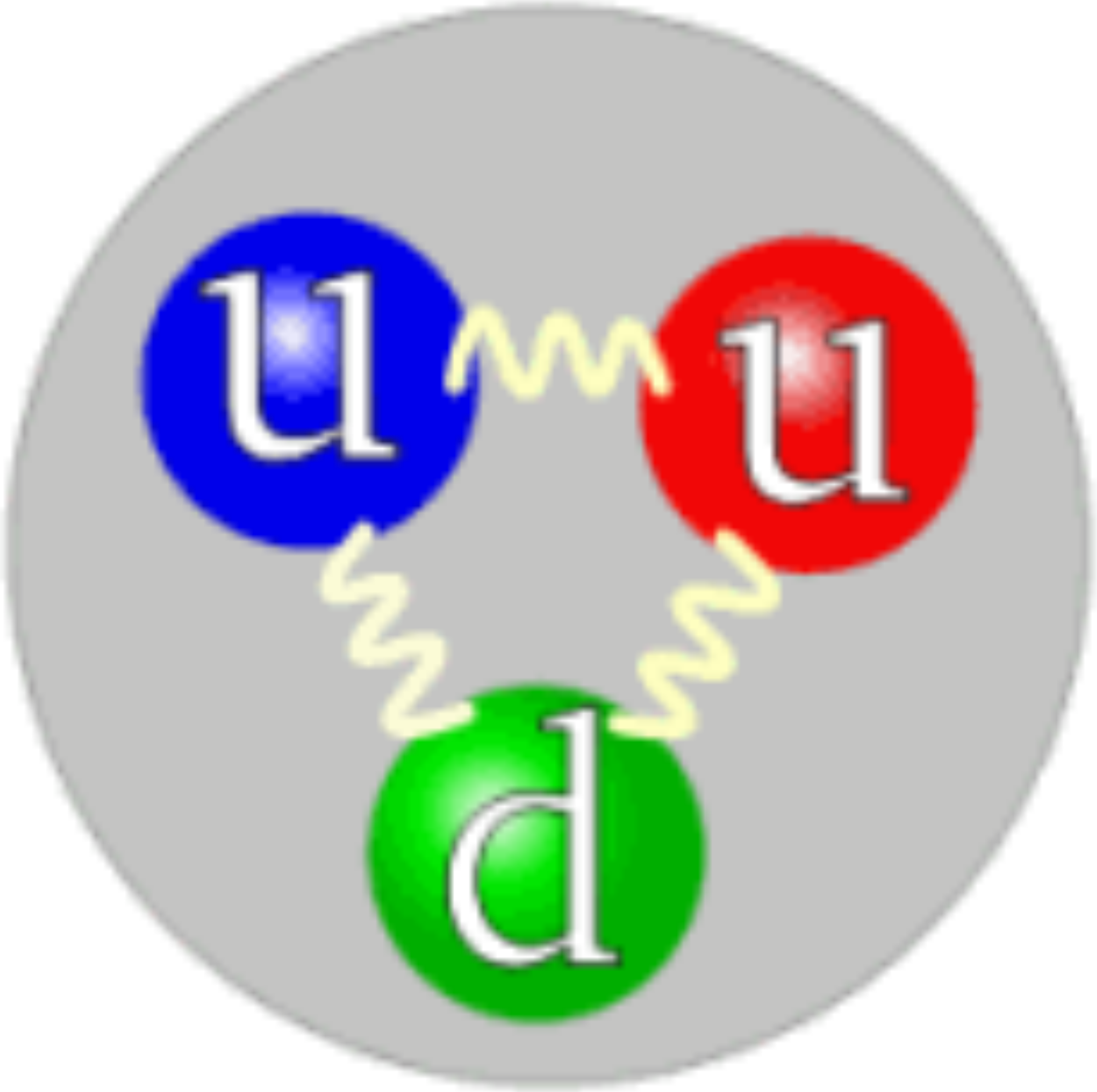
SIDIS @ CLAS12: Preliminary Measurements of $\pi^{\pm}$ Fragmentation Functions

Jason Phelan, MIT, 8/9/2024

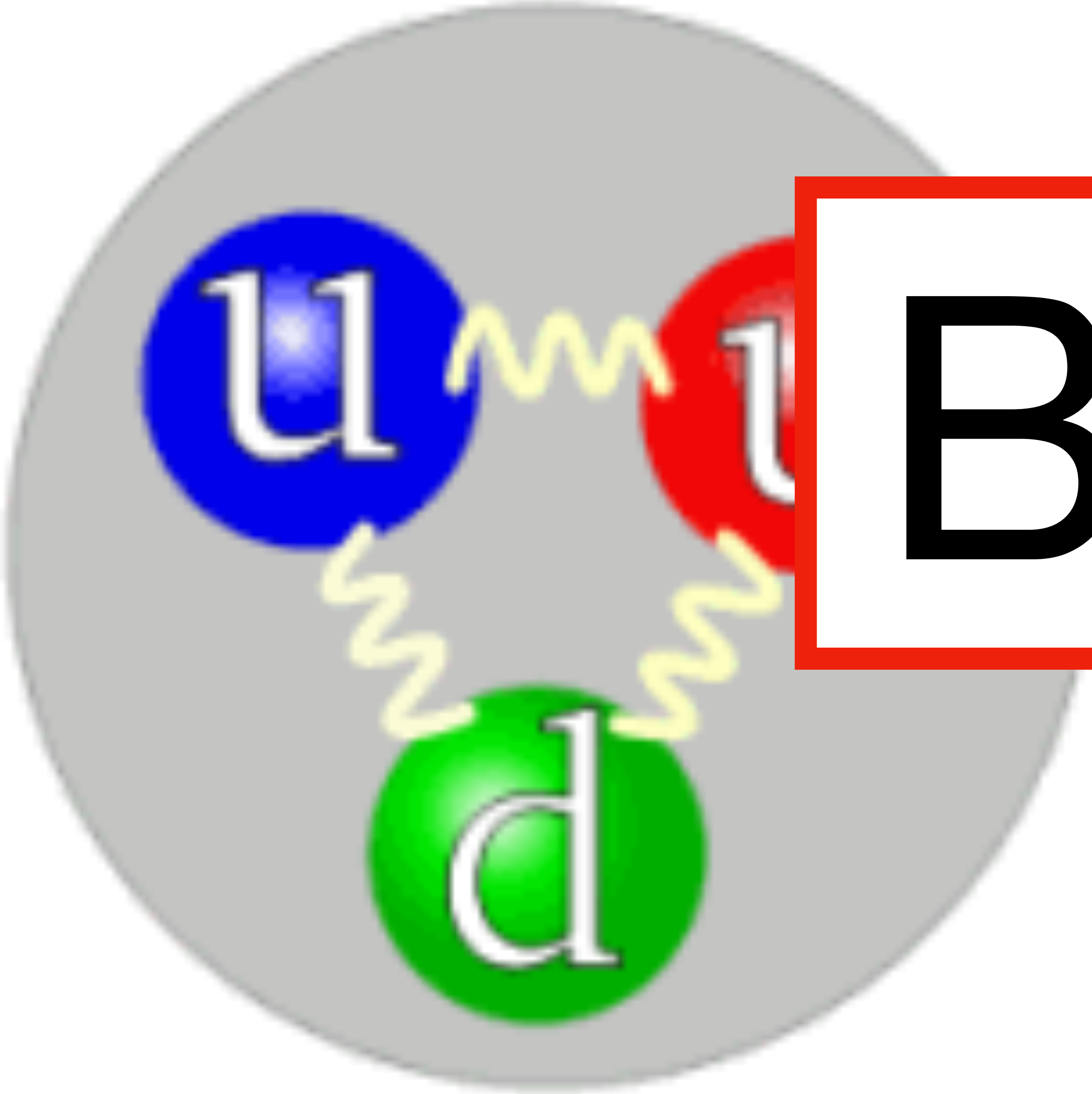
$SU(6)$ Spin-Flavor Symmetry



	Proton	Delta
M [GeV]	0.938	1.22
J	1/2	3/2

Image from wikipedia

$SU(6)$ **Spin-Flavor Symmetry**



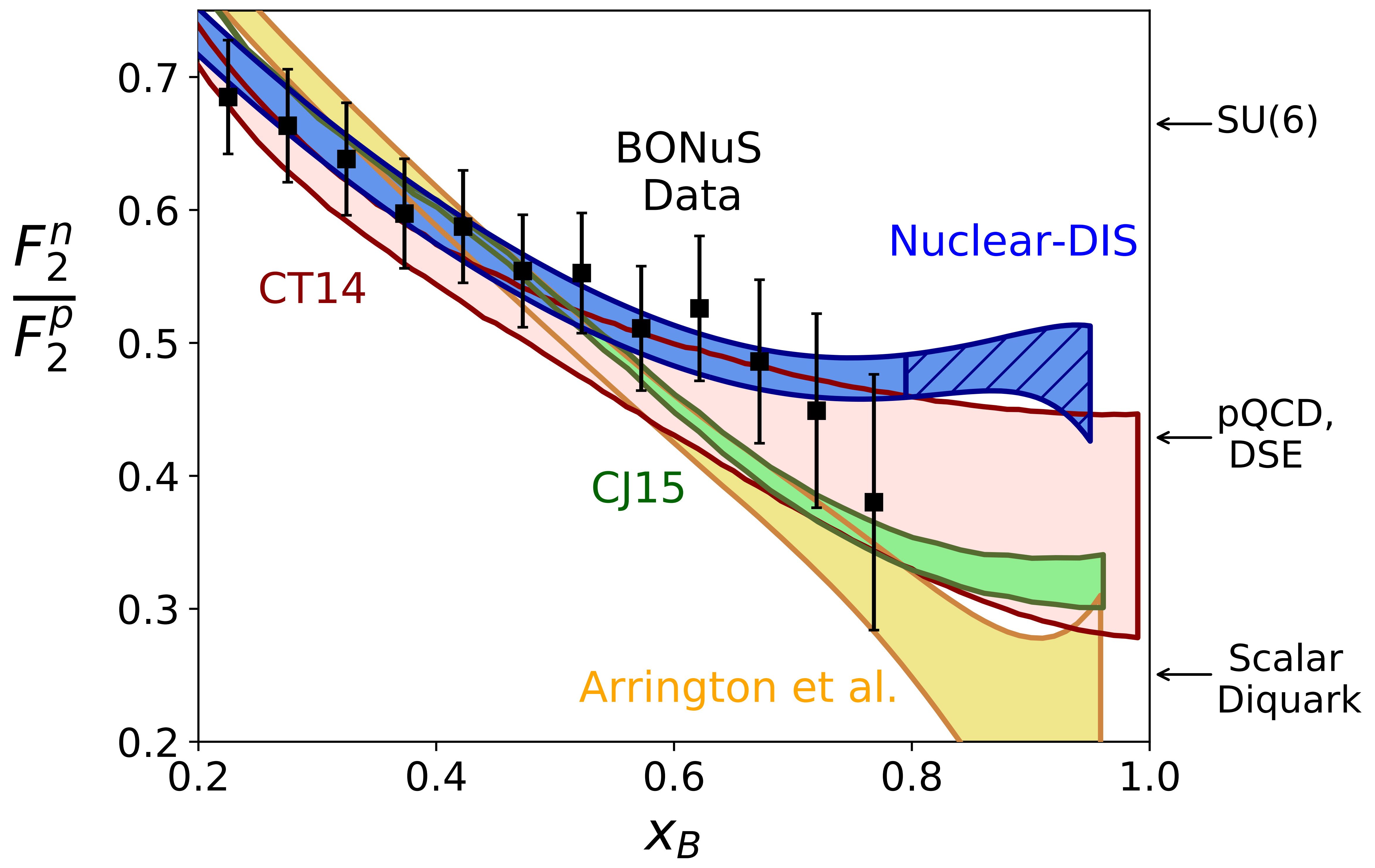
Broken!

	Proton	Delta
	0.938	1.22
J	1/2	3/2

Image from wikipedia

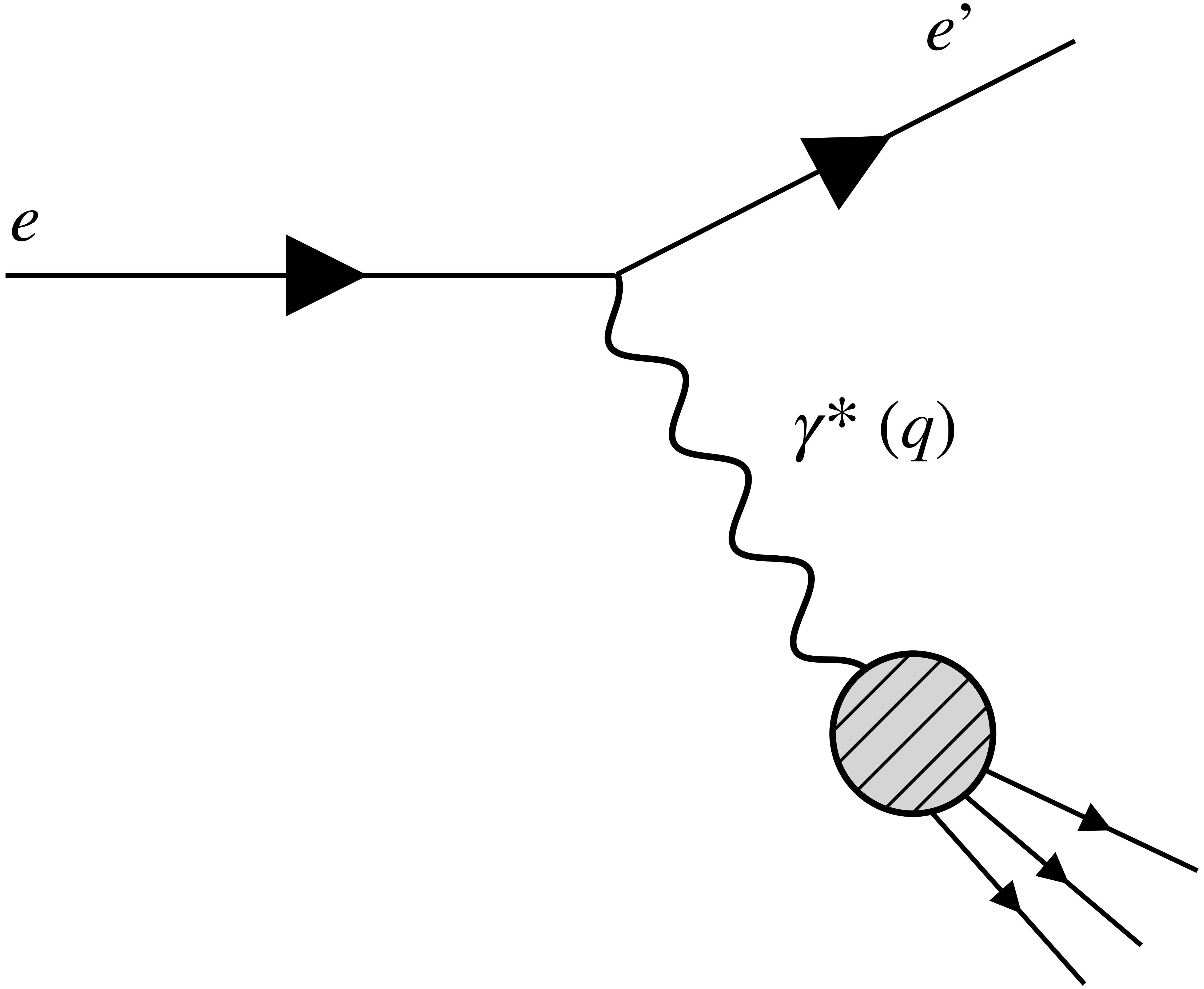
$SU(6)$ Spin-Flavor Symmetry Breaking

- Mechanism of symmetry breaking unknown
- Different models make different predictions about mechanisms
  - Look to d/u (or F_2^n/F_2^p) at extreme conditions
  - Traditionally extracted through fits



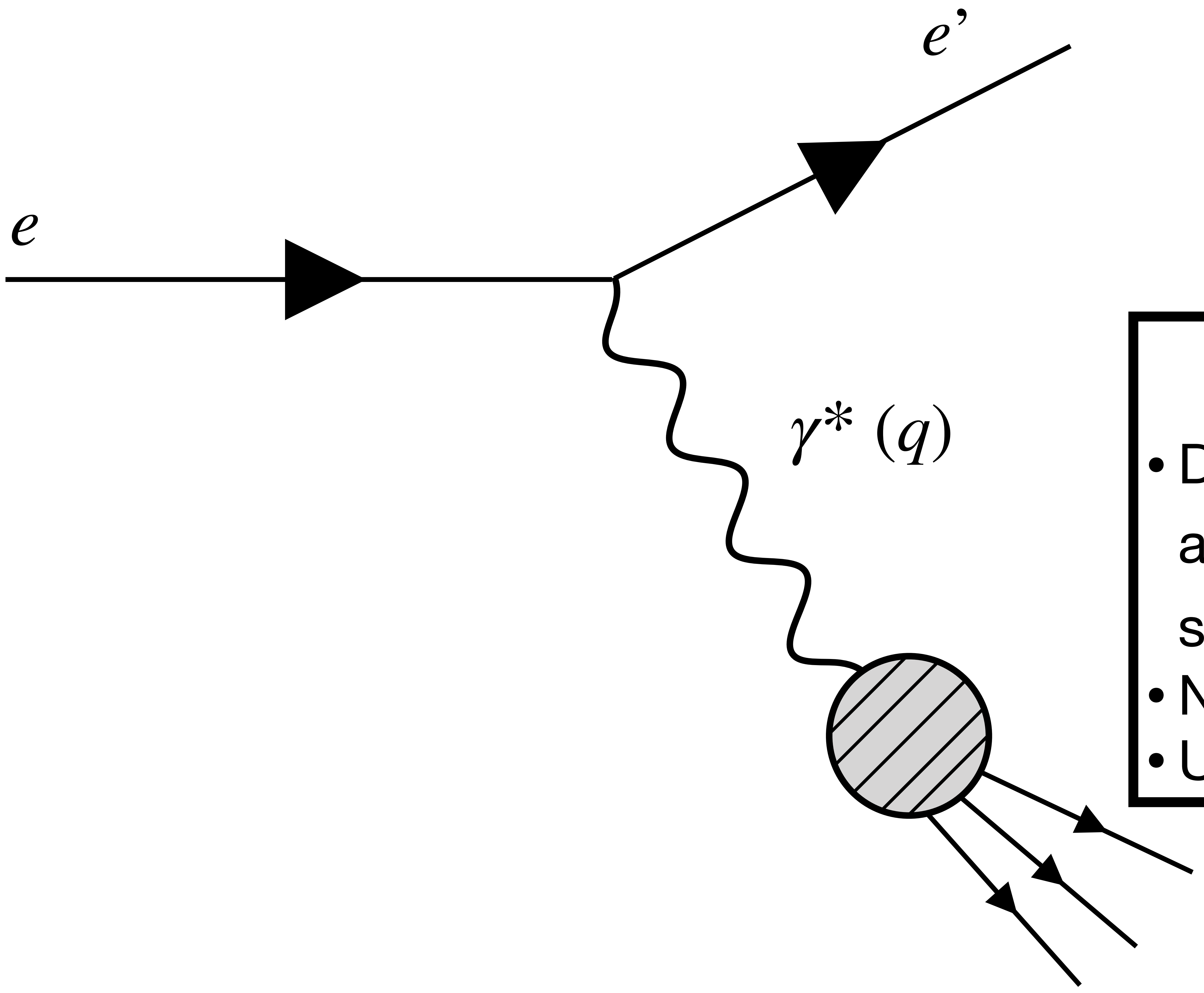
Segarra EP, Schmidt A, Kutz T, Higinbotham DW, Piasetzky E, Strikman M, Weinstein LB, Hen O. Neutron Valence Structure from Nuclear Deep Inelastic Scattering. Phys Rev Lett

Semi-Inclusive DIS



$$\sigma_{SIDIS} \propto \sigma_{DIS} \otimes PDF \otimes FF$$

Semi-Inclusive DIS



$$\sigma_{SIDIS} \propto \sigma_{DIS} \otimes PDF \otimes FF$$

Fragmentation Function: $FF = D_q^h(z, p_T)$

- Describes probability of producing hadron h at energy fraction $z = E_\pi/\omega$ and p_T by scattering off of quark q
- Non-perturbative part of cross section
- UNIVERSAL!

SIDIS in the Parton model

Flavor tagging at high z

- Mott cross section for nucleons:

$$\sigma_p^{\pi\pm} \propto 4u_p(x_B)D_u^{\pm}(z) + d_p(x_B)D_d^{\pm}(z) + \text{(sea contributions)}$$

$$\sigma_n^{\pi\pm} \propto 4u_n(x_B)D_u^{\pm}(z) + d_n(x_B)D_d^{\pm}(z) + \text{(sea contributions)}$$

SIDIS in the Parton model

Flavor tagging at high z

- Mott cross section for nucleons:

$$\sigma_p^{\pi\pm} \propto 4u_p(x_B)D_u^{\pm}(z) + d_p(x_B)D_d^{\pm}(z) + \text{(sea contributions)}$$

$$\sigma_n^{\pi\pm} \propto 4u_n(x_B)D_u^{\pm}(z) + d_n(x_B)D_d^{\pm}(z) + \text{(sea contributions)}$$

Isospin symmetry (i.e. $D_u^{\pm} = D_d^{\mp} = D^{\pm}$)

$$r = \frac{D^-}{D^+} = \frac{4\frac{u}{d} - (\sigma_p^{\pi+}/\sigma_p^{\pi-})}{4\frac{u}{d}(\sigma_p^{\pi+}/\sigma_p^{\pi-}) - 1}$$

SIDIS in the Parton model

Flavor tagging at high z

- Mott cross section for nucleons:

$$\sigma_p^{\pi\pm} \propto 4u_p(x_B)D_u^{\pm}(z) + d_p(x_B)D_d^{\pm}(z) + \text{~~(sea contributions)~~}$$

$$\sigma_n^{\pi\pm} \propto 4u_n(x_B)D_u^{\pm}(z) + d_n(x_B)D_d^{\pm}(z) + \text{~~(sea contributions)~~}$$

Isospin symmetry (i.e. $D_u^{\pm} = D_d^{\mp} = D^{\pm}$)

$$r = \frac{D^-}{D^+} = \frac{4\frac{u}{d} - (\sigma_p^{\pi+}/\sigma_p^{\pi-})}{4\frac{u}{d}(\sigma_p^{\pi+}/\sigma_p^{\pi-}) - 1}$$

$$r = \frac{4 - (\sigma_d^{\pi+}/\sigma_d^{\pi-})}{4(\sigma_d^{\pi+}/\sigma_d^{\pi-}) - 1}$$ for the deuteron!

SIDIS in the Parton model

Flavor tagging at high z

- Mott cross section for nucleons:

$$\sigma_p^{\pi\pm} \propto 4u_p(x_B)D_u^{\pm}(z) + d_p(x_B)D_d^{\pm}(z) + \sout{(sea\ contributions)}$$

$$\sigma_n^{\pi\pm} \propto 4u_n(x_B)D_u^{\pm}(z) + d_n(x_B)D_d^{\pm}(z) + \sout{(sea\ contributions)}$$

Isospin symmetry (i.e. $D_u^{\pm} = D_d^{\mp} = D^{\pm}$)

$$r = \frac{D^-}{D^+} = \frac{4\frac{u}{d} - (\sigma_p^{\pi+}/\sigma_p^{\pi-})}{4\frac{u}{d}(\sigma_p^{\pi+}/\sigma_p^{\pi-}) - 1}$$

$$r = \frac{4 - (\sigma_d^{\pi+}/\sigma_d^{\pi-})}{4(\sigma_d^{\pi+}/\sigma_d^{\pi-}) - 1}$$ for the deuteron!

Field-Feyman Model

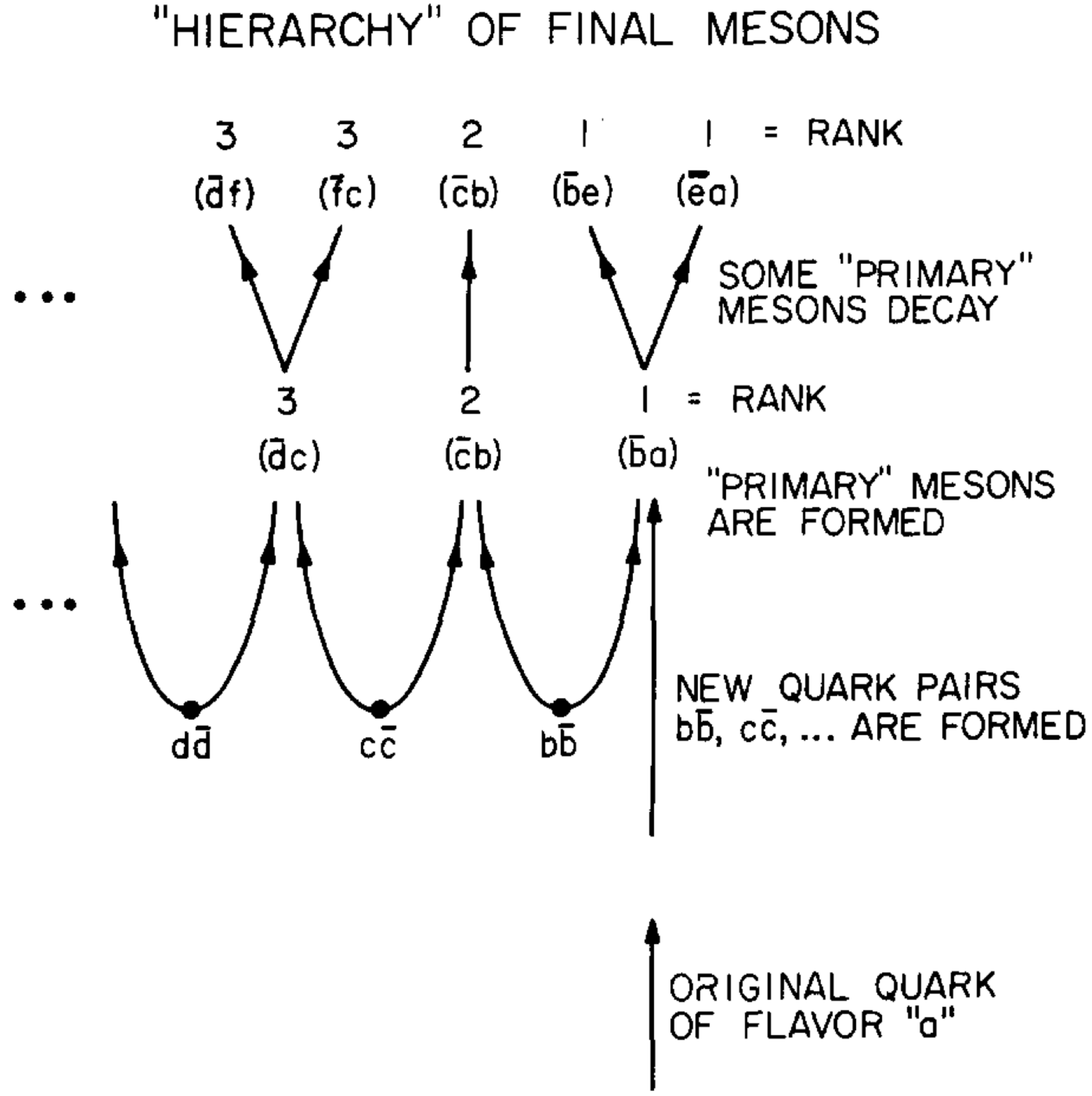
- Recursive model of hadronization

$$F(z) = f(1-z) + \int_0^1 \frac{d\eta}{\eta} f(\eta) F\left(\frac{z}{\eta}\right)$$

- Extract unfavored/favored fragmentation ratio

$$r(z) = \frac{D_d^{\pi+}}{D_u^{\pi+}} = \frac{D_u^{\pi-}}{D_d^{\pi-}} = \frac{1-z}{1-z+\frac{z}{\beta}}$$

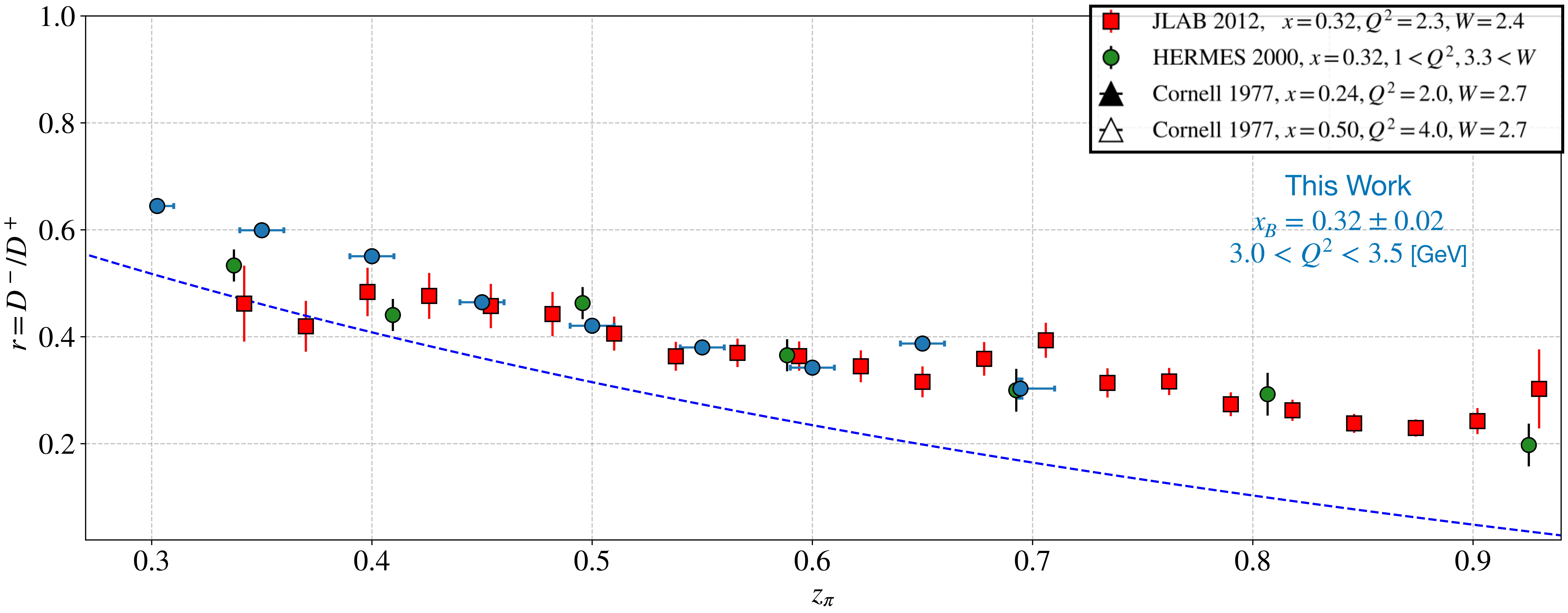
- $\beta \approx 0.46$ extracted from fits to data



R.D. Field and R.P. Feynman, Phys.Rev. D15 (1977) 2590

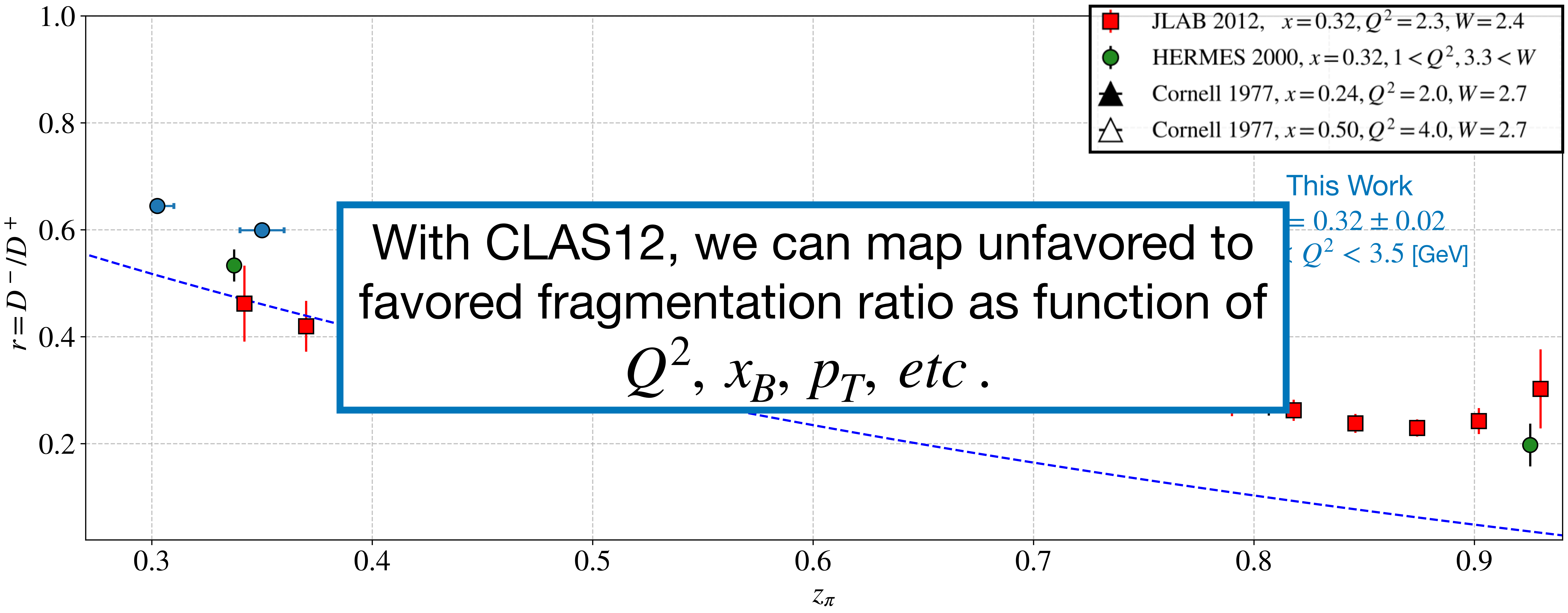
Our Data from CLAS12

$d(e, e'\pi)X$



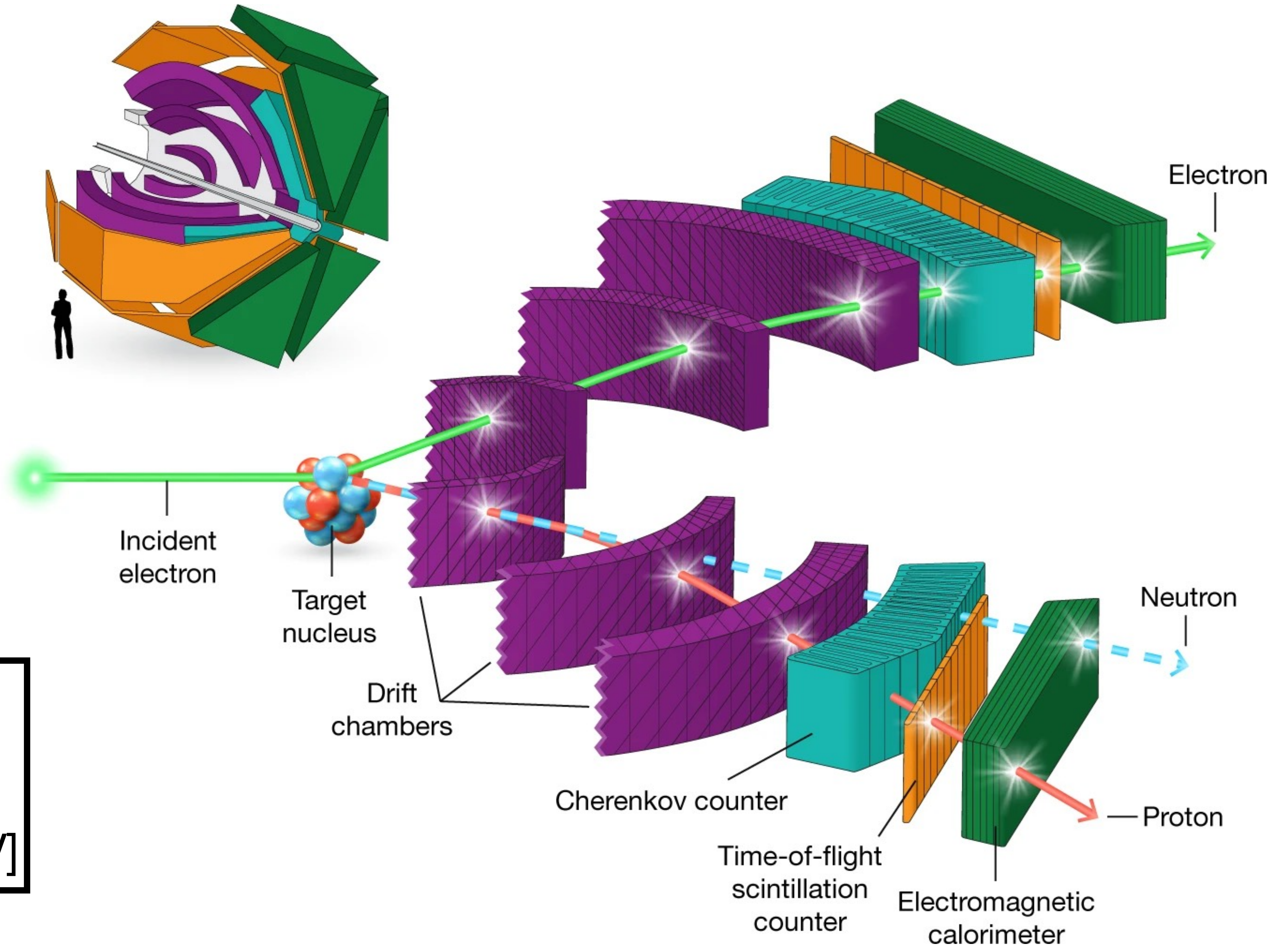
Our Data from CLAS12

$d(e, e'\pi)X$



With CLAS12, we can map unfavored to favored fragmentation ratio as function of Q^2, x_B, p_T, etc .

CLAS12 Forward Detector

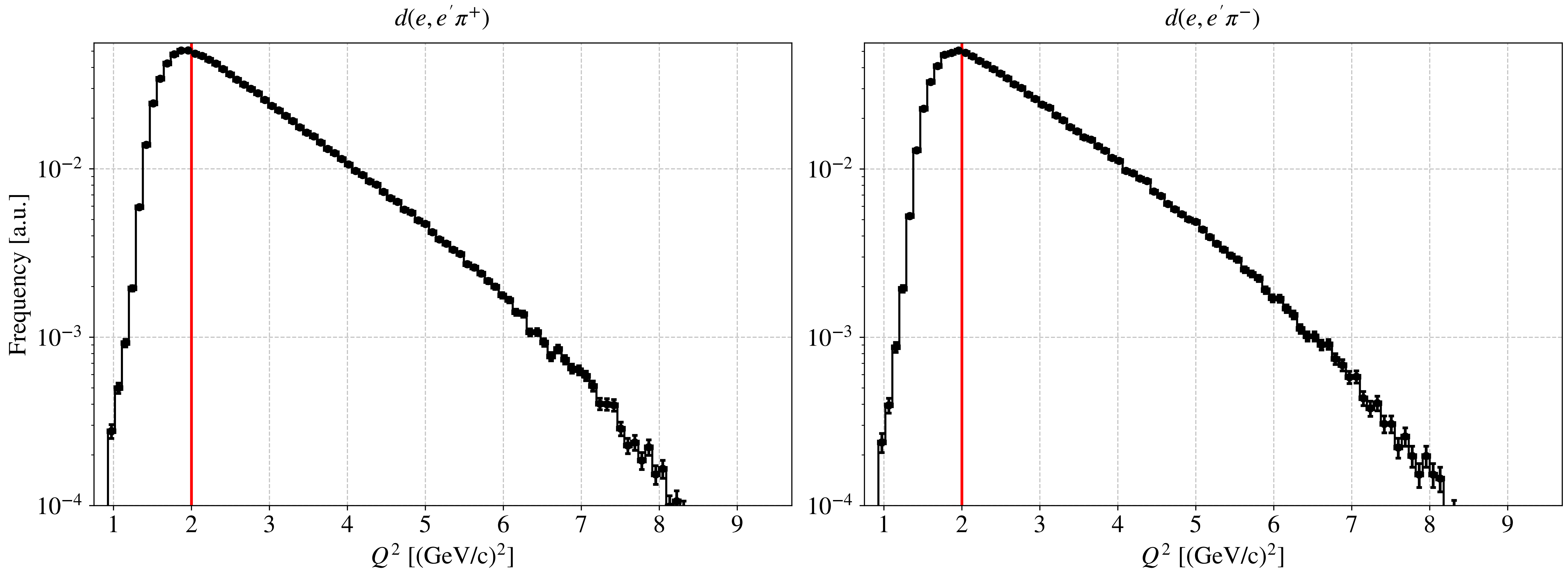


Using RG-B Deuterium data at
$E_{beam} = 10.2\ ,10.4,\ 10.6$ [GeV]

The CLAS Collaboration. Probing high-momentum protons and neutrons in neutron-rich nuclei. *Nature* **560**, 617–621 (2018). https://doi.org/10.1038/s41586-018-0400-z

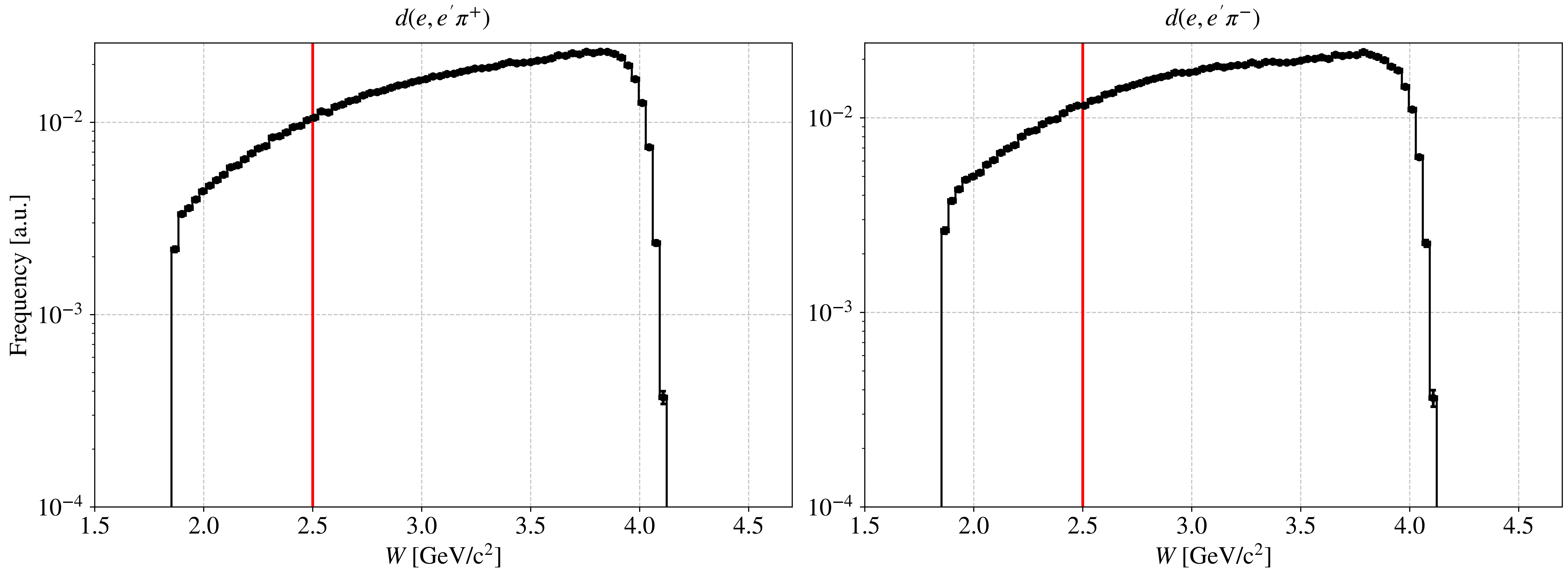
Event Selection: Electron

- $Q^2 > 2$ GeV^2
- $W > 2.5$ GeV
- $y < 0.75$
- $5 < \theta_e < 35$ deg.



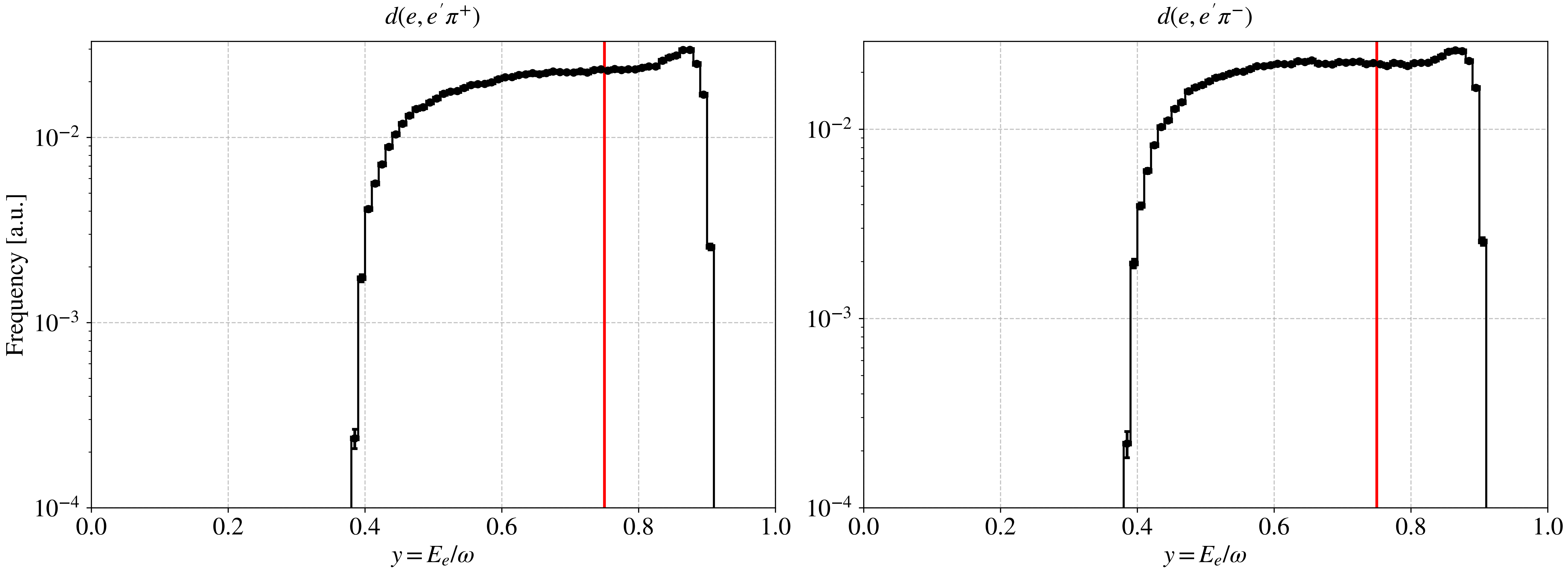
Event Selection: Electron

- $Q^2 > 2$ GeV^2
- $W > 2.5$ GeV
- $y < 0.75$
- $5 < \theta_e < 35$ deg.



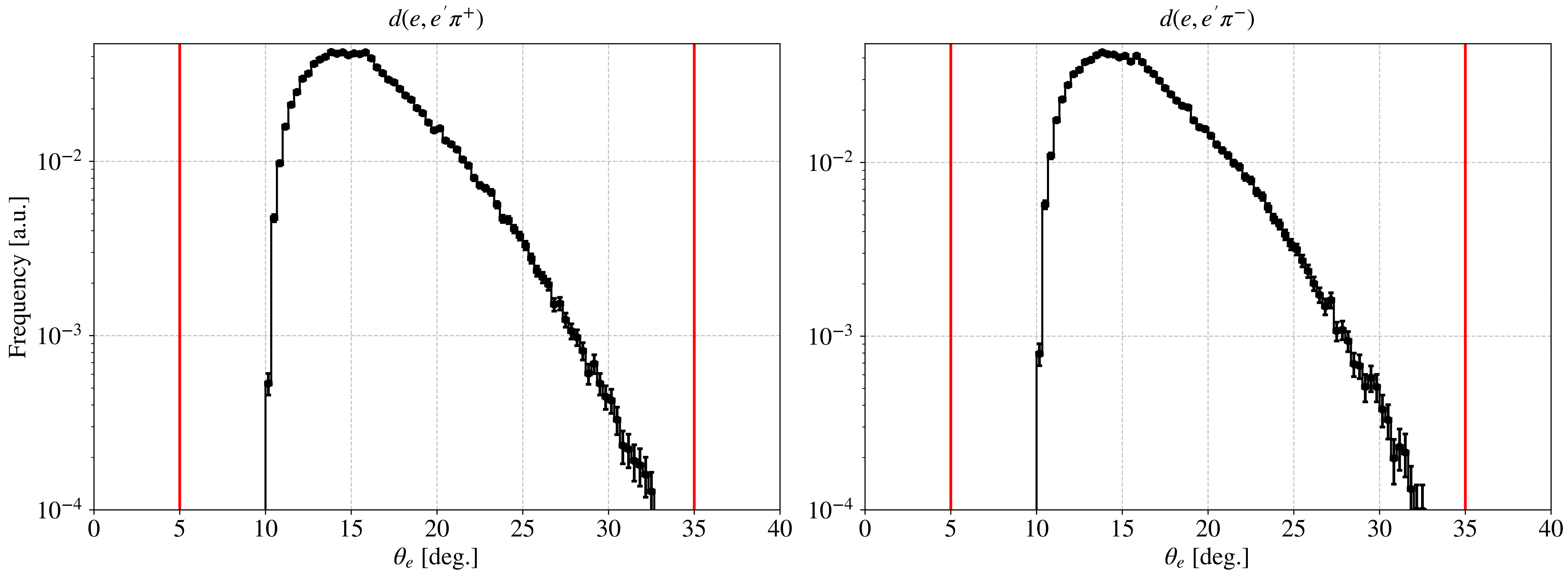
Event Selection: Electron

- $Q^2 > 2$ GeV^2
- $W > 2.5$ GeV
- $y < 0.75$
- $5 < \theta_e < 35$ deg.



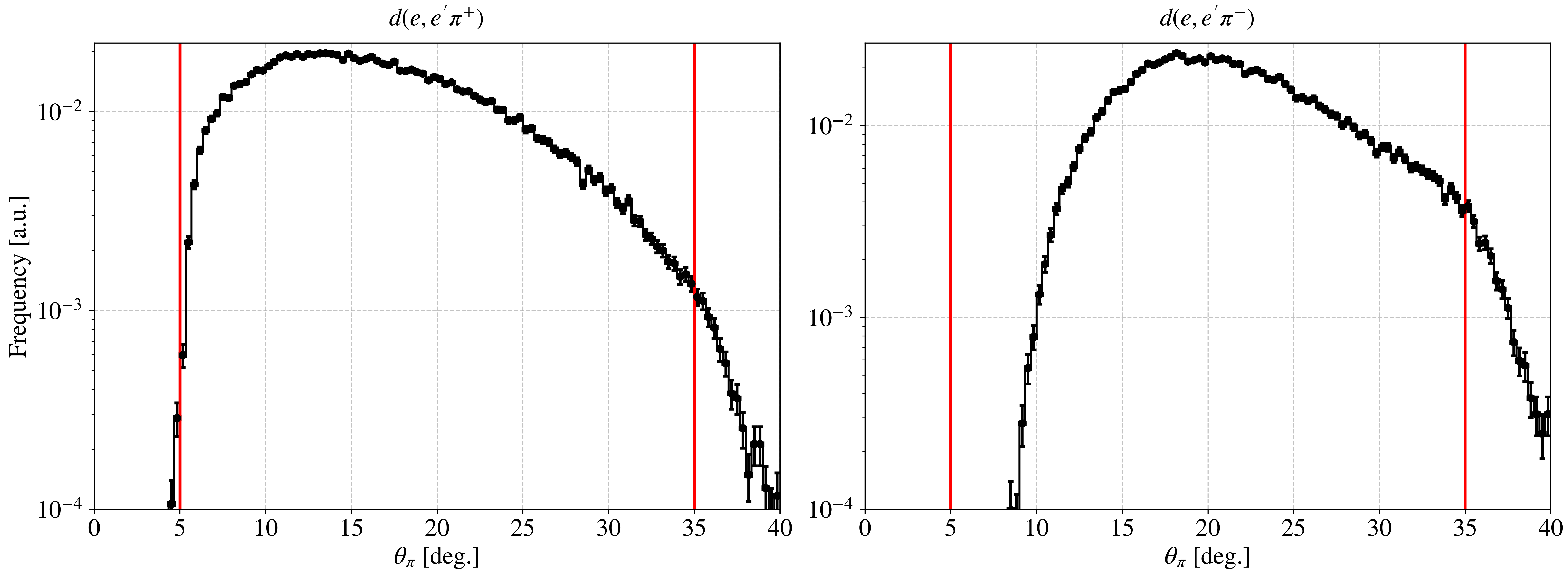
Event Selection: Electron

- $Q^2 > 2$ GeV^2
- $W > 2.5$ GeV
- $y < 0.75$
- $5 < \theta_e < 35$ deg.



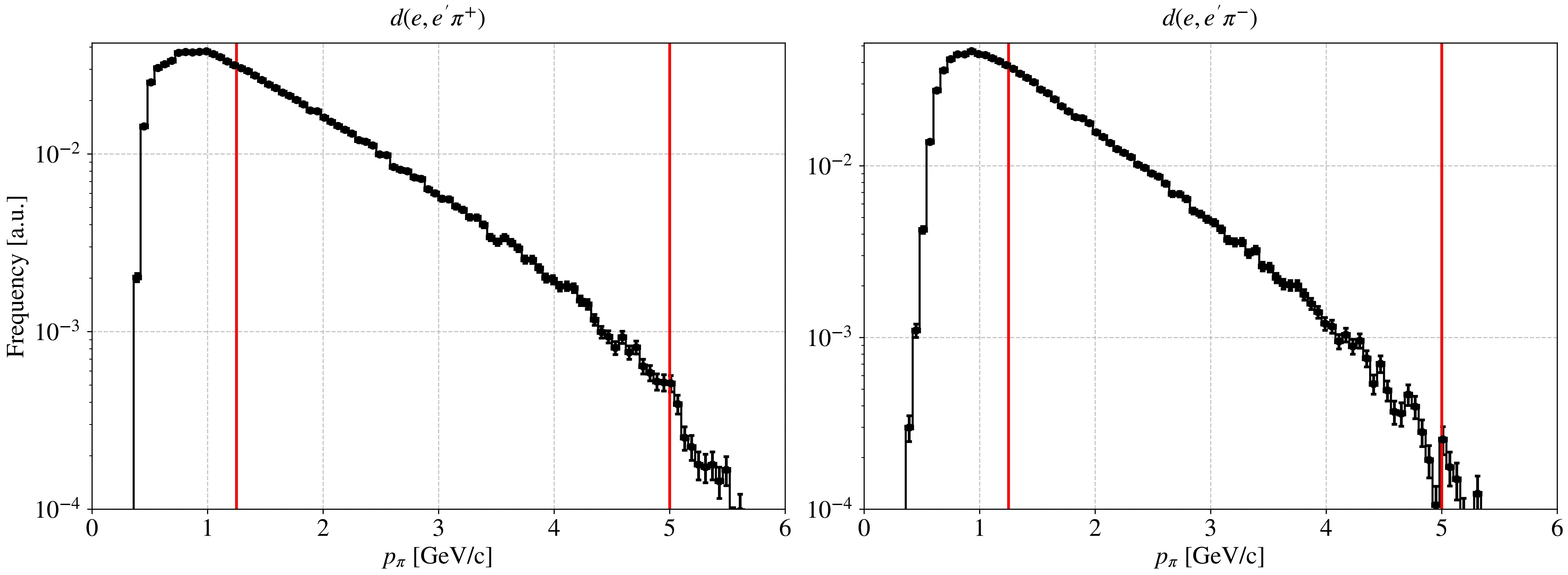
Event Selection: Pion

- $5 < \theta_\pi < 35$ deg.
- $1.25 < p_\pi < 5$ GeV
- $1.7 < M_X < 5$ GeV
- $.3 < Z < .8$



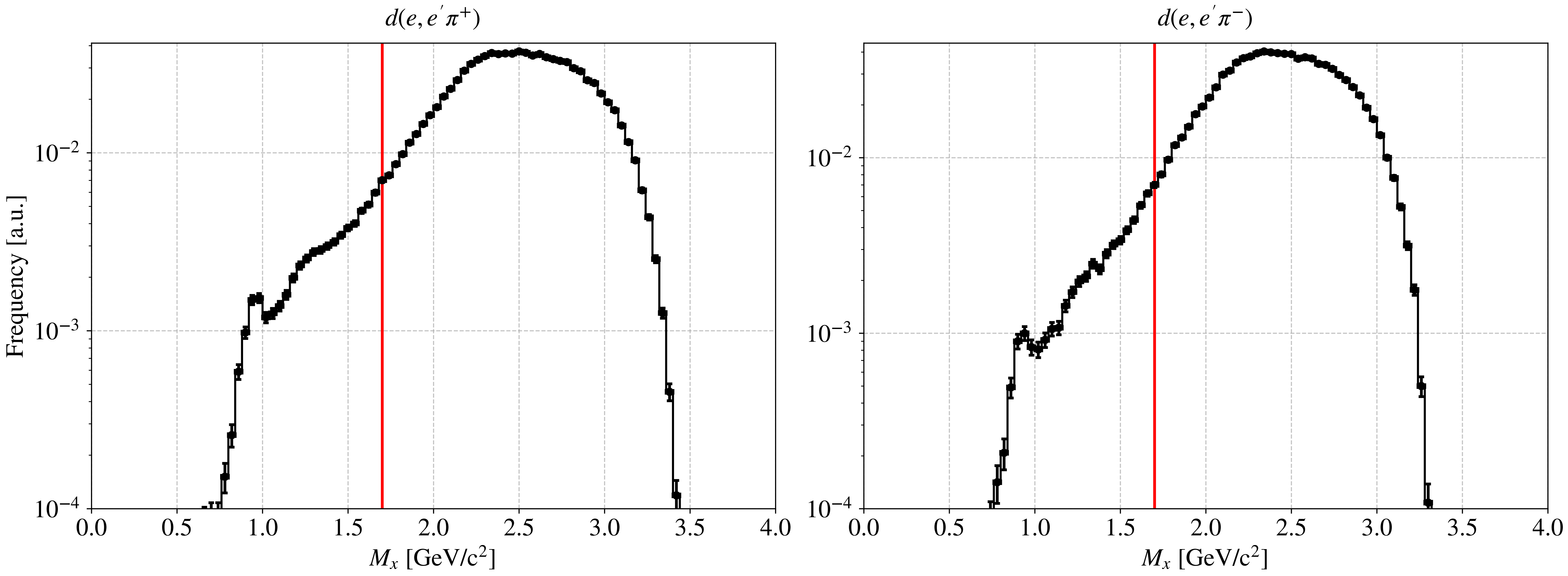
Event Selection: Pion

- $5 < \theta_\pi < 35$ deg.
- $1.25 < p_\pi < 5$ GeV
- $1.7 < M_X < 5$ GeV
- $.3 < Z < .8$



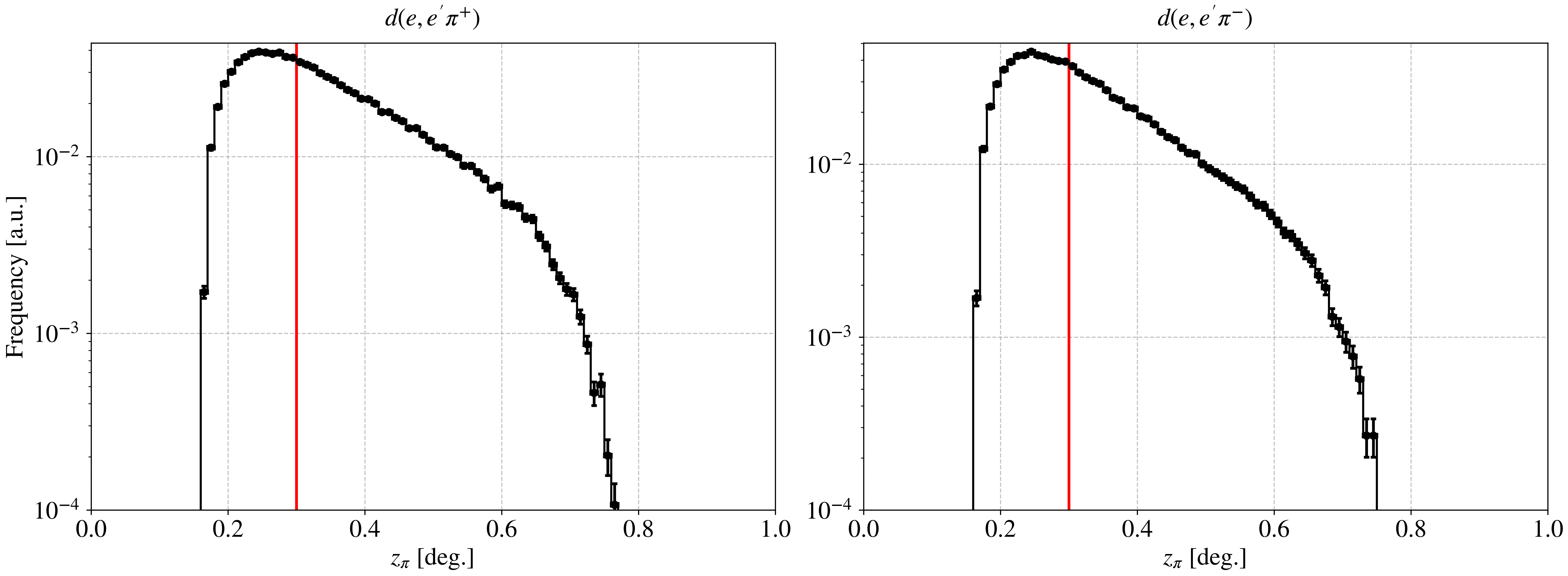
Event Selection: Pion

- $5 < \theta_\pi < 35$ deg.
- $1.25 < p_\pi < 5$ GeV
- $1.7 < M_X < 5$ GeV
- $.3 < Z < .8$



Event Selection: Pion

- $5 < \theta_\pi < 35$ deg.
- $1.25 < p_\pi < 5$ GeV
- $1.7 < M_X < 5$ GeV
- $.3 < Z < .8$

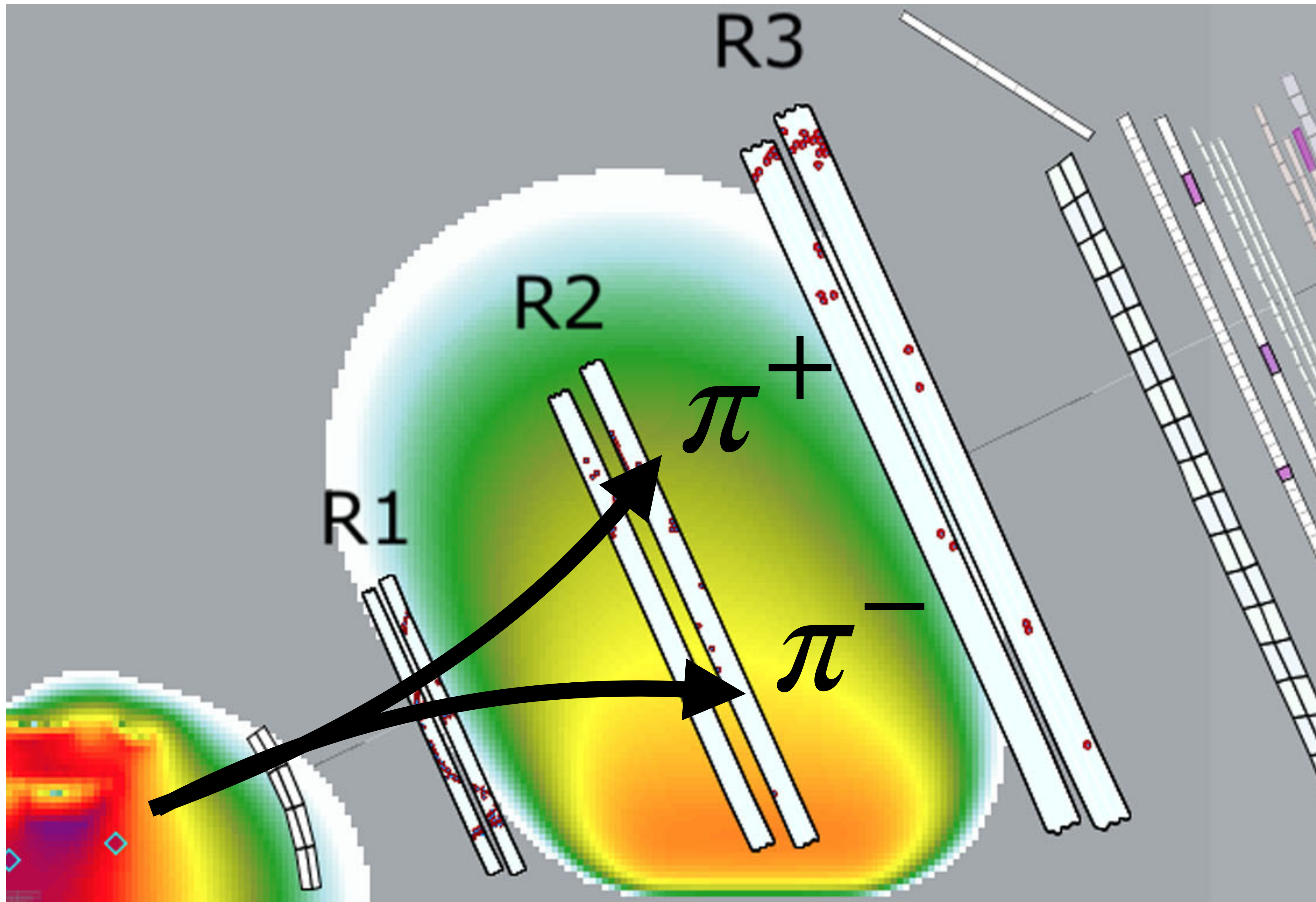


Matching Phase Space

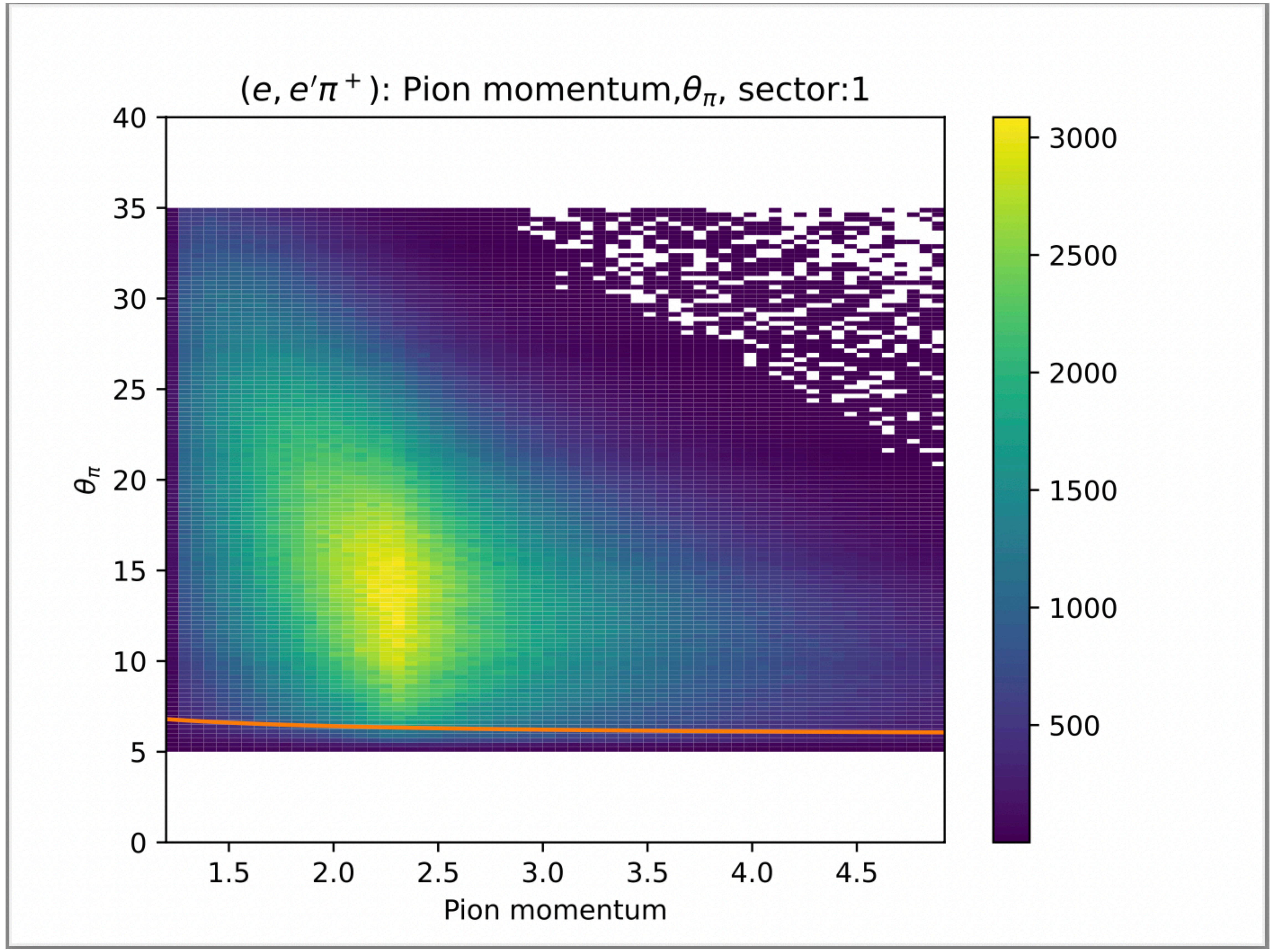
$$\frac{Y^{\pi+}(p^{\pi+},\ \theta^{\pi+},\ \phi^{\pi+})}{Y^{\pi-}(p^{\pi-},\ \theta^{\pi-},\ \phi^{\pi-})} \longrightarrow \frac{Y^{\pi+}(p,\ \theta,\ \phi)}{Y^{\pi-}(p,\ \theta,\ \phi)}$$

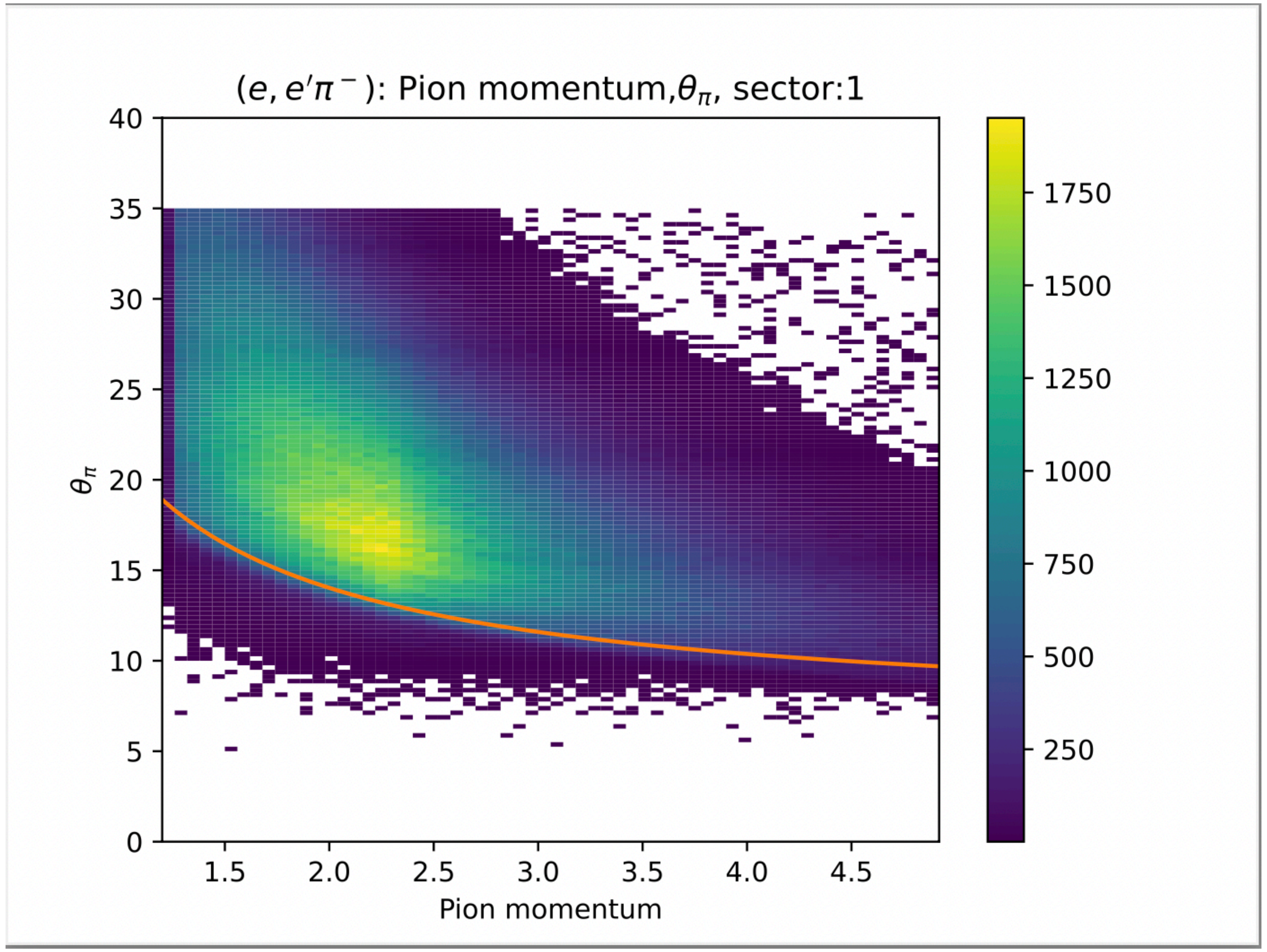
What we measure

What we want



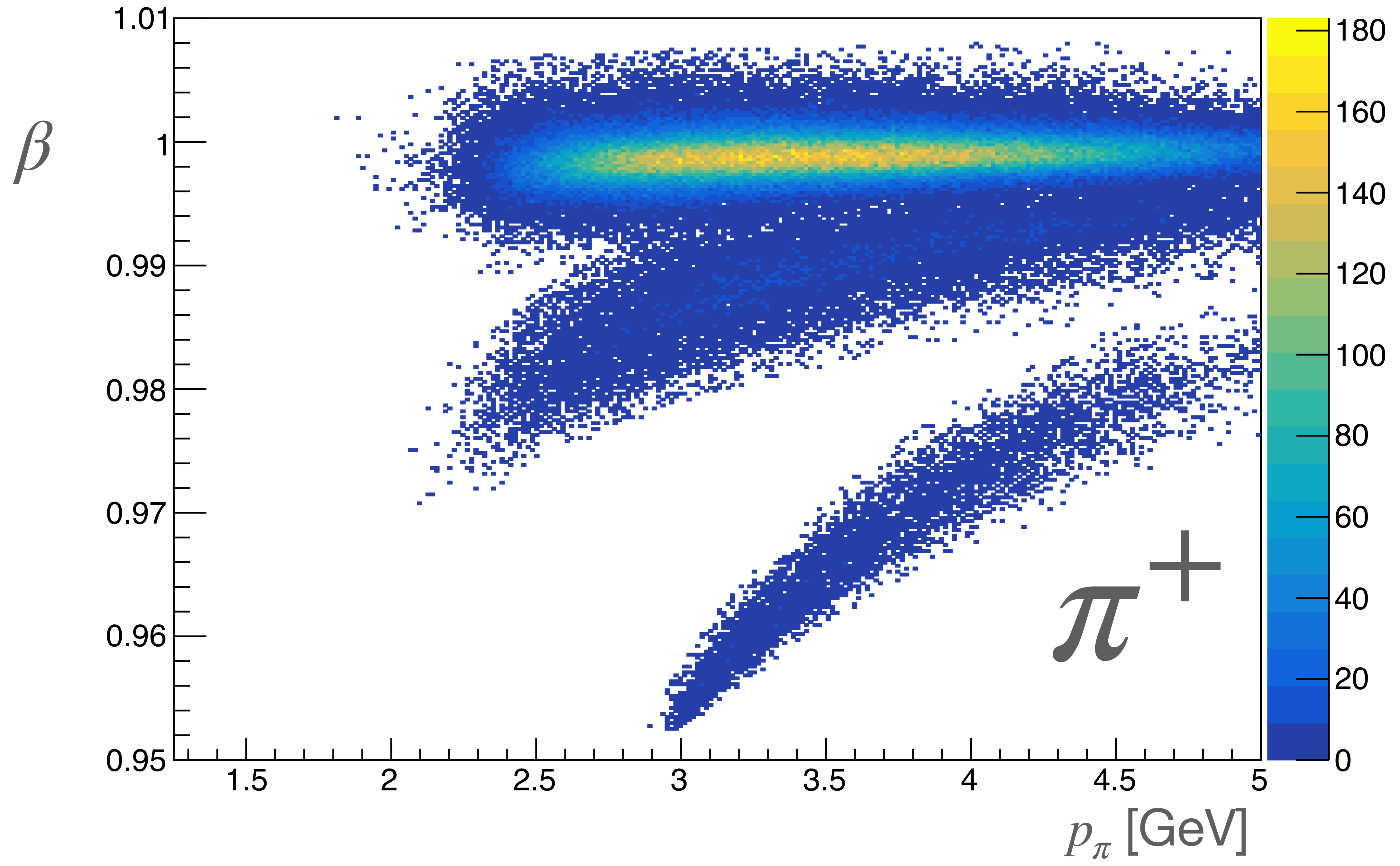
Matching Phase Space

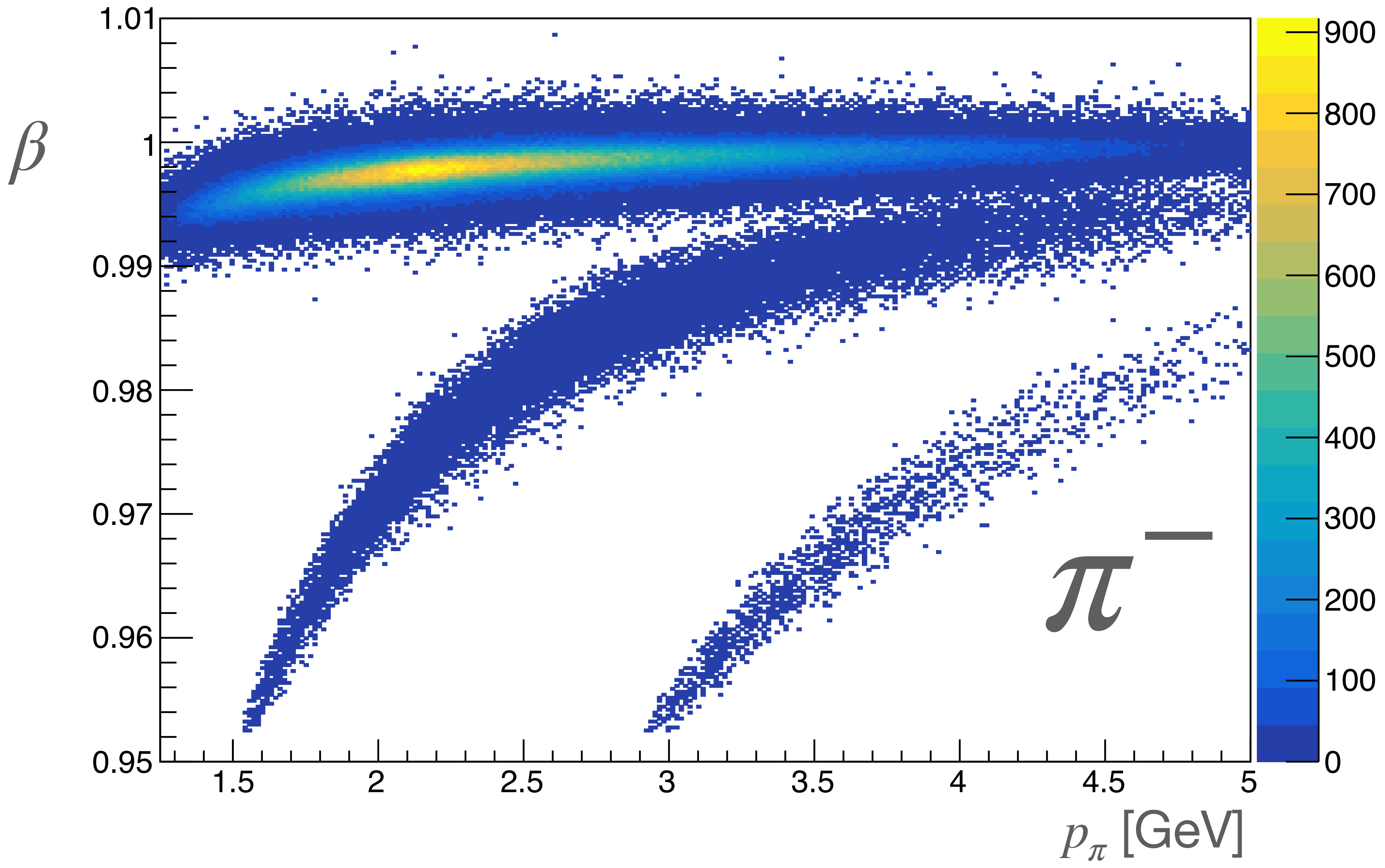




Kaon Contamination

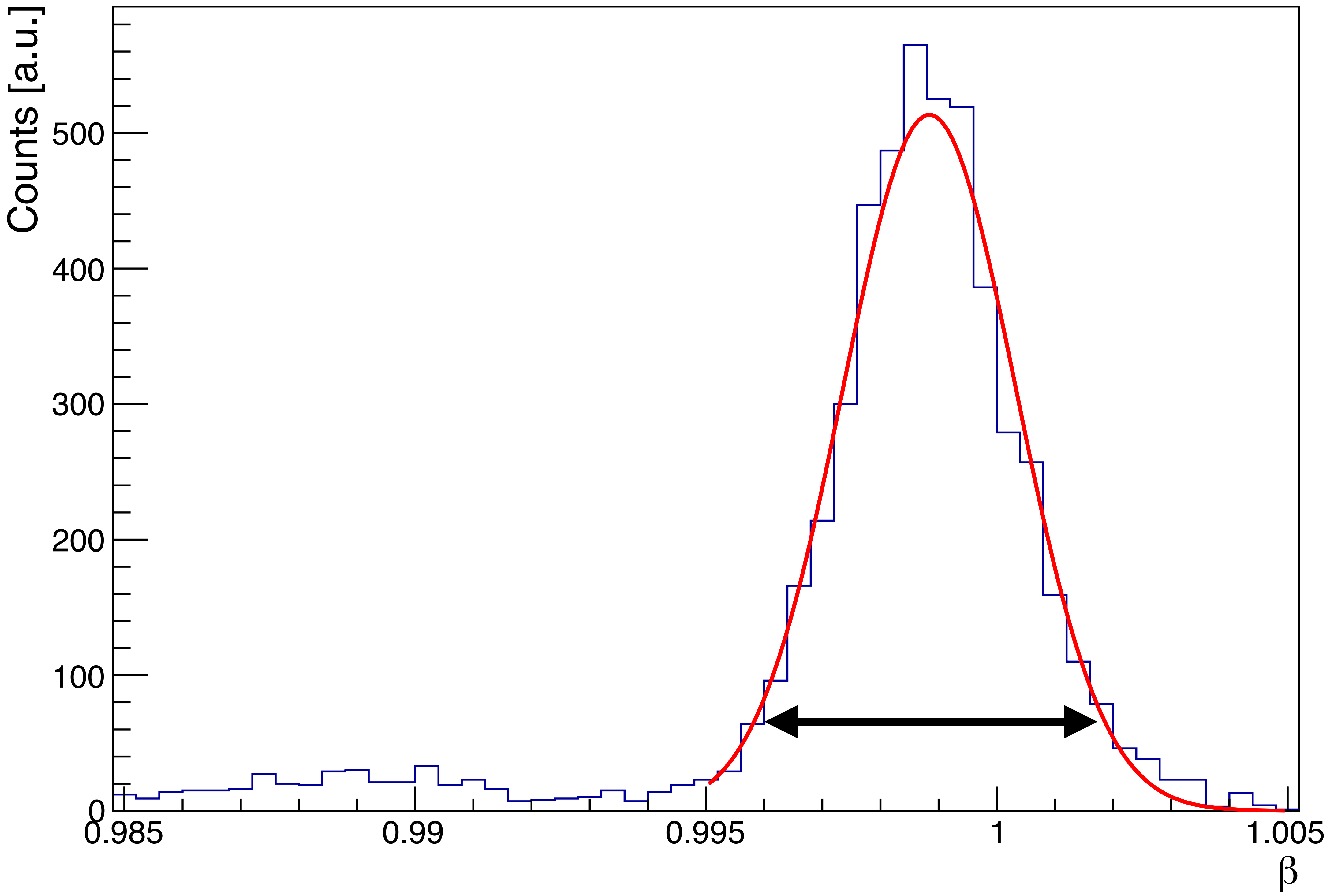
- TOF insufficient to identify pions and kaons above ~3 GeV
  - Use RICH (in one sector) to compute a correction





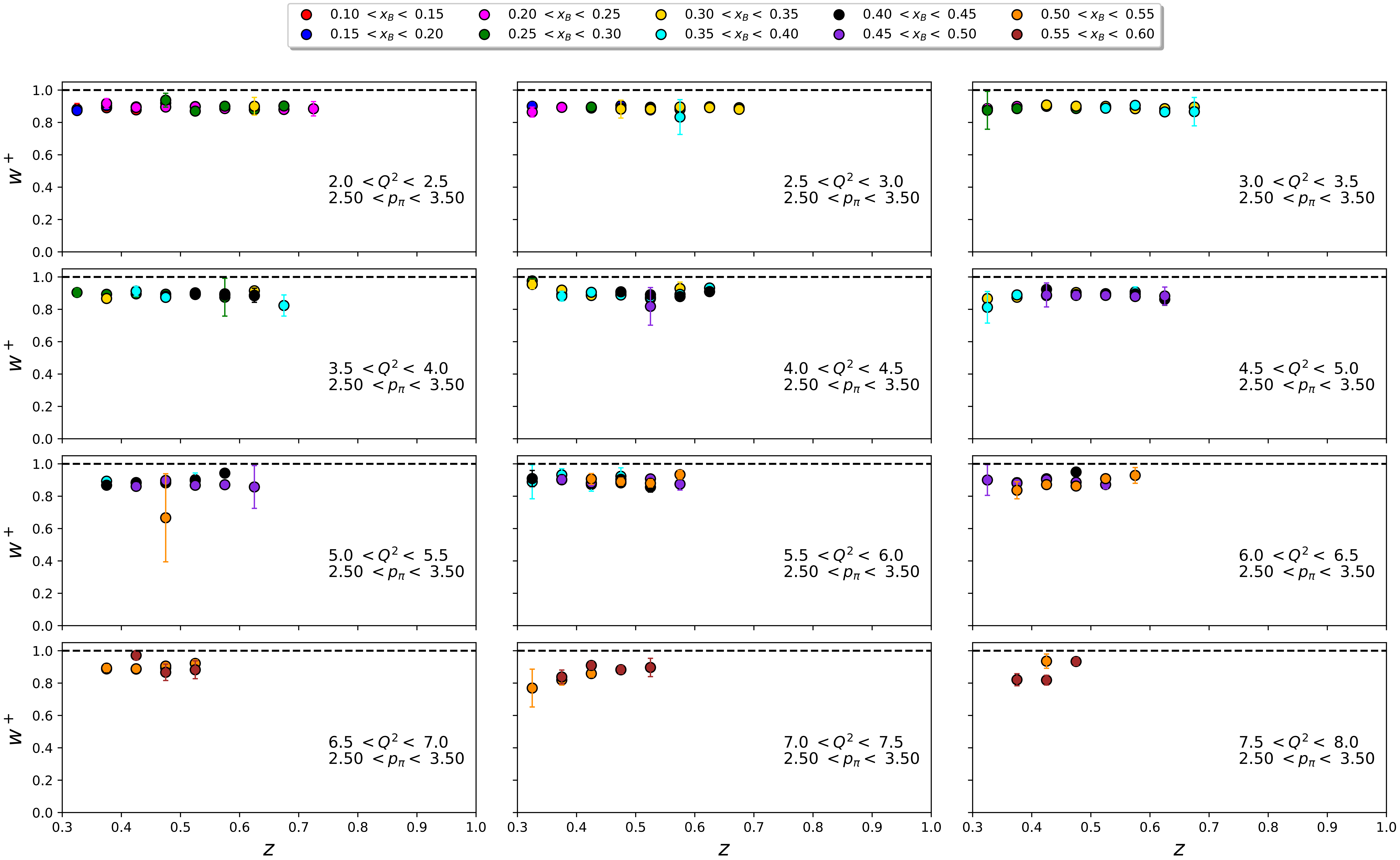
Kaon Contamination

$$Correction = \frac{Yield(\pi^{\pm})}{Yield(\pi^{\pm} + K^{\pm} + \ldots)}$$

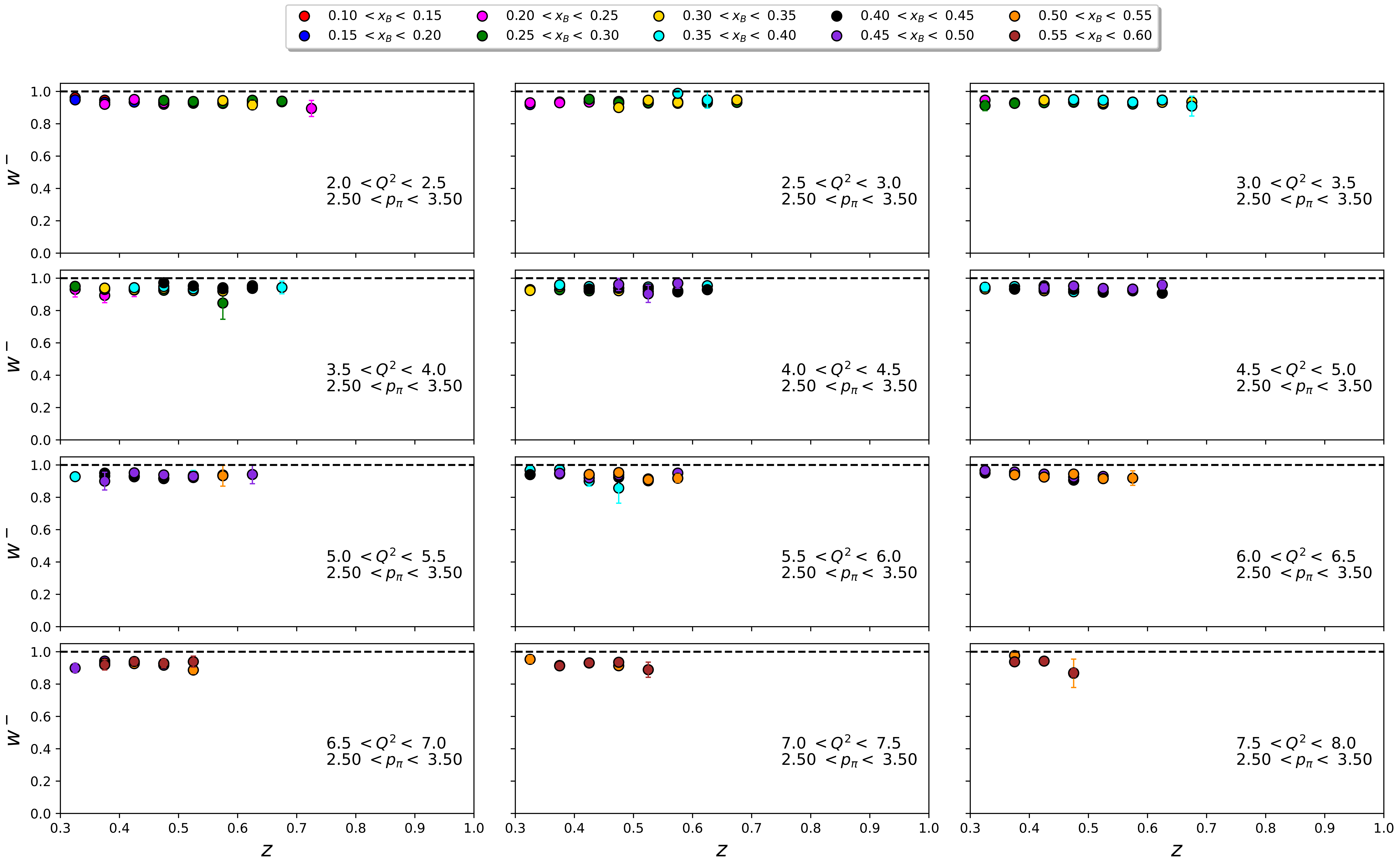


π yield determined by number of events within 2σ of fit mean

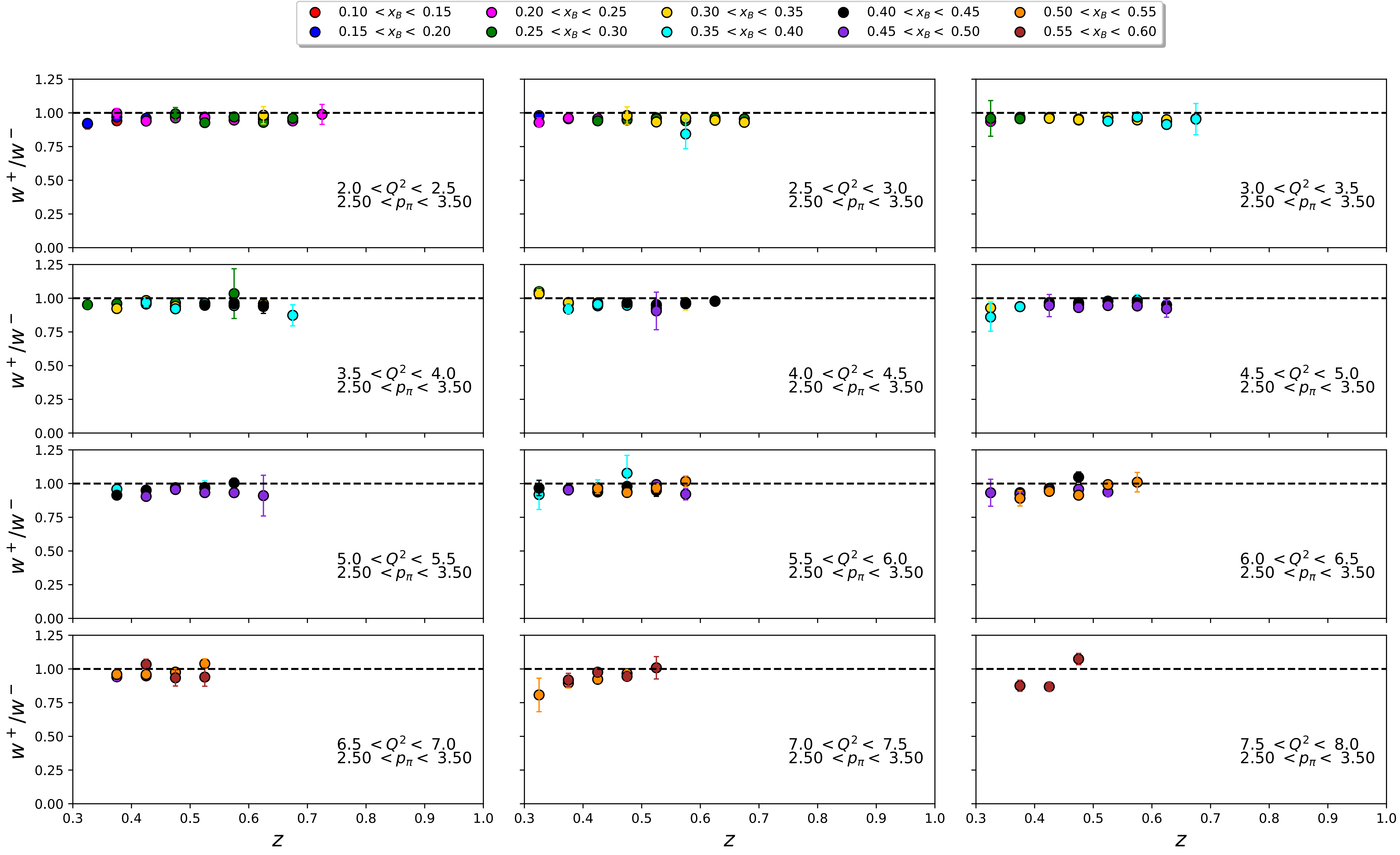
Kaon Correction: π^+



Kaon Correction: π^-



Kaon Correction: π^+/π^-



Going from Yields to Cross Sections

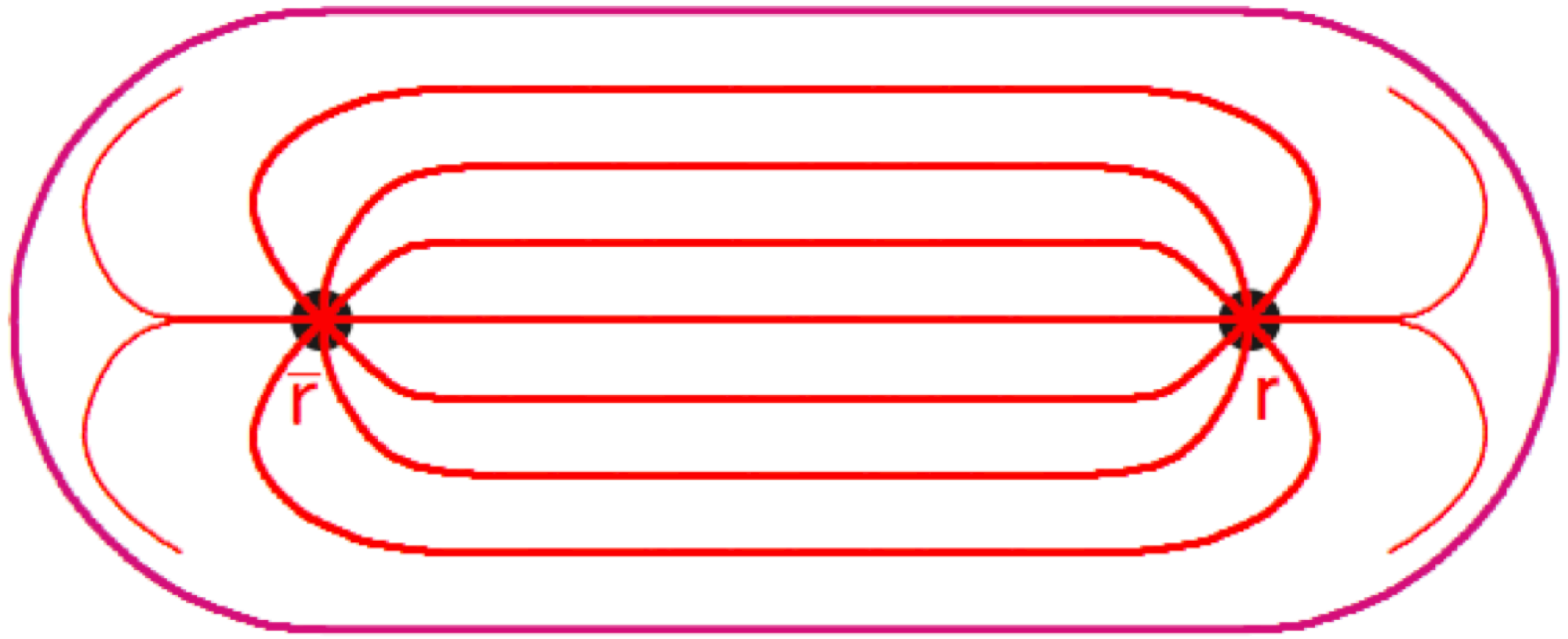
What we have

What we want

$$\boxed{Y^{rad}_{rec\ kin,acc\ event}}\left[\frac{Y^{born}_{rec\ kin,acc\ event}}{Y^{rad}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,acc\ event}}{Y^{born}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,gen\ event}}{Y^{born}_{gen\ kin,acc\ event}}\right]=\boxed{Y^{born}_{gen\ kin,gen\ event}}$$

Simulation - CLASDIS and GEMC

- Generator: CLADIS, a DIS generator with hadronization based on Lund-string model
- Monte Carlo: GEMC, a GEANT based detector simulation



Torbjorn Sjostrand

Going from Yields to Cross Sections

What we measure

What we want

$$Y^{rad}_{rec\ kin,acc\ event}\left[\frac{Y^{born}_{rec\ kin,acc\ event}}{Y^{rad}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,acc\ event}}{Y^{born}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,gen\ event}}{Y^{born}_{gen\ kin,acc\ event}}\right] = Y^{born}_{gen\ kin,gen\ event}$$

Going from Yields to Cross Sections

What we measure

What we want

$$Y^{rad}_{rec\ kin,acc\ event}\left[\frac{Y^{born}_{rec\ kin,acc\ event}}{Y^{rad}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,acc\ event}}{Y^{born}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,gen\ event}}{Y^{born}_{gen\ kin,acc\ event}}\right]=Y^{born}_{gen\ kin,gen\ event}$$

Radiation Correction

Going from Yields to Cross Sections

What we measure

What we want

$$Y^{rad}_{rec\ kin,acc\ event}\left[\frac{Y^{born}_{rec\ kin,acc\ event}}{Y^{rad}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,acc\ event}}{Y^{born}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,gen\ event}}{Y^{born}_{gen\ kin,acc\ event}}\right]=Y^{born}_{gen\ kin,gen\ event}$$

Radiation Correction

Cancels in ratio

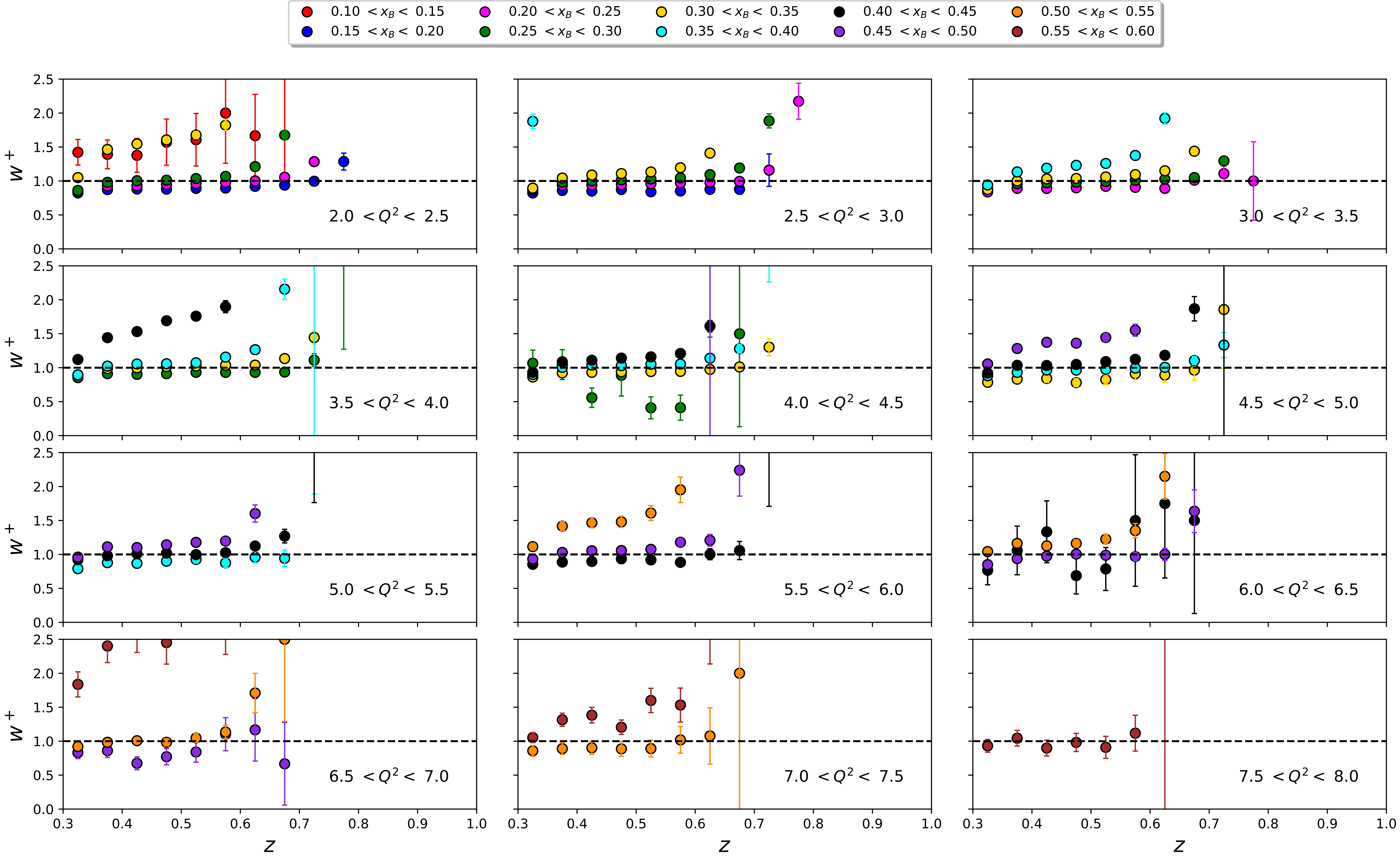
Going from Yields to Cross Sections

What we measure — What we want

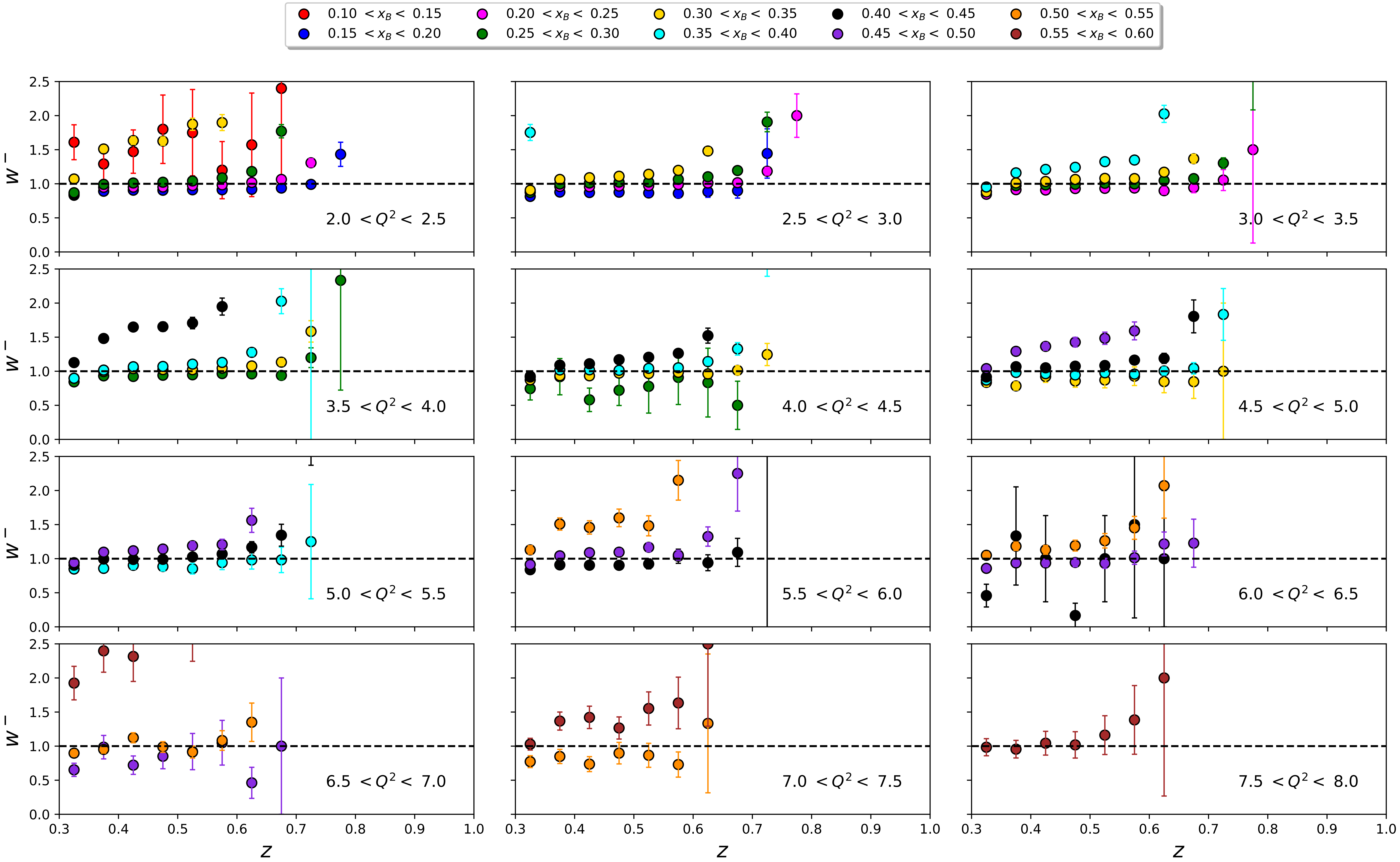
$$Y^{rad}_{rec\ kin,acc\ event}\left[\frac{Y^{born}_{rec\ kin,acc\ event}}{Y^{rad}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,acc\ event}}{Y^{born}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,gen\ event}}{Y^{born}_{gen\ kin,acc\ event}}\right] = Y^{born}_{gen\ kin,gen\ event}$$

Bin Migration Correction

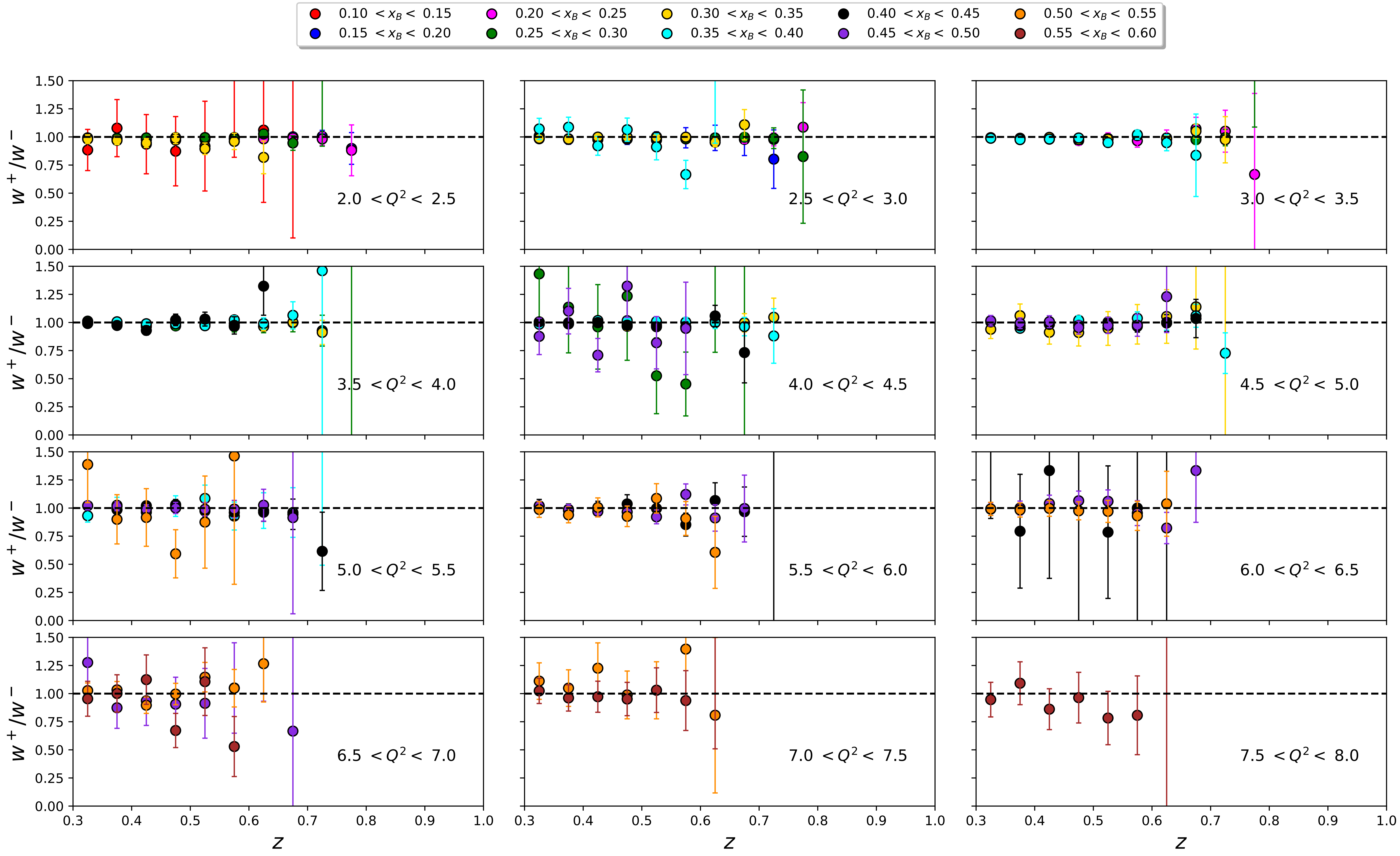
Bin Migration Corrections: π^+



Bin Migration Corrections: π^-



Bin Migration Corrections: π^+/π^-



MC Corrections

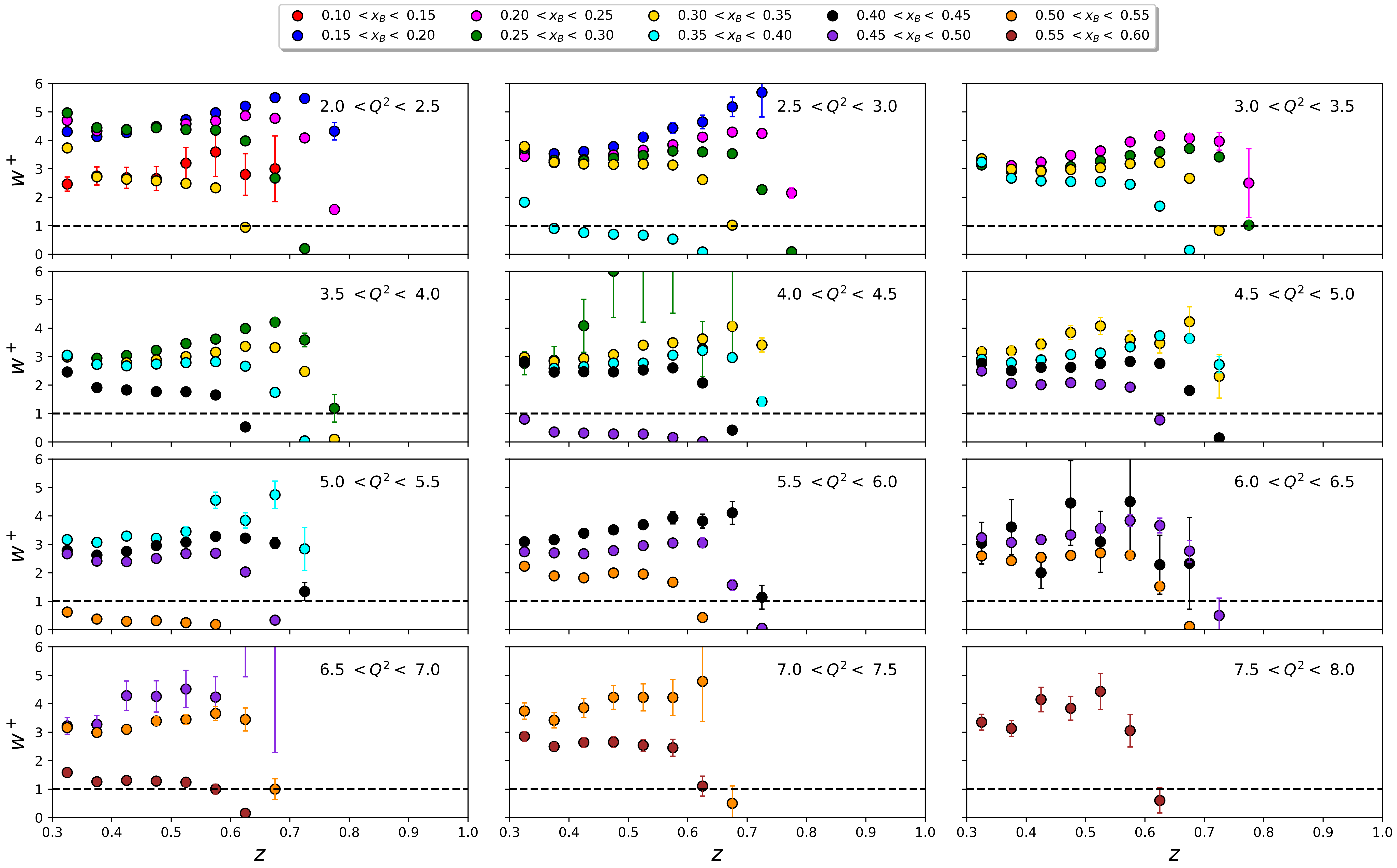
What we measure

What we want

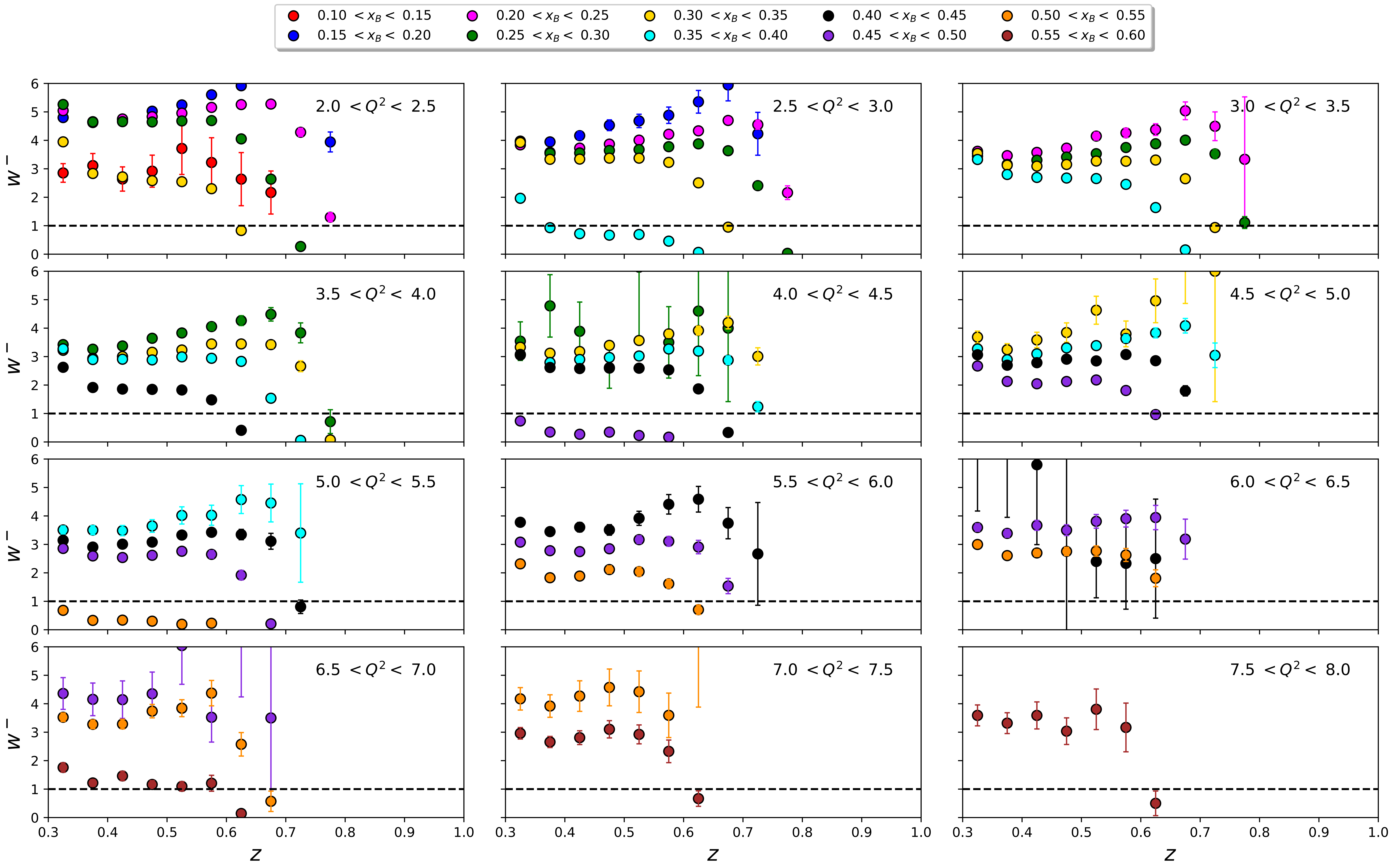
$$Y^{rad}_{rec\ kin,acc\ event}\left[\frac{Y^{born}_{rec\ kin,acc\ event}}{Y^{rad}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,acc\ event}}{Y^{born}_{rec\ kin,acc\ event}}\right]\left[\frac{Y^{born}_{gen\ kin,gen\ event}}{Y^{born}_{gen\ kin,acc\ event}}\right] = Y^{born}_{gen\ kin,gen\ event}$$

Acceptance correction

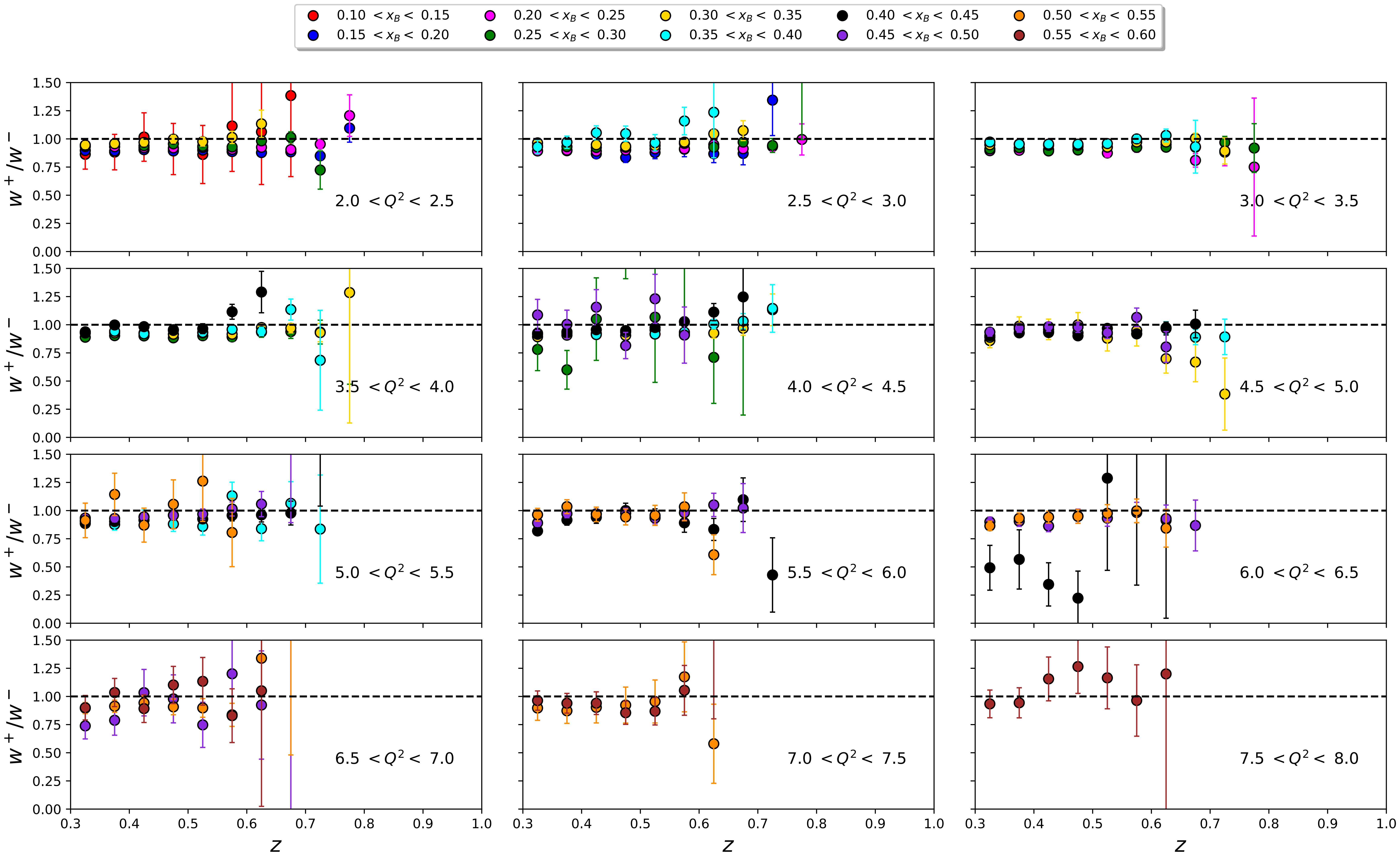
Acceptance Corrections: π^+



Acceptance Corrections: π^-

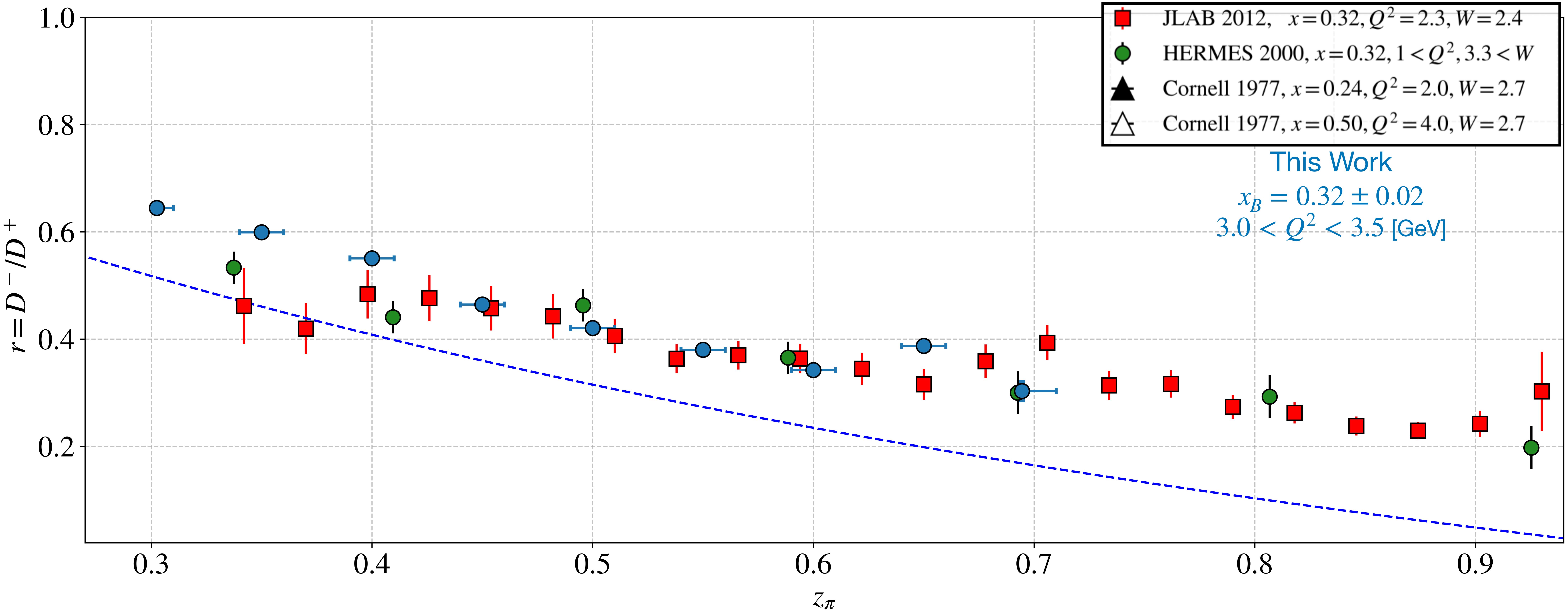


Acceptance Corrections: π^+/π^-



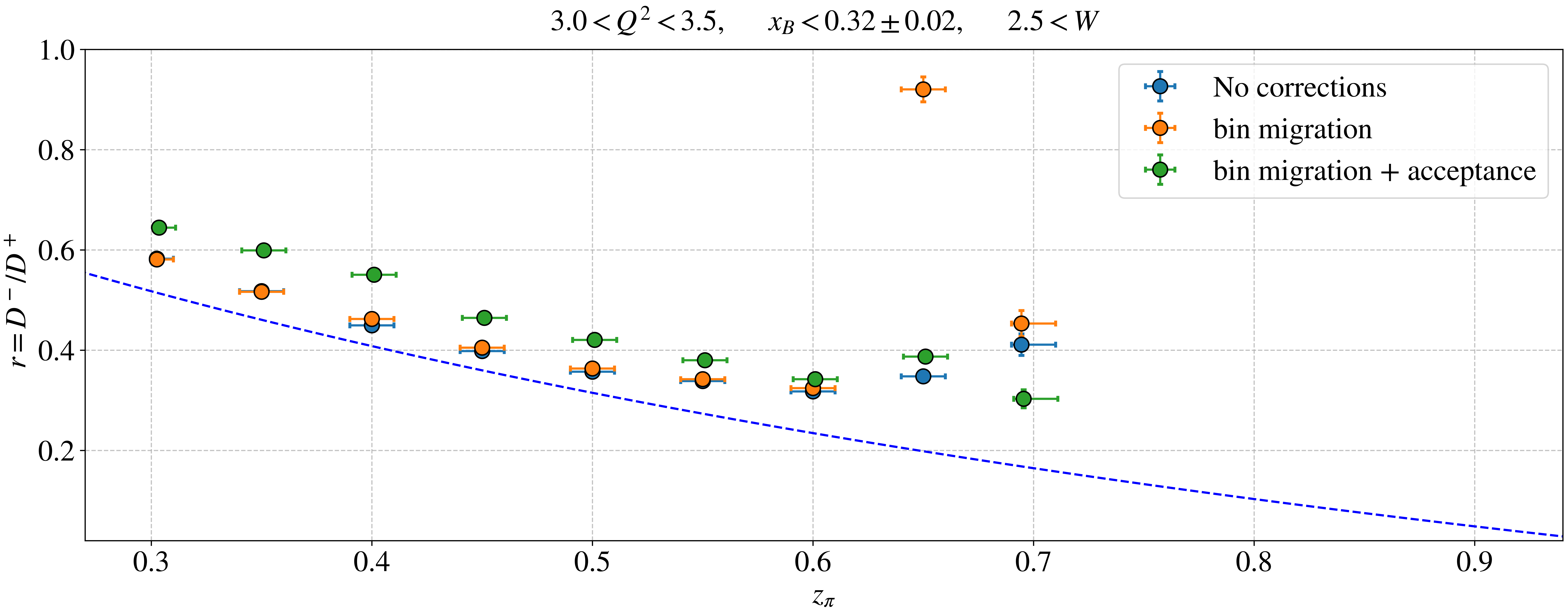
(Preliminary) Results

Results

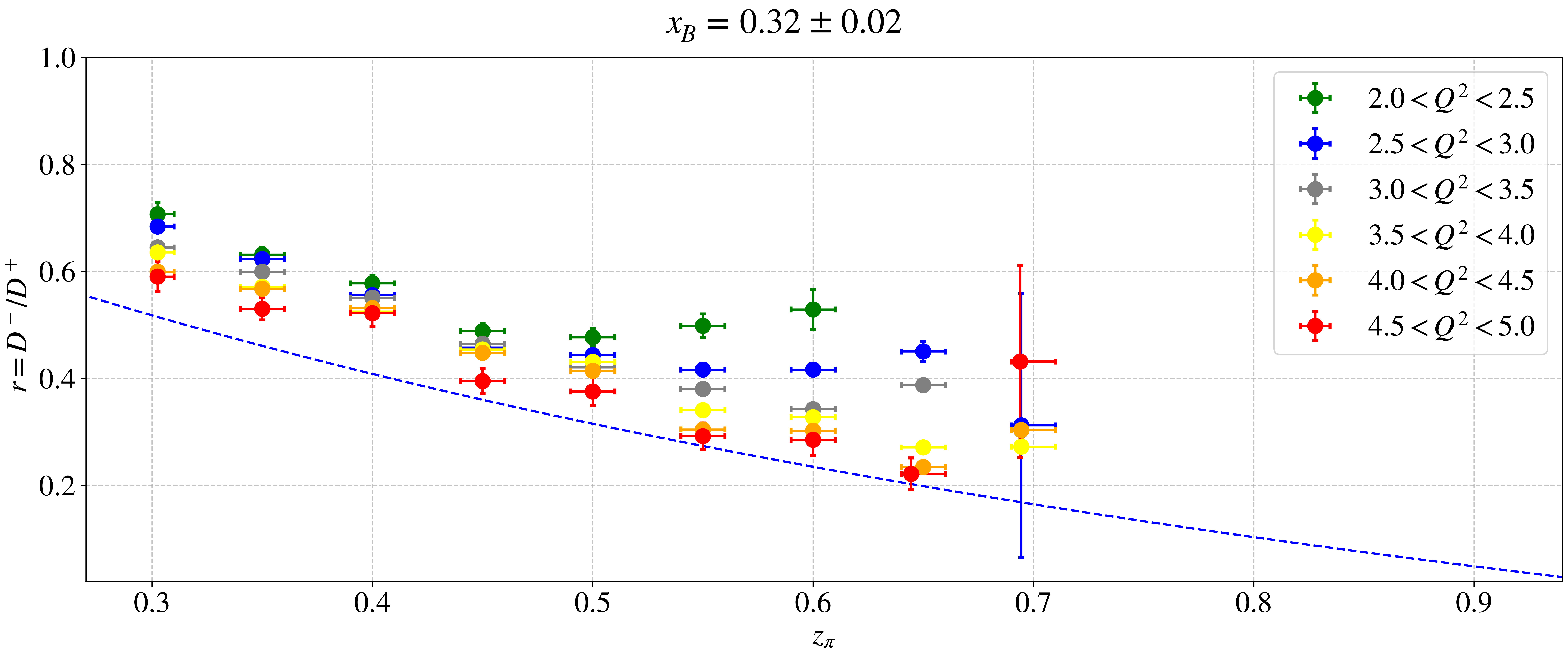


JLAB 2012, $x=0.32, Q^2=2.3, W=2.4$
HERMES 2000, $x=0.32, 1<Q^2, 3.3<W$
Cornell 1977, $x=0.24, Q^2=2.0, W=2.7$
Cornell 1977, $x=0.50, Q^2=4.0, W=2.7$
This Work
$x_B = 0.32 \pm 0.02$
$3.0 < Q^2 < 3.5$ [GeV]
$r = D^-/D^+$
z_π
1.0
0.8
0.6
0.4
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

Effect of Corrections

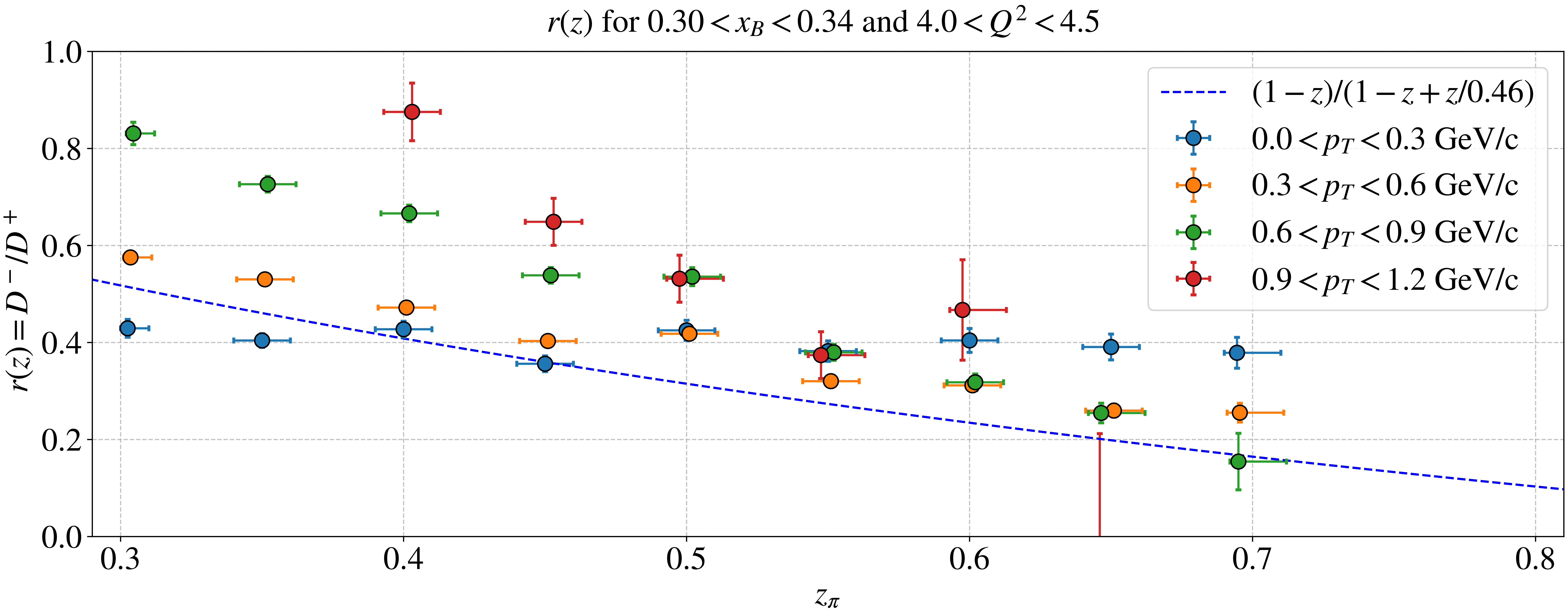


Binned in Q^2



$x_B = 0.32 \pm 0.02$
$r = D^-/D^+$
z_π
$2.0 < Q^2 < 2.5$
$2.5 < Q^2 < 3.0$
$3.0 < Q^2 < 3.5$
$3.5 < Q^2 < 4.0$
$4.0 < Q^2 < 4.5$
$4.5 < Q^2 < 5.0$

Binned in p_T



$r(z)$ for $0.30 < x_B < 0.34$ and $4.0 < Q^2 < 4.5$
$(1-z)/(1-z+z/0.46)$
$0.0 < p_T < 0.3$ GeV/c
$0.3 < p_T < 0.6$ GeV/c
$0.6 < p_T < 0.9$ GeV/c
$0.9 < p_T < 1.2$ GeV/c
$r(z) = D^-/D^+$
z_π
1.0
0.8
0.6
0.4
0.2
0.0
0.3
0.4
0.5
0.6
0.7
0.8

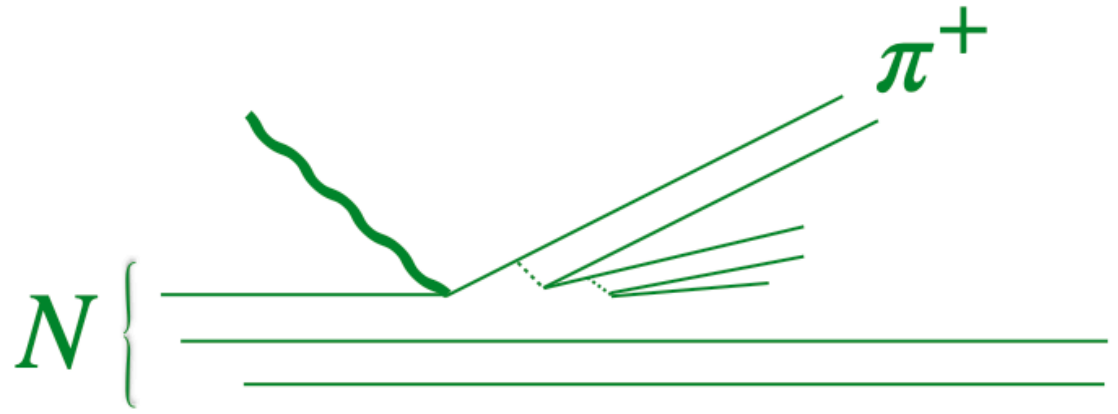
Summary

- SIDIS offers a technique to extract d/u PDF ratio using proton and deuterium targets
- CLAS12 allows us to map pion fragmentation function ratio as functions of Q^2, x_B, p_T
- Deuterium analysis is approaching completion!
  - Next up is proton analysis and tagged analysis

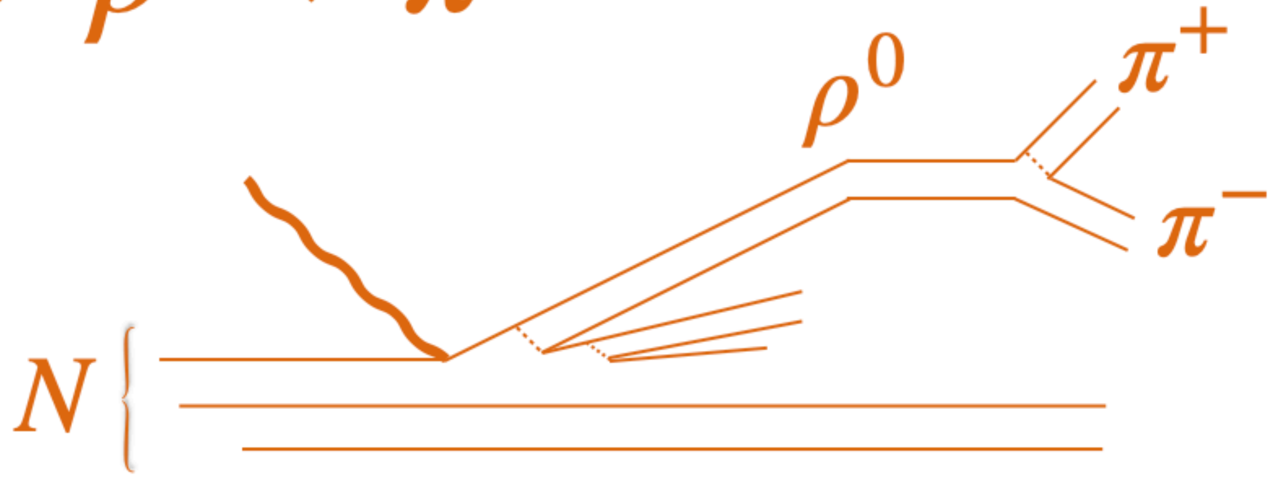
Supplementary

Diffractive ρ^0 Correction

1. Direct from quark $q^* + N \to \pi$

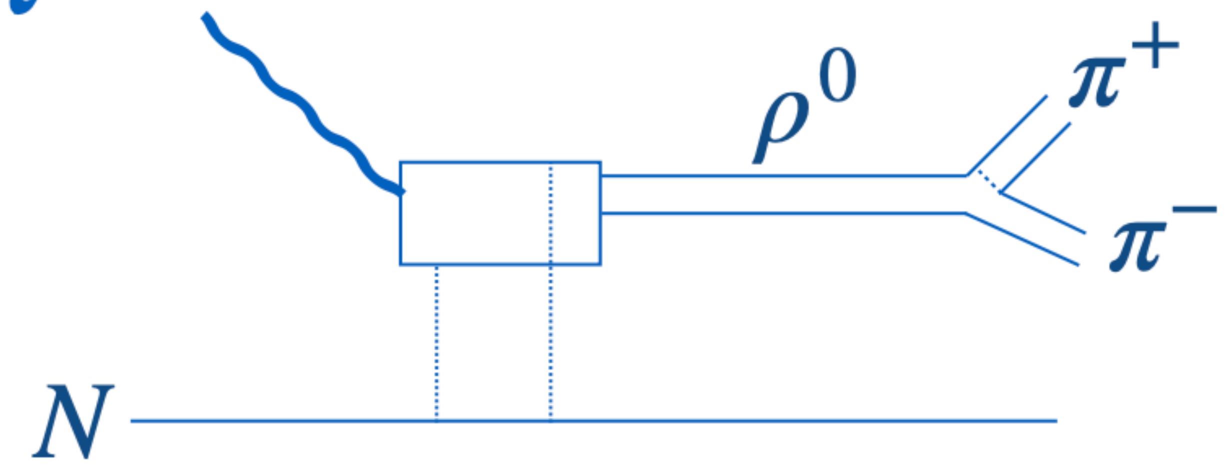


2. VM production $q^* + N \to \rho \to \pi$



The clasdis generator does not include diffractive VM production…
Take data driven approach

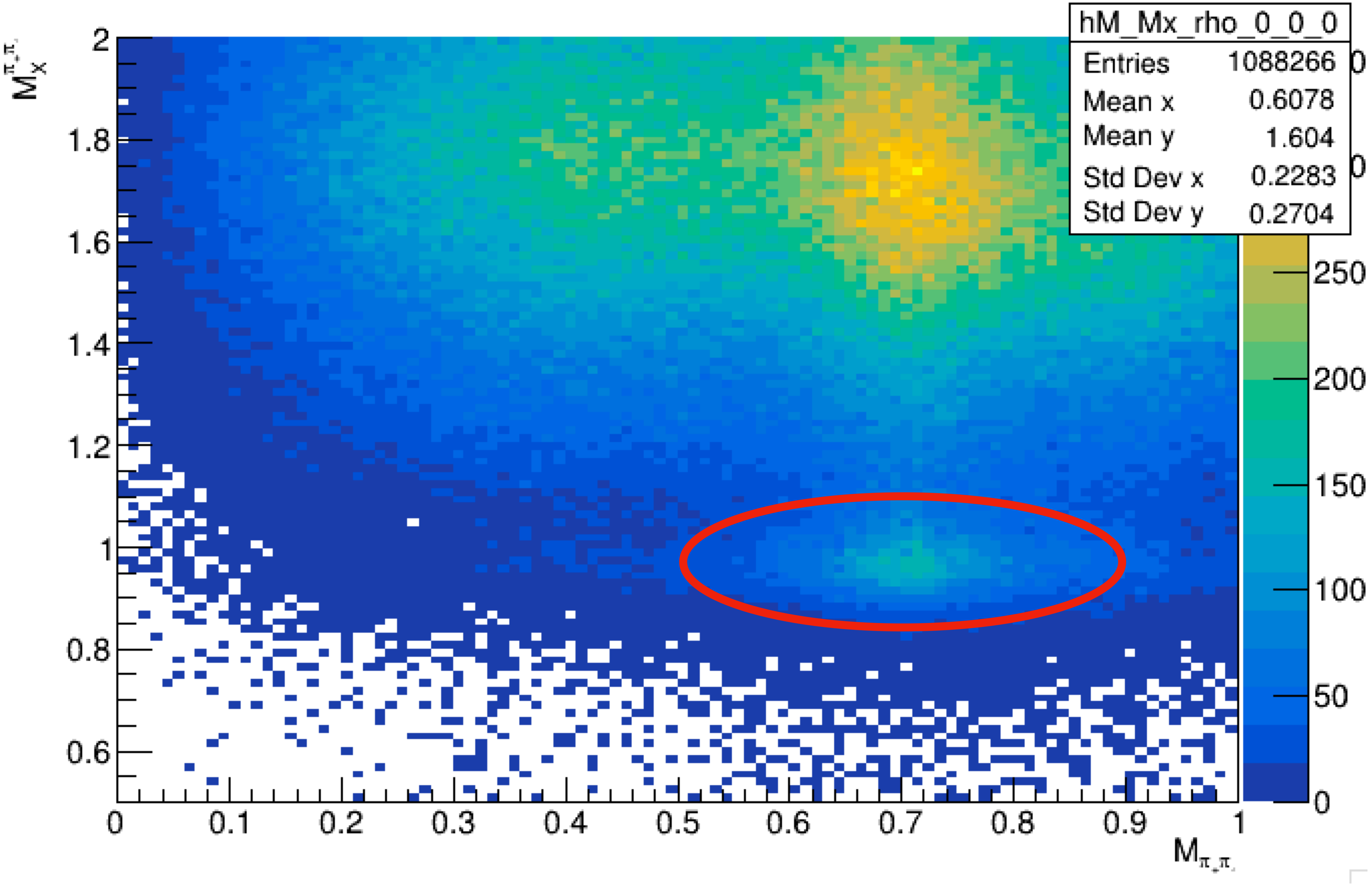
3. Diffractive $q^* \to \rho \to \pi$



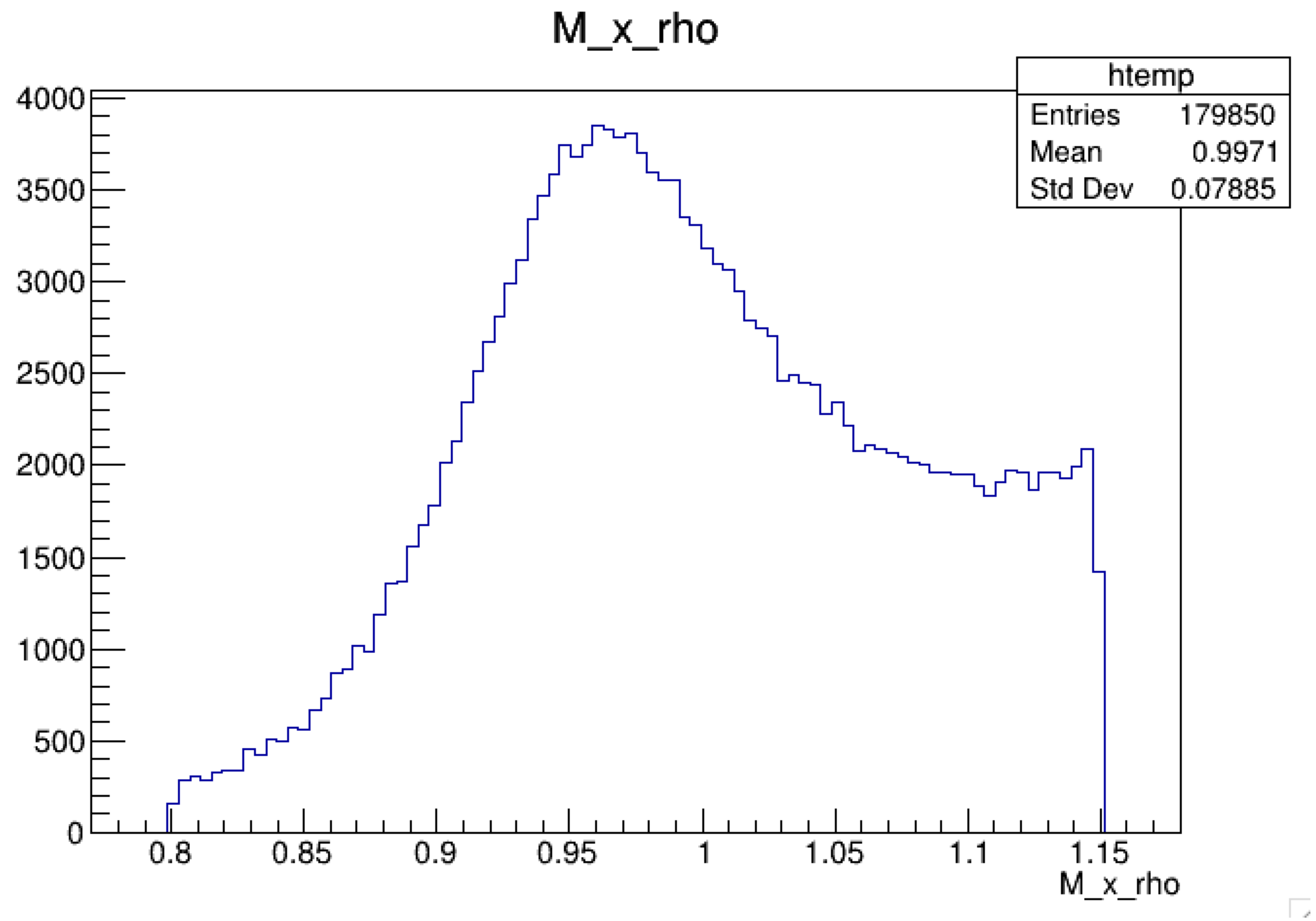
Rho Correction - Data Driven Approach

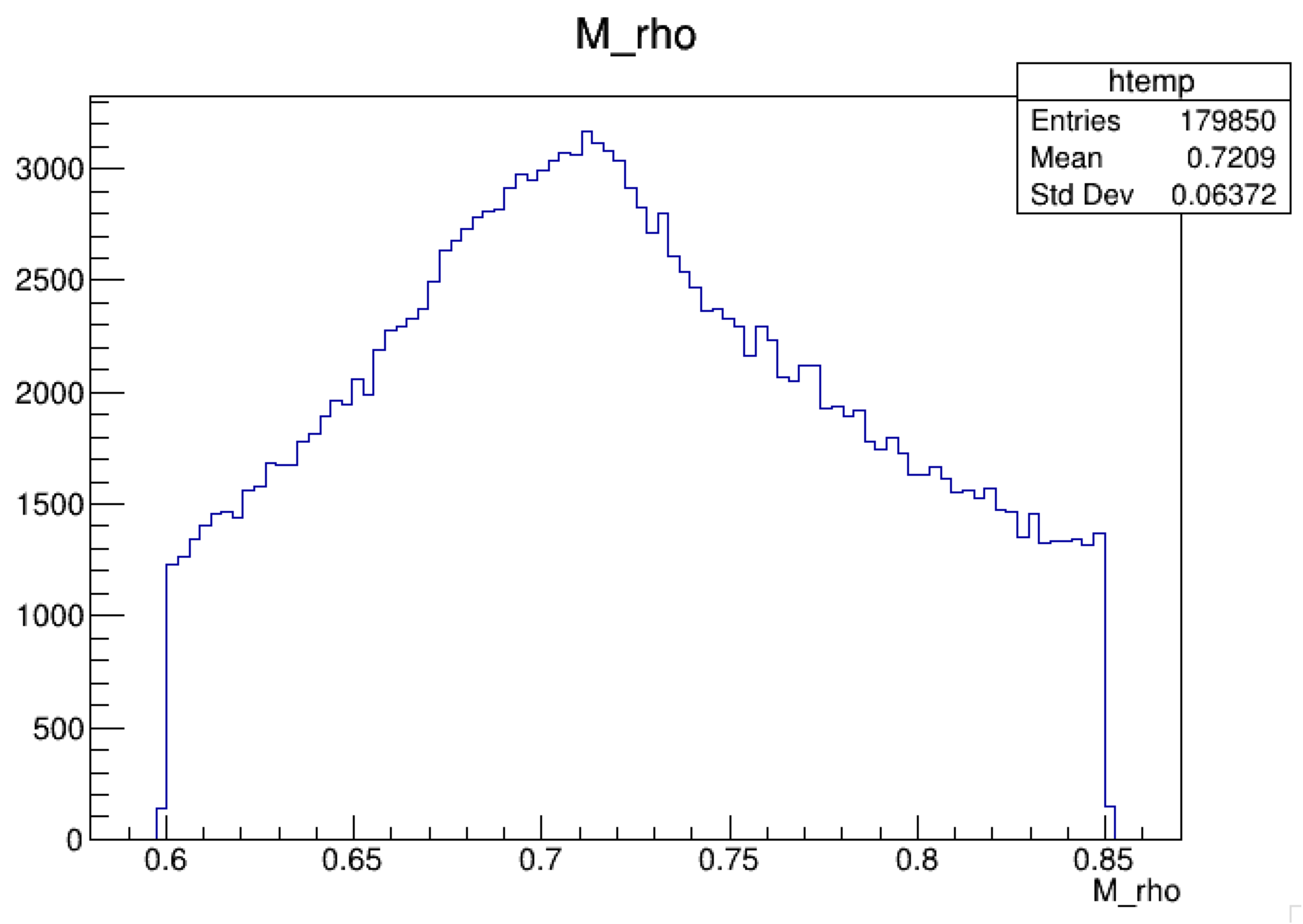
- Identify good diffractive rho events in data
  - 2 pion events with at least one pion passing kinematic cuts
  - Require M_x ~ 938 MeV (exclusive) and invariant mass of 2 pion system ~770 MeV
- Then, rotate events about the q-vector of the interaction and beam vector to produce “new” rho events
  - Introduce cos(2*phi) weighting to mimic physics in the q-vector rotation
- Run events through acceptance map
  - Events detected with only one pion then used to estimate number of rho events in data

5

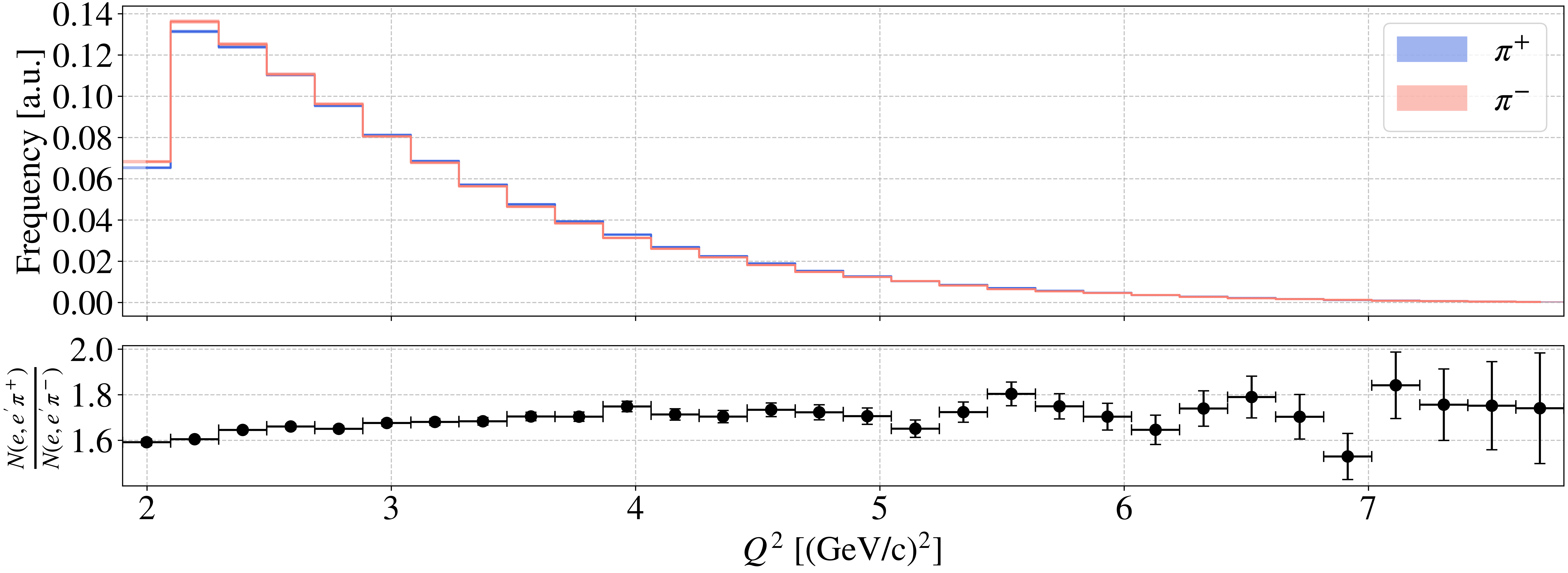


hM_Mx_rho_0_0_0
Entries 1088266
Mean x 0.6078
Mean y 1.604
Std Dev x 0.2283
Std Dev y 0.2704

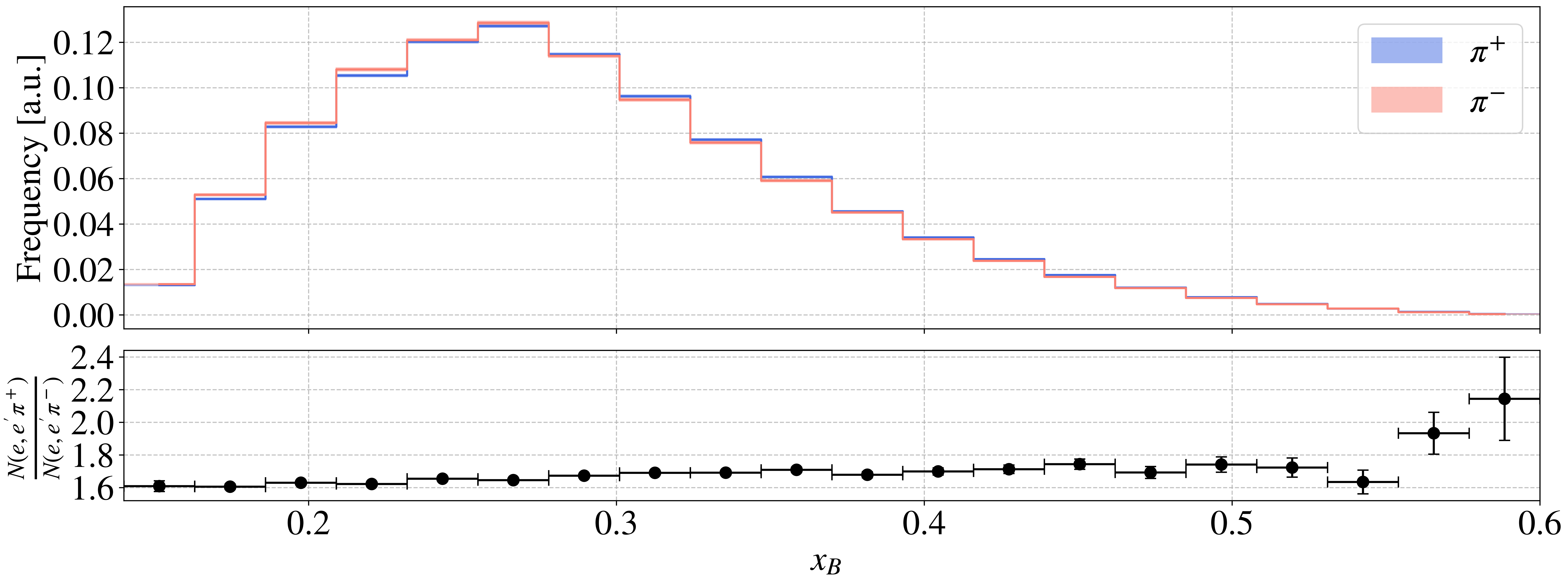

M_x_rho
htemp
Entries 179850
Mean 0.9971
Std Dev 0.07885
0
500
1000
1500
2000
2500
3000
3500
4000
0.8
0.85
0.9
0.95
1
1.05
1.1
1.15
M_x_rho


M_rho
htemp
Entries 179850
Mean 0.7209
Std Dev 0.06372
0
500
1000
1500
2000
2500
3000
0.6
0.65
0.7
0.75
0.8
0.85
M_rho

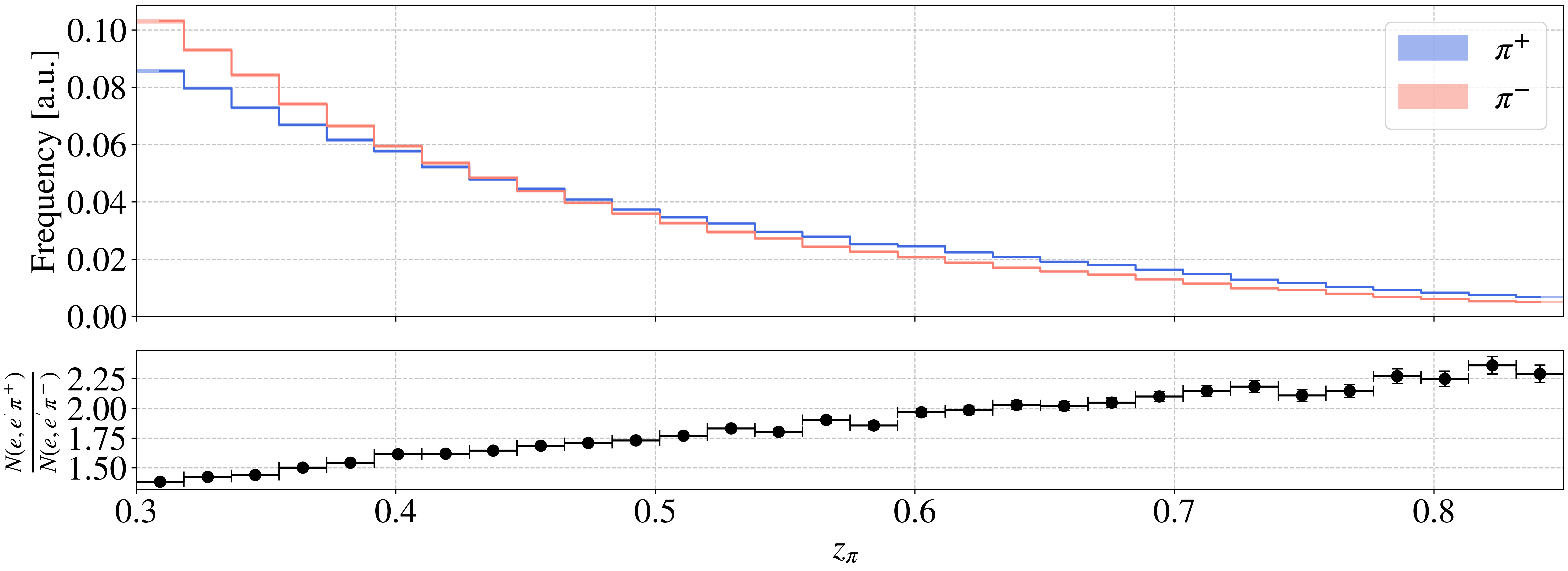
Kinematical Distributions



Kinematical Distributions

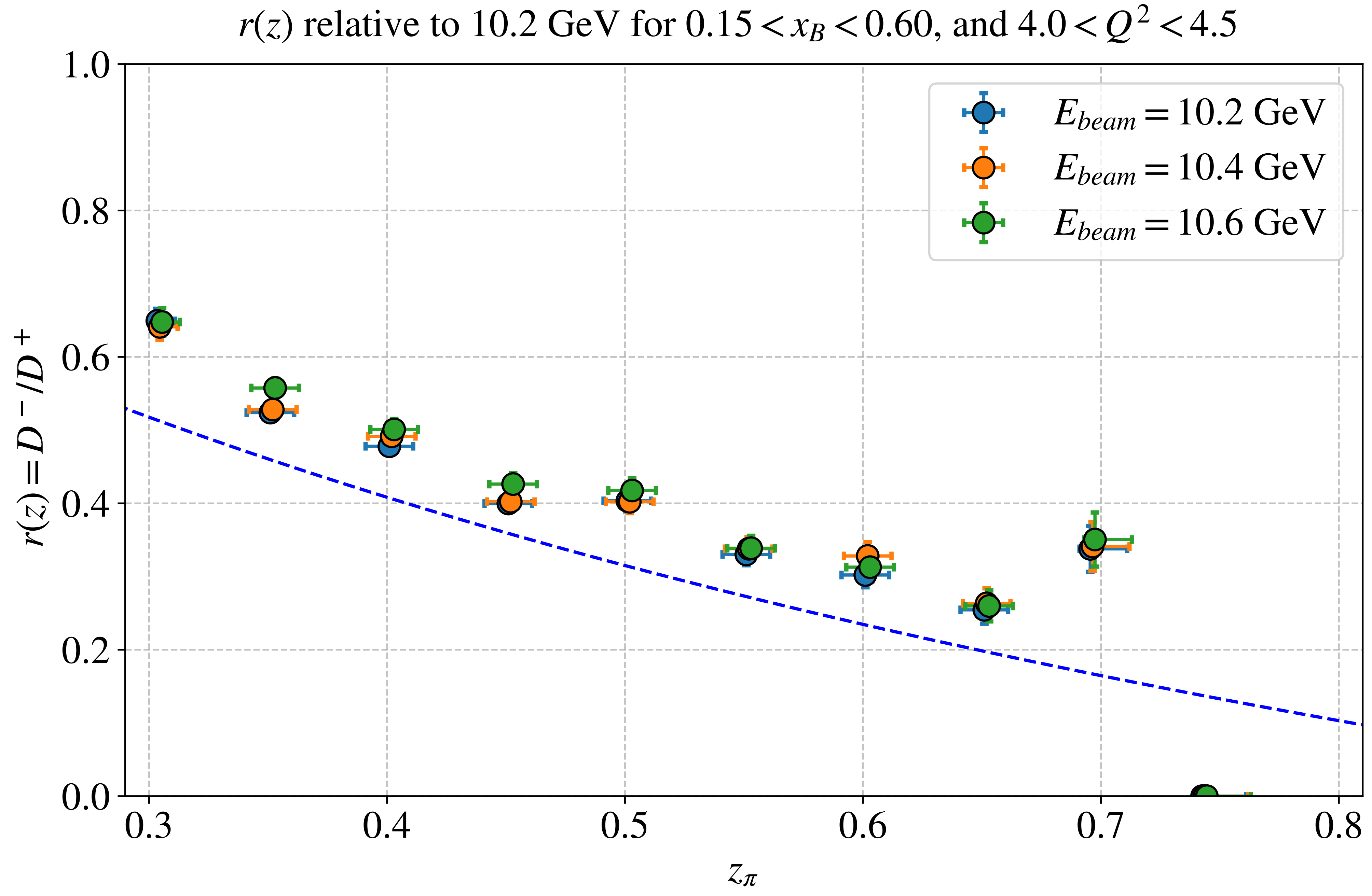


Kinematical Distributions

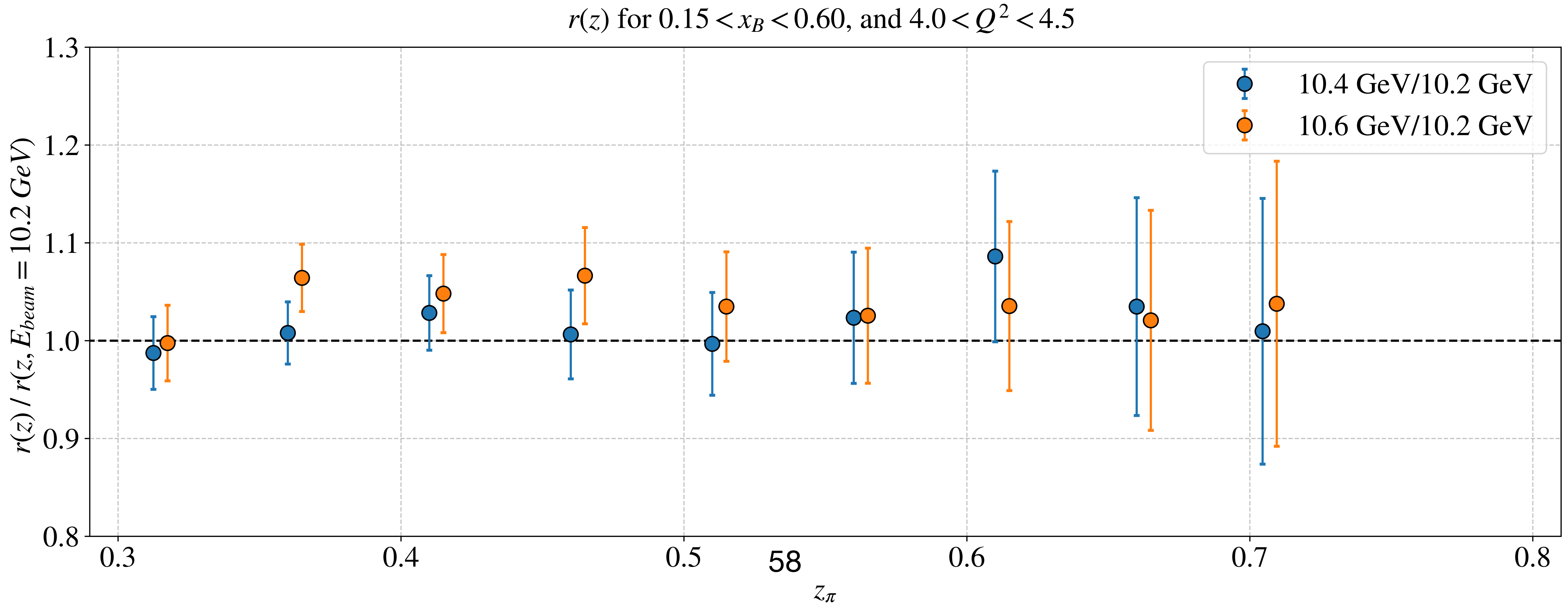


Systematics

Beam Energy

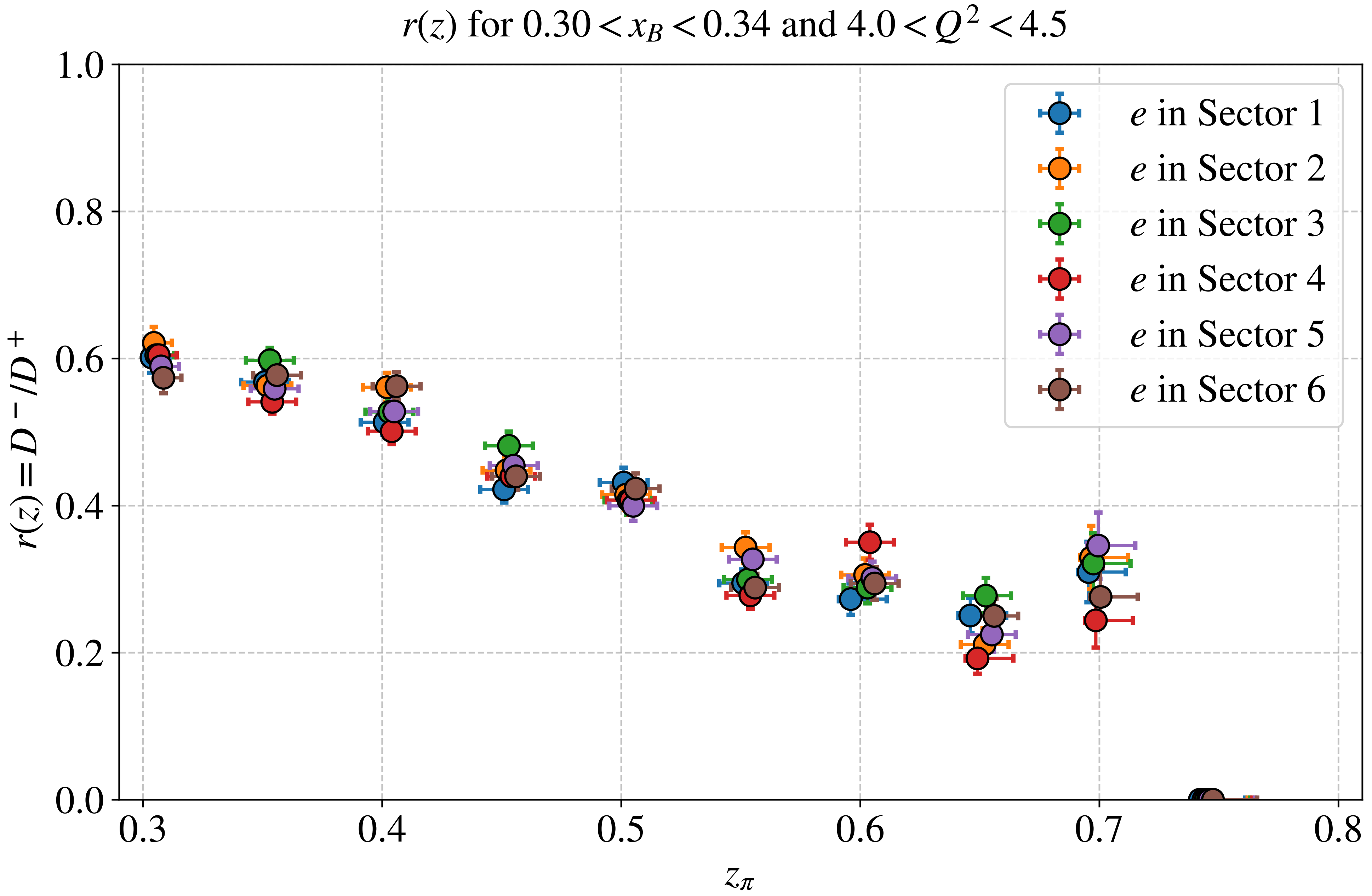


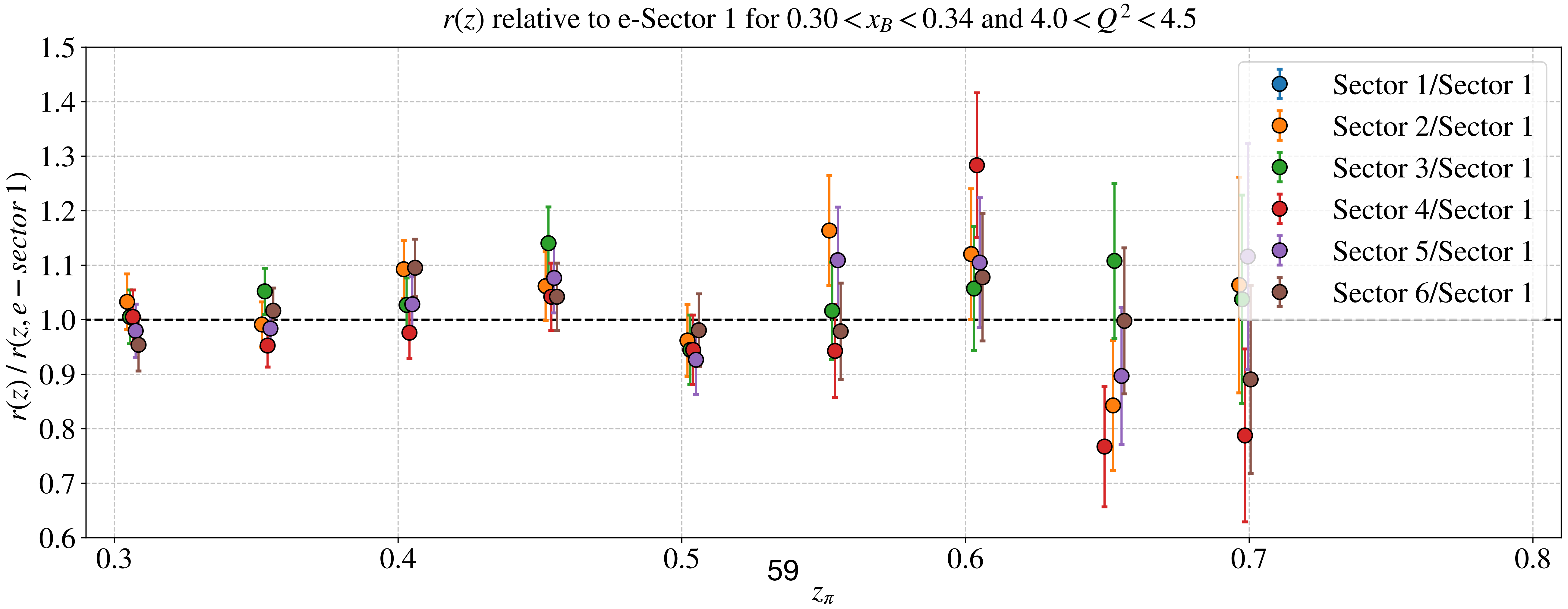
$r(z)$ relative to 10.2 GeV for $0.15 < x_B < 0.60$, and $4.0 < Q^2 < 4.5$
$E_{beam} = 10.2$ GeV
$E_{beam} = 10.4$ GeV
$E_{beam} = 10.6$ GeV
$r(z) = D^-/D^+$
z_π



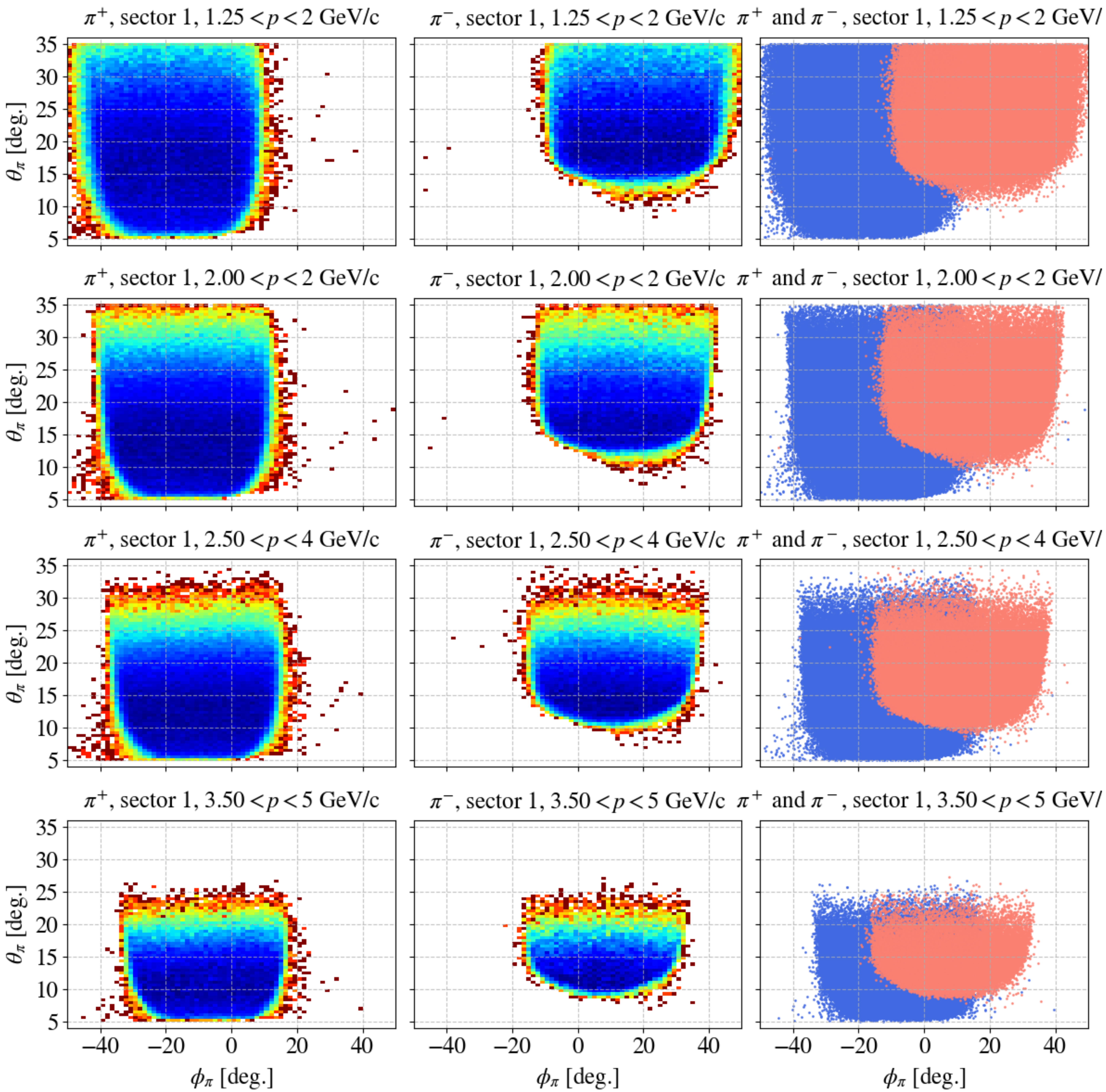
$r(z)$ for $0.15 < x_B < 0.60$, and $4.0 < Q^2 < 4.5$
10.4 GeV/10.2 GeV
10.6 GeV/10.2 GeV
$r(z)$ / $r(z, E_{beam} = 10.2\ GeV)$
z_π

Electron Sector

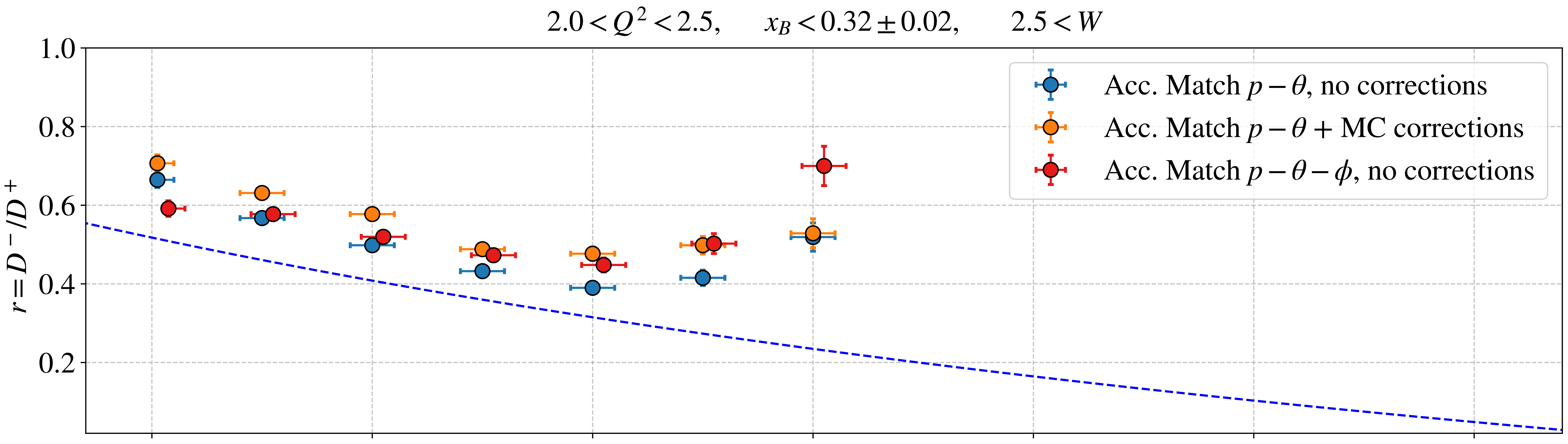


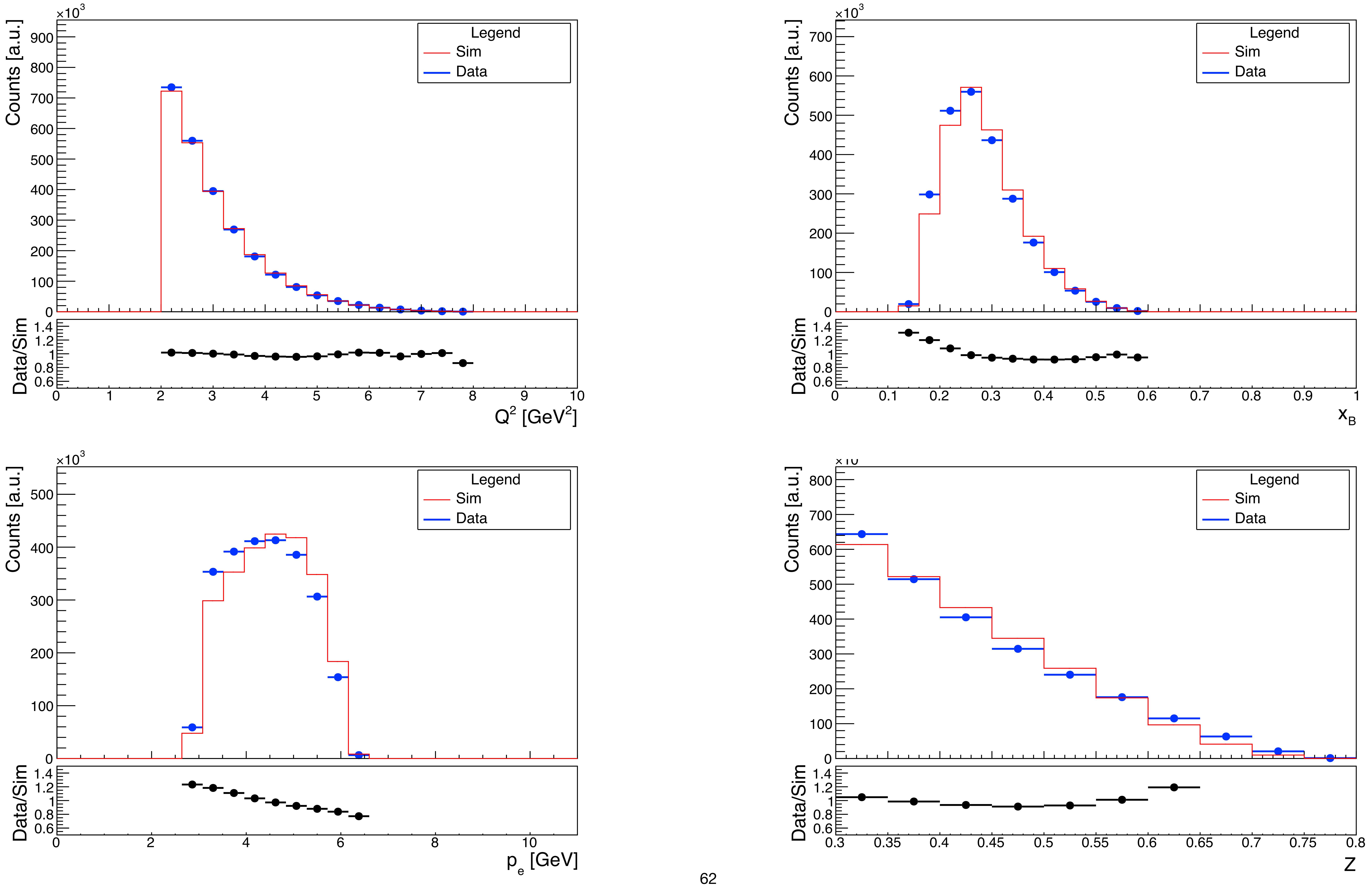


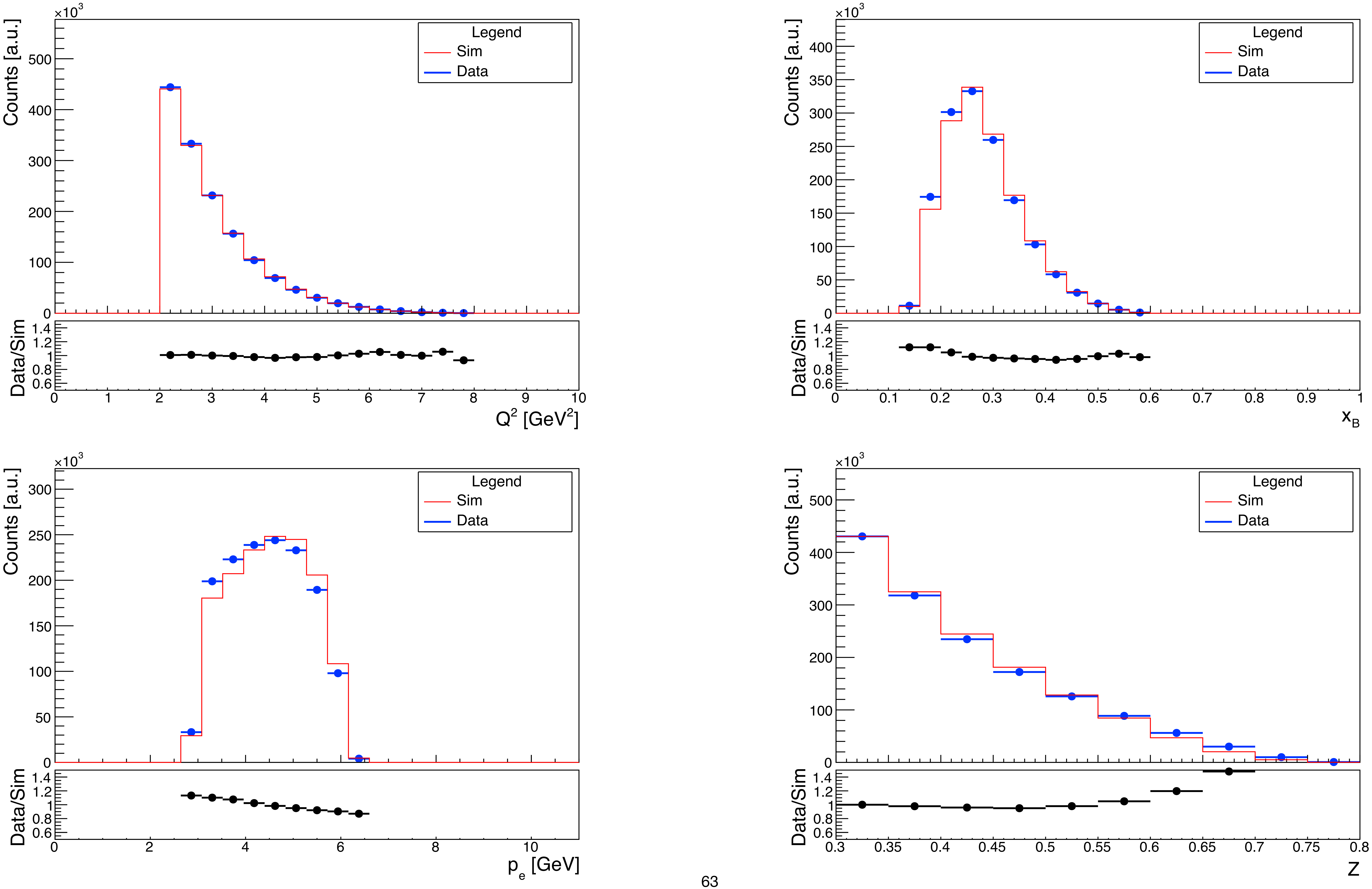
ϕ_π Matching



ϕ_π Matching




Legend
Sim
Data
Counts [a.u.]
Data/Sim
$\times 10^3$
Q^2 [GeV^2]
x_B
p_e [GeV]
Z



Legend
Sim
Data
Counts [a.u.]
Data/Sim
Q^2 [GeV^2]
x_B
p_e [GeV]
Z