Accessing TMDs with an unpolarised target at HERMES

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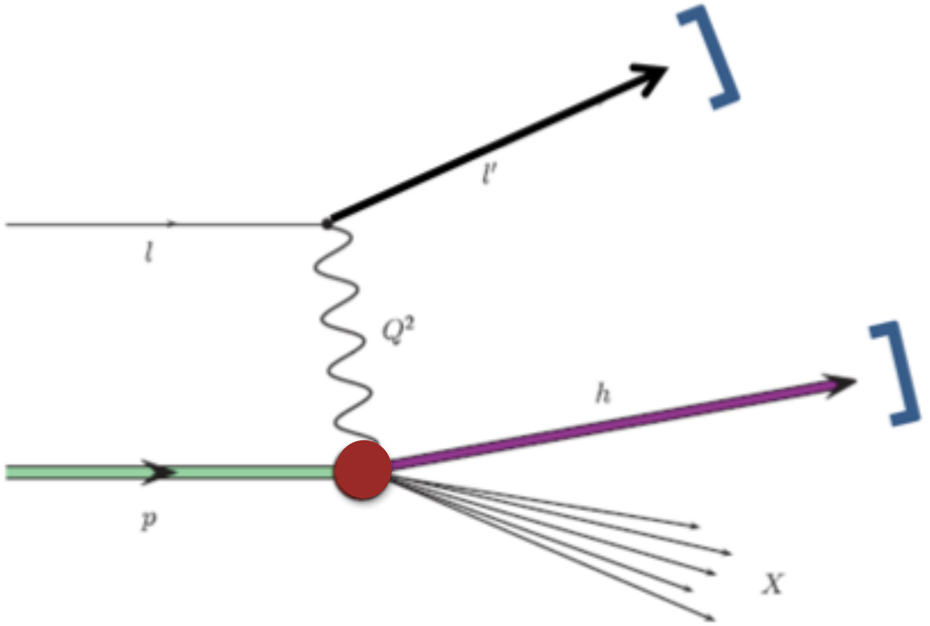
Outline

- Hadron multiplicities on H and D target
- Spin-independent azimuthal modulations on H and D target
- Beam-helicity asymmetries on H and D target

Charged pion and kaon multiplicities

$$Q^2 > 1 \text{ GeV}^2$$
$$W^2 > 10 \text{ GeV}^2$$
$$0.023 < x < 0.6$$



targets=unpolarised H and D

Hadron multiplicities

$$M^h(x, Q^2, z, P_{h\perp}) = \frac{1}{d^2 N^{\mathrm{DIS}}(x, Q^2)} \frac{d^4 N^h(x, Q^2, z, P_{h\perp})}{dz\, dP_{h\perp}}$$

$$= \frac{\sum_q e_q^2\, \mathcal{C}\left[f_1^q(x, k_\perp^2, Q^2) \times \mathcal{W}\; D_1^q(z, p_\perp^2, Q^2)\right]}{\sum_q e_q^2\; f_1^q(x, Q^2)}$$

QPM,
leading twist,
LO

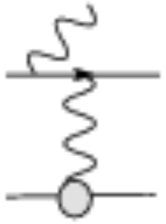
- Access to spin-independent TMD PDF and TMD fragmentation function
- Complementary to e^+e^- to probe fragmentation function:
  - disentangle favoured ($u \to \pi^+$) and disfavoured ($u \to \pi^-$) fragmentation

Extraction of Born multiplicities

$M^h_{\mathrm{Born}}(j)$ $M^h_{\mathrm{meas}}(i)$

Extraction of Born multiplicities

$$M^{h}_{\mathrm{Born}}(j) \longleftarrow M^{h}_{\mathrm{meas}}(i)$$

- QED radiative effects 

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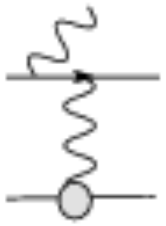
- QED radiative effects 

- limited geometric and kinematic acceptance of detector

Extraction of Born multiplicities

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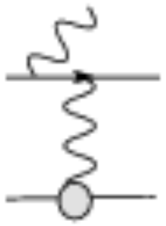
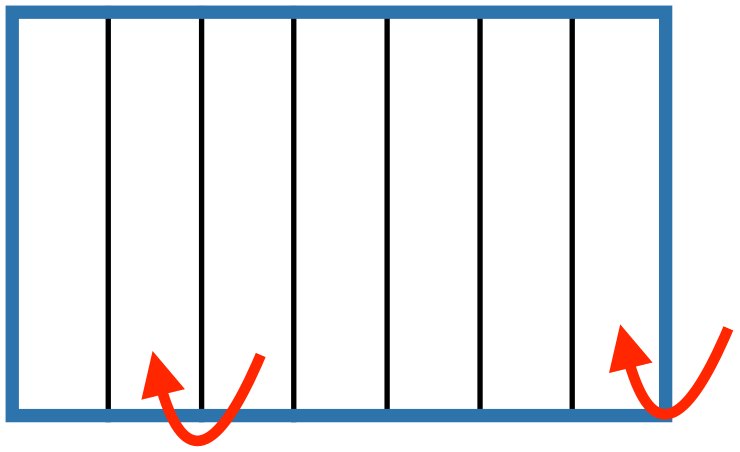
- QED radiative effects



- limited geometric and kinematic acceptance of detector
- limited detector resolution



- migration of events from one bin to another
- migration of events outside acceptance into acceptance

Extraction of Born multiplicities

$$M^{h}_{\mathrm{Born}}(j) = \frac{1}{n^{\mathrm{DIS}}_{\mathrm{Born}}(j)} \sum_{i} \left[S_h^{-1}\right](j,i) \left[M^{h}_{\mathrm{meas}}(i) N^{\mathrm{DIS}}_{\mathrm{meas}}(i) R_{\mathrm{norm}} - n^{h}(i,0)\right]$$

- Smearing matrix from LEPTO+JETSET Monte-Carlo simulation

$$S_h = \frac{n^{h}(i,j)}{n^{h}_{Born}(j)}$$

reconstructed

generated (Born)

- Smearing of events from outside acceptance into acceptance, $n^{h}(i,0)$, from Monte Carlo

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- Additional corrections:
    - trigger efficiencies, charge-symmetric background, RICH PID unfolding
    - optionally: correction for exclusive vector mesons

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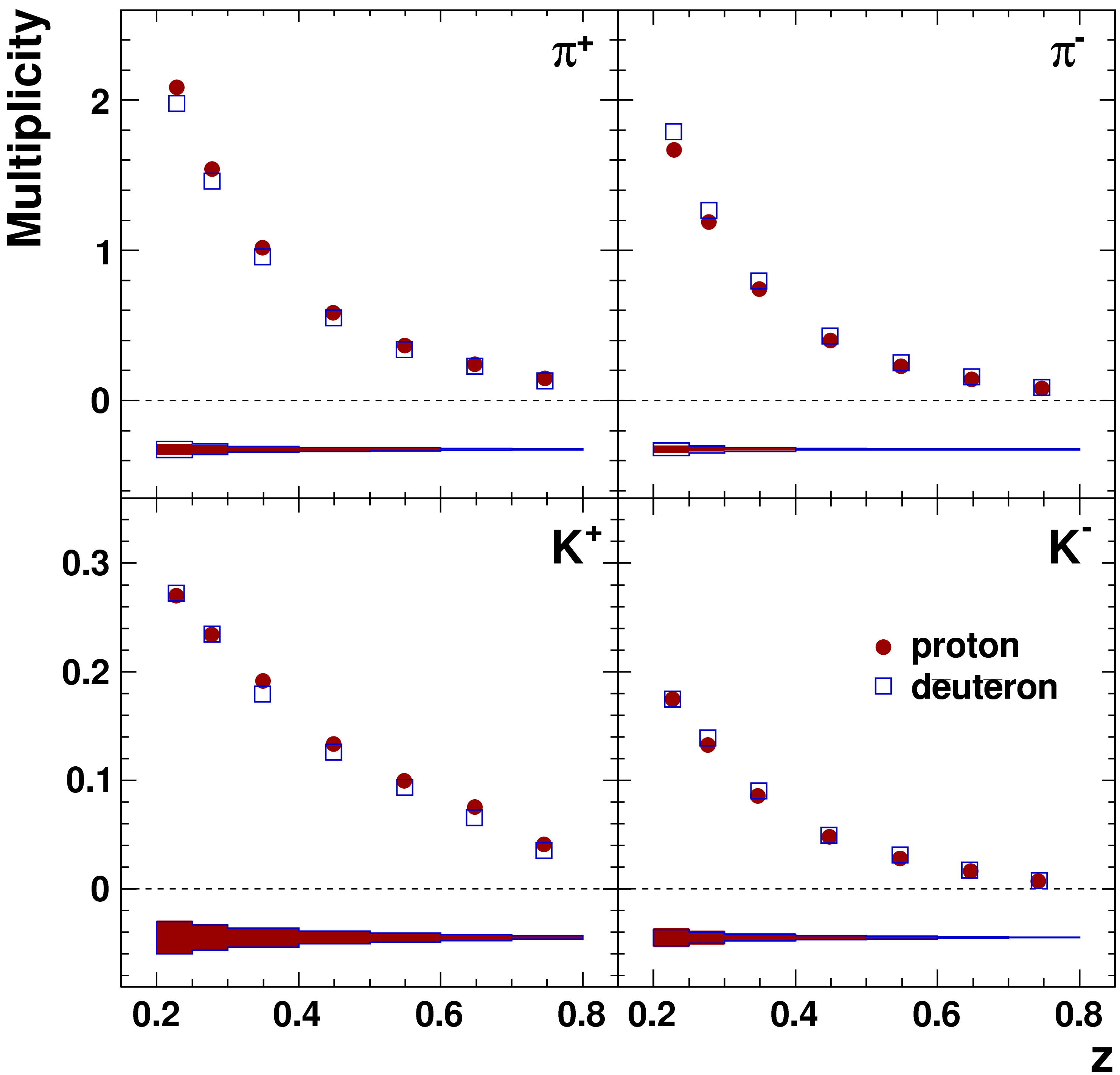
- Multiplicities provided in $(x,z,P_{h\perp})$ and in $(Q^2,z,P_{h\perp})$

Results projected in z

Phys. Rev. D87 (2013) 074029



$$\frac{M_{p(d)}^{\pi^+}}{M_{p(d)}^{\pi^-}} = 1.2 \;-\; 2.6 \;(1.1 \;-\; 1.8)$$

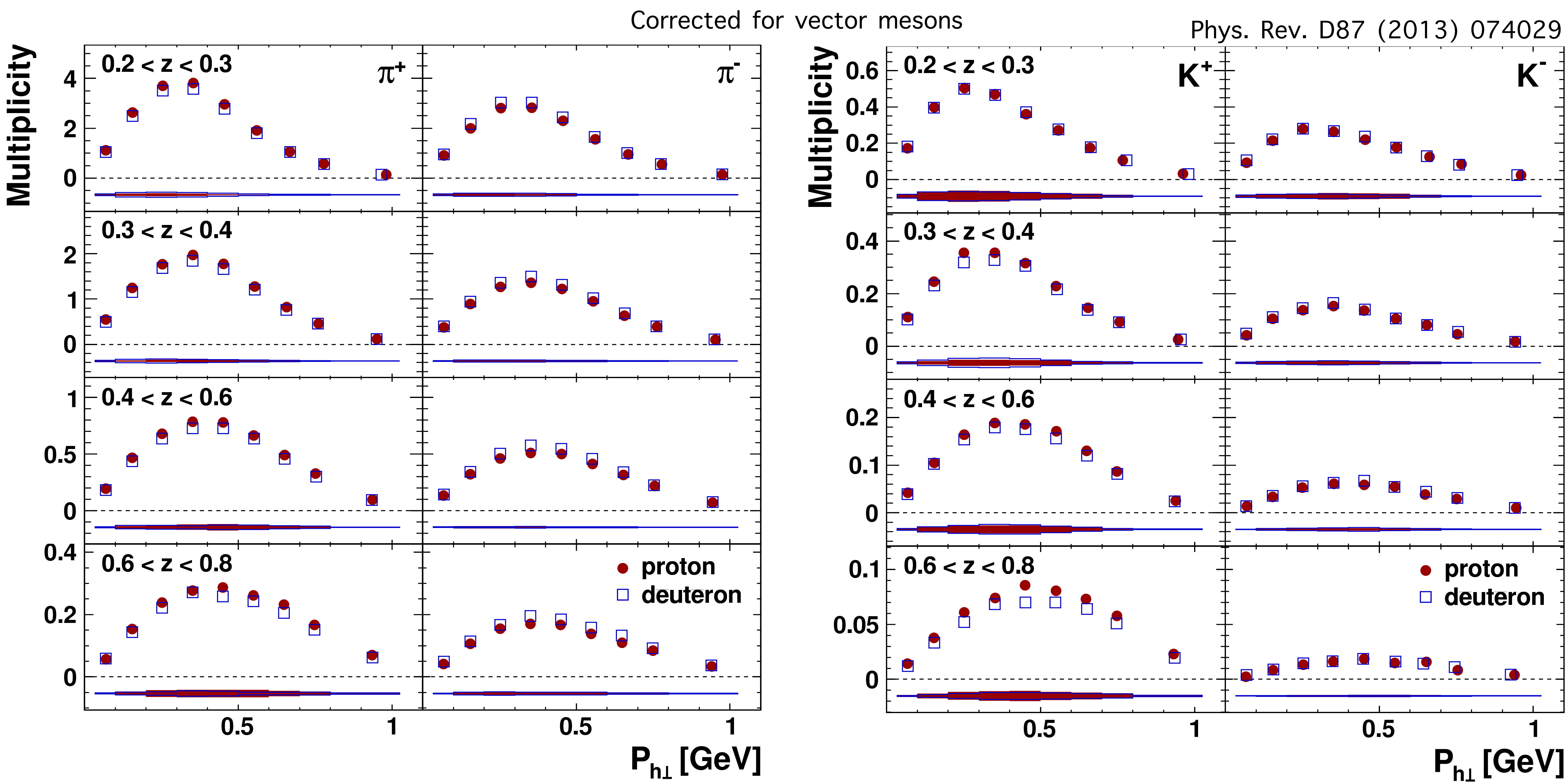
low z high z

$$\frac{M_{p(d)}^{K^+}}{M_{p(d)}^{K^-}} = 1.5 \;-\; 5.7 \;(1.3 \;-\; 4.6)$$

$$\frac{M_{p(d)}^{K^+}}{M_{p(d)}^{\pi^+}} \approx 1/3 \quad \text{at high z}$$

Corrected for vector mesons

Results projected in z and $P_{h\perp}$

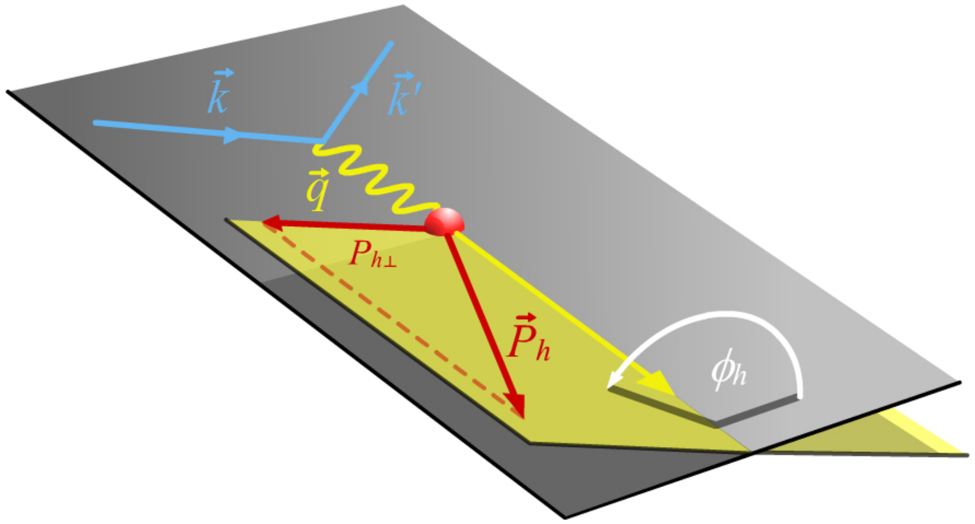


- $P_{h\perp}$ reflects transverse momentum inside nucleon and from fragmentation process
- $P_{h\perp}$ distribution broader for K^- than for K^+

Azimuthal dependence of the SIDIS cross section for unpolarised target

$$\begin{aligned}\sigma^h(\phi,\phi_S) &= \sigma^h_{UU}\left\{1+2\langle\cos(\phi)\rangle^h_{UU}\,\cos(\phi)+2\langle\cos(2\phi)\rangle^h_{UU}\,\cos(2\phi)\right.\\ &\left.+\ \boxed{\lambda_l}\,2\langle\sin(\phi)\rangle^h_{LU}\,\sin(\phi)\right\}\end{aligned}$$

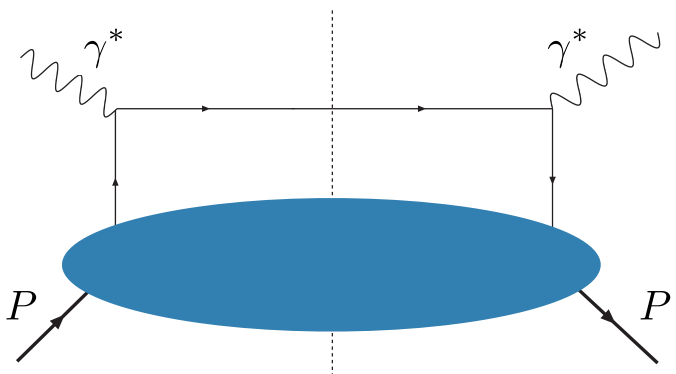
beam helicity



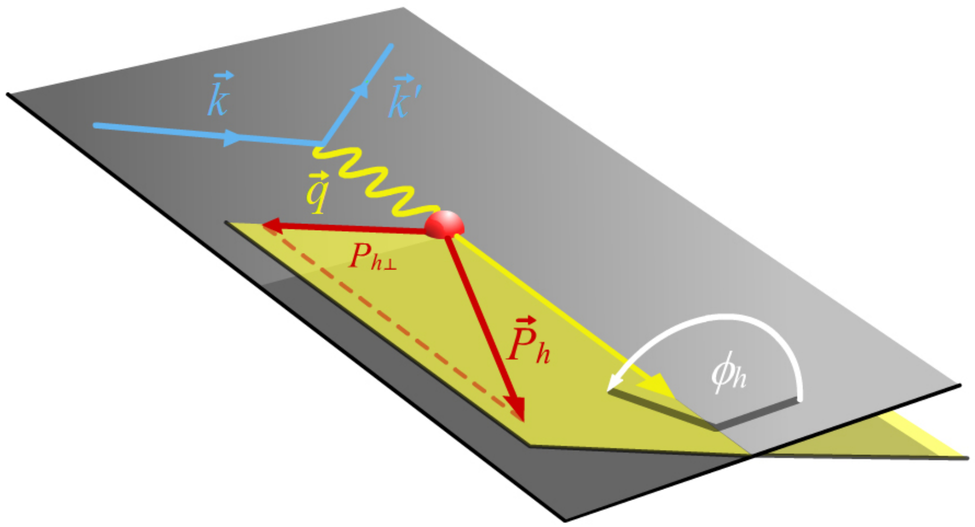
Azimuthal dependence of the SIDIS cross section for unpolarised target

$$\sigma^h(\phi,\phi_S) = \sigma^h_{UU}\Big\{1 + 2\langle\cos(\phi)\rangle^h_{UU}\cos(\phi) + \boxed{2\langle\cos(2\phi)\rangle^h_{UU}}\cos(2\phi) + \lambda_l\, 2\langle\sin(\phi)\rangle^h_{LU}\sin(\phi)\Big\}$$

beam helicity



leading twist



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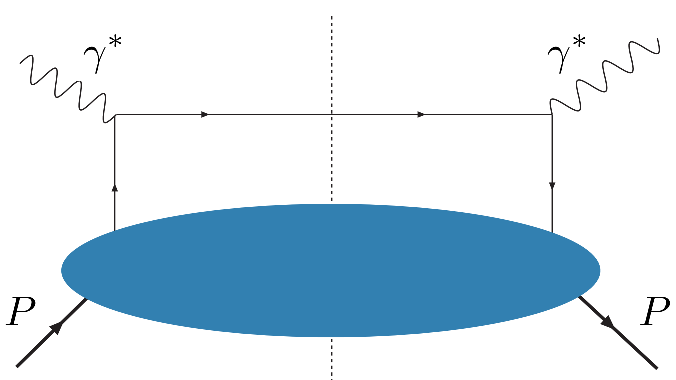

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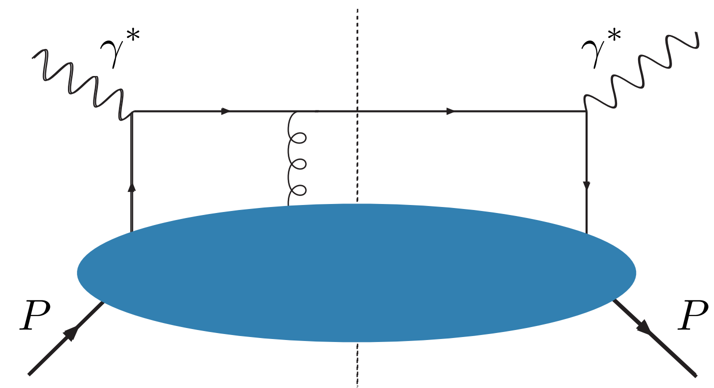
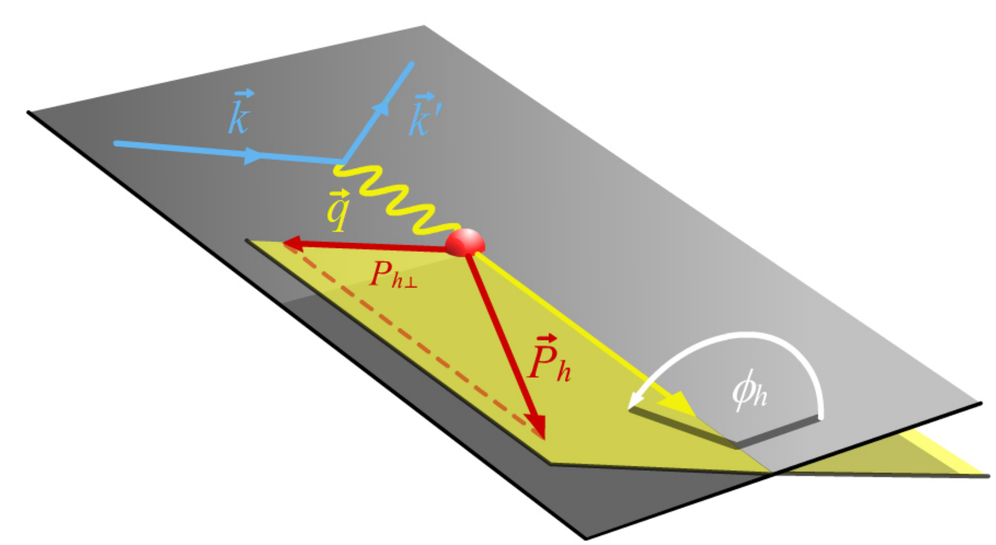


sub-leading twist



Azimuthal dependence of the SIDIS cross section for unpolarised target

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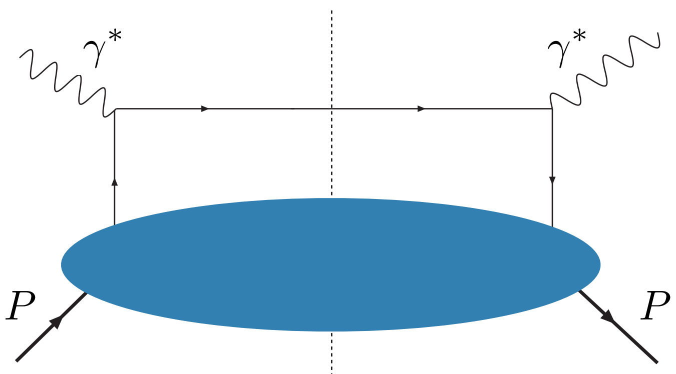
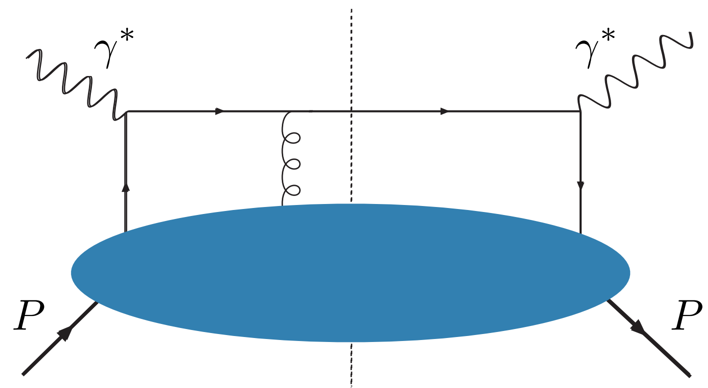
beam helicity



leading twist



sub-leading twist

- Unpolarised/longitudinally polarised e+/e- beam
- Unpolarised H and D target

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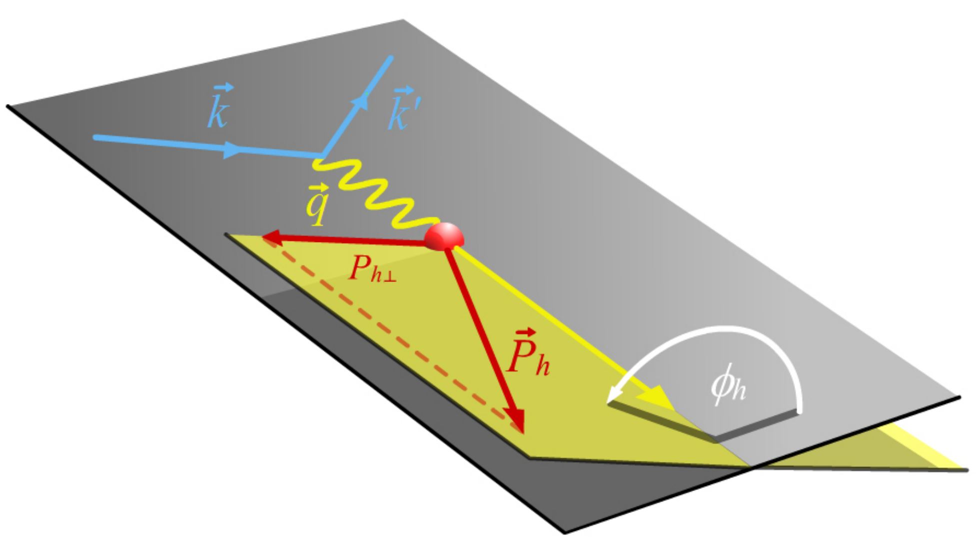
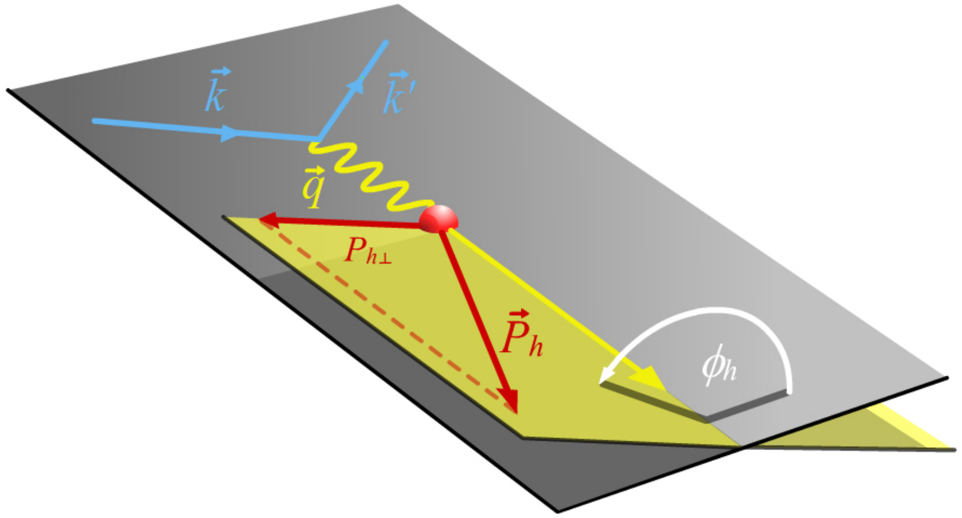
$$W^2 > 10\ \mathrm{GeV}^2$$
$$0.023 < x < 0.6$$



Spin-independent azimuthal modulations

Results for charged pions and kaons

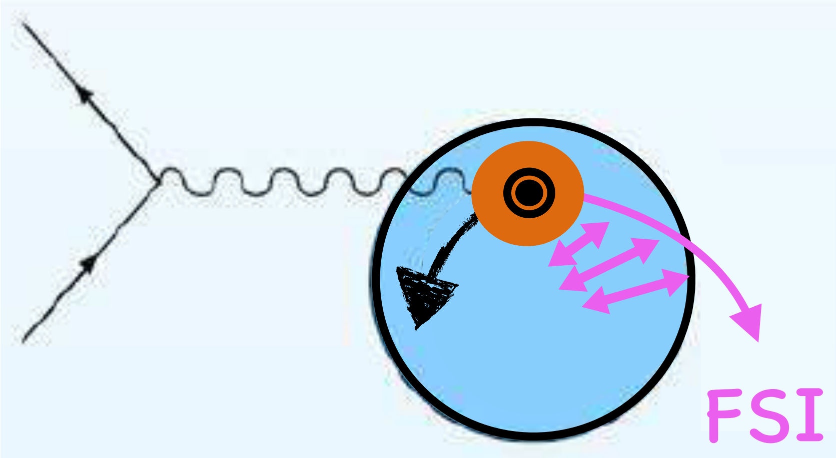


Spin-independent azimuthal modulations

$$\langle\cos(2\phi_h)\rangle \propto \mathcal{C}\left[h_1^\perp \times H_1^\perp\right]_{\text{twist-2}}$$

Boer-Mulders PDF

Collins FF

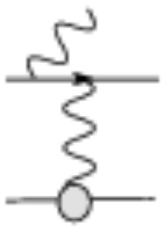


$$\langle\cos(\phi_h)\rangle \propto \mathcal{C}\left[\underbrace{\hat{P}_{h\perp}\cdot\vec{k}_\perp\, f_1 \times D_1}_{\text{Cahn effect}}, h_1^\perp \times H_1^\perp + \ldots\right]_{\text{twist-3}}$$

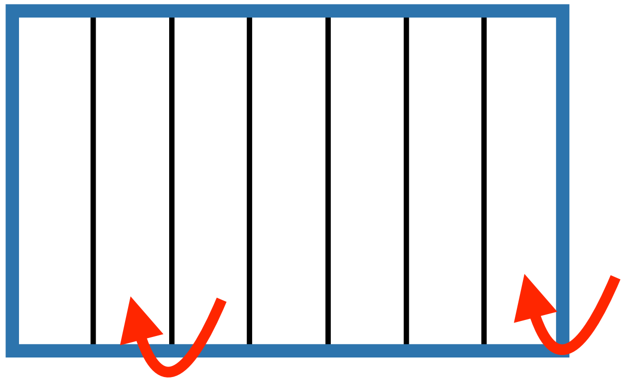
Extraction of $\langle \cos(2\phi_h) \rangle$ moments

$\langle \cos(2\phi_h) \rangle_{Born}(j)$ $\langle \cos(2\phi_h) \rangle_{meas}(i)$

- QED radiative effects



- limited geometric and kinematic acceptance of detector
- limited detector resolution



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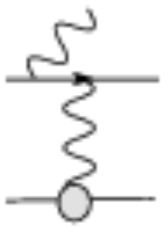

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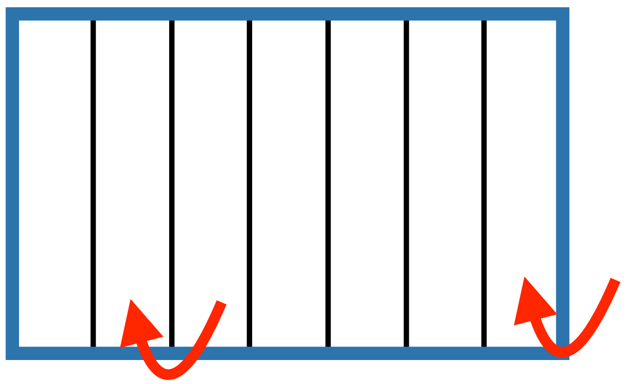

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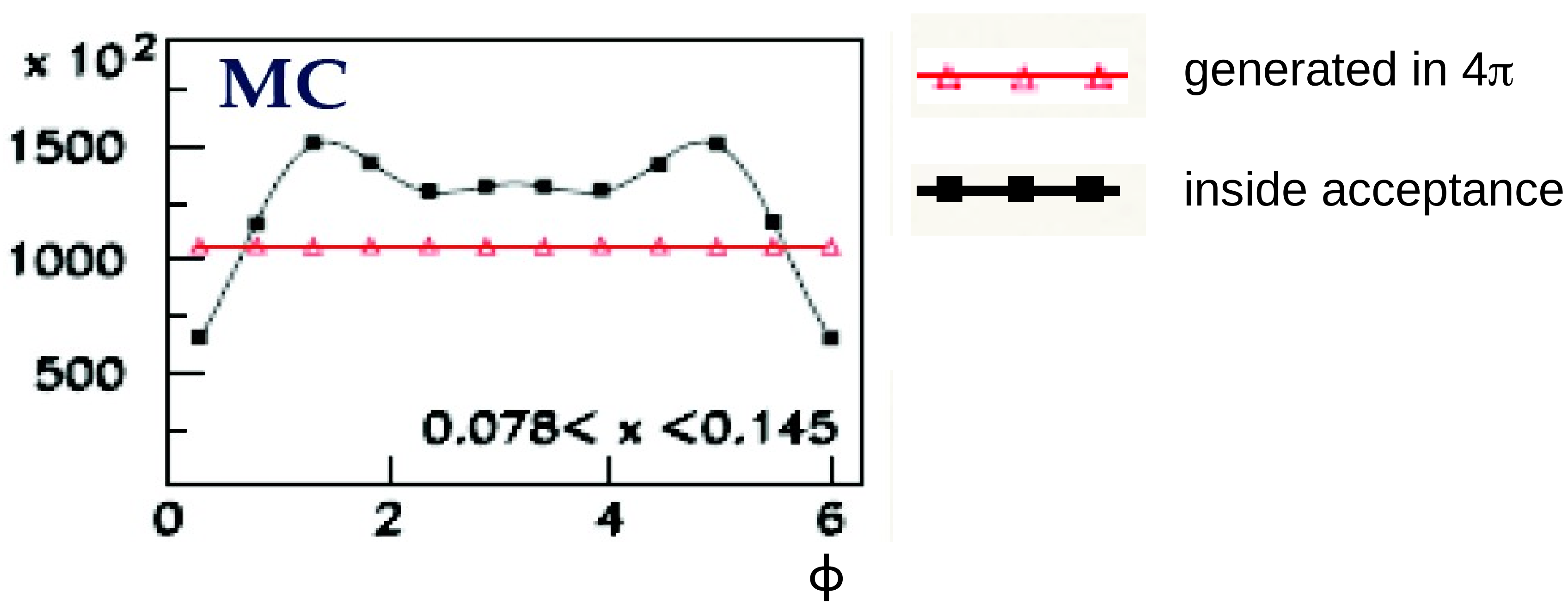


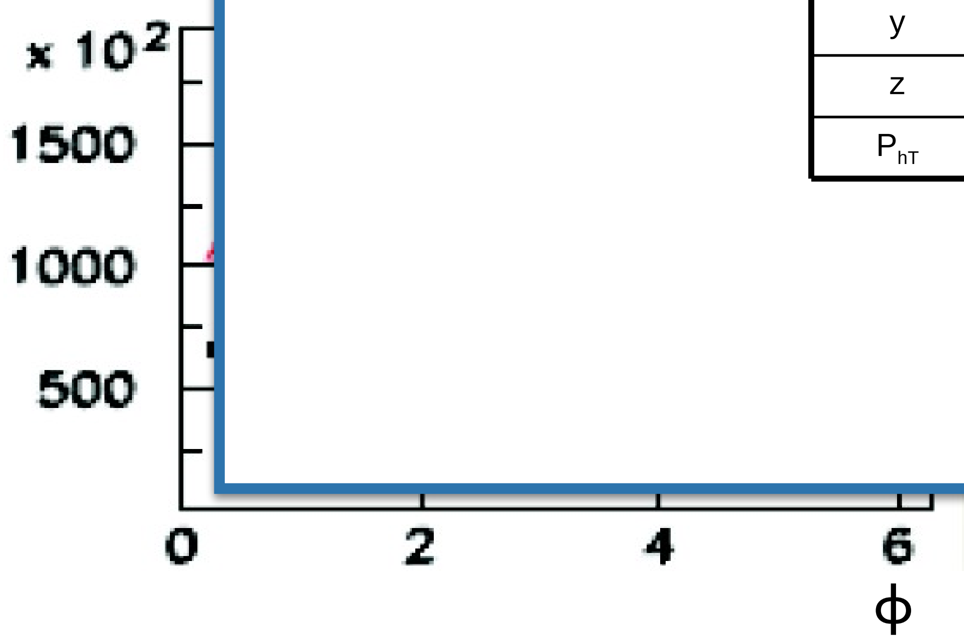
Extraction of $\langle \cos(2\phi_h) \rangle$ moments

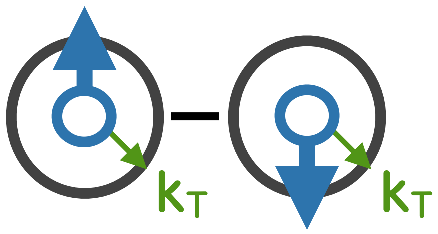
$\langle$co

Fully differential analysis

Unfolding in 400 x 12 bins

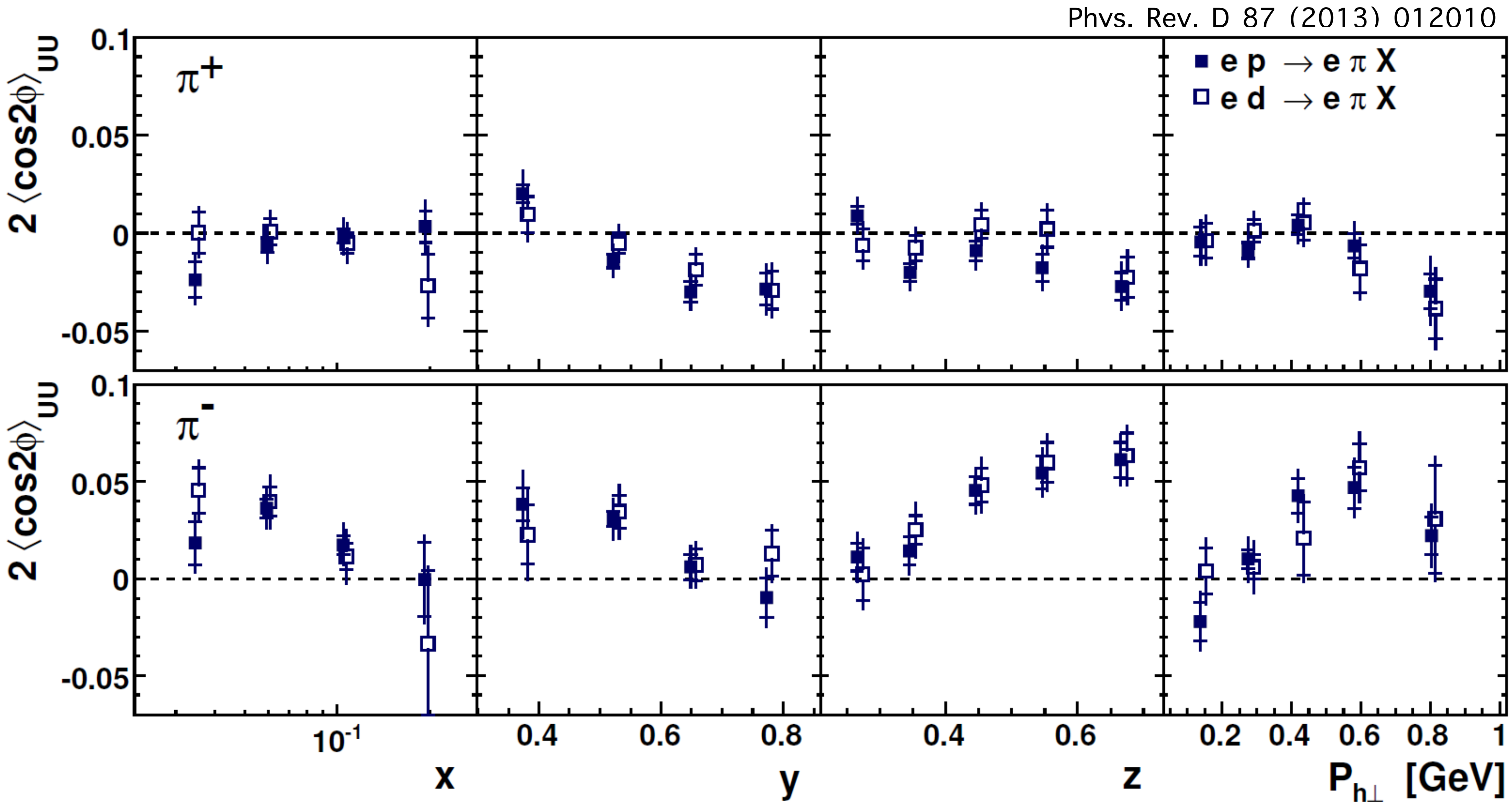
BINNING 400 kinematic bins x 12 ϕ-bins							
Variable	Bin limits						#
x	0.023	0.042	0.078	0.145	0.27	1	5
y	0.3	0.45	0.6	0.7	0.85		4
z	0.2	0.3	0.45	0.6	0.75	1	5
P_{hT}	0.05	0.2	0.35	0.5	0.75		4



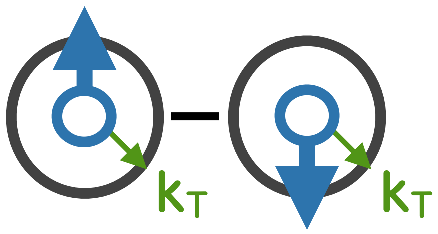


Boer-Mulders amplitudes

$$\mathcal{C}\left[h_1^{\perp} \times H_1^{\perp}\right]$$



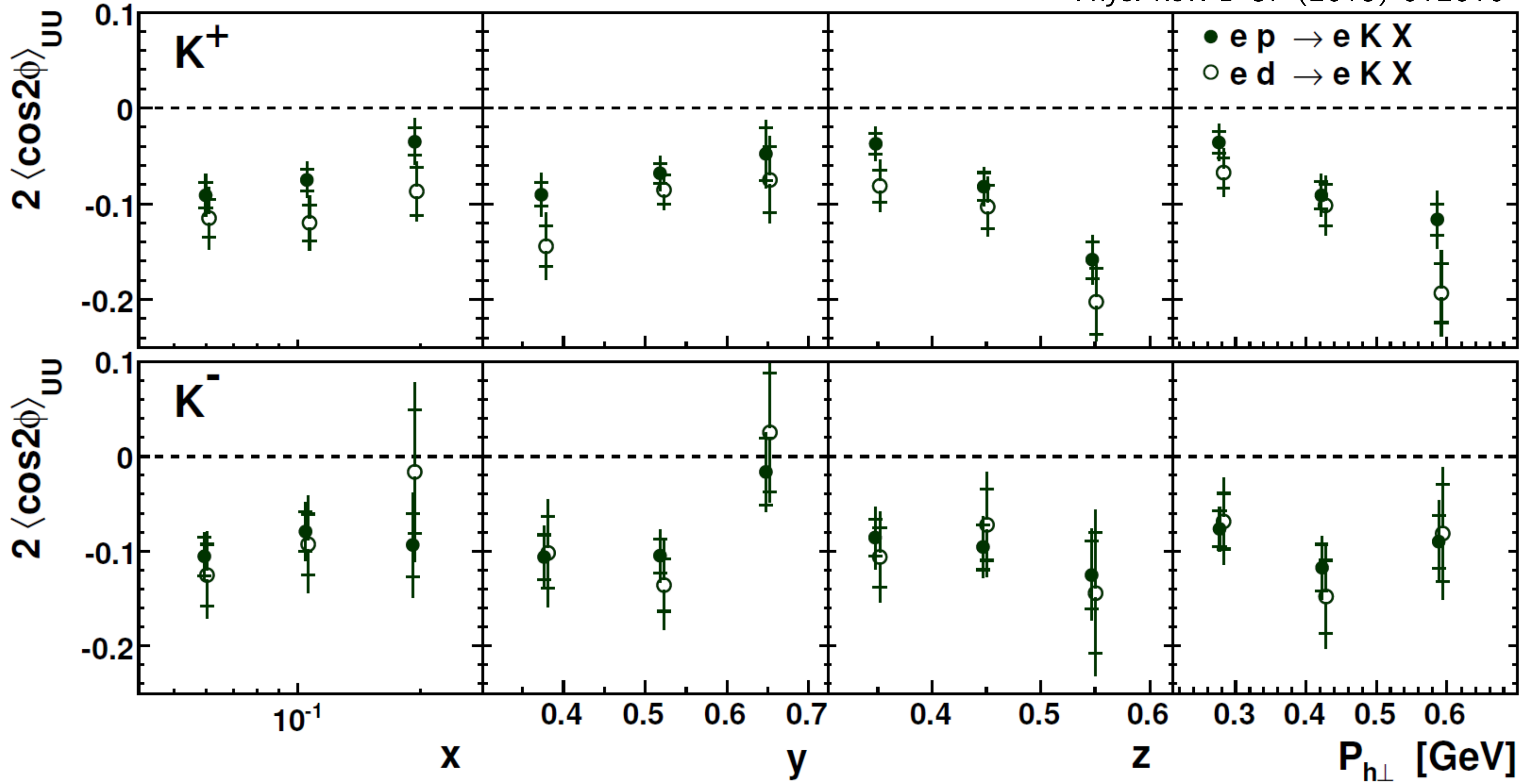
- Significant non-zero ⟶ non-zero orbital angular momentum
- naive T-odd: final-state interactions
- p-d comparison: $h_1^{\perp,u} \approx h_1^{\perp,d}$
- $\pi^- > 0 \iff \pi^+ \leq 0$: $H_1^{\perp,u\to\pi^+} \approx -H_1^{\perp,u\to\pi^-}$



Boer-Mulders amplitudes

$\mathcal{C}\left[h_1^{\perp} \times H_1^{\perp}\right]$

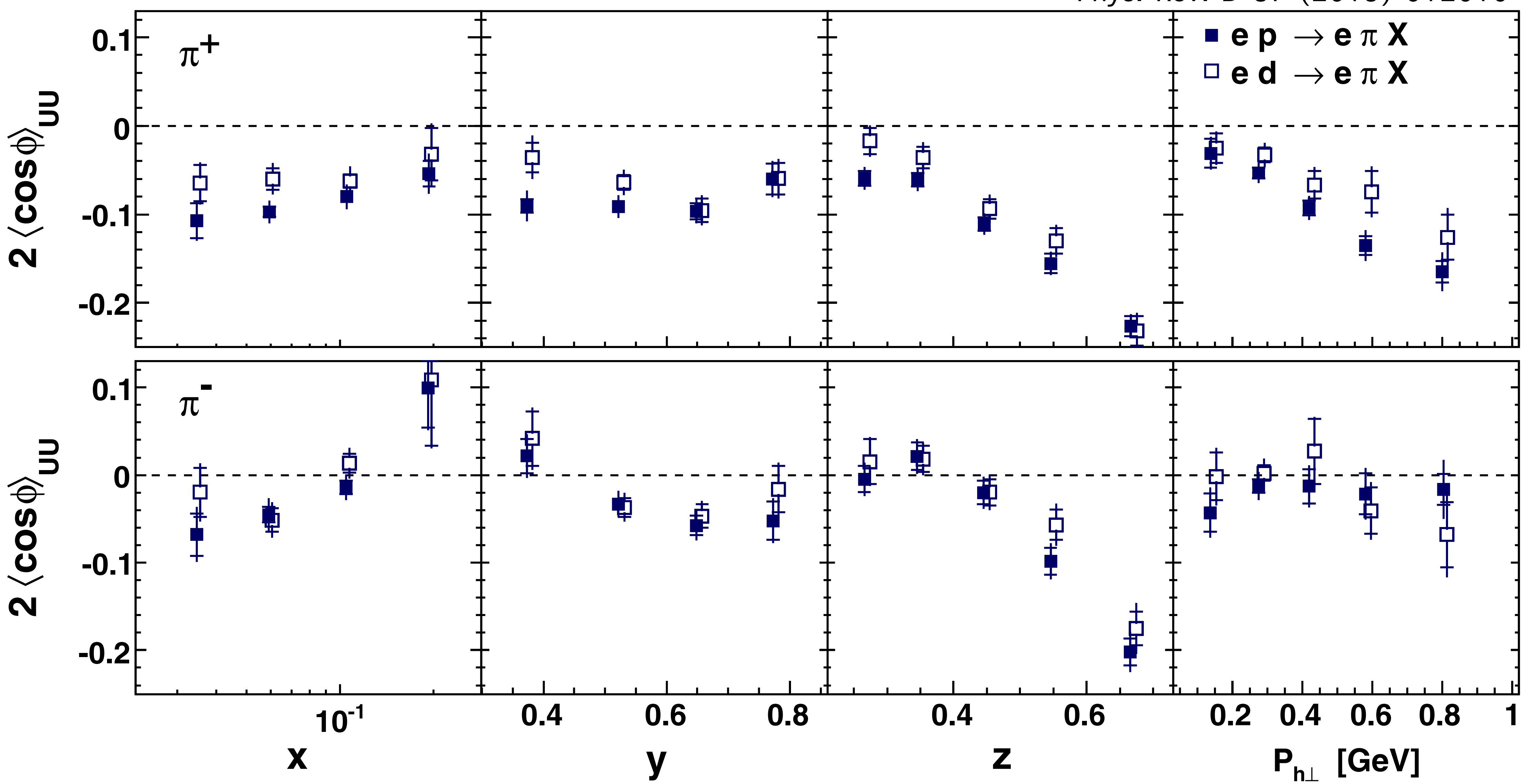
Phys. Rev. D 87 (2013) 012010



- $K^{\pm}$ large and negative amplitudes
- $K^{+} \approx K^{-}$ at variance with $\pi^{\pm}$
- amplitudes for p and d similar (p smaller for K^{+})

$\langle \cos(\phi_h) \rangle$ amplitudes

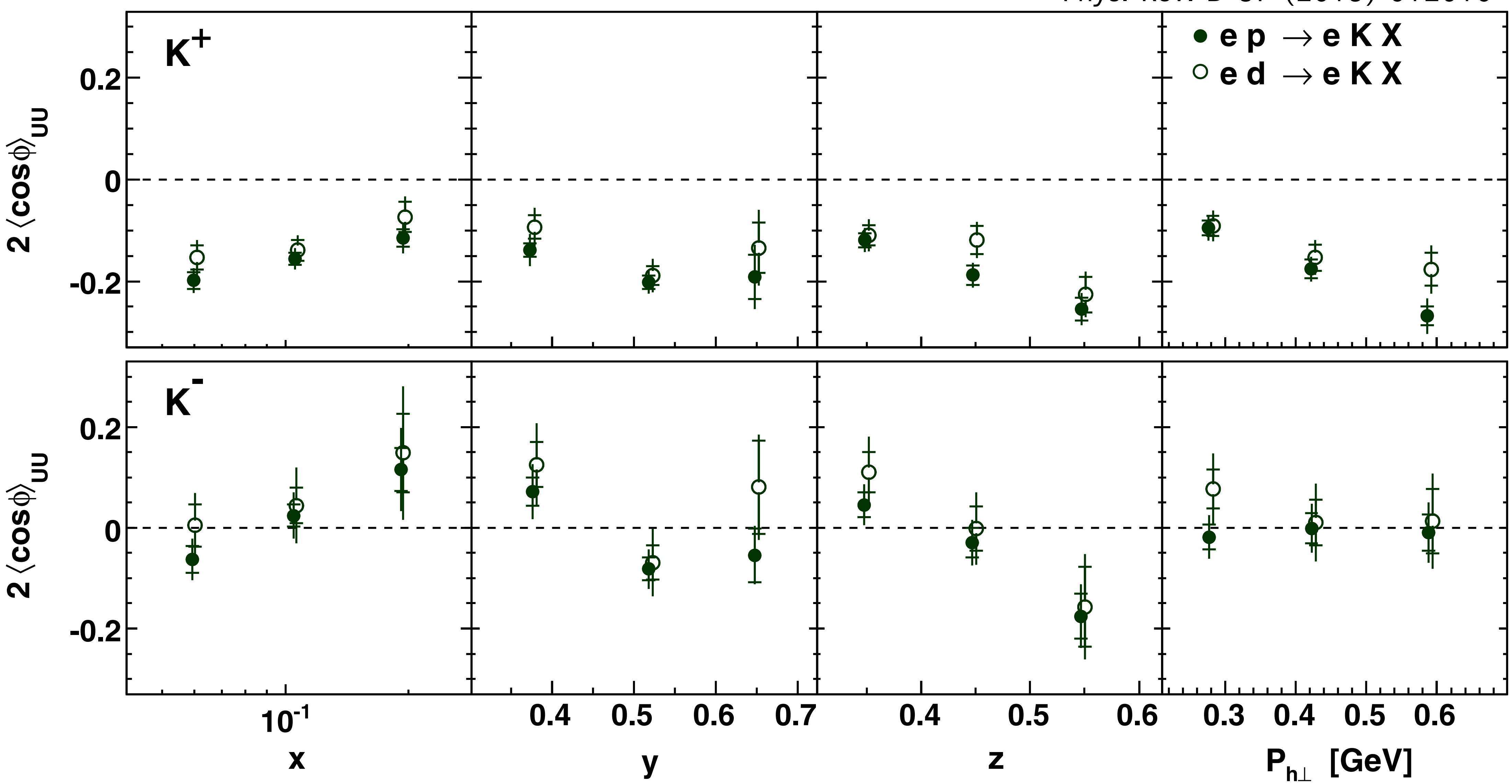
Phys. Rev. D 87 (2013) 012010



- amplitudes for p and d similar (d smaller for π^+)
- amplitudes rise with z, $\pi^+ \approx \pi^-$ at highest z
- amplitudes rise with $P_{h\perp}$ for π^+

$\langle\cos(\phi_h)\rangle$ amplitudes

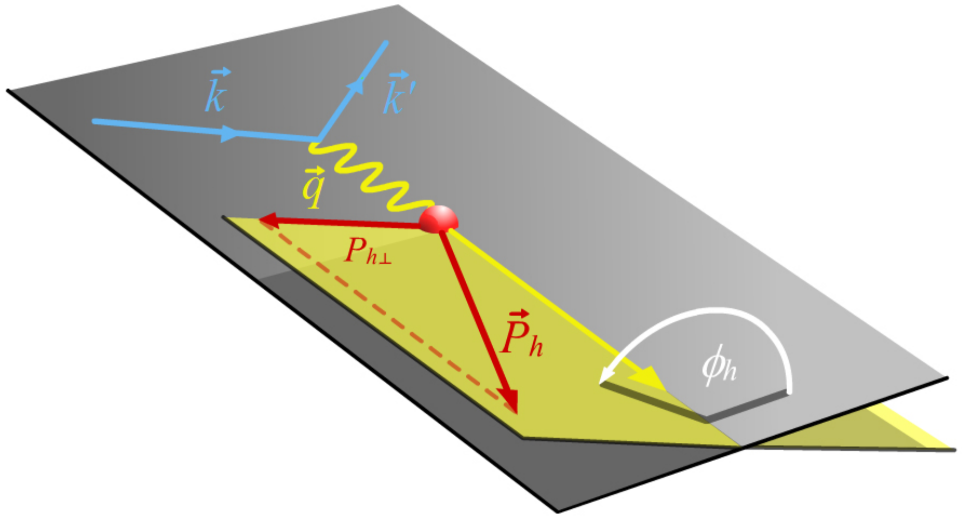
Phys. Rev. D 87 (2013) 012010



- amplitudes for p and d similar (d smaller for K^+)
- amplitudes are large and negative for K^+ and ≈ 0 for K^-
- K^+ amplitudes rise with z and $P_{h\perp}$

Beam-helicity asymmetry

Results for charged pions, kaons, (anti-)protons



Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$

$$\langle \sin(\phi) \rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^{\perp} \times \tilde{E}, e \times H_1^{\perp}, g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp} \right]$$

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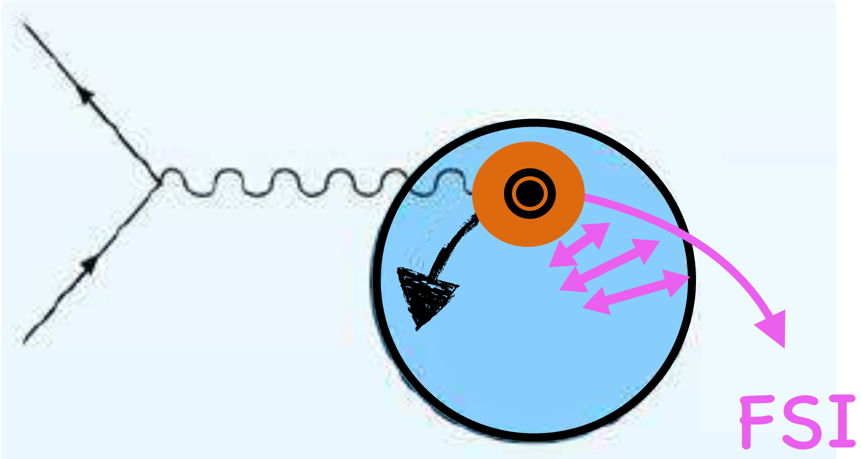
Boer-Mulders PDF

Chiral-odd T-even twist-3 FF

Boer-Mulders PDF



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Chiral-odd T-even twist-3 PDF

Collins FF

$$e(x) = e^{\mathrm{WW}}(x) + \bar{e}(x)$$

Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$

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Chiral-odd T-even twist-3 PDF

Collins FF

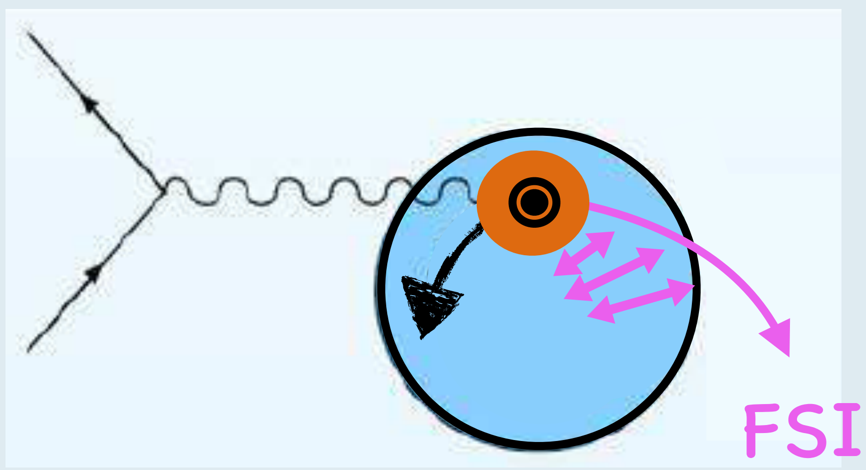
$$e(x) = e^{\mathrm{WW}}(x) + \bar{e}(x)$$

$$e_2 \equiv \int_0^1 dx\, x^2 \bar{e}(x)$$

force on struck quark at t=0

M. Burkardt, arXiv:0810.3589

Boer-Mulders PDF



FSI: t=0→∞

Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$

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Chiral-even T-odd twist-3 PDF

spin-independent FF

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Chiral-even T-odd twist-3 PDF

spin-independent FF

Only term to survive in TMD single-jet inclusive DIS

$$e + p \rightarrow e' + \mathrm{jet} + X$$

Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$

$$\langle \sin(\phi) \rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^{\perp} \times \tilde{E}, e \times H_1^{\perp}, g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp}\right]$$

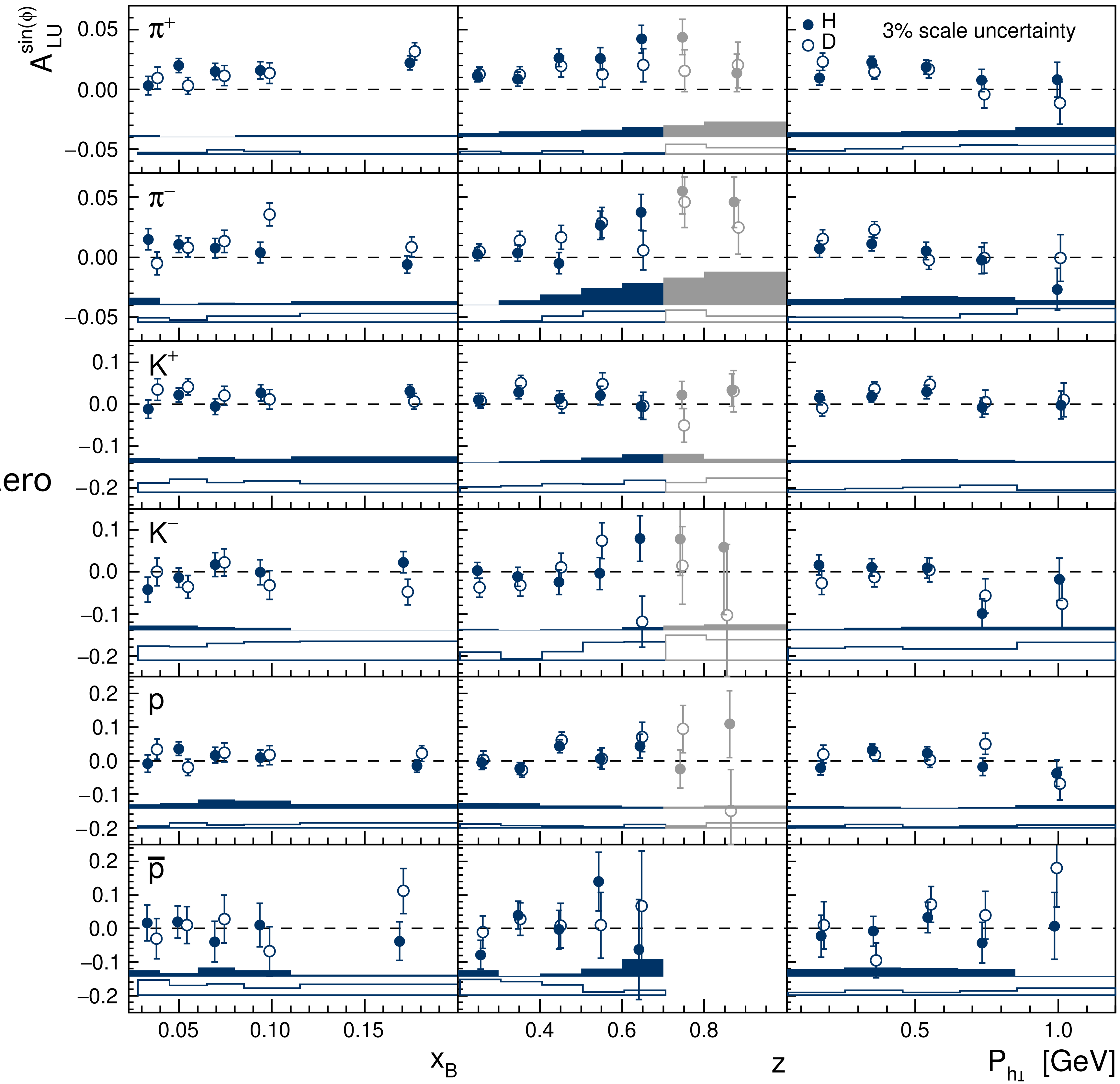
spin-independent PDF

chiral-even, T-odd twist-3 FF

1D virtual-photon asymmetry

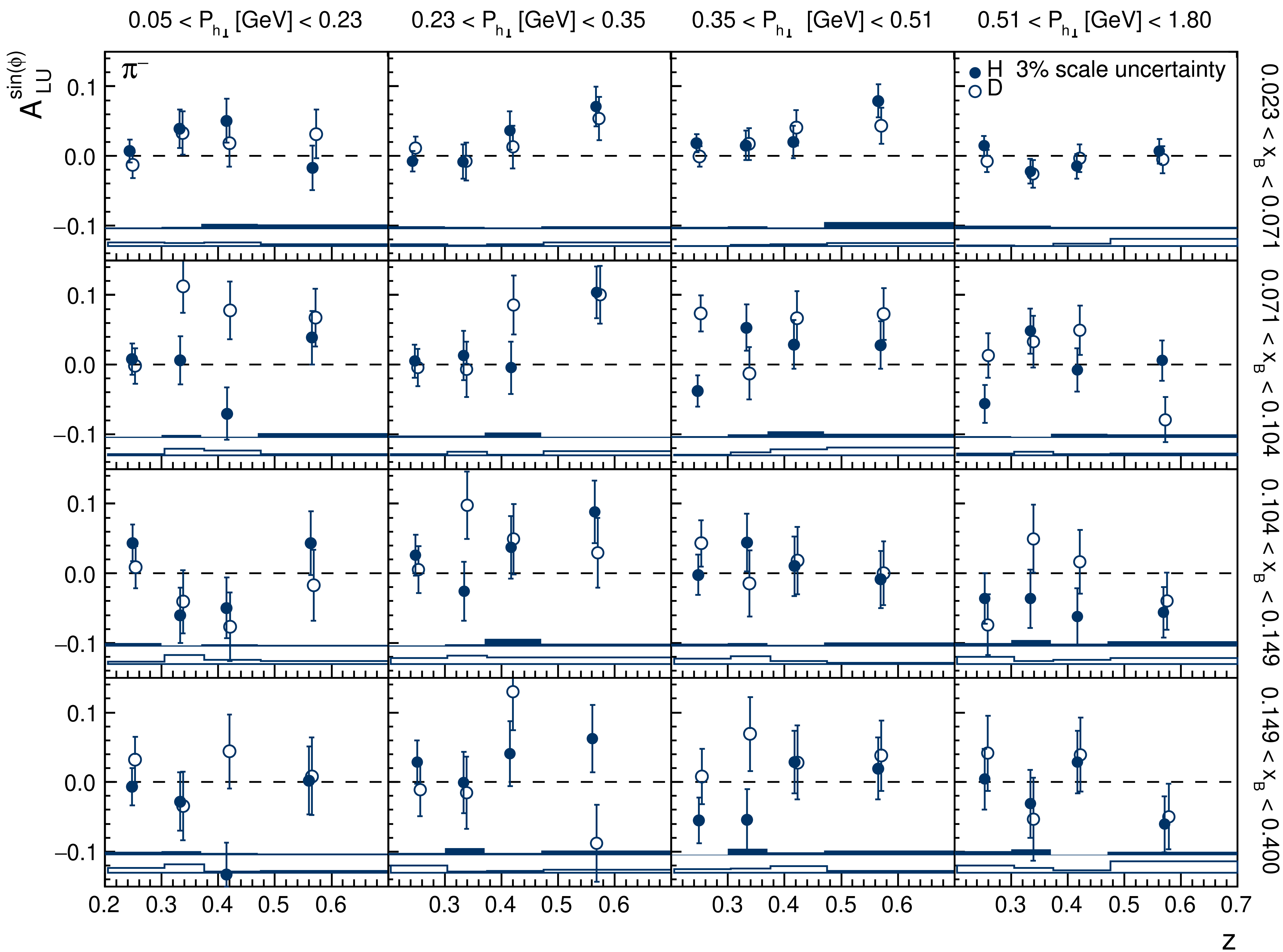
Phys. Lett. B 797 (2019) 134886

- Agreement H and D data
- Positive results for pions
- Slightly positive for K⁺
- Other hadrons consistent with zero

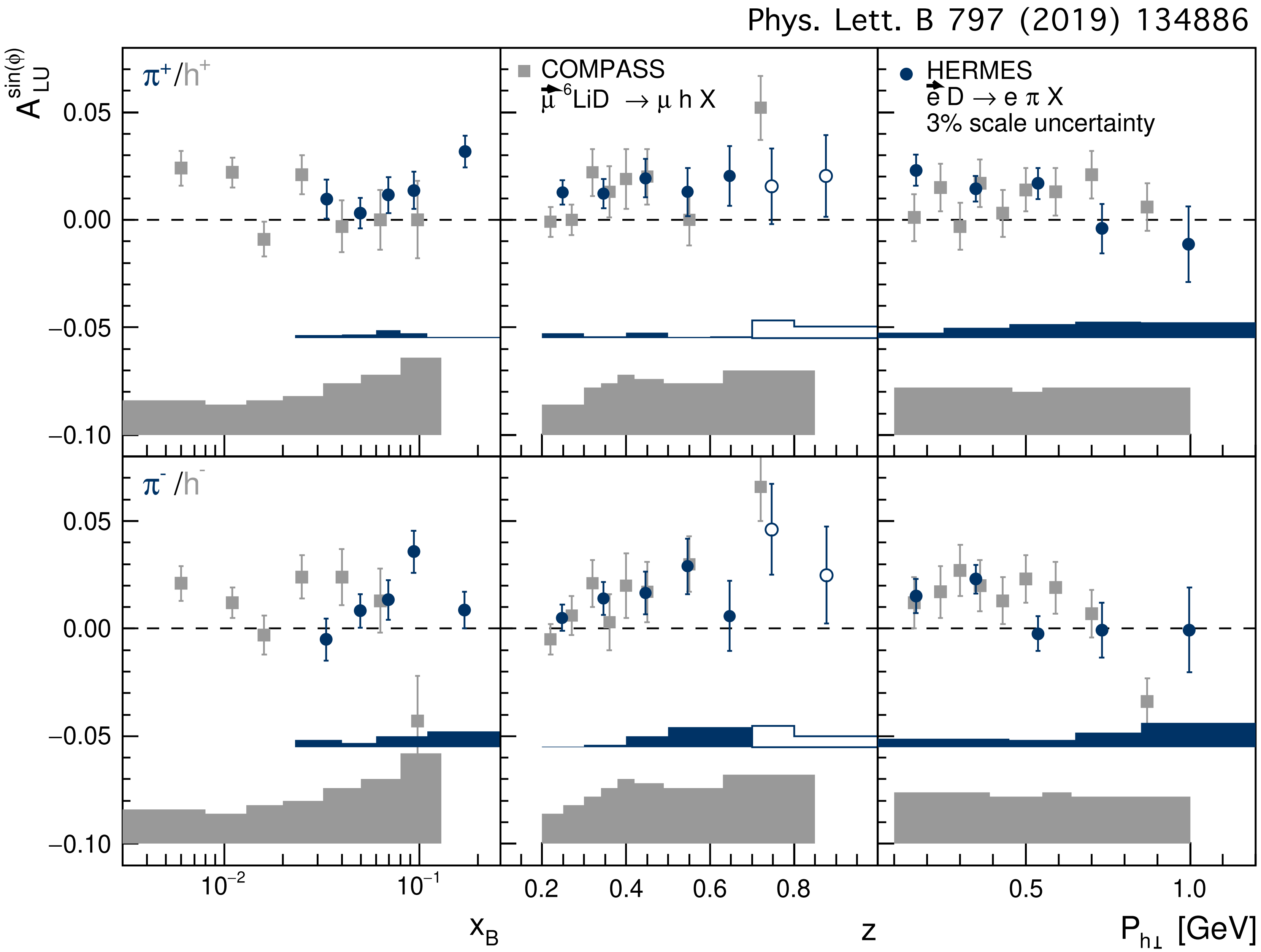


3D virtual-photon asymmetry

Phys. Lett. B 797 (2019) 134886

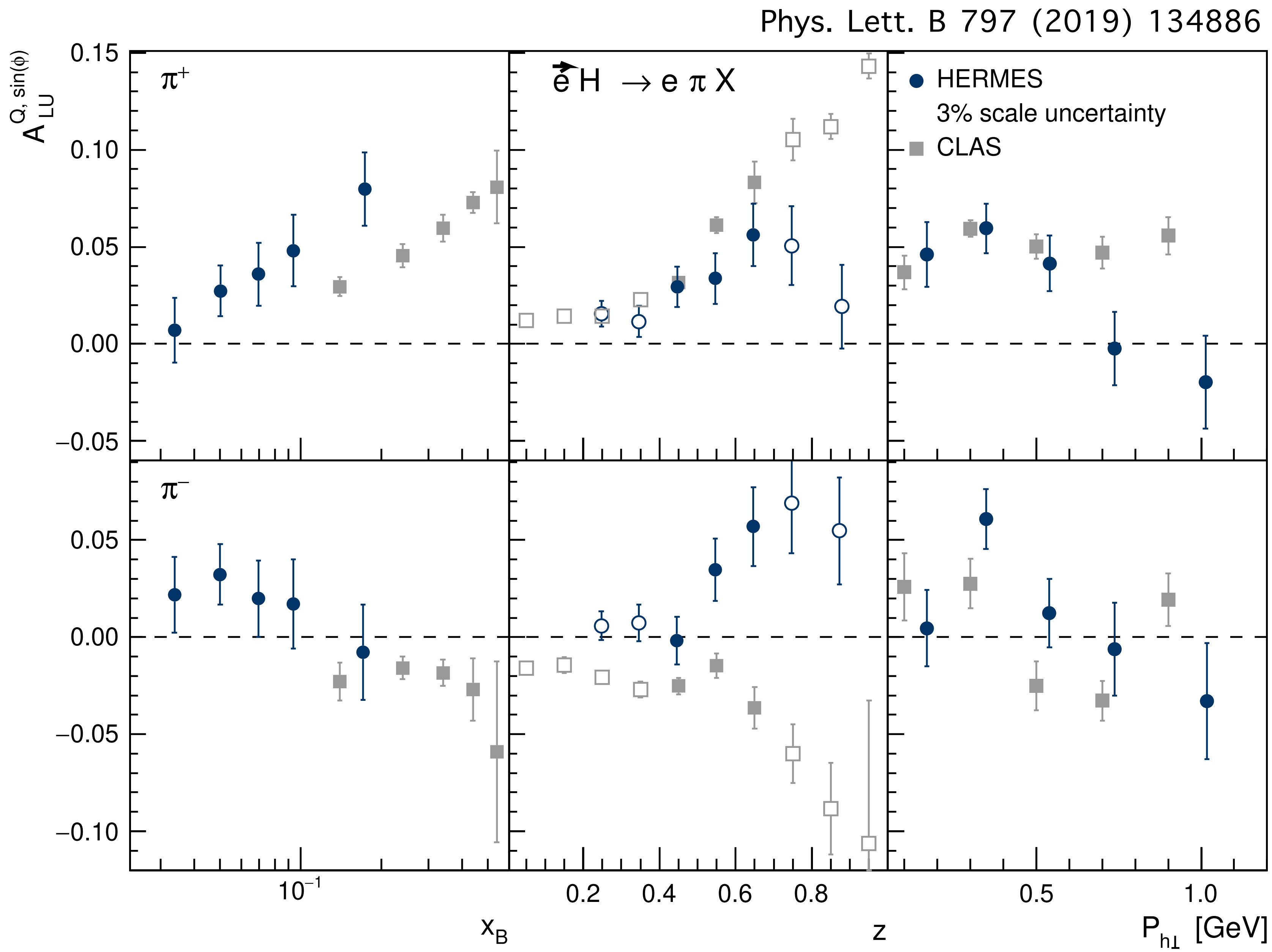


Comparison with COMPASS



Both measurements give compatible results

Comparison with CLAS

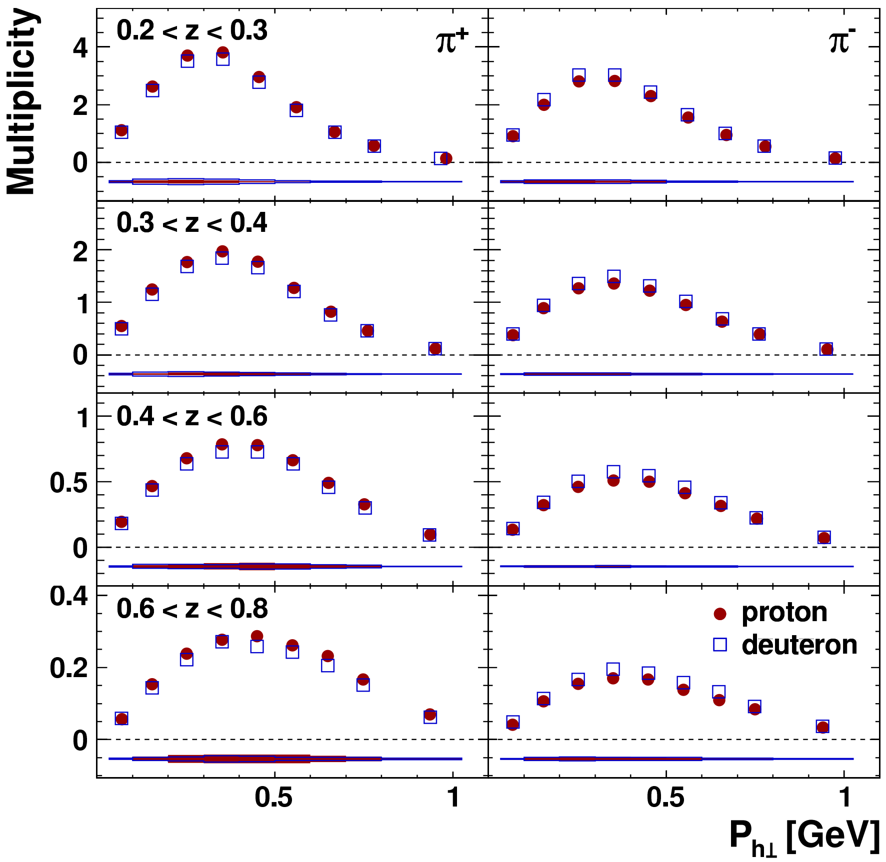


- Opposite behaviour for π^- z projection due to different x range probed
- CLAS probes higher x region: more sensitive to $e \times H_1^{\perp}$?

$$\langle \sin(\phi) \rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^{\perp} \times \tilde{E}, \boxed{x\,e \times H_1^{\perp}}, x\,g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp}\right]$$

Summary

$\longrightarrow \mathcal{C}[f_1 \times D_1]$



Summary

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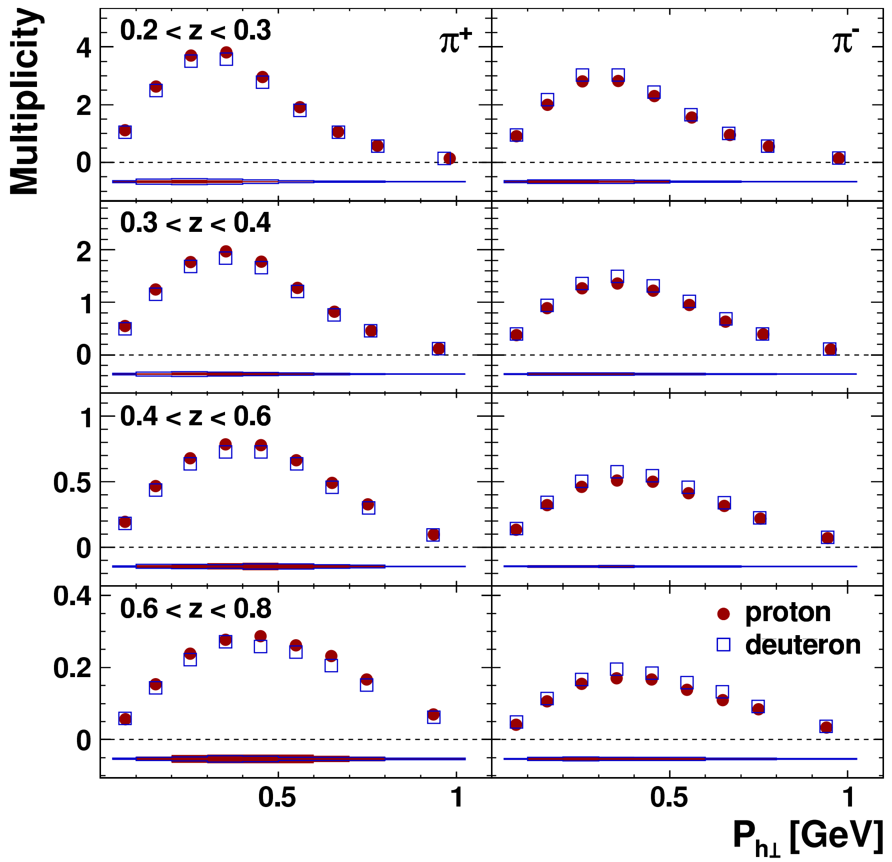
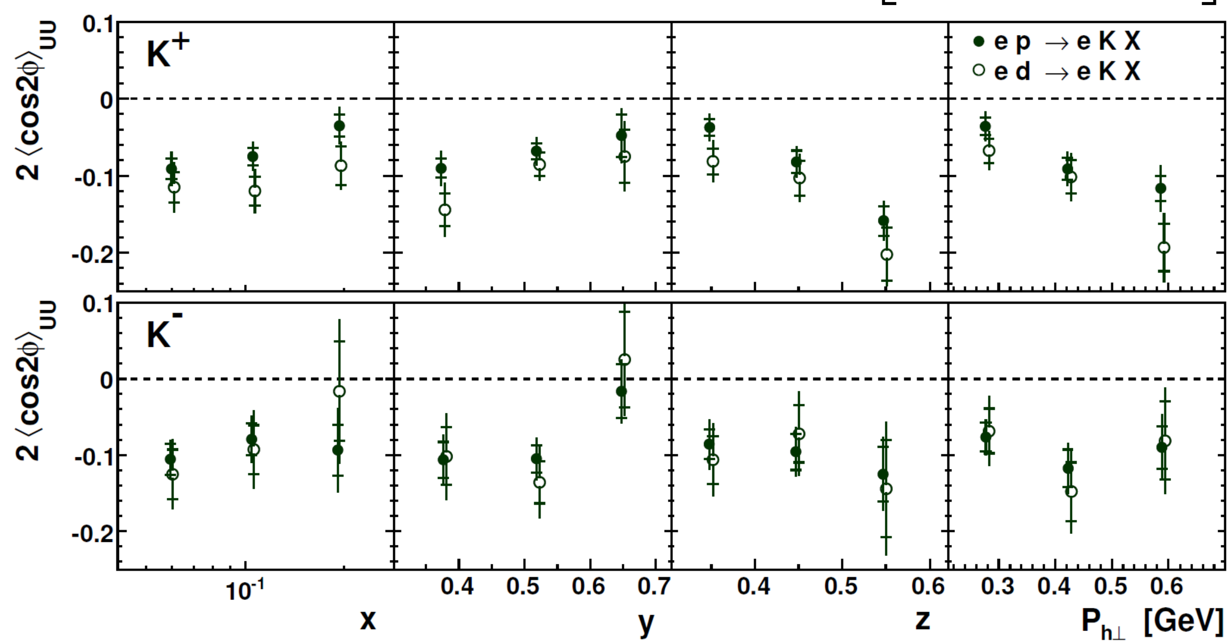
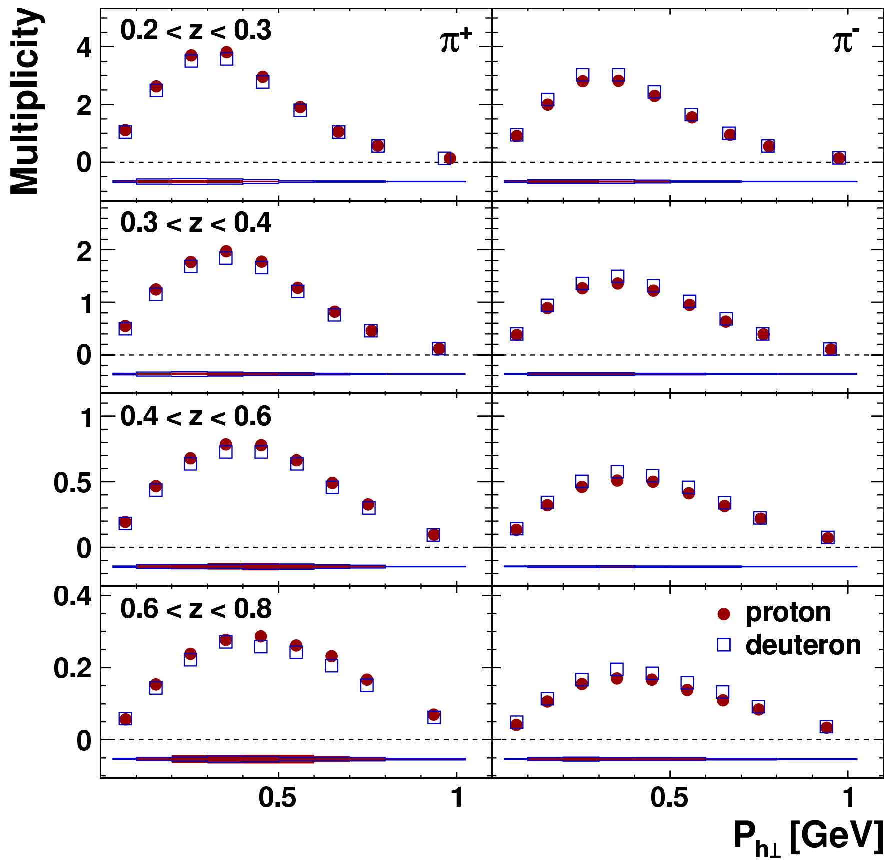


$\longrightarrow \mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$

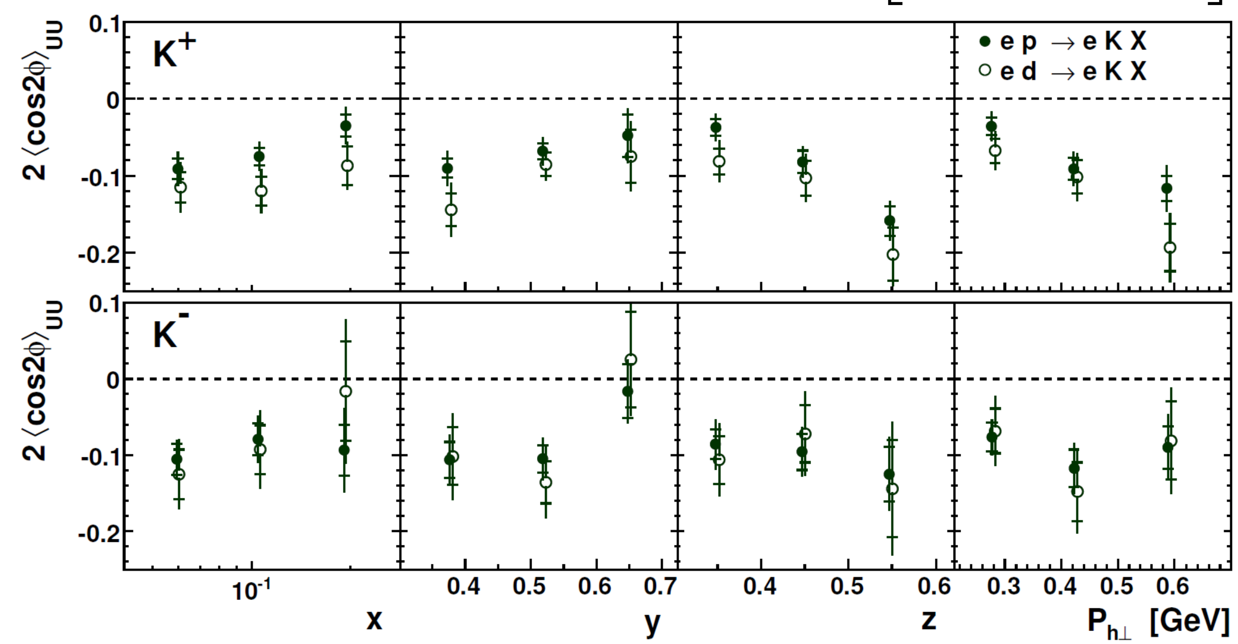


Summary

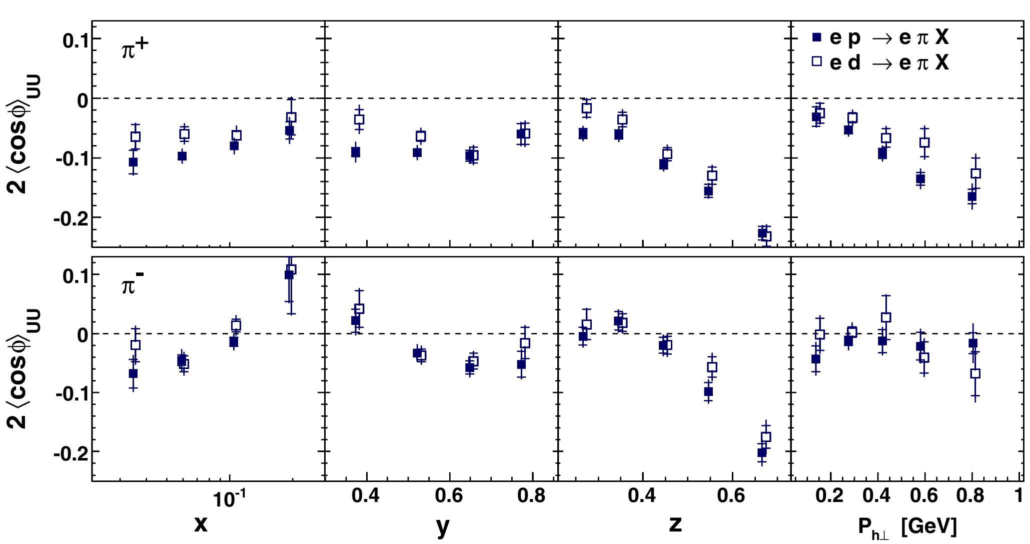
$\longrightarrow \mathcal{C}[f_1 \times D_1]$



$\longrightarrow \mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$

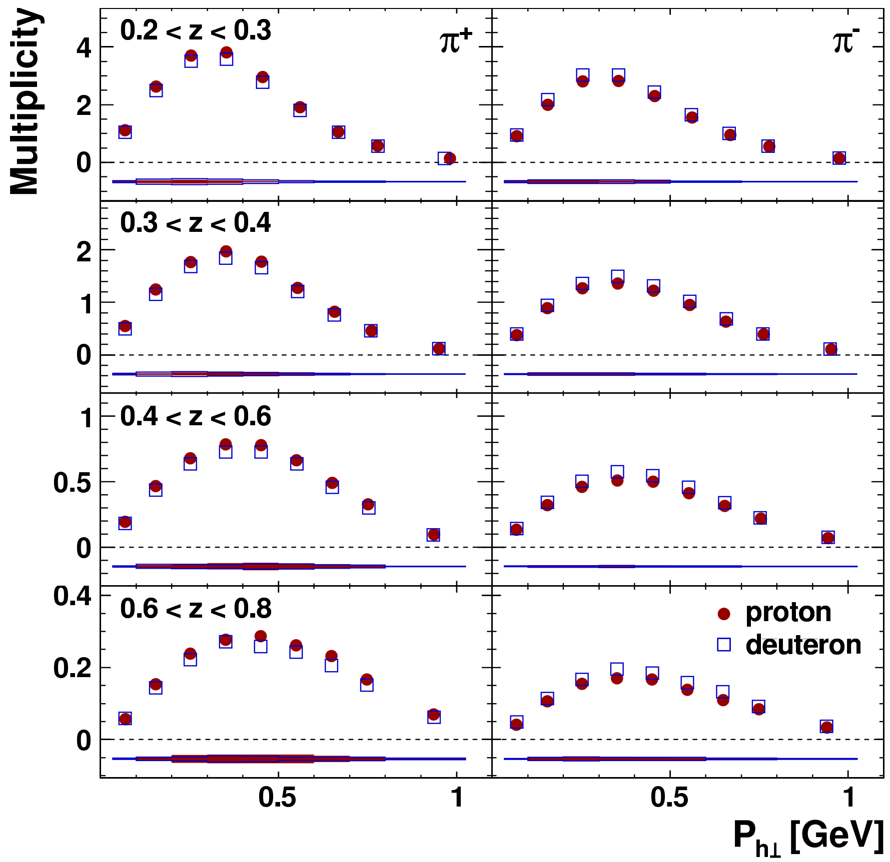


$\longrightarrow$ twist 3: Cahn effect, $\mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$

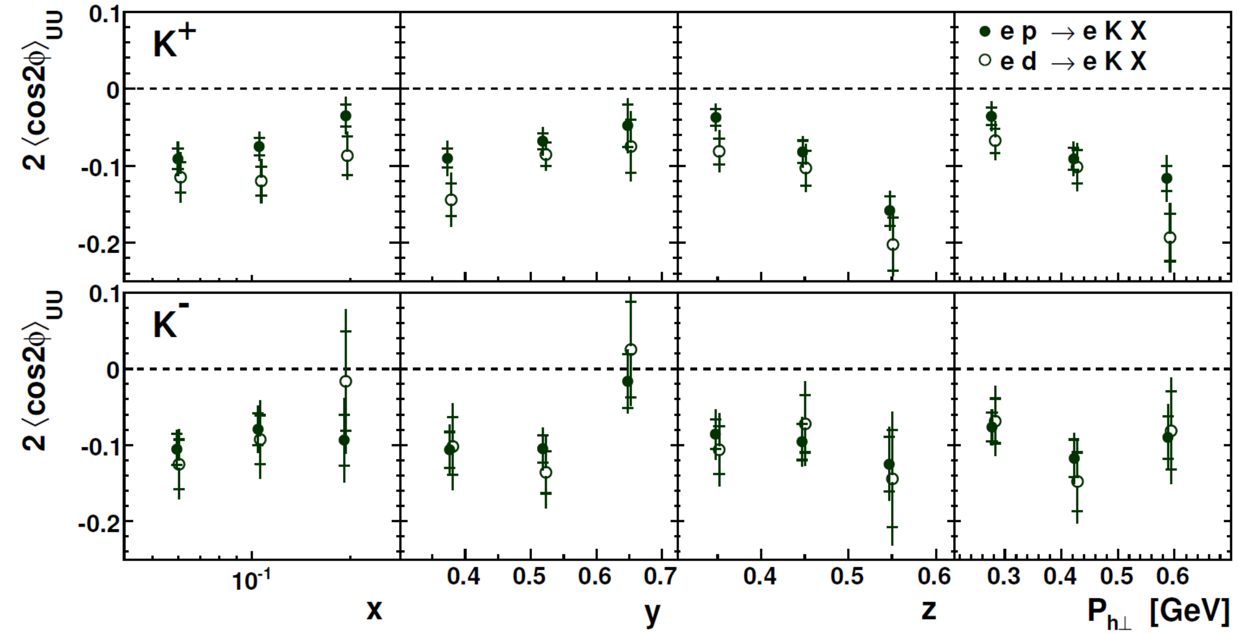


Summary

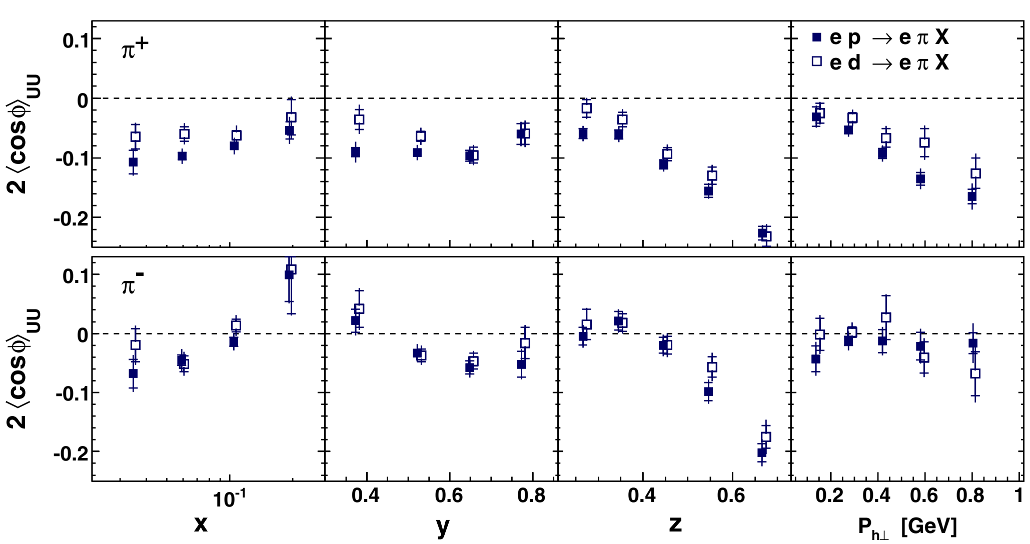
$\longrightarrow \mathcal{C}[f_1 \times D_1]$



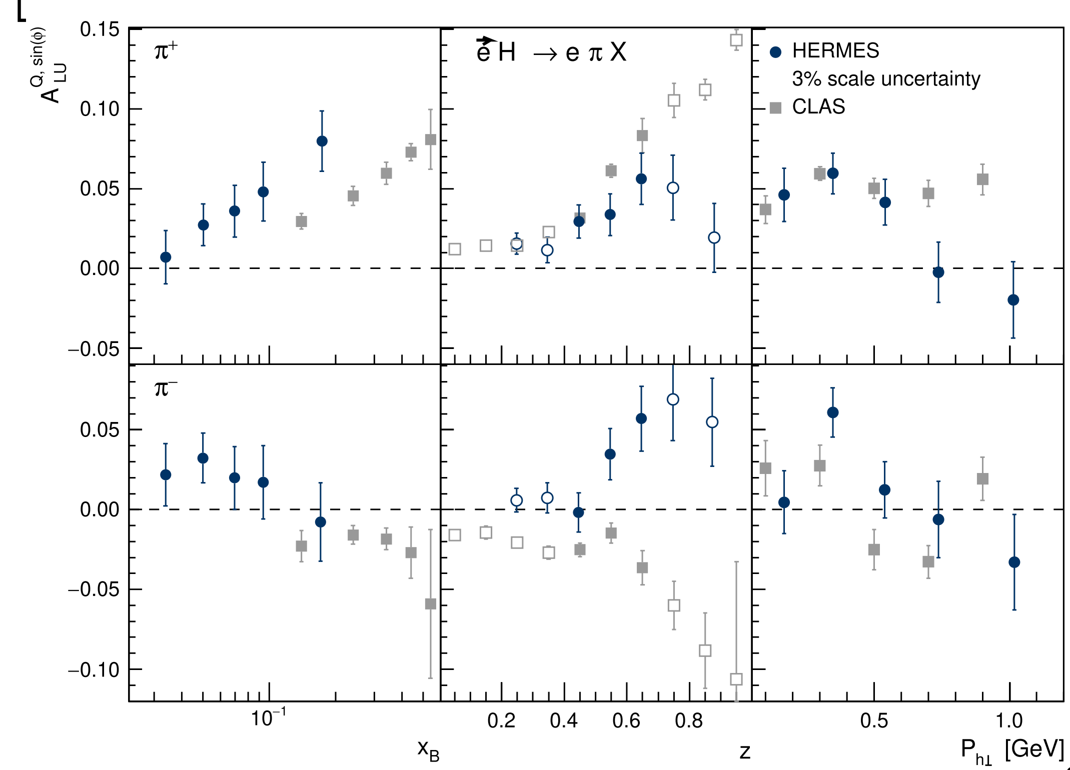
$\longrightarrow \mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$



$\longrightarrow$ twist 3: Cahn effect, $\mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$

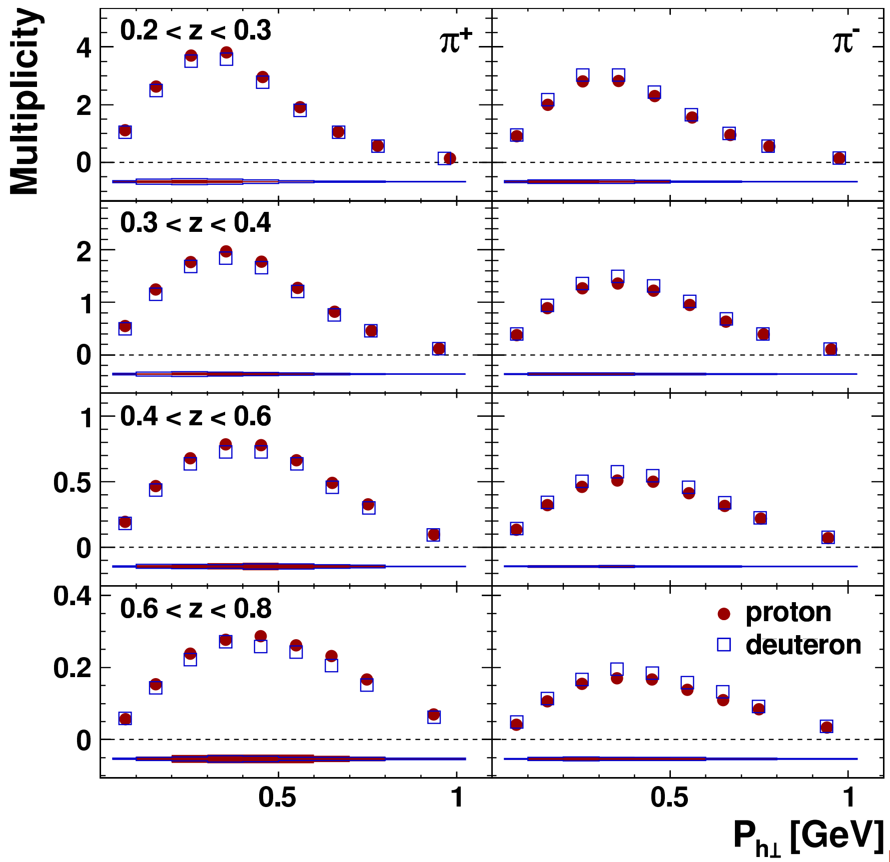


$\longrightarrow \left[h_1^\perp \times \tilde{E}, e \times H_1^\perp, g^\perp \times D_1, f_1 \times \tilde{G}^\perp\right]$

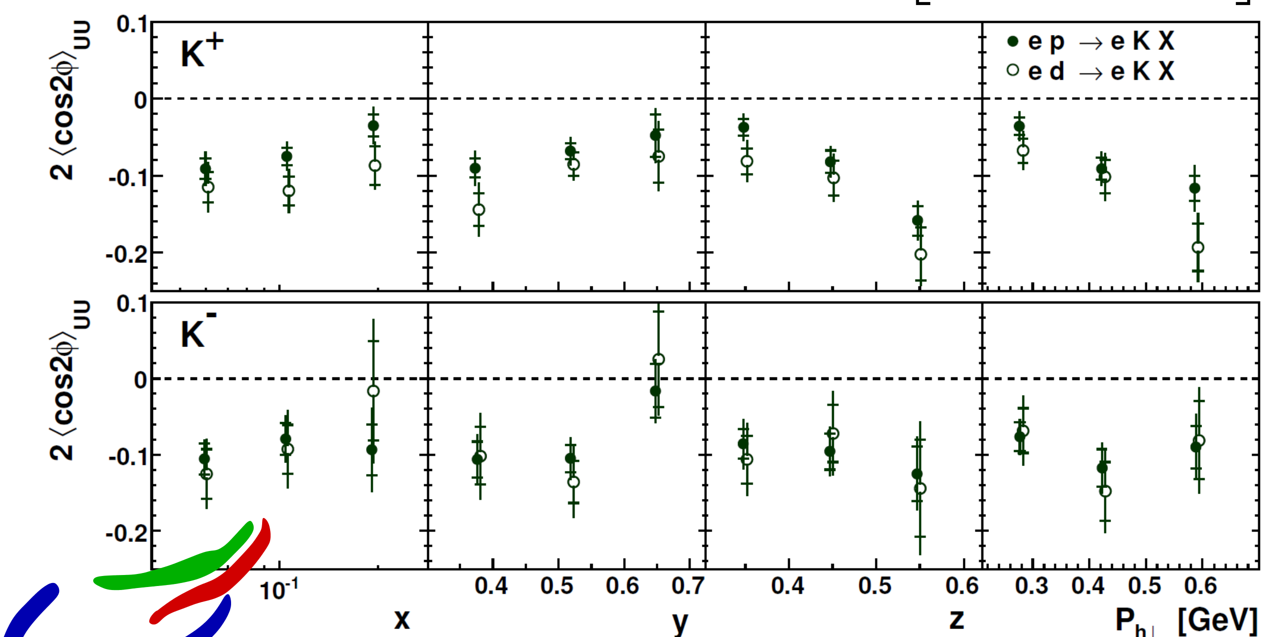


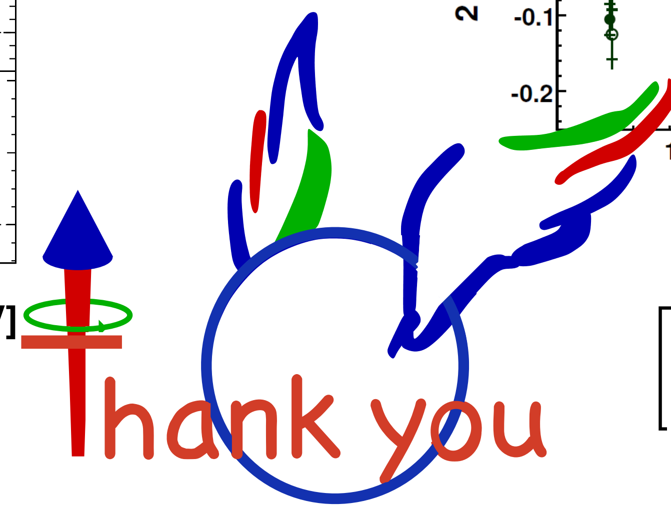
Summary

$\longrightarrow \mathcal{C}[f_1 \times D_1]$

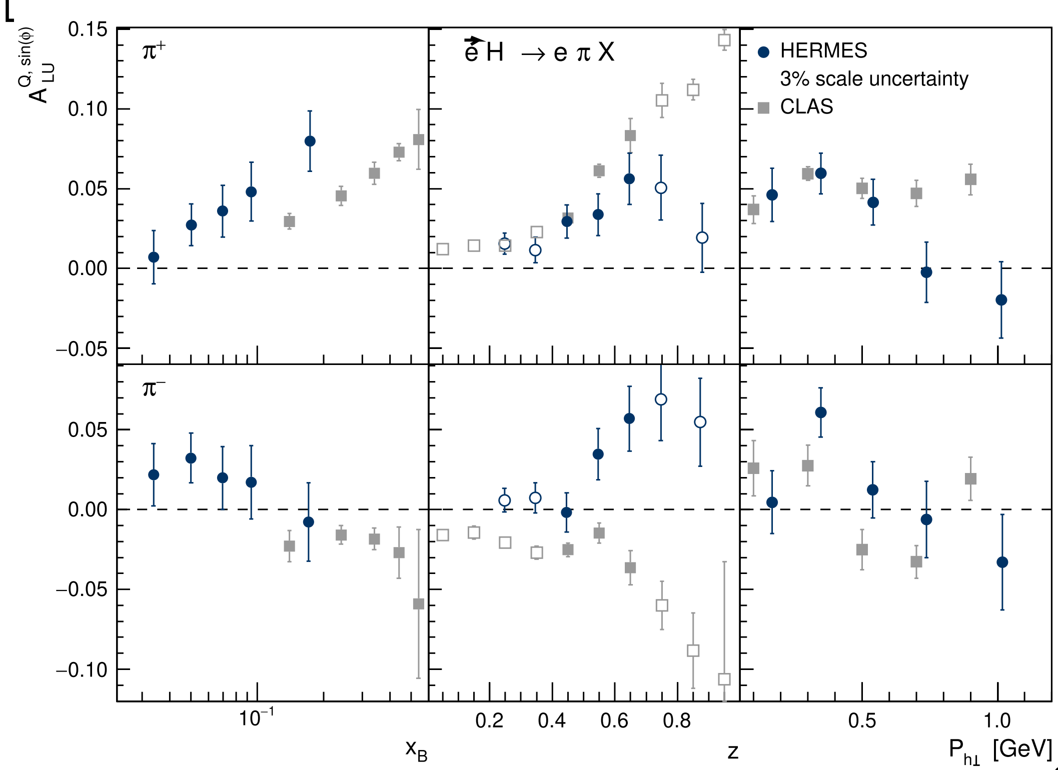


$\longrightarrow \mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$

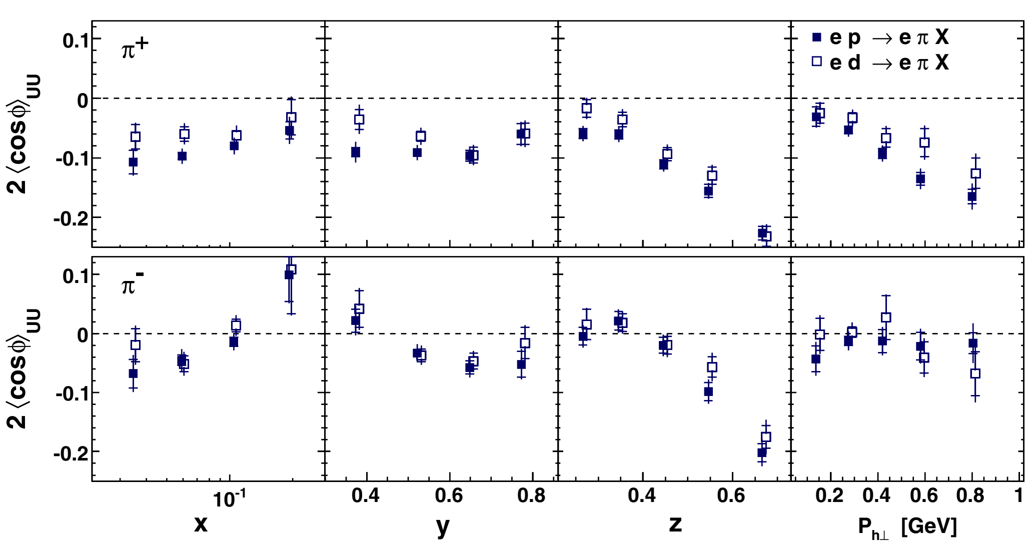




$\left[h_1^\perp \times \tilde{E}, e \times H_1^\perp, g^\perp \times D_1, f_1 \times \tilde{G}^\perp\right]$



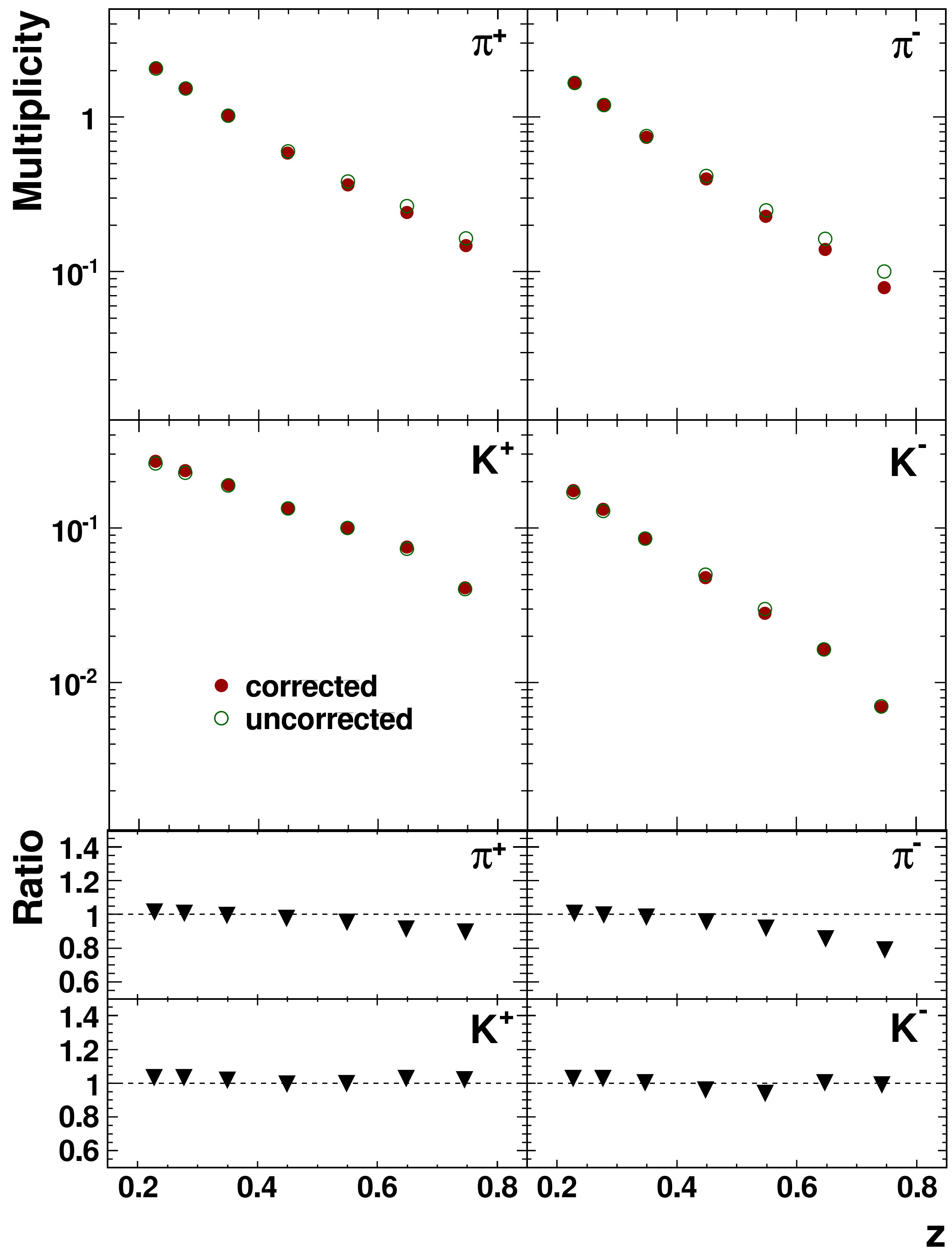
$\longrightarrow$ twist 3: Cahn effect, $\mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$



Back up

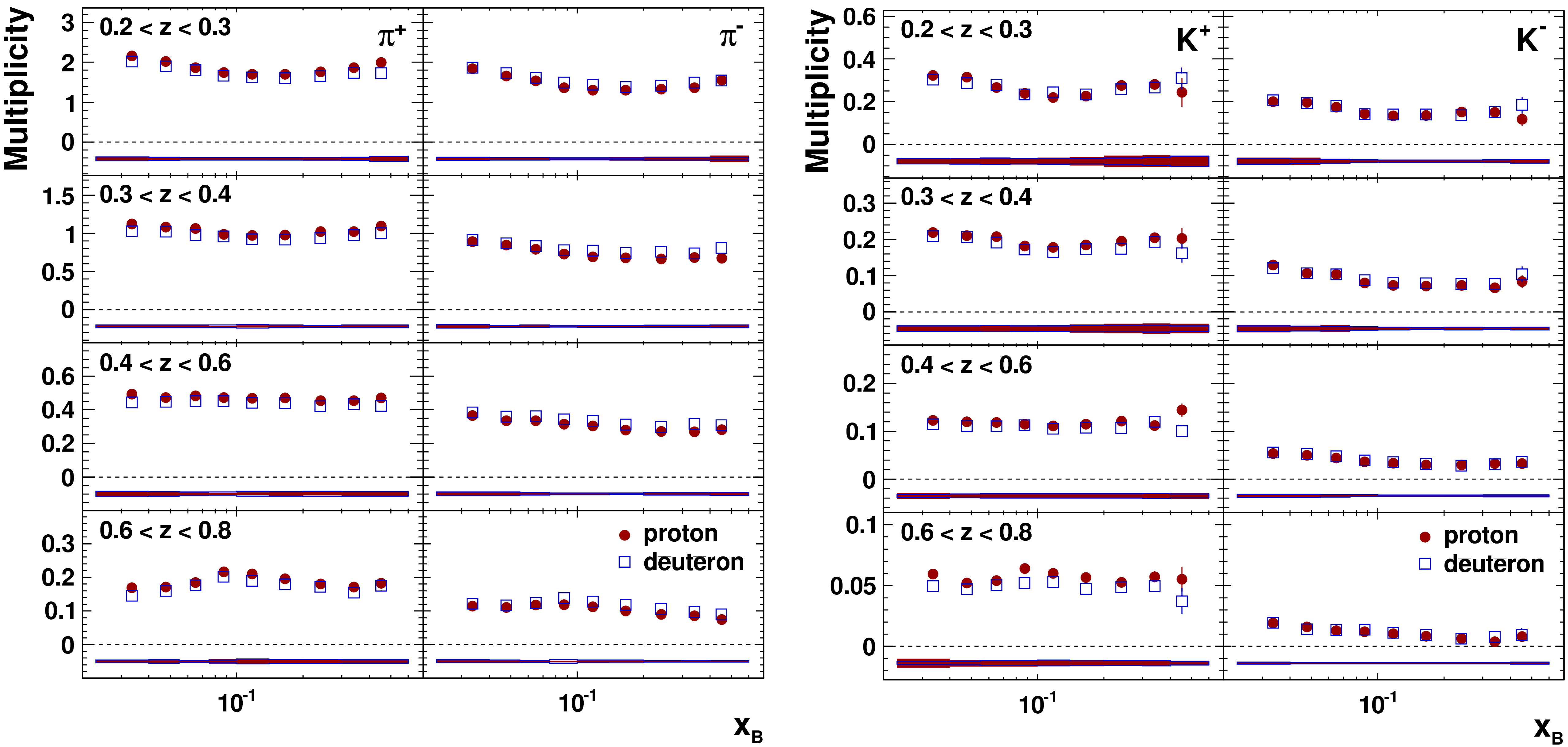
Correction for vector mesons

Phys. Rev. D87 (2013) 074029



Results projected in z and x

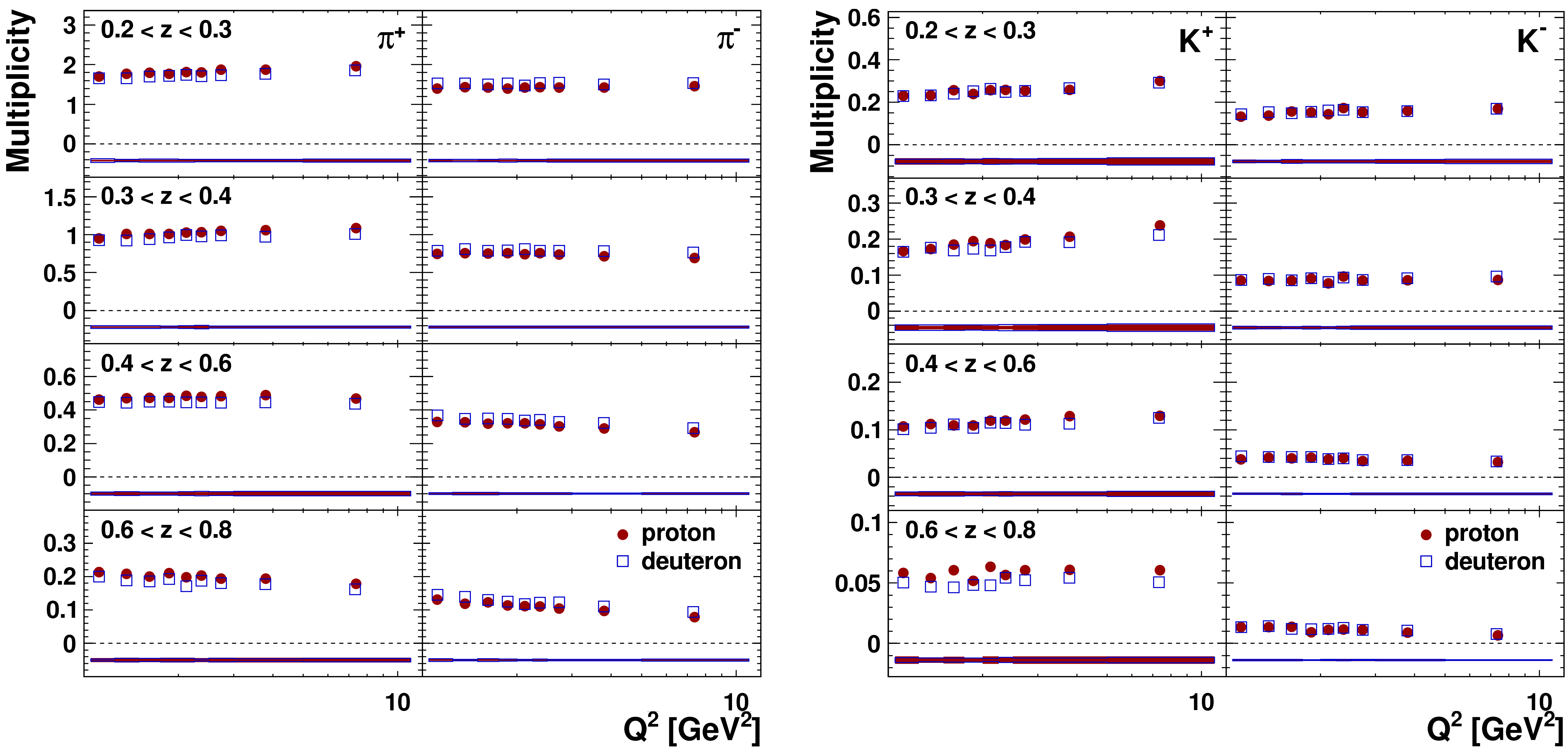
Corrected for vector mesons	Phys. Rev. D87 (2013) 074029



- No strong dependence on x

Results projected in z and Q²

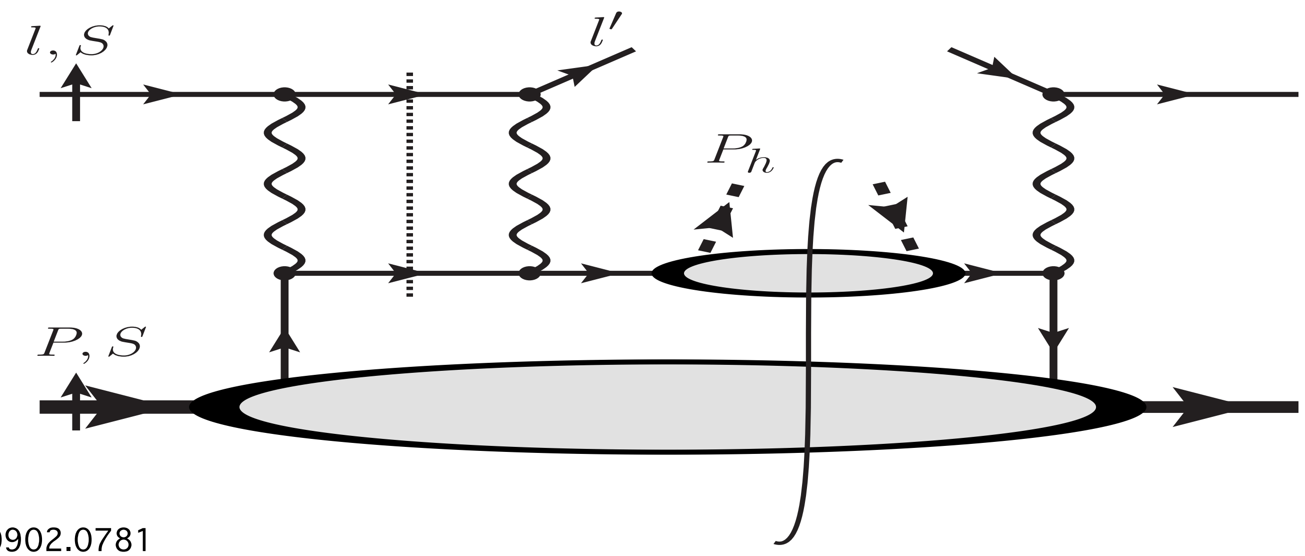
Corrected for vector mesons Phys. Rev. D87 (2013) 074029



- Strong correlation x and Q^2

Two-photon exchange A_{LU}

$$\langle \sin(2\phi) \rangle_{LU} \propto \mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$$



A. Metz and M. Schlegel, arXiv:0902.0781

compatible with zero in present measurement