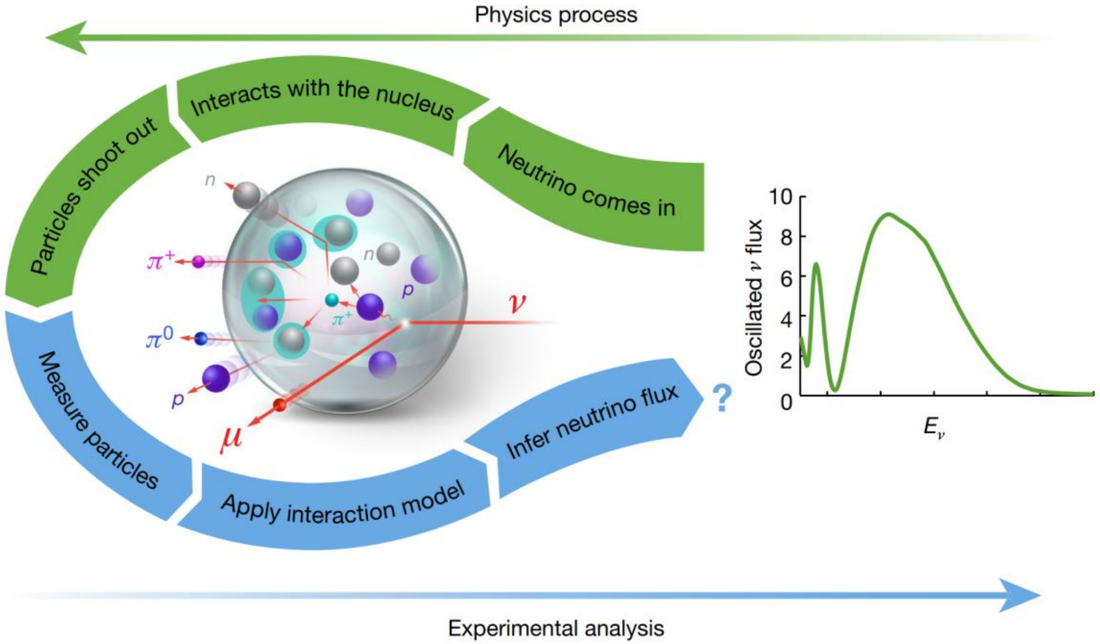
Measured Flux Simulated

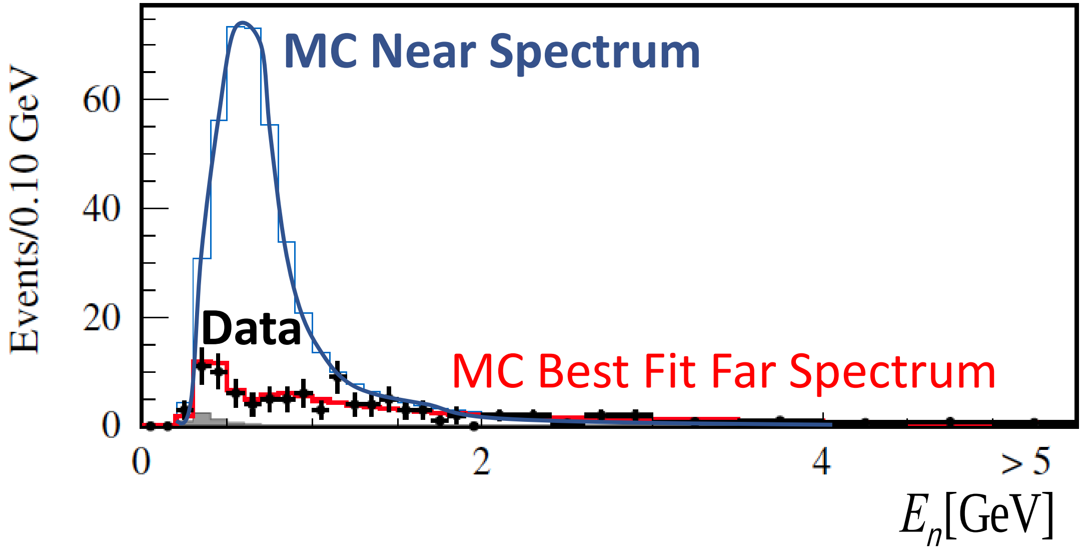
Neutrino experiments are difficult

- Large beam energy spread
- Small cross sections

Need GENIE to extract the neutrino flux from data

How to validate GENIE?

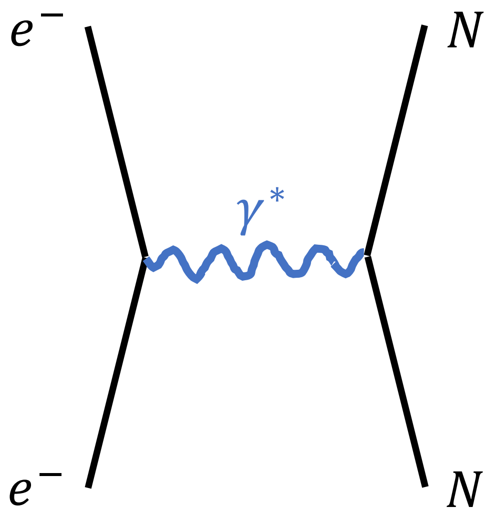


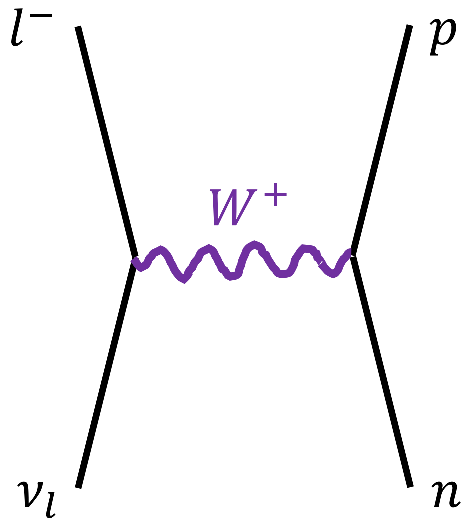


PRD 91, 072010 (2015)

Electrons vs. Neutrinos

- Monoenergetic
- Larger cross sections
- Similar interactions
  - Electro-weak
  - Currents





If GENIE can describe neutrinos, it can describe electrons

EM Current:

$$j_\mu^{em} = \bar{u}\gamma^\mu u$$

Vector

Charge-Coupling Weak Current:

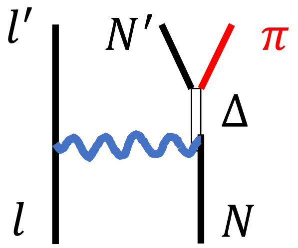
$$j_\mu^{\pm} = \bar{u}\frac{-ig_W}{2\sqrt{2}}(\gamma^\mu - \gamma^\mu\gamma^5)u$$

Vector Axial

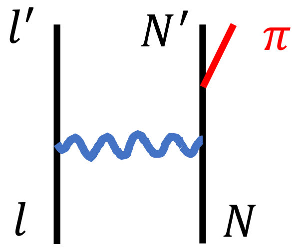
Motivation

- 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 will measure 4.2 GeV RG-B D(e,e’π) Forward Detector cross sections to improve GENIE

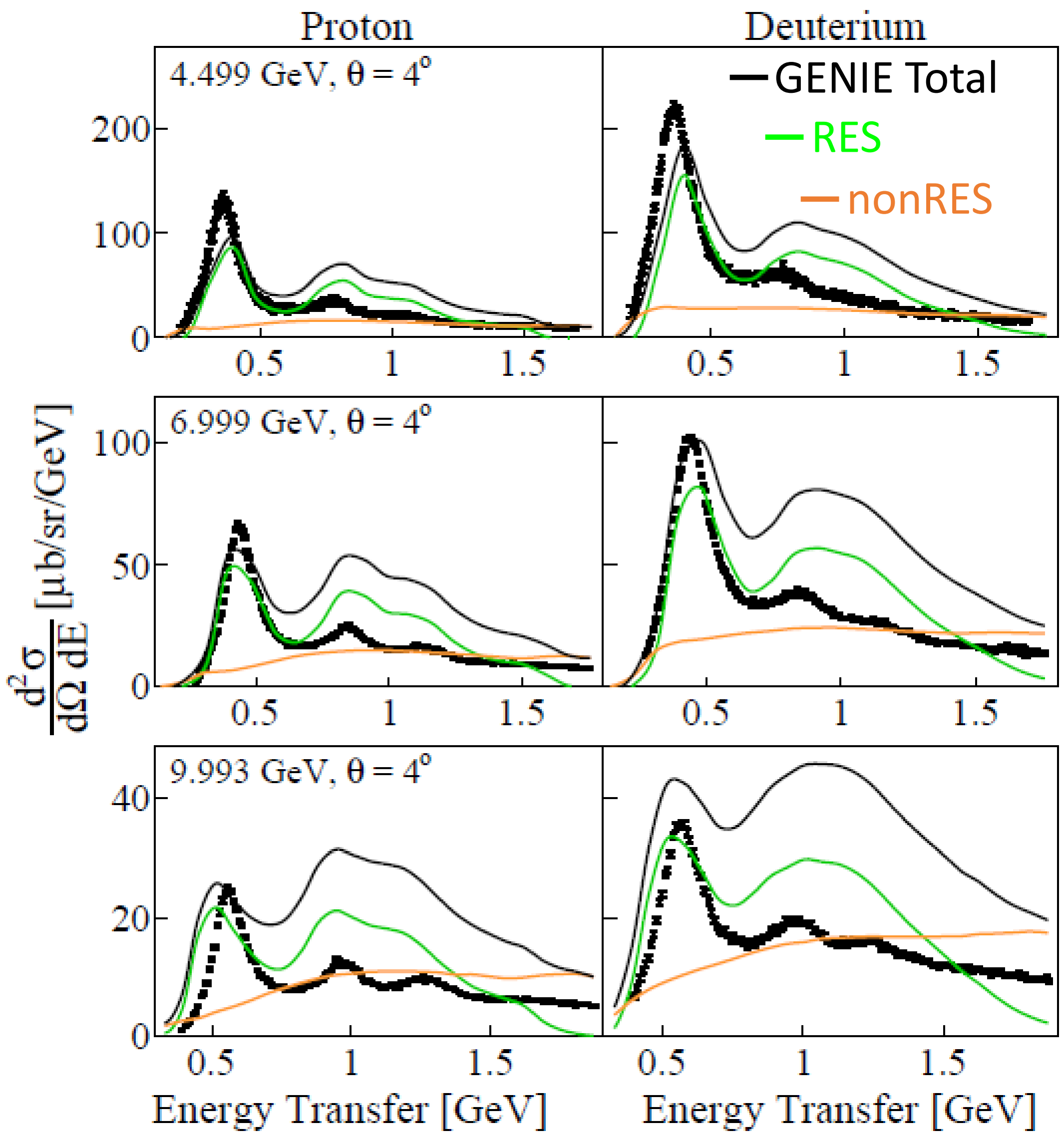
Resonance Decay



Non-Resonant



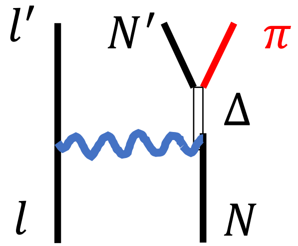
(e,e’)



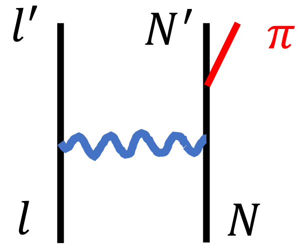
PRD 103, 113003 (2021)

Model Descriptions

Resonant Production



Non-Resonant Production



Onepigen

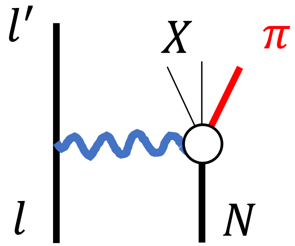
Nucl.Phys. A645 (1999) 145-174
arXiv:nucl-th/9807001v2

- Single pion event generator
- MAID2007 unitary isobar model

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

GENIE

DIS Production



- 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

Compare data to models run through GEMC

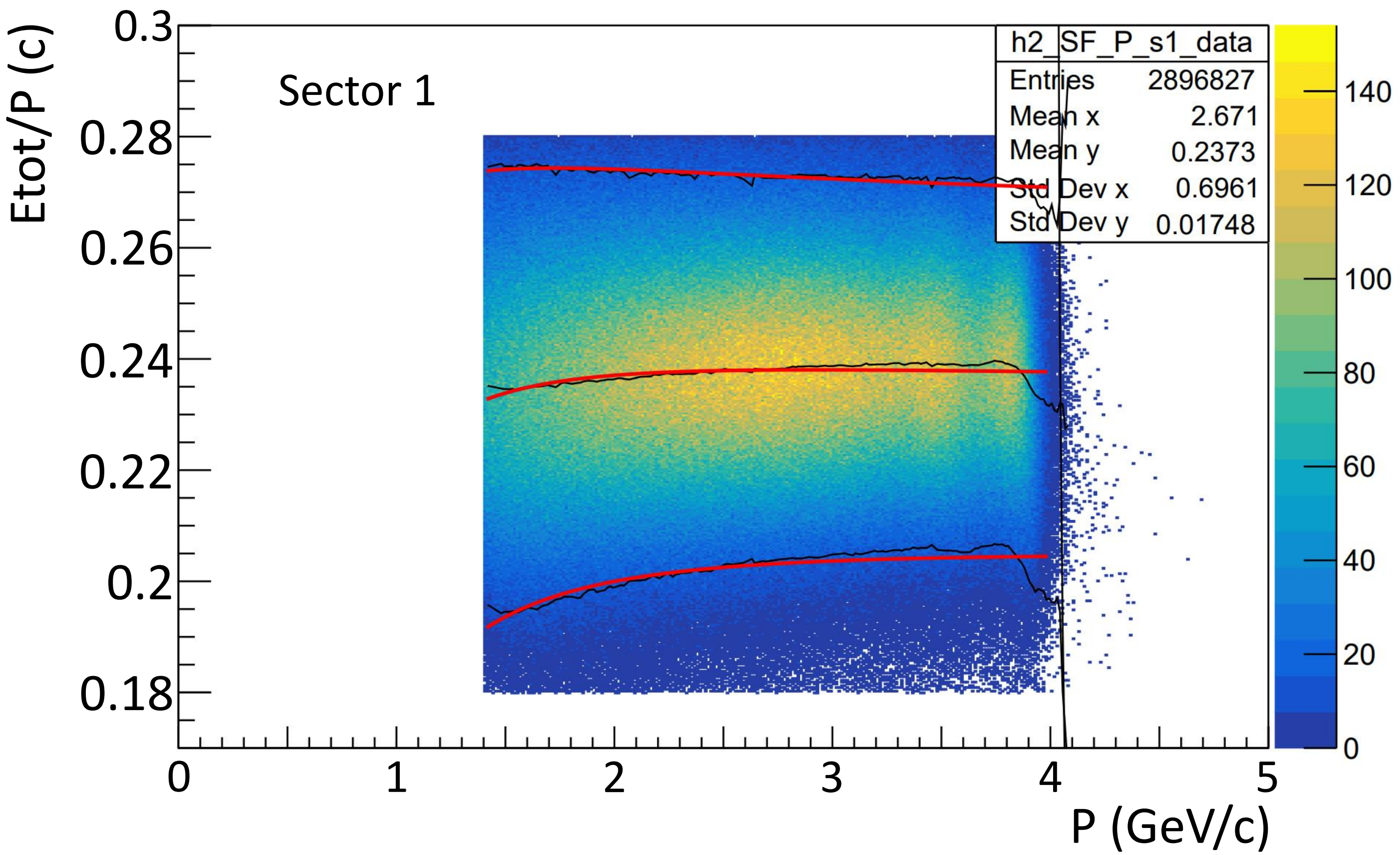
Average radiative corrections (Rad/NoRad) calculated using onepigen
π^+: 0.65 ± 0.07
π^-: 0.5 ± 0.1

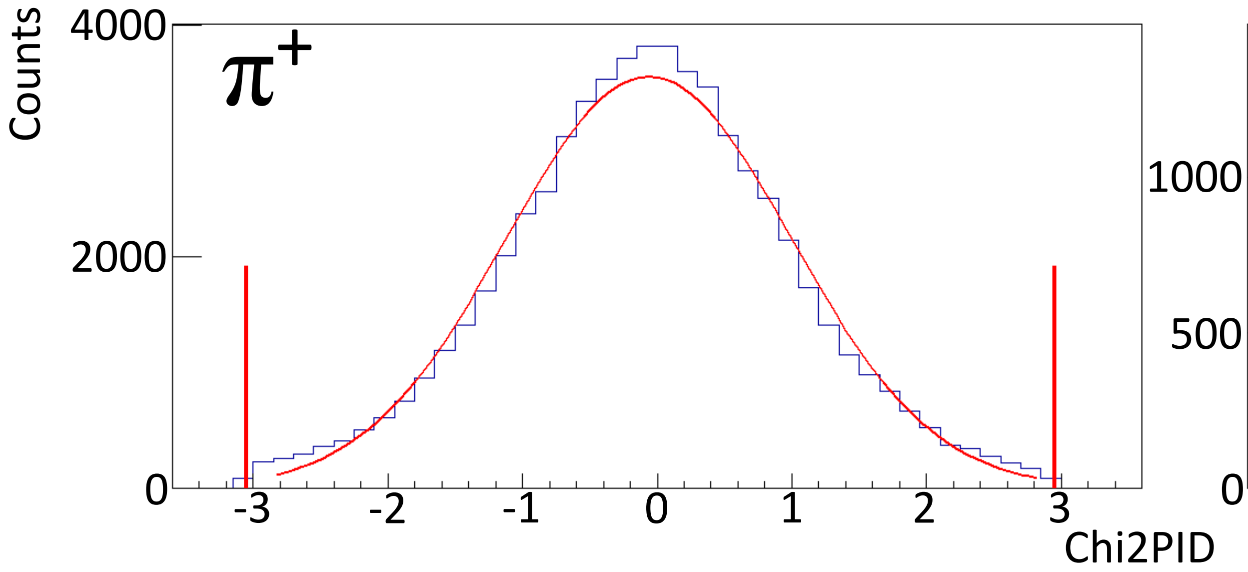
FD Particle Identification

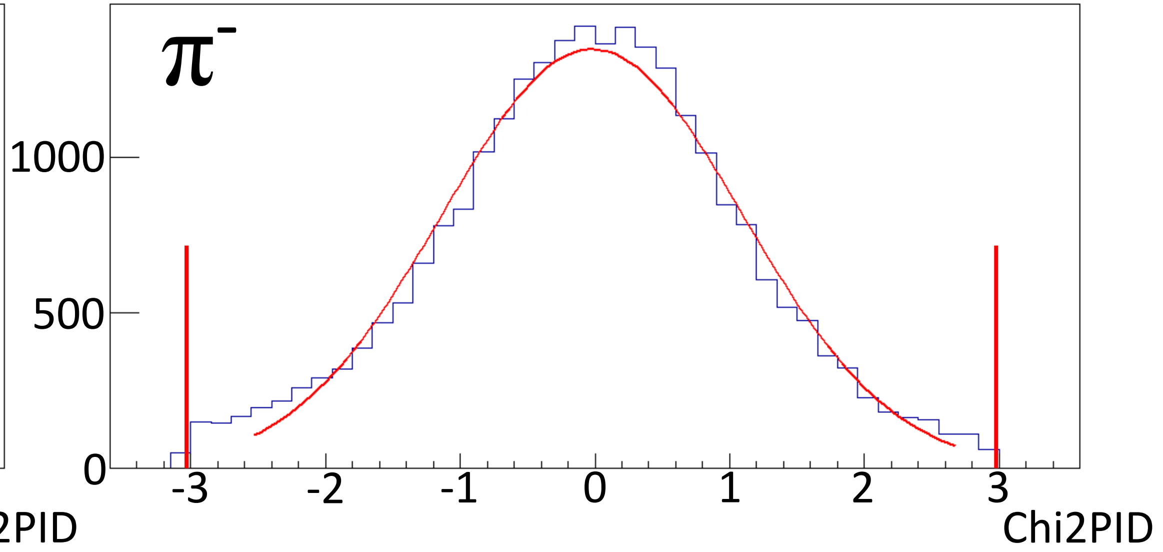
Electron PID:
EC sampling fraction cut < 2σ

Hadron PID:
chi2pid < 3σ

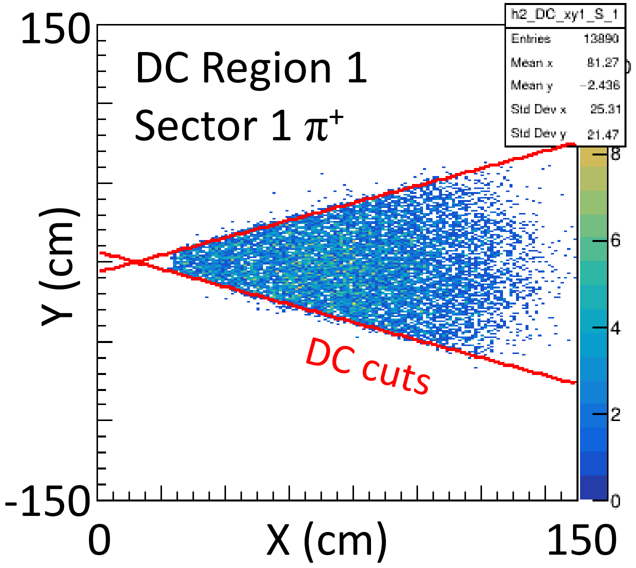
Data taken during RG-B (Fall 2019)

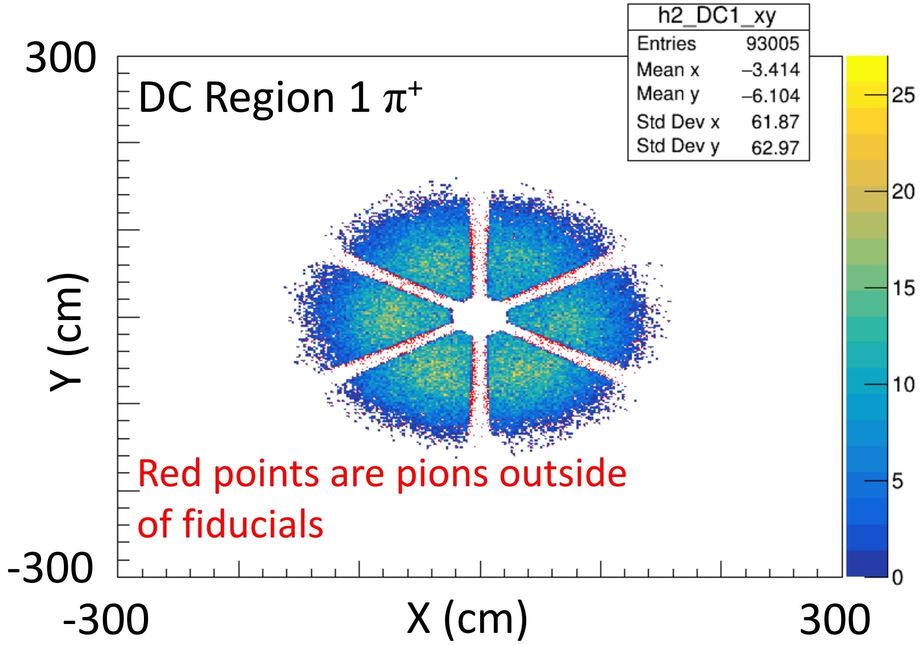






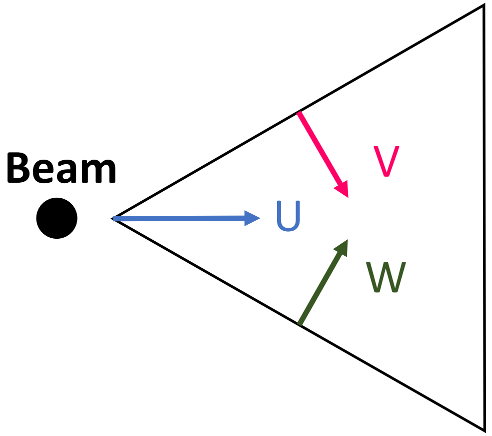
Fiducial Cuts

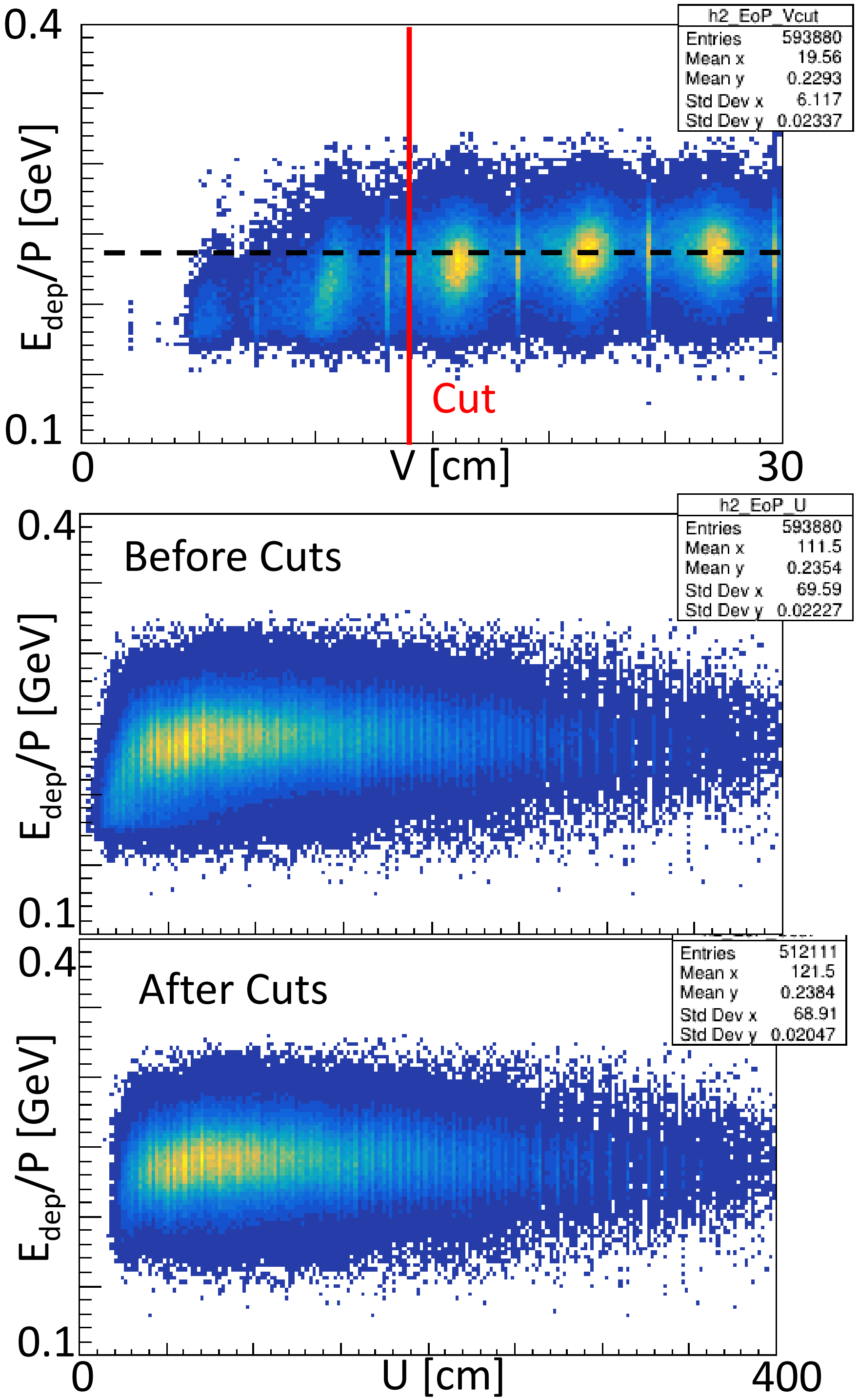




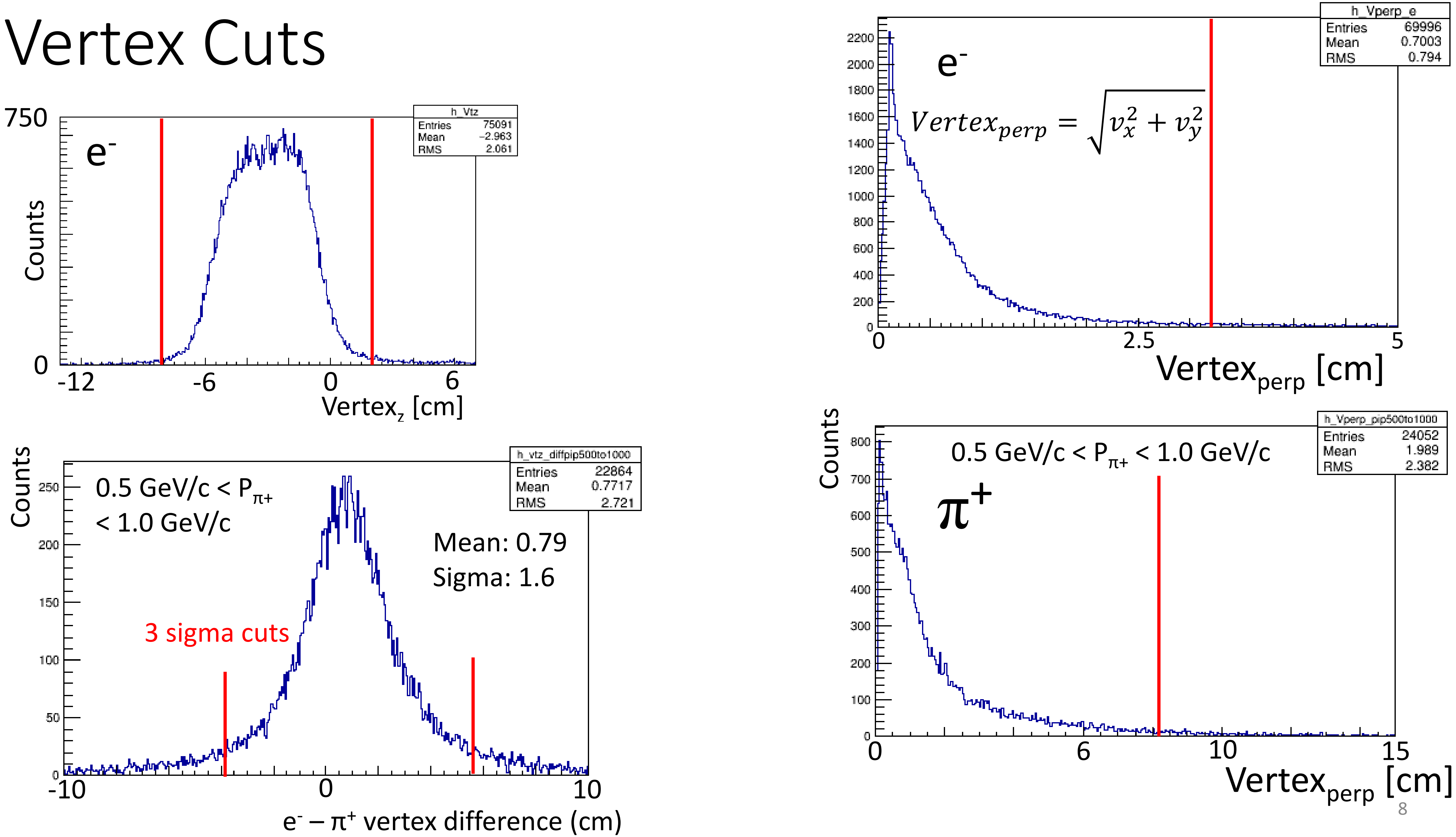
DC

EC



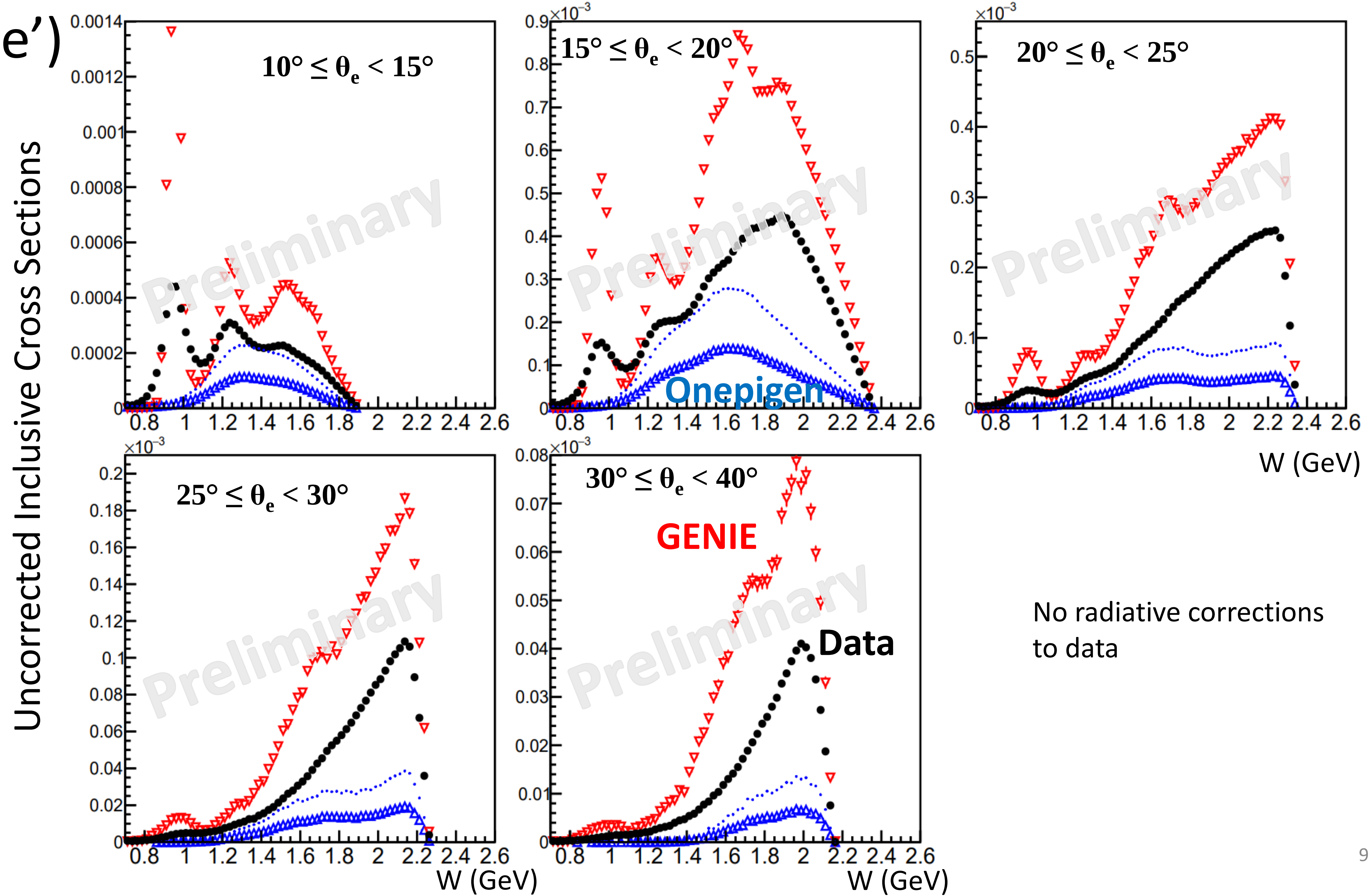


Vertex Cuts



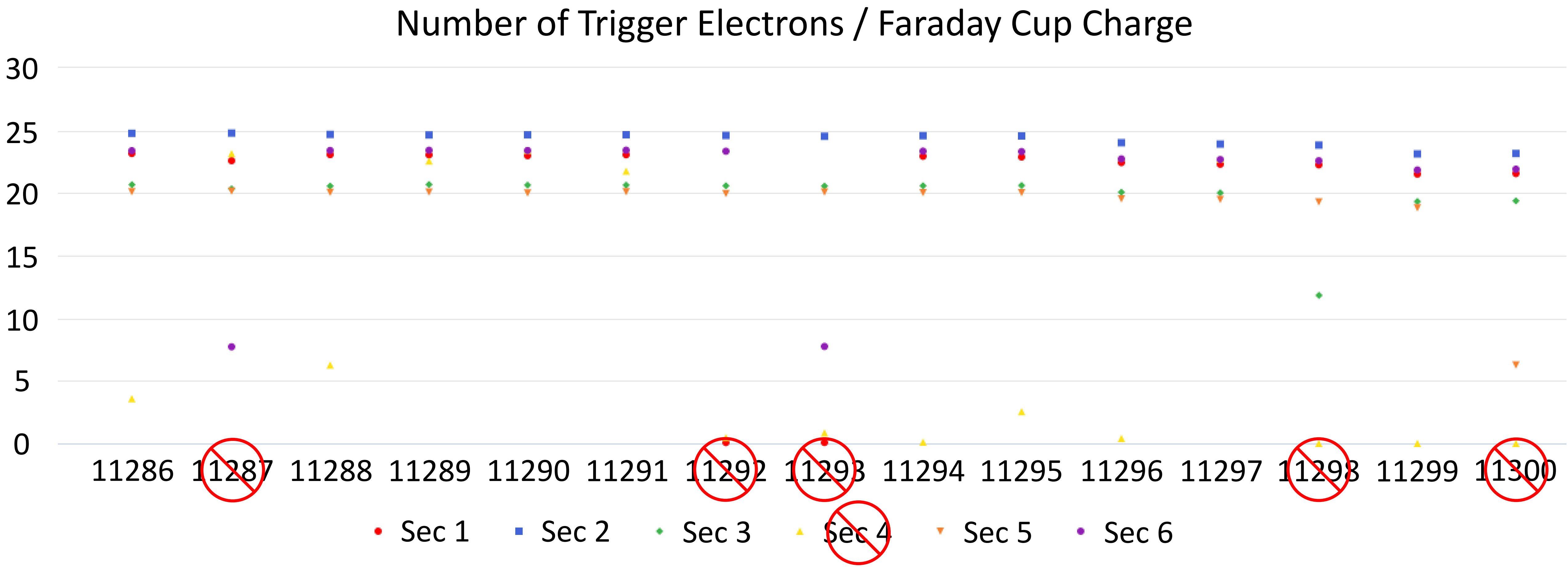
h_Vtz
Entries 75091
Mean -2.963
RMS 2.061
e-
750
0
Counts
-12
-6
0
6
Vertex$_z$ [cm]
h_Vperp_e
Entries 69996
Mean 0.7003
RMS 0.794
e-
$Vertex_{perp} = \sqrt{v_x^2 + v_y^2}$
0
2.5
5
Vertex$_{perp}$ [cm]
h_vtz_diffpip500to1000
Entries 22864
Mean 0.7717
RMS 2.721
Counts
0.5 GeV/c < $P_{\pi+}$ < 1.0 GeV/c
Mean: 0.79
Sigma: 1.6
3 sigma cuts
-10
0
10
e- – π+ vertex difference (cm)
h_Vperp_pip500to1000
Entries 24052
Mean 1.989
RMS 2.382
Counts
0.5 GeV/c < $P_{\pi+}$ < 1.0 GeV/c
π+
0
6
10
15
Vertex$_{perp}$ [cm]

D(e,e')



No radiative corrections to data

Run Selection



About 400 M events

Systematic Uncertainties

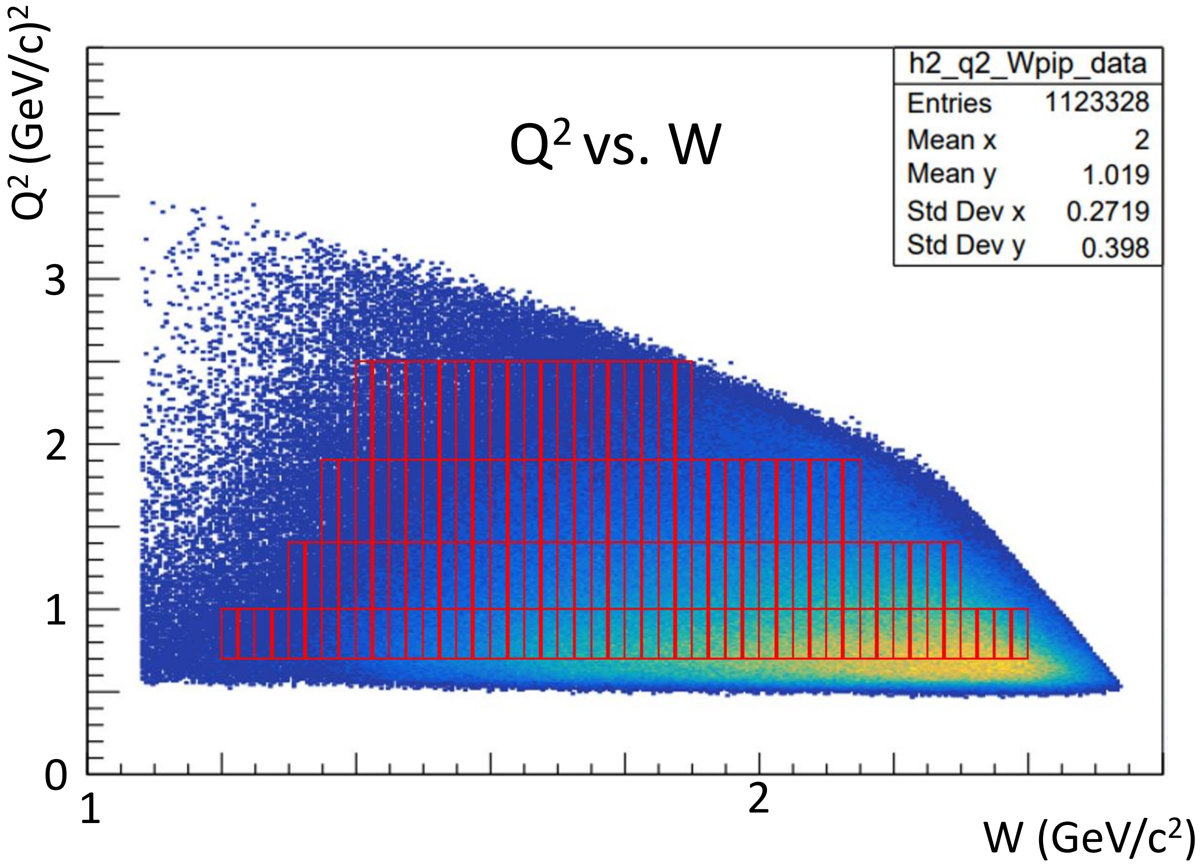
- Radiative 20% of correction

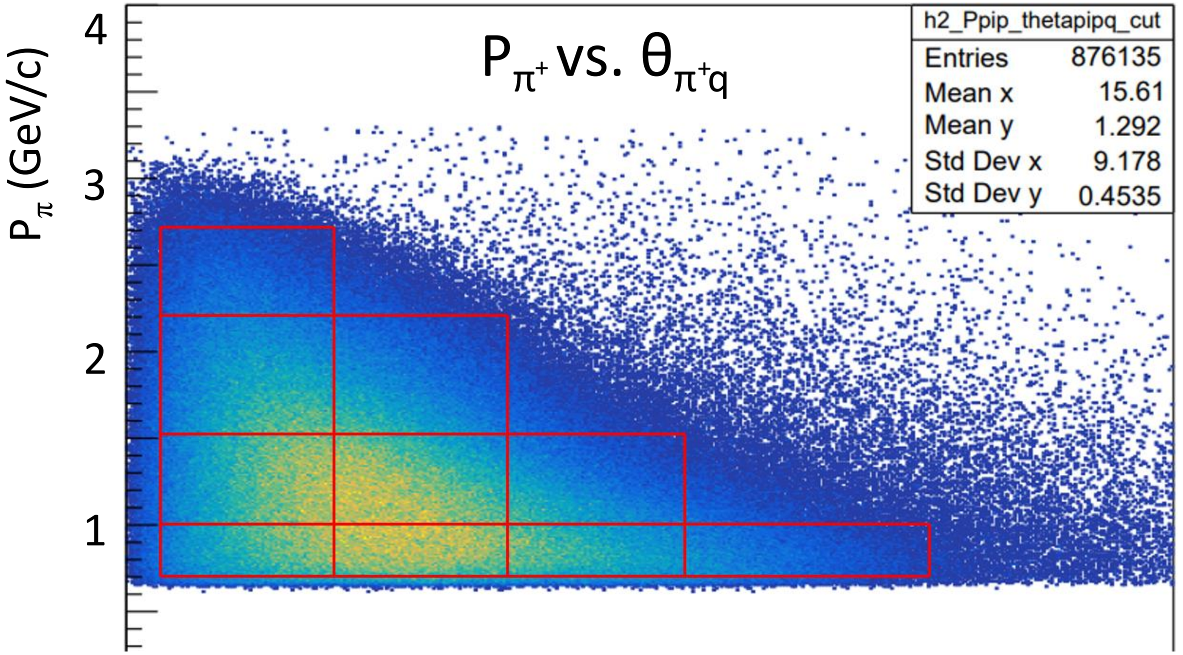
- Sector-to-sector variation

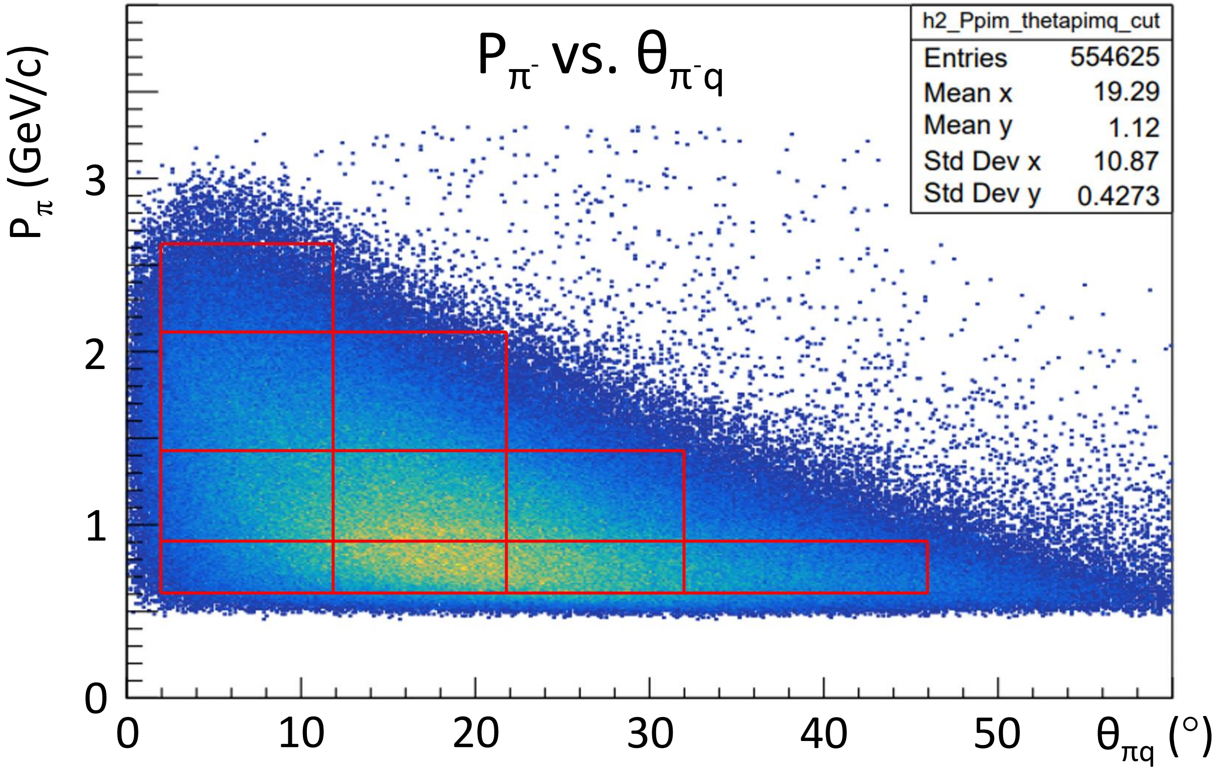
$$var = \frac{1}{4}\sum_{i}^{sec}(y_i - \bar{y})^2 - \frac{1}{5}\sum_{i}^{sec}\sigma_i^2$$

- Normalization 10%?

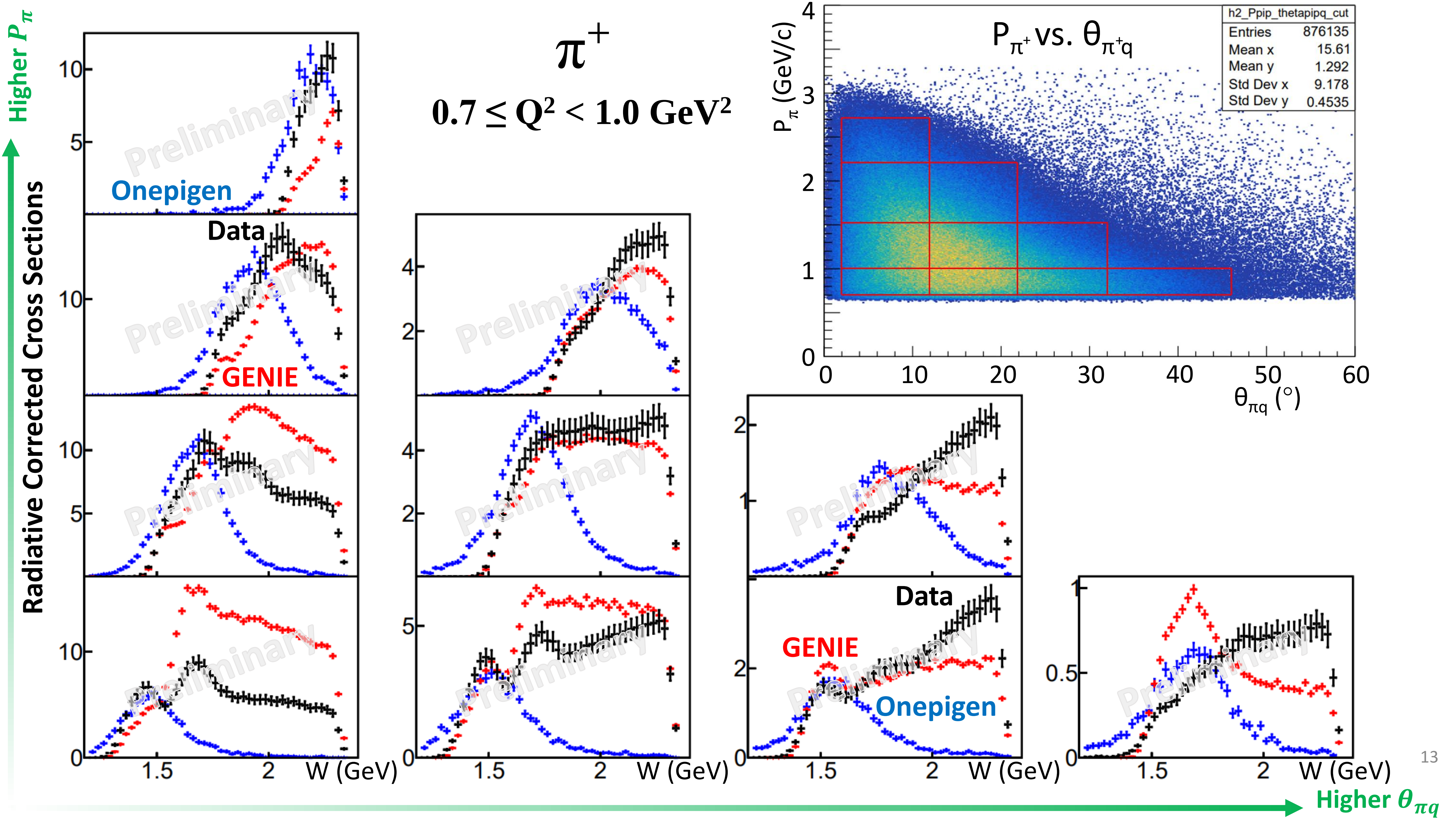
Binning (Q^2, W, $\theta_{\pi q}$, P_π)



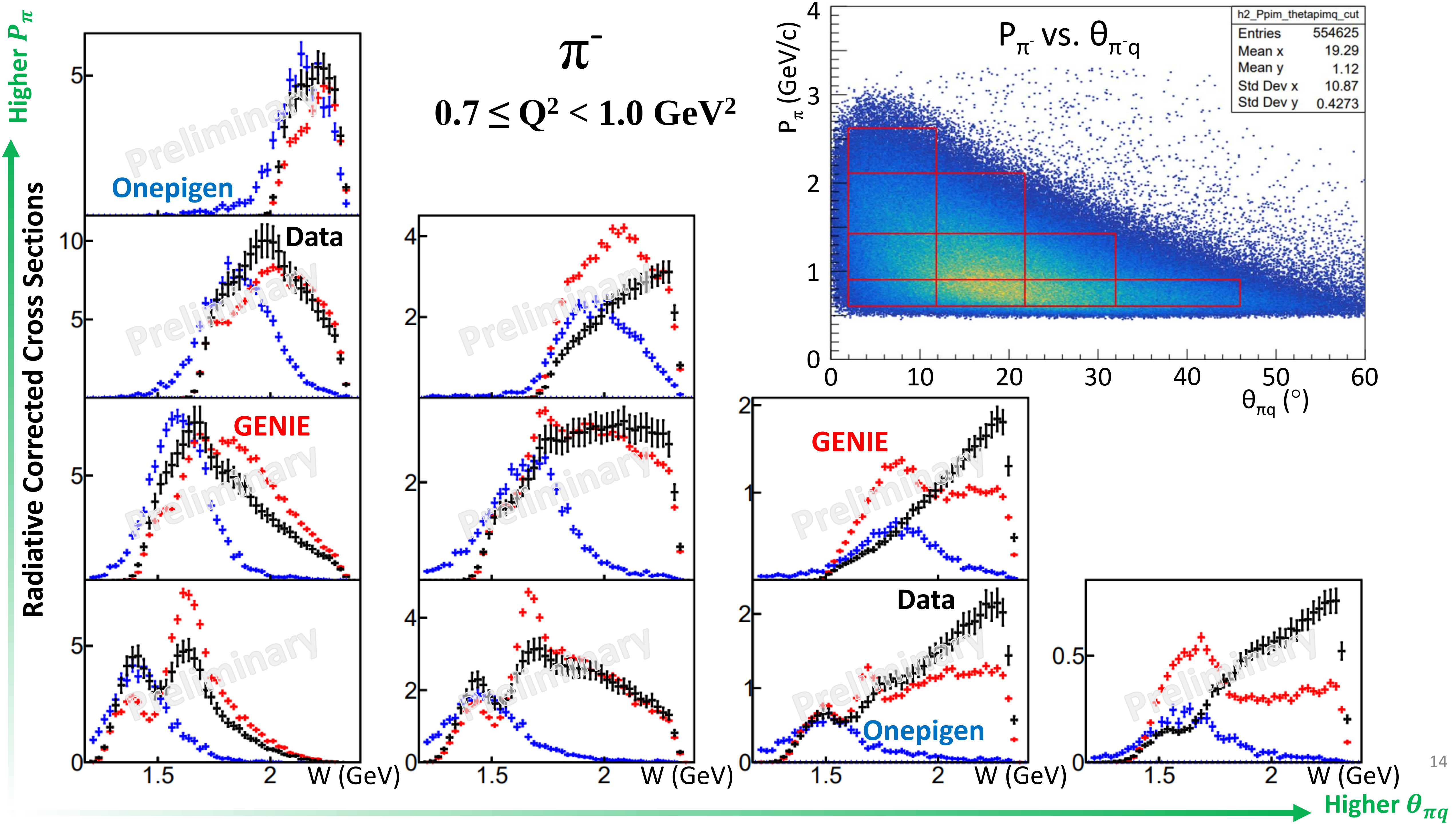


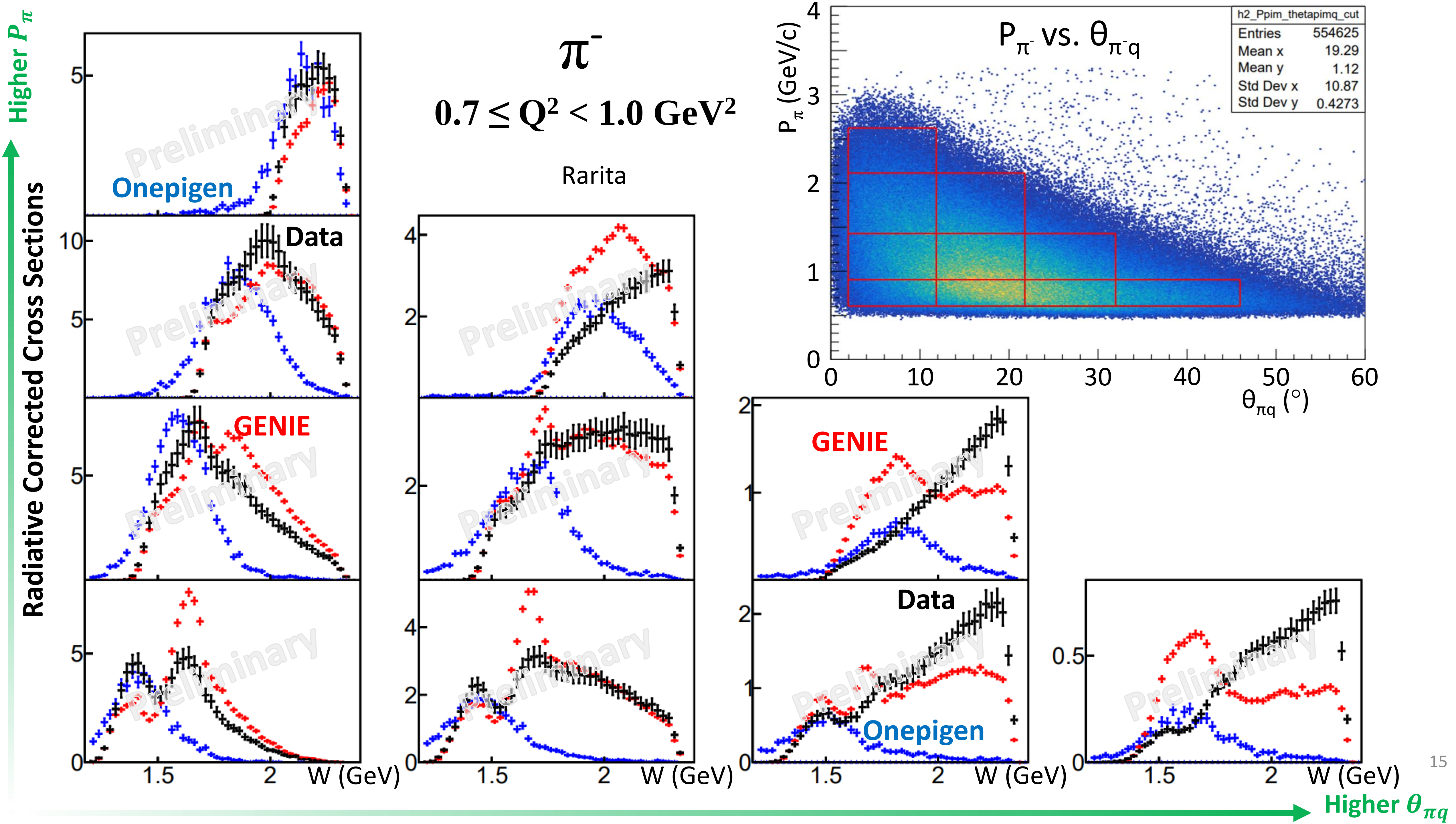


Also binning in (Q^2, W, θ_π, P_π)



π^+
$0.7 \leq Q^2 < 1.0$ GeV^2
Higher P_π
Higher $\theta_{\pi q}$
Radiative Corrected Cross Sections
Onepigen
Data
GENIE
Preliminary
W (GeV)
P_{π^+} vs. $\theta_{\pi^+ q}$
h2_Ppip_thetapipq_cut
Entries 876135
Mean x 15.61
Mean y 1.292
Std Dev x 9.178
Std Dev y 0.4535
P_π (GeV/c)
$\theta_{\pi q}$ (°)


π-
0.7 ≤ Q2 < 1.0 GeV2
Pπ- vs. θπ-q
h2_Ppim_thetapimq_cut
Entries 554625
Mean x 19.29
Mean y 1.12
Std Dev x 10.87
Std Dev y 0.4273
Pπ (GeV/c)
θπq (°)
Higher Pπ
Higher θπq
Radiative Corrected Cross Sections
Onepigen
Data
GENIE
Preliminary
W (GeV)



π-
0.7 ≤ Q2 < 1.0 GeV2
Rarita
Pπ- vs. θπ-q
h2_Ppim_thetapimq_cut
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Pπ (GeV/c)
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Higher Pπ
Higher θπq
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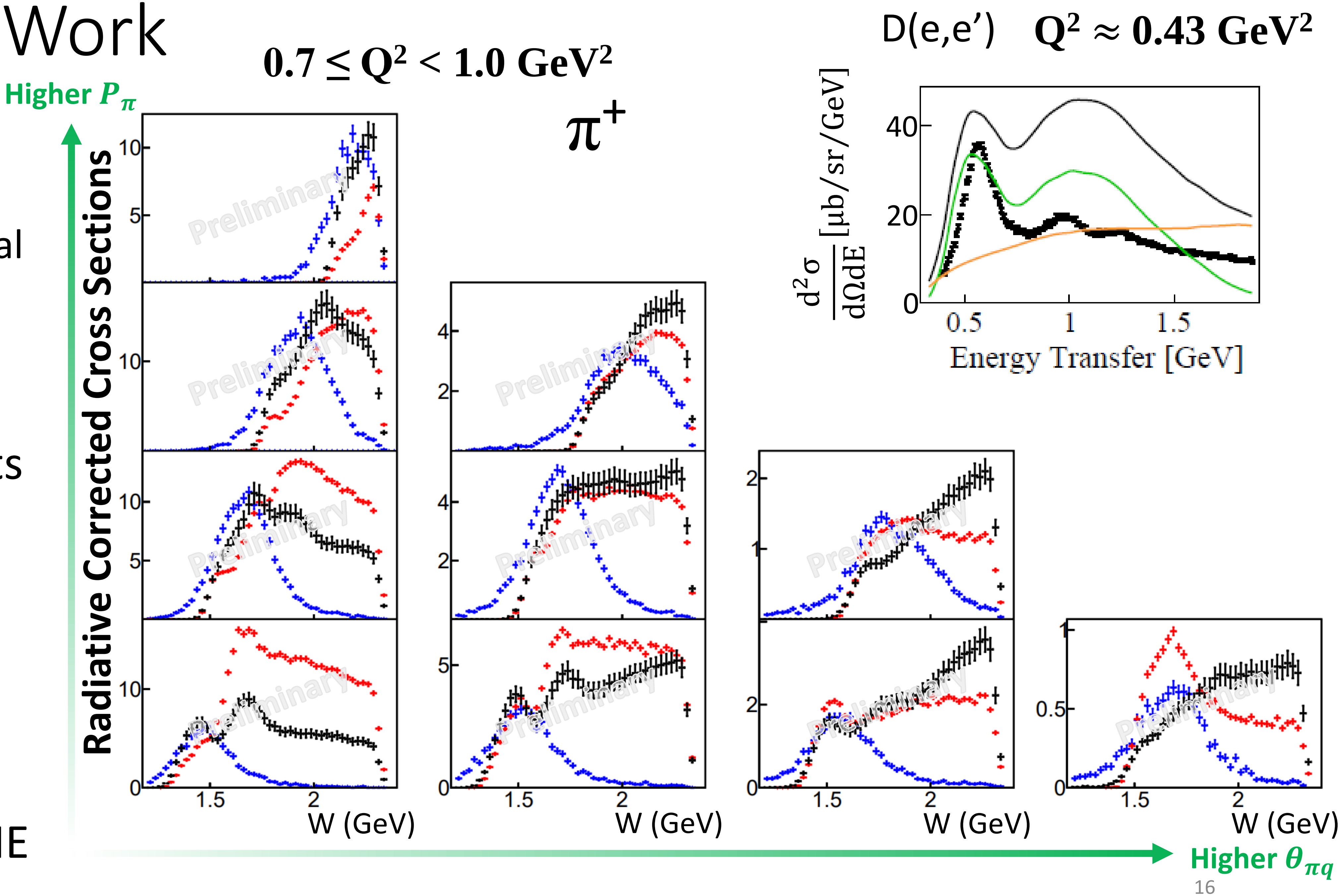
W (GeV)

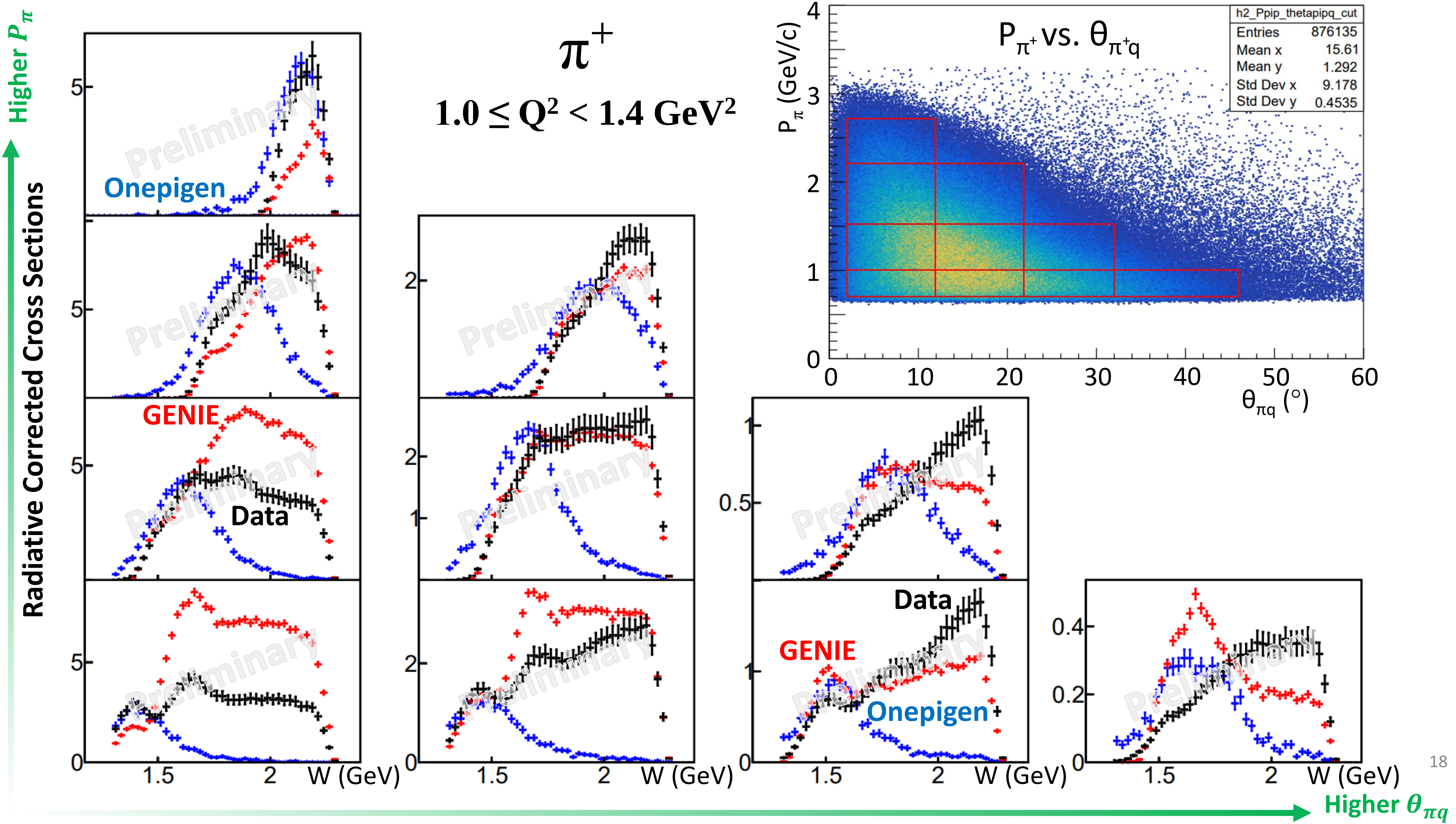
Future Work

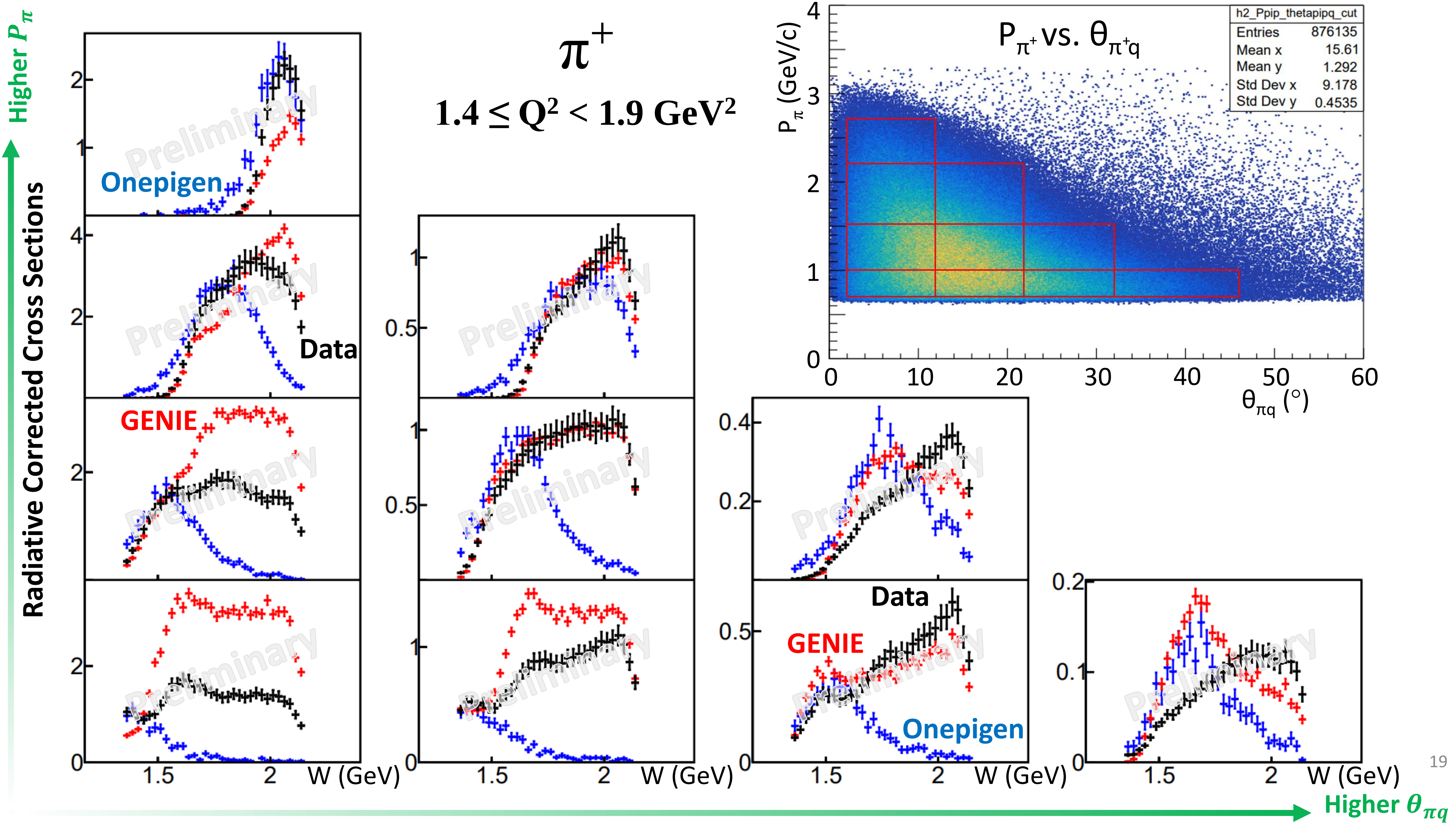
- Finalize uncertainties
  - May effect final cuts
- Add more onepigen events
- Graduate

This will help improve GENIE



Backup Slides

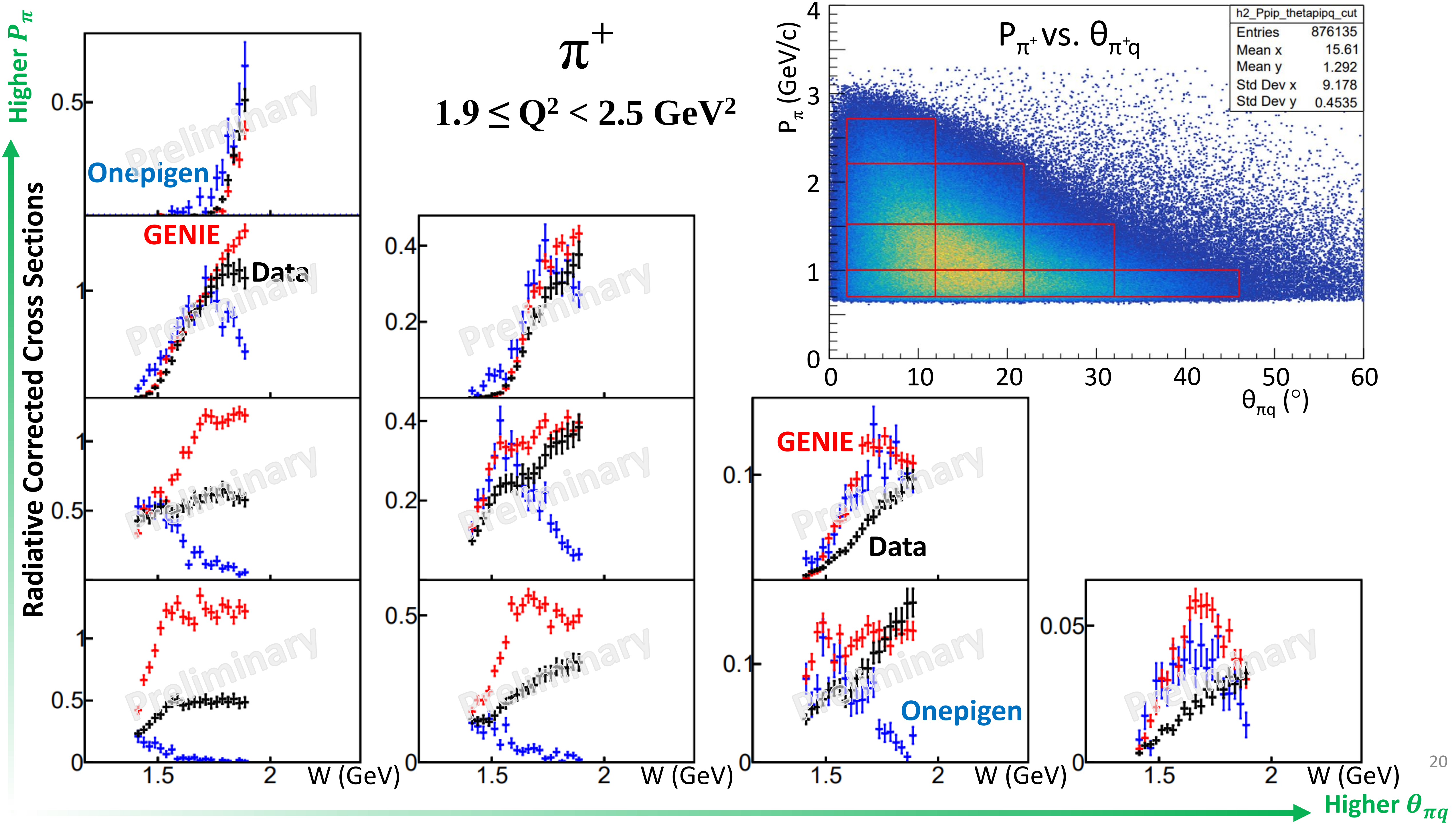

π+
1.0 ≤ Q² < 1.4 GeV²
Higher P_π
Radiative Corrected Cross Sections
P_π+ vs. θ_π+q
h2_Ppip_thetapipq_cut
Entries 876135
Mean x 15.61
Mean y 1.292
Std Dev x 9.178
Std Dev y 0.4535
P_π (GeV/c)
θ_πq (°)
Onepigen
GENIE
Data
GENIE
Data
Onepigen
Preliminary
W (GeV)
W (GeV)
W (GeV)
W (GeV)
Higher θ_πq

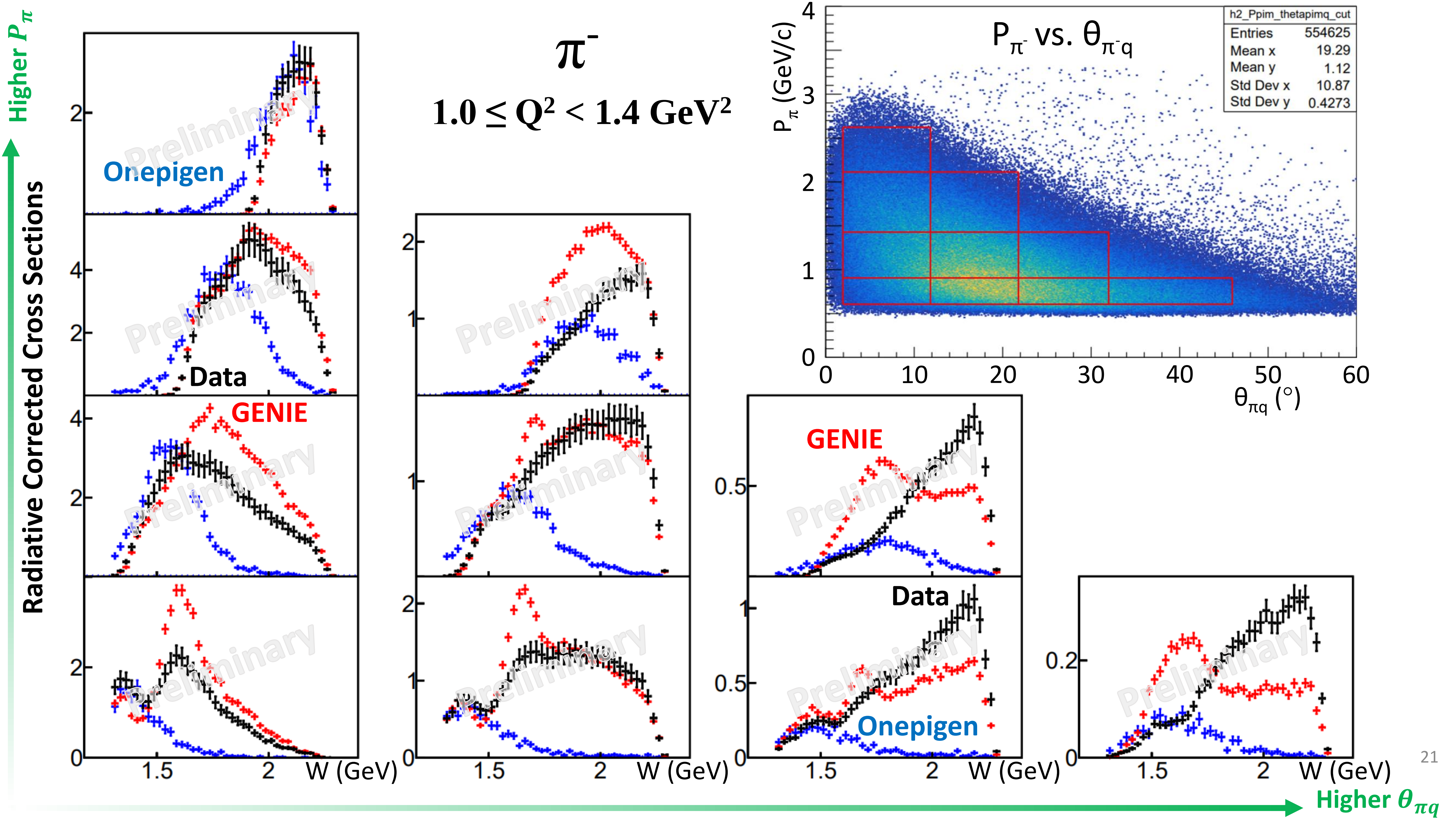


Higher P_π
Radiative Corrected Cross Sections
π^+
$1.4 \leq Q^2 < 1.9$ GeV^2
P_{π^+} vs. θ_{π^+q}
h2_Ppip_thetapipq_cut
Entries 876135
Mean x 15.61
Mean y 1.292
Std Dev x 9.178
Std Dev y 0.4535
P_π (GeV/c)
$\theta_{\pi q}$ (°)
Onepigen
Data
GENIE
Preliminary
W (GeV)
Higher $\theta_{\pi q}$

π^+

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





π-
1.0 ≤ Q² < 1.4 GeV²
Higher P_π
Radiative Corrected Cross Sections
Higher $\theta_{\pi q}$
Onepigen
Data
GENIE
Preliminary
W (GeV)
P_{π^-} vs. $\theta_{\pi^- q}$
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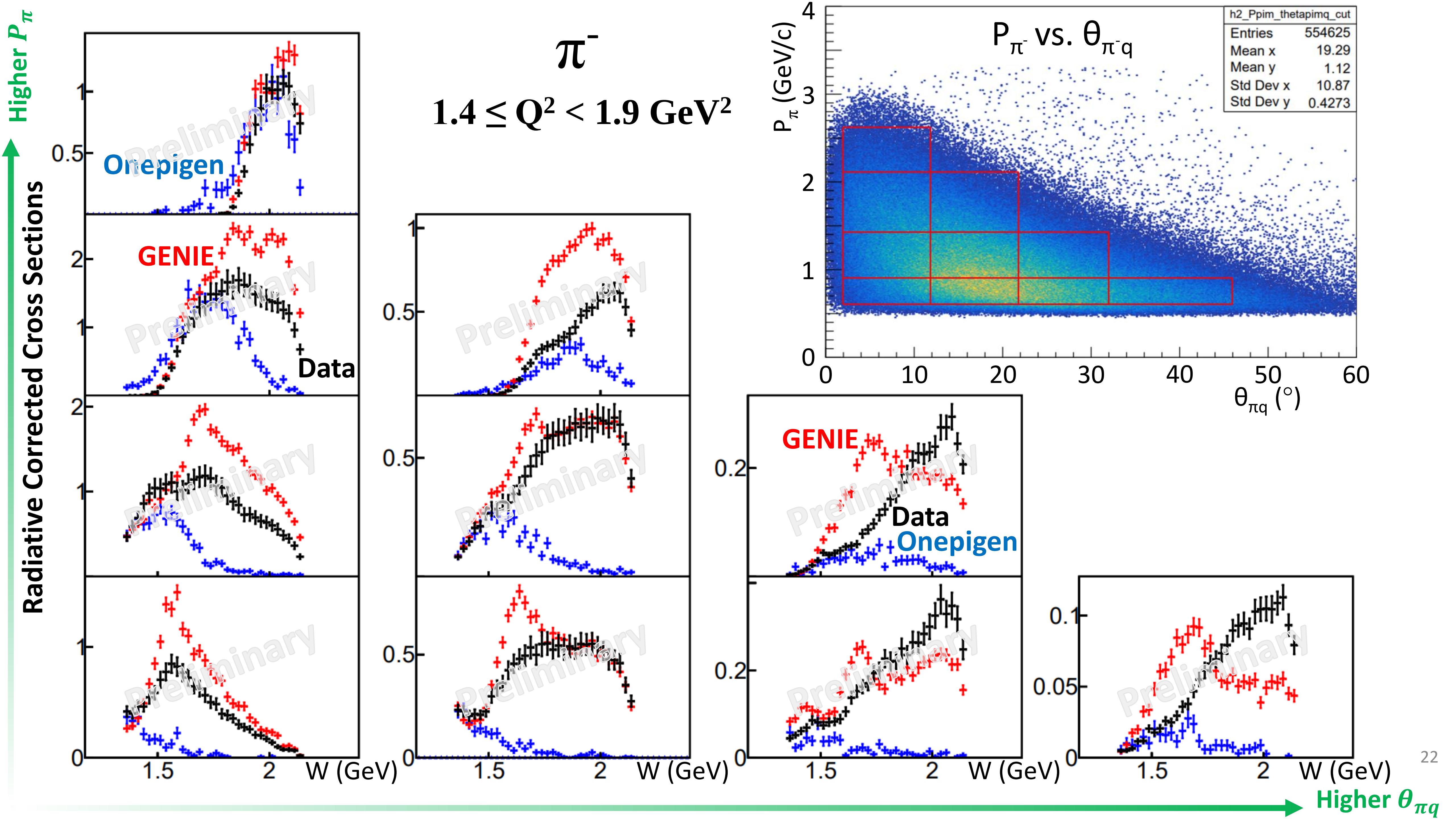
Std Dev y 0.4273
P_π (GeV/c)
$\theta_{\pi q}$ (°)



π-
1.4 ≤ Q2 < 1.9 GeV2
Pπ- vs. θπ-q
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Pπ (GeV/c)
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Higher Pπ
Higher θπq
Radiative Corrected Cross Sections
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GENIE
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W (GeV)

π^-

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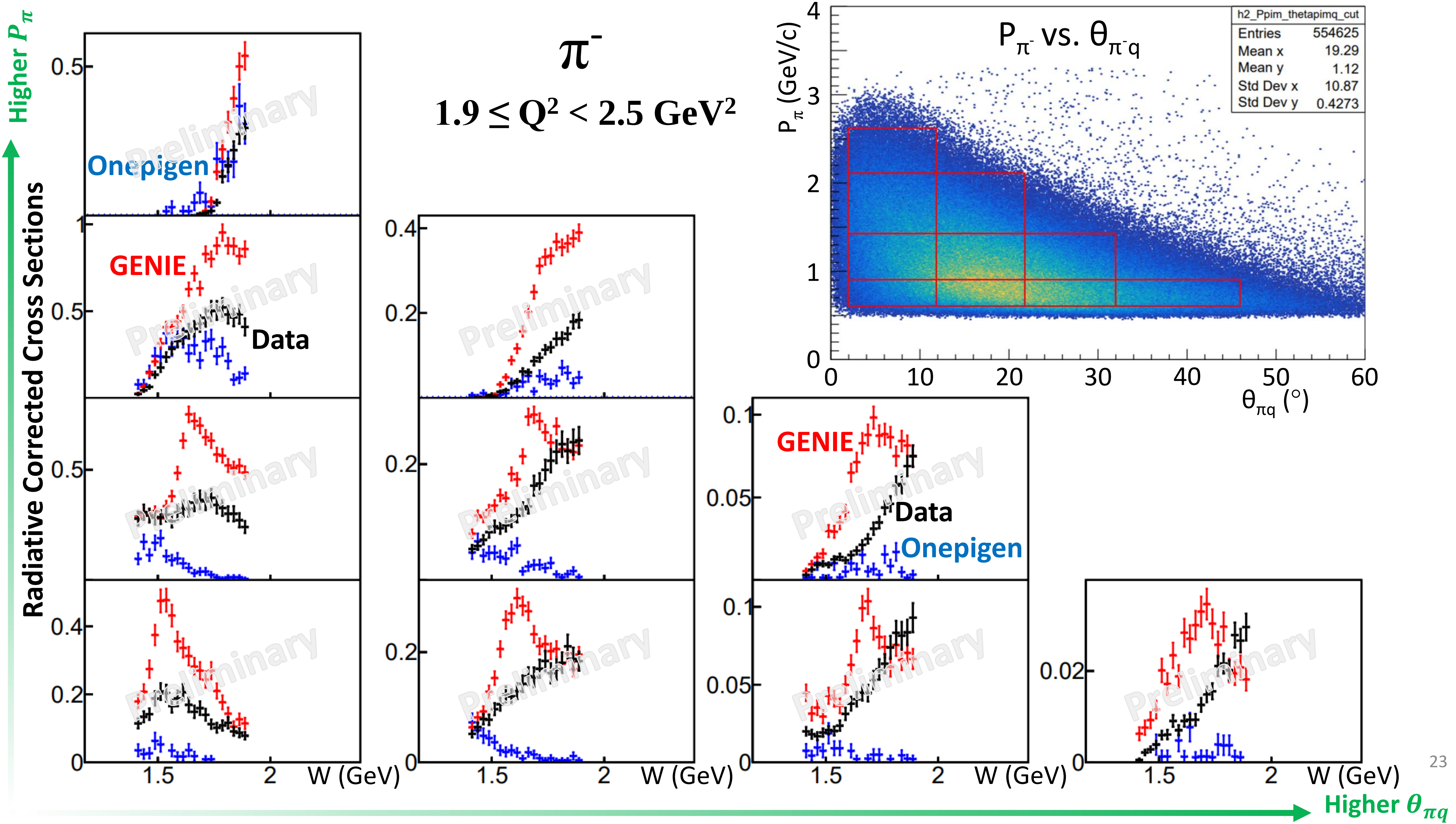
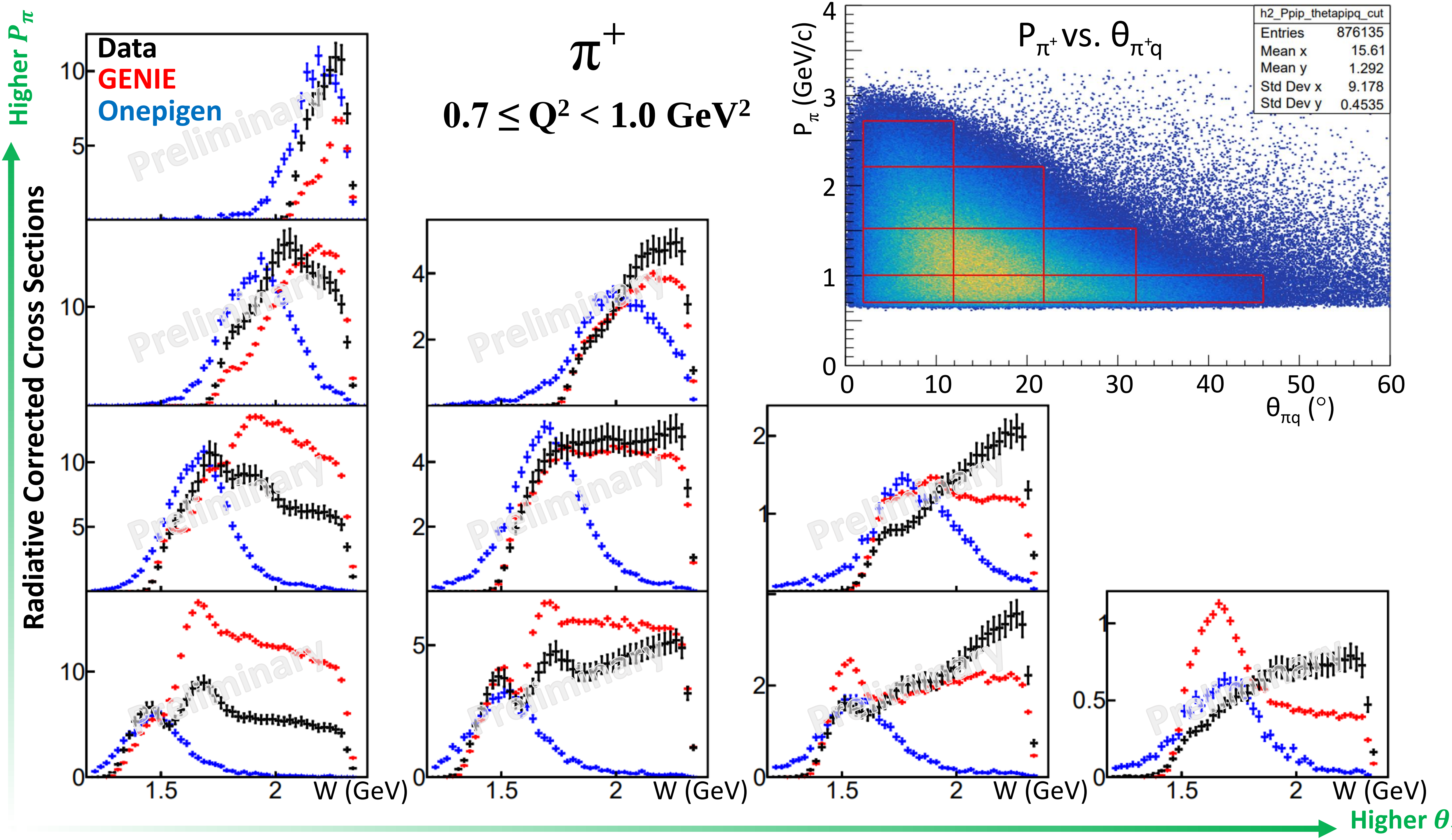
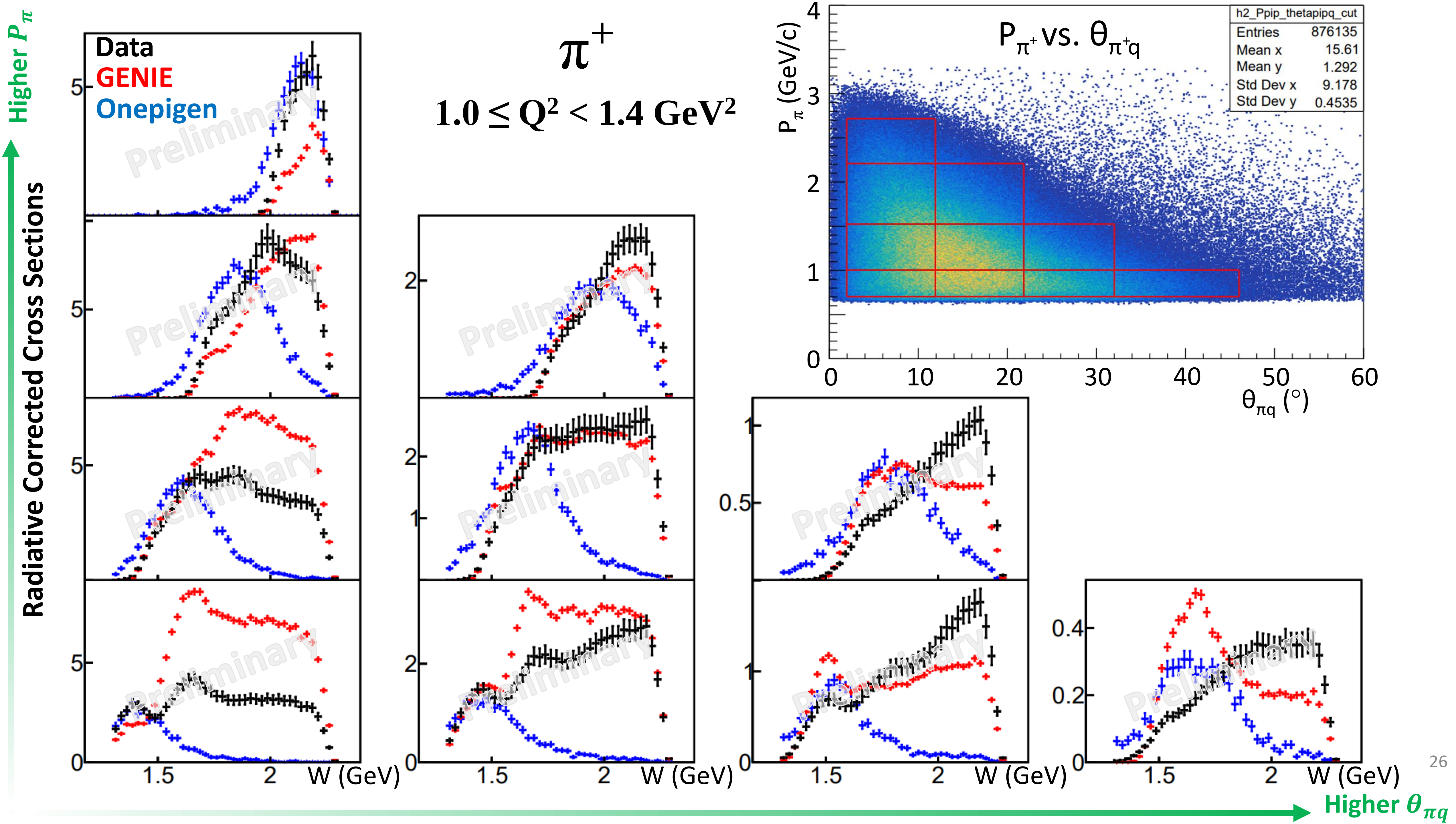


Rarita

π^+

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





Higher P_π
Radiative Corrected Cross Sections
Data
GENIE
Onepigen
π^+
$1.0 \leq Q^2 < 1.4$ GeV^2
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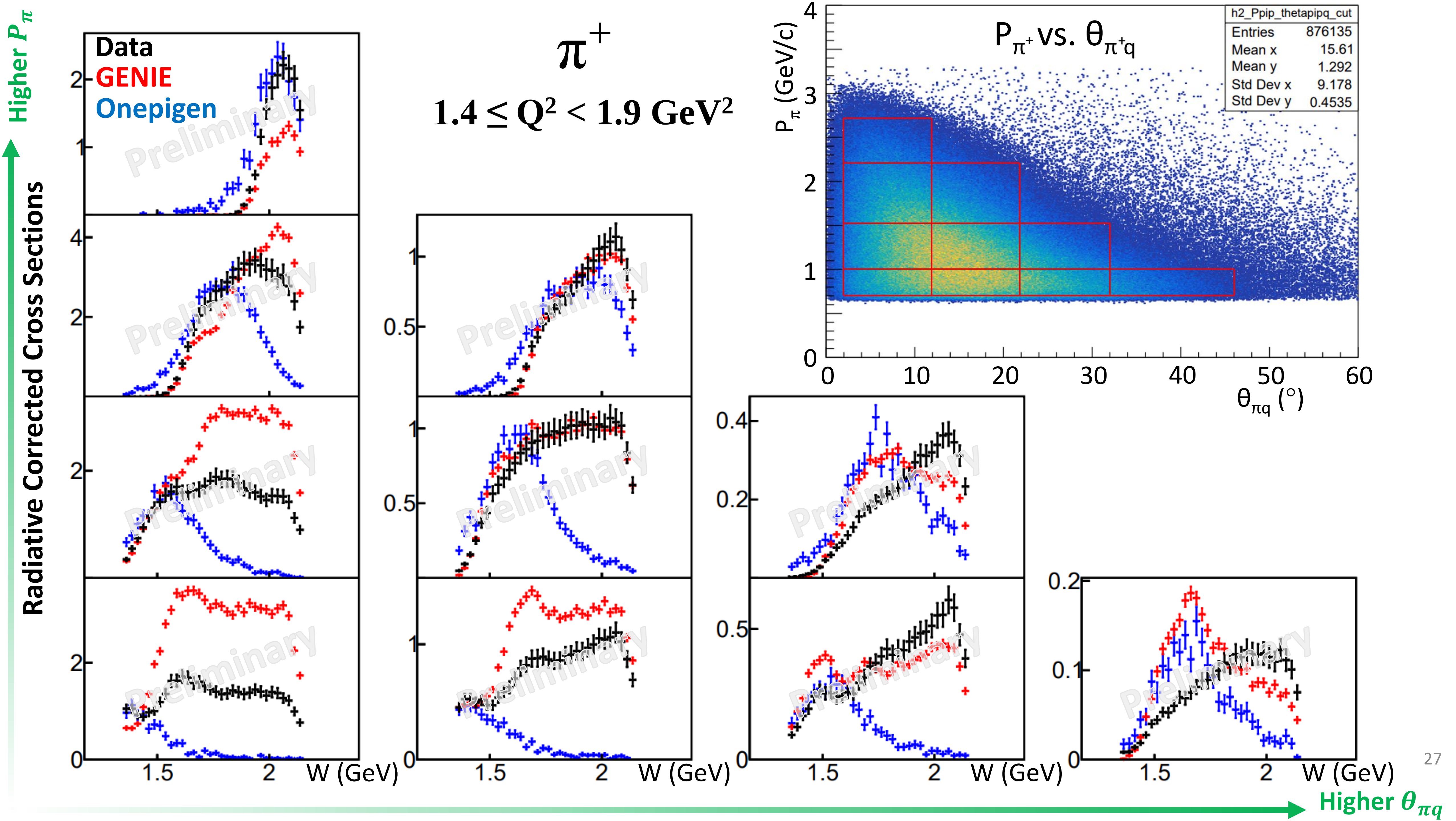
P_{π^+} vs. θ_{π^+q}
P_π (GeV/c)
$\theta_{\pi q}$ (°)
W (GeV)
Preliminary
Higher $\theta_{\pi q}$



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GENIE
Onepigen
Preliminary
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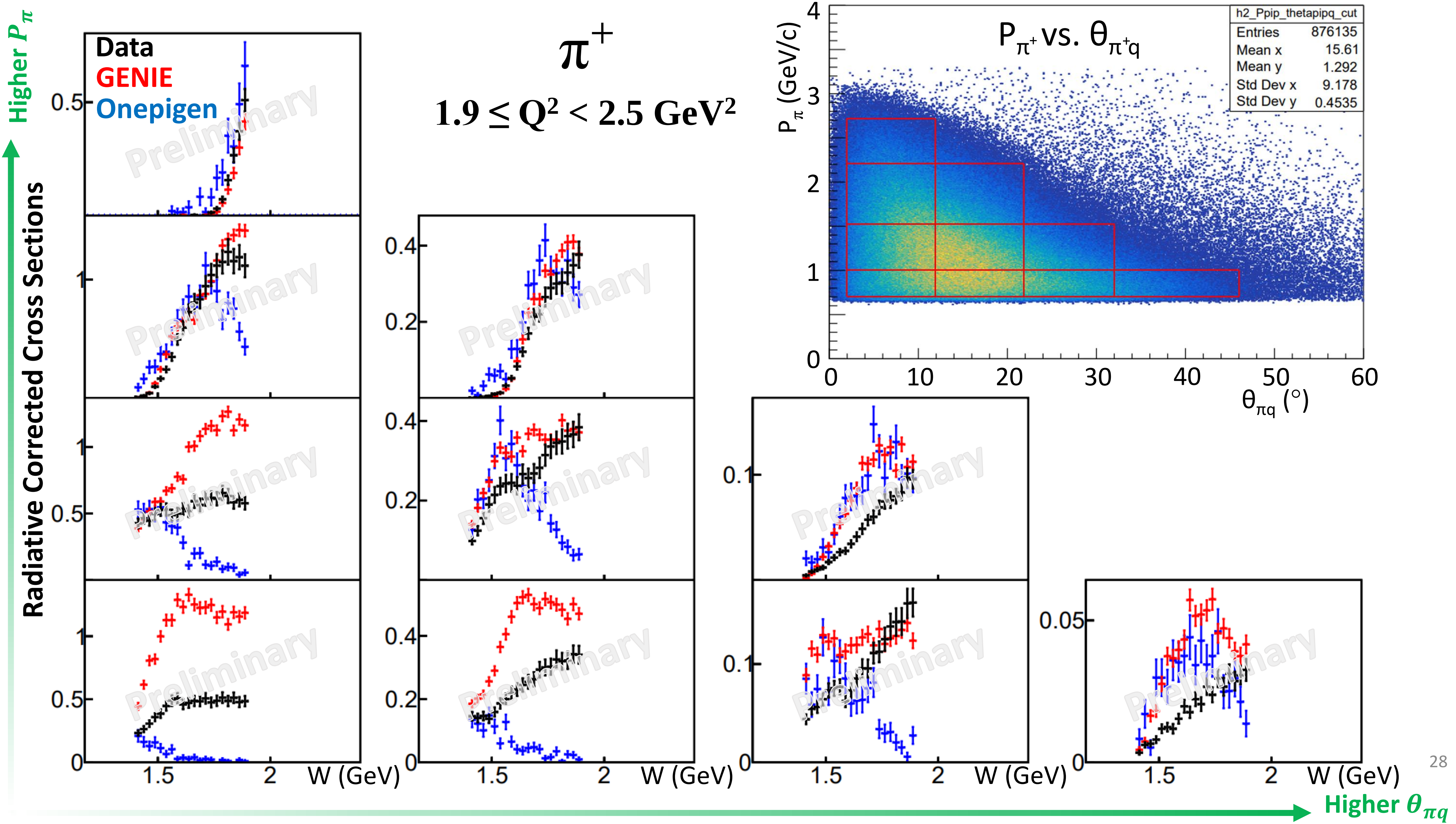
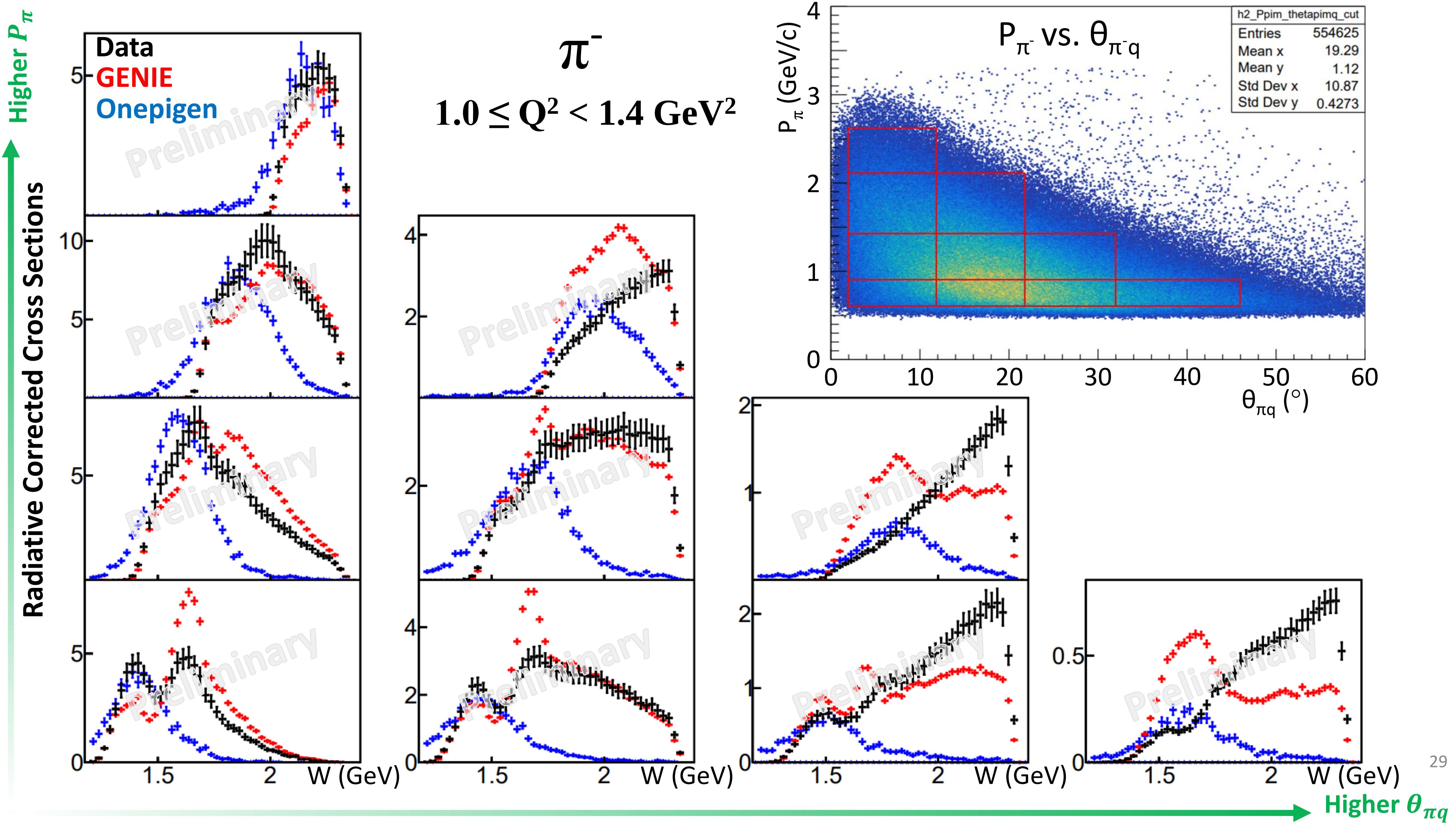
Radiative Corrected Cross Sections
Higher P_π
Higher θ_πq
W (GeV)

π^+

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





Higher P_π
Radiative Corrected Cross Sections
Data
GENIE
Onepigen
Preliminary
π^-
$1.0 \le Q^2 < 1.4\ \mathrm{GeV}^2$
P_{π^-} vs. $\theta_{\pi^- q}$
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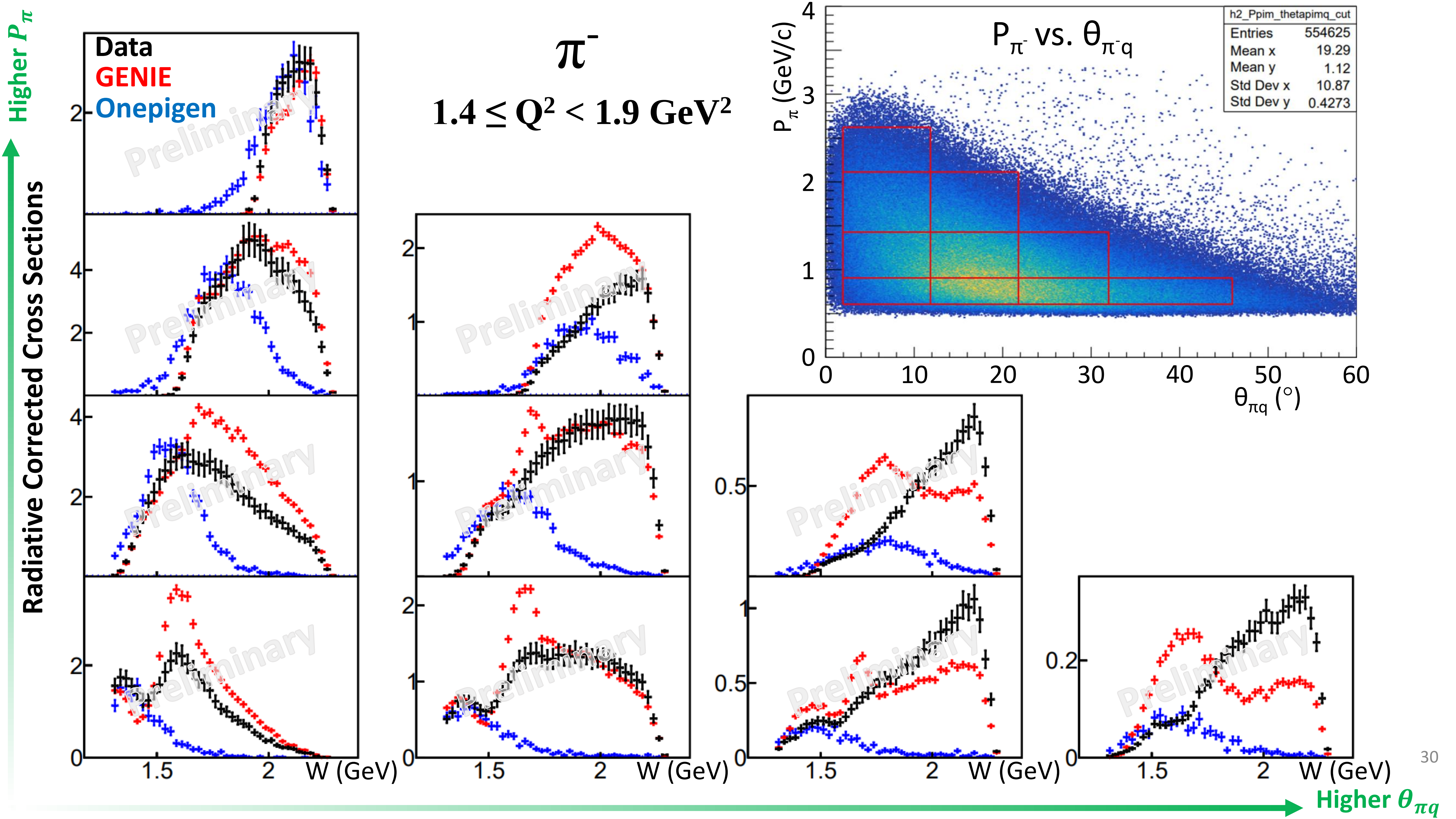
P_π (GeV/c)
$\theta_{\pi q}$ (°)
W (GeV)
Higher $\theta_{\pi q}$



Higher P_π
Radiative Corrected Cross Sections
Data
GENIE
Onepigen
π^-
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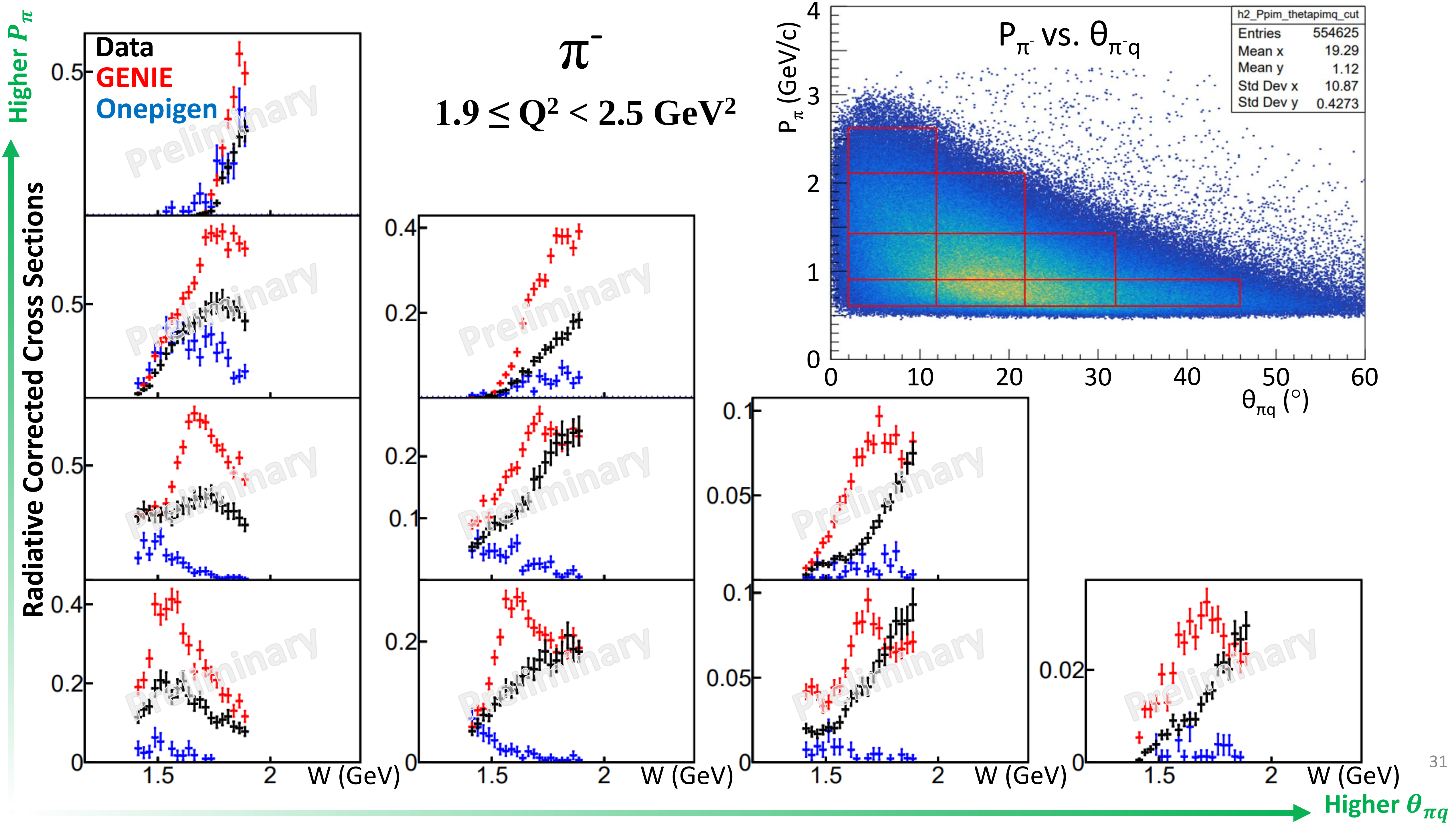
P_π (GeV/c)
$\theta_{\pi q}$ (°)
W (GeV)
Preliminary
Higher $\theta_{\pi q}$



Higher P_π
Data
GENIE
Onepigen
π^-
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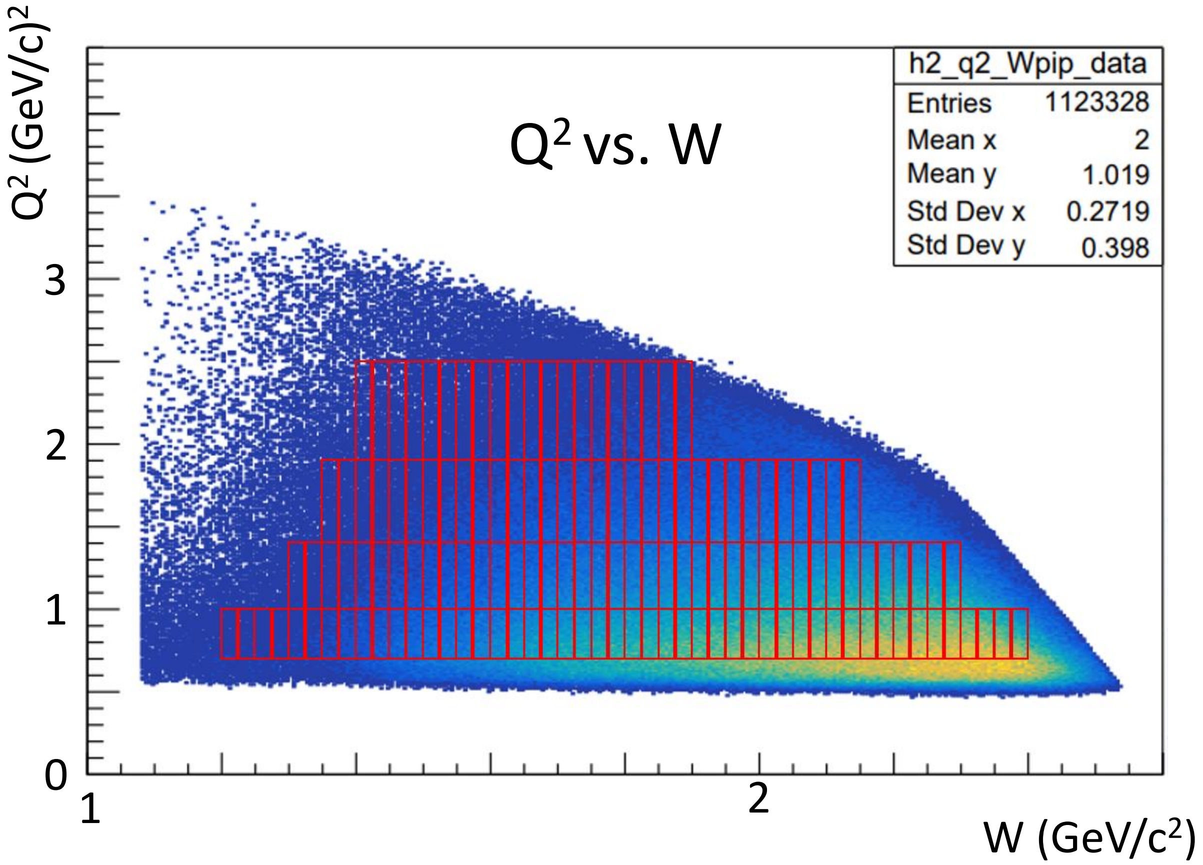
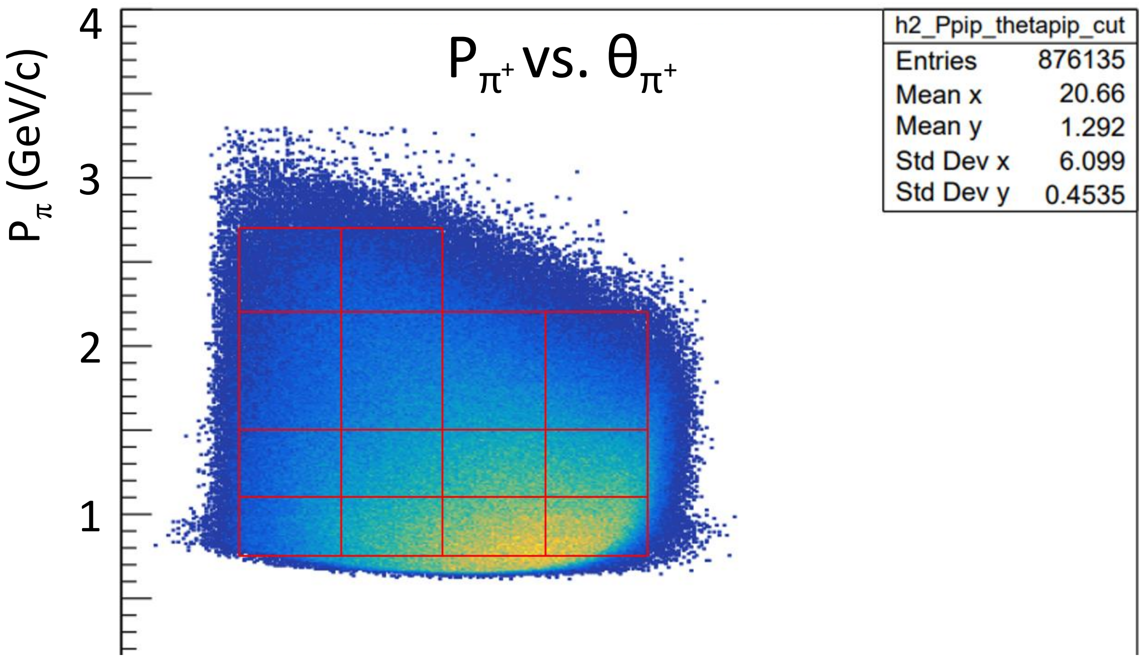
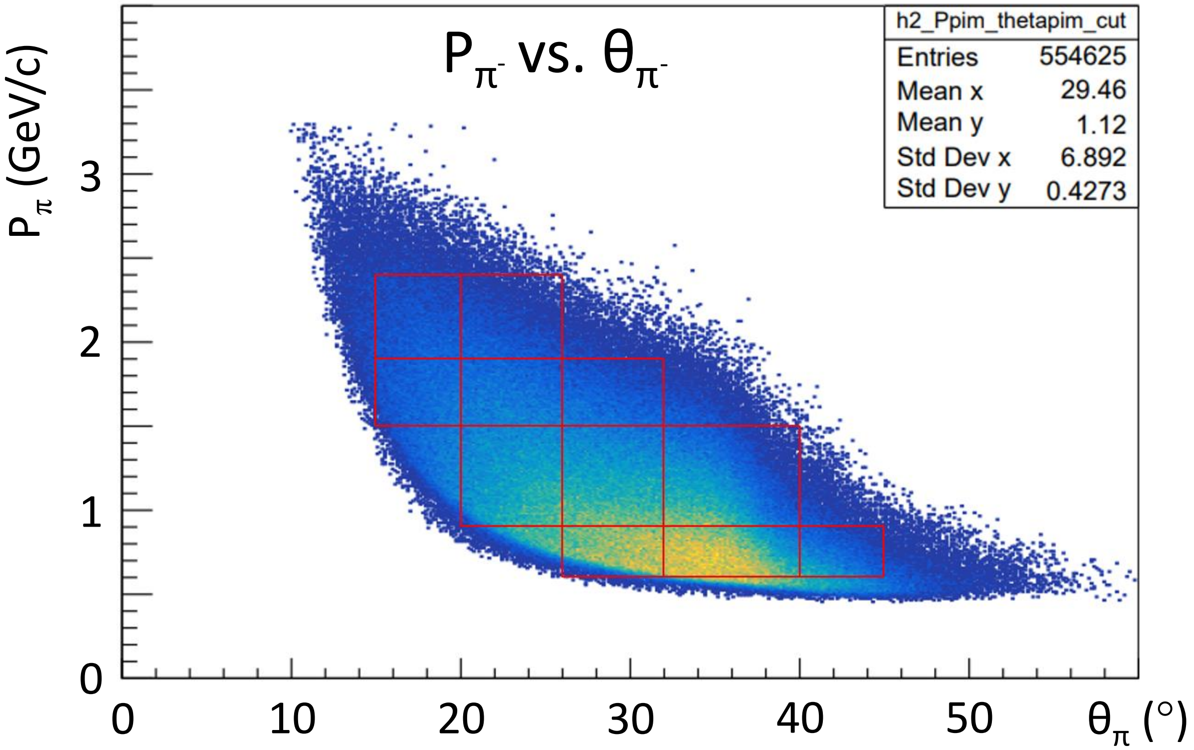
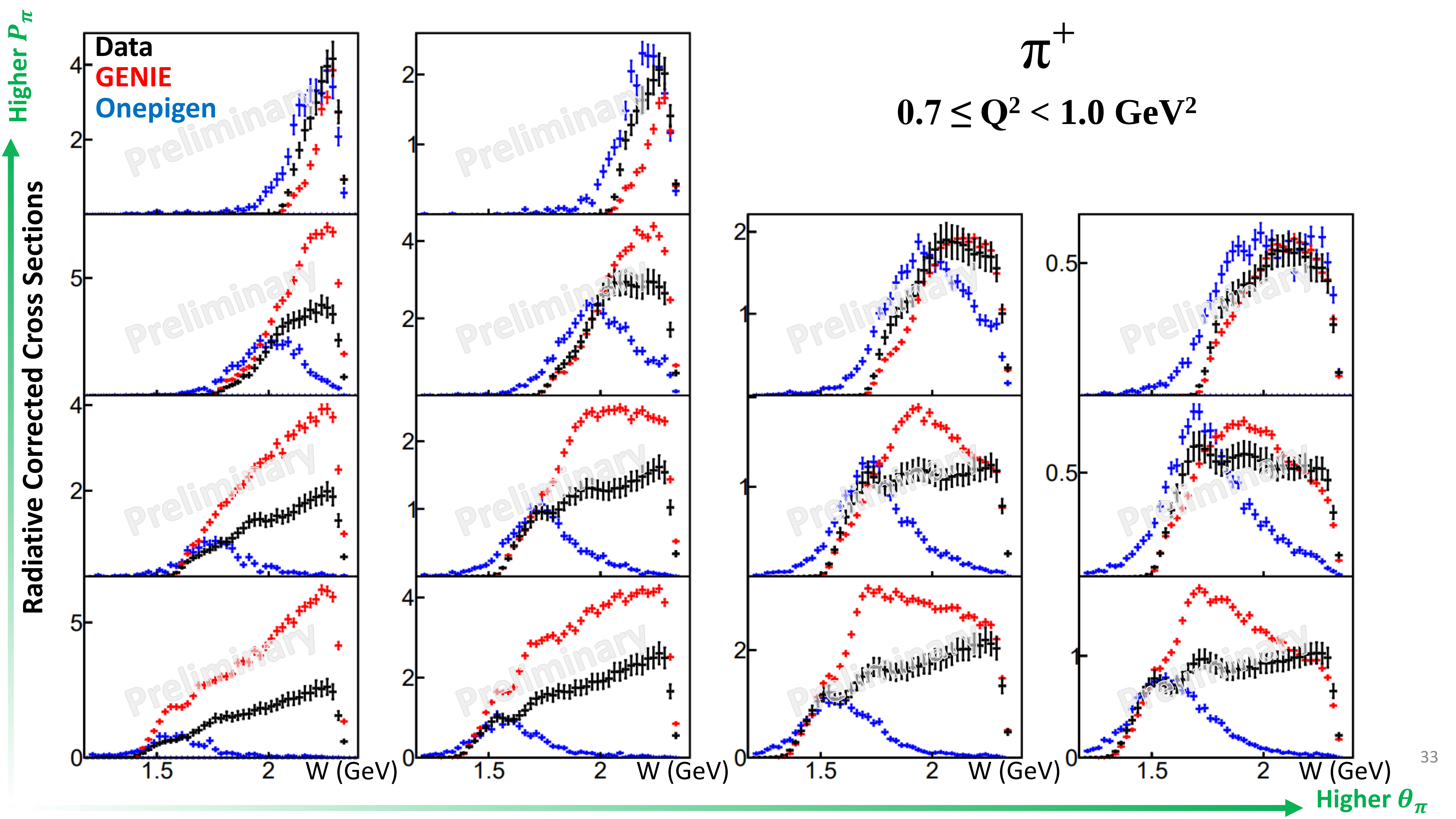
P_π (GeV/c)
$\theta_{\pi q}$ (°)
Preliminary
Higher $\theta_{\pi q}$

Binning (Q^2, W, θ_π, P_π)

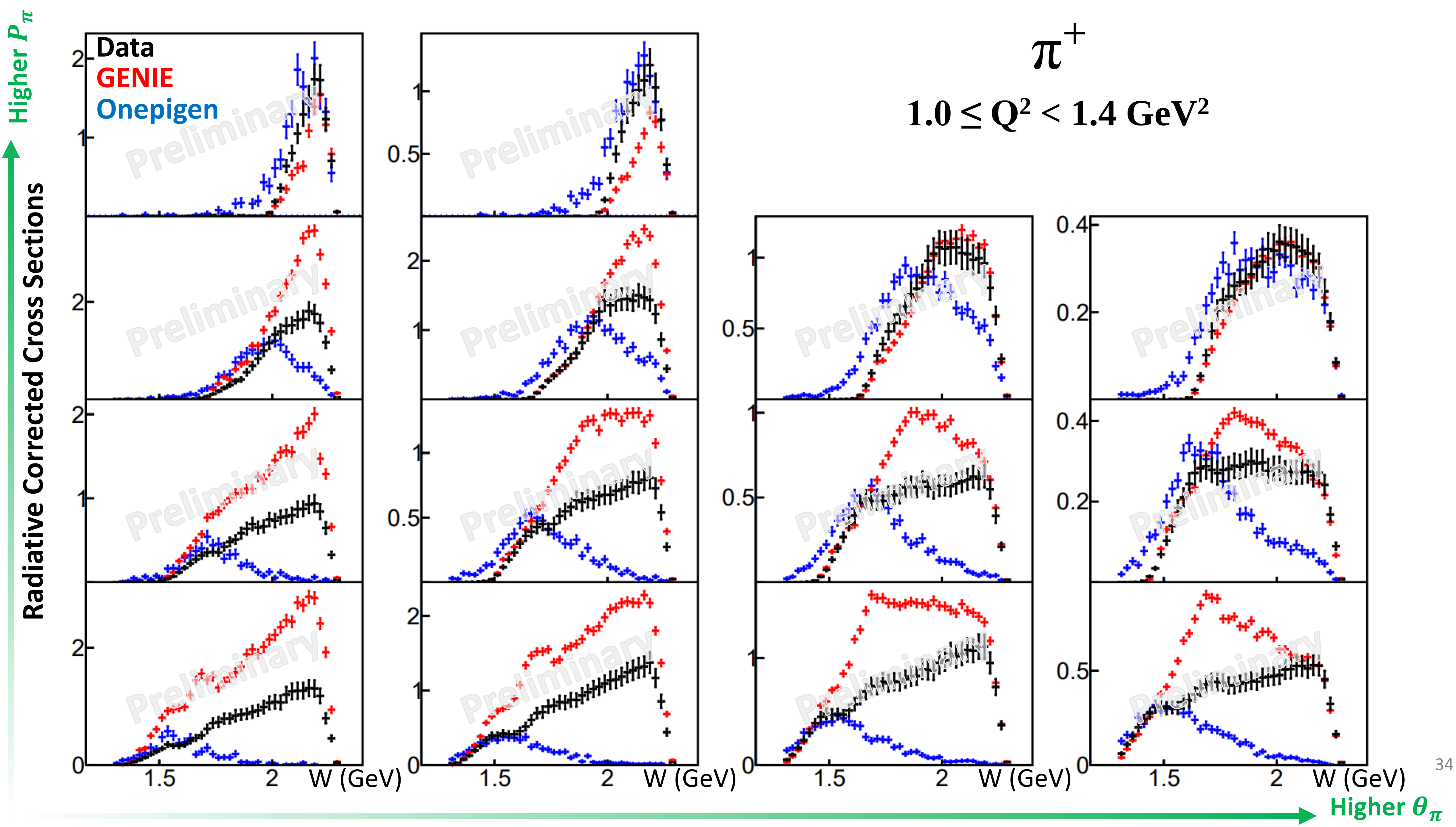




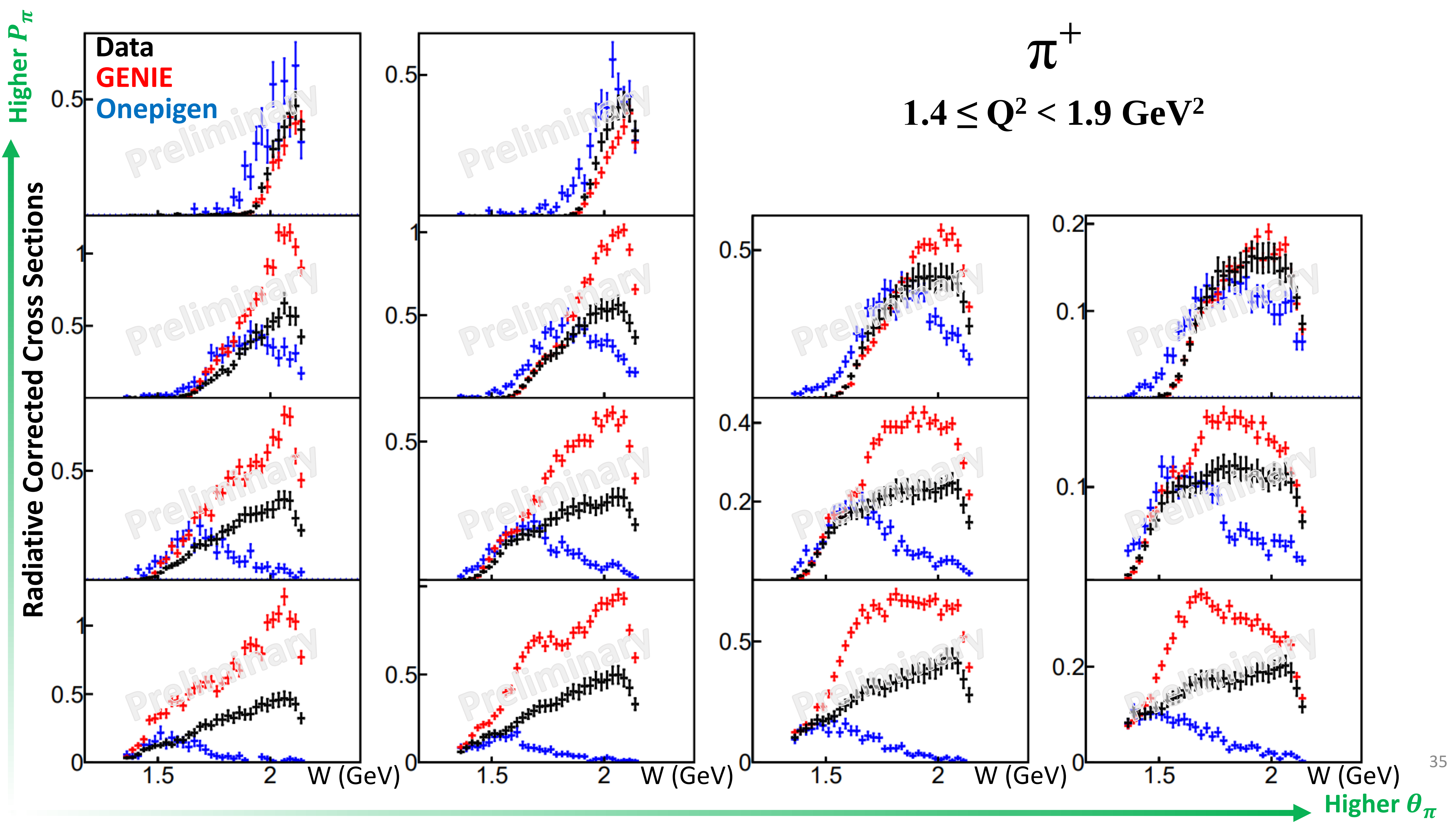




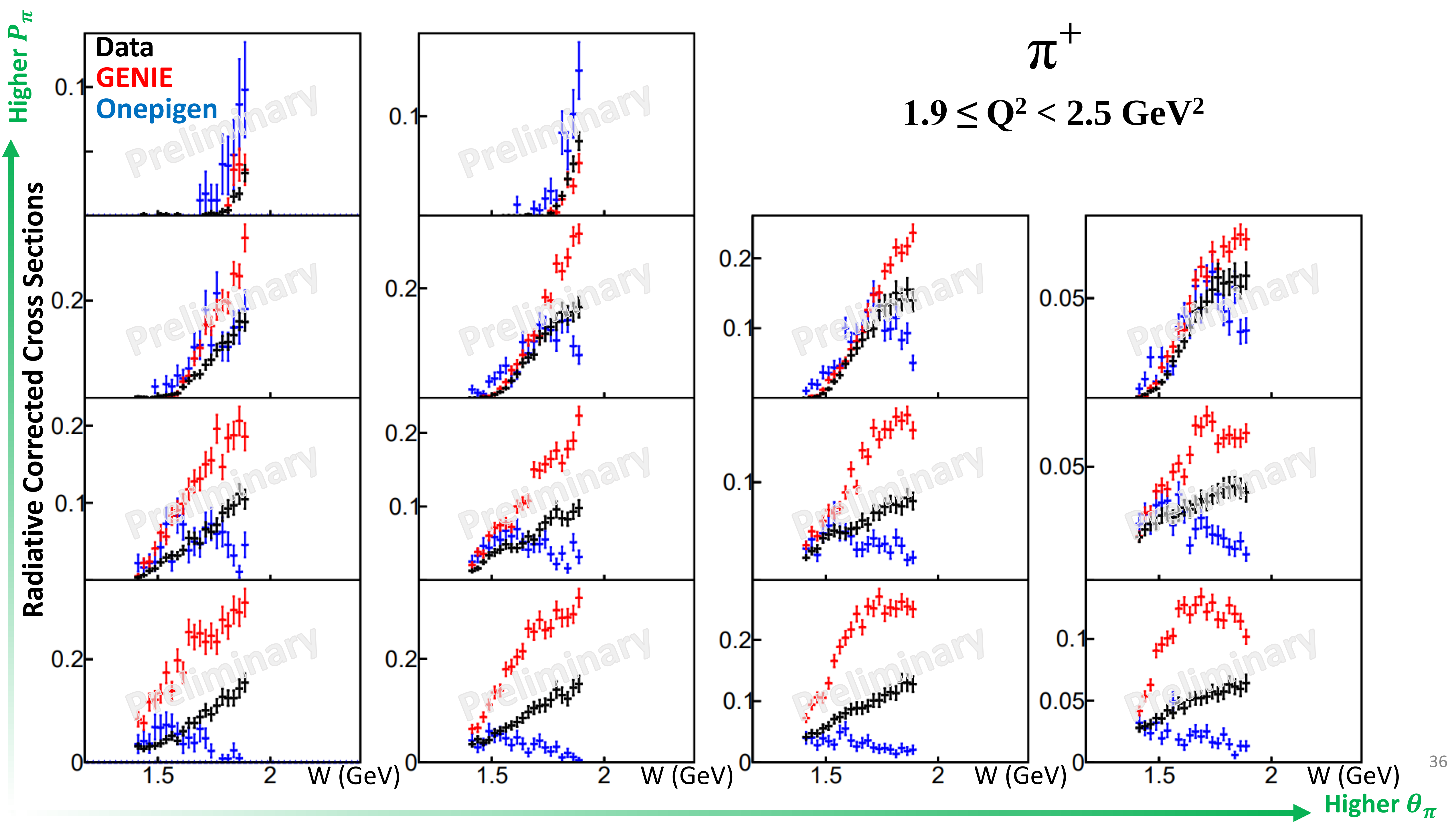
Data
GENIE
Onepigen
Preliminary
π^+
$0.7 \leq Q^2 < 1.0$ GeV^2
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)



Higher P_π
Radiative Corrected Cross Sections
Data
GENIE
Onepigen
Preliminary
π^+
$1.0 \leq Q^2 < 1.4$ GeV^2
W (GeV)
Higher θ_π



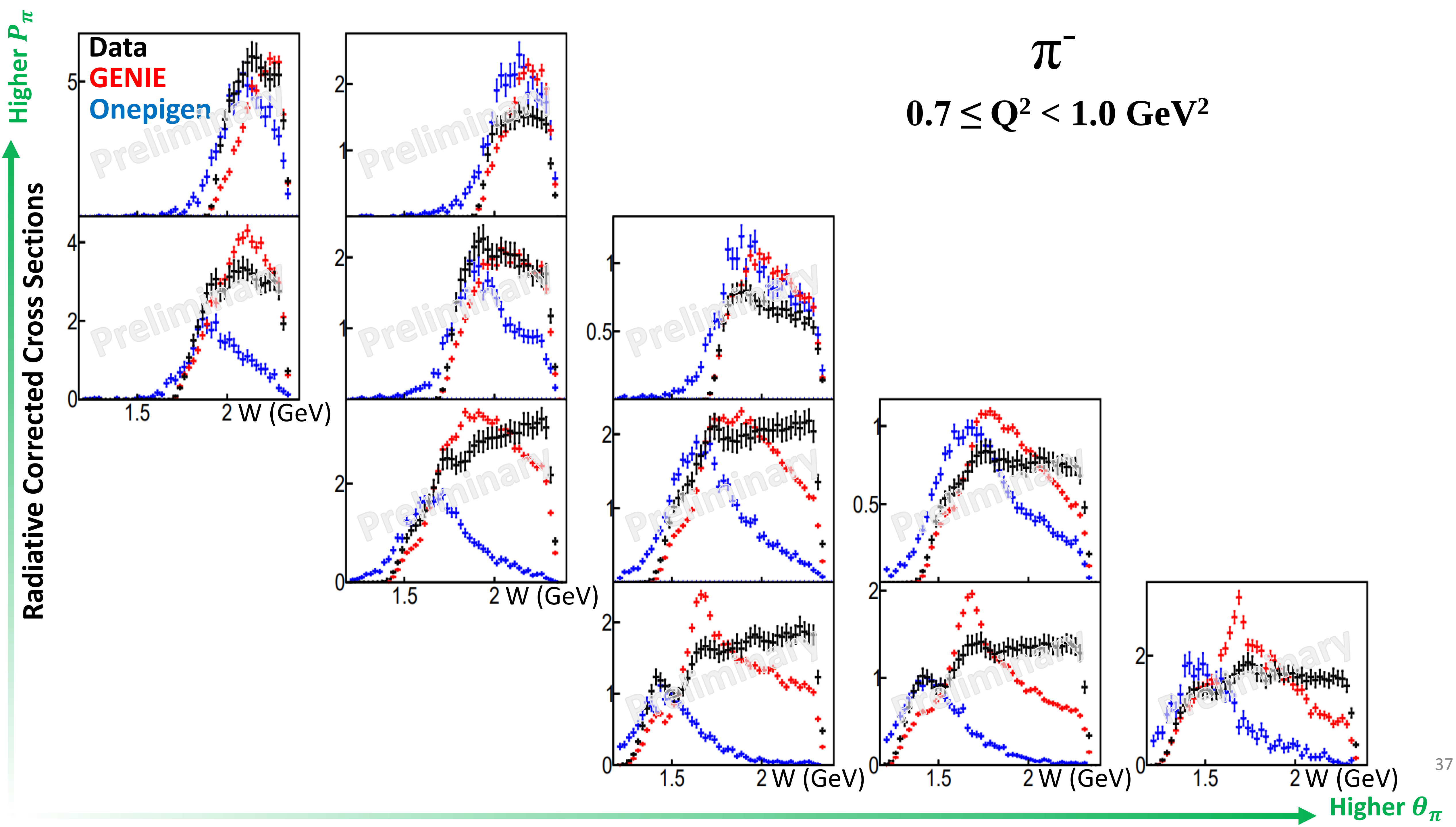
π^+
$1.4 \leq Q^2 < 1.9$ GeV^2
Data
GENIE
Onepigen
Preliminary
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)



π^+
$1.9 \leq Q^2 < 2.5$ GeV^2
Data
GENIE
Onepigen
Preliminary
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)

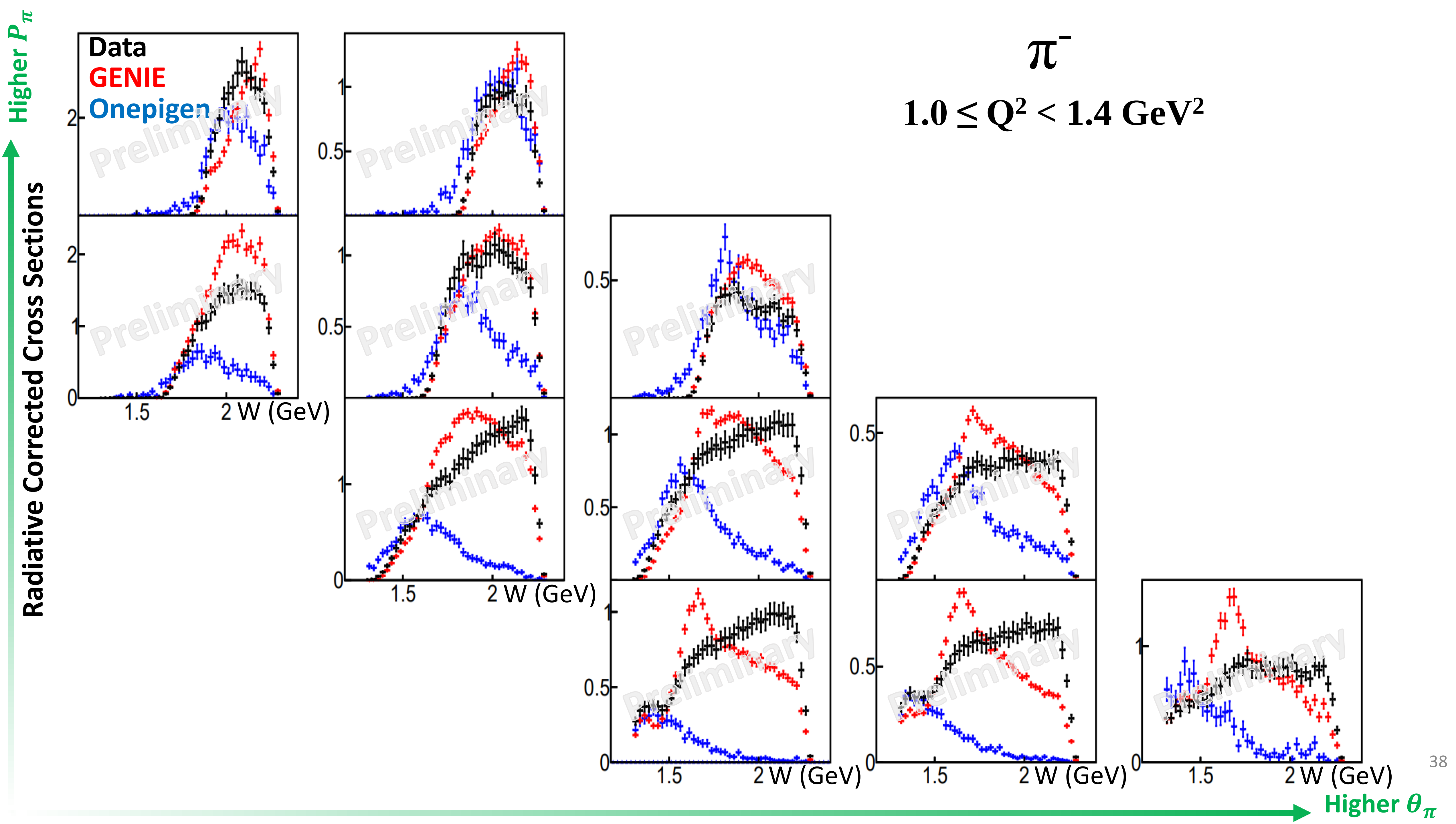
π^-

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



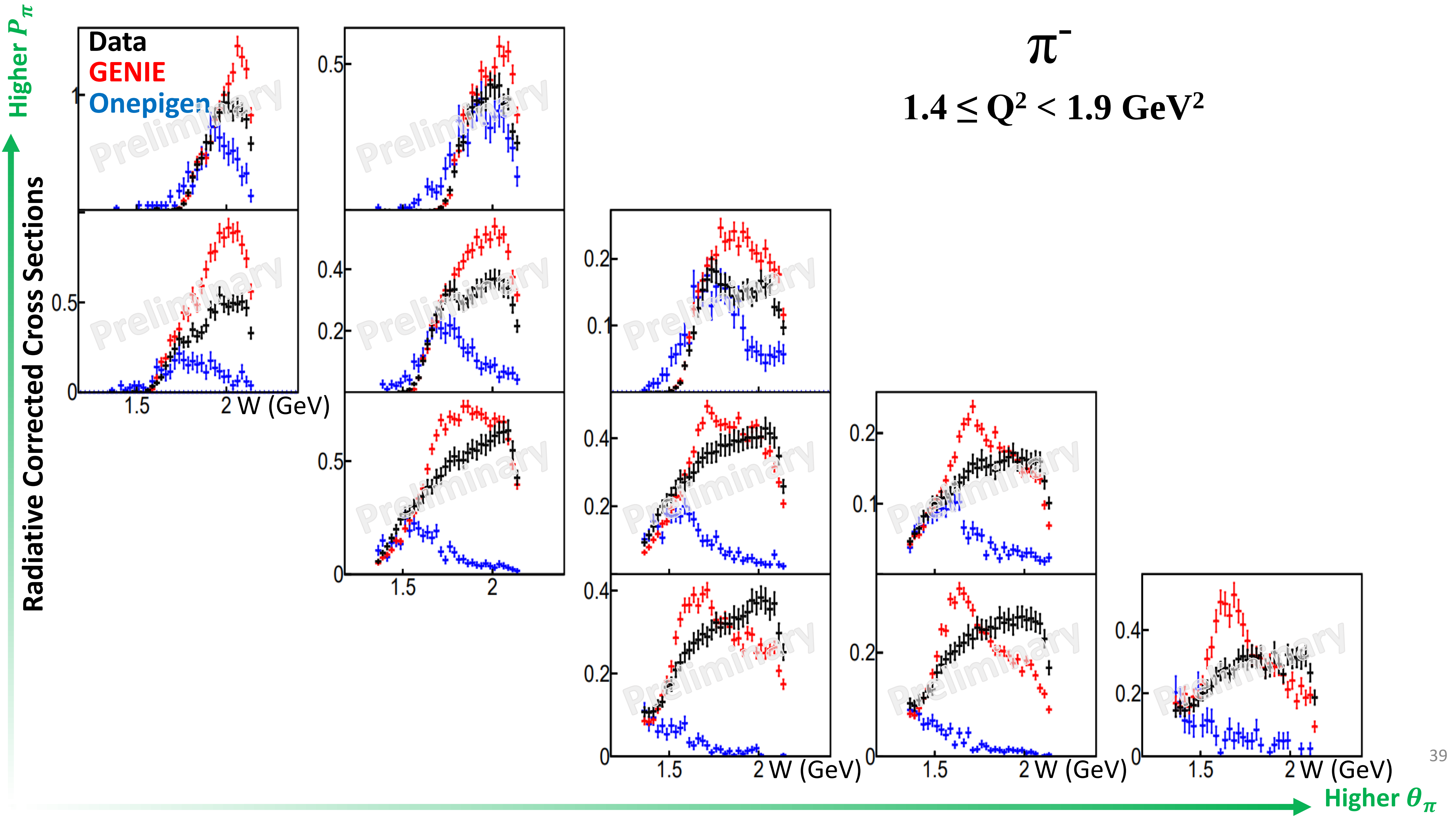
π^-

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



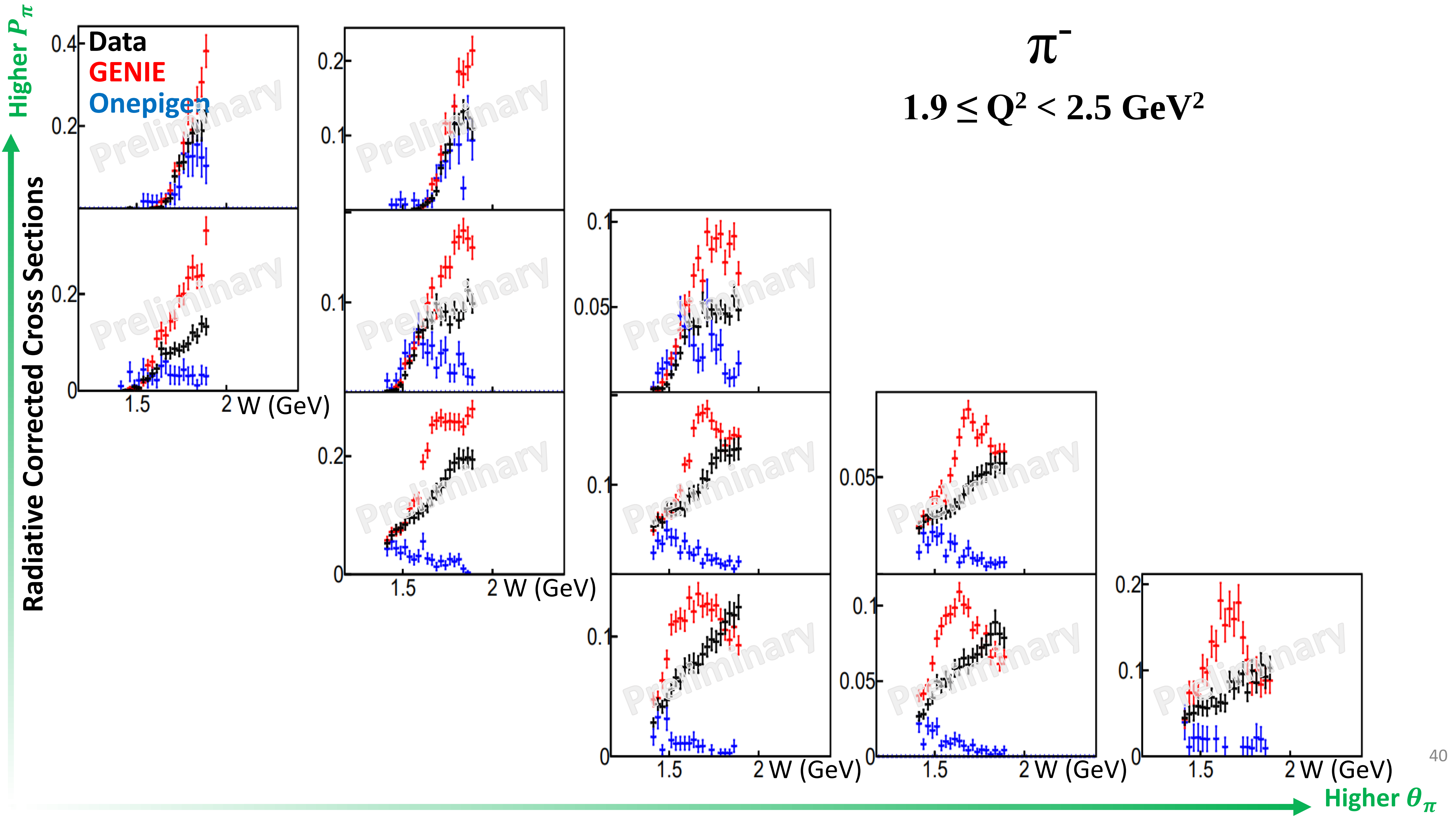
π^-

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

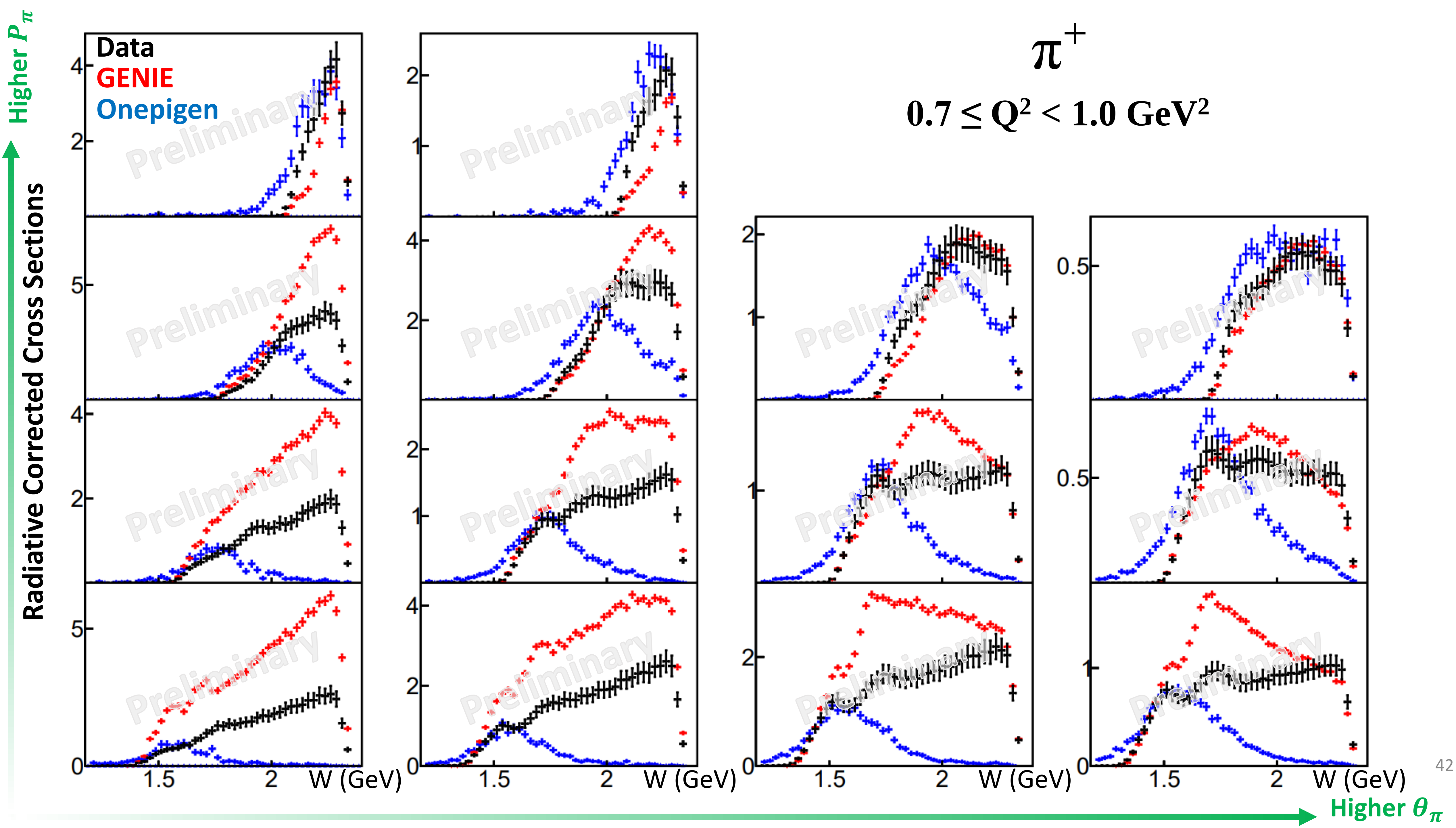


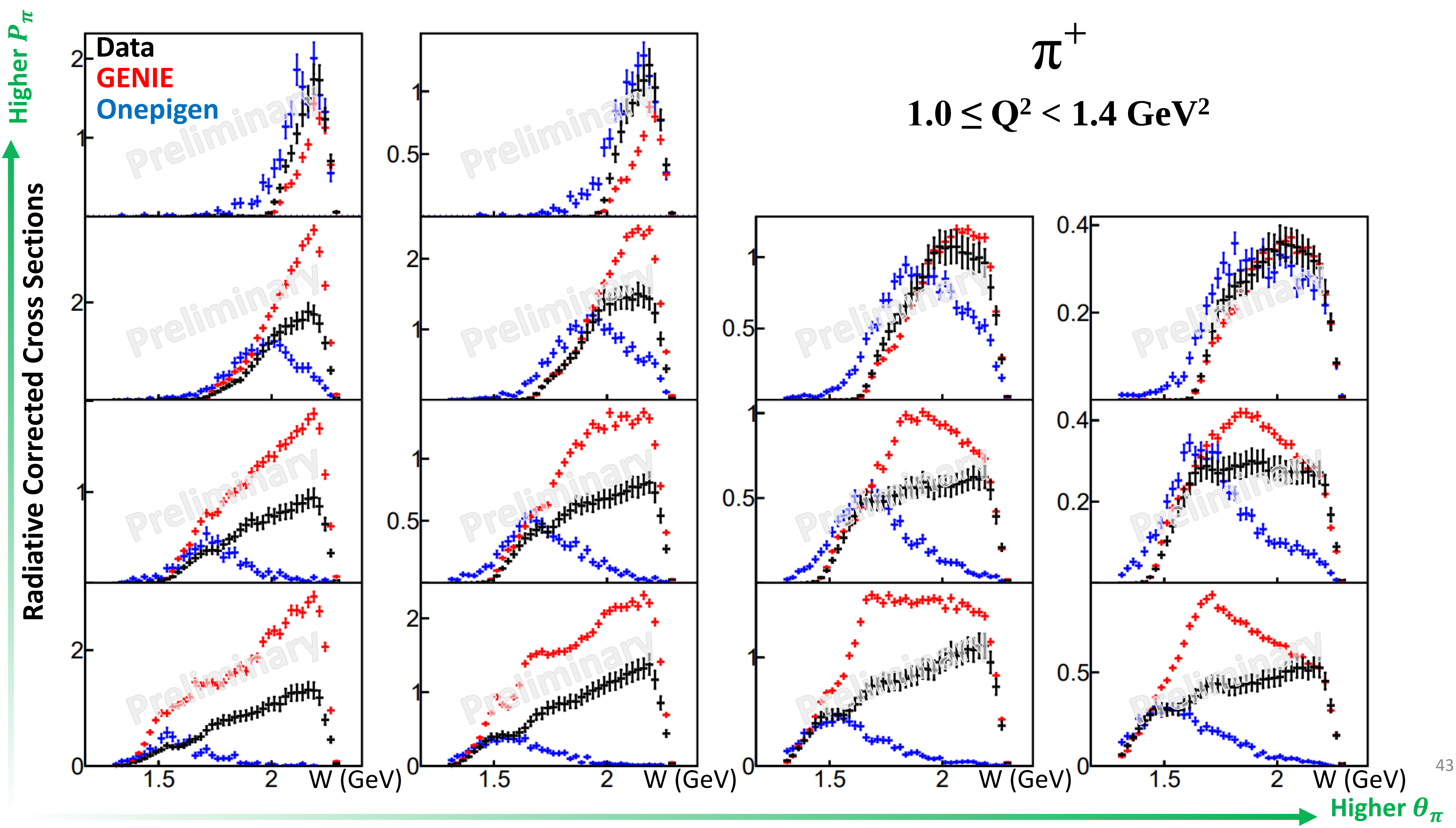
π^-

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

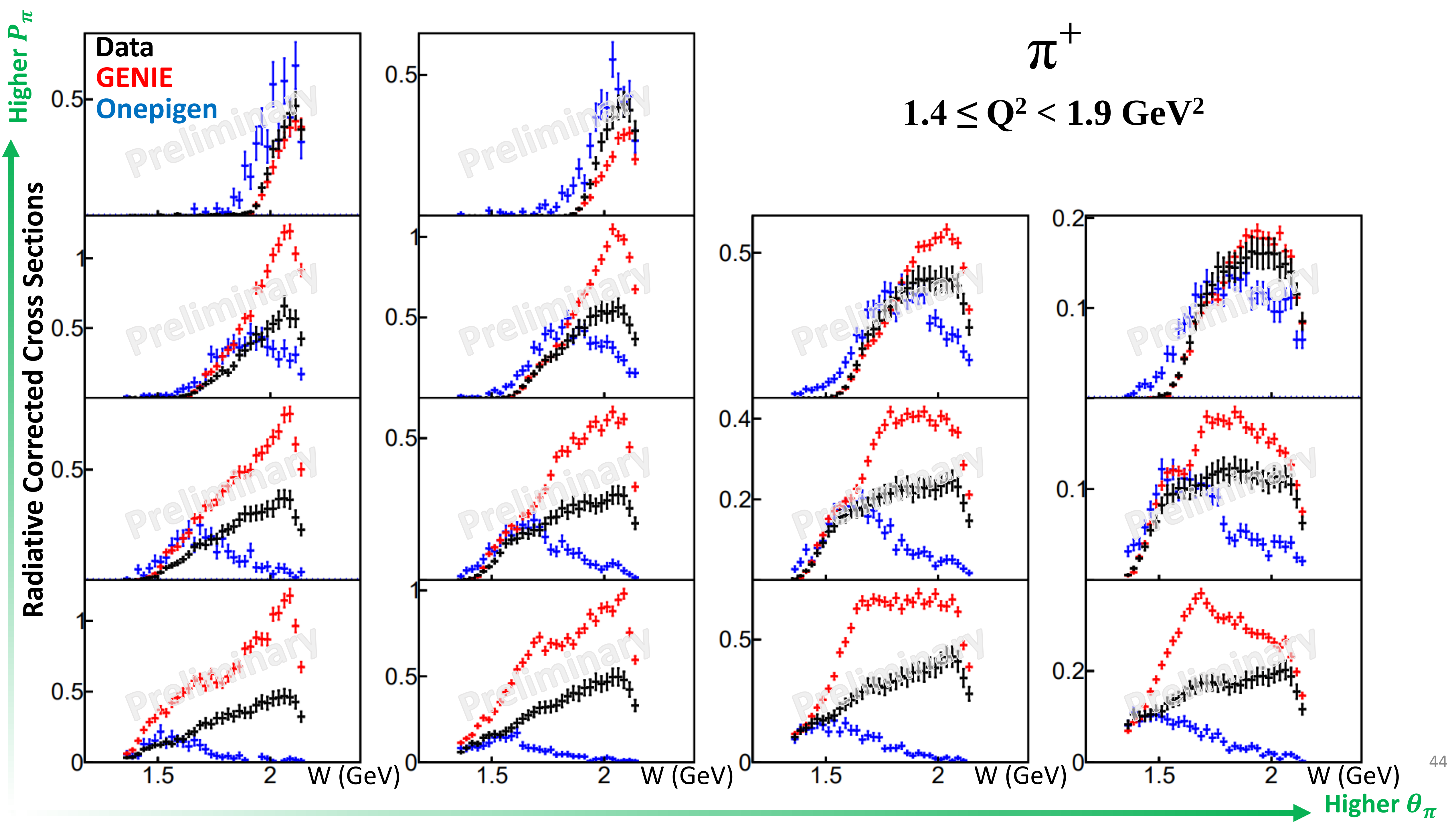


Rarita

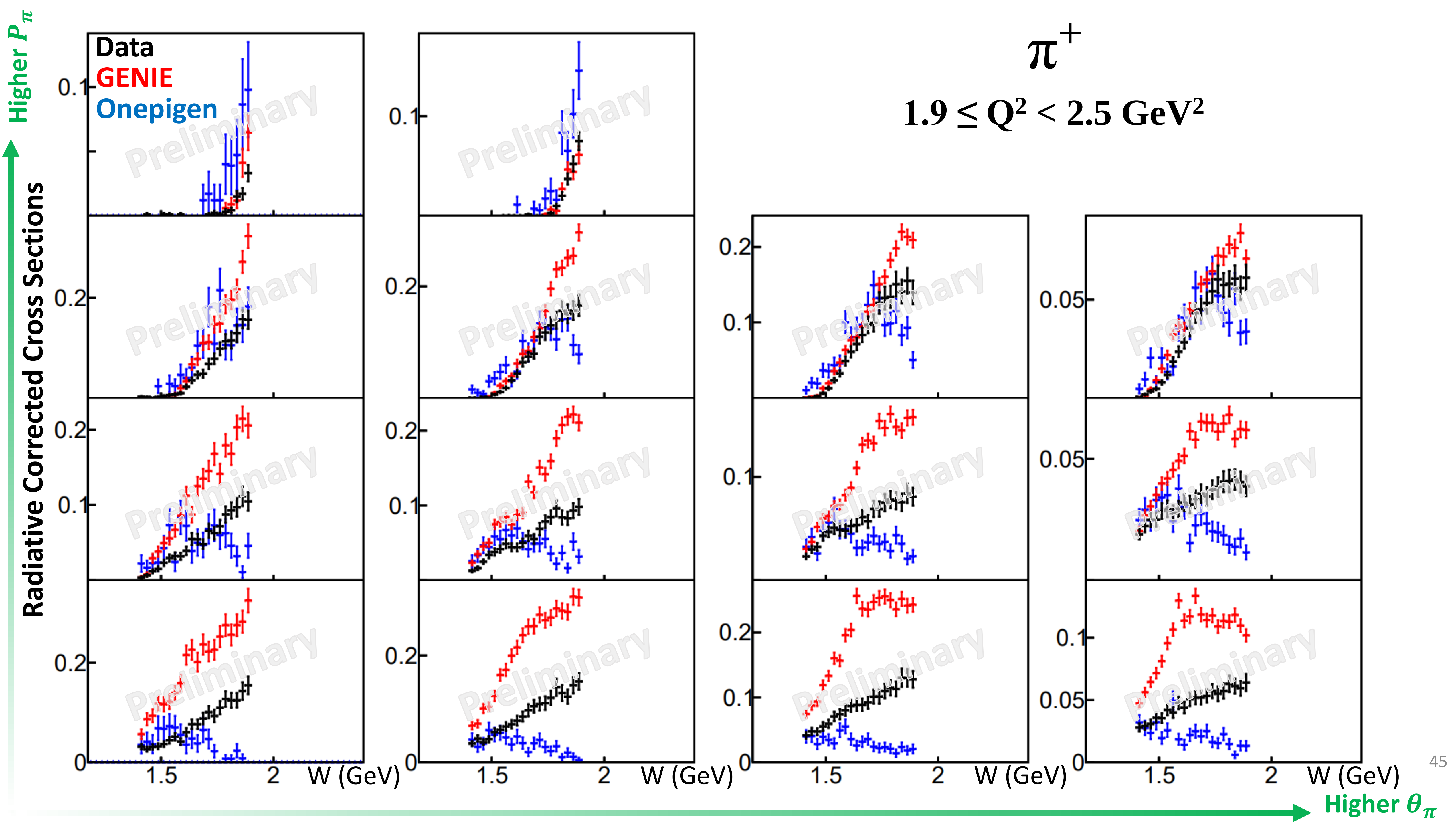

π^+
$0.7 \le Q^2 < 1.0$ GeV^2
Data
GENIE
Onepigen
Preliminary
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)



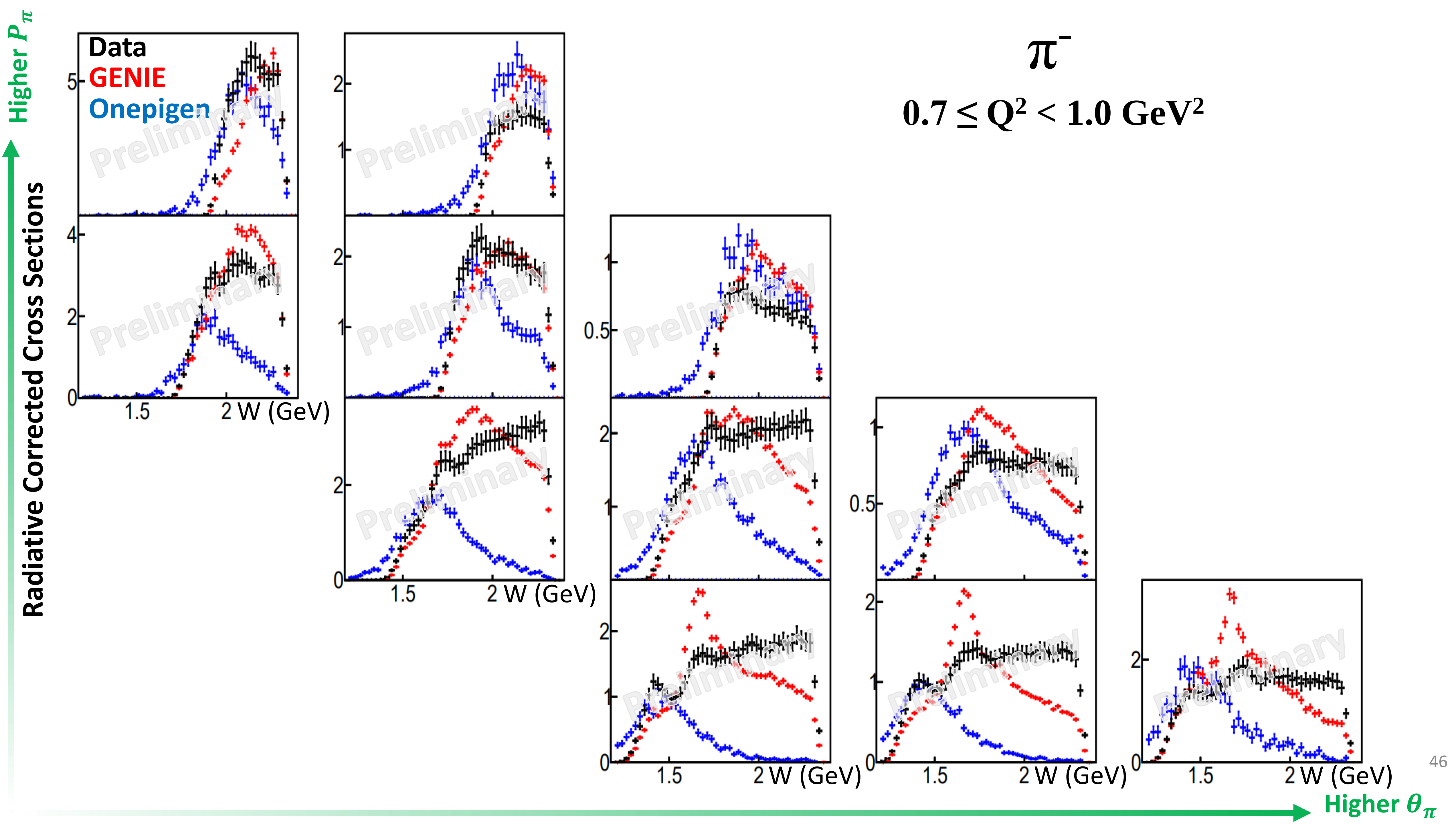
π^+
$1.0 \leq Q^2 < 1.4$ GeV^2
Data
GENIE
Onepigen
Preliminary
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)

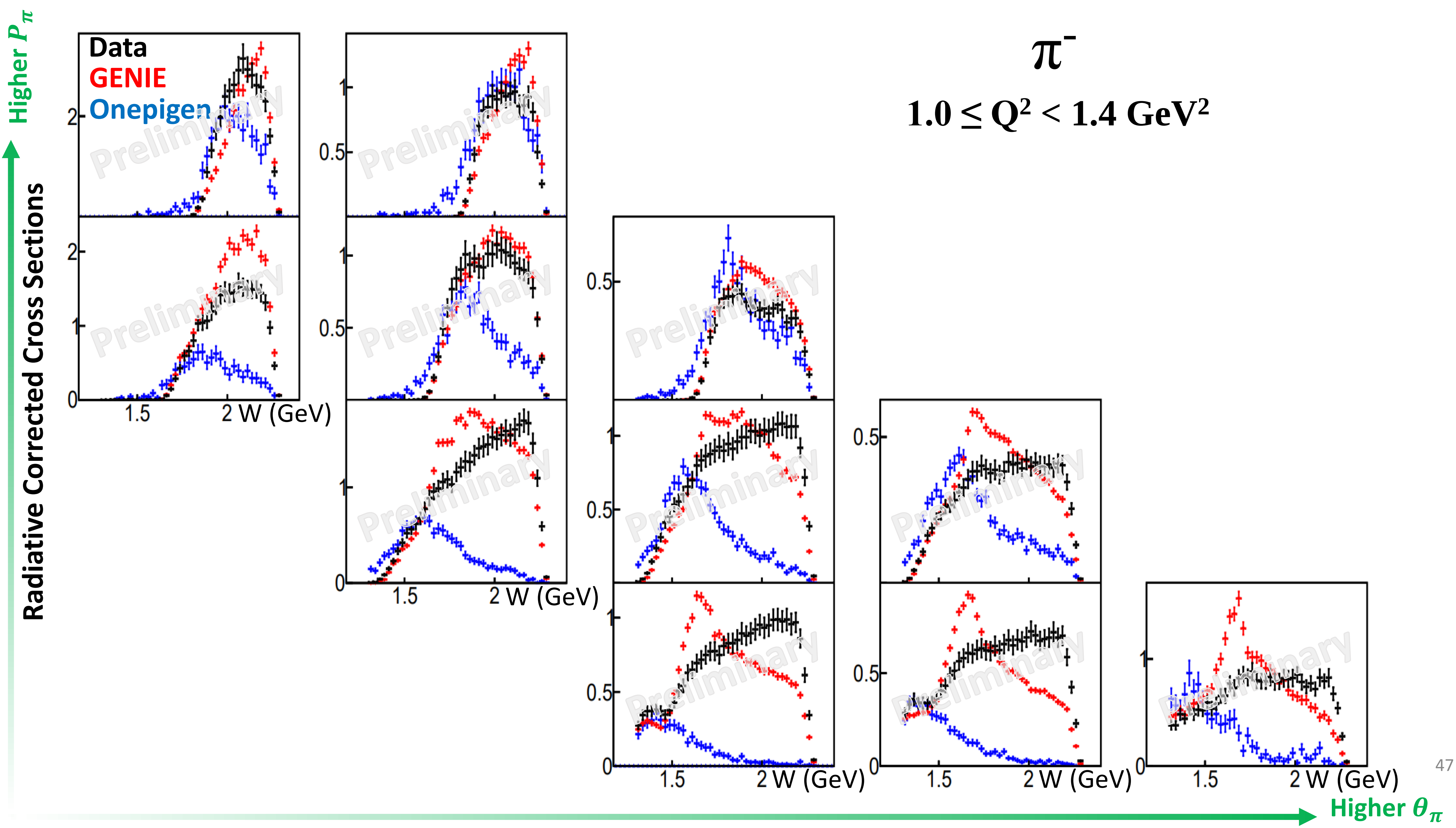


π^+
$1.4 \leq Q^2 < 1.9$ GeV^2
Data
GENIE
Onepigen
Higher P_π
Radiative Corrected Cross Sections
Higher θ_π
W (GeV)
Preliminary

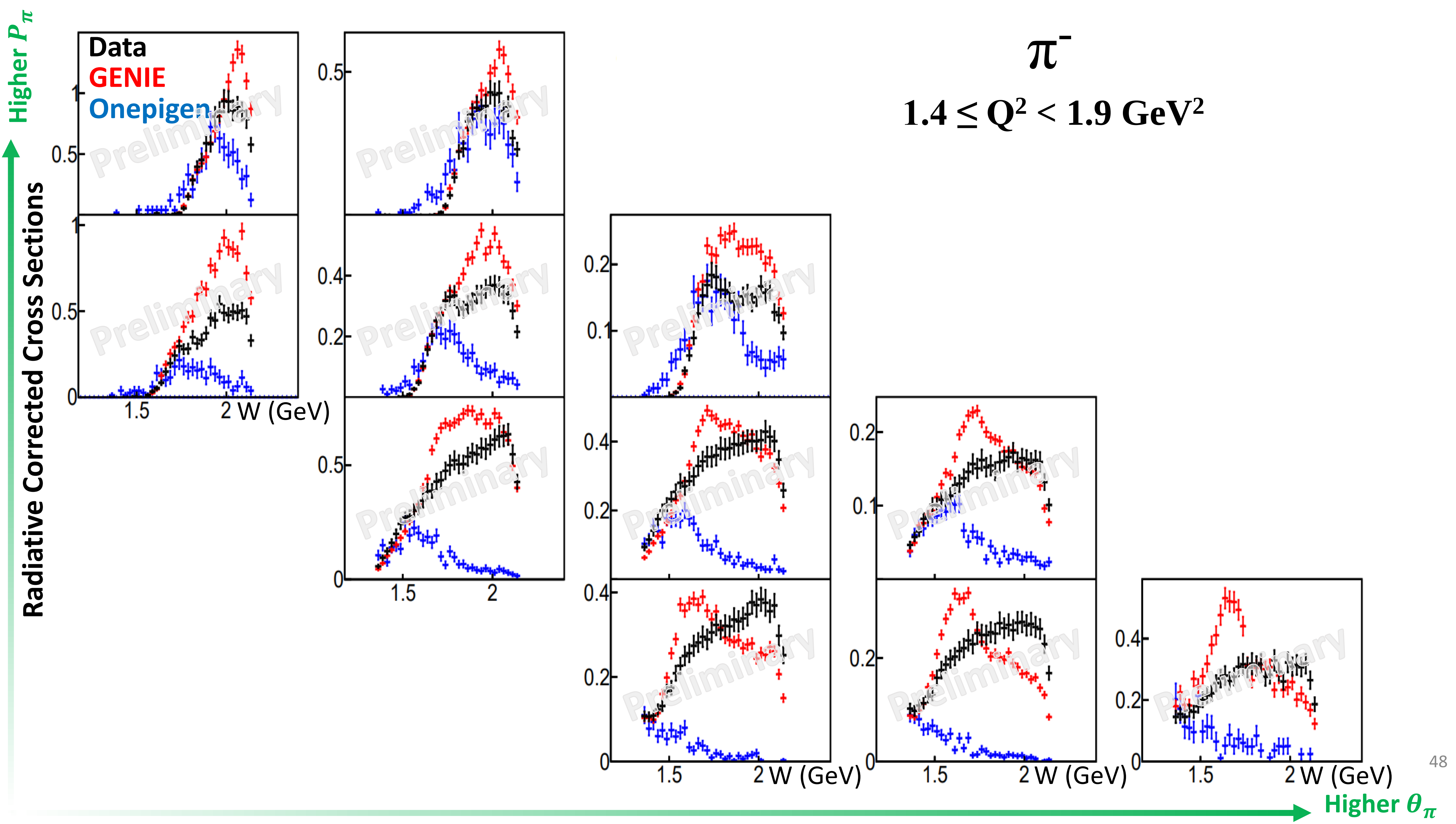


π^+
$1.9 \le Q^2 < 2.5\ \mathrm{GeV}^2$
Data
GENIE
Onepigen
Preliminary
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)

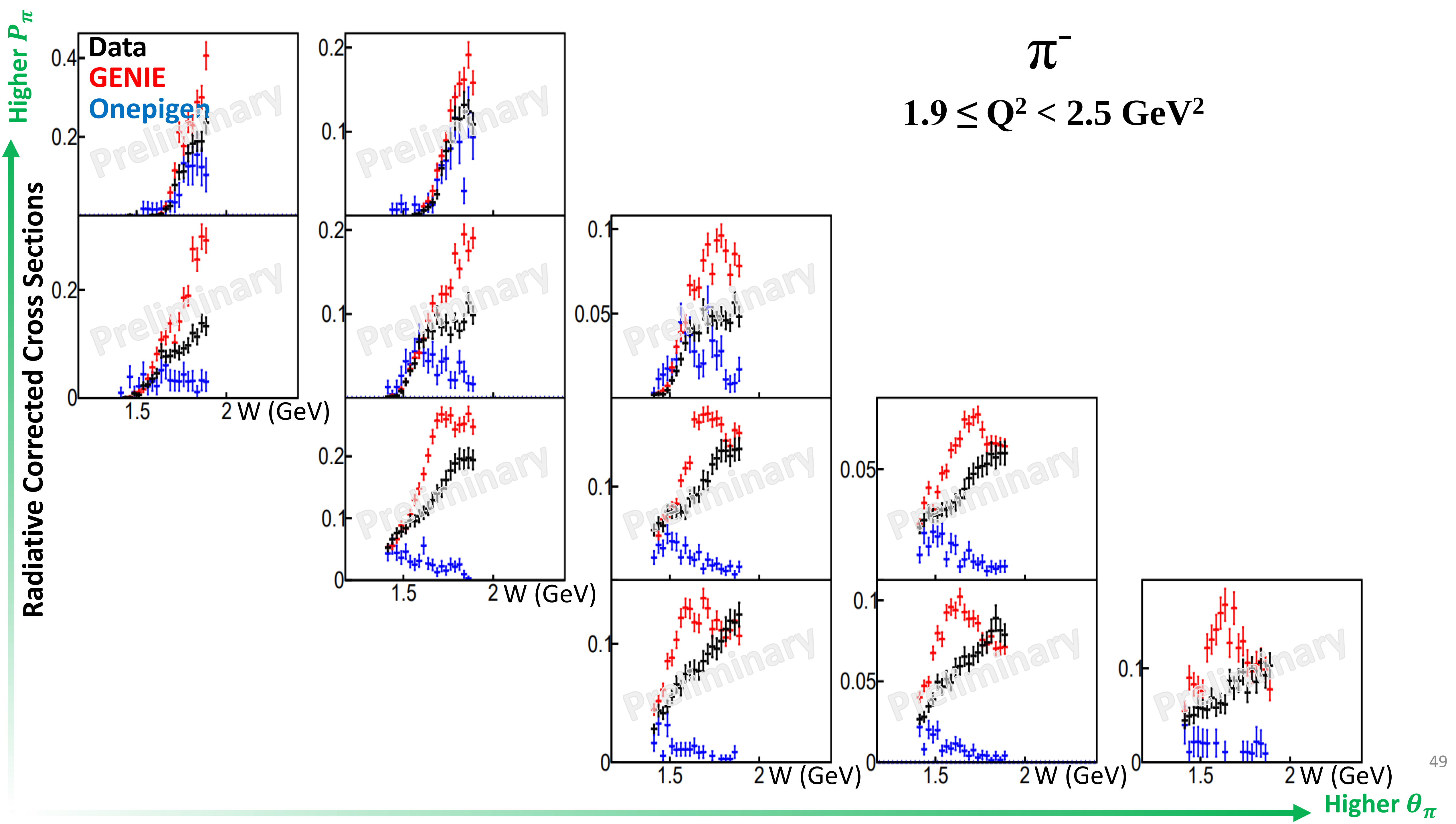

π^-
$0.7 \leq Q^2 < 1.0$ GeV^2
Data
GENIE
Onepigen
Preliminary
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)



π⁻
1.0 ≤ Q² < 1.4 GeV²
Data
GENIE
Onepigen
Preliminary
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)



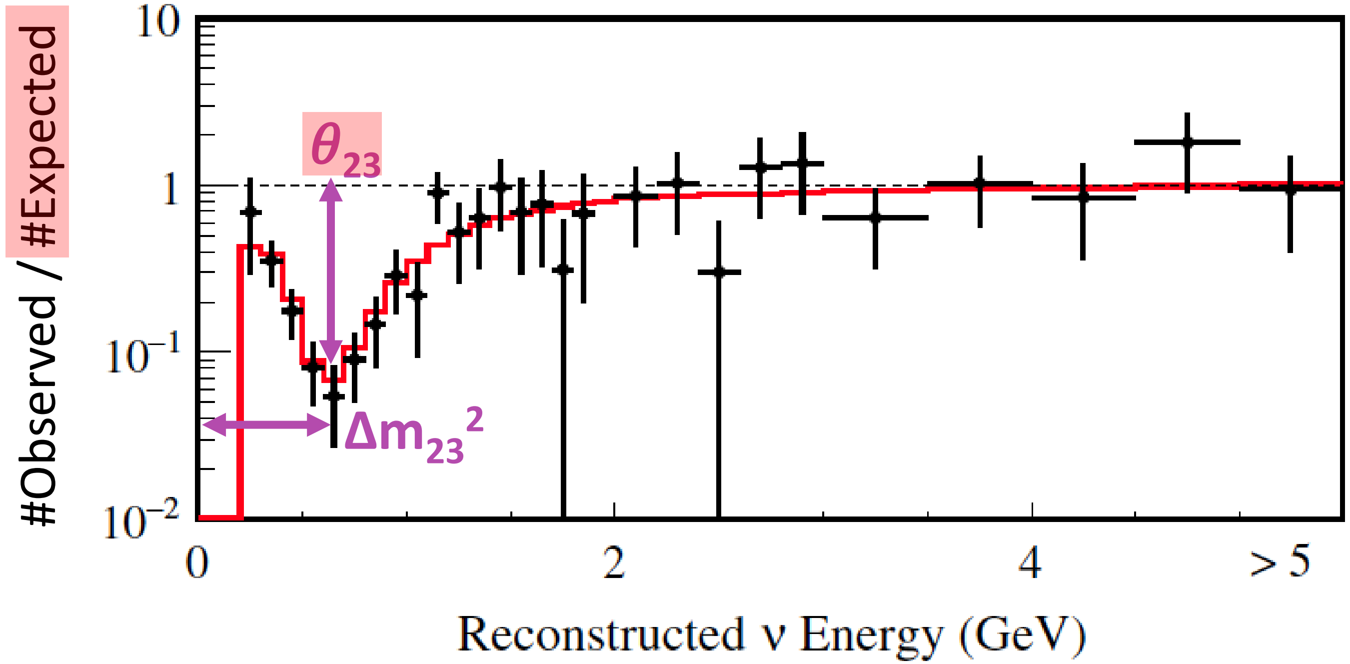
π⁻
1.4 ≤ Q² < 1.9 GeV²
Data
GENIE
Onepigen
Preliminary
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)



π⁻
1.9 ≤ Q² < 2.5 GeV²
Data
GENIE
Onepigen
Radiative Corrected Cross Sections
Higher P_π
Higher θ_π
W (GeV)
Preliminary

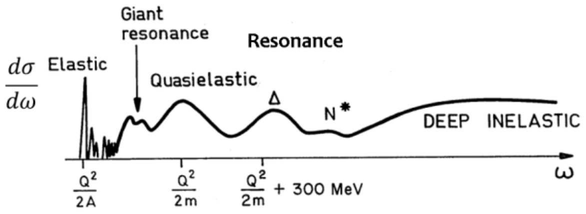
Oscillation Probability

$$P(n_m \rightarrow n_m) = \sin^2\left(2q_{23}\right) \times \sin^2\left(\frac{Dm_{32}{}^2 L}{4E_n}\right)$$

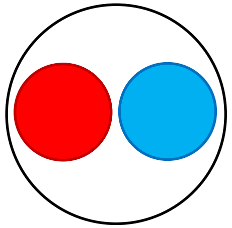


T2K PRD (2015)

Pion Physics



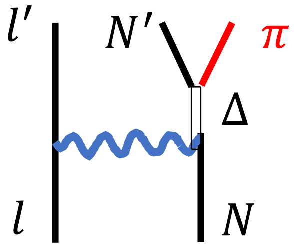
- Mesons consisting of combinations of u and d quarks and antiquarks
- Commonly produced in scattering experiments



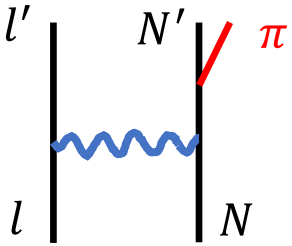
$$e + p \to e' + n + \pi^+ \qquad e + n \to e' + p + \pi^-$$

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

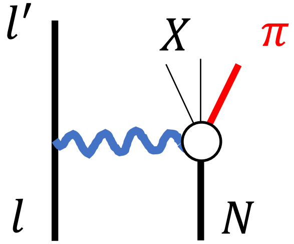
Resonance Decay Production

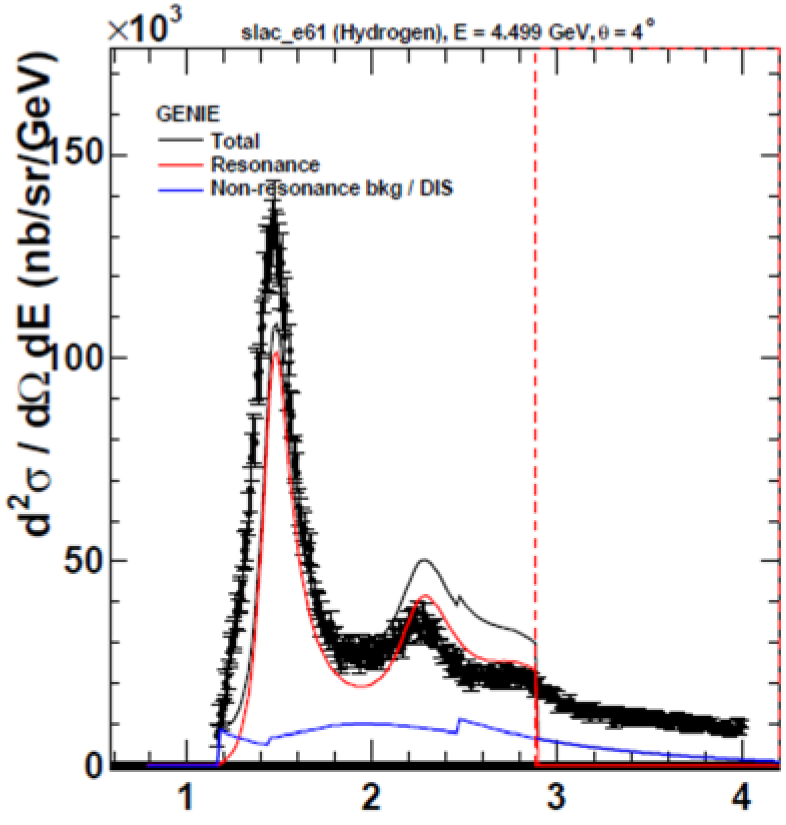


Non-Resonant Production



DIS Production

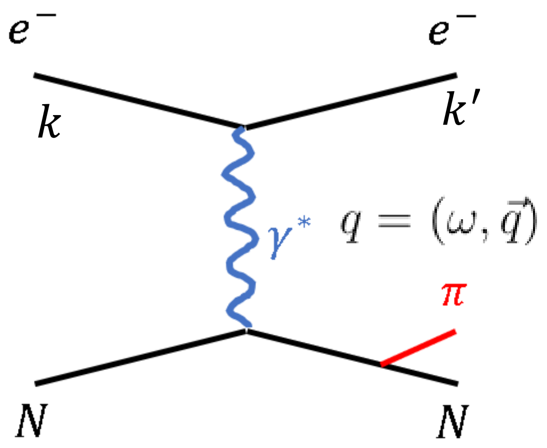




Steve Dytman (Univ. of Pittsburgh)
FUNFACT at JLab
May 15, 2015

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

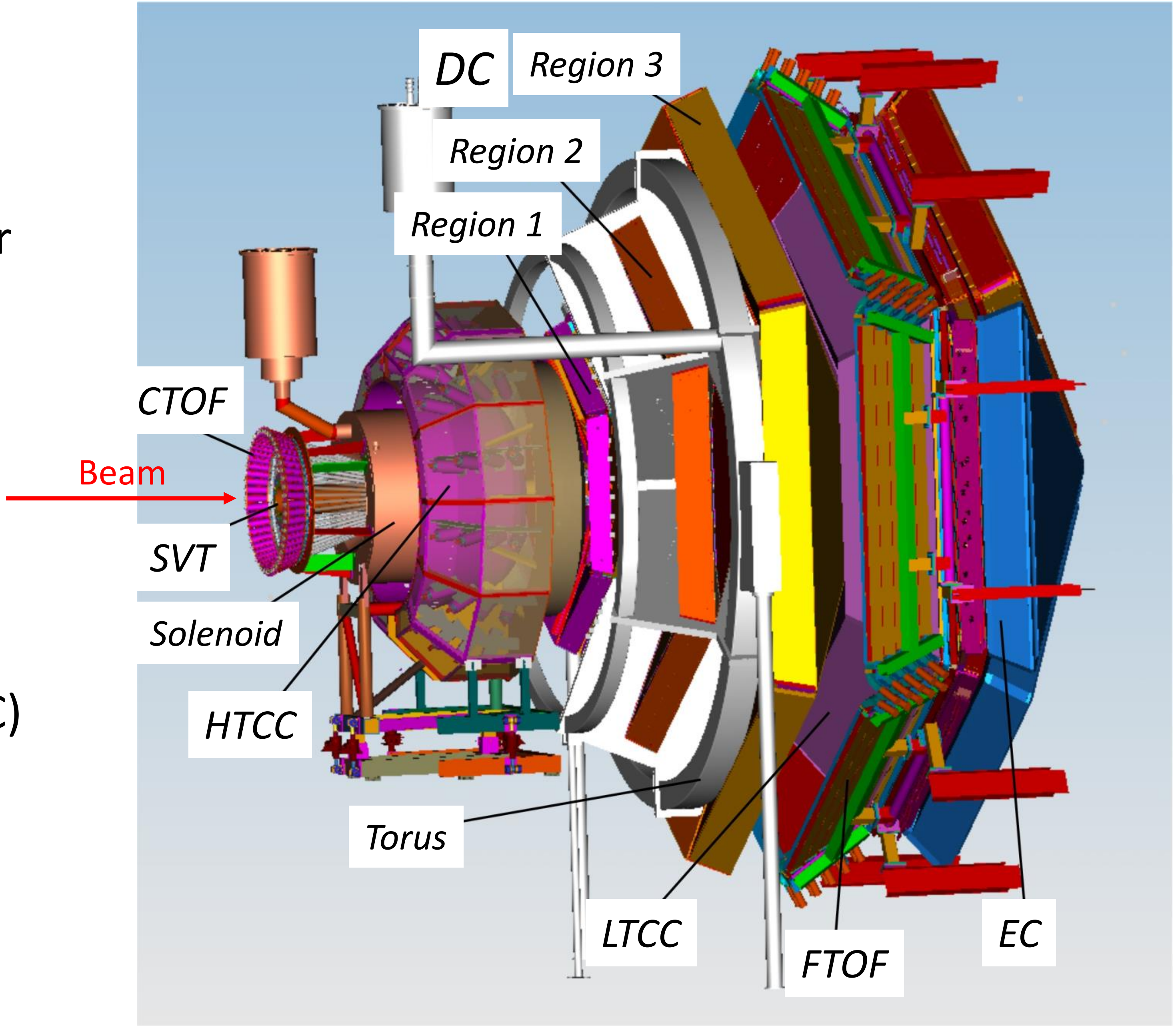
$$W = \sqrt{M_N^2 + 2M_N\omega - Q^2}$$



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

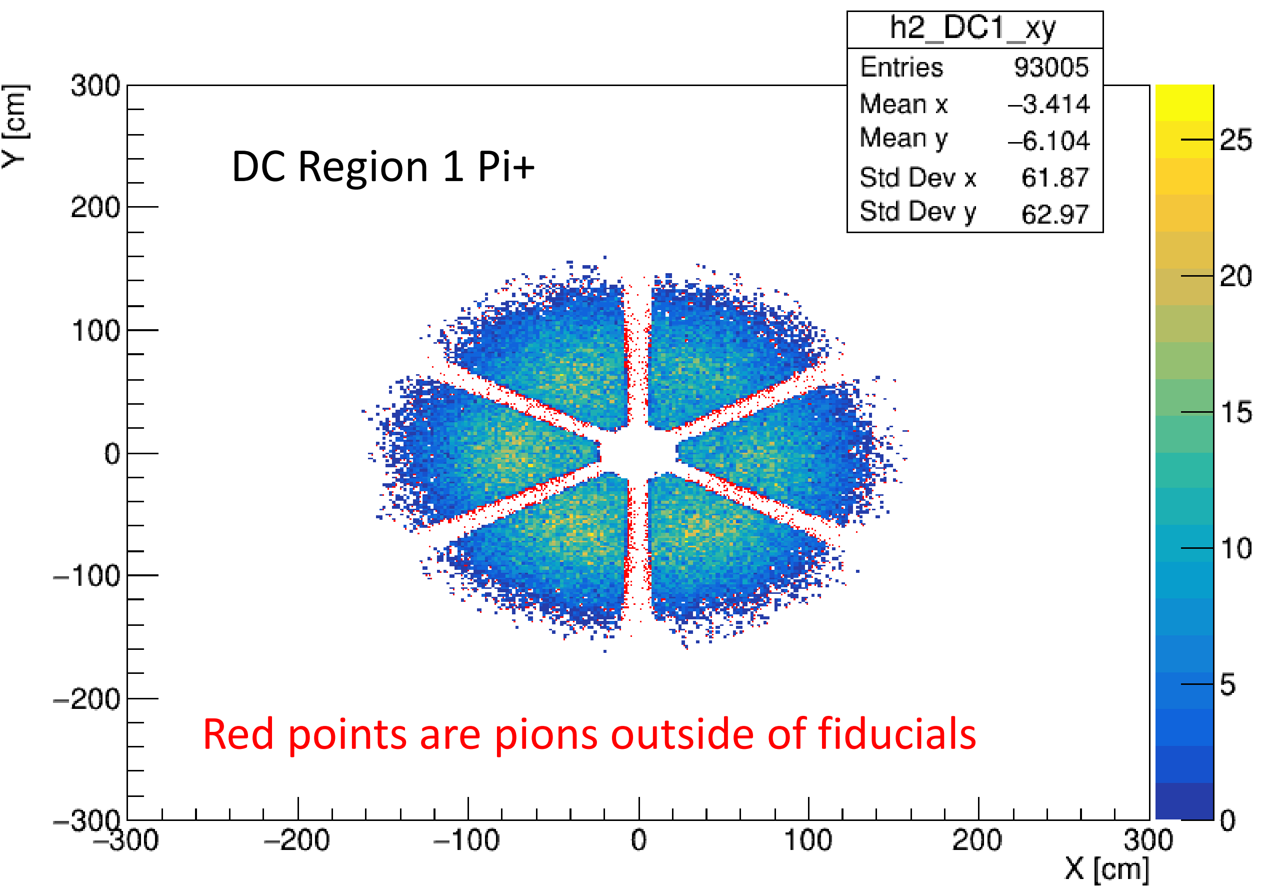


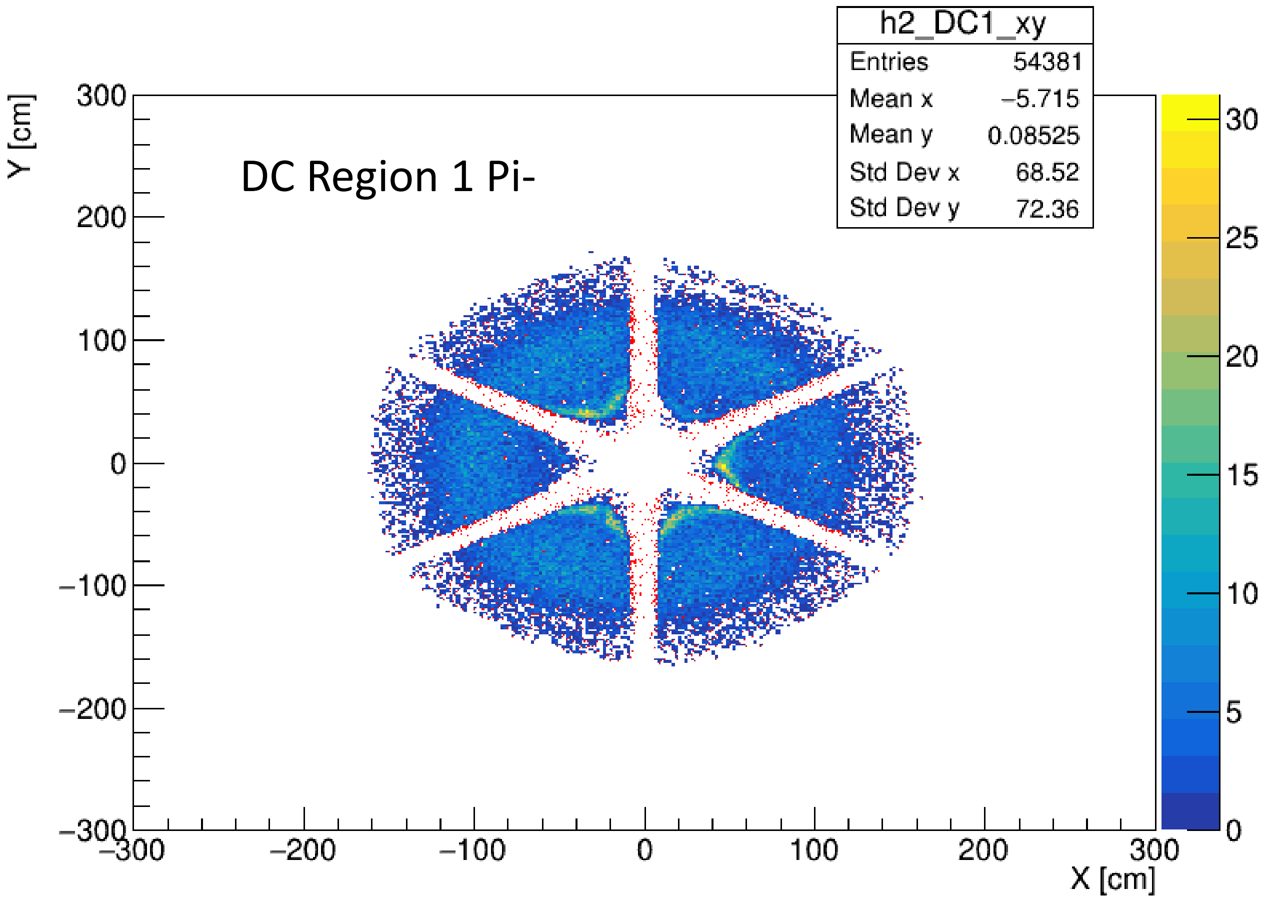
FTOF Best Fit

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

DC Fiducial Cuts

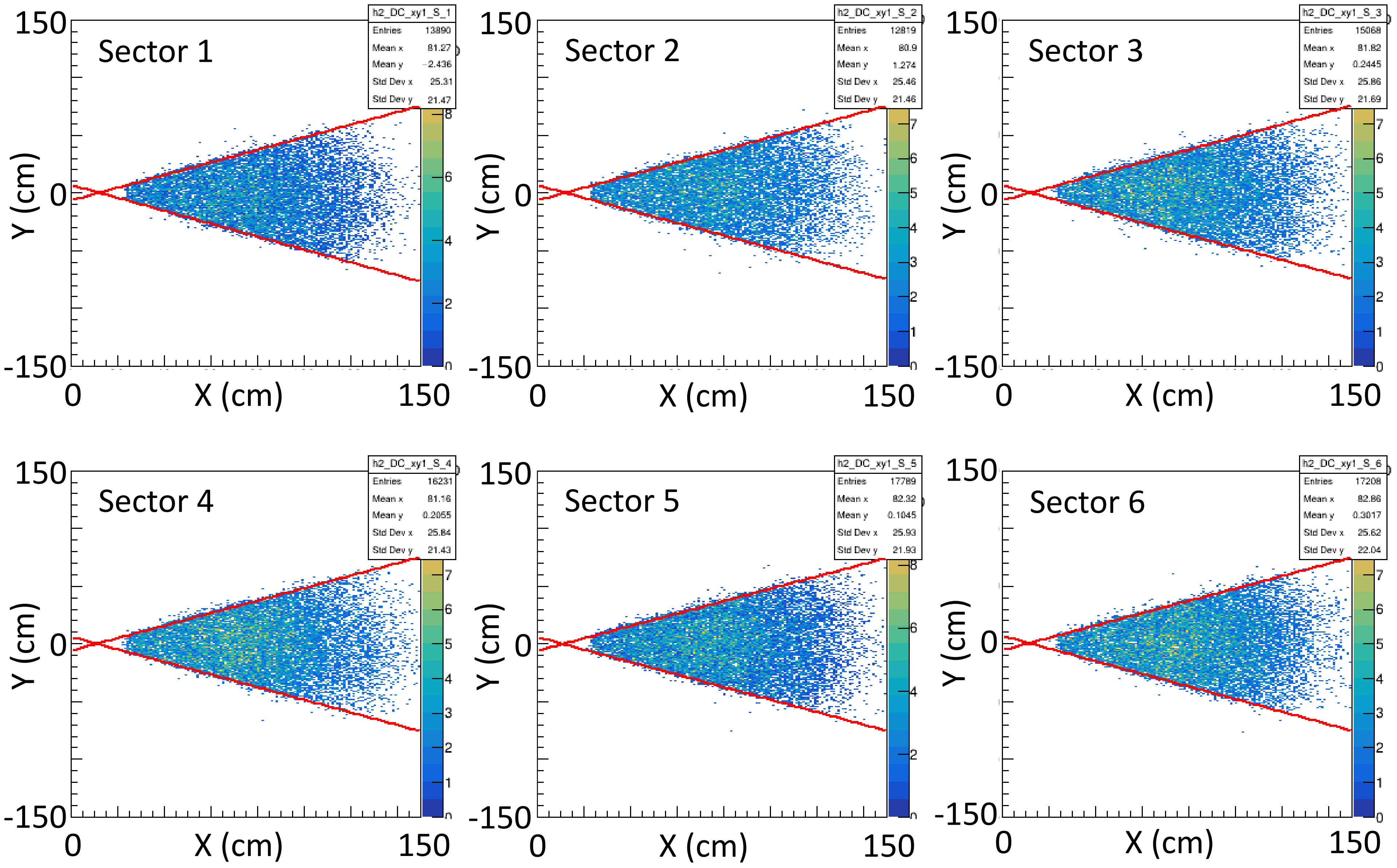
- Fiducial cuts select hits (or tracks) with near 100% efficiency





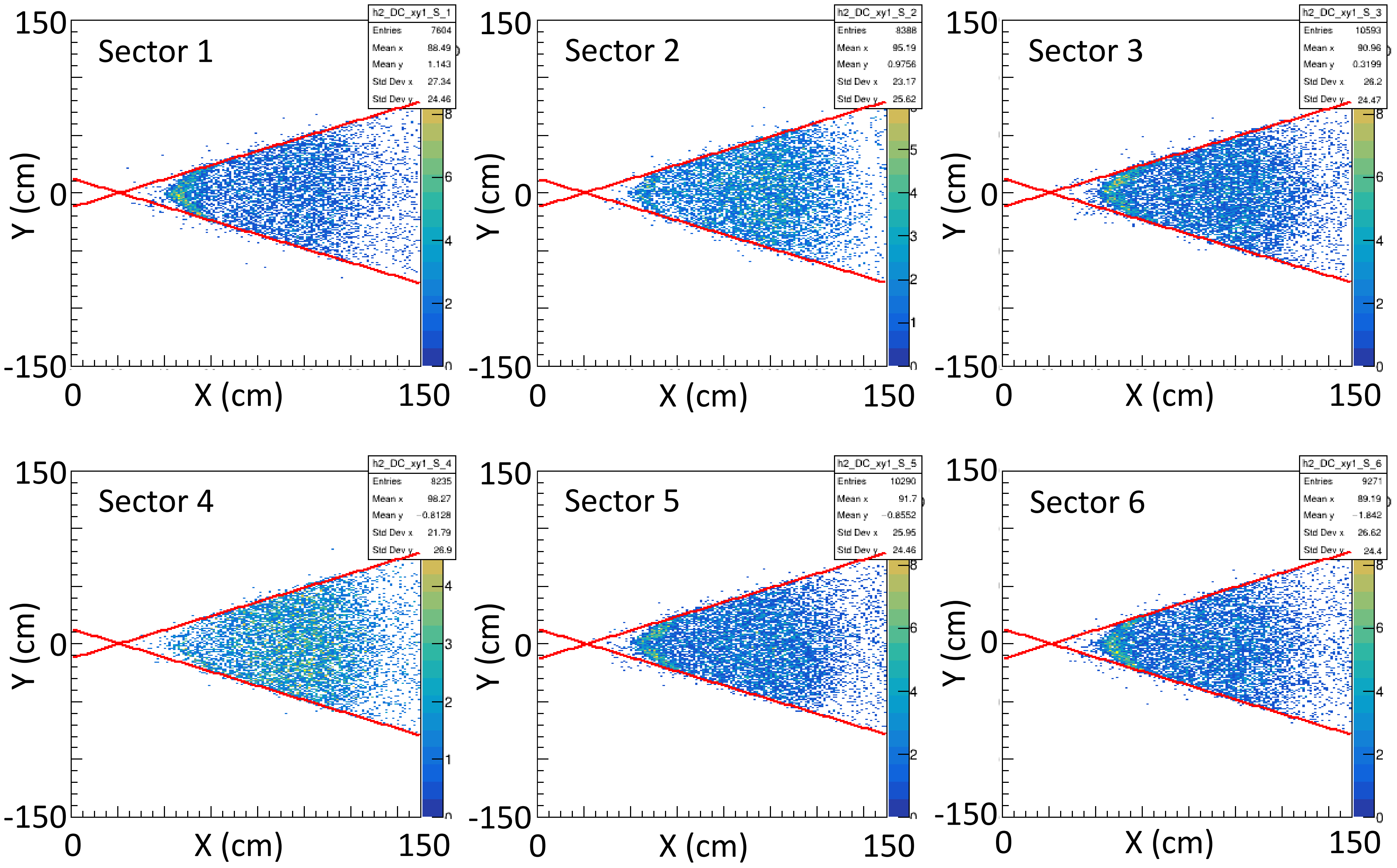
DC Fiducial Cuts

Region 1 (Pi+)

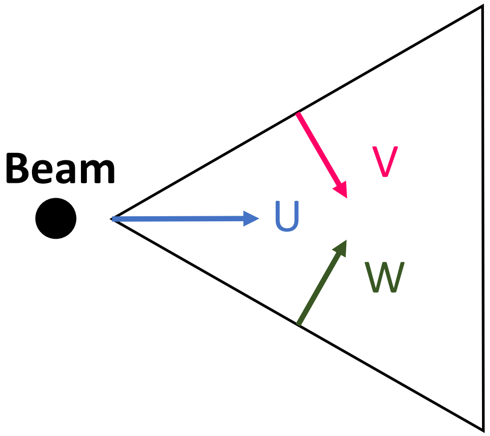


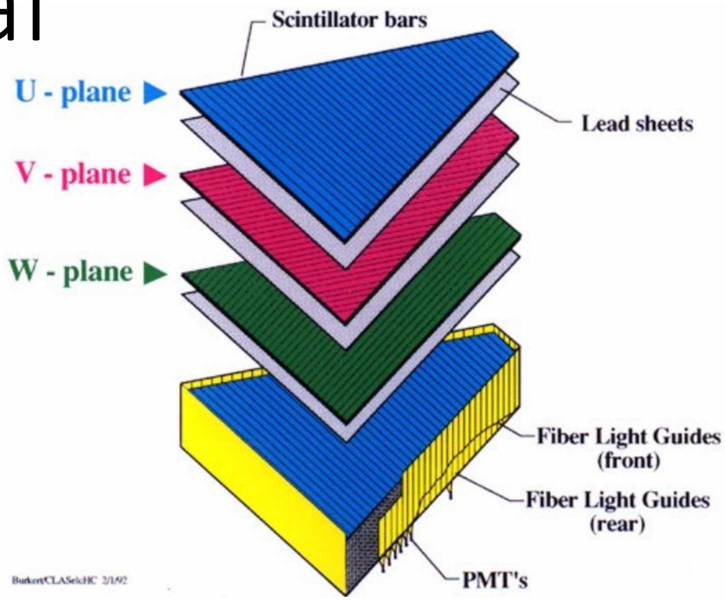
DC Fiducial Cuts

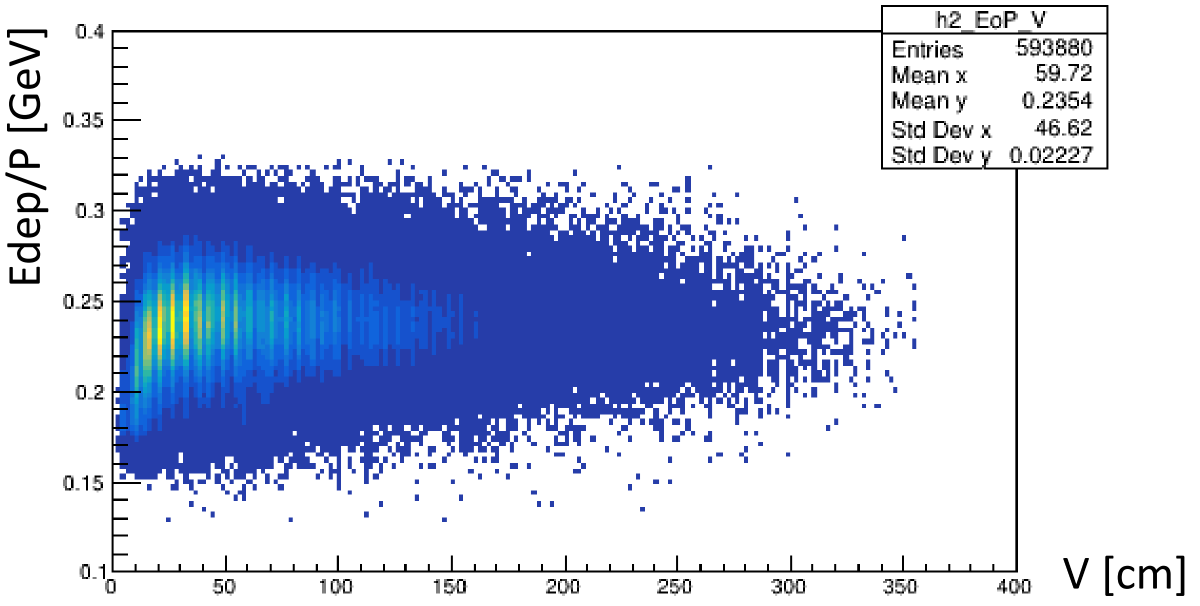
Region 1 (Pi-)

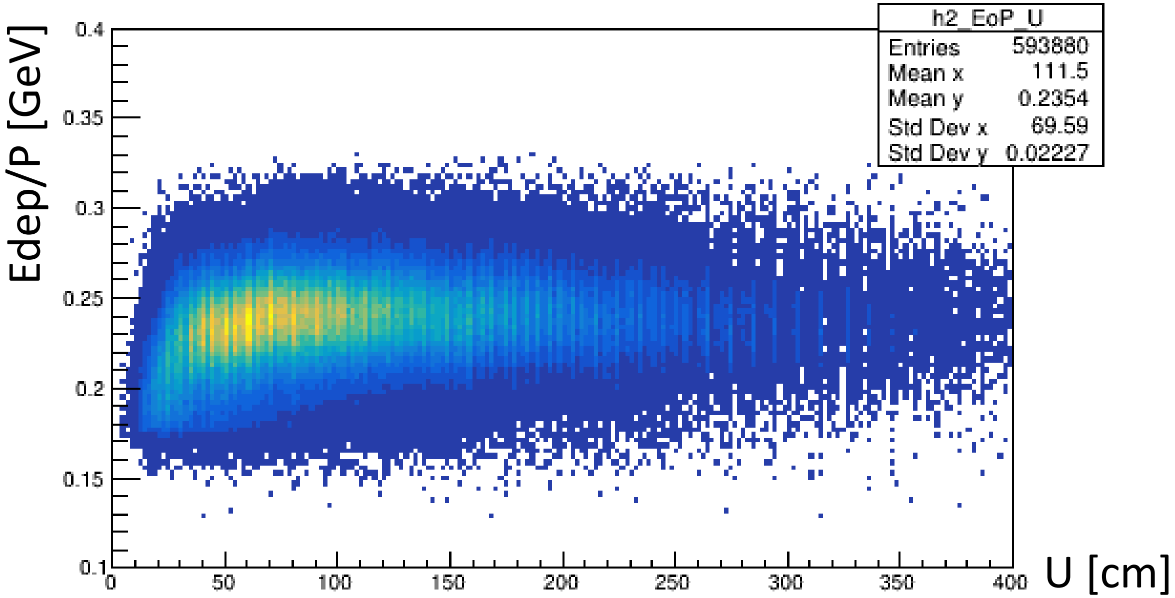


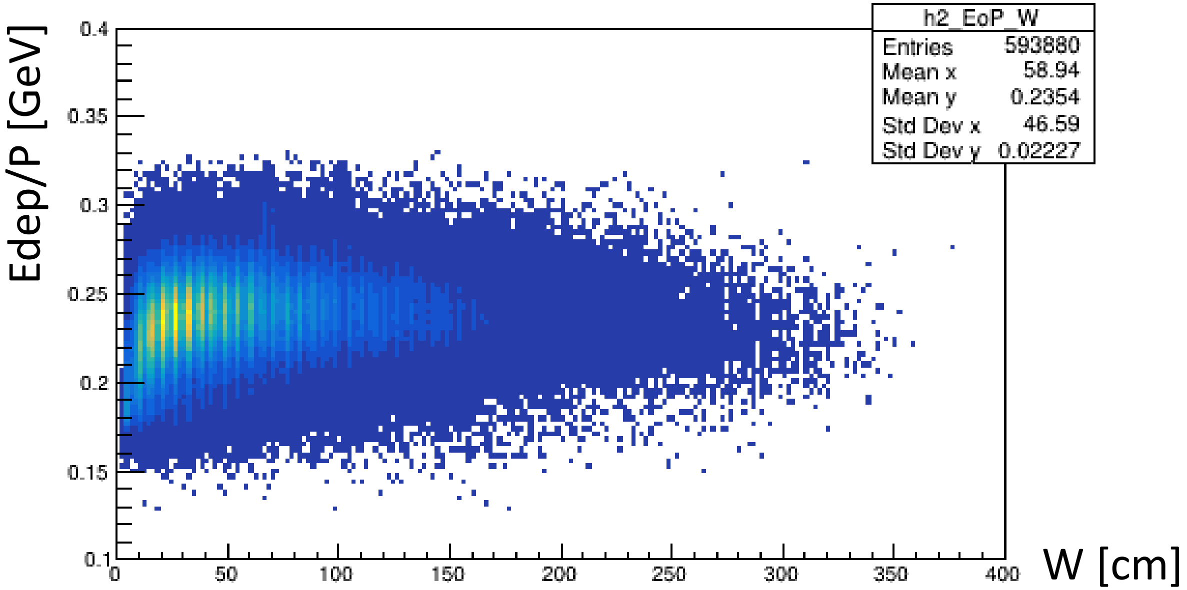
EC Fiducial Cuts





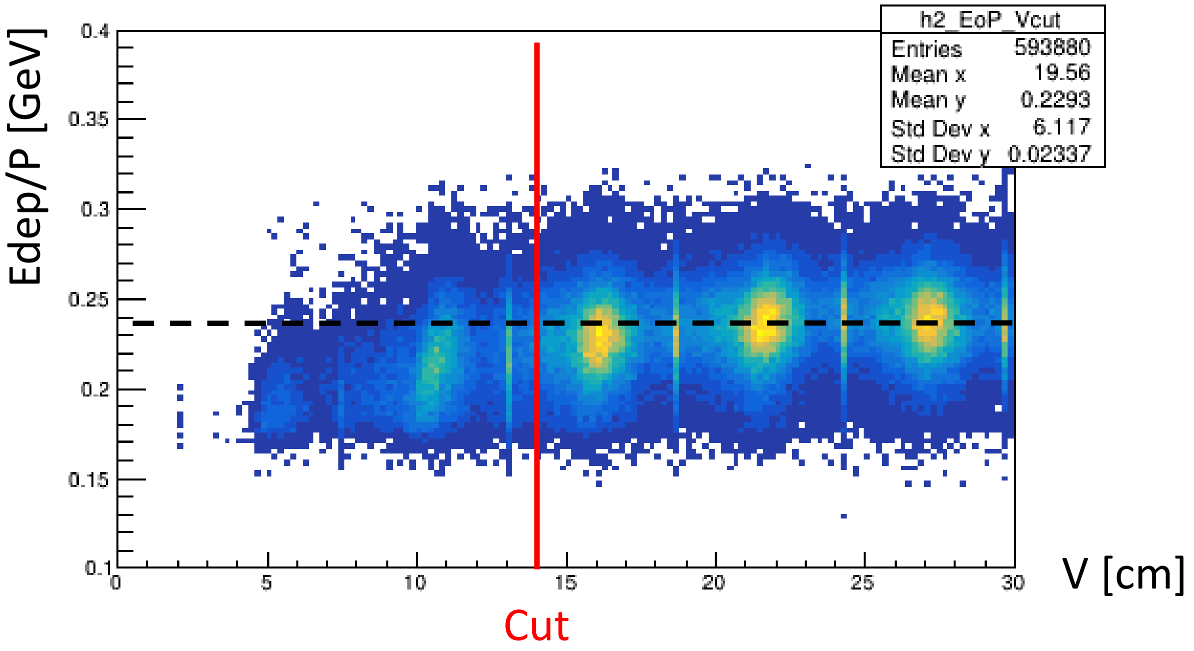


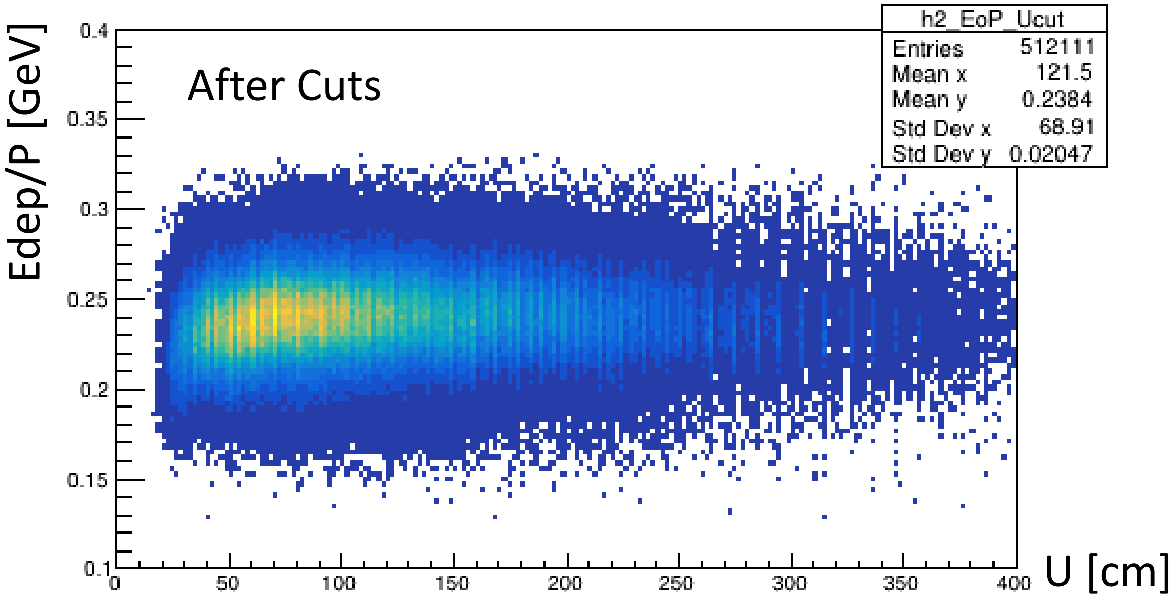


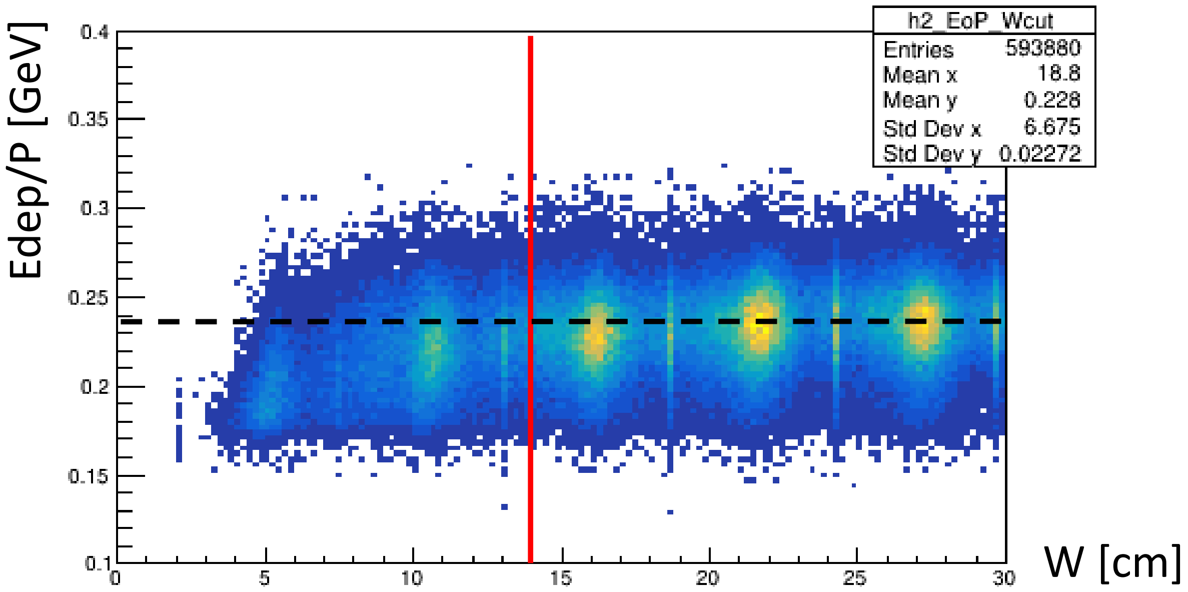


EC Fiducial Cuts

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

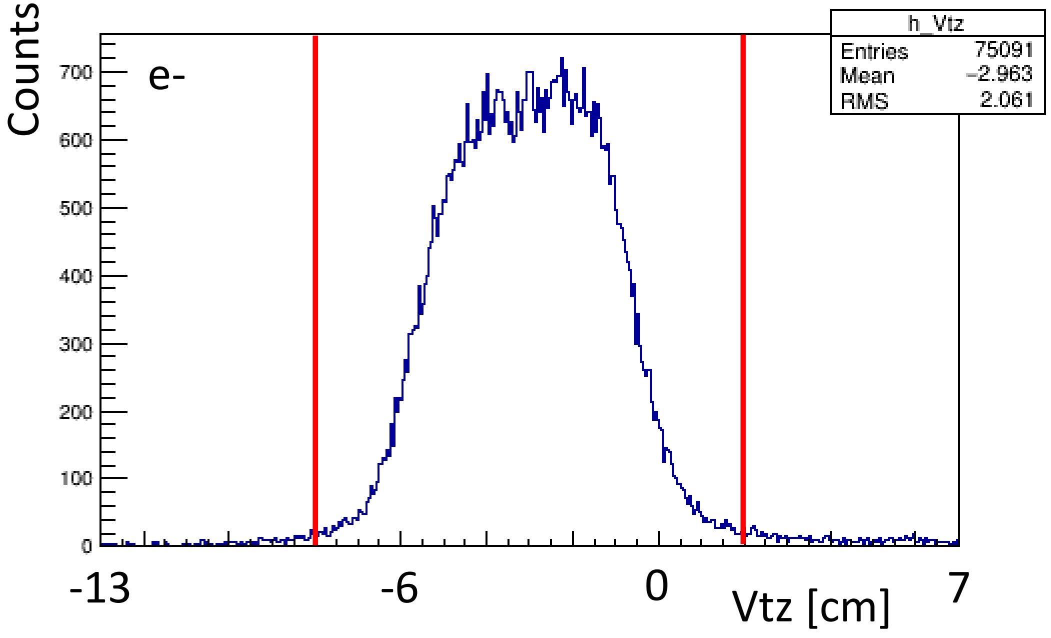


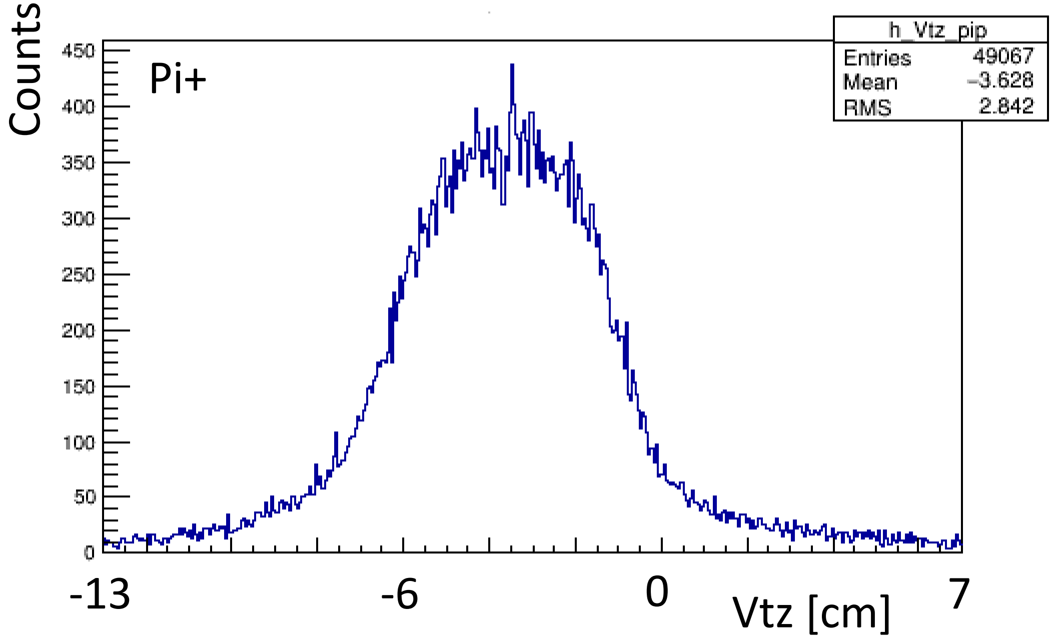


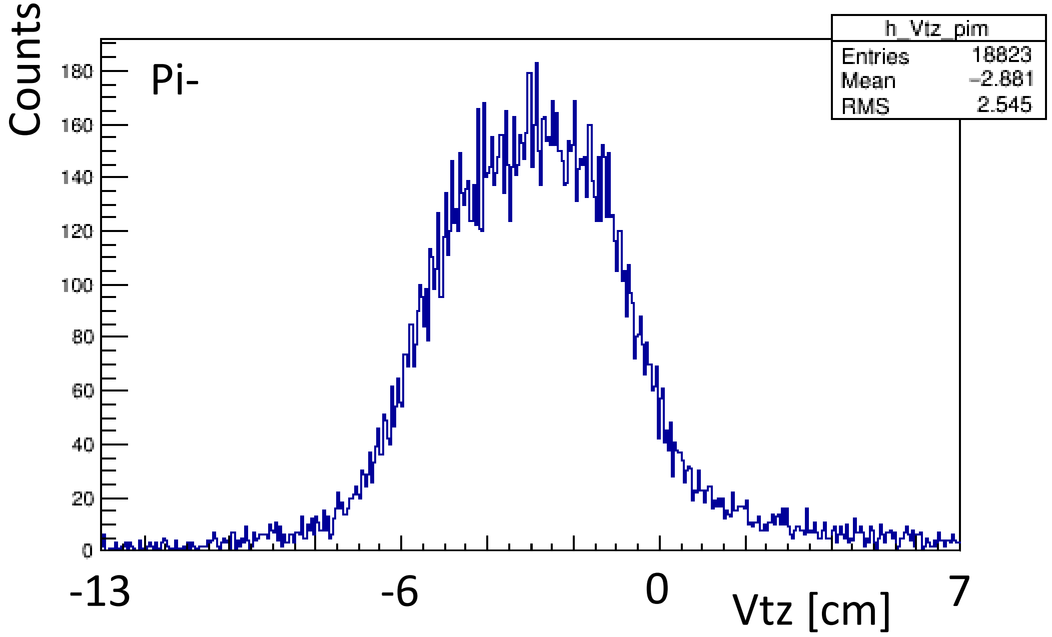


Electron and Pion z Vertices

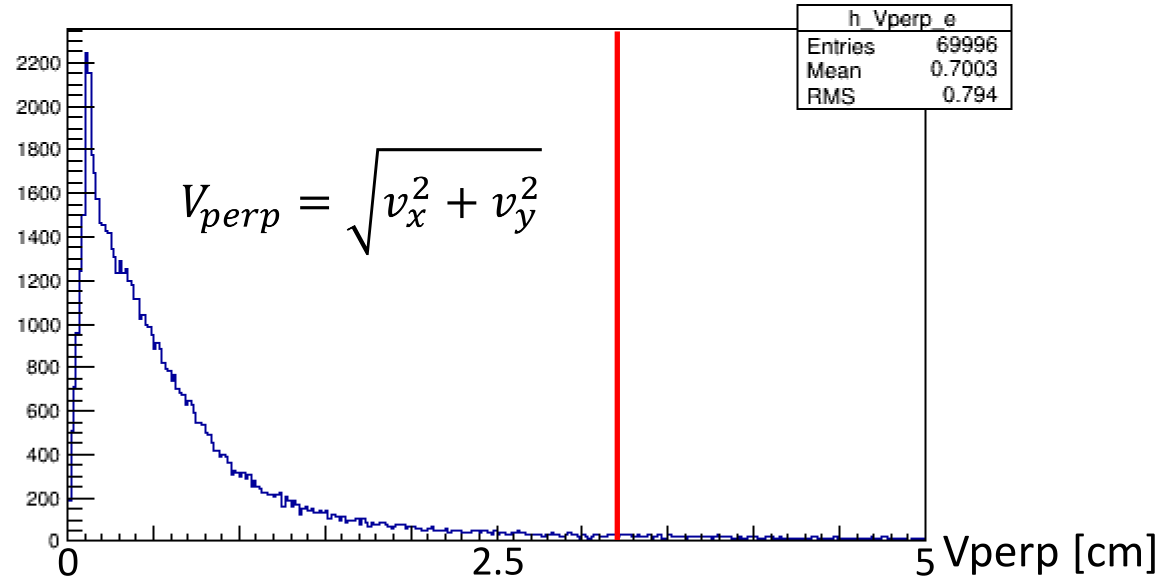
-8 cm < Vtz_e < 2 cm

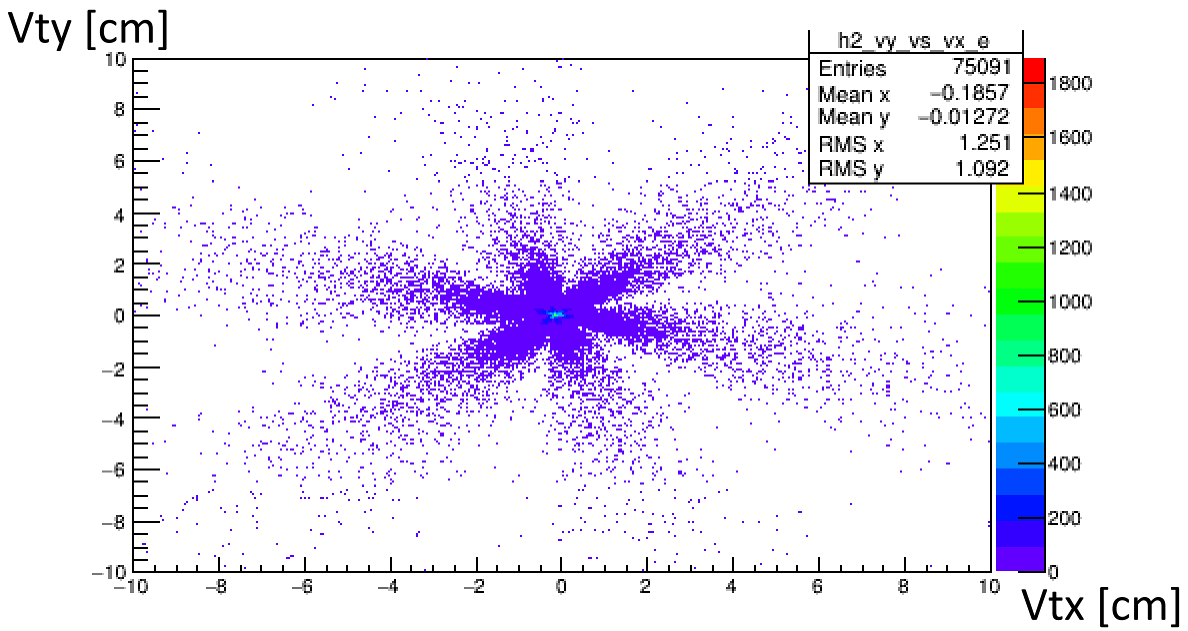


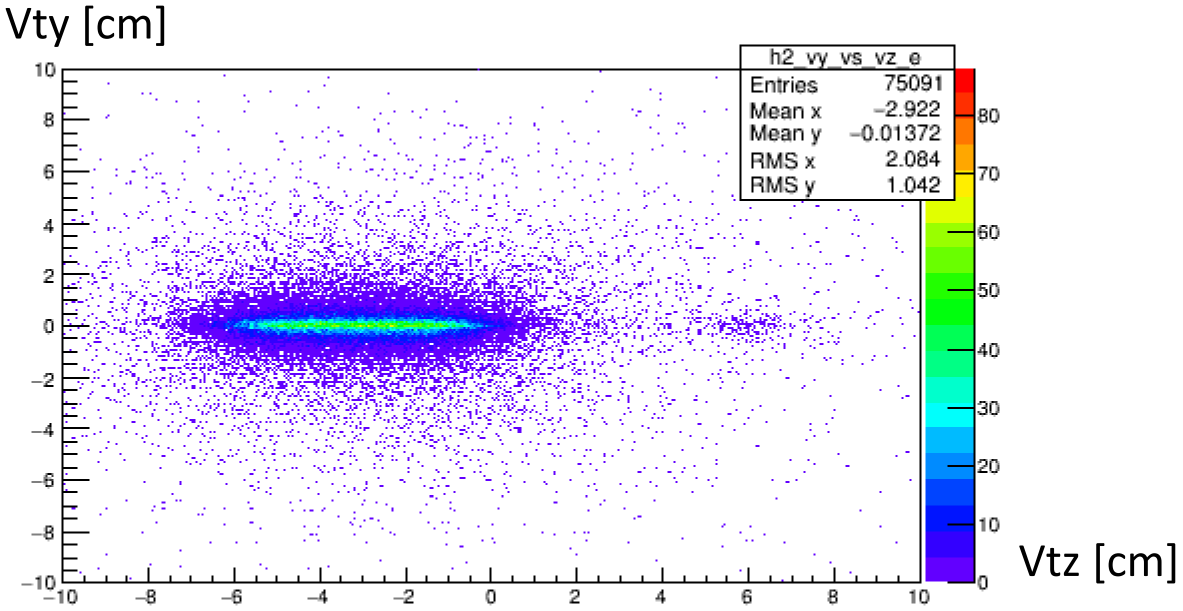


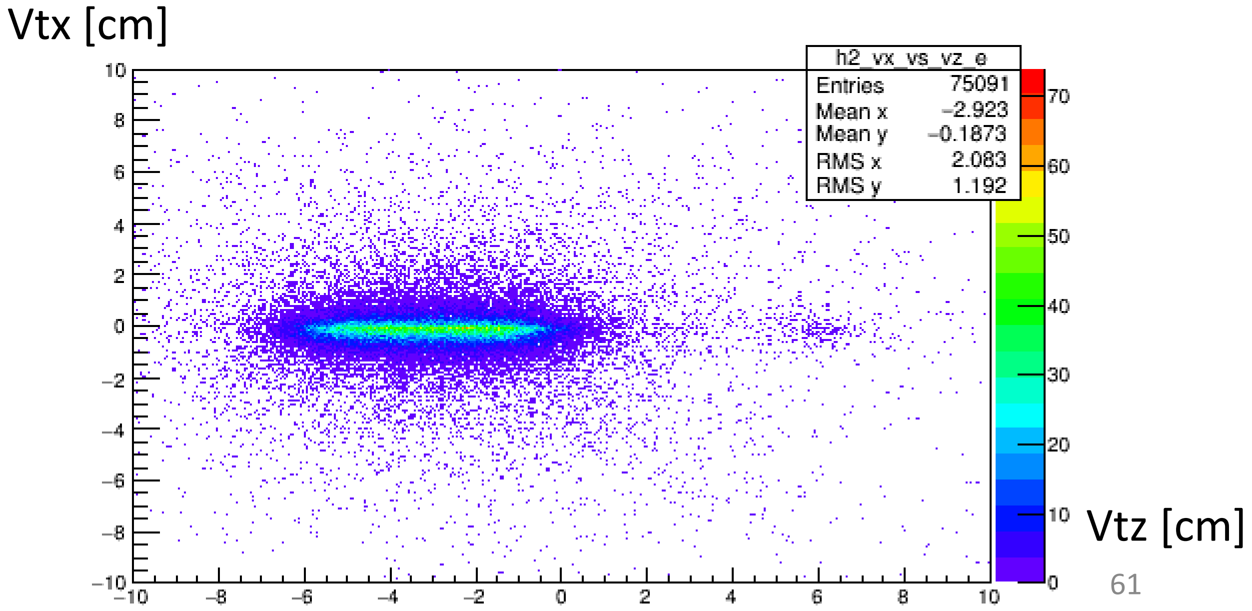


Electron Perpendicular Vertices

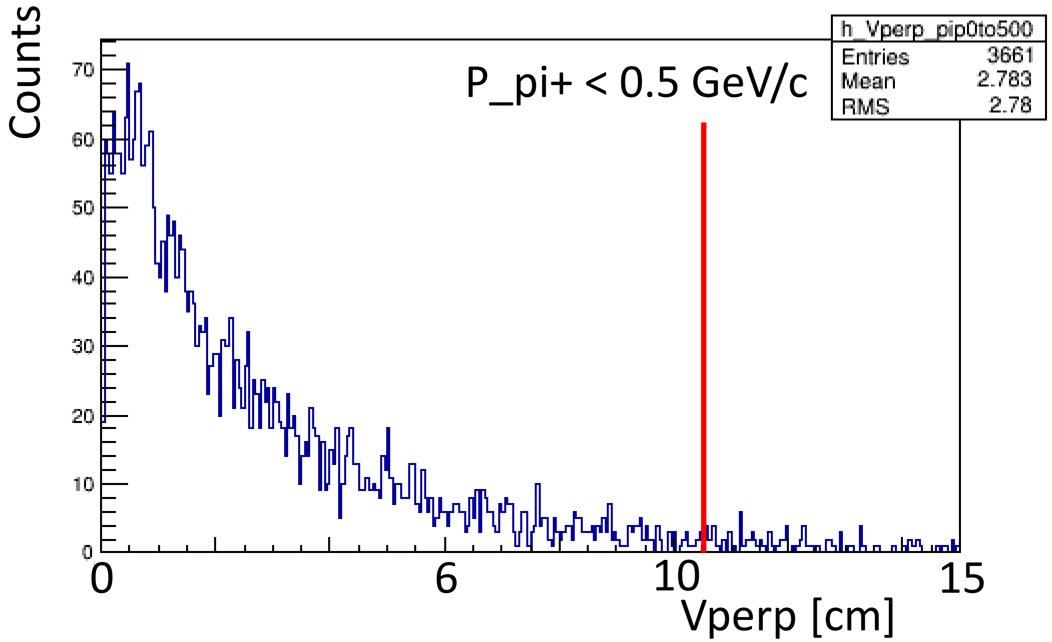


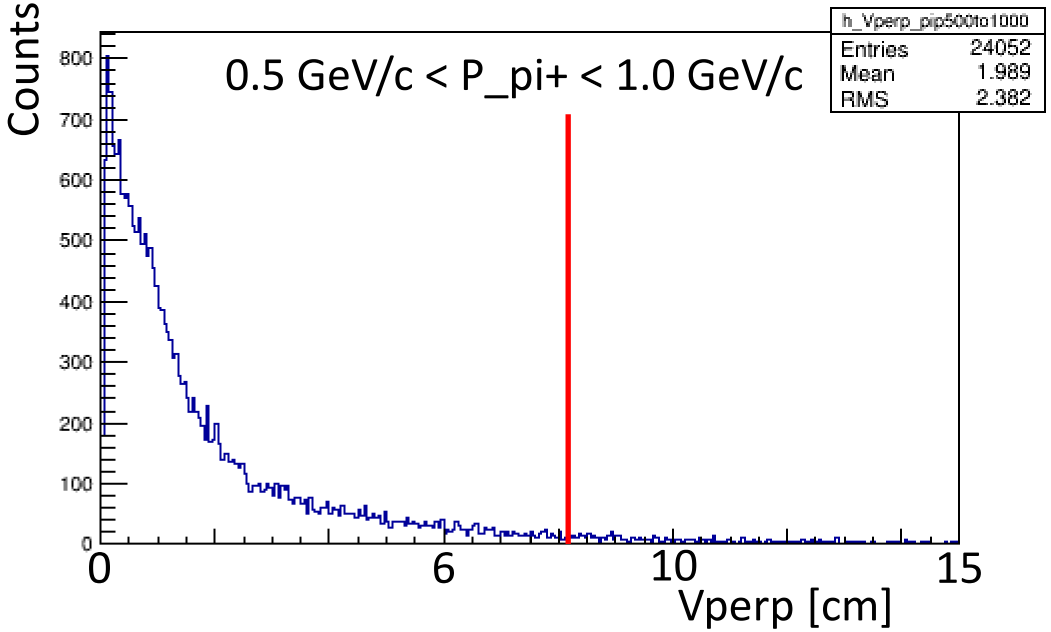


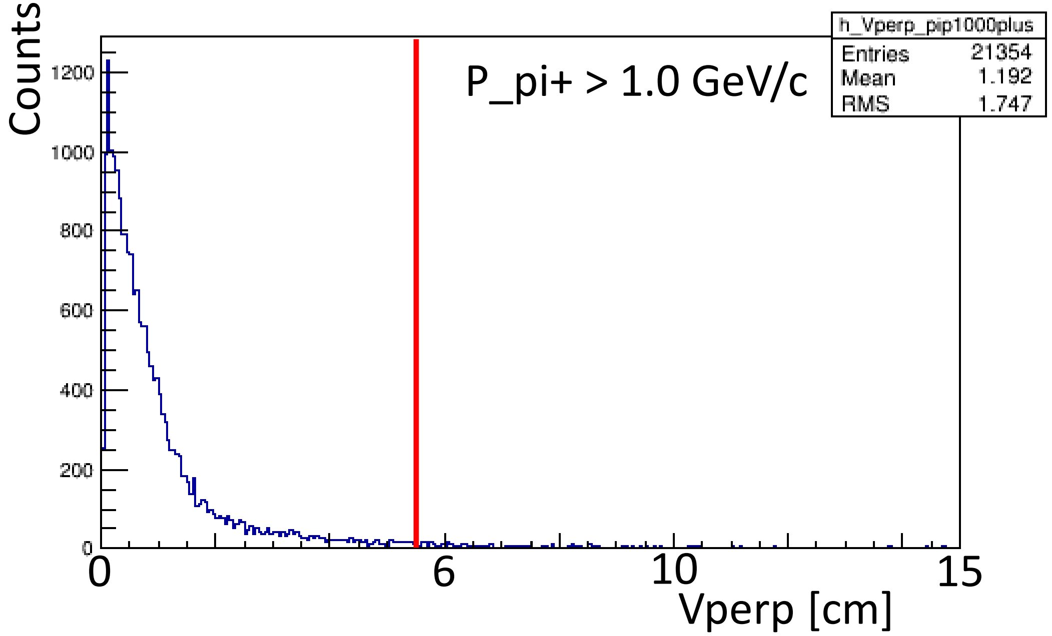




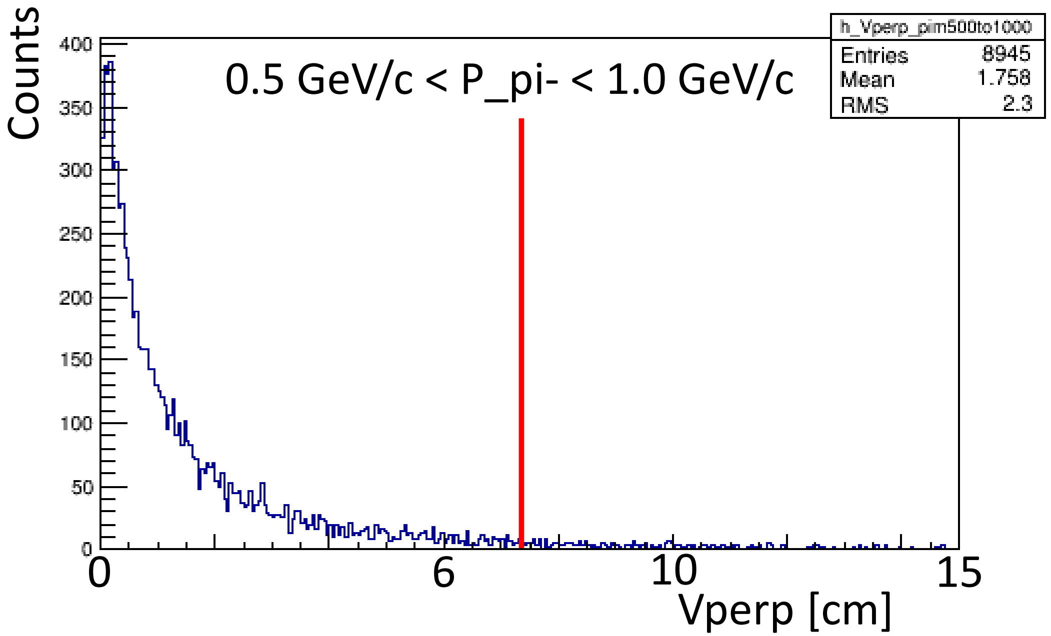
Pi+ Perpendicular Vertices

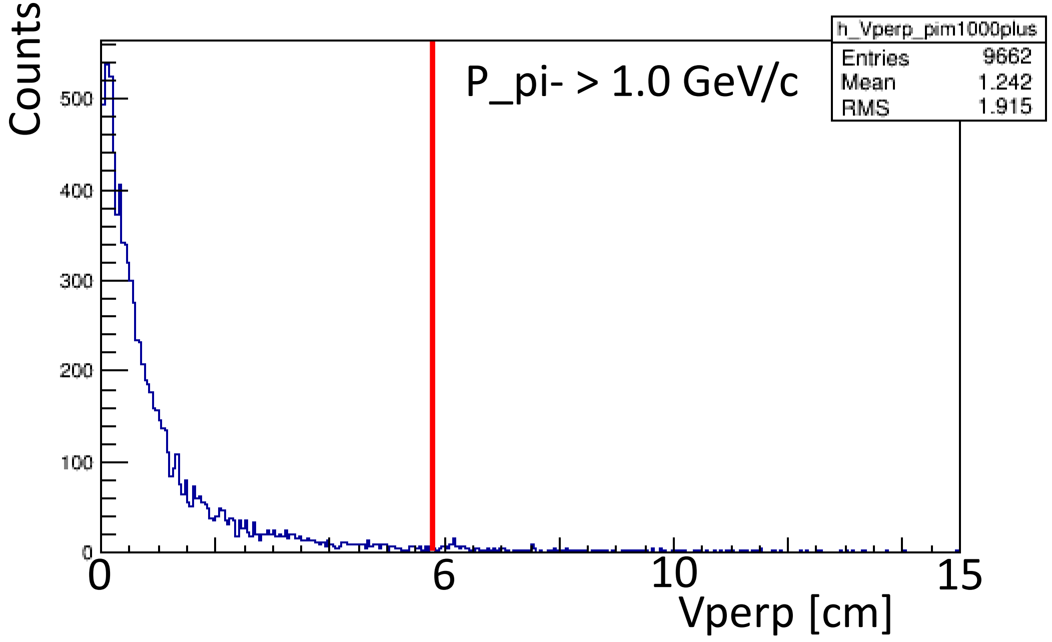






Pi- Perpendicular Vertices

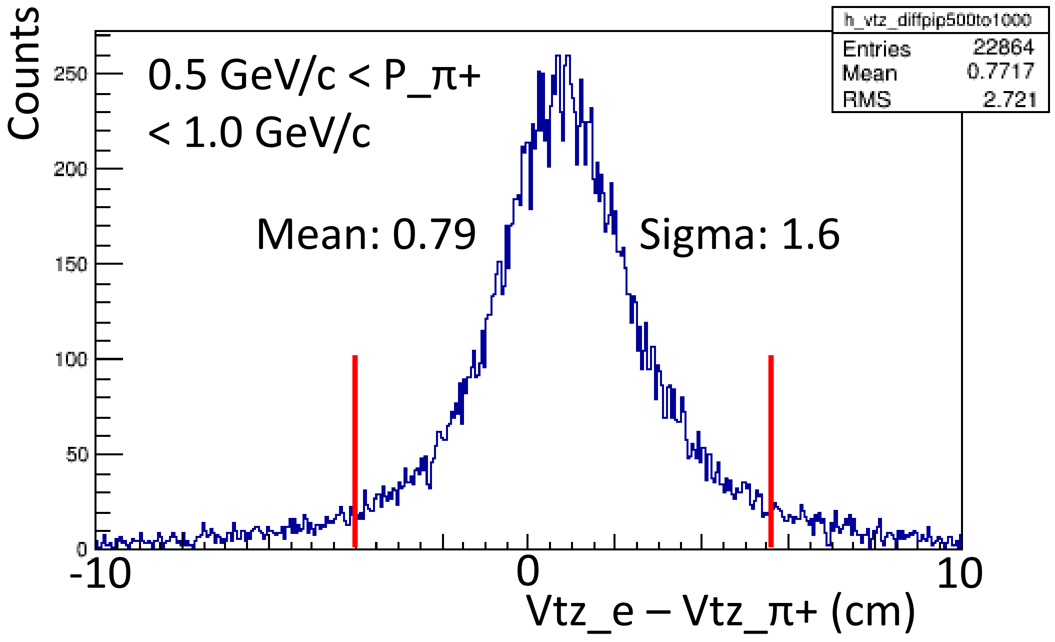


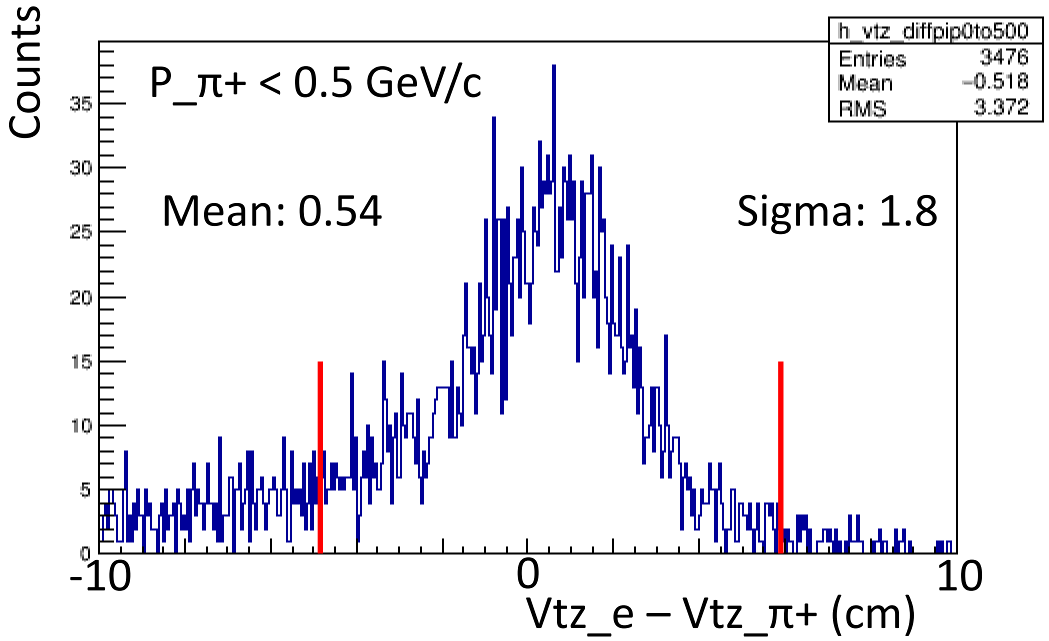


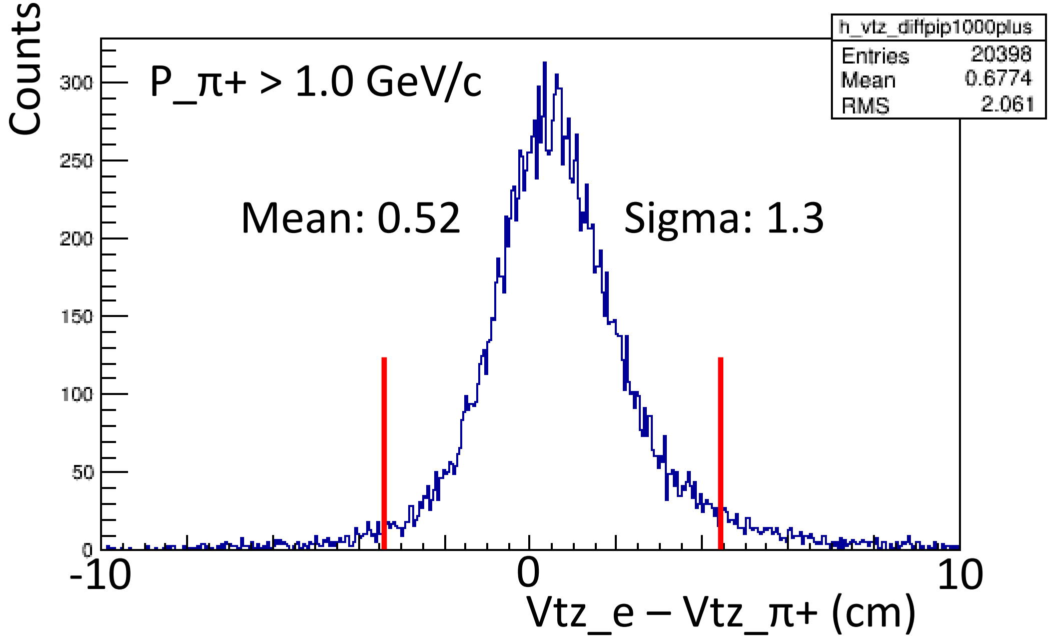
Vertex Z Difference (Electron – Pi+)

Fitted with gaussian

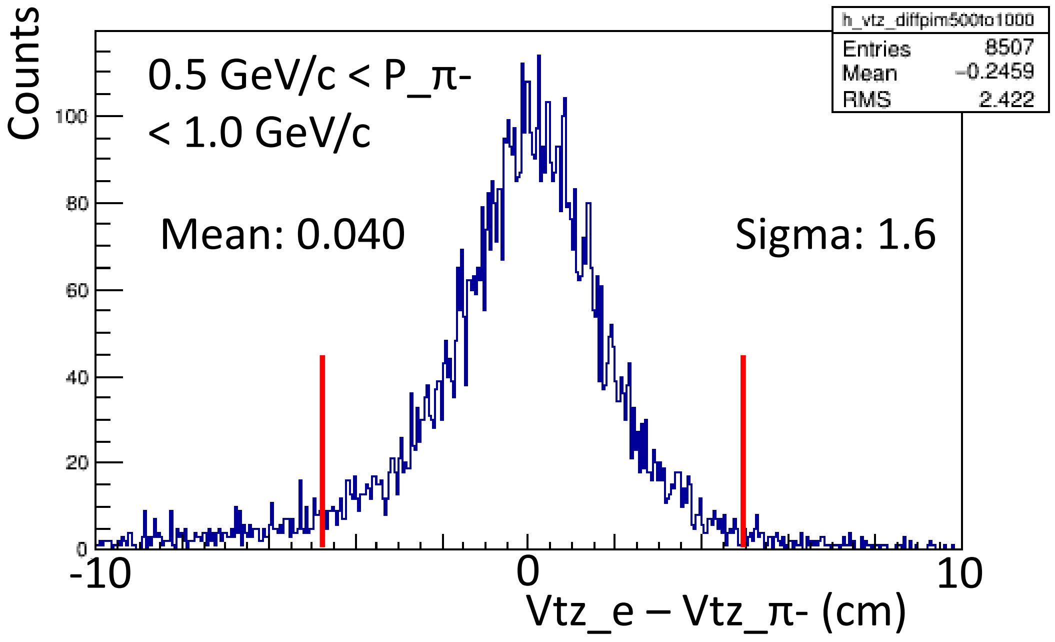
Cut = mean ± 3 * σ

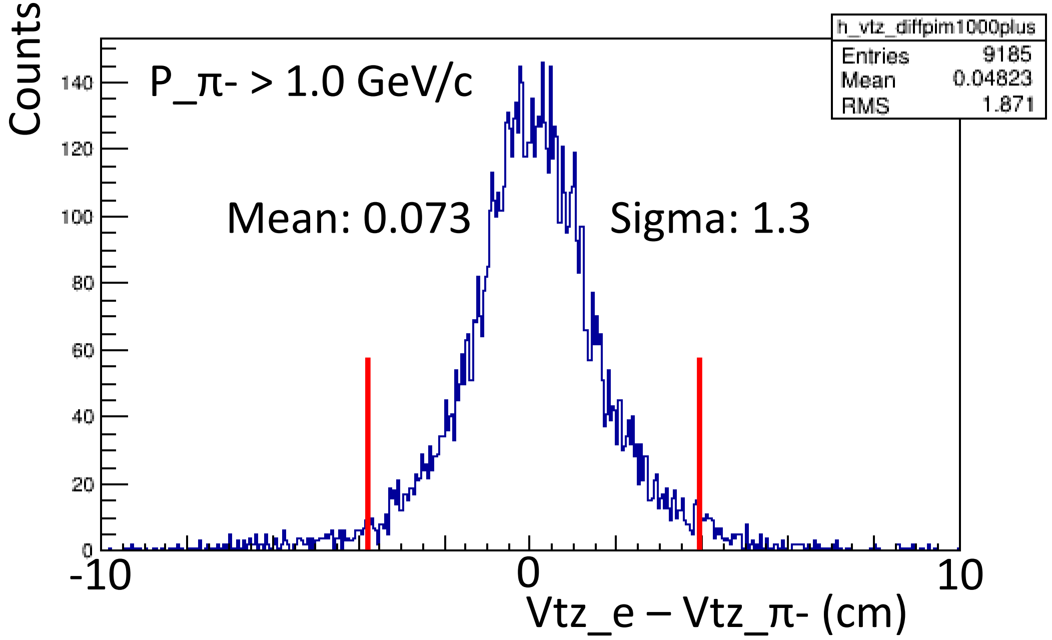






Vertex Z Difference (Electron – Pi-)

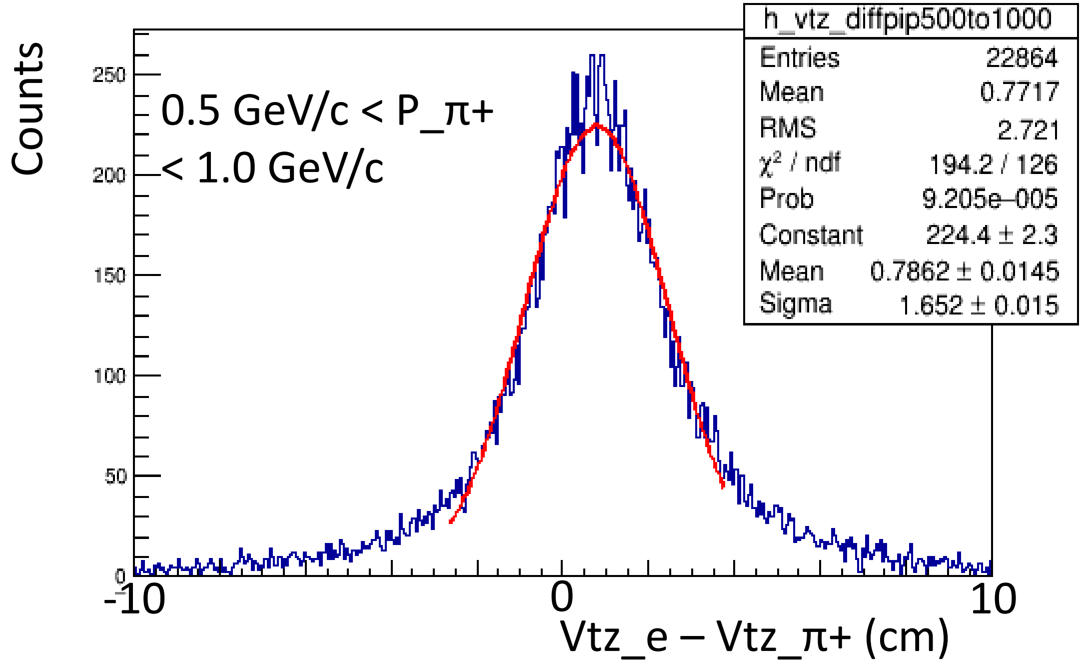


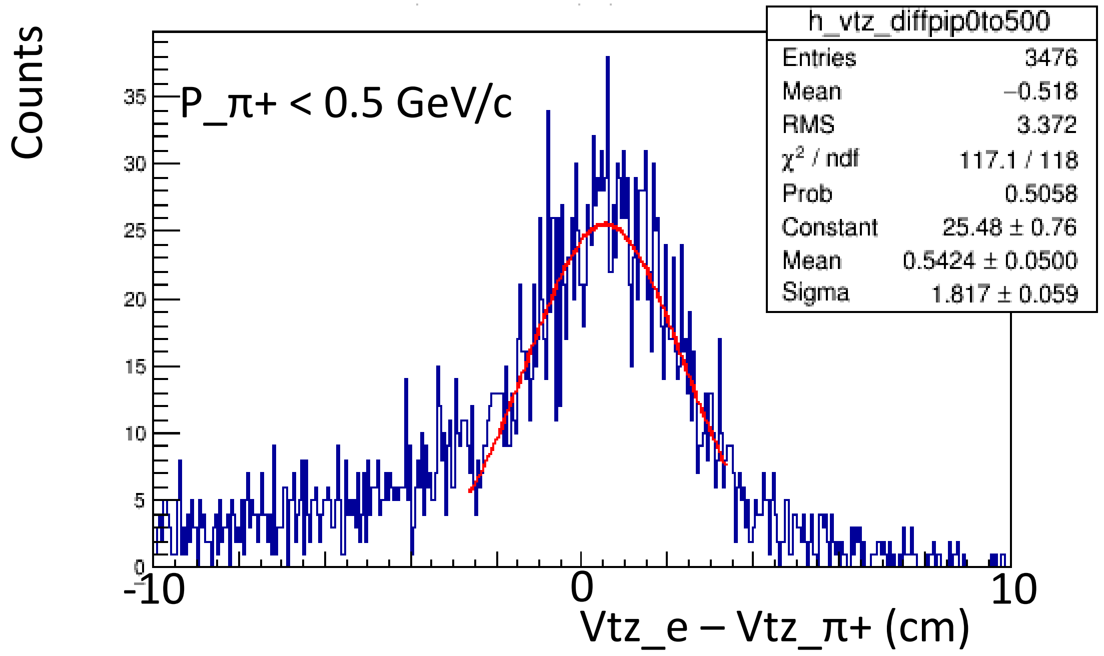


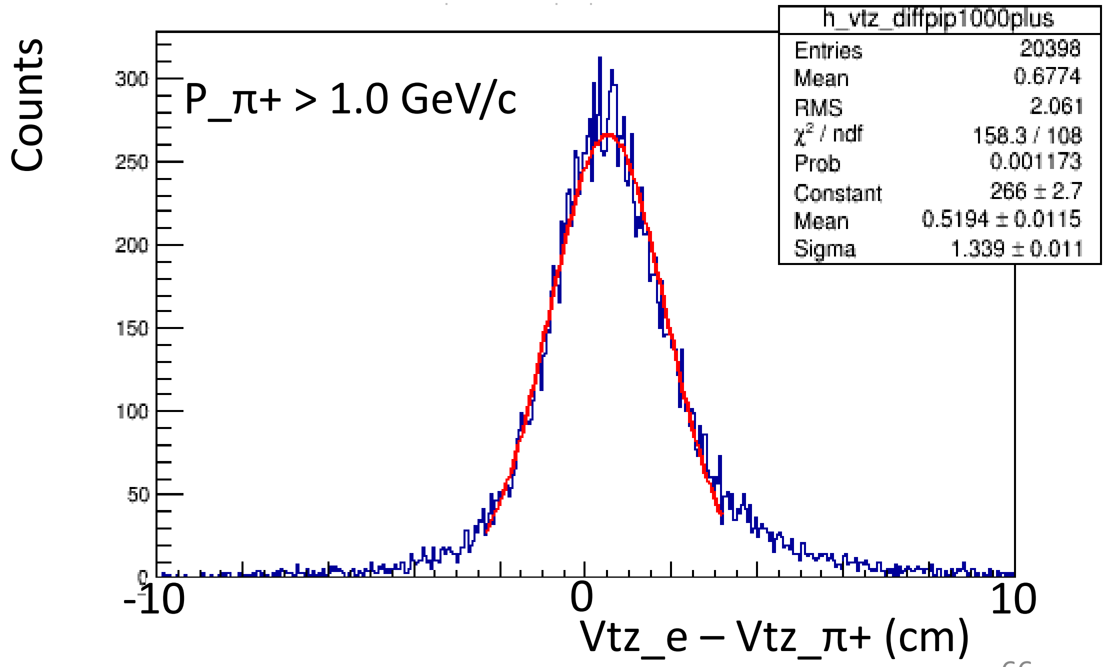
Vertex Z Difference (Electron – Pi+)

Fitted with gaussian

Cut = mean ± 3 * σ



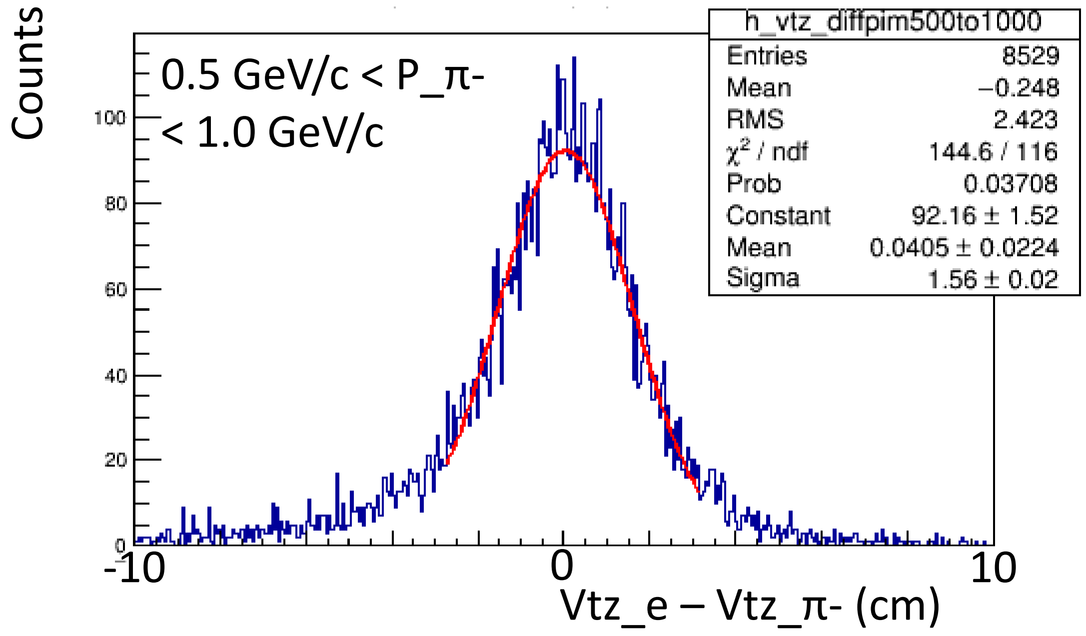


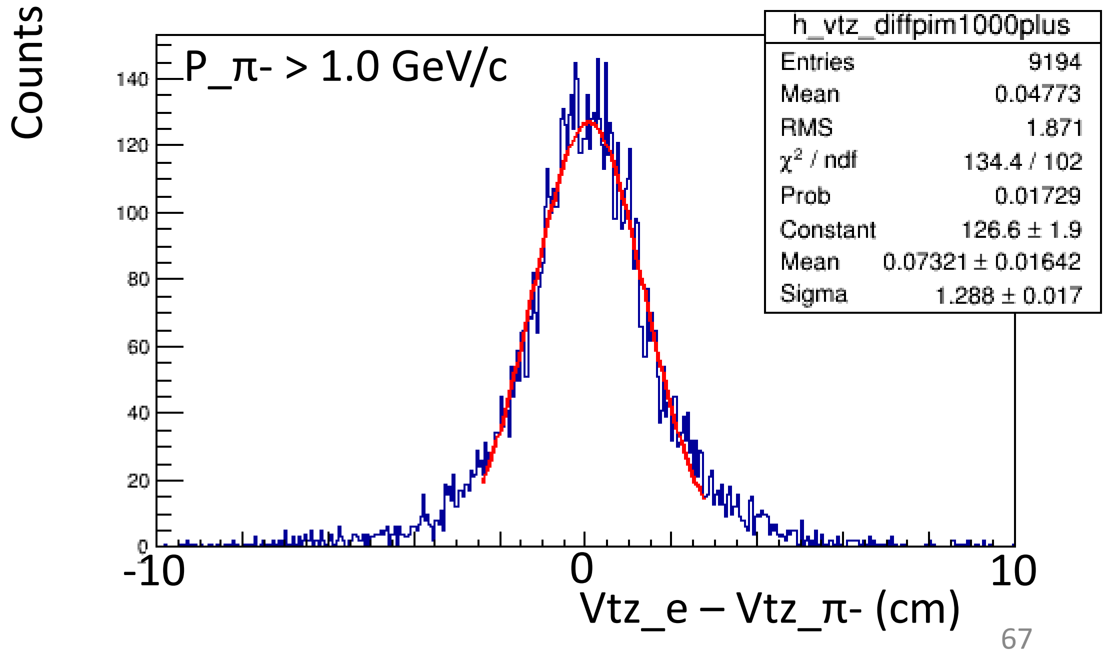


Vertex Z Difference (Electron – Pi-)

Fitted with gaussian

Cut = mean ± 3 * σ





D(e,e'pi) Cross Sections

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

What we want

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

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

Our formula

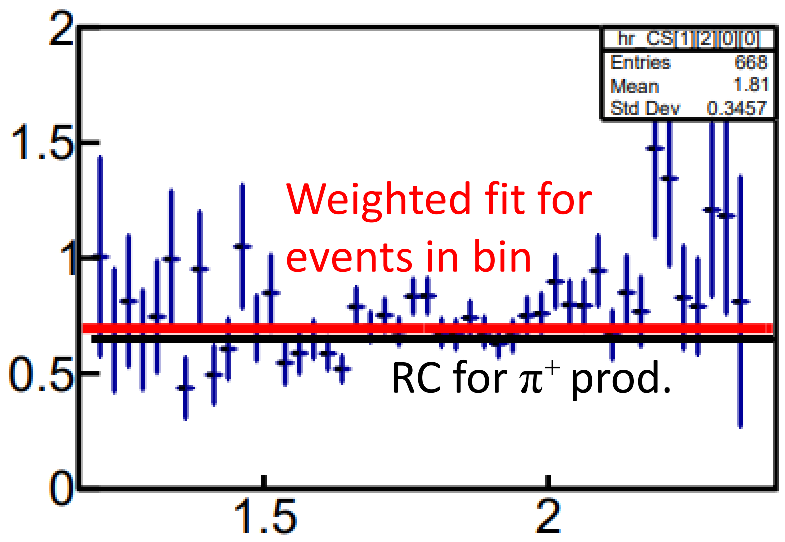
$$L = N_e * t_{tgt} \qquad N_e = \frac{Q_{tot}}{q_e} \qquad t_{tgt} = \frac{\rho_{tgt} l_{tgt} N_A}{mol_{tgt}}$$

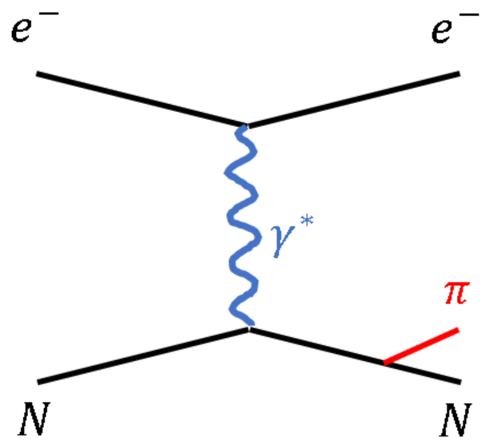
Radiative Correction

- with onepigen

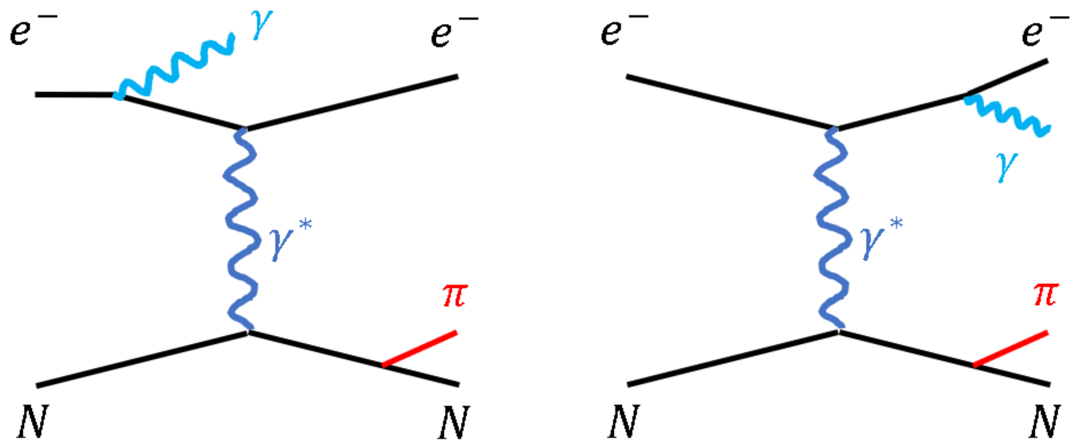
$$RC = \frac{CS_{norad}^{onepigen}}{CS_{rad}^{onepigen}}$$

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

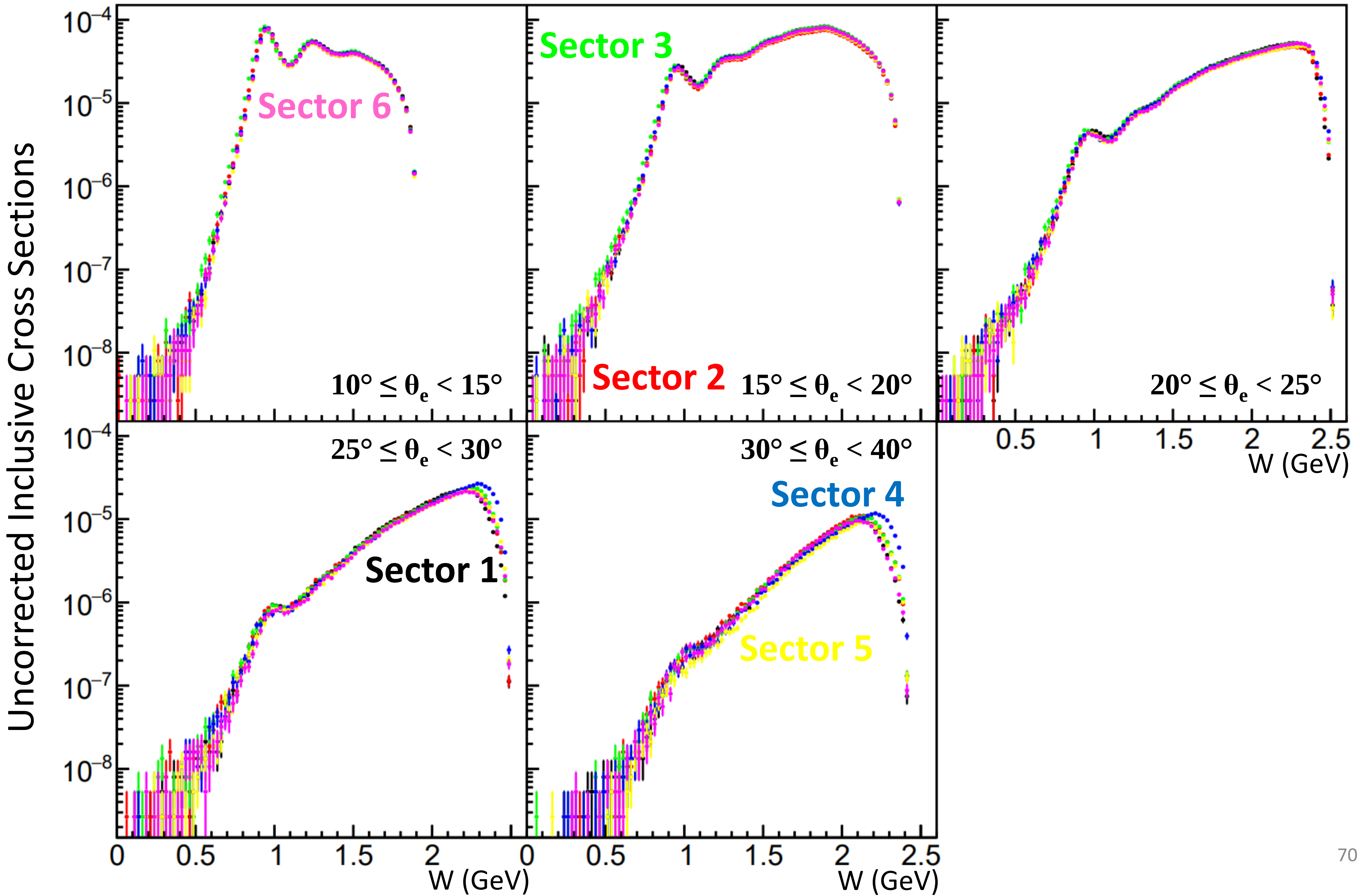




Non-radiative Event



Radiative Events



Uncorrected Inclusive Cross Sections
Sector 6
Sector 3
Sector 2
Sector 1
Sector 4
Sector 5
$10° \leq \theta_e < 15°$
$15° \leq \theta_e < 20°$
$20° \leq \theta_e < 25°$
$25° \leq \theta_e < 30°$
$30° \leq \theta_e < 40°$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
0.5
1
1.5
2
2.5
W (GeV)

Systematic Uncertainty

- Inclusive sector

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

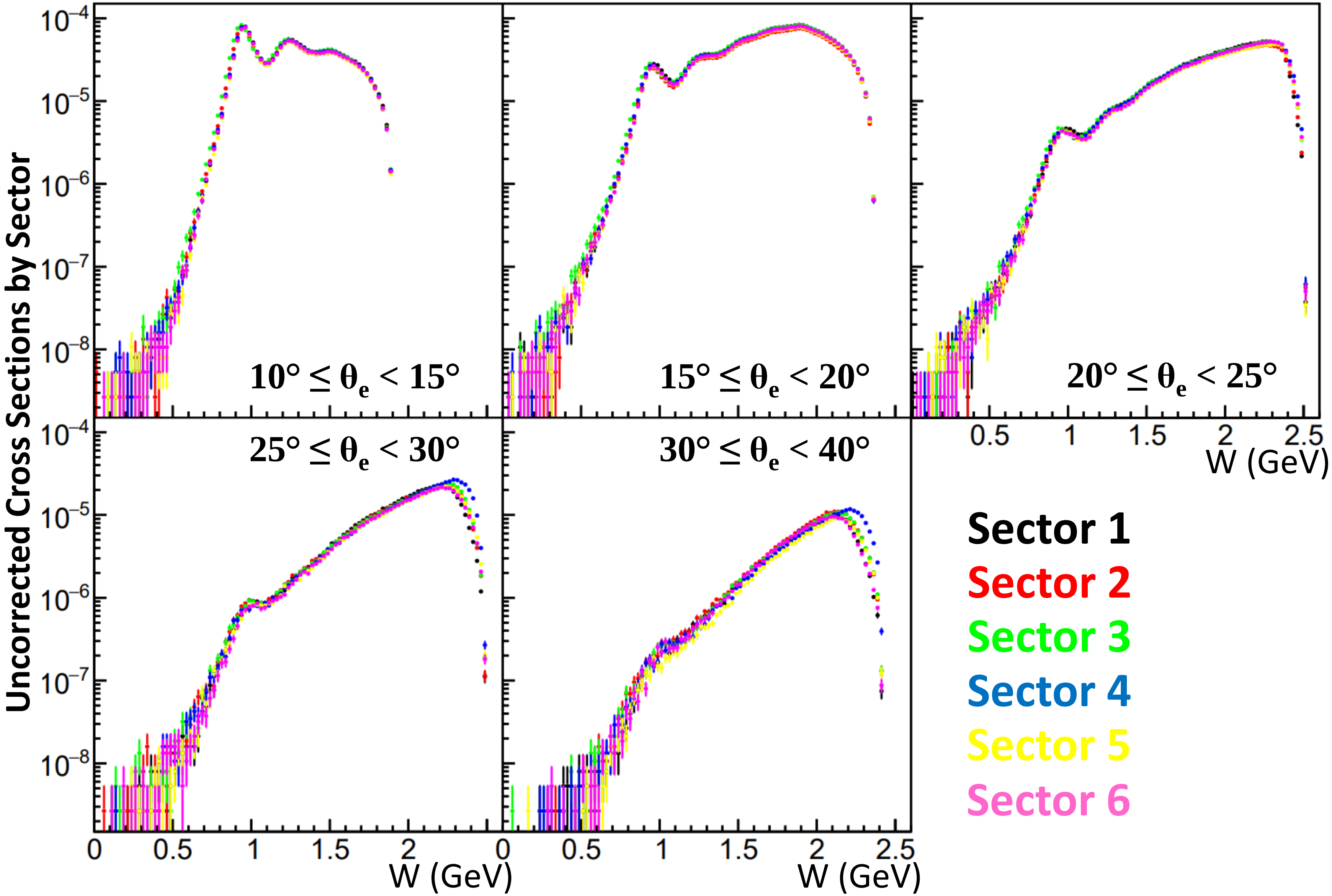
$$var = \frac{1}{5}\sum_{i}^{sec}(y_i - \bar{y})^2 - \frac{1}{6}\sum_{i}^{sec}\sigma_i^2$$

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

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

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

D(e,e')



Used similar procedure for semi-inc. cross sections

D(e,e')

All sectors divided by Sector 1

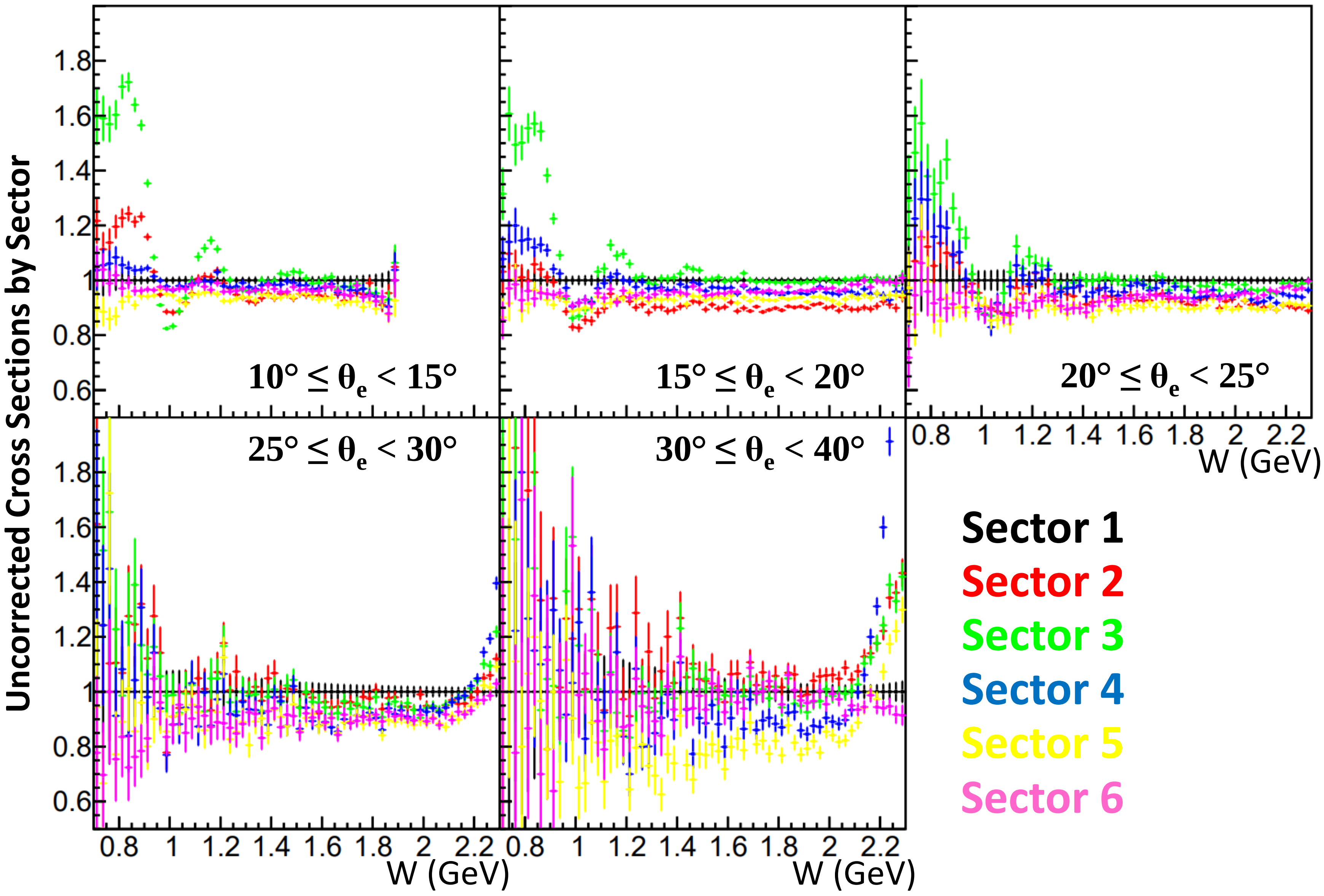
$$SysUnc_{sec} = \sqrt{var}$$

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

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

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

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



Used similar procedure for semi-inc. cross sections