Recent HERMES results on TMDs from unpolarized targets

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on behalf of the HERMES Collaboration

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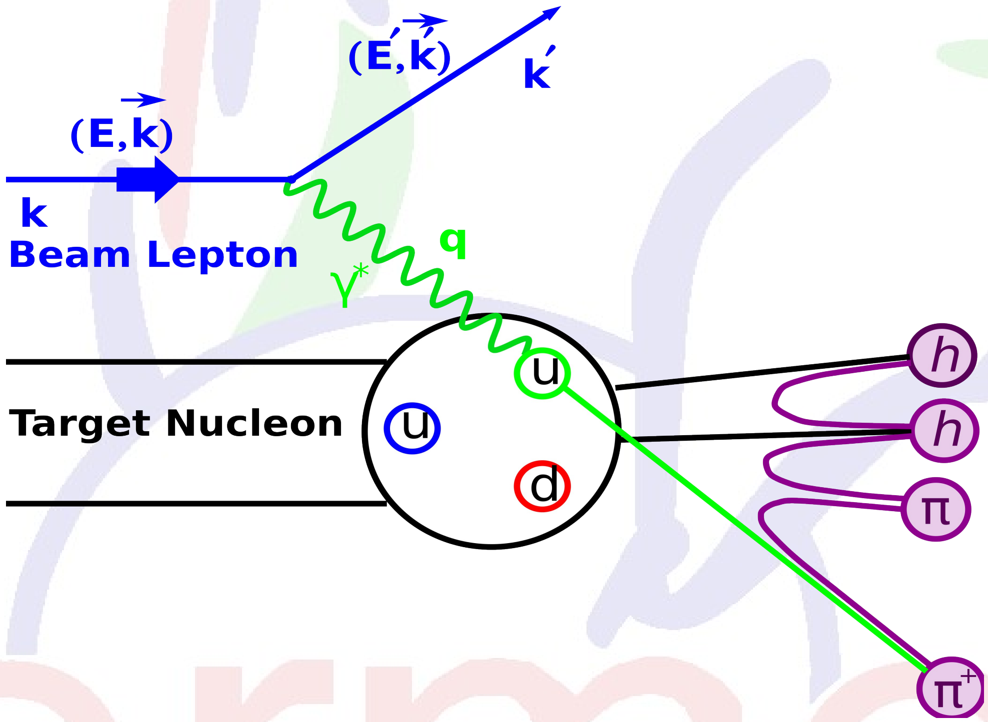
Semi-Inclusive Deep-Inelastic Scattering

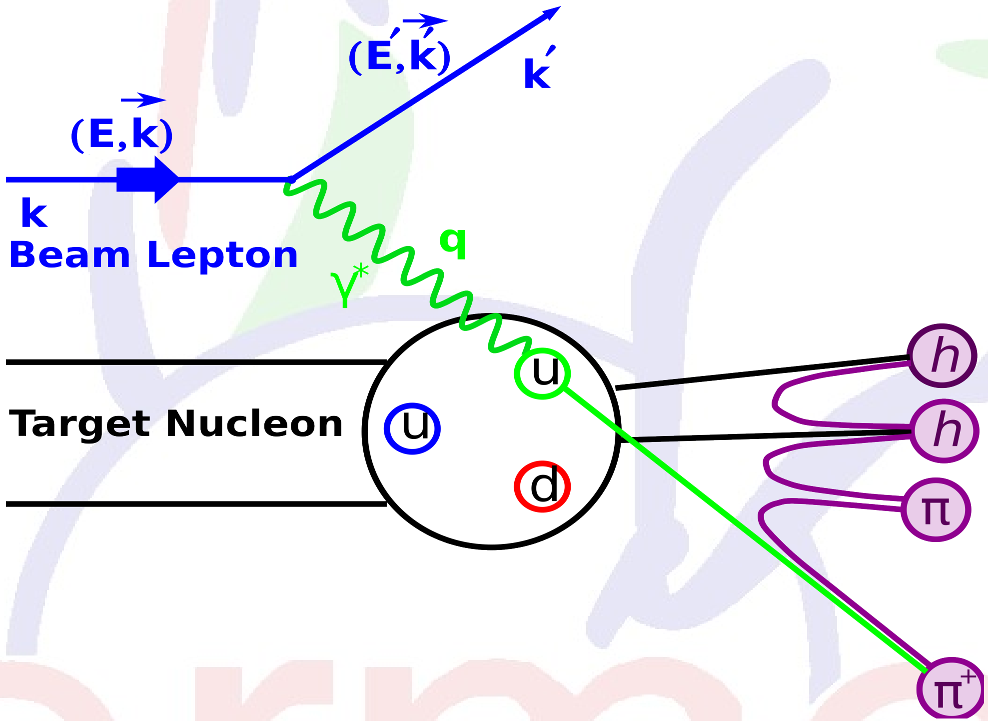


Semi-Inclusive Deep-Inelastic Scattering

$$Q^2 = -(k - k')^2$$

$$\nu = E - E'$$

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



$$x_B = \frac{Q^2}{2 \cdot M_N \cdot \nu}$$

$$z = E_h / \nu$$

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

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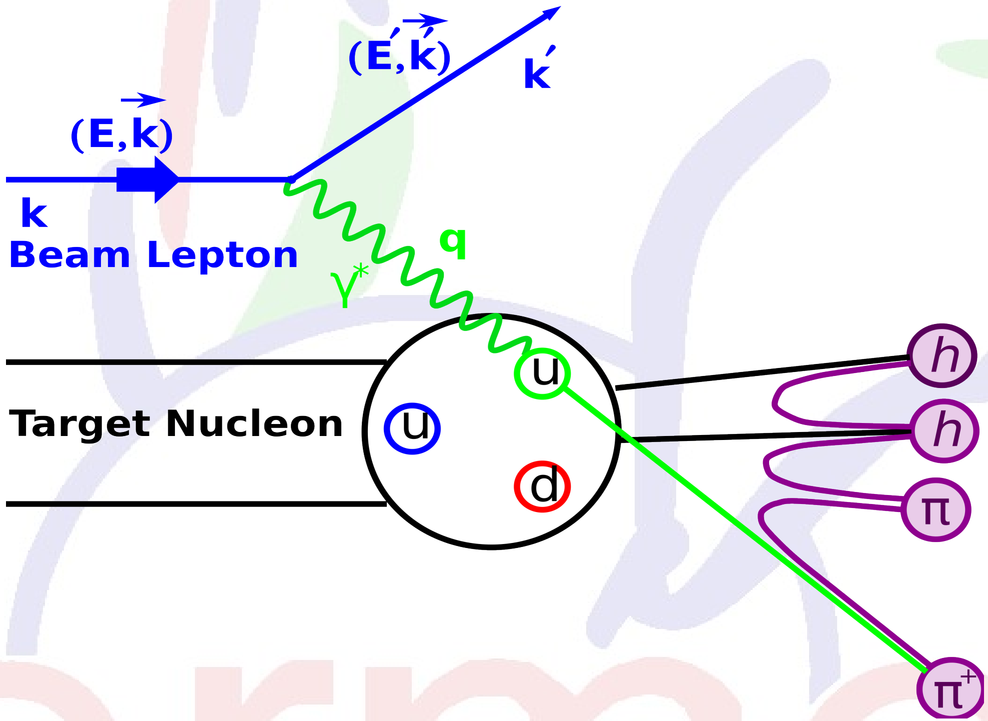

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TMD factorization at leading order in $(k_\perp/Q)$, $P_{h\perp} \simeq k_\perp \ll Q$

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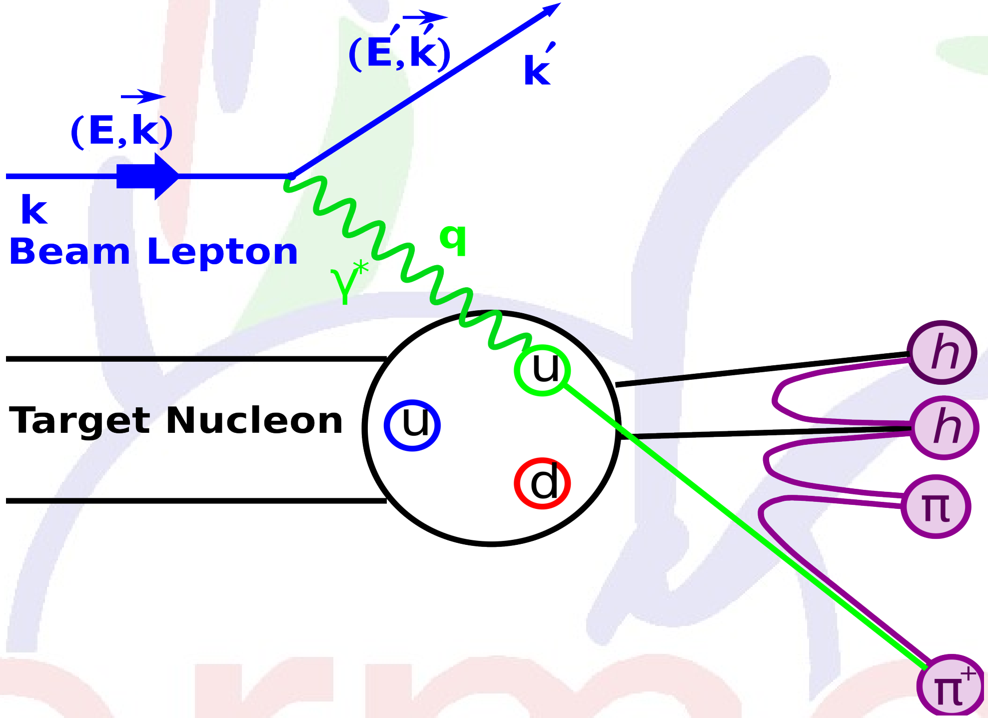

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$$\sigma_{eN \to ehX} \sim \sum_q e_q^2 f_q(x_B, Q^2, k_\perp^2)\, \sigma^{eq \to eq} D_q^h(z, Q^2, p_\perp^2)$$

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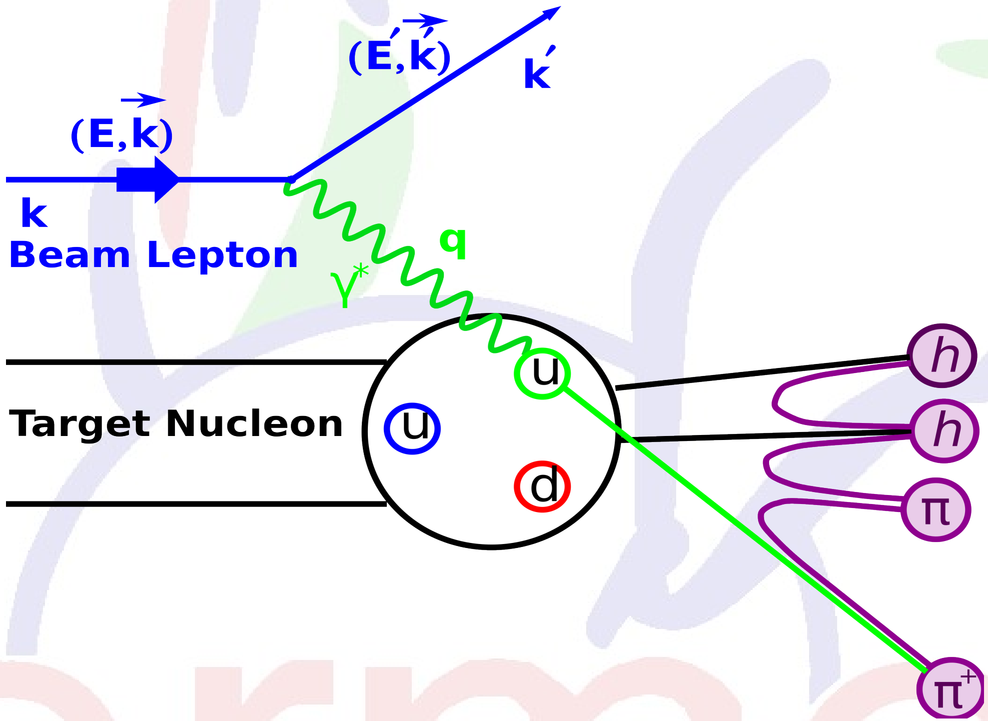

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TMD-PDF

TMD-FF

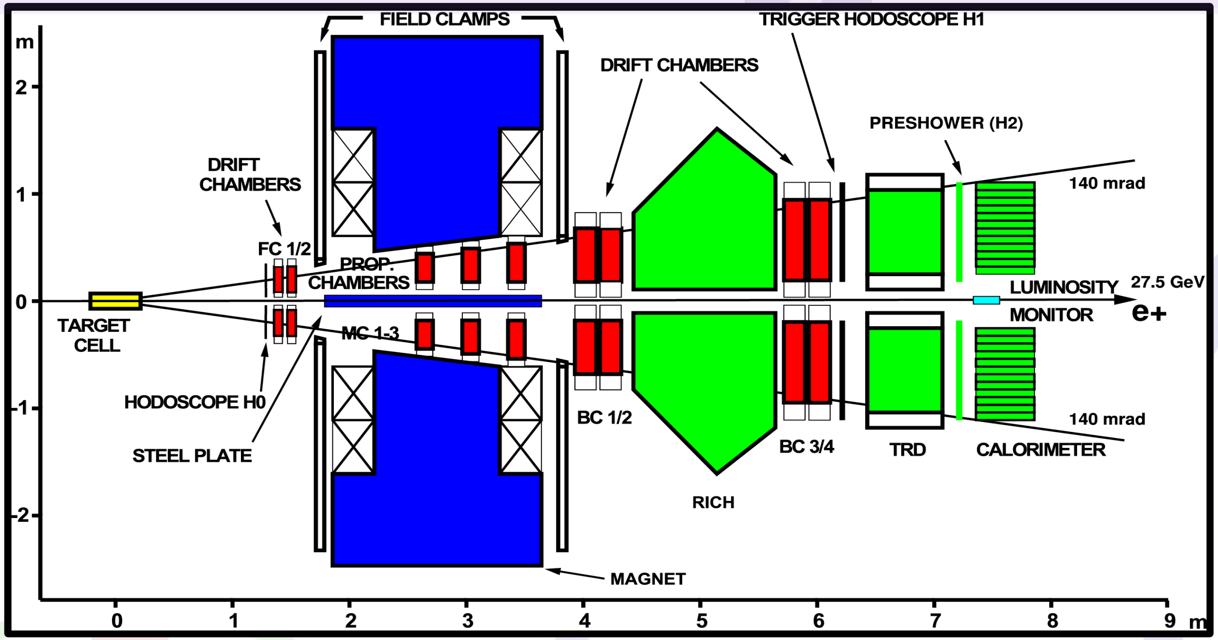
Experimental observable

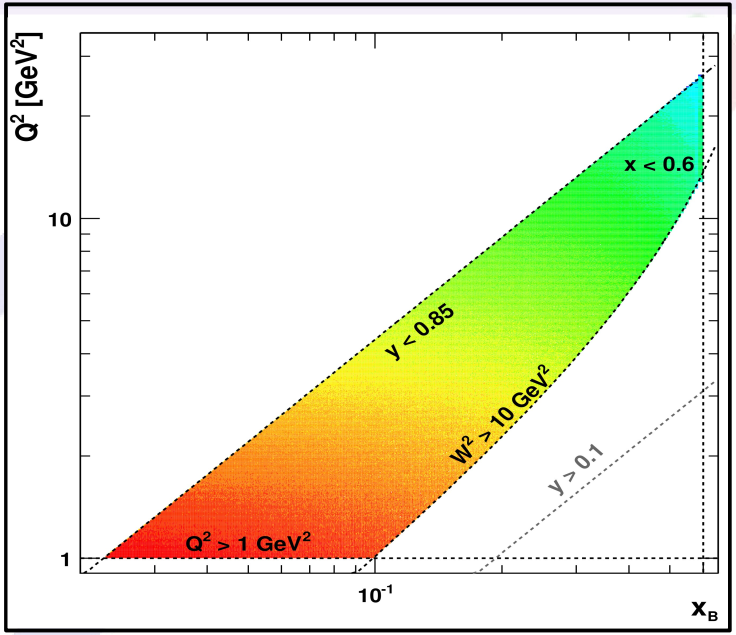
SIDIS hadron yields

$$M^h(x_B, Q^2, z, P_{h\perp}, \phi_h) = \frac{N^h(x_B, Q^2, z, P_{h\perp}, \phi_h)}{N^e(x_B, Q^2)}$$

DIS event yields

Experiment





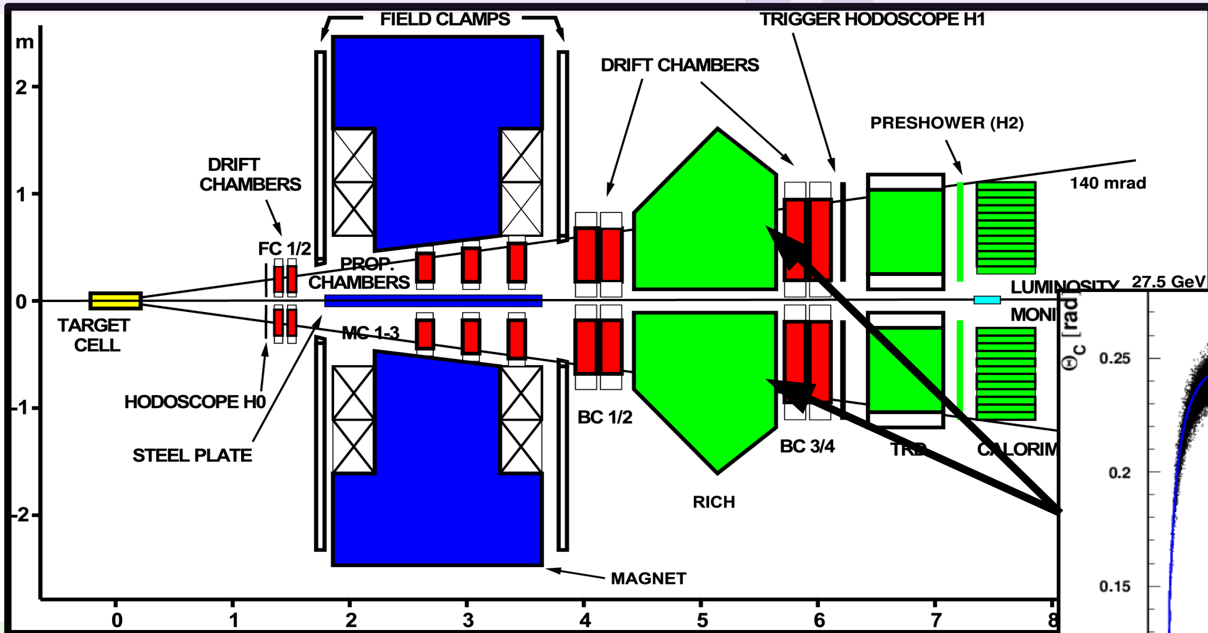
Beam : e^-/e^+ 27.6 GeV

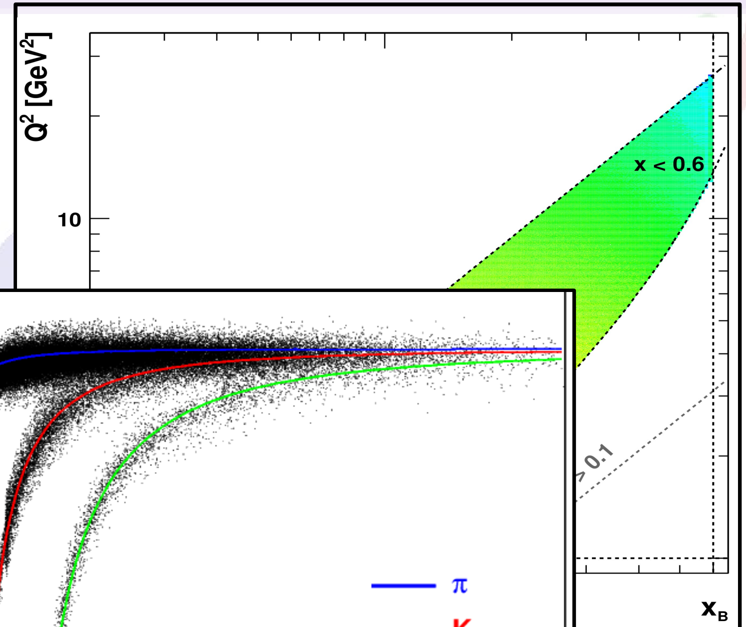
Target : H/D pure gaseous

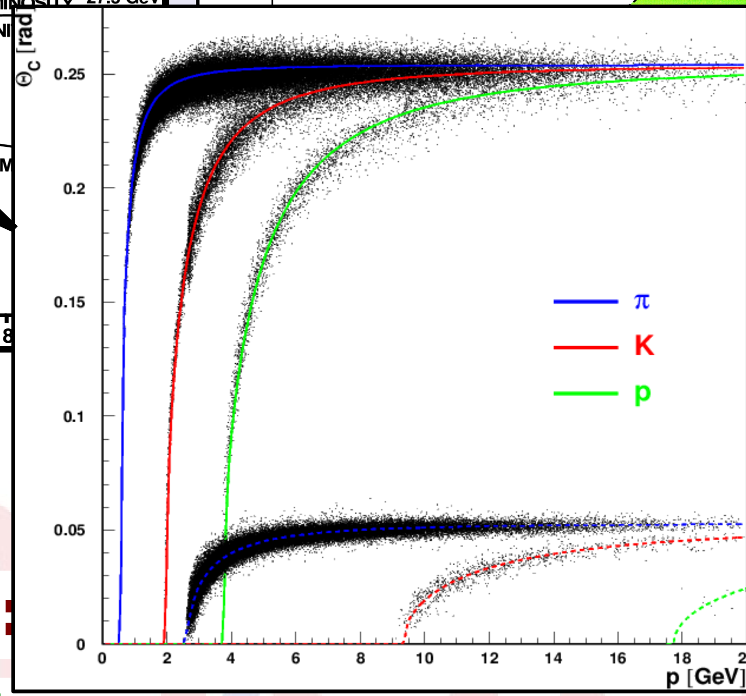
Good momentum resolution : $\frac{\delta p}{p} < 2\ \%$

Excellent particle identification

Experiment







Beam : e^-/e^+ 27.6 GeV

Target : H/D pure gaseous

Good momentum resolution :

Excellent particle identification

Data selection

DIS regime

- $Q^2 > 1$ GeV ^{2}
- $W^2 > 10$ GeV ^{2}
- $0.1 < \nu/E_{beam} < 0.85$

SIDIS selection

- 2 GeV < p < 15 GeV
- 0.2 < z < 0.8
- $x_F > 0.2$

Raw Data

Data analysis

Raw Data

Charge Symmetric Background
(Dalitz decay, $\gamma \rightarrow e^+e^-$)

RICH Unfolding

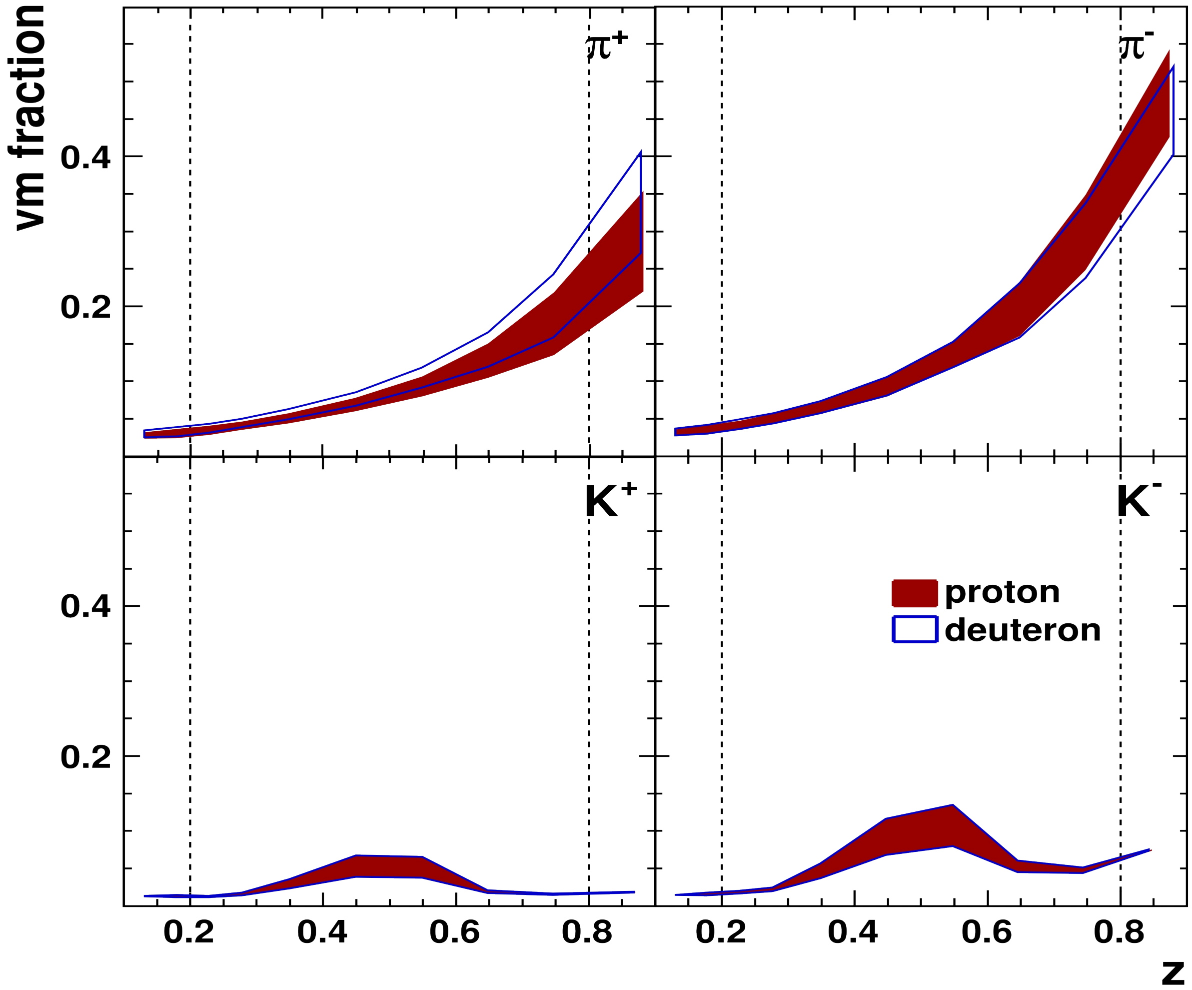
Trigger Efficiencies

Diffractive Vector Meson Contribution

Detector Smearing & QED Radiative Effects

Final Data

Diffractive vector meson contribution



Due to diffractively produced exclusive $\rho^0 \to \pi^+\pi^-$ and $\phi \to K^+K^-$

- **Results with and without VM subtraction.**

Experimental observable

SIDIS hadron yields

$$M^h(x_B, Q^2, z, P_{h\perp}, \phi_h) = \frac{N^h(x_B, Q^2, z, P_{h\perp}, \phi_h)}{N^e(x_B, Q^2)}$$

DIS event yields

Experimental observable

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$$M^{h}(x_B, Q^2, z) = \frac{N^{h}(x_B, Q^2, z)}{N^{e}(x_B, Q^2)}$$

Collinear framework

DIS event yields

Underlying physics

Collinear framework

$$M^h \sim \frac{\sum_q e_q^2 \underbrace{f_q(x_B, Q^2)}_{\text{PDF}} \underbrace{D_q^h(z, Q^2)}_{\text{FF}}}{\sum_q e_q^2 \underbrace{f_q(x_B, Q^2)}_{\text{PDF}}}$$

using collinear PDFs (well known)

extract collinear FFs

Underlying physics

$$M^h \sim \frac{\sum_q e_q^2 \underbrace{f_q(x_B, Q^2)}_{\text{PDF}} \underbrace{D_q^h(z, Q^2)}_{\text{FF}}}{\sum_q e_q^2 \underbrace{f_q(x_B, Q^2)}_{\text{PDF}}}$$

CTEQ6L, GRV, ...

DSS, Kretzer, ...

Universality

SIDIS(e+N), SIA($e^+ + e^-$), HS(p+p)

Advantage of SIDIS

Charge separated FFs

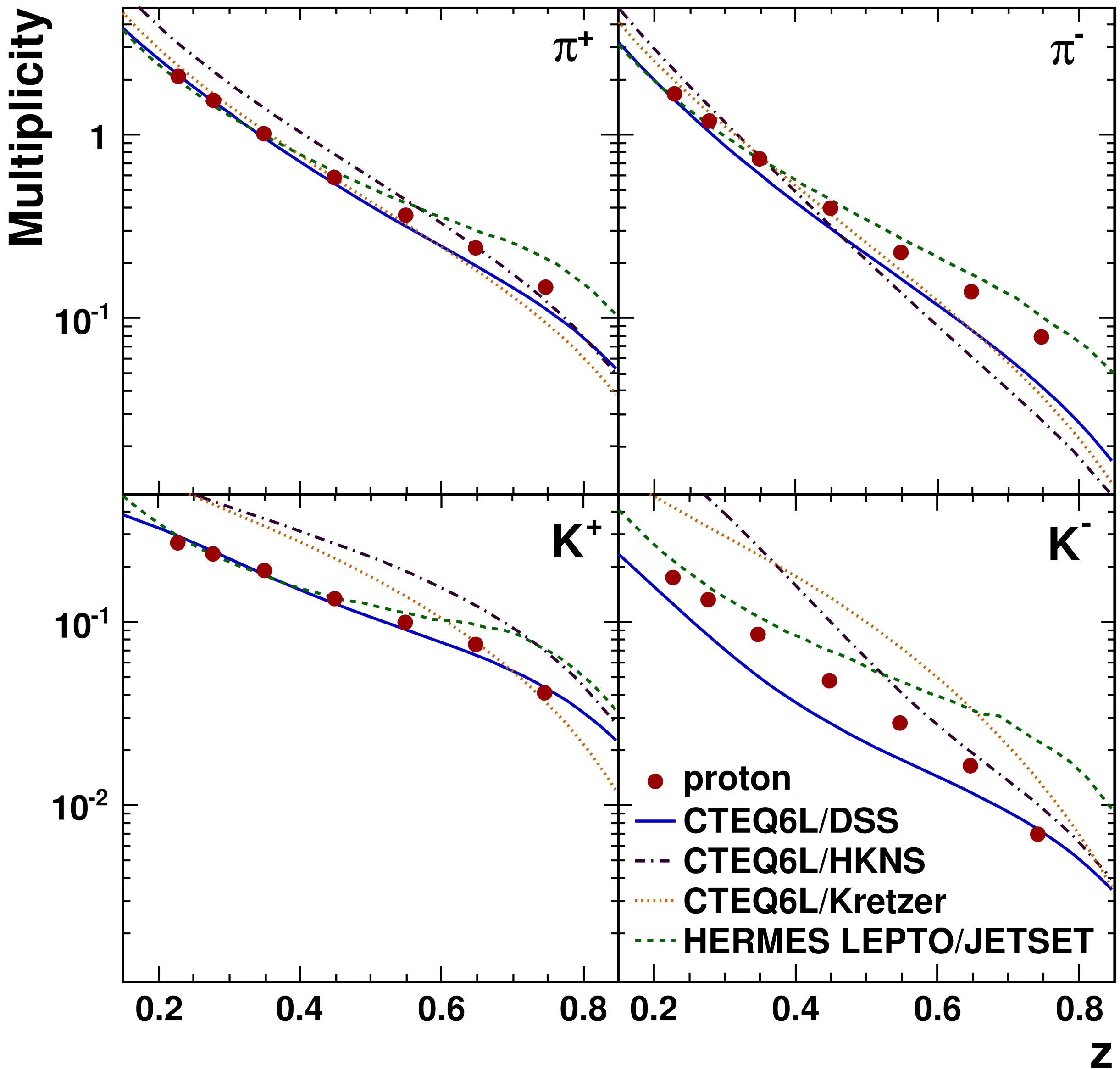
$(D_u^{\pi}, D_{\bar{u}}^{K}, \ldots)$

SIDIS

$(D_u^{\pi}, D_s^{K}, \ldots)$

Flavor separated FFs

$M^h(x_B, Q^2, z, P_{h\perp})$



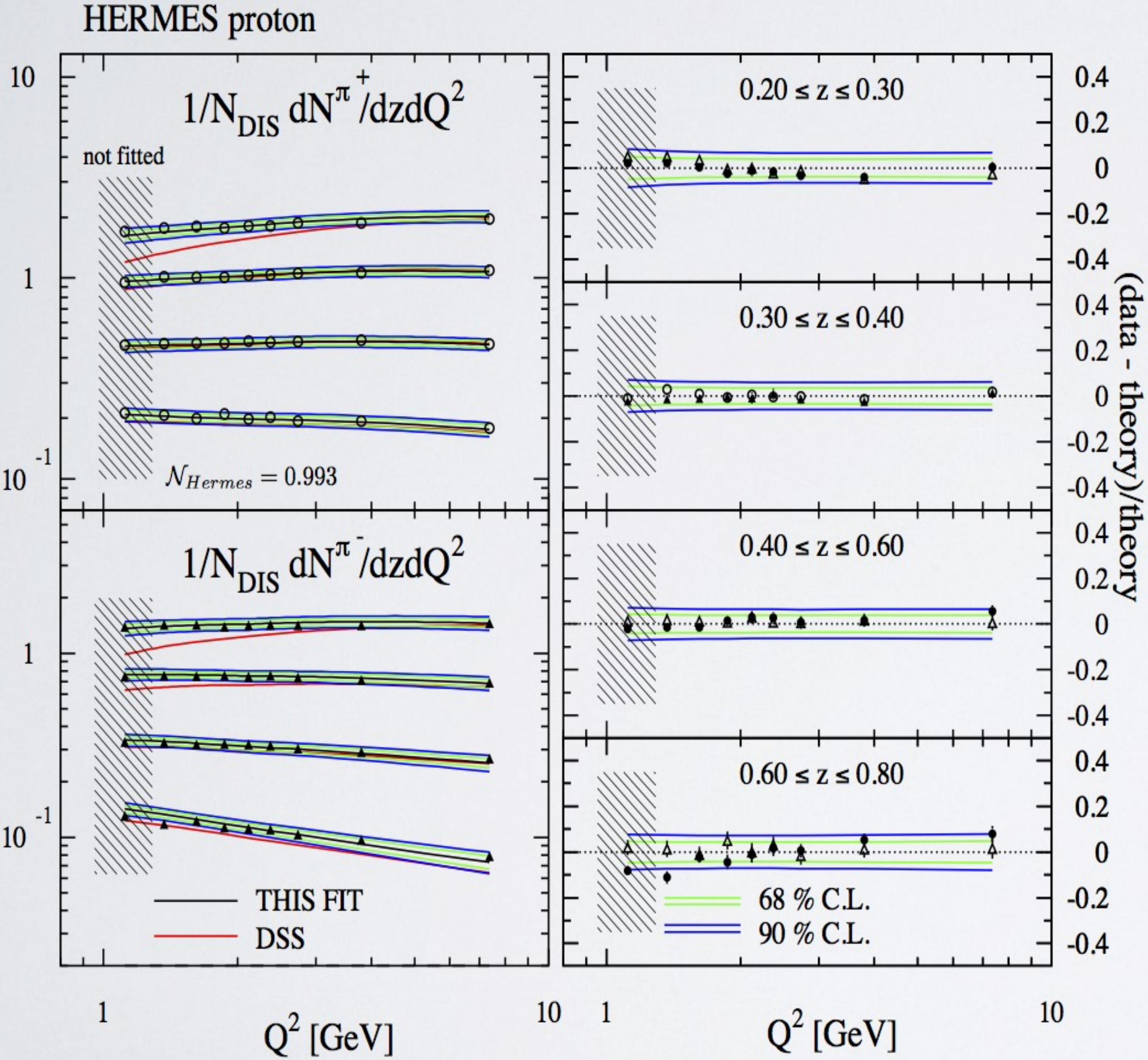
Proton target

LO calculations

- **Reasonable agreement between DSS FFs and Data for positively charged pions and kaons.**

- **Substantial differences between all FFs and Data for negatively charged kaons.**

$M^h(x_B, Q^2, z, P_{h\perp})$



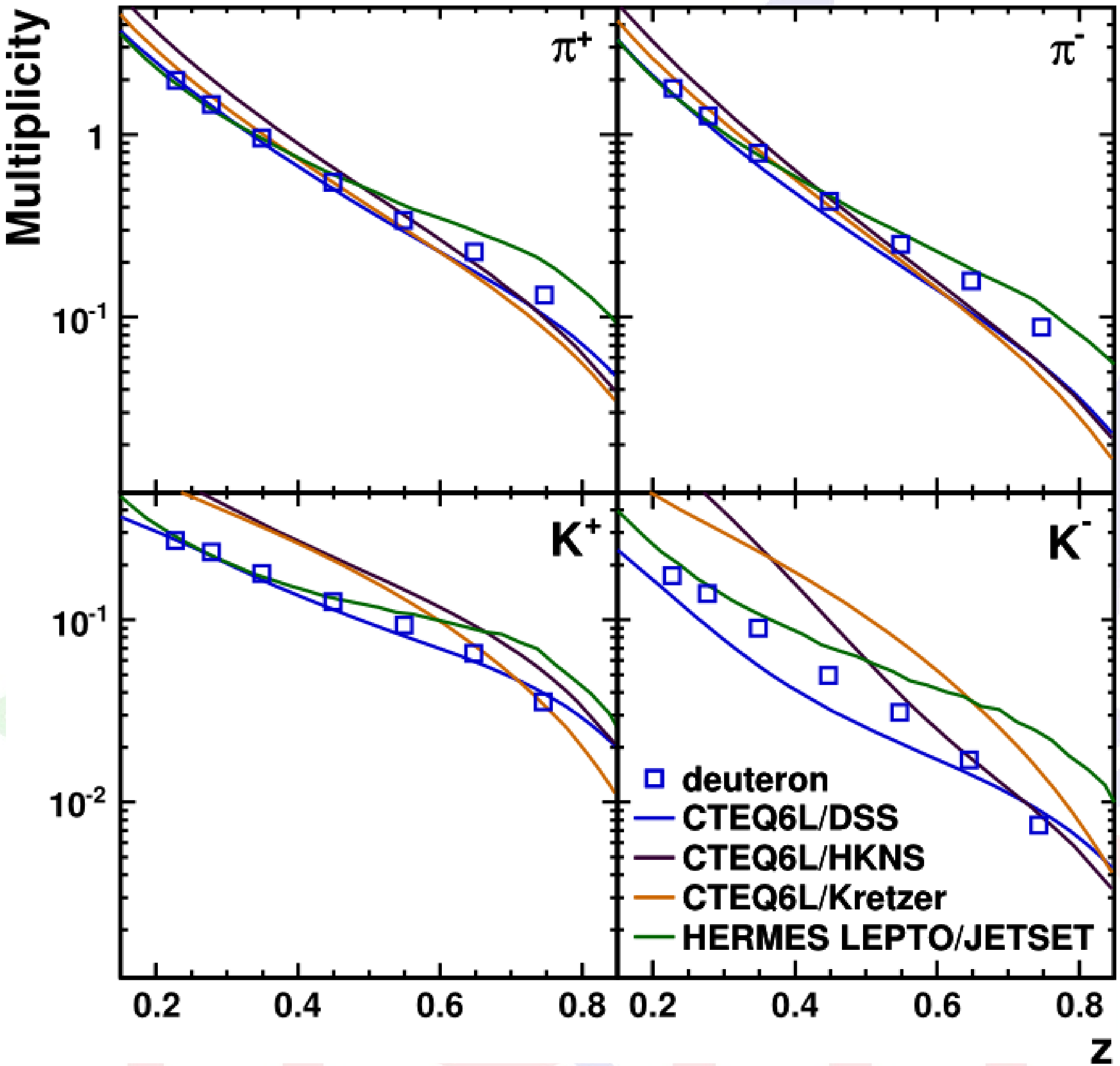
Proton target

NLO calculations(DSS+)

- **Much better agreement for both π^+ and π^-.**

- **Workshop on fragmentation functions, Bloomington, 2013**

$M^h(x_B, Q^2, z, P_{h\perp})$

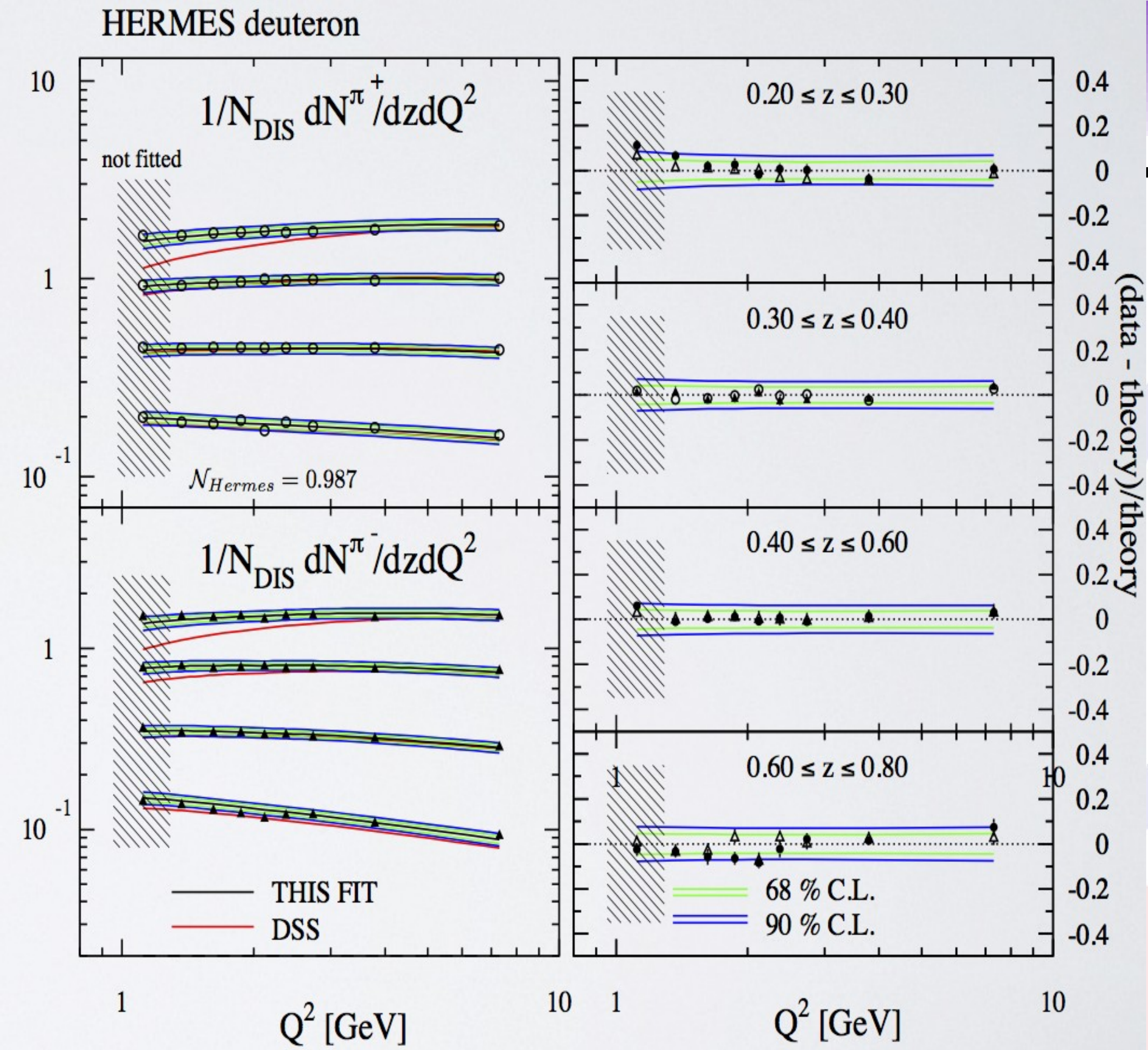


Deuteron target

LO calculations

- **Reasonable agreement between DSS FFs and Data for positively charged pions and kaons.**

- **Substantial differences between all FFs and Data for negatively charged kaons.**



$M^h(x_B, Q^2, z, P_{h\perp})$

Deuteron target

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DIS event yields

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TMDs via $P_{h\perp}$

DIS event yields

Flavor-dependent Gaussian ansatz

$$f_q\left(x_B, Q^2, k_\perp^2\right) = f_q\left(x_B, Q^2\right)\frac{1}{\pi < k_{\perp,q}^2 >} e^{-k_\perp^2/< k_{\perp,q}^2 >}$$

$$D_q^h\left(z, Q^2, p_\perp^2\right) = D_q^h\left(z, Q^2\right)\frac{1}{\pi < p_{\perp,q\to h}^2 >} e^{-p_\perp^2/< p_{\perp,q\to h}^2 >}$$

$$< P_{h\perp,q}^2 > = < p_{\perp,q\to h}^2 > + z^2 < k_{\perp,q}^2 >$$

A. Signori, A. Bacchetta, M. Radici and G. Schnell(JHEP, 2013)

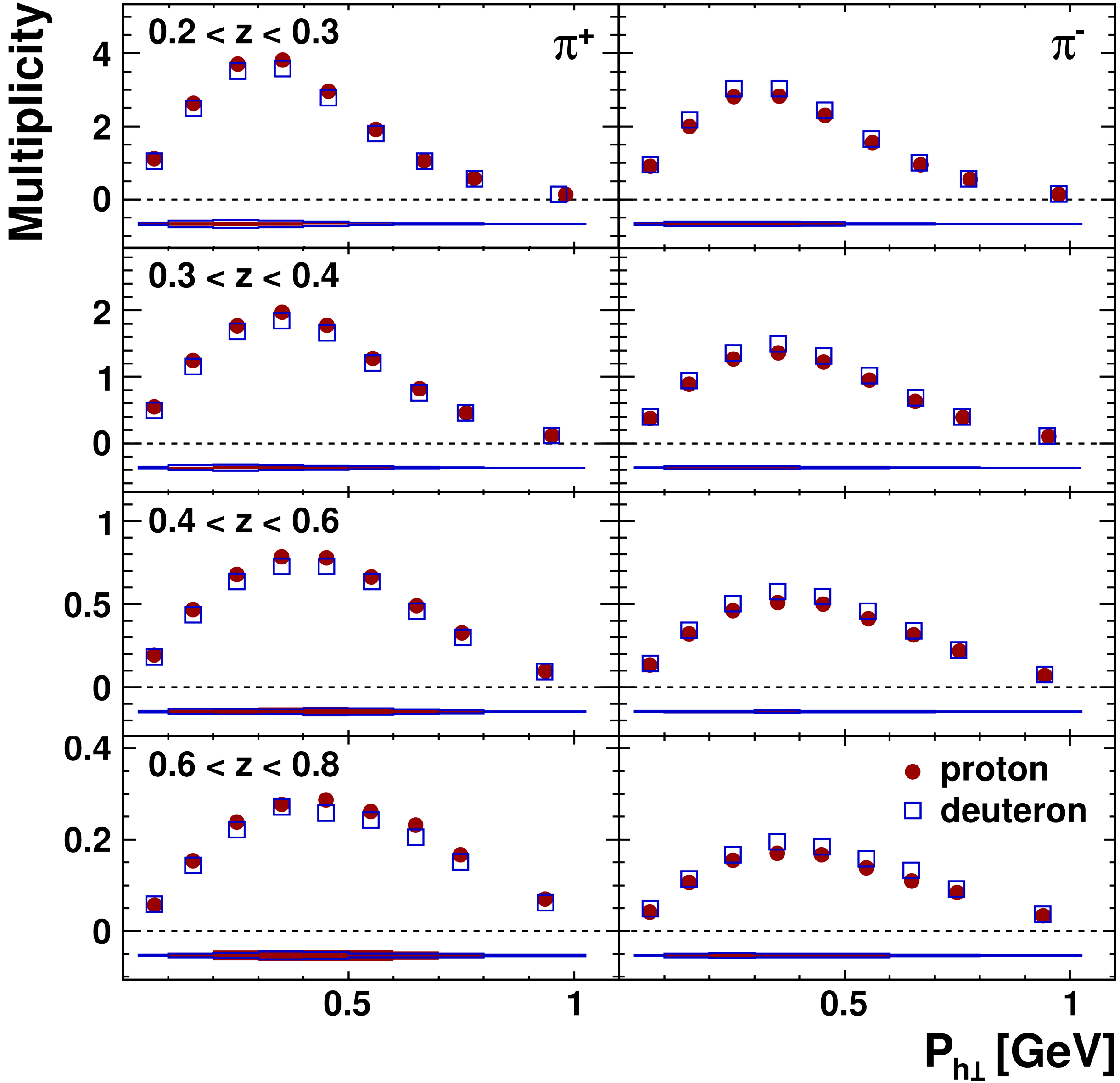
Flavor-dependent Gaussian ansatz

$$f_q\left(x_B, Q^2, k_\perp^2\right) = \underbrace{f_q\left(x_B, Q^2\right)}_{\text{PDF}} \frac{1}{\pi \langle k^2_{\perp,q} \rangle} e^{-k_\perp^2/\langle k^2_{\perp,q} \rangle}$$

$$\boxed{\int f_q\left(x_B, Q^2, k_\perp^2\right) d^2 k_\perp} \qquad \boxed{\int D_q^h\left(z, Q^2, p_\perp^2\right) d^2 p_\perp}$$

$$D_q^h\left(z, Q^2, p_\perp^2\right) = \underbrace{D_q^h\left(z, Q^2\right)}_{\text{FF}} \frac{1}{\pi \langle p^2_{\perp,q\to h} \rangle} e^{-p_\perp^2/\langle p^2_{\perp,q\to h} \rangle}$$

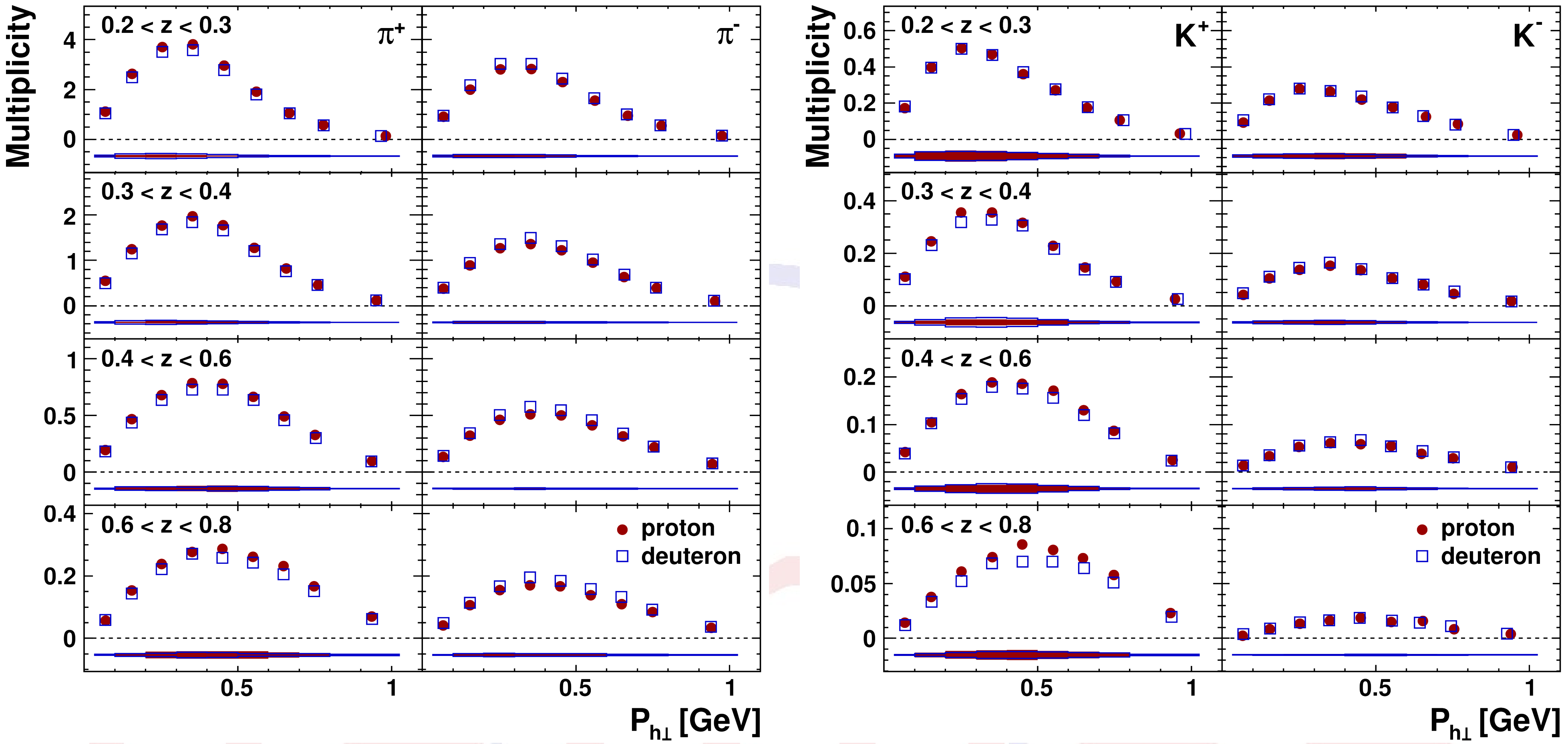
$\mathrm{M}^h(\, x_B,\, Q^2,\, z,\, P_{h\perp}\,)$



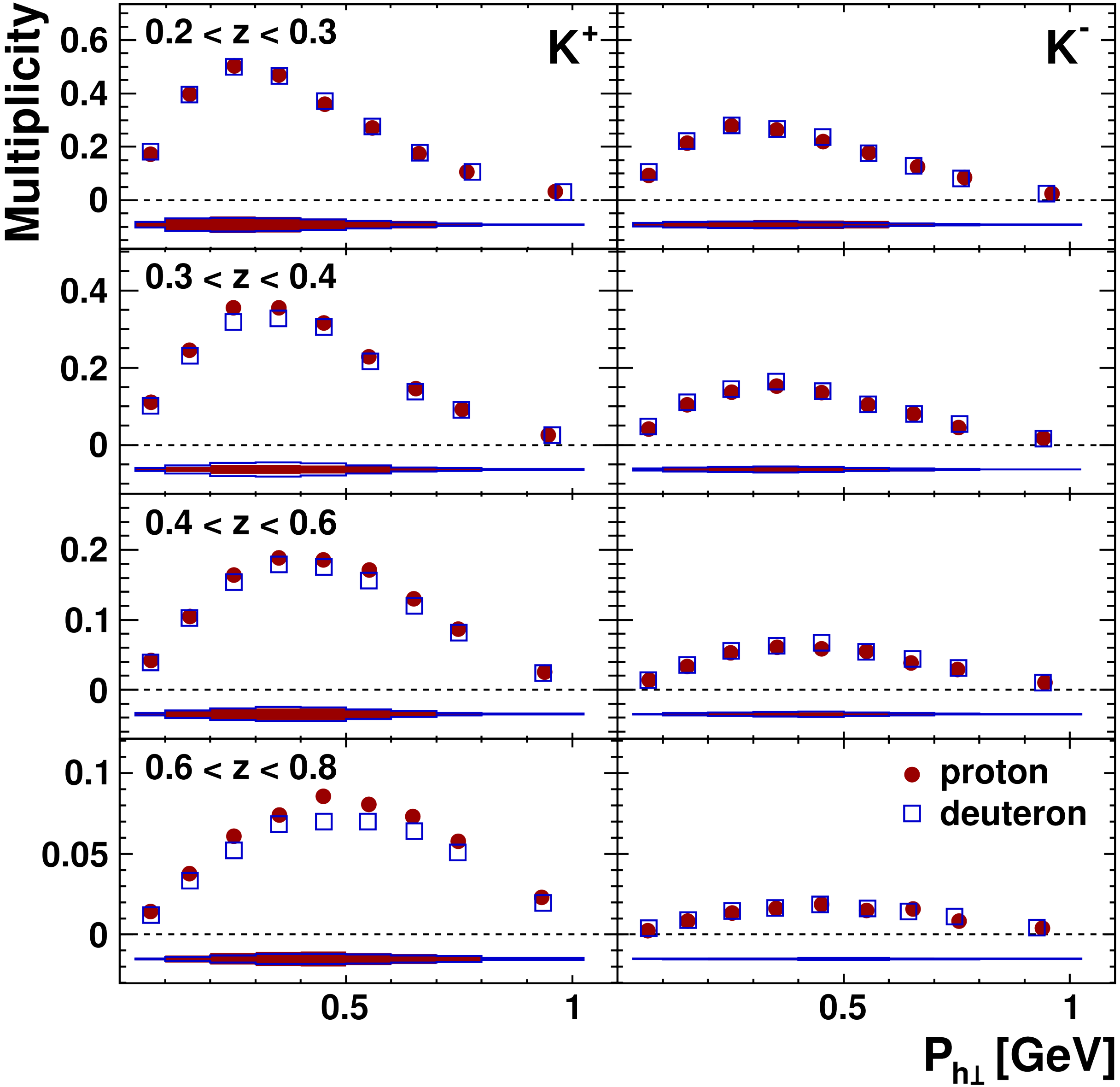
Arises from combined effect : initial transverse motion of the struck quark and the transverse momentum component generated by the fragmentation process :

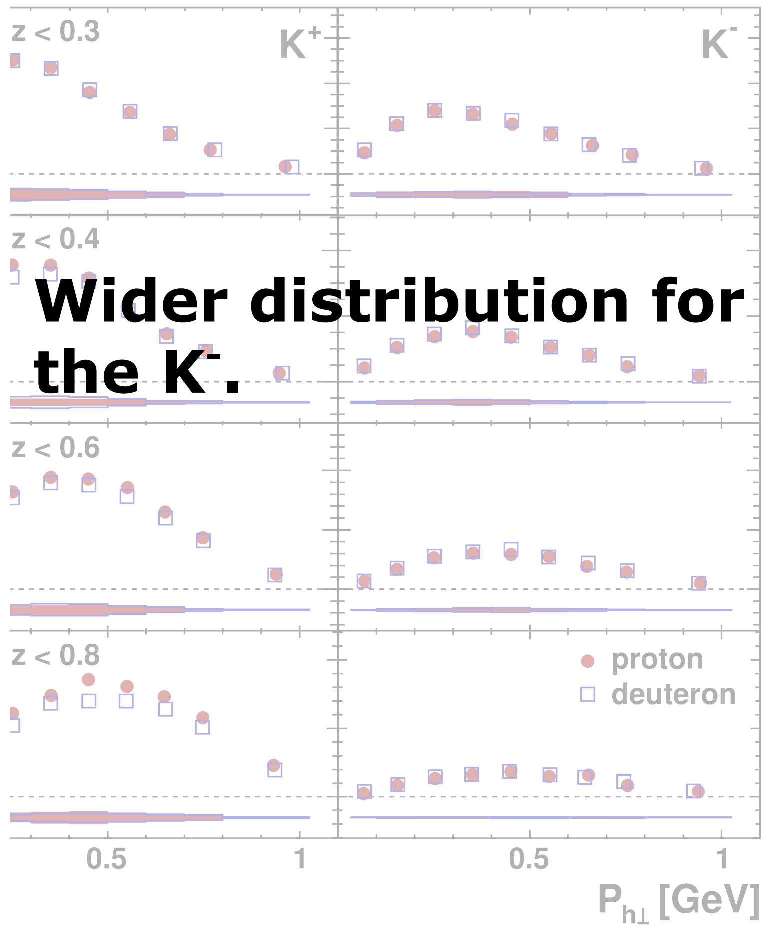
$$\vec{P}_{h\perp} = z\,\vec{k}_\perp + \vec{p}_\perp - \mathrm{O}\left(\frac{k_\perp^2}{Q^2}\right)$$

$M^h(x_B, Q^2, z, P_{h\perp})$

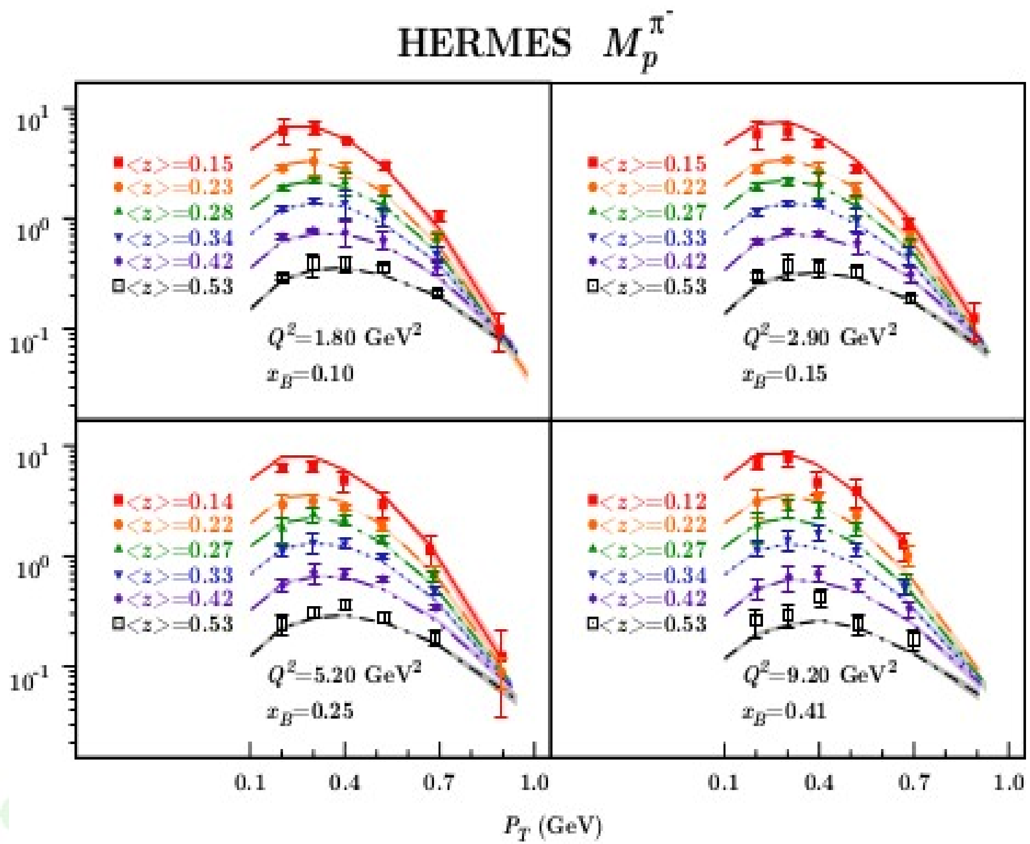


$M^h(x_B, Q^2, z, P_{h\perp})$

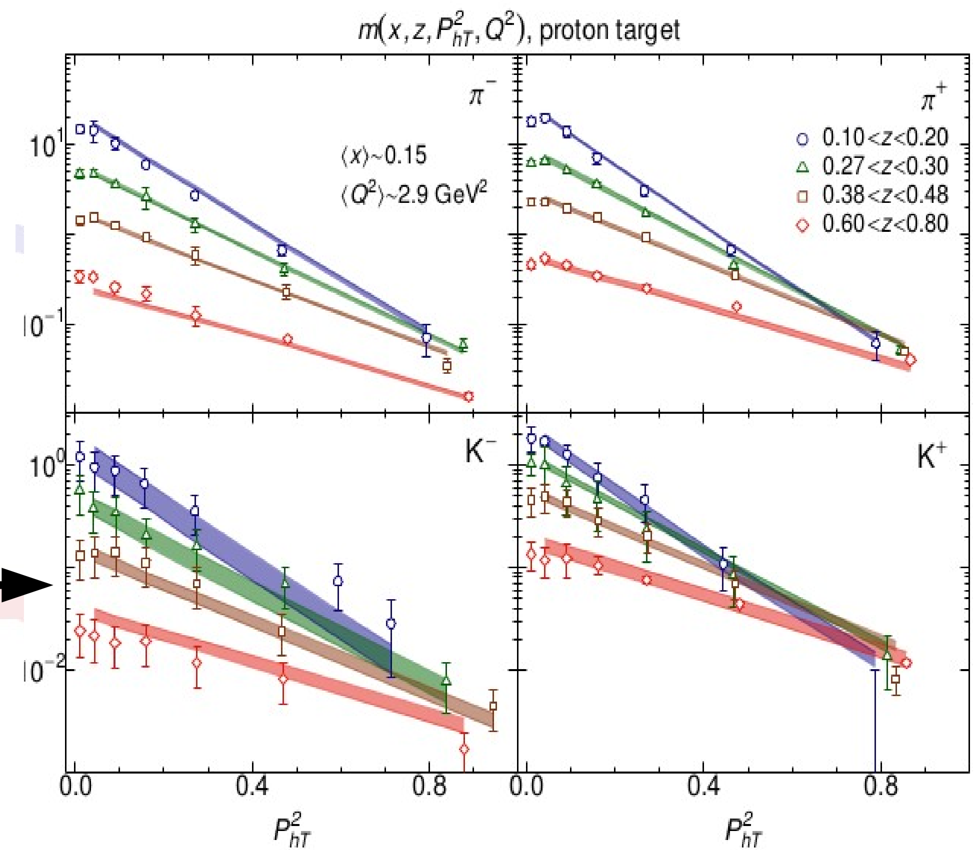




Wider distribution for the K⁻.



M. Anselmino, M. Boglione, J.O. Gonzalez H., S. Melis, A. Prokudin JHEP (2014)



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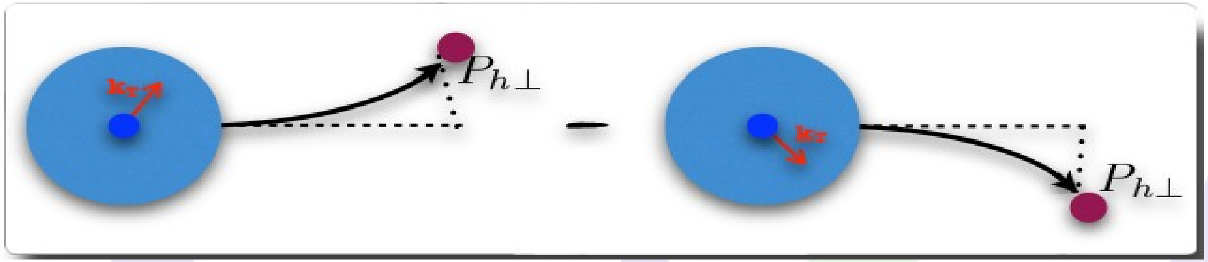
TMDs via ϕ_h

DIS event yields

Azimuthal modulations

Cahn effect



kinematic effect caused by quark intrinsic transverse momentum.

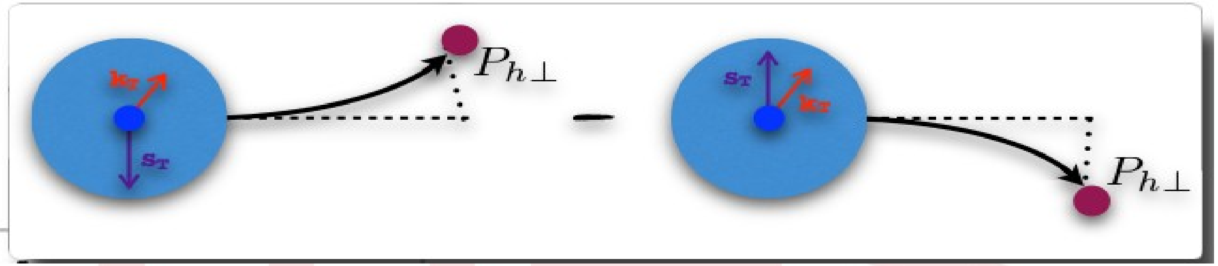
$(\cos\phi_h)$

R.N. Cahn, Phys. Lett. B78, (1978)

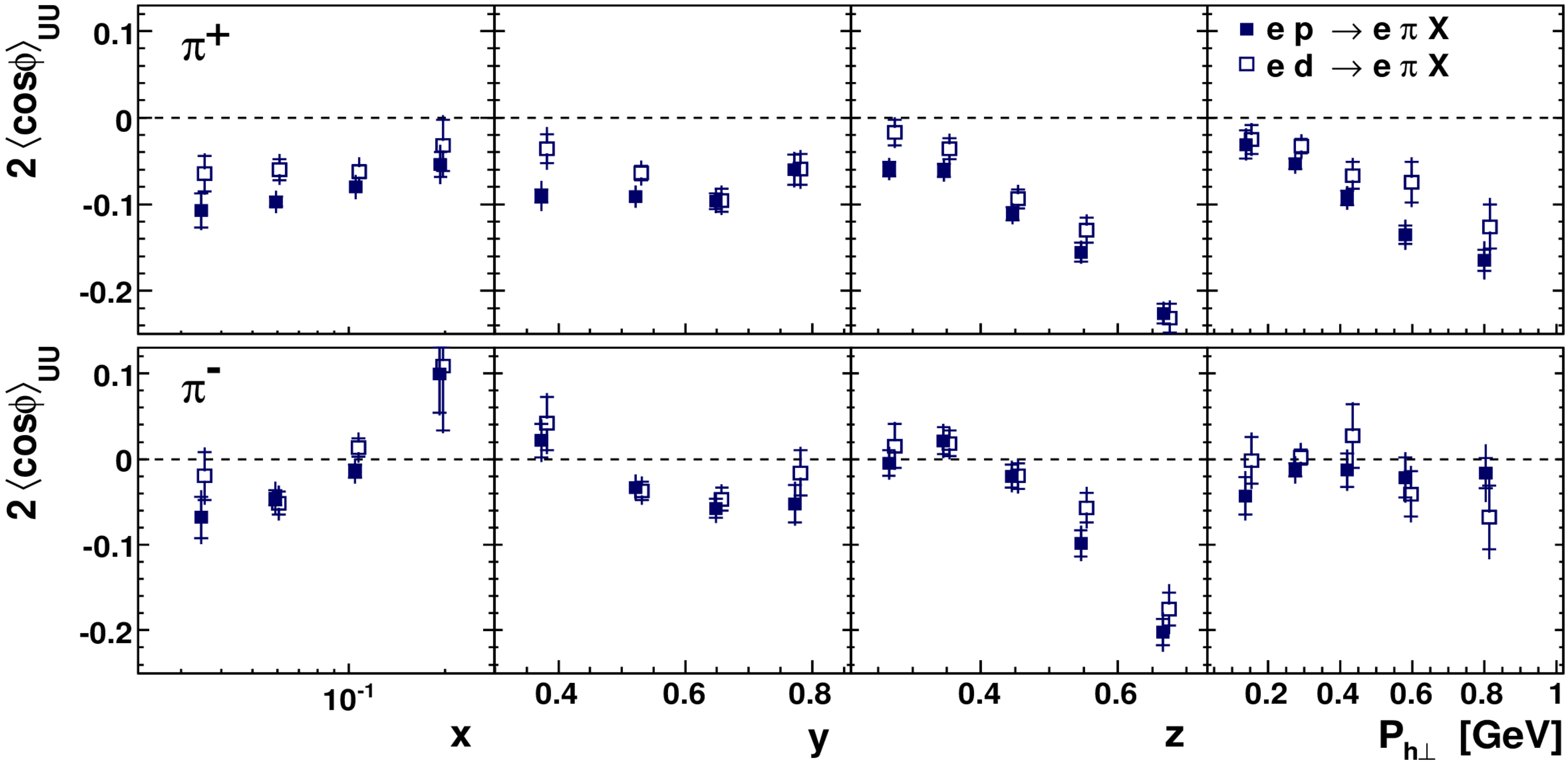
Boer-Mulders effect

correlation between quark transverse momentum and quark transverse spin.

$(\cos 2\phi_h)$



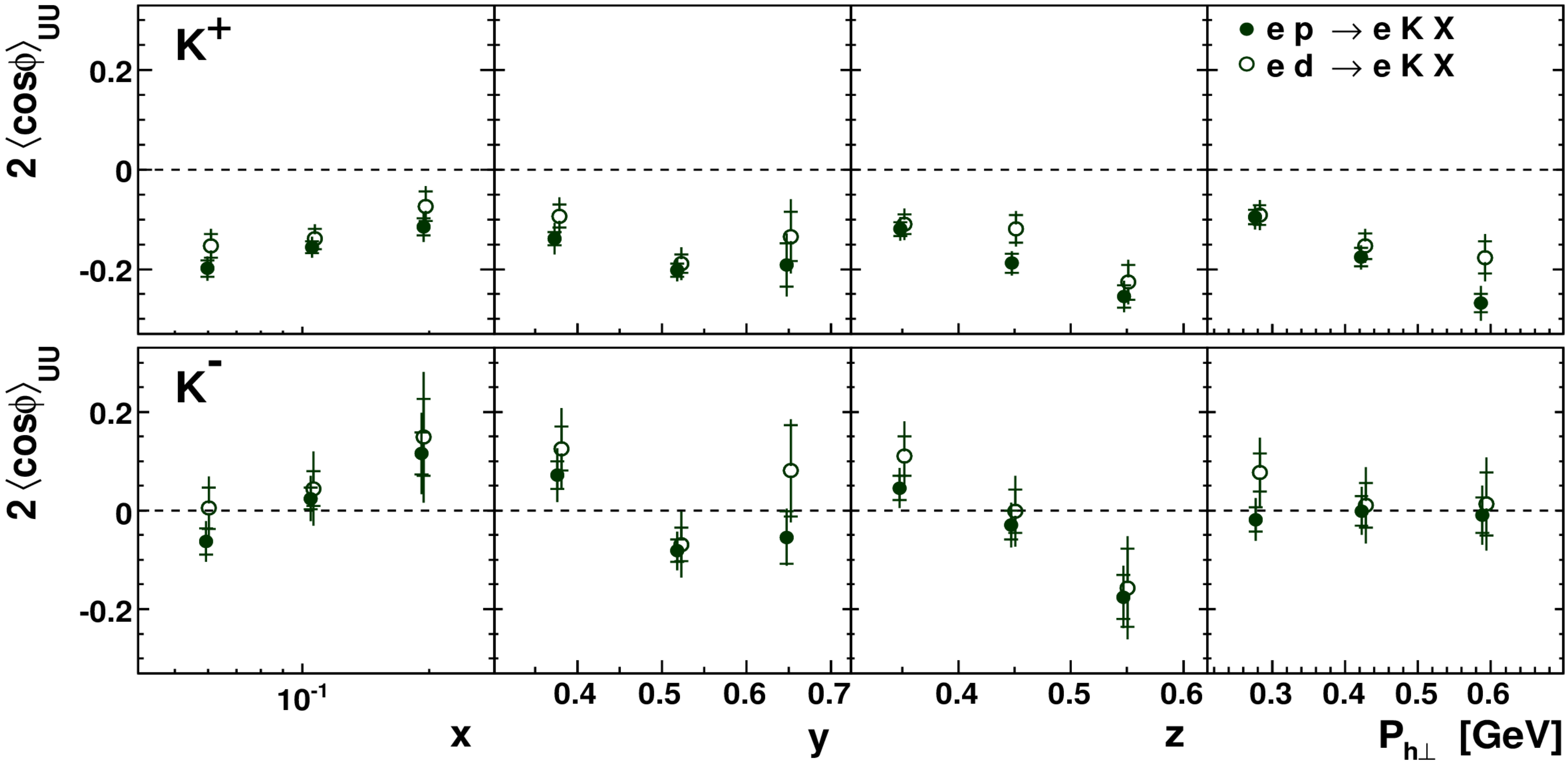
D. Boer and P.J. Mulders, Phys. Rev. D57, (1998)



Both π^+ and π^- have negative asymmetry amplitudes.

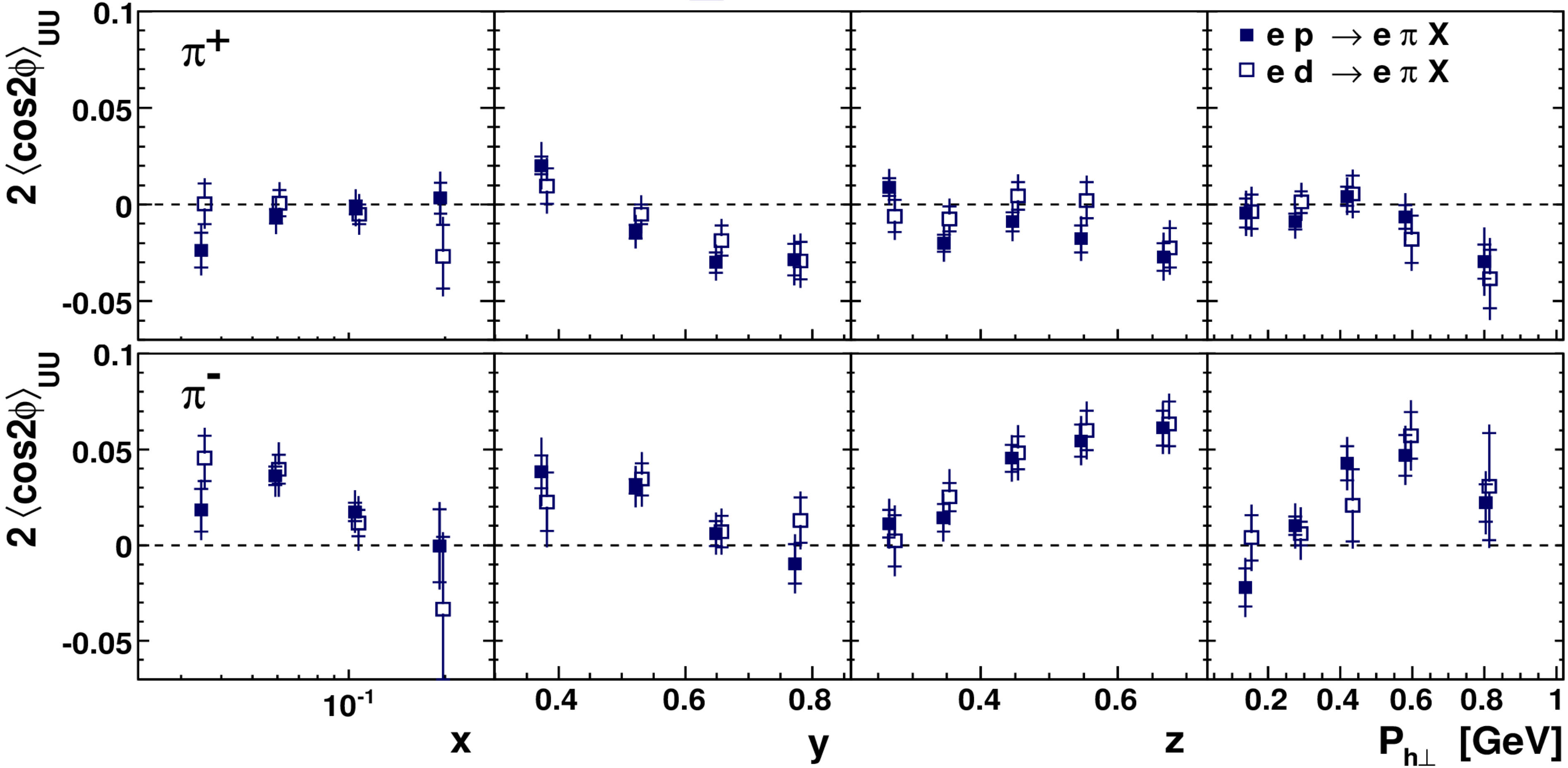
The magnitude of π^+ asymmetry amplitude is smaller on deuterium than on hydrogen target.

For both particles the asymmetry amplitude is the largest in magnitude at high z.



Large negative amplitudes for positively charged kaons.

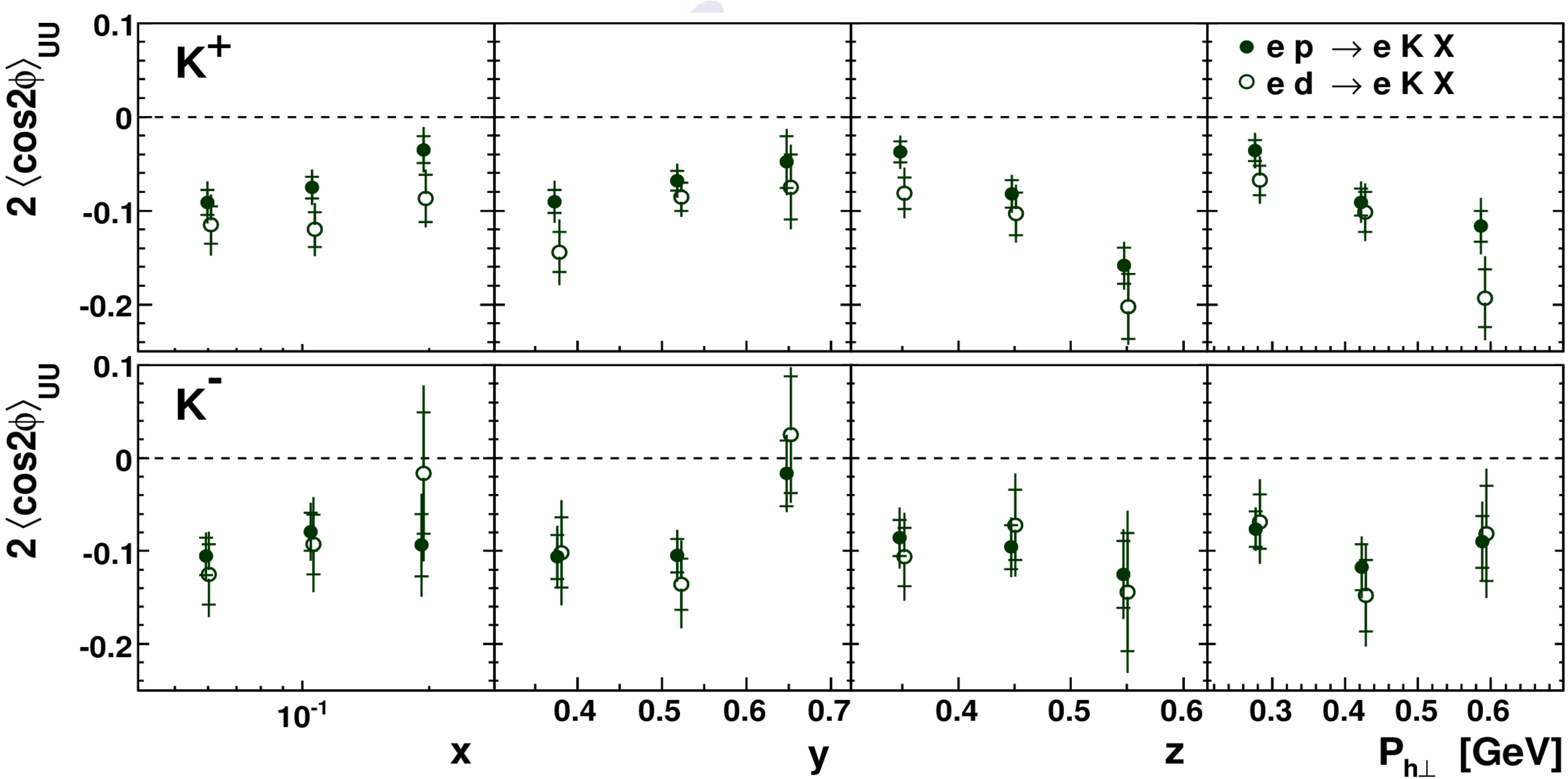
Similar results for hydrogen and deuterium targets.



The amplitudes for oppositely charged pions have the opposite signs.

π^+ and π^- asymmetry amplitudes have different magnitudes.

Similar results for hydrogen and deuterium targets.



The asymmetry amplitudes have negative sign for both K^+ and K^-.

Both kaons have large asymmetry amplitudes in magnitude.

Similar results for hydrogen and deuterium targets.

(**hadron multiplicities**)

A. Airapetian et. al, Phys. Rev. D87 (2013) 074029
http://www-hermes.desy.de/multiplicities

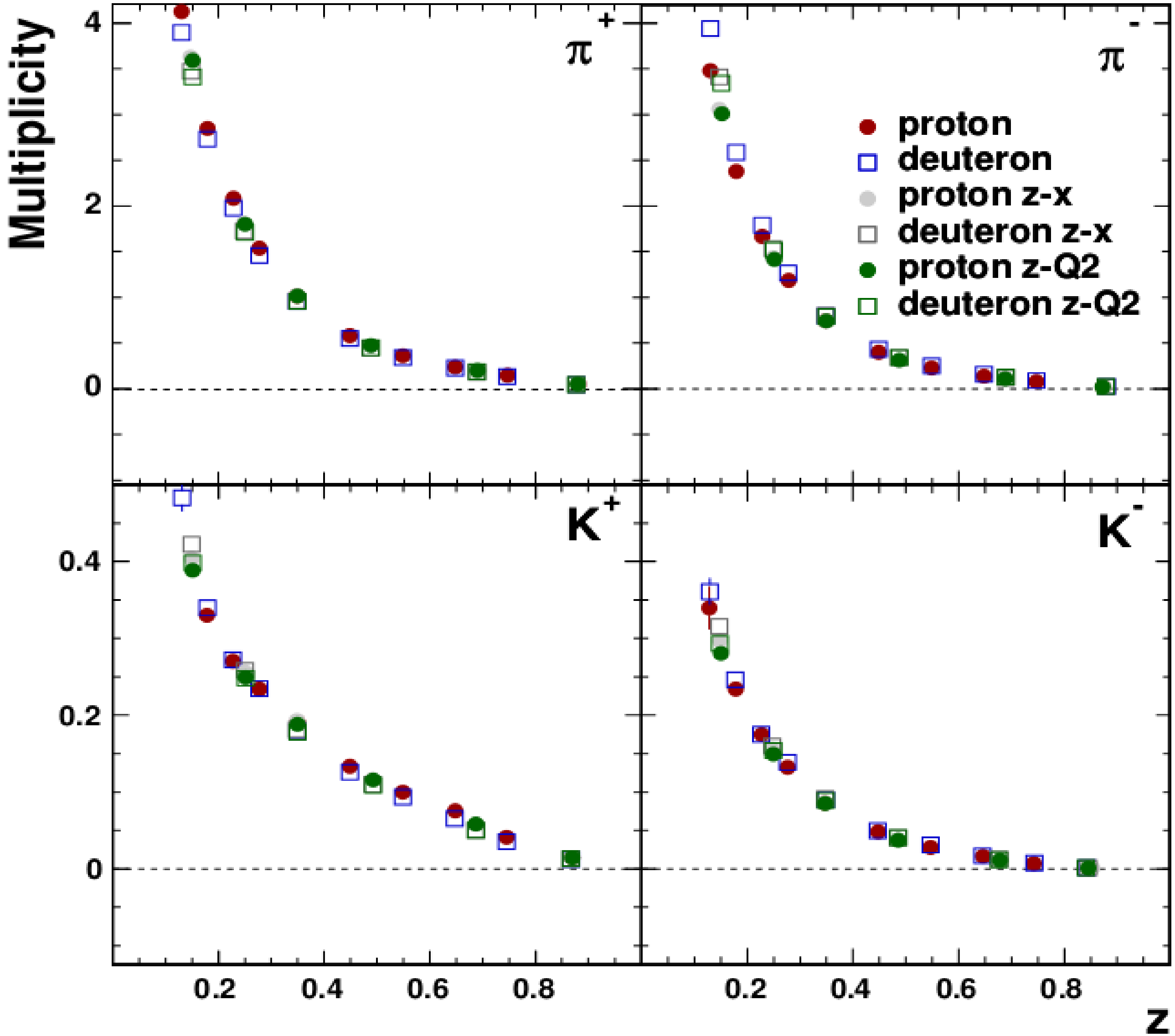
(**hadron azimuthal modulations**)

A. Airapetian et. al, Phys. Rev. D87 (2013) 012010
http://www-hermes.desy.de/cosnphi

Summary

- High statistical data set for positively/negatively charged pion and kaon multiplicities on proton and deuteron.
- The extracted multiplicities integrated over hadron transverse momentum give an access to collinear fragmentation functions.
- The azimuthal modulations of produced hadrons indicate the presence of non-vanishing intrinsic transverse momentum of quarks inside an unpolarized nucleon.
- Dependence of multiplicities on hadron transverse momentum provides constraints on transverse momentum dependent distribution and fragmentation functions.
- A_{LU} results are coming soon!

Backup



Multiplicity
4
2
0
0.4
0.2
0
π+
π-
K+
K-
proton
deuteron
proton z-x
deuteron z-x
proton z-Q2
deuteron z-Q2
0.2
0.4
0.6
0.8
z