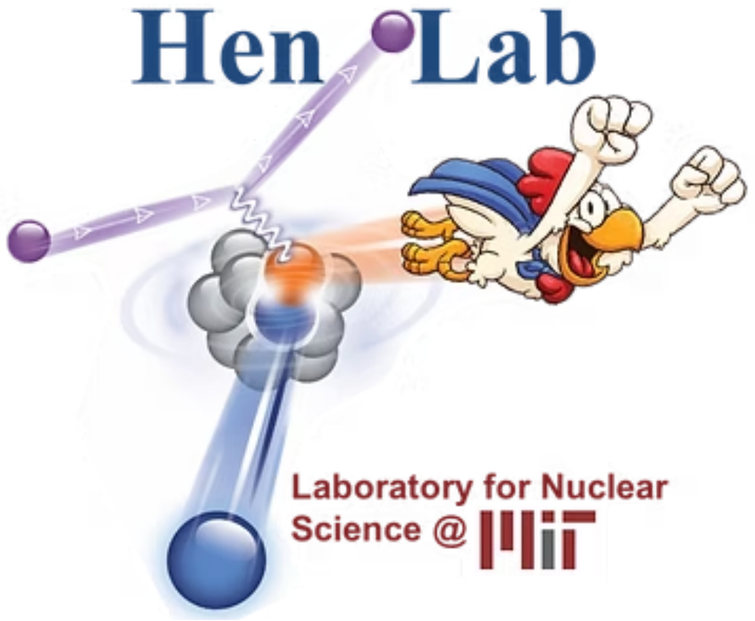
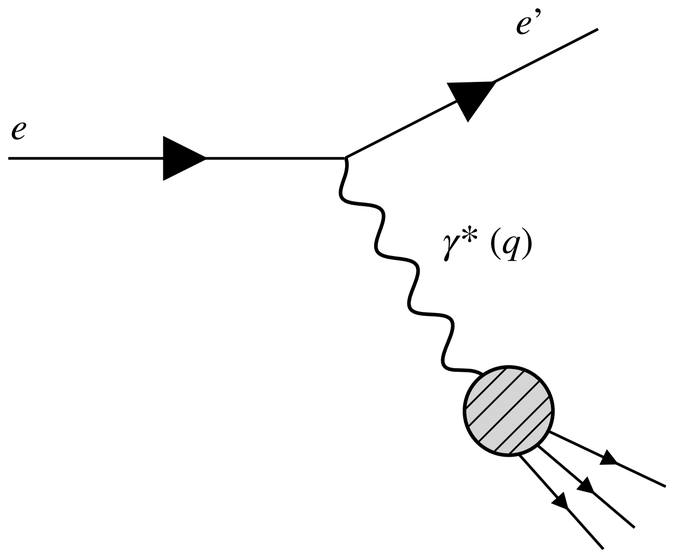
SIDIS @ CLAS12:
The Unfavored-to-favored pion fragmentation ratio off the deuteron



Jason Phelan, MIT
CLAS Collaboration Meeting 2026

Leading order SIDIS in the parton model



$$\sigma^h_{SIDIS} \sim \sum_q e_q^2 f_q(x) D_q^h(z)$$

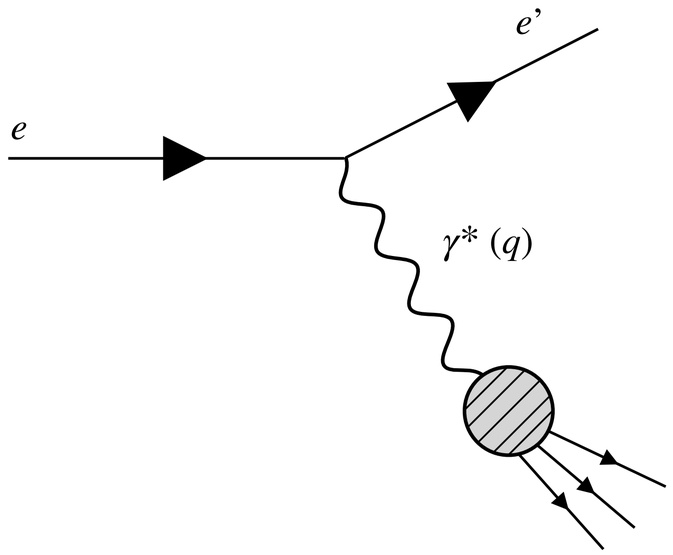
$D_q^h(z) \equiv$ Fragmentation Function

- Prob of producing hadron h at $z = E_\pi/\omega$ by scattering off quark q
- Universal, non-perturbative

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

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

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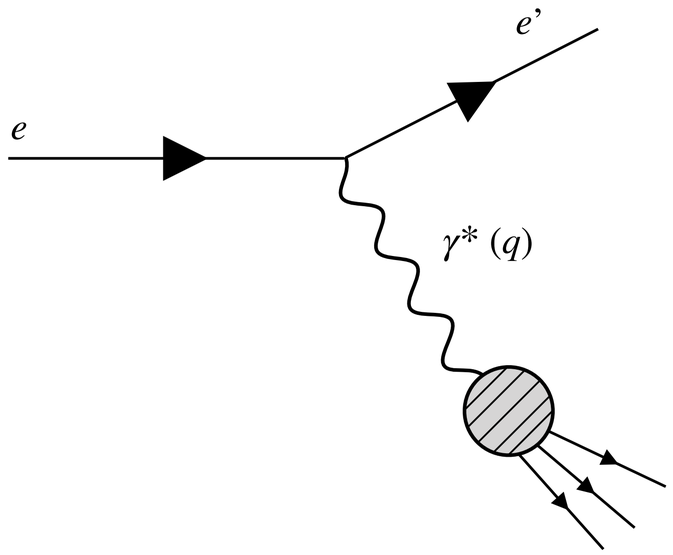
$$\sigma_n^{\pi\pm} \propto 4u_n(x_B)D_u^{\pi\pm}(z) + d_n(x_B)D_d^{\pi\pm}(z)$$

Isospin symmetry:

$$D_u^{\pi\pm} = D_d^{\pi\mp} = D^{\pm}$$
$$u_p = d_n = u$$
$$d_p = u_n = d$$

$$r = \frac{D^-(z)}{D^+(z)} = \frac{4 - (\sigma_d^{\pi+}/\sigma_d^{\pi-})}{4(\sigma_d^{\pi+}/\sigma_d^{\pi-}) - 1}$$

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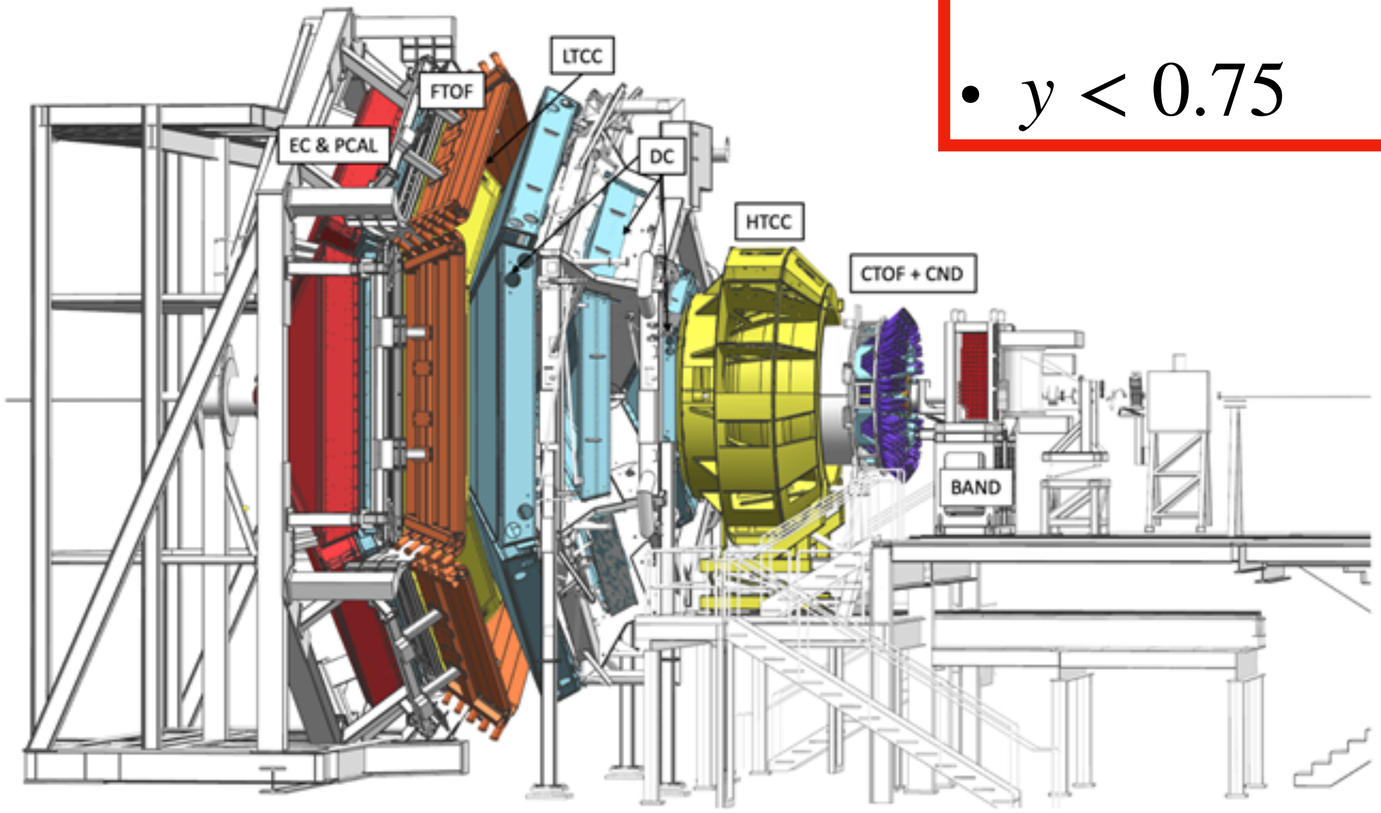
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$$r = \frac{D^-(z)}{D^+(z)} = \frac{4 - (\sigma_d^{\pi+}/\sigma_d^{\pi-})}{4(\sigma_d^{\pi+}/\sigma_d^{\pi-}) - 1}$$

With CLAS12, map $r(z)$as function of Q^2, x_B, z, etc .

SIDIS @ CLAS12



Electrons

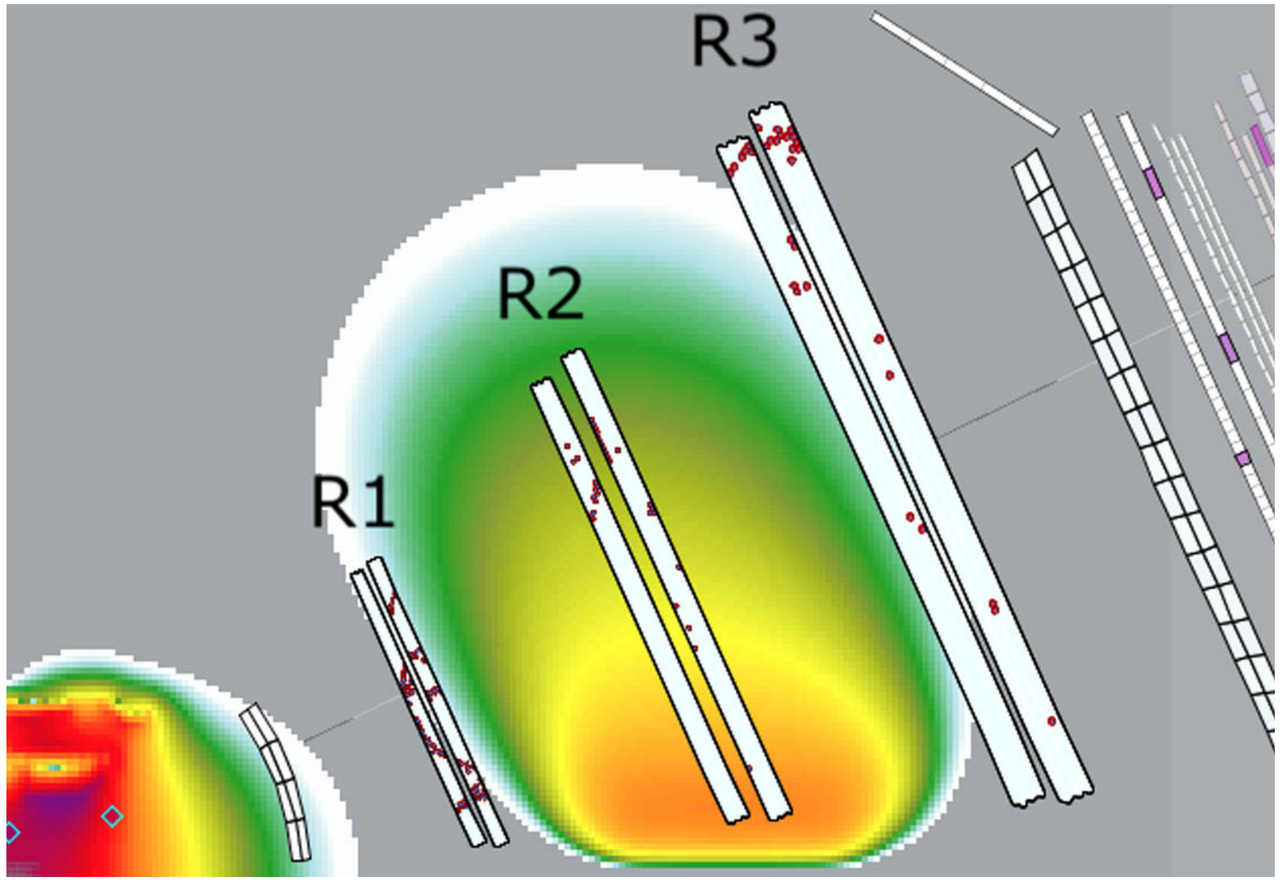
- $Q^2 > 2$ GeV^2
- $W > 2.5$ GeV
- $y < 0.75$

Pions

- $1.25 < p_\pi < 5$ GeV
- $1.7 < M_X < 5$ GeV
- $.3 < z = E_\pi/\omega < 1$

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

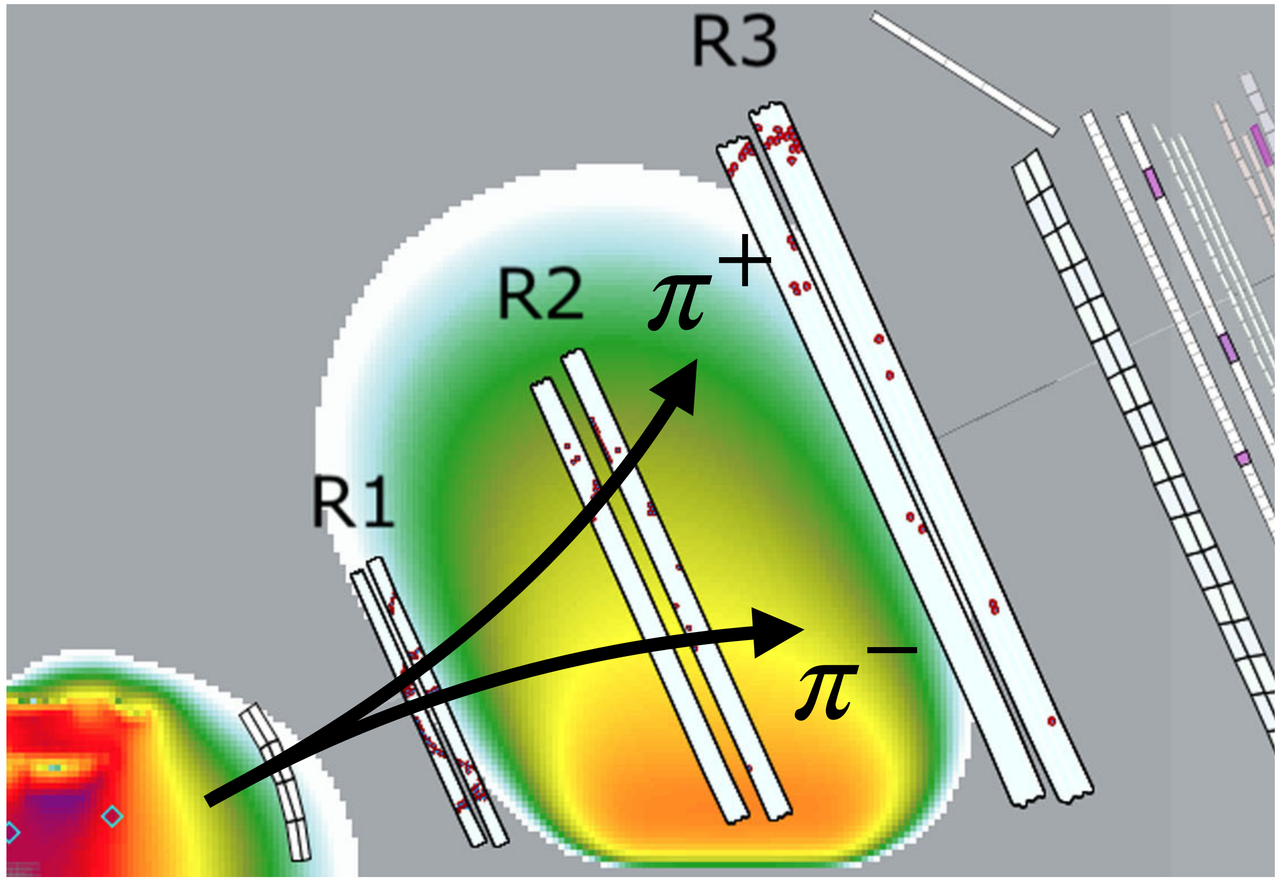
Matching Phase Space



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

What we measure

Matching Phase Space



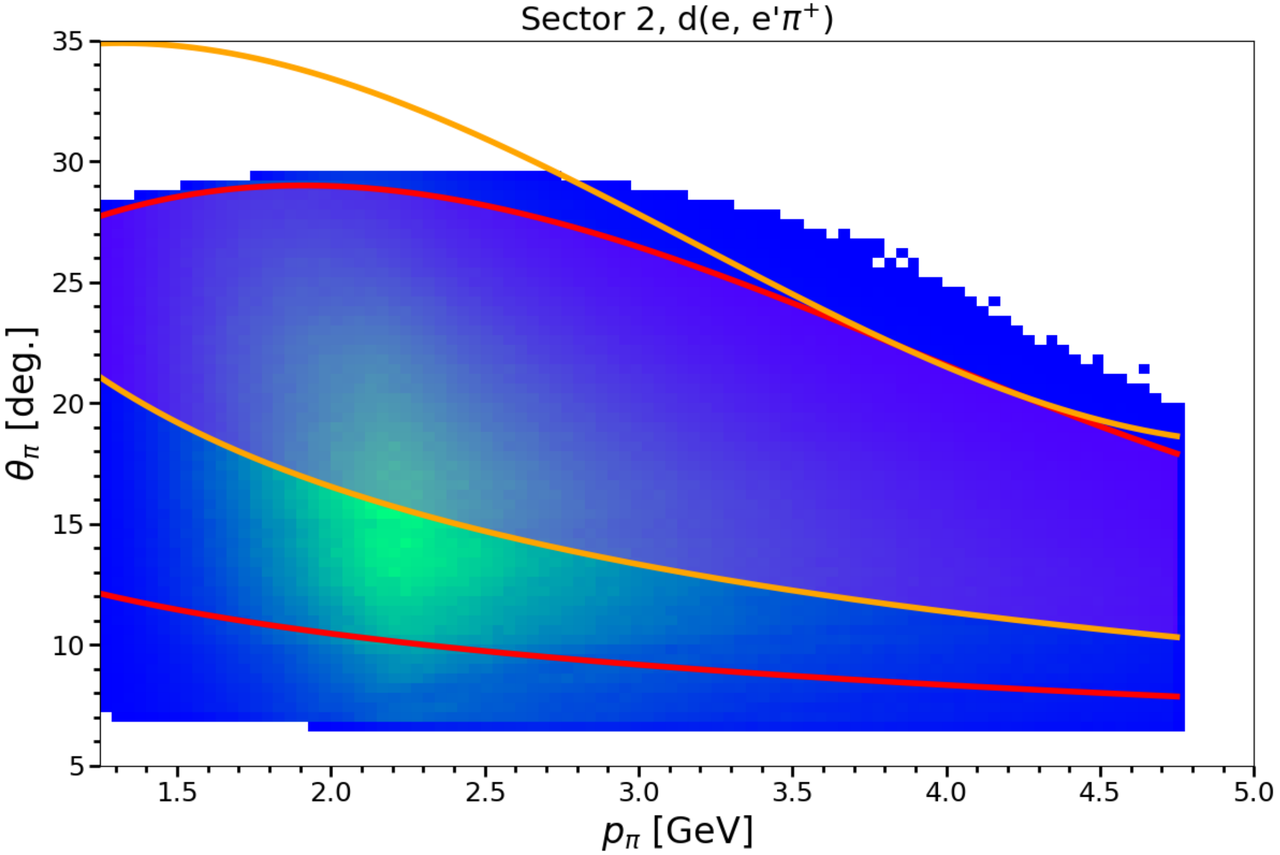
$$\frac{Y^{\pi+}(p^{\pi+},\,\theta^{\pi+},\,\phi^{\pi+})}{Y^{\pi-}(p^{\pi-},\,\theta^{\pi-},\,\phi^{\pi-})} \longrightarrow \frac{Y^{\pi+}(p,\,\theta,\,\phi)}{Y^{\pi-}(p,\,\theta,\,\phi)}$$

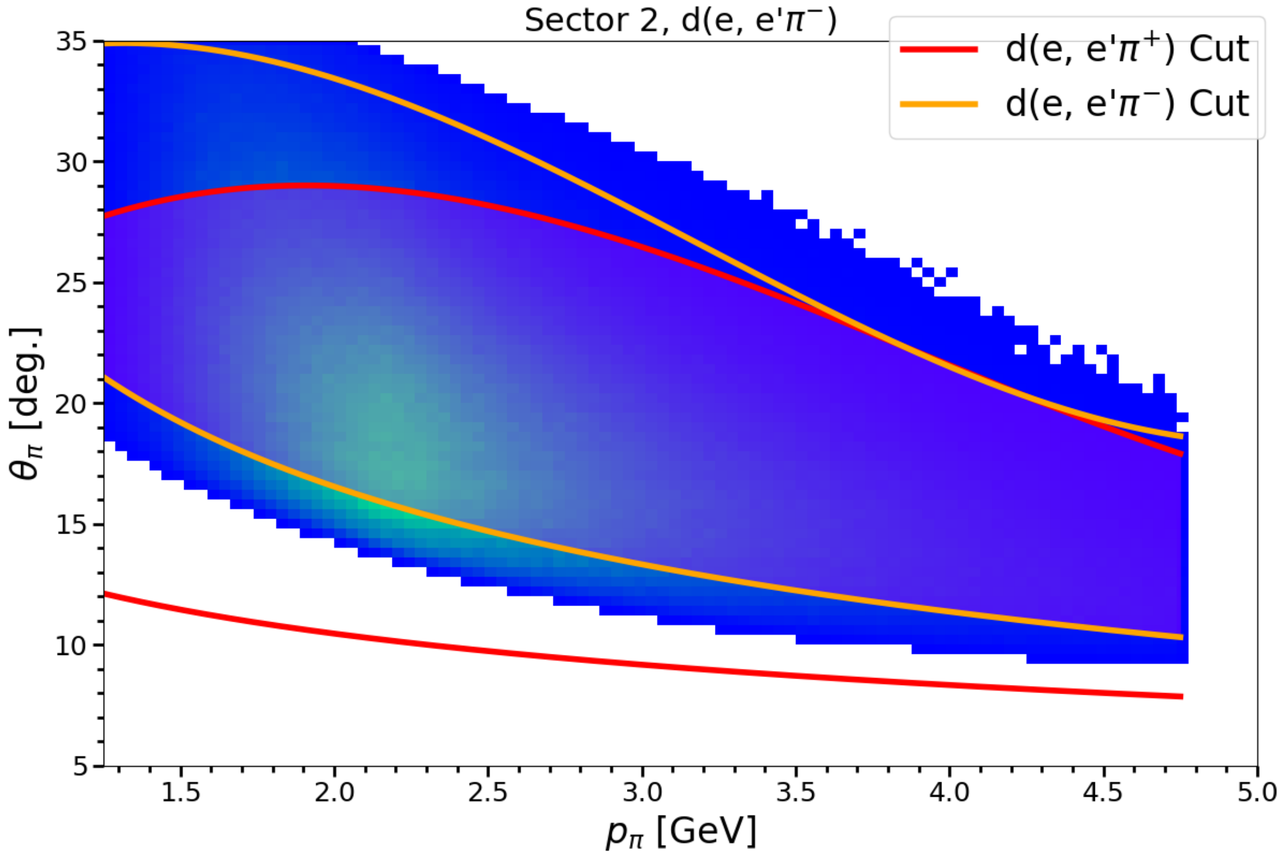
What we measure

What we want

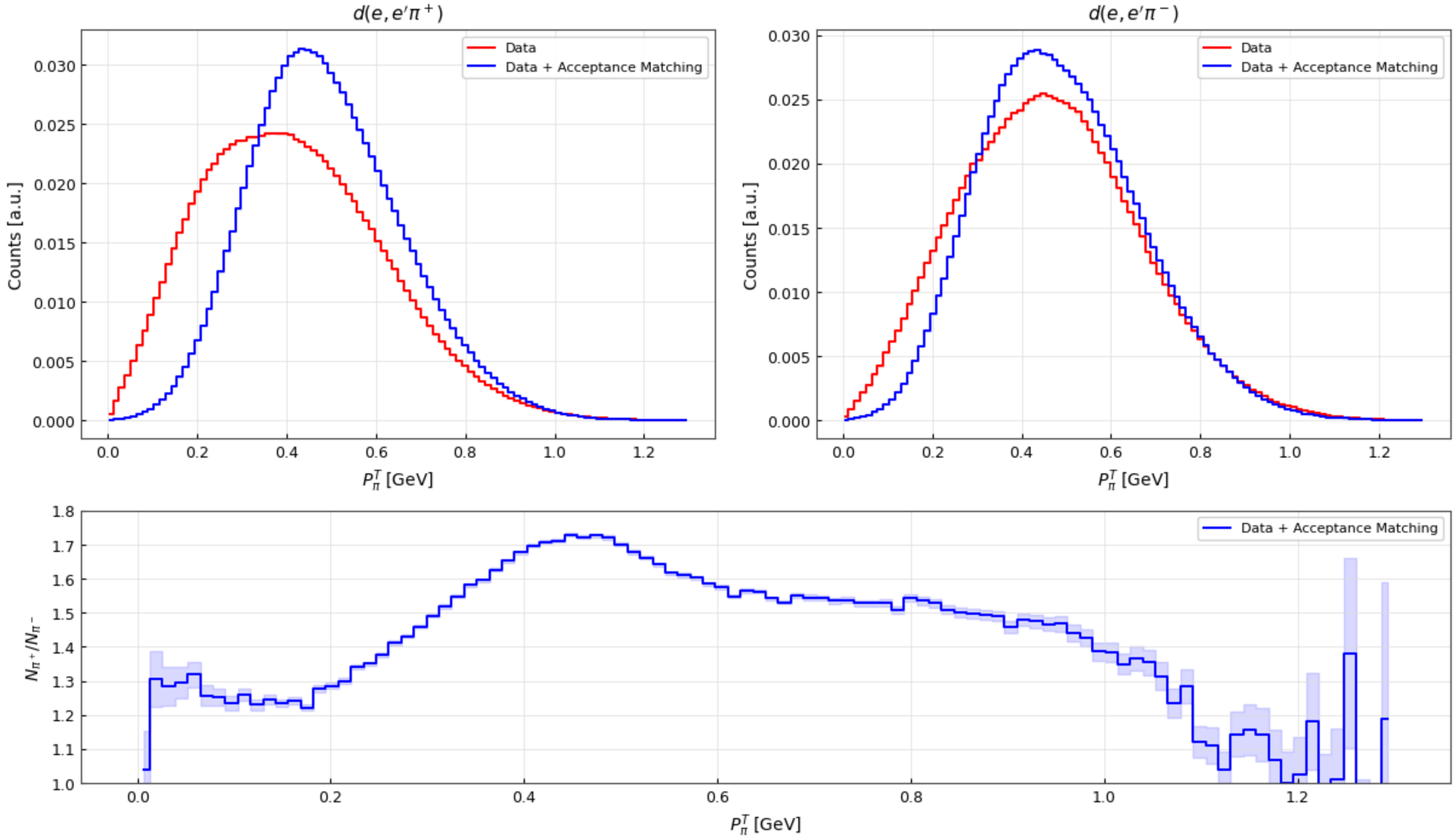
Acceptance Matching

Use a 10% threshold cut to identify good regions for both π^+ and π^- in p_π and θ_π

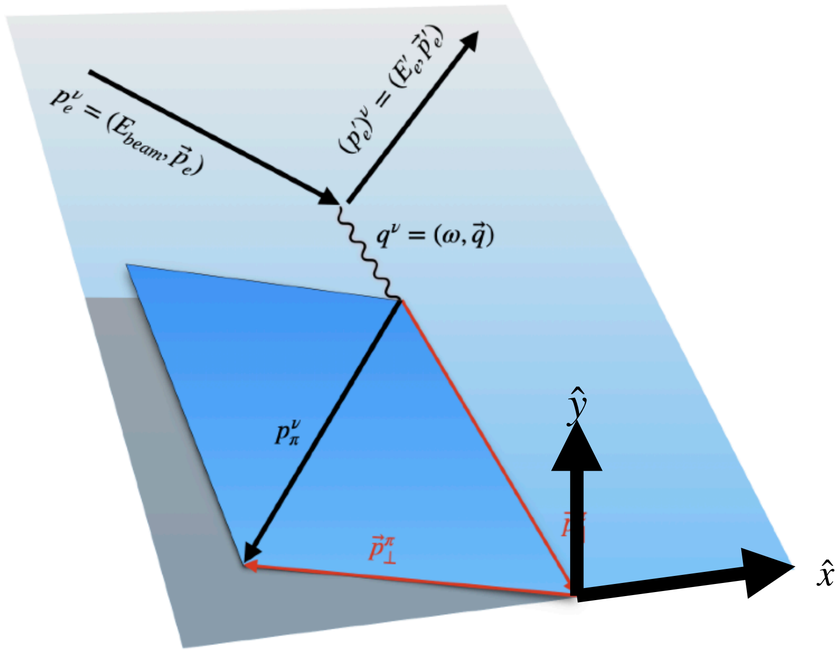


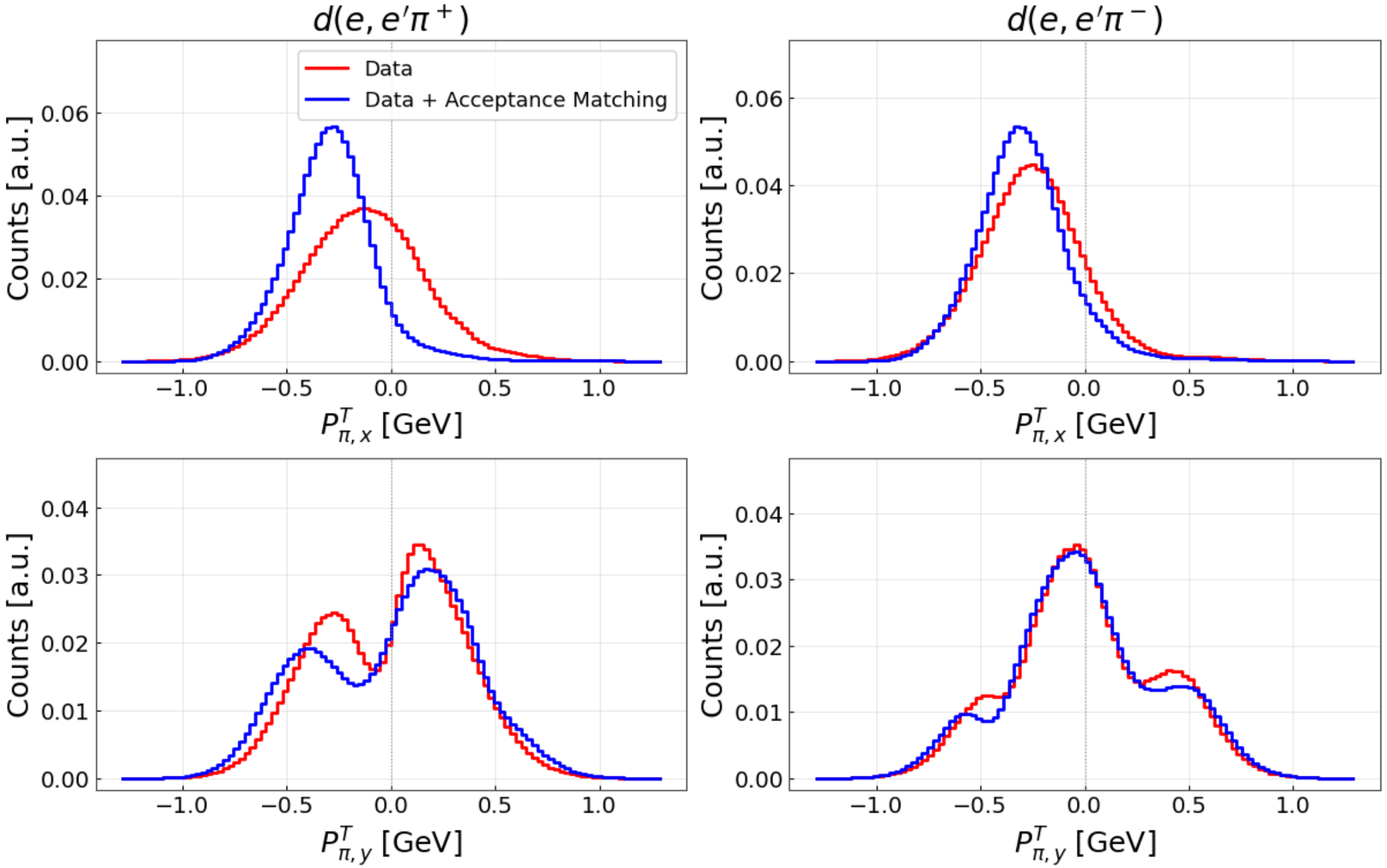


But acceptance matching cuts out low p_T

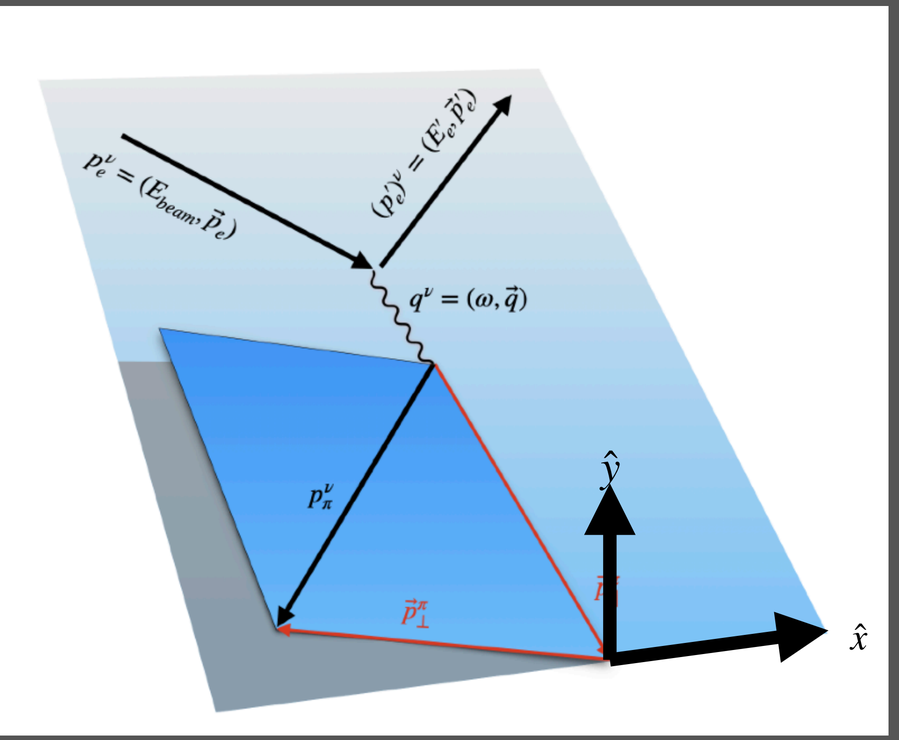


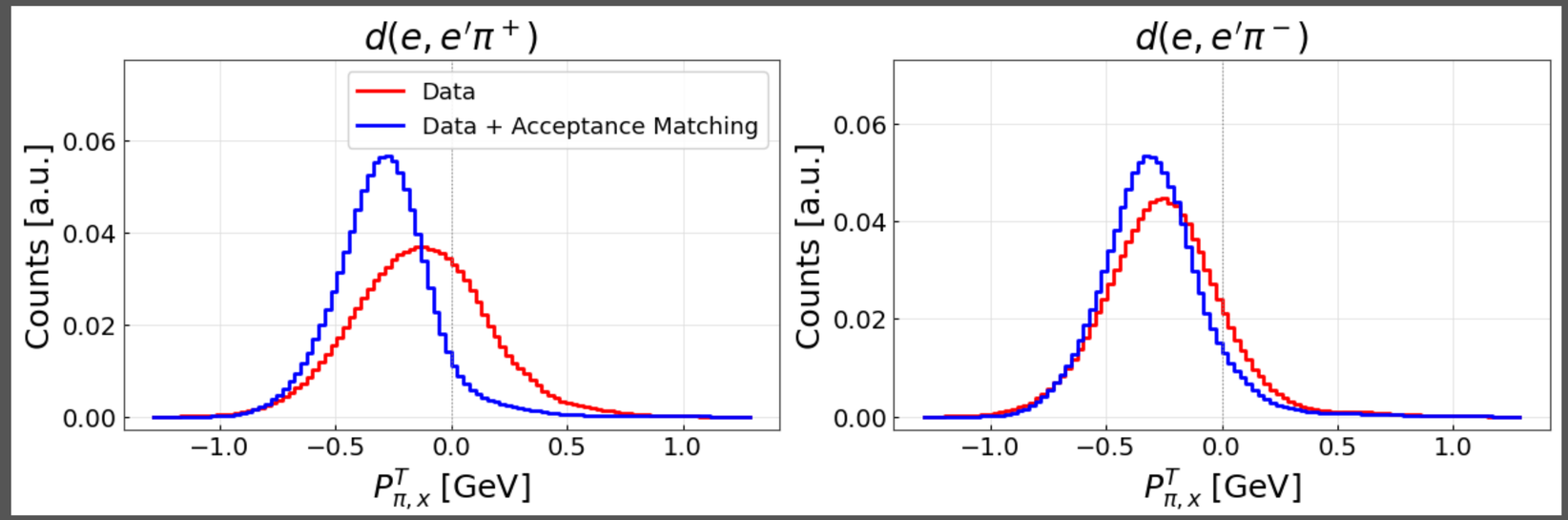
The components of p_T illuminate this effect

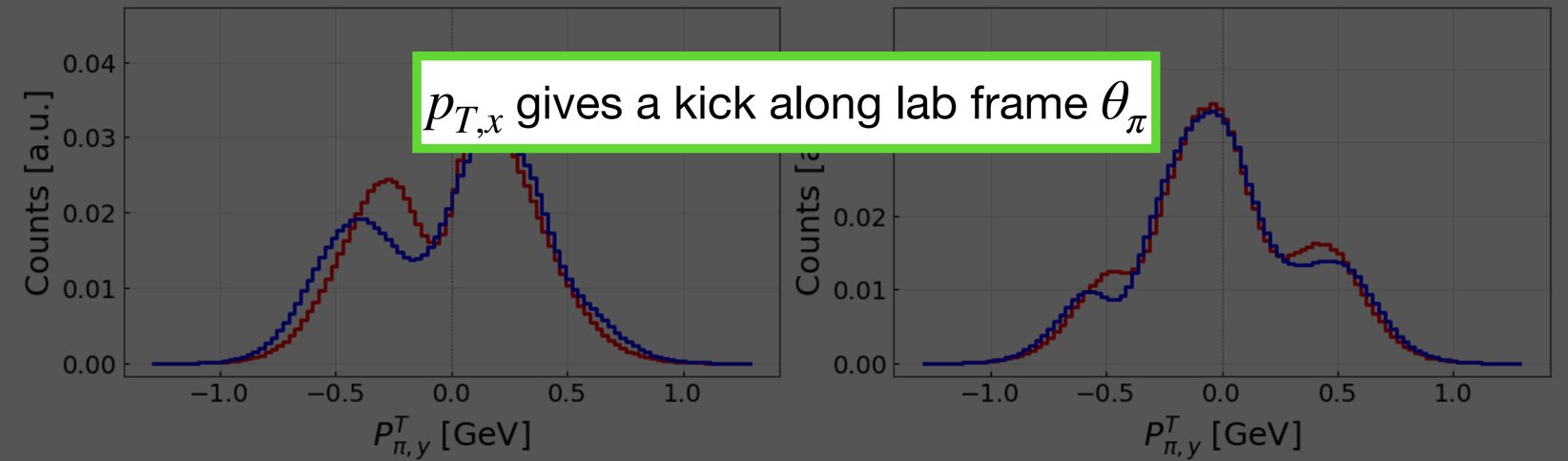




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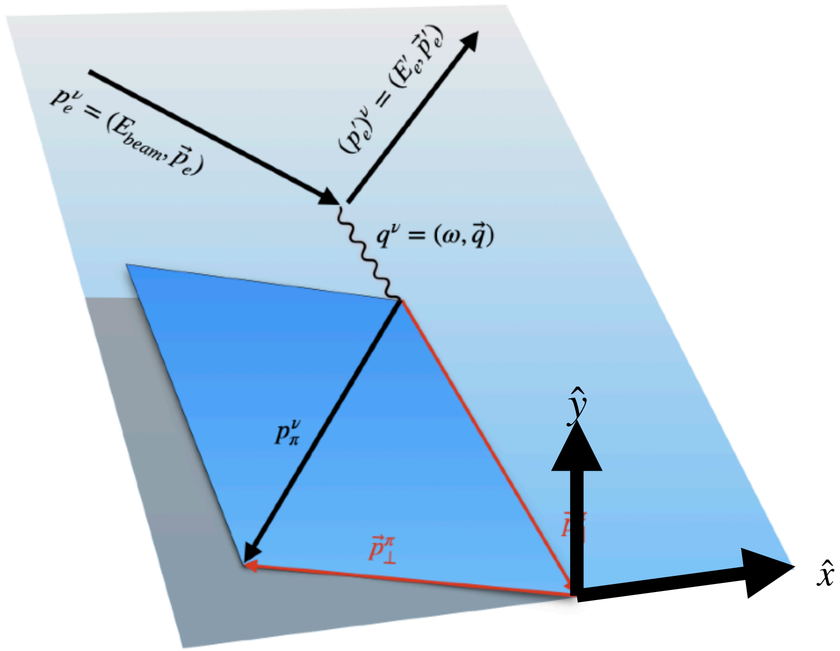


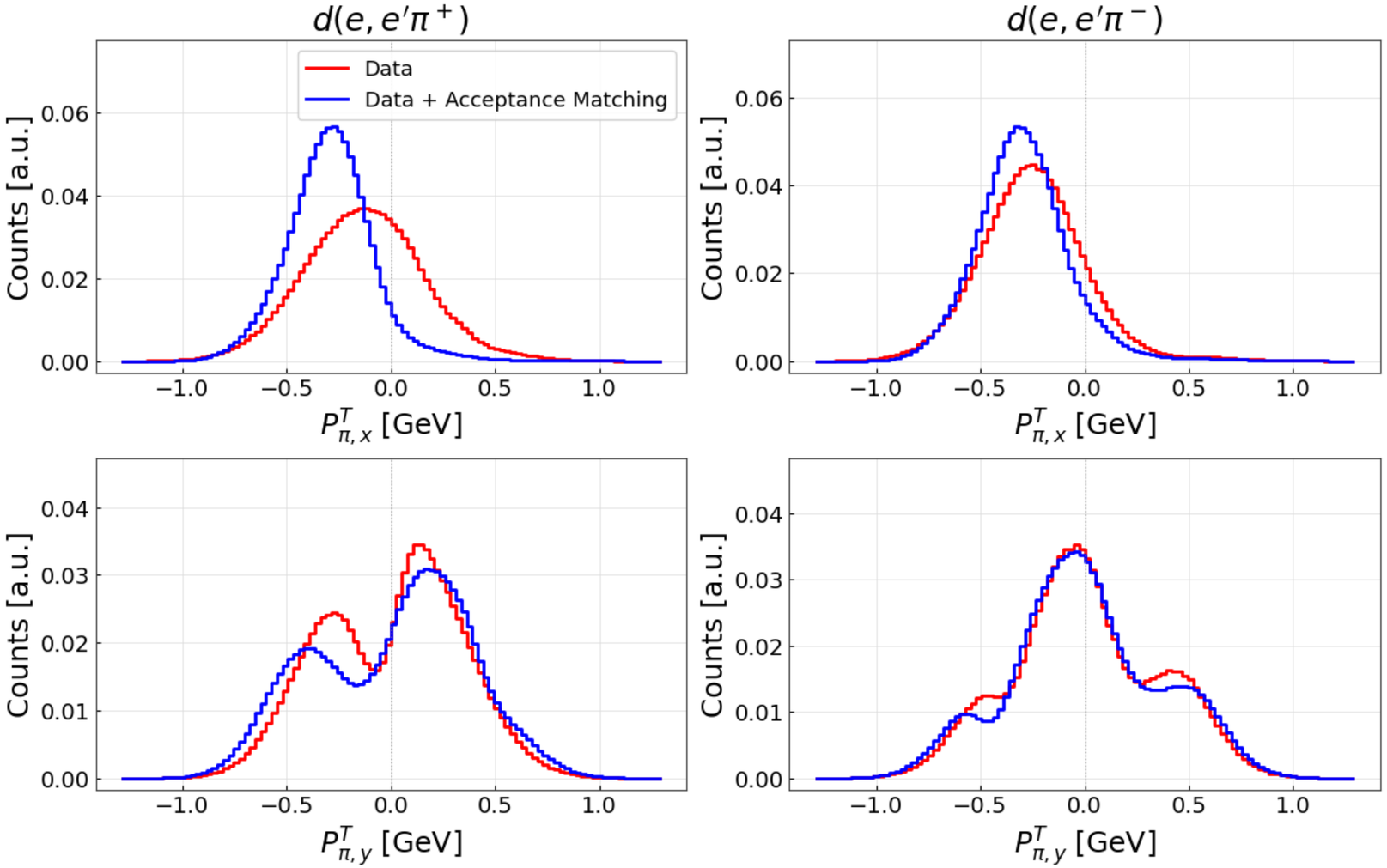




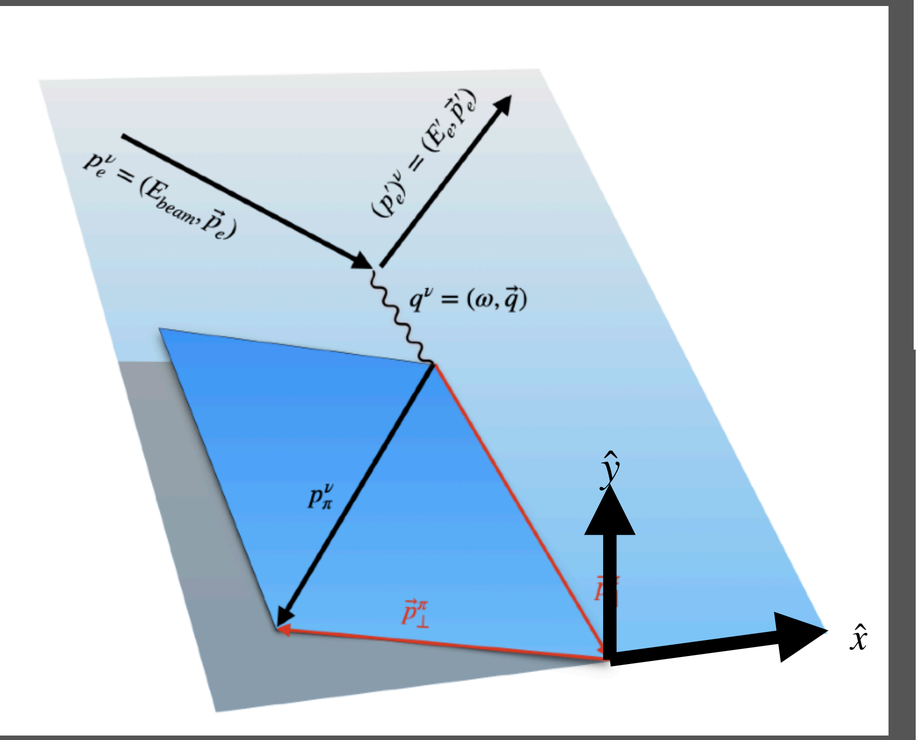
$p_{T,x}$ gives a kick along lab frame θ_π

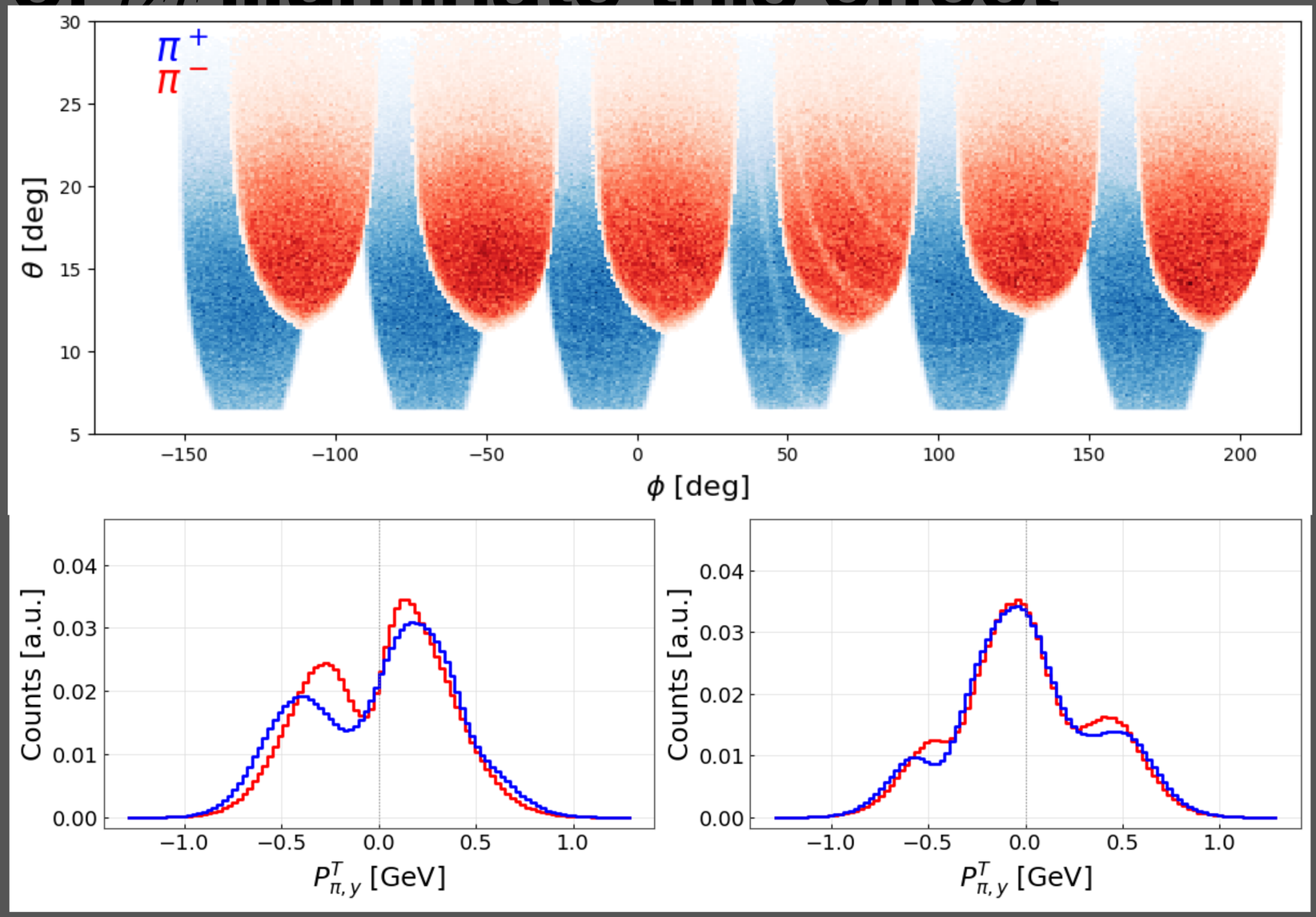
The components of p_T illuminate this effect





The components of p_T illuminate this effect





Solenoid gives inbending/outbending particles azimuthal kick

Detector effects can be corrected

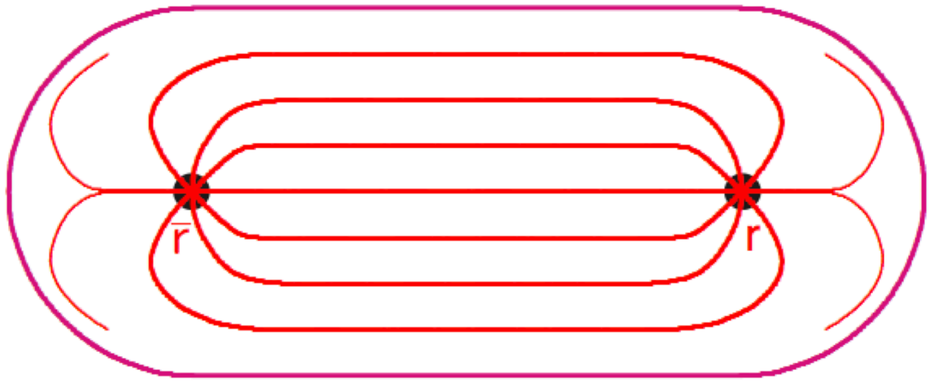
What we measure

$$Y_{rec\ kin,acc\ event}\left[\frac{Y_{gen\ kin,acc\ event}}{Y_{rec\ kin,acc\ event}}\right]\left[\frac{Y_{gen\ kin,gen\ event}}{Y_{gen\ kin,acc\ event}}\right] = Y_{gen\ kin,gen\ event}$$

What we want

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

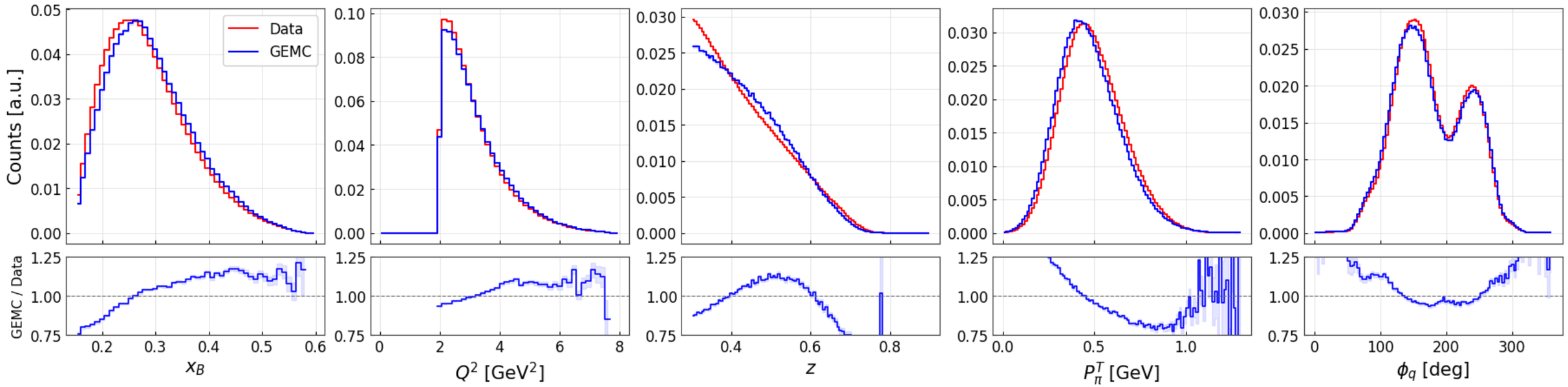
We correct in
$x_B, Q^2, z, p_T,$ and ϕ_q^π



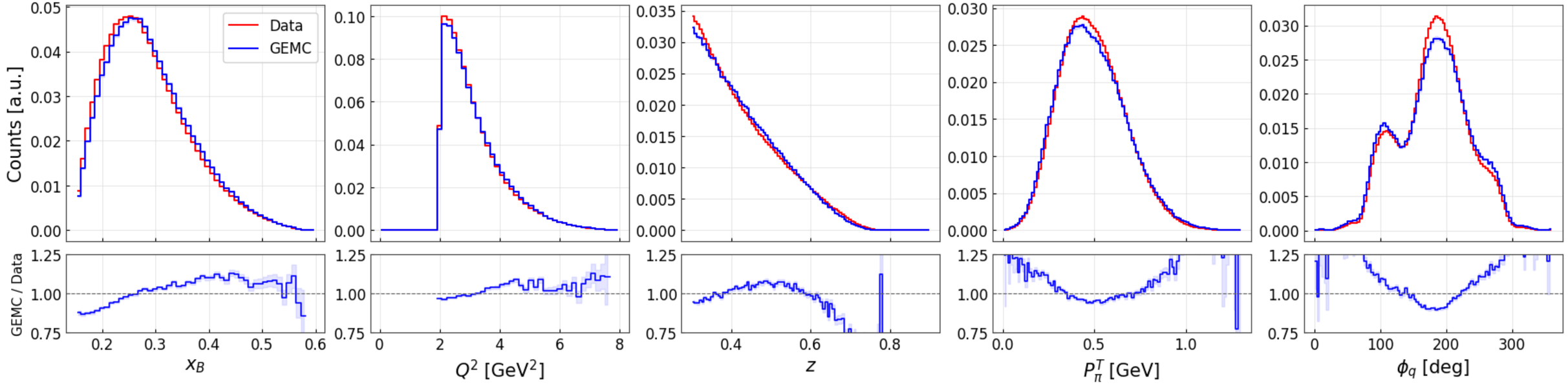
Torbjorn Sjostrand

Data/Sim Comparisons

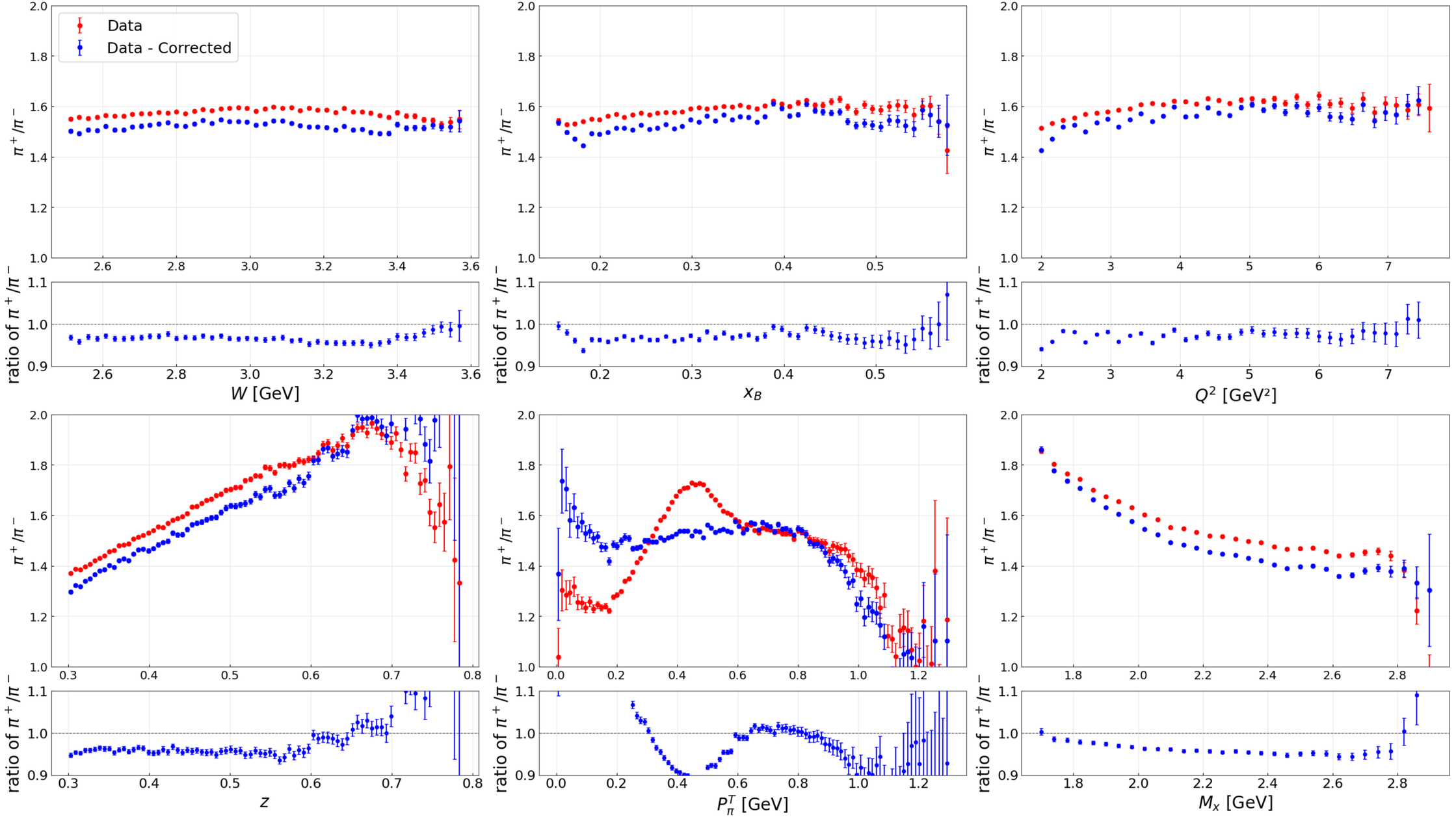
(e', π^+)



(e', π^-)

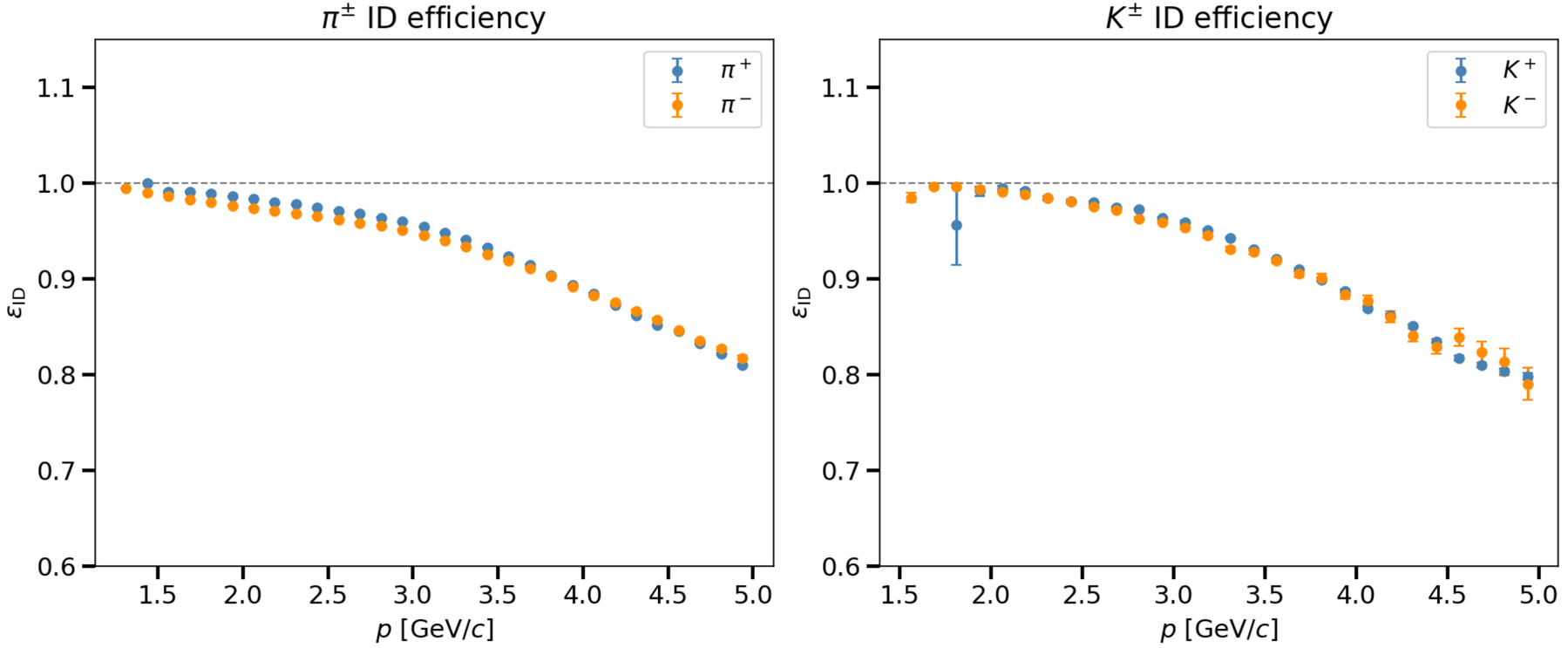


Detector effects can be corrected



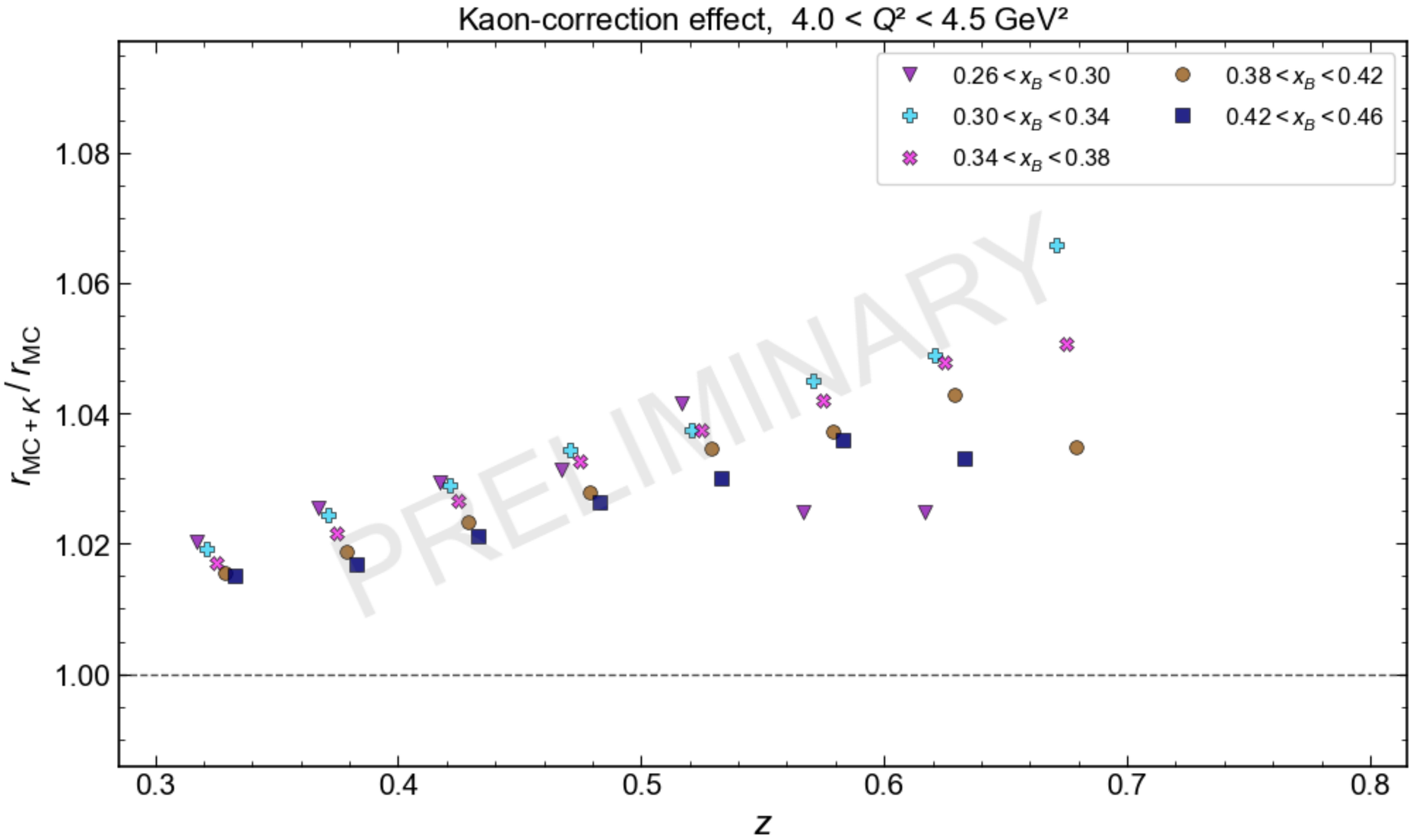
Kaon Contamination with the RICH

- PID efficiency calculated as
$$\epsilon^h = \frac{N(EB\ h \,|\, RICH\ h)}{N(RICH\ h)}$$
- $N_{phe} \geq 3$
- $R_Q = 1 - \frac{LL_{first}}{LL_{second}} > .35$



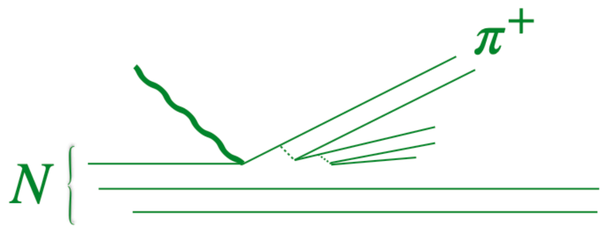
$$\vec{Y}_{EB} = \begin{pmatrix} Y^{\pi}_{\mathrm{EB}} \\ Y^{K}_{\mathrm{EB}} \\ Y^{p}_{\mathrm{EB}} \end{pmatrix} = \begin{pmatrix} \epsilon(\pi \to \pi) & \epsilon(K \to \pi) & \epsilon(p \to \pi) \\ \epsilon(\pi \to K) & \epsilon(K \to K) & \epsilon(p \to K) \\ \epsilon(\pi \to p) & \epsilon(K \to p) & \epsilon(p \to p) \end{pmatrix} \begin{pmatrix} Y^{\pi}_{\mathrm{true}} \\ Y^{K}_{\mathrm{true}} \\ Y^{p}_{\mathrm{true}} \end{pmatrix} = M\vec{Y}_{true}$$

Impact of misidentification

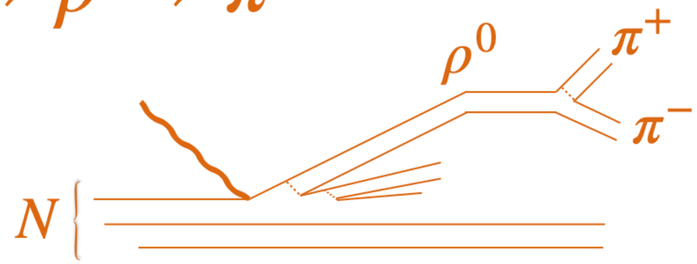


Diffractive vector mesons are a major background

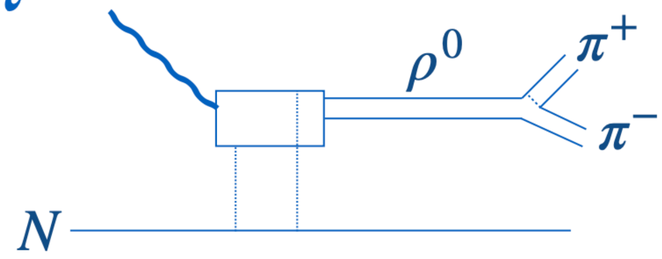
1. Direct from quark $q^* + N \to \pi$



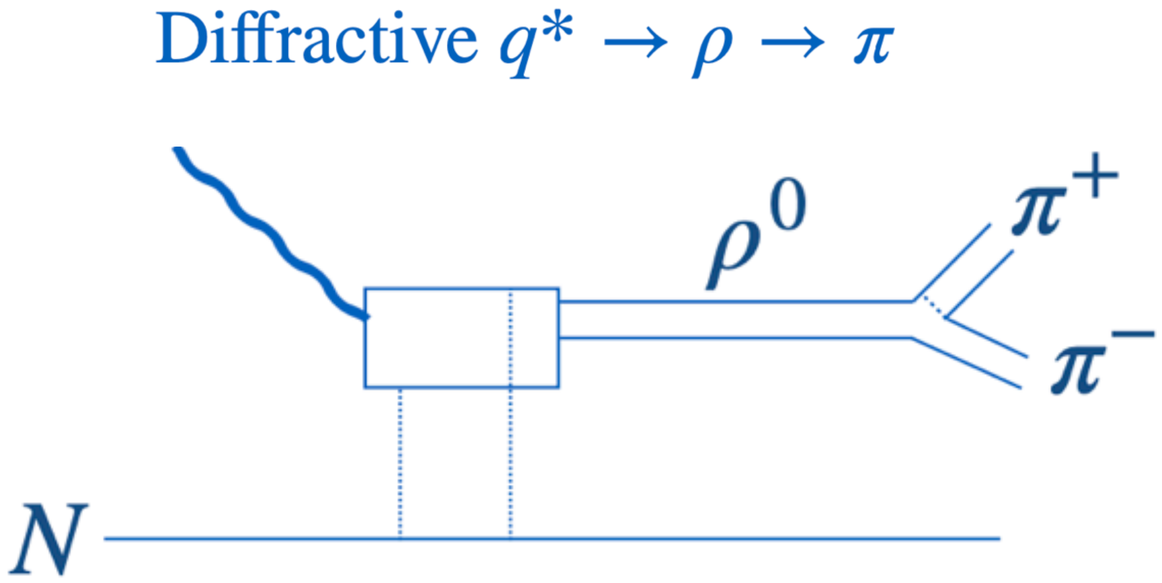
2. VM production $q^* + N \to \rho \to \pi$



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



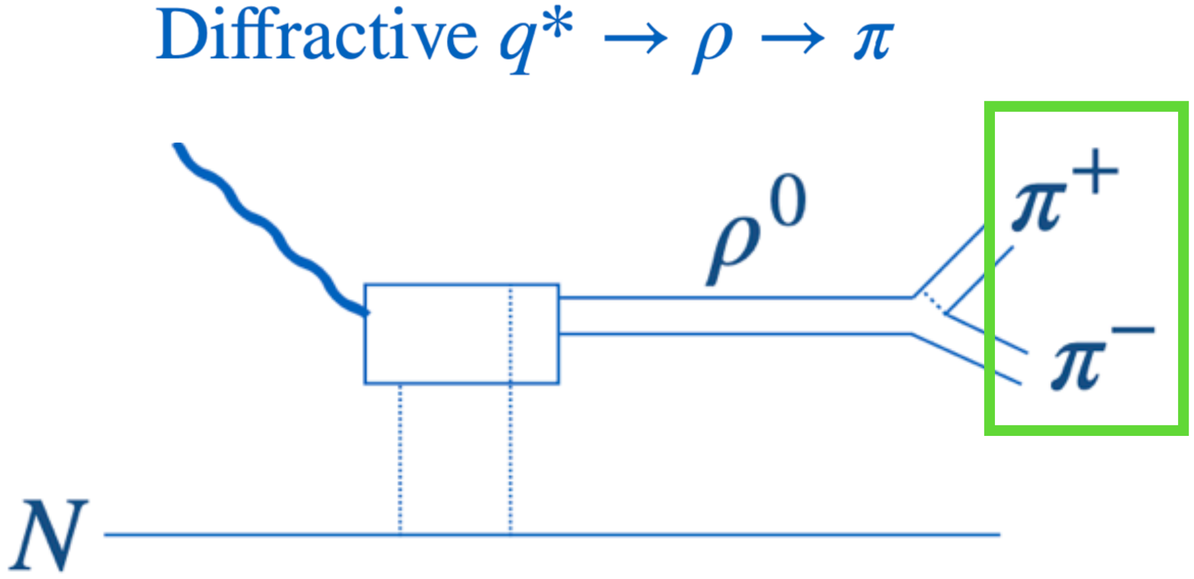
Data driven approach to subtracting the ρ_0



Two possibilities:

$$\left(M_X^{(e',\pi^+\pi^-)}\right)^2 = |\,q + m_N - p_{\pi^+} - p_{\pi^-}\,|^2 > 1.25\ [\mathrm{GeV}^2]$$

Data driven approach to subtracting the ρ_0

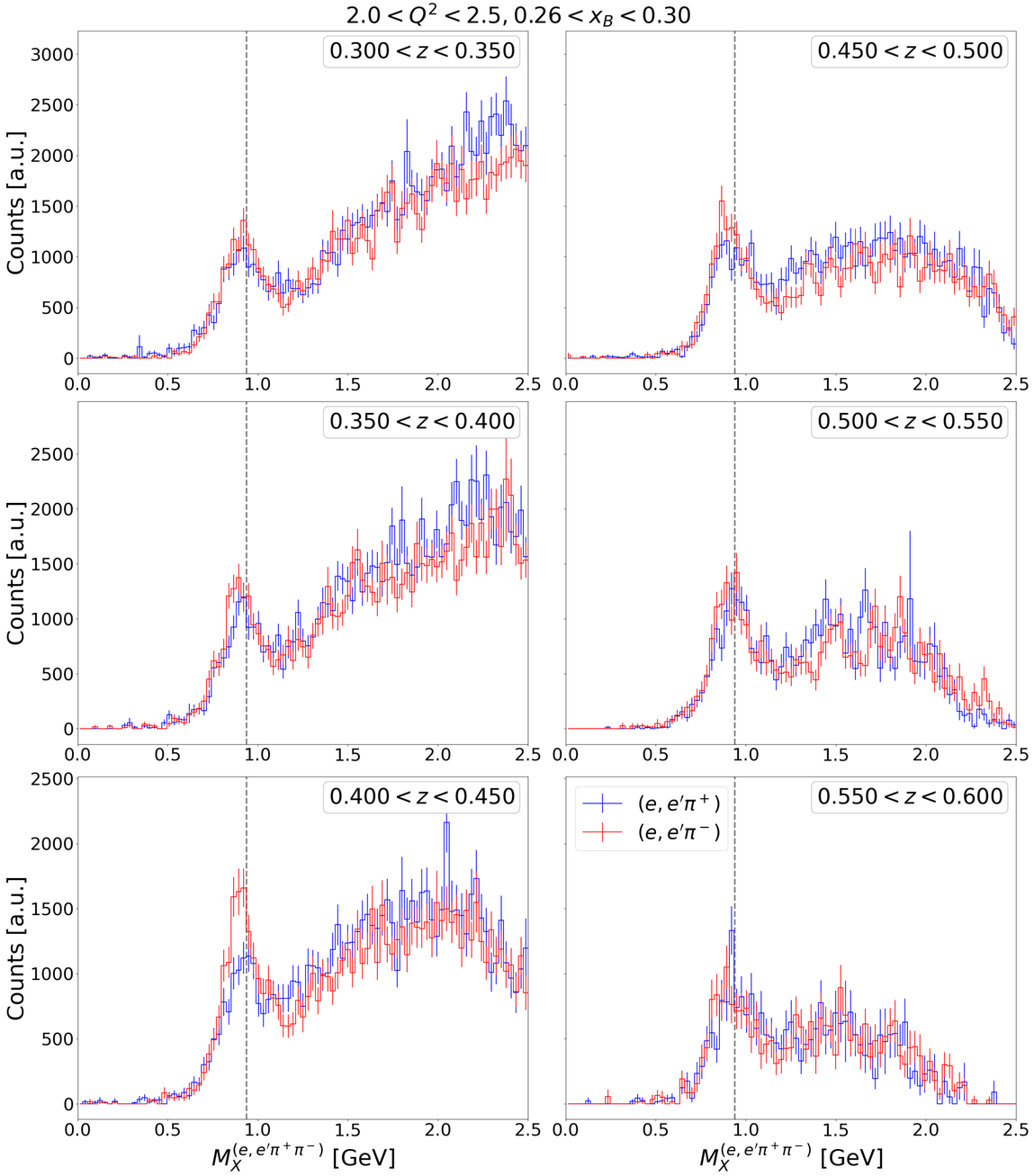


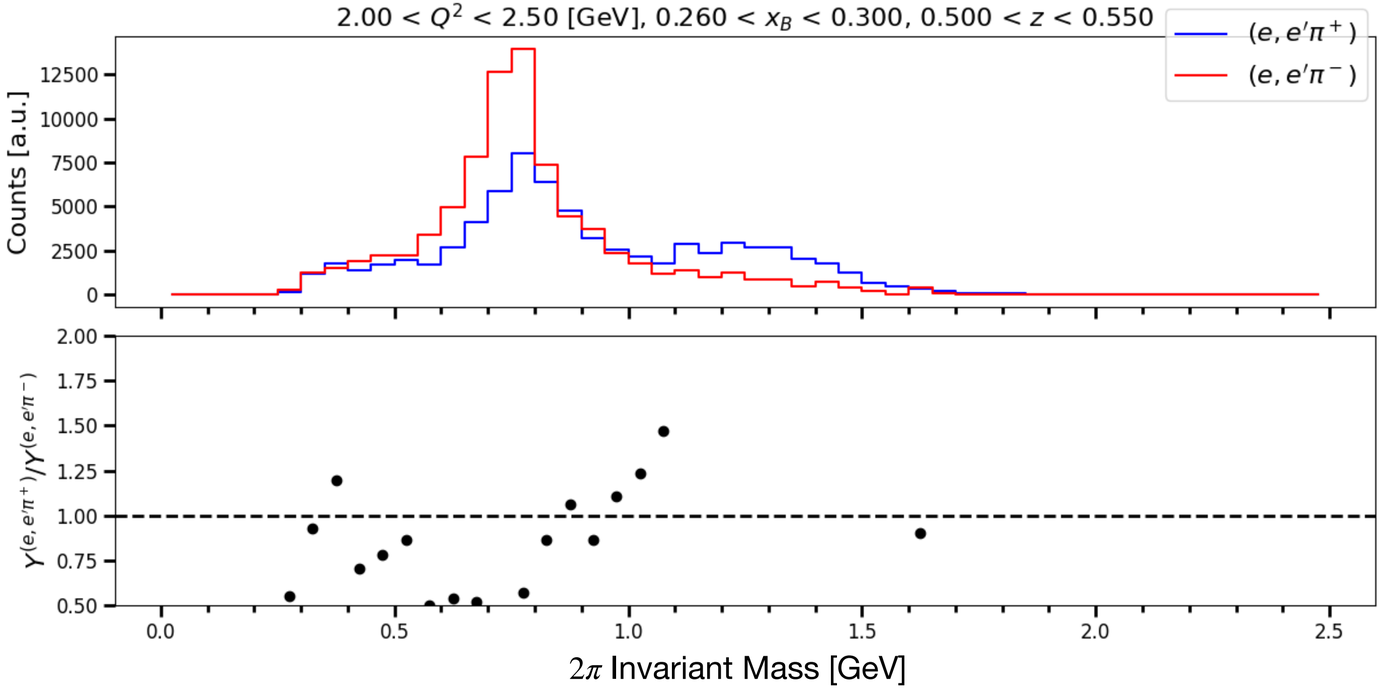
Two possibilities:

1. Detect both pions→Directly subtract

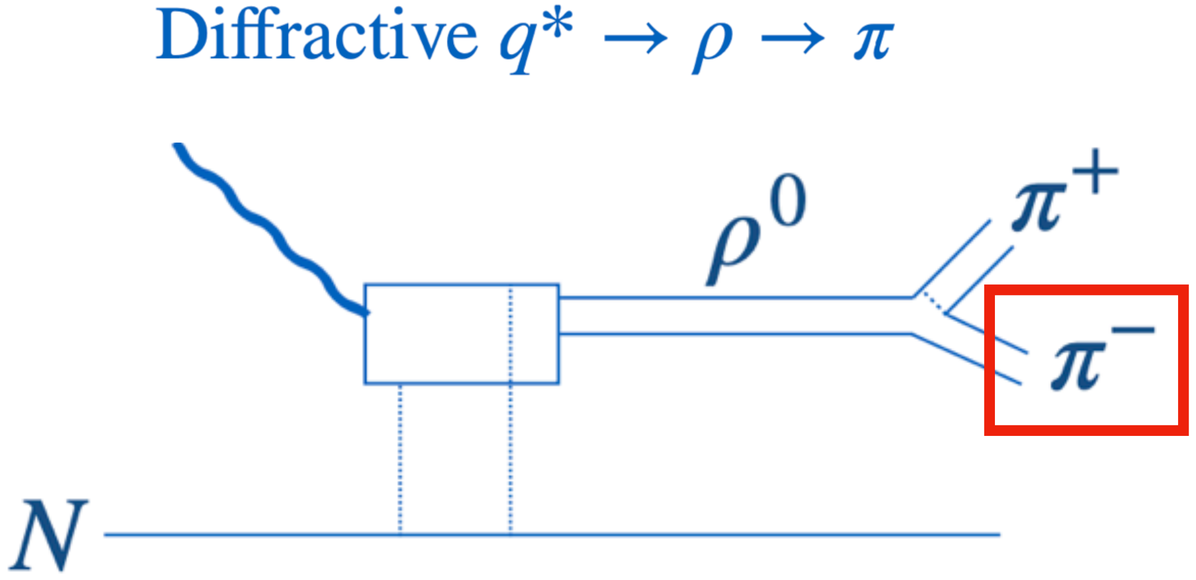
$$\left(M_X^{(e',\pi^+\pi^-)}\right)^2 = |q + m_N - p_{\pi^+} - p_{\pi^-}|^2 > 1.25 \text{ [GeV}^2\text{]}$$

Data driven approach to subtracting the ρ_0





Data driven approach to subtracting the ρ_0



Two possibilities:

1. Detect both pions→Directly subtract
2. Detect one pion→Estimate contribution by studying detector acceptance with rotated 2π events

$$\left(M_X^{(e',\pi^+\pi^-)}\right)^2 = |\,q + m_N - p_{\pi^+} - p_{\pi^-}\,|^2 > 1.25\ [\mathrm{GeV}^2]$$

Vector Meson Reweighting

1. Identify diffractive VM events with $\left(M_X^{(e',\pi^+\pi^-)}\right)^2 < 1.25$ [GeV^2]
2. Estimate contribution of 1π diffractive VM events using quasi-events produced by randomly rotating about the **beam axis** and q **vector**
   - Determine if 0π, 1π or 2π detected in each quasi-event
3. Reweight events with factor $w_{VM} = 1 + \dfrac{1\pi \text{ quasi-events}}{2\pi \text{ quasi-events}}$

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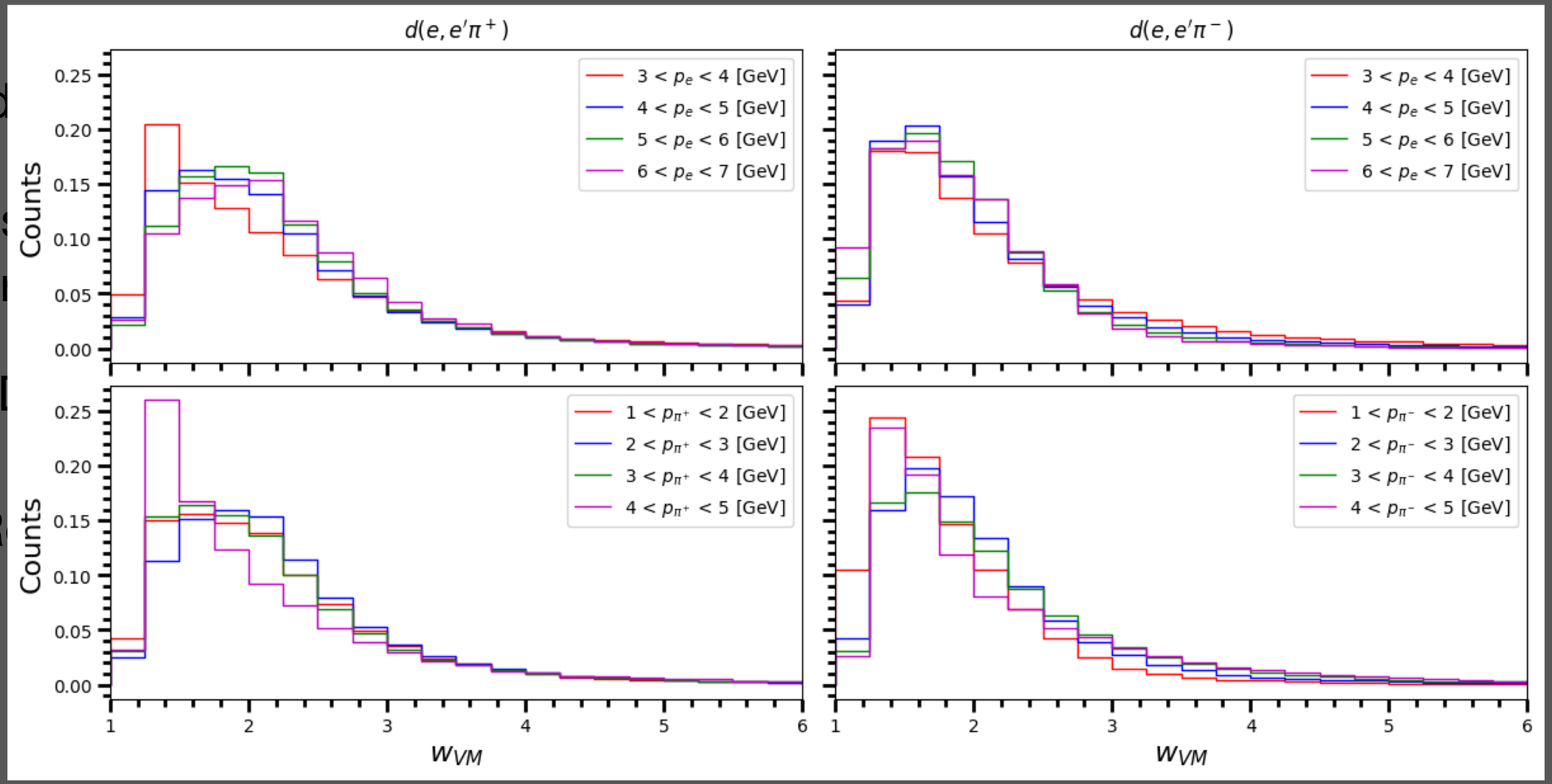
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Vector Meson Reweighting

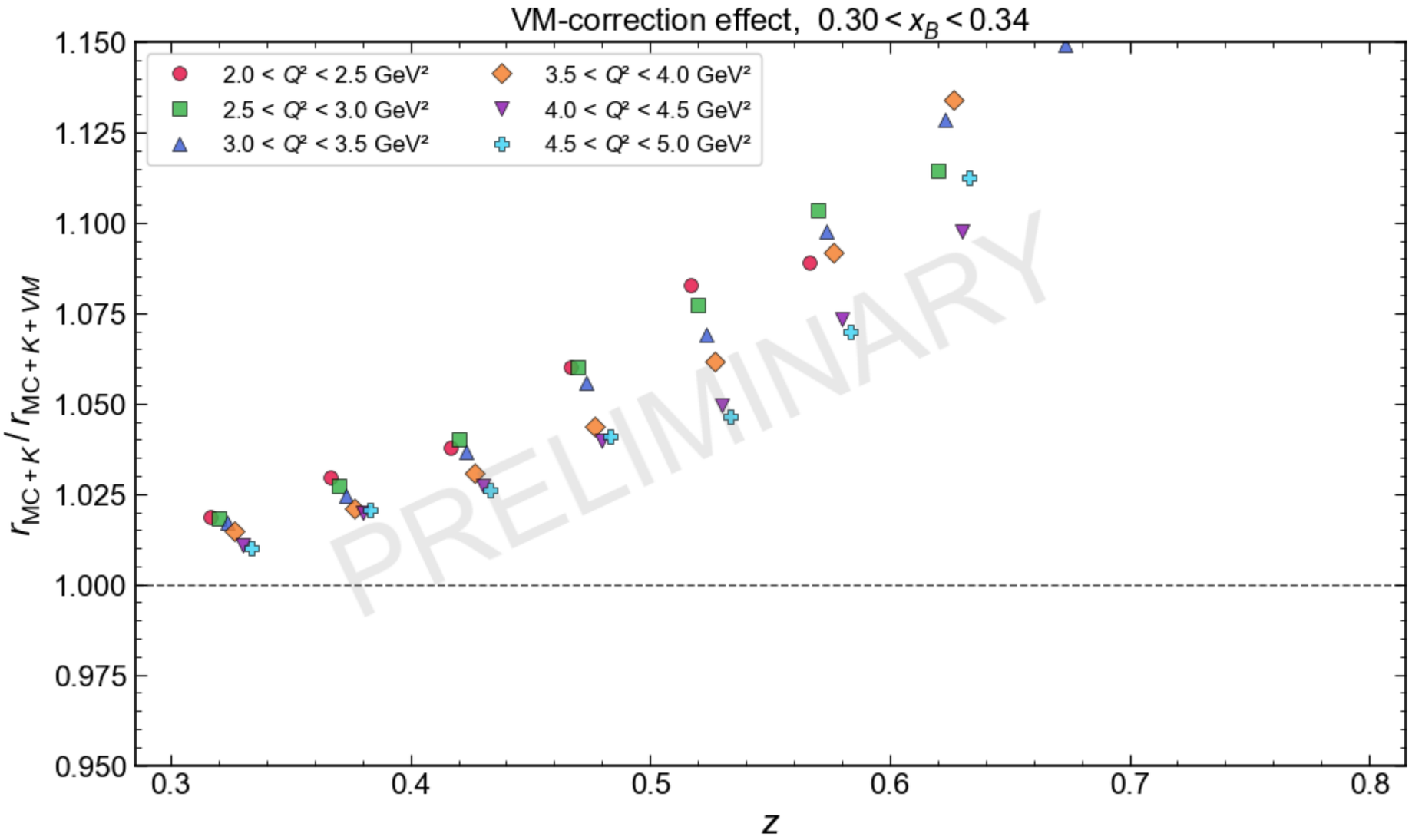
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Vector Meson Reweighting

1. Id
2. Es
   pr
   - [
3. R



Impact of subtraction on cross section ratio

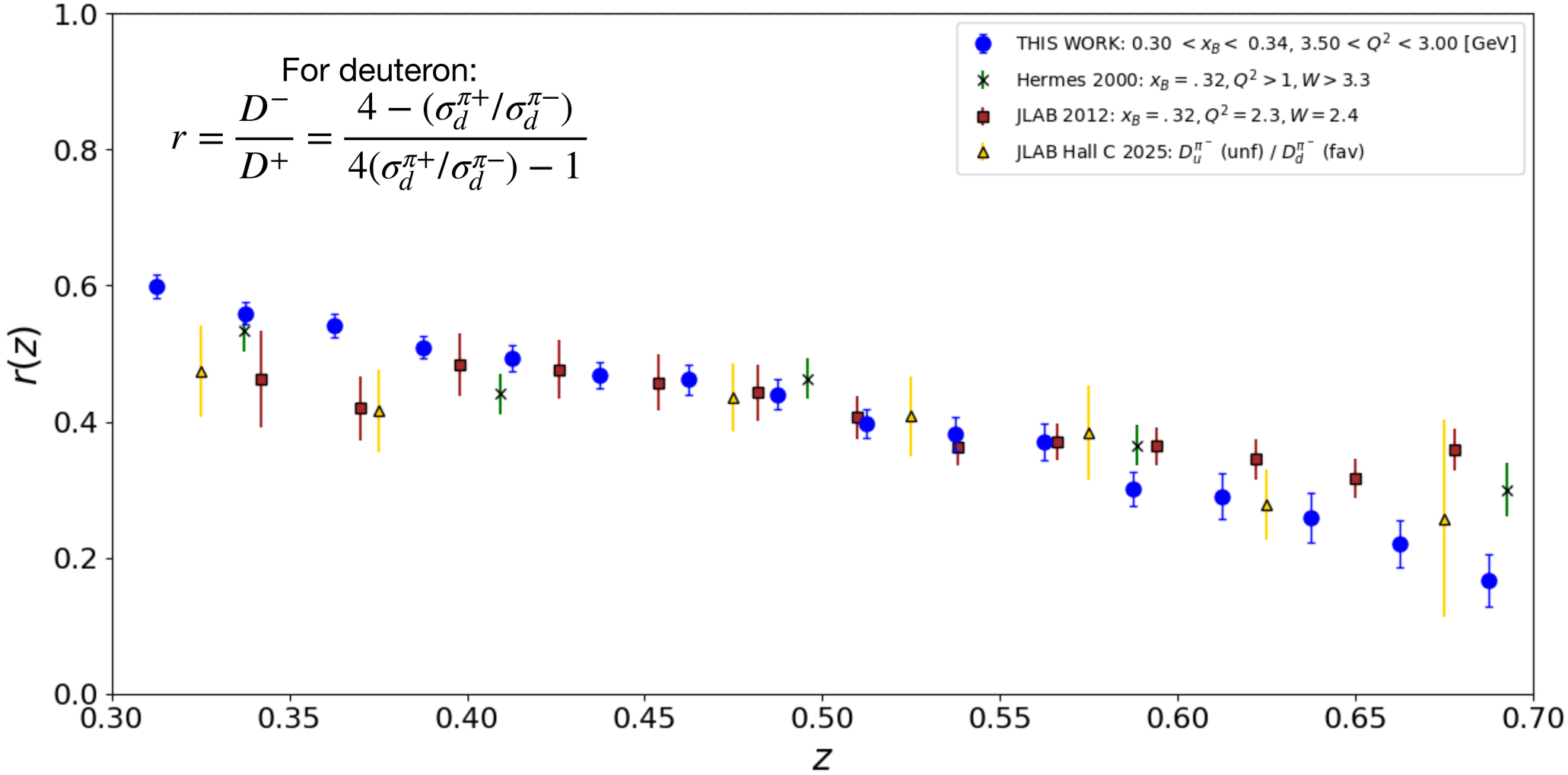


Preliminary Results

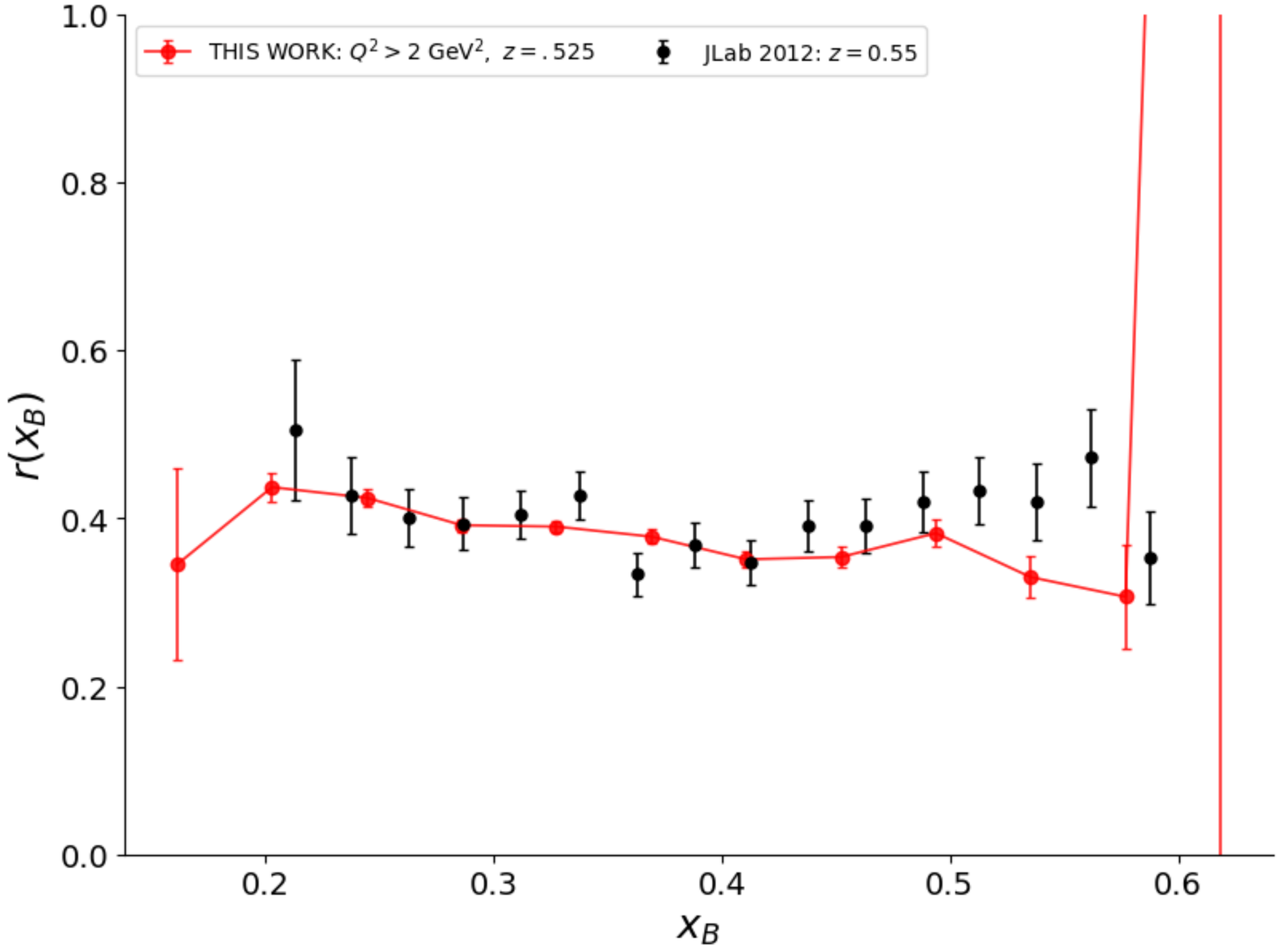
Excellent agreement with previous measurements

For deuteron:

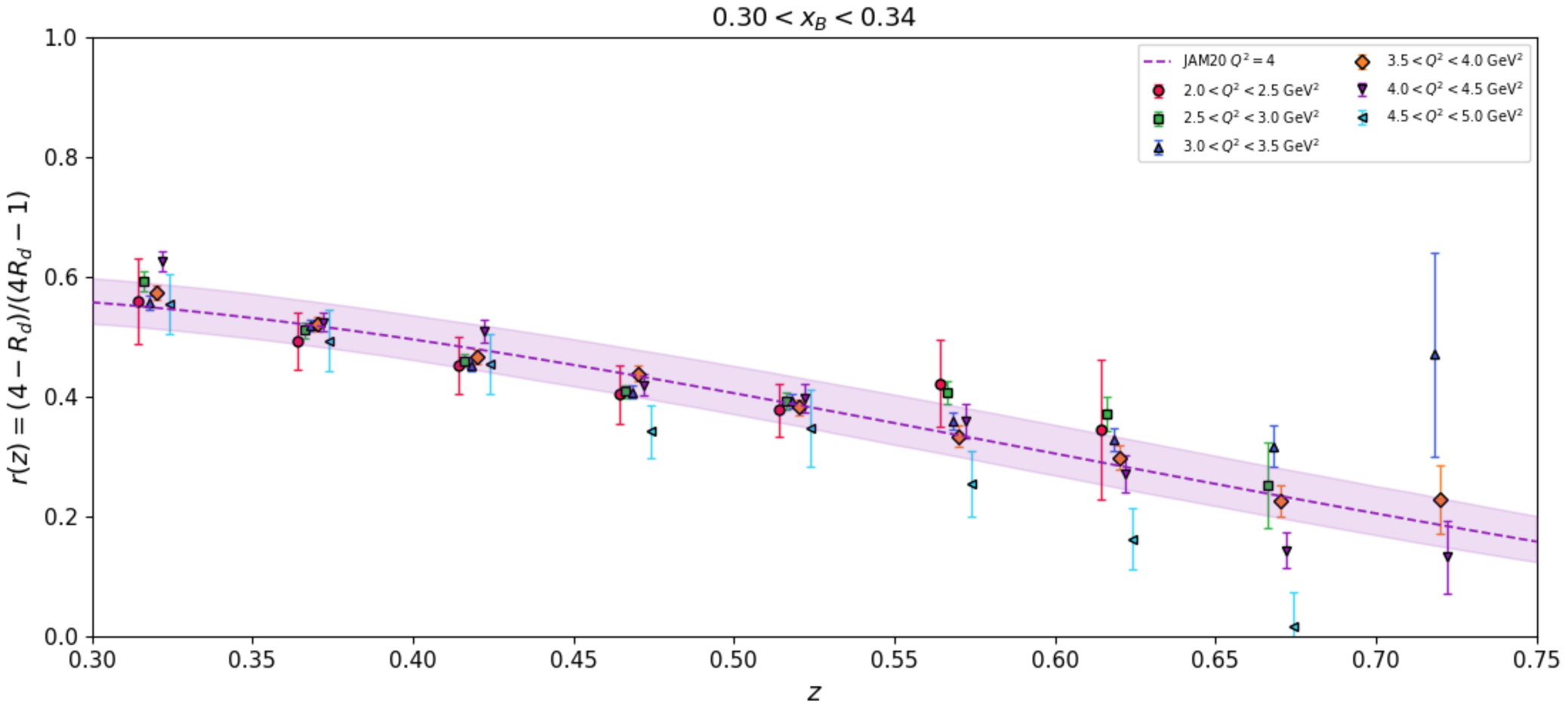
$$r = \frac{D^-}{D^+} = \frac{4 - (\sigma_d^{\pi+}/\sigma_d^{\pi-})}{4(\sigma_d^{\pi+}/\sigma_d^{\pi-}) - 1}$$



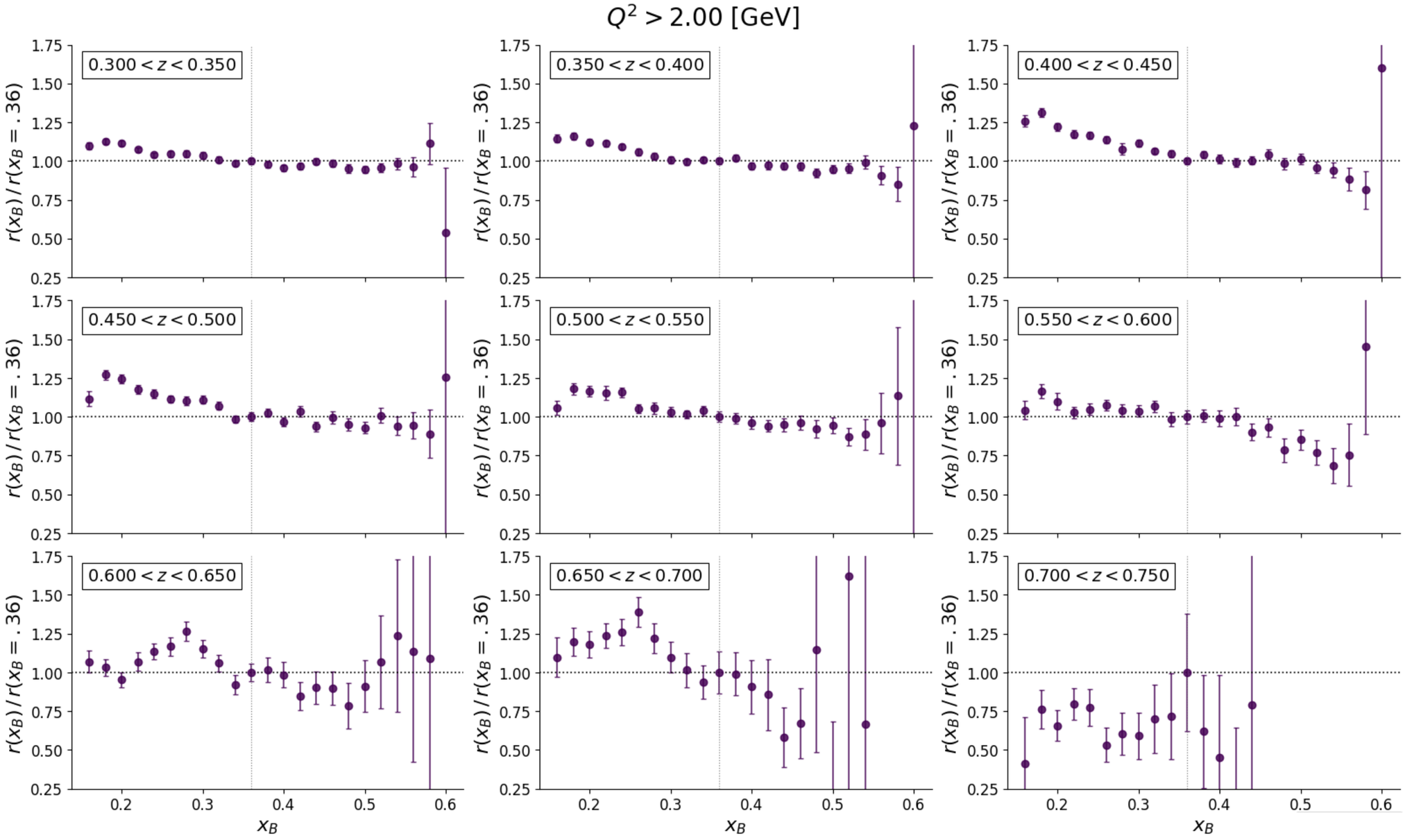
x_B dependence consistent with previous measurement



CLAS12 data supports factorization in Q^2



Data shows factorization in x_B in valence region



Note: plots normalized to $x_B = 0.36$

Towards extracting d/u

For proton:

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

For deuteron:

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

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

What we have:

- High precision measurement of D^-/D^+ (and σ_d^+/σ_d^-)
- Multi-dimensional binning of this observable
- Phase space coverage in all dimensions to identify regions where factorization holds

What we need:

- Full accounting of systematics
- High precision measurement of $\sigma_p^+/\sigma_p^- \Rightarrow$ We can use the same tools we developed!

Questions?

Backup

Vector Meson Subtraction

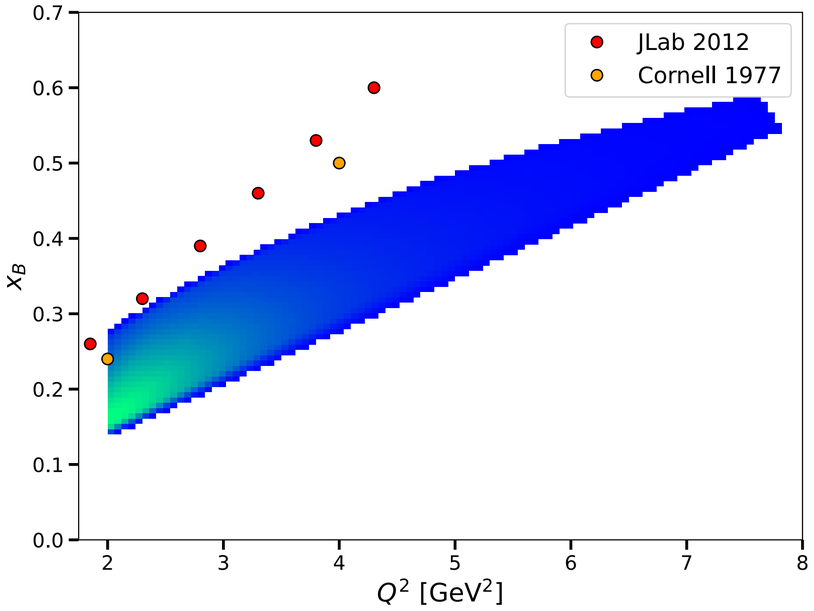
Constructing VM sample

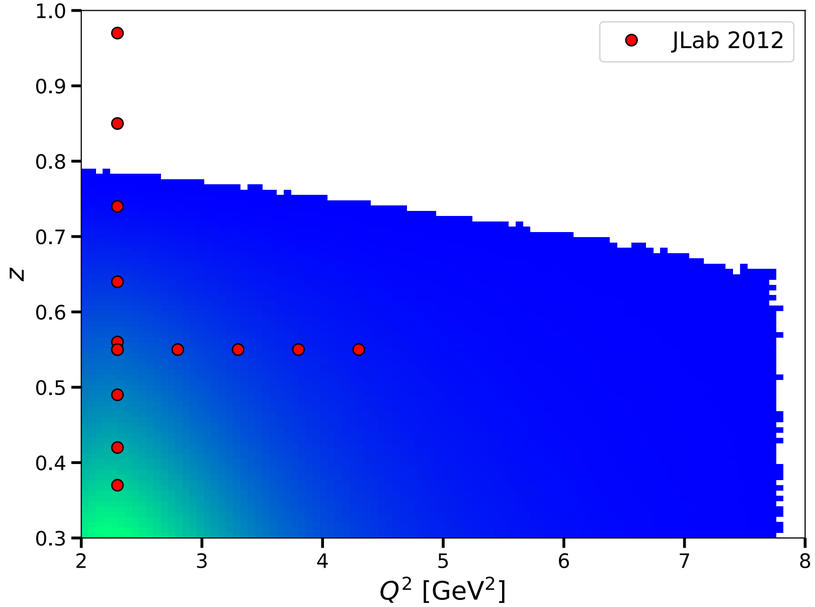
- VM decay is isotropic→Identify in each event an *analysis* π and a *tagging* π
  - Choose π^+ as tagging pion to minimize DIS contribution to sample
  - IF a good analysis π^- is unavailable, check if π^- is detected outside of π^+ acceptance to use as tagging pion to ensure that tagging pions sweep the entire θ space
- Subtract this sample from both Y^{π^+} and Y^{π^-}

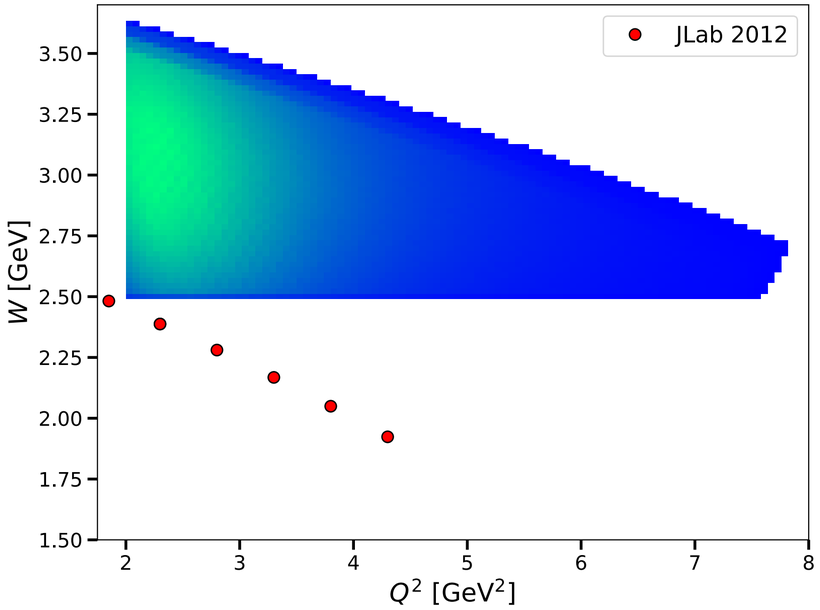
Rho Correction - Data Driven Approach

- Due to symmetry of decay, we can choose one pion as a “tagging” pion and subtract the other one from both π^+ and π^- for each event
  - Tagging pion chosen to be π^+, because of lower DIS contribution
  - At θ where we can’t tag a π^+, we use π^- instead

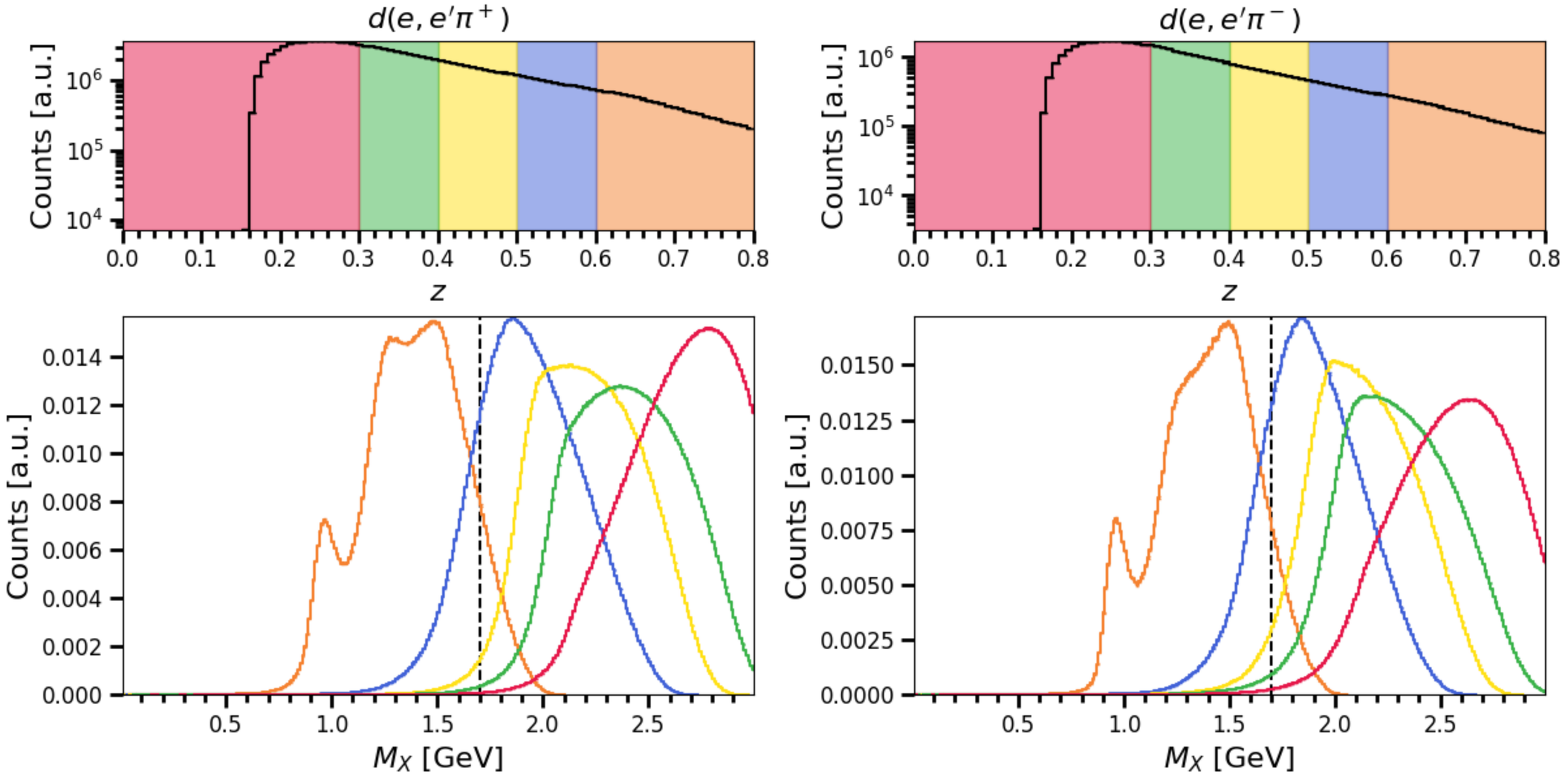
Kinematic Reach







M_X Dependence



Kaon Contamination with the RICH

$$Y_{EB}^{\pi^\pm} = \epsilon^{\pi^\pm} Y^{\pi^\pm} + (1 - \epsilon^{K^\pm}) Y^{K^\pm},$$

$$Y_{EB}^{K^\pm} = (1 - \epsilon^{\pi^\pm}) Y^{\pi^\pm} + \epsilon^{K^\pm} Y^{K^\pm},$$



$$Y^{\pi^\pm} = \frac{\epsilon^{K^\pm} Y_{\pi}^{EB} - (1 - \epsilon^{K^\pm}) Y_{EB}^{K^\pm}}{\epsilon^{\pi^\pm} + \epsilon^{K^\pm} - 1}$$

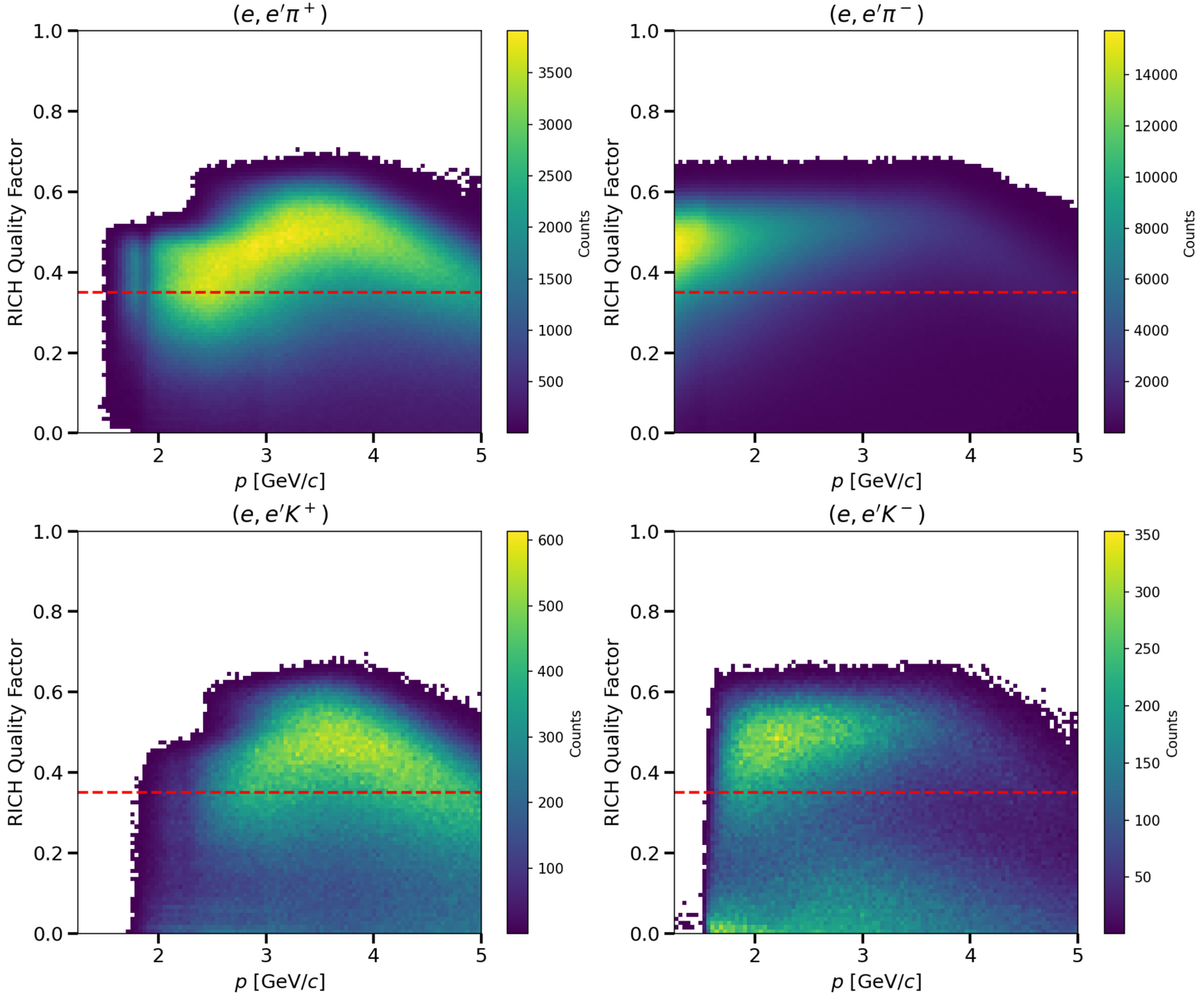
$$Y^{K^\pm} = \frac{\epsilon^{\pi^\pm} Y_{K}^{EB} - (1 - \epsilon^{\pi^\pm}) Y_{EB}^{\pi^\pm}}{\epsilon^{\pi^\pm} + \epsilon^{K^\pm} - 1}$$



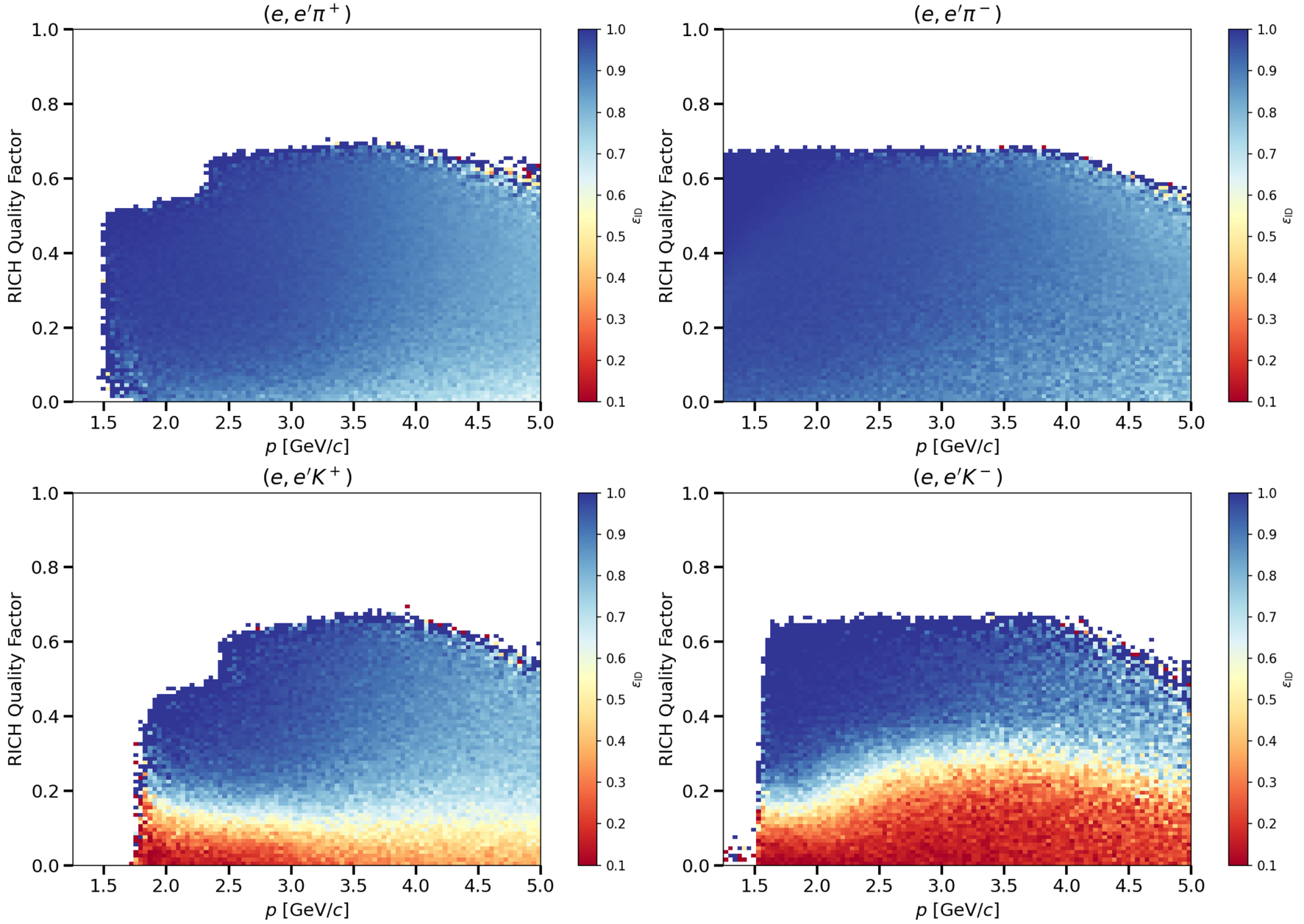
$$C_{\pi^\pm} = \frac{\epsilon^{K^\pm}}{\epsilon^{\pi^\pm} + \epsilon^{K^\pm} - 1}$$

$$C_{K^\pm} = \frac{1 - \epsilon^{K^\pm}}{\epsilon^{\pi^\pm} + \epsilon^{K^\pm} - 1}$$

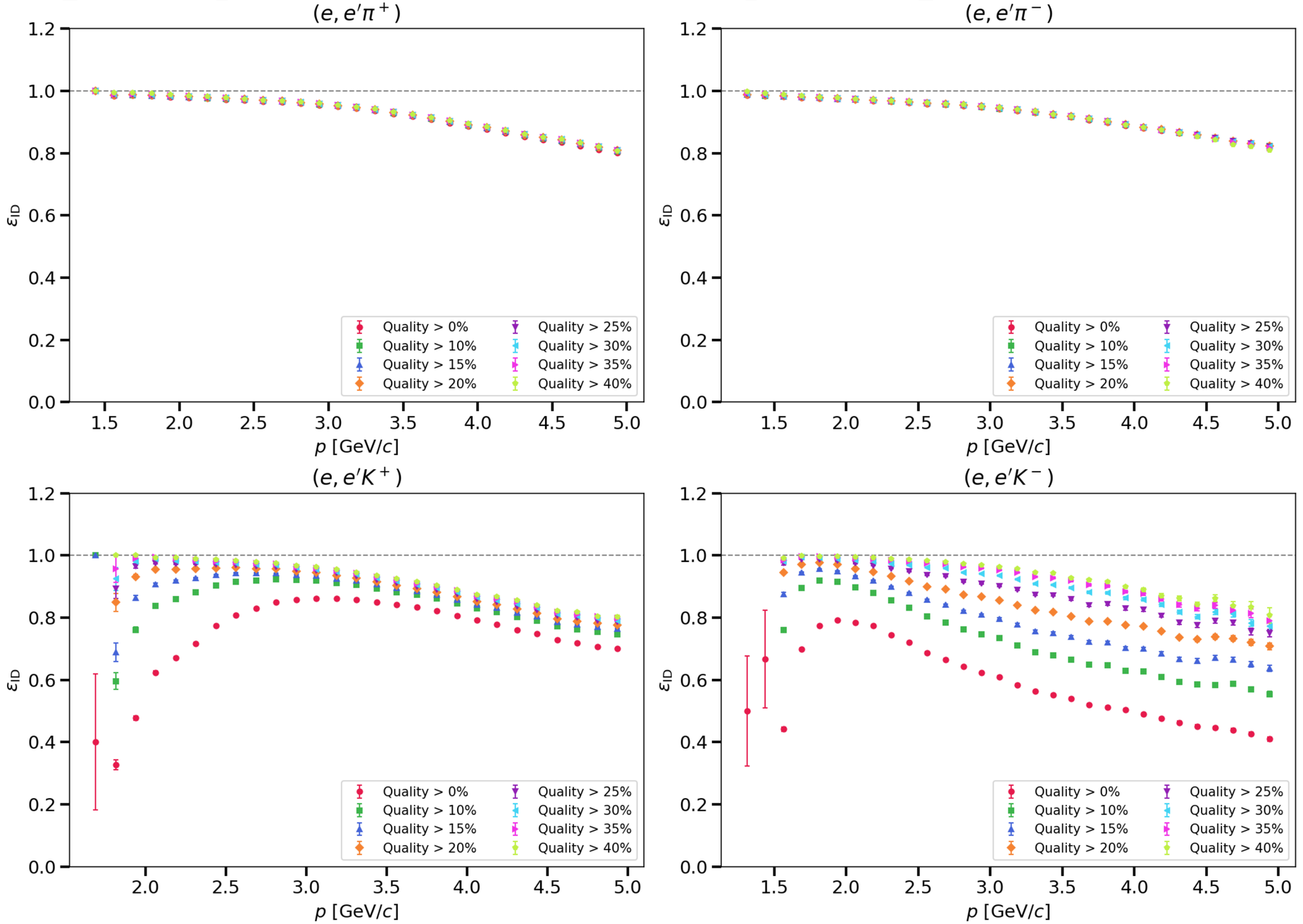
Quality Factor



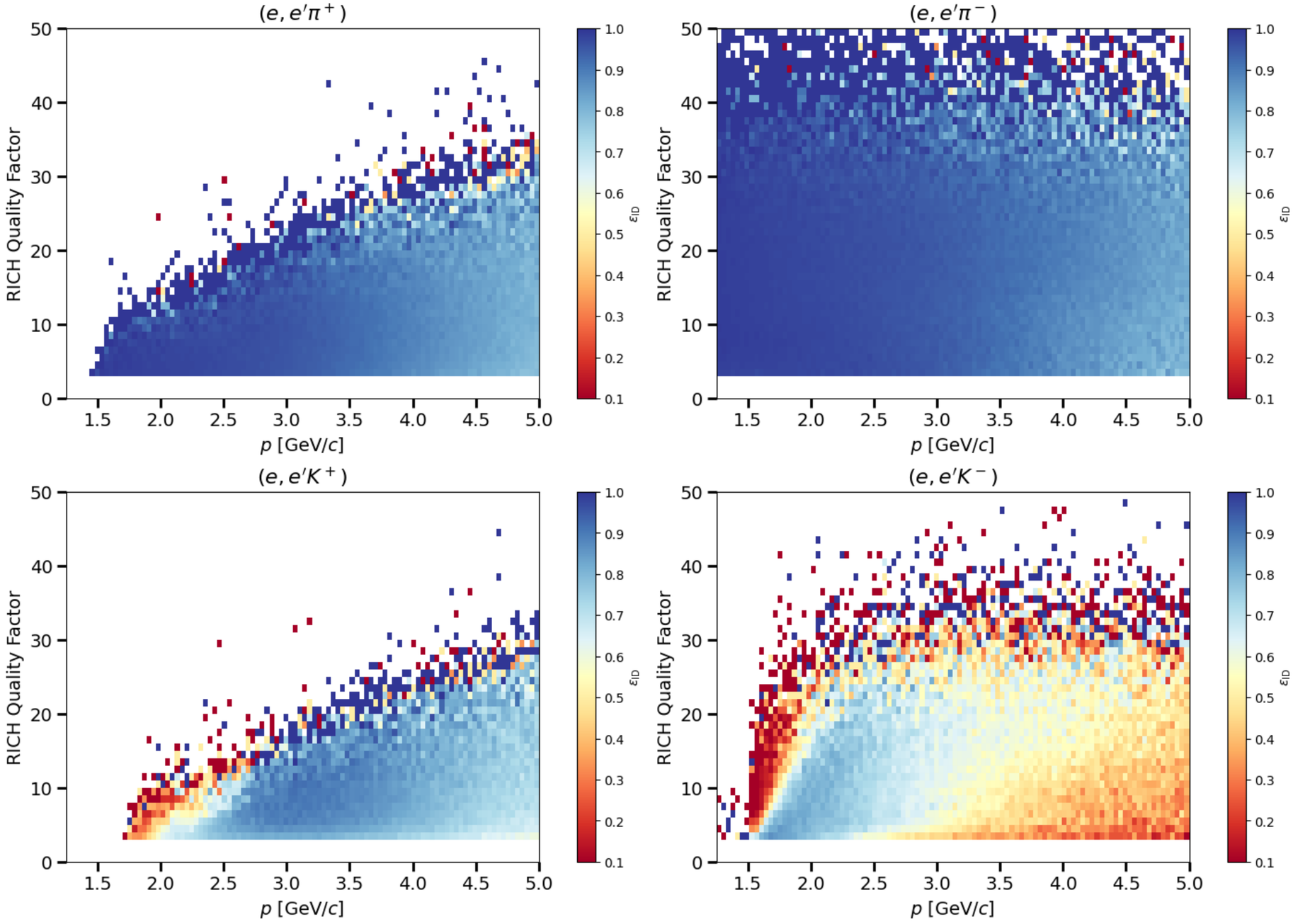
Quality Factor



Efficiency dependence on quality factor



Dependence on photoelectrons (no quality factor cut)



Dependence on photoelectrons (no quality factor cut)

