Accessing TMDs with an unpolarised target at HERMES

Charlotte Van Hulse, University College Dublin

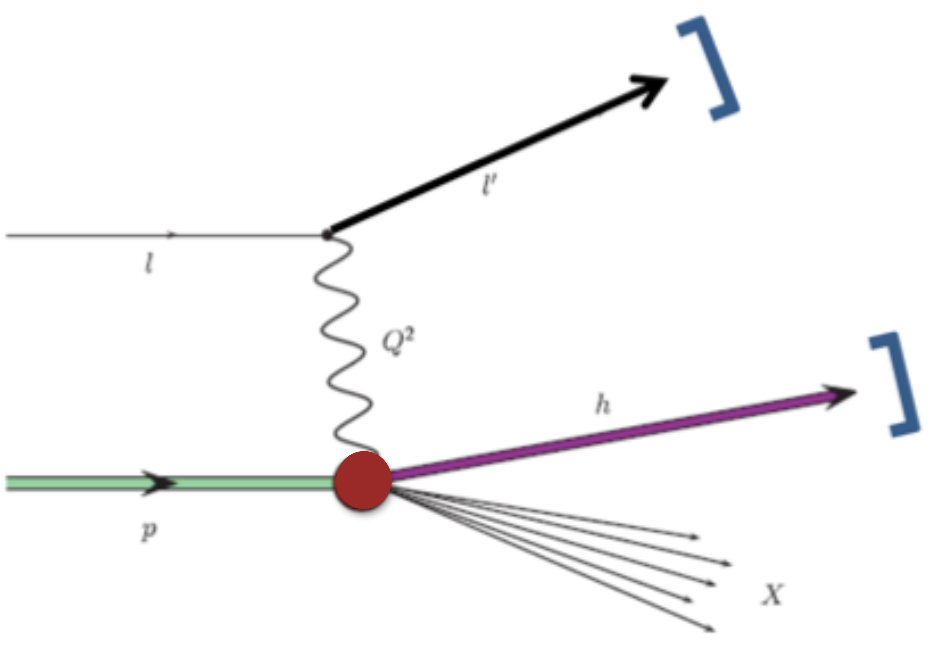
CPHI-2020,
CERN
3-7 February 2020

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

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

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

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

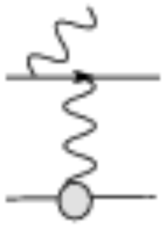
Extraction of Born multiplicities

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

Extraction of Born multiplicities

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

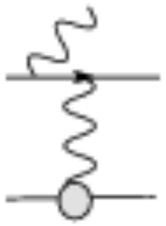
- QED radiative effects



Extraction of Born multiplicities

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

- QED radiative effects

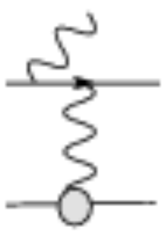


- limited geometric and kinematic acceptance of detector

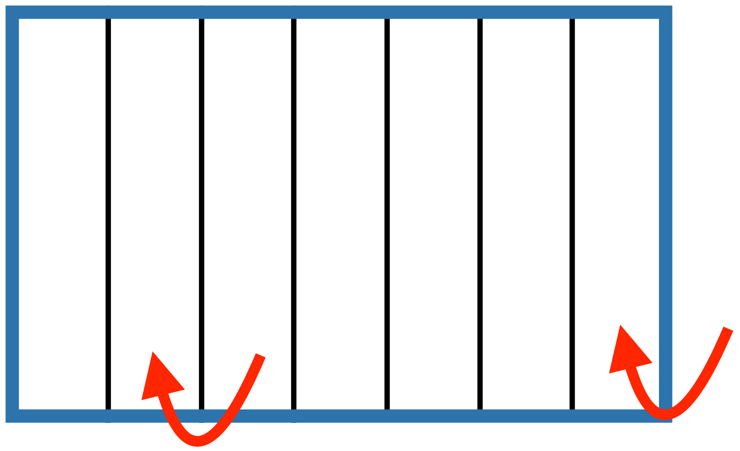
Extraction of Born multiplicities

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

- 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

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

- Smearing matrix from LEPTO+JETSET Monte-Carlo simulation

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

i → reconstructed

j → generated (Born)

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

Extraction of Born multiplicities

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

- Smearing matrix from LEPTO+JETSET Monte-Carlo simulation

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

i → reconstructed

j → generated (Born)

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

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

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

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

i → reconstructed

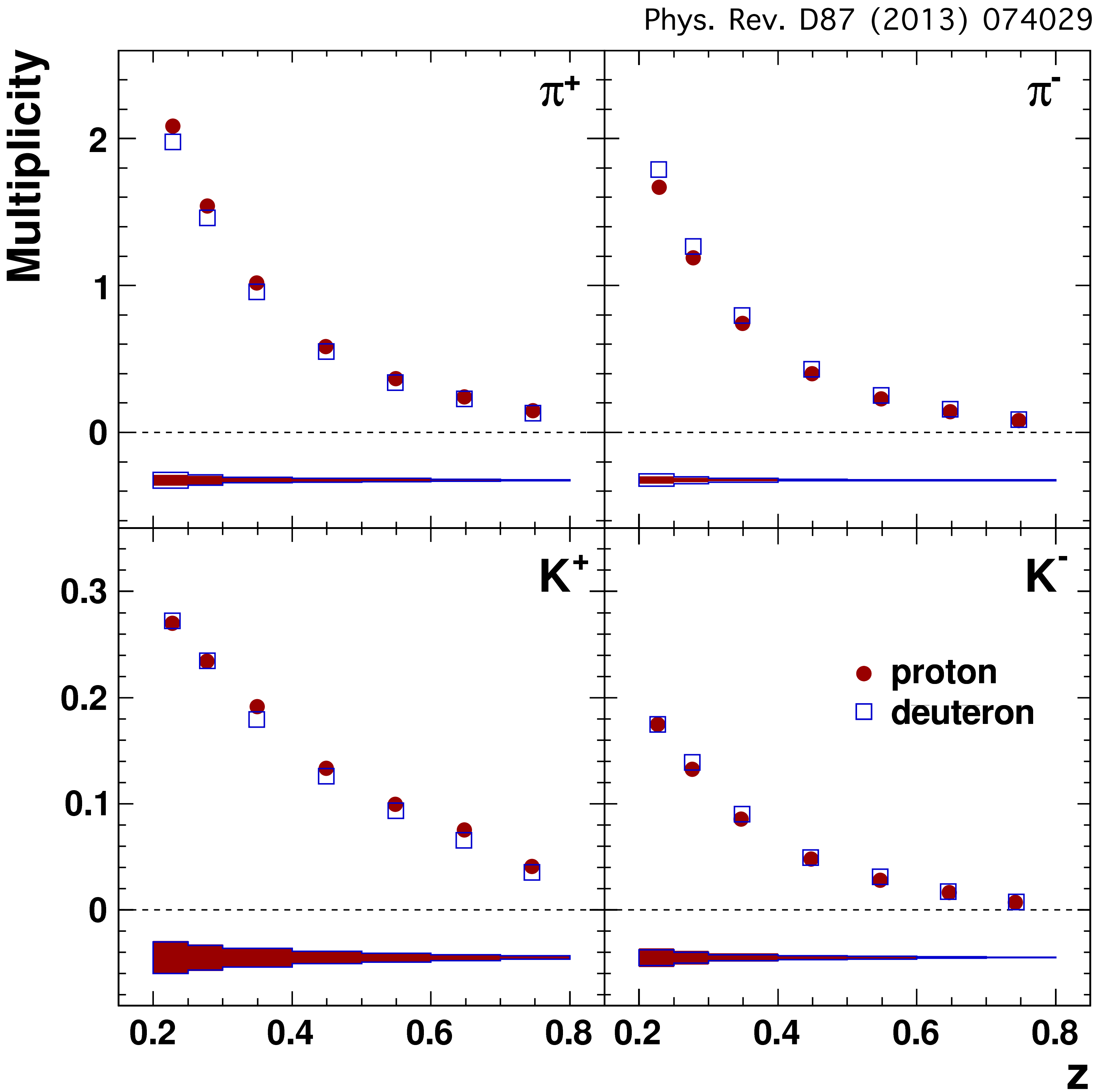
j → generated (Born)

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

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

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

Results projected in z



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

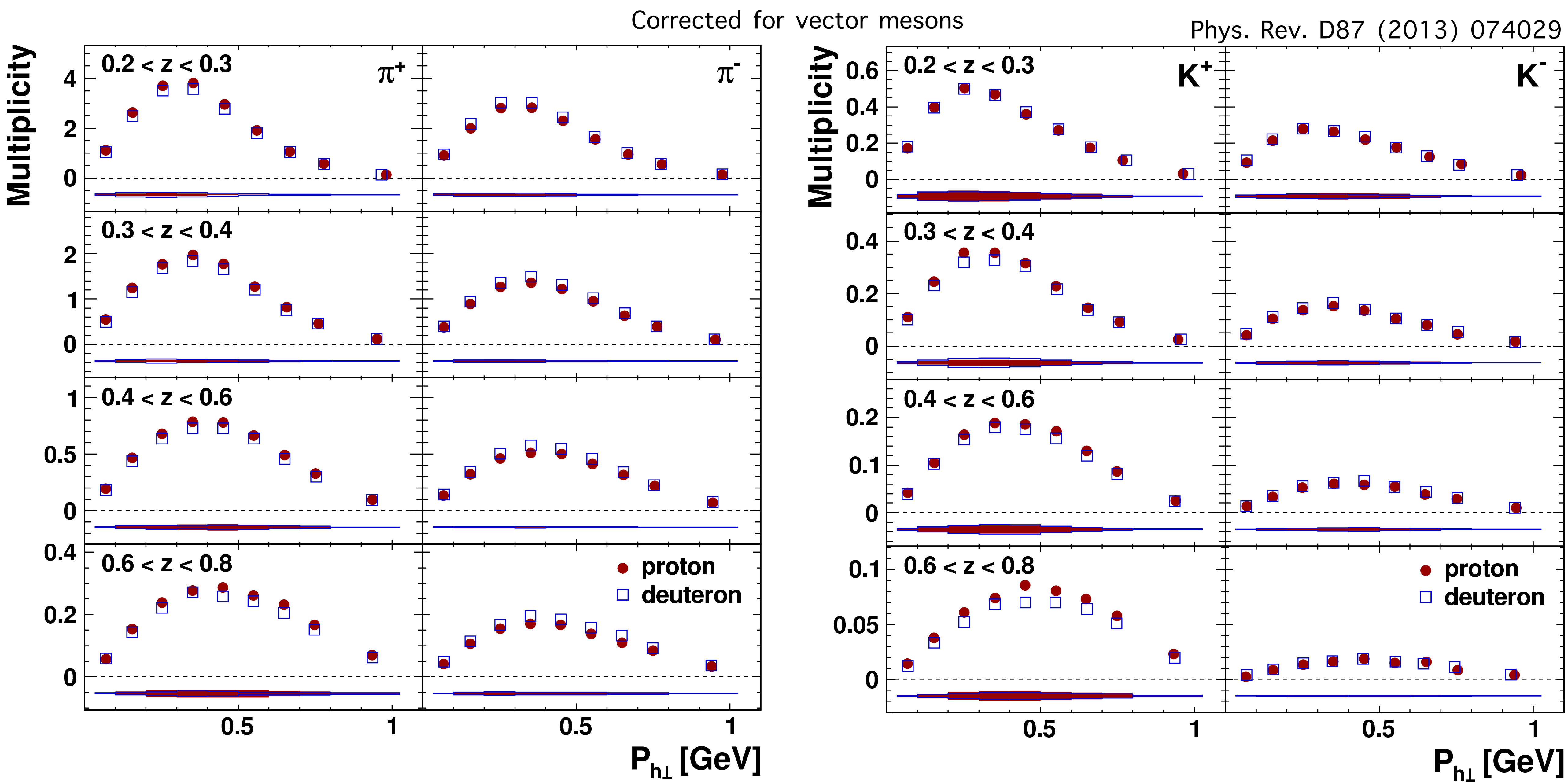
low z high z

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

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

Corrected for vector mesons

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

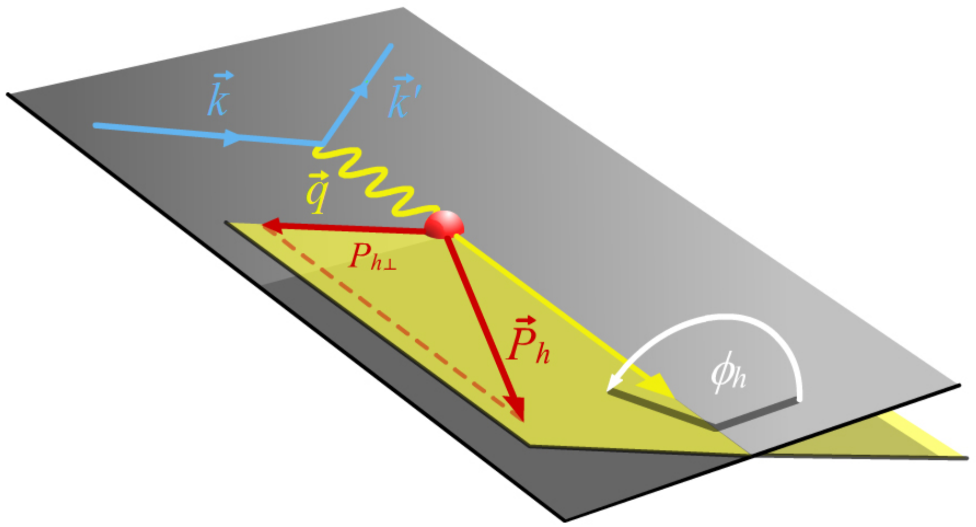


- $P_{h\perp}$ reflects transverse momentum inside nucleon and from fragmentation process
- $P_{h\perp}$ distribution broader for K^- than for K^+

Azimuthal dependence of the SIDIS cross section for unpolarised target

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

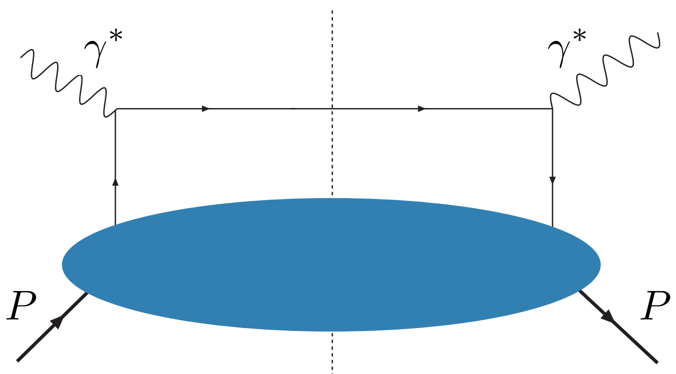
beam helicity



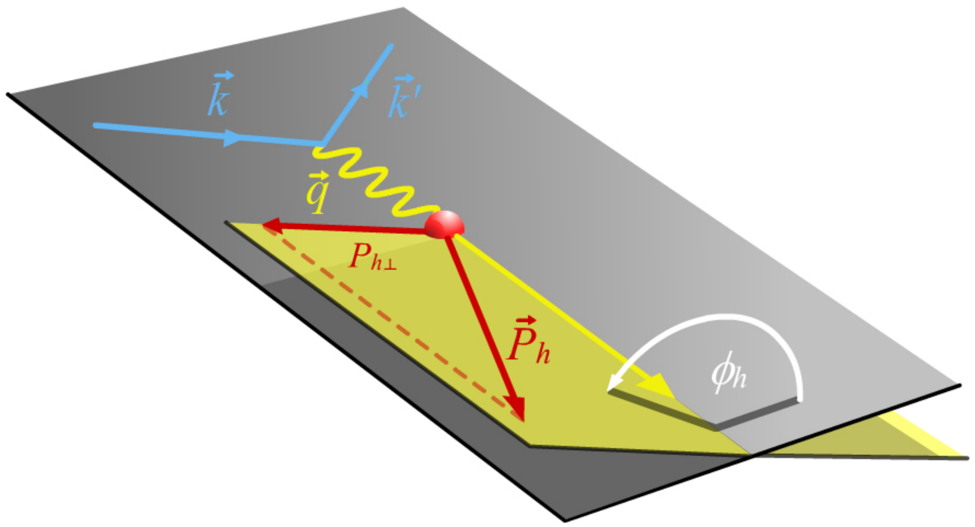
Azimuthal dependence of the SIDIS cross section for unpolarised target

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

beam helicity



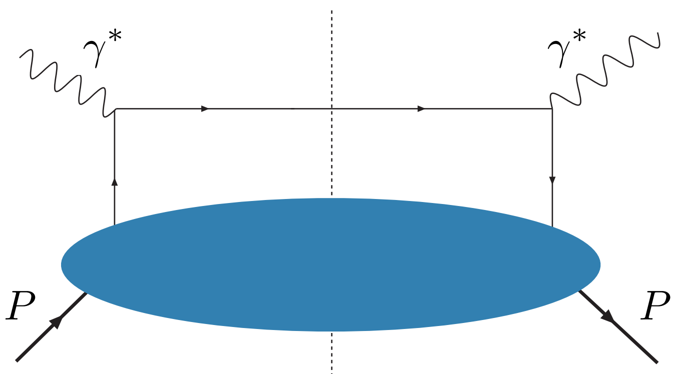
leading twist



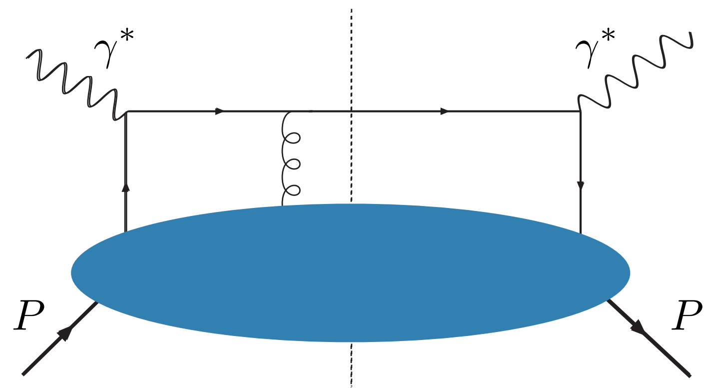
Azimuthal dependence of the SIDIS cross section for unpolarised target

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

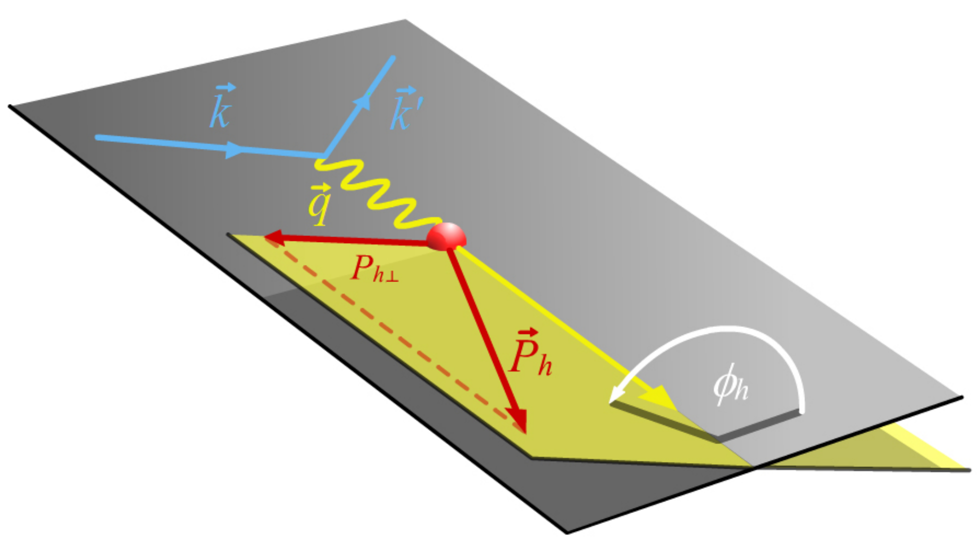
beam helicity



leading twist



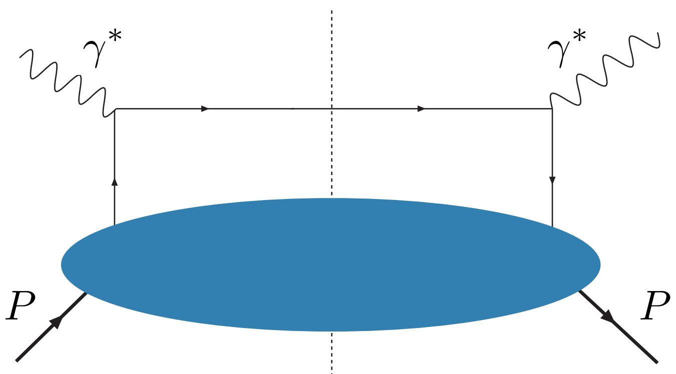
sub-leading twist



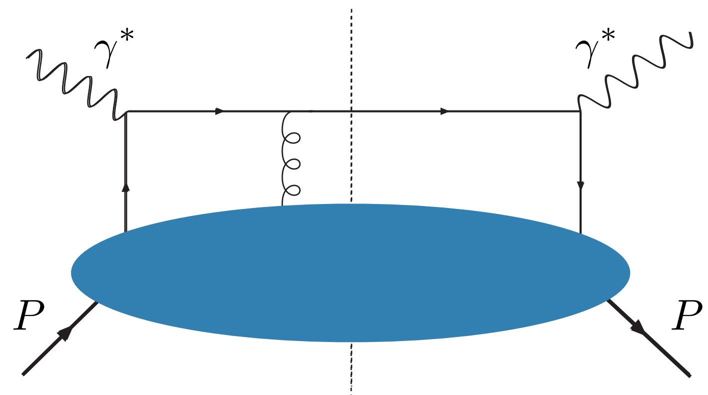
Azimuthal dependence of the SIDIS cross section for unpolarised target

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

beam helicity



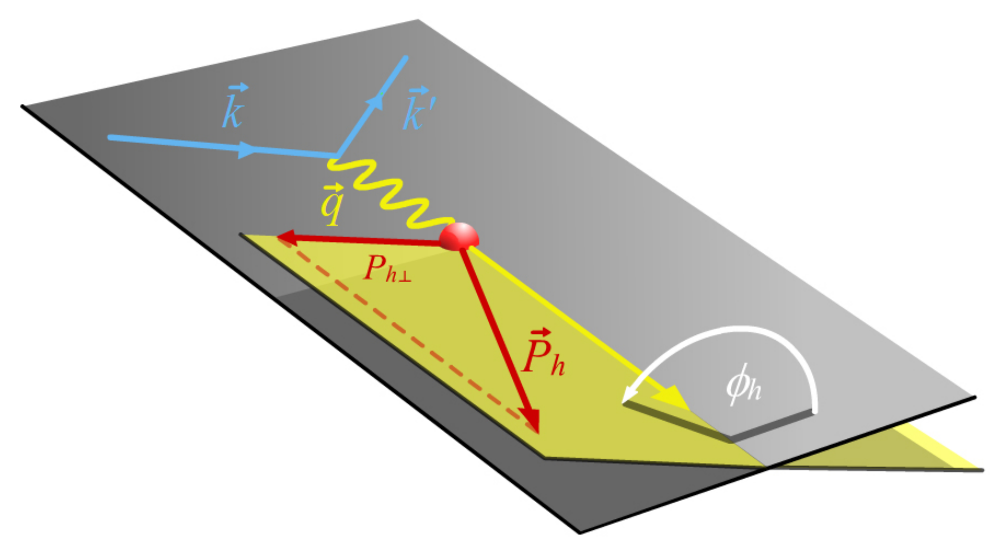
leading twist



sub-leading twist

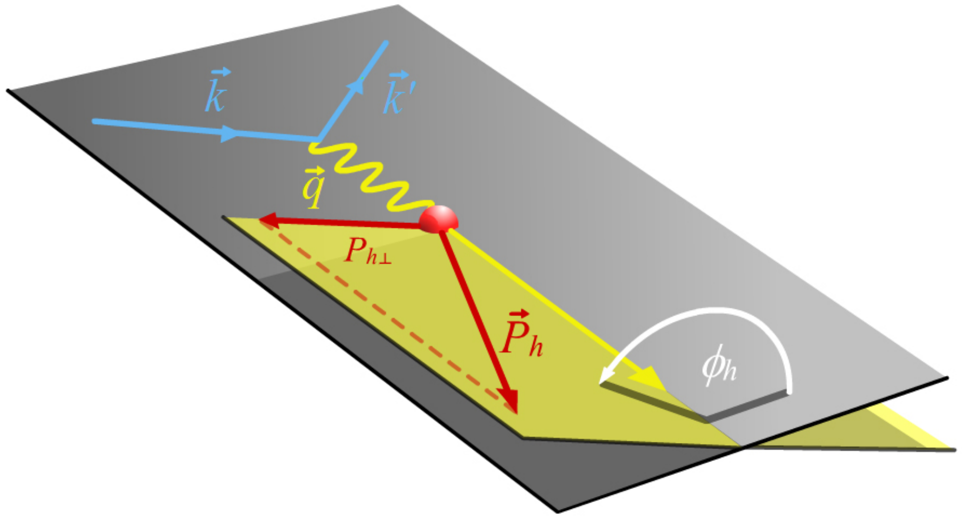
- Unpolarised/longitudinally polarised e+/e- beam
- Unpolarised H and D target

$Q^2 > 1$ GeV^2
$W^2 > 10$ GeV^2
$0.023 < x < 0.6$



Spin-independent azimuthal modulations

Results for charged pions and kaons

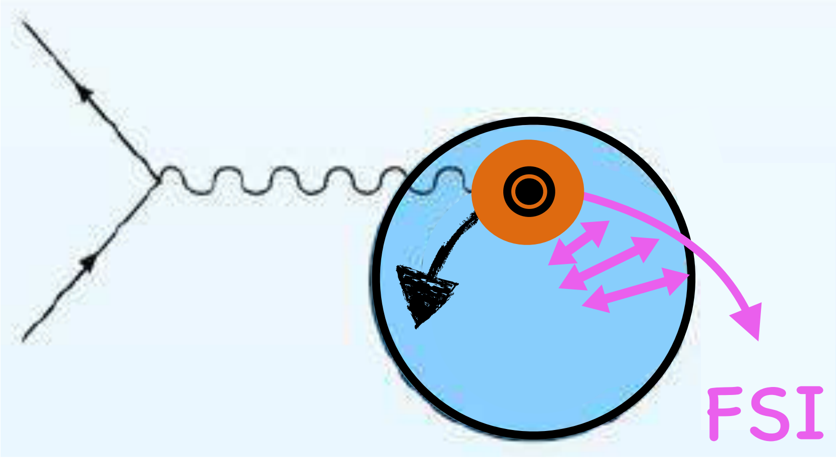


Spin-independent azimuthal modulations

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

Boer-Mulders PDF

Collins FF

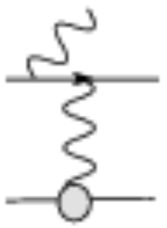


$$\langle \cos(\phi_h) \rangle \propto \mathcal{C}\left[\underbrace{\hat{P}_{h\perp} \cdot \vec{k}_\perp \, f_1 \times D_1}_{\text{Cahn effect}}, h_1^\perp \times H_1^\perp + \ldots\right]_{\text{twist-3}}$$

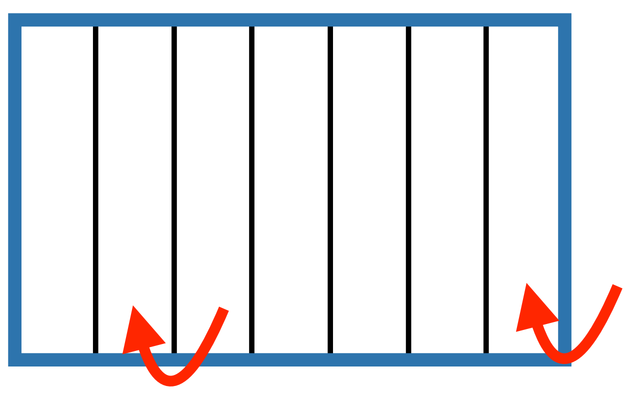
Extraction of $\langle \cos(2\phi_h) \rangle$ moments

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

- QED radiative effects



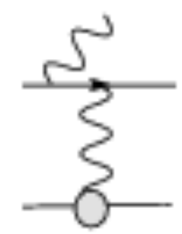
- limited geometric and kinematic acceptance of detector
- limited detector resolution



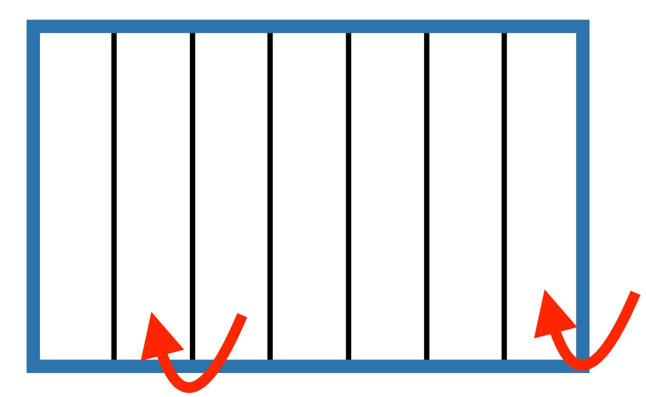
Extraction of $\langle\cos(2\phi_h)\rangle$ moments

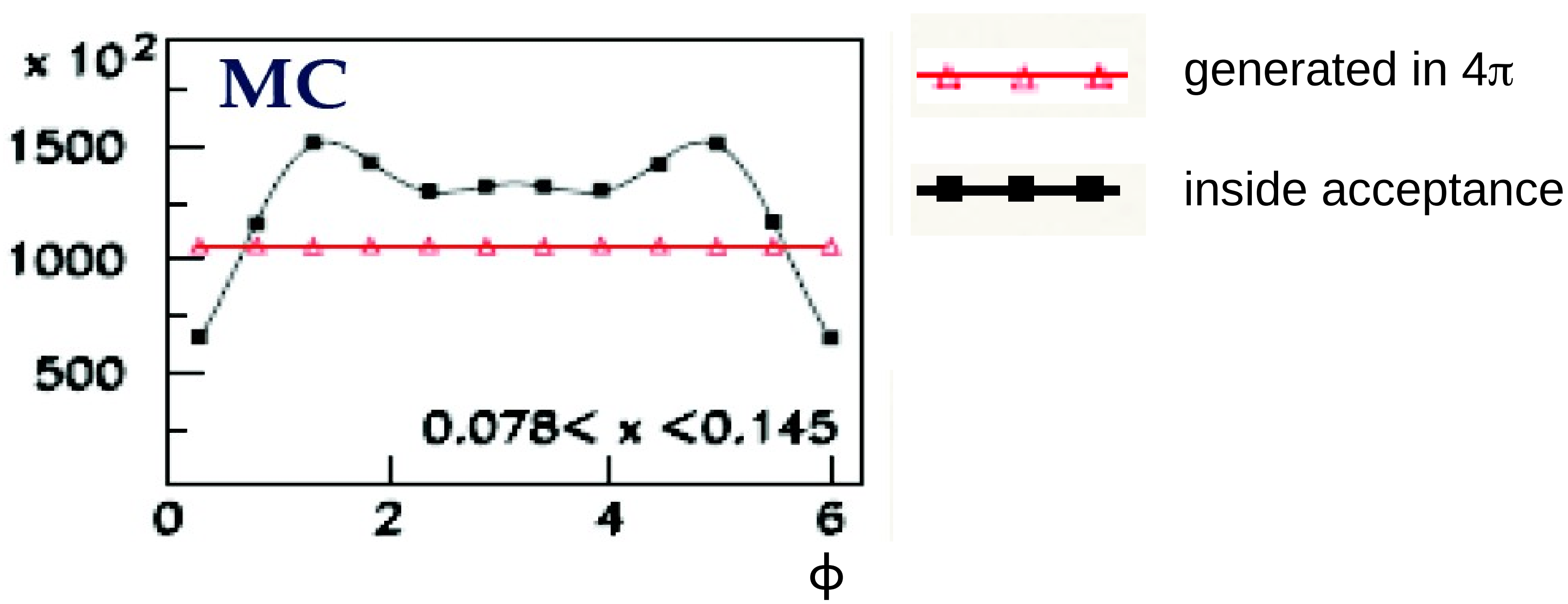
$\langle\cos(2\phi_h)\rangle_{Born}(j)$ ← $\langle\cos(2\phi_h)\rangle_{meas}(i)$

- QED radiative effects



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





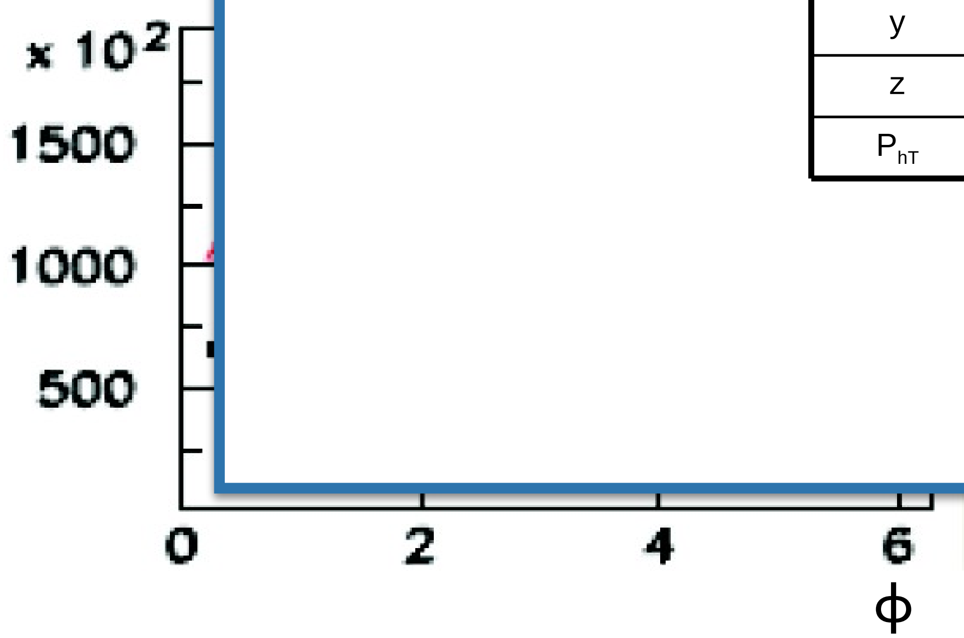
Extraction of $\langle \cos(2\phi_h) \rangle$ moments

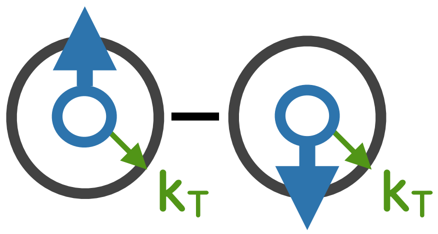
$\langle$co

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

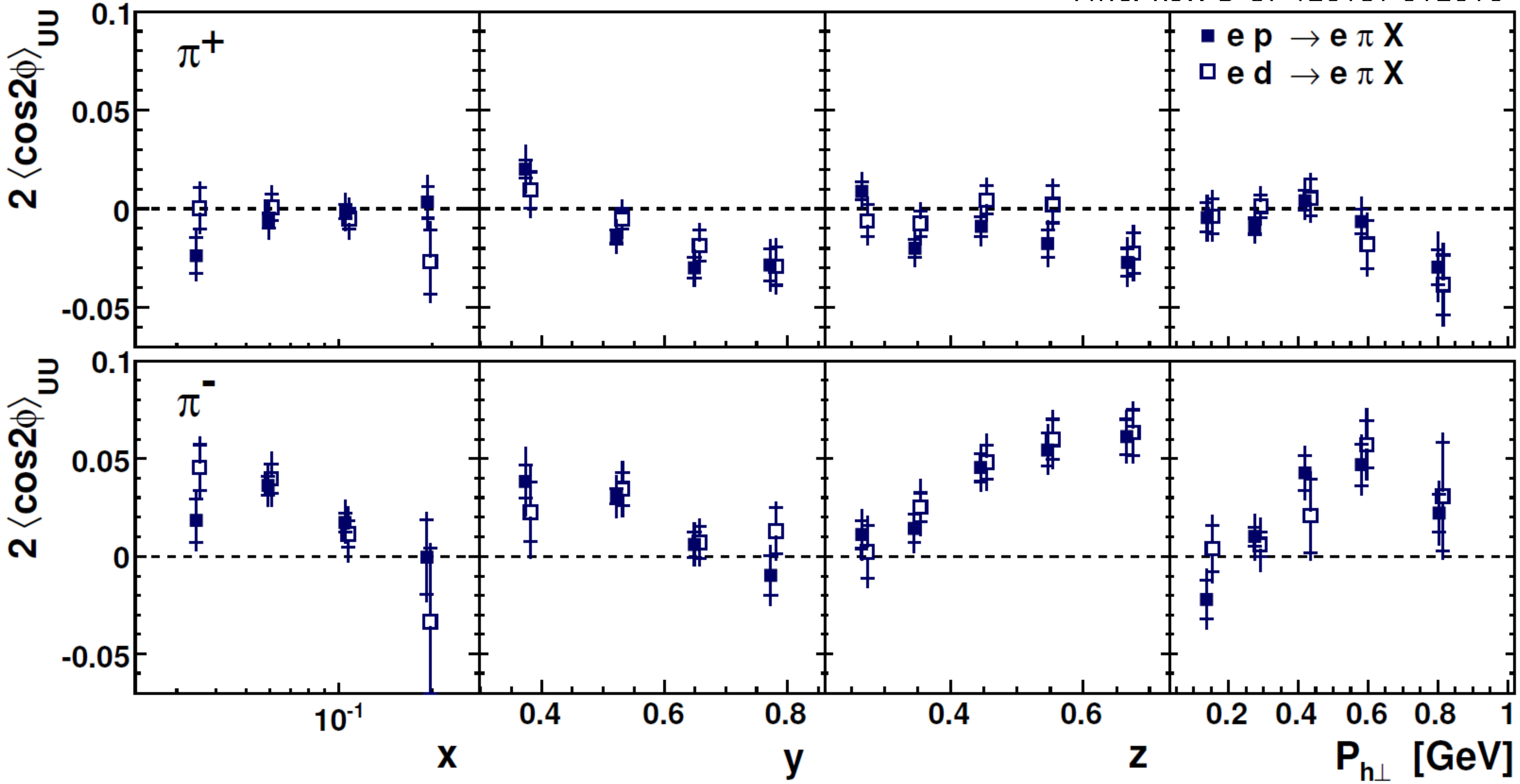




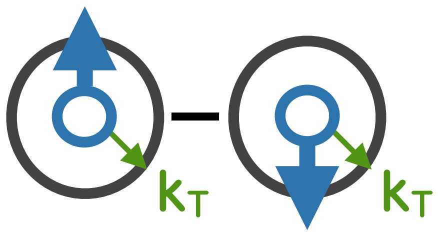
Boer-Mulders amplitudes

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

Phys. Rev. D 87 (2013) 012010



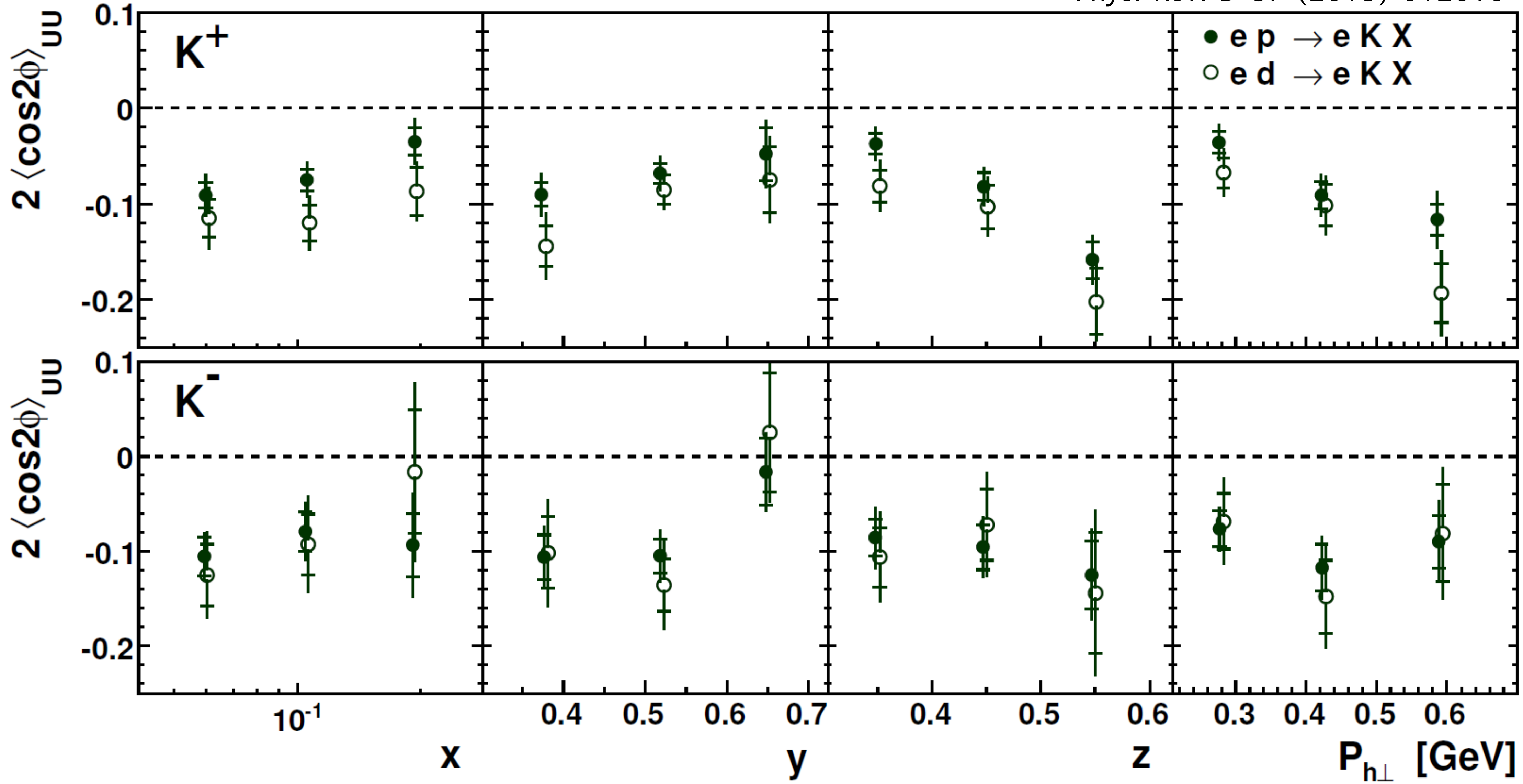
- Significant non-zero ⟶ non-zero orbital angular momentum
- naive T-odd: final-state interactions
- p-d comparison: $h_1^{\perp,u} \approx h_1^{\perp,d}$
- $\pi^- > 0 \iff \pi^+ \leq 0$: $H_1^{\perp,u\to\pi^+} \approx -H_1^{\perp,u\to\pi^-}$



Boer-Mulders amplitudes

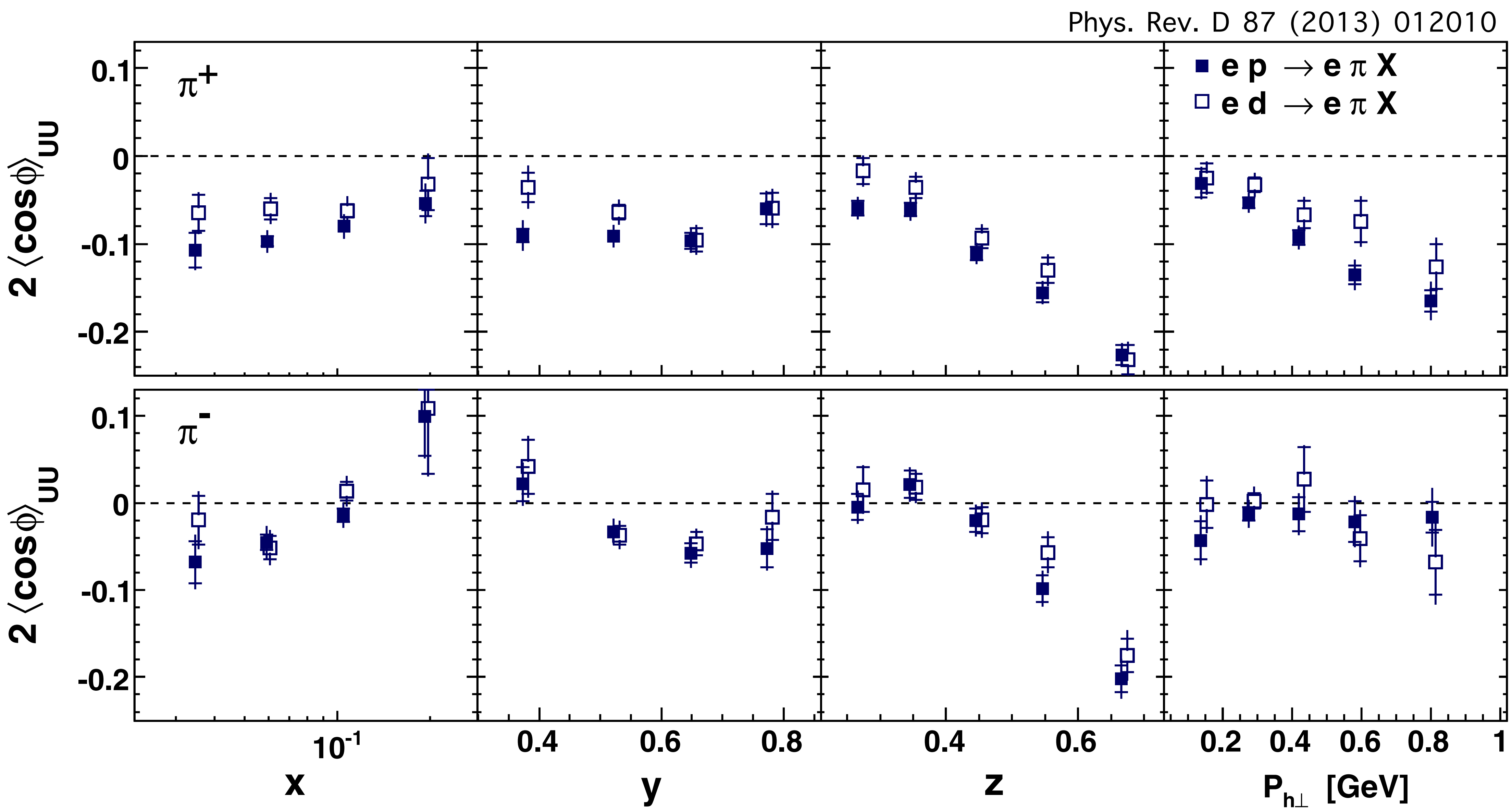
$$\mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$$

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^+)

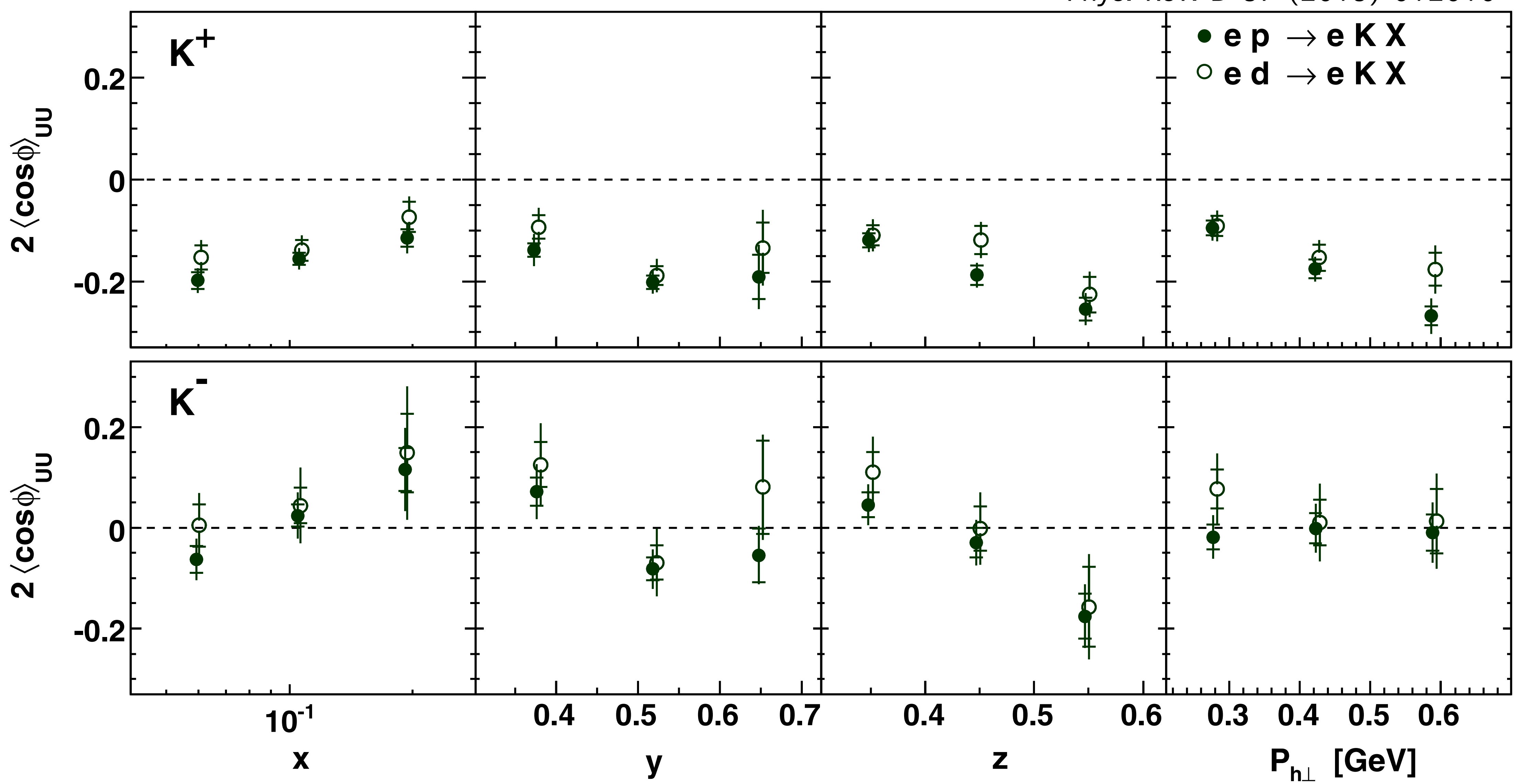
$\langle \cos(\phi_h) \rangle$ amplitudes



- 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

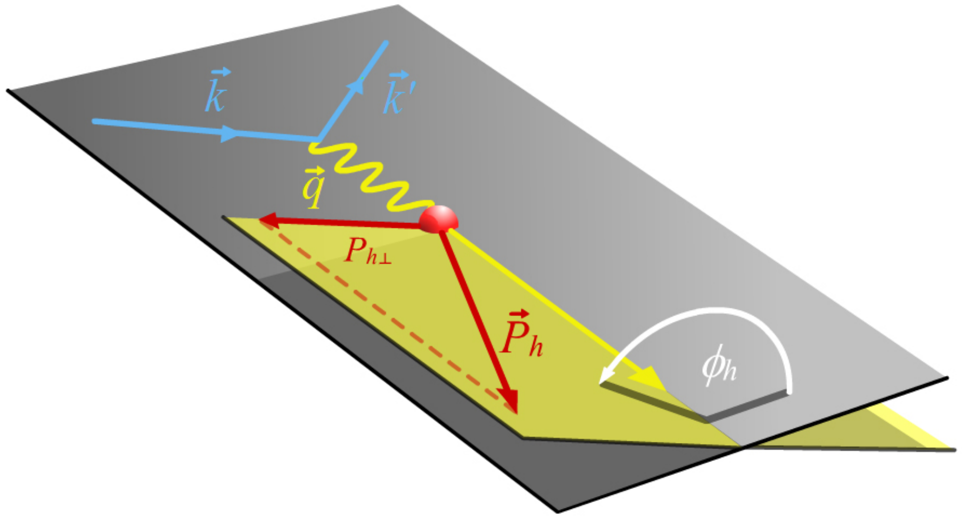
Phys. Rev. D 87 (2013) 012010



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

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

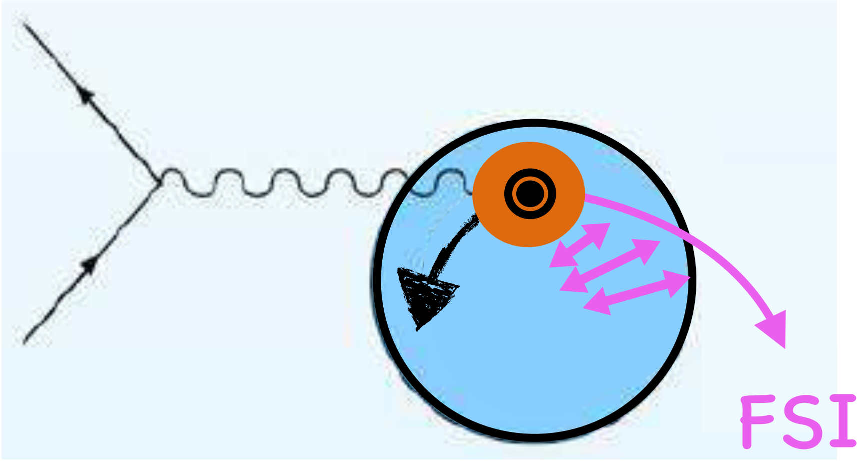
Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$

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

Boer-Mulders PDF

Chiral-odd T-even twist-3 FF

Boer-Mulders PDF



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

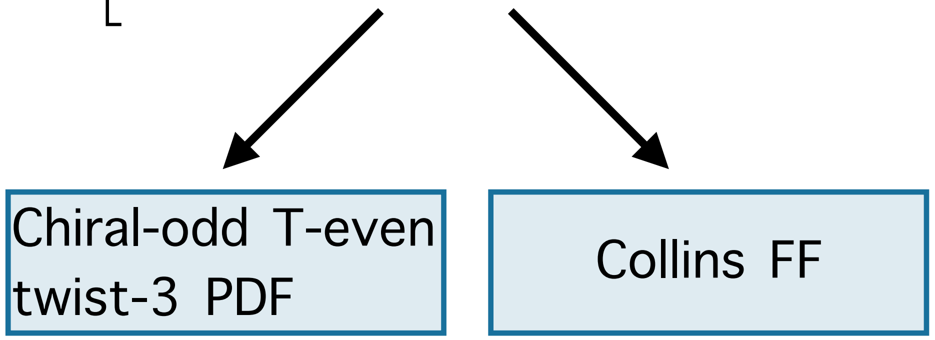
$$\langle \sin(\phi) \rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^{\perp} \times \tilde{E}, e \times H_1^{\perp}, g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp}\right]$$

Chiral-odd T-even twist-3 PDF

Collins FF

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

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



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

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

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

Chiral-odd T-even twist-3 PDF

Collins FF

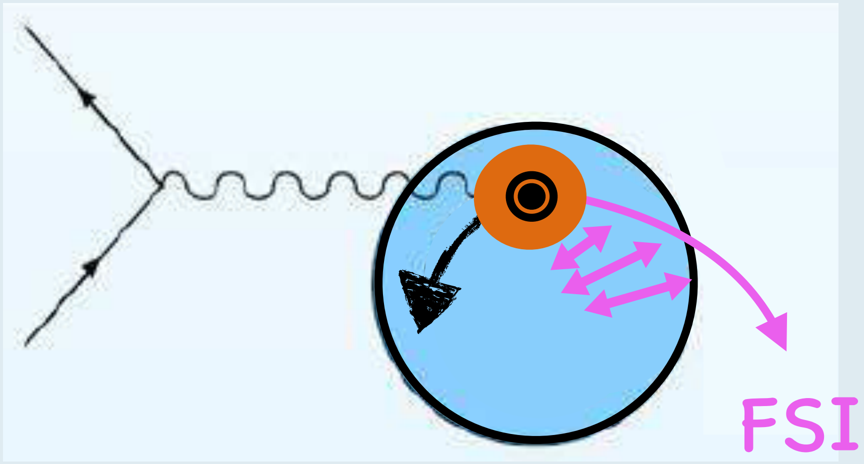
$$e(x) = e^{\mathrm{WW}}(x) + \bar{e}(x)$$

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

→ force on struck quark at t=0

M. Burkardt, arXiv:0810.3589

Boer-Mulders PDF



FSI: t=0→∞

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

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

Chiral-even T-odd twist-3 PDF

spin-independent FF

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

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

Chiral-even T-odd twist-3 PDF

spin-independent FF

Only term to survive in TMD single-jet inclusive DIS

$$e + p \to e' + \text{jet} + X$$

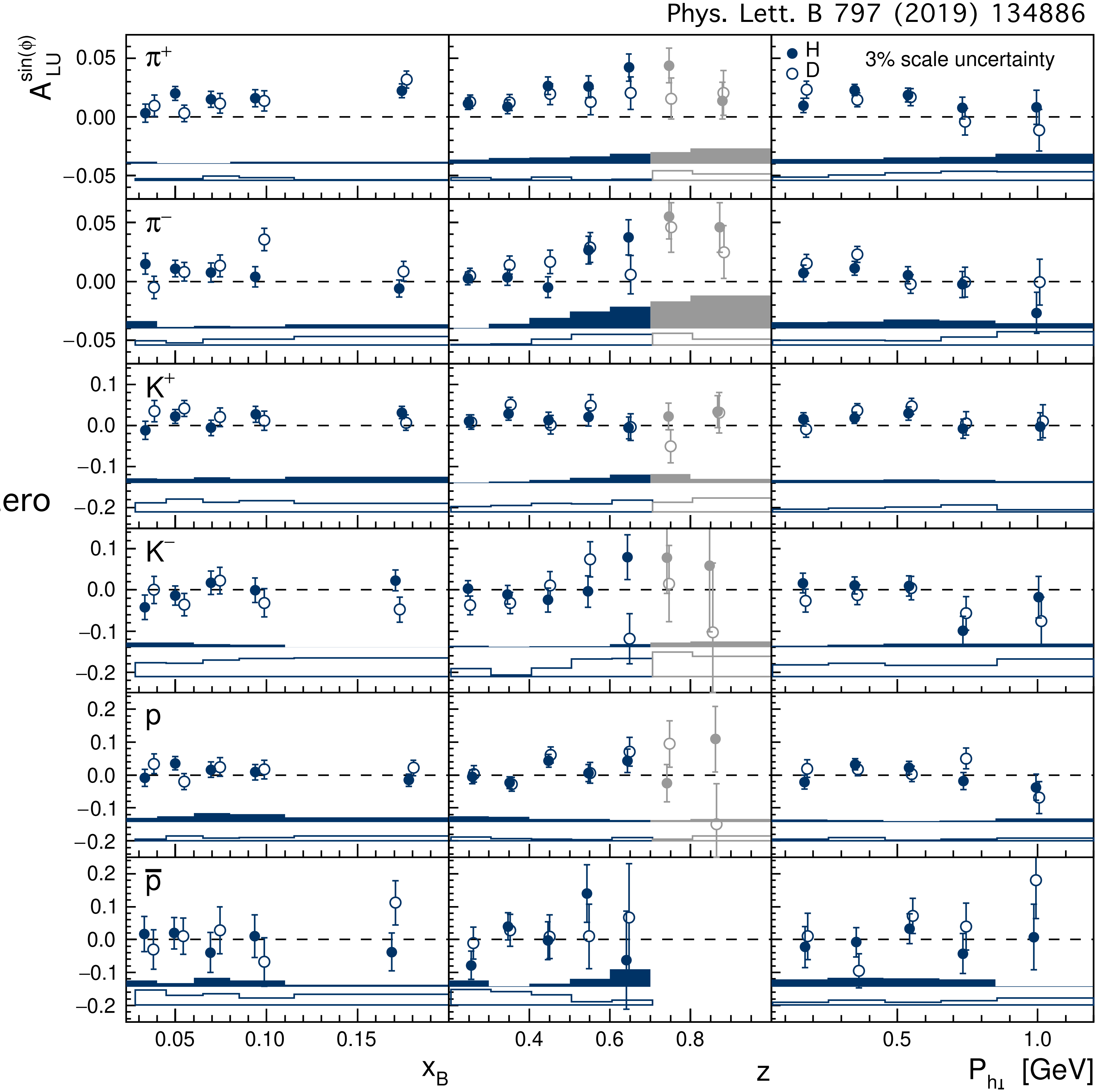
Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$

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

f_1: spin-independent PDF

$\tilde{G}^{\perp}$: chiral-even, T-odd twist-3 FF

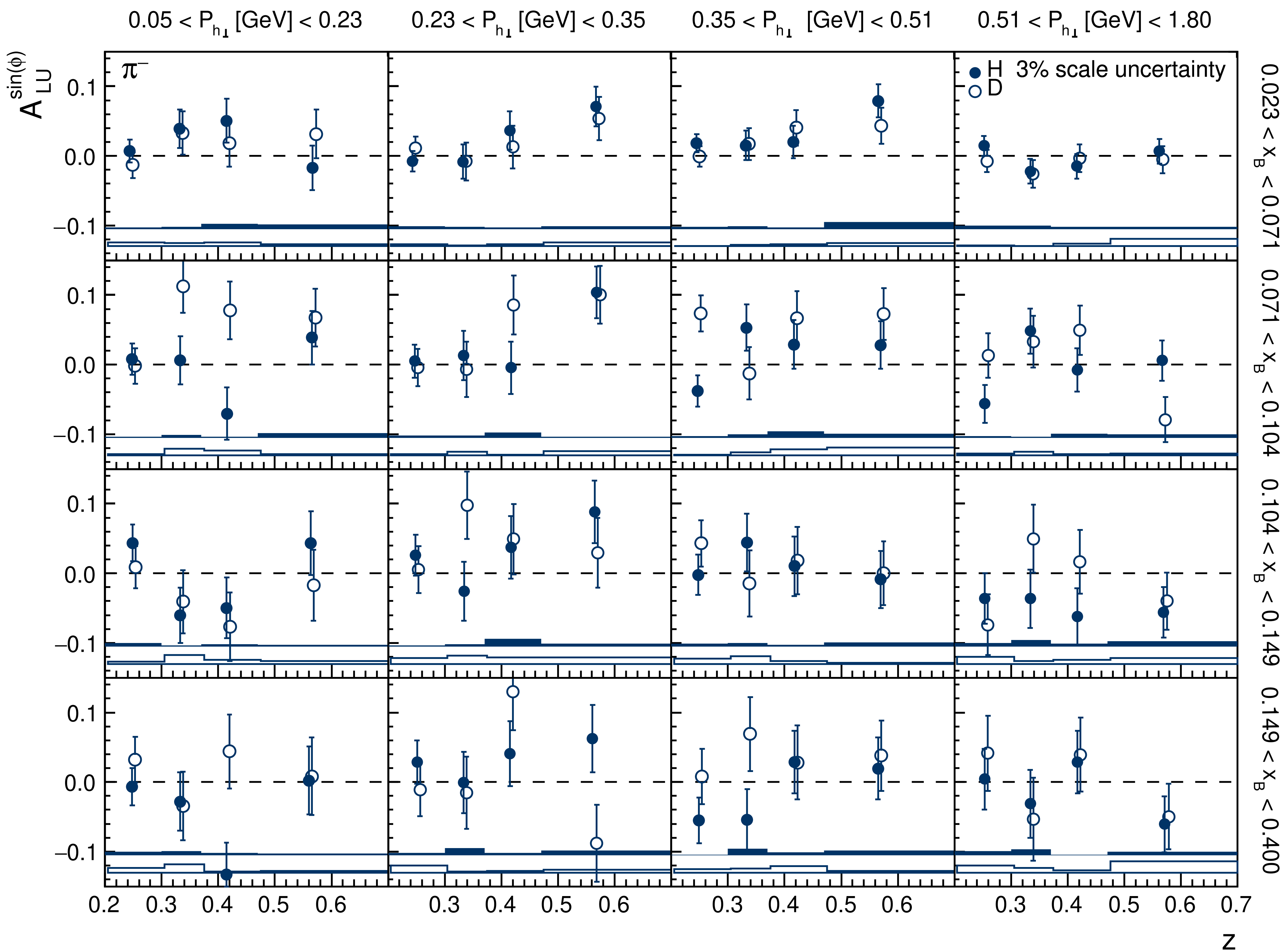
1D virtual-photon asymmetry



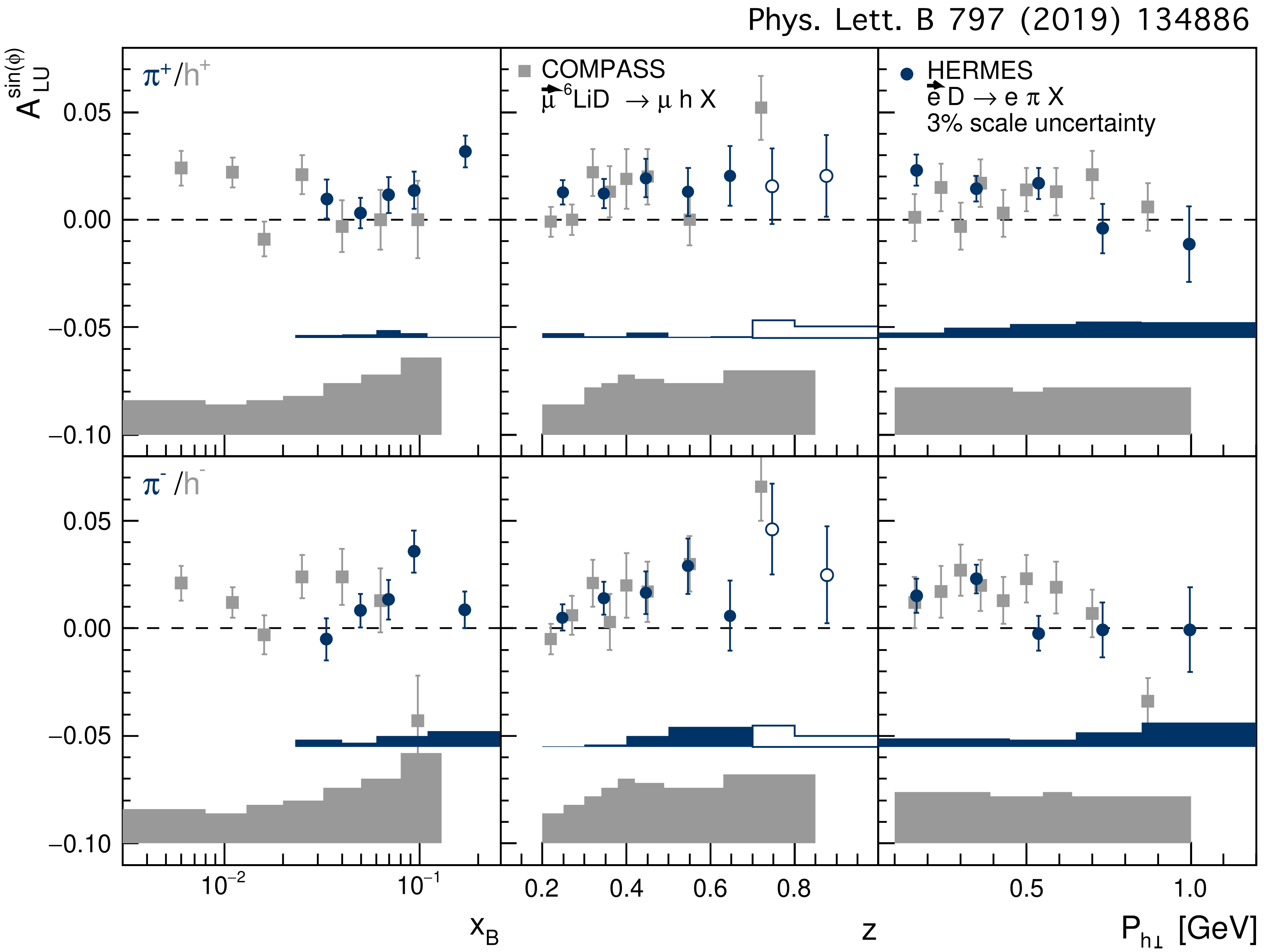
- Agreement H and D data
- Positive results for pions
- Slightly positive for K+
- Other hadrons consistent with zero

3D virtual-photon asymmetry

Phys. Lett. B 797 (2019) 134886

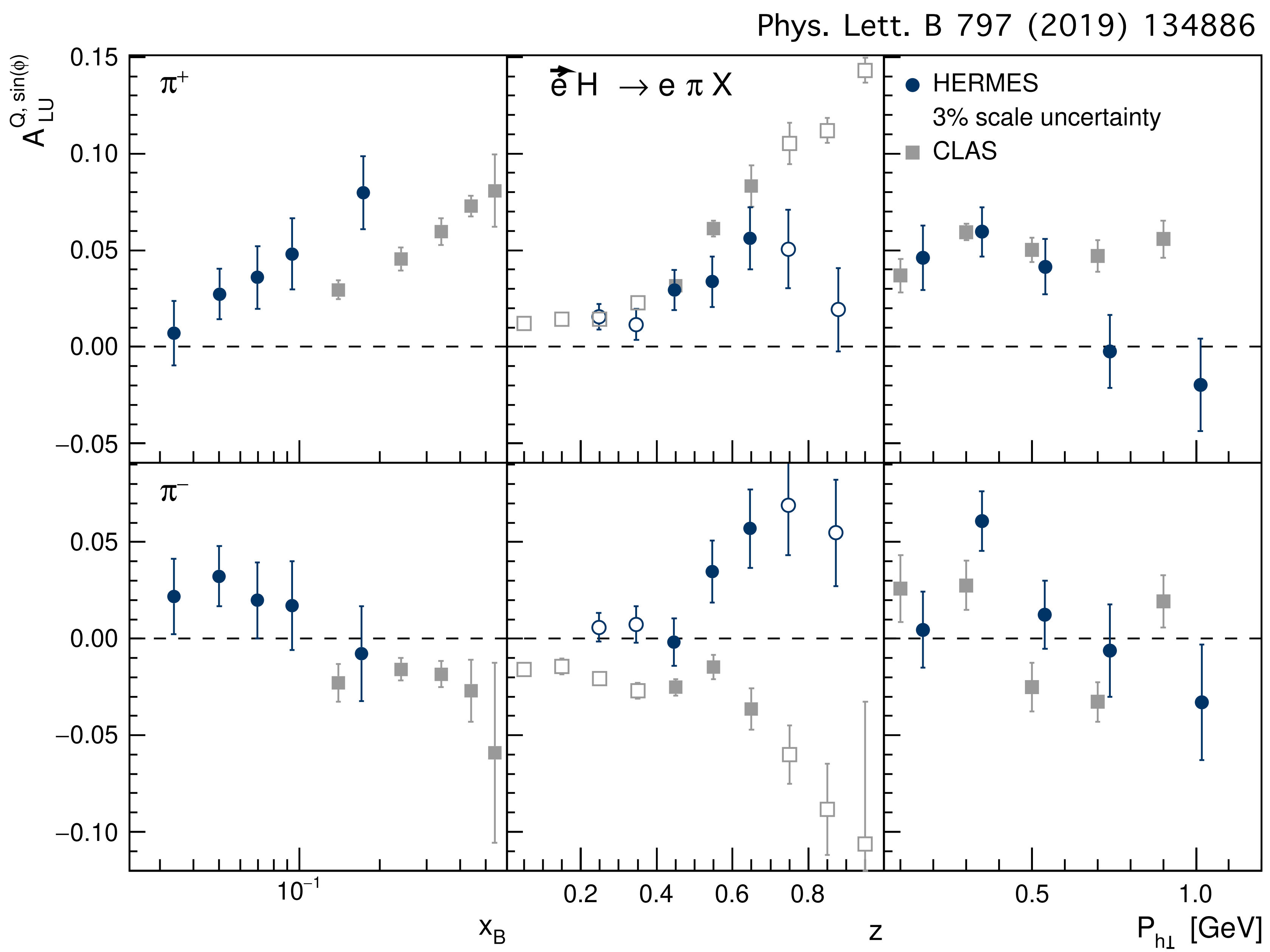


Comparison with COMPASS



Both measurements give compatible results

Comparison with CLAS



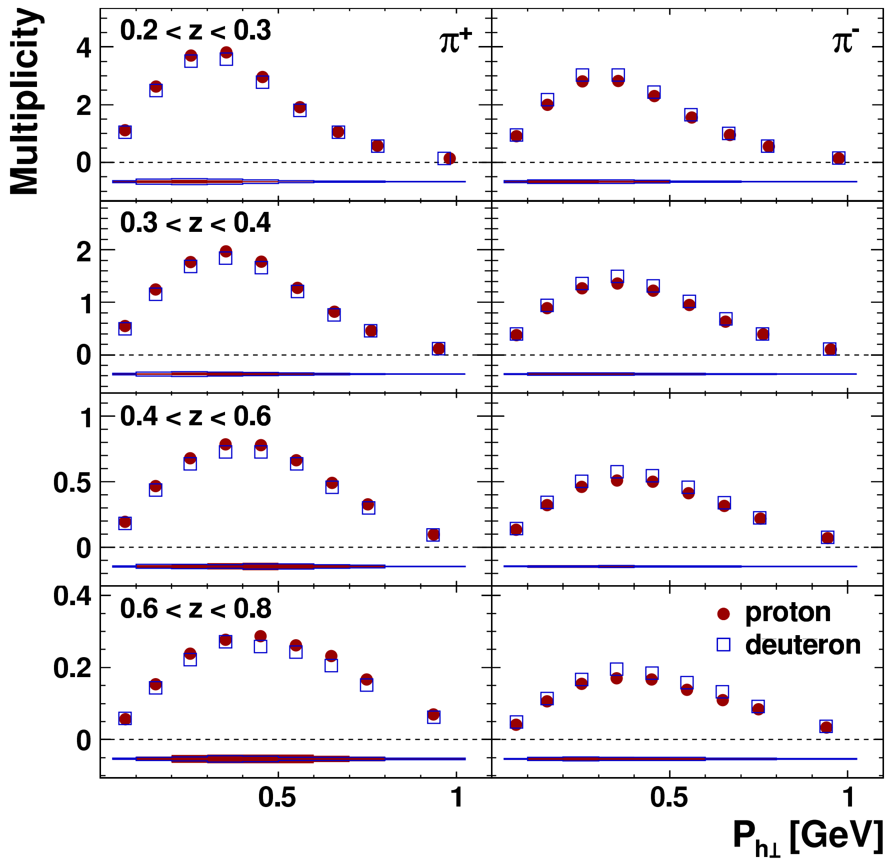
- Opposite behaviour for π^- z projection due to different x range probed
- CLAS probes higher x region: more sensitive to $e \times H_1^{\perp}$?

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

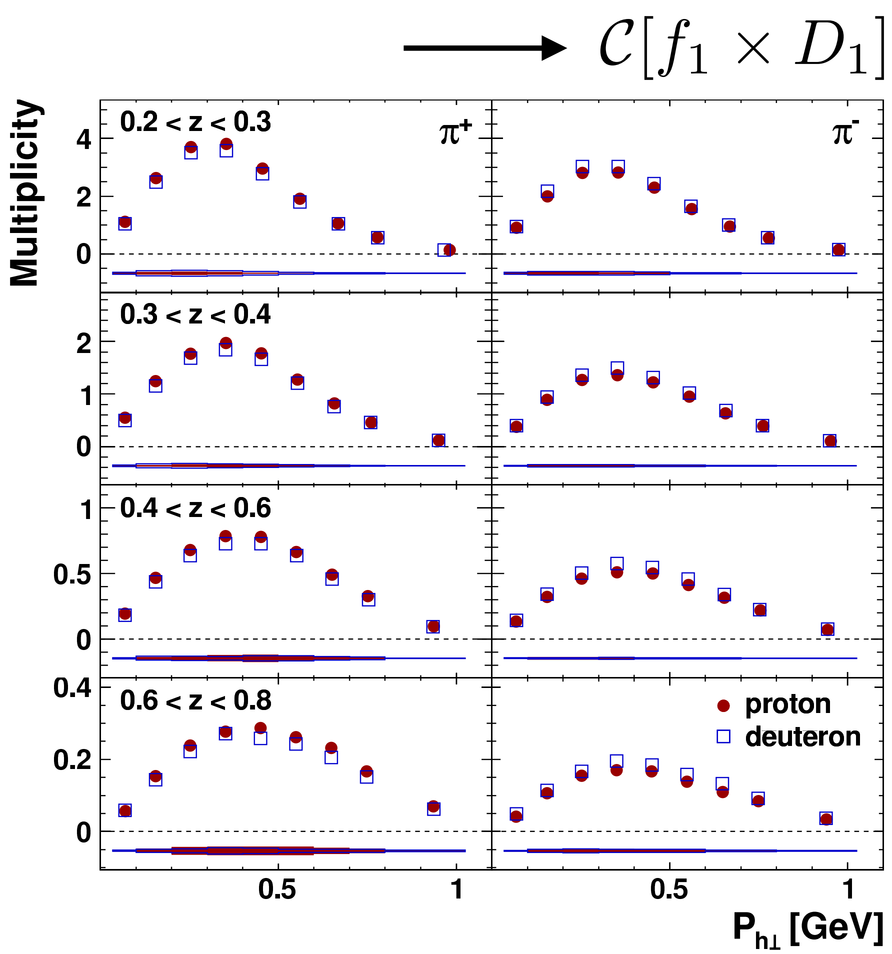
Summary

Summary

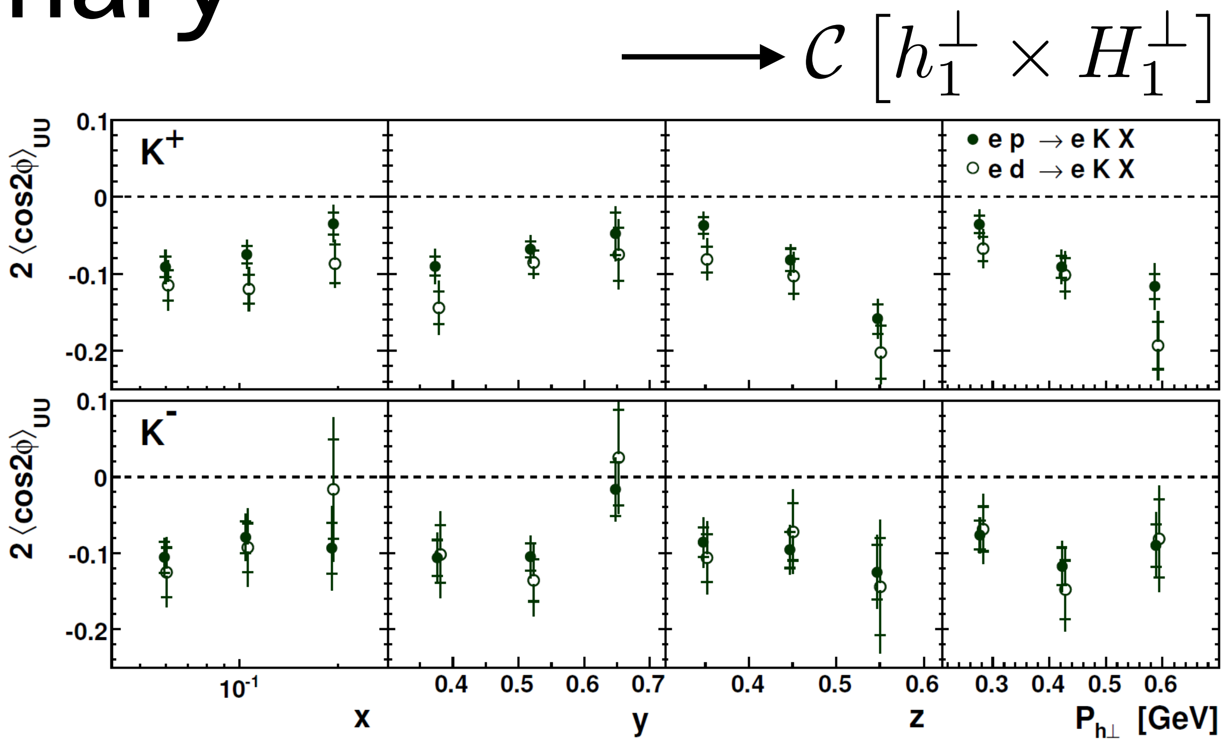
$\longrightarrow \mathcal{C}[f_1 \times D_1]$



Summary



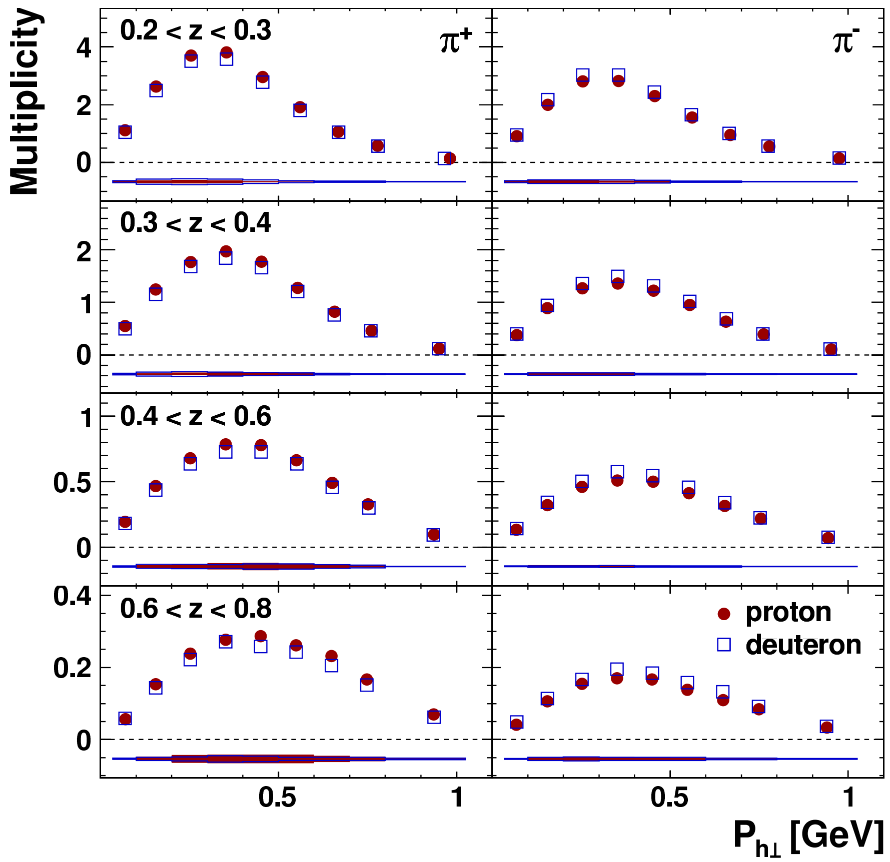
$\longrightarrow \mathcal{C}[f_1 \times D_1]$
Multiplicity
0.2 < z < 0.3
0.3 < z < 0.4
0.4 < z < 0.6
0.6 < z < 0.8
π+
π-
proton
deuteron
P h⊥ [GeV]



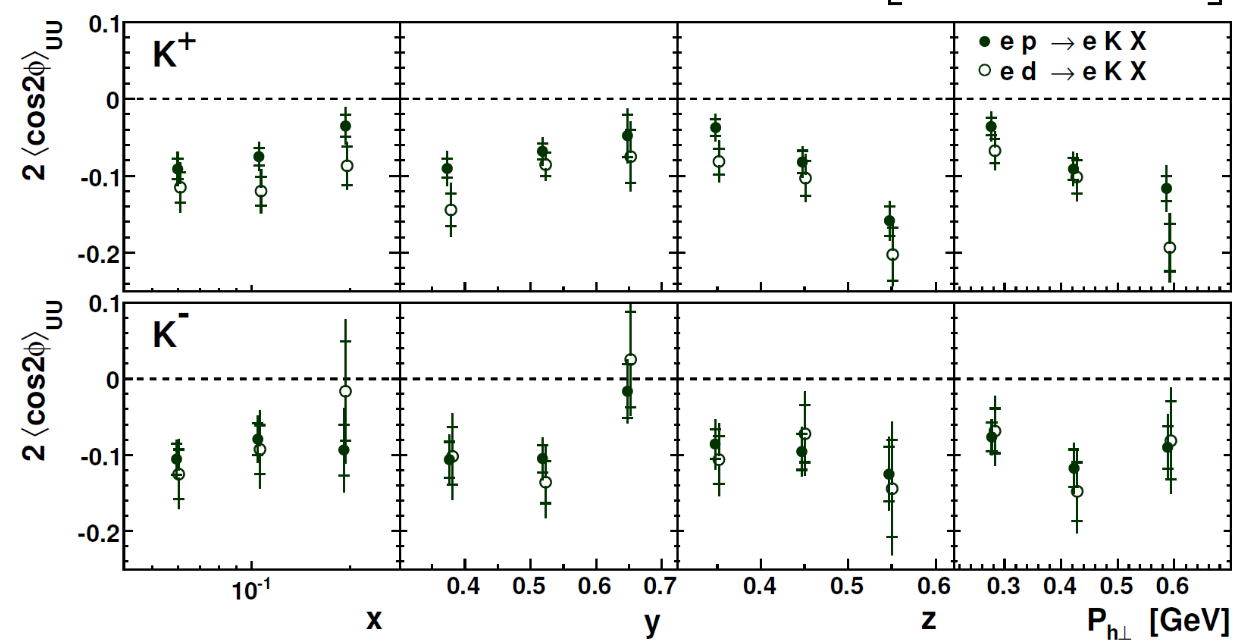
$\longrightarrow \mathcal{C}\left[h_1^\perp \times H_1^\perp\right]$
2 ⟨cos2ϕ⟩ UU
K+
K-
e p → e K X
e d → e K X
x
y
z
P h⊥ [GeV]

Summary

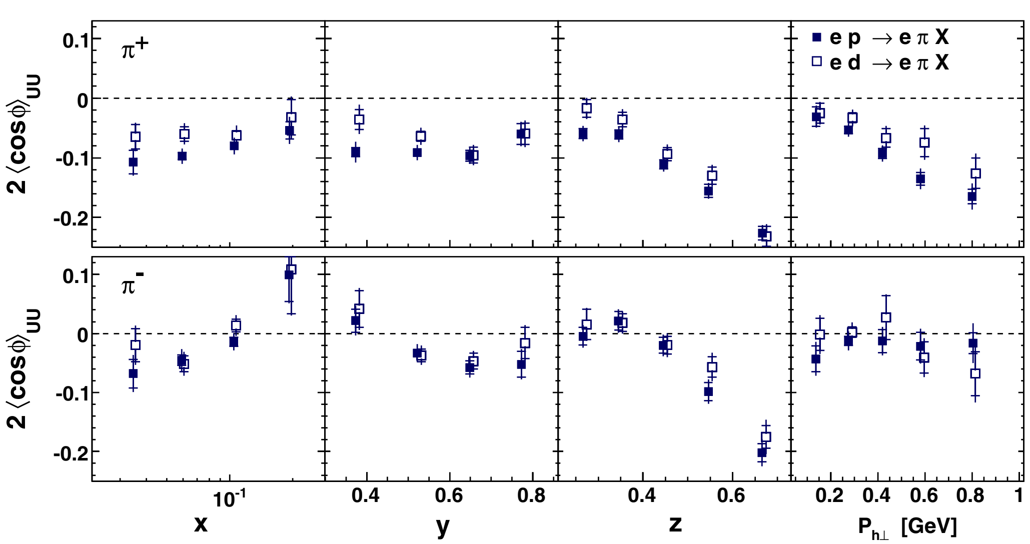
→ $\mathcal{C}[f_1 \times D_1]$



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

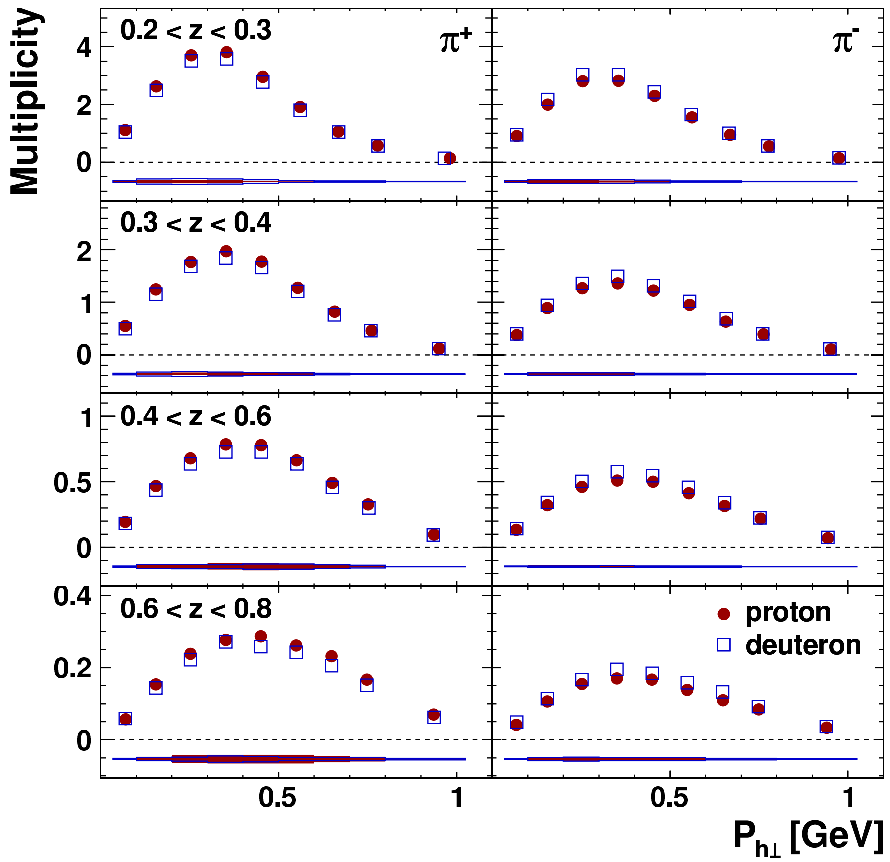


→ twist 3: Cahn effect, $\mathcal{C}\left[h_1^{\perp} \times H_1^{\perp}\right]$

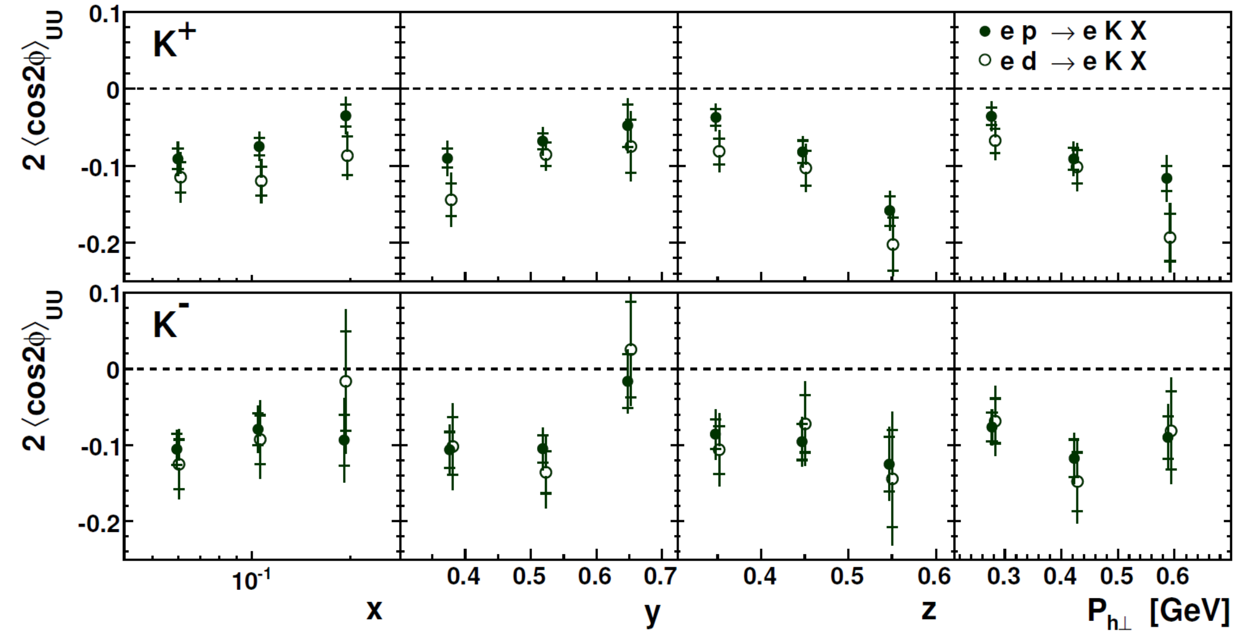


Summary

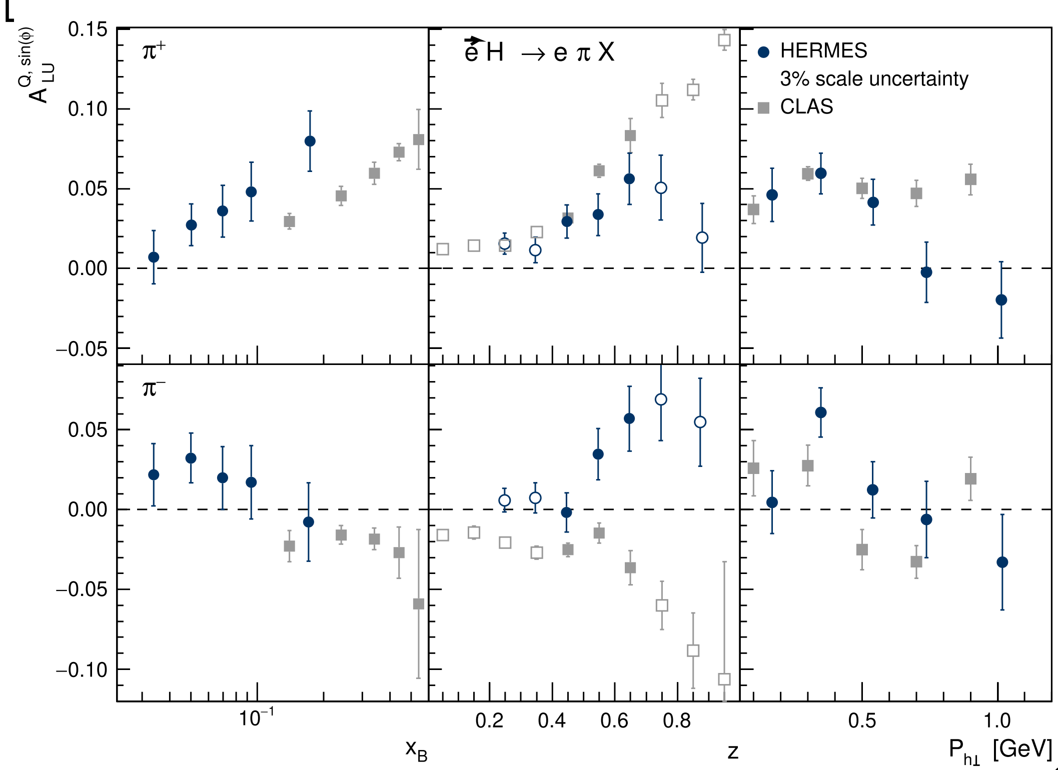
→ $\mathcal{C}[f_1 \times D_1]$



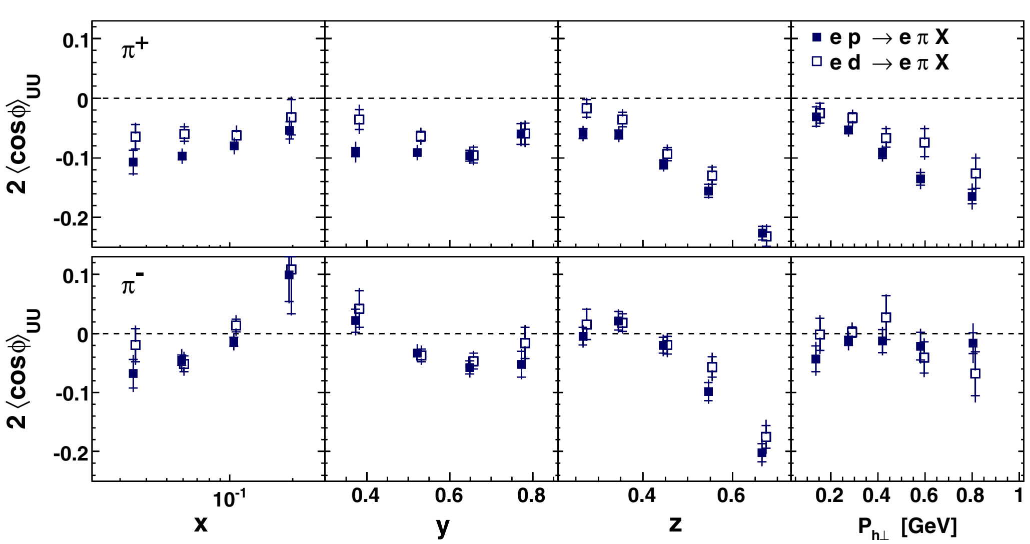
→ $\mathcal{C}\left[h_1^{\perp} \times H_1^{\perp}\right]$



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

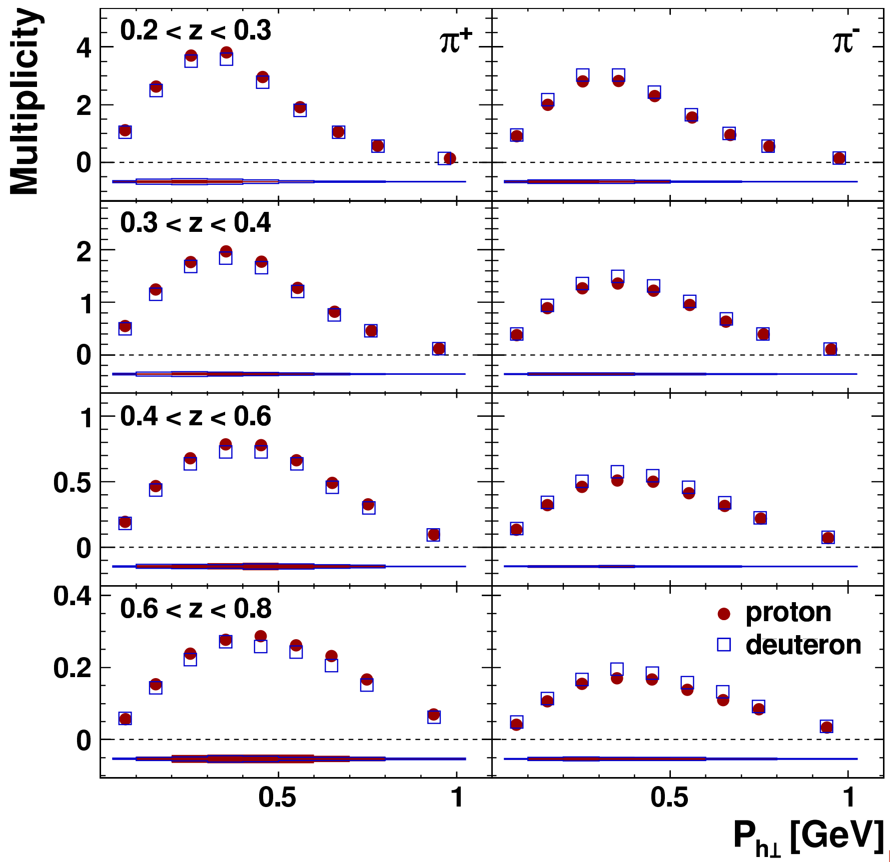


→ twist 3: Cahn effect, $\mathcal{C}\left[h_1^{\perp} \times H_1^{\perp}\right]$

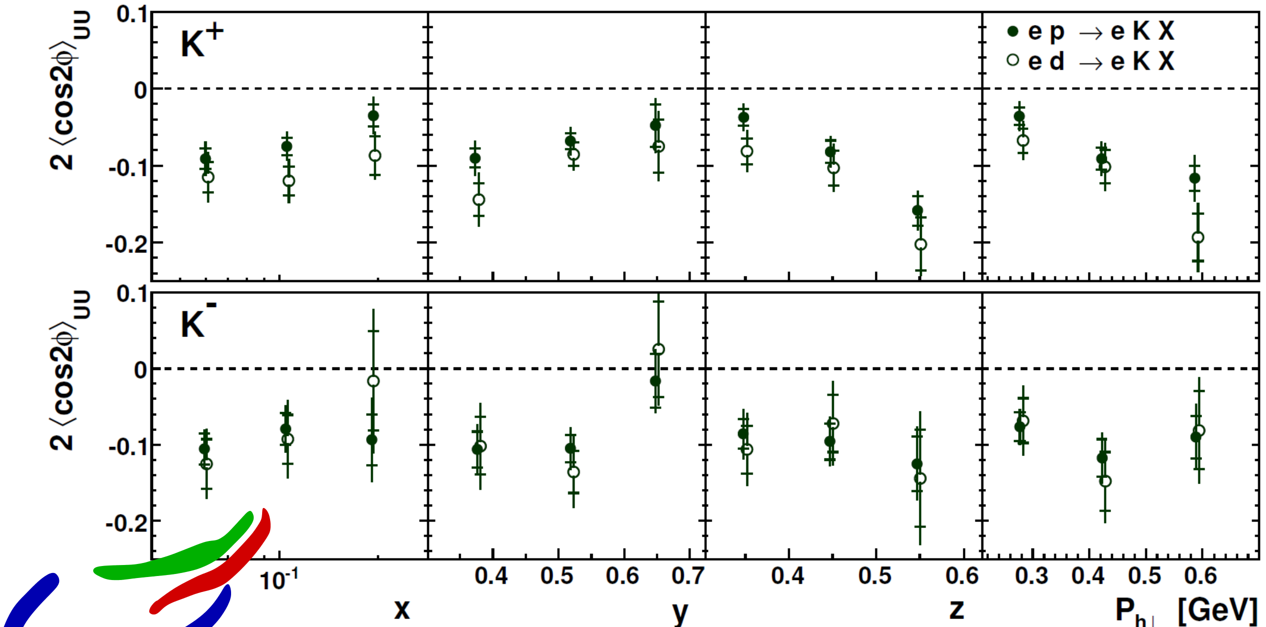


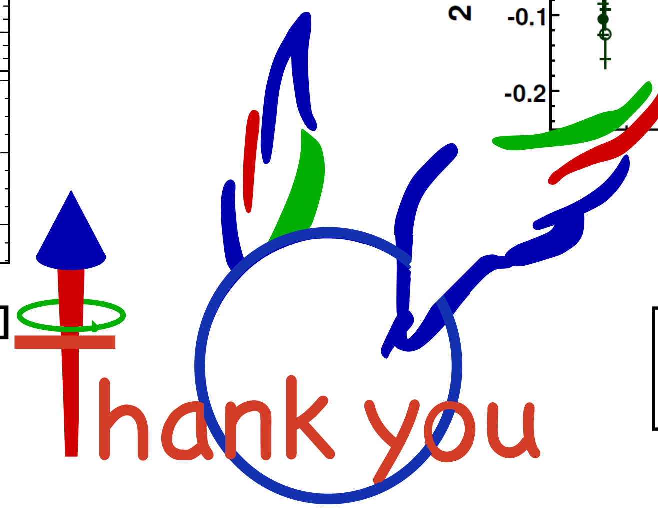
Summary

→ $\mathcal{C}[f_1 \times D_1]$

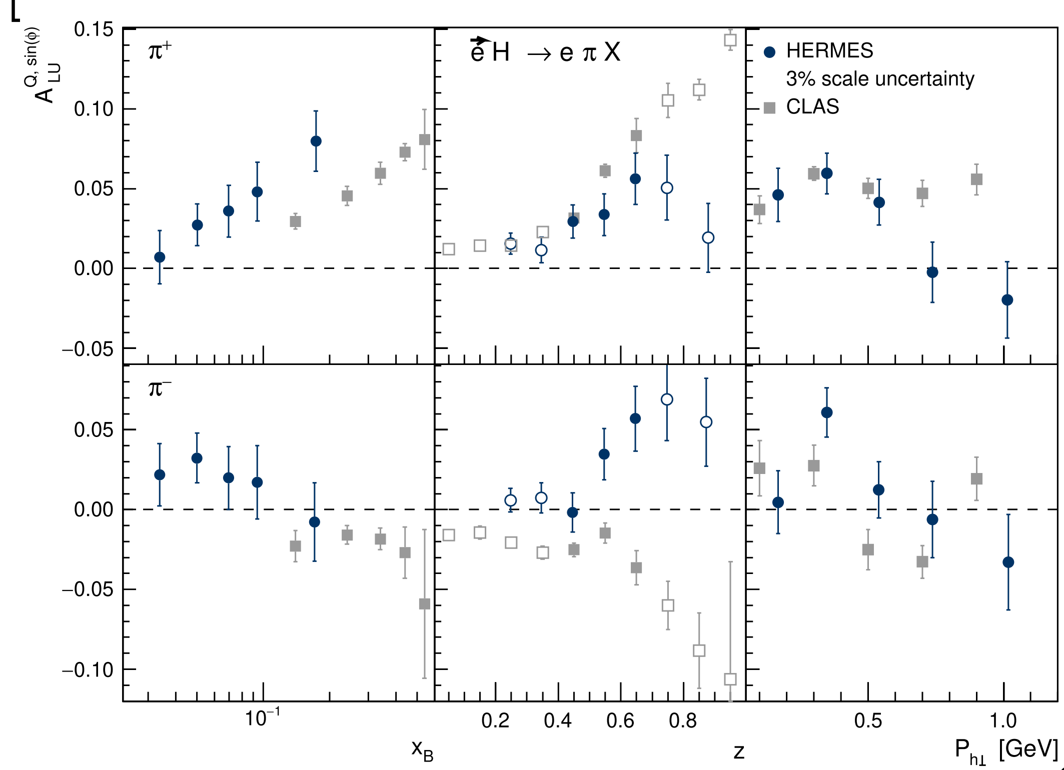


→ $\mathcal{C}\left[h_1^{\perp} \times H_1^{\perp}\right]$

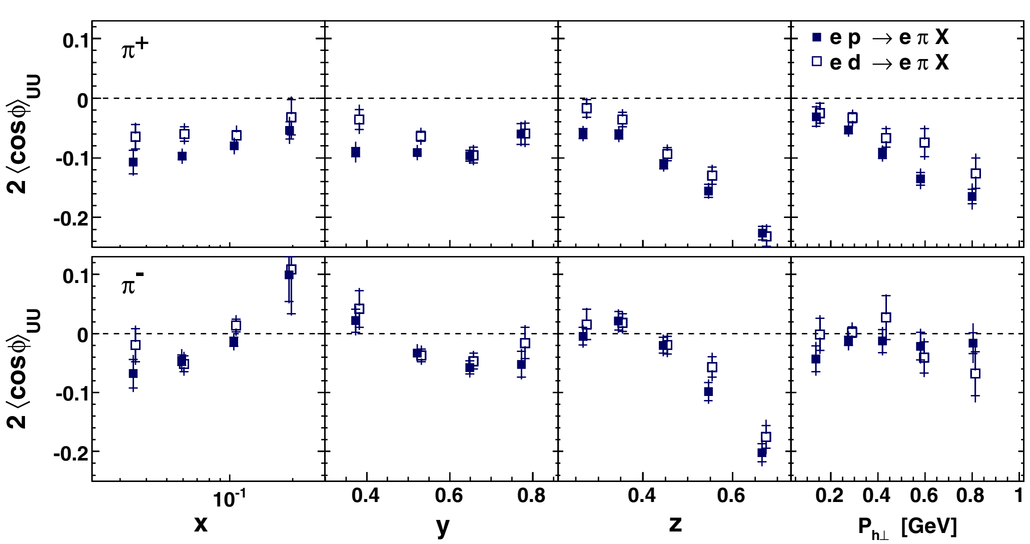




$\left[h_1^{\perp} \times \tilde{E}, e \times H_1^{\perp}, g^{\perp} \times D_1, f_1 \times \tilde{G}^{\perp}\right]$



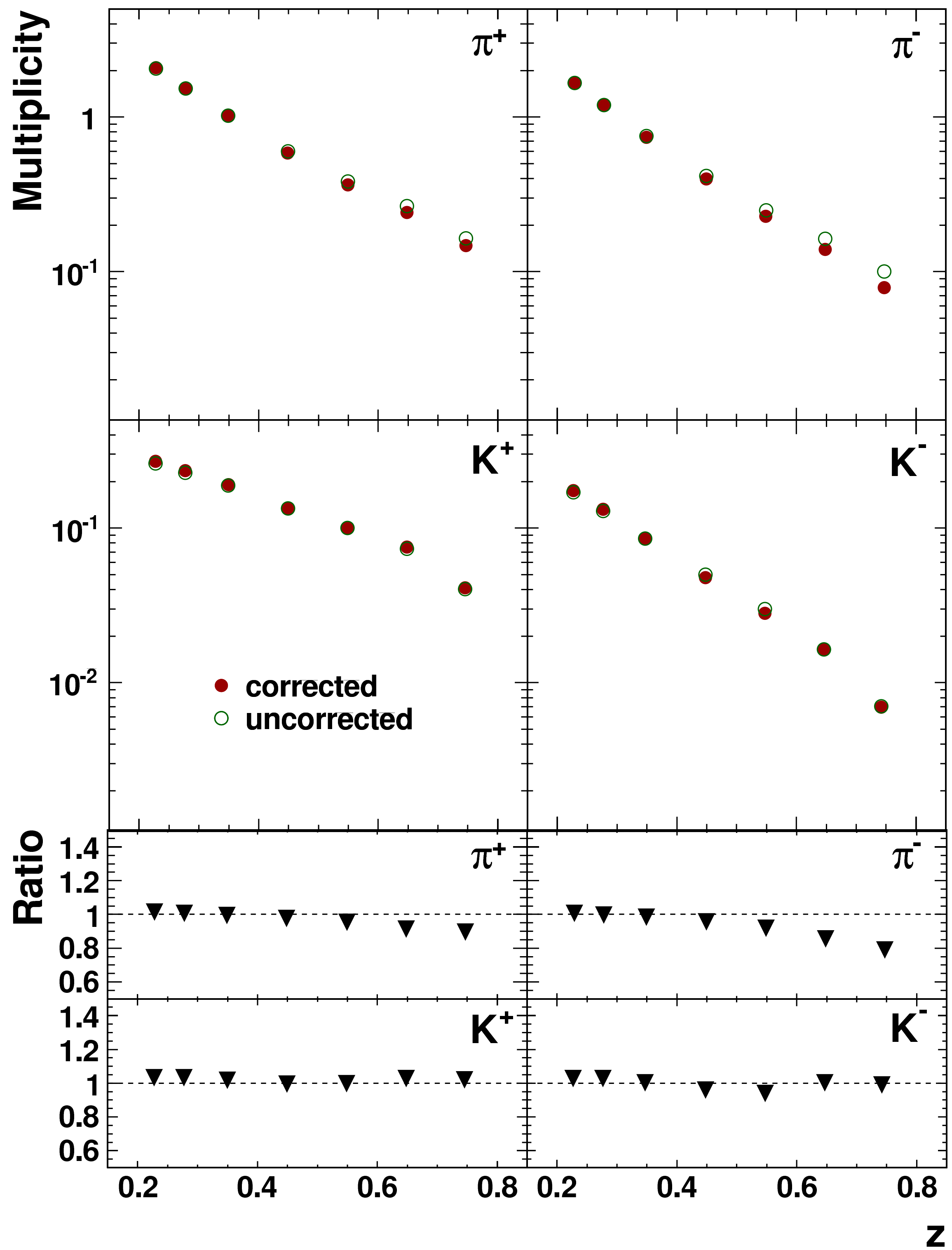
→ twist 3: Cahn effect, $\mathcal{C}\left[h_1^{\perp} \times H_1^{\perp}\right]$



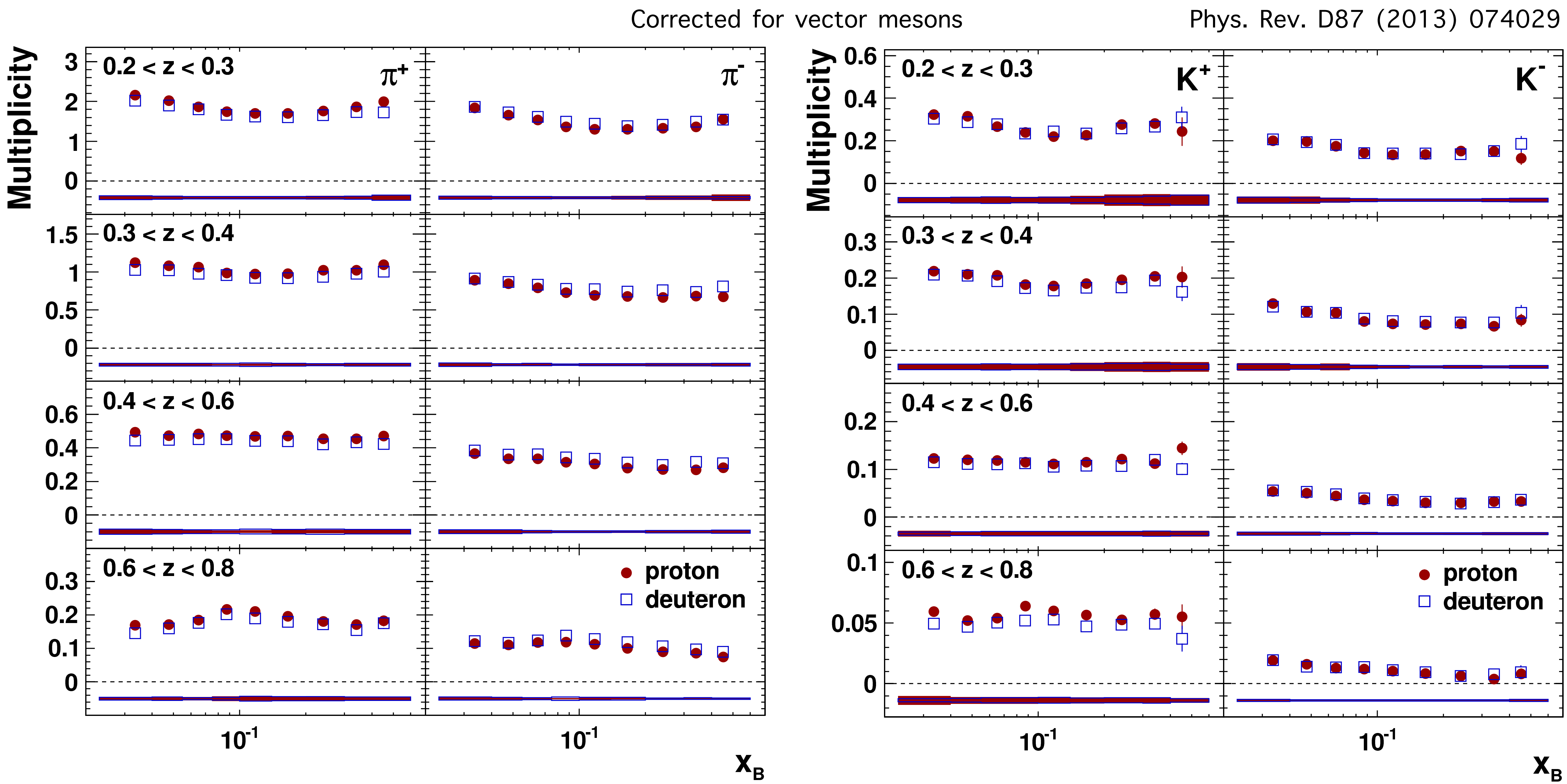
Back up

Correction for vector mesons

Phys. Rev. D87 (2013) 074029



Results projected in z and x

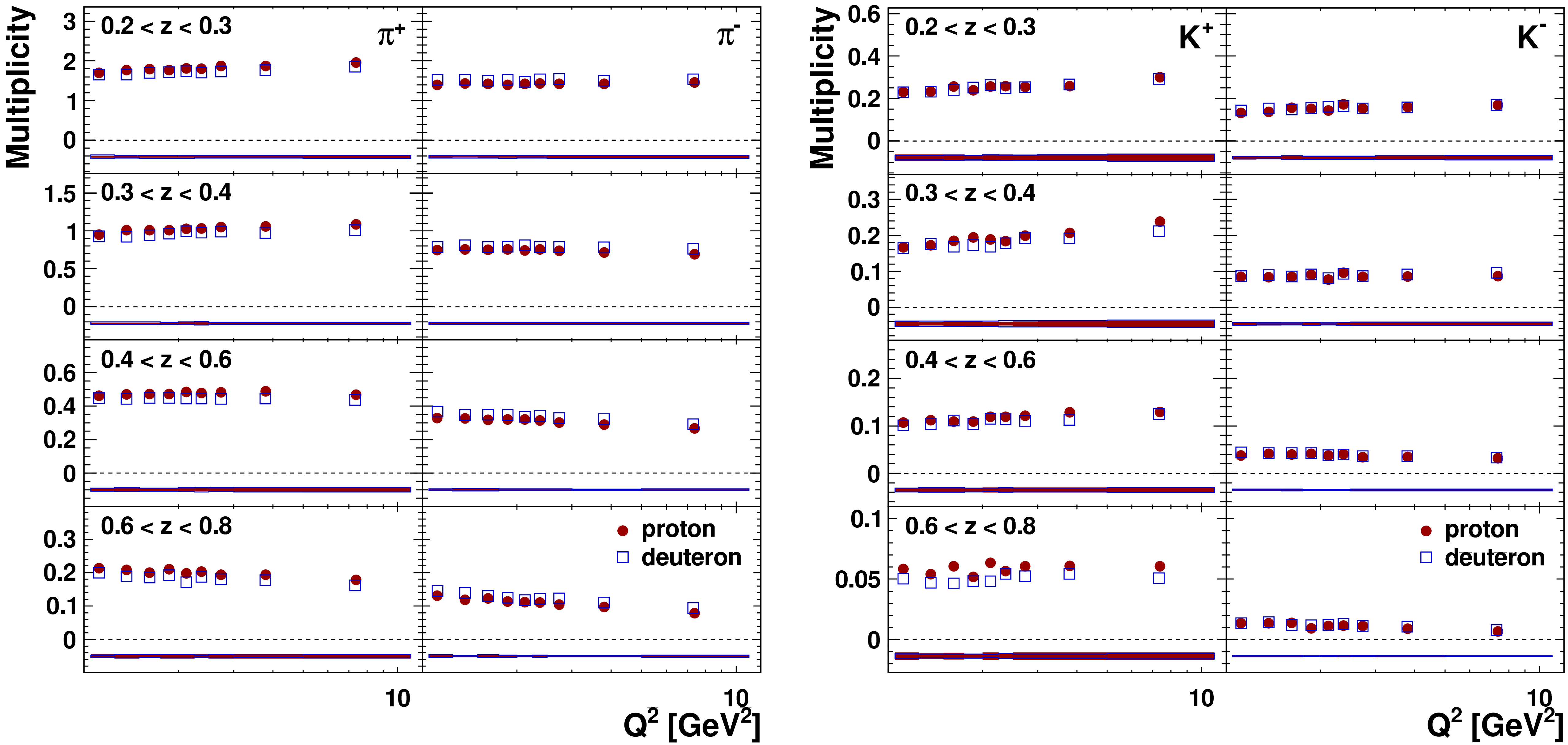


- No strong dependence on x

Results projected in z and Q^2

Corrected for vector mesons

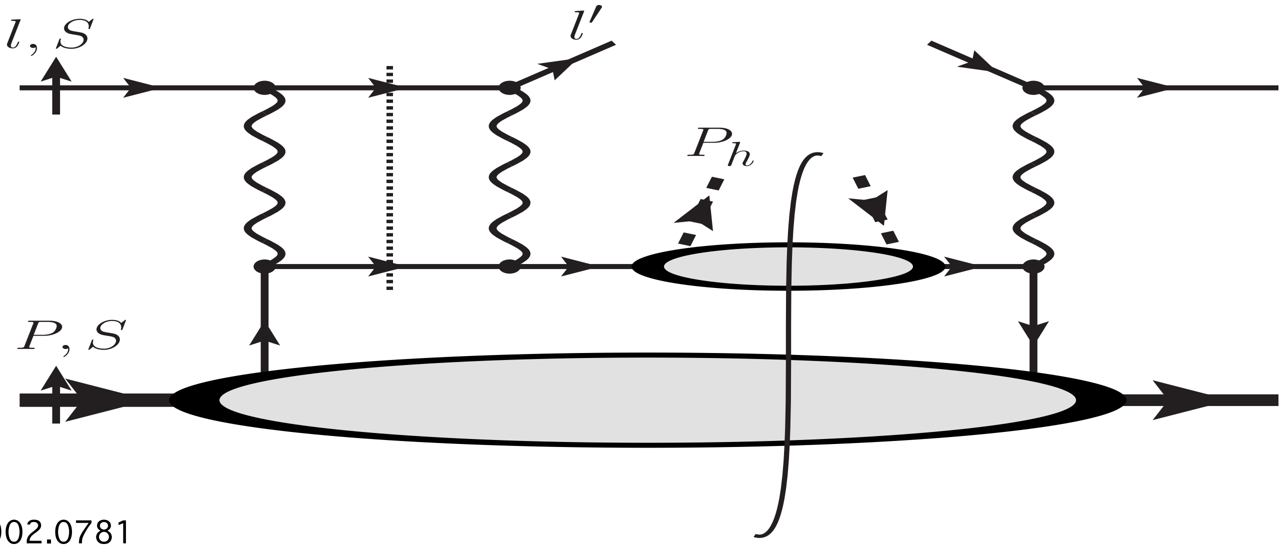
Phys. Rev. D87 (2013) 074029



- 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