

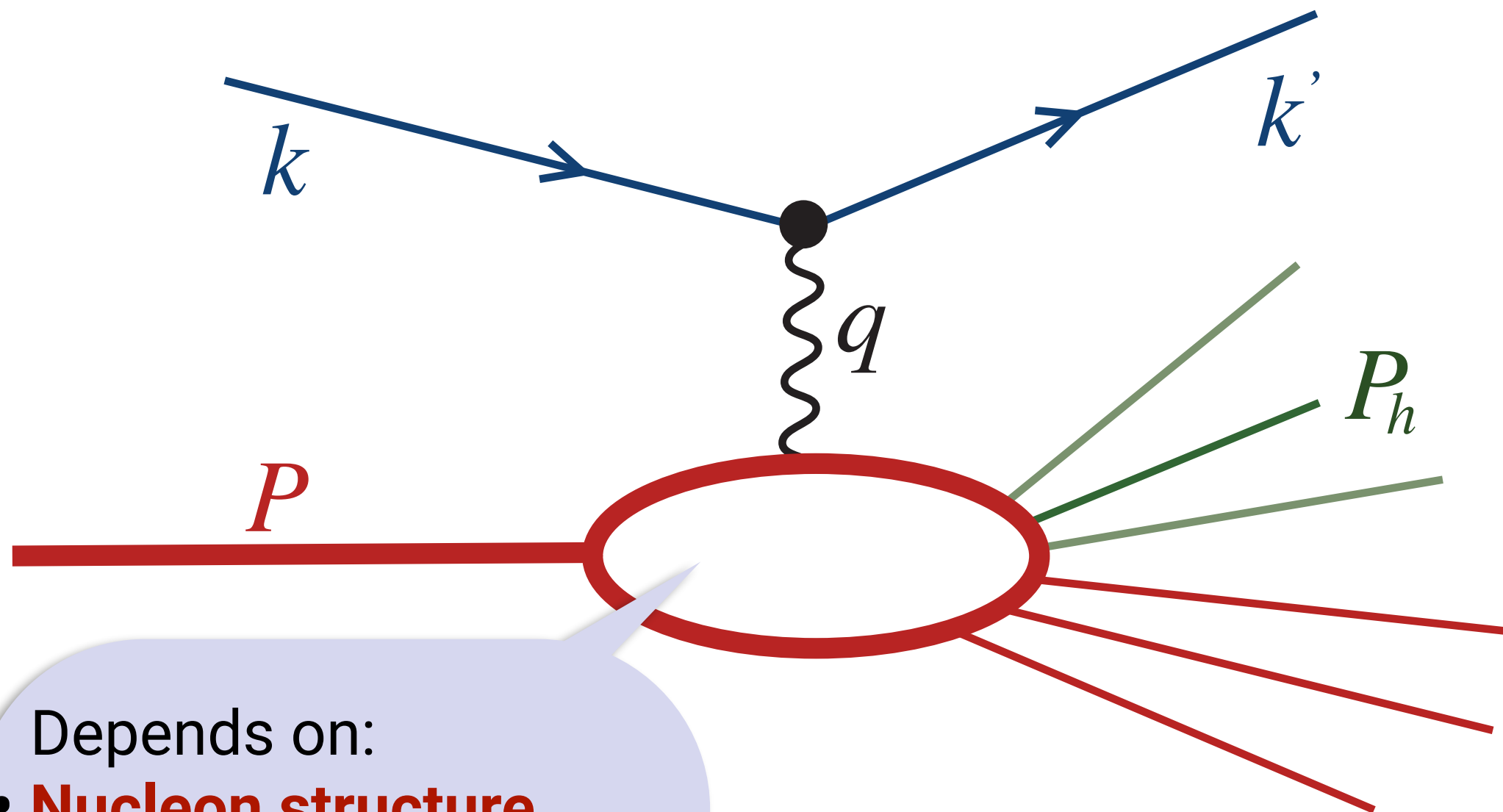
Fragmentation and factorization in semi-inclusive deep-inelastic scattering at the HERMES experiment

Sylvester Johannes Joosten

ECT*, April 11, 2016

semi-inclusive deep-inelastic scattering

A **hadron h** is detected in coincidence with the **scattered lepton**

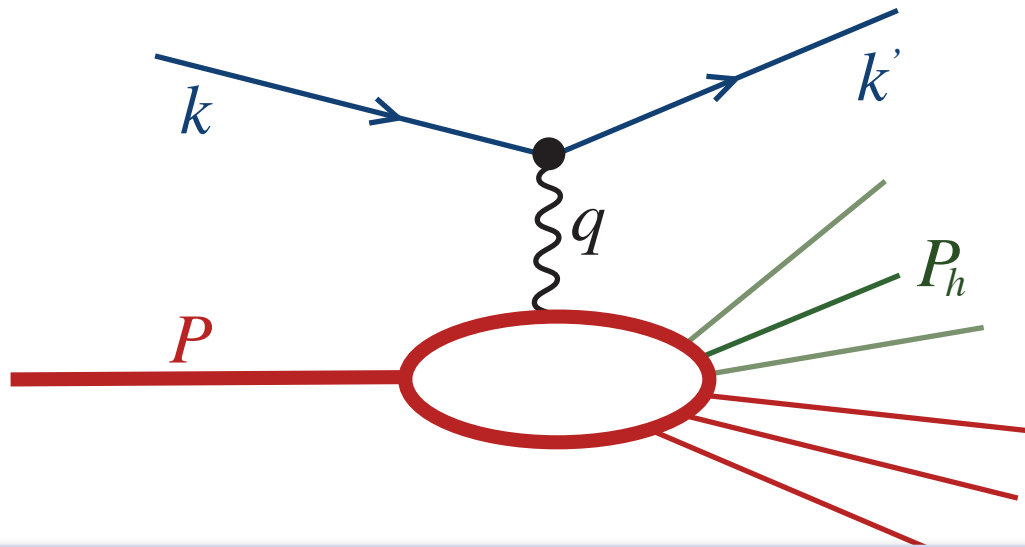


Depends on:

- **Nucleon structure**
- **Hard interaction**
- **Hadron formation**

semi-inclusive deep-inelastic scattering

A **hadron h** is detected in coincidence with the **scattered lepton**



Kinematic variables (SIDIS)

- fractional hadron energy

$$z = \frac{P \cdot P_h}{P \cdot q}$$

- hadron transverse momentum

$$P_{h\perp} = \frac{|\vec{q} \times \vec{P}_h|}{|\vec{q}|}$$

- hadron azimuthal angle ϕ_h

Kinematic variables (inclusive)

- momentum transfer

$$Q^2 = -q^2$$

- photon-nucleon invariant mass

$$W^2 = (P + q)^2$$

- Bjorken scaling variable

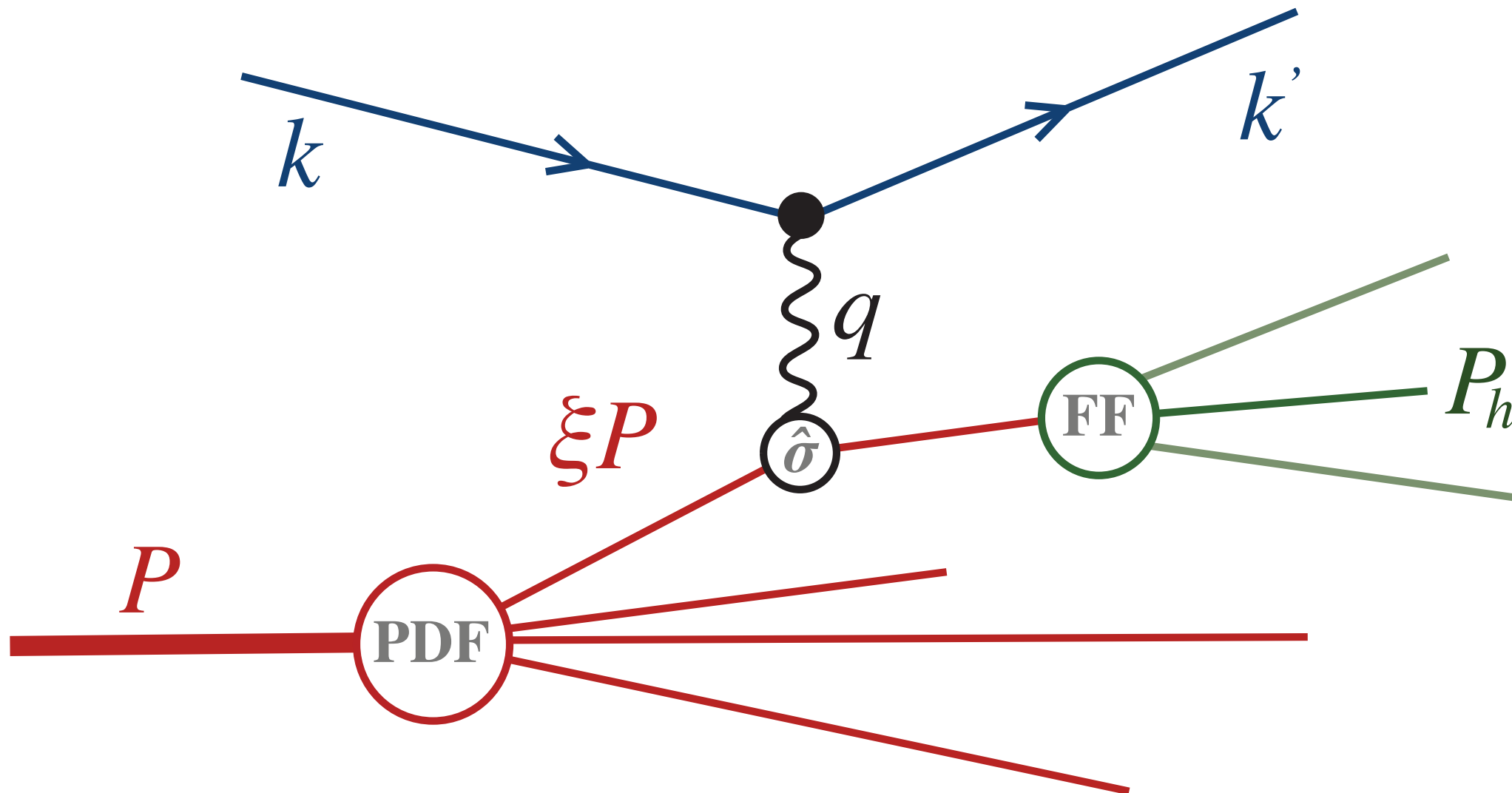
$$x = \frac{Q^2}{2P \cdot q}$$

- fractional photon energy

$$y = \frac{p \cdot q}{p \cdot k}$$

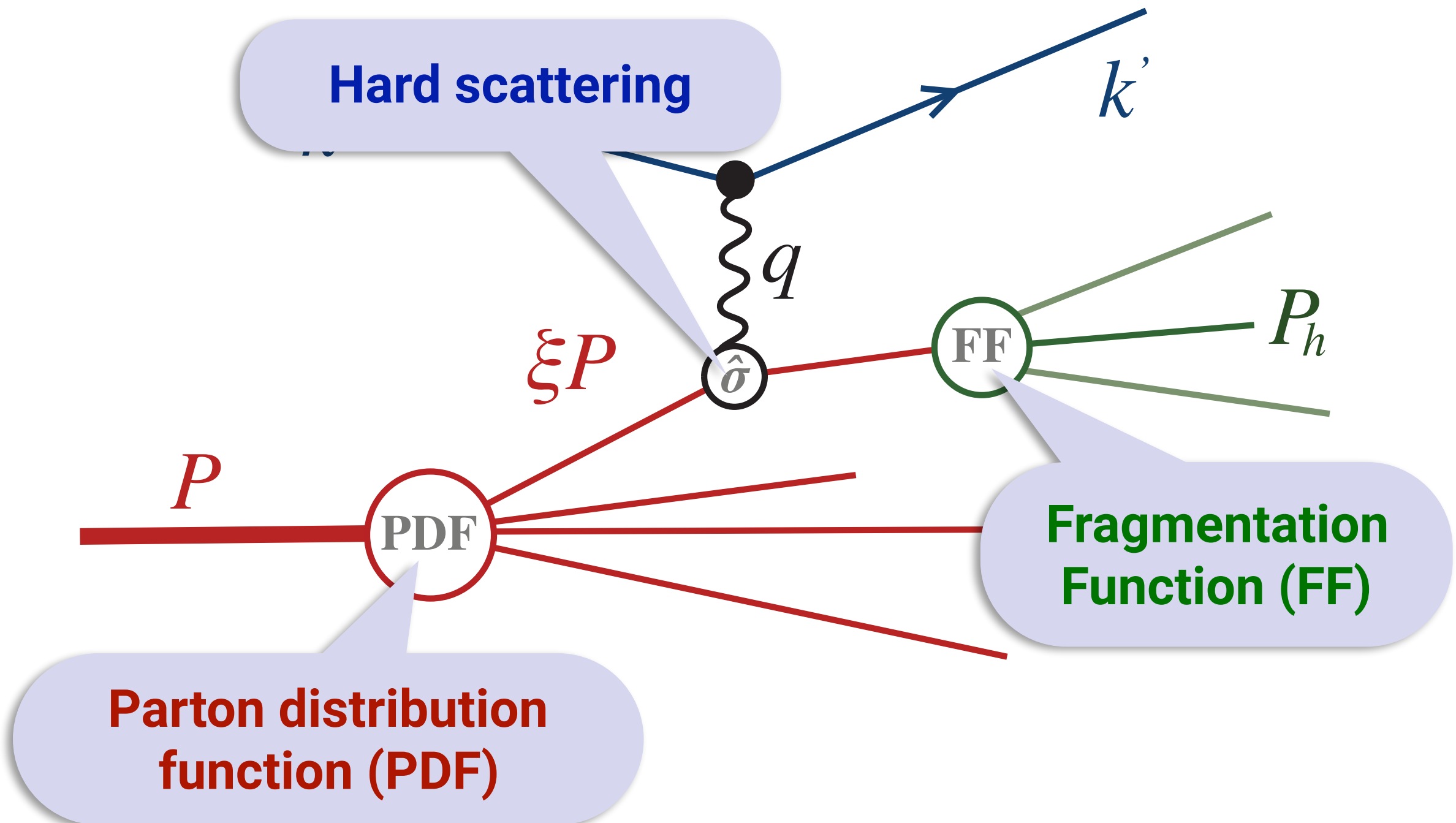
factorization: separation of distance scales

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



factorization: separation of distance scales

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



factorization: separation of distance scales

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Perturbative

Hard scattering

k'

q

ξP

$\hat{\sigma}$

FF

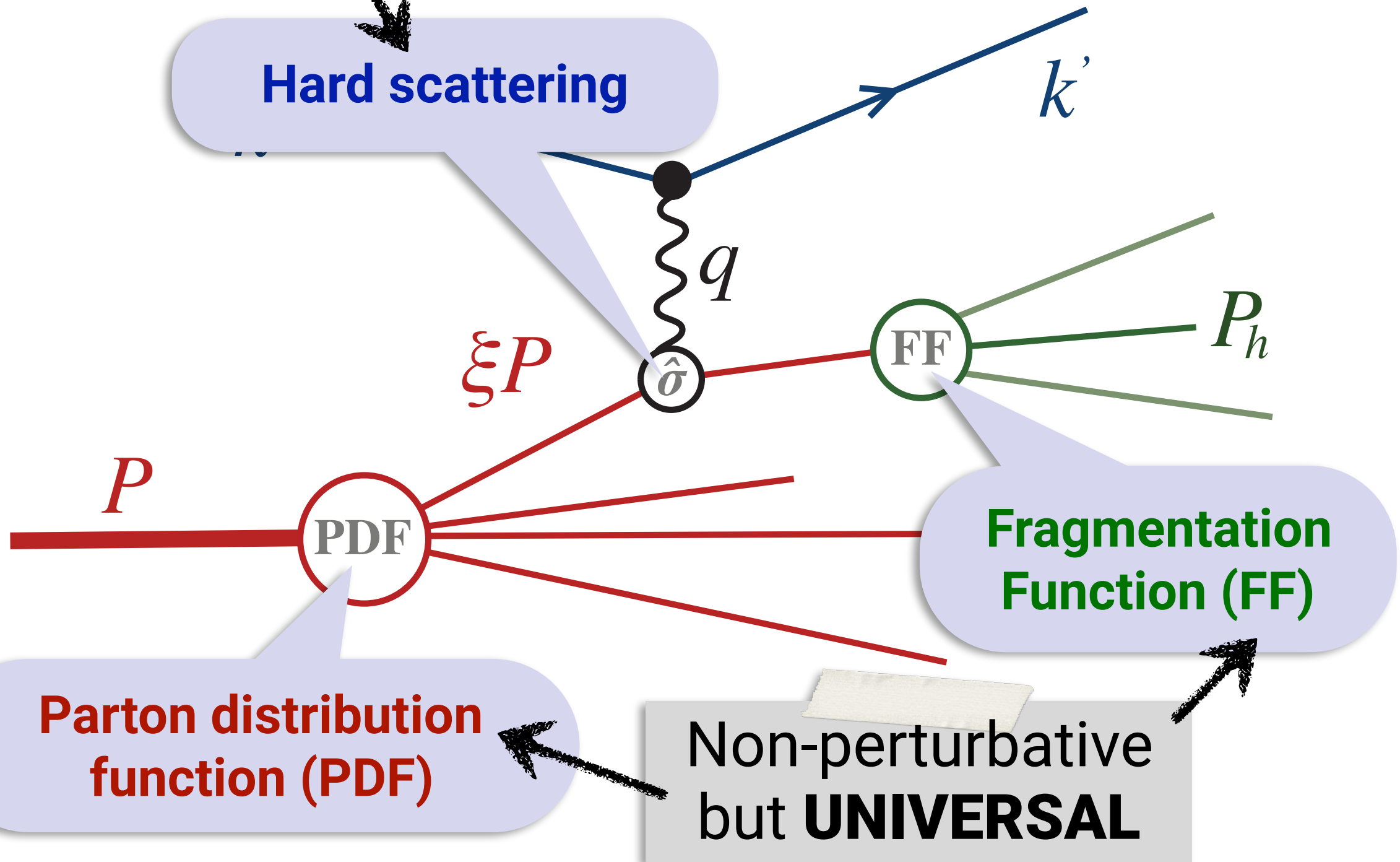
P_h

Fragmentation
Function (FF)

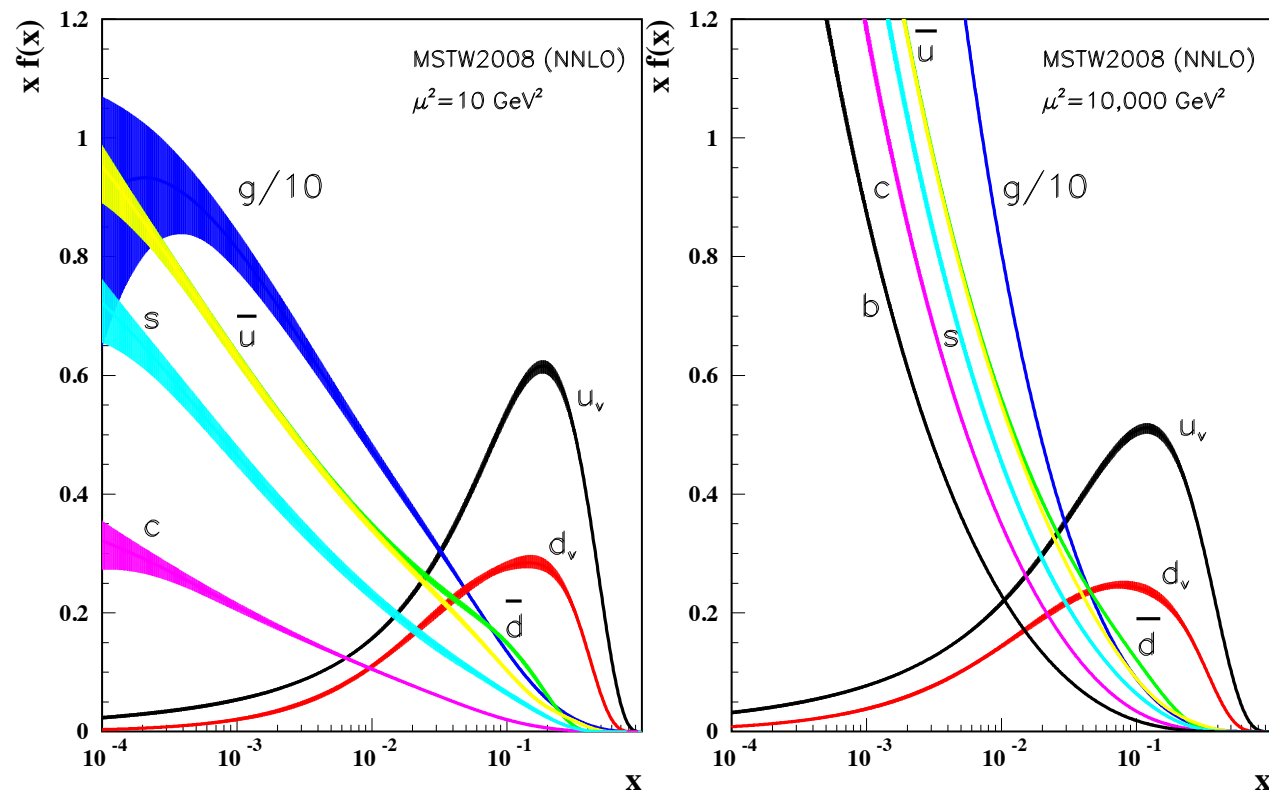
PDF

Parton distribution
function (PDF)

Non-perturbative
but **UNIVERSAL**

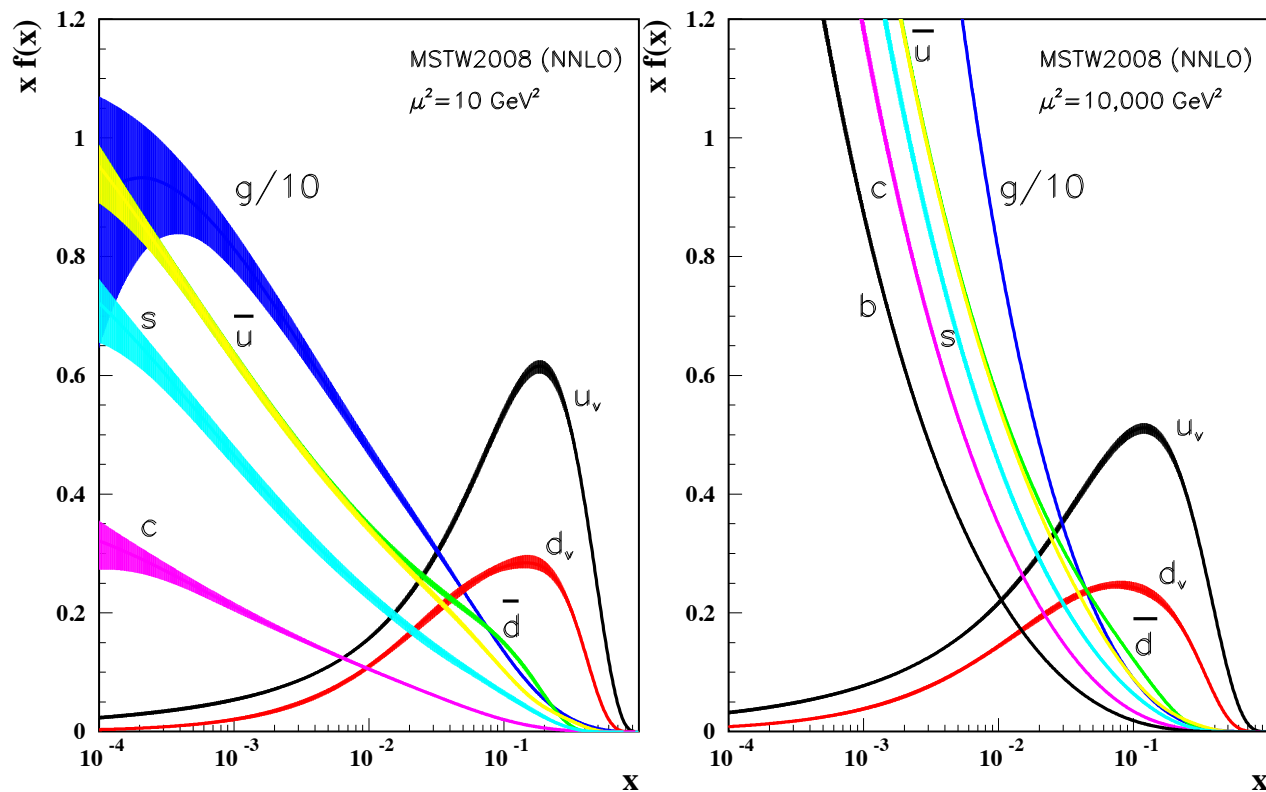


parameterizations



- Knowledge of **PDFs**:
- Well constrained
 - Up to **NNLO**
 - Recent **parameterizations**
(CTEQ6/CT14, MSTW2008, HeraPDF, NNPDF)
 - agree** within uncertainties
 - calculable in lattice QCD

parameterizations

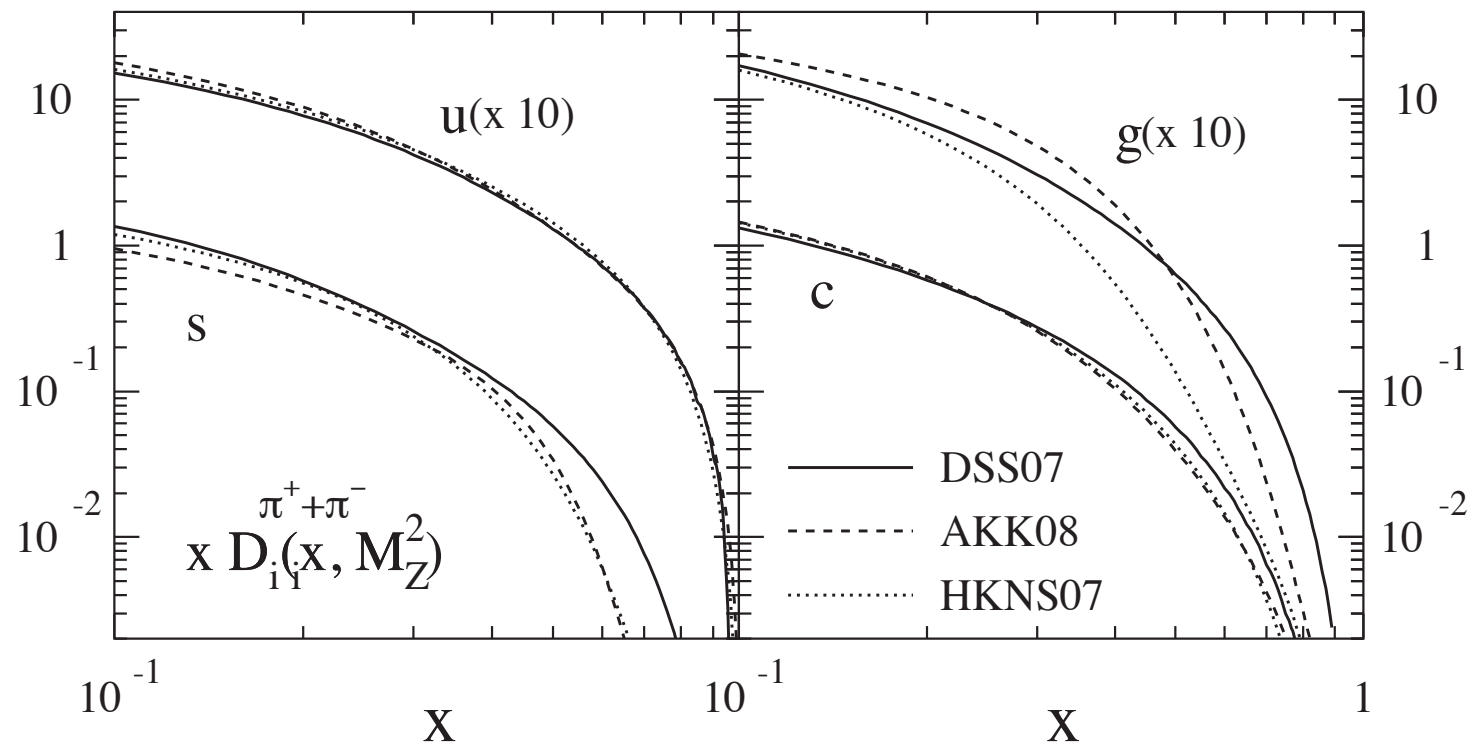


Knowledge of **PDFs**:

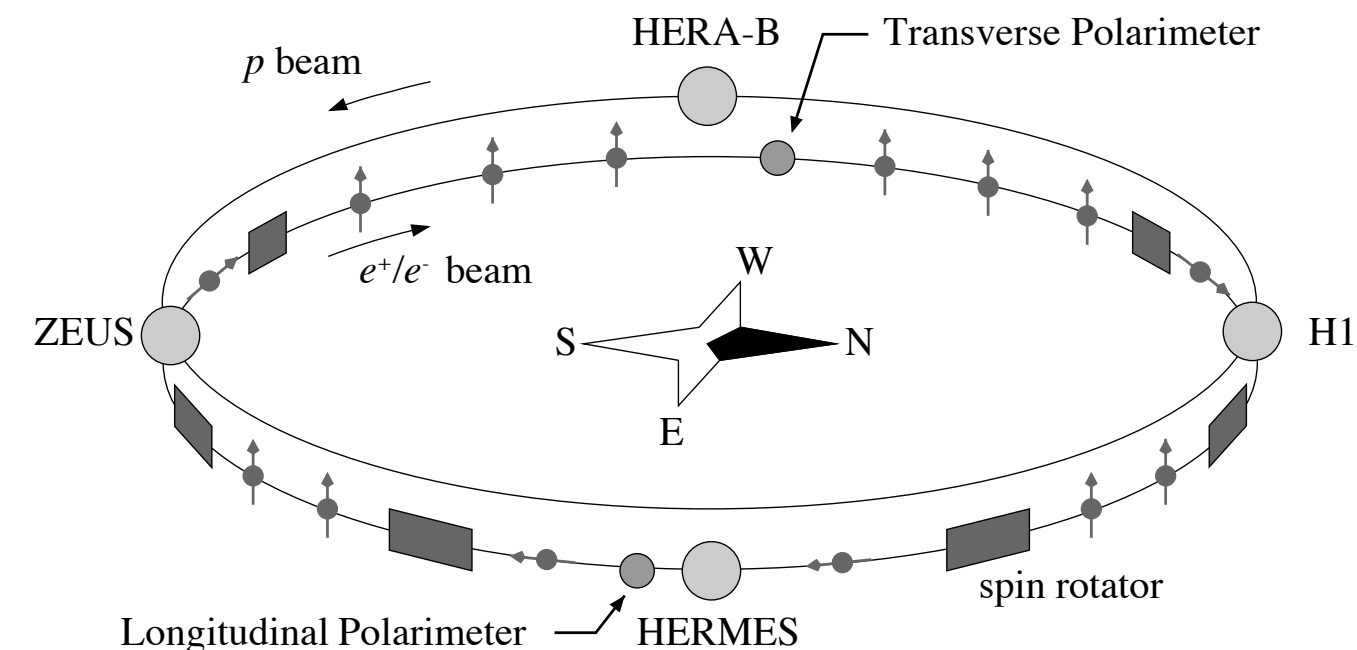
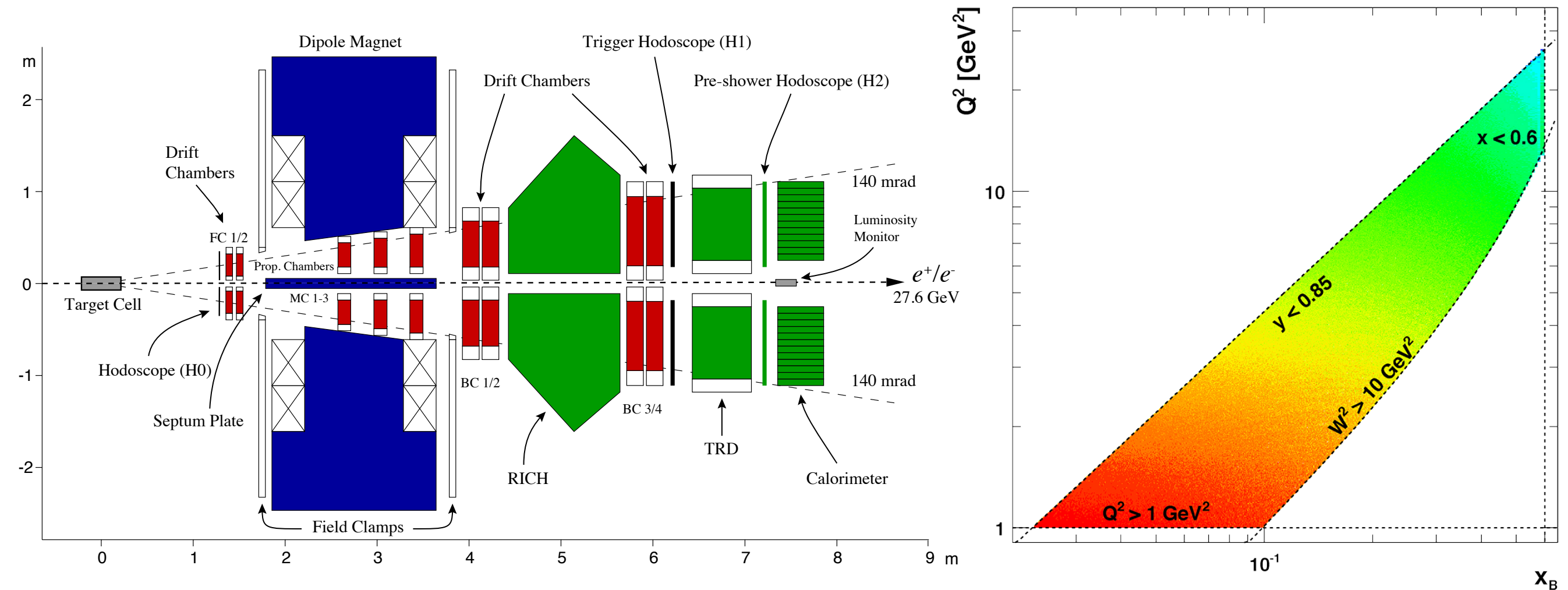
- Well constrained
- Up to **NNLO**
- Recent **parameterizations** (CTEQ6/CT14, MSTW2008, HeraPDF, NNPDF)
- agree** within uncertainties
- calculable in lattice QCD

Knowledge of **FFs**:

- Mostly from SIA (**no individual quark contributions**)
- Up to **NLO**
- Leading **parameterizations** (DSS07/AKK08/HKNS07) **differ**
- Room for **improvement!**



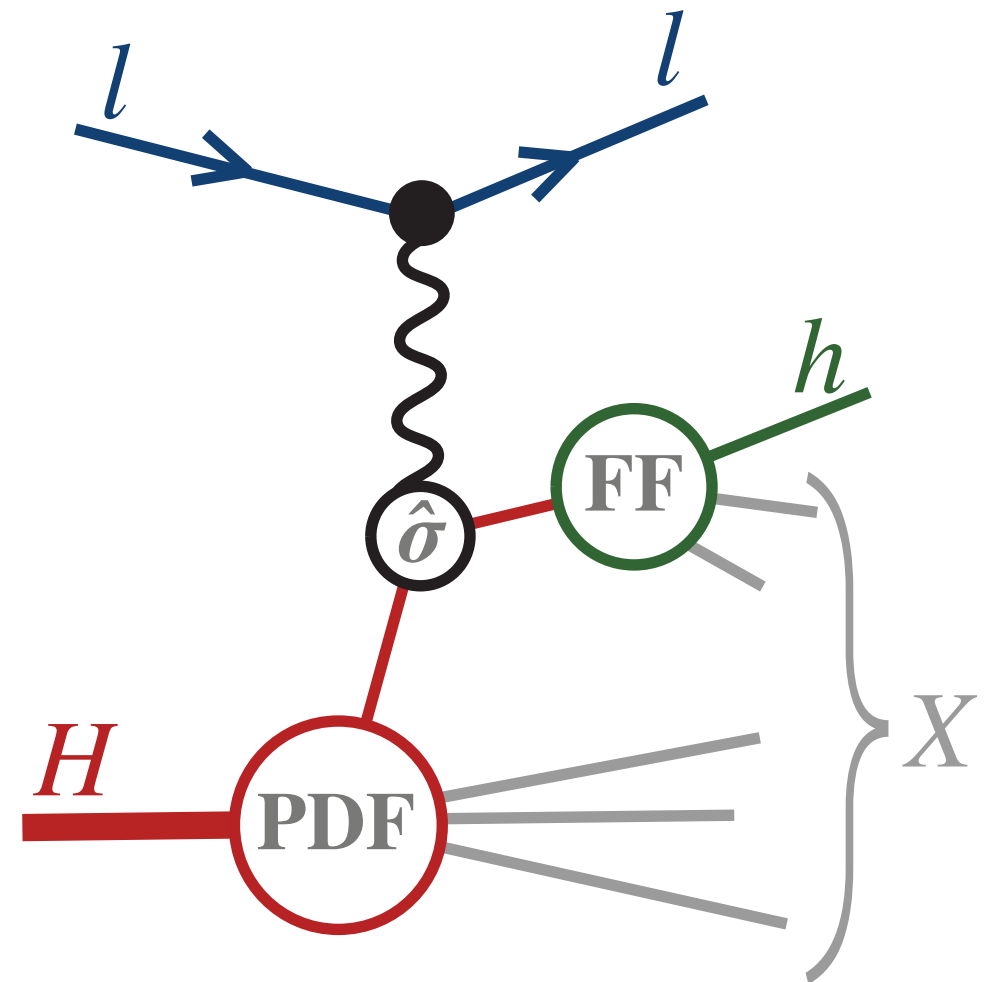
The HERMES experiment



- HERA 27.6 GeV $e^\pm$ beam
- Forward spectrometer
 - Pure H and D atomic gas target
 - Clean lepton-hadron identification
 - Very good pion-kaon separation with the RICH

What is a **SIDIS** multiplicity?

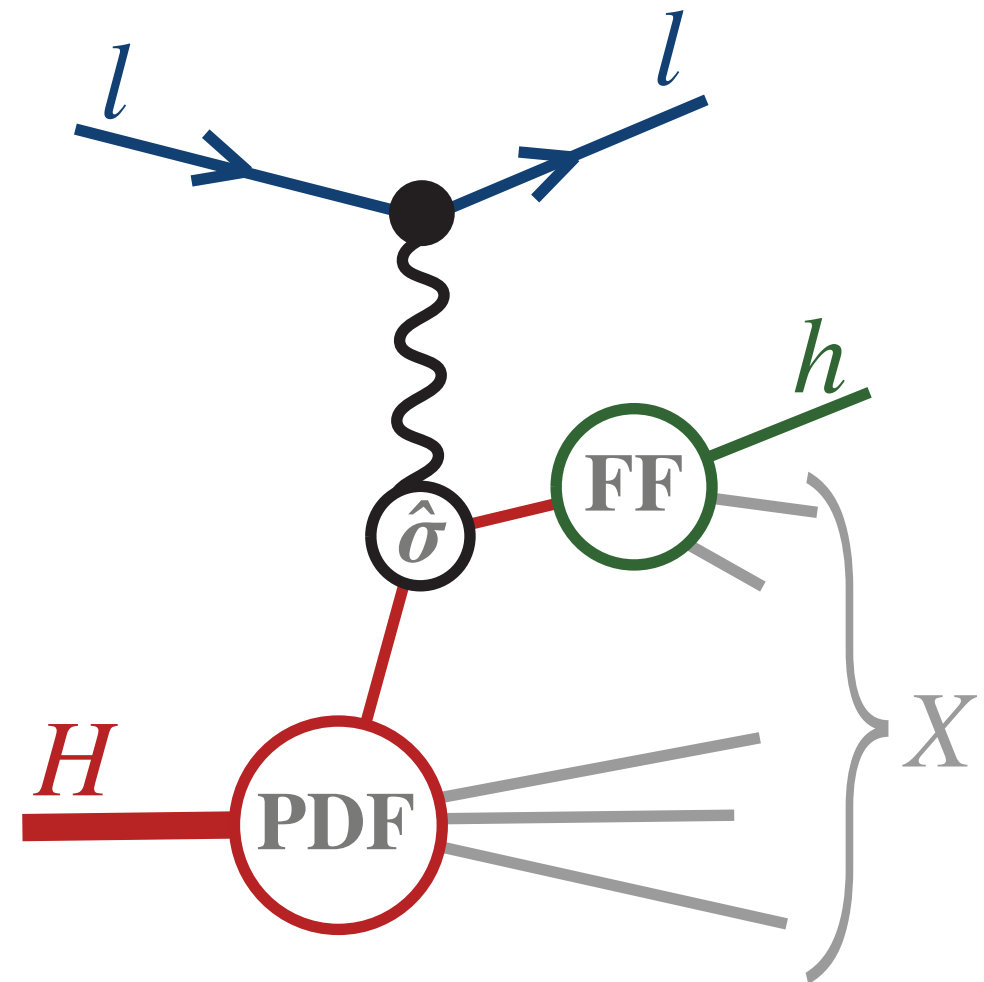
Multiplicity: Number of hadrons h produced in SIDIS off a nucleon H , relative to the number of inclusive DIS events.



$$M_H^h(x, Q^2, z, P_{h\perp}) \equiv \frac{1}{\frac{d^2 N_{\text{DIS}}(x, Q^2)}{dx dQ^2}} \int_0^{2\pi} d\phi_h \frac{d^5 N^h(x, Q^2, z, P_{h\perp}, \phi_h)}{dx dQ^2 dP_{h\perp} d\phi_h},$$

What is a **SIDIS** multiplicity?

Multiplicity: Number of hadrons h produced in SIDIS off a nucleon H , relative to the number of inclusive DIS events.



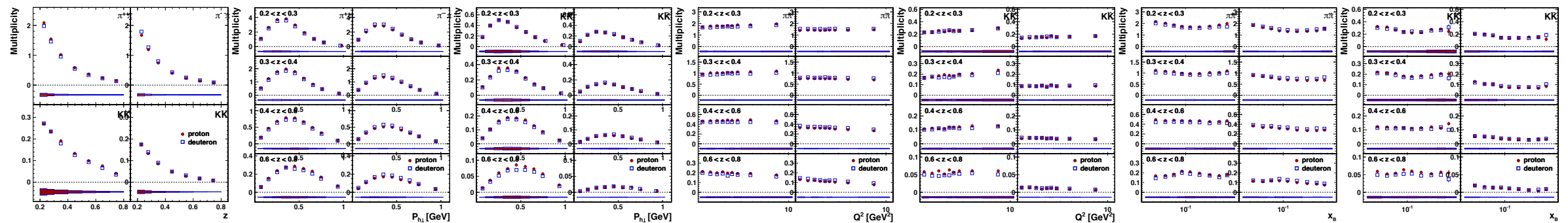
$$M_H^h(x, Q^2, z, P_{h\perp}) \equiv \frac{1}{\frac{d^2 N_{\text{DIS}}(x, Q^2)}{dx dQ^2}} \int_0^{2\pi} d\phi_h \frac{d^5 N^h(x, Q^2, z, P_{h\perp}, \phi_h)}{dx dQ^2 dP_{h\perp} d\phi_h},$$

1/DIS **SIDIS**

SIDIS Multiplicities: **HERMES** results

(A. Airapetian et al, Phys. Rev. D 87 (2013) 074029)

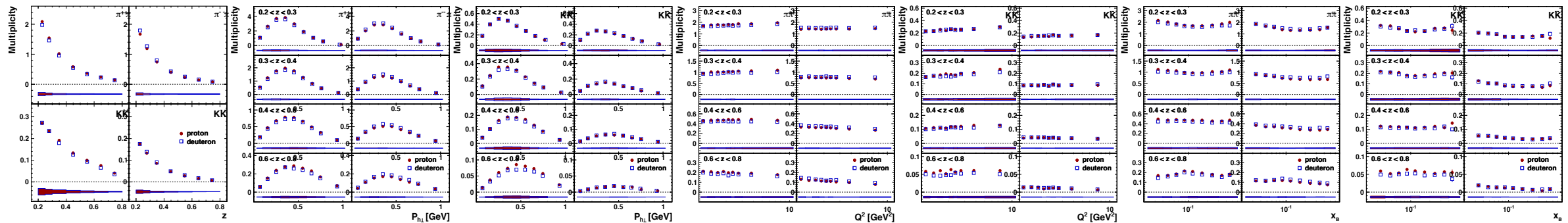
- **High statistics**
- **3D analysis** ($x/Q^2, z, P_{h\perp}$)



SIDIS Multiplicities: **HERMES** results

(A. Airapetian et al, Phys. Rev. D 87 (2013) 074029)

- **High statistics**
- **3D analysis** ($x/Q^2, z, P_{h\perp}$)



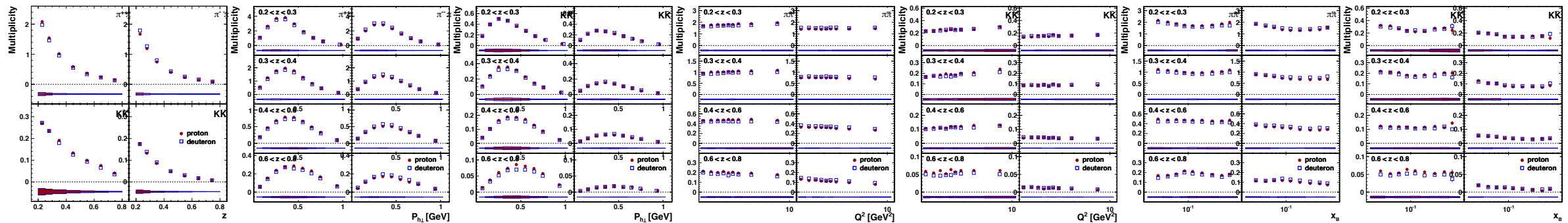
High precision requires **sophisticated analysis**:

- Trigger efficiencies
- Charge-symmetric background
- **RICH unfolding**
- (optional): correction for **exclusive vector mesons**
- **Multidimensional smearing-unfolding** for radiative effects, limited acceptance, and detector smearing

SIDIS Multiplicities: **HERMES** results

(A. Airapetian et al, Phys. Rev. D 87 (2013) 074029)

- **High statistics**
- **3D analysis** ($x/Q^2, z, P_{h\perp}$)



High precision requires **sophisticated analysis**:

- Trigger efficiencies
- Charge-symmetric background
- **RICH unfolding**
- (optional): correction for **exclusive vector mesons**
- **Multidimensional smearing-unfolding** for radiative effects, limited acceptance, and detector smearing

Final results in 4π Born
(one-photon exchange)

Systematics
dominated

Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section

$$\sigma_{\text{M}}(i) = B(i) + \sum_j \frac{\left(\int_{\text{bin } i} dY \int d\bar{X} \int_{\text{bin } j} dX R(Y|\bar{X}) A(\bar{X}) Q(\bar{X}|X) \frac{d\sigma_{\text{B}}}{dX} \right) \sigma_{\text{B}}(j)}{\int_{\text{bin } j} dX \frac{d\sigma_{\text{B}}}{dX}}$$

Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section

$$\sigma_{\text{M}}(i) = B(i) + \sum_j \frac{\left(\int_{\text{bin } i} dY \int d\bar{X} \int_{\text{bin } j} dX R(Y|\bar{X}) A(\bar{X}) Q(\bar{X}|X) \frac{d\sigma_{\text{B}}}{dX} \right) \sigma_{\text{B}}(j)}{\int_{\text{bin } j} dX \frac{d\sigma_{\text{B}}}{dX}}$$

Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section

The diagram illustrates the relationship between the measured cross section $\sigma_M(i)$ and the Born cross section $\sigma_B(j)$. The equation is presented as:

$$\sigma_M(i) = B(i) + \sum_j \frac{\left(\int_{\text{bin } i} dY \int d\bar{X} \int_{\text{bin } j} dX R(Y|\bar{X}) A(\bar{X}) Q(\bar{X}|X) \frac{d\sigma_B}{dX} \right) \sigma_B(j)}{\int_{\text{bin } j} dX \frac{d\sigma_B}{dX}}$$

Annotations in the diagram include:

- A green dashed circle around $\sigma_M(i)$ on the left, with an arrow pointing from the word "measured" in the title to it.
- A red dashed circle around $\sigma_B(j)$ on the right, with an arrow pointing from the word "Born" in the title to it.
- An orange dashed circle around the integrand term $\left(\int_{\text{bin } i} dY \int d\bar{X} \int_{\text{bin } j} dX R(Y|\bar{X}) A(\bar{X}) Q(\bar{X}|X) \frac{d\sigma_B}{dX} \right)$.
- A grey box at the bottom right labeled "Radiative effects" with an arrow pointing up to the orange dashed circle.

Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section

The diagram illustrates the relationship between the measured cross section $\sigma_M(i)$ and the Born cross section $\sigma_B(j)$ in SIDIS. The equation is:

$$\sigma_M(i) = B(i) + \sum_j \frac{\left(\int_{\text{bin } i} dY \int d\bar{X} \int_{\text{bin } j} dX R(Y|\bar{X}) A(\bar{X}) Q(\bar{X}|X) \frac{d\sigma_B}{dX} \right) \sigma_B(j)}{\int_{\text{bin } j} dX \frac{d\sigma_B}{dX}}$$

Annotations and arrows in the diagram:

- An arrow points from the word **measured** in the title to the term $\sigma_M(i)$ in the equation.
- An arrow points from the word **Born** in the title to the term $\sigma_B(j)$ in the equation.
- Three overlapping dashed circles are positioned above the integrand of the sum, containing the terms $R(Y|\bar{X})$ (purple), $A(\bar{X})$ (orange), and $Q(\bar{X}|X)$ (red).
- An arrow points from the text **Limited acceptance** to the $R(Y|\bar{X})$ term.
- An arrow points from the text **Radiative effects** to the $Q(\bar{X}|X)$ term.

Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section

$$\sigma_M(i) = B(i) + \sum_j \frac{\left(\int_{\text{bin } i} dY \int d\bar{X} \int_{\text{bin } j} dX R(Y|\bar{X}) A(\bar{X}) Q(\bar{X}|X) \frac{d\sigma_B}{dX} \right) \sigma_B(j)}{\int_{\text{bin } j} dX \frac{d\sigma_B}{dX}}$$

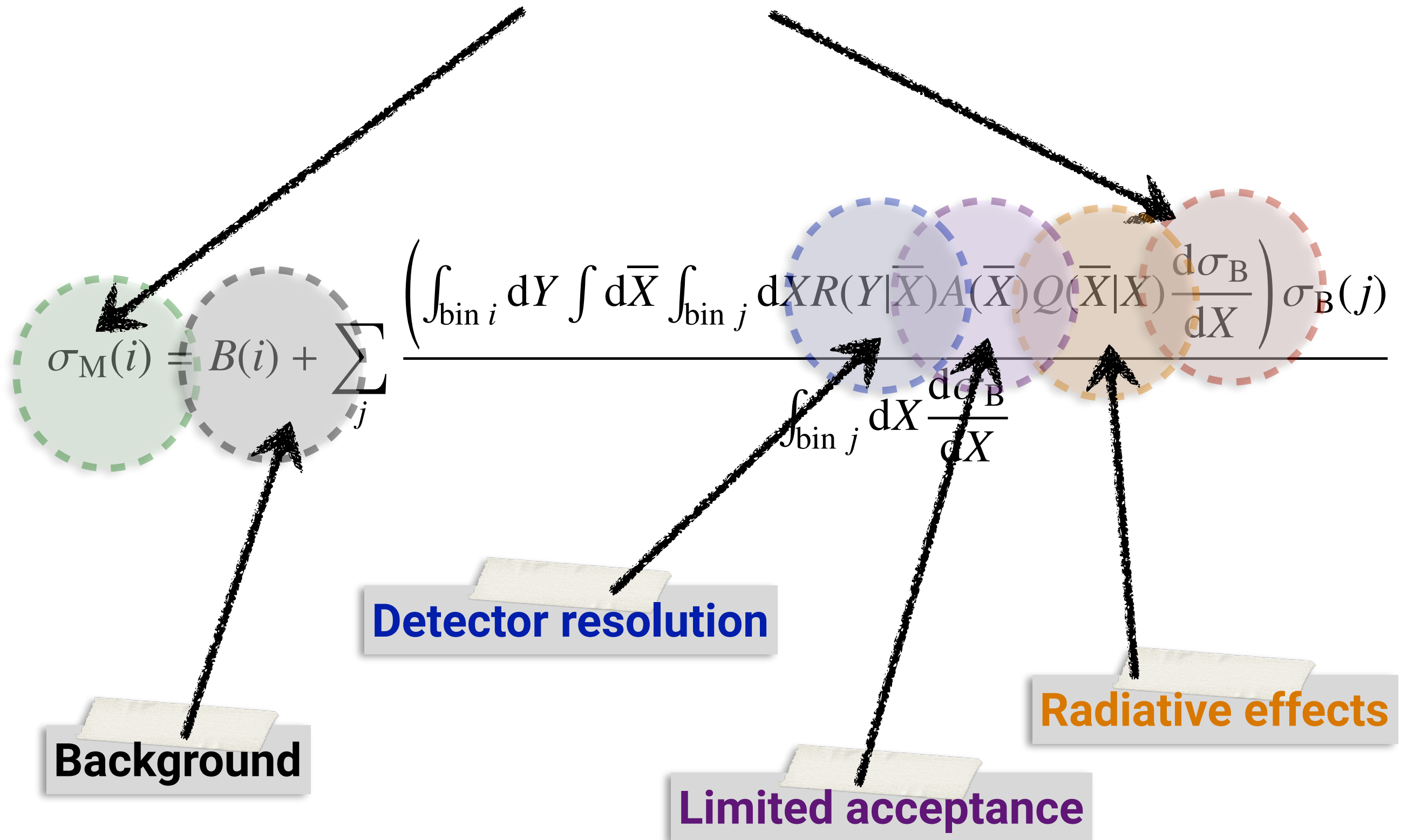
The diagram illustrates the relationship between the measured cross section $\sigma_M(i)$ and the Born cross section $\sigma_B(j)$. The equation shows that the measured cross section is the sum of the Born cross section $B(i)$ and a correction term. The correction term is a sum over bins j of the Born cross section $\sigma_B(j)$ multiplied by a factor in parentheses. This factor represents the probability of a Born event in bin j being measured in bin i , accounting for detector resolution, limited acceptance, and radiative effects. The three effects are highlighted with arrows pointing to the corresponding parts of the equation:

- Detector resolution** (blue box) points to the $R(Y|\bar{X})$ term.
- Limited acceptance** (purple box) points to the $A(\bar{X})$ term.
- Radiative effects** (orange box) points to the $Q(\bar{X}|X)$ term.

The Born cross section $\sigma_B(j)$ is also indicated by an arrow from the title. The measured cross section $\sigma_M(i)$ is indicated by an arrow from the title. The integral $\int_{\text{bin } j} dX \frac{d\sigma_B}{dX}$ is shown below the denominator of the correction term.

Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section



Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section

$$\sigma_M(i) = B(i) + \sum_j \frac{\left(\int_{\text{bin } i} dY \int d\bar{X} \int_{\text{bin } j} dX R(Y|\bar{X}) A(\bar{X}) Q(\bar{X}|X) \frac{d\sigma_B}{dX} \right) \sigma_B(j)}{\int_{\text{bin } j} dX \frac{d\sigma_B}{dX}}$$
$$= \sum_j S(i, j) \sigma_B(j) + B(i)$$

Radiative effects

Limited acceptance

Detector resolution

Background

Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section

$$\sigma_M(i) = B(i) + \sum_j \frac{\left(\int_{\text{bin } i} dY \int d\bar{X} \int_{\text{bin } j} dX R(Y|\bar{X}) A(\bar{X}) Q(\bar{X}|X) \frac{d\sigma_B}{dX} \right) \sigma_B(j)}{\int_{\text{bin } j} dX \frac{d\sigma_B}{dX}}$$

$$= \sum_j S(i, j) \sigma_B(j) + B(i)$$

SMEARING MATRIX

Radiative effects

Limited acceptance

Detector resolution

Background

Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section

$$\sigma_{\text{M}}(i) = \sum_j S(i, j) \sigma_{\text{B}}(j) + B(i)$$

SMEARING MATRIX

Radiative effects

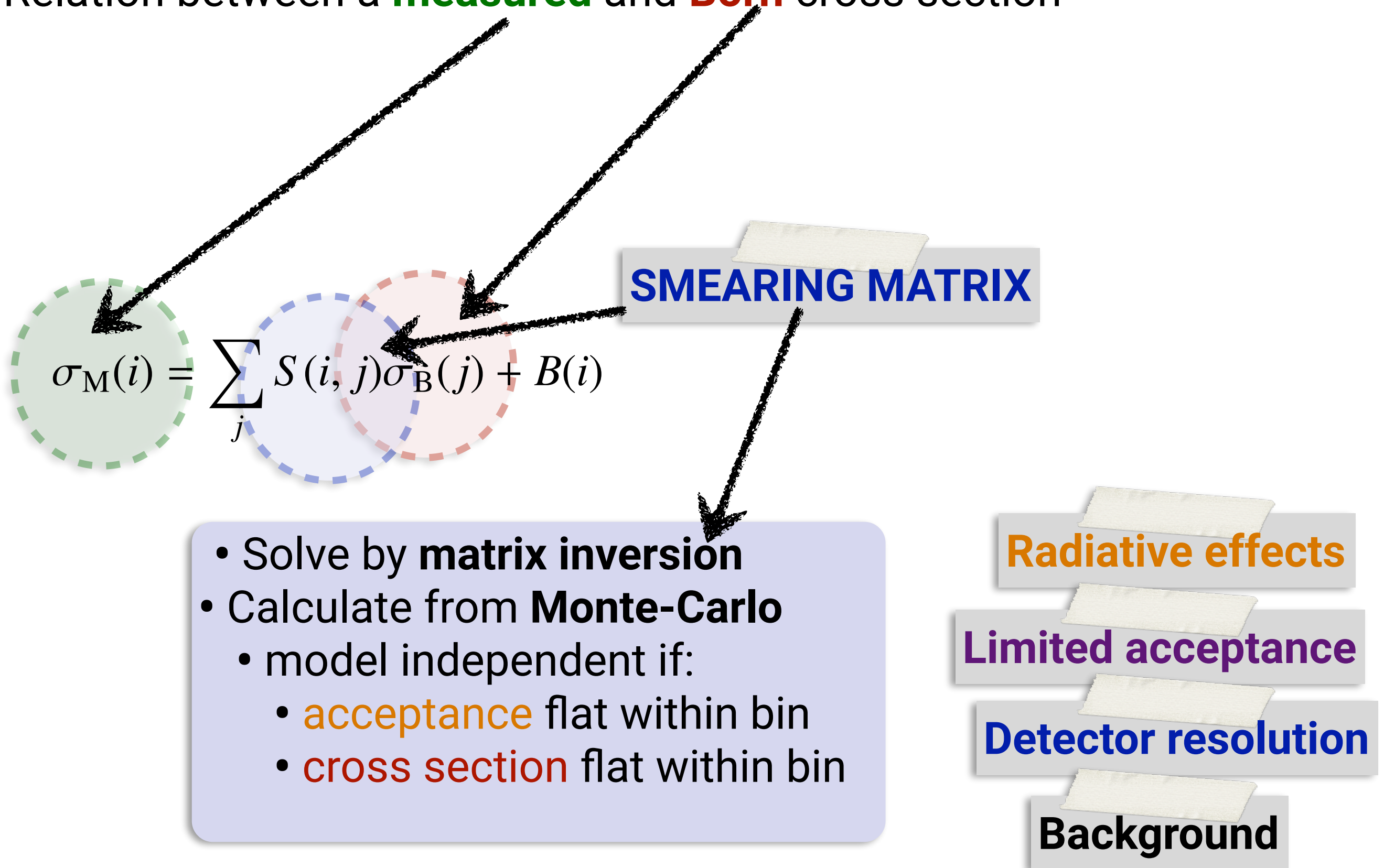
Limited acceptance

Detector resolution

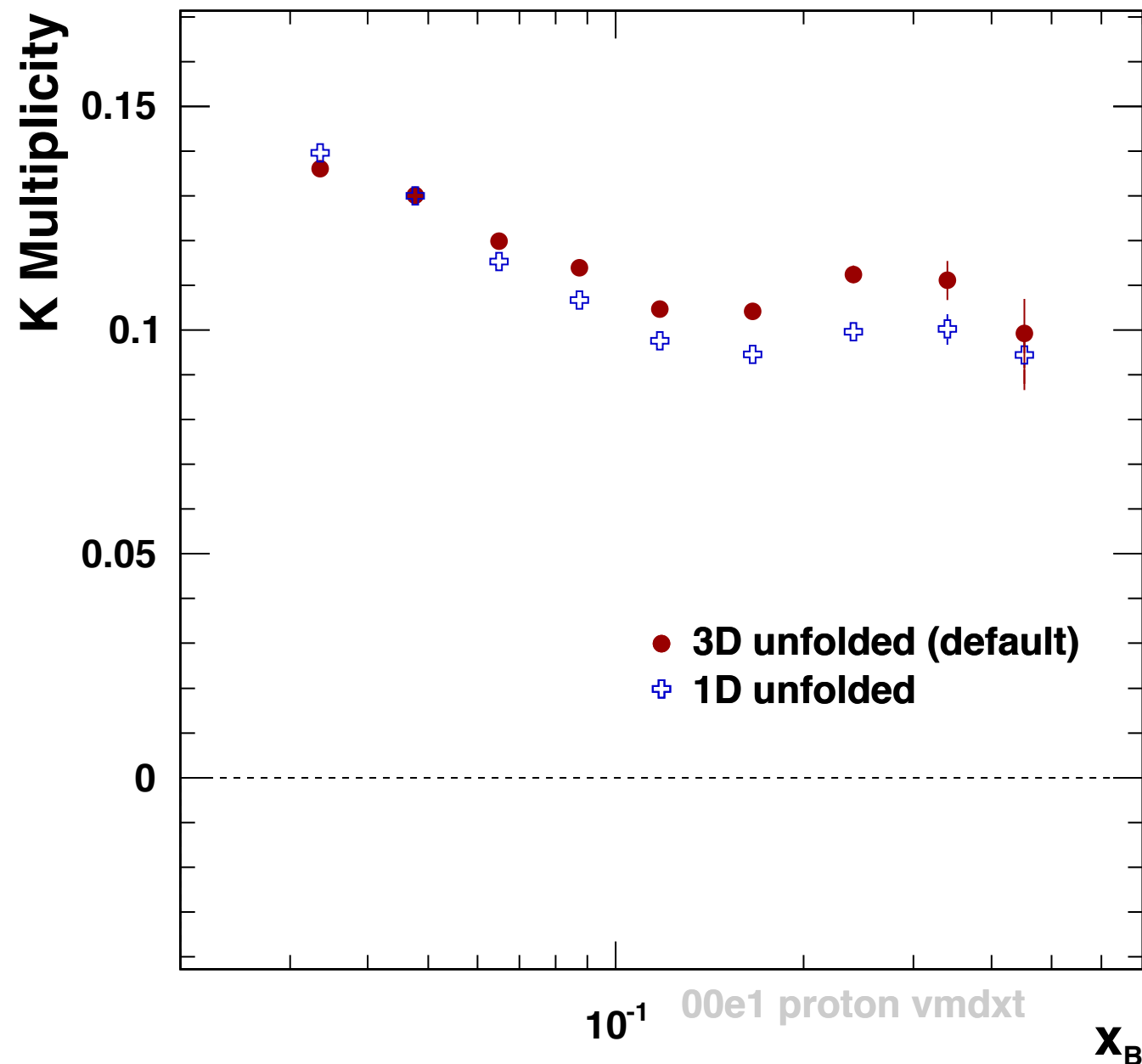
Background

Smearing-unfolding in SIDIS

Relation between a **measured** and **Born** cross section

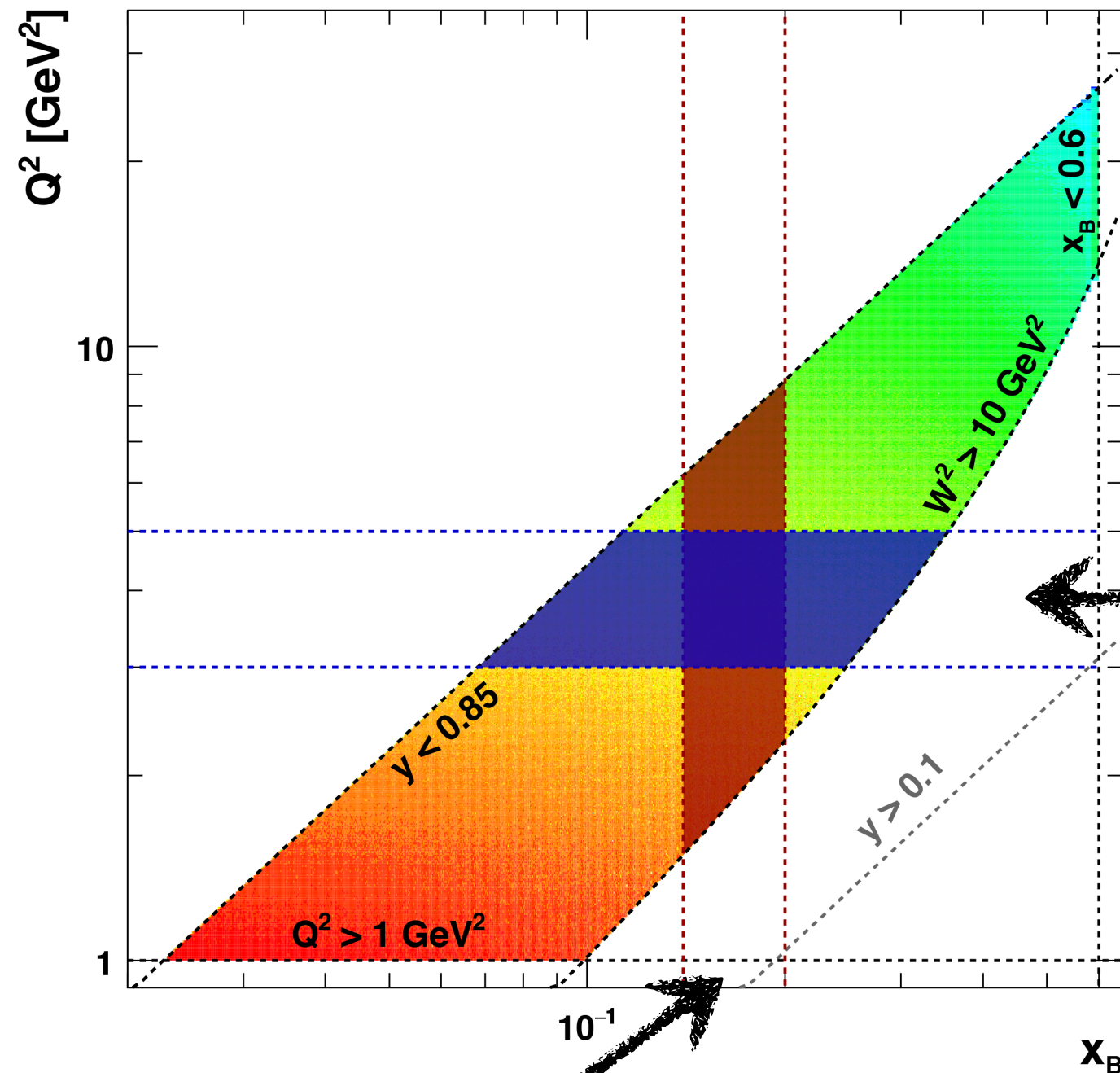


Importance of a **multidimensional approach**



- Neglecting to unfold in z **changes the x dependence dramatically**
- cf: Phys.Lett. B666 (2008) 446-450, Phys.Rev. D89 (2014) no.9, 097101

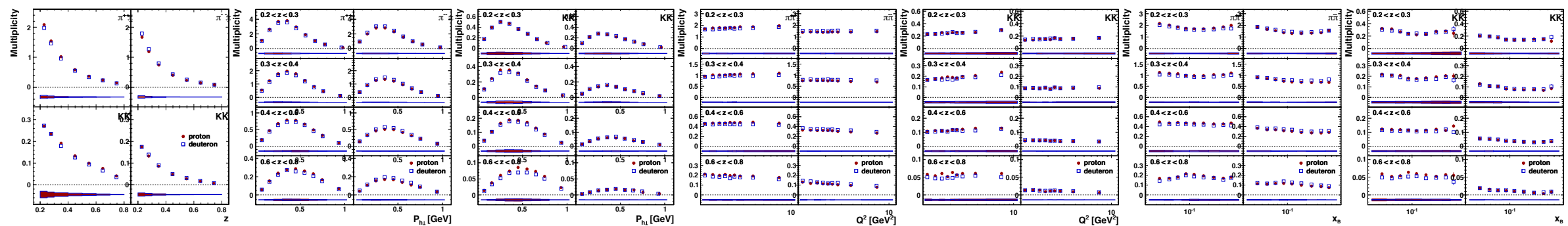
Integrated (not average)



$$M_H^h(x, z, P_{h\perp}) \equiv \frac{\int dQ^2 d\phi_h n^{\text{SIDIS}}(\dots)}{\int dQ^2 n^{\text{incl}}(\dots)}$$

$$M_H^h(Q^2, z, P_{h\perp}) \equiv \frac{\int dx d\phi_h n^{\text{SIDIS}}(\dots)}{\int dx n^{\text{incl}}(\dots)}$$

the multiplicity **website**



A. Airapetian et al, Phys. Rev. D 87 (2013) 074029

<http://www-hermes.desy.de/multiplicities>

A screenshot of a web browser showing the 'HERMES Multiplicity Download' page. The browser's address bar shows 'http://hermes.phys.uni-heidelberg.de/'. The page has a dark header with 'About' and 'Contact' links. The main content area has a light gray background. On the left, there is a logo for 'hermes' in red lowercase letters, with a blue circle around the 'e' and stylized blue and green lines above it. To the right of the logo, there is a large heading 'Multiplicity Download' in dark gray. Below the heading, there is a paragraph of text: 'The HERMES multiplicities of charged particles from semi-inclusive DIS on the proton represent a unique high-precision multiplicity set that will significantly enhance our understanding of the fragmentation of quarks into final-state particles.' Below this paragraph, there is another paragraph: 'The full data set consists of a large amount of data due to the multitude of binnings and parameters. Find your way using the filters below to locate the files you are looking for.' At the bottom of the page, there is a dark gray footer with the text 'This is a placeholder for the full Journal reference.' and four buttons: 'Browse Data »', 'Read Publication »', 'Preprint »', and 'Download All Data »'.

(1/3) Multiplicities vs z

The figure displays four plots showing multiplicities versus z for different particles: π^+ , π^- , K^+ , and K^- . The x-axis represents z (ranging from 0.2 to 0.8), and the y-axis represents Multiplicity (ranging from 0 to 2). The legend indicates that red circles represent protons and blue squares represent deuterons. The plots show that multiplicities generally decrease as z increases. The π^+ and π^- plots show higher multiplicities (up to 2) compared to the K^+ and K^- plots (up to 0.3). The deuteron multiplicities (blue squares) are consistently higher than the proton multiplicities (red circles) for all particles shown.

Filter All Target: All Option: All Binning: All Projection: All Extra: All

1-10 11-20 20-30 31-40 41-50 51-58

#	What	Binning	Projection
1	Multiplicities	Proton	VM Subtracted

x: 2 / z: 10 / Ph.L: 5

Download the final results

h.L: 5 Download

h.L: 5

h.L: 5 z View Plot »

h.L: 5 z View Plot »

L: 9

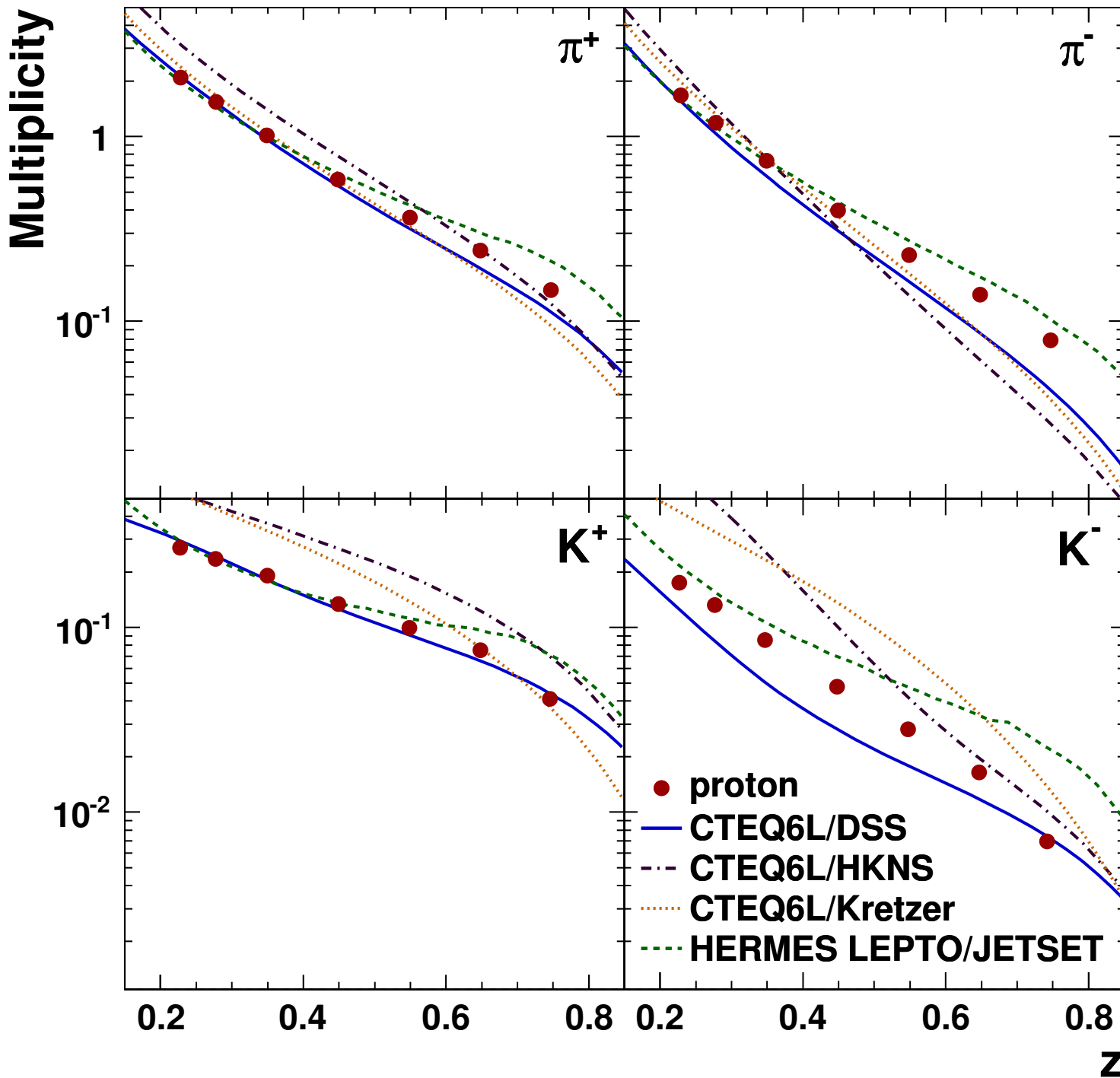
π^+
 π^-
 K^+
 K^-
 Covariance Matrix

Download the final results

1D comparison with LO predictions

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

- **DSS/HKNS/Kretzer: FFs**
- **CTEQ6L: PDFs**



CTEQ6L/DSS: π^+ and K^+ well described, larger deviations for π^- and K^-

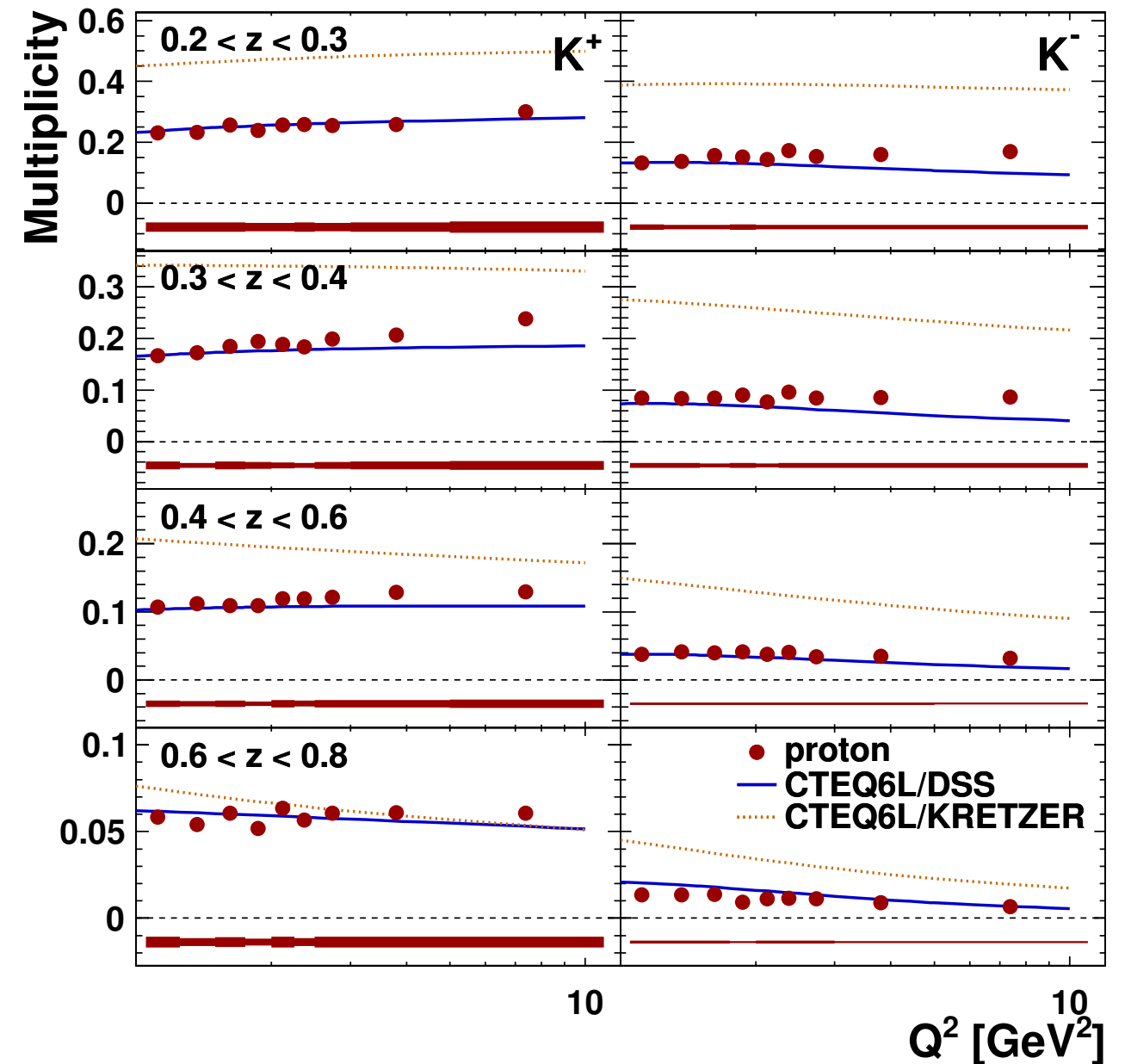
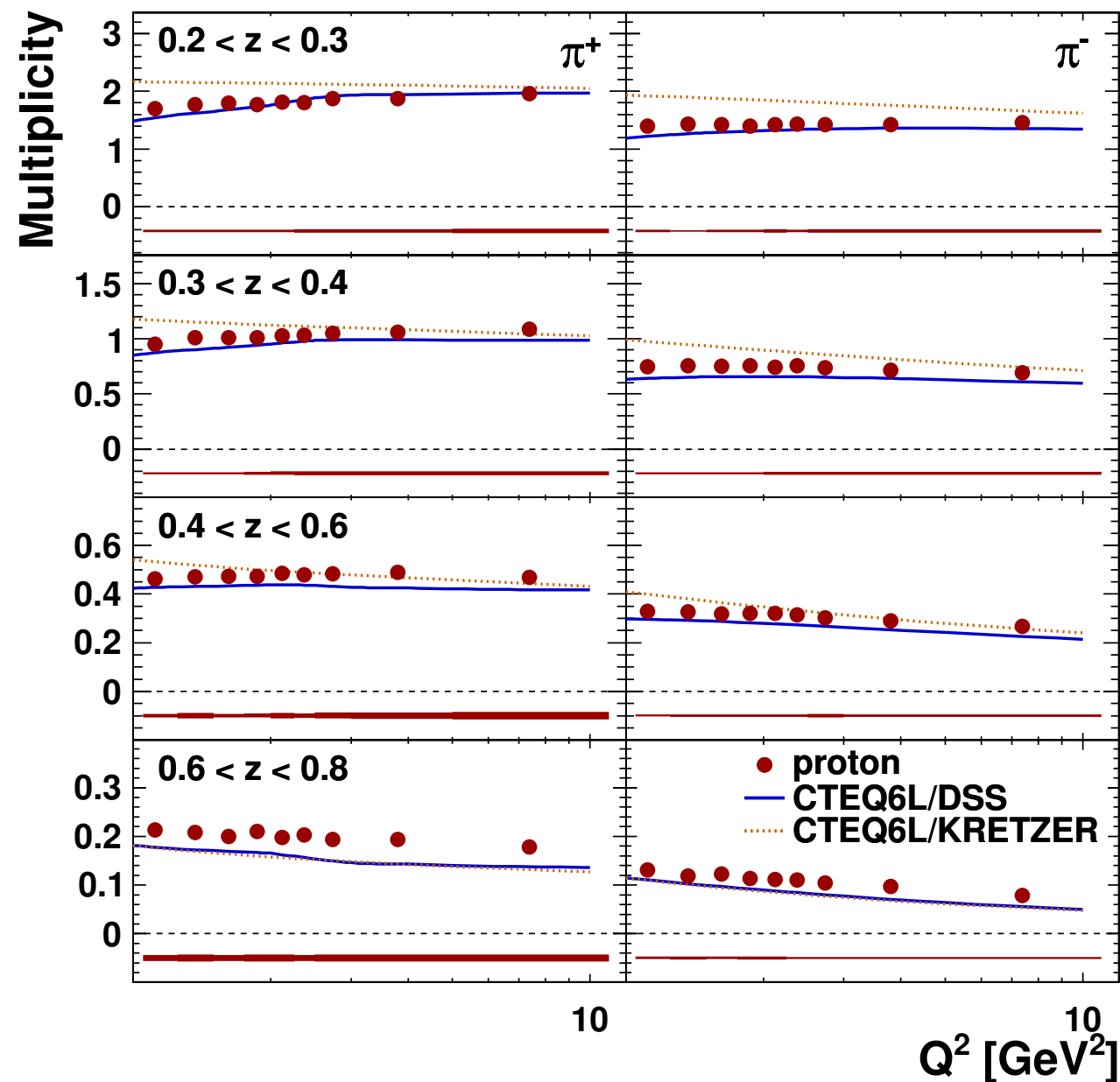
CTEQ6L/Kretzer, HKNS: perform reasonable well for pions

Improvement in the disfavored sector!

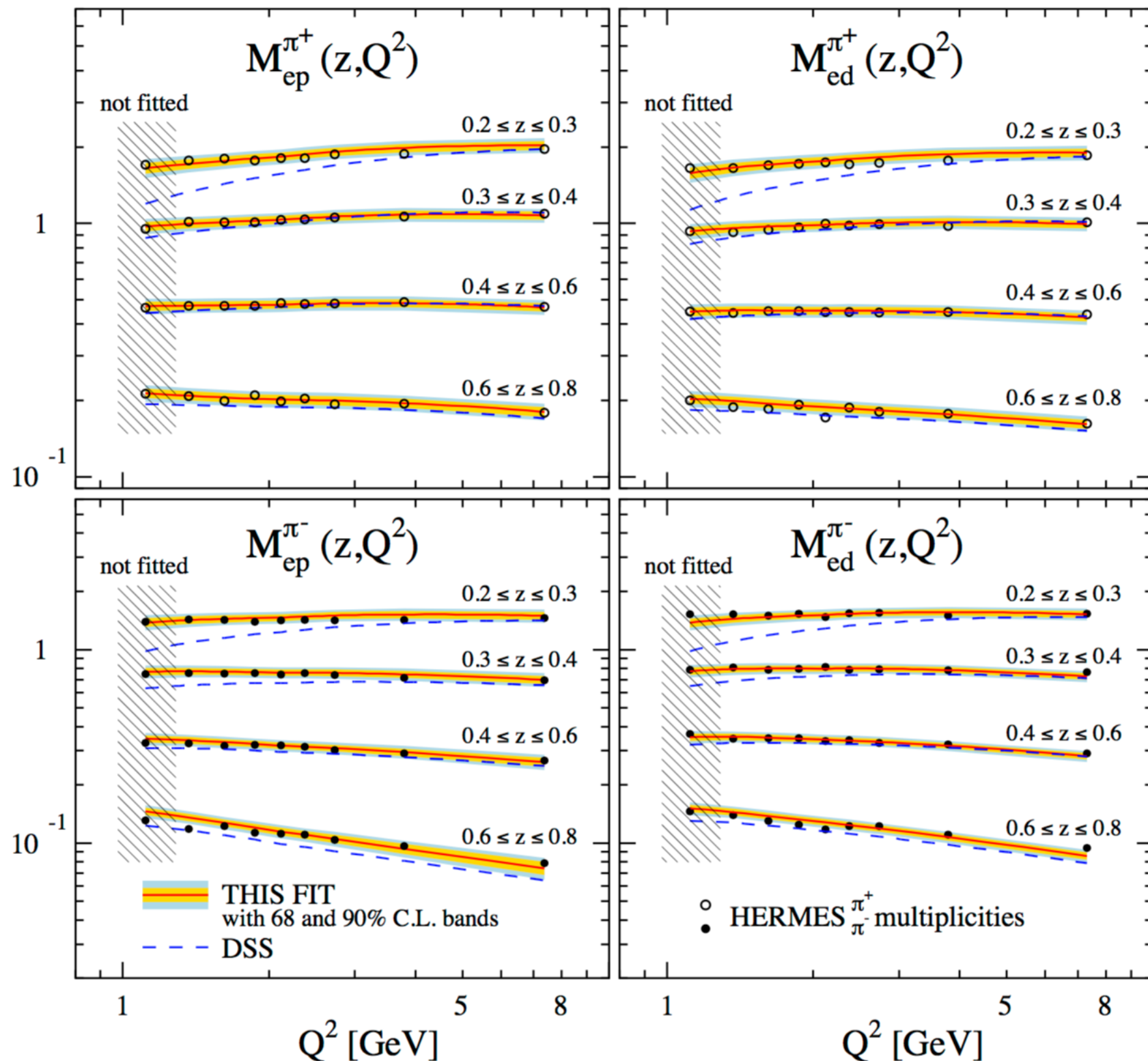
FFs before these data

CTEQ6L/DSS: perform well
up to medium z

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



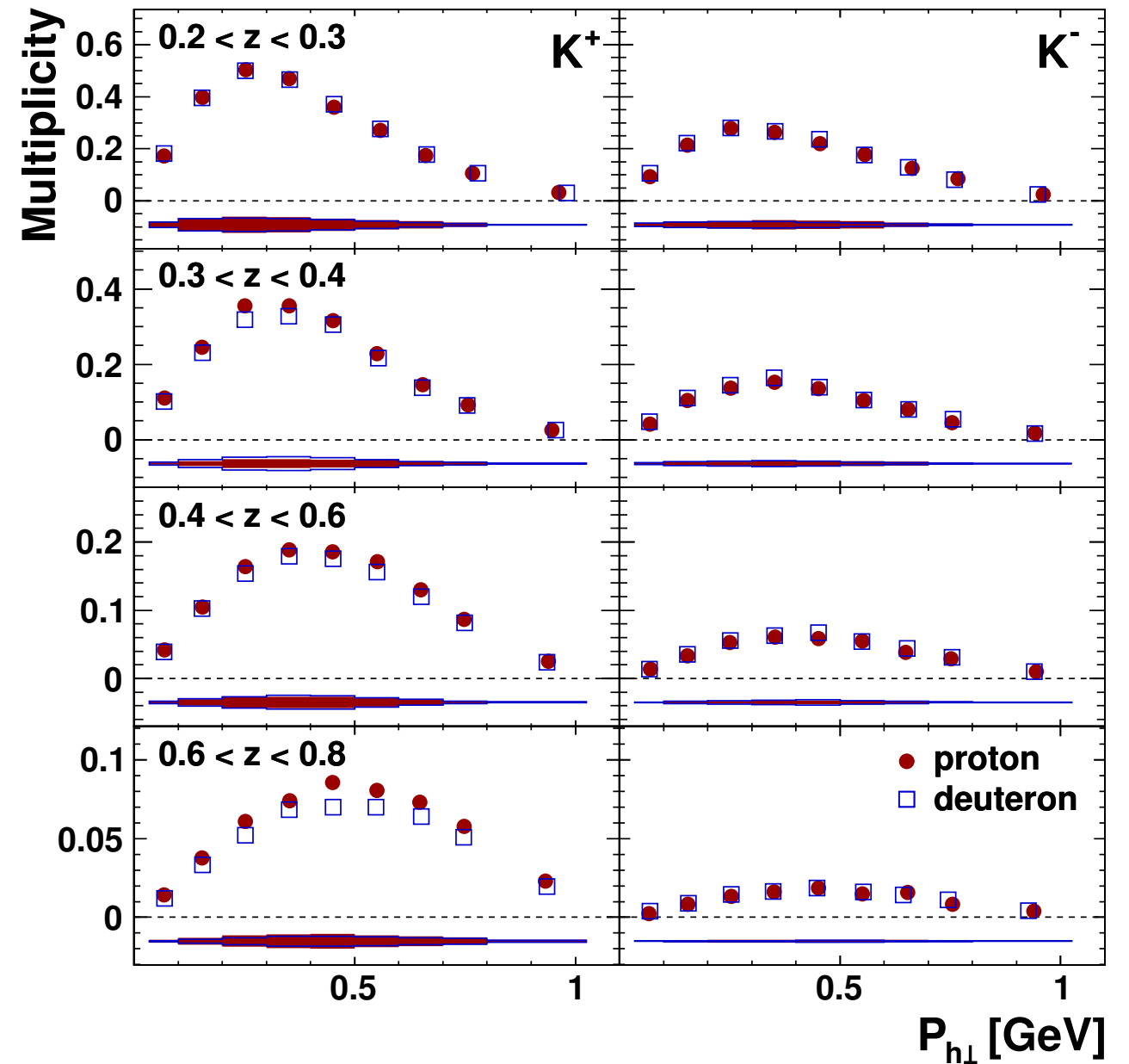
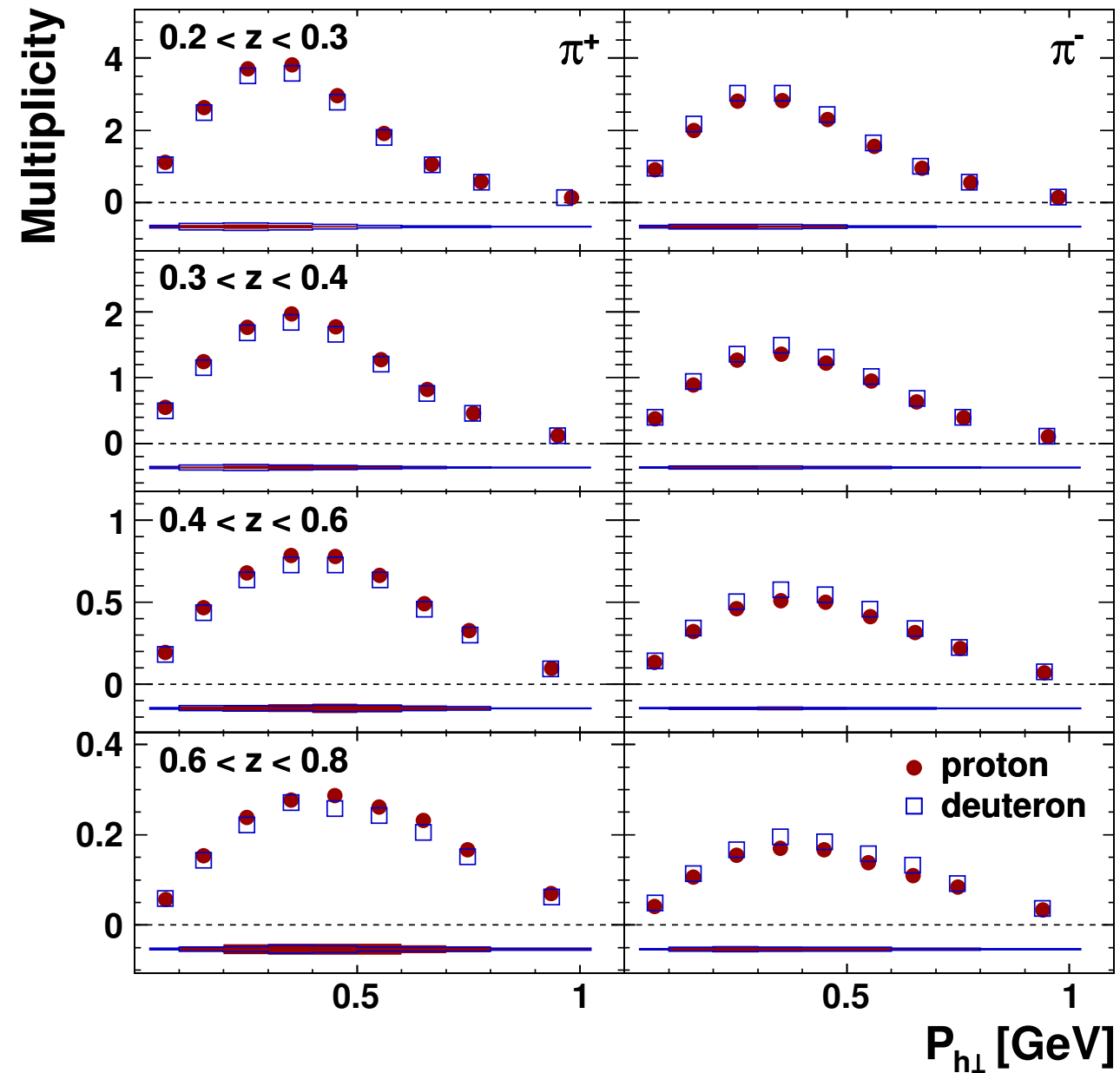
Next Generation of FFs



“DSS+” global extraction: very good fit to **both** HERMES and COMPASS pion multiplicities

Kaon multiplicities were harder to control (upcoming!)

The shape of $P_{h\perp}$ in z -slices

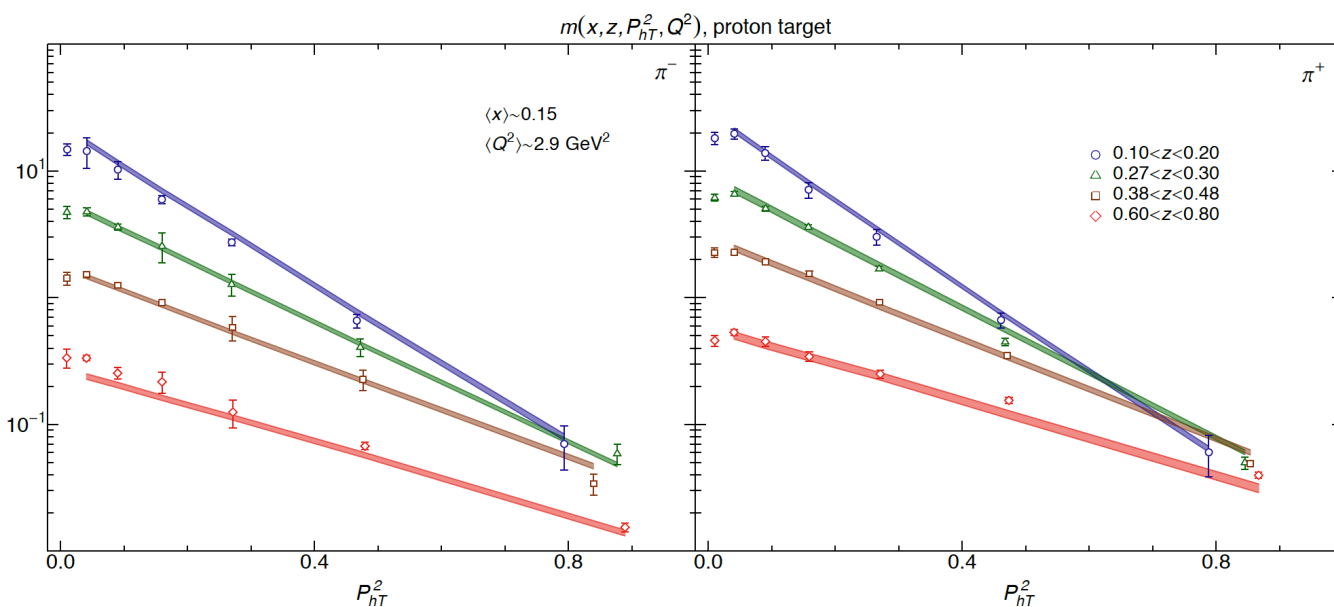


Superficially consistent with
Gaussian ansatz

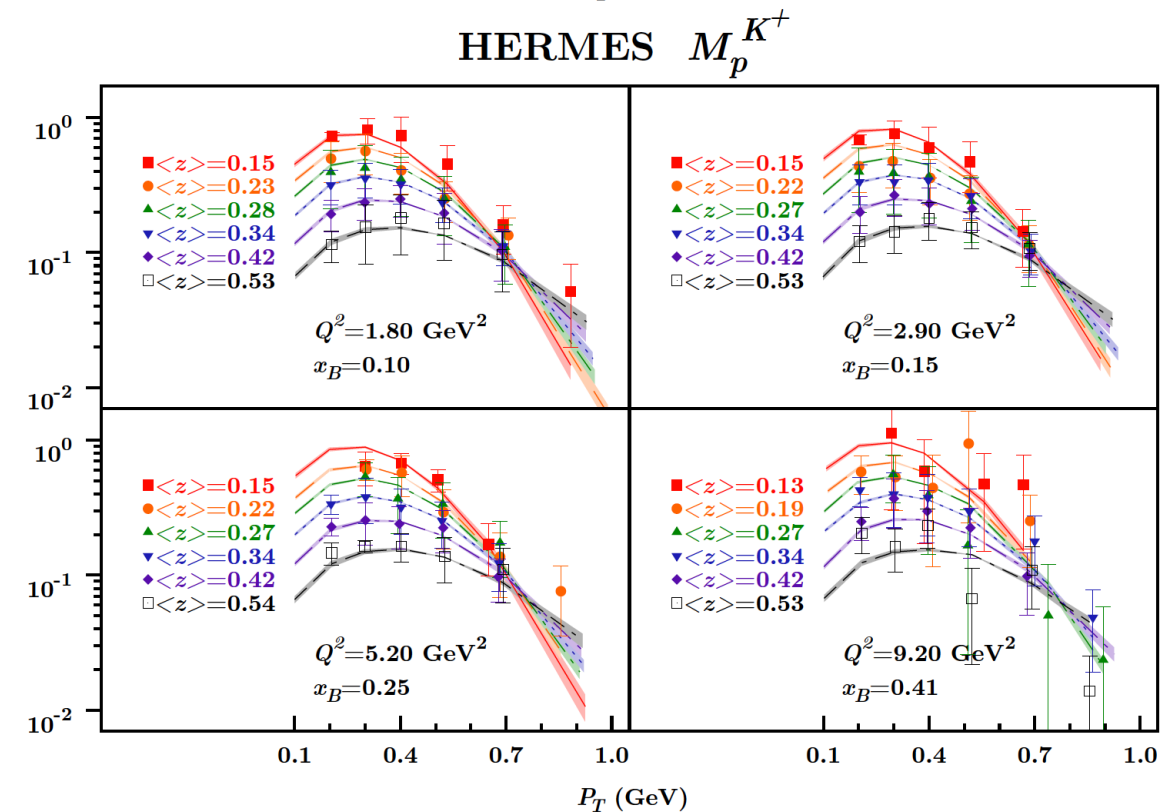
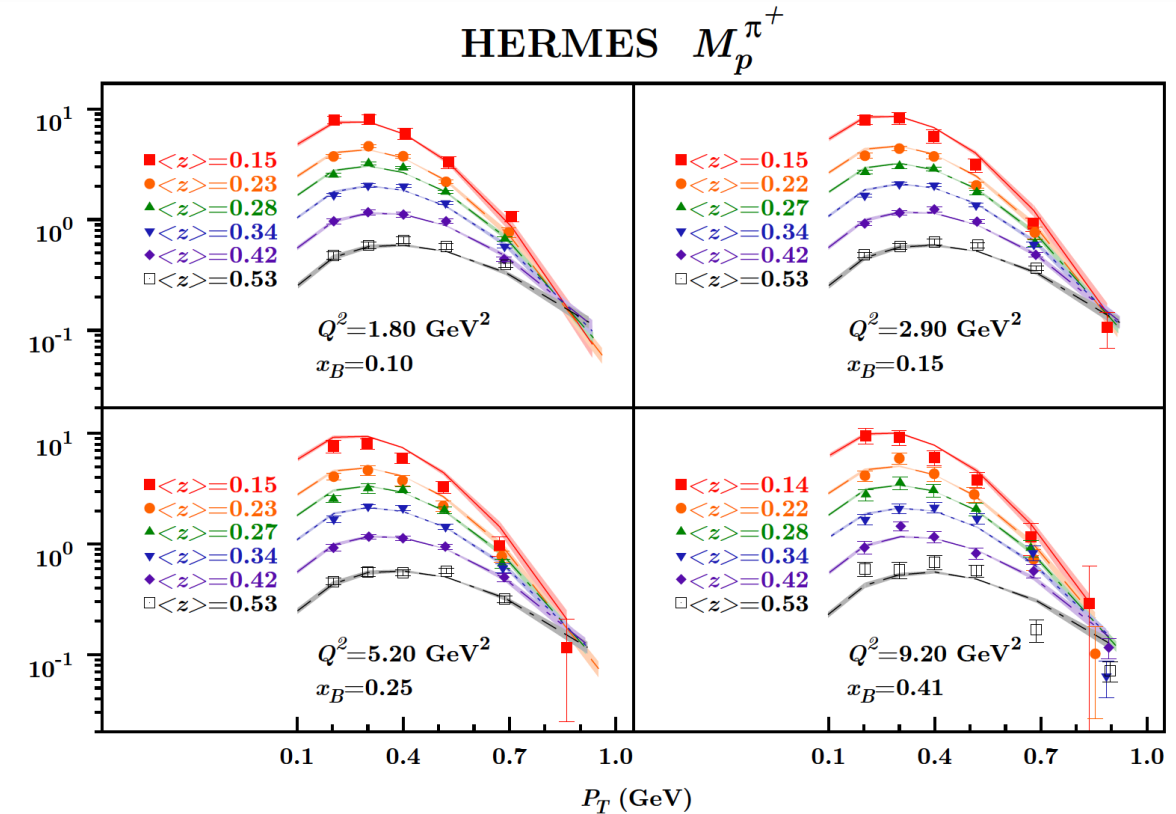
Recent TMD fits

Gaussian Ansatz works!

Evidence for flavor dependence of the TMD FFs



A. Signori *et al.*, JHEP 1311 (2013) 194



M. Anselmino *et al.*, JHEP 1404 (2014) 005

Limits of Factorization and Precocious Scaling

Limits of factorization: from QCD

Factorization is derived in the
scaling limit of **large Q^2** for fixed x

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Limits of factorization: from QCD

Factorization is derived in the
scaling limit of **large Q^2** for fixed x



Complications when Q not $\gg M$

- Mass effects
- Power corrections in M/Q (higher-twist)
- Higher-order terms in α_s
- ...

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Limits of factorization: from QCD

Factorization is derived in the
scaling limit of **large Q^2** for fixed x

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



Complications when Q not $\gg M$

- Mass effects
- Power corrections in M/Q (higher-twist)
- Higher-order terms in α_s
- ...

Only break factorization if not
properly accounted for

Limits of factorization: from QCD

Factorization is derived in the **scaling limit** of **large Q^2** for fixed x



Complications when Q not $\gg M$

- Mass effects
- Power corrections in M/Q (higher-twist)
- Higher-order terms in α_s
- ...

Only break factorization if not properly accounted for

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

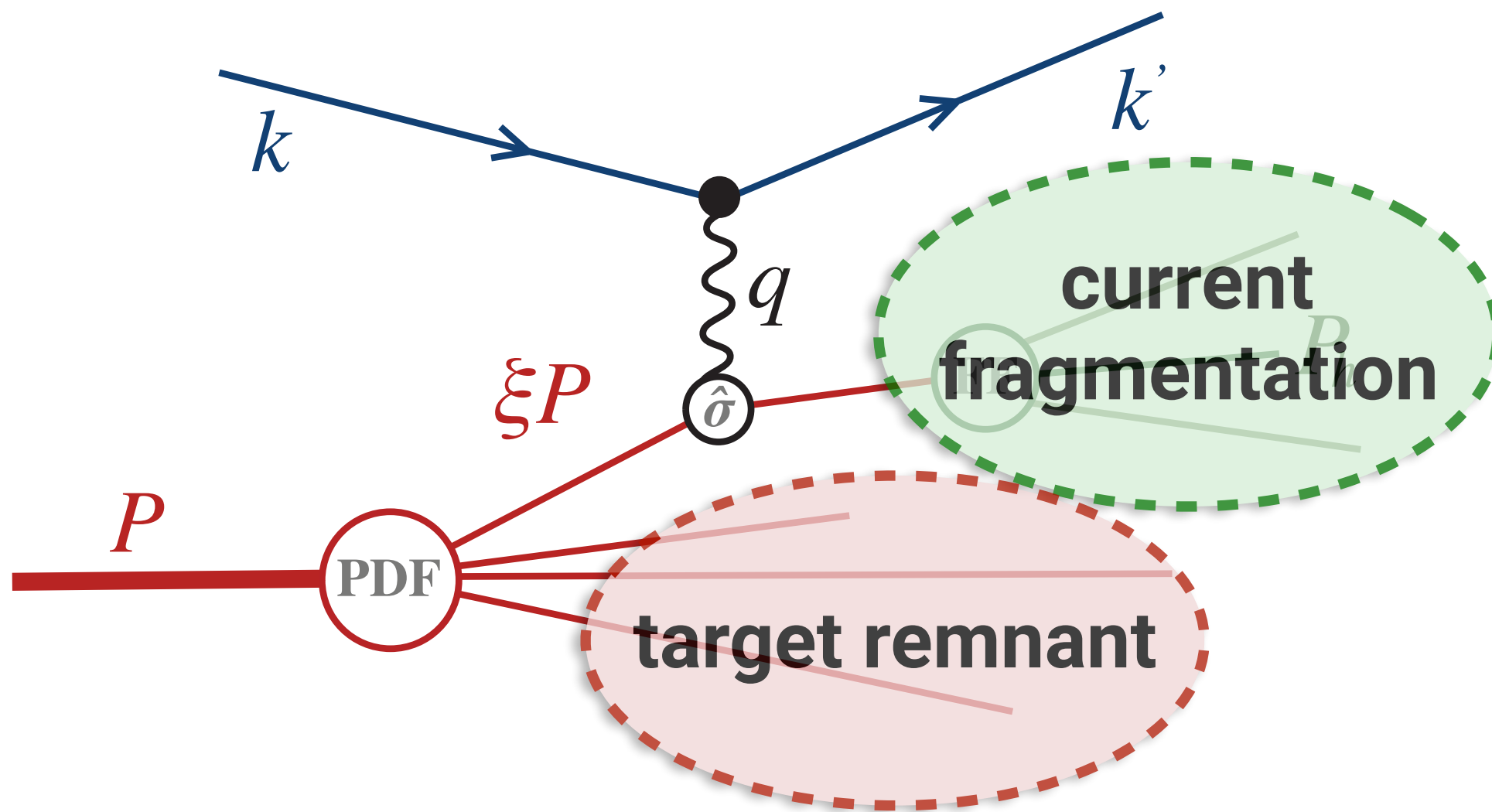


Simple probabilistic interpretation impossible

Limits on factorization: target remnant

The **fragmentation function** D_q^h depends on the **struck quark** q only

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

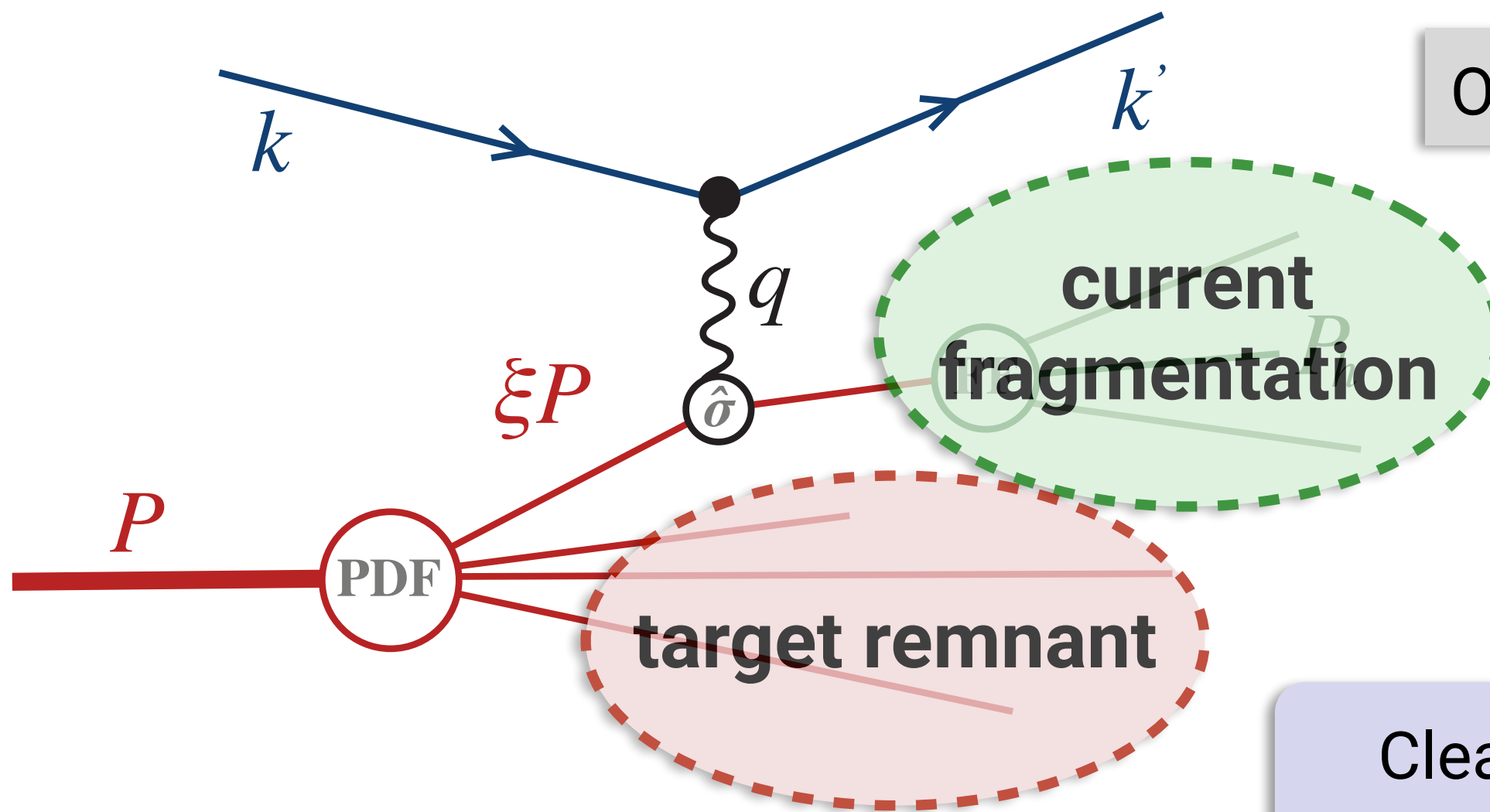


Limits on factorization: target remnant

The **fragmentation function** D_q^h depends on the **struck quark** q only

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Only a function of z

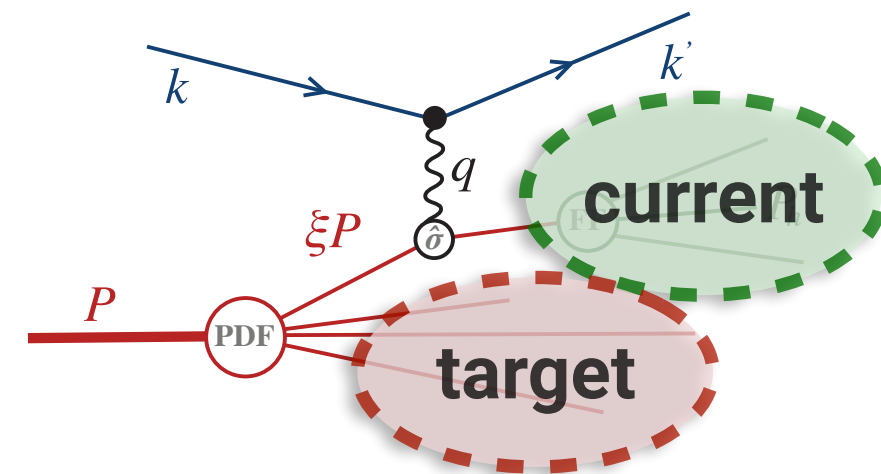


Clear **experimental** separation of **current** and **target** “jets” required

Limits on factorization: target remnant

Clear **experimental separation** of **current** and **target** “jets” required

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



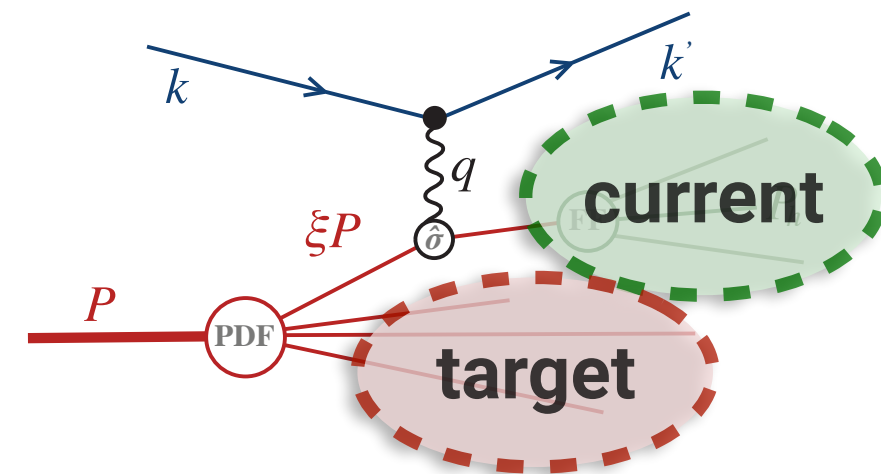
Limits on factorization: target remnant

Clear **experimental separation** of **current** and **target** “jets” required

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Compare **forward** to **backward** hemisphere:
study the **center-of-mass rapidity**

$$\eta_{\text{CM}} = \frac{1}{2} \ln \left. \frac{E_h + P_{h\parallel}}{E_h - P_{h\parallel}} \right|_{\text{CM}}$$

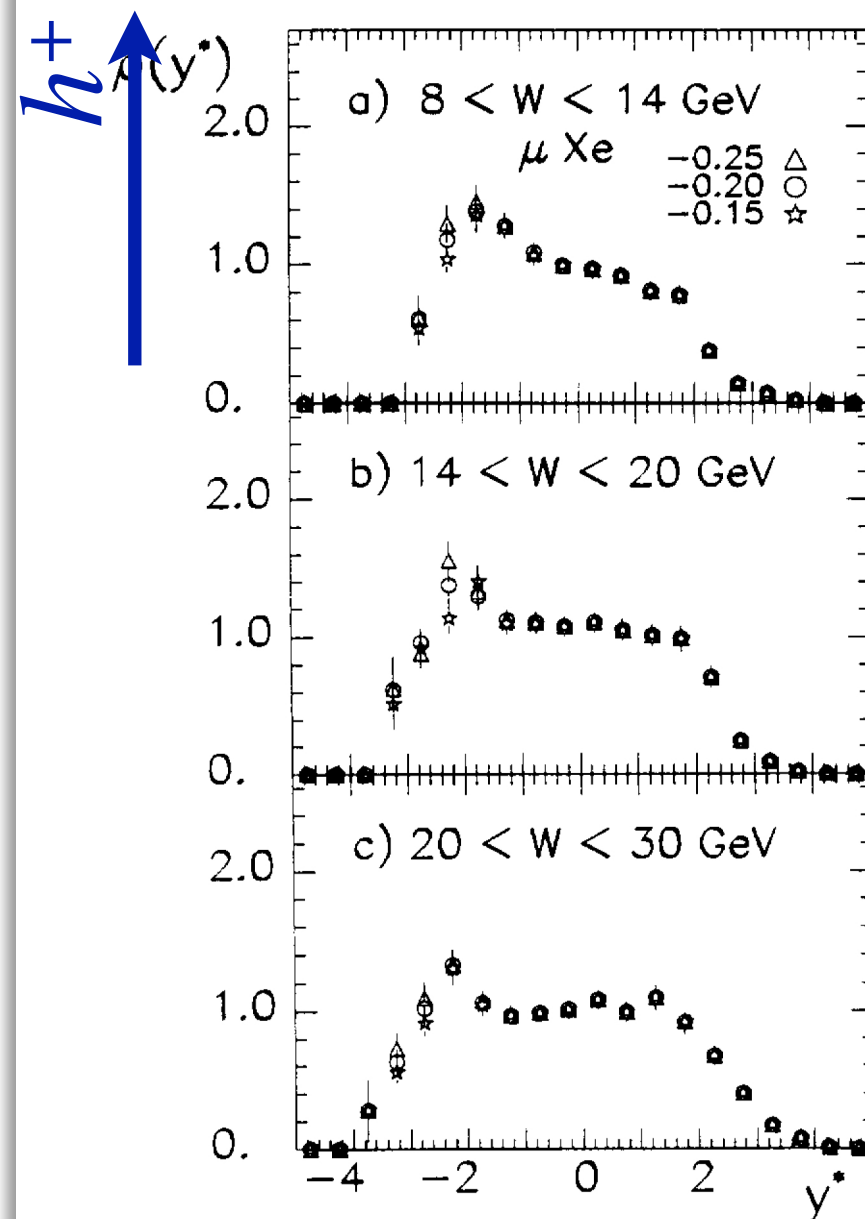


Limits on factorization: target remnant

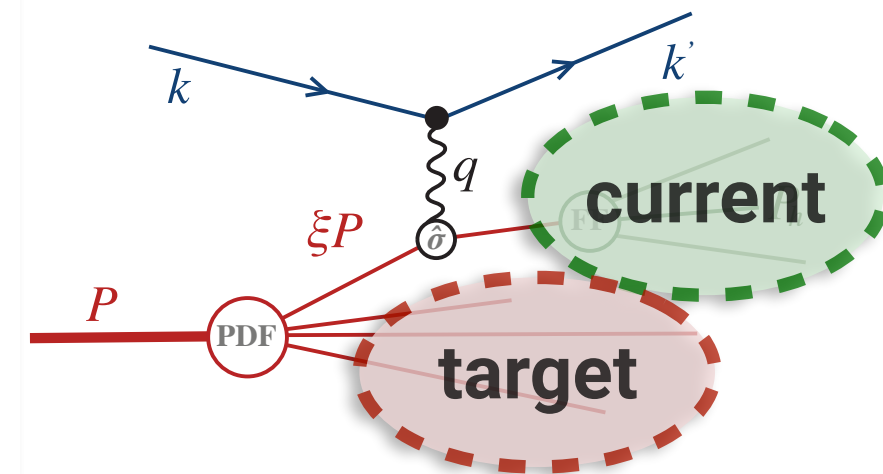
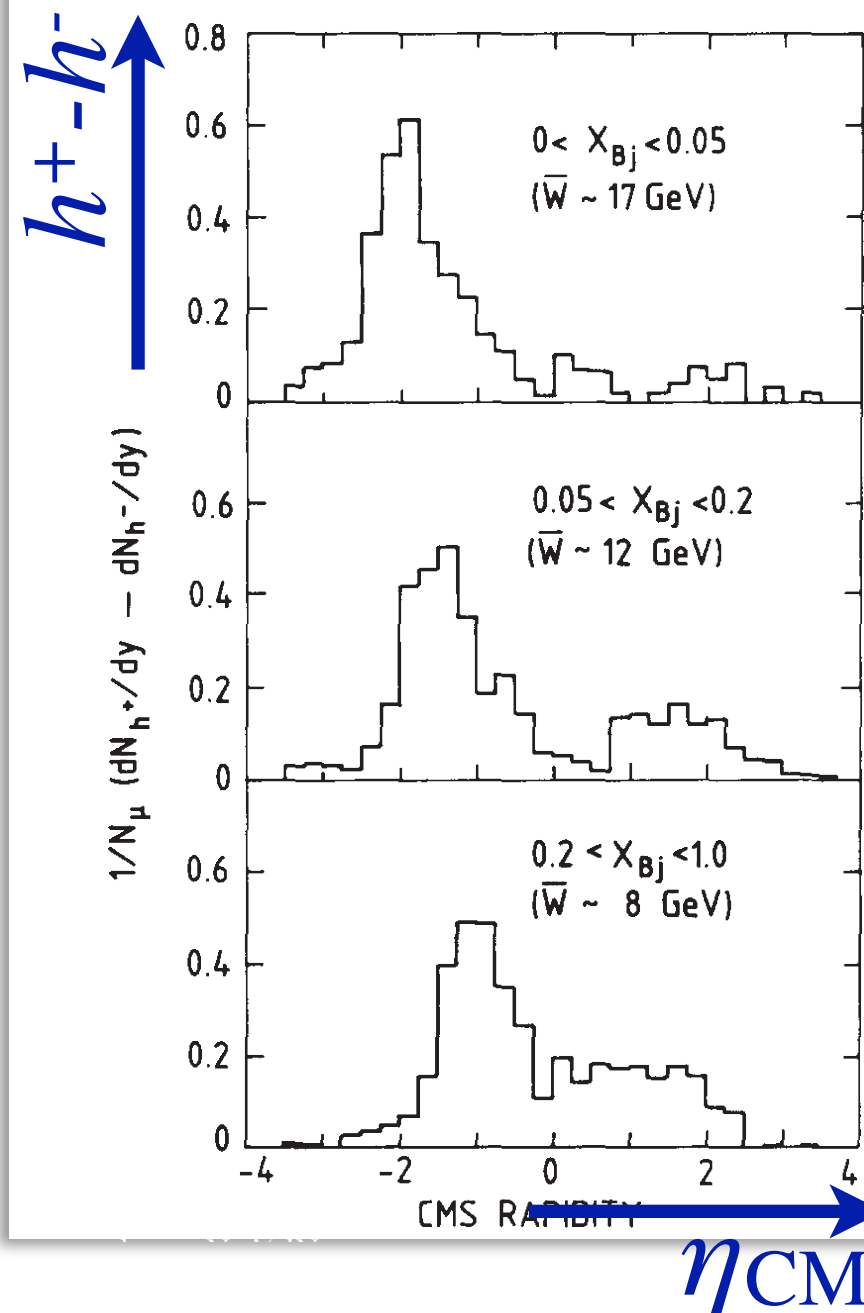
Clear **experimental separation** of **current** and **target** “jets” required

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

E665, ZPC (1993)



EMC, PR162 (1988)

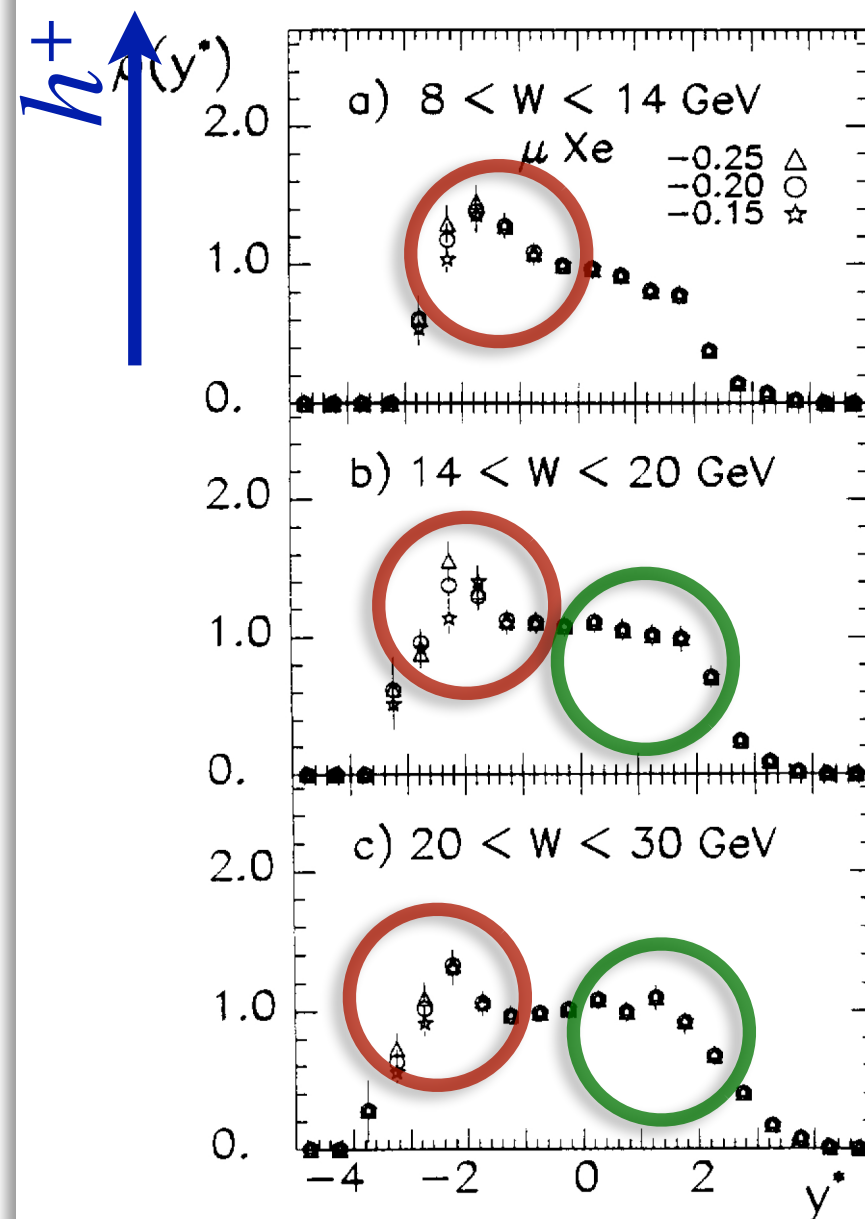


Limits on factorization: target remnant

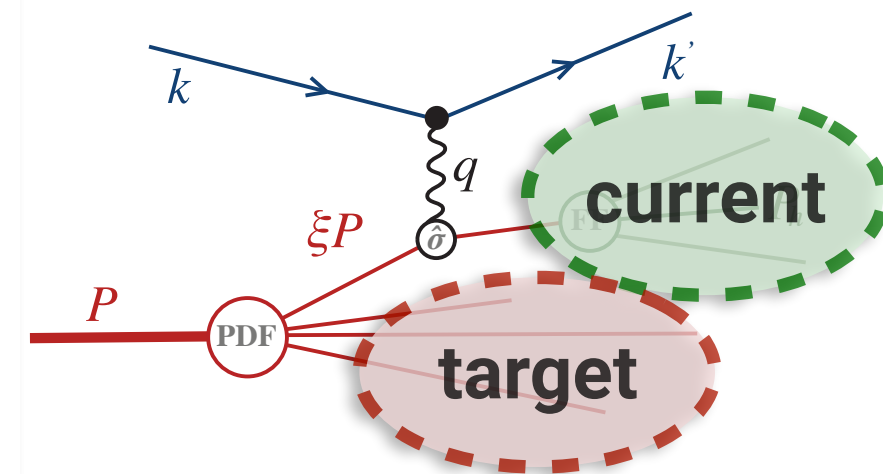
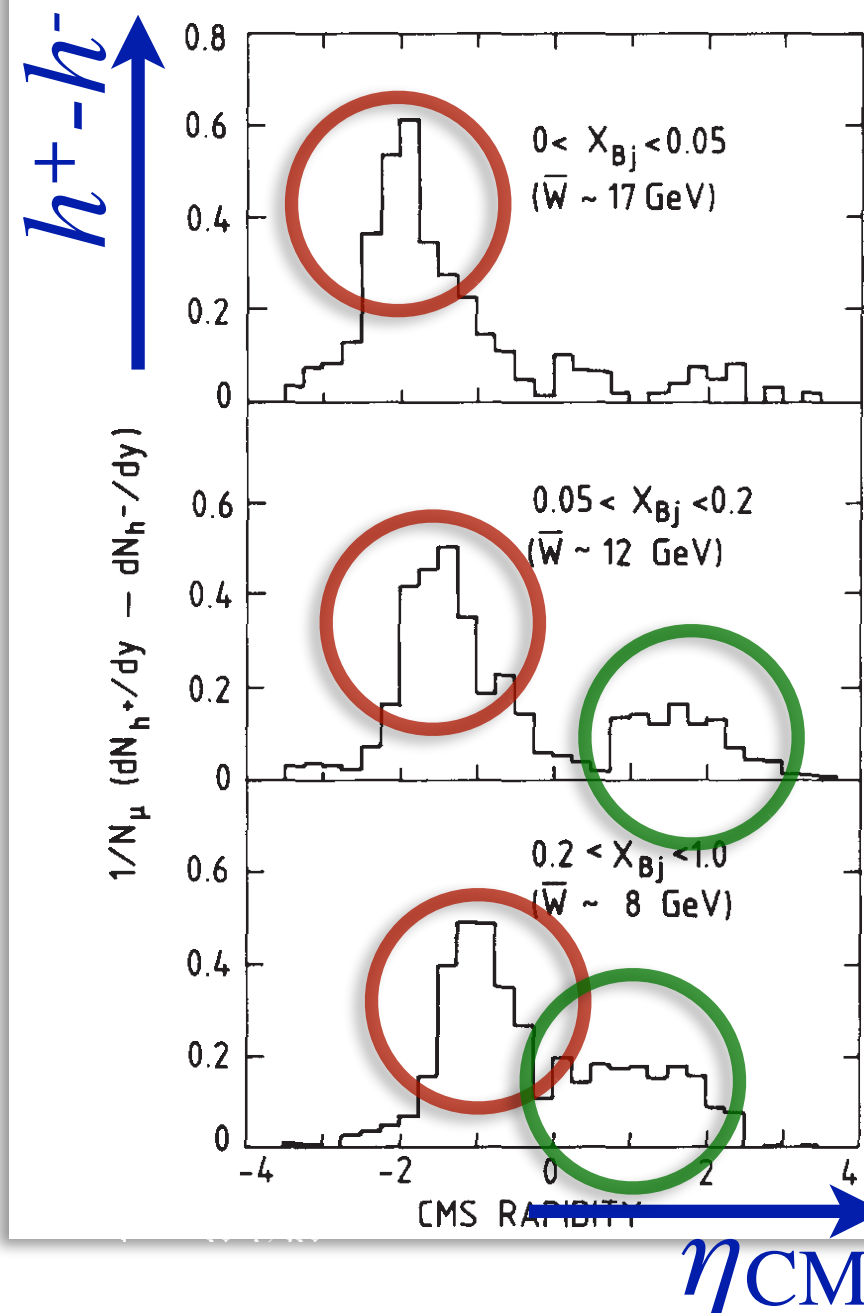
Clear **experimental separation** of **current** and **target** “jets” required

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

E665, ZPC (1993)



EMC, PR162 (1988)

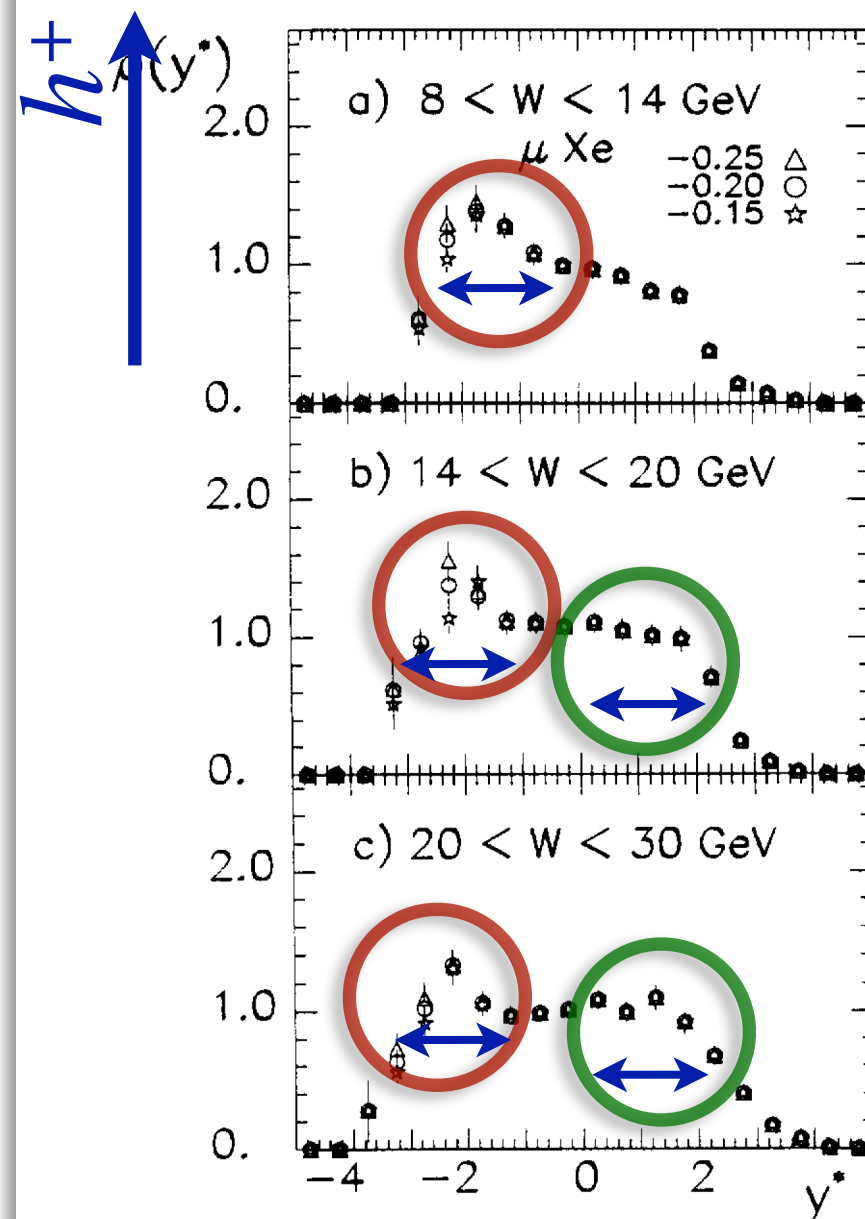


Limits on factorization: target remnant

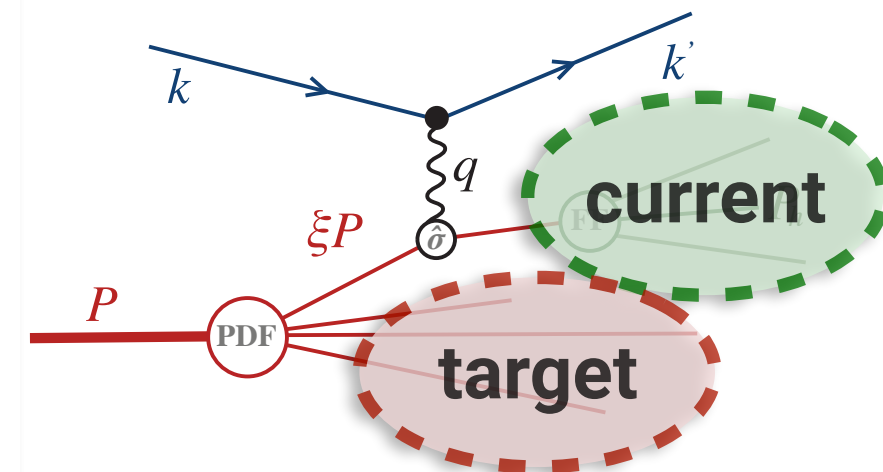
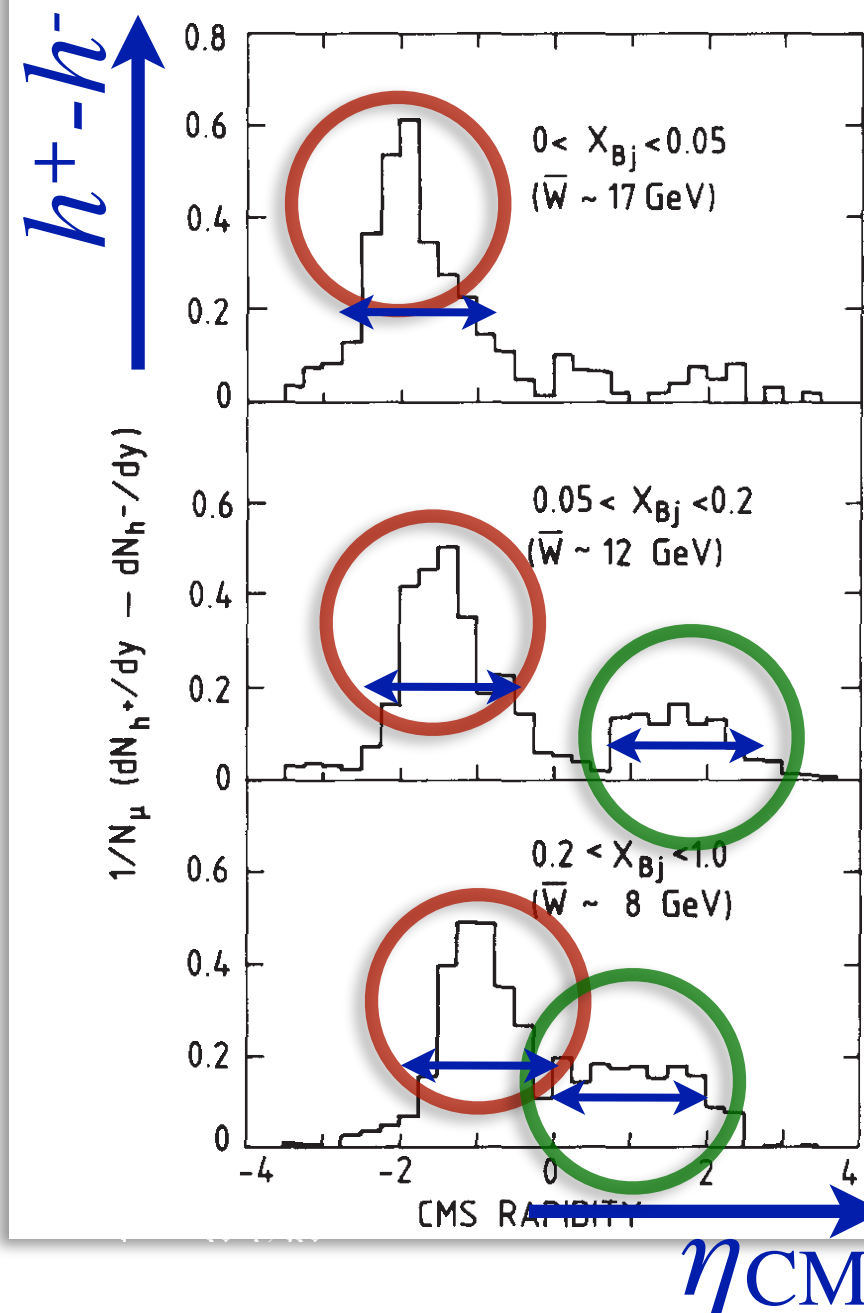
Clear **experimental separation** of **current** and **target** “jets” required

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

E665, ZPC (1993)



EMC, PR162 (1988)



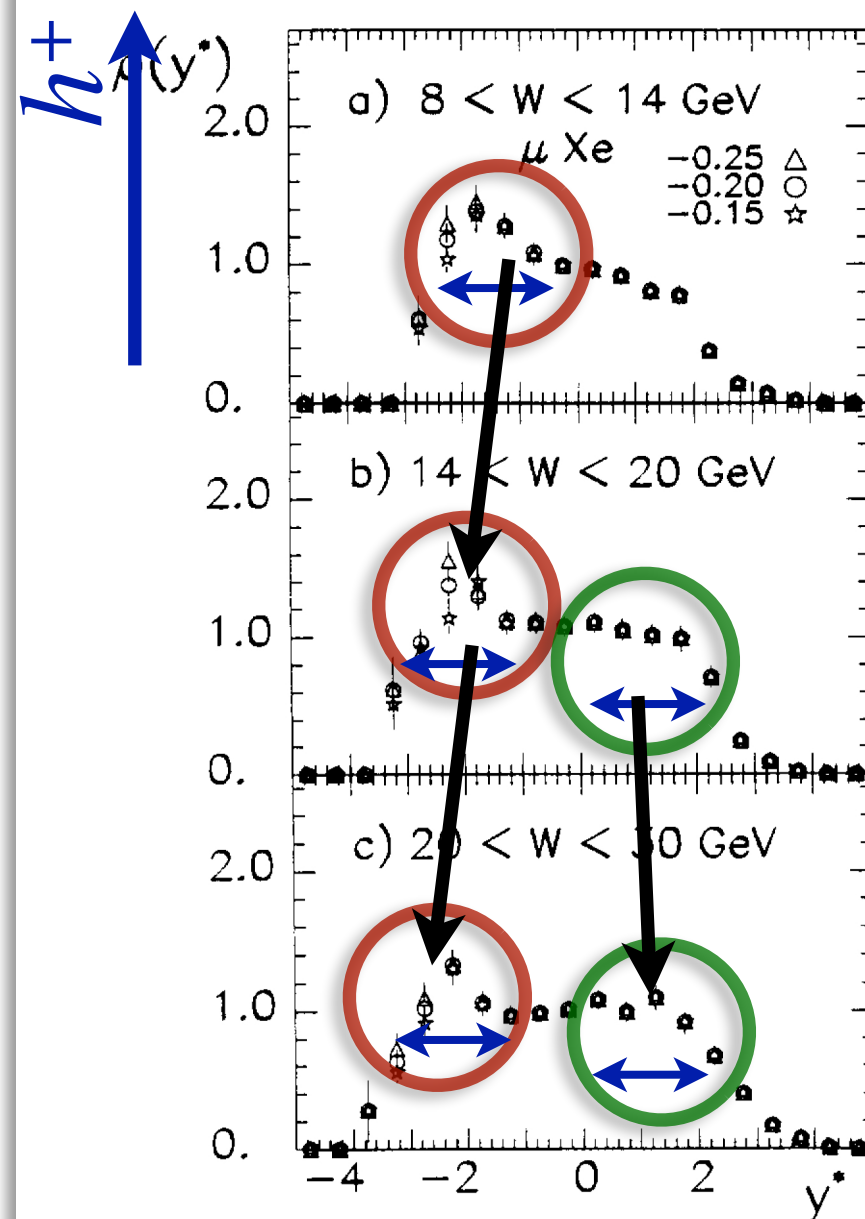
Jet FWHM: $\Delta\eta_{CM} \approx 2$

Limits on factorization: target remnant

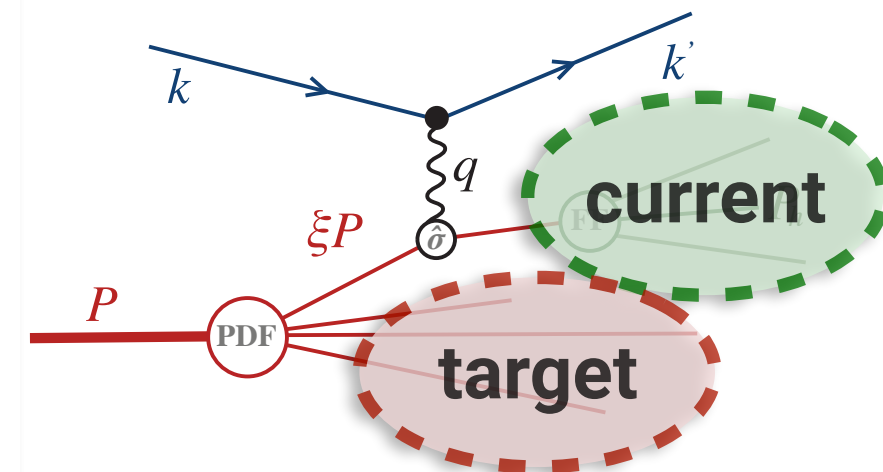
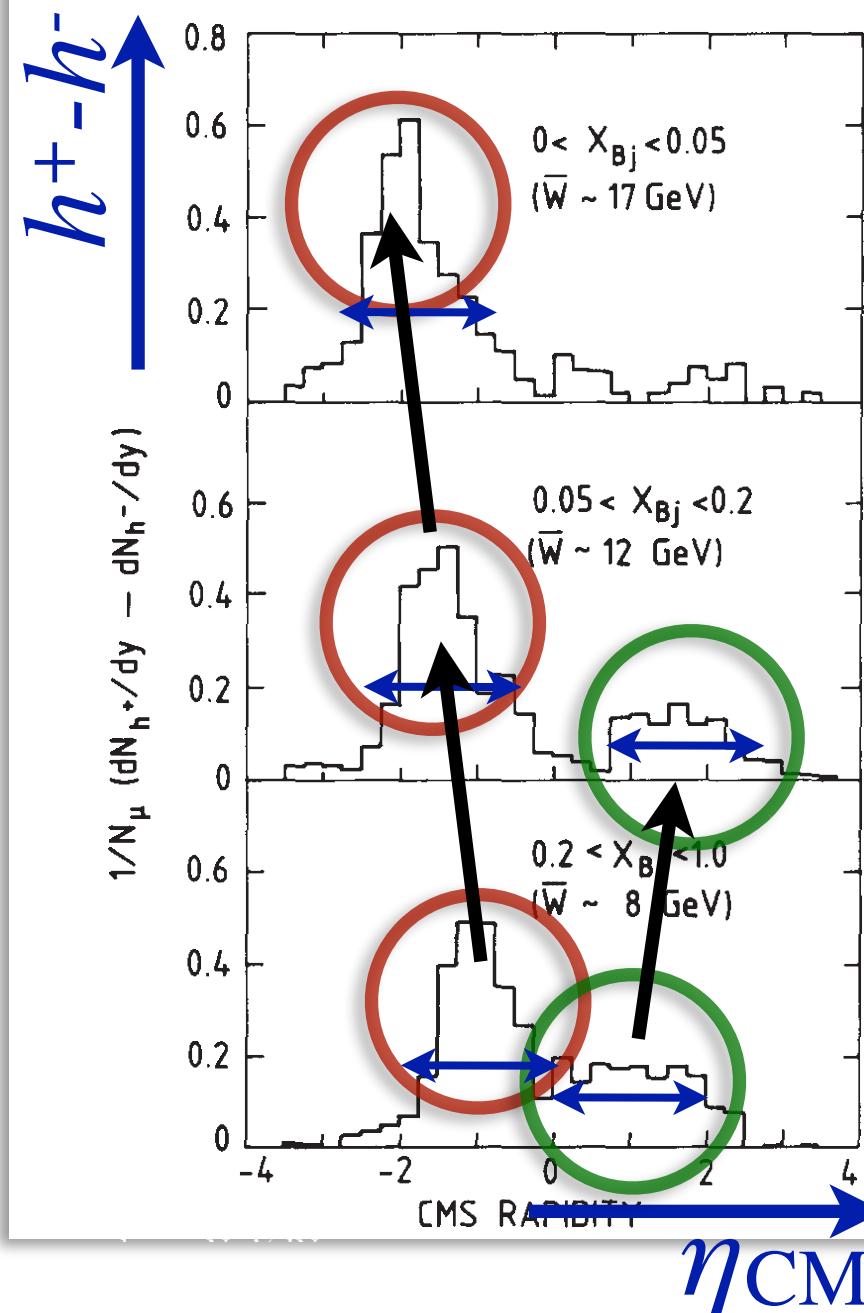
Clear **experimental separation** of **current** and **target** “jets” required

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

E665, ZPC (1993)



EMC, PR162 (1988)



Jet FWHM: $\Delta\eta_{CM} \approx 2$

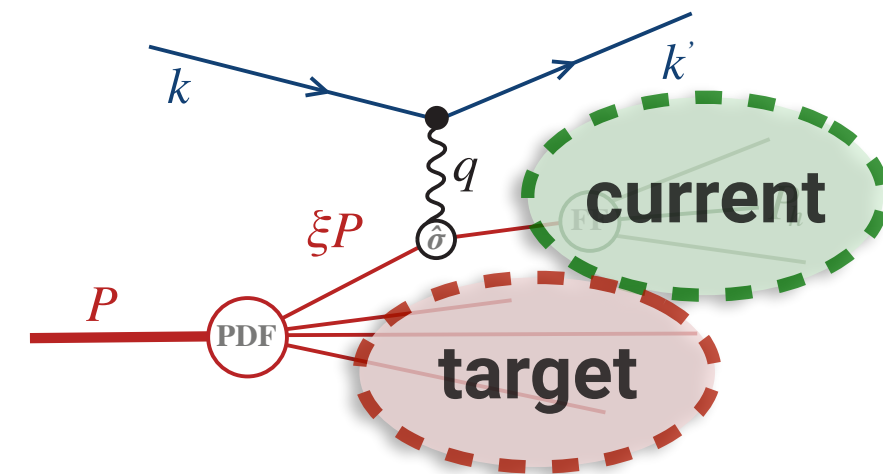
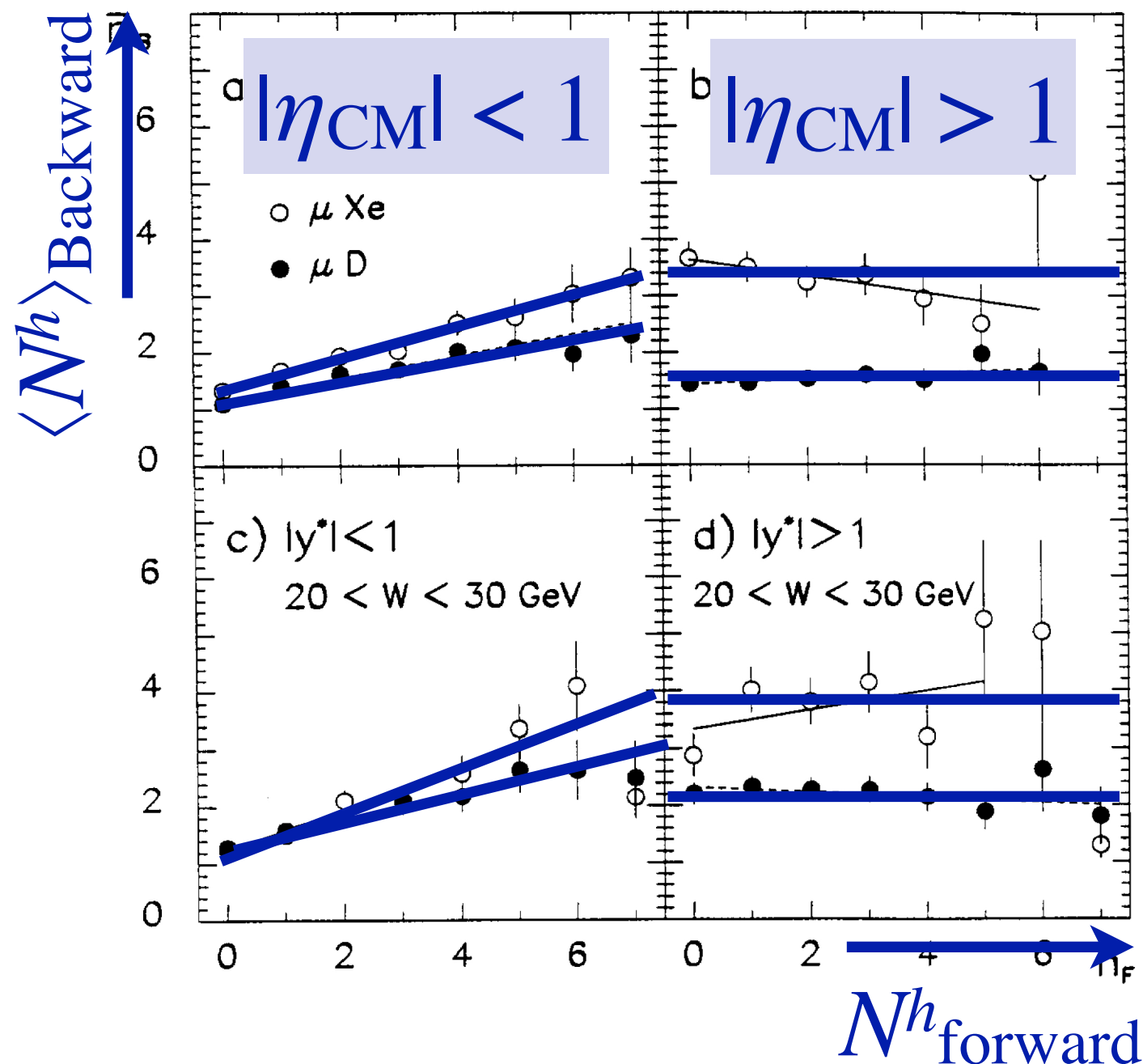
Rising W : jet separation **improves**

Limits on factorization: target remnant

Clear **experimental separation** of **current** and **target** “jets” required

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

E665, ZPC (1993)



Jet FWHM: $\Delta\eta_{\text{CM}} \approx 2$

Rising W : jet separation **improves**

A η_{CM} **cut** can **separate** the jets

Limits on factorization: target remnant

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Observations:

- **Jet FWHM**: $\Delta\eta_{\text{CM}} \approx 2$
- **Rising W** : jet separation **improves**
- A η_{CM} **cut** can **separate** the jets

Limits on factorization: target remnant

Observations:

- **Jet FWHM**: $\Delta\eta_{\text{CM}} \approx 2$
- **Rising W** : jet separation **improves**
- A η_{CM} **cut** can **separate** the jets

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

“Berger Criterion”:
Full separation requires
 $\Delta\eta_{\text{CM}} > 4$ **between the jets**

Limits on factorization: target remnant

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Observations:

- **Jet FWHM**: $\Delta\eta_{\text{CM}} \approx 2$
- **Rising W** : jet separation **improves**
- A η_{CM} **cut** can **separate** the jets

“Berger Criterion”:
Full separation requires
 $\Delta\eta_{\text{CM}} > 4$ **between the jets**

Lower limit in W for
this to be possible

$$\eta_{\text{CM}}^{\text{max}} \approx \ln \left. \frac{2P_h^{\text{max}}}{M_h} \right|_{\text{CM}}$$
$$P_h^{\text{max}} \approx W/2$$

Limits on factorization: target remnant

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Observations:

- **Jet FWHM**: $\Delta\eta_{\text{CM}} \approx 2$
- **Rising W** : jet separation **improves**
- A η_{CM} **cut** can **separate** the jets

“Berger Criterion”:
Full separation requires
 $\Delta\eta_{\text{CM}} > 4$ **between the jets**

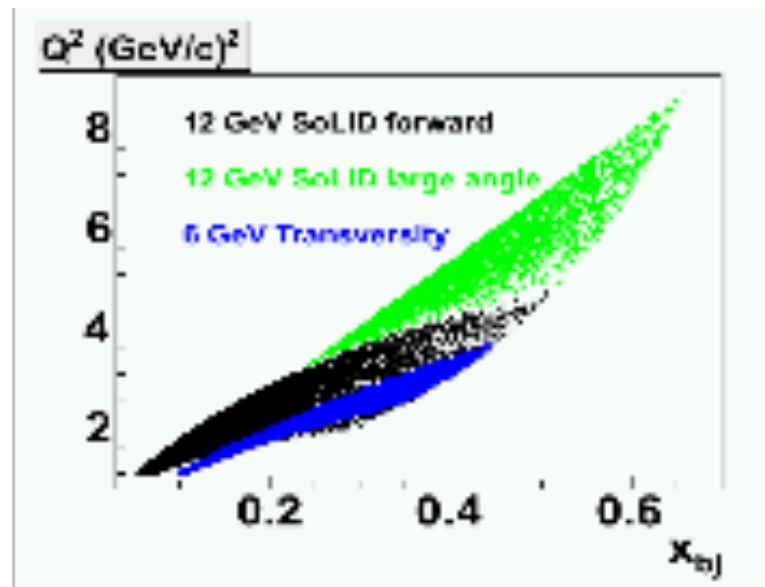
Lower limit in W for
this to be possible

Implies a **lower limit in z**

$$\eta_{\text{CM}}^{\text{max}} \approx \ln \left. \frac{2P_h^{\text{max}}}{M_h} \right|_{\text{CM}}$$
$$P_h^{\text{max}} \approx W/2$$

HERMES as a measure of future challenges

SOLID



$$E_{\text{beam}} = 11 \text{ GeV}$$

$$\sqrt{s} = 4.8 \text{ GeV}$$

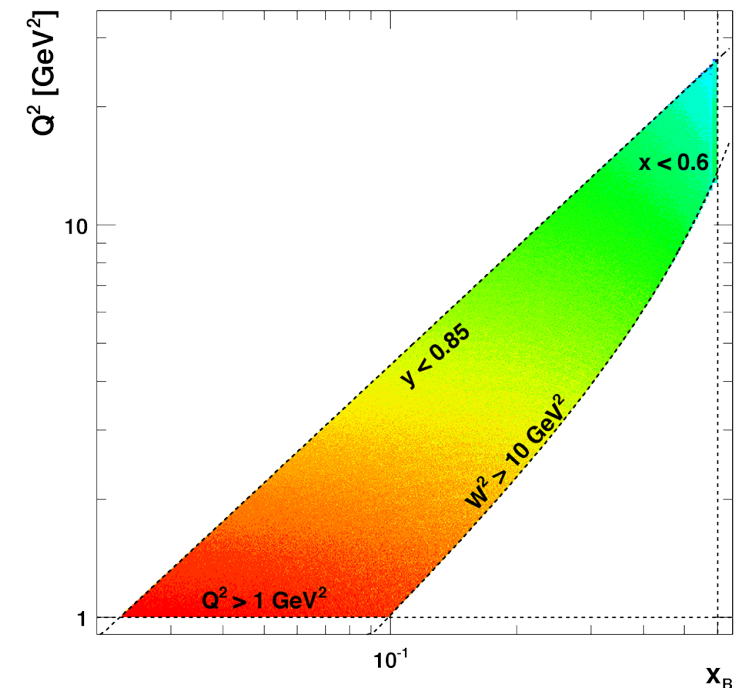
$$2 \text{ GeV} < W < 4.8 \text{ GeV}$$

Berger Criterion:

$$\eta_{\text{CM}}^{\text{max}} \approx \ln W/M_h = 4$$

→ pions: $W > 7.6 \text{ GeV}$
 → kaons: $W > 27 \text{ GeV}$

HERMES



$$E_{\text{beam}} = 27.5 \text{ GeV}$$

$$\sqrt{s} = 7.5 \text{ GeV}$$

$$3.2 \text{ GeV} < W < 7.5 \text{ GeV}$$

Problematic?
 Factorization seems
 to hold at HERMES

“Demonstrating” factorization at medium energies

Extract “indicator” quantities

example: $\int d_v / \int u_v = 1/2$

Multi-dimensional if possible to
identify problem corners

Can only **show absence** of evidence
for factorization breaking

L0 factorization is **intuitive**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Semi-inclusive pion production

$$\sigma_p^{\pi^+} \propto 4uD_u^{\pi^+} + dD_d^{\pi^+} + 4\bar{u}D_{\bar{u}}^{\pi^+} + \bar{d}D_{\bar{d}}^{\pi^+} + sD_s^{\pi^+} + \bar{s}D_s^{\pi^+}$$

$$\sigma_p^{\pi^-} \propto 4uD_u^{\pi^-} + dD_d^{\pi^-} + 4\bar{u}D_{\bar{u}}^{\pi^-} + \bar{d}D_{\bar{d}}^{\pi^-} + sD_s^{\pi^-} + \bar{s}D_s^{\pi^-}$$

$$\sigma_d^{\pi^+} \propto \frac{1}{2} \left[(u + d)(4D_u^{\pi^+} + D_d^{\pi^+}) + (\bar{u} + \bar{d})(4D_{\bar{u}}^{\pi^+} + D_{\bar{d}}^{\pi^+}) \right] + sD_s^{\pi^+} + \bar{s}D_s^{\pi^+}$$

$$\sigma_d^{\pi^-} \propto \frac{1}{2} \left[(u + d)(4D_u^{\pi^-} + D_d^{\pi^-}) + (\bar{u} + \bar{d})(4D_{\bar{u}}^{\pi^-} + D_{\bar{d}}^{\pi^-}) \right] + sD_s^{\pi^-} + \bar{s}D_s^{\pi^-}$$

isospin invariance of the **PDFs**
(between proton and neutron): $u_n \equiv d_p, \dots$

L0 factorization is **intuitive**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Semi-inclusive pion production

$$\sigma_p^{\pi^+} \propto 4u D_u^{\pi^+}$$

$$\sigma_p^{\pi^-} \propto 4u D_u^{\pi^-}$$

$$\sigma_d^{\pi^+} \propto \frac{1}{2} \left[(u + \bar{u}) D_u^{\pi^+} + (d + \bar{d}) D_d^{\pi^+} \right]$$

$$\sigma_d^{\pi^-} \propto \frac{1}{2} \left[(u + \bar{u}) D_u^{\pi^-} + (d + \bar{d}) D_d^{\pi^-} \right]$$

charge conjugation symmetry:

$$D_u^{\pi^+} = D_{\bar{u}}^{\pi^-} \equiv D_1$$

$$D_d^{\pi^-} = D_{\bar{d}}^{\pi^+} \equiv D_2$$

$$D_u^{\pi^-} = D_{\bar{u}}^{\pi^+} \equiv D_3$$

$$D_d^{\pi^+} = D_{\bar{d}}^{\pi^-} \equiv D_4$$

$$D_s^{\pi^+} = D_{\bar{s}}^{\pi^-} \equiv D_{s,1}$$

$$D_s^{\pi^-} = D_{\bar{s}}^{\pi^+} \equiv D_{s,2}$$

← favored

← unfavored

← strange

isospin invariance of the **PDFs**

(between proton and neutron): $u_n \equiv d_p, \dots$

L0 factorization is **intuitive**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Semi-inclusive pion production

$$\sigma_p^{\pi^+} \propto 4uD_1 + dD_4 + 4\bar{u}D_3 + \bar{d}D_2 + sD_{s,1} + \bar{s}D_{s,2}$$

$$\sigma_p^{\pi^-} \propto 4uD_3 + dD_2 + 4\bar{u}D_1 + \bar{d}D_4 + sD_{s,2} + \bar{s}D_{s,1}$$

$$\sigma_d^{\pi^+} \propto \frac{1}{2} \left[(u + d)(4D_1 + D_4) + (\bar{u} + \bar{d})(4D_3 + D_2) \right] + sD_{s,1} + \bar{s}D_{s,2}$$

$$\sigma_d^{\pi^-} \propto \frac{1}{2} \left[(u + d)(4D_3 + D_2) + (\bar{u} + \bar{d})(4D_1 + D_4) \right] + sD_{s,2} + \bar{s}D_{s,1}$$

isospin symmetry:

$$D_1 = D_2 \equiv D_f \leftarrow \text{favored}$$

$$D_3 = D_4 \equiv D_u \leftarrow \text{unfavored}$$

L0 factorization is **intuitive**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Semi-inclusive pion production

$$\sigma_p^{\pi^+} \propto (4u + \bar{d})D_f + (d + 4\bar{u})D_u + \text{strange}$$

$$\sigma_p^{\pi^-} \propto (4u + \bar{d})D_u + (d + 4\bar{u})D_f + \text{strange}$$

$$\sigma_d^{\pi^+} \propto \frac{1}{2} \left[(u + d)(4D_f + D_u) + (\bar{u} + \bar{d})(4D_u + D_f) \right] + \text{strange}$$

$$\sigma_d^{\pi^-} \propto \frac{1}{2} \left[(u + d)(4D_u + D_f) + (\bar{u} + \bar{d})(4D_f + D_u) \right] + \text{strange}$$

Define:

$$R^\pi \equiv 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1 \quad \rho^\pi \equiv \frac{\sigma_p^{\pi^-} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_d^{\pi^+}}$$

L0 factorization is **intuitive**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Semi-inclusive pion production

Define:

$$R^\pi \equiv 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1 \quad \rho^\pi \equiv \frac{\sigma_p^{\pi^-} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_d^{\pi^+}}$$

$$\sigma_p^{\pi^+} \propto (4u + \bar{d})D_f + (d + 4\bar{u})D_u + \text{strange}$$

$$\sigma_p^{\pi^-} \propto (4u + \bar{d})D_u + (d + 4\bar{u})D_f + \text{strange}$$

$$\sigma_d^{\pi^+} \propto \frac{1}{2} \left[(u + d)(4D_f + D_u) + (\bar{u} + \bar{d})(4D_u + D_f) \right] + \text{strange}$$

$$\sigma_d^{\pi^-} \propto \frac{1}{2} \left[(u + d)(4D_u + D_f) + (\bar{u} + \bar{d})(4D_f + D_u) \right] + \text{strange}$$

$$\frac{d_v}{u_v} = \frac{4R^\pi + 1}{4 + R^\pi}$$

$$\frac{\bar{d} - \bar{u}}{u - d} = \frac{4k^{\text{sea}} - \rho^\pi}{1 - k^{\text{sea}}\rho^\pi}$$

$$k^{\text{sea}} = \frac{4 - \eta}{4\eta - 1} \quad \text{where} \quad \eta = \frac{D_{\text{unf}}}{D_{\text{fav}}}$$

L0 factorization is **intuitive**

$$R^\pi \equiv 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1 \quad \rho^\pi \equiv \frac{\sigma_p^{\pi^-} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_d^{\pi^+}}$$

$$d\sigma^h \propto \sum_q e_q^2 \textcolor{red}{f}_q(\textcolor{red}{x}) \otimes \textcolor{blue}{\hat{\sigma}} \otimes \textcolor{green}{D}_q^h(z)$$

$$\frac{d_v}{u_v} = \frac{4R^\pi + 1}{4 + R^\pi} \quad \frac{\bar{d} - \bar{u}}{u - d} = \frac{4k^{\text{sea}} - \rho^\pi}{1 - k^{\text{sea}}\rho^\pi}$$
$$k^{\text{sea}} = \frac{4 - \eta}{4\eta - 1} \quad \text{where} \quad \eta = \frac{D_{\text{unf}}}{D_{\text{fav}}}$$

L0 factorization is **intuitive**

$$R^\pi \equiv 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1 \quad \rho^\pi \equiv \frac{\sigma_p^{\pi^-} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_d^{\pi^+}}$$

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Requires additional input

$$\frac{d_v}{u_v} = \frac{4R^\pi + 1}{4 + R^\pi} \quad \frac{\bar{d} - \bar{u}}{u - d} = \frac{4k^{\text{sea}} - \rho^\pi}{1 - k^{\text{sea}}\rho^\pi}$$
$$k^{\text{sea}} = \frac{4 - \eta}{4\eta - 1} \quad \text{where} \quad \eta = \frac{D_{\text{unf}}}{D_{\text{fav}}}$$

Signature of factorization:
should depend on x , not z

Factorization and **precocious scaling**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

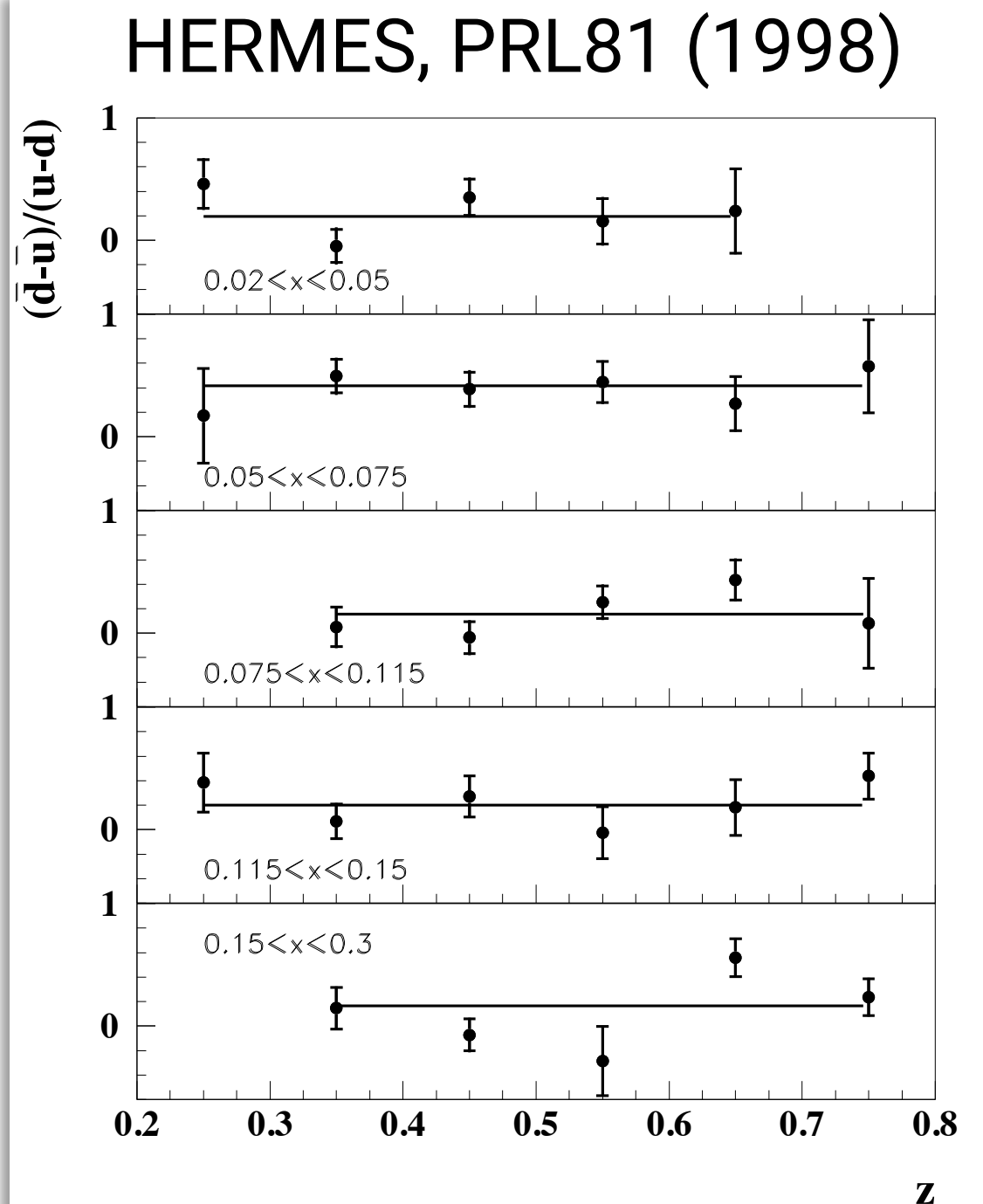
Precocious scaling: factorized QCD appears to be working in energy regimes down to $Q \sim M$, and for SIDIS far below the Berger threshold.

Factorization and **precocious scaling**

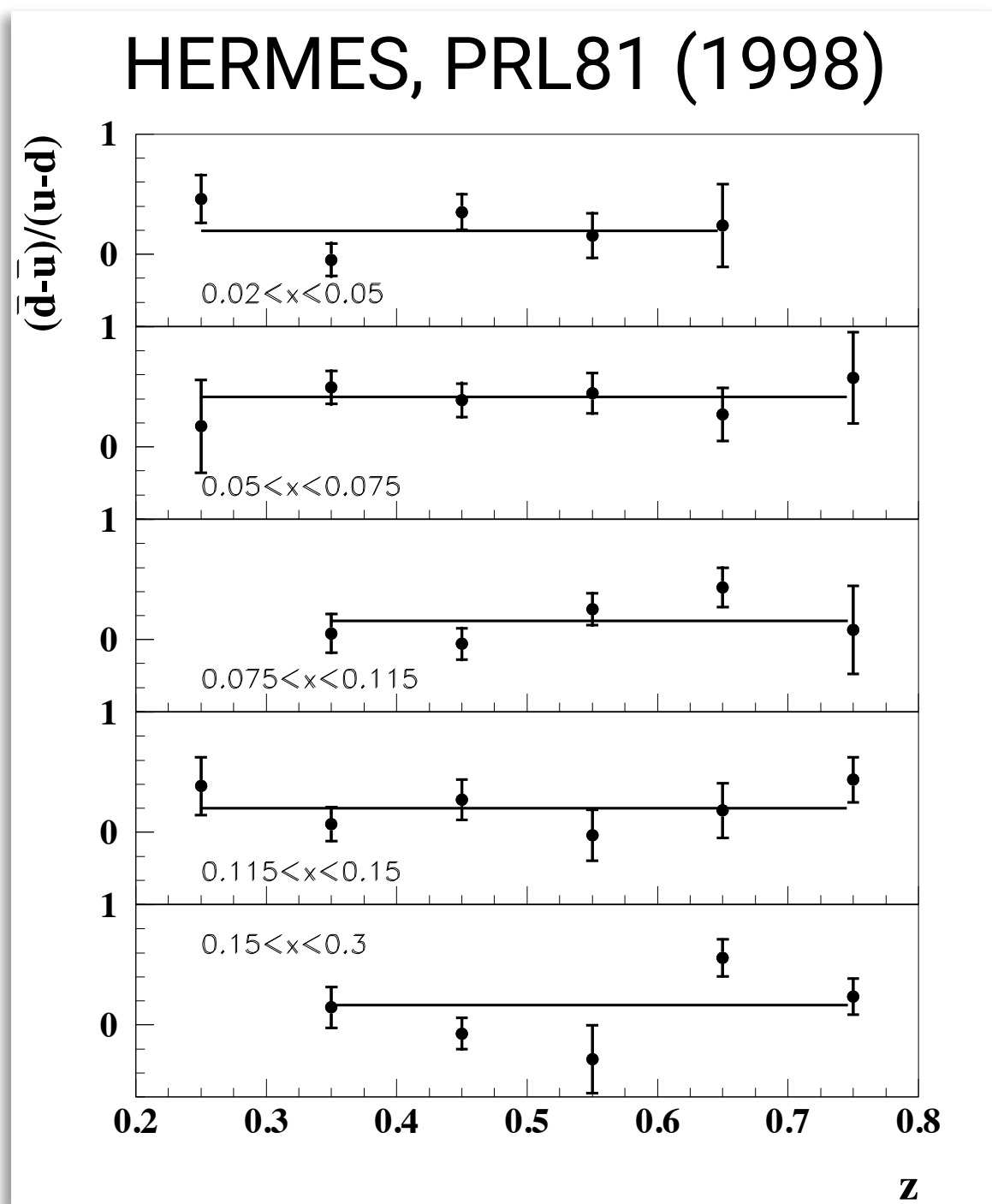
Precocious scaling: factorized QCD appears to be working in energy regimes down to $Q \sim M$, and for SIDIS far below the Berger threshold.

- Independent of z
- Simple LO-factorization holds at HERMES
- Caveat:
 - Model dependent (FFs, isospin invariance, ...)
 - Low statistics (only 1996-97)
 - Can we do better?

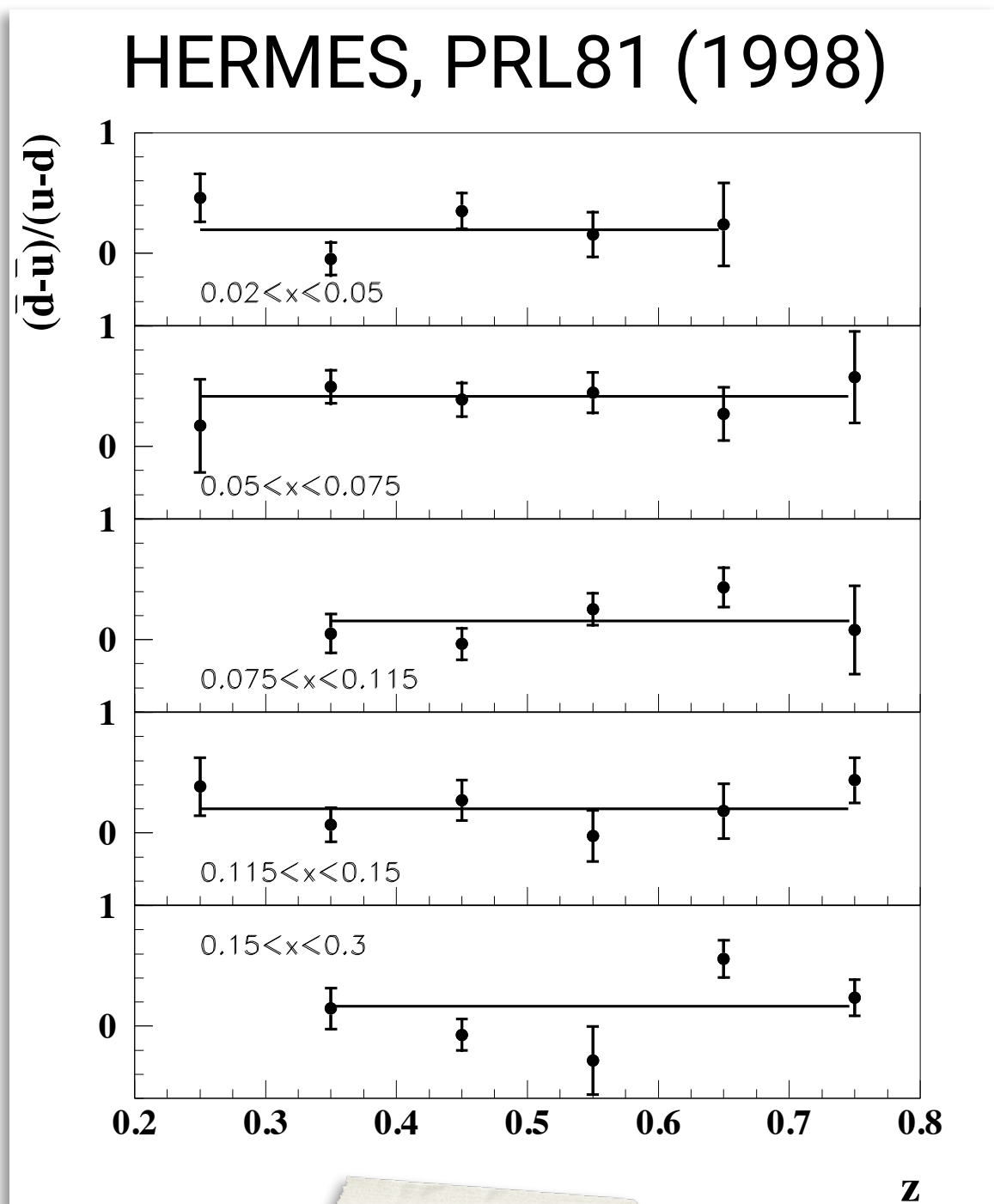
$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



Beyond $\bar{d} - \bar{u}$

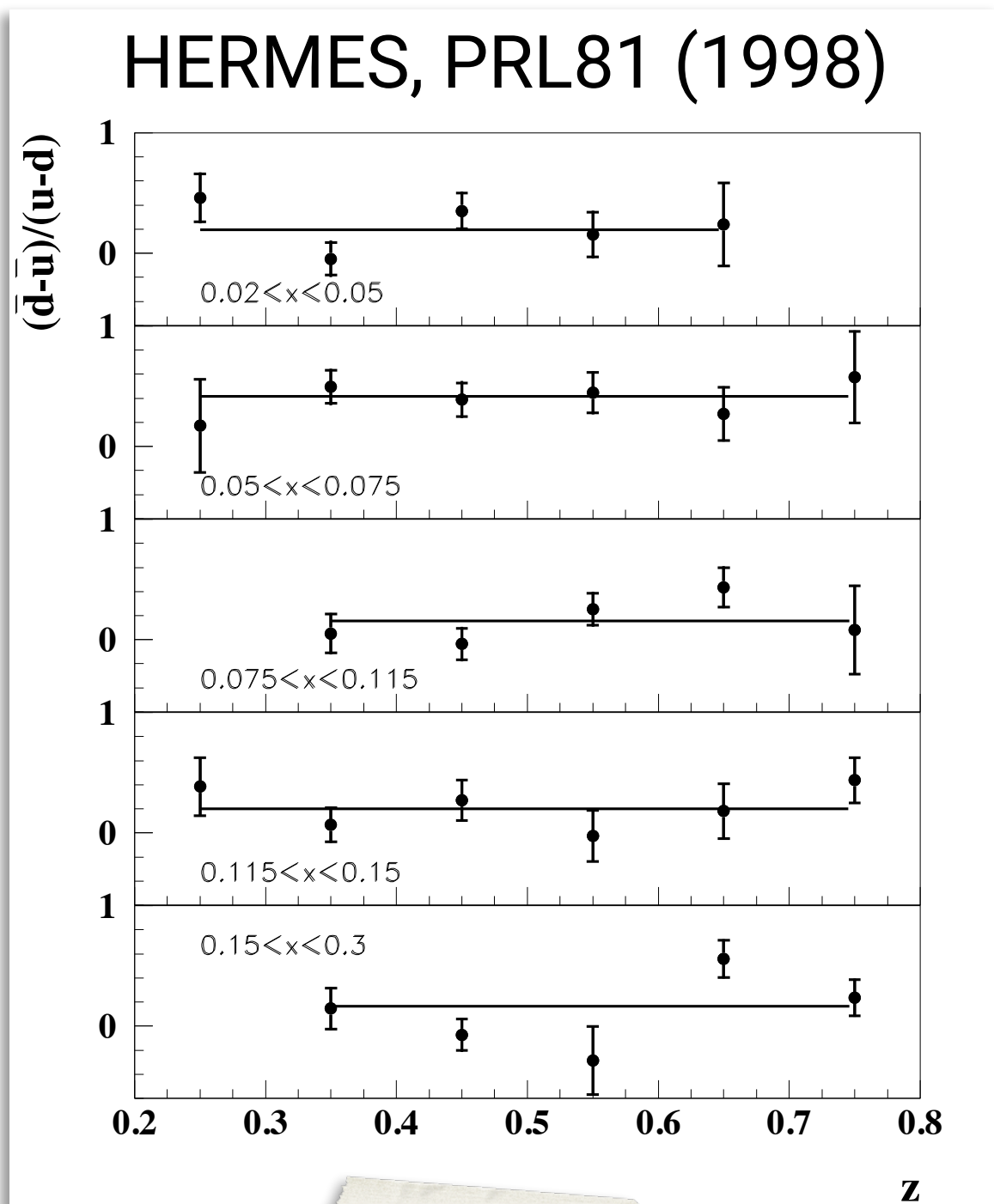


Beyond $\bar{d} - \bar{u}$



Signature of factorization:
should depend on x , not z

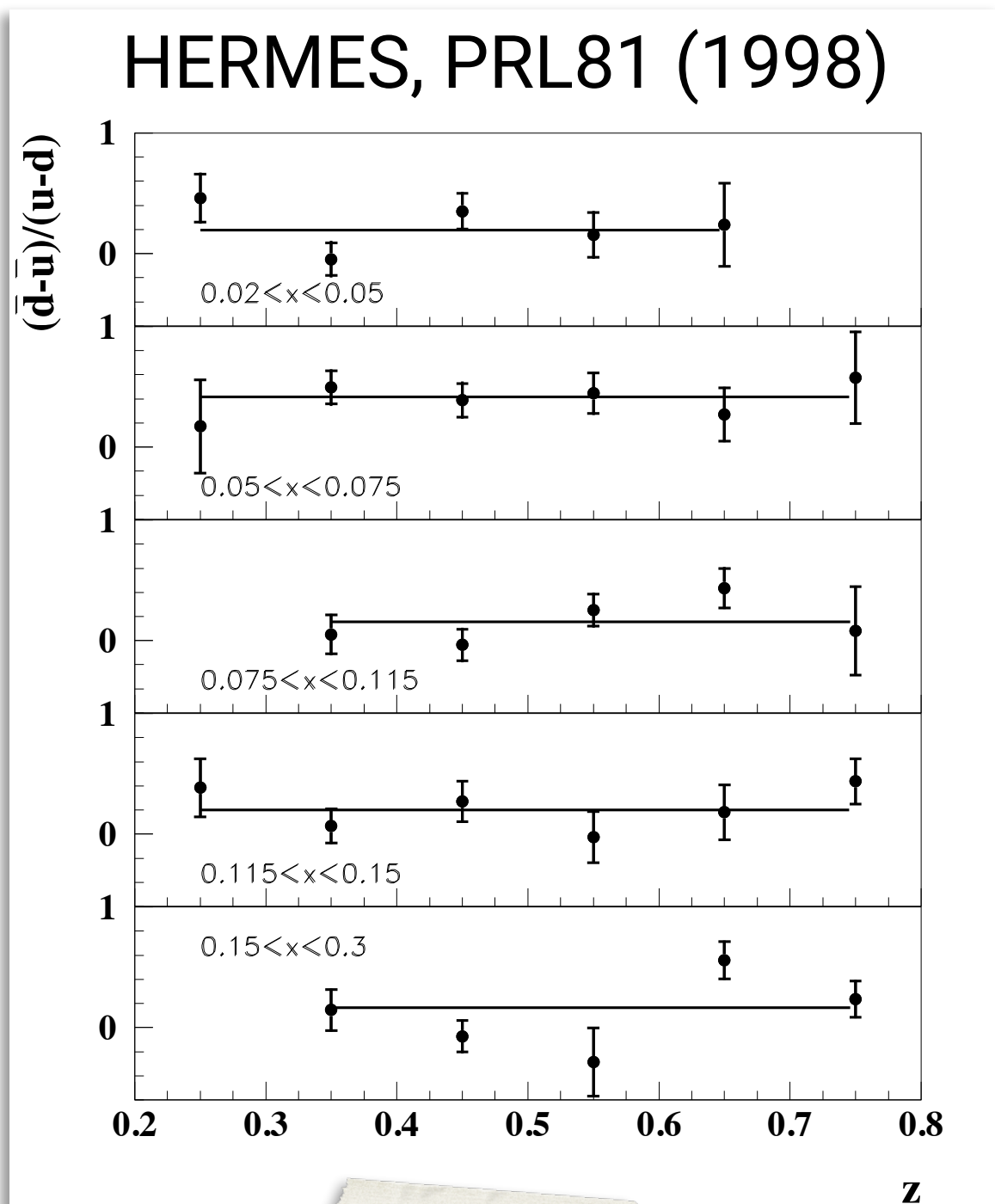
Beyond $\bar{d} - \bar{u}$



Important test, but **not ideal**
(model dependent)

Signature of factorization:
should depend on x , not z

Beyond $\bar{d} - \bar{u}$



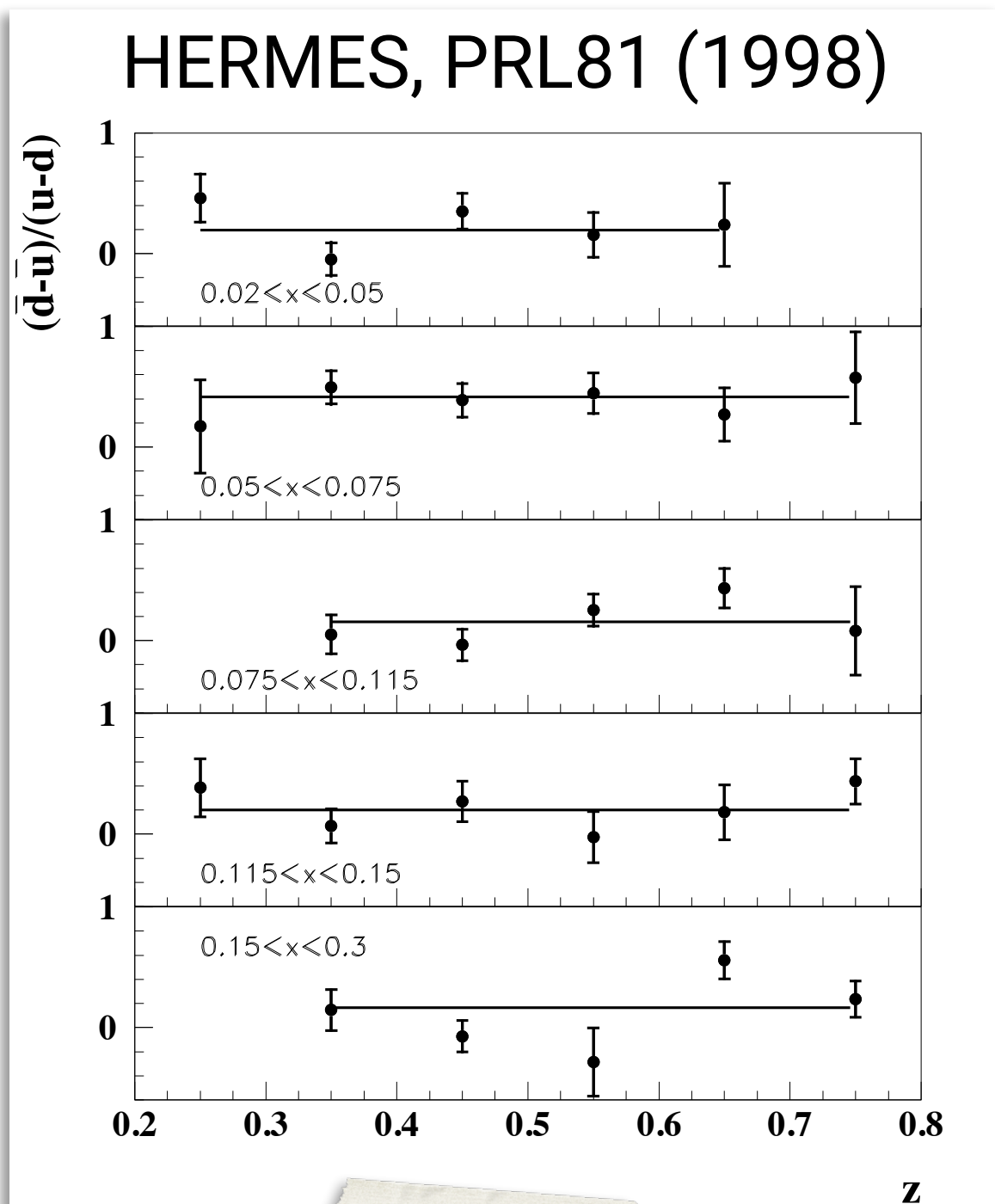
Important test, but **not ideal**
(model dependent)

$\int d_v / \int u_v$ finally possible!

- **RICH** and RICH unfolding
- multi-dimensional **smearing-unfolding**
- Very good grasp of interplay between the **systematics**

Signature of factorization:
should depend on x , not z

Beyond $\bar{d} - \bar{u}$



Signature of factorization:
should depend on x , not z

Important test, but **not ideal**
(model dependent)

$\int d_v / \int u_v$ finally possible!

- **RICH** and RICH unfolding
- multi-dimensional **smearing-unfolding**
- Very good grasp of interplay between the **systematics**

Expected problem areas:

- high z (**exclusive**)
- low z (**target remnant**)

L0 factorization is **intuitive**

L0 access

$$\frac{d_v}{u_v} = \frac{4R^\pi + 1}{4 + R^\pi} \quad R^\pi \equiv 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1$$

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

L0 factorization is **intuitive**

L0 access

$$\frac{d_v}{u_v} = \frac{4R^\pi + 1}{4 + R^\pi} \quad R^\pi \equiv 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1$$

Signature of factorization:
should depend on x , not z

sensitive for:

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

L0 factorization is **intuitive**

L0 access

$$\frac{d_v}{u_v} = \frac{4R^\pi + 1}{4 + R^\pi} \quad R^\pi \equiv 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1$$

Signature of factorization:
should depend on x , not z

sensitive for:

Experimental precision,
need good knowledge of the
correlated systematics

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

L0 factorization is **intuitive**

L0 access

$$\frac{d_v}{u_v} = \frac{4R^\pi + 1}{4 + R^\pi} \quad R^\pi \equiv 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1$$

Signature of factorization:
should depend on x , not z

sensitive for:

Experimental precision,
need good knowledge of the
correlated systematics

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

isospin symmetry:

$$D_1 = D_2 \equiv D_f$$

$$D_3 = D_4 \equiv D_u$$

Broken in the DSS fit!

$$\frac{D_2 + D_4}{D_1 + D_3} = 1.10 \text{ at } \mu_0 = 1 \text{ GeV}$$

L0 factorization is **intuitive**

L0 access

$$\frac{d_v}{u_v} = \frac{4R^\pi + 1}{4 + R^\pi} \quad R^\pi \equiv 2 \frac{\sigma_d^{\pi^+} - \sigma_d^{\pi^-}}{\sigma_p^{\pi^+} - \sigma_p^{\pi^-}} - 1$$

Signature of factorization:
should depend on x , not z

sensitive for:

Experimental precision,
need good knowledge of the
correlated systematics

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

Applicability of
LO, leading-twist
framework

isospin symmetry:

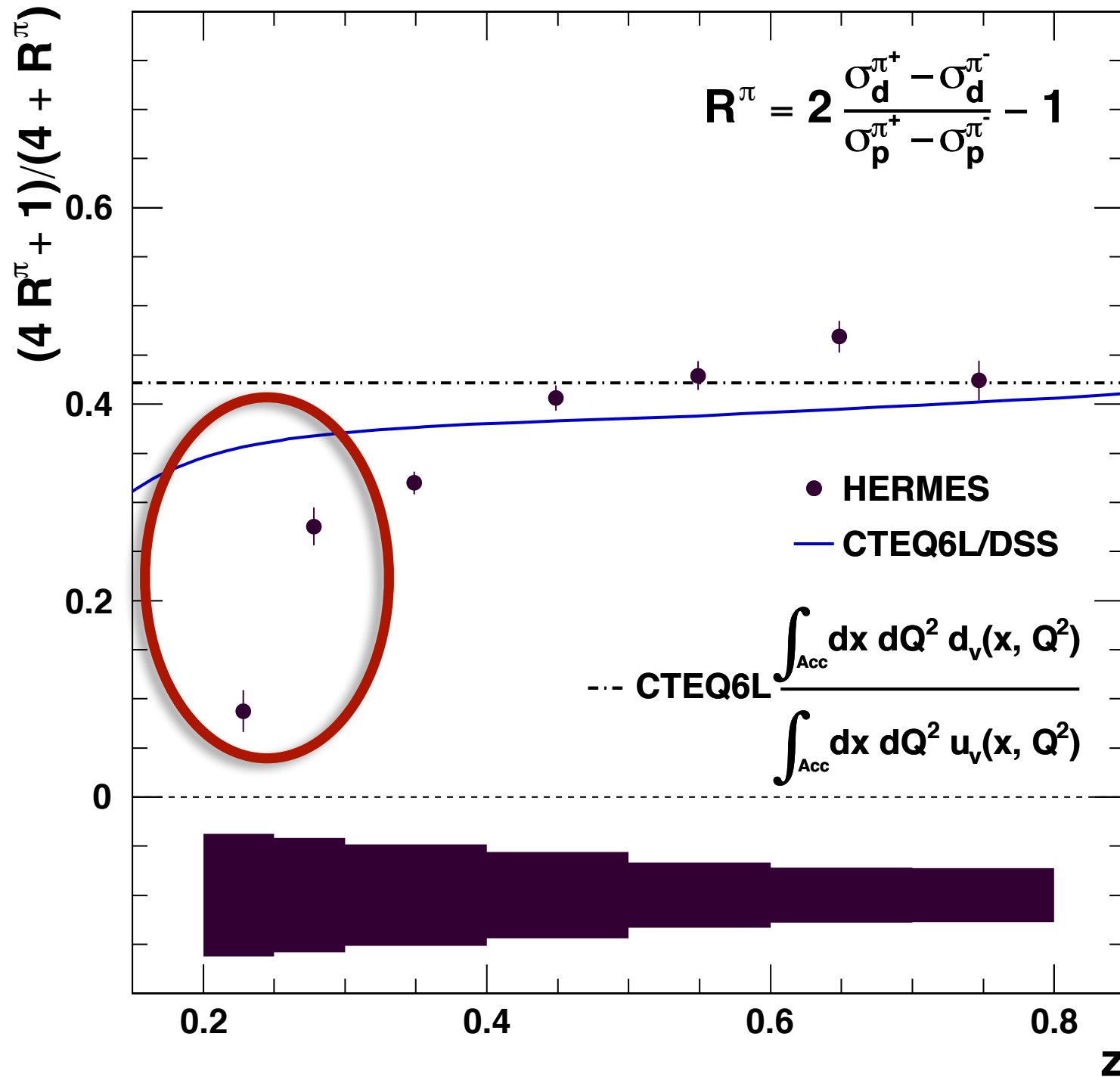
$$D_1 = D_2 \equiv D_f$$

$$D_3 = D_4 \equiv D_u$$

Broken in the DSS fit!

$$\frac{D_2 + D_4}{D_1 + D_3} = 1.10 \text{ at } \mu_0 = 1 \text{ GeV}$$

Evidence for **factorization breaking**?



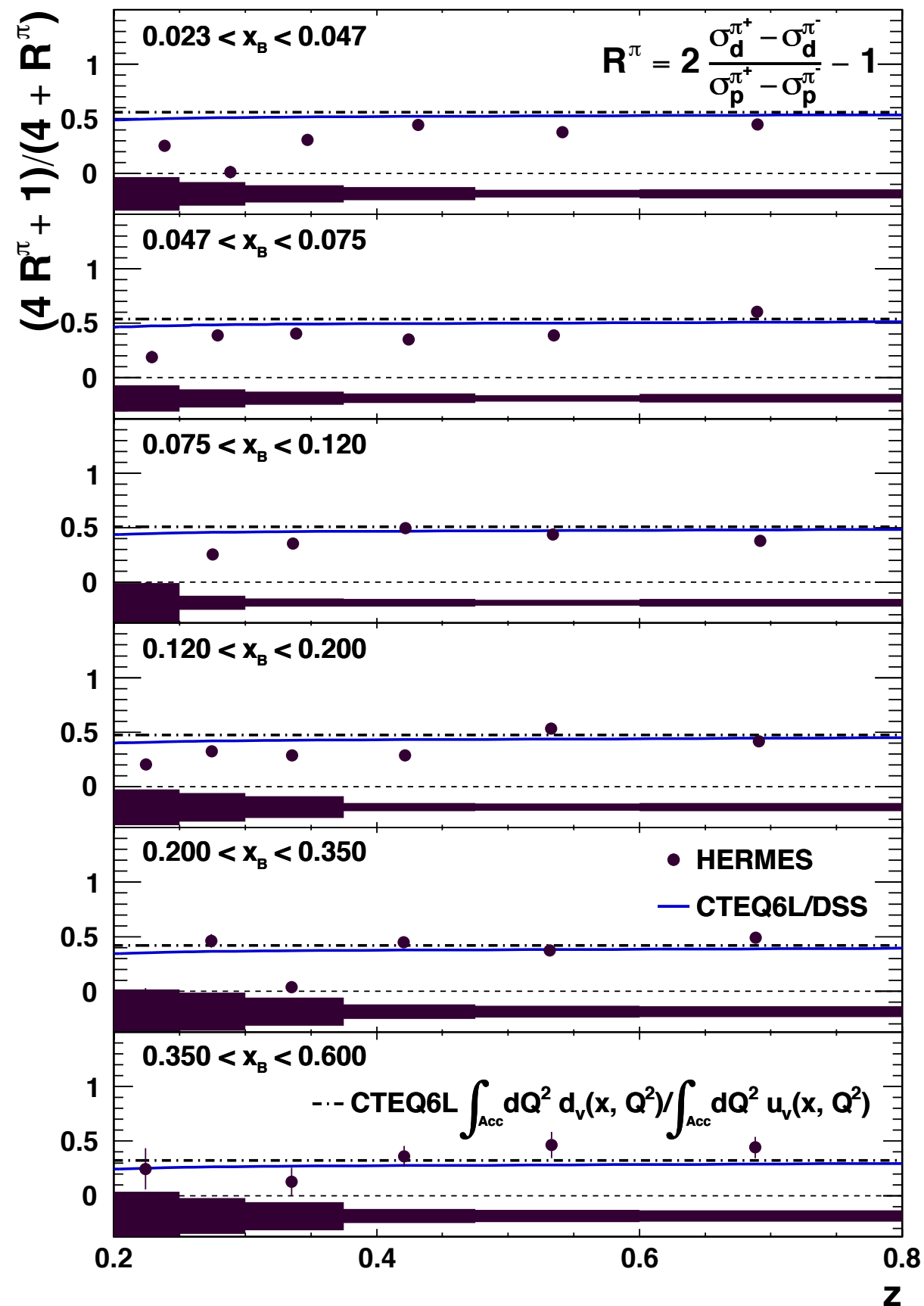
Very good **agreement** for **mid-to-high z**

Lowest point $> 3\sigma$ from the prediction:

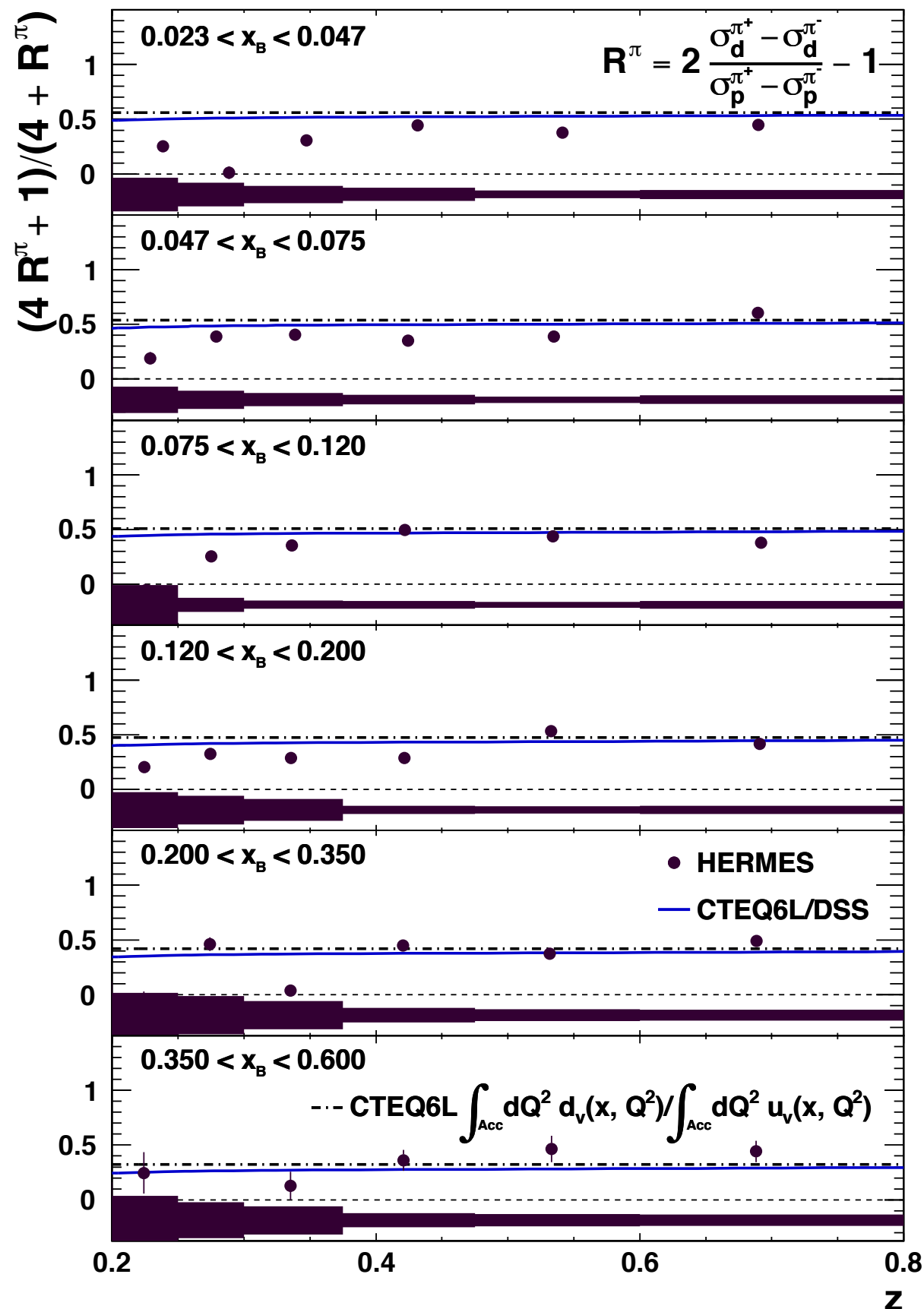
- Target remnant or theory?
- “Realistic” FF assumption lessens the discrepancy
→ Probably mix

Results **systematics dominated**

Evidence for **factorization breaking**?



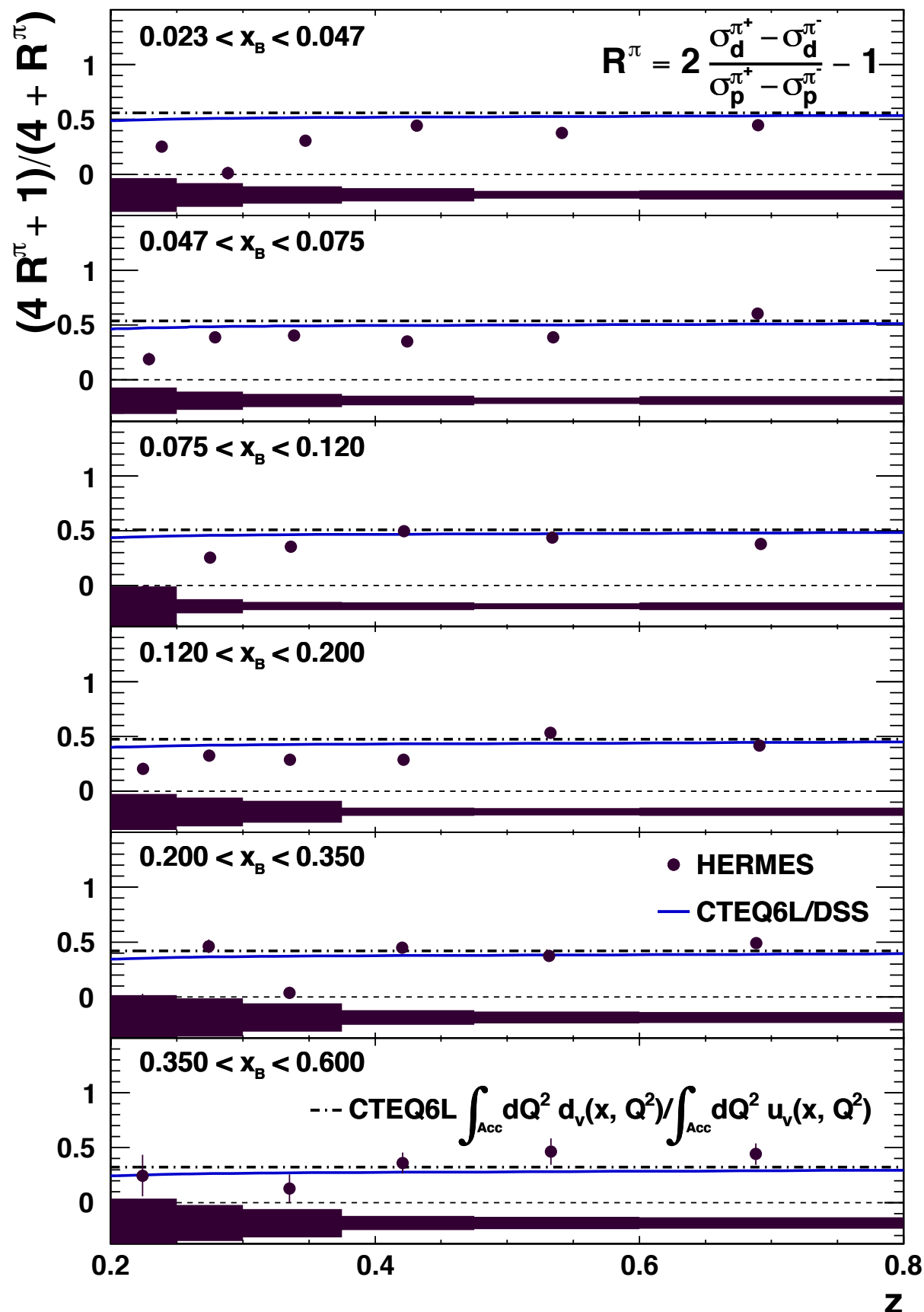
Evidence for **factorization breaking**?



Lessons:

- **Discrepancy HAS to occur at low z**
- **Precocious scaling** holds very well **mid-to-high z**
- More **precise knowledge FF symmetries** required

Evidence for **factorization breaking**?



Lessons:

- **Discrepancy HAS to occur at low z**
- **Precocious scaling** holds very well **mid-to-high z**
- More **precise knowledge FF symmetries** required

SYSTEMATICS!

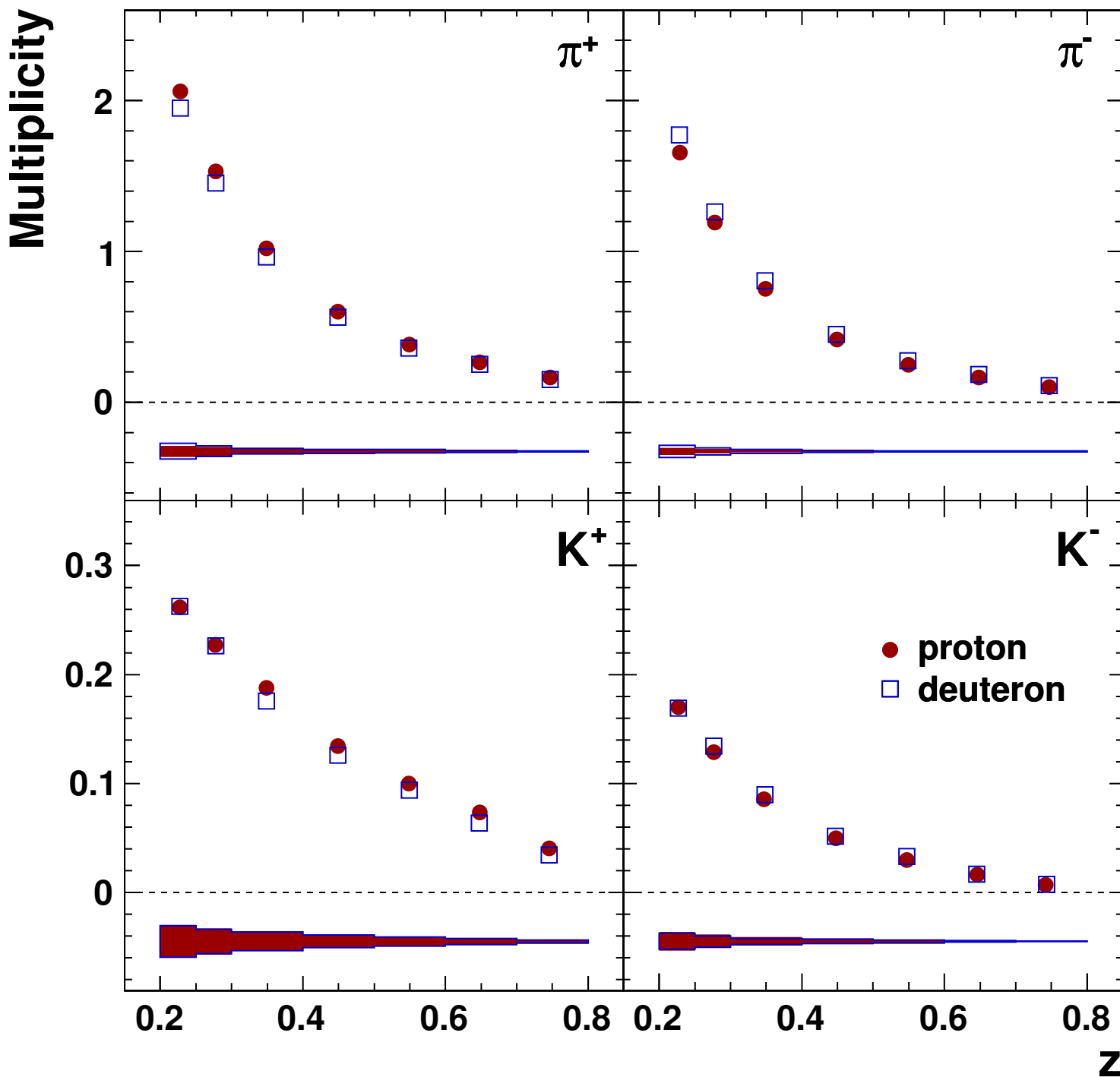
- Systematics dominant: pushing the limit of HERMES
- **On to CEBAF!**
- **Multi-D binning key**, for unfolding, but also for interpretation

THE END

This work is supported in part by the U.S. Department of Energy Grant Award DE-FG02-94ER4084

Multiplicities: **Projected vs z**

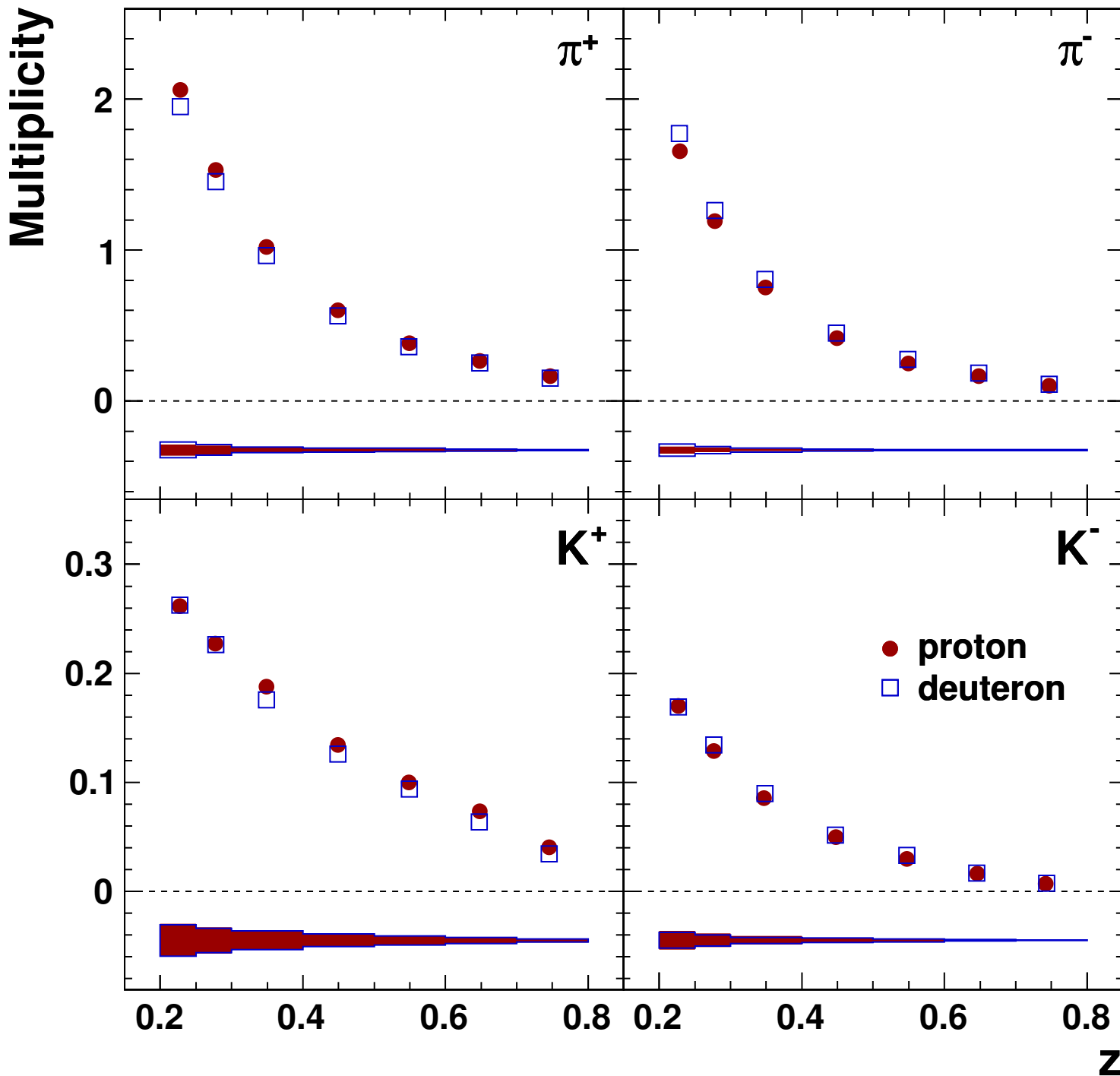
$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



Multiplicities: **Projected vs z**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

u-quark dominance

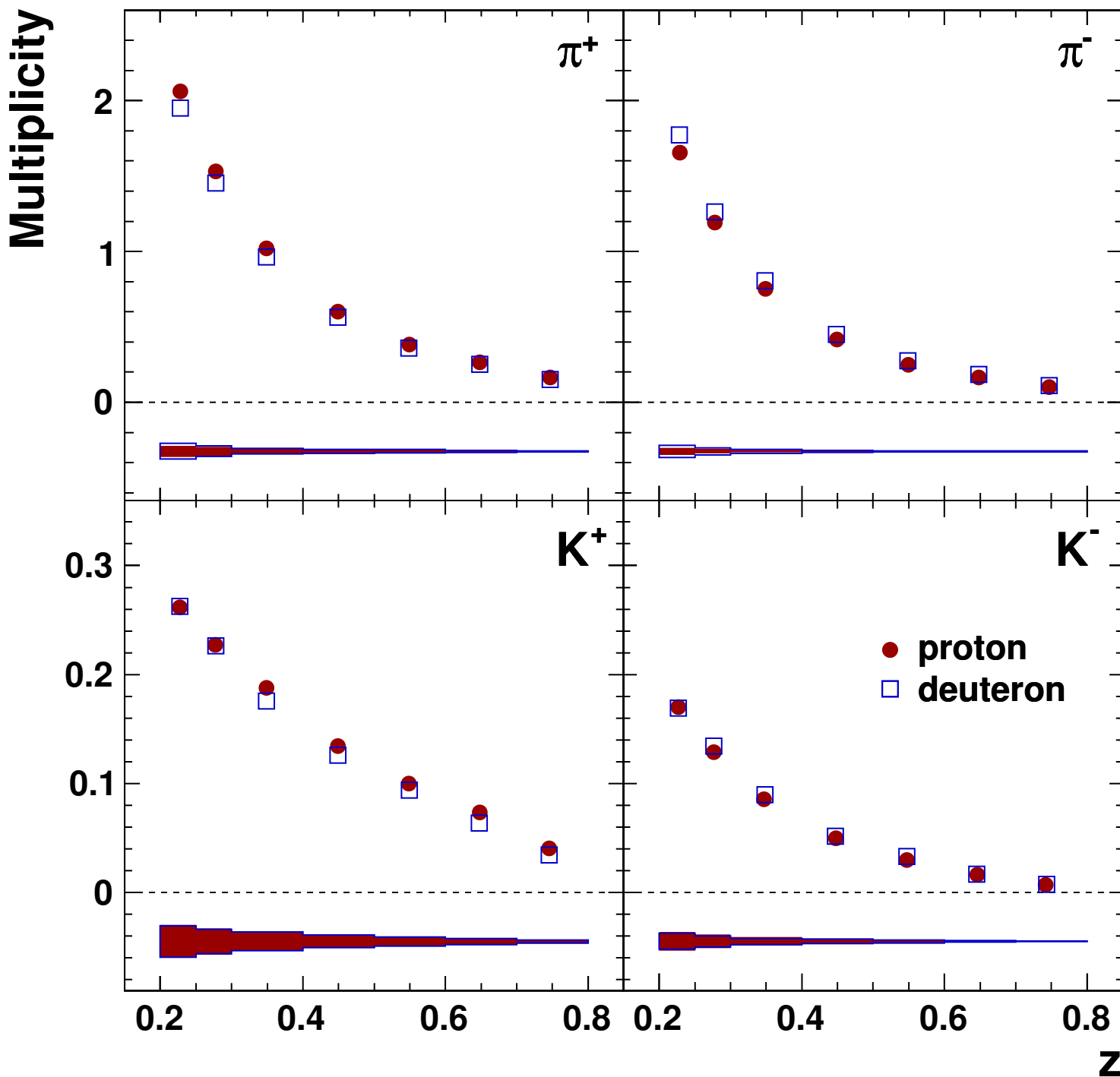


Multiplicities: **Projected vs z**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

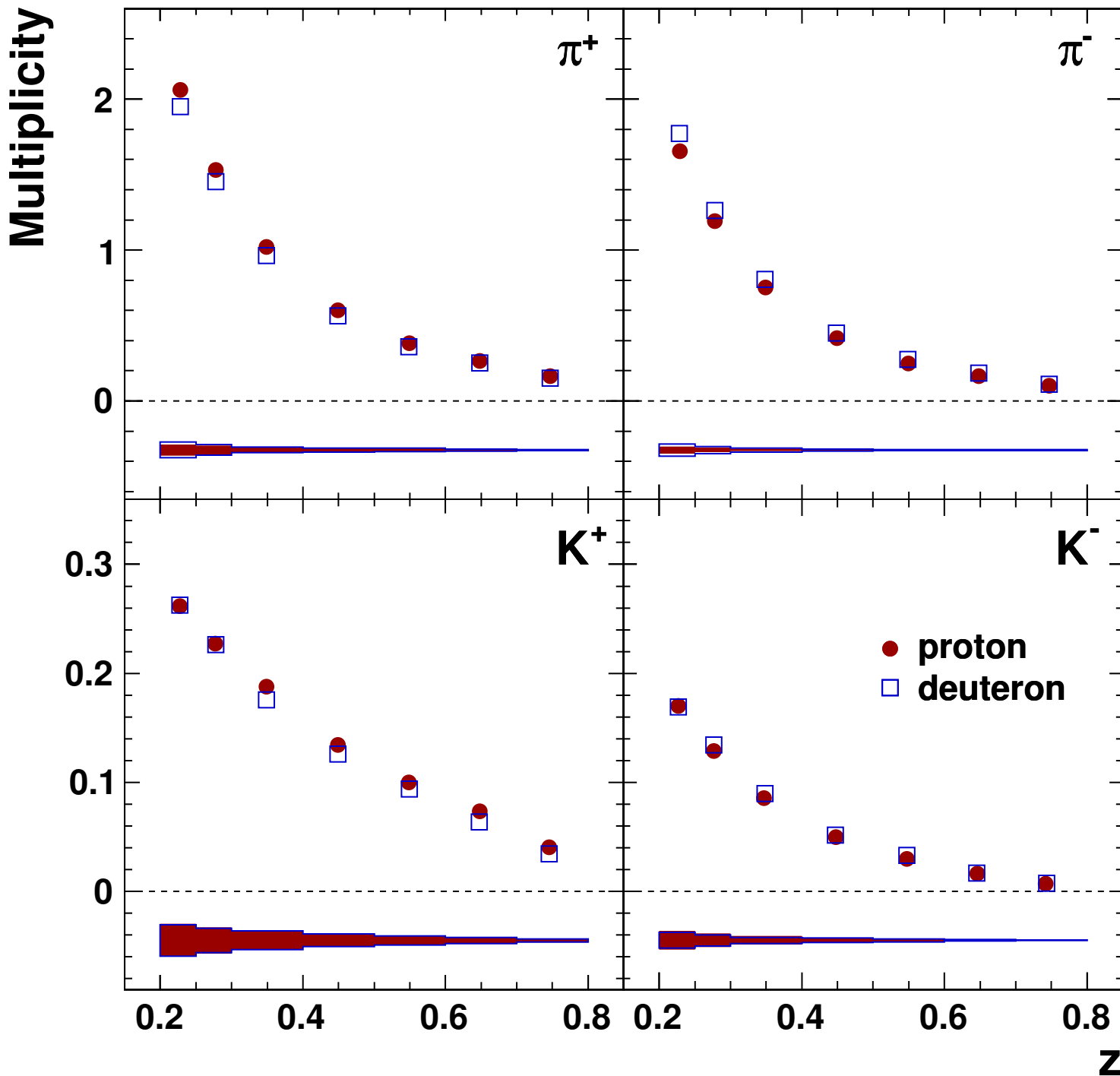
u-quark dominance

deuteron has less *u*-quarks



Multiplicities: **Projected vs z**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



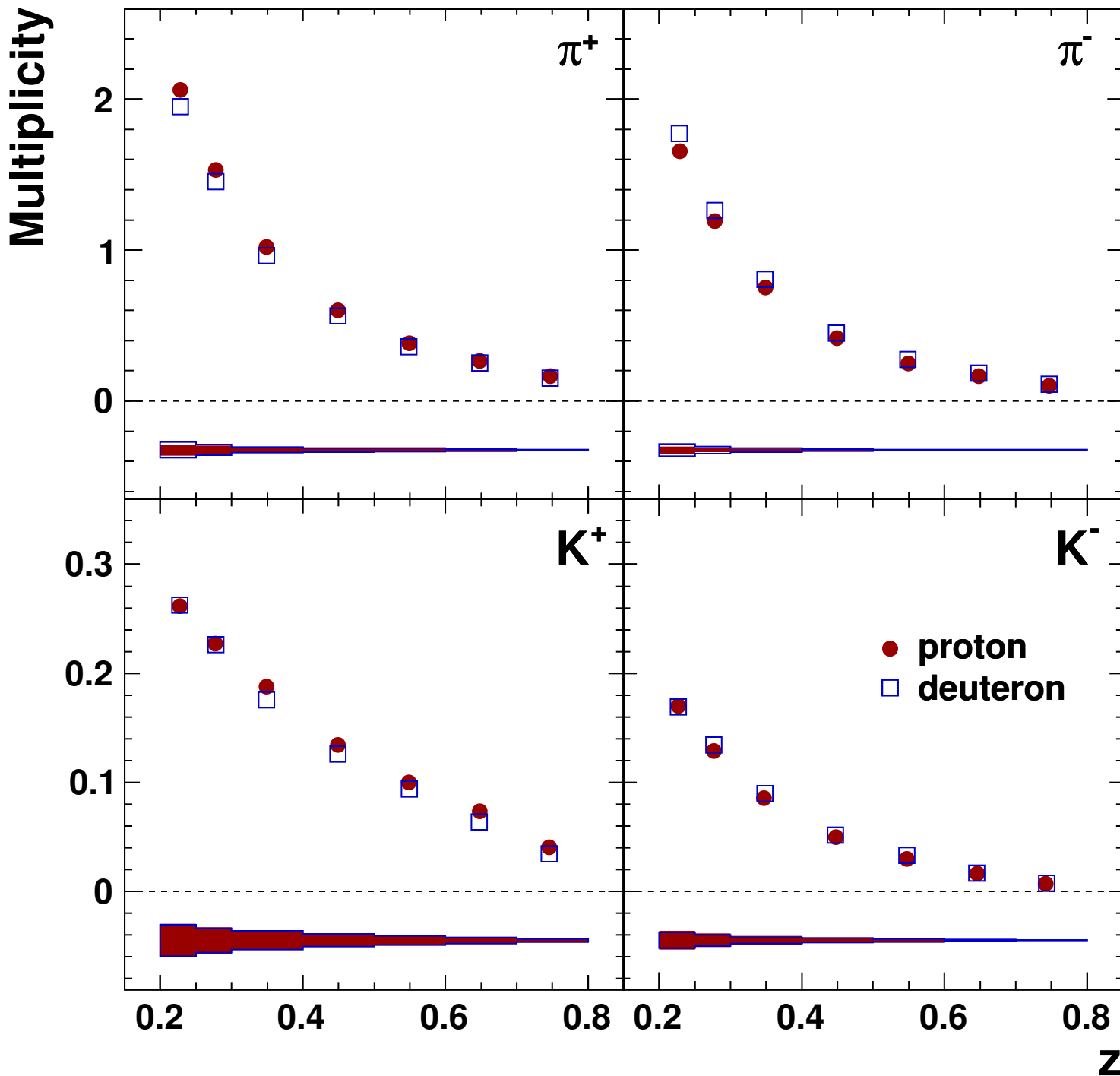
u-quark dominance

deuteron has less *u*-quarks

K- pure sea object ($s\bar{u}$)

Multiplicities: **Projected vs z**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



u -quark dominance

deuteron has less u -quarks

K^- pure sea object ($s\bar{u}$)

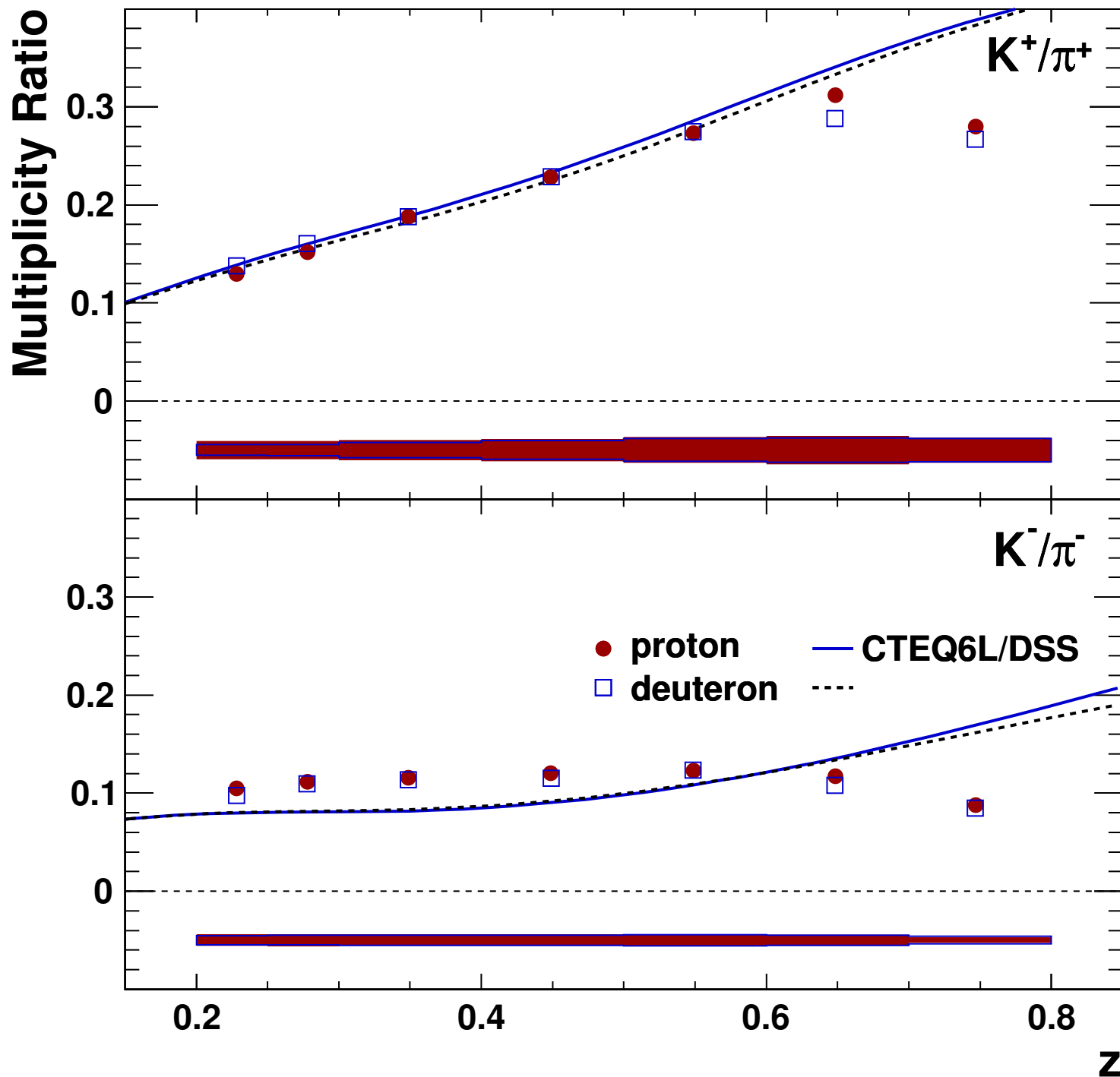
Systematics highly
correlated



Asymmetries and ratios to
increase precision

K/π and **strangeness suppression**

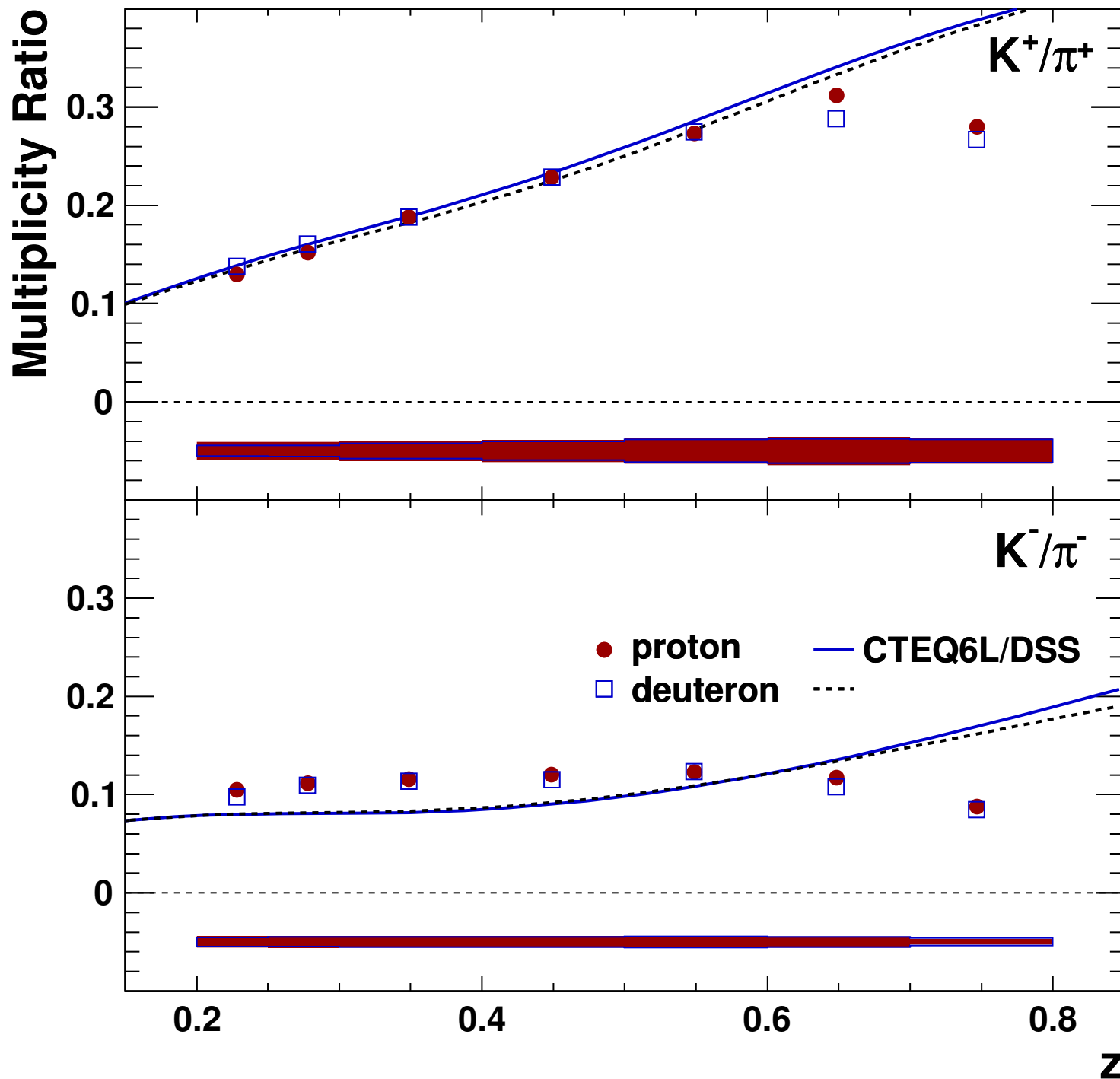
$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$



strangeness suppression:
the extra cost to produce $s\bar{s}$
compared to $d\bar{d}$
Visible at high z due to
 u -quark dominance.

K/π and **strangeness suppression**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

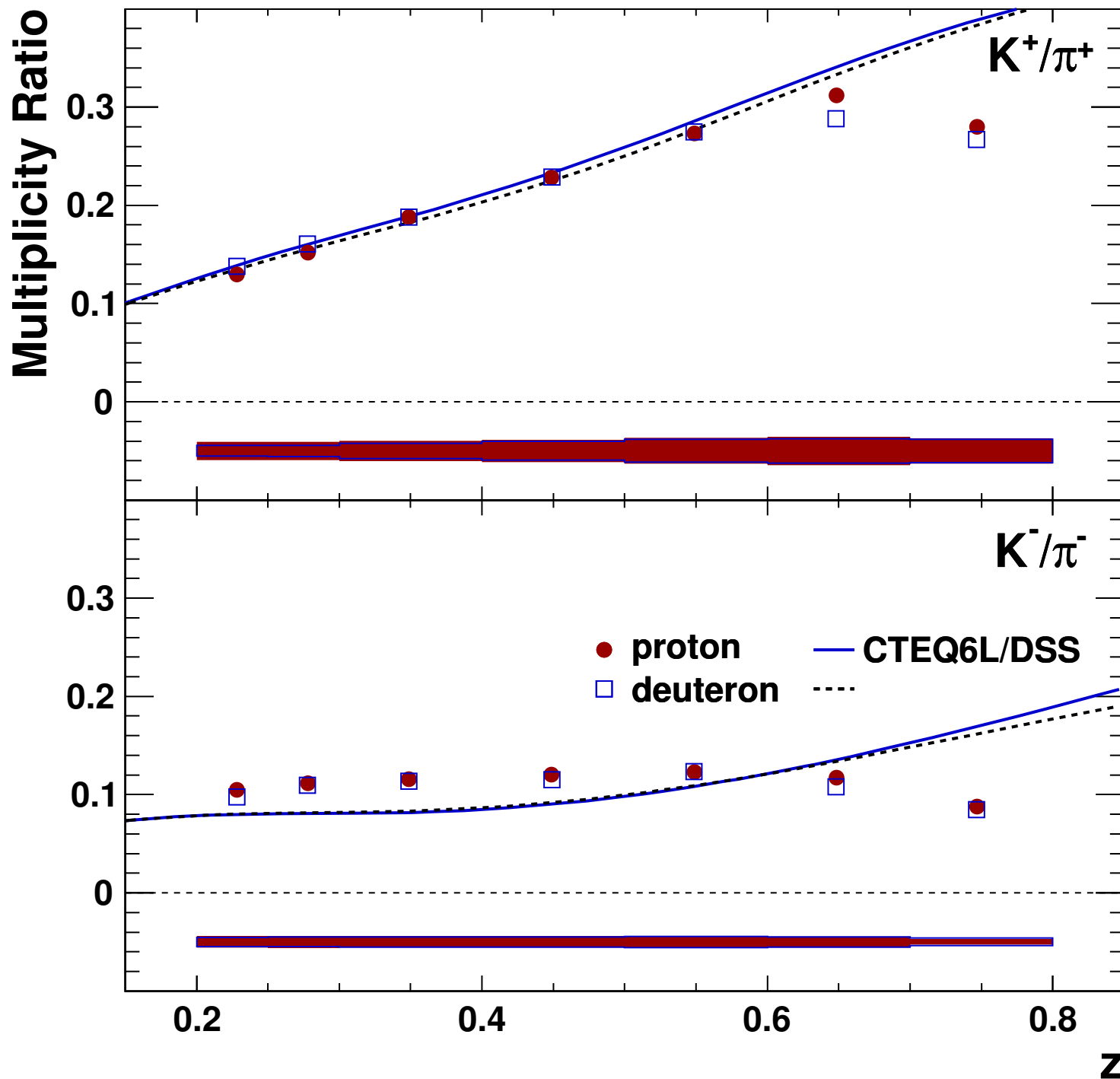


strangeness suppression:
the extra cost to produce $s\bar{s}$
compared to $d\bar{d}$
Visible at high z due to
 u -quark dominance.

strangeness suppression
larger than in previous fits

K/π and **strangeness suppression**

$$d\sigma^h \propto \sum_q e_q^2 f_q(x) \otimes \hat{\sigma} \otimes D_q^h(z)$$

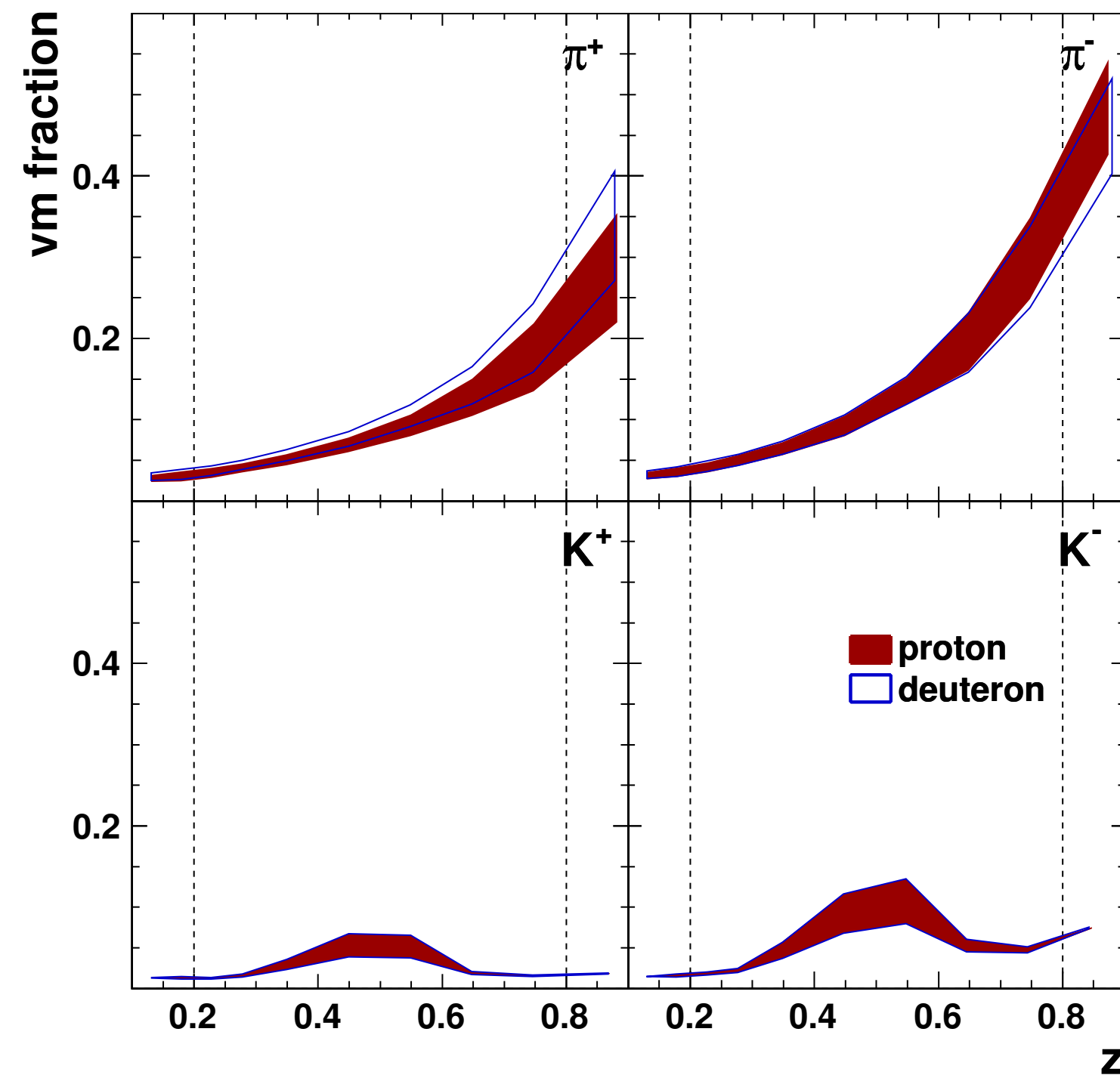


strangeness suppression:
the extra cost to produce $s\bar{s}$
compared to $d\bar{d}$
Visible at high z due to
 u -quark dominance.

strangeness suppression
larger than in previous fits

also observed during
HERMES LUND MC tuning

exclusive vector meson contamination



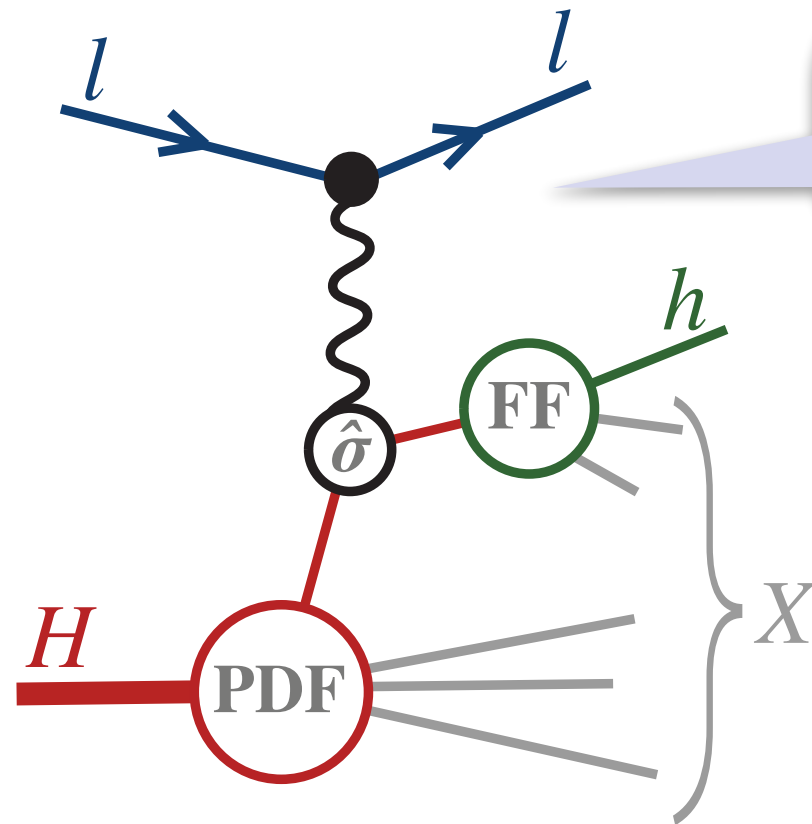
- Decay of exclusive ρ^0 and ϕ contaminate the SIDIS $\pi^\pm$ and $K^\pm$ sample
- Correction obtained from tuned PYTHIA
 - Applied at fully differential level
 - Most of the correction canceled by the inclusive correction
 - **systematic** $< 1\%$
- **results** available both **with** and **without** this correction

• This presentation: **with** VM correction

lepton-hadron processes and **universality**

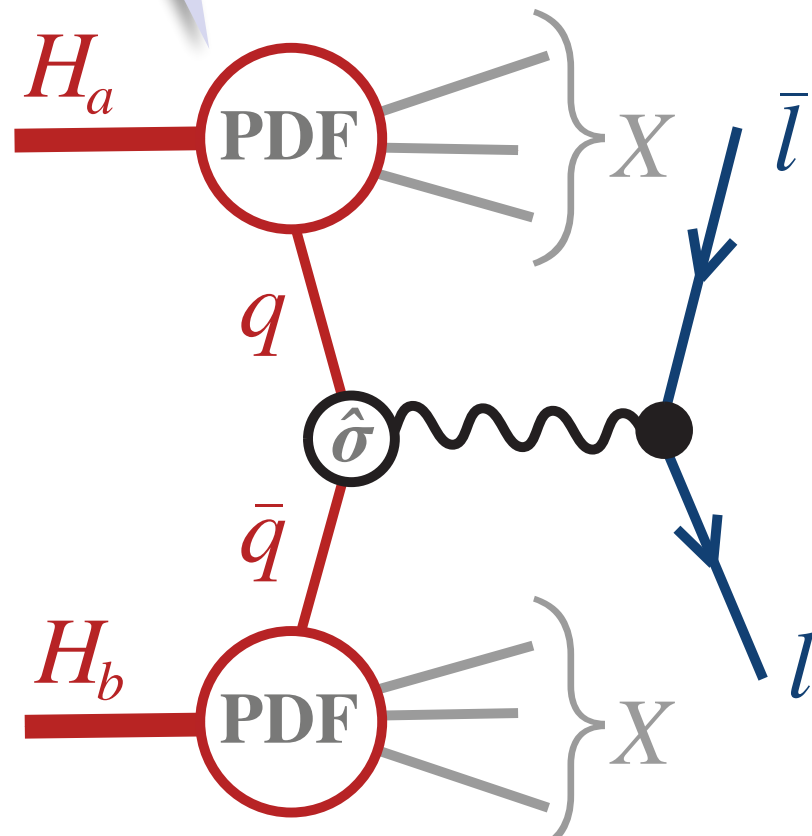
SIDIS

$$l + p \rightarrow l' + h + X$$



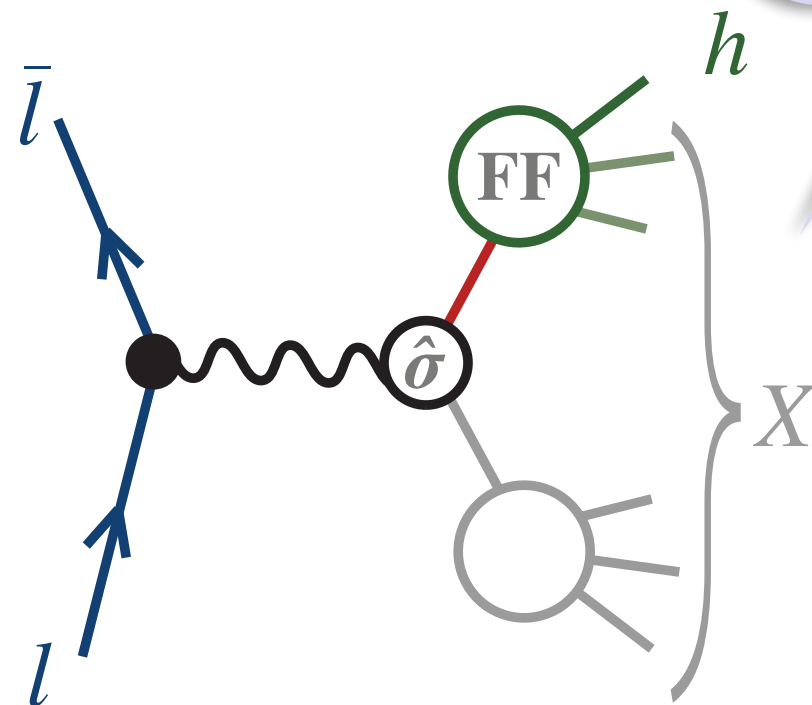
Drell-Yan

$$p + p \rightarrow l + \bar{l} + X$$



SIA

$$l + \bar{l} \rightarrow h + X$$



lepton-hadron processes and **universality**

