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

Sylvester Johannes Joosten

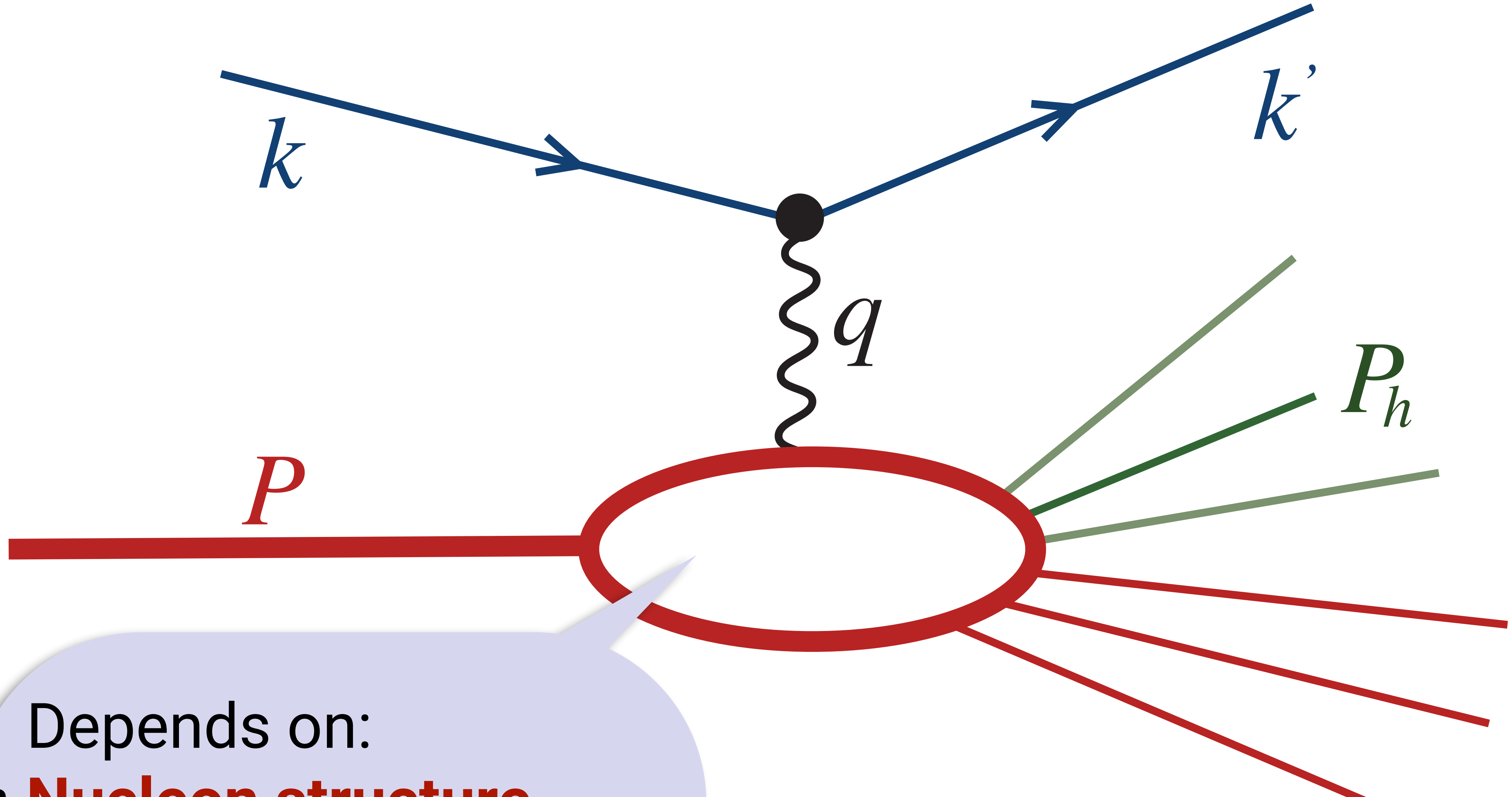
ECT*, April 11, 2016

TEMPLE UNIVERSITY

hermes

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

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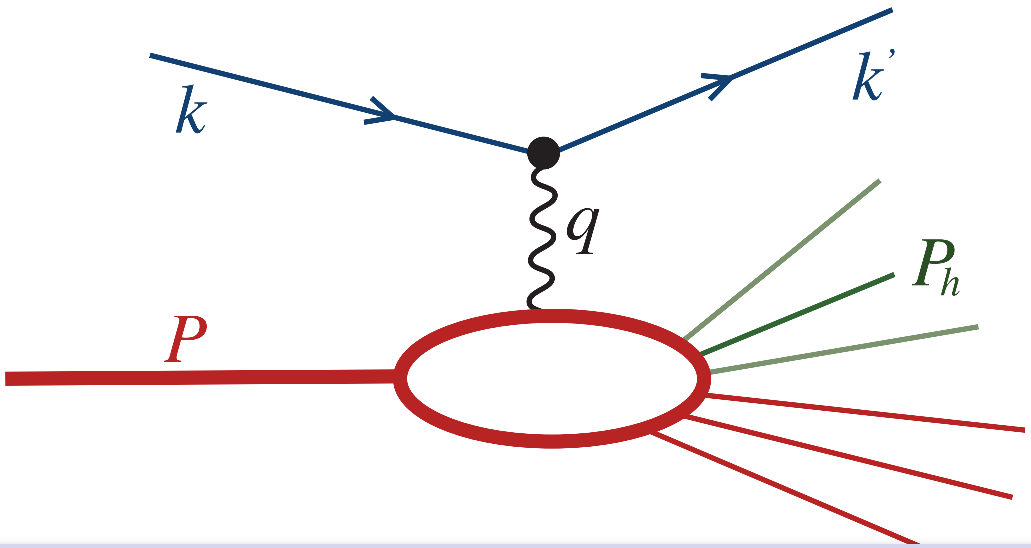


Kinematic variables (SIDIS)

- fractional hadron energy

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

- hadron transverse momentum

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

- 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

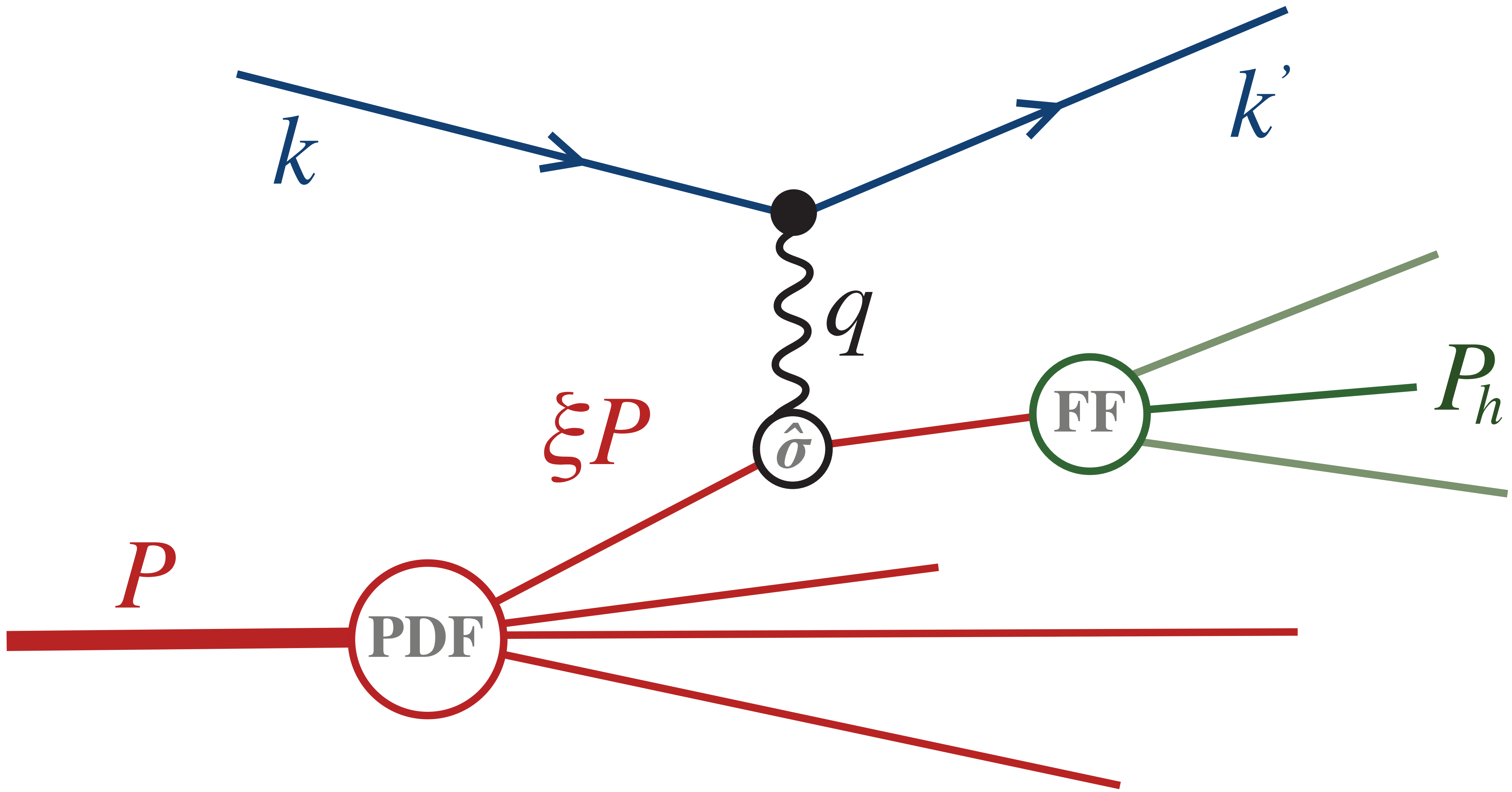
$$x = \frac{Q^2}{2P \cdot q}$$

- fractional photon energy

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

factorization: separation of distance scales

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



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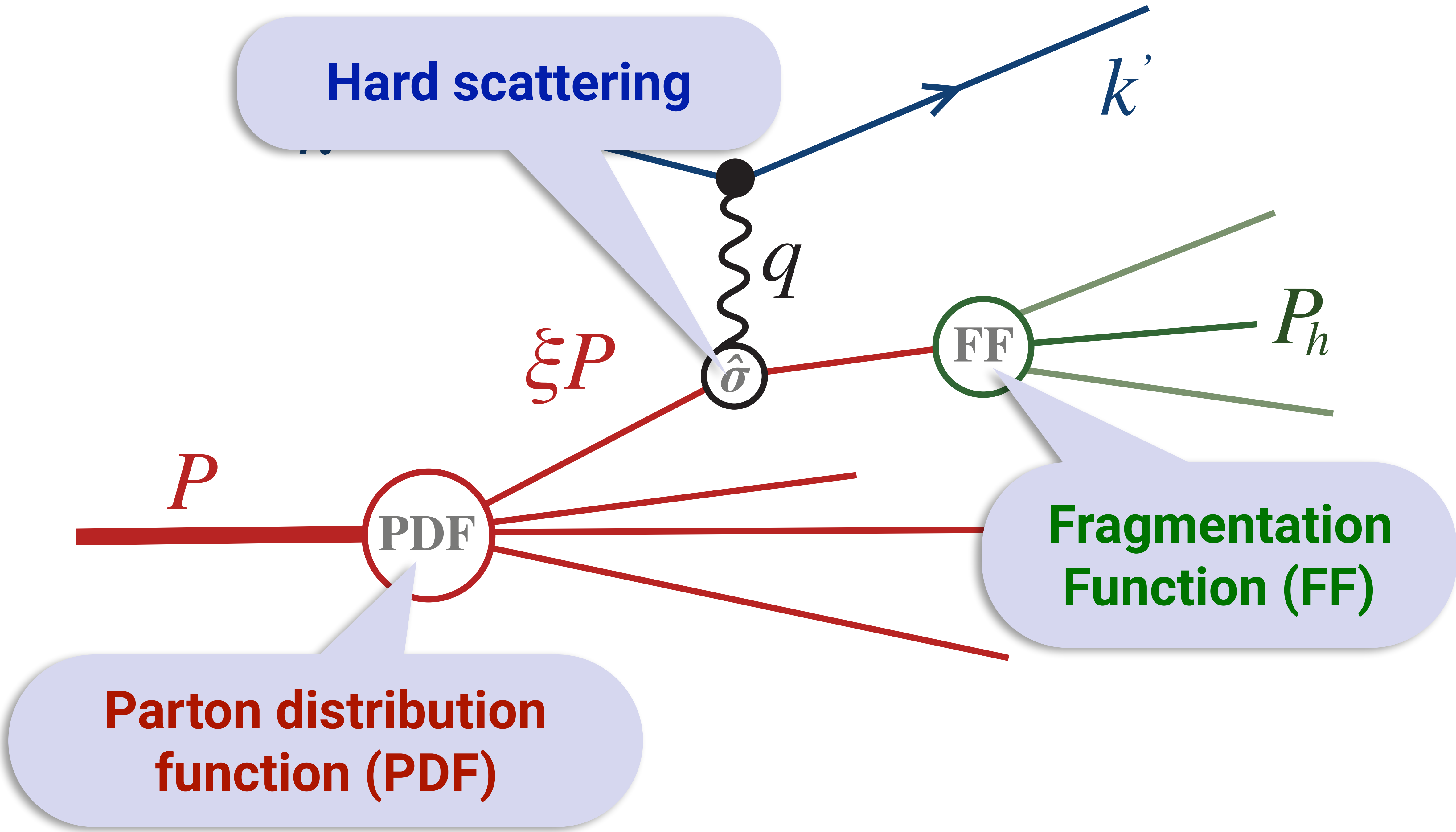

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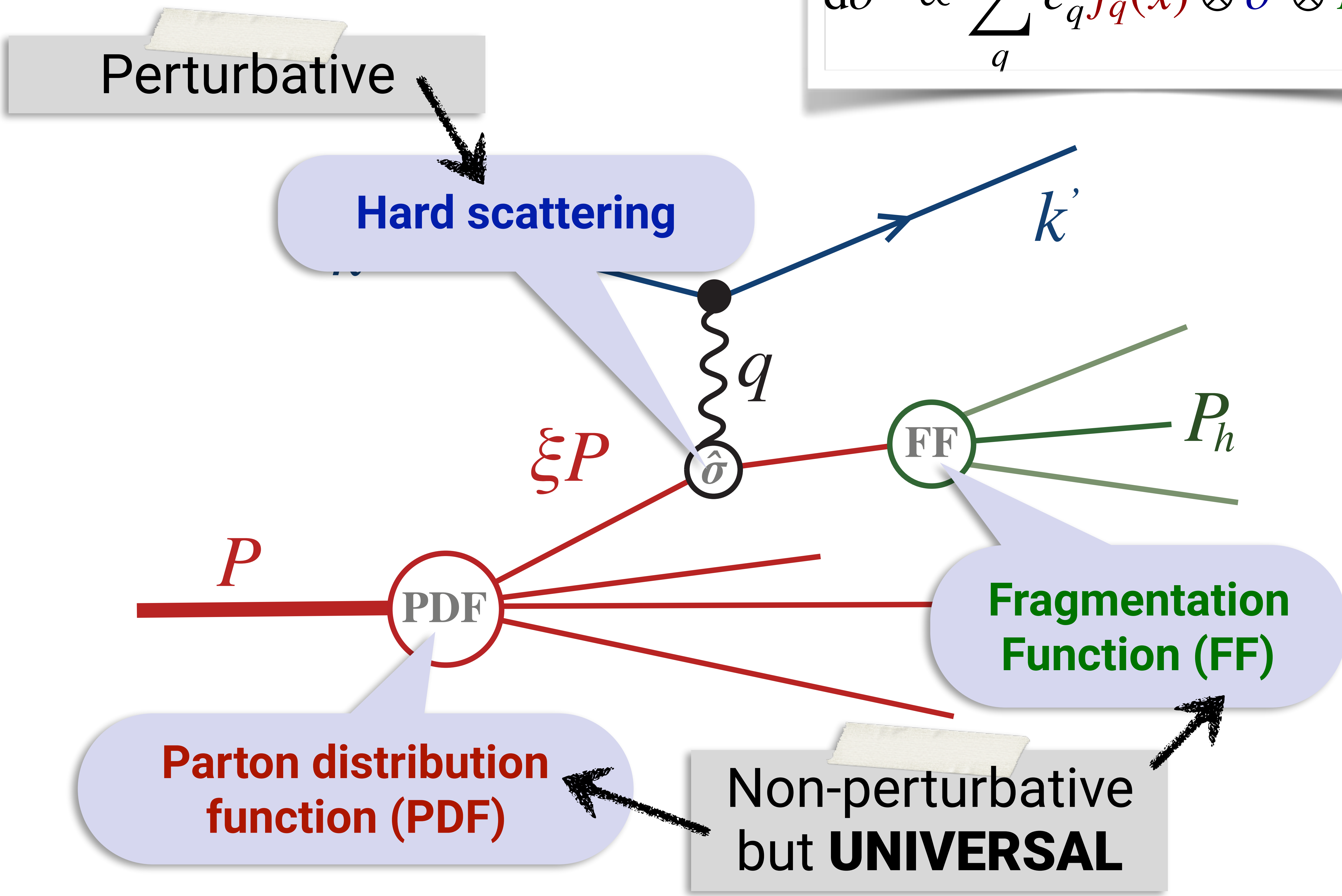
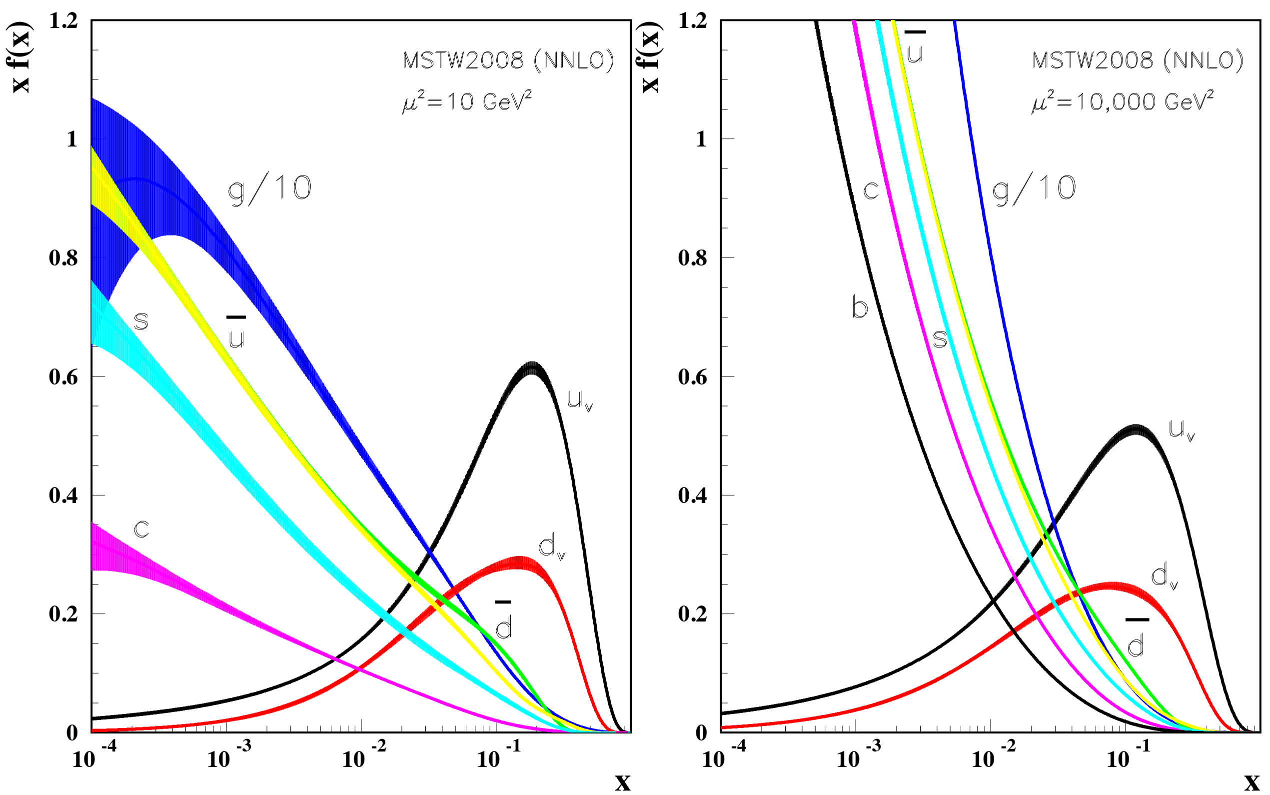


parameterizations



Knowledge of **PDFs**:

→ Well constrained

→ Up to **NNLO**

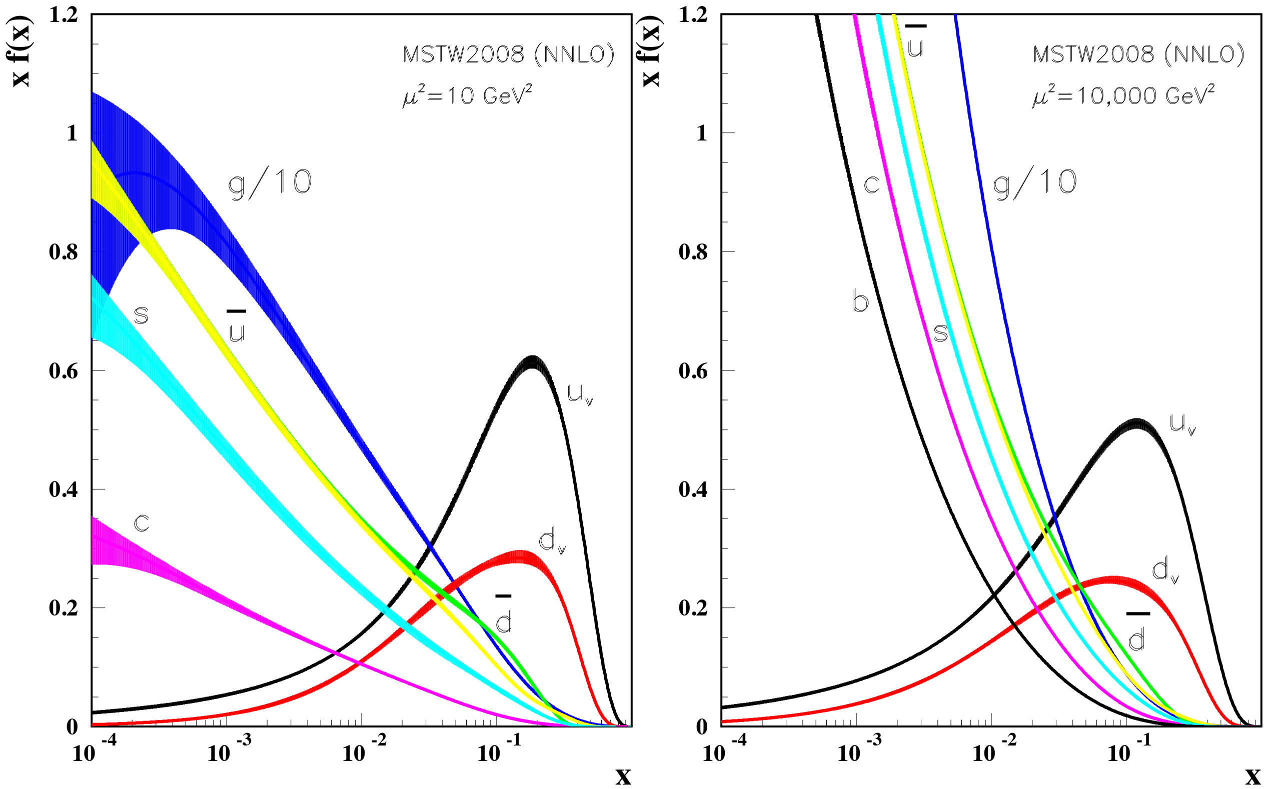
→ Recent **parameterizations**

(CTEQ6/CT14, MSTW2008, HeraPDF, NNPDF)

agree within uncertainties

→ calculable in lattice QCD

parameterizations



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Knowledge of **FFs**:

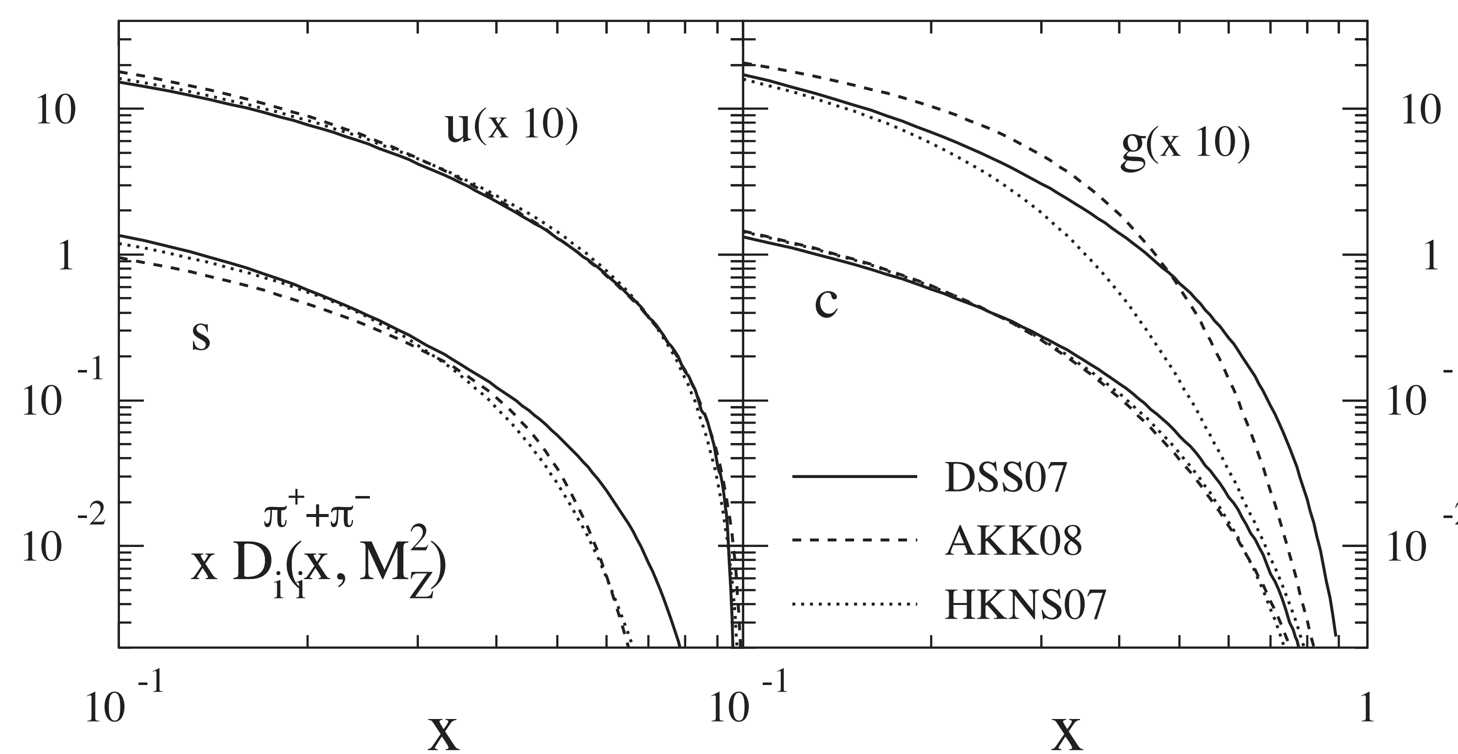
→ Mostly from SIA (**no individual quark** contributions)

→ Up to **NLO**

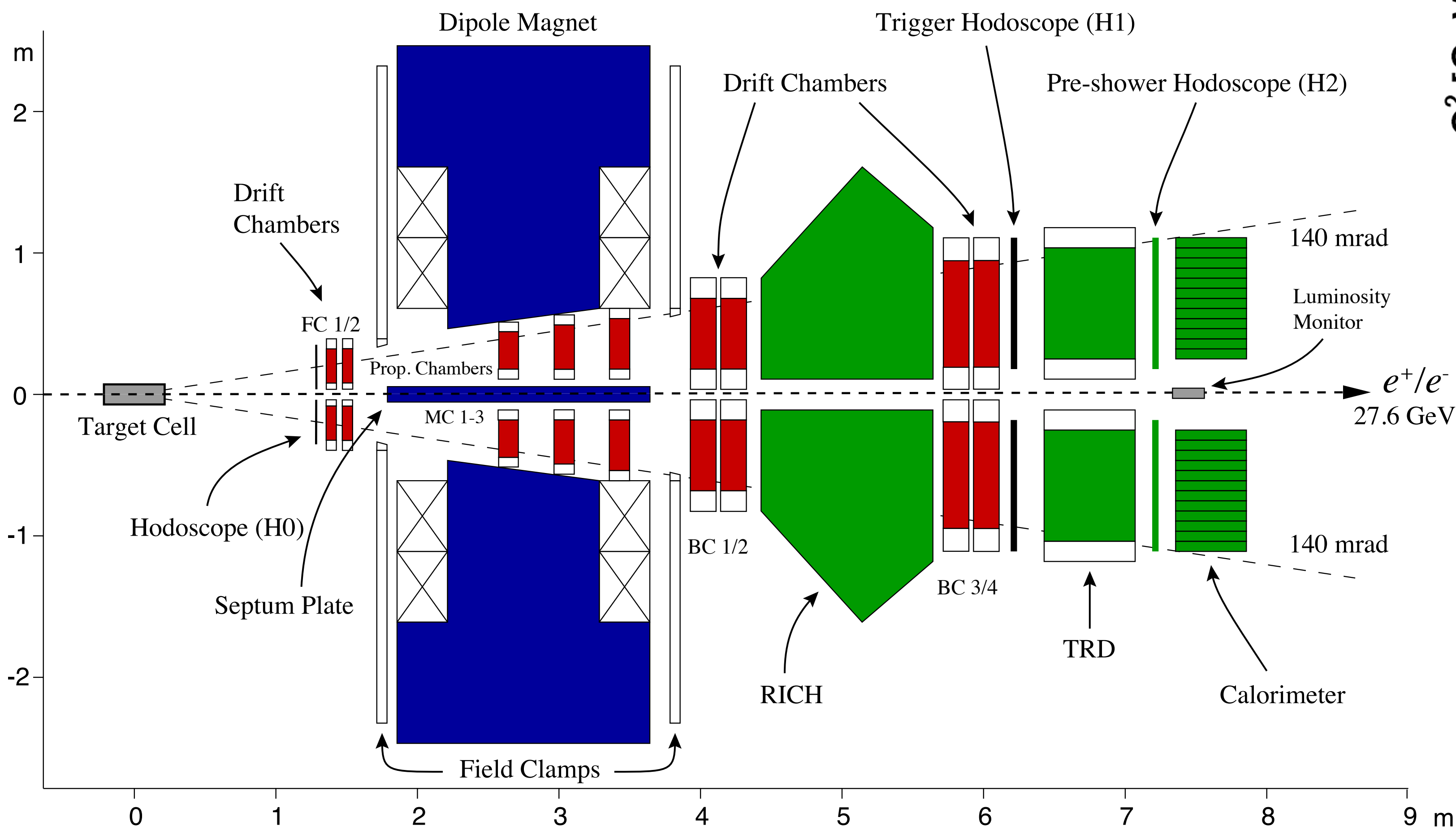
→ Leading **parameterizations**

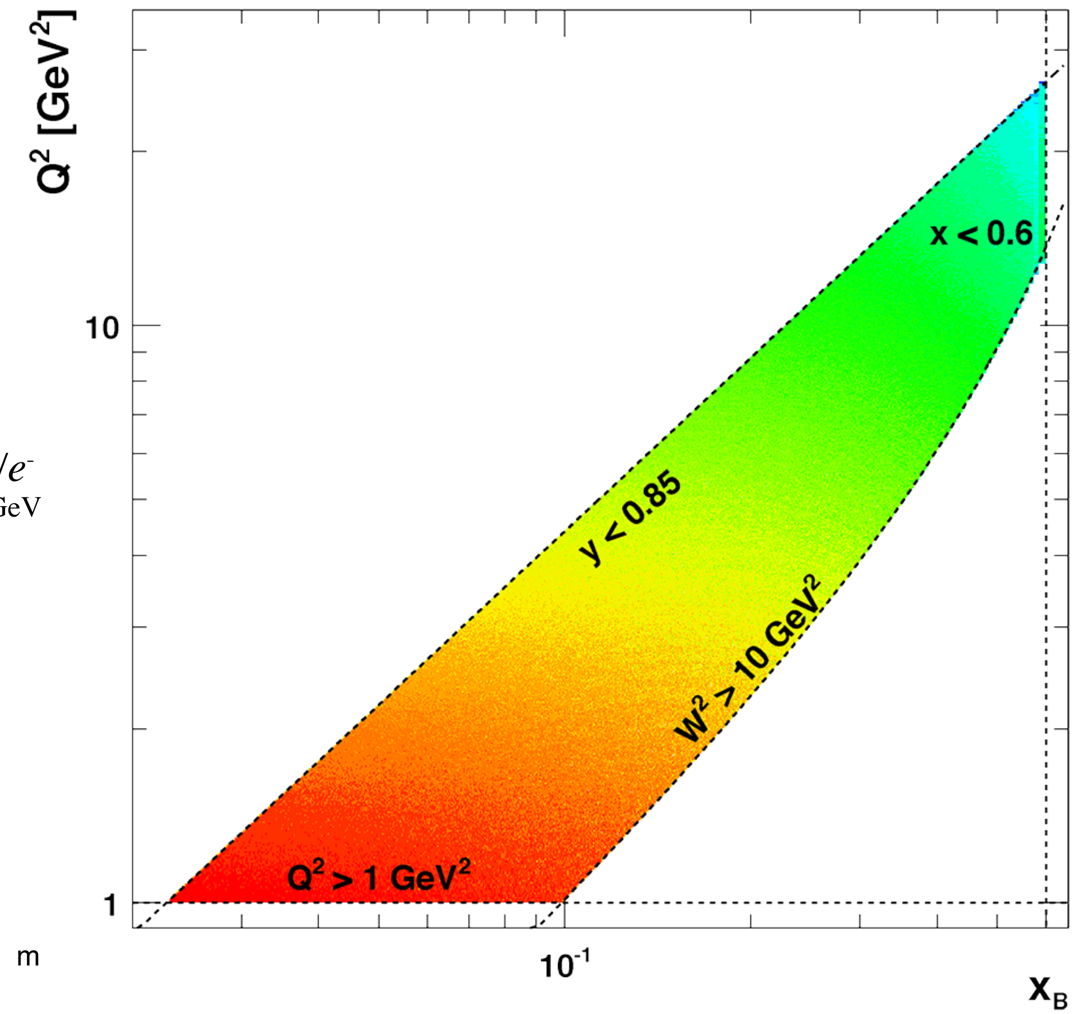
(DSS07/AKK08/HKNS07) **differ**

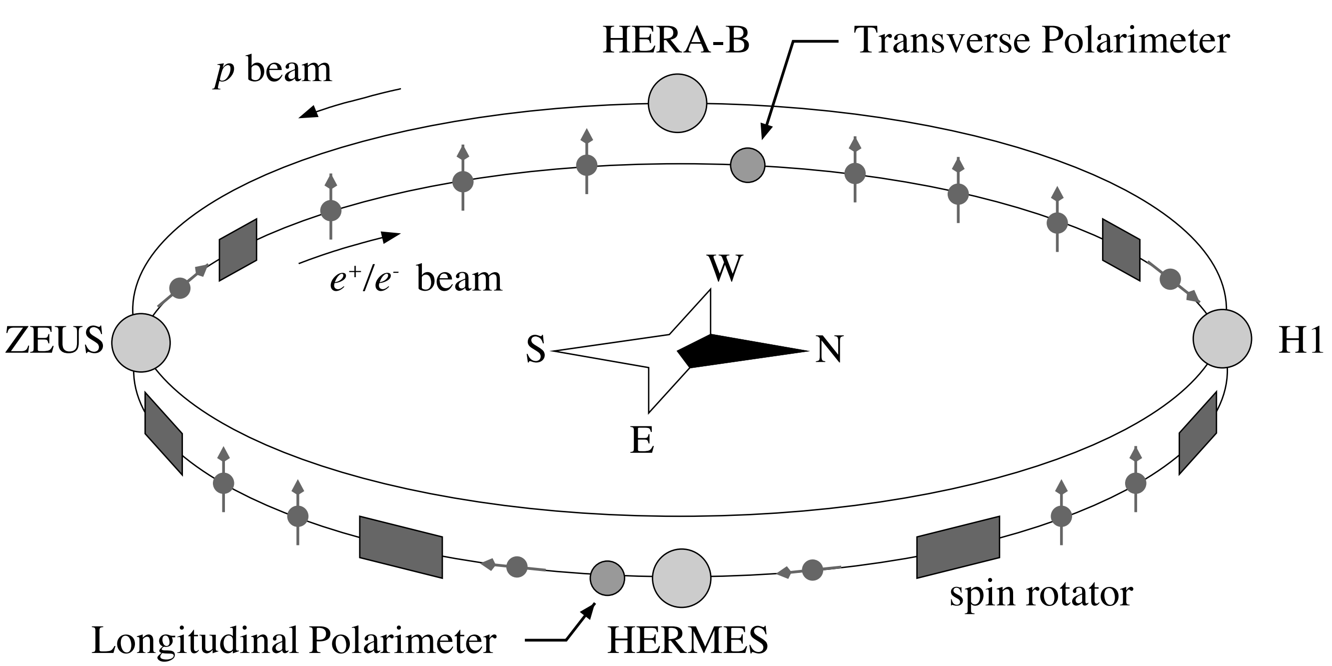
→ Room for **improvement!**



The **HERMES** experiment



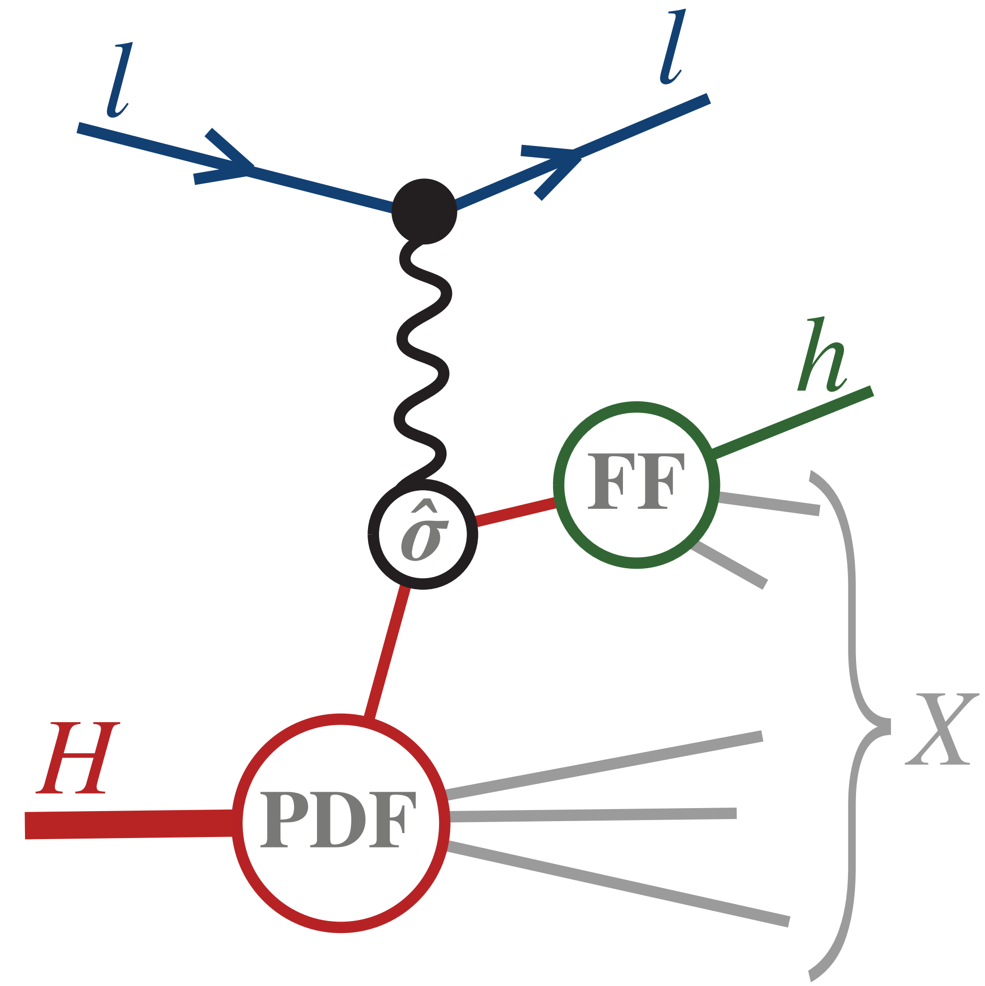




- HERA 27.6 GeV $e^{\pm}$ beam
- Forward spectrometer
  - → Pure H and D atomic gas target
  - → Clean lepton-hadron identification
  - → Very good pion-kaon separation with the RICH

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.



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

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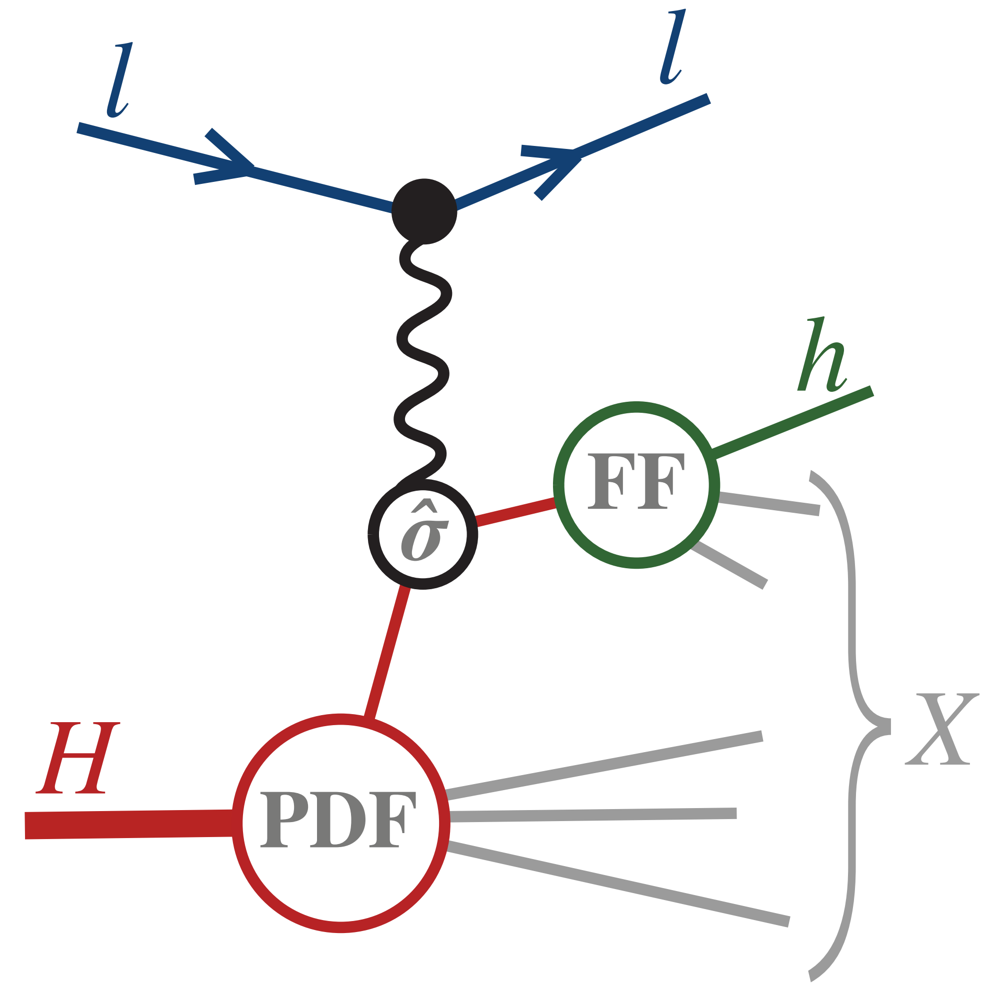

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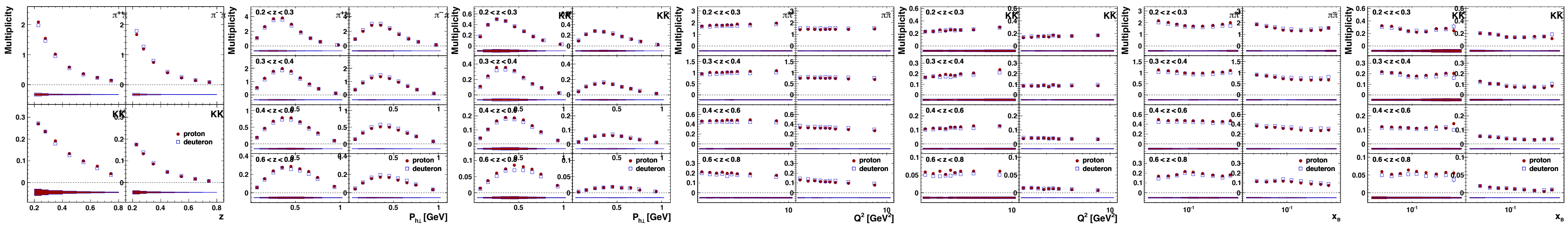
SIDIS Multiplicities: **HERMES results**

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

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



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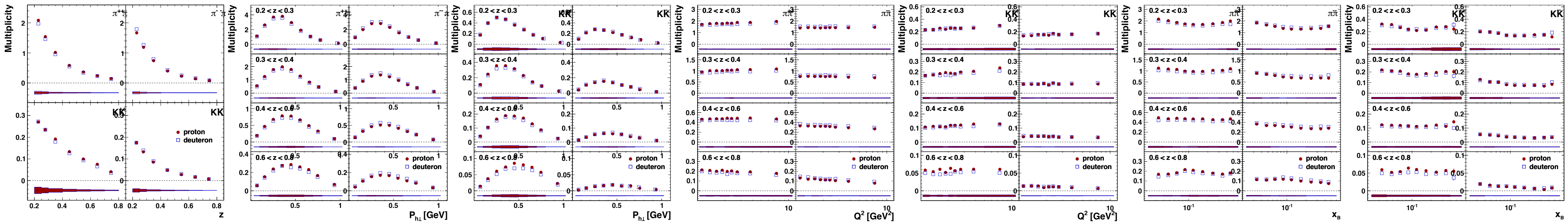

High precision requires **sophisticated analysis**:

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

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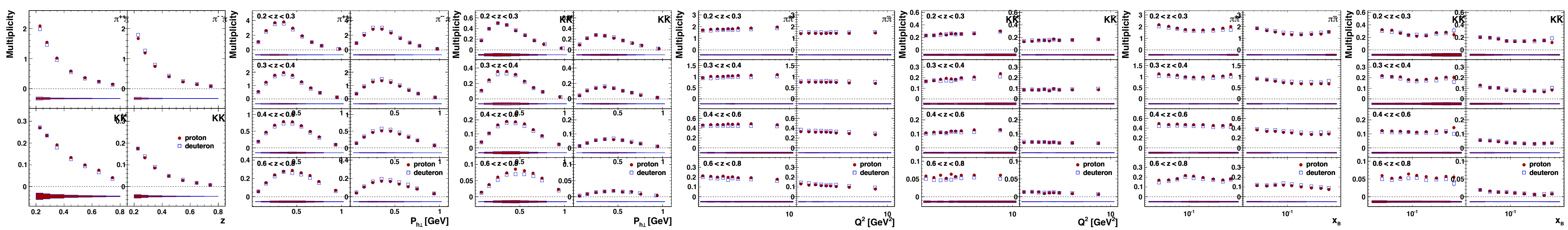

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Final results in 4π Born (one-photon exchange)

Systematics dominated

Smearing-unfolding in SIDIS

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

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

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Detector resolution

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

Radiative effects

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SMEARING MATRIX

Radiative effects

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SMEARING MATRIX

- Solve by **matrix inversion**
- Calculate from **Monte-Carlo**
  - model independent if:
    - acceptance flat within bin
    - cross section flat within bin

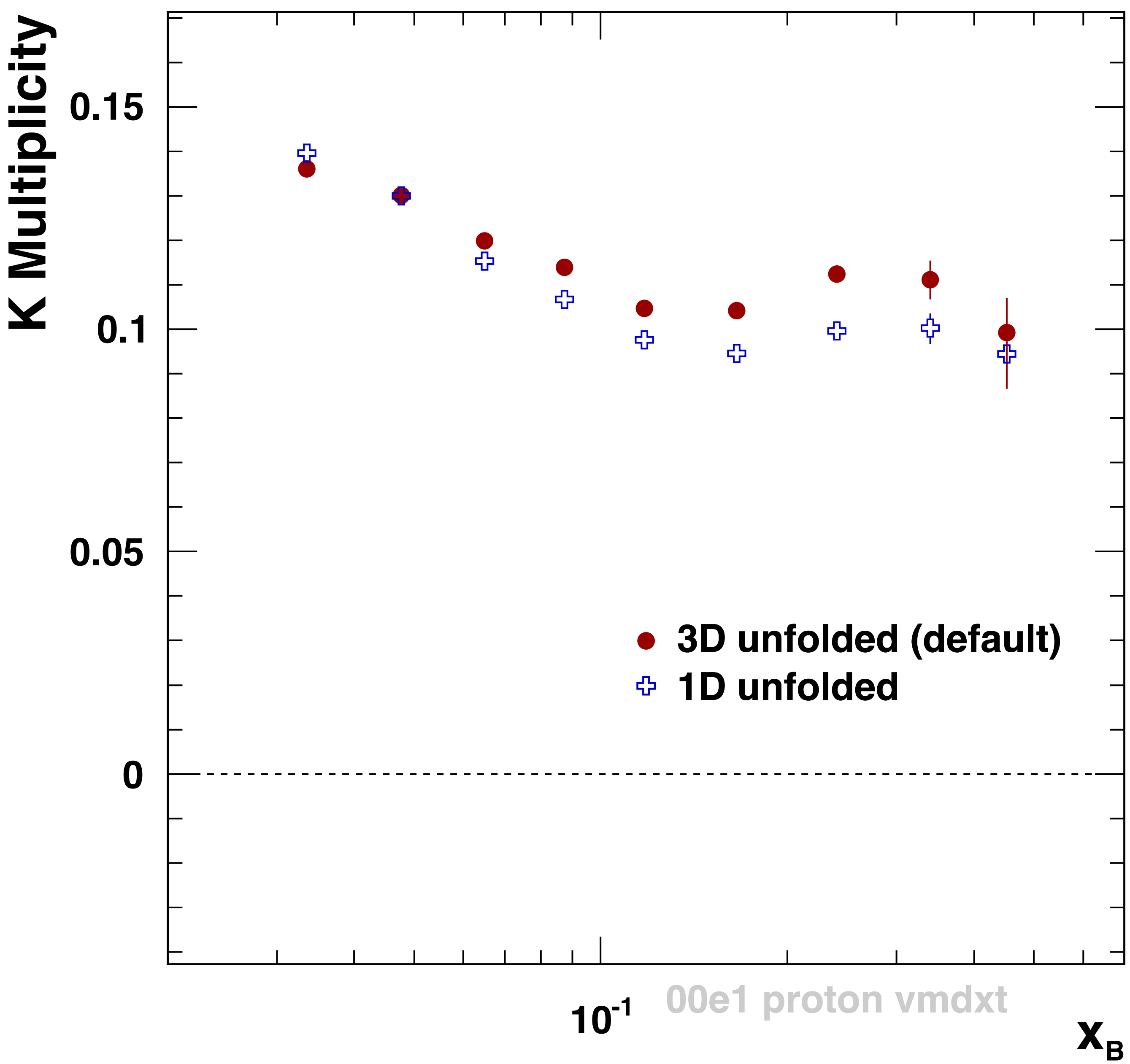
Radiative effects

Limited acceptance

Detector resolution

Background

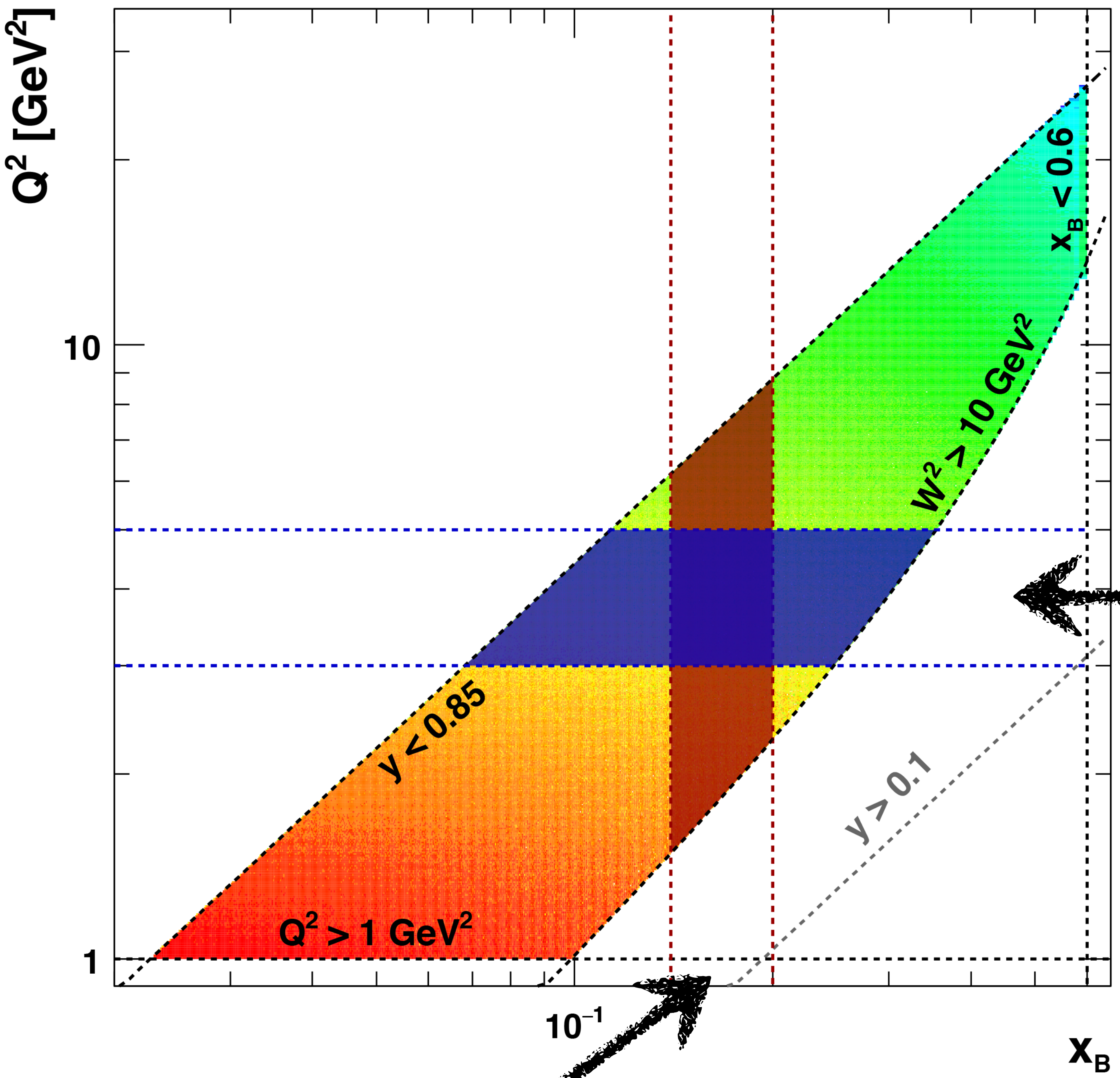
Importance of a **multidimensional approach**



- Neglecting to unfold in z **changes the x dependence dramatically**

- cf: Phys.Lett. B666 (2008) 446-450, Phys.Rev. D89 (2014) no.9, 097101

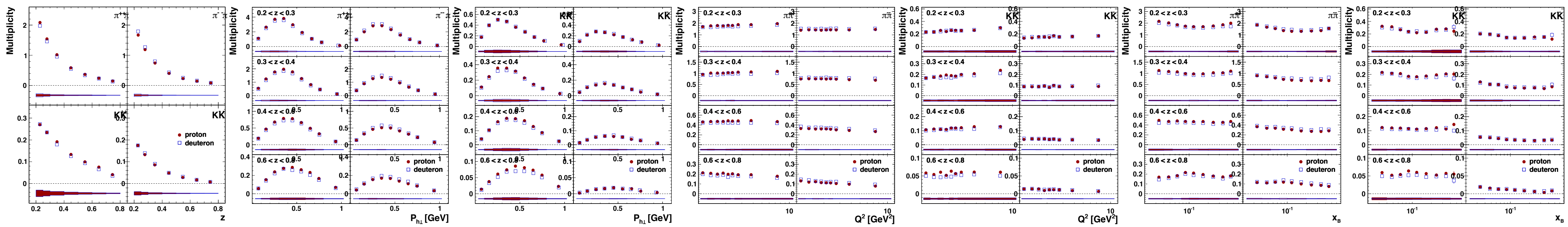
Integrated (not average)



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

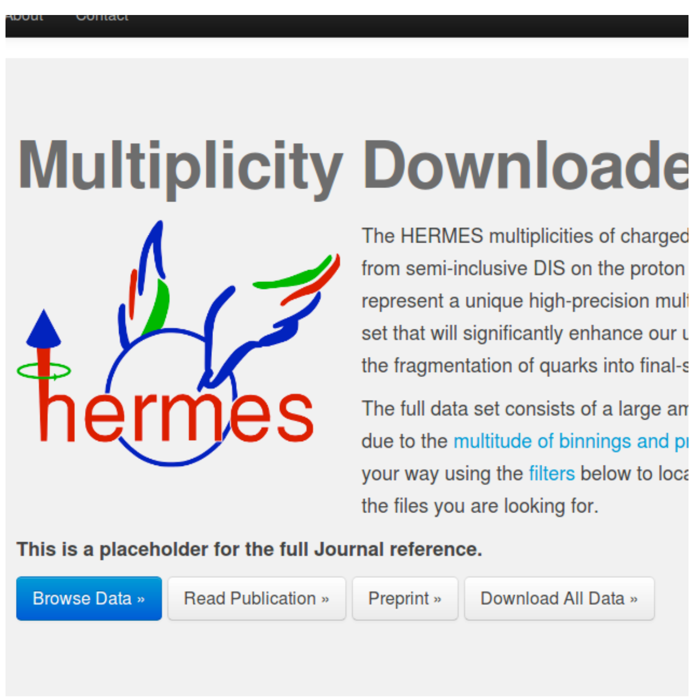
$$M_H^h(x, z, P_{h\perp}) \equiv \frac{\int dQ^2 d\phi_h \, n^{\mathrm{SIDIS}}(\dots)}{\int dQ^2 \, n^{\mathrm{incl}}(\dots)}$$

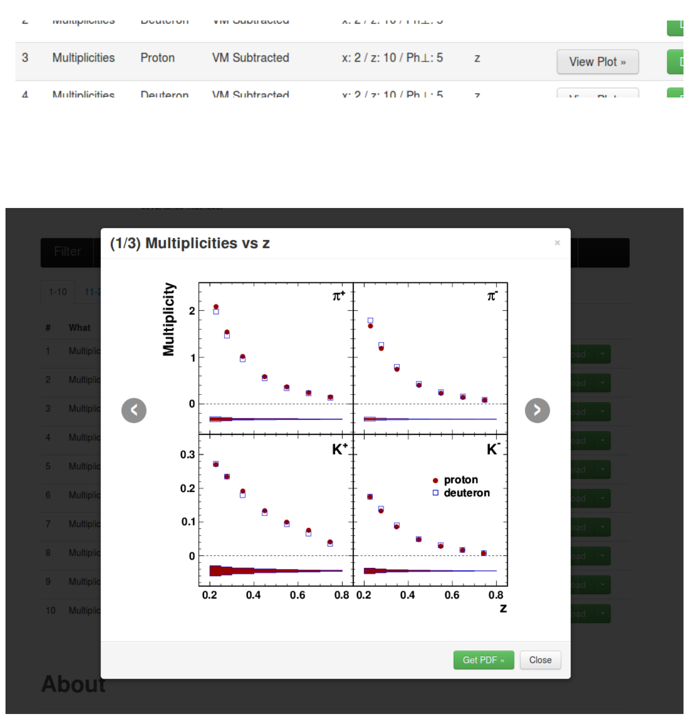
the multiplicity **website**

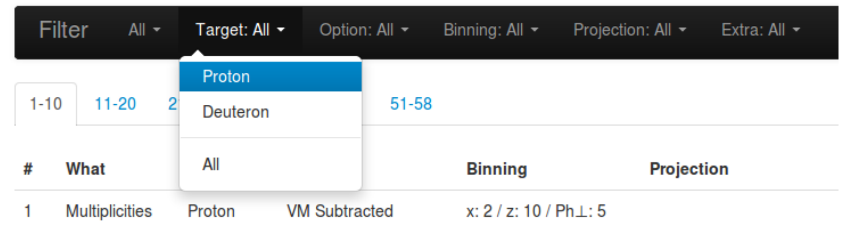


A. Airapetian et al, Phys. Rev. D 87 (2013) 074029

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







Download the final results

1D **comparison with LO** predictions

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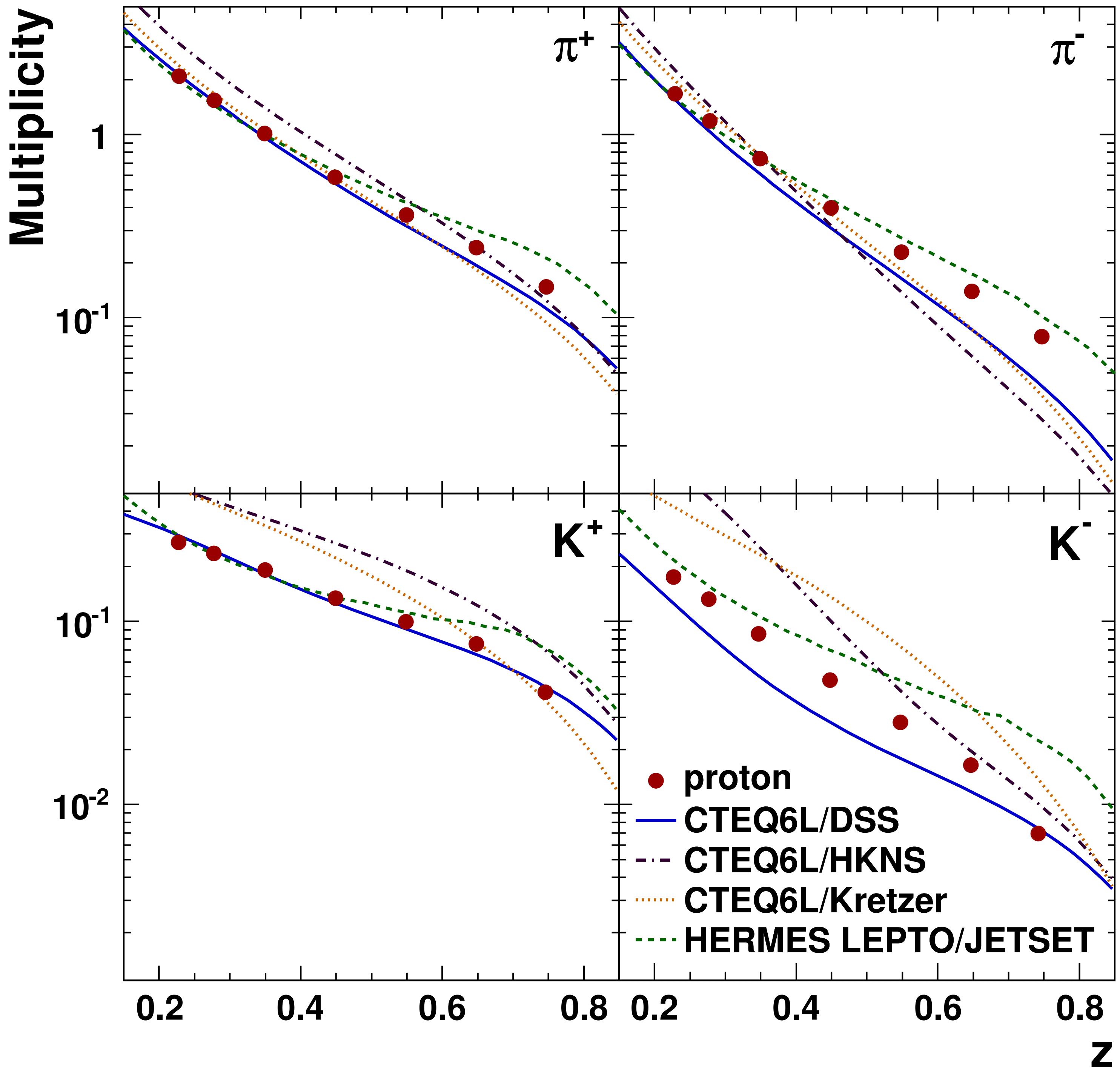

- **DSS/HKNS/Kretzer: FFs**
- **CTEQ6L: PDFs**

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

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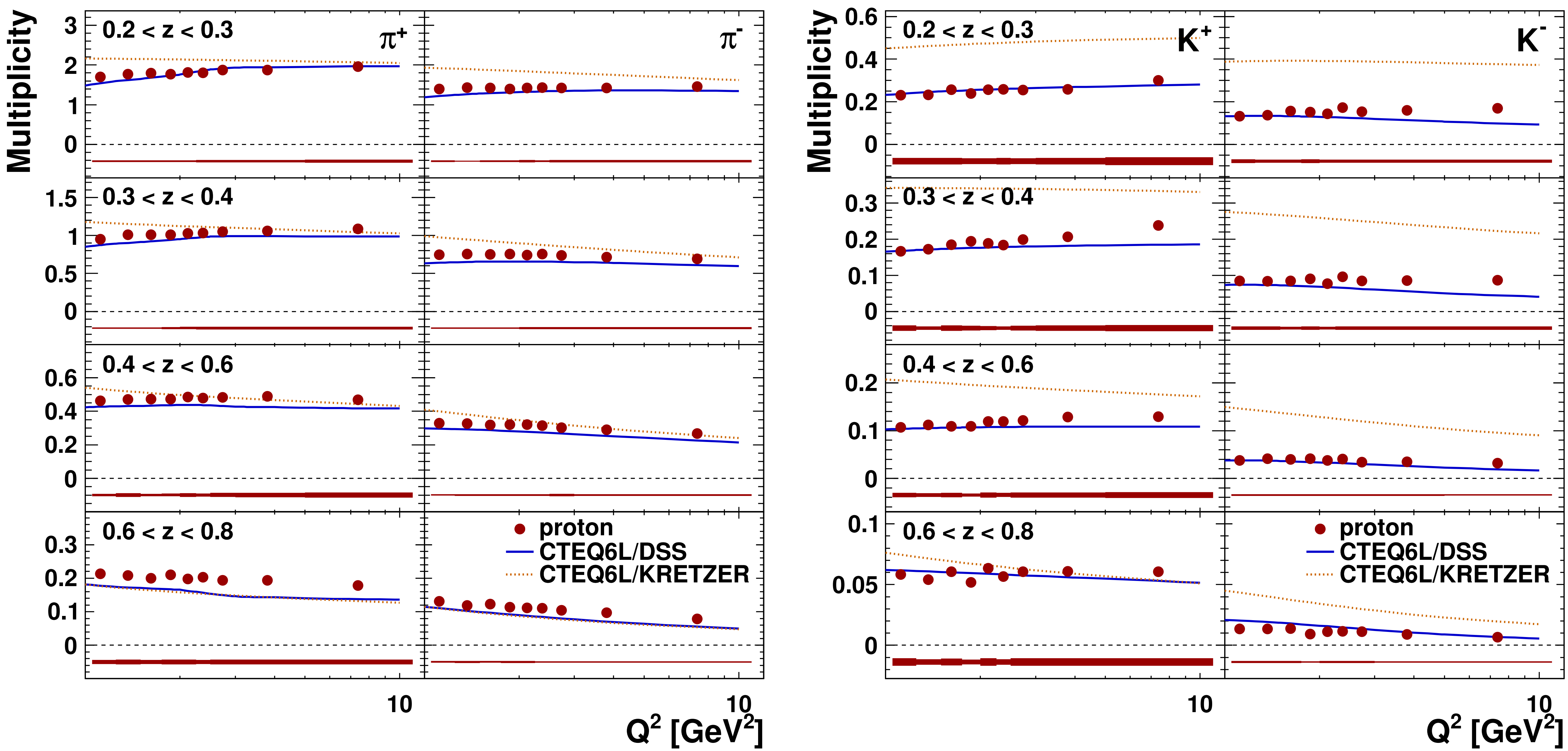
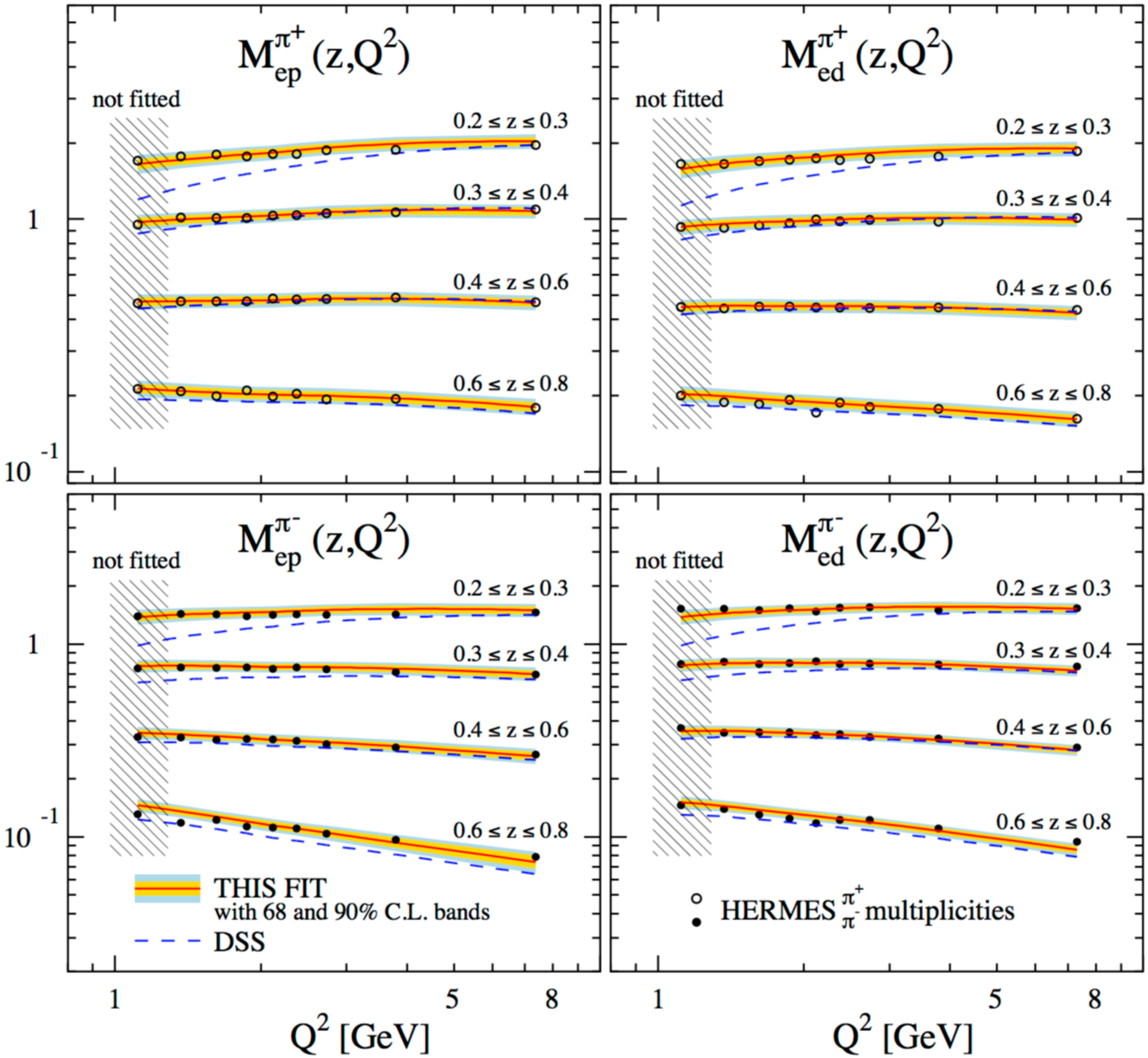


Next Generation of FFs

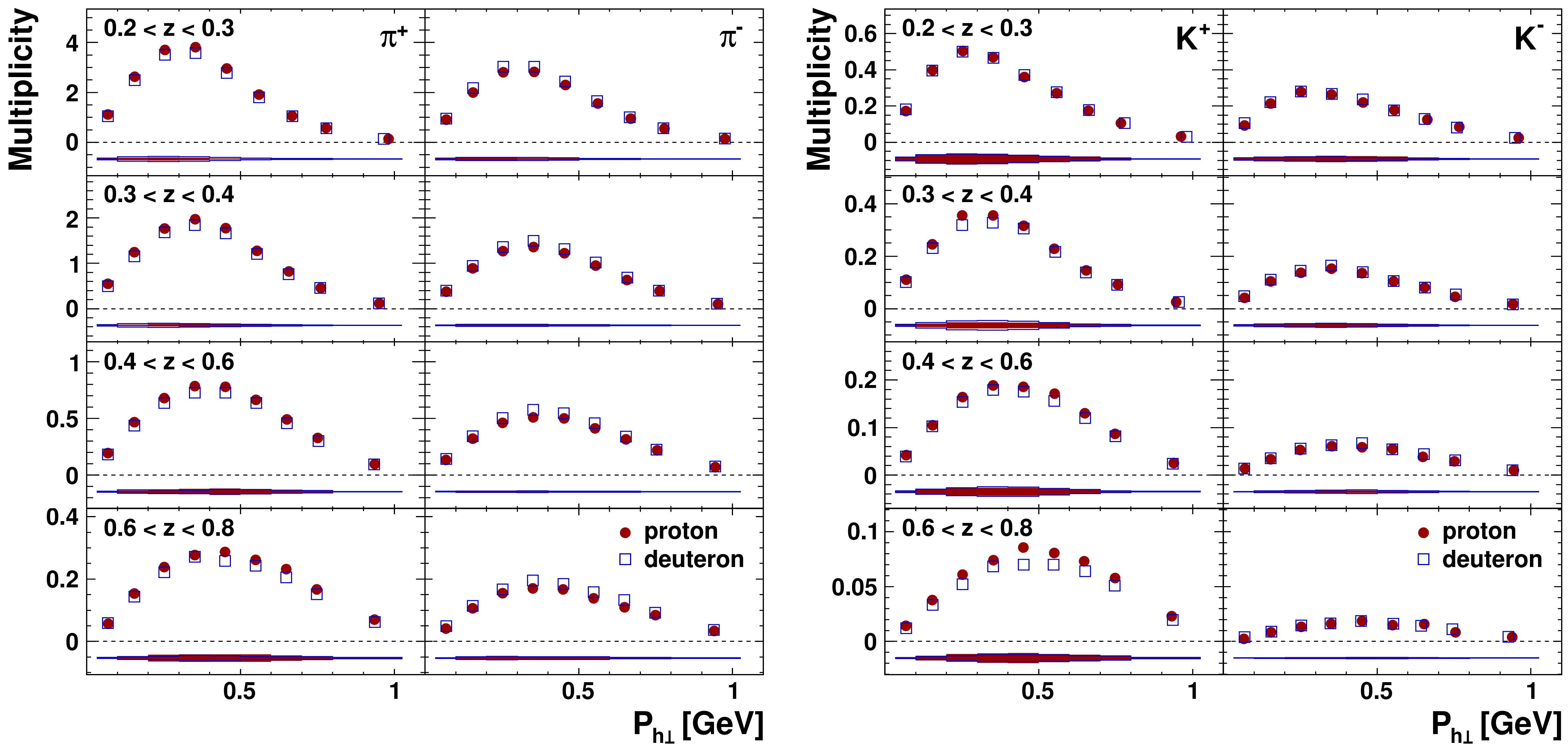


de Florian *et al.*, Phys.Rev. D91 (2015) no.1, 014035

"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

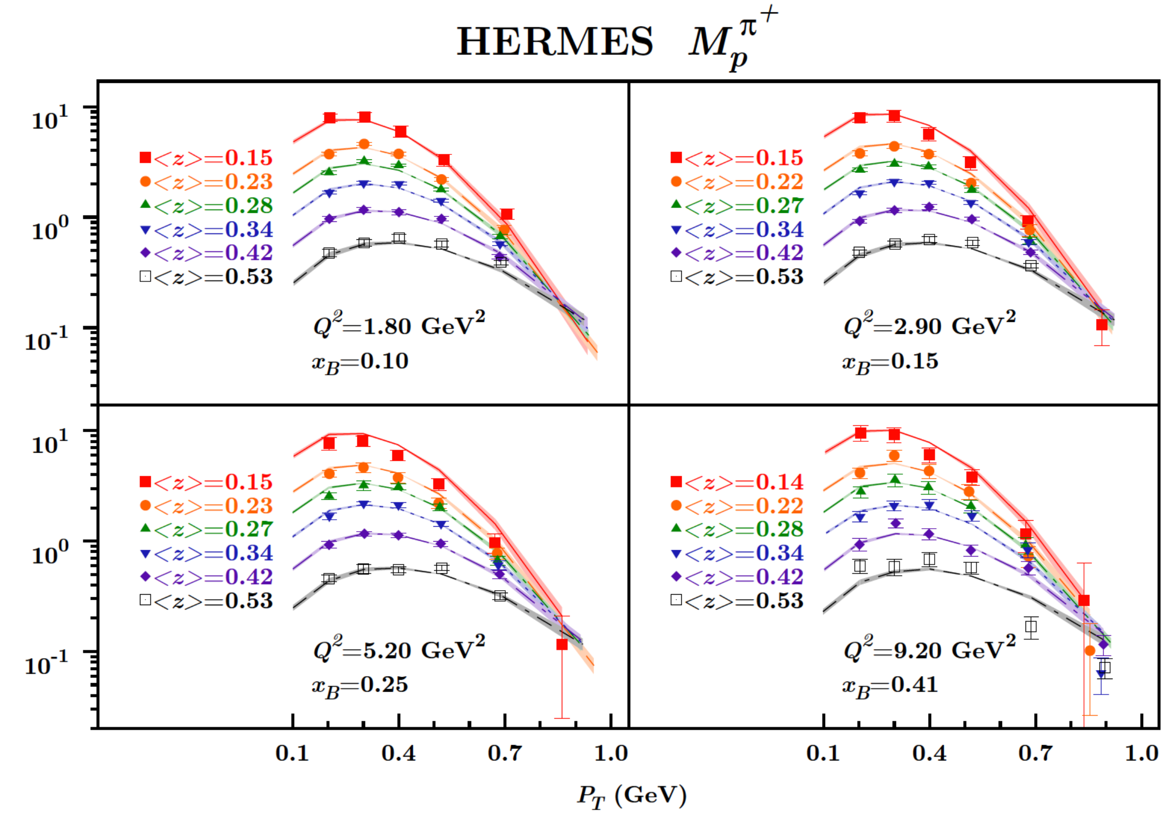


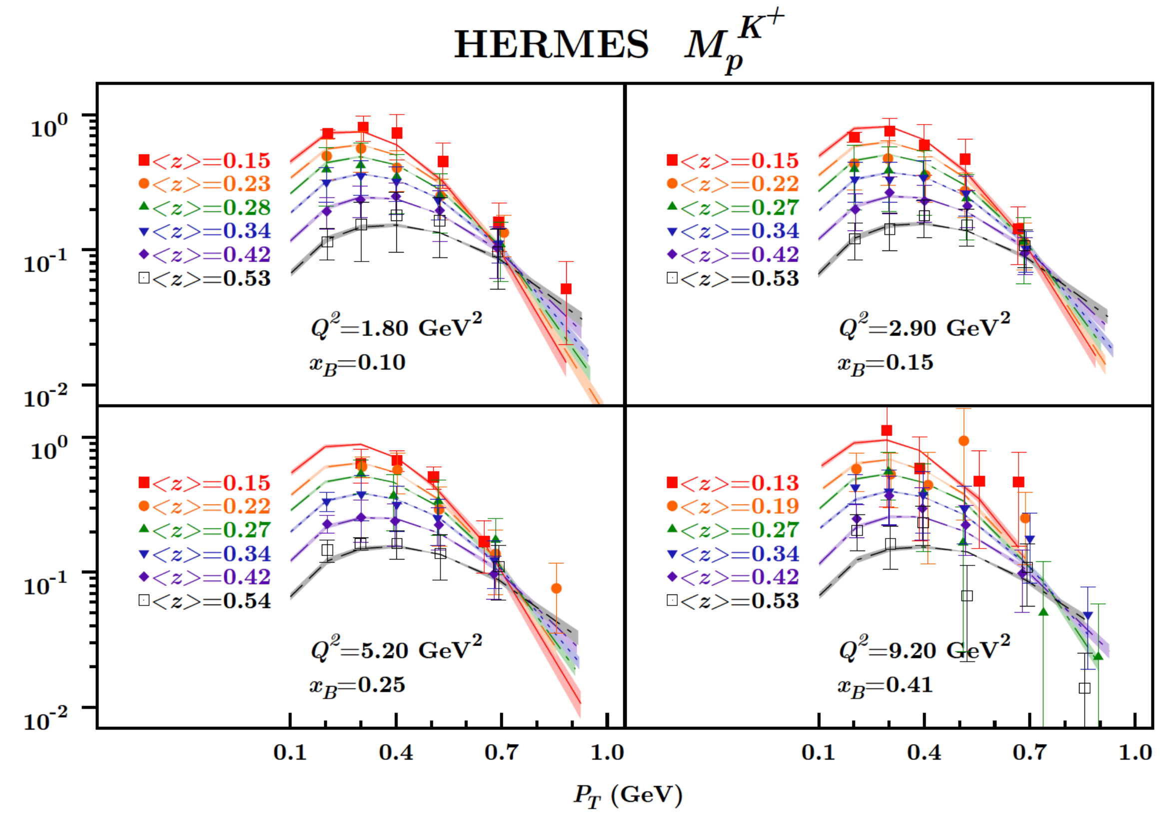
Superficially consistent with
Gaussian ansatz

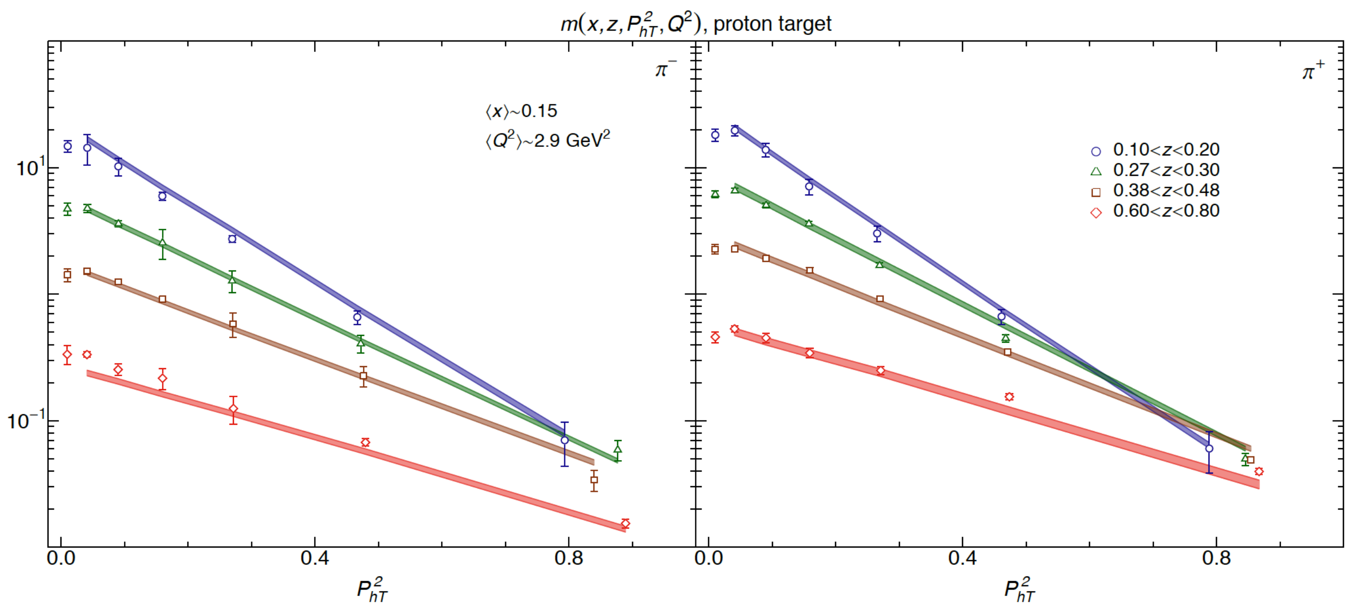
Recent TMD fits

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

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

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

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$\Updownarrow$

Complications when Q not $\gg M$

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

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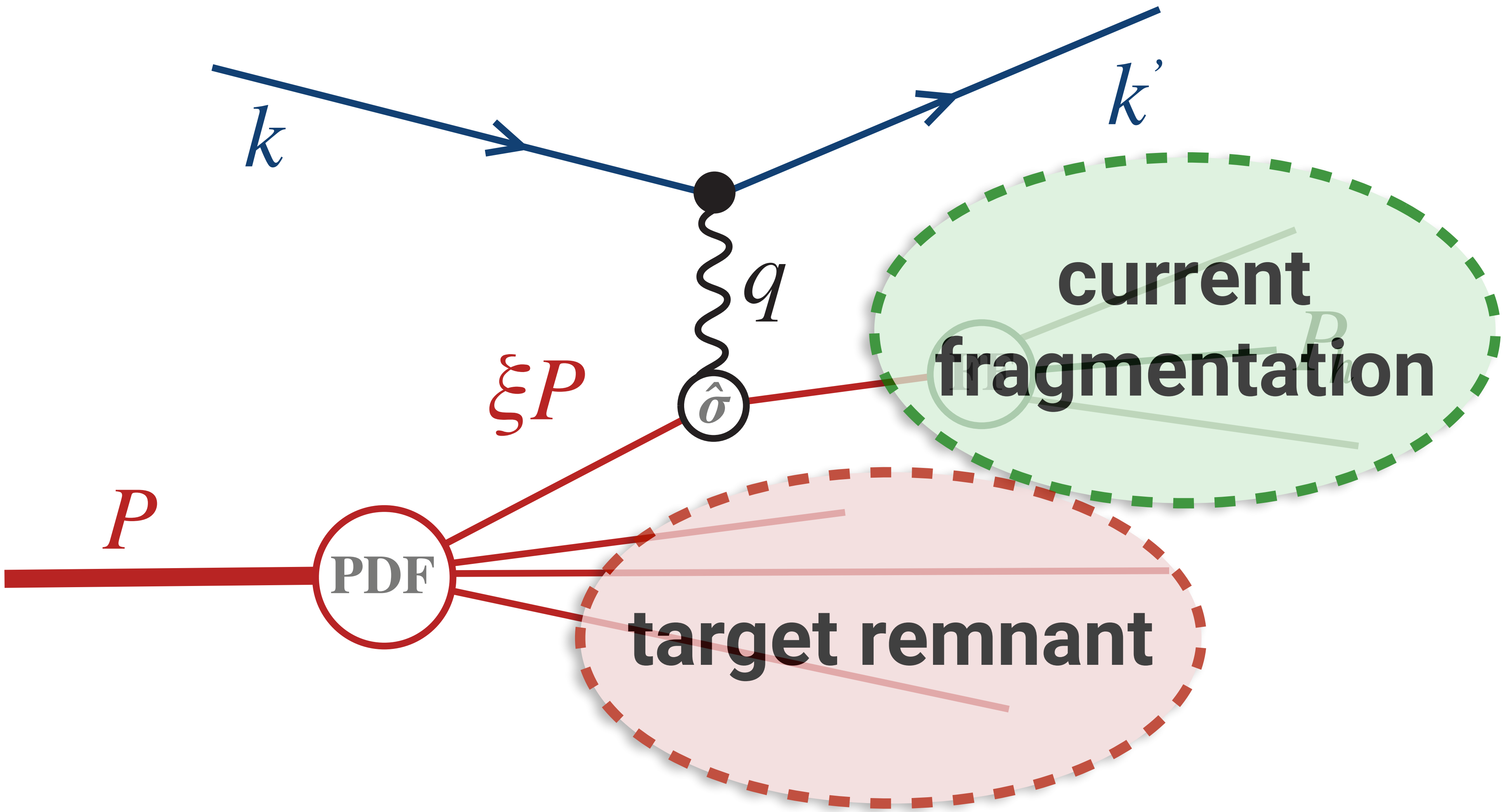
Only break factorization if not properly accounted for

Simple probabilistic interpretation impossible

Limits on factorization: target remnant

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

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



Limits on factorization: target remnant

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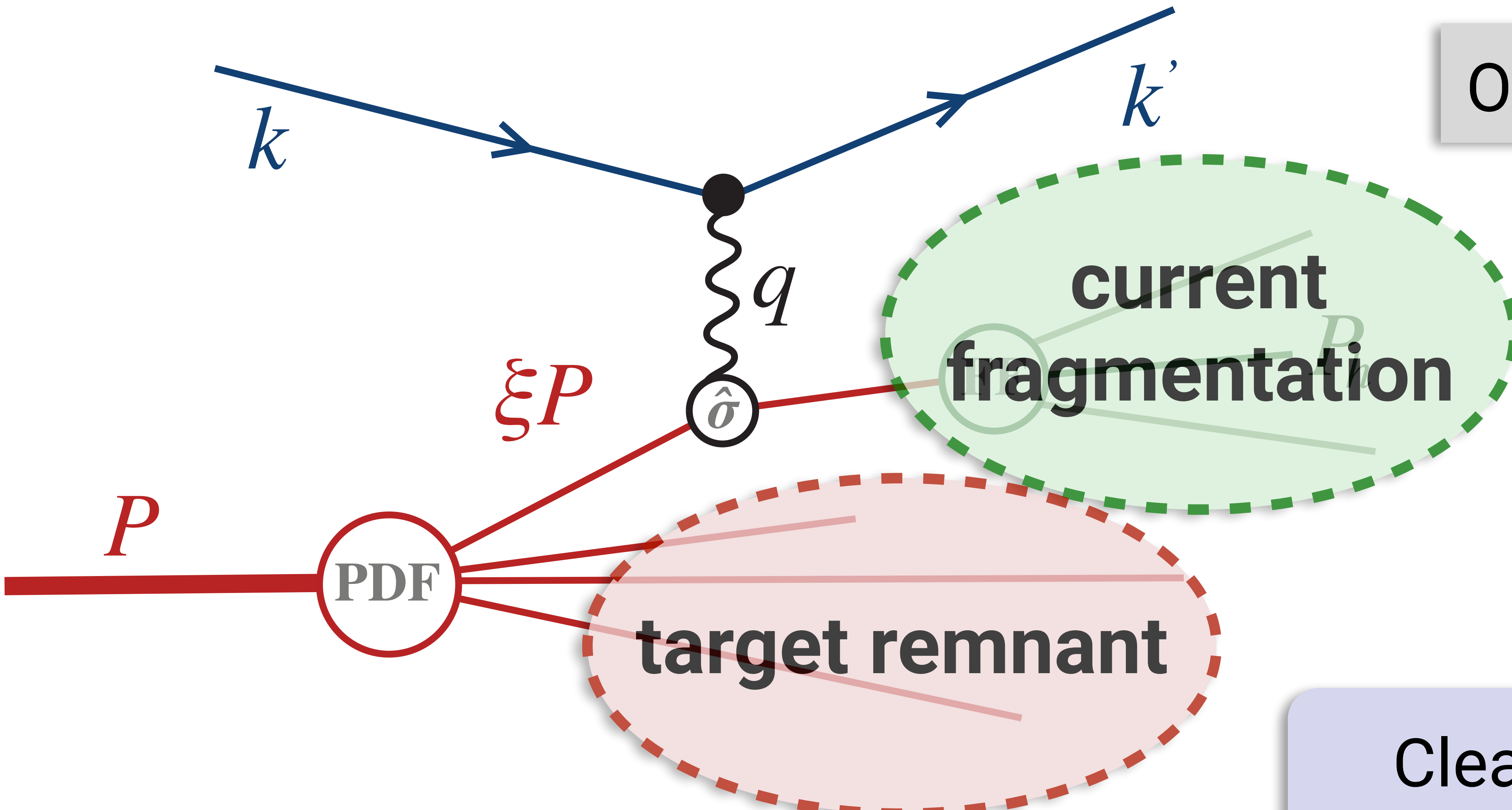
Only a function of z

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



Clear **experimental separation** of **current** and **target** "jets" required

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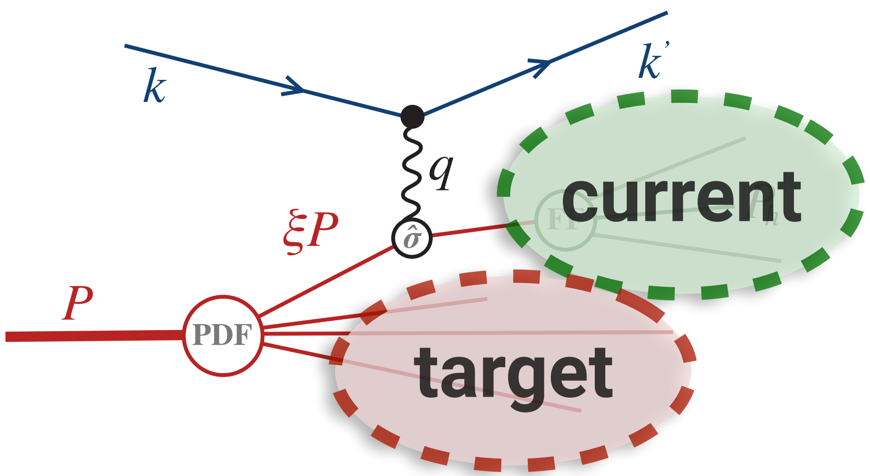

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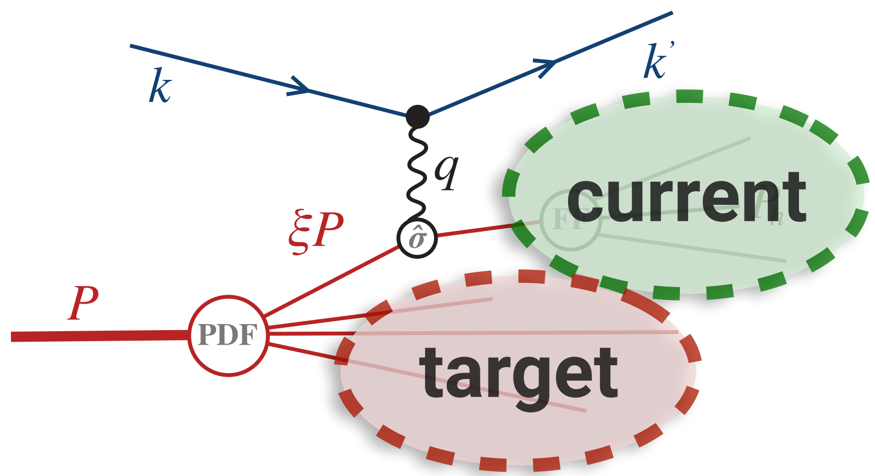

Compare **forward** to **backward** hemisphere: study the **center-of-mass rapidity**

$$\eta_{\mathrm{CM}} = \frac{1}{2} \ln \frac{E_h + P_{h\|}}{E_h - P_{h\|}}\Bigg|_{\mathrm{CM}}$$

Limits on factorization: target remnant

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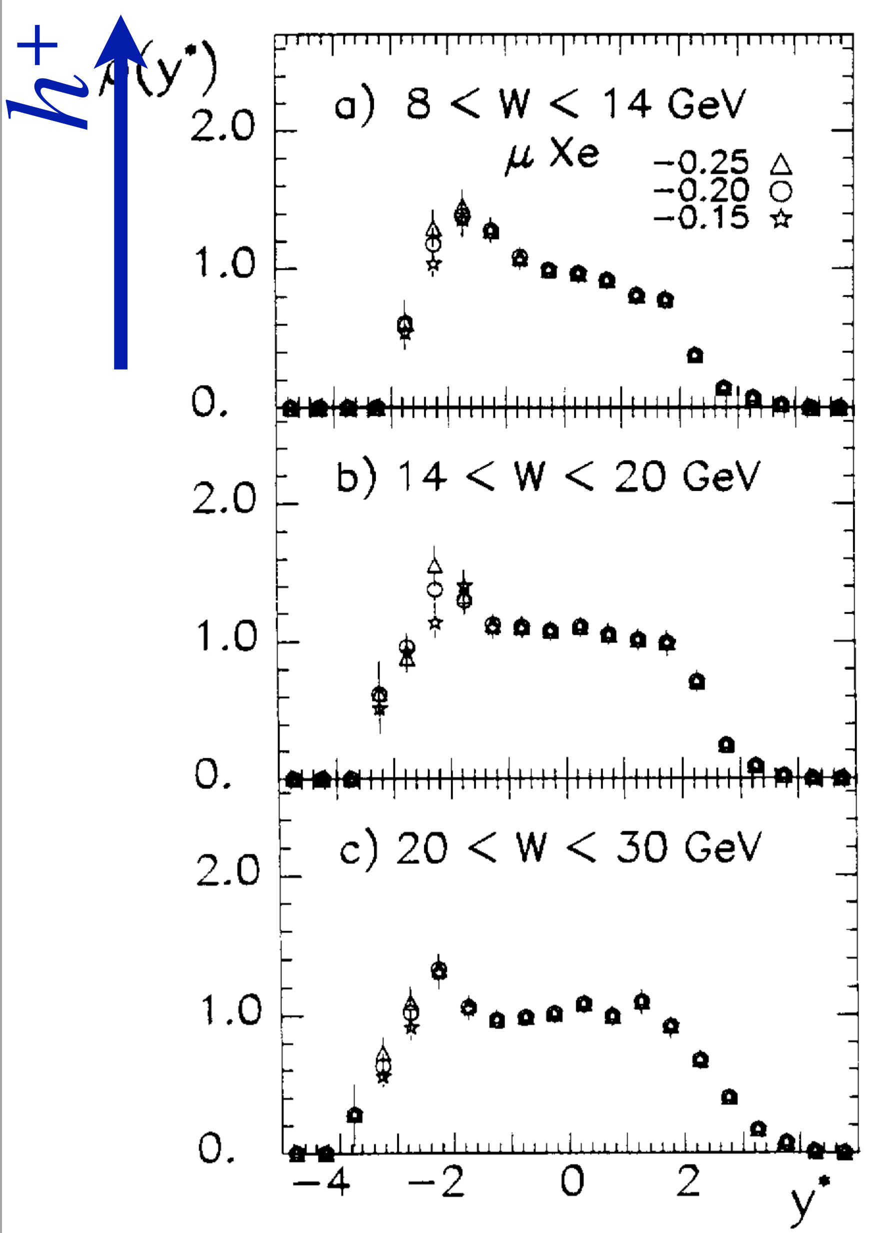
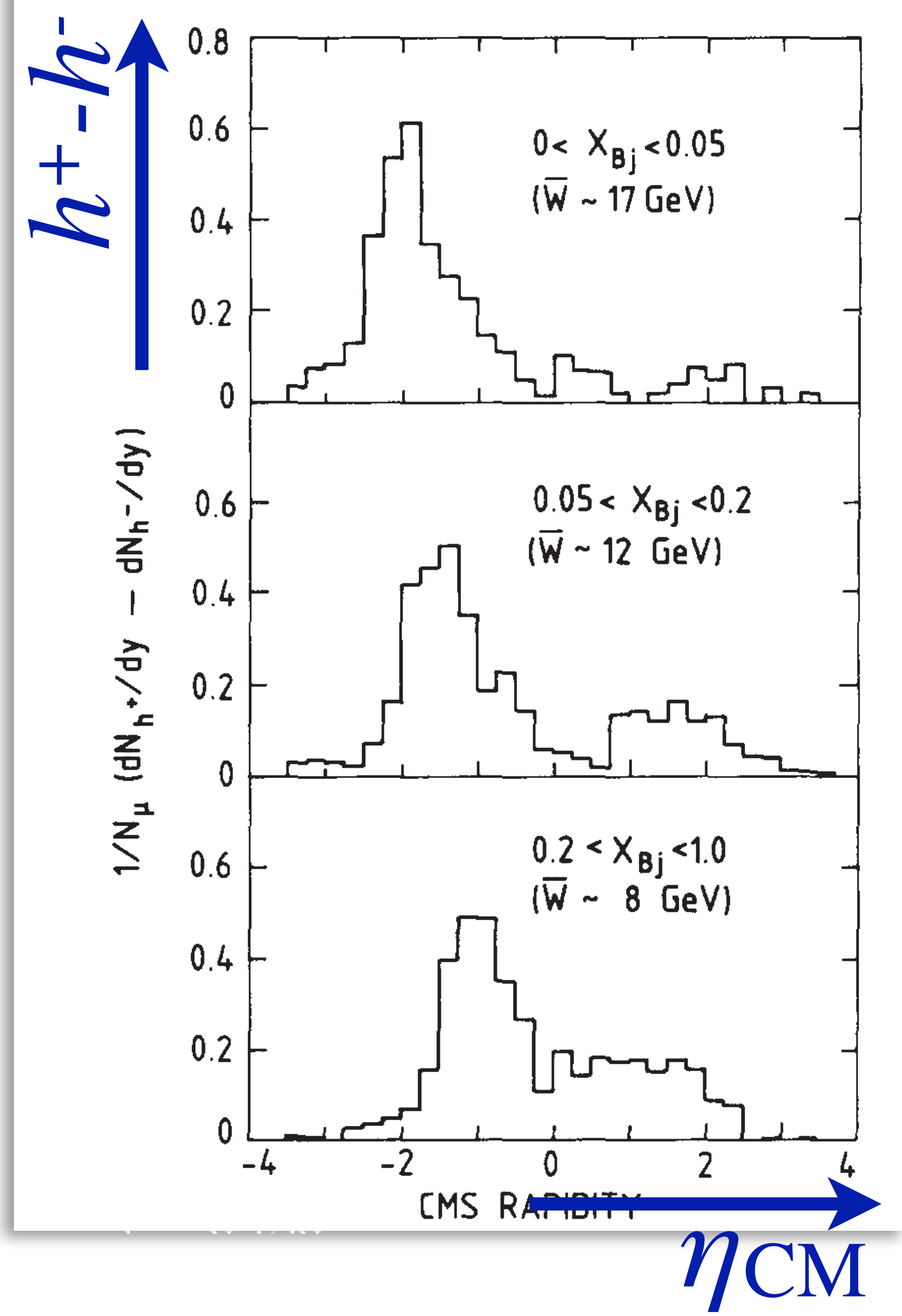
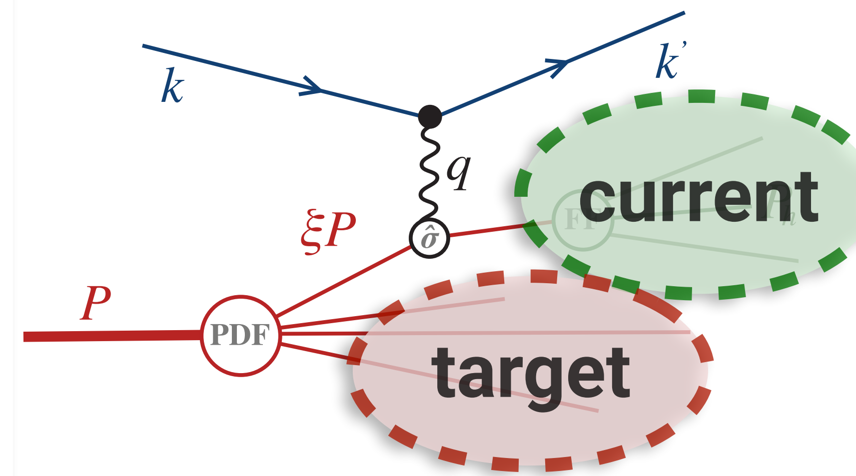
E665, ZPC (1993)



EMC, PR162 (1988)





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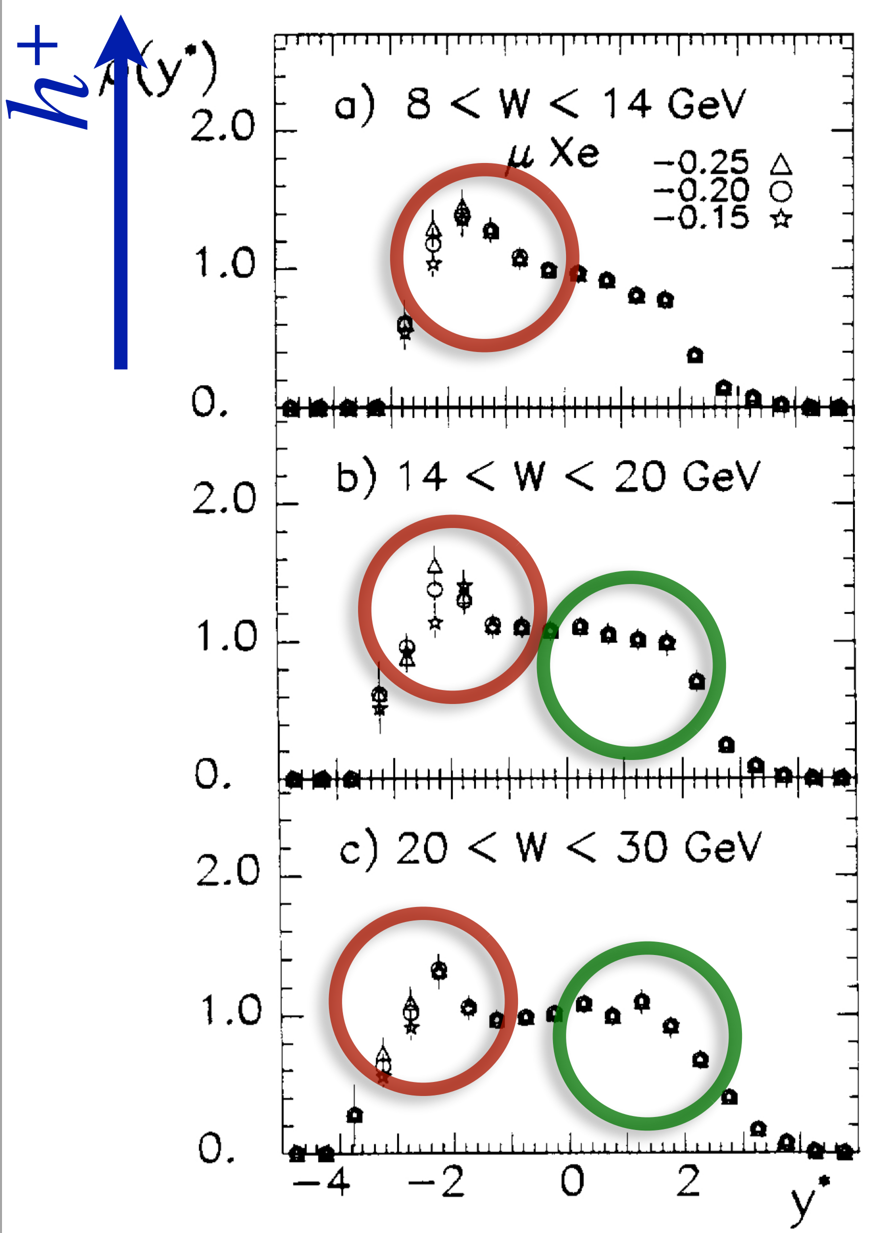

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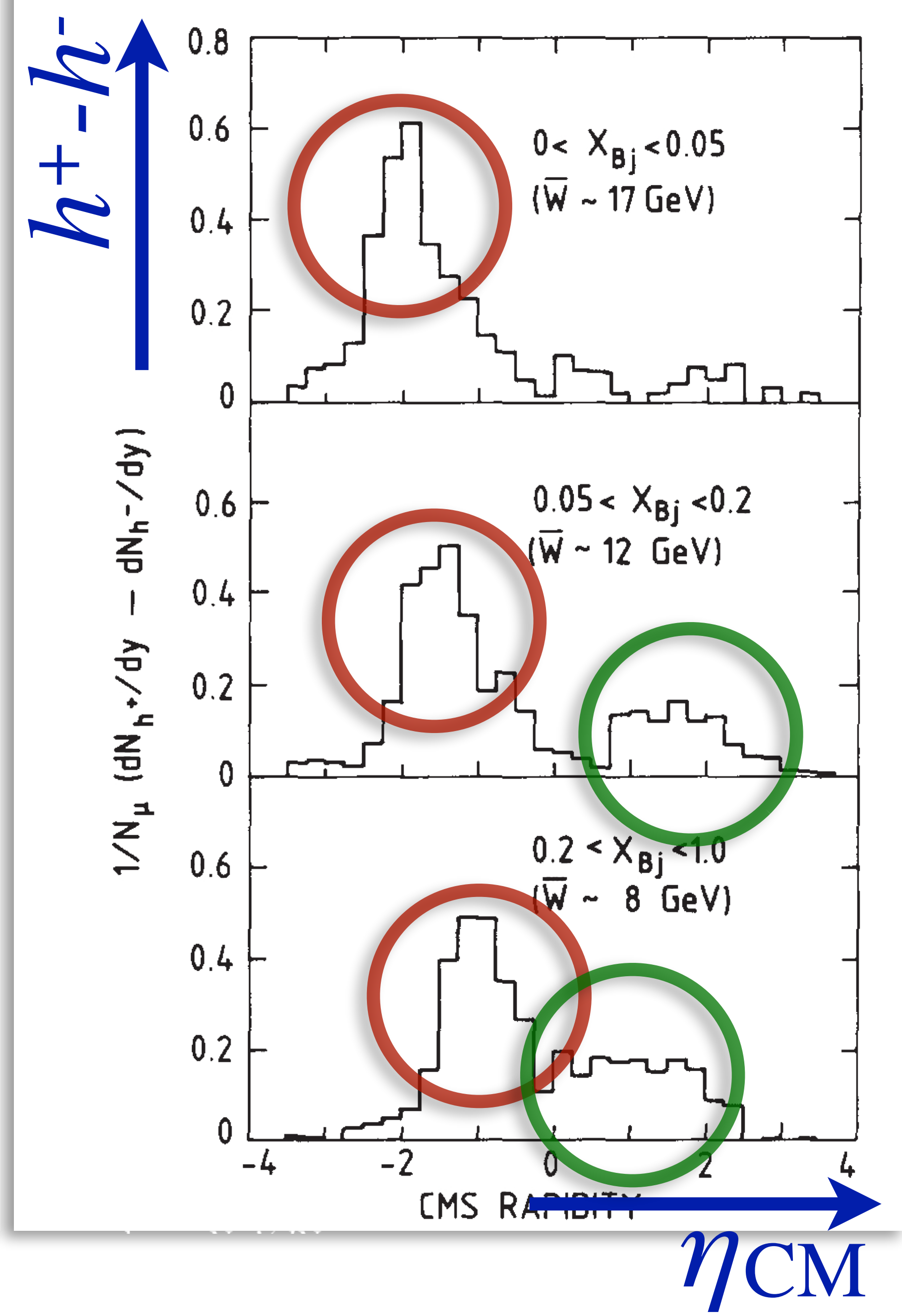

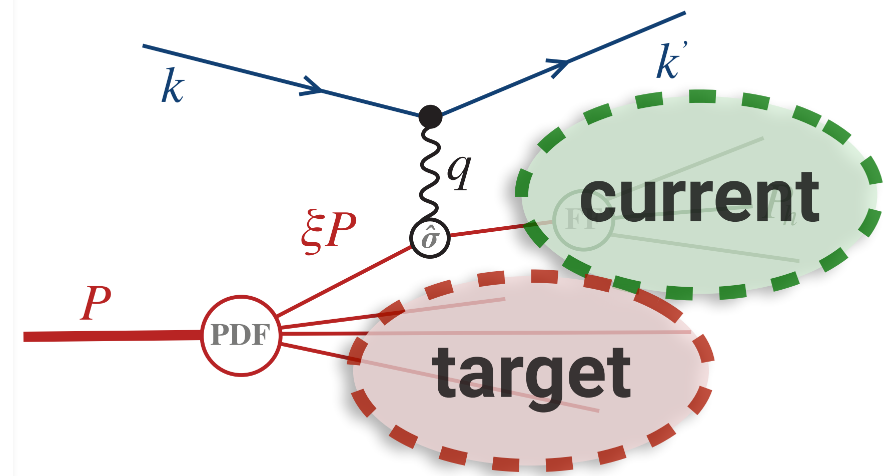

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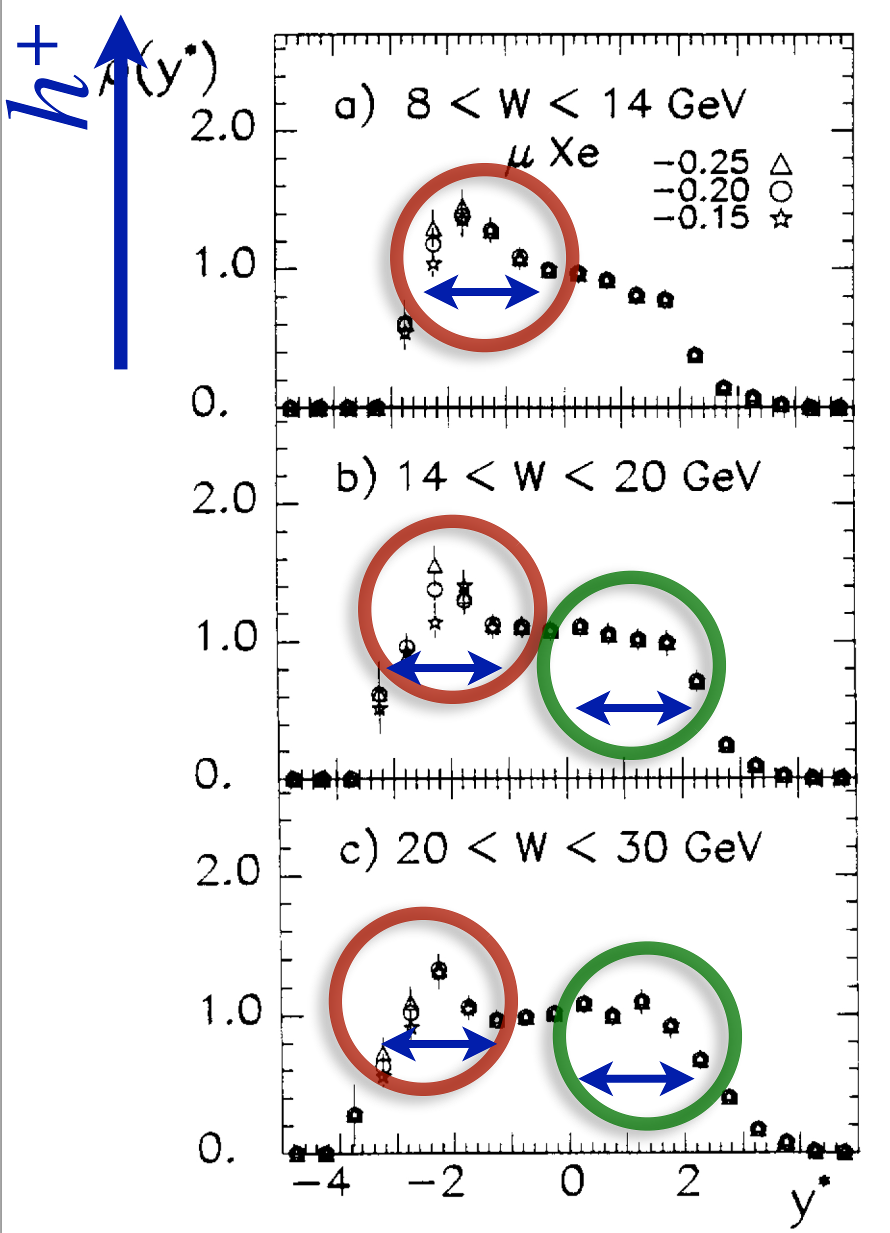

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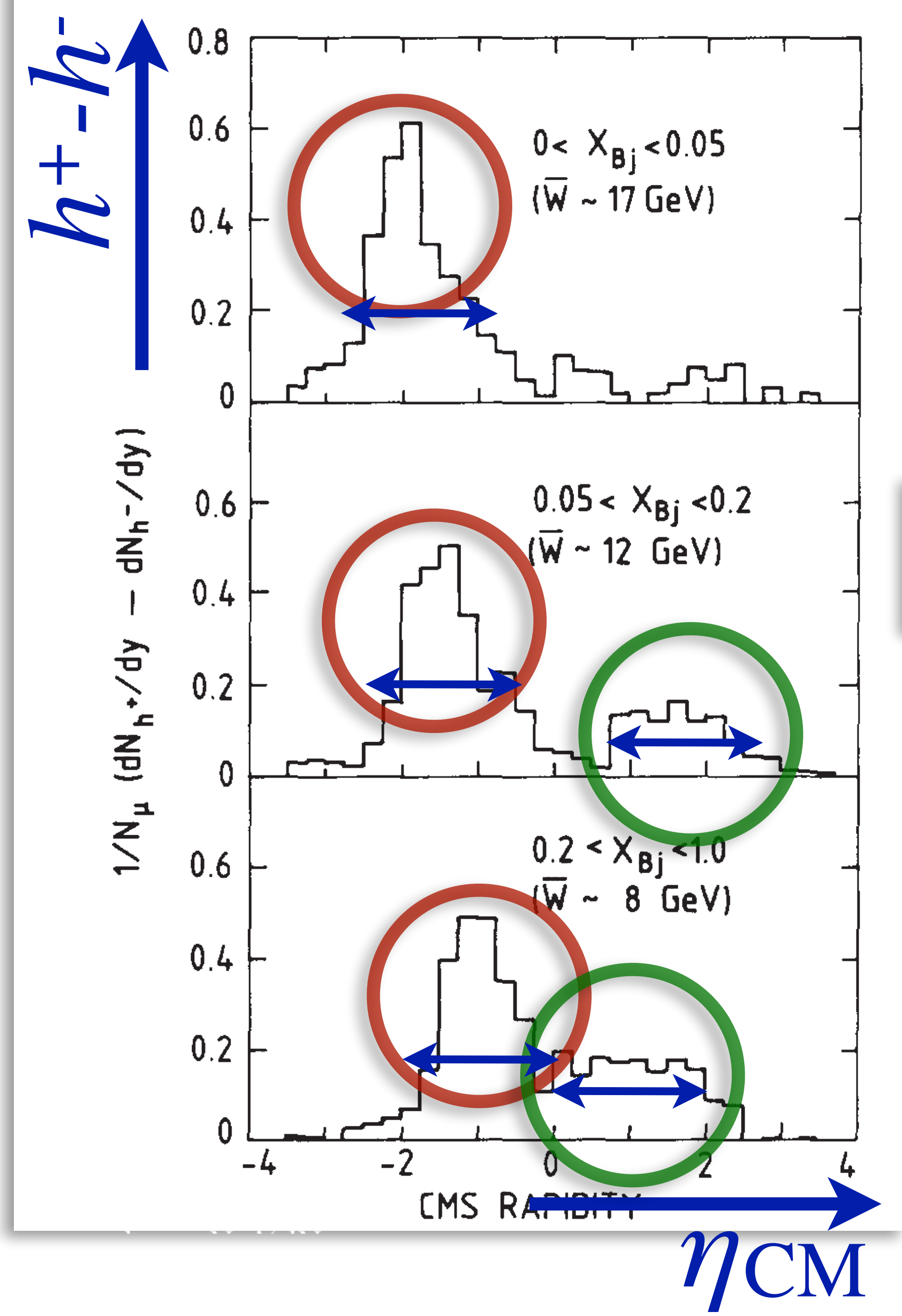

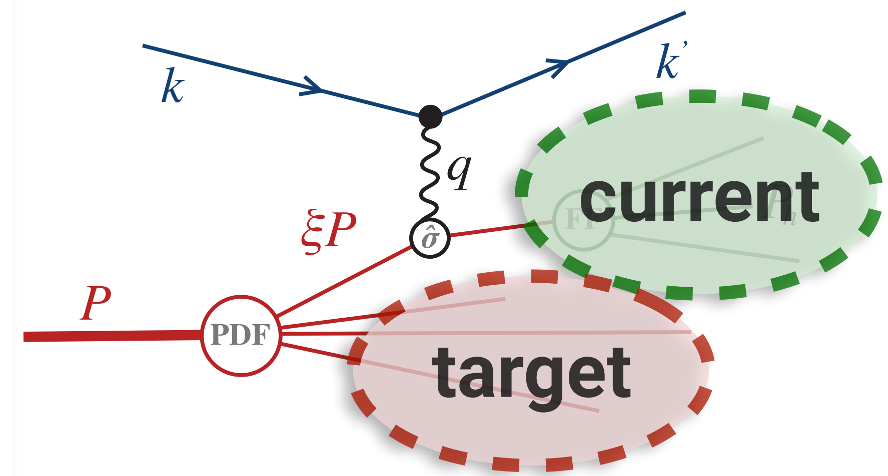

Jet FWHM: $\Delta\eta_{\rm CM} \approx 2$

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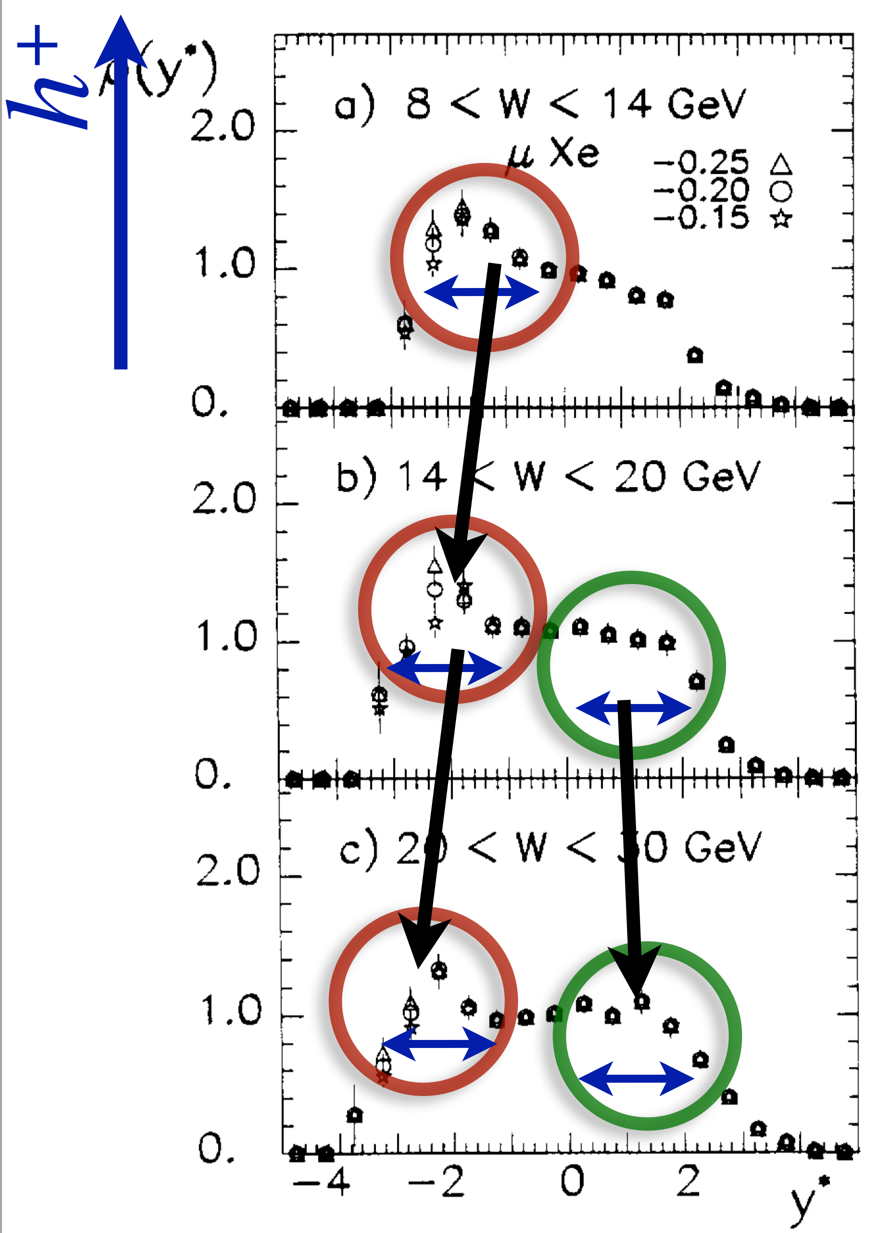

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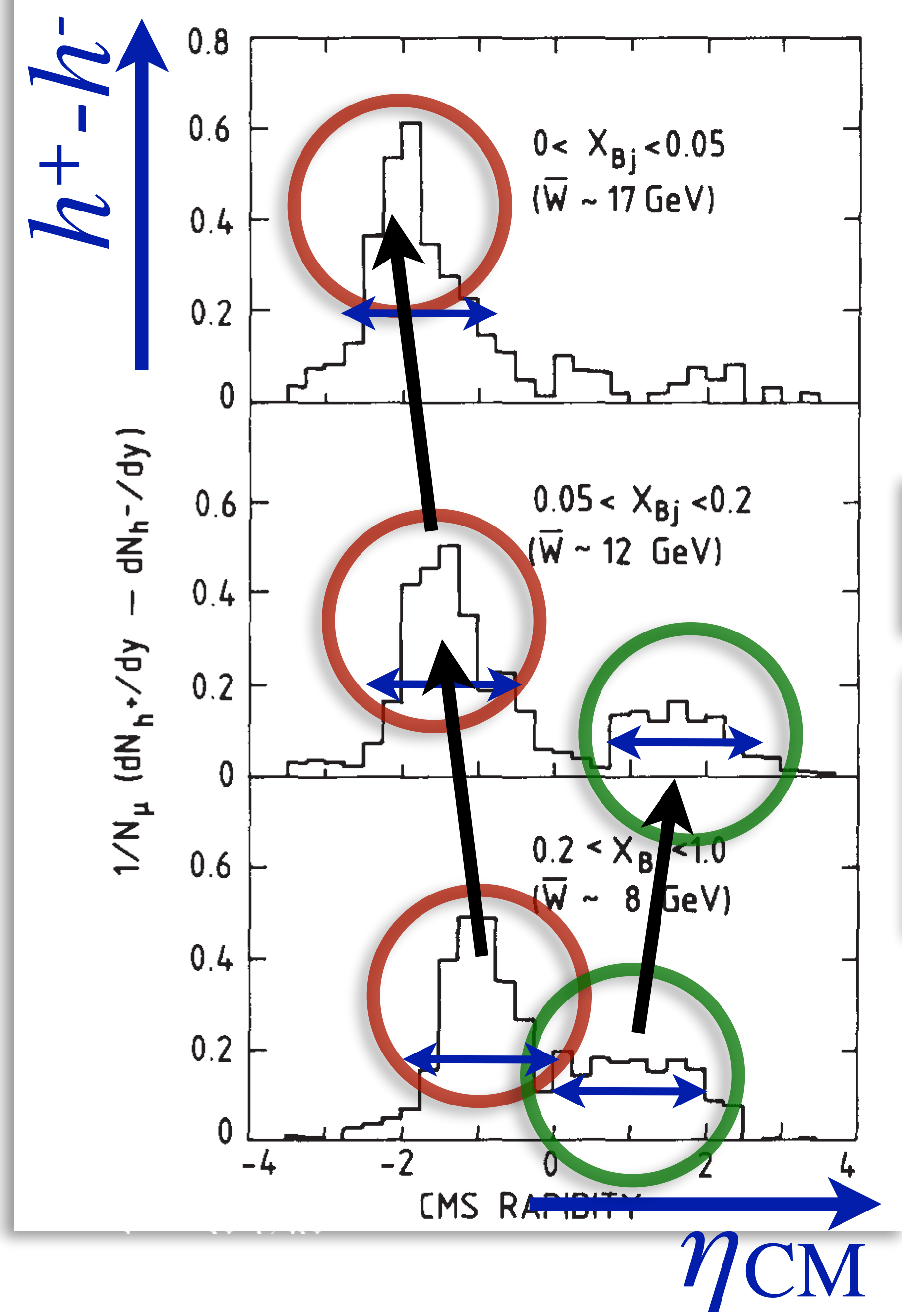

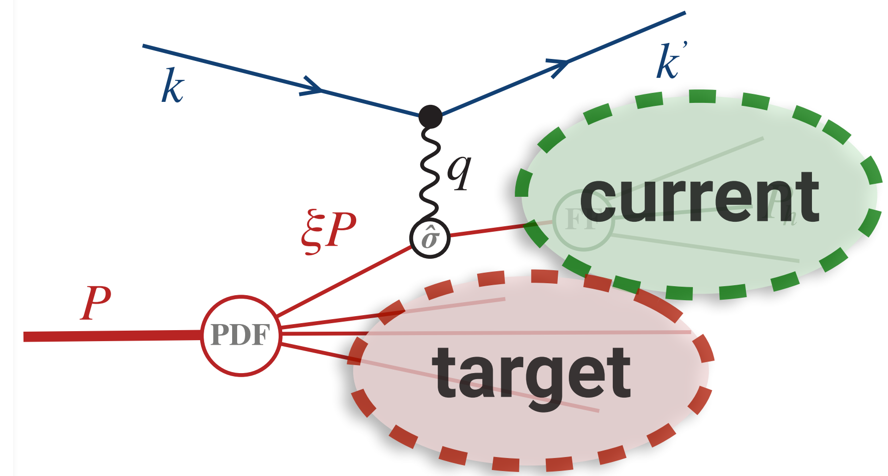

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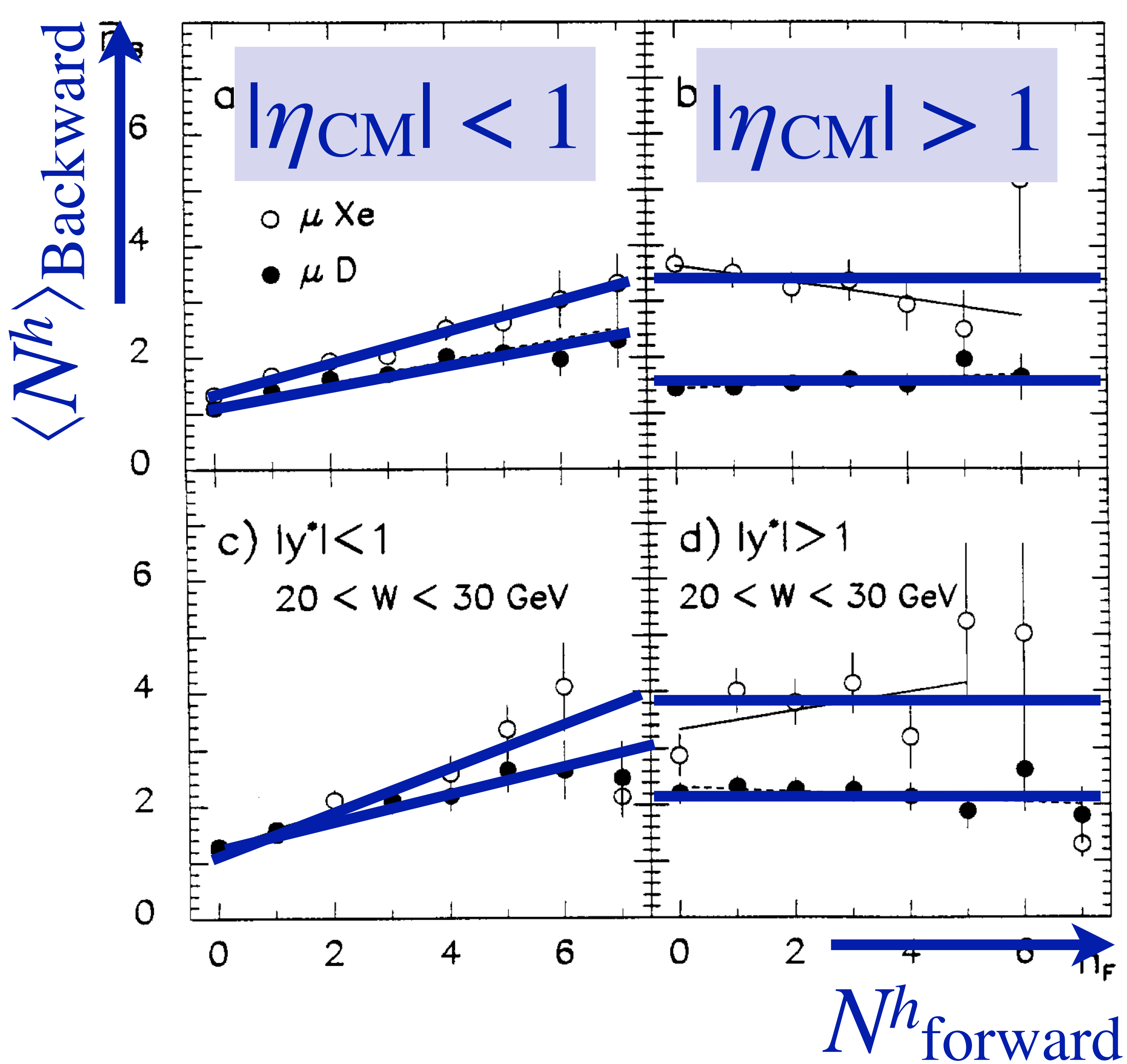

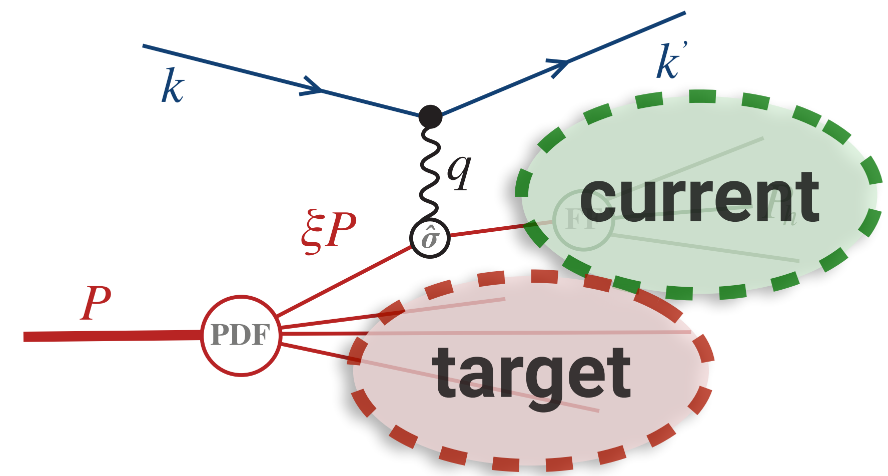

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A η_{CM} **cut** can **separate** the jets

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Observations:

- → **Jet FWHM**: $\Delta\eta_{\mathrm{CM}} \approx 2$
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"Berger Criterion":
Full separation requires
$\Delta\eta_{\mathrm{CM}} > 4$ **between the jets**

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Lower limit in W for this to be possible

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

$$P_h^{\max} \approx W/2$$

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Lower limit in W for this to be possible

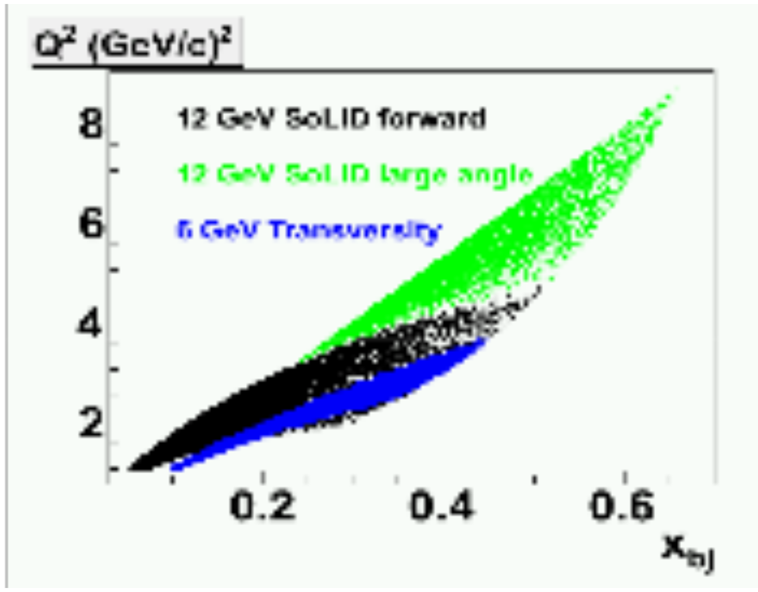
Implies a **lower limit in z**

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

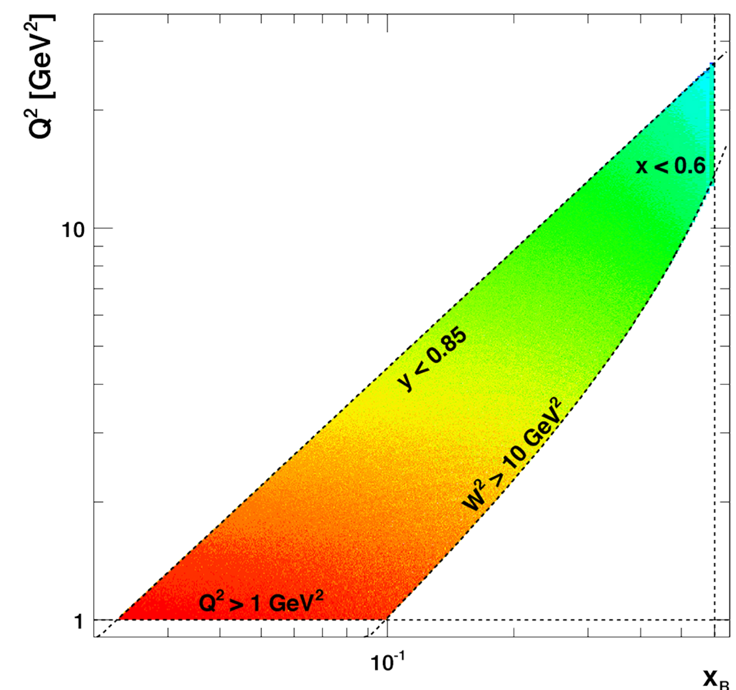
$$P_h^{\max} \approx W/2$$

HERMES as a measure of **future challenges**

SOLID



HERMES



$$E_{\mathrm{beam}} = 11\,\mathrm{GeV}$$
$$\sqrt{s} = 4.8\,\mathrm{GeV}$$

$$W_{\max} = \sqrt{s}$$

$$E_{\mathrm{beam}} = 27.5\,\mathrm{GeV}$$
$$\sqrt{s} = 7.5\,\mathrm{GeV}$$

$$2\,\mathrm{GeV} < W < 4.8\,\mathrm{GeV}$$

$$3.2\,\mathrm{GeV} < W < 7.5\,\mathrm{GeV}$$

Berger Criterion:
$\eta^{\max}_{\mathrm{CM}} \approx \ln W/M_h = 4$

→pions: $W > 7.6$ GeV
→kaons: $W > 27$ 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

LO factorization is **intuitive**

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

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): $u_n \equiv d_p, \ldots$

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$$\sigma_p^{\pi^+} \propto 4uD_u^{\pi^+} \ldots$$

$$\sigma_p^{\pi^-} \propto 4uD_u^{\pi^-} \ldots$$

$$\sigma_d^{\pi^+} \propto \frac{1}{2}\left[(u + \ldots\right.$$

$$\sigma_d^{\pi^-} \propto \frac{1}{2}\left[(u + \ldots\right]$$

charge conjugation symmetry:

$$D_u^{\pi^+} = D_{\bar{u}}^{\pi^-} \equiv D_1 \qquad D_d^{\pi^-} = D_{\bar{d}}^{\pi^+} \equiv D_2$$

$$D_u^{\pi^-} = D_{\bar{u}}^{\pi^+} \equiv D_3 \qquad D_d^{\pi^+} = D_{\bar{d}}^{\pi^-} \equiv D_4$$

$$D_s^{\pi^+} = D_{\bar{s}}^{\pi^-} \equiv D_{s,1} \qquad D_s^{\pi^-} = D_{\bar{s}}^{\pi^+} \equiv D_{s,2}$$

favored

unfavored

strange

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

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

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isospin symmetry:

$$D_1 = D_2 \equiv D_\mathrm{f}$$ favored

$$D_3 = D_4 \equiv D_\mathrm{u}$$ unfavored

LO 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

$$\sigma_p^{\pi^+} \propto (4u + \bar{d})D_{\mathrm{f}} + (d + 4\bar{u})D_{\mathrm{u}} + \text{strange}$$

$$\sigma_p^{\pi^-} \propto (4u + \bar{d})D_{\mathrm{u}} + (d + 4\bar{u})D_{\mathrm{f}} + \text{strange}$$

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Define:

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

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$$\frac{d_v}{u_v} = \frac{4R^\pi + 1}{4 + R^\pi} \qquad \frac{\bar{d} - \bar{u}}{u - d} = \frac{4k^\mathrm{sea} - \rho^\pi}{1 - k^\mathrm{sea}\rho^\pi}$$

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

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

Requires additional input

$$\frac{d_v}{u_v} = \frac{4R^{\pi} + 1}{4 + R^{\pi}} \qquad \frac{\bar{d} - \bar{u}}{u - d} = \frac{4k^{\mathrm{sea}} - \rho^{\pi}}{1 - k^{\mathrm{sea}}\rho^{\pi}}$$

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Signature of factorization:
should depend on x, not z

Factorization and **precocious scaling**

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

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

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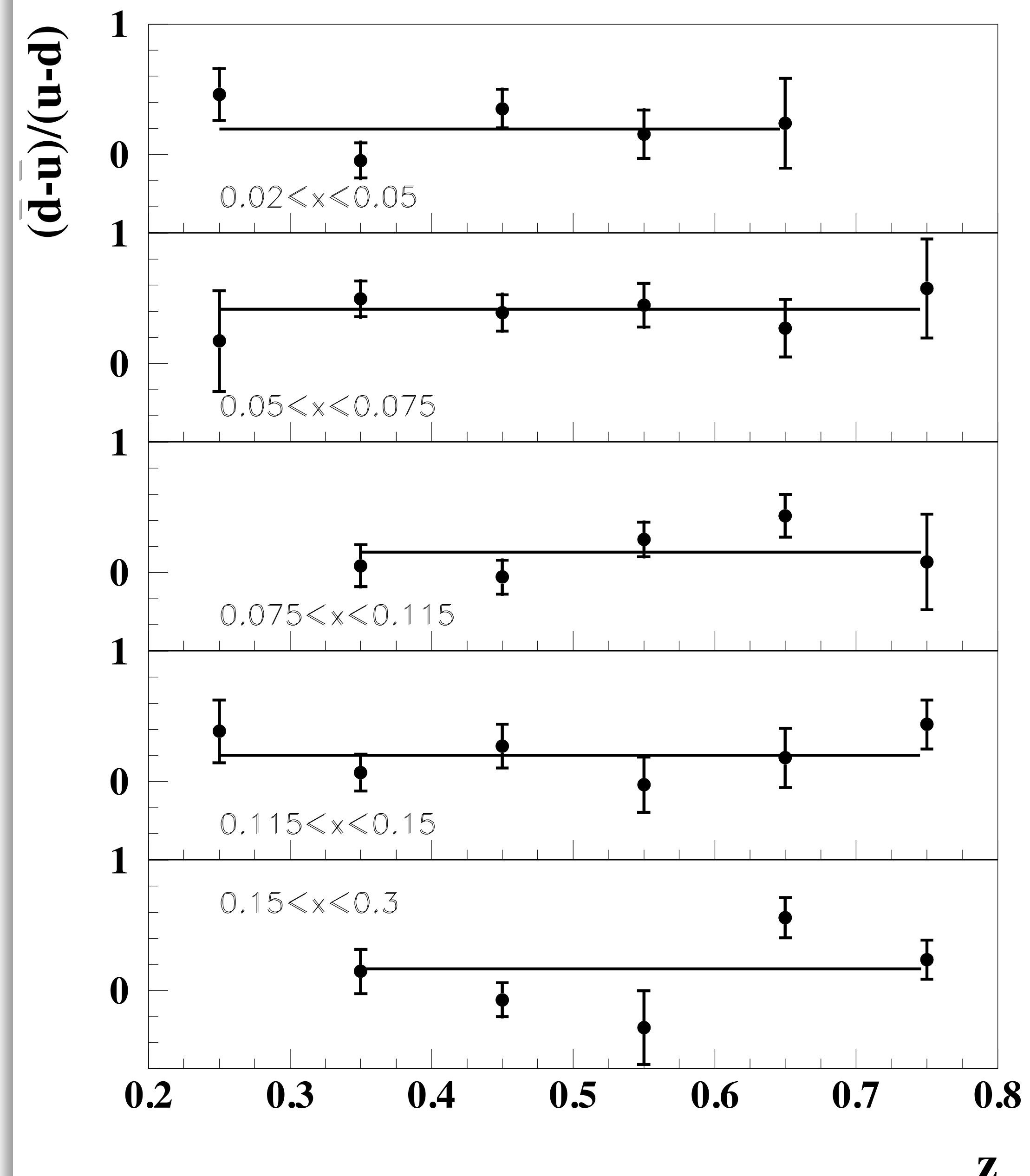
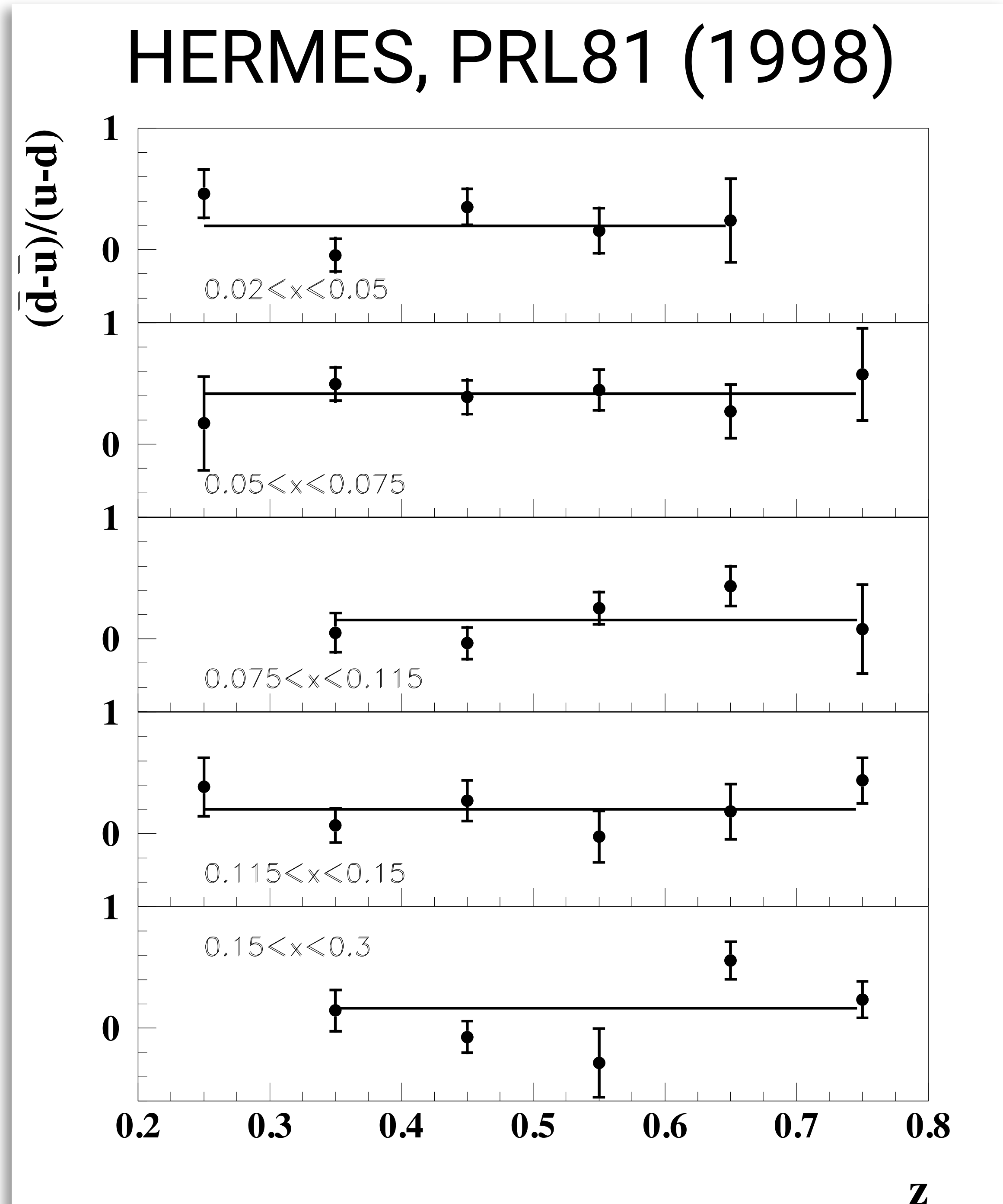
HERMES, PRL81 (1998)



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

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



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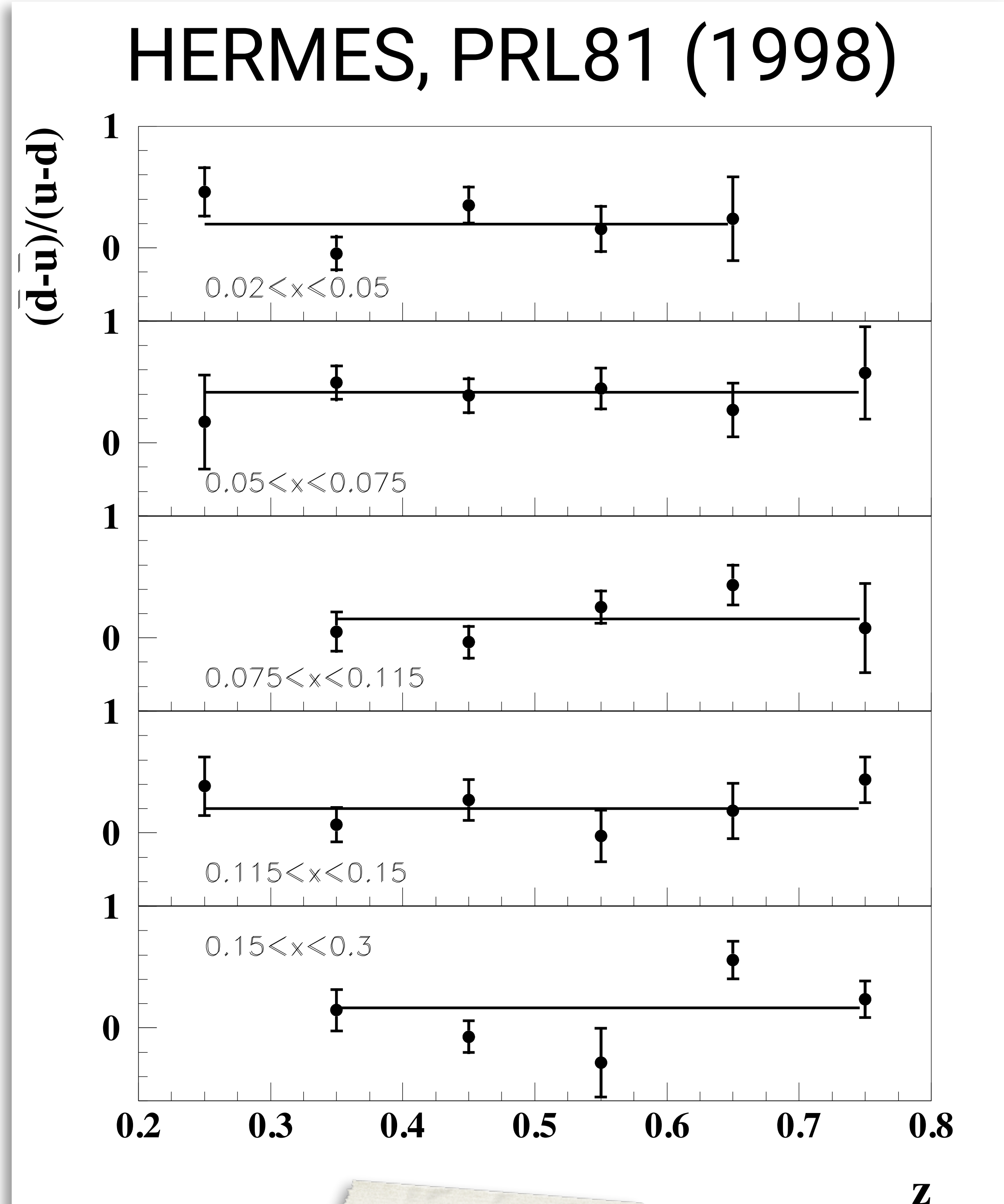

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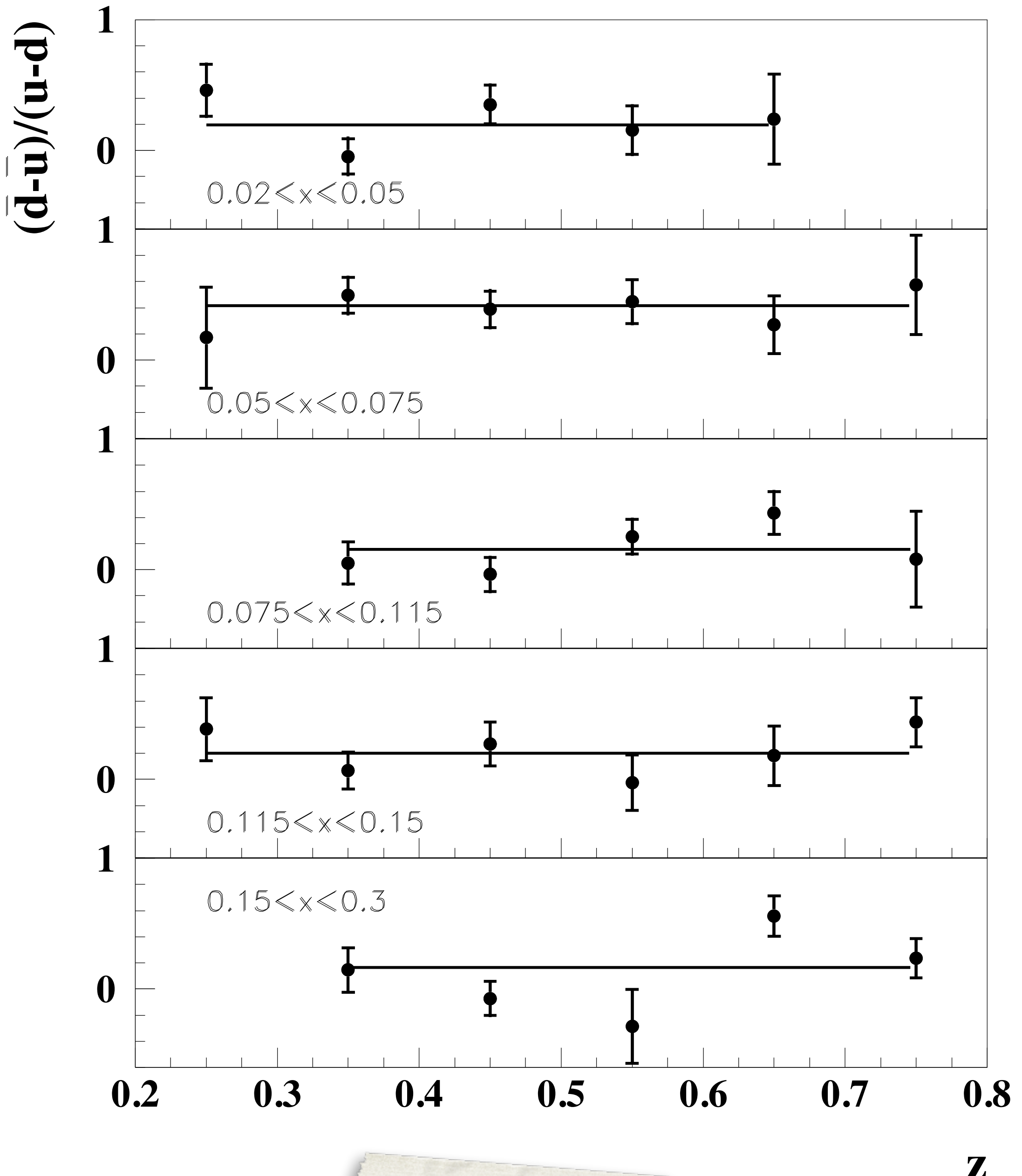

Important test, but **not ideal** (model dependent)

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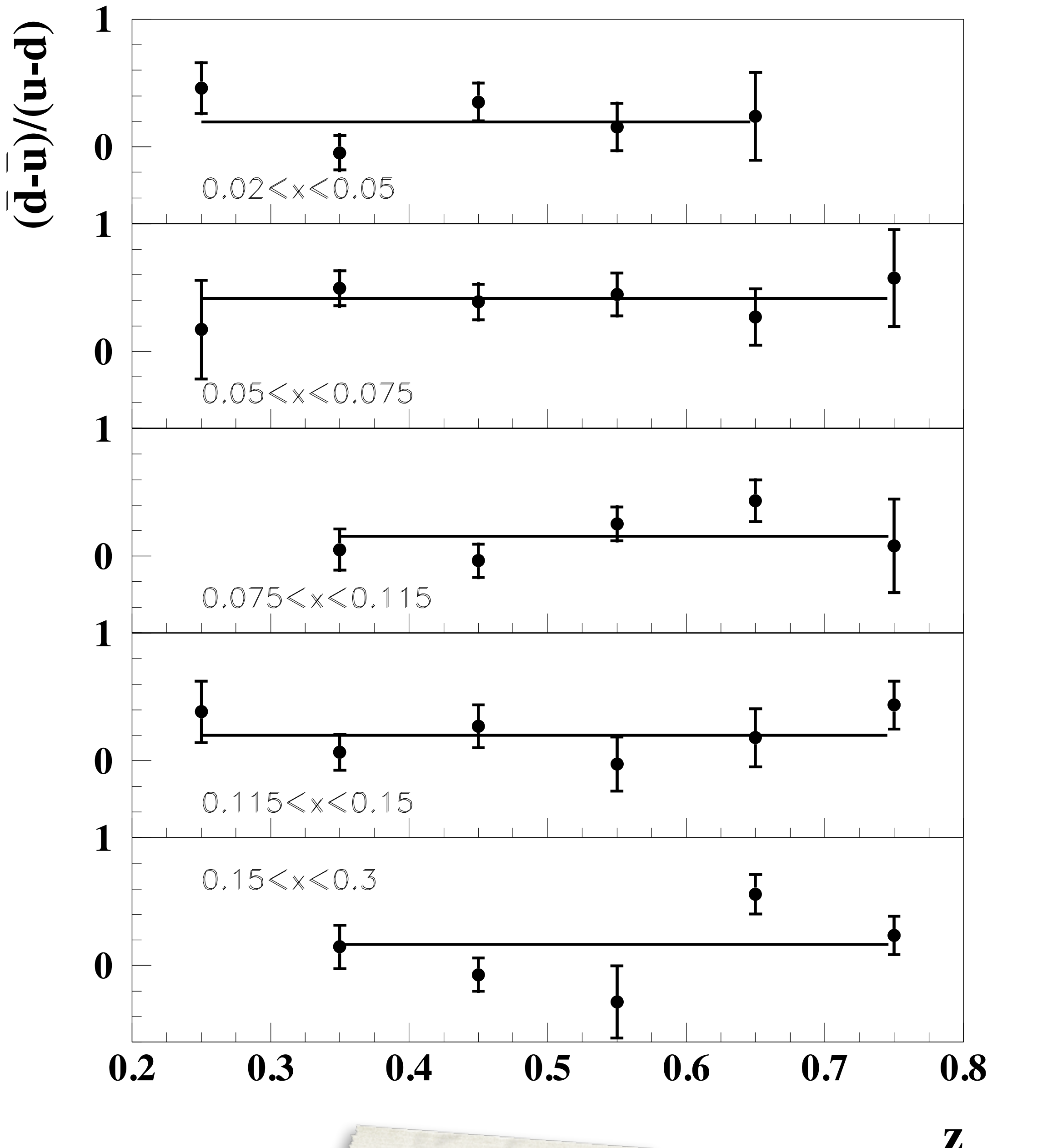

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$\int d_v / \int u_v$ finally possible!

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

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

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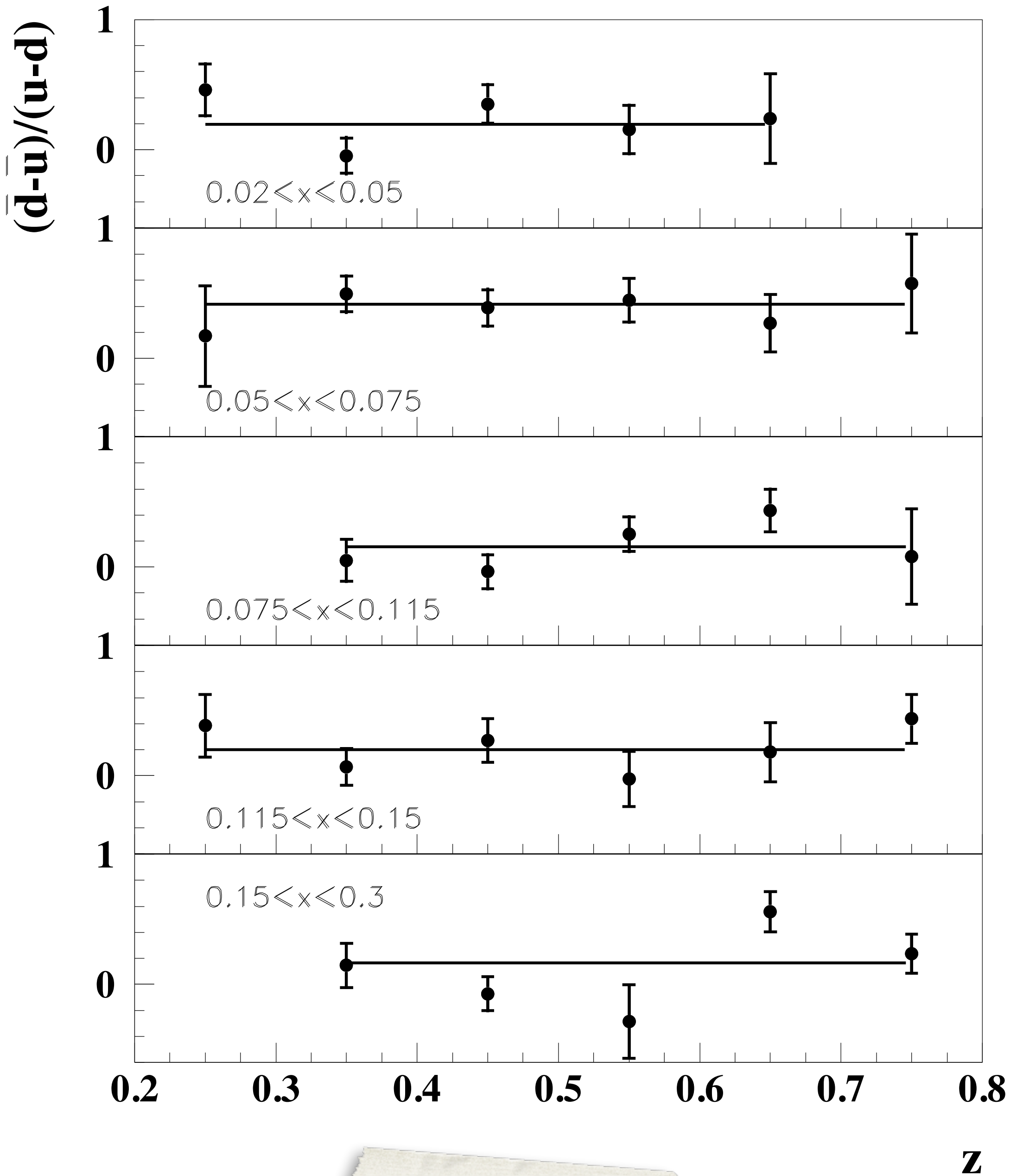

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- multi-dimensional **smearing-unfolding**
- Very good grasp of interplay between the **systematics**

Expected problem areas:
- high z (**exclusive**)
- low z (**target remnant**)

LO factorization is **intuitive**

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

LO access

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

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sensitive for:

Experimental precision,
need good knowledge of the
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Signature of factorization:
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Experimental precision, need good knowledge of the **correlated systematics**

isospin symmetry:

$$D_1 = D_2 \equiv D_\mathrm{f}$$
$$D_3 = D_4 \equiv D_\mathrm{u}$$

Broken in the DSS fit!

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

LO factorization is **intuitive**

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

LO access

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

Signature of factorization:
should depend on x, not z

sensitive for:

Applicability of
LO, leading-twist
framework

isospin symmetry:

$$D_1 = D_2 \equiv D_{\mathrm{f}}$$

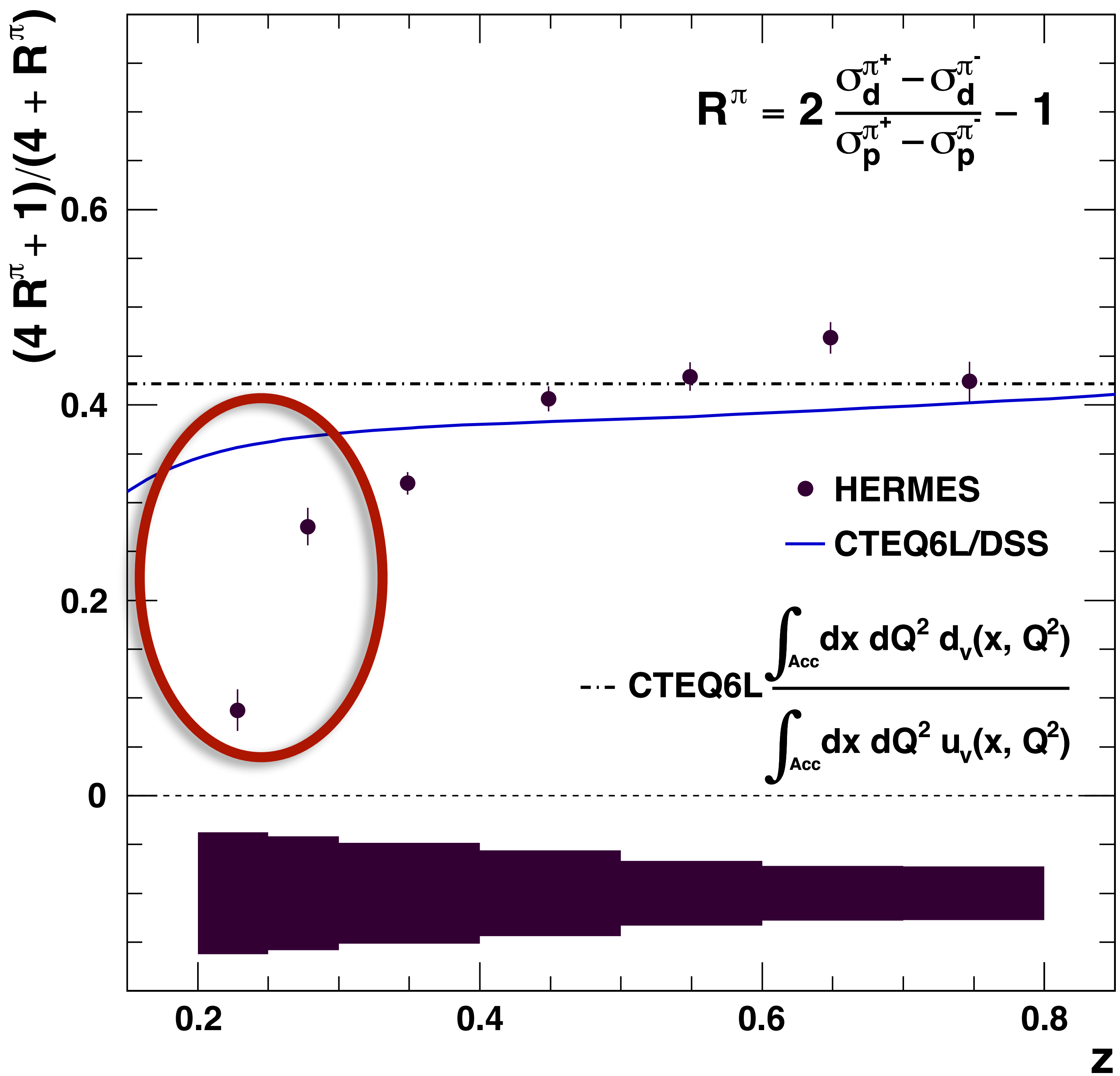
$$D_3 = D_4 \equiv D_{\mathrm{u}}$$

Broken in the DSS fit!

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

Experimental precision,
need good knowledge of the
correlated systematics

Evidence for **factorization breaking?**



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

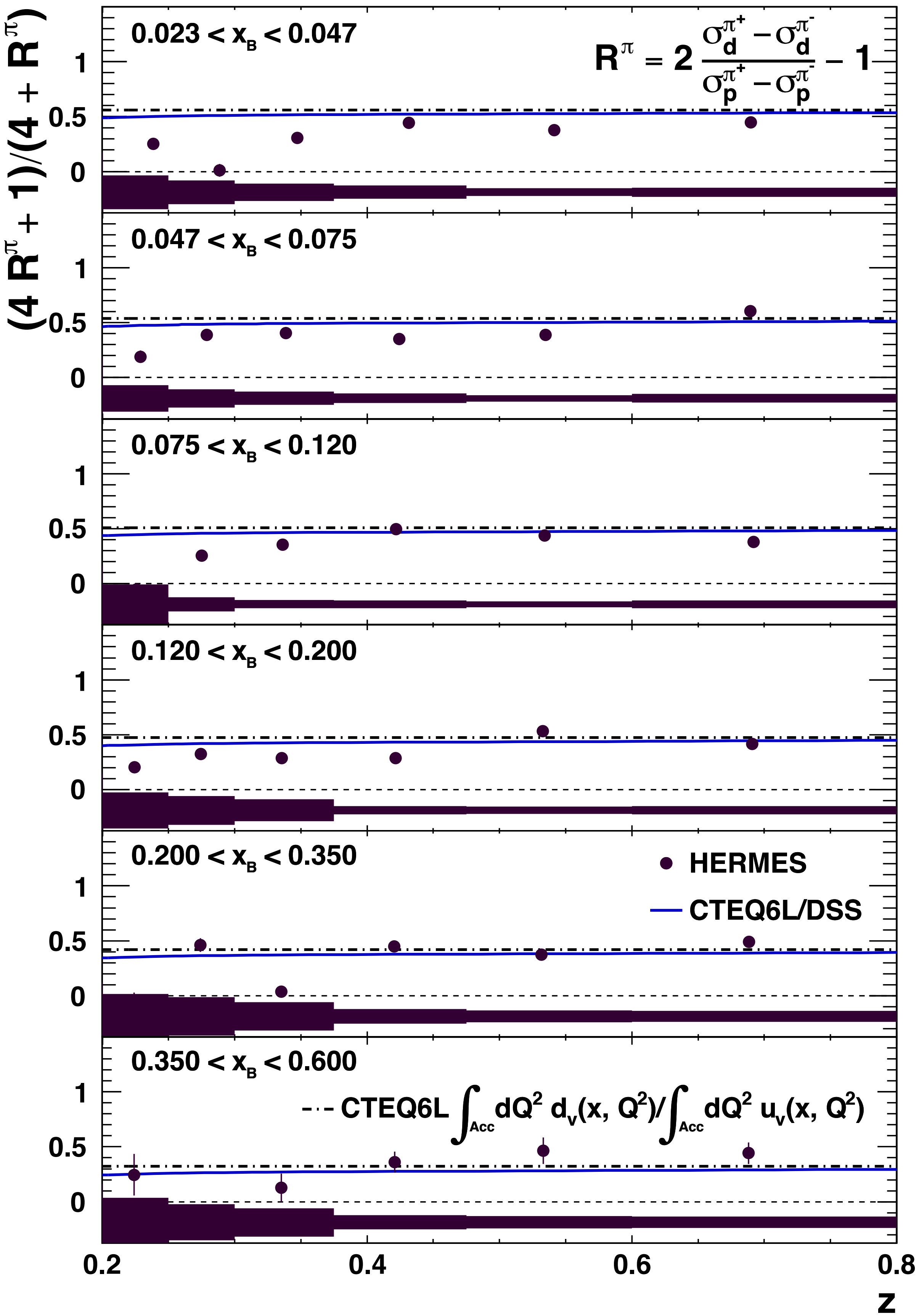
Lowest point $> 3\sigma$ from the prediction:

- Target remnant or theory?
- "Realistic" FF assumption lesses the discrepancy

→ Probably mix

Results **systematics dominated**

Evidence for **factorization breaking?**



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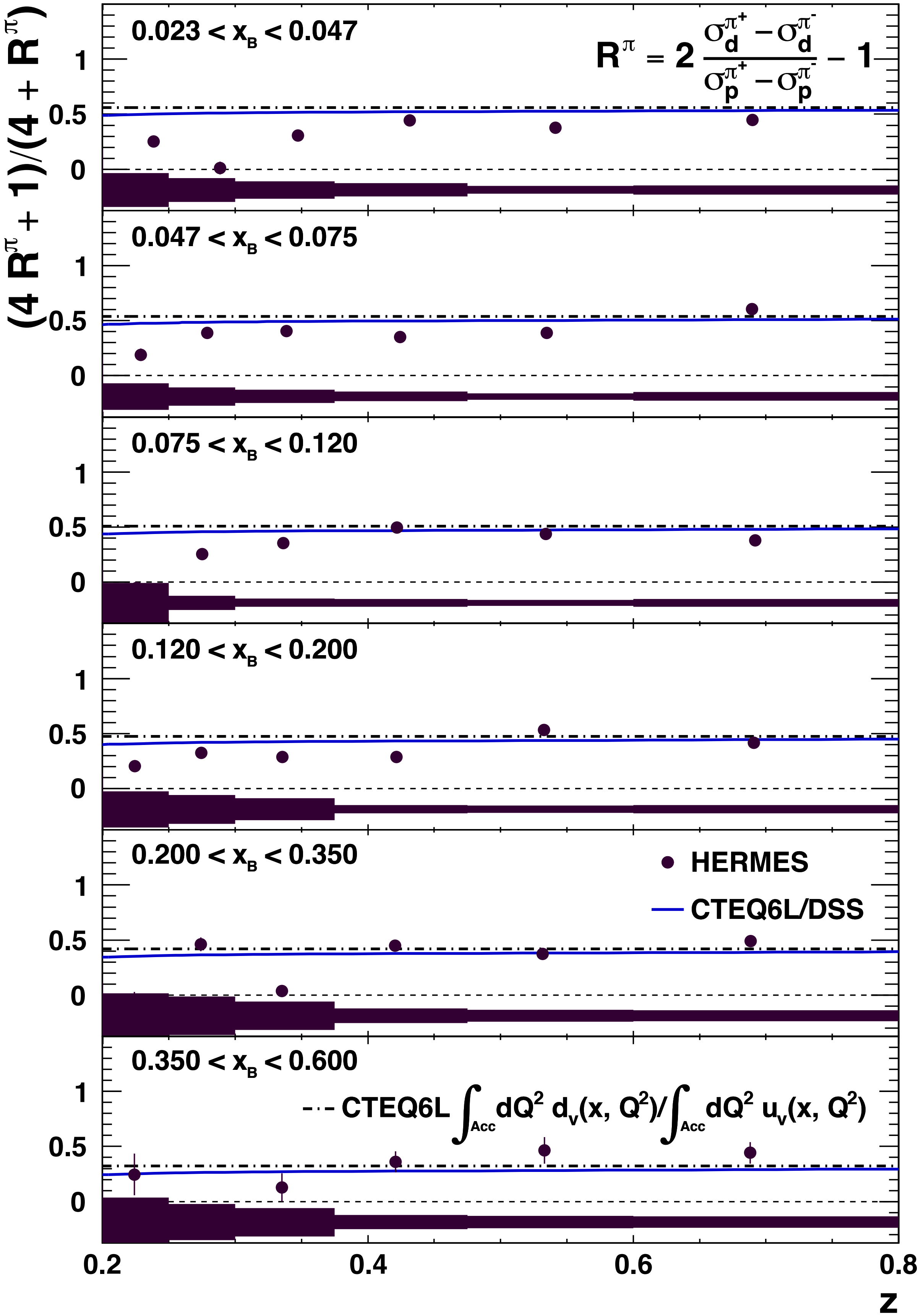

Lessons:

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

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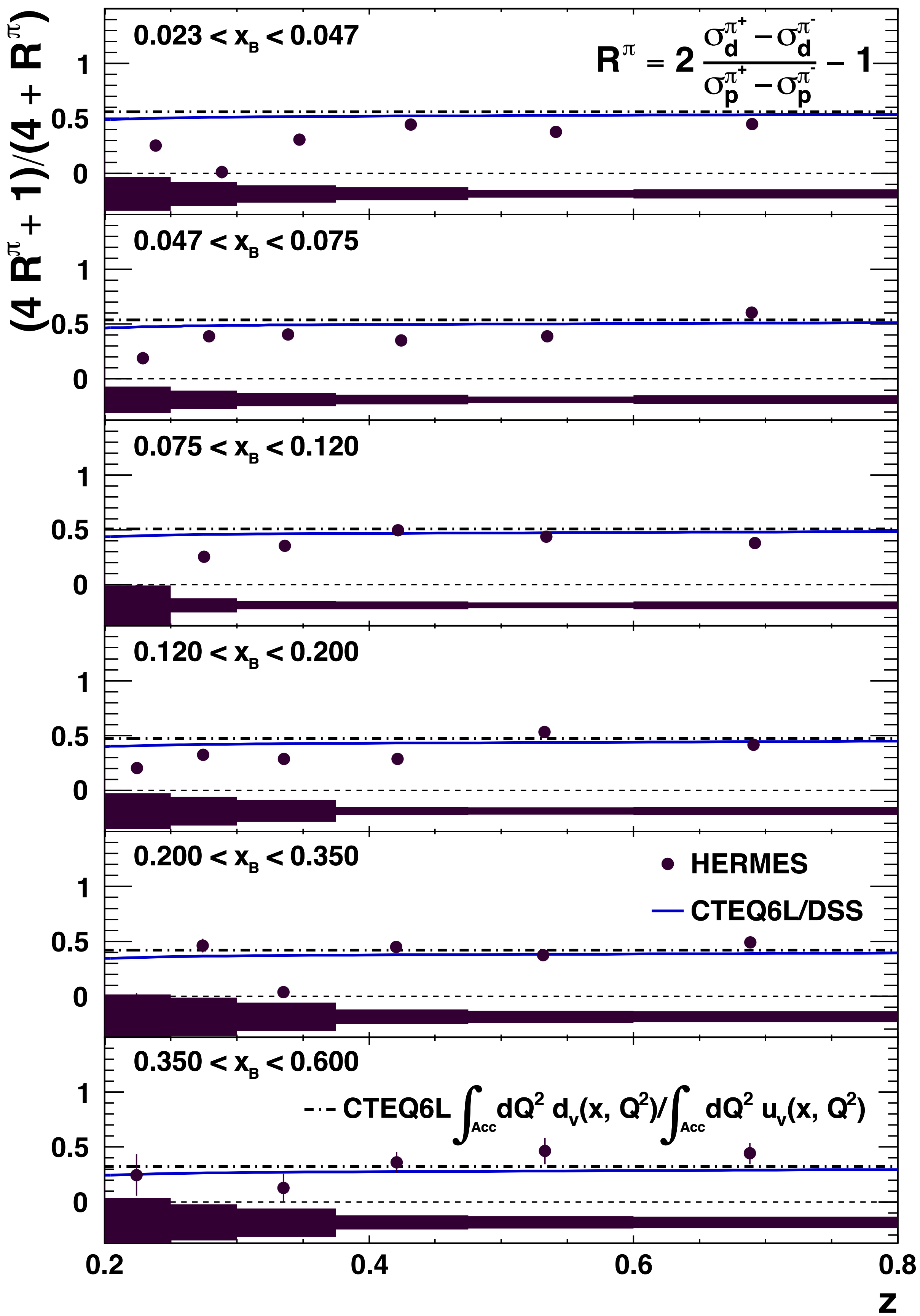

Lessons:

- **Discrepancy HAS to occur at low z**
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- More **precise knowledge FF symmetries** required

SYSTEMATICS!

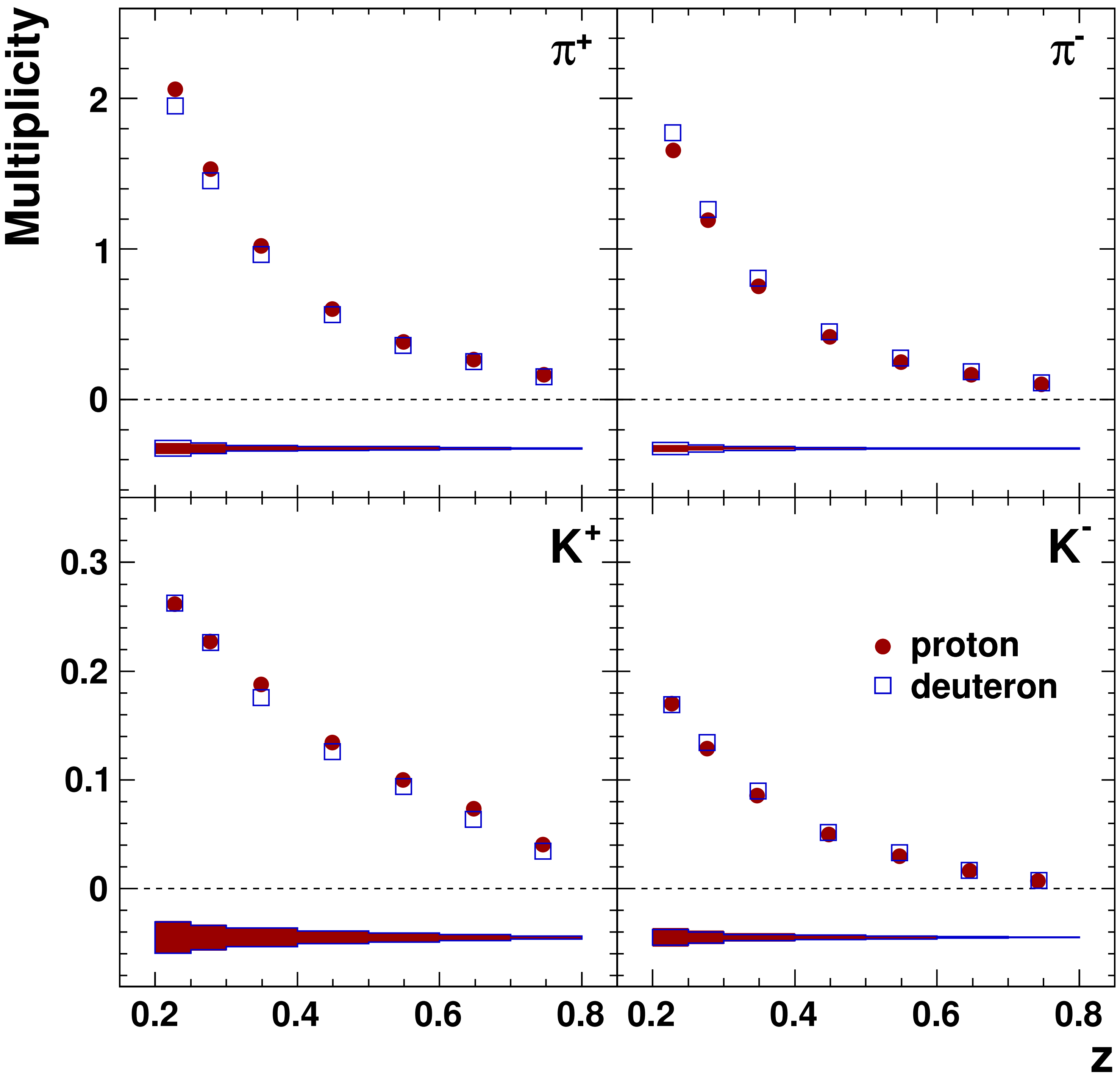
- Systematics dominant: pushing the limit of HERMES
- **On to CEBAF!**
- **Multi-D binning key**, for unfolding, but also for interpretation

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**

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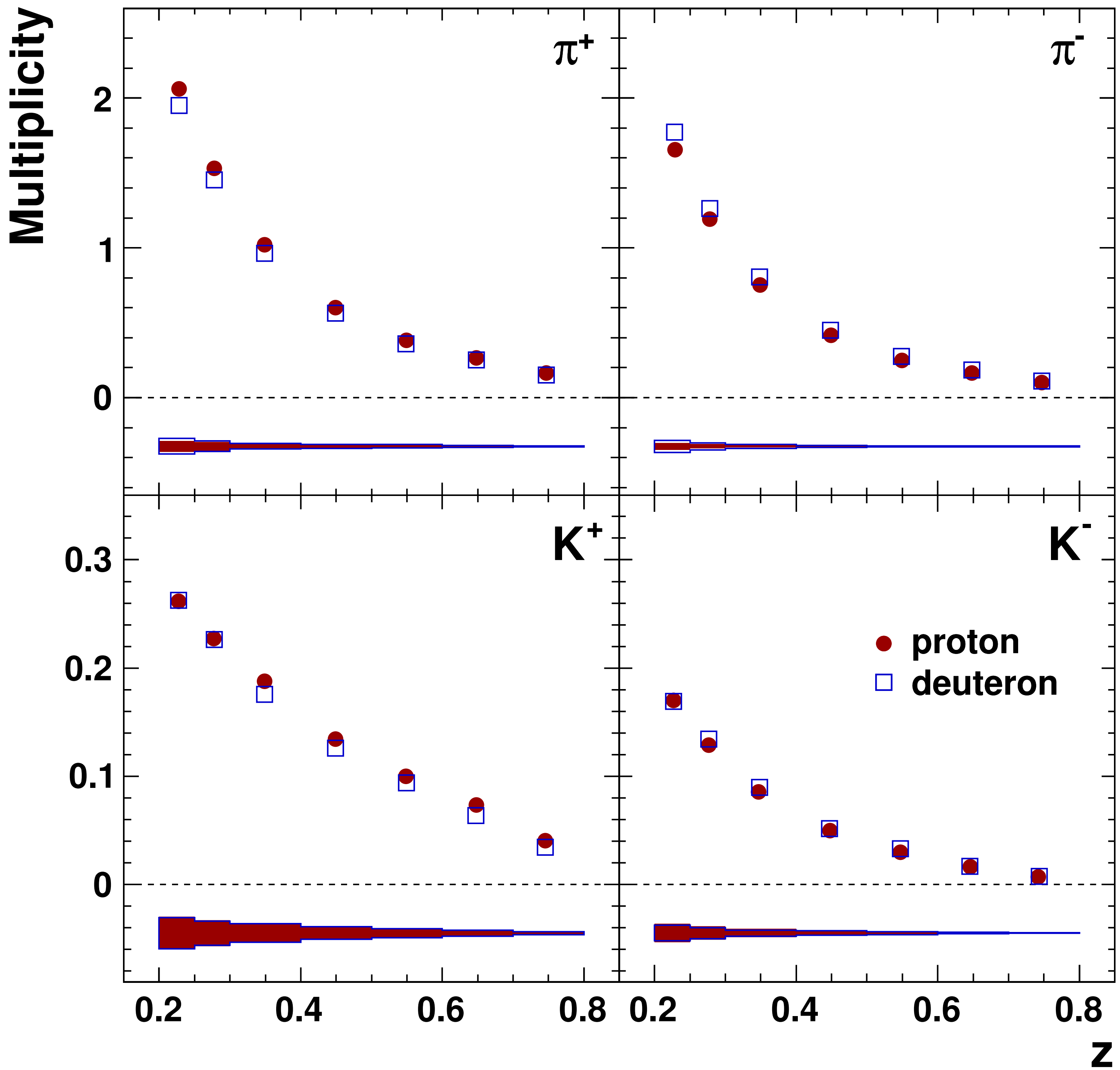
u-**quark** dominance



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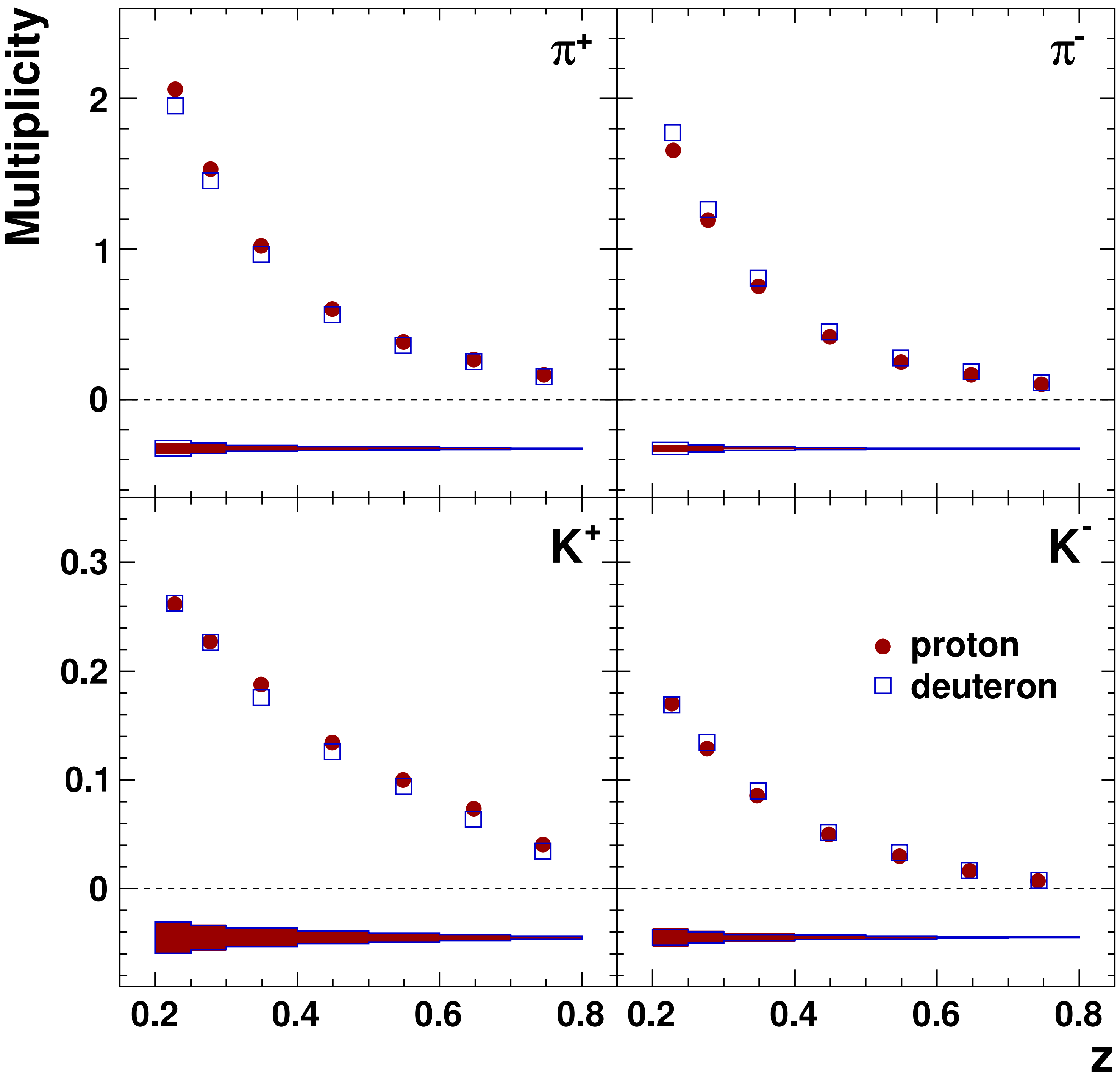

u-**quark** dominance

deuteron has less *u*-quarks

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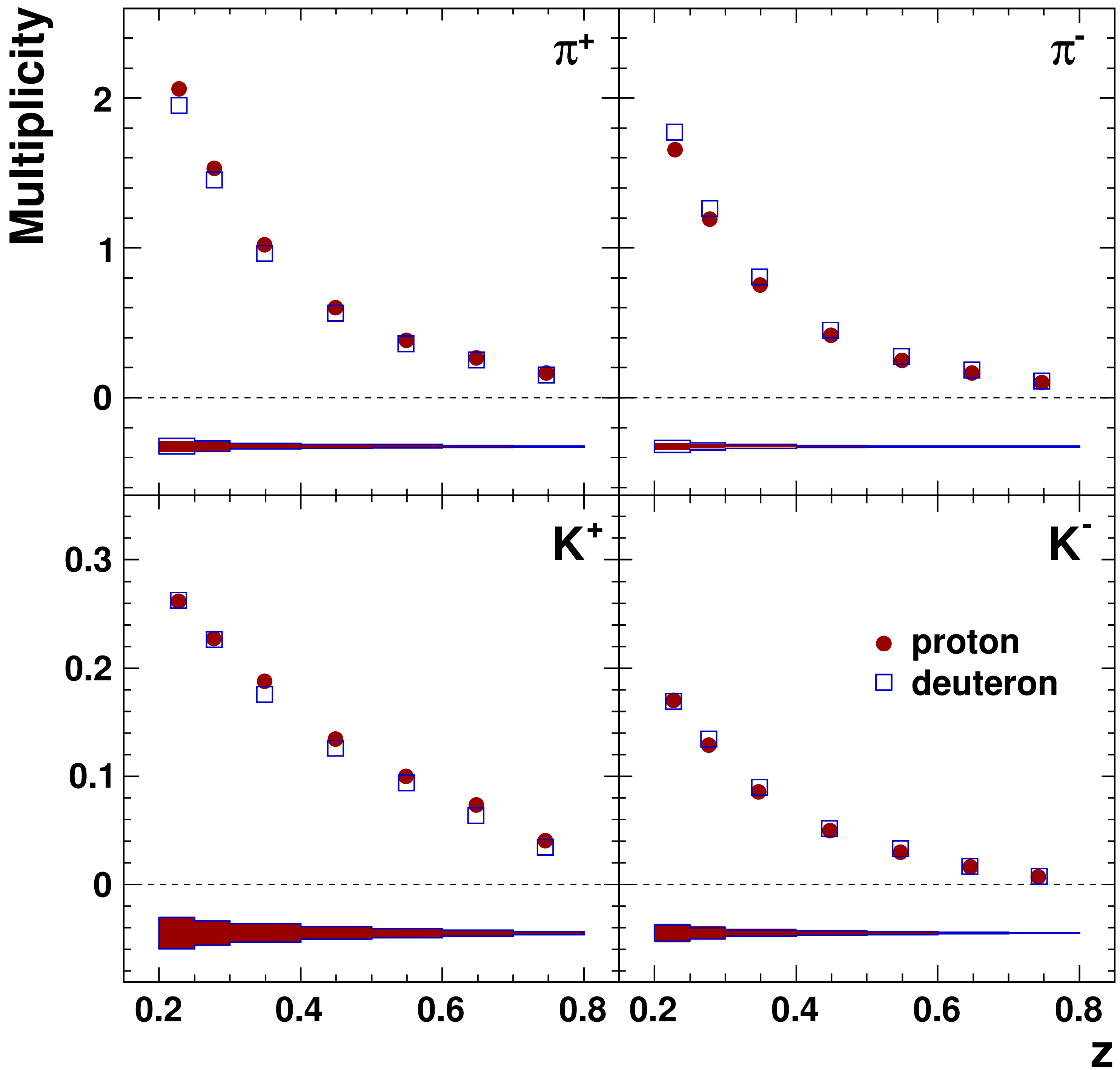

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K^- **pure sea** object ($s\bar{u}$)

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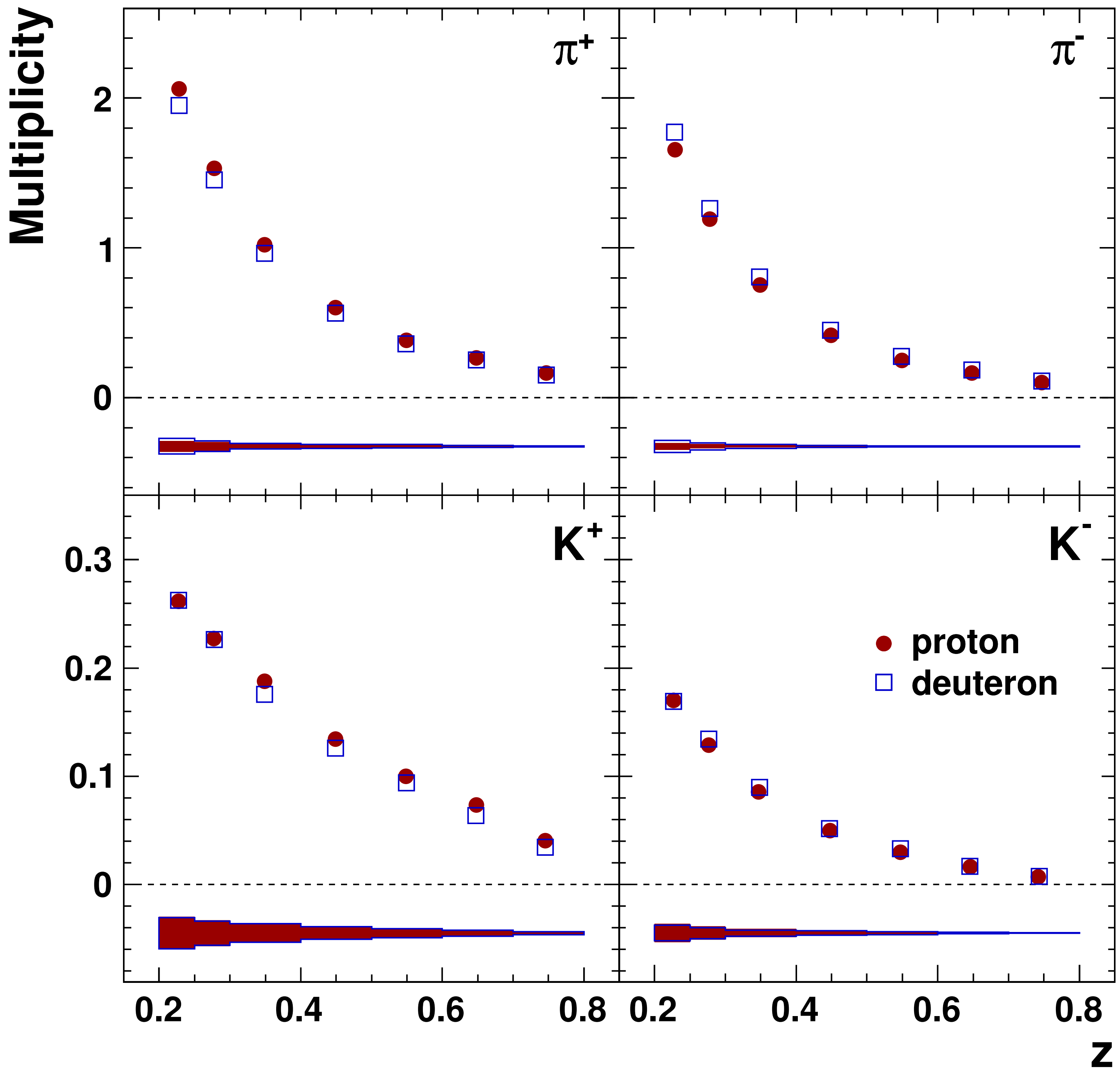

u**-quark** dominance

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**

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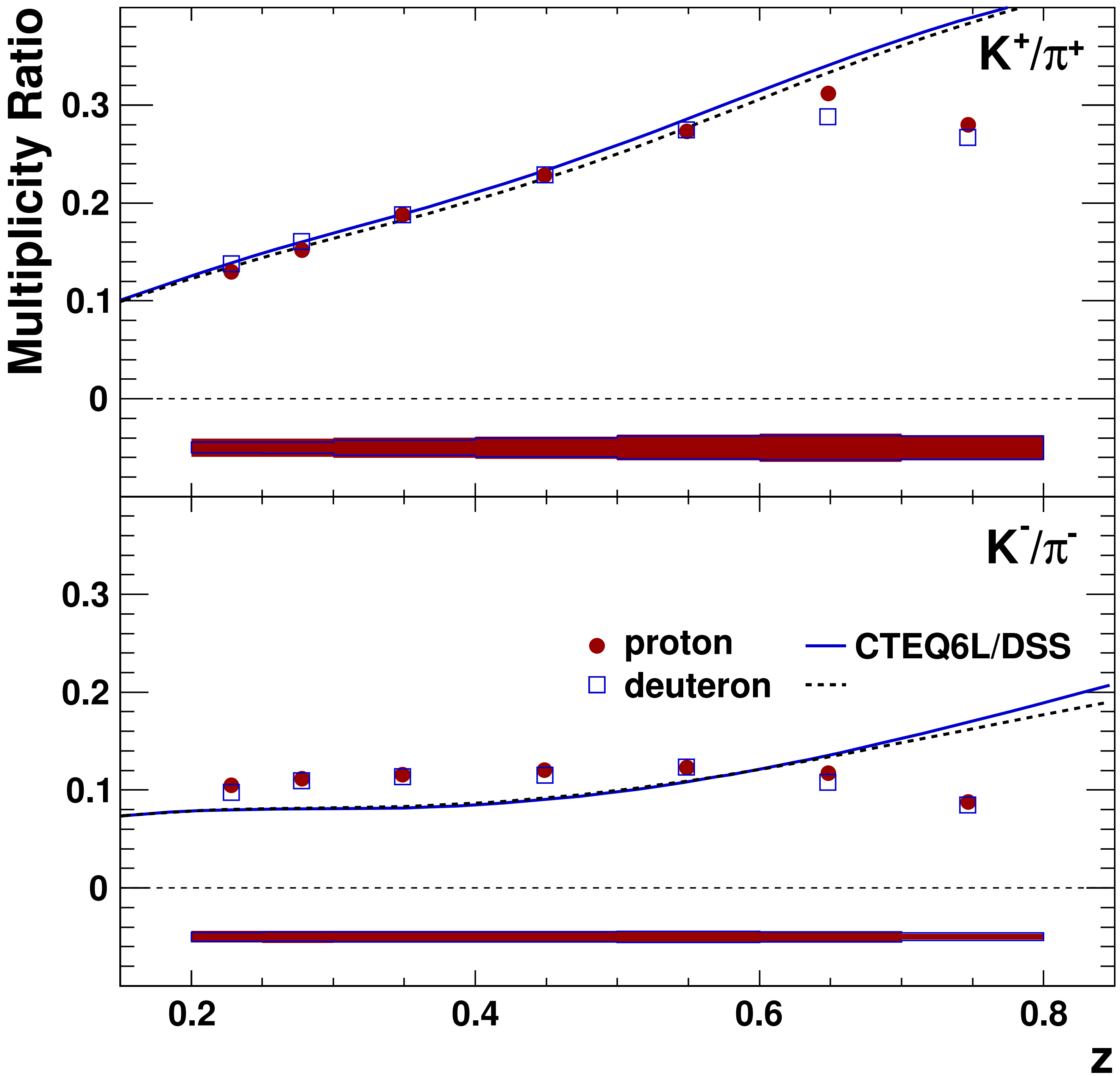
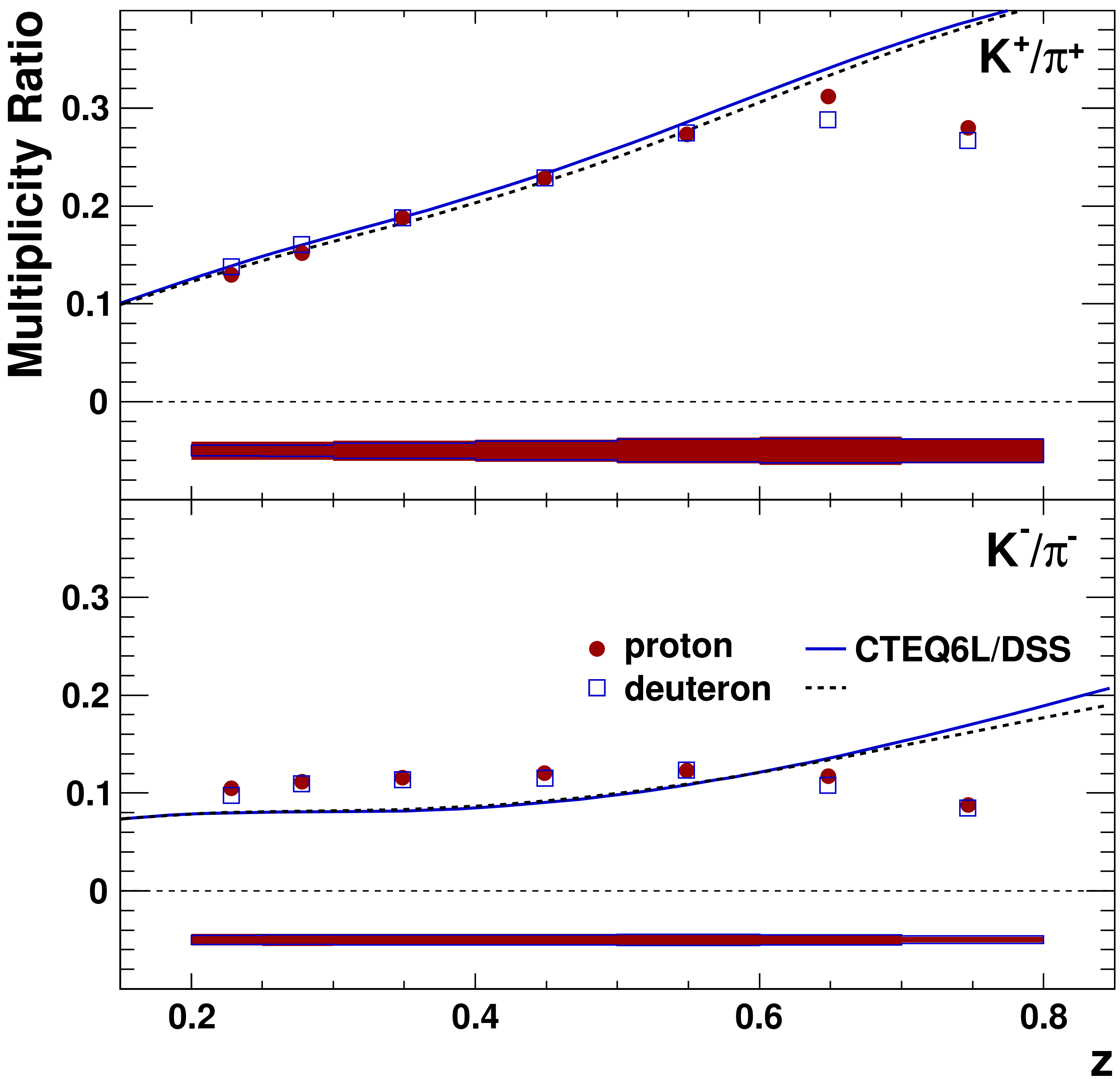


strangeness suppression:
the extra cost to produce $s\bar{s}$
compared to $d\bar{d}$
Visible at high z due to
u-quark dominance.

K/π and **strangeness suppression**



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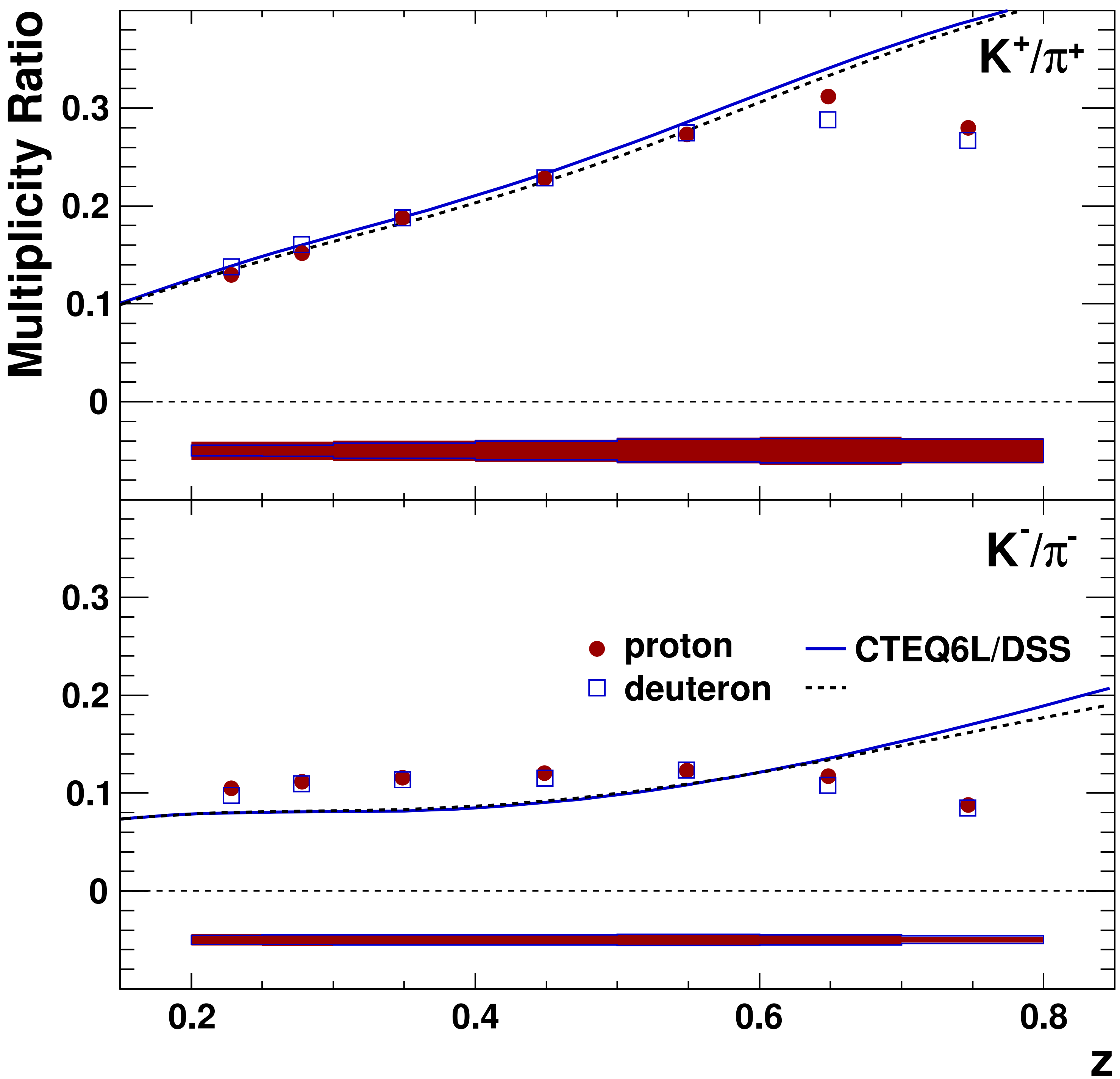

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strangeness suppression:
the extra cost to produce $s\bar{s}$ compared to $d\bar{d}$
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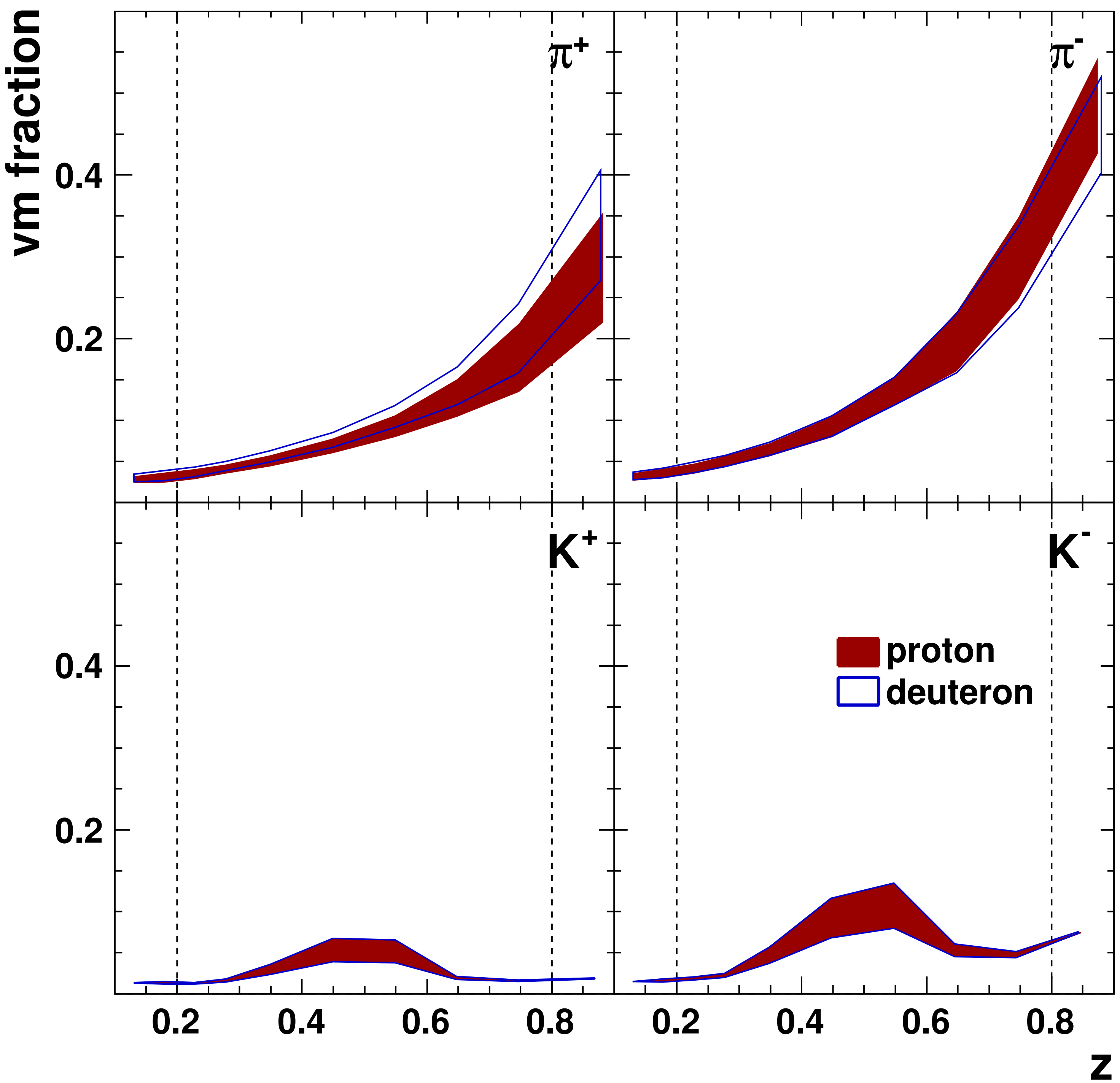
strangeness suppression larger than in previous fits

also observed during HERMES LUND MC tuning

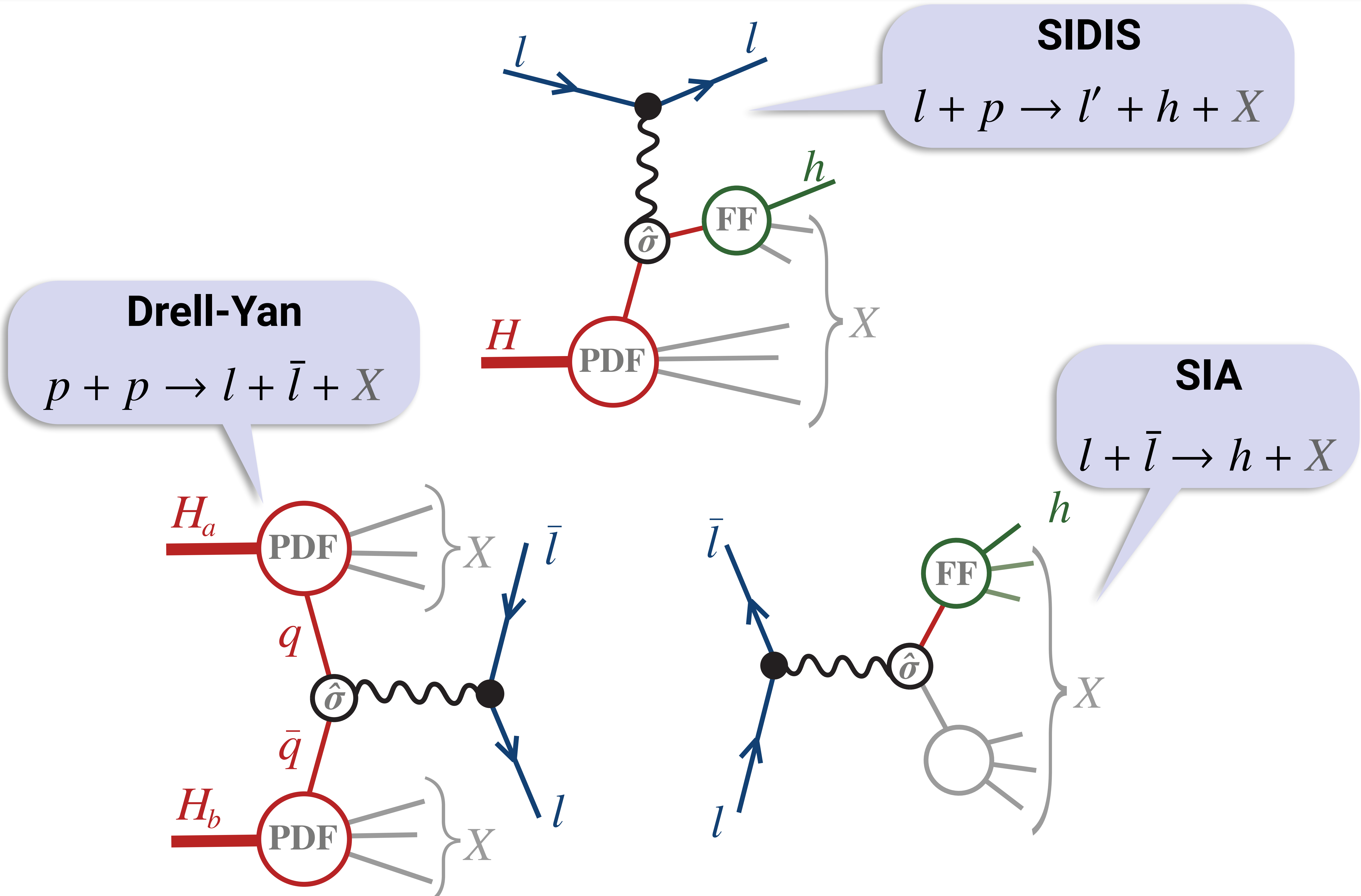
exclusive vector meson contamination



- **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**



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