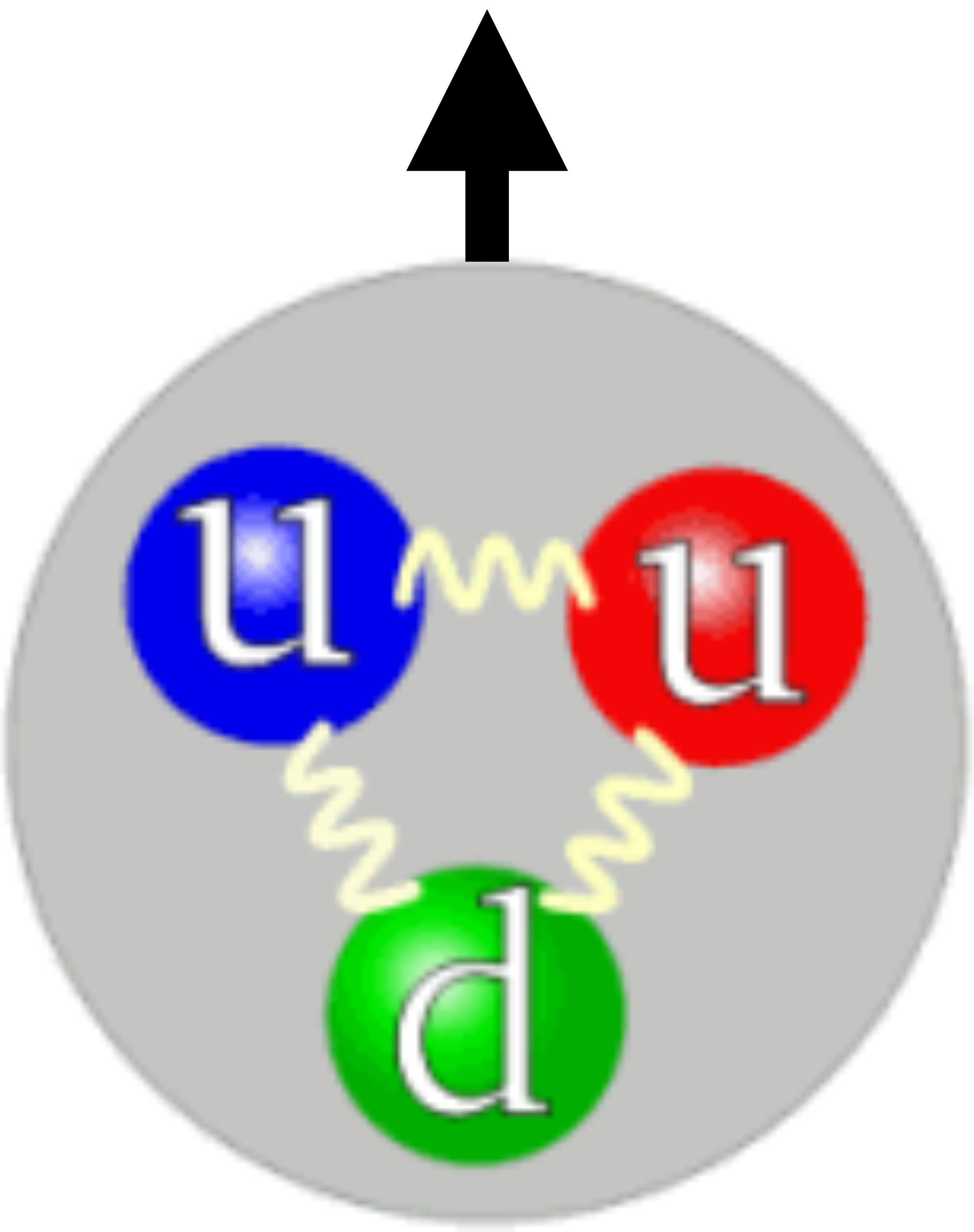
SIDIS @ CLAS12: Extracting d/u at large x_B

Jason Phelan, MIT
SRC Quantitative Challenges Workshop 2026

$SU(6)$ Spin-Flavor Symmetry

$J = 1/2$



$$\stackrel{?}{=}$$

$J = 3/2$

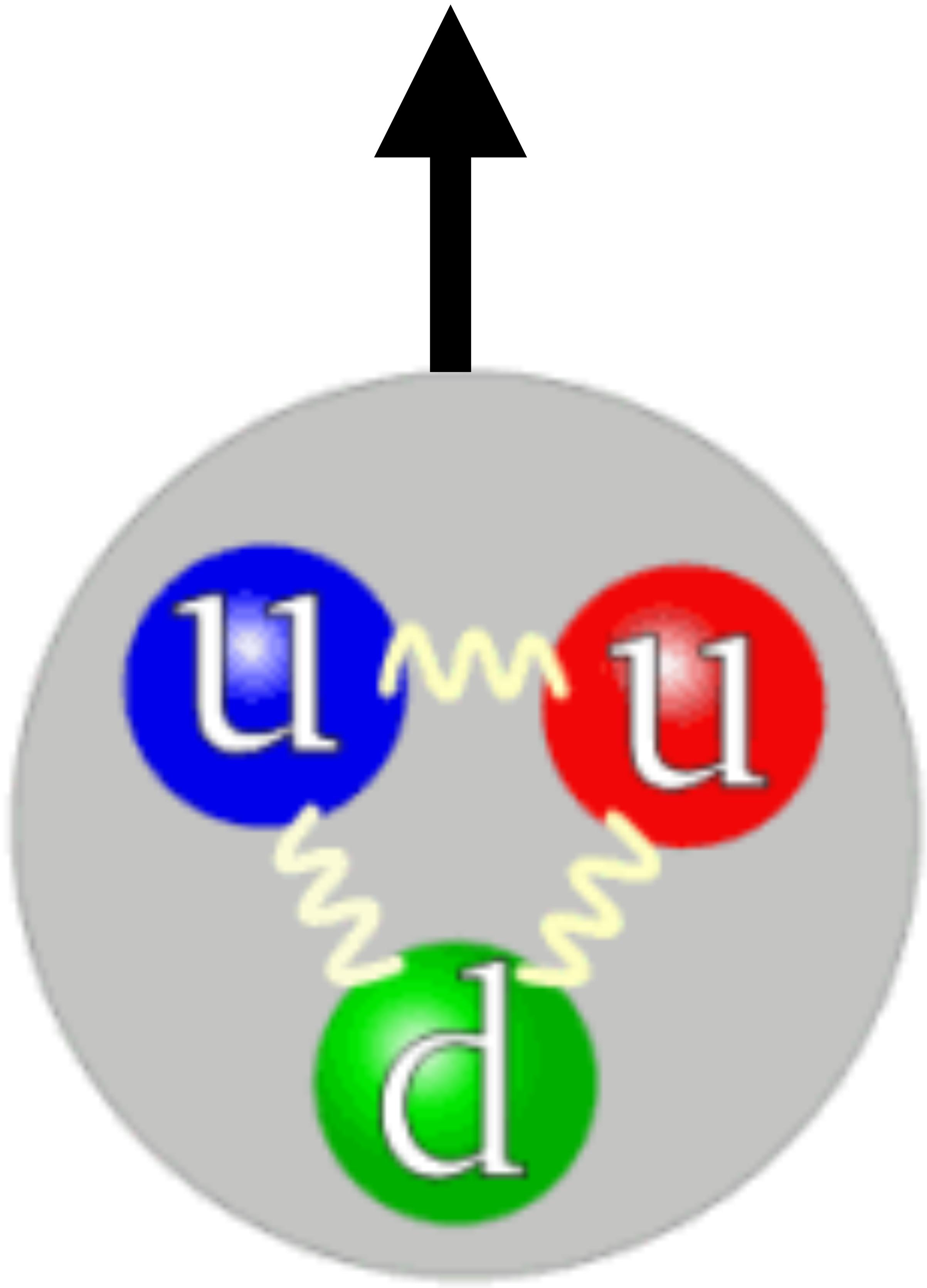


Image from wikipedia

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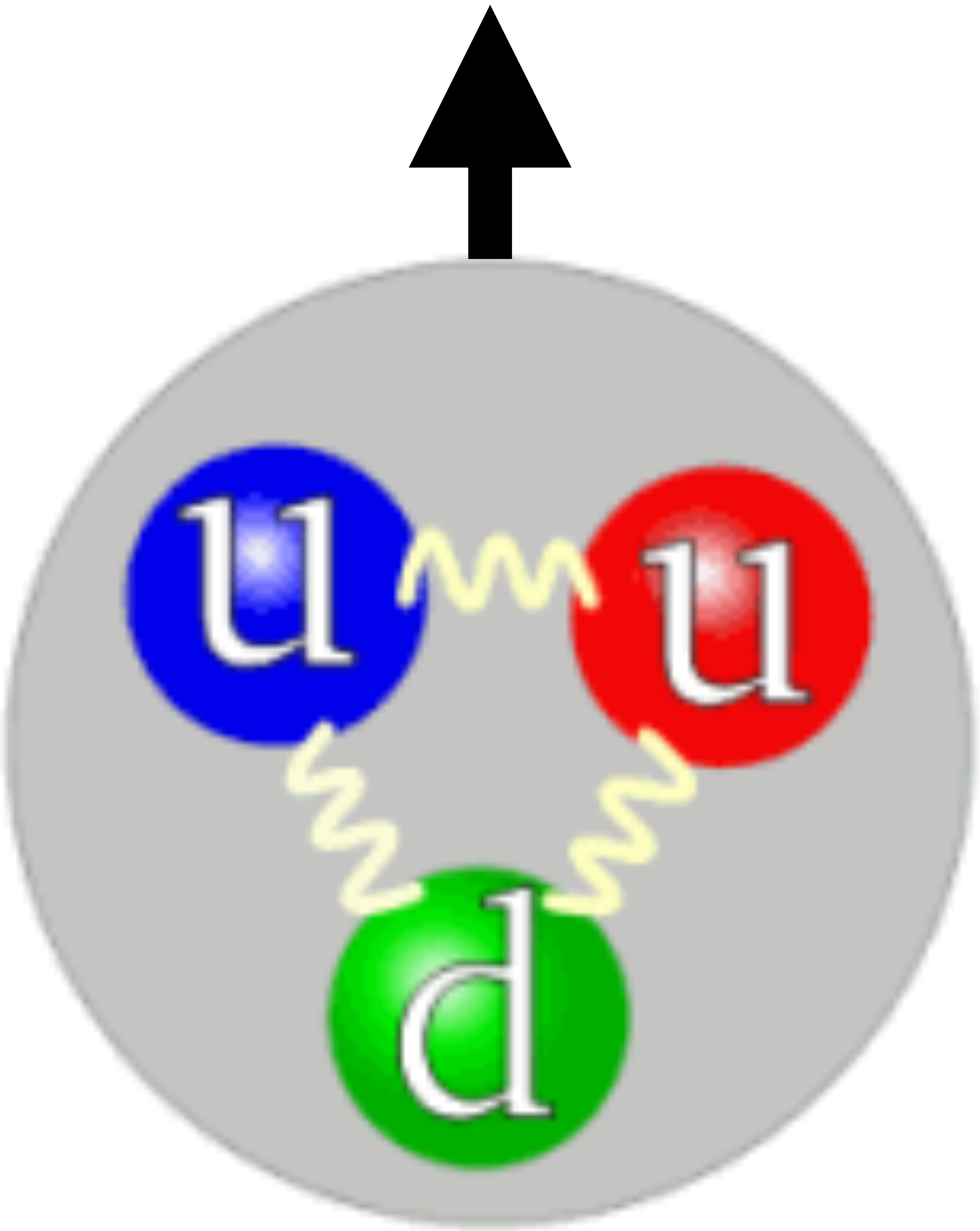

$M = 0.938$ [GeV]

BROKEN!

$\neq$

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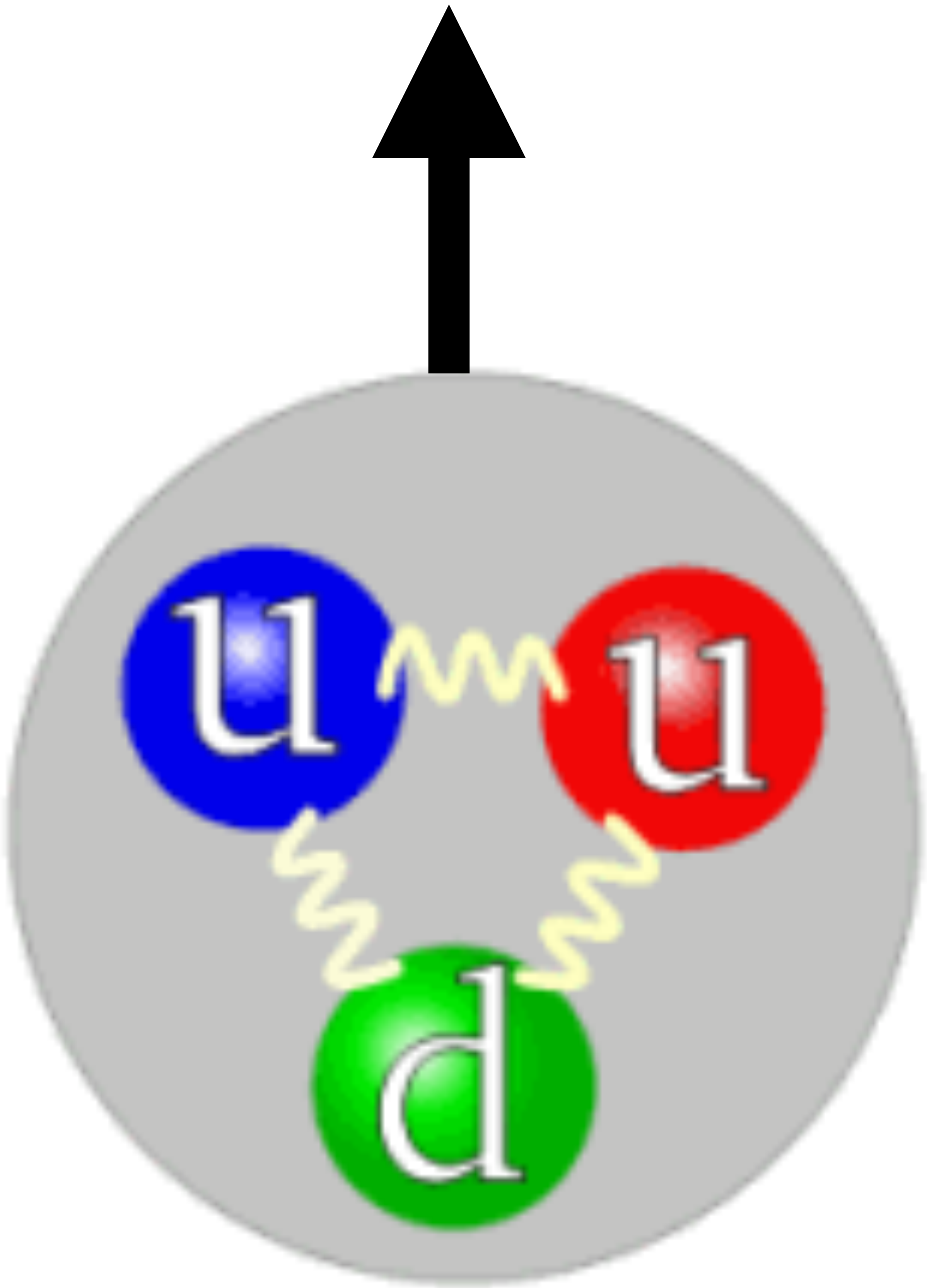
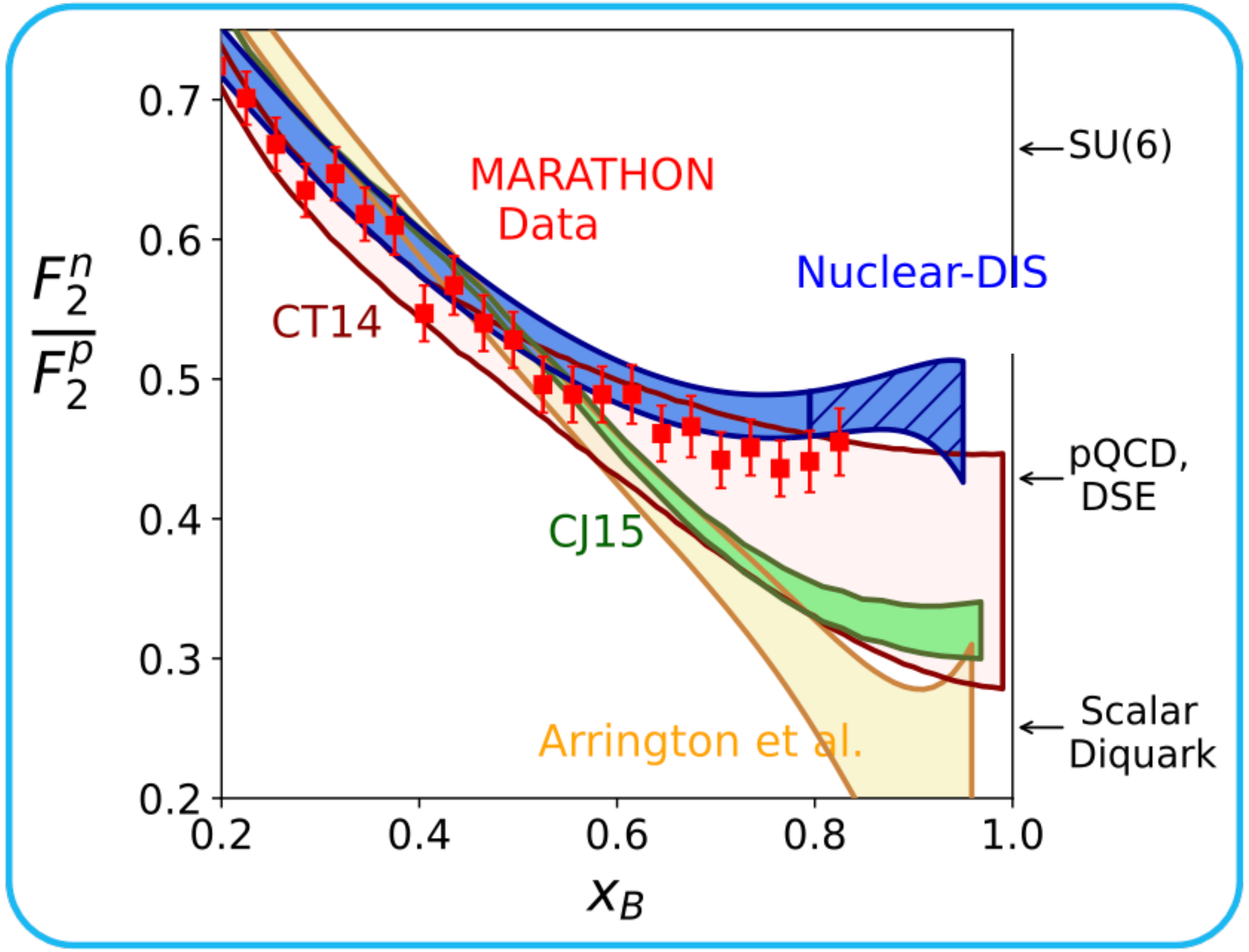


$M = 1.22$ [GeV]

Image from wikipedia

The Mechanism of $SU(6)$ Spin-Flavor Symmetry Breaking is Unknown

d/u (or equivalently F_2^n/F_2^p) at extreme conditions gives insight into this mechanism



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

The Mechanism of $SU(6)$ Spin-Flavor Symmetry Breaking is Unknown

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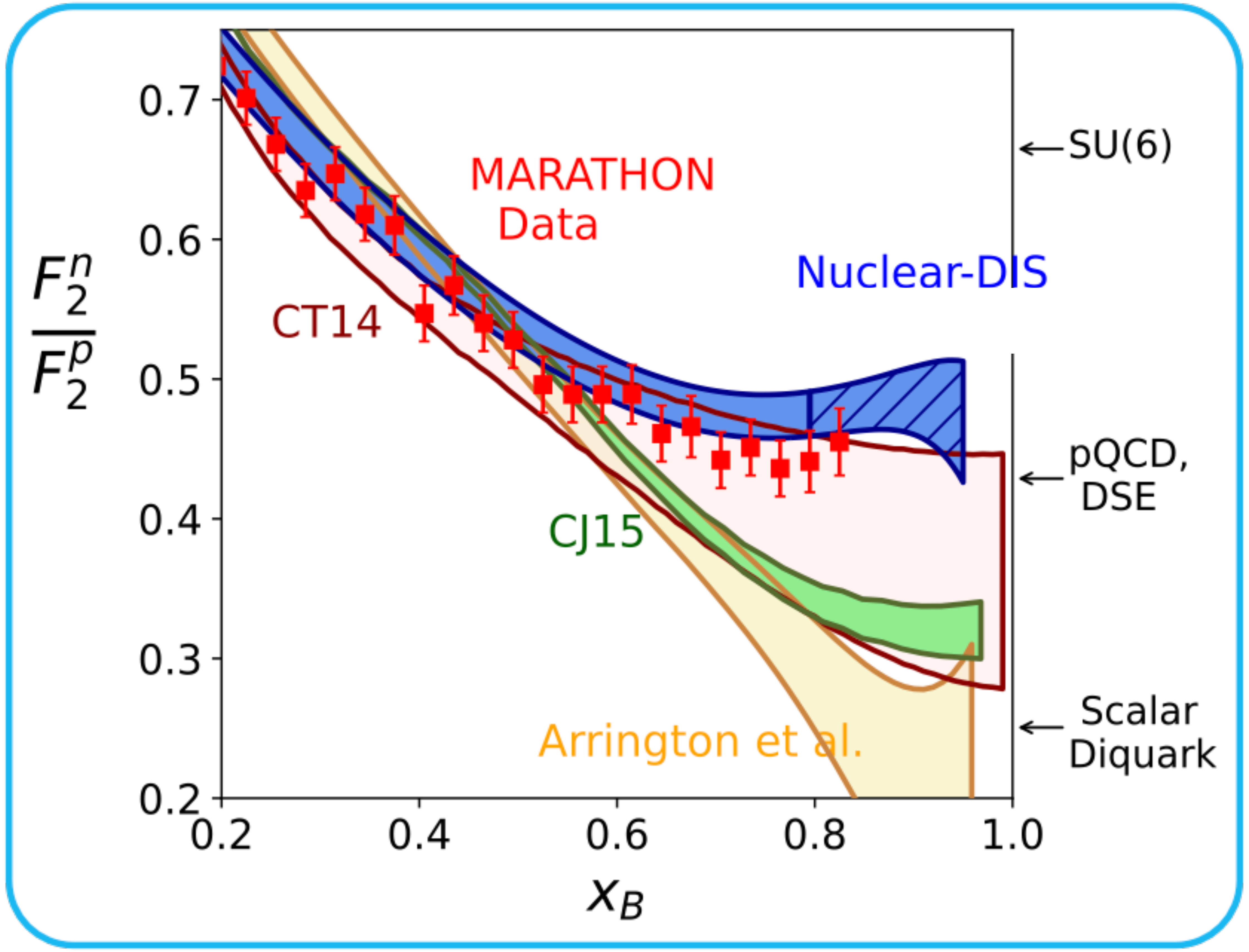
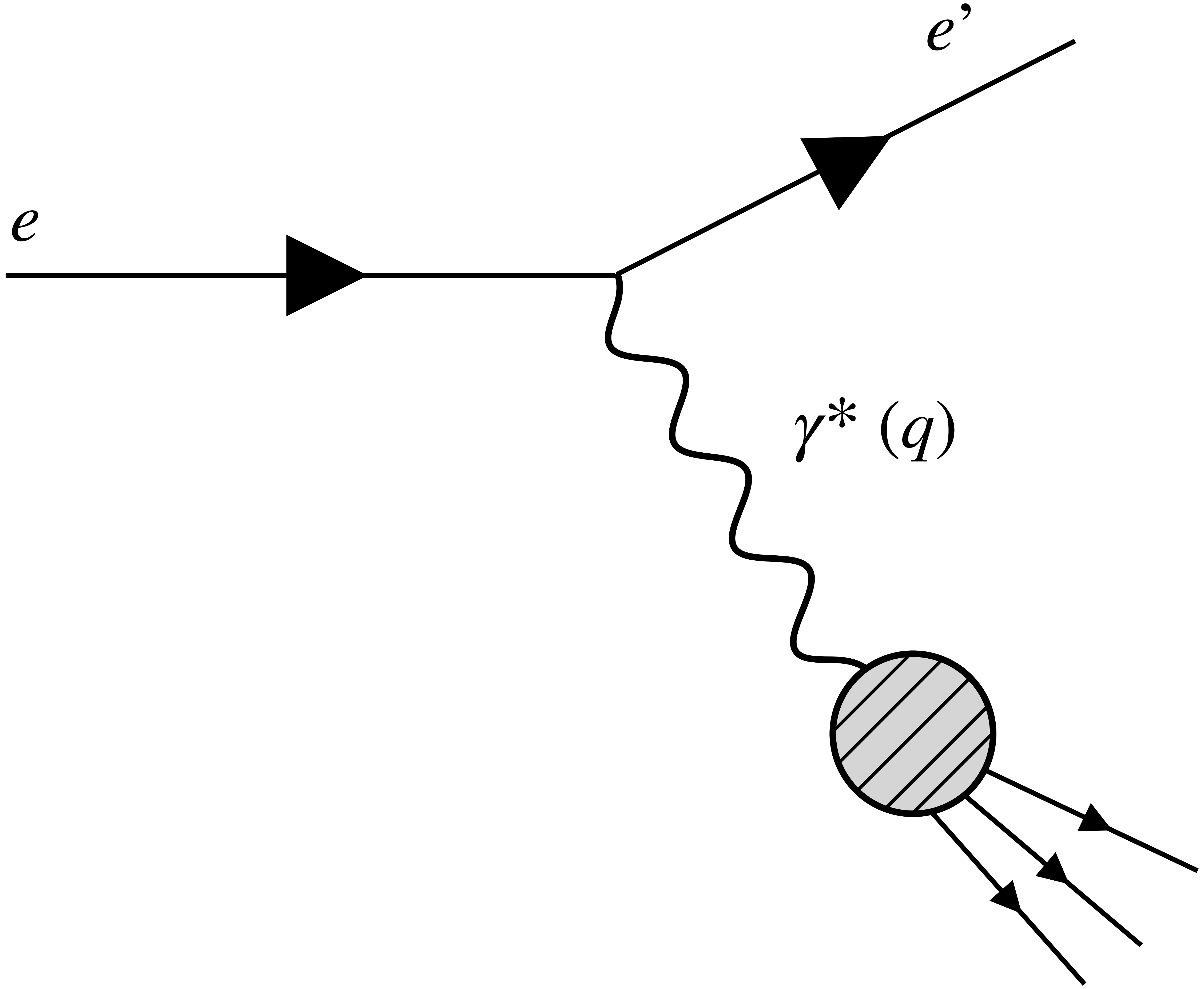


Global fits can be extrapolated to $x_B = 1$, but inclusive data cannot constrain high x_B behavior

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

Leading order SIDIS in the parton model



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

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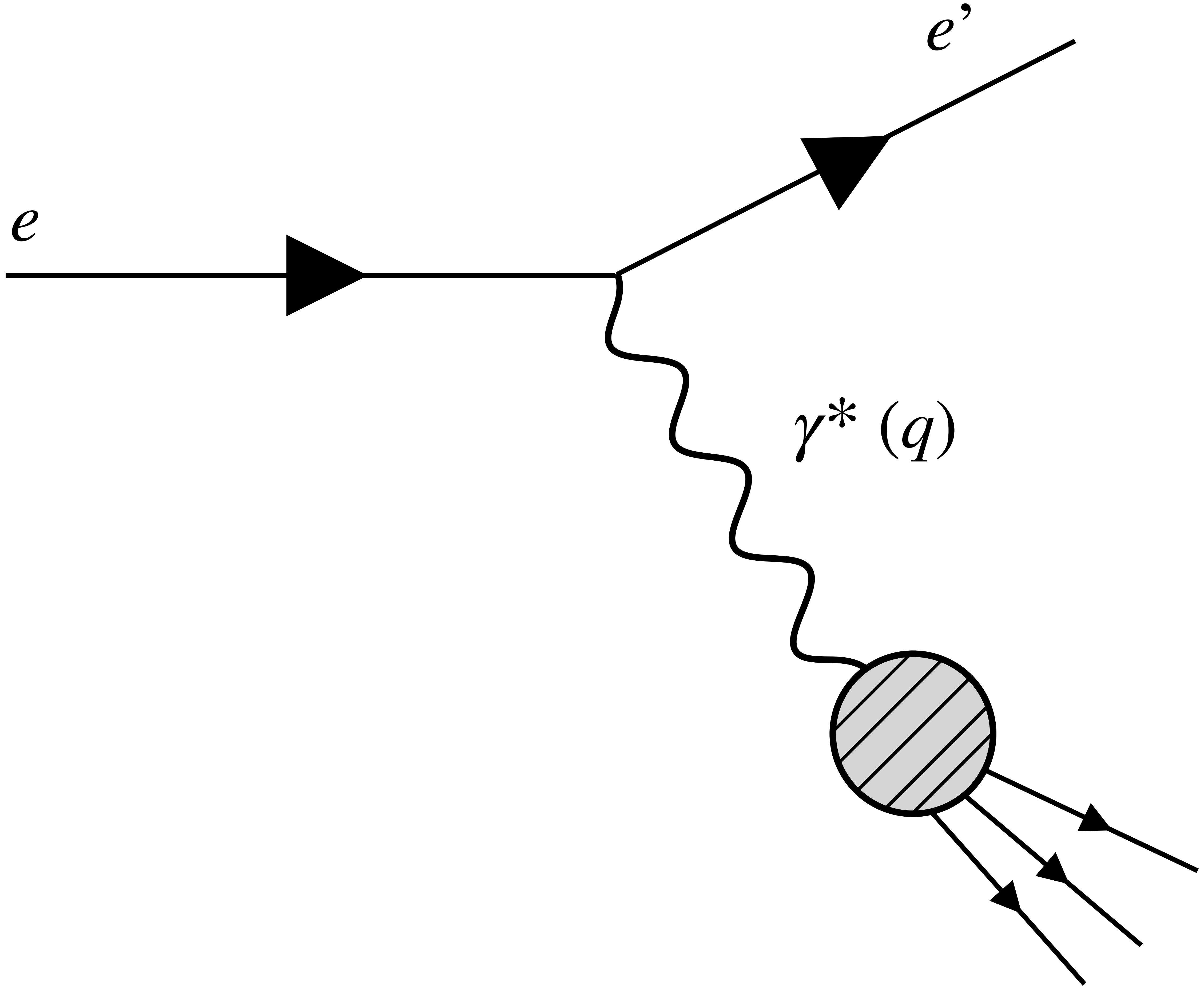

$$\sigma^h_{SIDIS} \sim \sum_q e_q^2 f_q(x) D_q^h(z)$$

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

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

Leading order SIDIS in the parton model

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

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Isospin symmetry: $D_u^{\pi\pm} = D_d^{\pi\mp} = D^{\pm}$

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

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

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

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$r = \frac{D^-}{D^+} = \frac{4\frac{u}{d} \ldots}{4\frac{u}{d} \ldots}$

$\ldots - 1$ for the deuteron!

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

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

SIDIS @ CLAS12

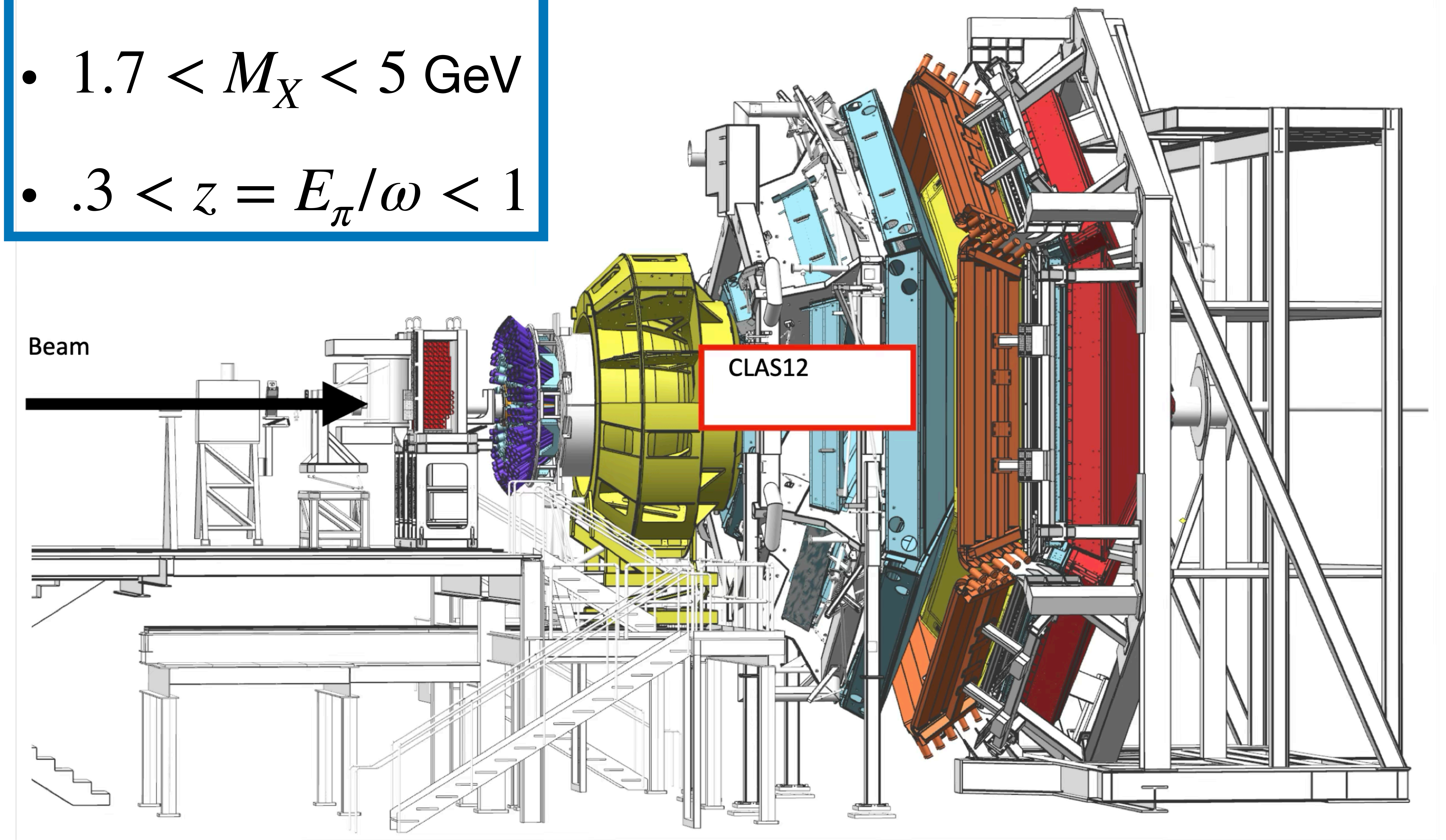
Electrons

- $Q^2 > 2$ 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]



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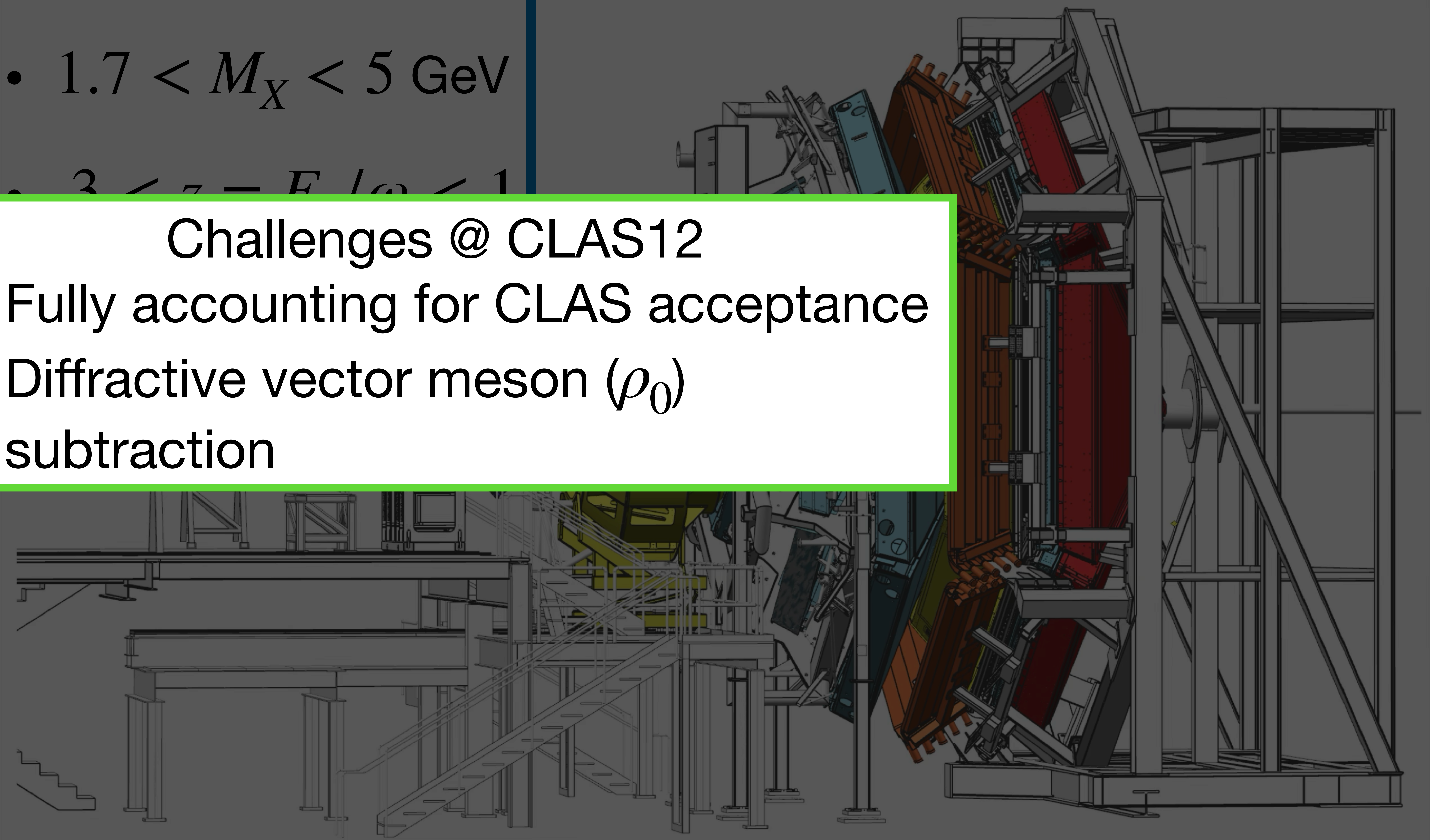
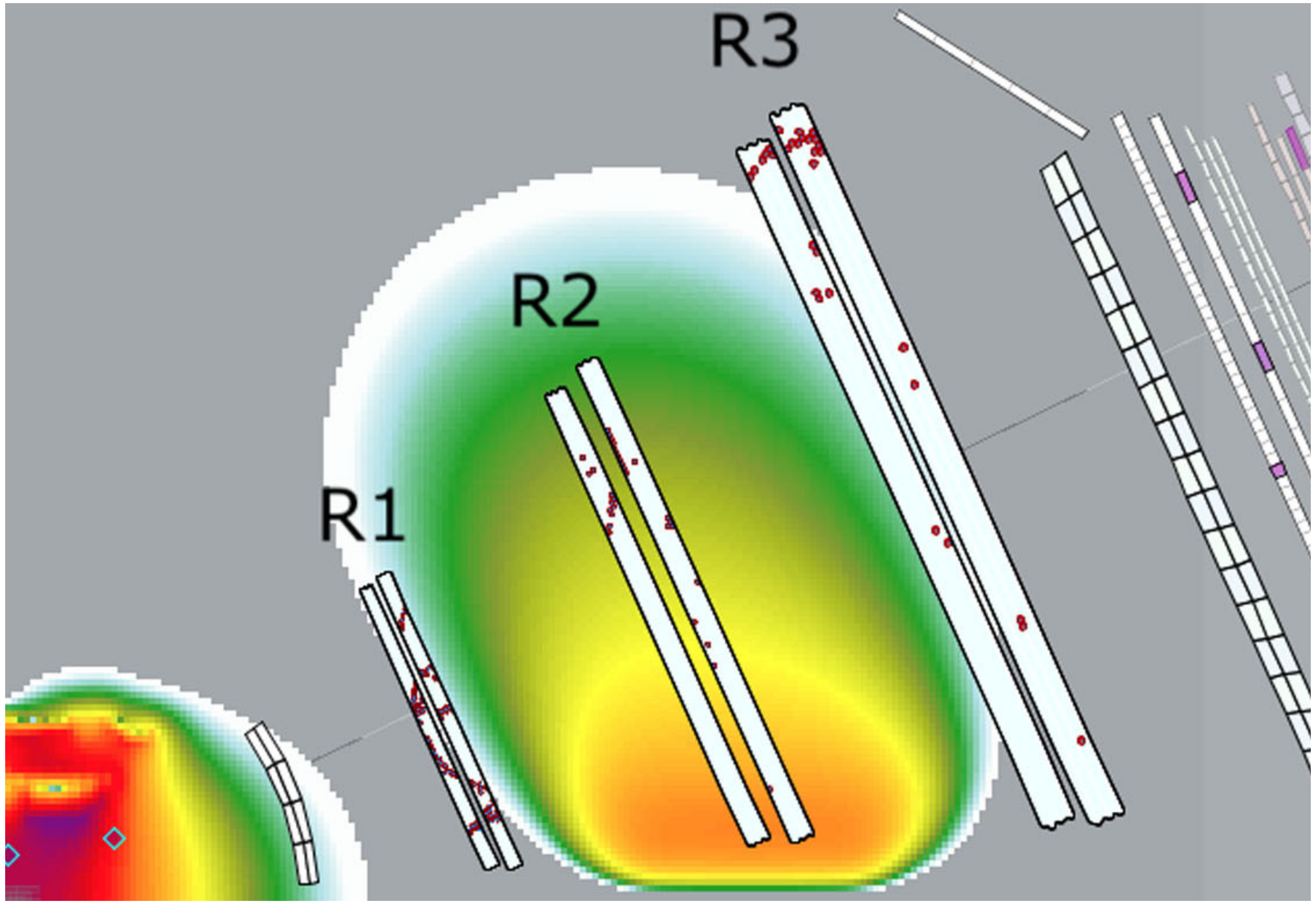
Challenges @ CLAS12

1. Fully accounting for CLAS acceptance
2. Diffractive vector meson (ρ_0) subtraction

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



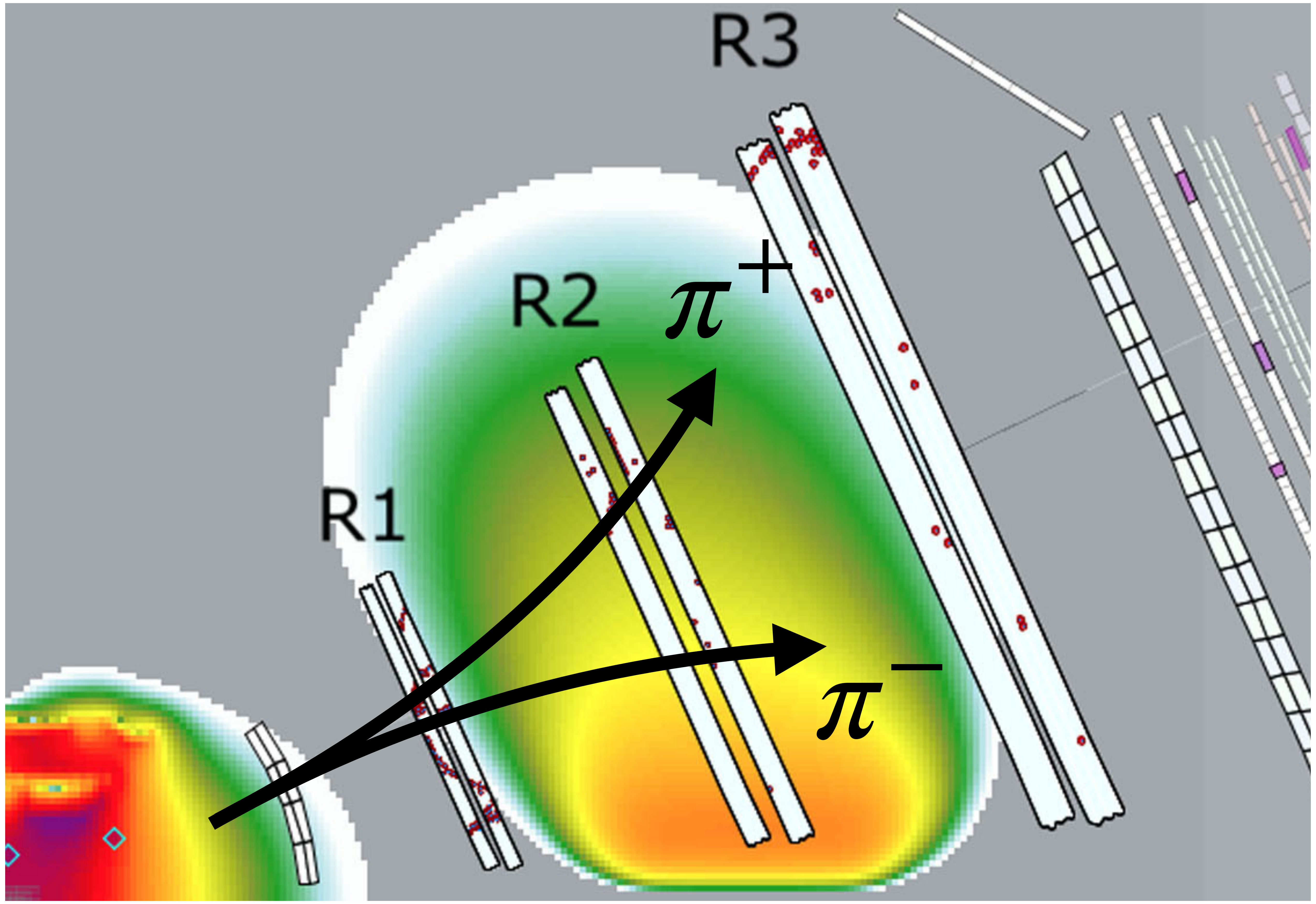
Matching Phase Space



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

What we measure

Matching Phase Space



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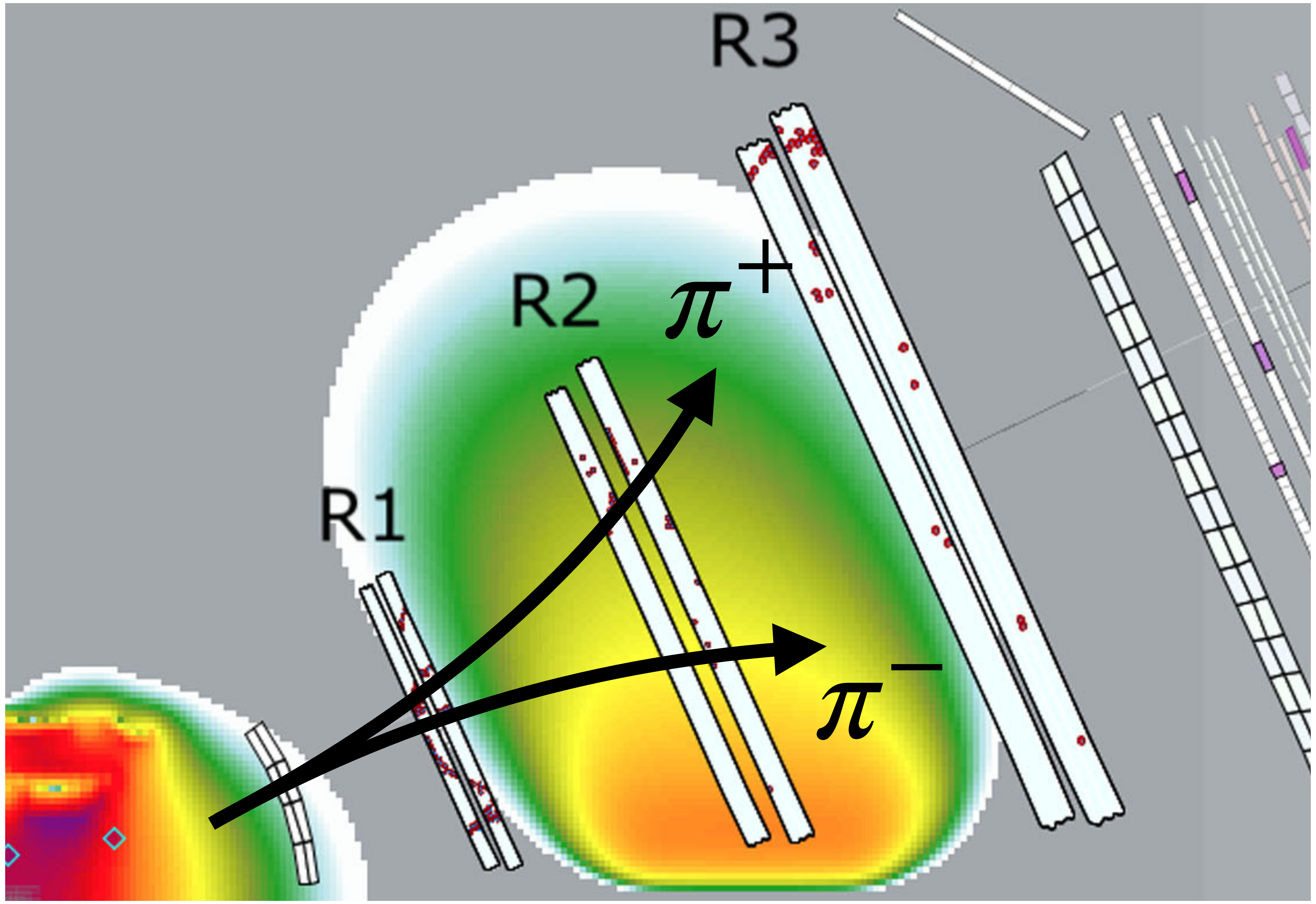
What we measure

Matching Phase Space



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

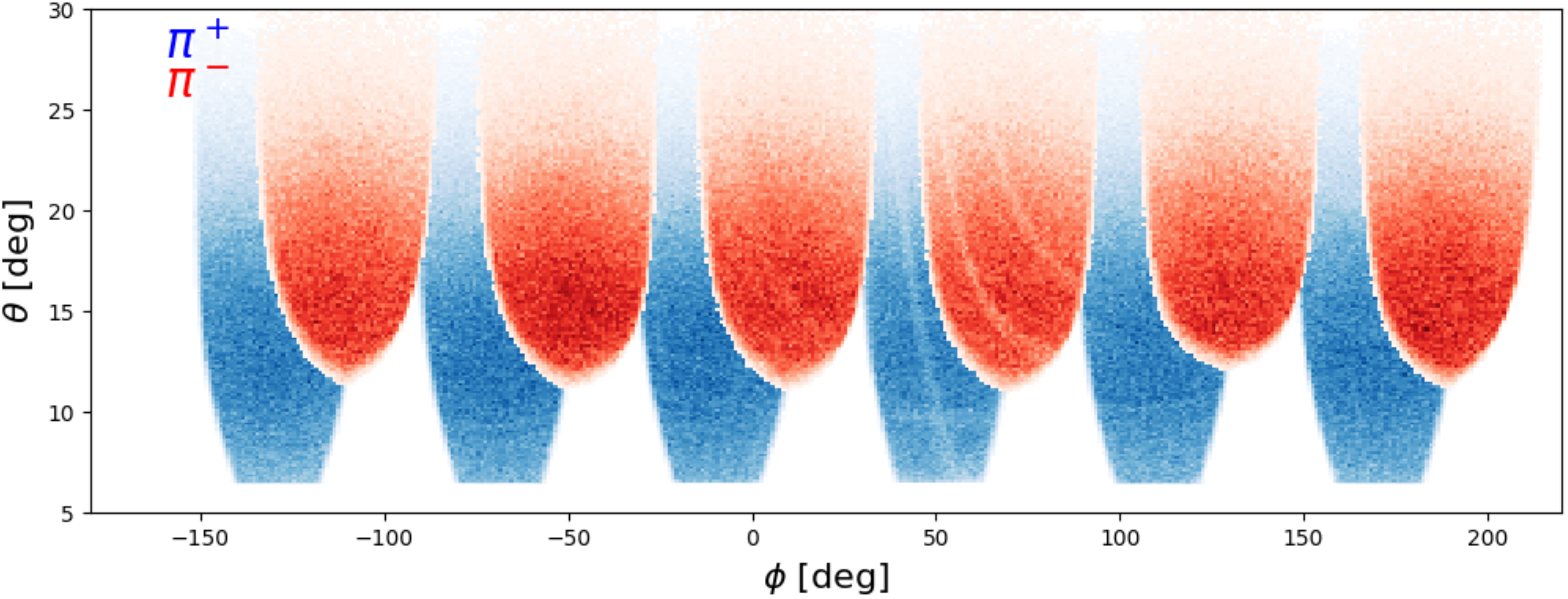
What we measure — What we want

Matching Phase Space

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

What about $\phi_\pi, \overrightarrow{p_e}$?

$2.75 < p_\pi < 3.25$ [GeV]



We use Monte Carlo to go from yields to cross section ratios

What we measure

What we want

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

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What we measure

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

Bin Migration Correction

We use Monte Carlo to go from yields to cross section ratios

What we measure

What we want

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

Bin Migration Correction

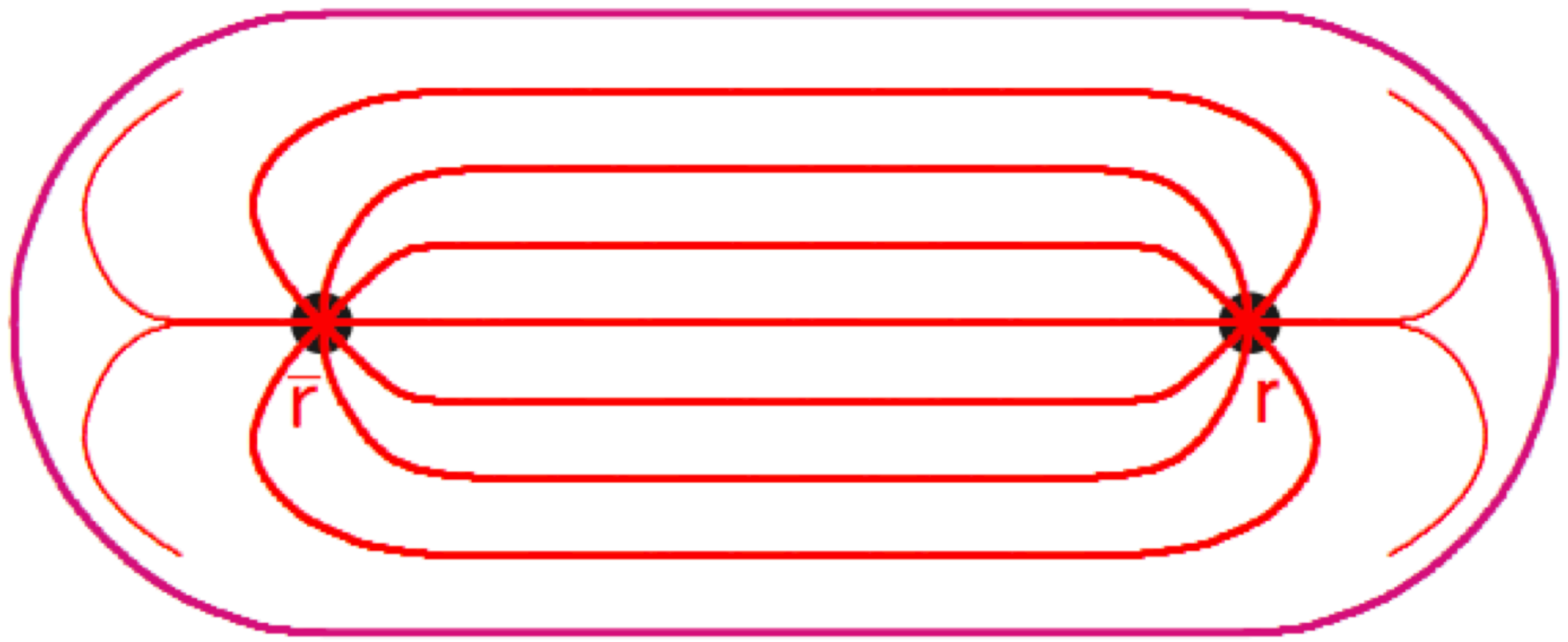
Acceptance Correction

We use Monte Carlo to go from yields to cross section ratios

What we measure $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ What we want

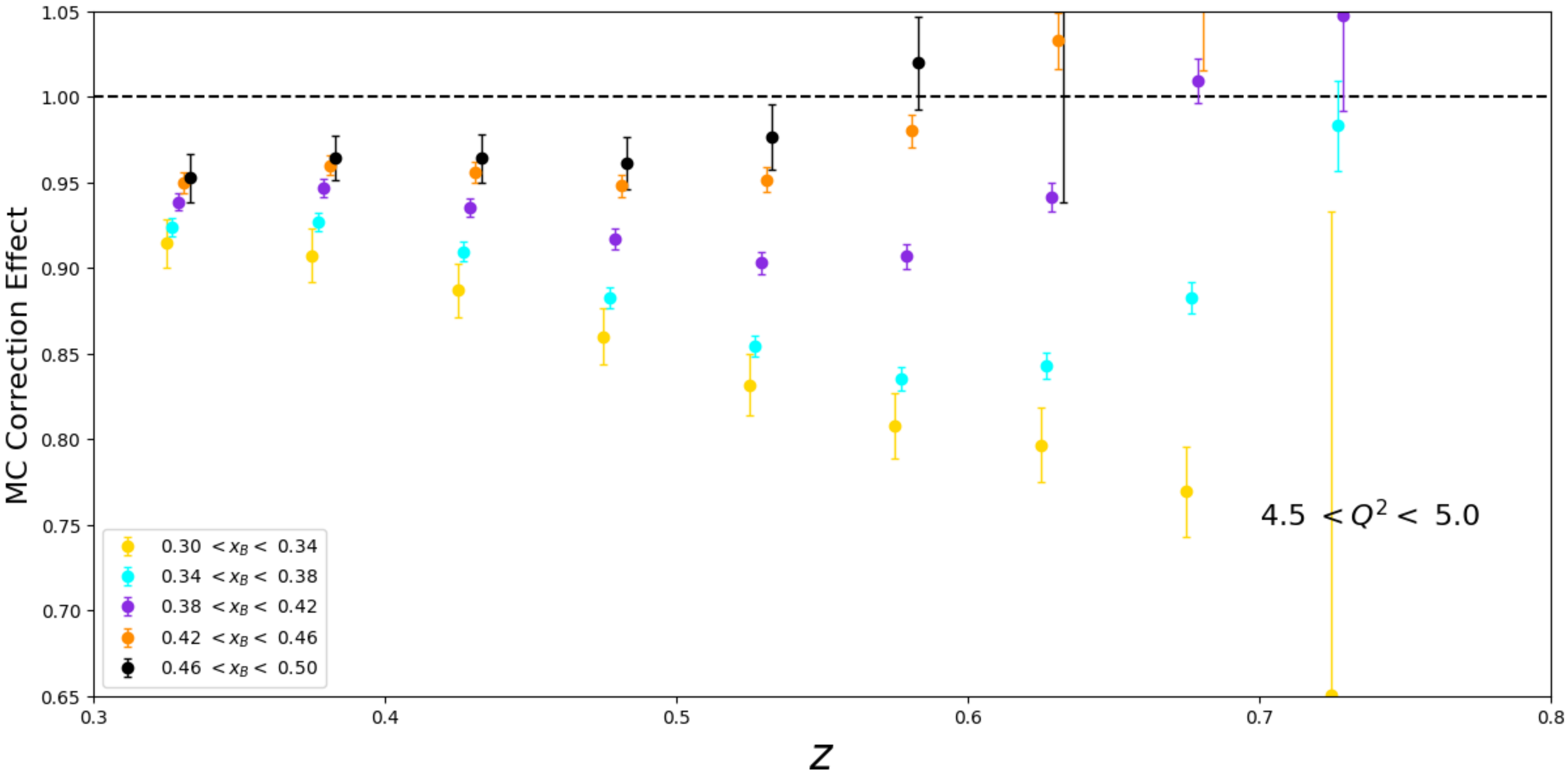
$$\boxed{Y_{rec\ kin,acc\ event}}\left[\frac{Y_{gen\ kin,acc\ event}}{Y_{rec\ kin,acc\ event}}\right]\left[\frac{Y_{gen\ kin,gen\ event}}{Y_{gen\ kin,acc\ event}}\right]=\boxed{Y_{gen\ kin,gen\ event}}$$

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



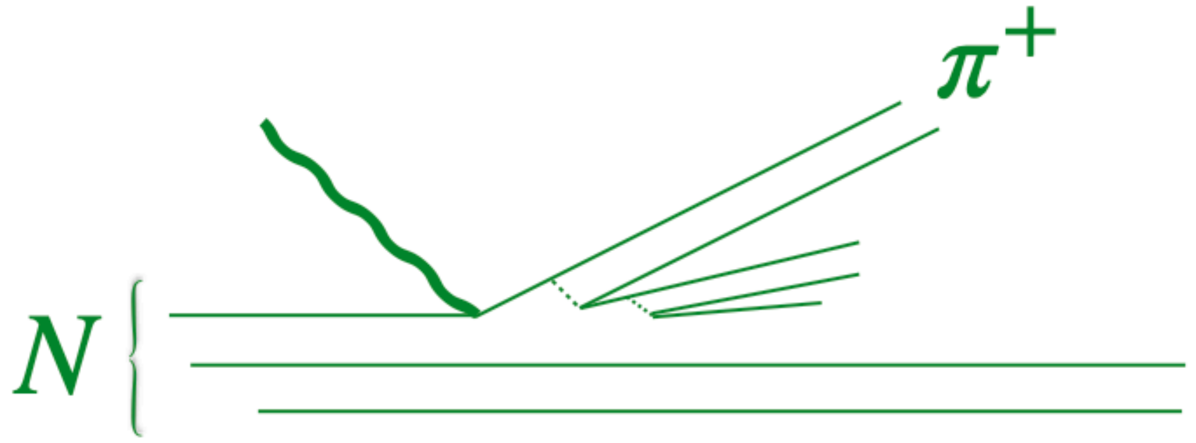
Torbjorn Sjostrand

Corrections significantly cancel in cross section ratio

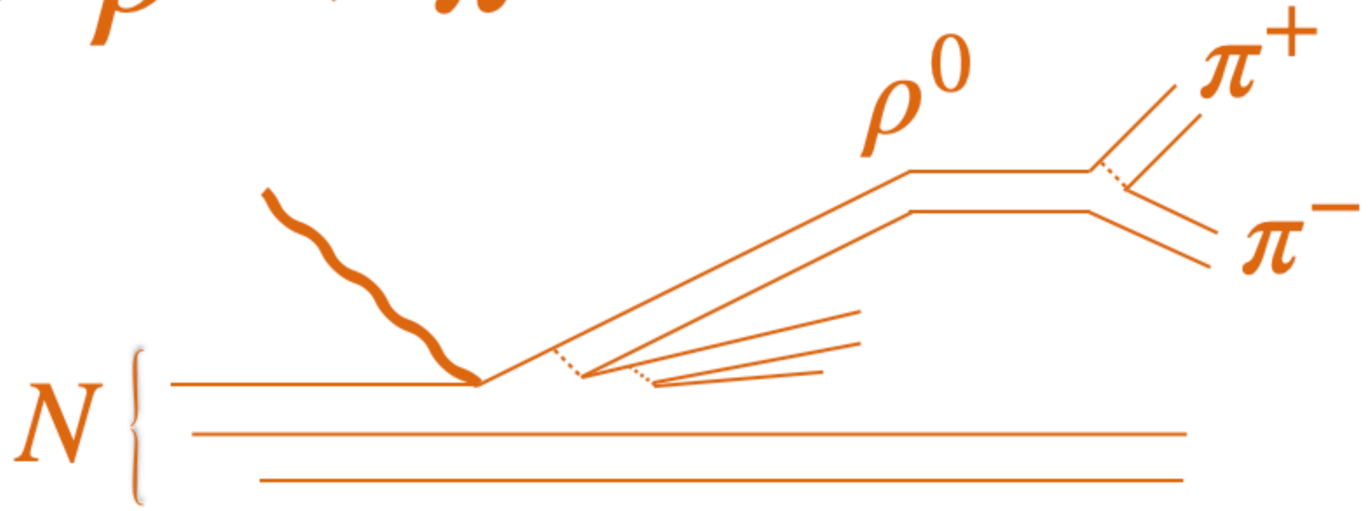


Diffractive vector mesons are a major background

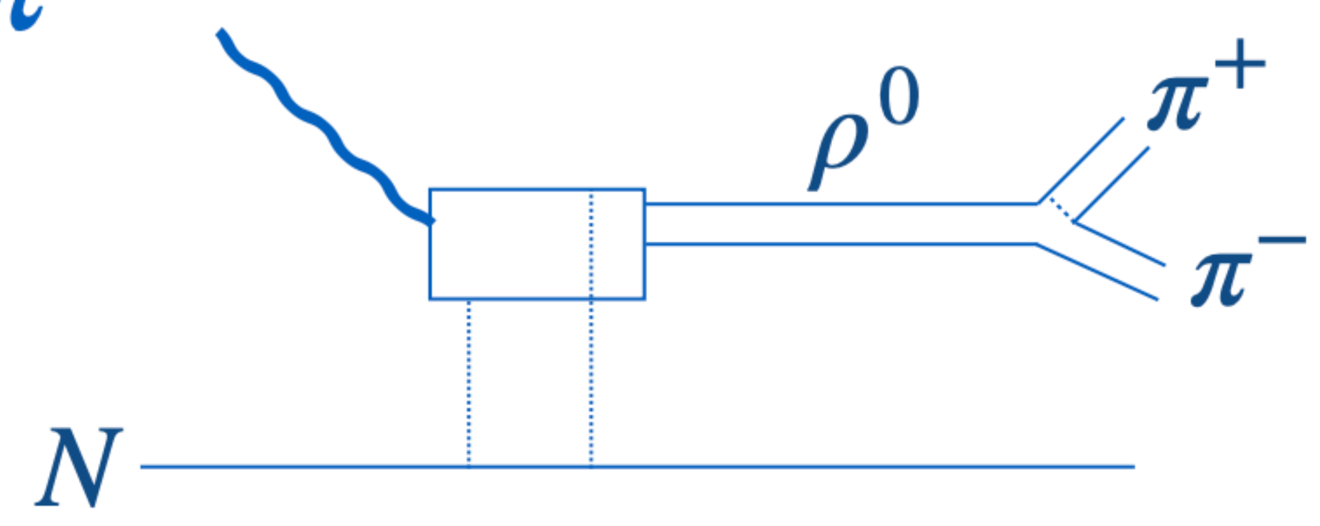
1. Direct from quark $q^* + N \to \pi$



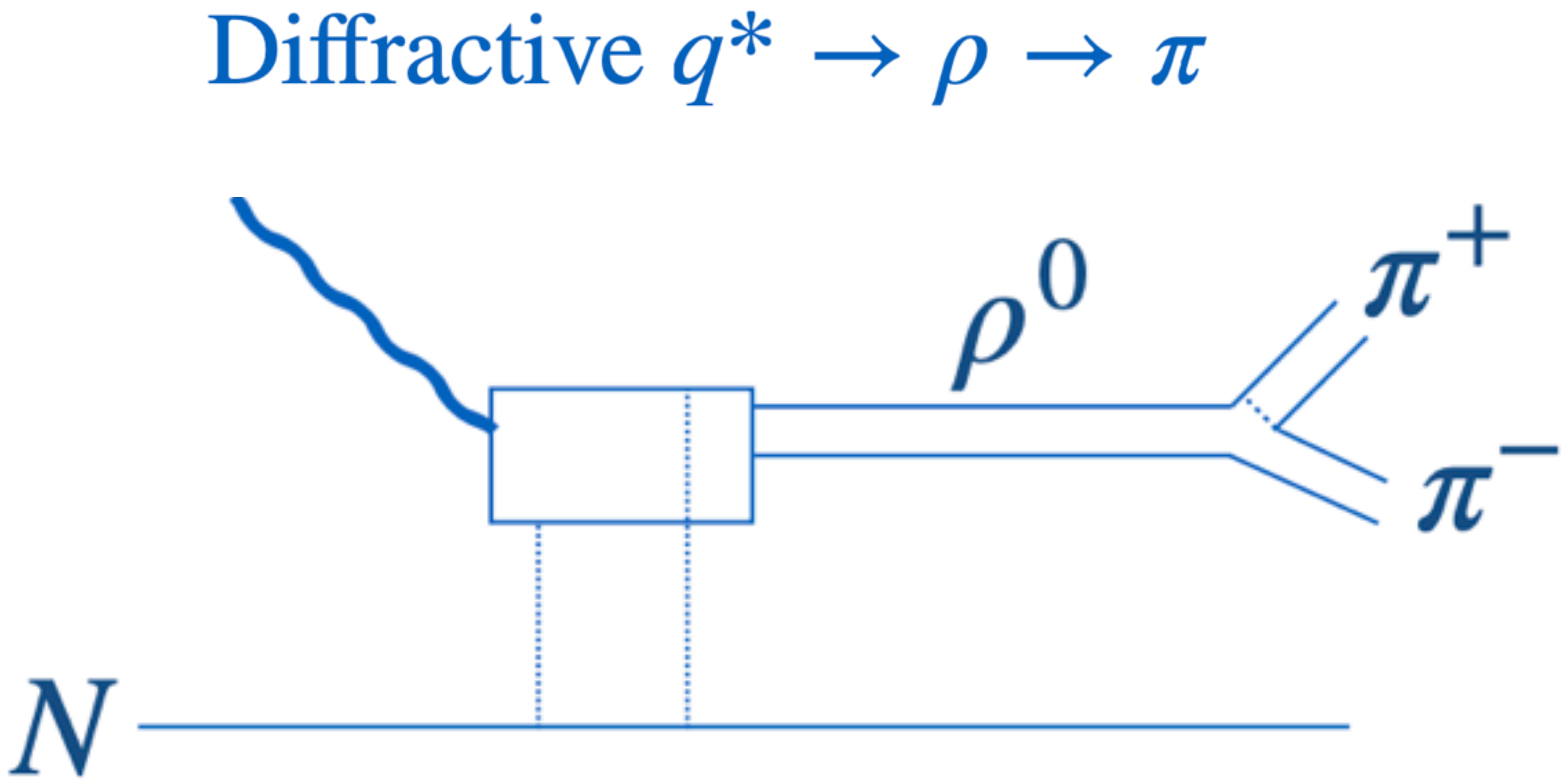
2. VM production $q^* + N \to \rho \to \pi$



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



Data driven approach to subtracting the ρ_0



Two possibilities:

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

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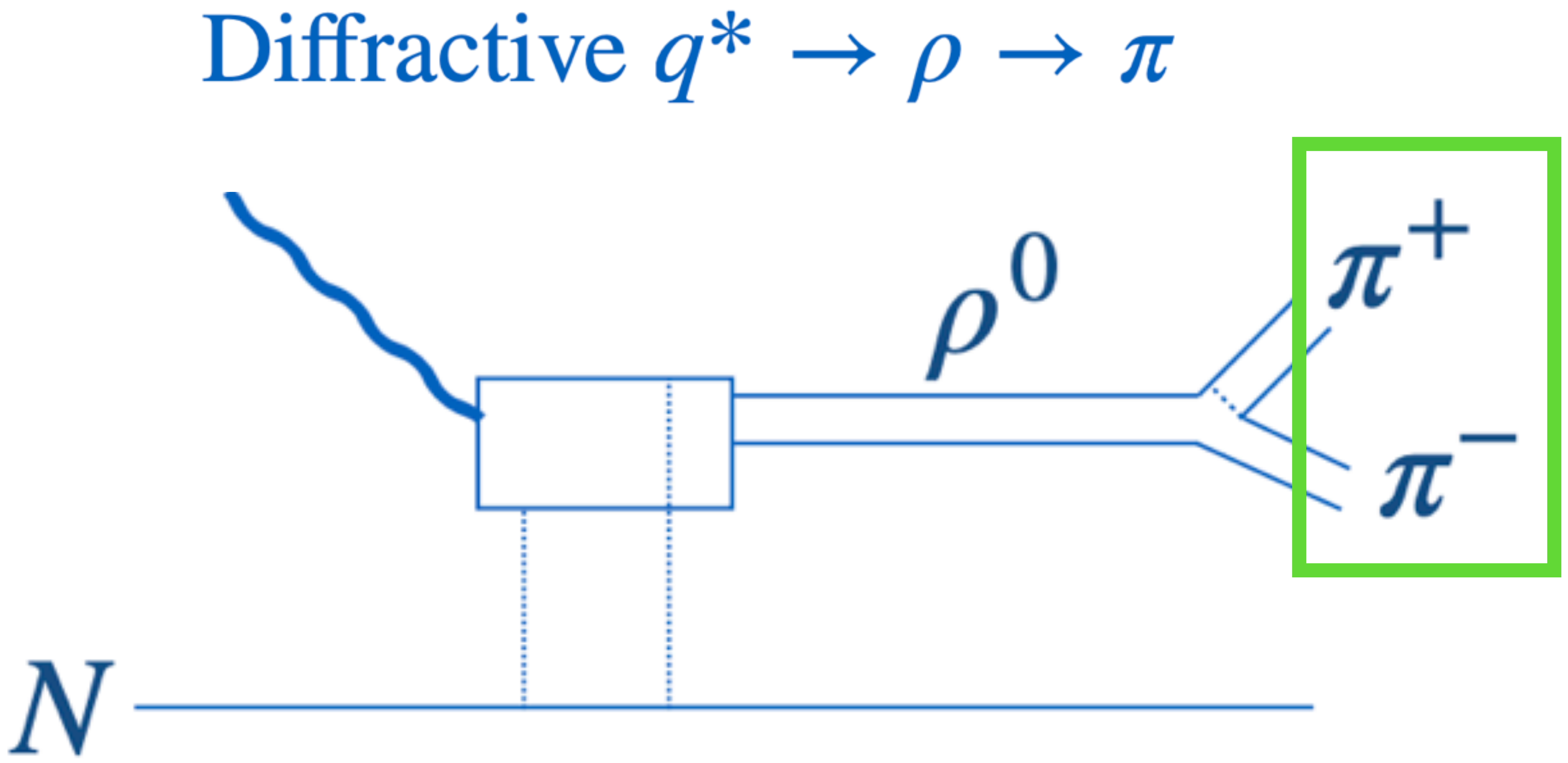

Two possibilities:

1. Detect both pions→Directly subtract

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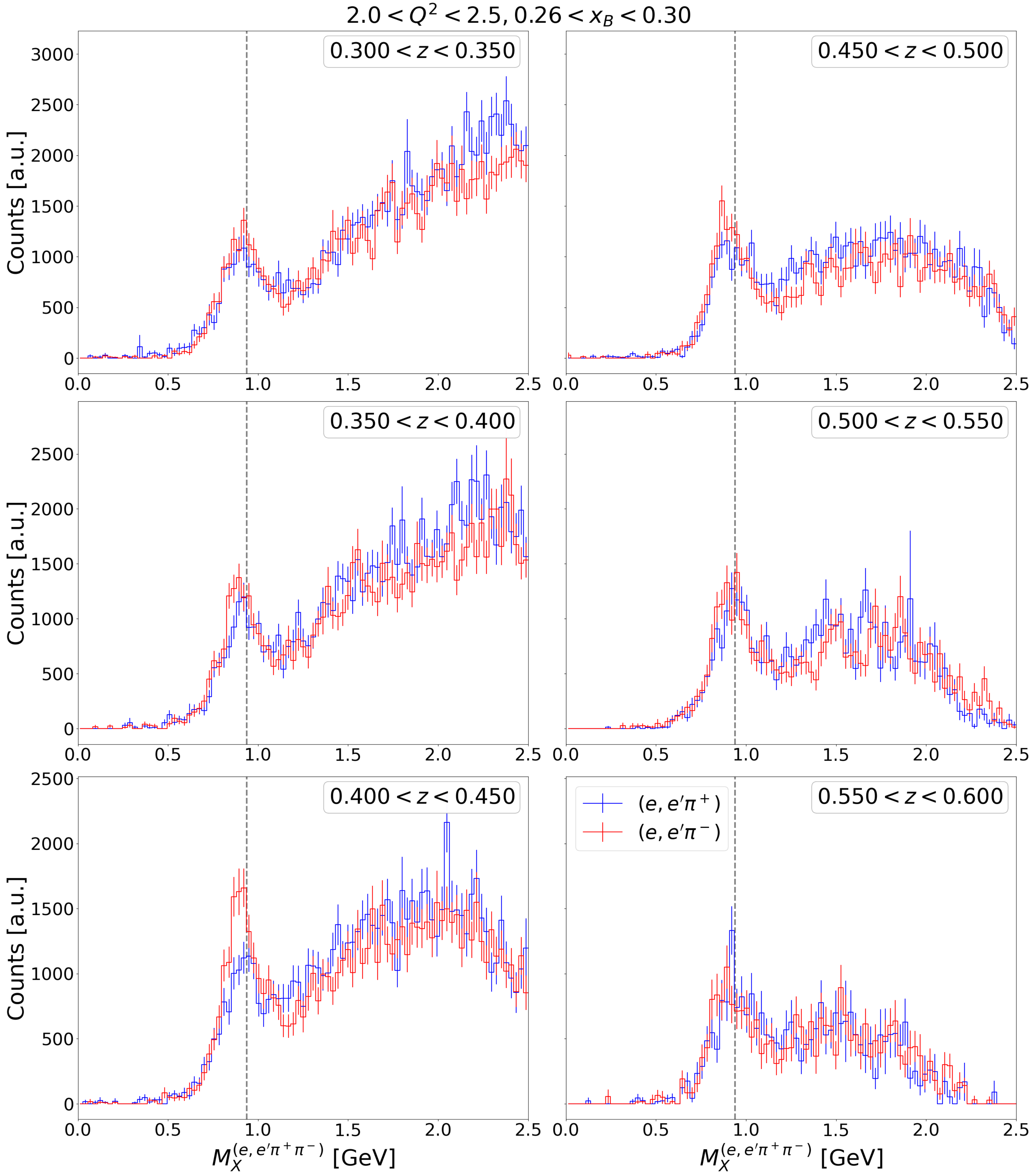

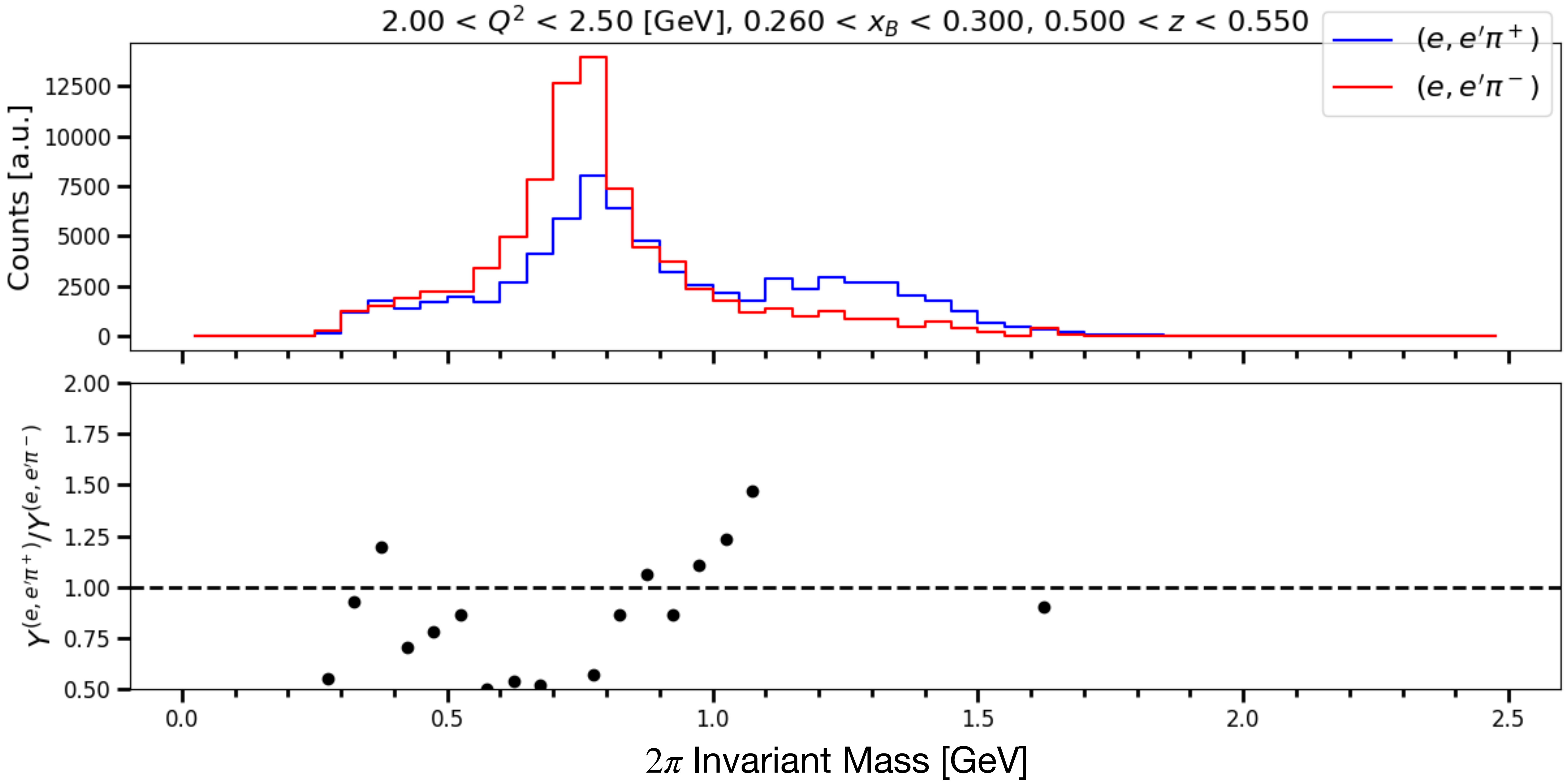

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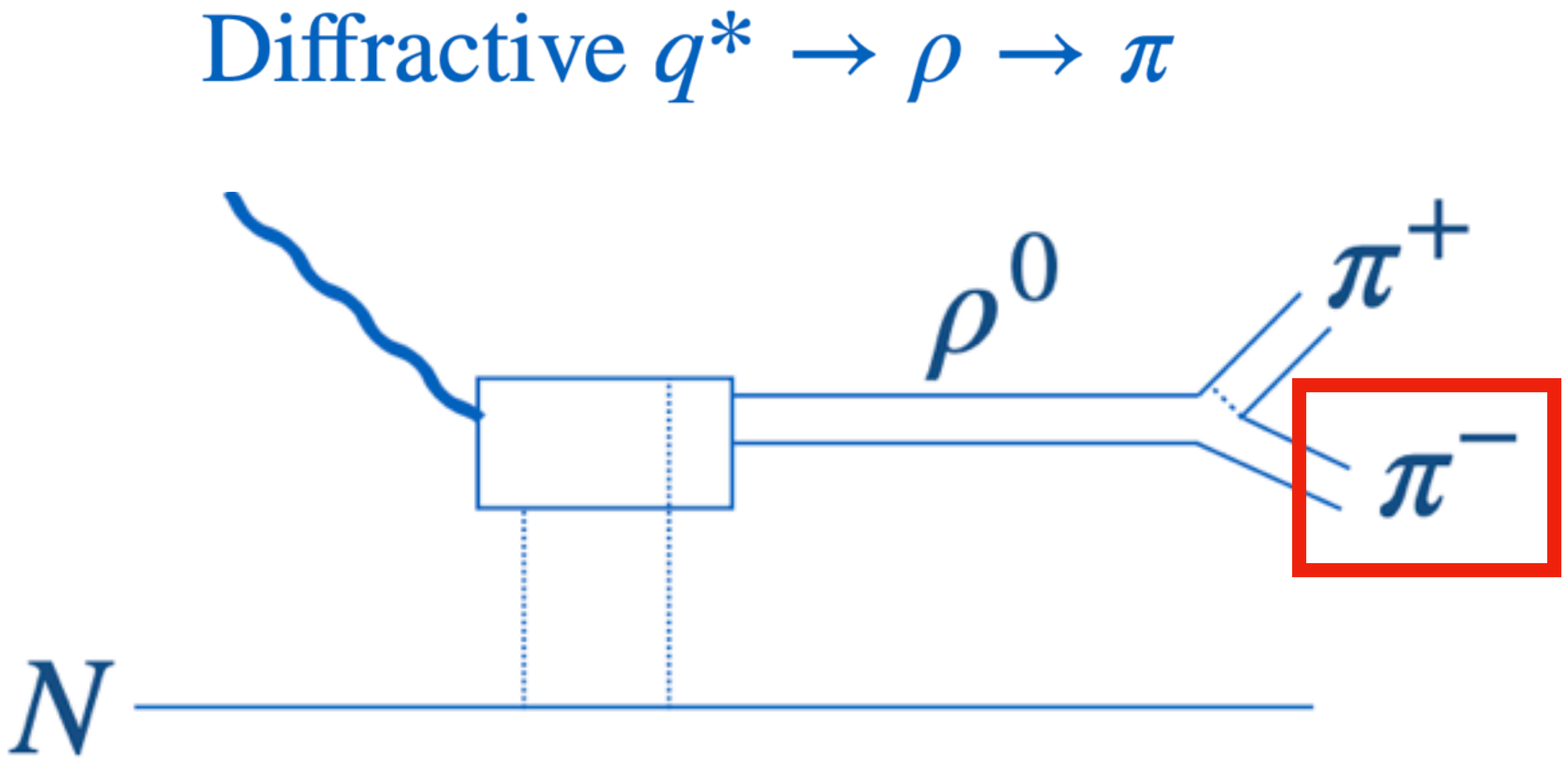

Two possibilities:

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

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

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 $0\pi,\ 1\pi$ or 2π detected in each quasi-event

3. Reweight events with factor $w_{VM} = 1 + \frac{1\pi \text{ quasi-events}}{2\pi \text{ quasi-events}}$

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Vector Meson Reweighting

1. Id
2. Es
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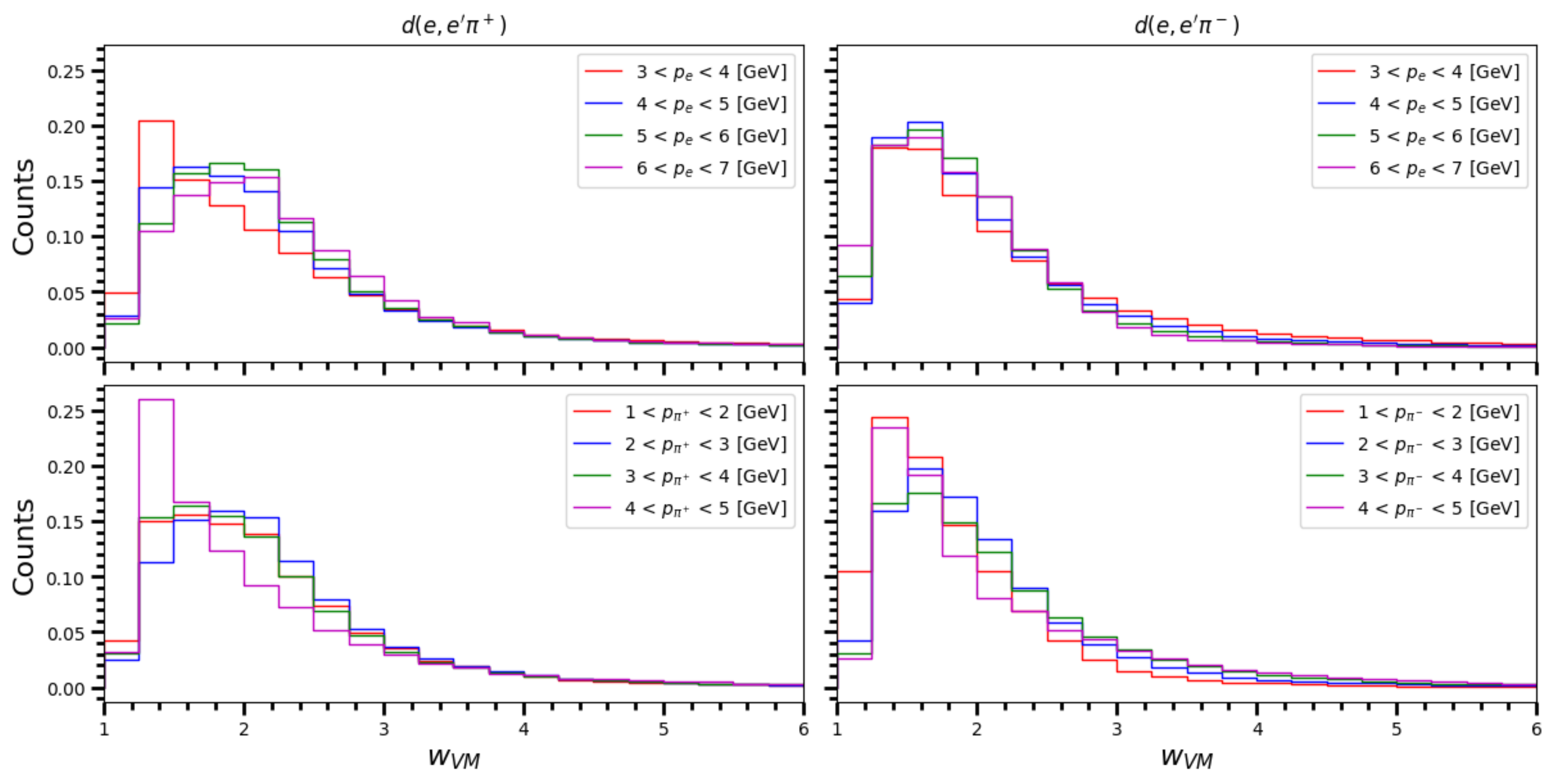
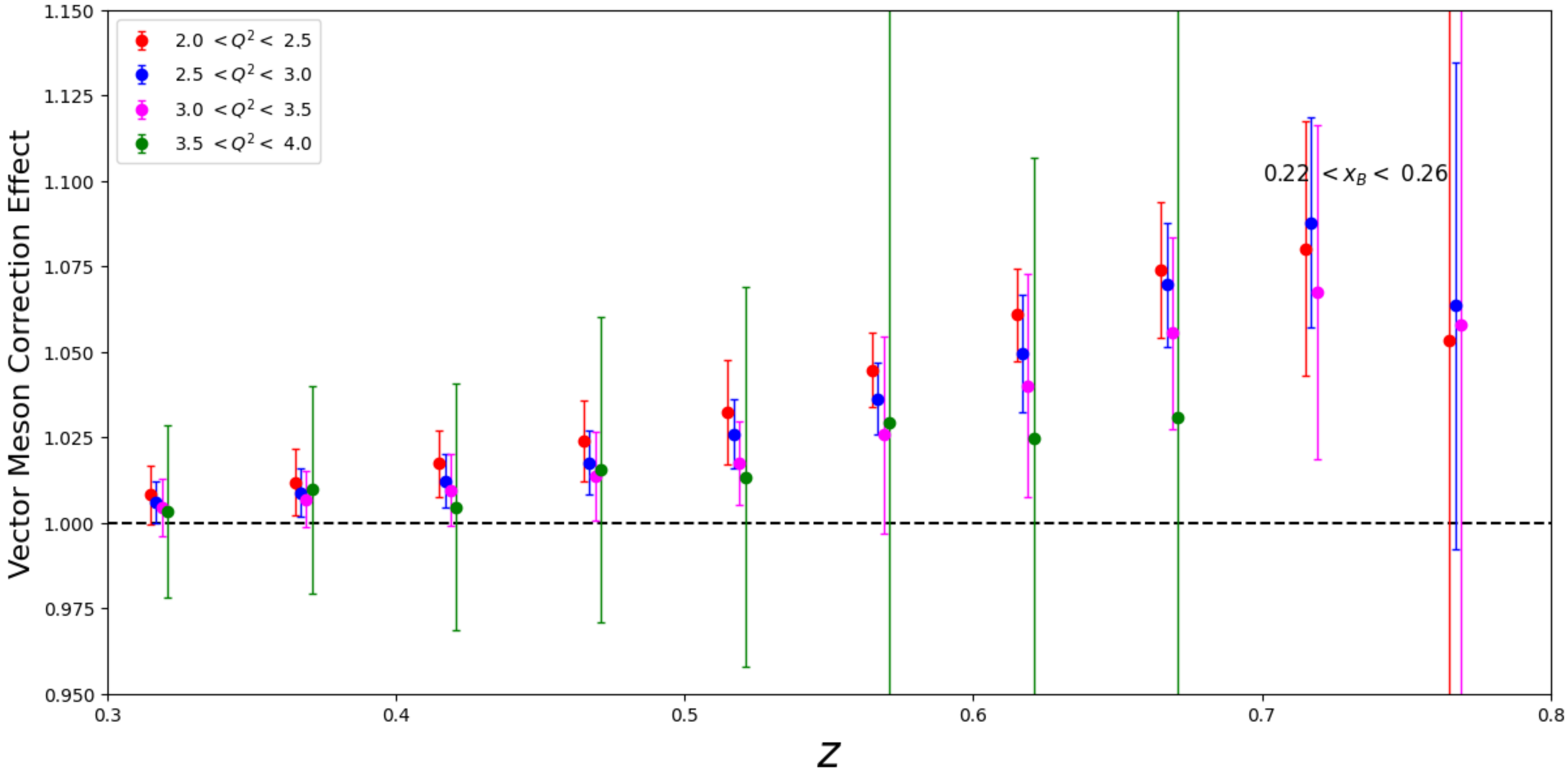
3. R

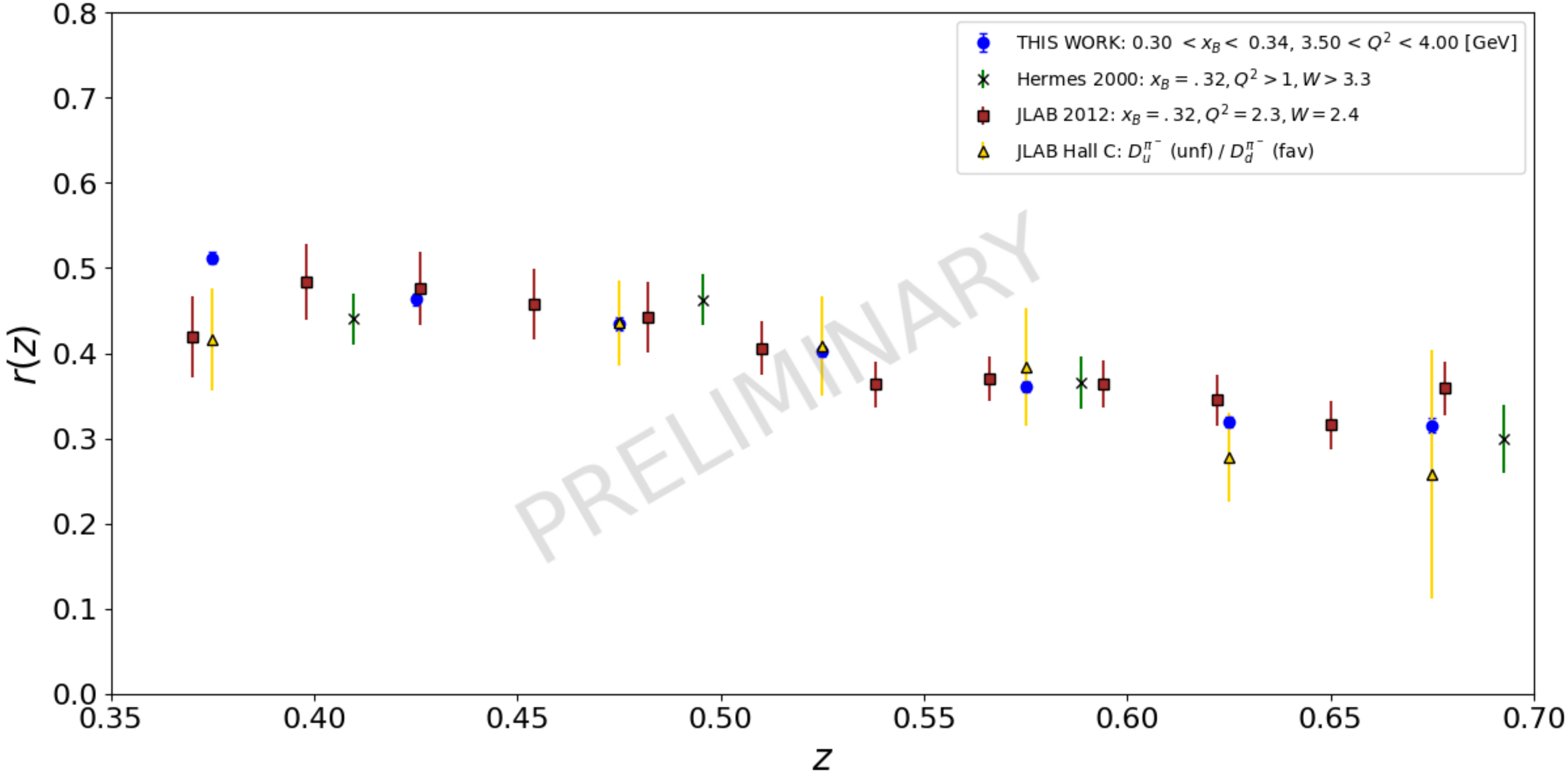


Impact of subtraction on cross section ratio

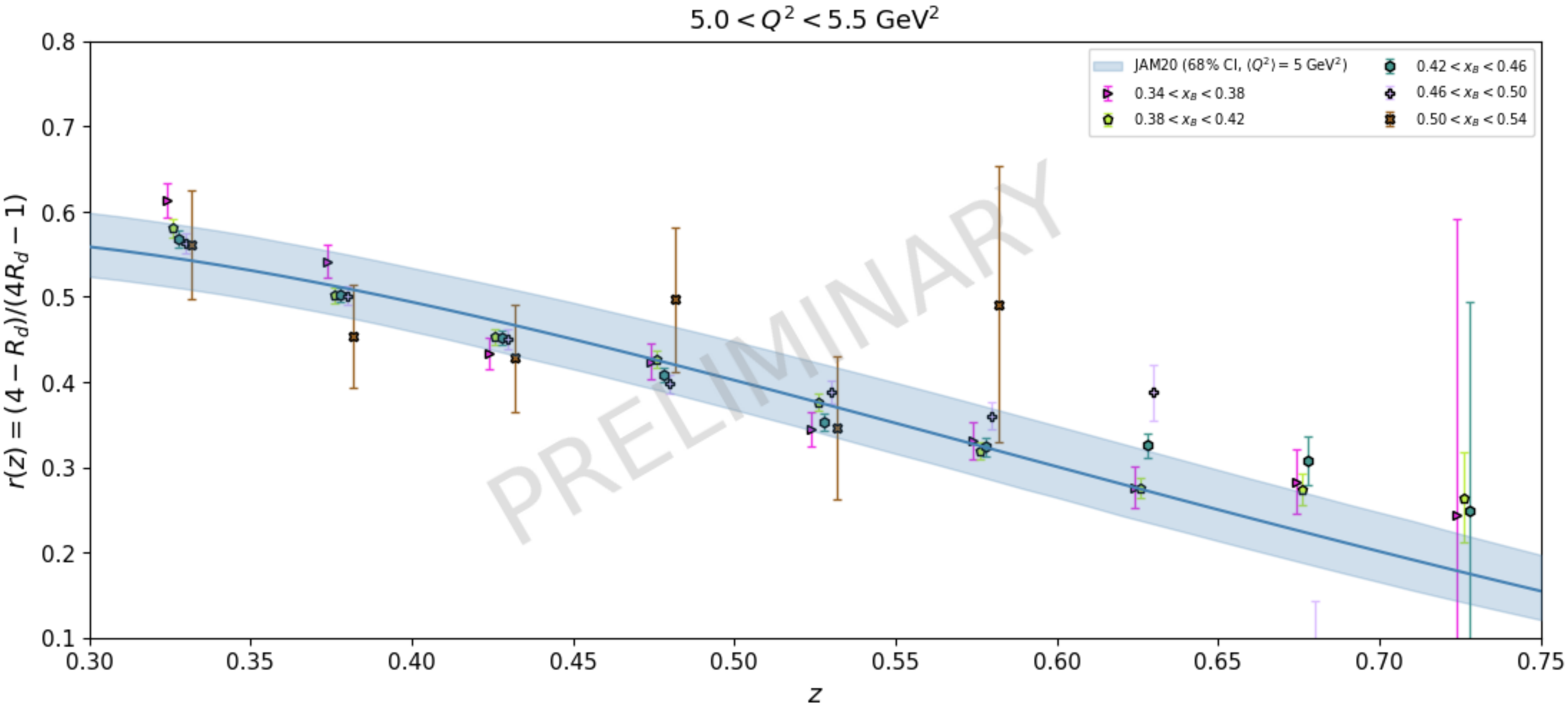


Preliminary Results

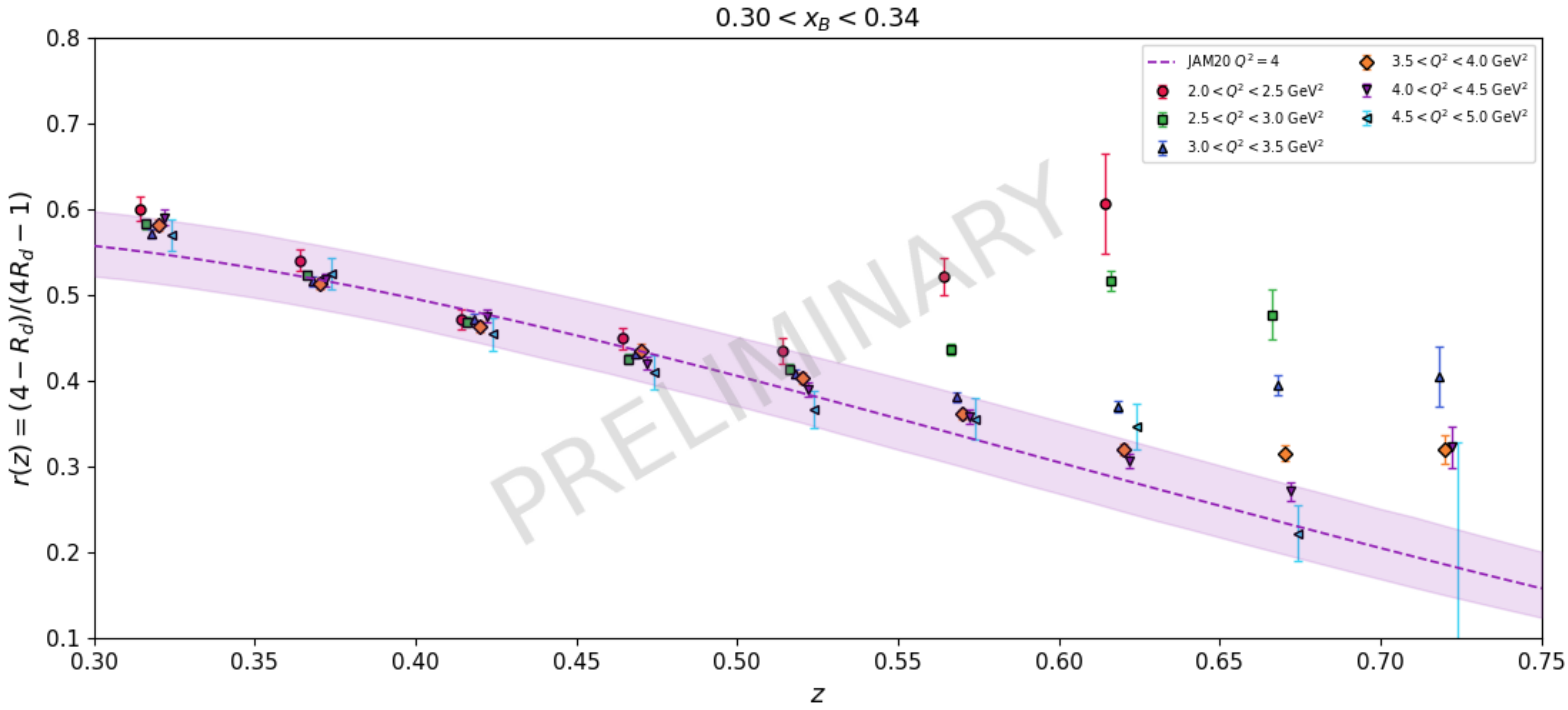
Our Data from CLAS12



Binning in x_B shows consistency with JAM



Binning in Q^2 shows independence at low to moderate z



Summary

- We have extracted the *leading order unfavored-to-favored* pion fragmentation functions, with full acceptance accounting and vector meson subtraction

- We have performed multi-dimensional binning of this observable

Outlook

- Submit analysis note

- Finish analysis of the proton cross section ratio

- Combine these two analyses to extract d/u!

Questions?

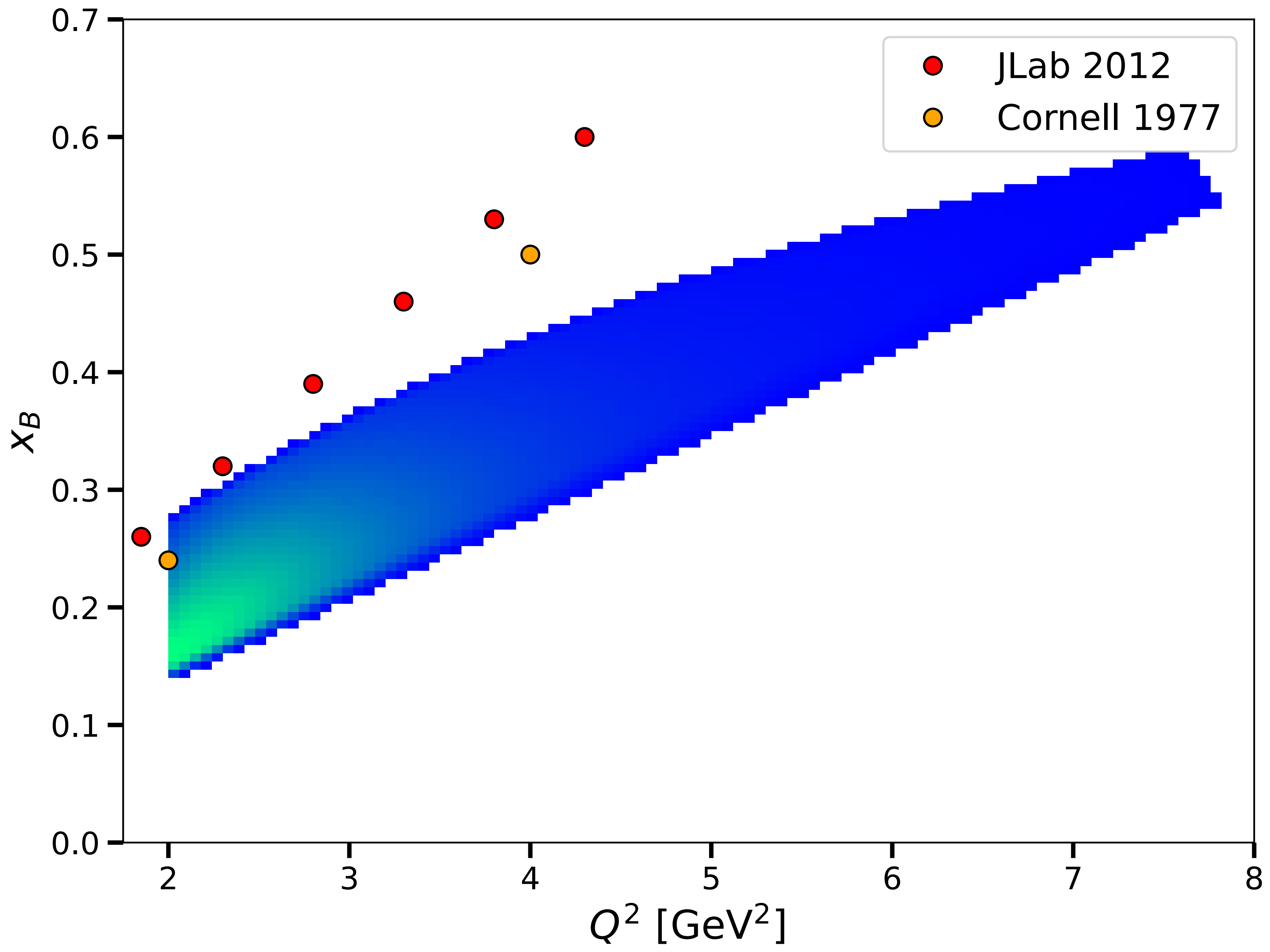
Backup

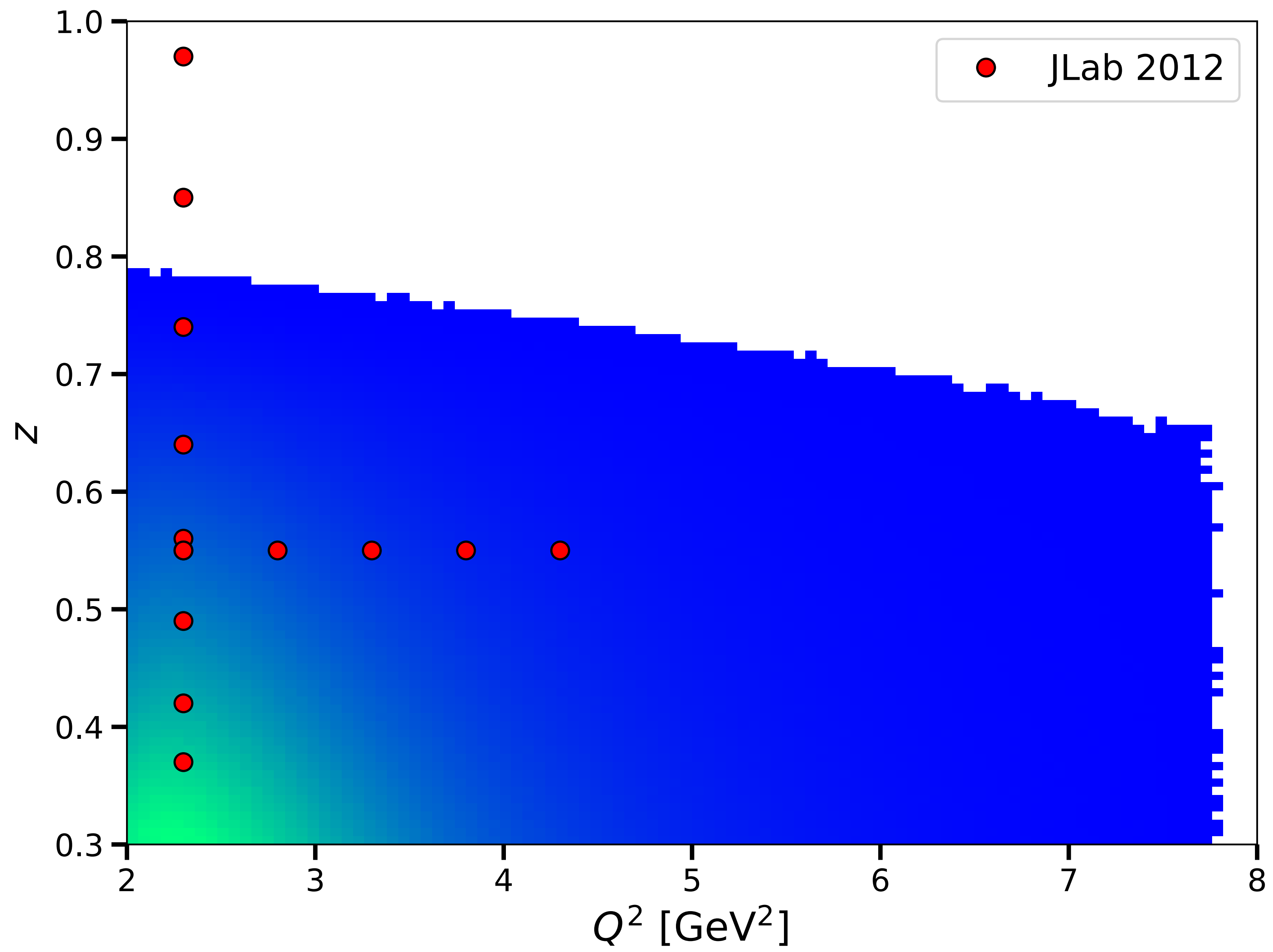
Vector Meson Subtraction

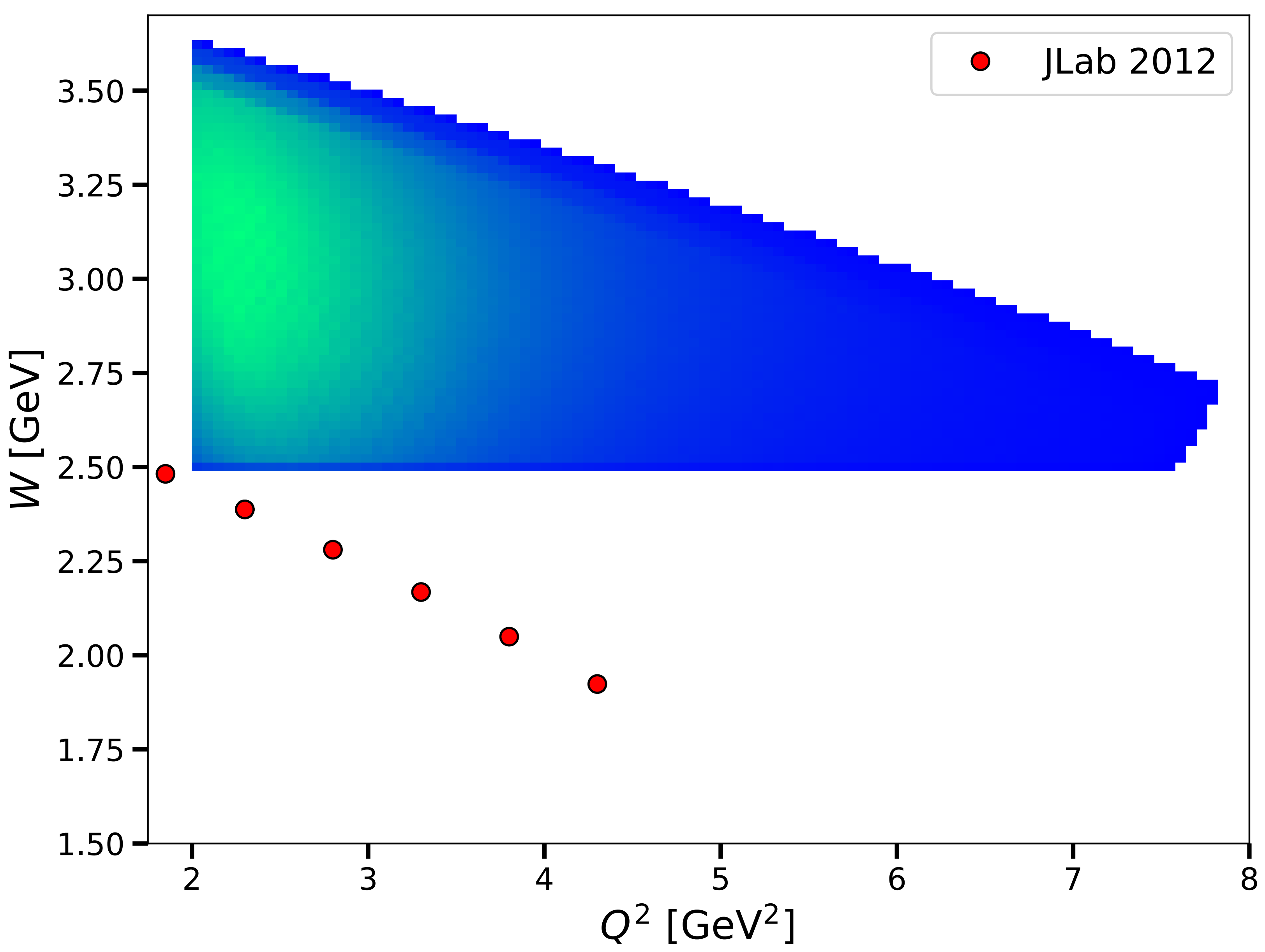
Constructing VM sample

- 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^-}

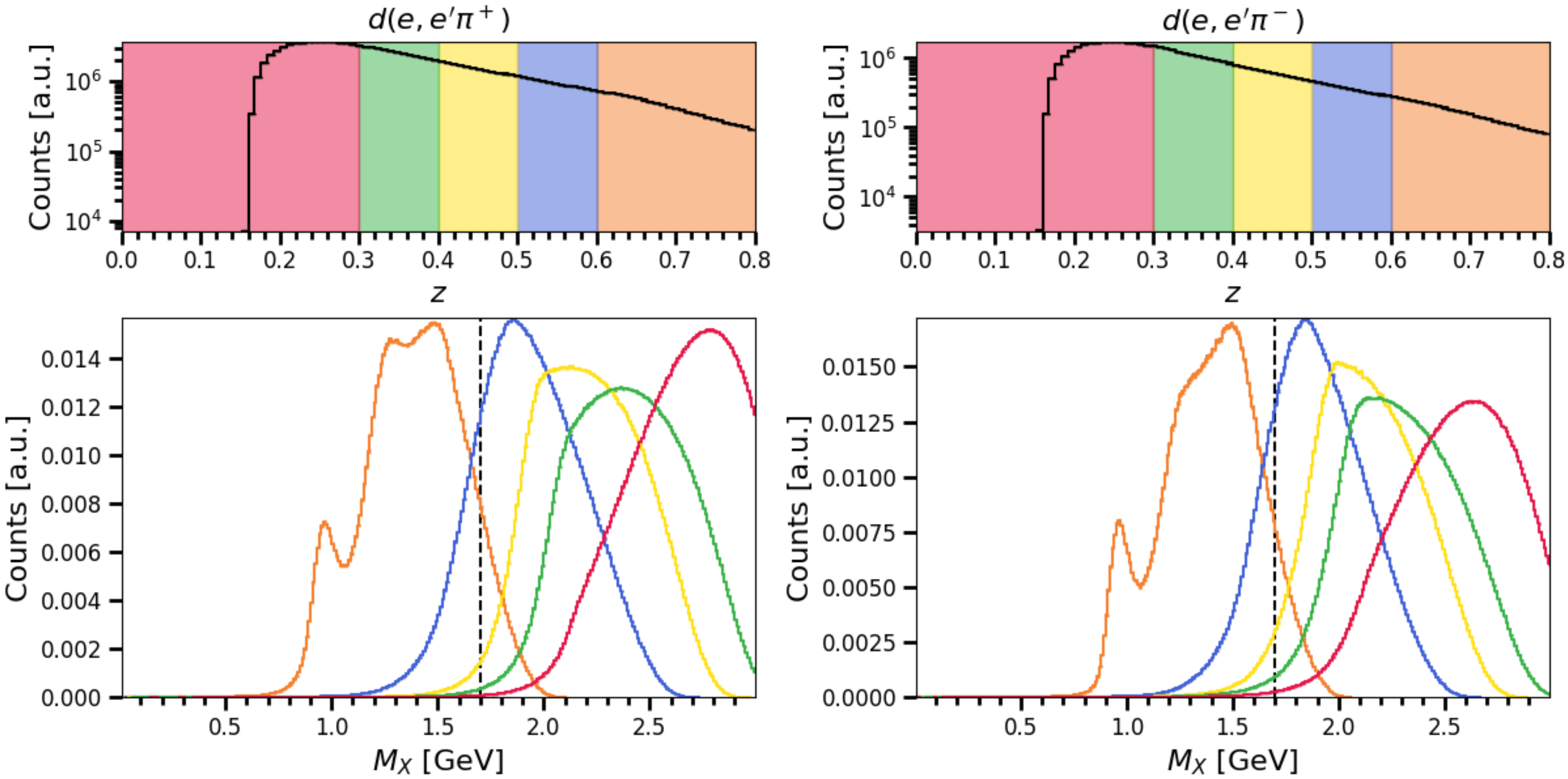
Kinematic Reach



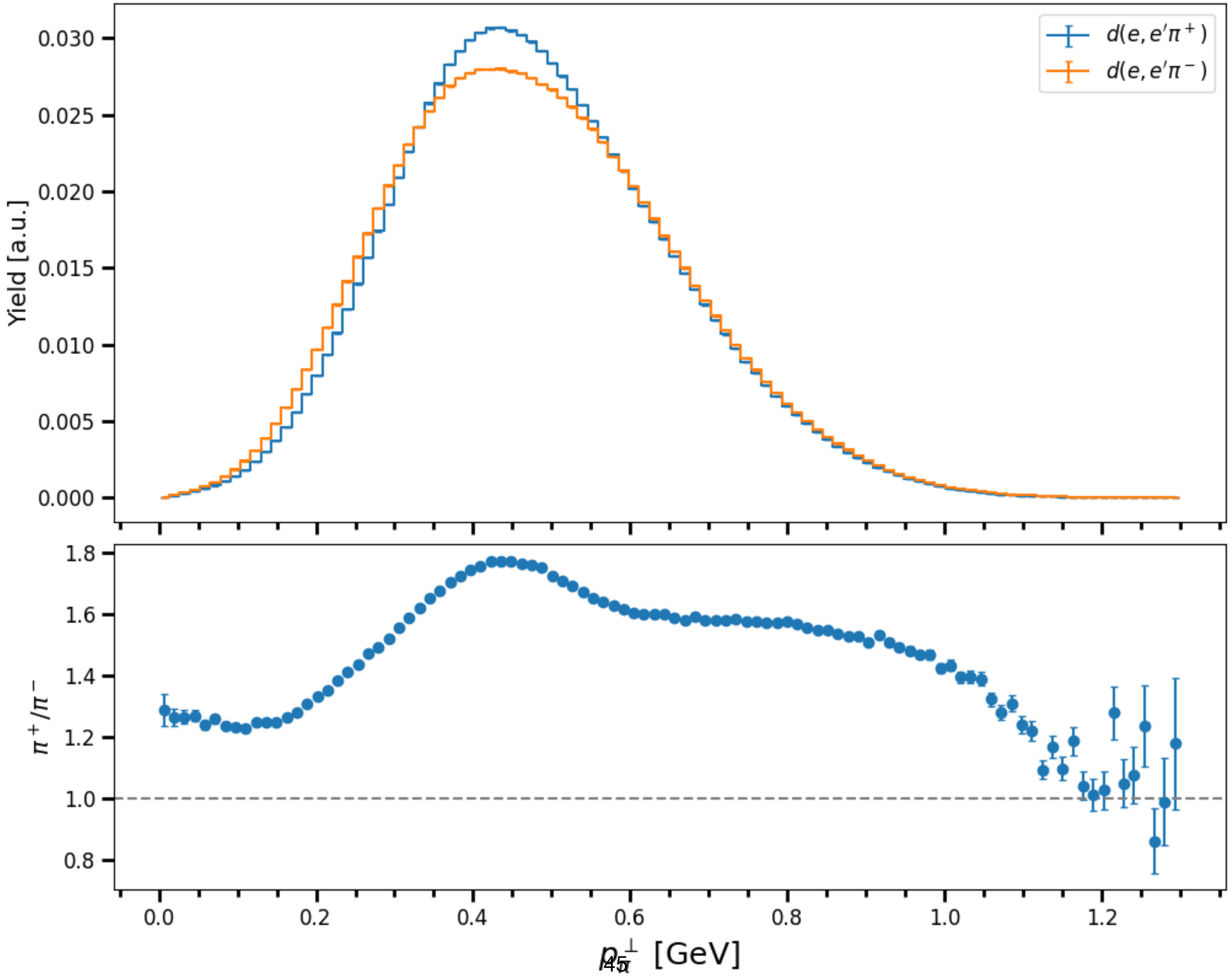




M_X Dependence



p_T Distributions



Kaon Contamination with the RICH

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

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

↓

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

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

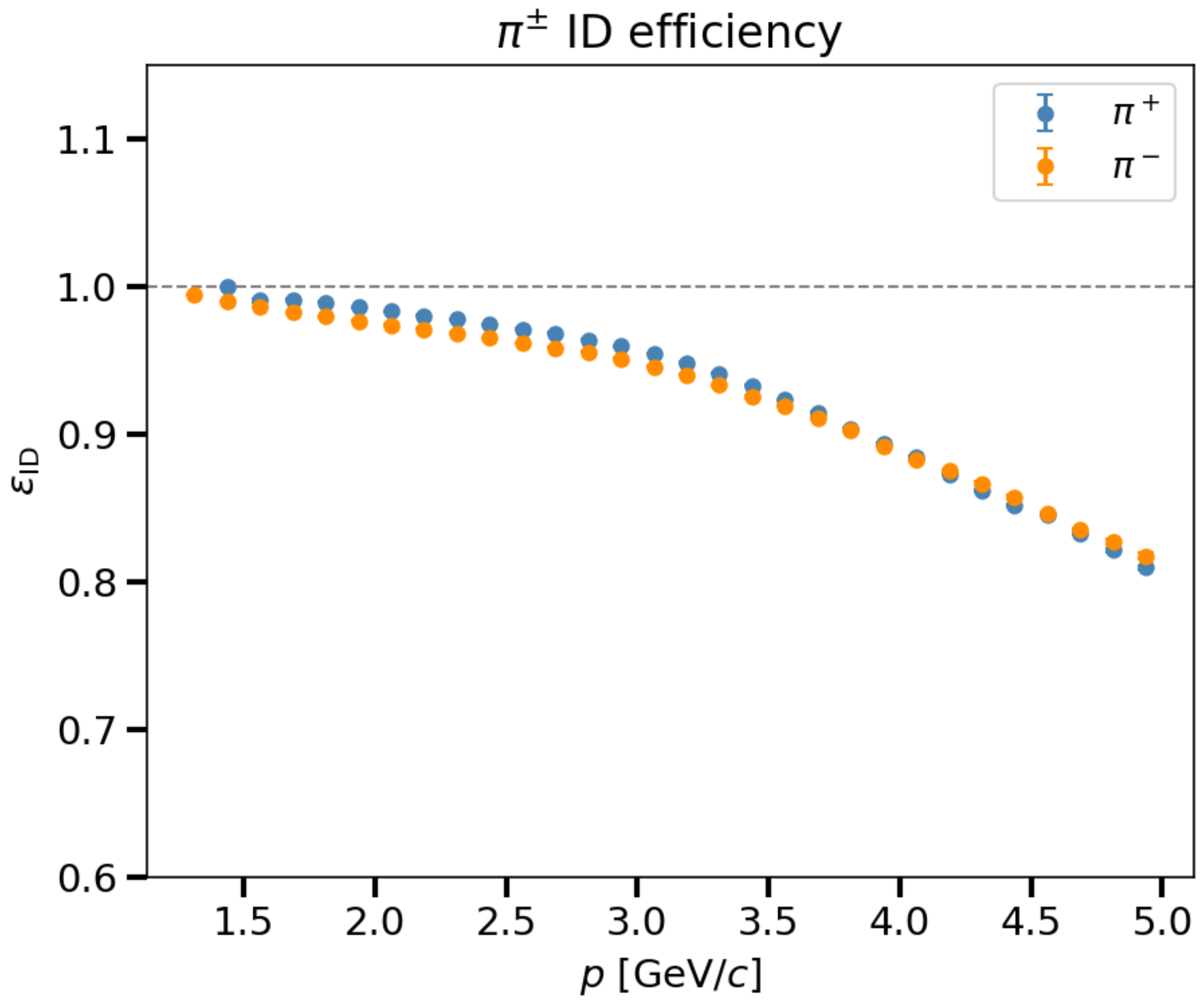
→

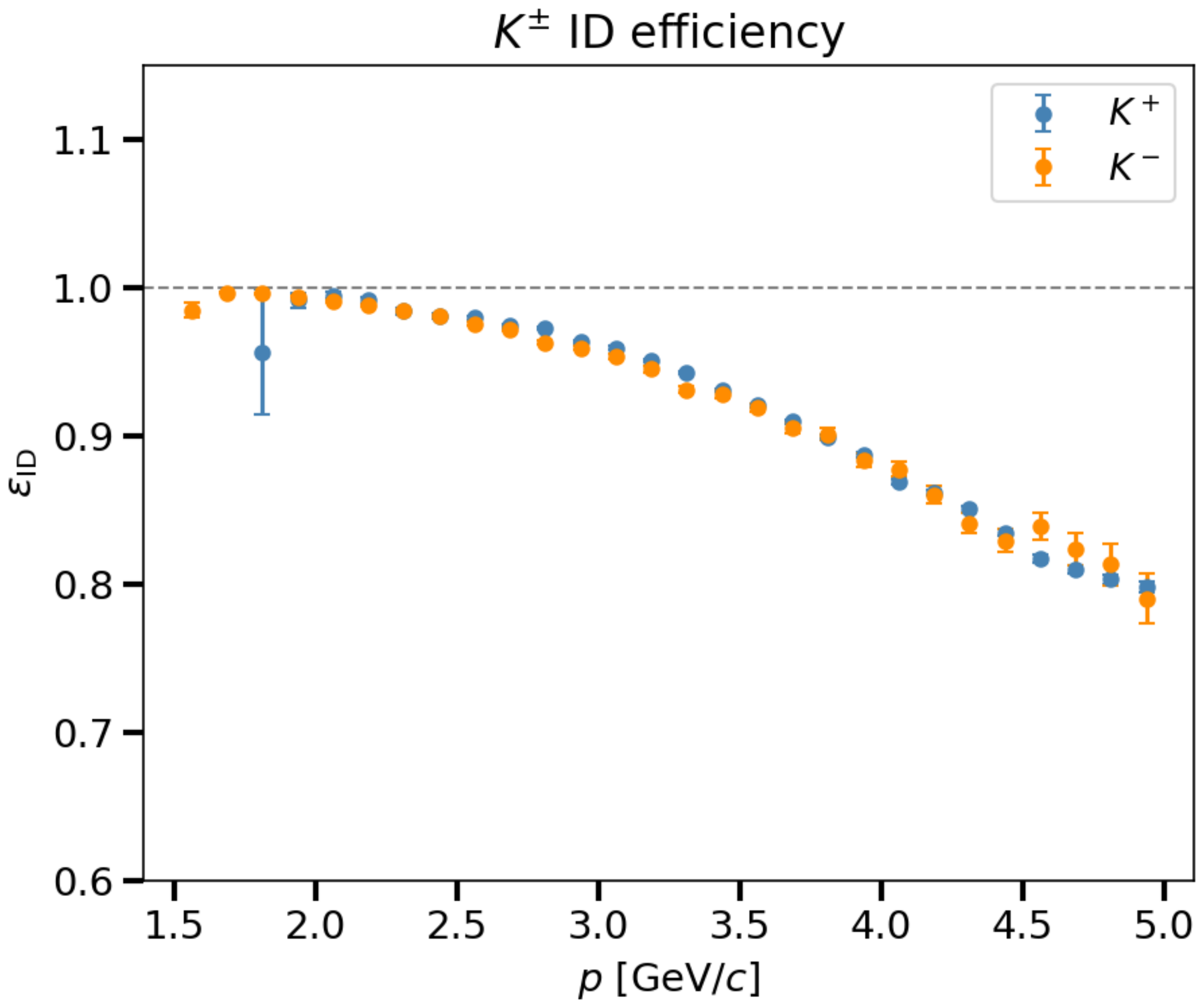
$$C_{\pi^\pm} = \frac{\epsilon^{K^\pm}}{\epsilon^{\pi^\pm} + \epsilon^{K^\pm} - 1}$$

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

Kaon Contamination with the RICH

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





Kaon Contamination with the RICH

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