HERMES results on TMDs and GPDs

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University of the Basque Country

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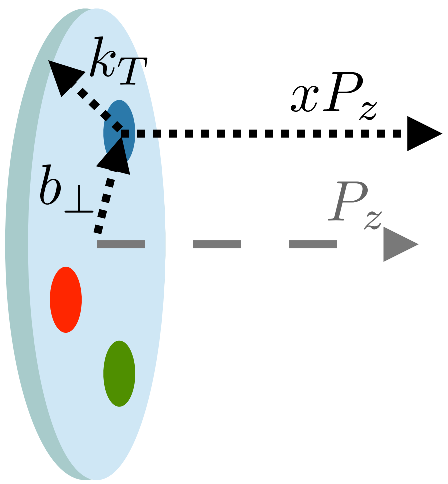
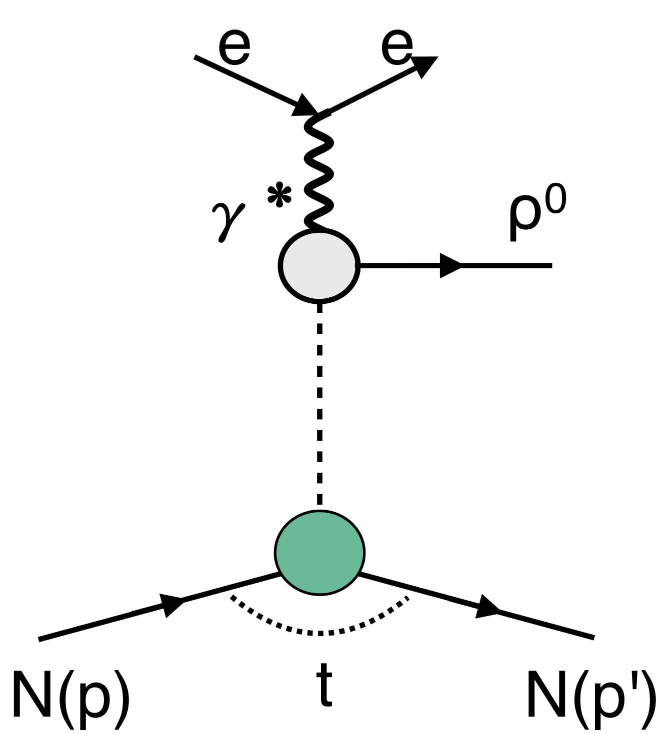
Outline

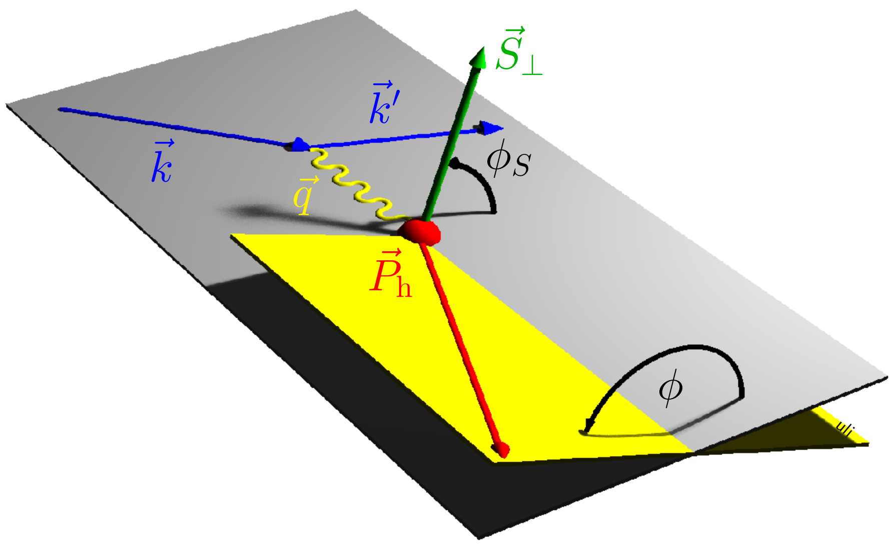


- Helicity amplitude ratios for hard exclusive ρ^0 production
- Spin-asymmetries in semi-inclusive DIS on transversely polarized hydrogen target
- Beam-helicity asymmetry in semi-inclusive DIS on unpolarized hydrogen and deuterium targets

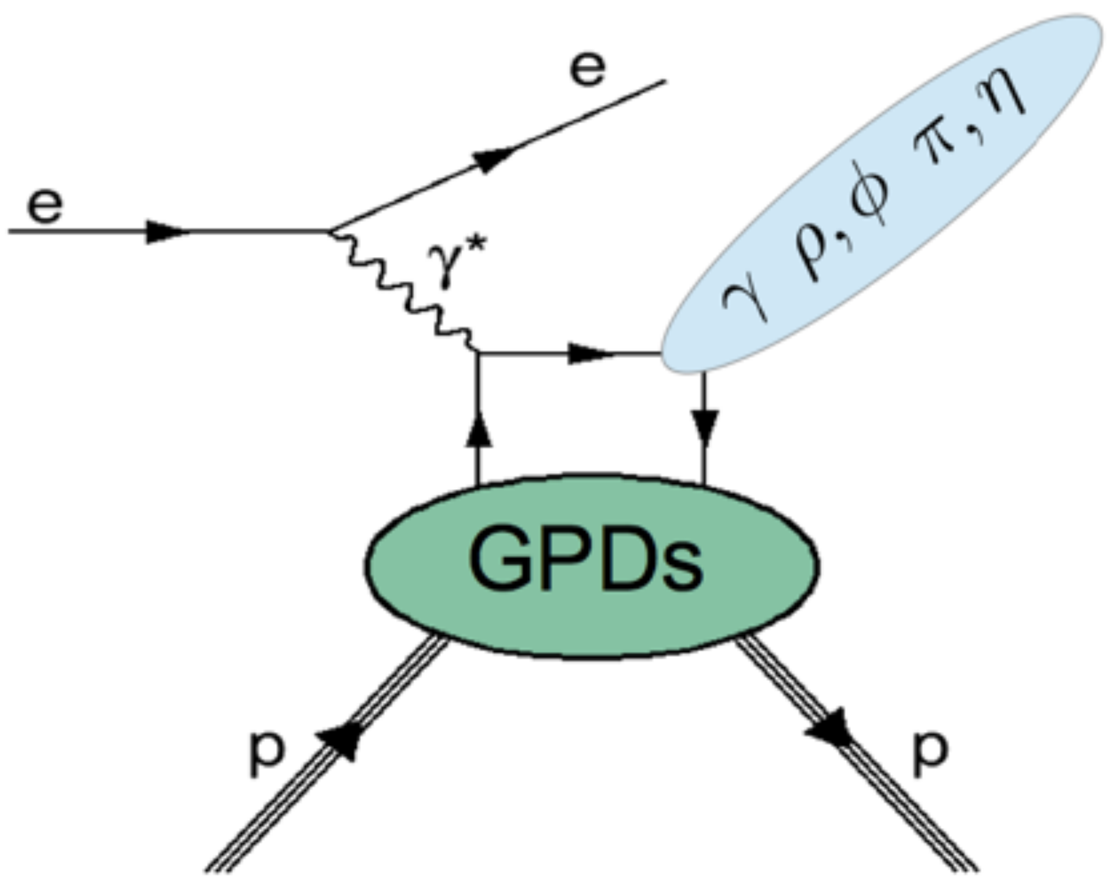
Helicity amplitude ratios for exclusive ρ^0



- transversely polarized H target



Exclusive meson production



Exclusive meson production

- probe various types of GPDs with different sensitivity and different flavour combinations
- complementary to DVCS

Target polarization state

- unpolarized target: nucleon-helicity-non-flip GPDs H, $\tilde{H}$ and $\bar{E}_T = 2H_T + \tilde{E}_T$.
- transversely polarized target: nucleon-helicity-flip GPDs E, $\tilde{E}$ and H_T.

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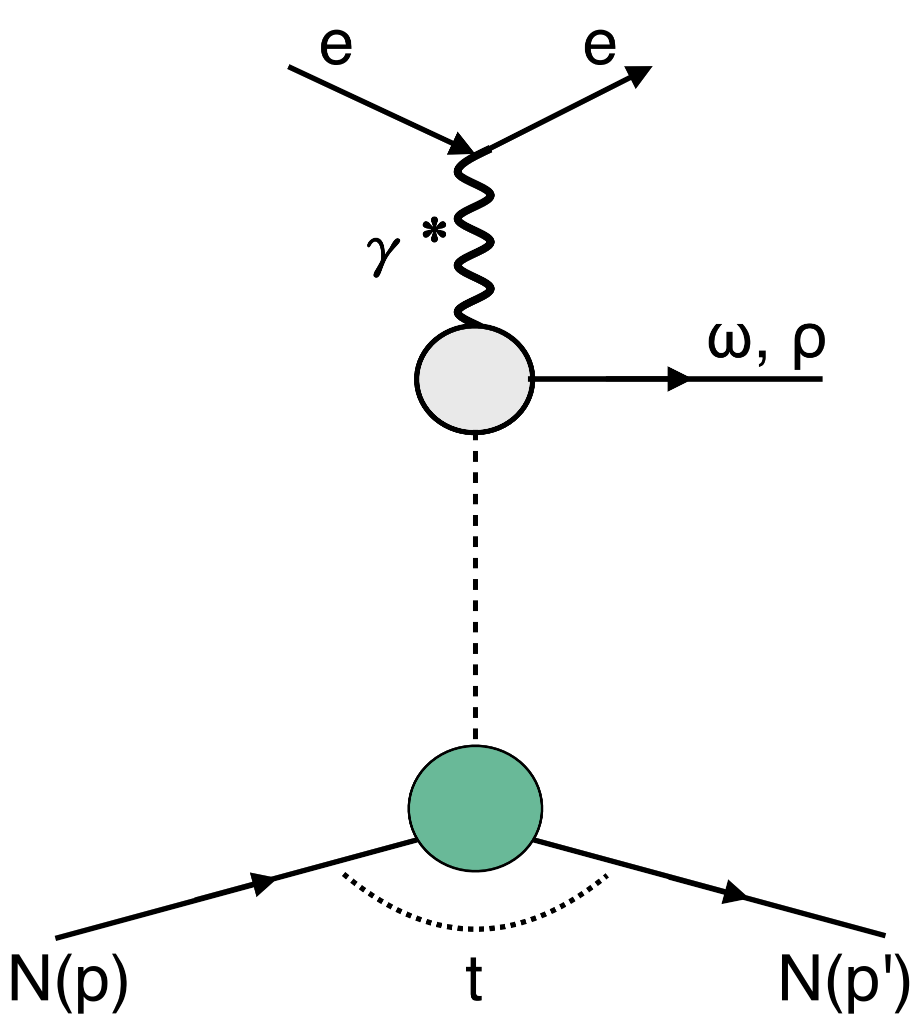

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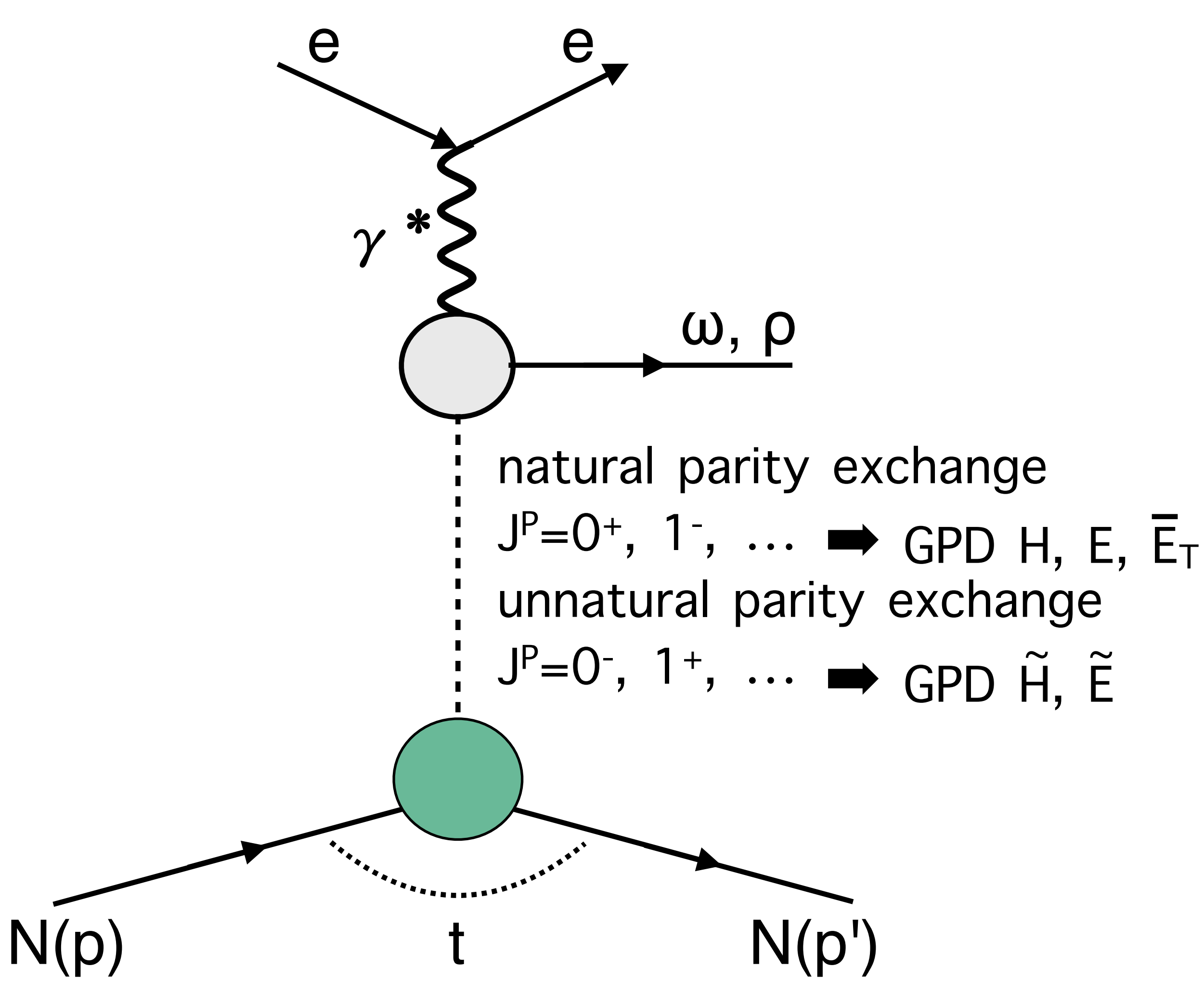

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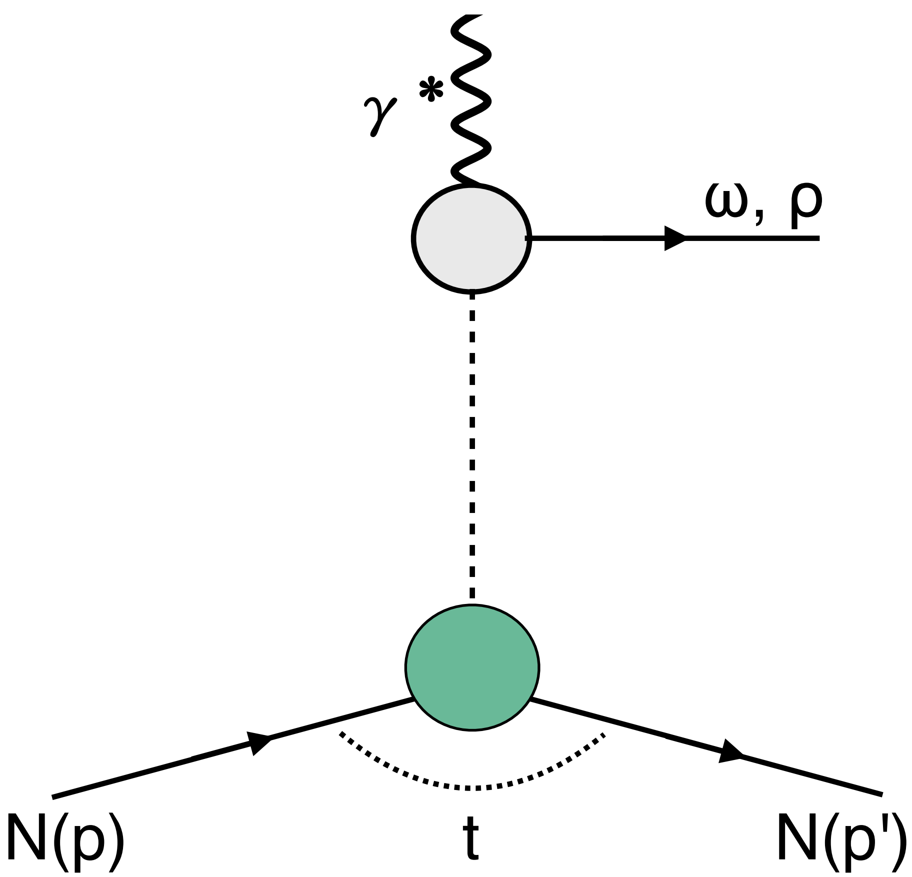
Helicity amplitude ratios and SDMEs

$$\gamma^*(\lambda_\gamma) + N(\lambda_N) \to V(\lambda_V) + N(\lambda'_N)$$



- Helicity amplitude $F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$

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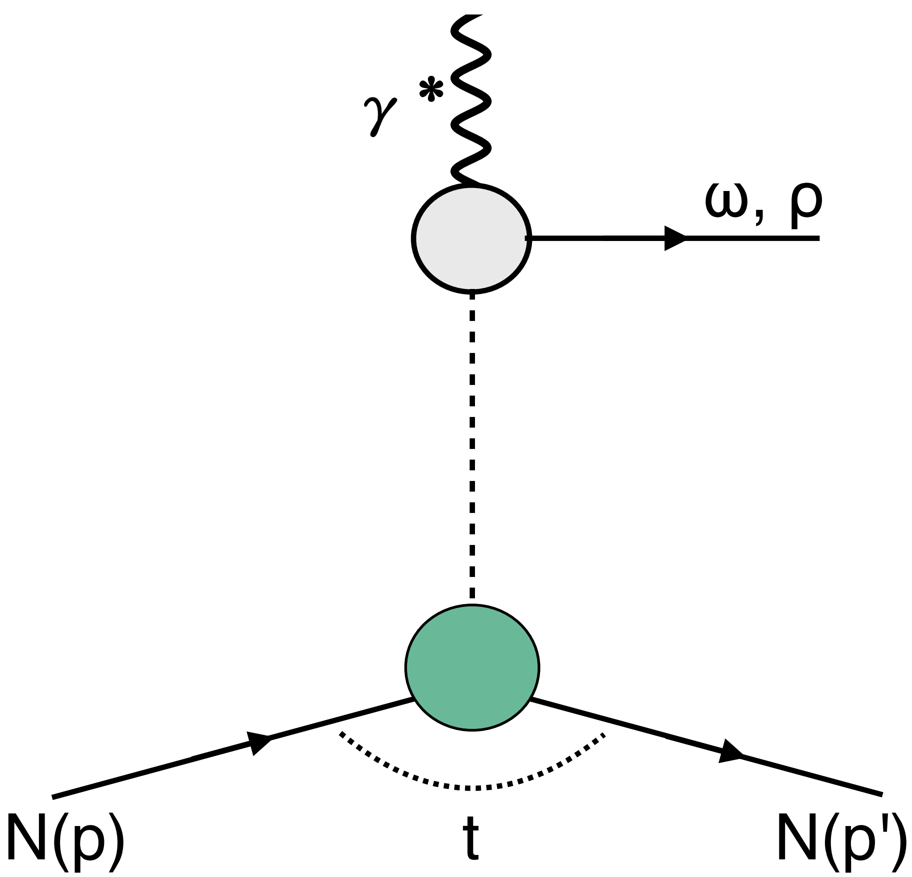

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$$F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} = T_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} + U_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N}$$

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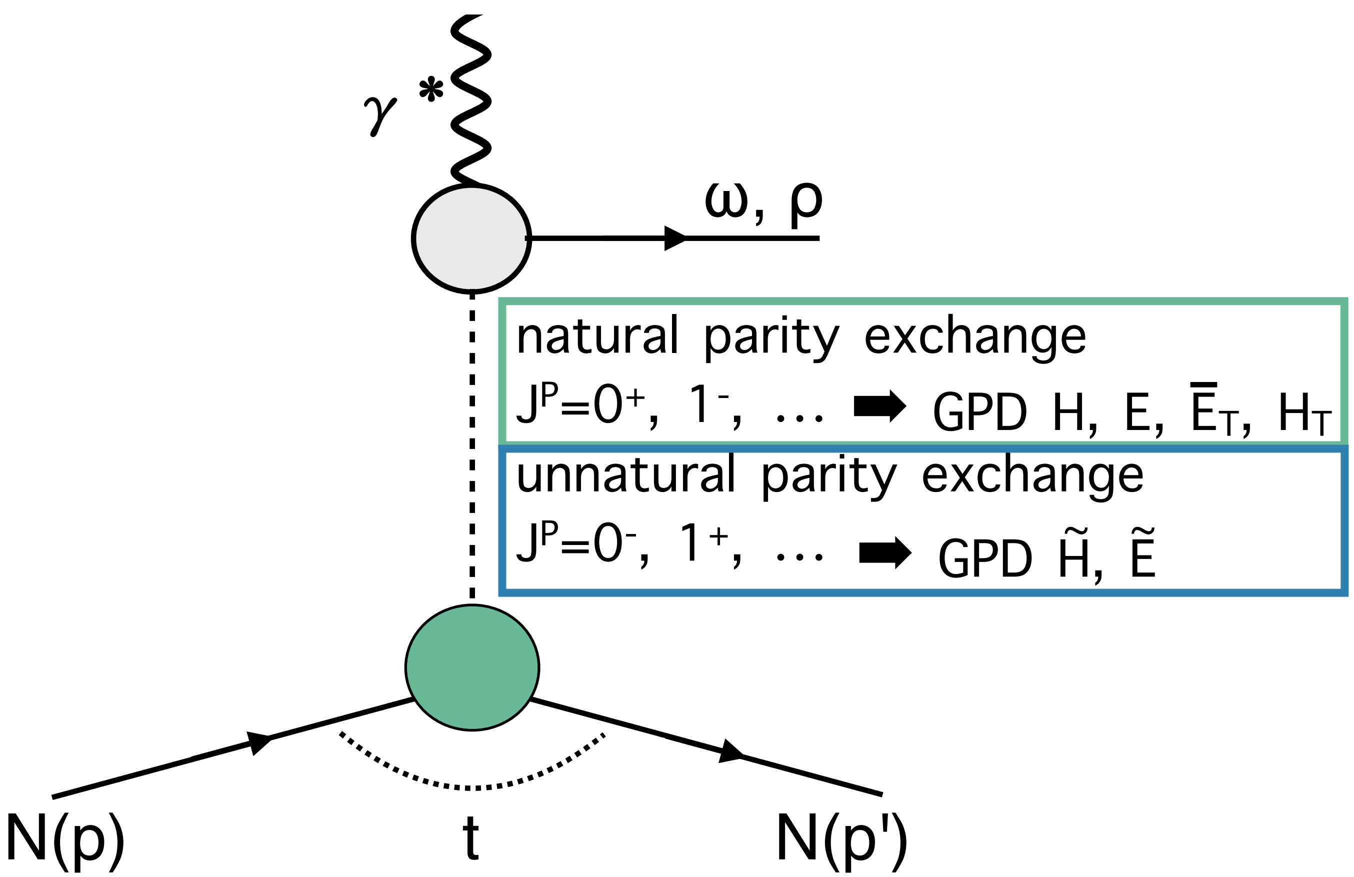

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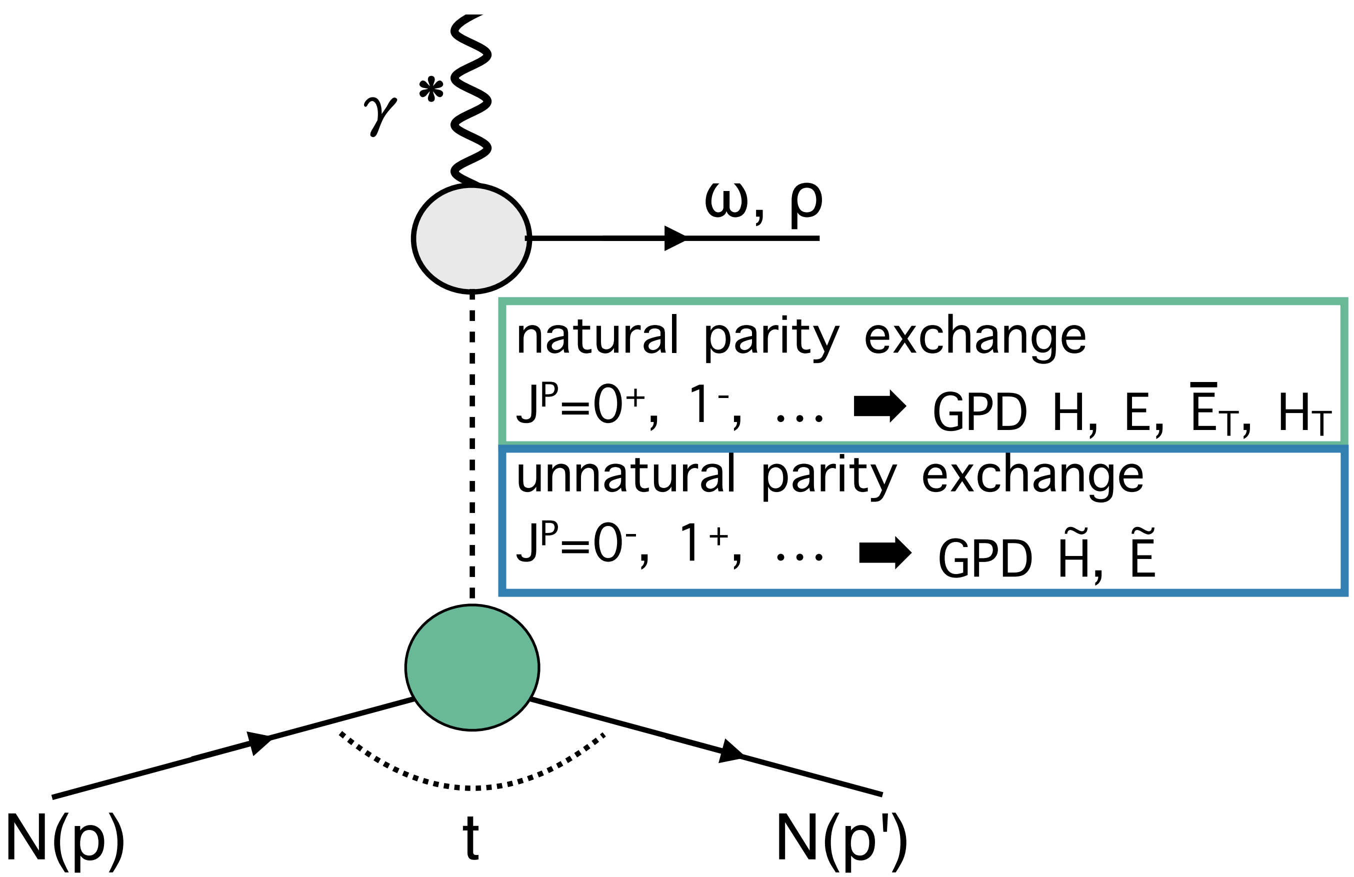

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$$t^{(n)}_{\lambda_V \lambda_\gamma} = T^{(n)}_{\lambda_V \lambda_\gamma} / T_{0\frac{1}{2}0\frac{1}{2}}$$

$$u^{(n)}_{\lambda_V \lambda_\gamma} = U^{(n)}_{\lambda_V \lambda_\gamma} / T_{0\frac{1}{2}0\frac{1}{2}}$$

$$n = 1 \quad \lambda_N = \lambda'_N$$
$$n = 2 \quad \lambda_N \neq \lambda'_N$$

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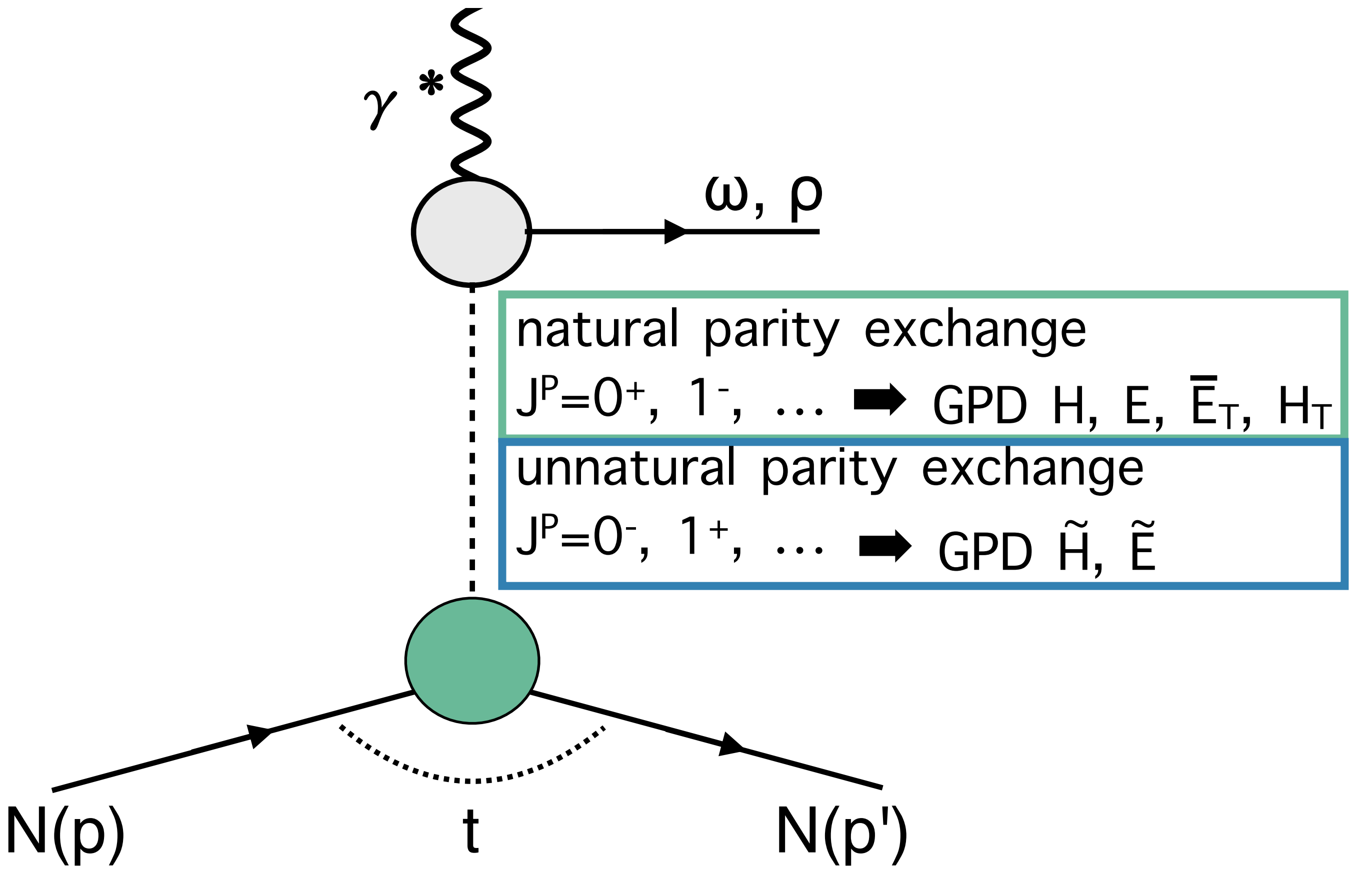

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- SDMEs

$$\propto F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \Sigma^{\alpha}_{\lambda_\gamma \lambda'_\gamma} F^*_{\lambda'_V \lambda'_N \lambda'_\gamma \lambda_N}$$

Exclusive ρ^0 production: angular distribution

$$e + N \rightarrow e + N + \rho^0$$
$$\rho^0 \rightarrow \pi^+ + \pi^-$$

Exclusive ρ⁰ production: angular distribution

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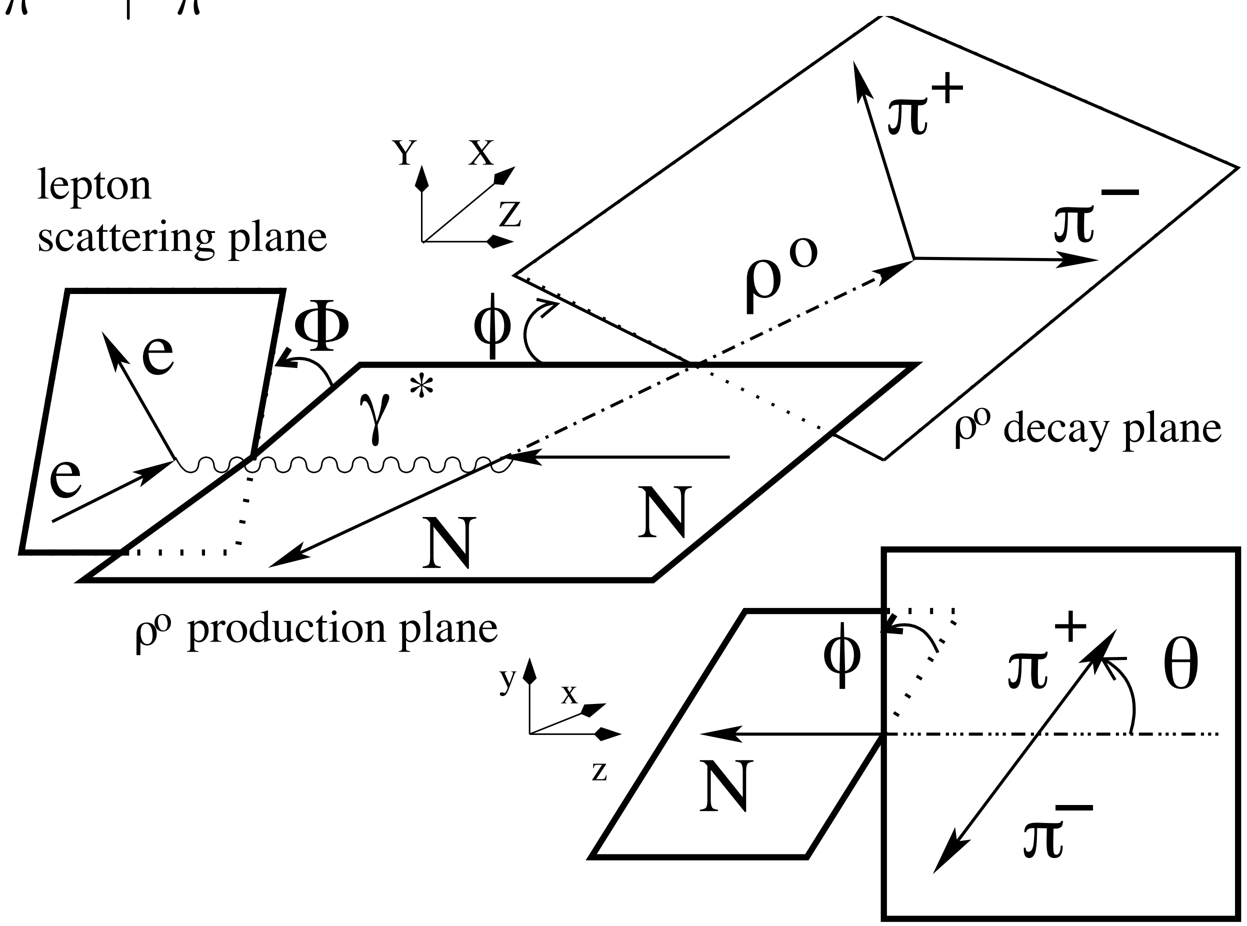


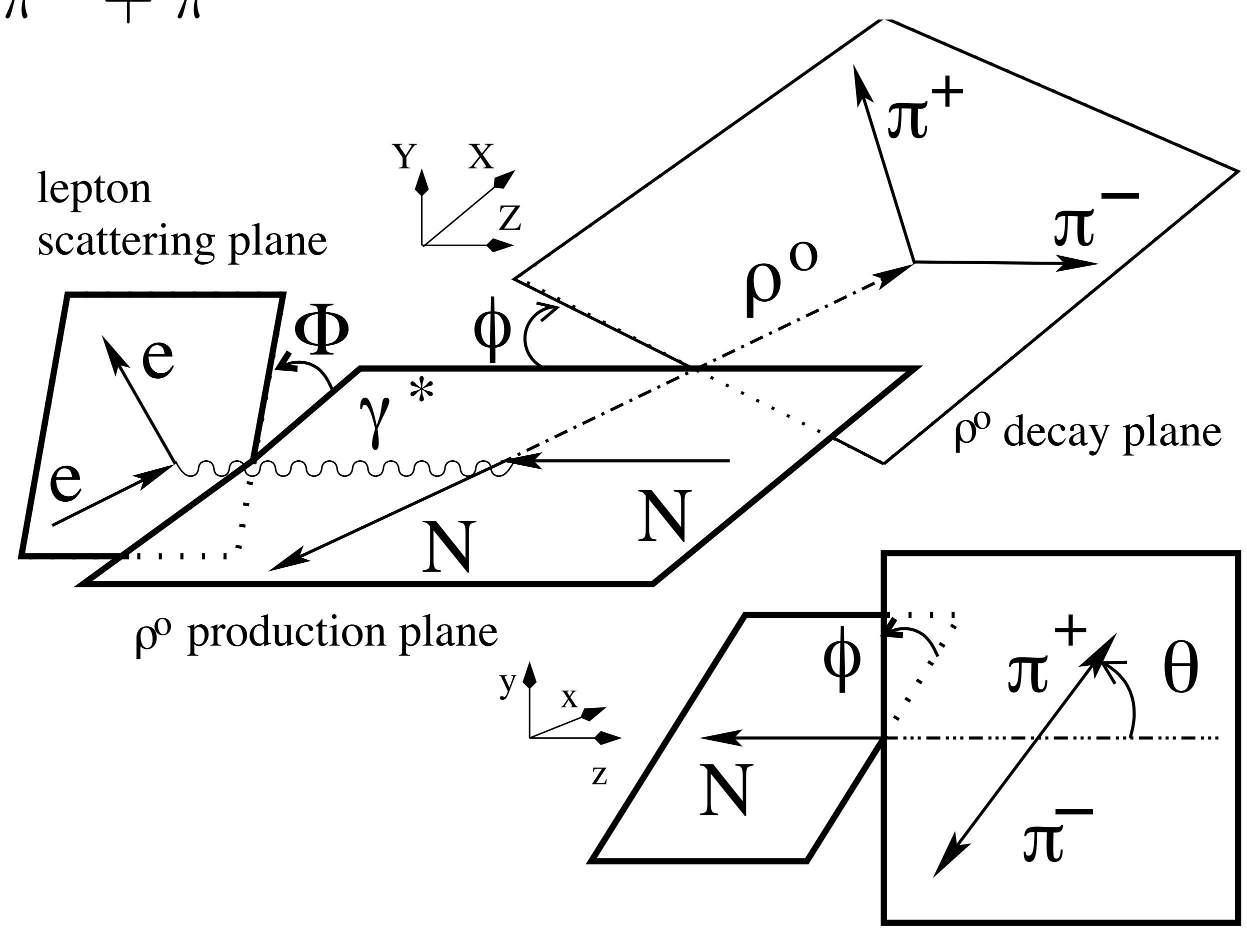
Fit angular distribution of decay pions $\mathcal{W}(\Phi, \phi, \Theta, \Psi)$ and extract either Spin Density Matrix Elements (SDMEs) or helicity amplitude ratios

Exclusive ρ^0 production: angular distribution

$$e + N \to e + \cancel{N} + \rho^0$$
$$\rho^0 \to \pi^+ + \pi^-$$

- transversely polarized H target
- longitudinally polarized $e^{\pm}$
- 8741 hard exclusive ρ^0 events

$$\boxed{\begin{aligned} 3.0\ \mathrm{GeV} &\le W \le 6.3\ \mathrm{GeV} \\ 1.0\ \mathrm{GeV}^2 &\le Q^2 \le 7.0\ \mathrm{GeV}^2 \\ 0.0\ \mathrm{GeV}^2 &\le -t' \le 0.4\ \mathrm{GeV}^2 \end{aligned}}$$



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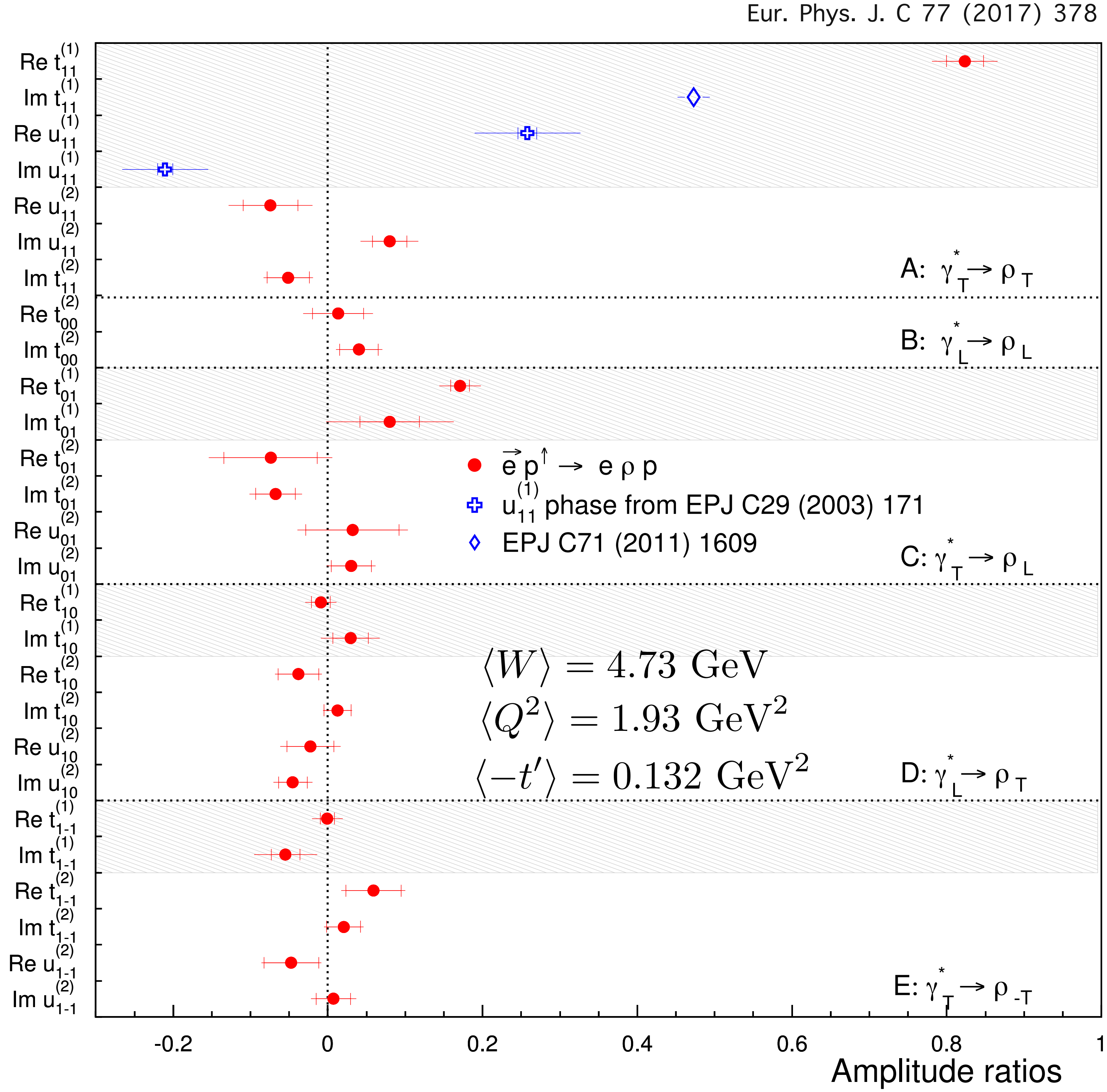
Results helicity ρ^0 amplitude ratios



8% uncertainty target polarization
2% uncertainty beam polarization

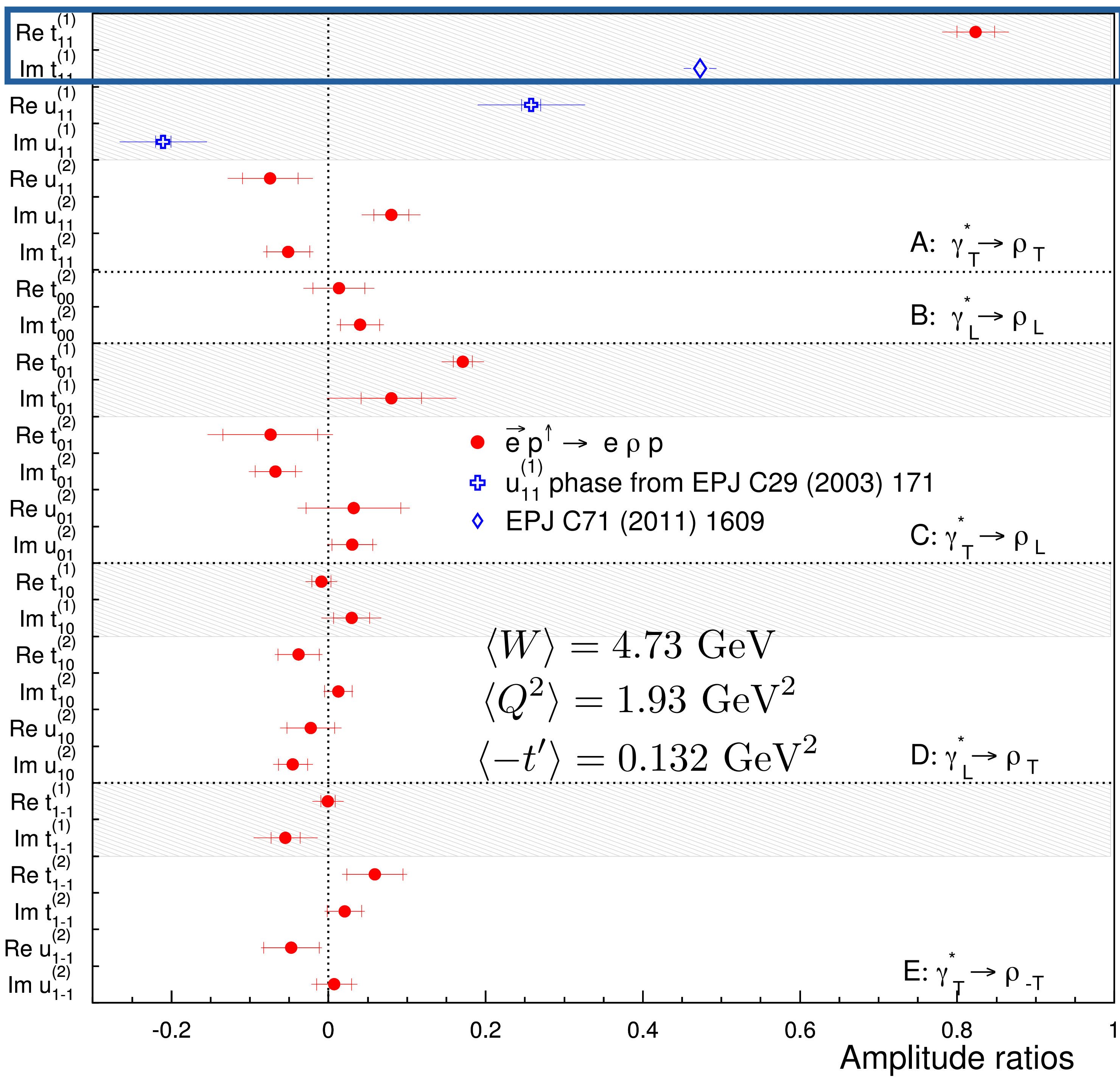
already obtained in EPJ C71 (2011) 1609

extracted for first time

- 5 classes of helicity amplitude ratios

Results helicity ρ^0 amplitude ratios

Eur. Phys. J. C 77 (2017) 378



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- dominant amplitude: natural parity nucleon-helicity non-flip $t_{11}^{(1)}$ (≠0 by >5σ)

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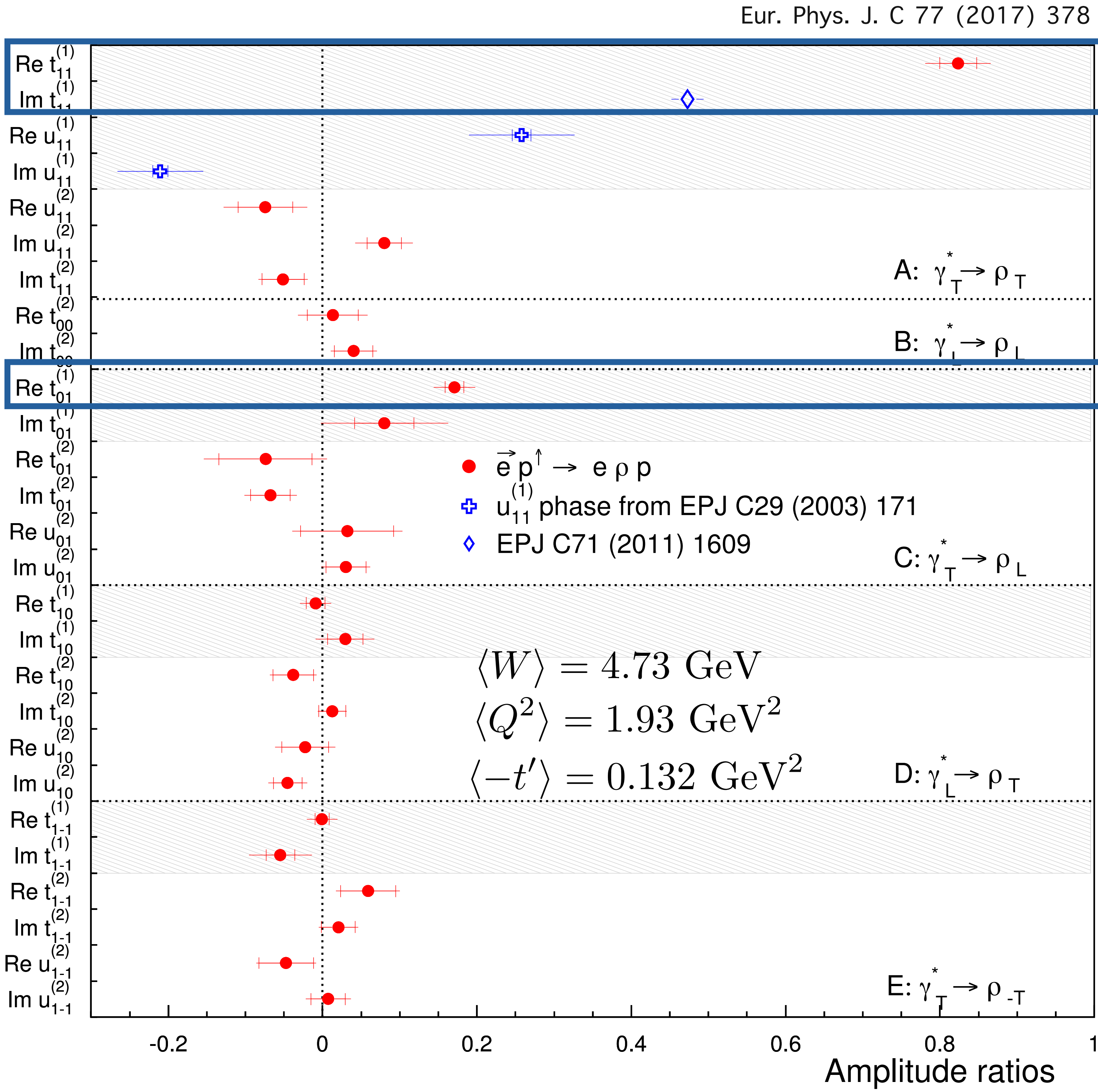

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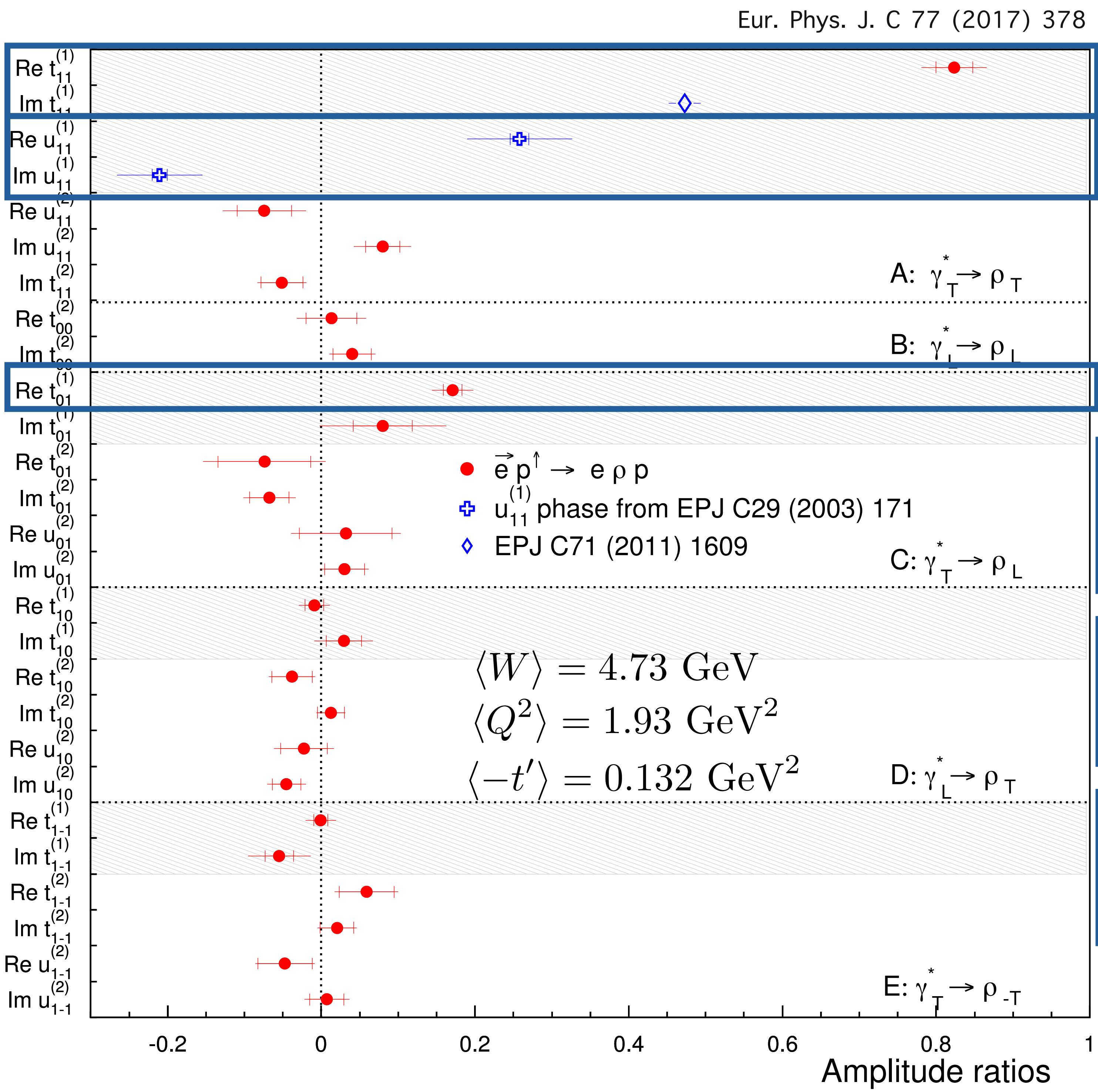

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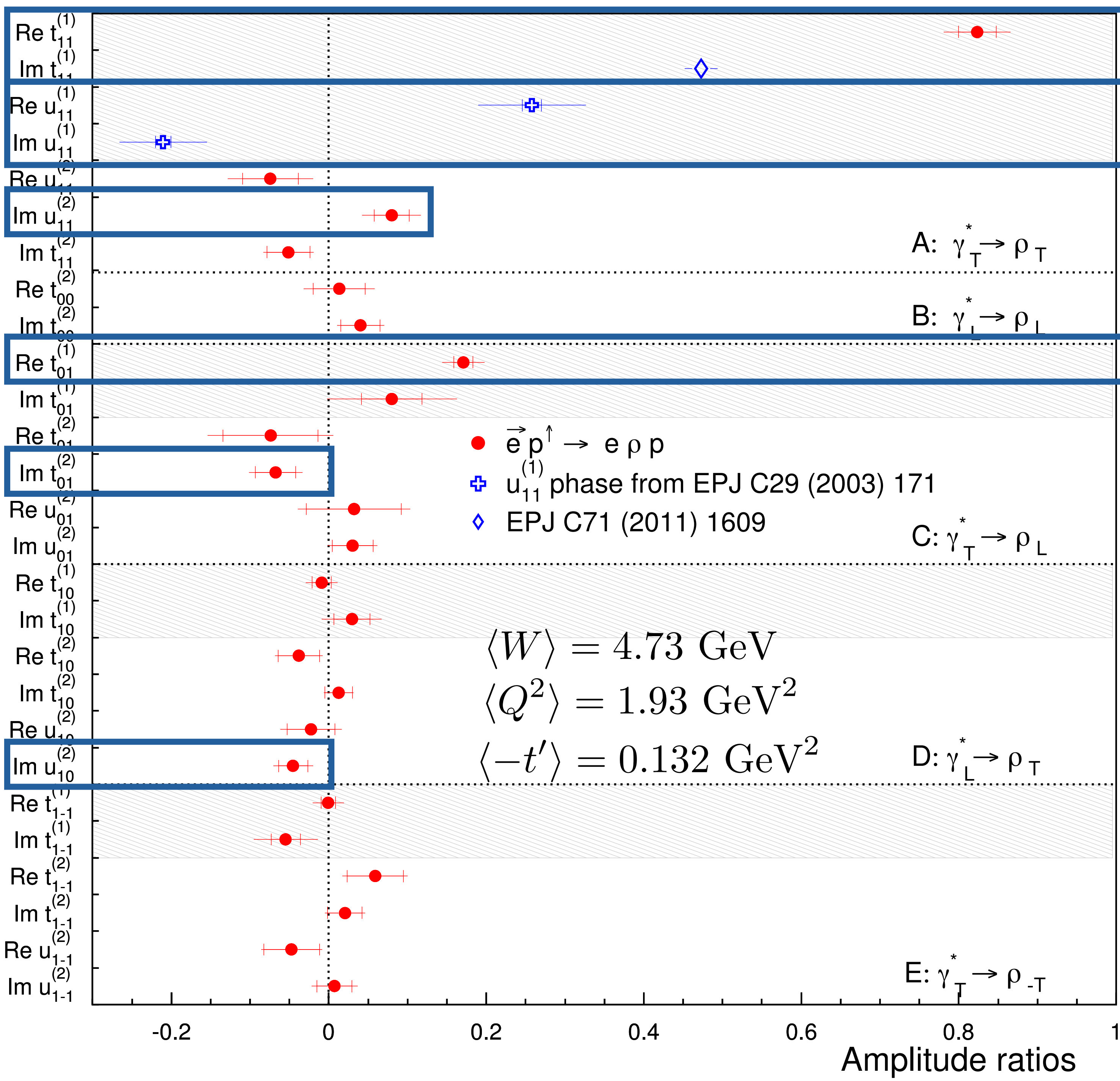

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- nucleon-helicity flip $\Im\, t_{01}^{(2)}, \Im\, u_{11}^{(2)}, \Im\, u_{10}^{(2)}$ ≠ 0 by 2σ

8% uncertainty target polarization
2% uncertainty beam polarization

GK model

model for protons - S. Goloskokov and P. Kroll,
Eur. Phys. J. C 50 (2007) 829; 53 (2008) 367, Eur. Phys. J. A 50 (2014) 146

$$F_{\lambda_V \frac{1}{2} \lambda_\gamma = \lambda_V \frac{1}{2}} \propto \sum_{q,g} \mathcal{I} \left[\mathcal{A} \times \left(H^a, \frac{\xi^2}{1-\xi^2} E^a \right) + \mathcal{A}' \times \left(\tilde{H}^a, \frac{\xi^2}{1-\xi^2} \tilde{E}^a \right) \right]$$

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natural parity

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natural parity
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Factorization only proven for $\gamma^*_L \to V_L$.
Assumed for other transitions.
IR singularities regularised by modified perturbative approach.

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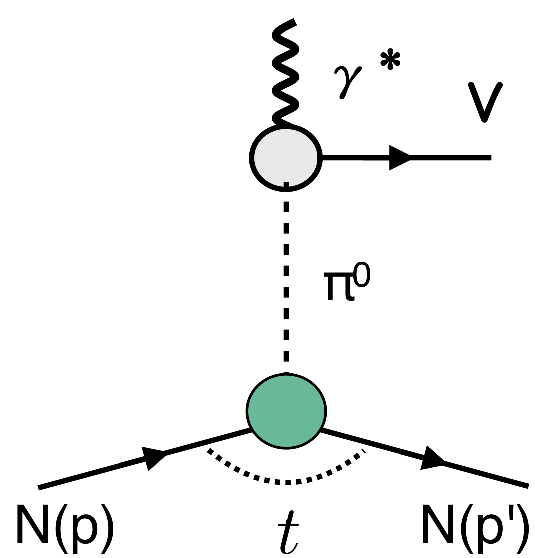
Pion pole $\left(\propto \frac{1}{t-m_\pi^2}\right)$ through

one-particle exchange

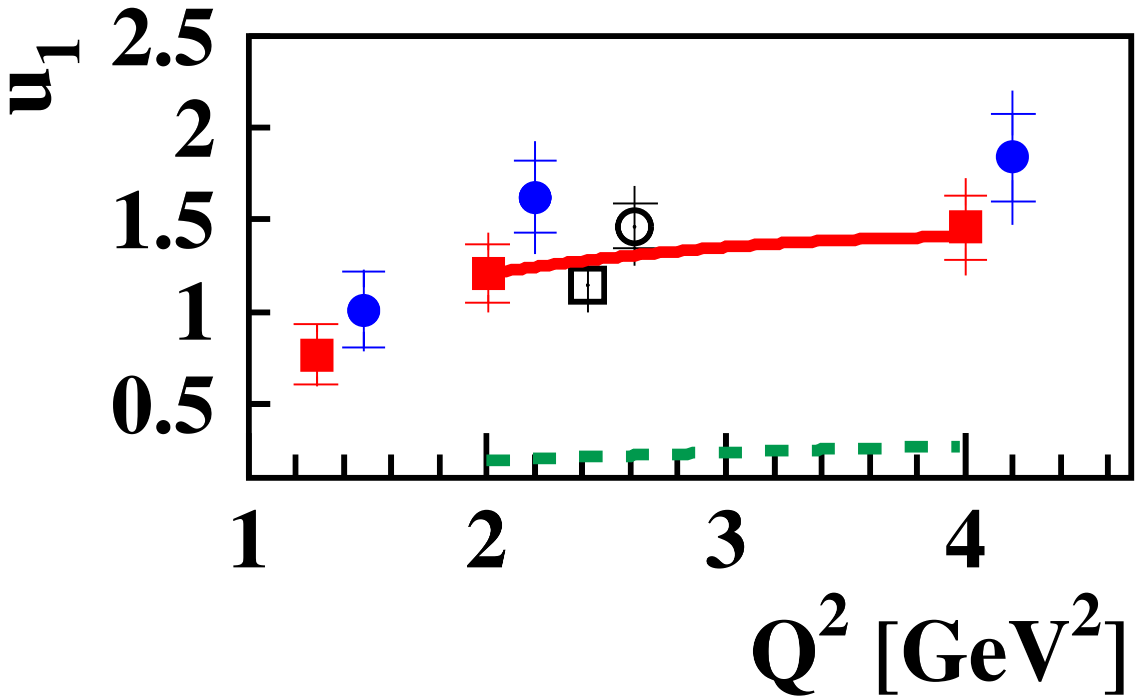


$$g_{\gamma^*\pi V}(Q^2,t) \simeq g_{\pi V}(Q^2)$$
at small t

πω transition form factor extracted from ω SDMEs

$$u_1 = 1 - r^{04}_{00} + 2\,r^{04}_{1-1} - 2\,r^{1}_{11} - 2\,r^{1}_{1-1}$$

GK, Eur. Phys. J. A 50 (2014) 146
HERMES, Eur. Phys. J. C 74 (2014) 3110



without pion-pole contribution
with pion-pole contribution
pion-pole contribution seems to account completely
for unnatural-parity exchange

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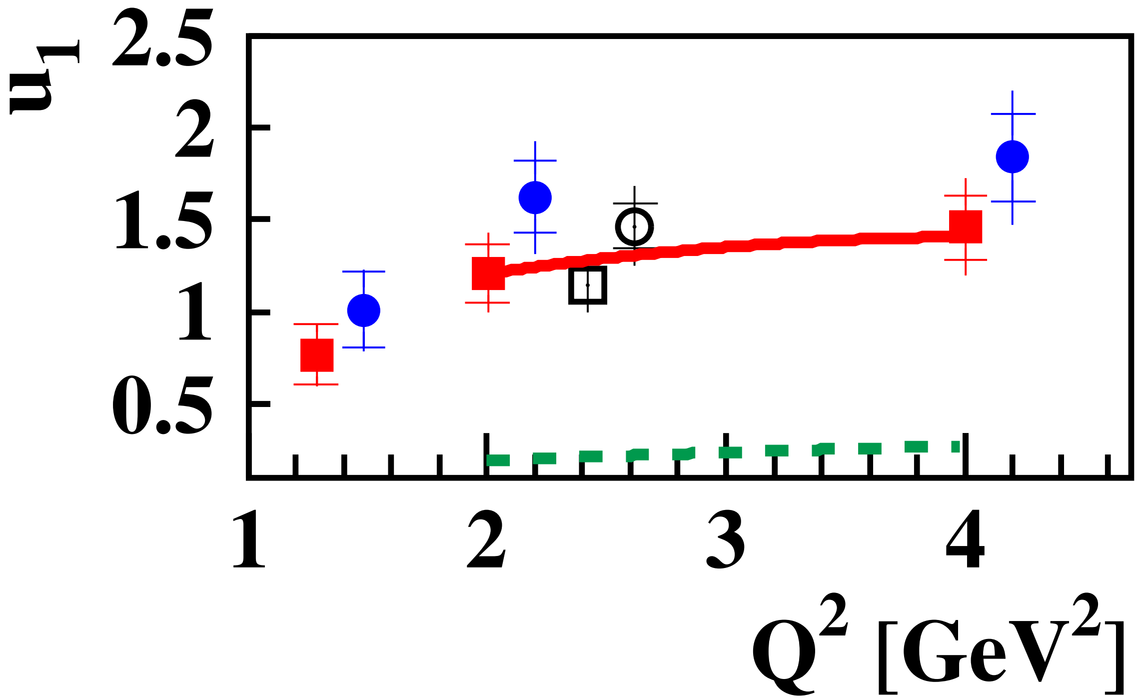

Only magnitude of transition form factor, not sign

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with pion-pole contribution
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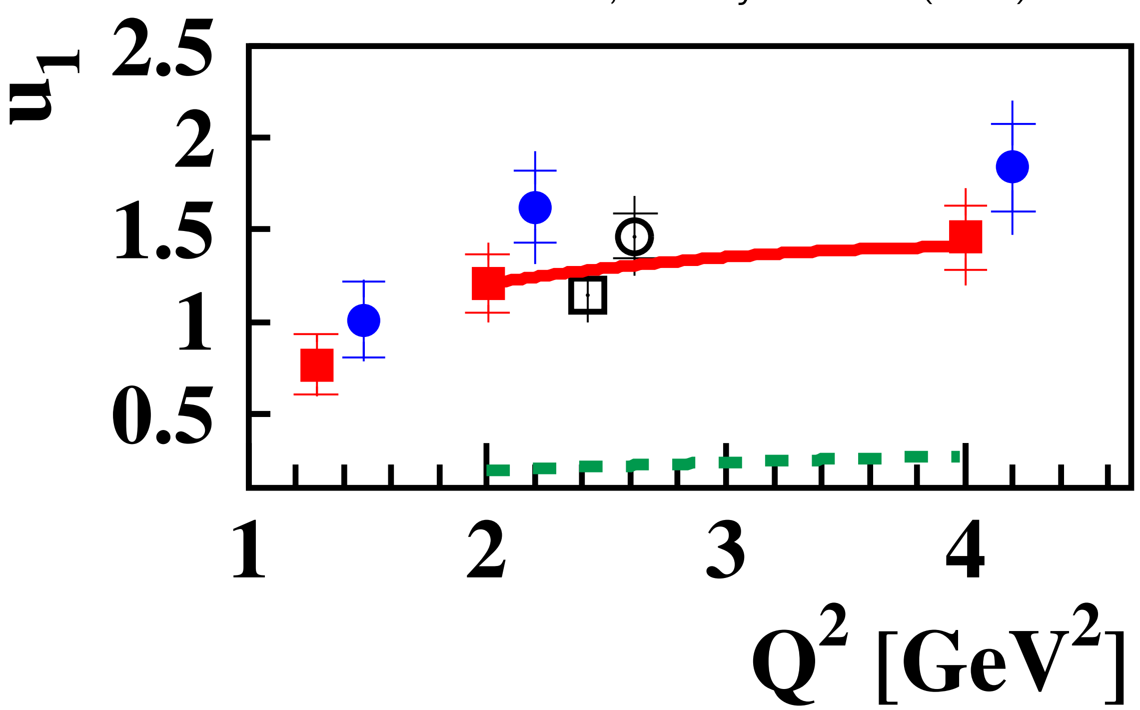
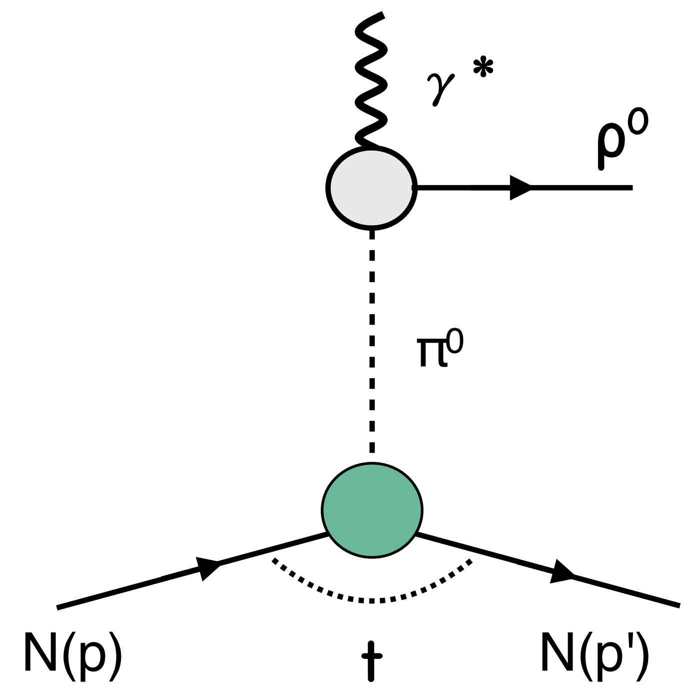
$$g_{\pi\rho} \simeq \frac{e_u + e_d}{e_u - e_d} g_{\pi\omega}$$

GK, Eur. Phys. J. A 50 (2014) 146
HERMES, Eur. Phys. J. C 74 (2014) 3110





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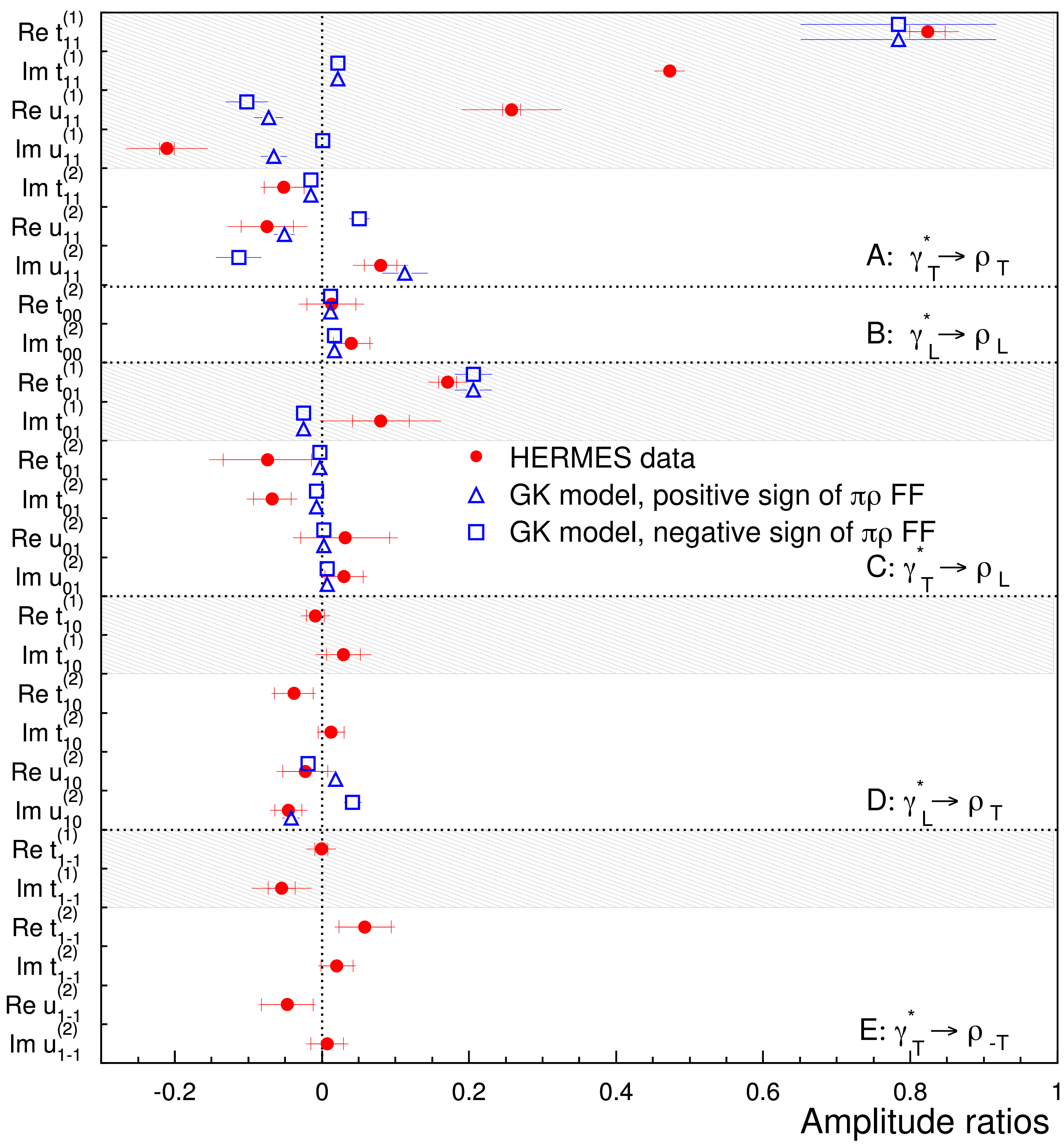
Comparison ρ^0 helicity amplitude ratios with GK model

Eur. Phys. J. C 77 (2017) 378



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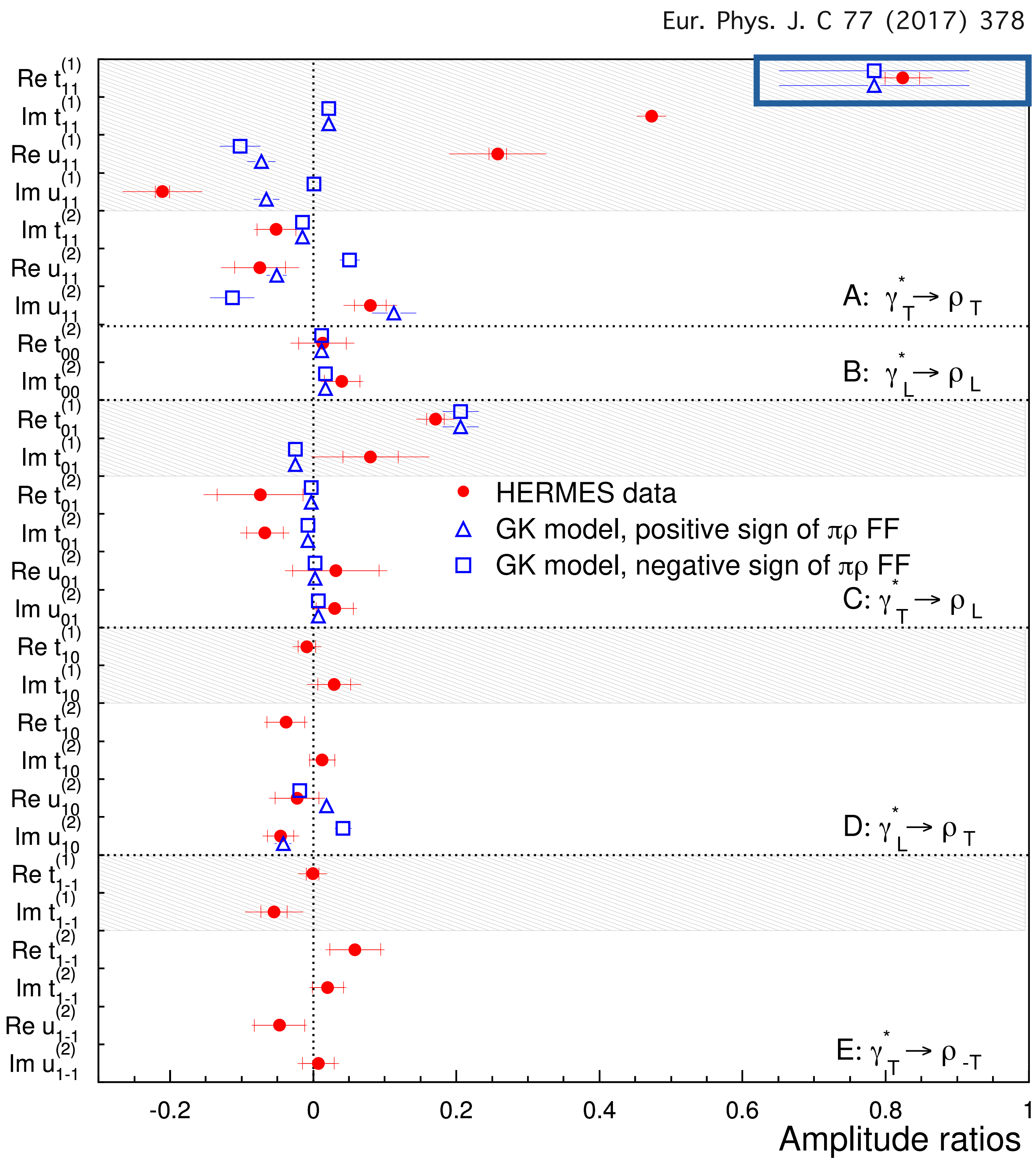

- GPD H.

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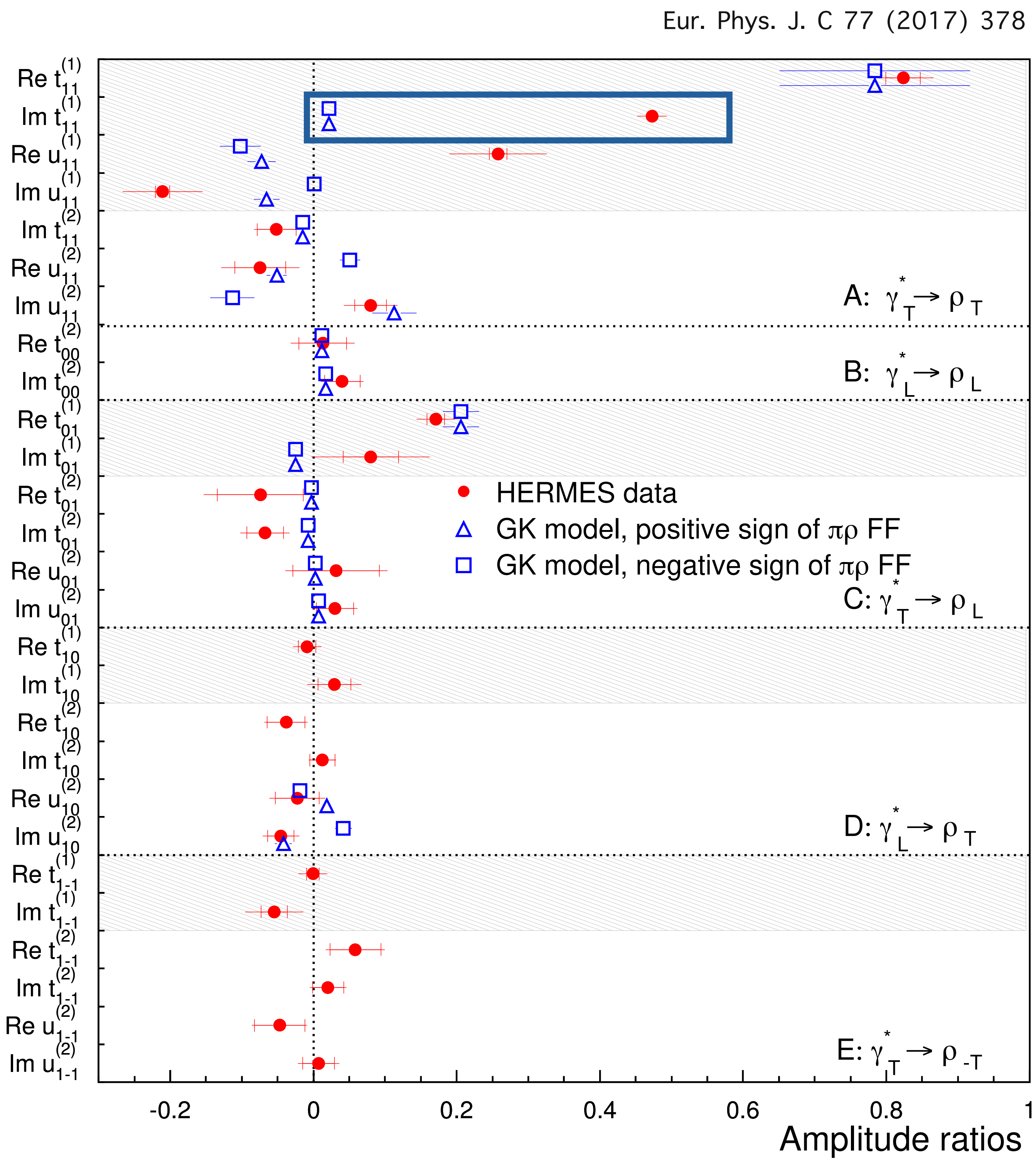

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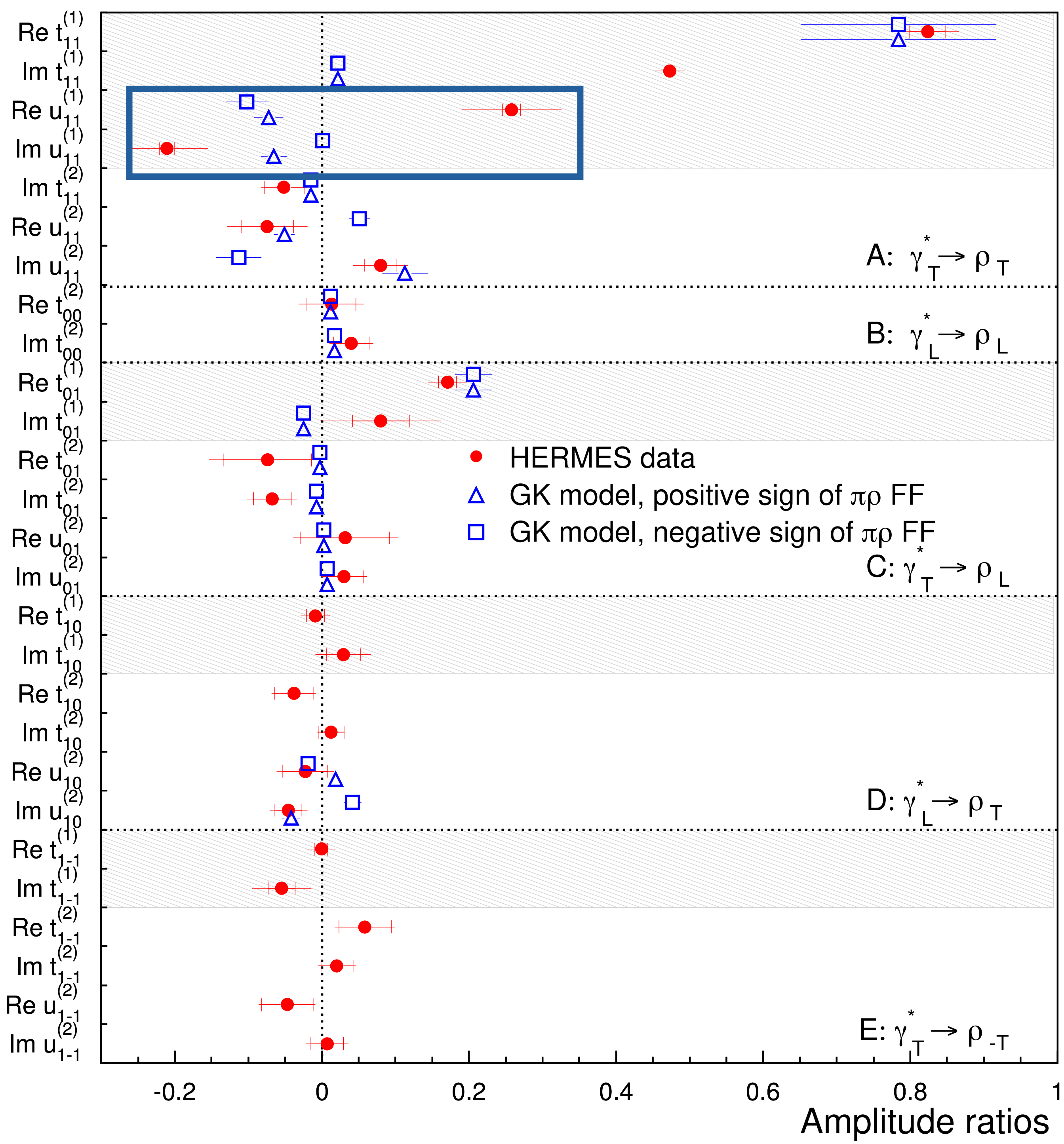

- GPD $\widetilde{H}$ + pion pole.

Comparison ρ^0 helicity amplitude ratios with GK model

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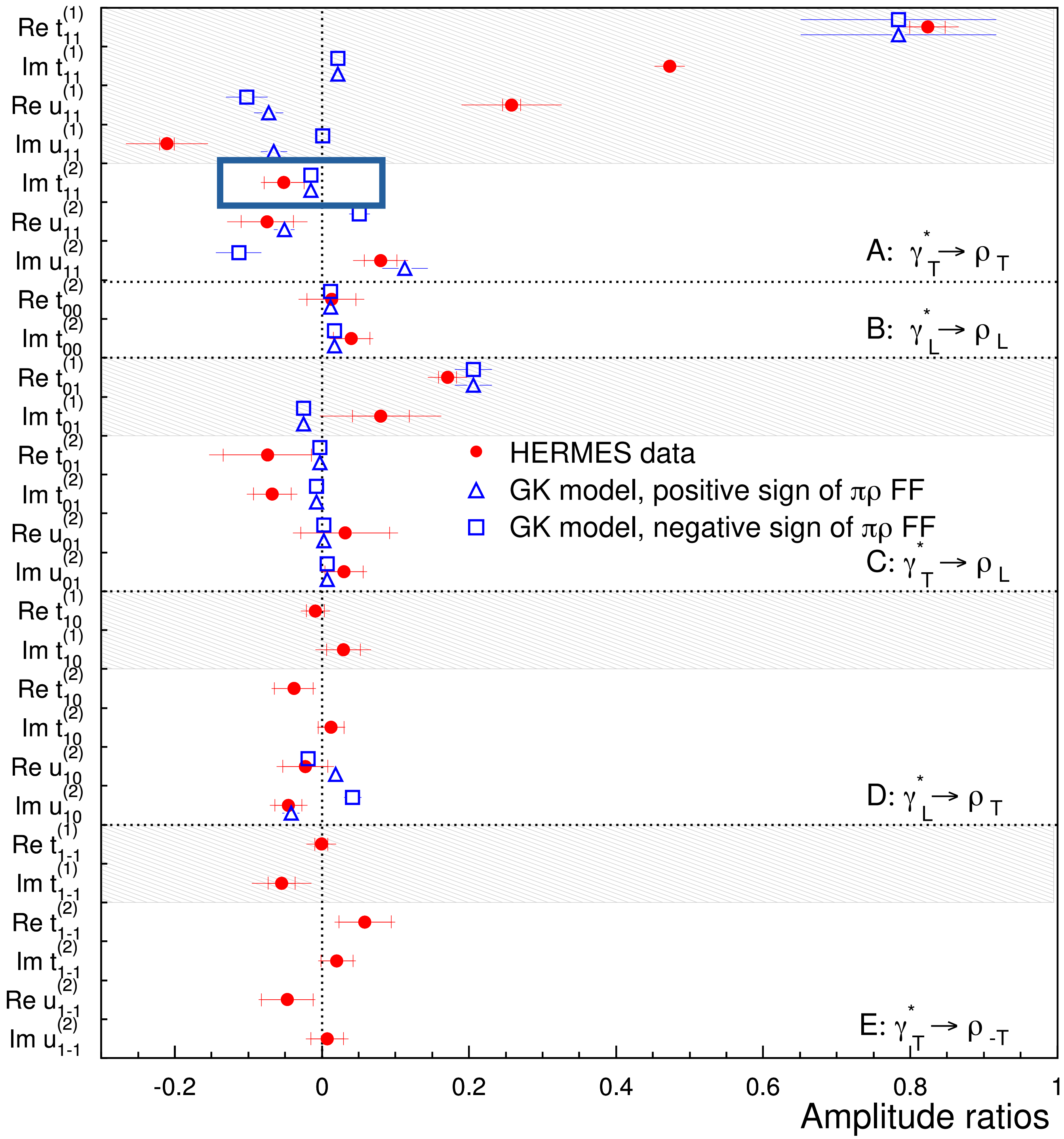

- GPD E.

Comparison ρ^0 helicity amplitude ratios with GK model

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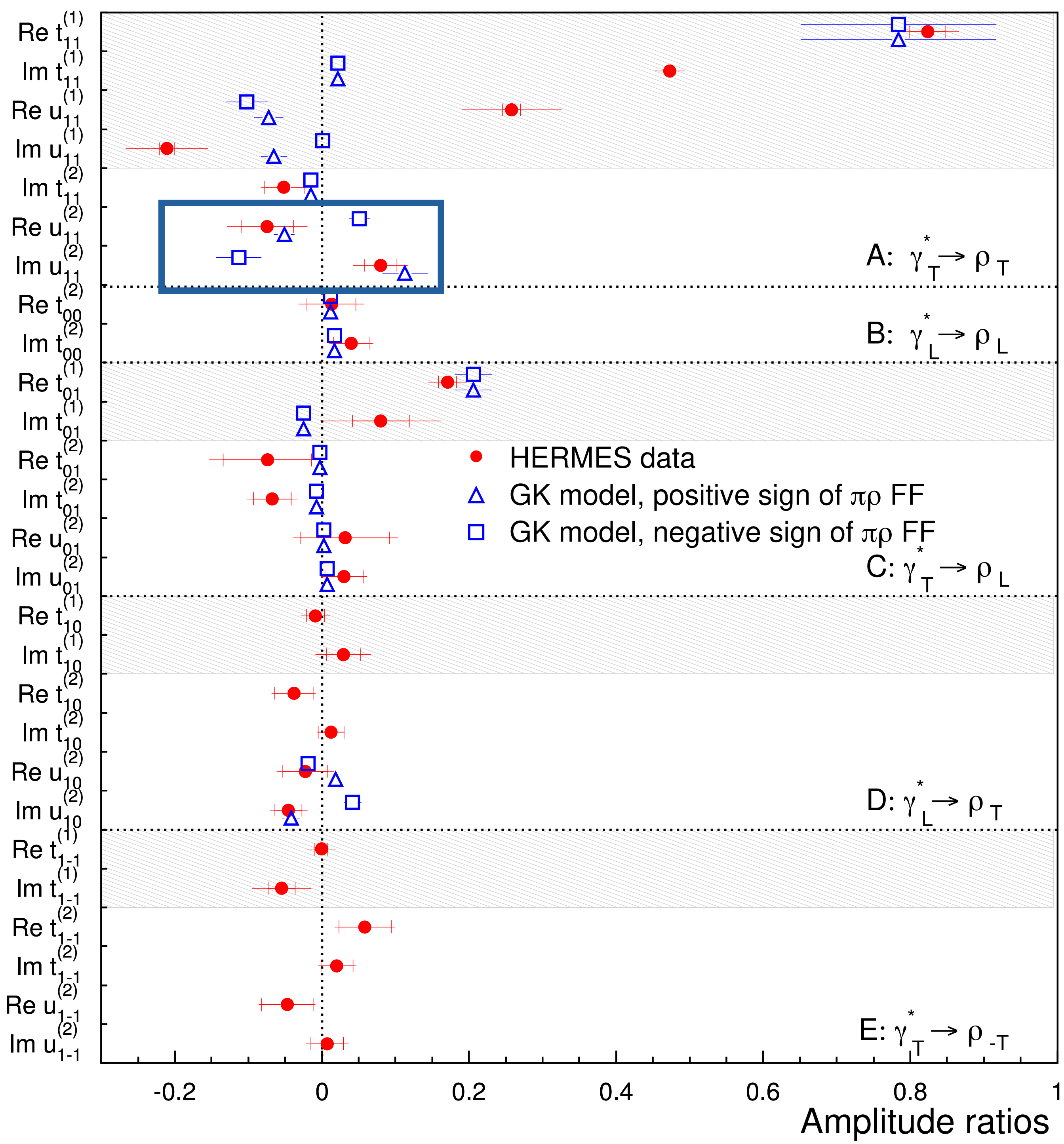
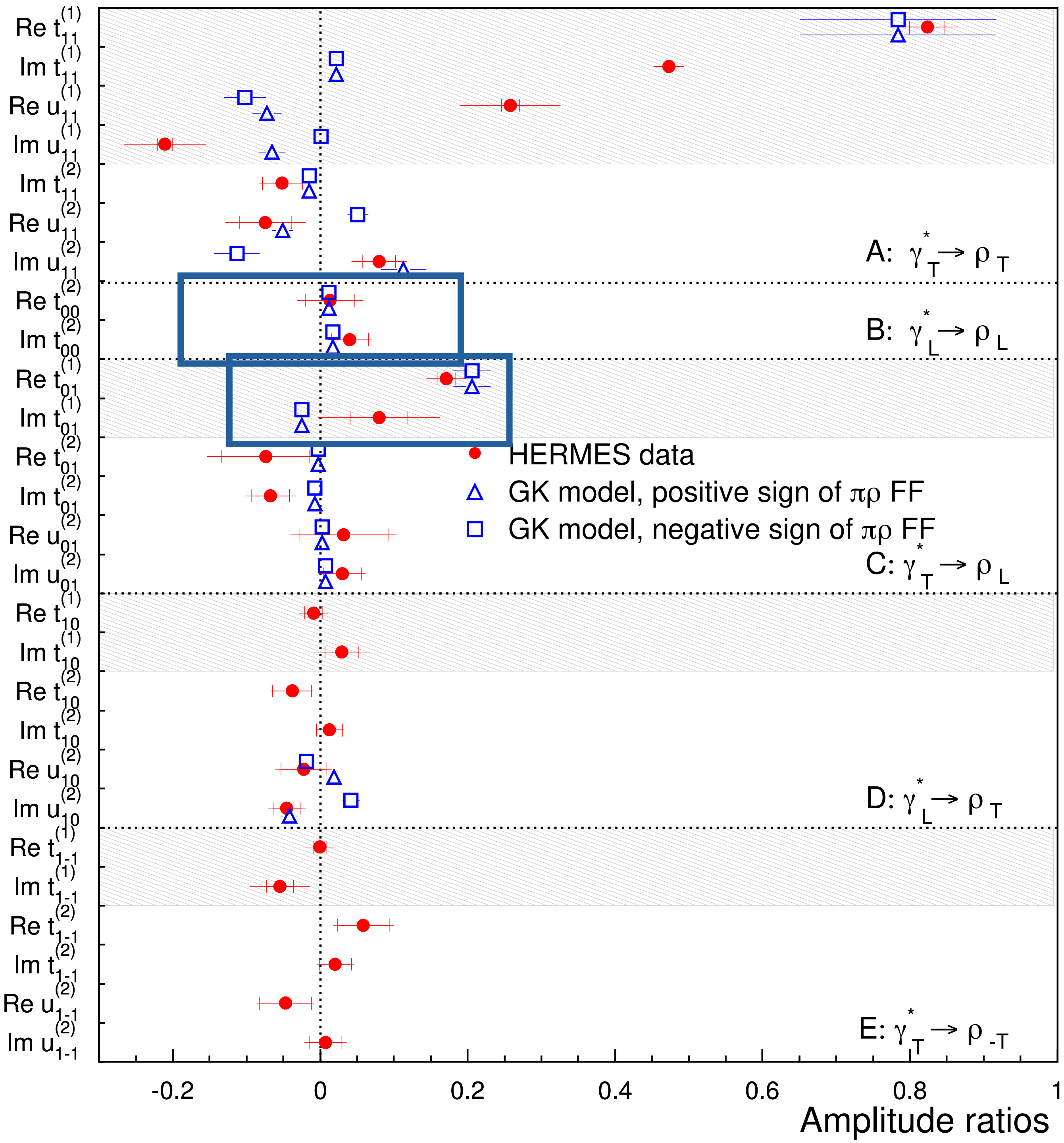


- Only pion pole. Positive form factor.

Comparison ρ^0 helicity amplitude ratios with GK model

Eur. Phys. J. C 77 (2017) 378



- GPD E.
- GPD $\bar{E}_T$.

Comparison ρ^0 helicity amplitude ratios with GK model

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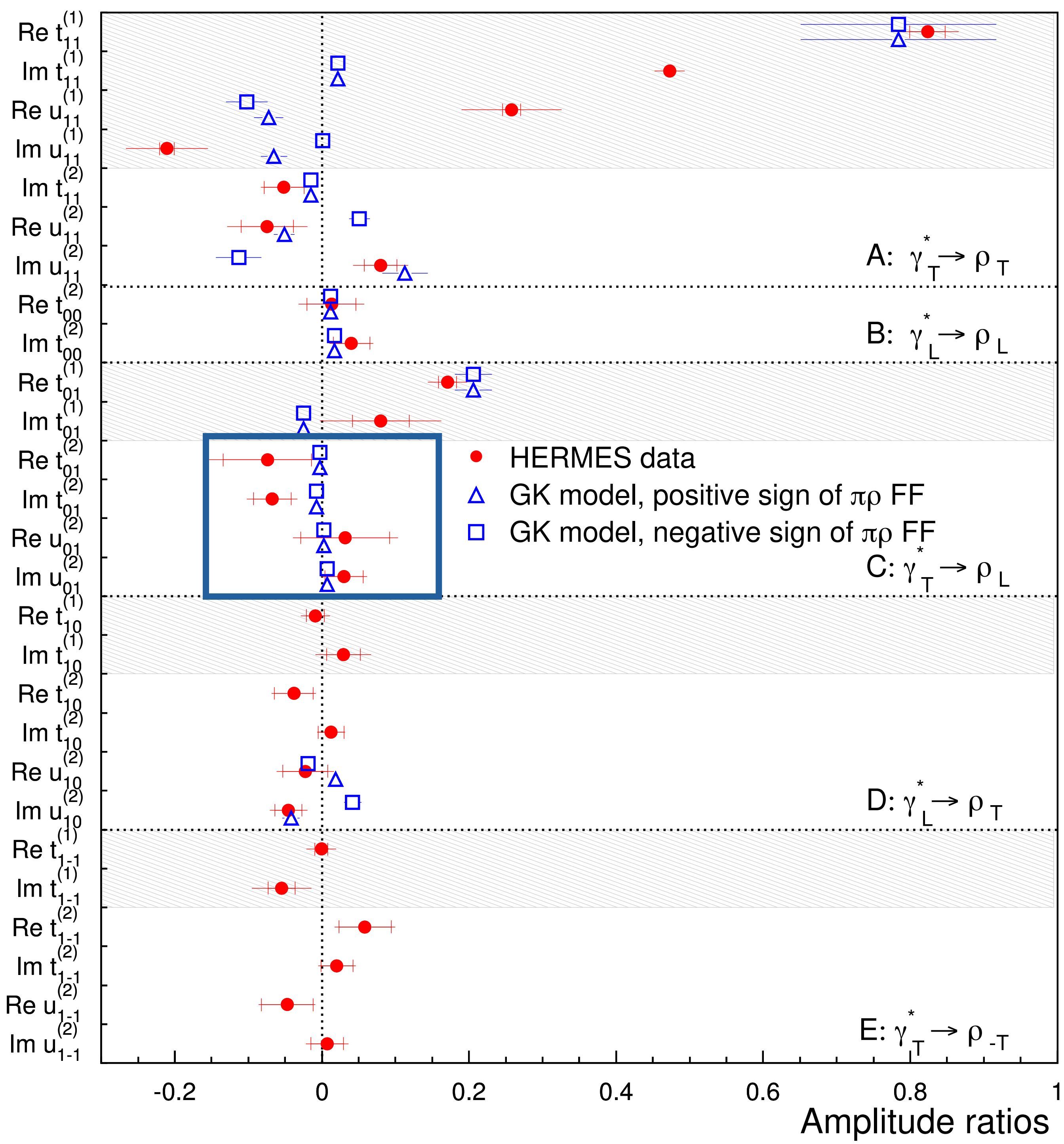
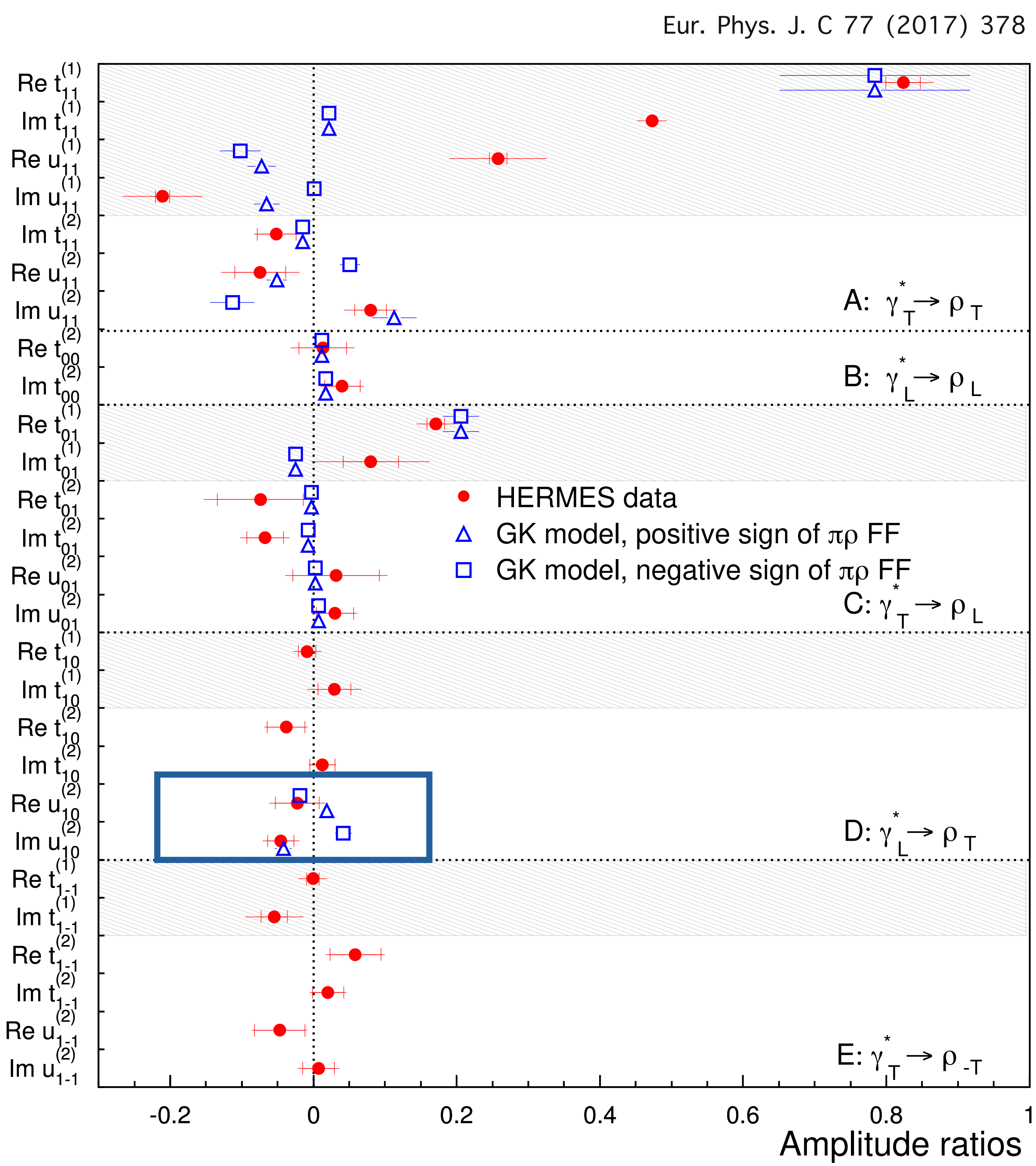


- GPD H_T.

Comparison ρ^0 helicity amplitude ratios with GK model



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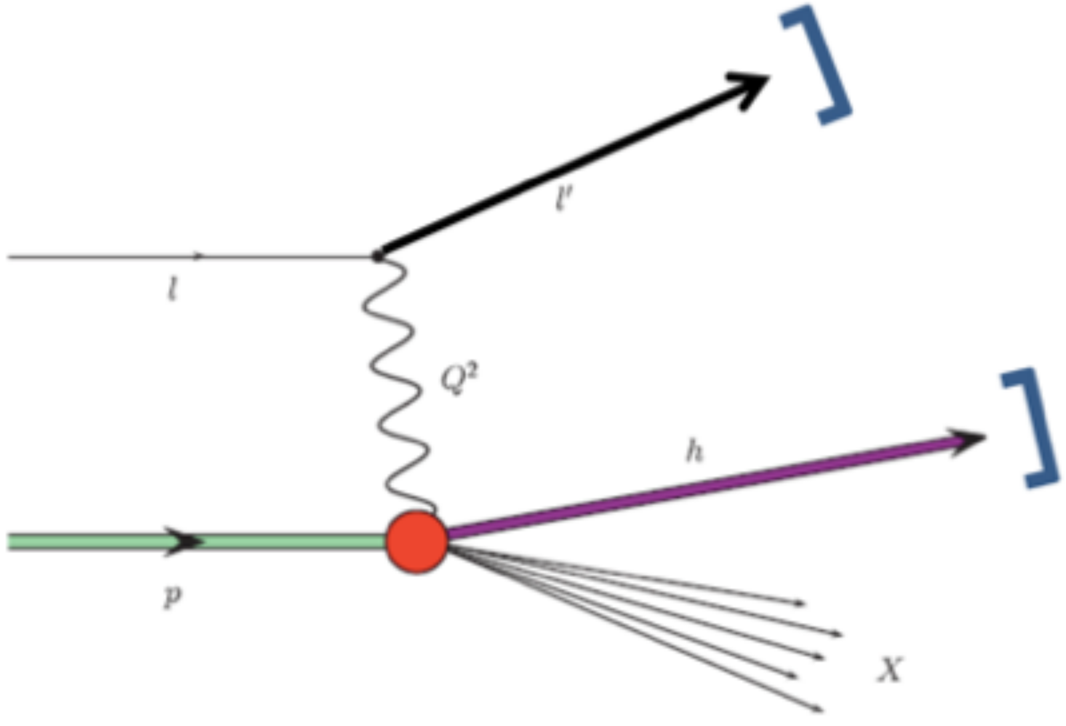
Semi-inclusive DIS
single-hadron production



Presented amplitudes

$$
\begin{aligned}
\sigma^h(\phi,\phi_S) \quad = \quad & \sigma^h_{UU} \Big\{ 1 + 2\langle\cos(\phi)\rangle^h_{UU}\, \cos(\phi) + 2\langle\cos(2\phi)\rangle^h_{UU}\, \cos(2\phi) \\
+ \quad & \lambda_l \boxed{2\langle\sin(\phi)\rangle^h_{LU}}\, \sin(\phi) \\
+ \quad & S_L \Big[2\langle\sin(\phi)\rangle^h_{UL}\, \sin(\phi) + 2\langle\sin(2\phi)\rangle^h_{UL}\, \sin(2\phi) \\
+ \quad & \lambda_l \Big(2\langle\cos(0\phi)\rangle^h_{LL}\, \cos(0\phi) + 2\langle\cos(\phi)\rangle^h_{LL}\, \cos(\phi) \Big) \Big] \\
+ \quad & S_T \Big[\boxed{2\langle\sin(\phi-\phi_S)\rangle^h_{UT}}\, \sin(\phi-\phi_S) + \boxed{2\langle\sin(\phi+\phi_S)\rangle^h_{UT}}\, \sin(\phi+\phi_S) \\
+ \quad & \boxed{2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}}\, \sin(3\phi-\phi_S) + \boxed{2\langle\sin(\phi_S)\rangle^h_{UT}}\, \sin(\phi_S) \\
+ \quad & 2\langle\sin(2\phi-\phi_S)\rangle^h_{UT}\, \sin(2\phi-\phi_S) \\
+ \quad & \lambda_l \Big(2\langle\cos(\phi-\phi_S)\rangle^h_{LT}\, \cos(\phi-\phi_S) \\
+ \quad & 2\langle\cos(\phi_S)\rangle^h_{LT}\, \cos(\phi_S) + 2\langle\cos(2\phi-\phi_S)\rangle^h_{LT}\, \cos(2\phi-\phi_S) \Big) \Big] \Big\}
\end{aligned}
$$

Presented here

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

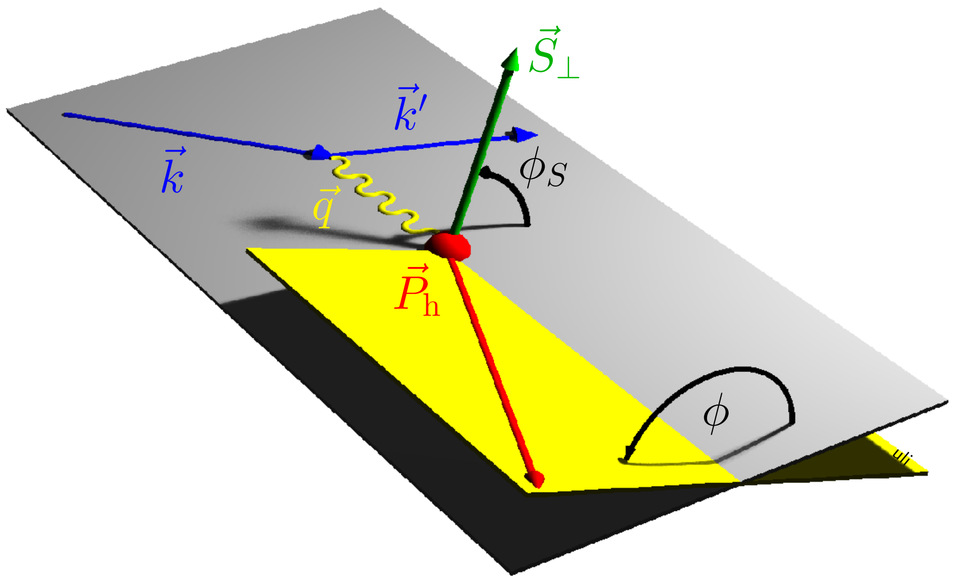
Presented amplitudes

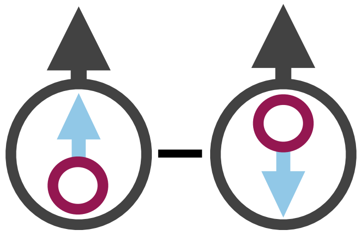
- Longitudinally polarized e+/e- beam
- Transversely polarized H target: fit all amplitudes simultaneously

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

$$
\begin{aligned}
+ \quad & S_T \left[\boxed{2\langle\sin(\phi-\phi_S)\rangle_{UT}^{h}} \sin(\phi-\phi_S) + \boxed{2\langle\sin(\phi+\phi_S)\rangle_{UT}^{h}} \sin(\phi+\phi_S)\right. \\
+ \quad & \boxed{2\langle\sin(3\phi-\phi_S)\rangle_{UT}^{h}} \sin(3\phi-\phi_S) + \boxed{2\langle\sin(\phi_S)\rangle_{UT}^{h}} \sin(\phi_S) \\
+ \quad & 2\langle\sin(2\phi-\phi_S)\rangle_{UT}^{h} \sin(2\phi-\phi_S) \\
+ \quad & \lambda_l \left(2\langle\cos(\phi-\phi_S)\rangle_{LT}^{h} \cos(\phi-\phi_S)\right. \\
+ \quad & \left.\left.2\langle\cos(\phi_S)\rangle_{LT}^{h} \cos(\phi_S) + 2\langle\cos(2\phi-\phi_S)\rangle_{LT}^{h} \cos(2\phi-\phi_S)\right)\right]\Big\}
\end{aligned}
$$

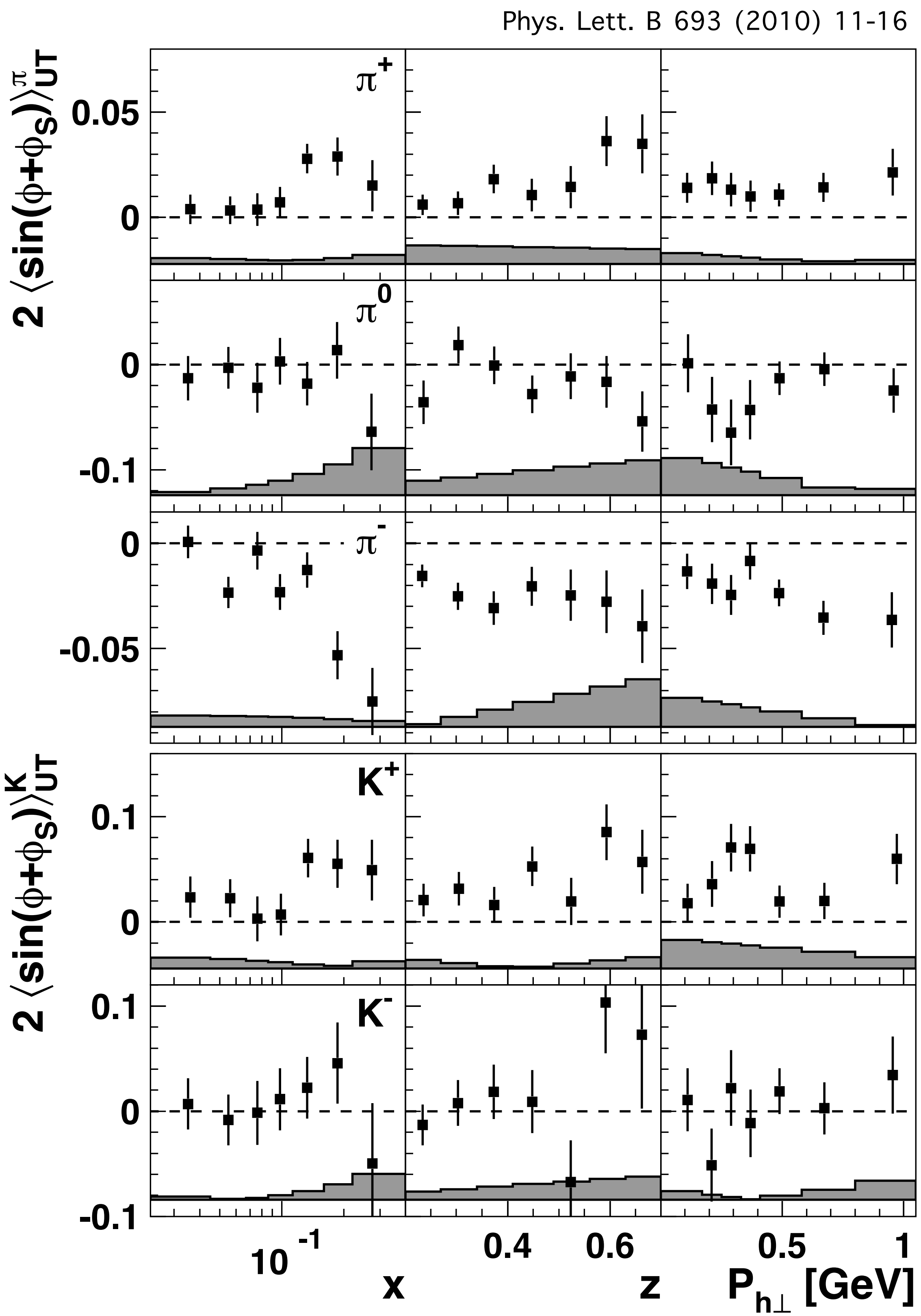
$$
\begin{aligned}
& Q^2 > 1\ \mathrm{GeV}^2 \\
& W^2 > 10\ \mathrm{GeV}^2 \\
& 0.023 < x < 0.6
\end{aligned}
$$

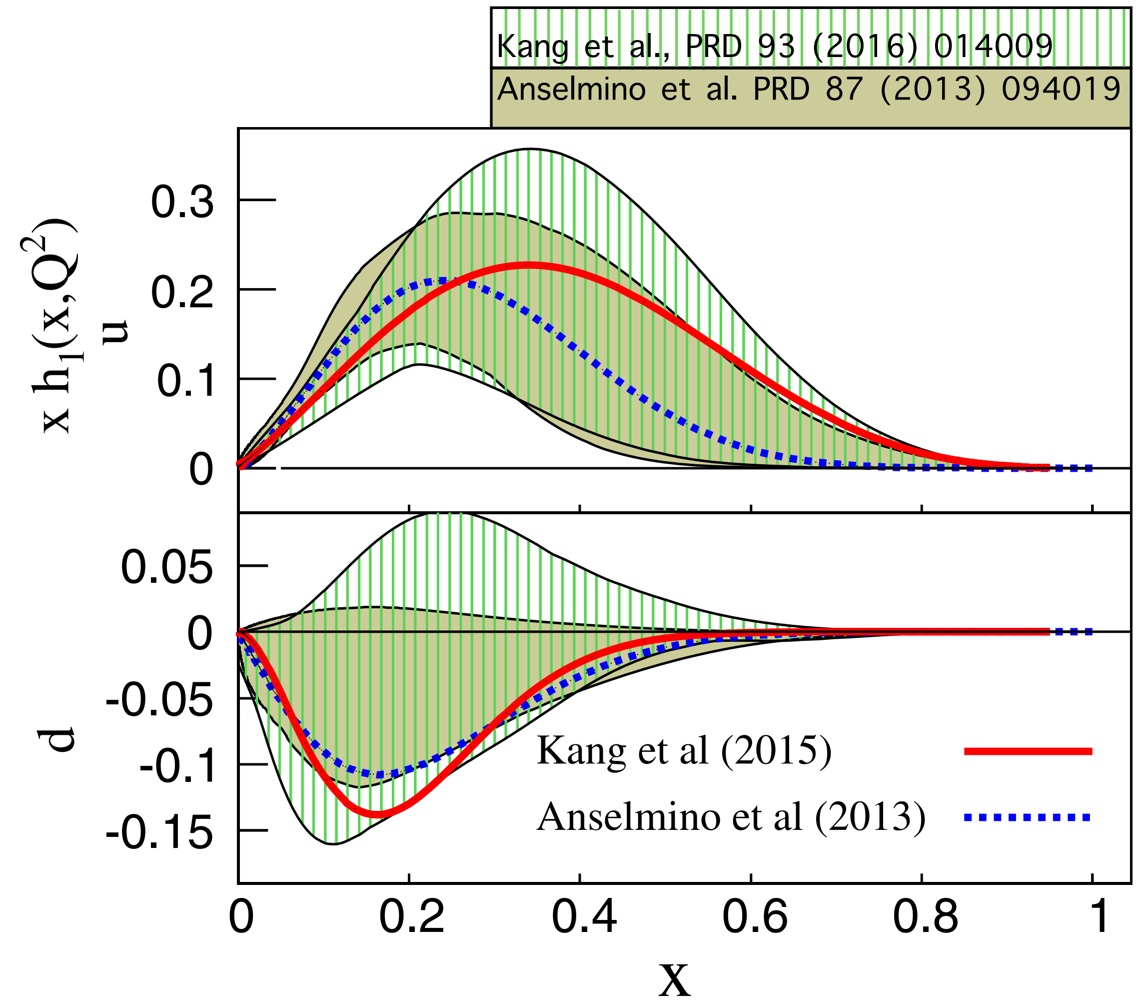




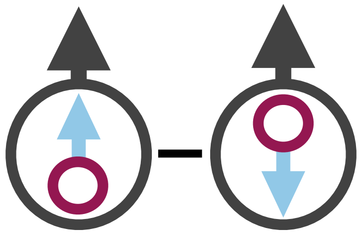
Collins amplitudes

$\mathcal{C}[h_{1T}^q \times H_1^{\perp,q}]$





data from Belle, Babar, COMPASS, HERMES, Jefferson Lab Hall A



Collins amplitudes

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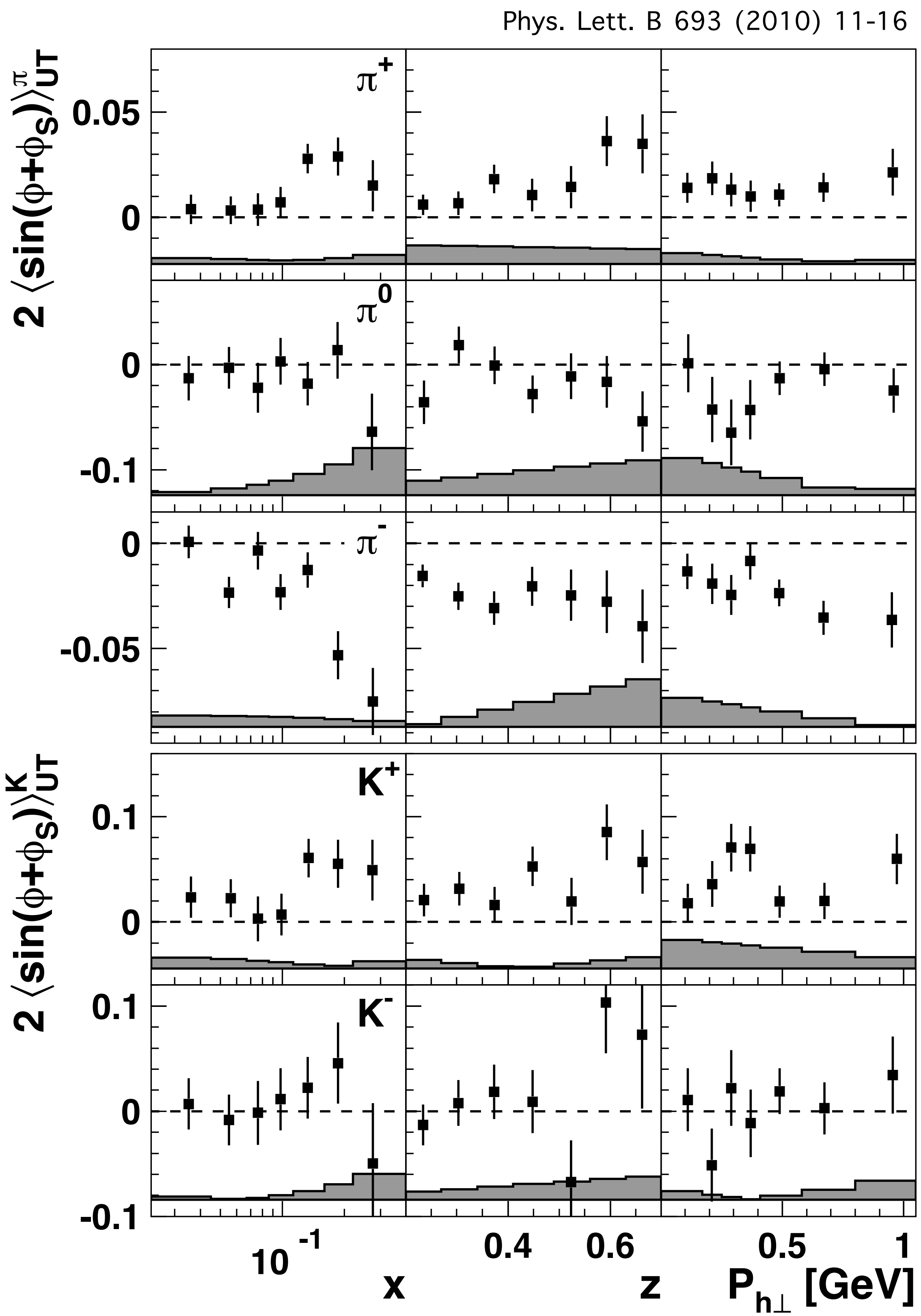

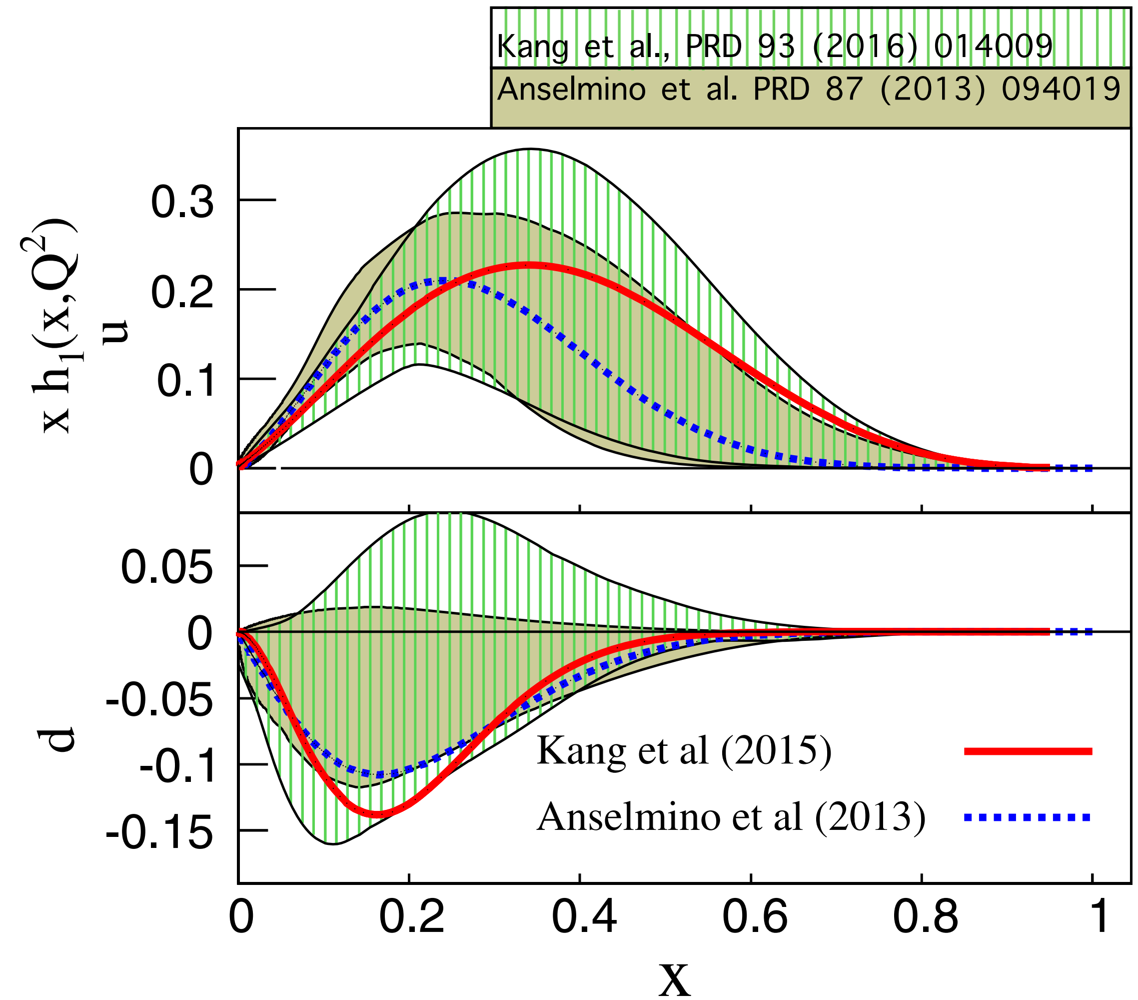

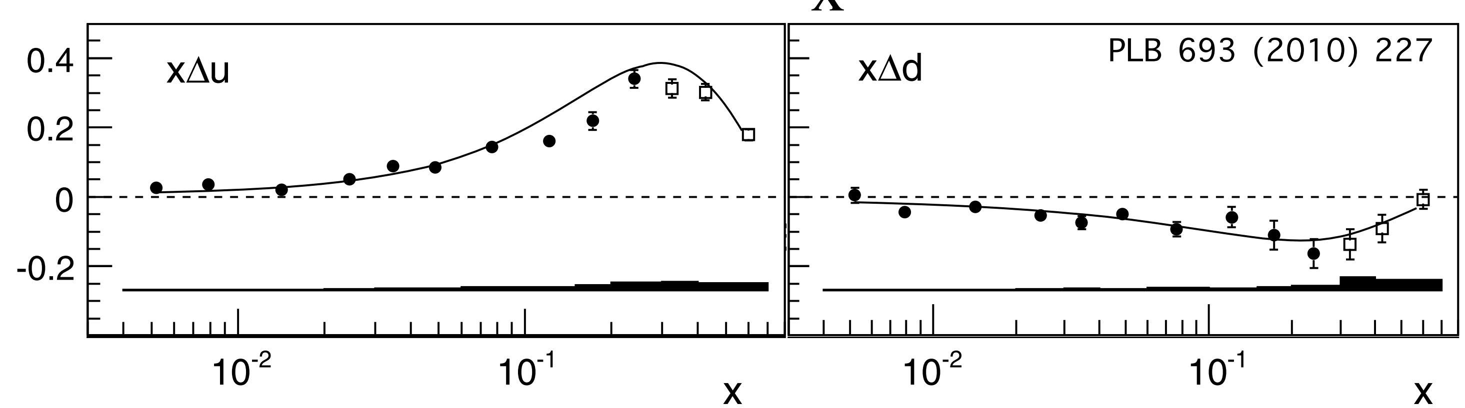

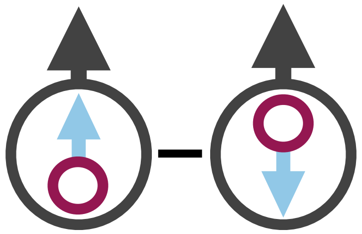

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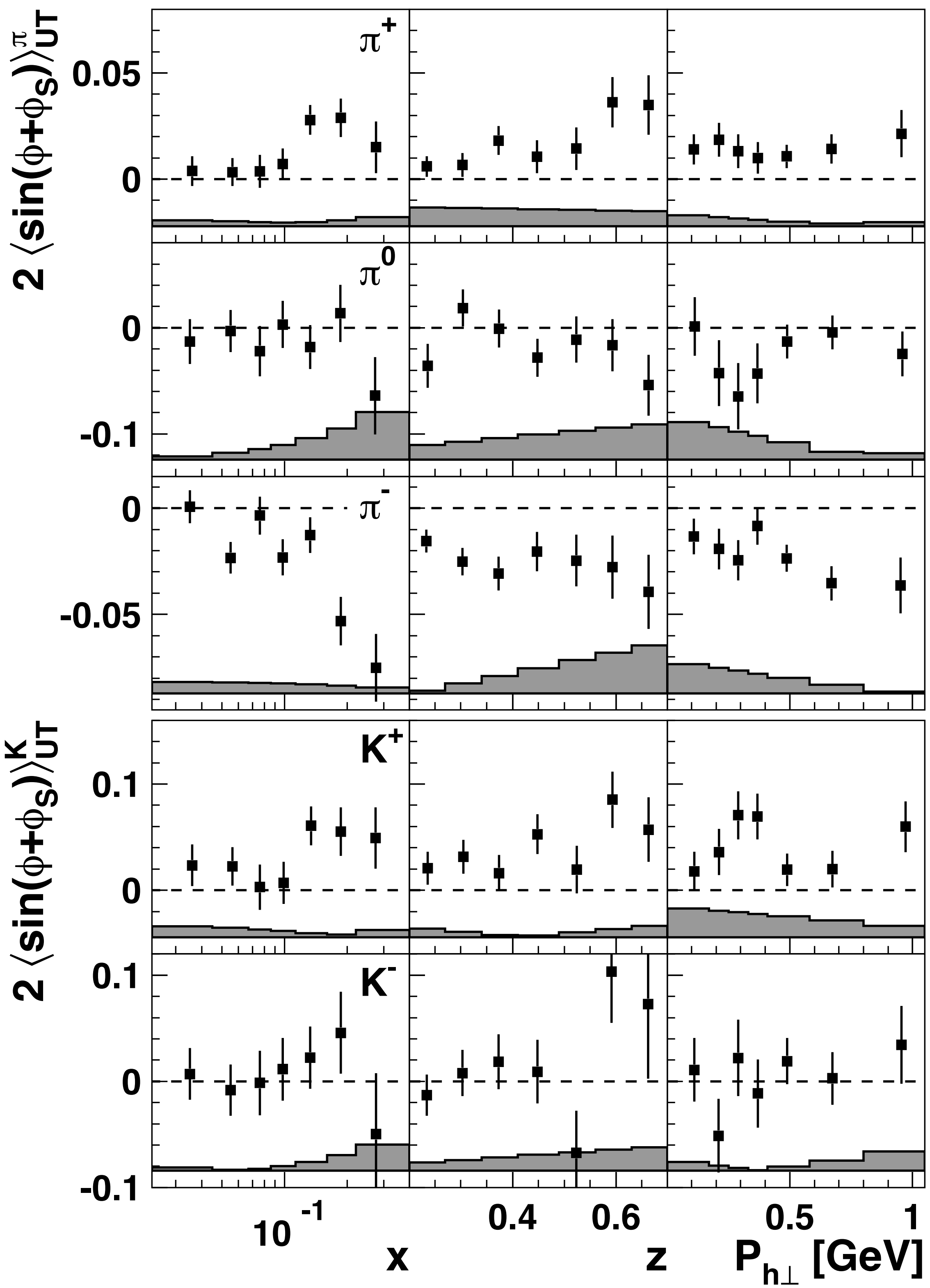
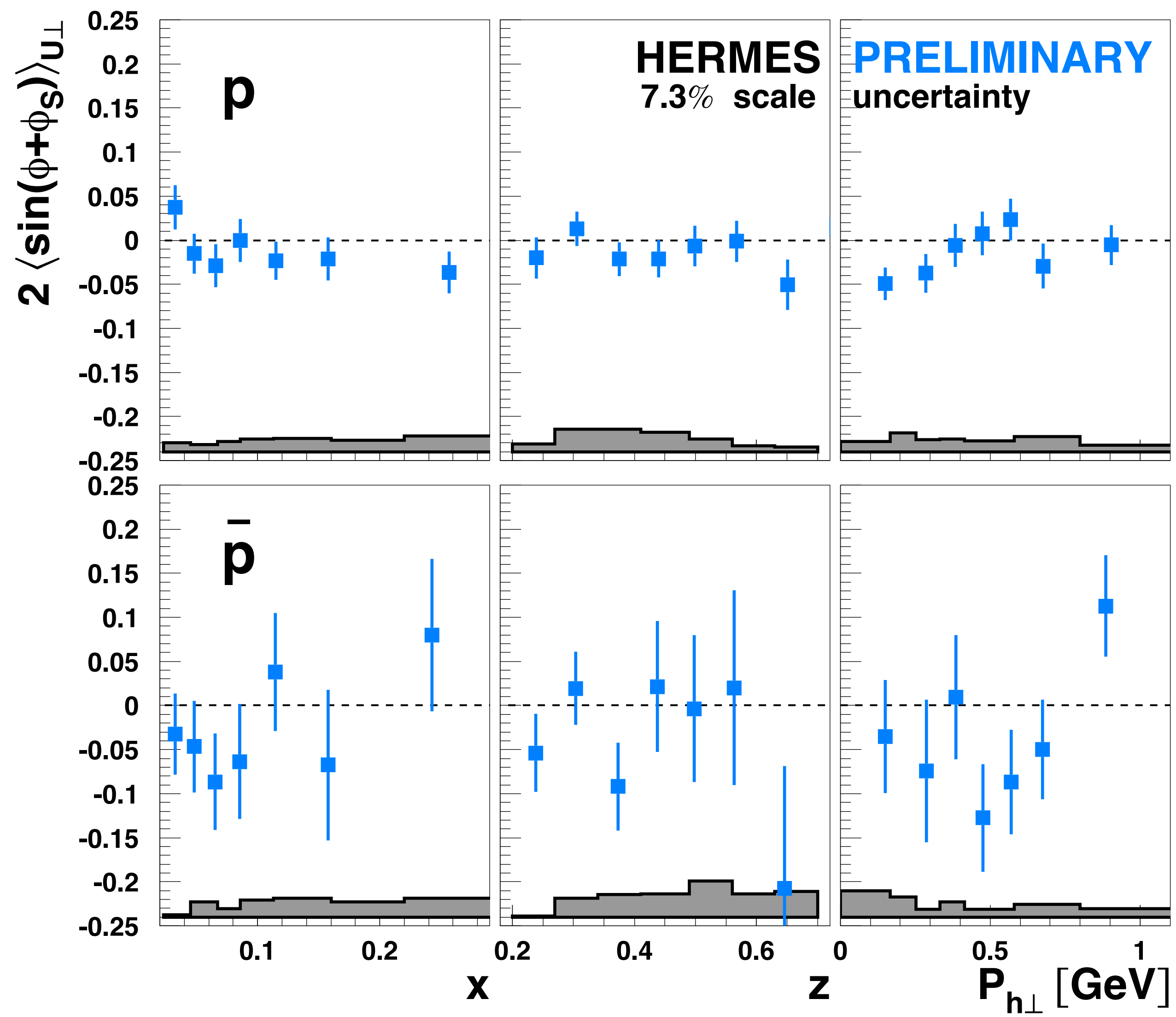
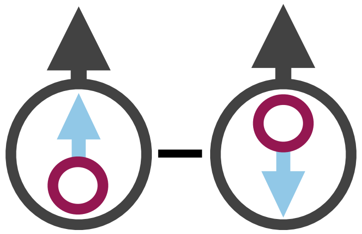
Phys. Lett. B 693 (2010) 11-16







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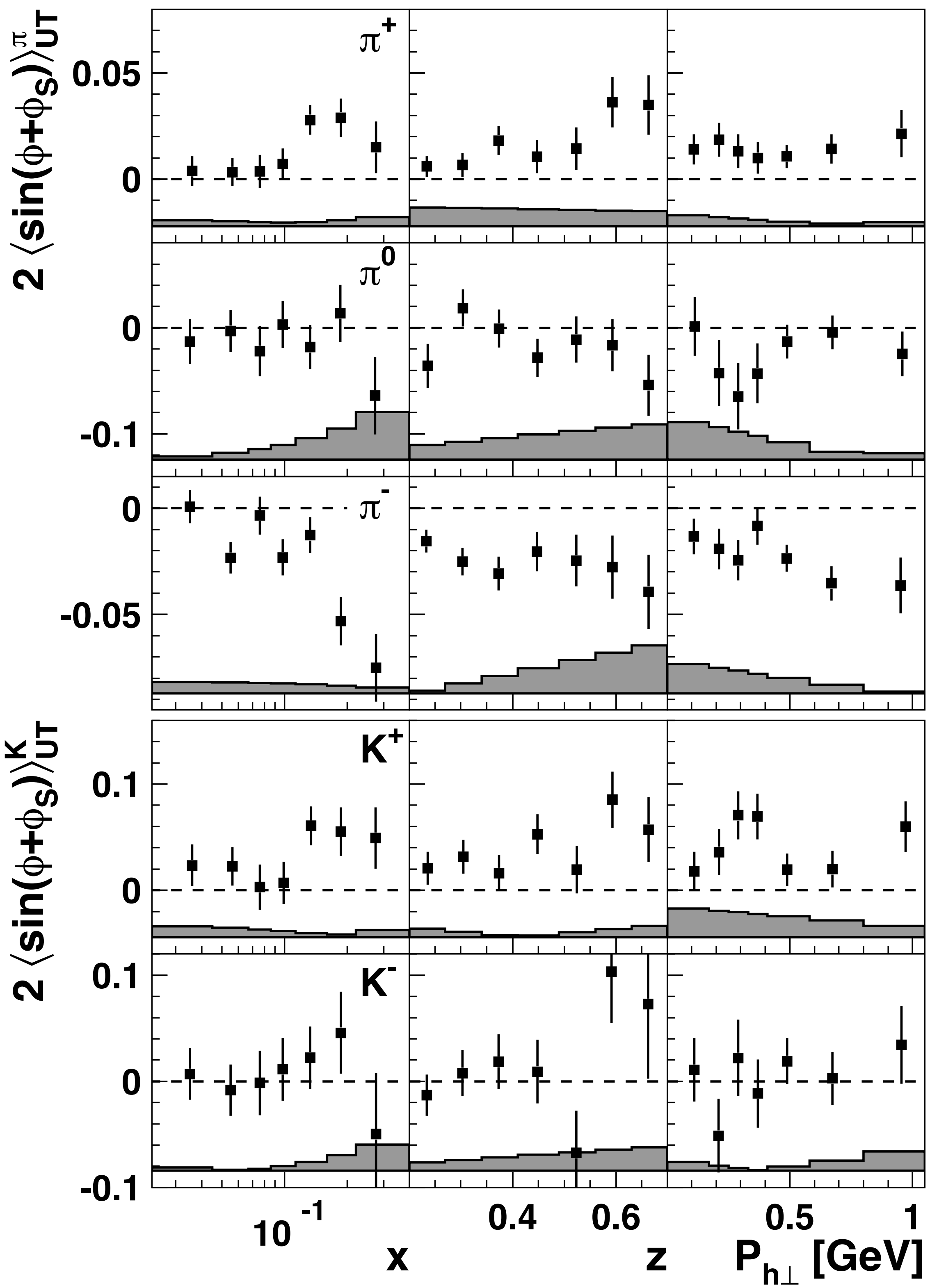
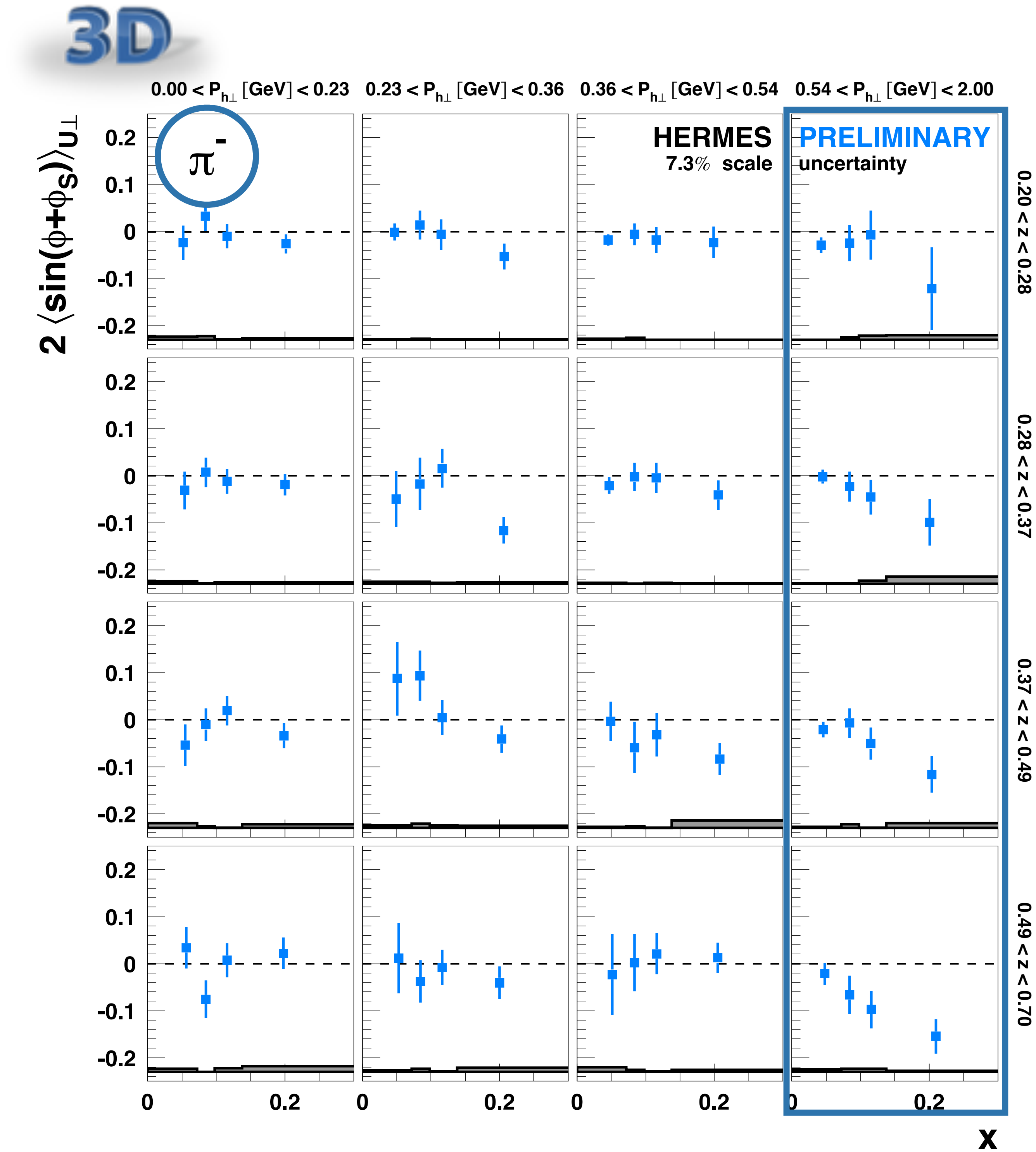
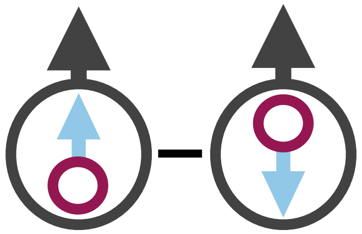
Phys. Lett. B 693 (2010) 11-16





π^- amplitudes increasing with x at large $P_{h\perp}$, increasing with z.



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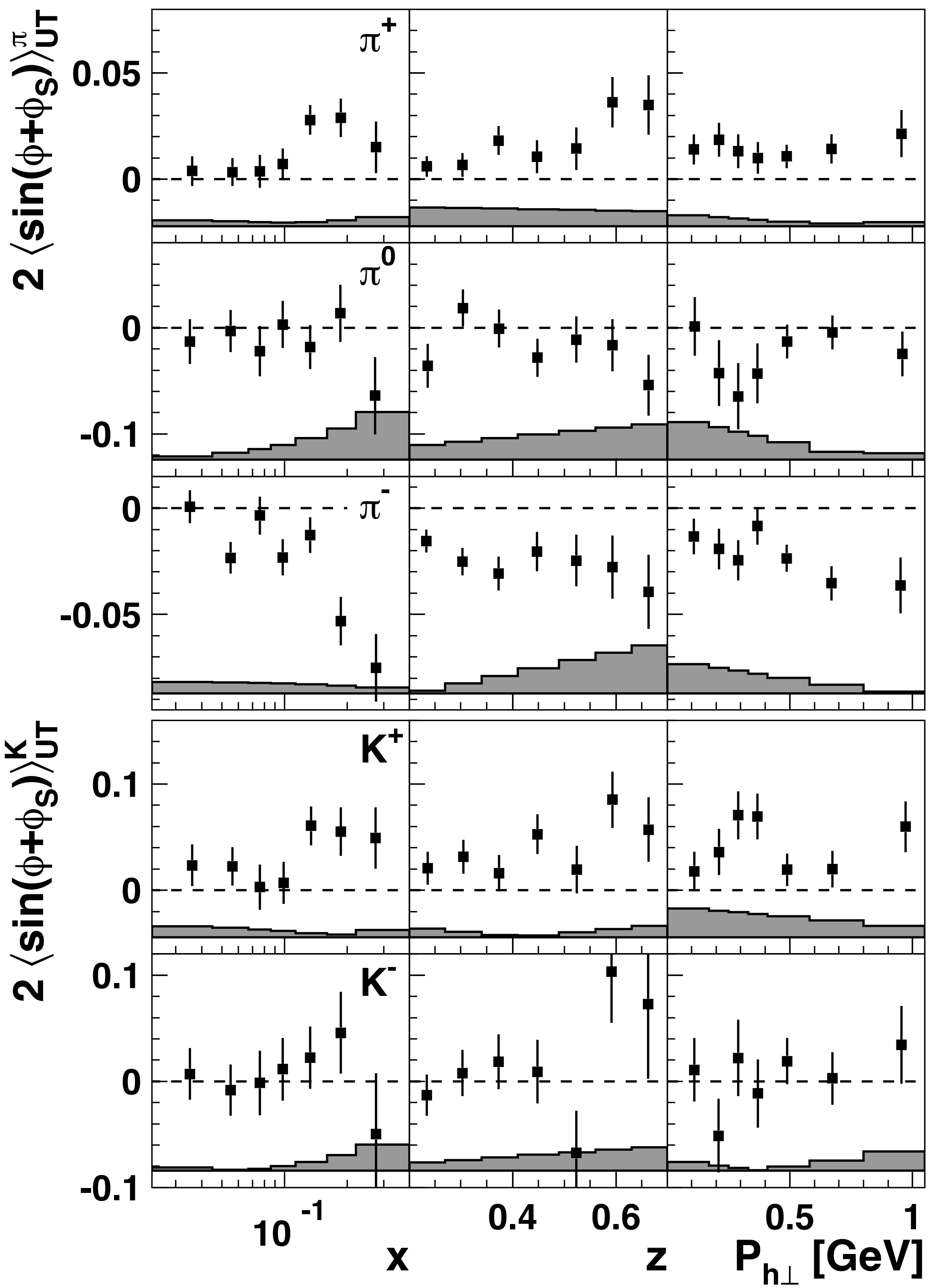
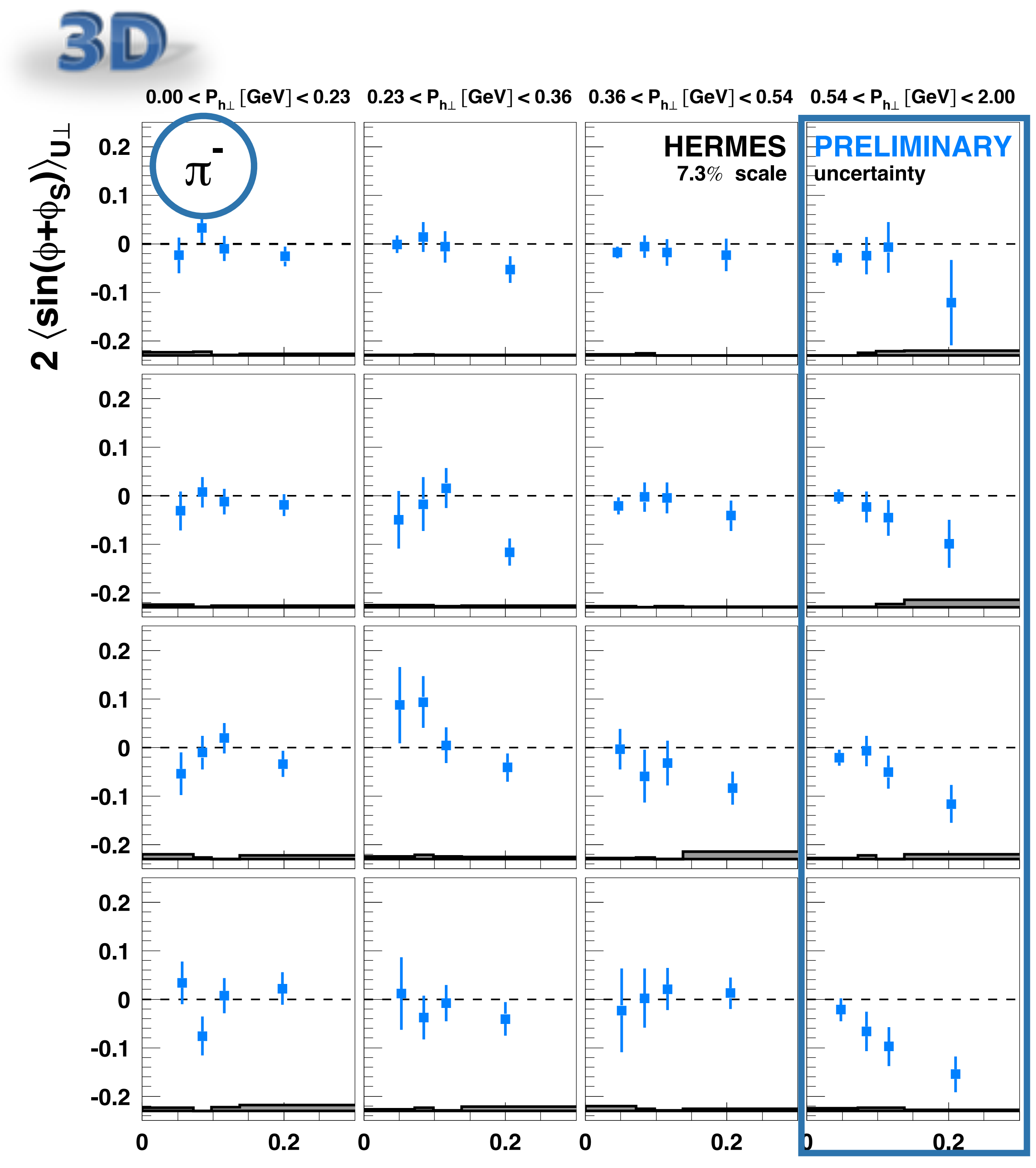
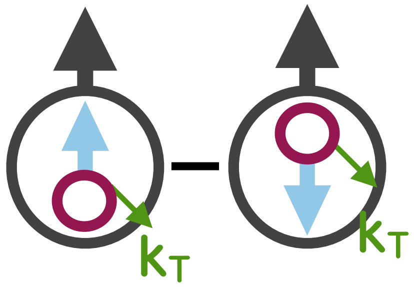
Phys. Lett. B 693 (2010) 11-16





- Other hadrons, no clear kinematic dependencies in 3D
- No 3D for antiprotons



Pretzelosity amplitudes

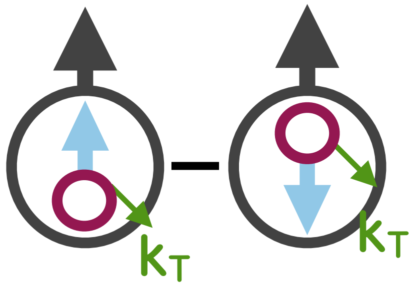
$\mathcal{C}[h_{1T}^{\perp,q} \times H_1^{\perp,q}]$

- Pretzelosity
  - requires non-zero orbital angular momentum (model)
  - models:

$$h_{1T}^{\perp(1),q}(x) = g_{1L}^q(x) - h_{1T}^q(x)$$

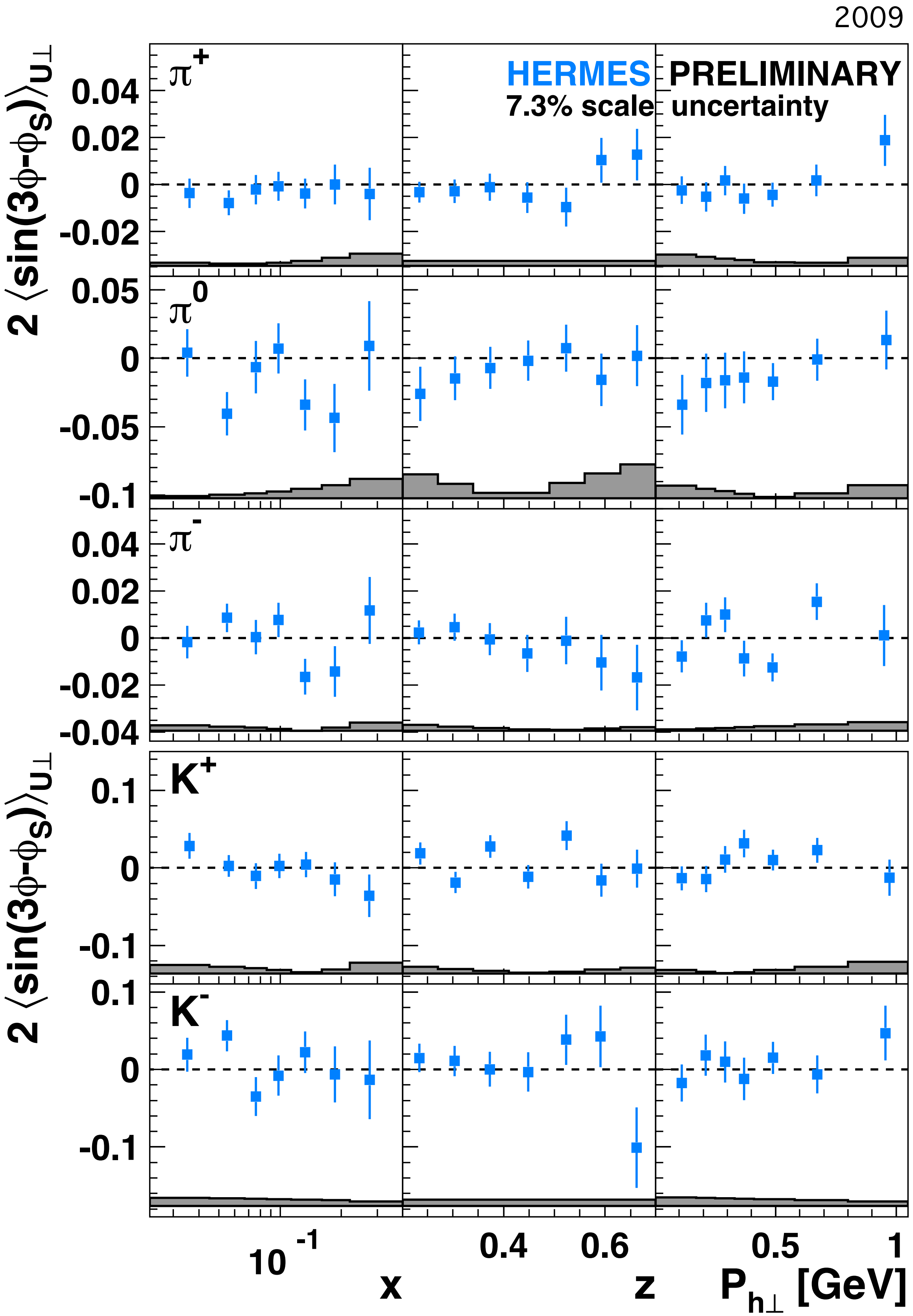
$\longrightarrow$ measure for relativistic effects

  - suppressed as $1/P_{h\perp}^2$ compared to Collins amplitude



Pretzelosity amplitudes

$$\mathcal{C}[h_{1T}^{\perp,q} \times H_1^{\perp,q}]$$



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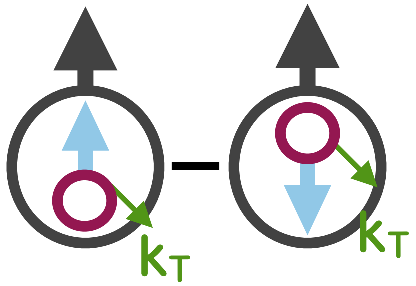

Pretzelosity amplitudes

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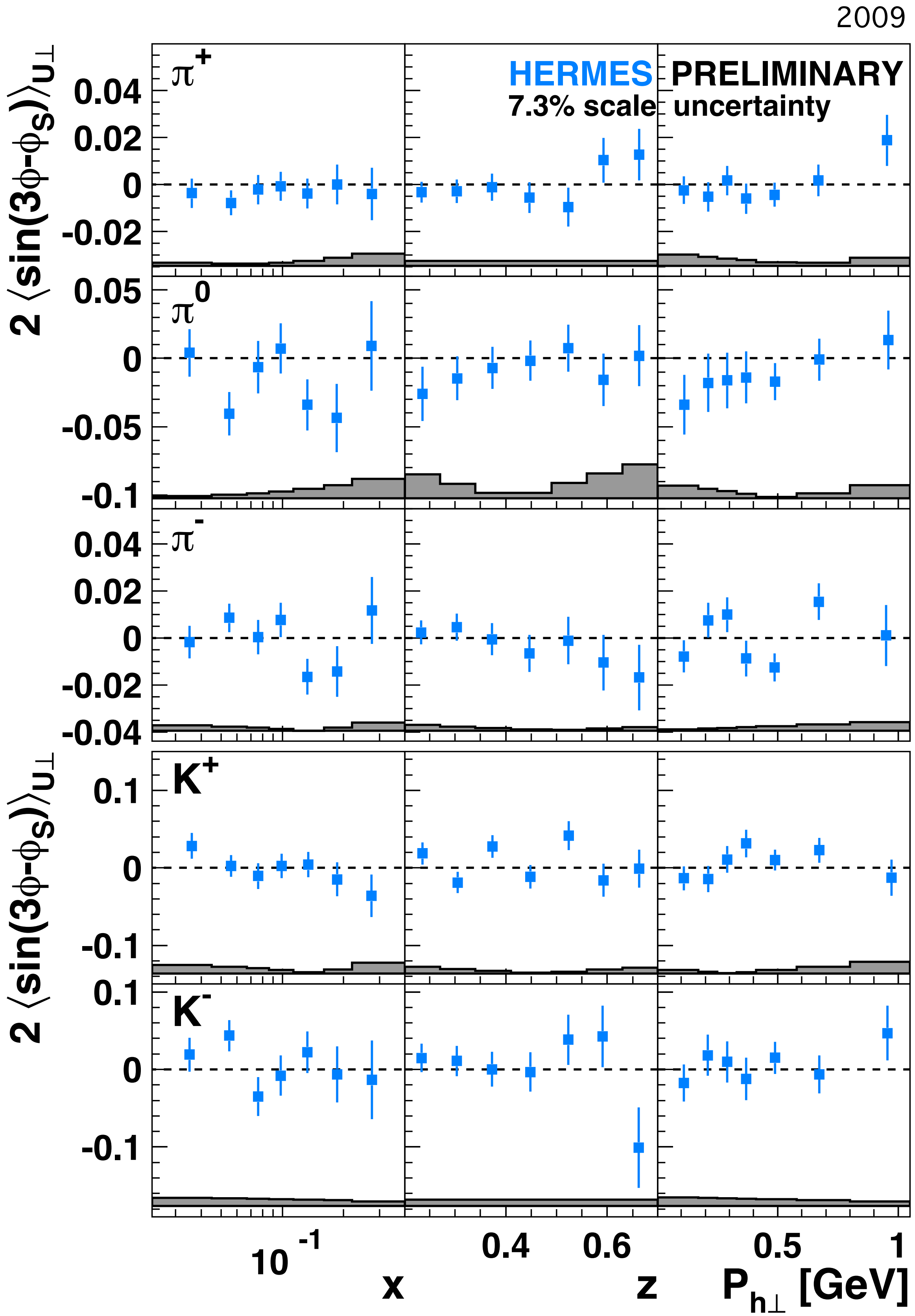

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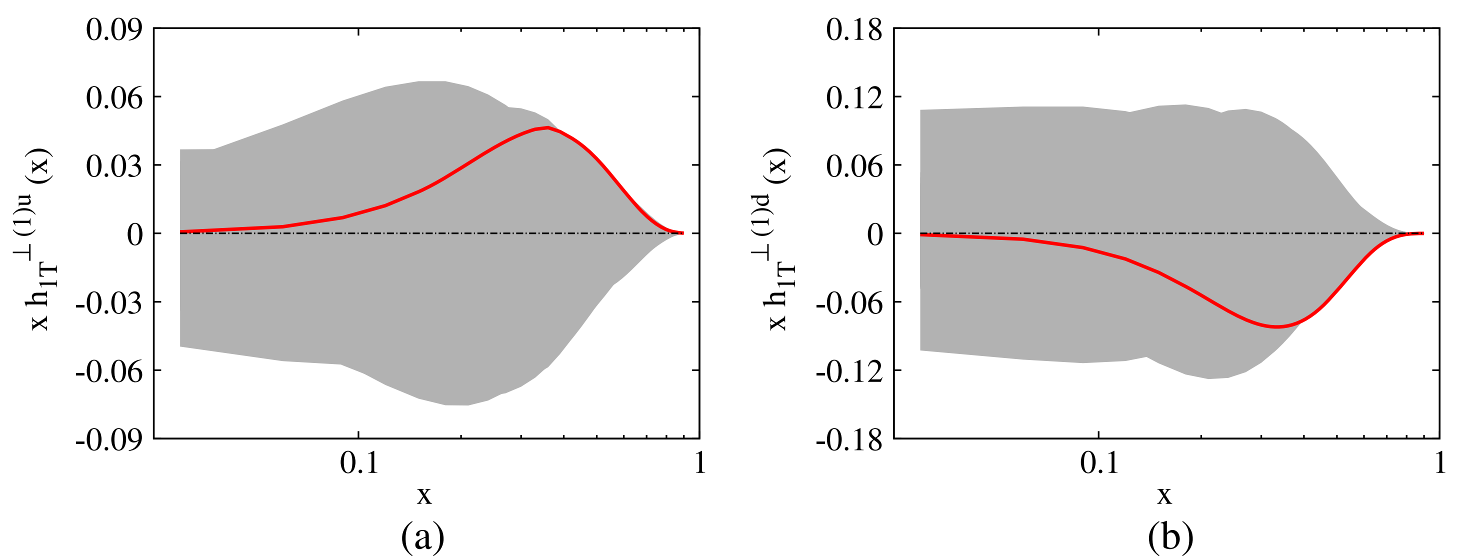
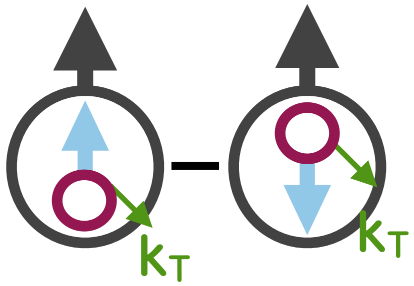
C. Lefky and A. Prokudin, PRD 91 (2015) 034010



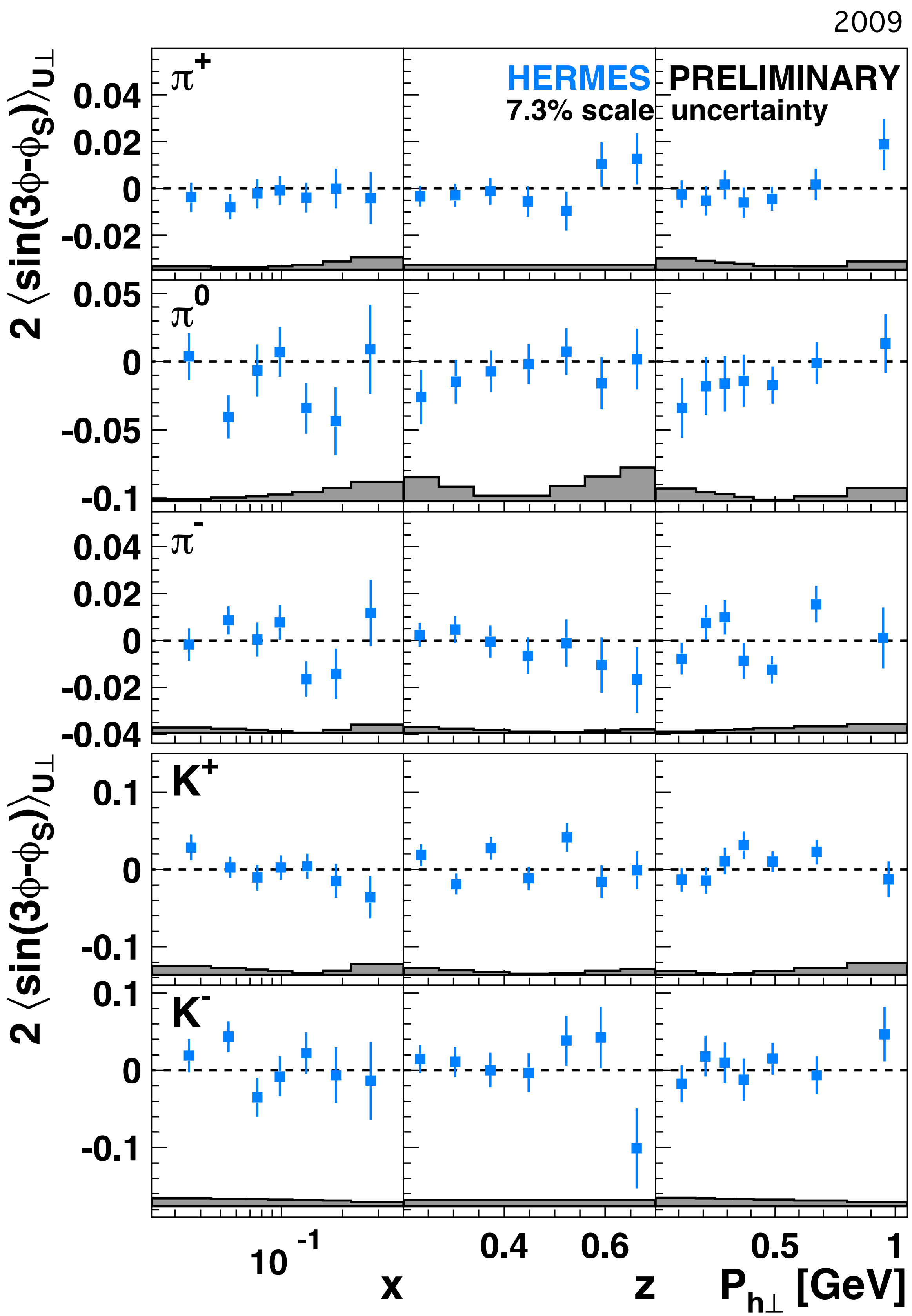
data from Jefferson Lab Hall A

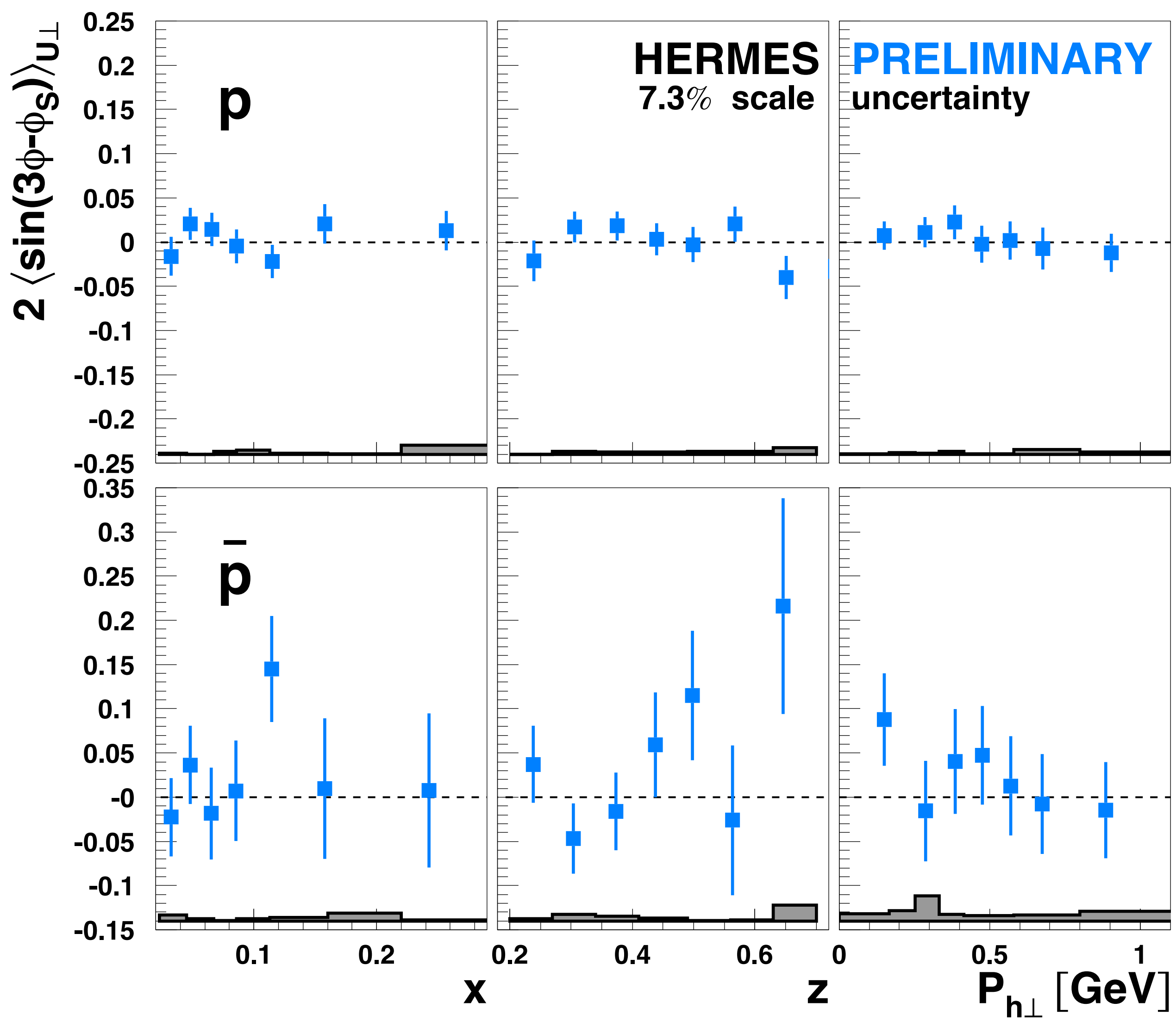
preliminary data from COMPASS, HERMES



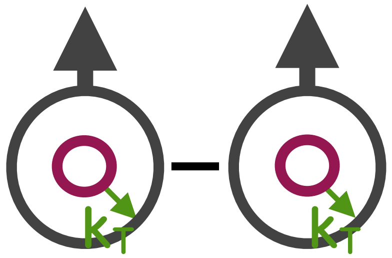
Pretzelosity amplitudes

$$\mathcal{C}[h_{1T}^{\perp,q} \times H_1^{\perp,q}]$$





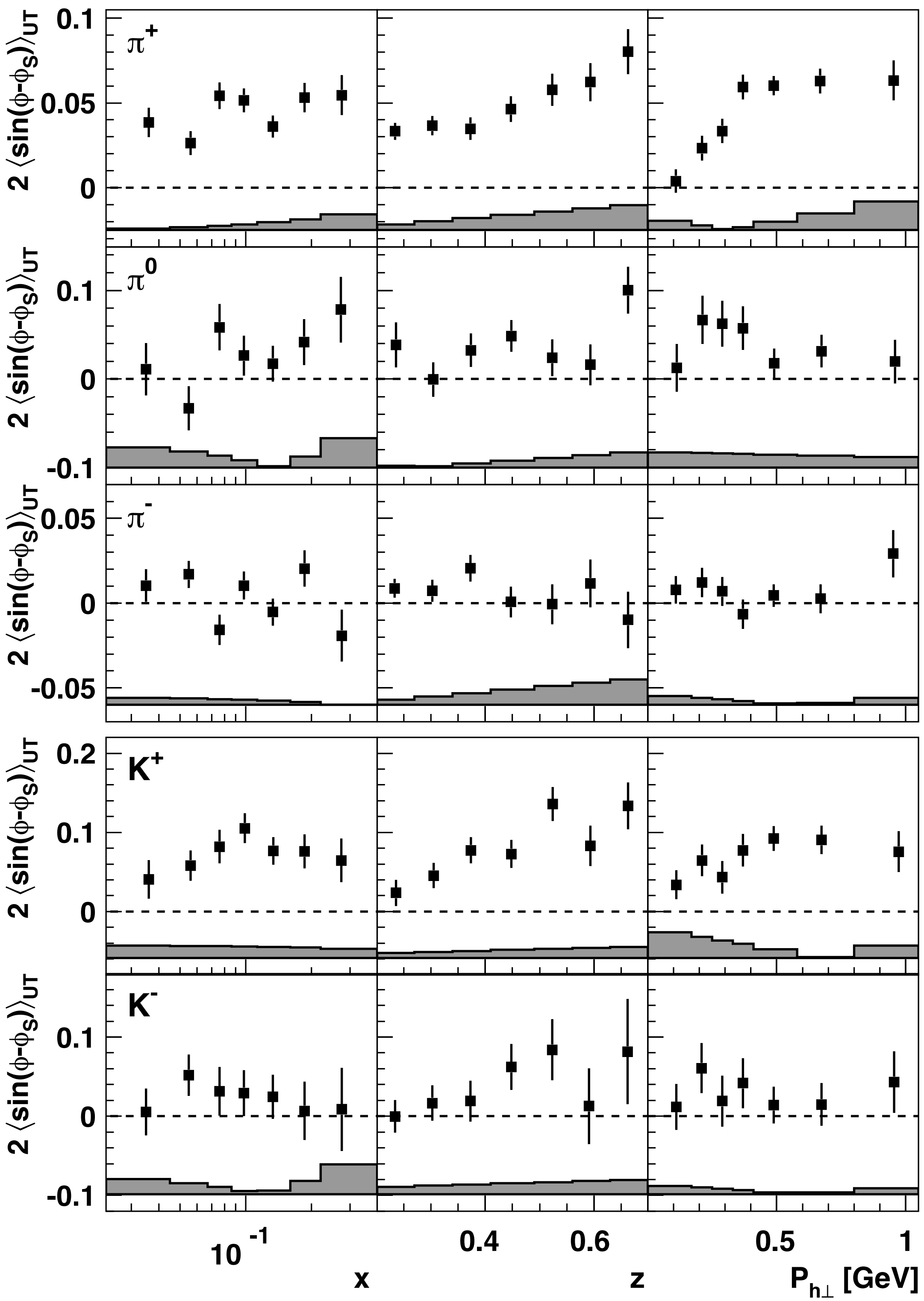
- Consistent with zero
- No clear kinematic dependencies in 3D
- No 3D for antiprotons

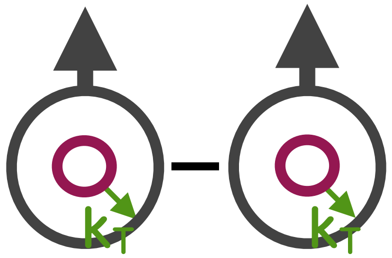


Sivers amplitudes

$$\mathcal{C}[f_{1T}^{\perp,q} \times D_1^q]$$

Phys. Rev. Lett. 103 (2009) 152002





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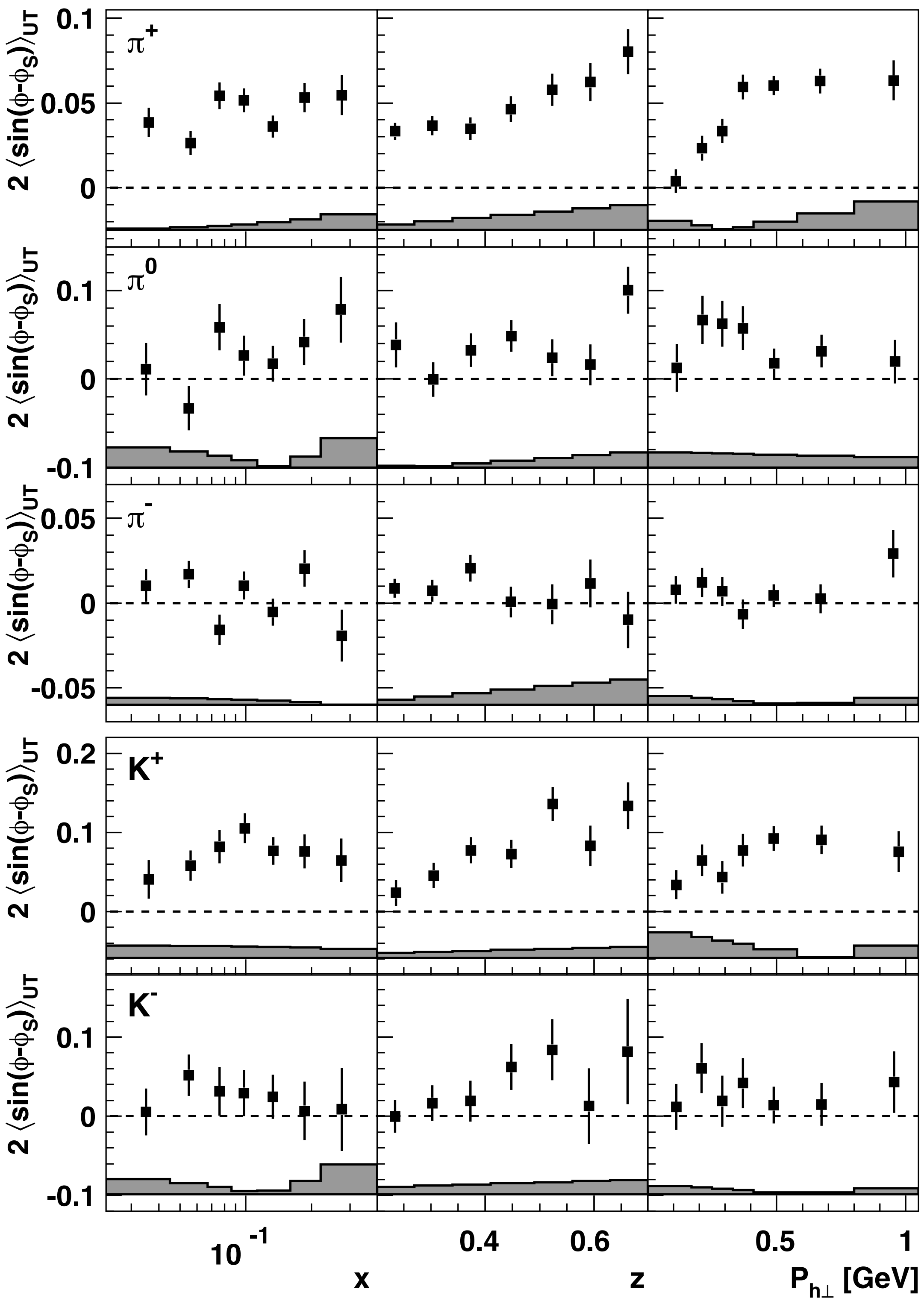
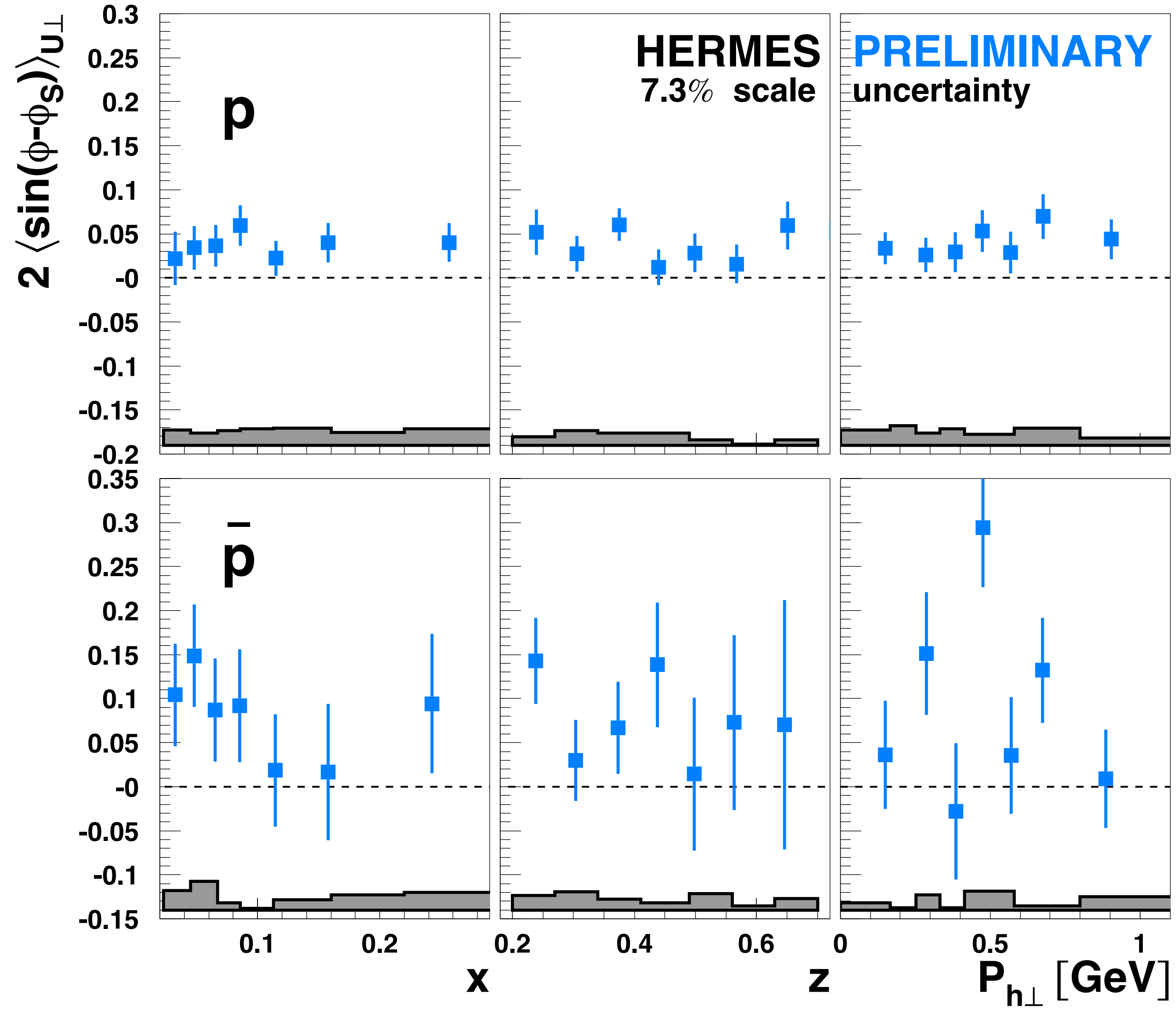
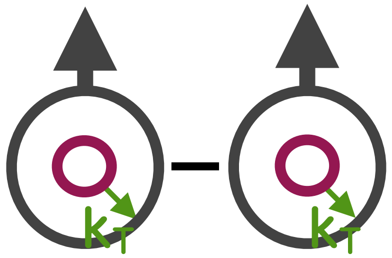
Phys. Rev. Lett. 103 (2009) 152002



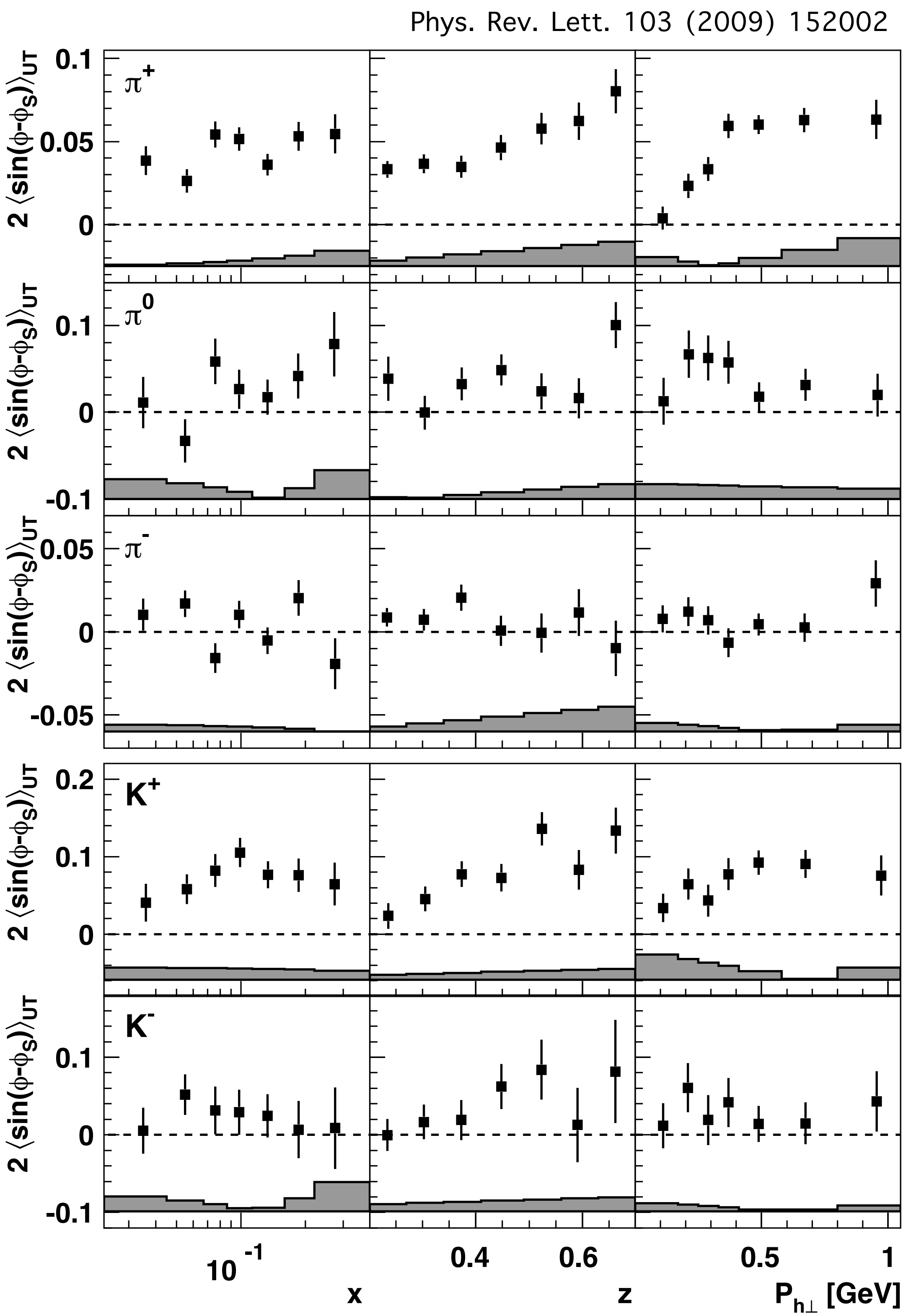


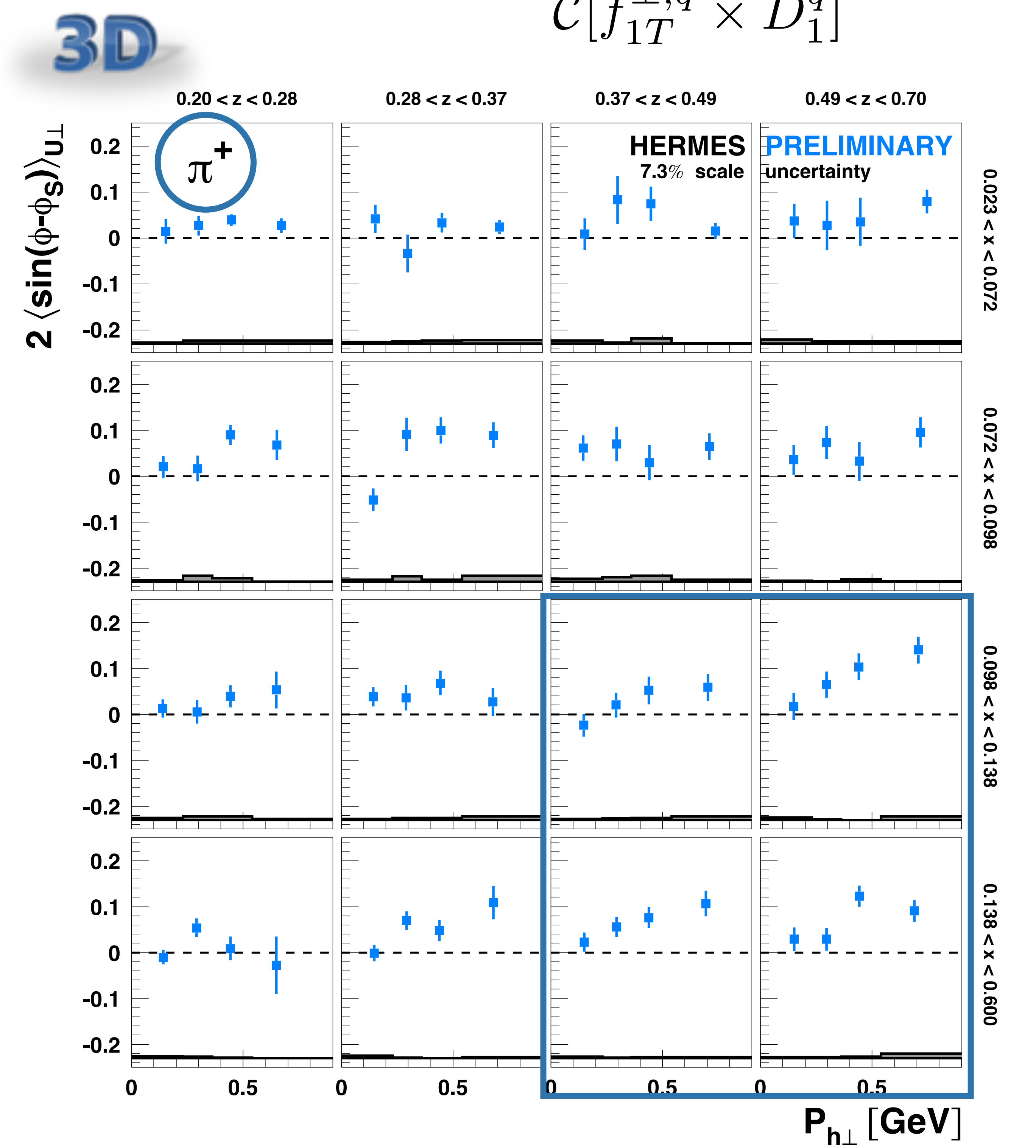
Positive Sivers amplitude for (anti-)protons, same size as for π^+

Sivers amplitudes

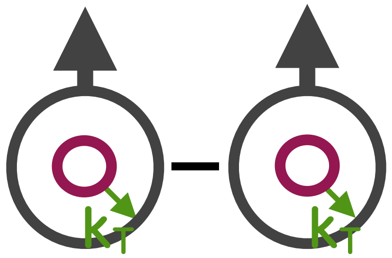


$$\mathcal{C}[f_{1T}^{\perp,q} \times D_1^q]$$





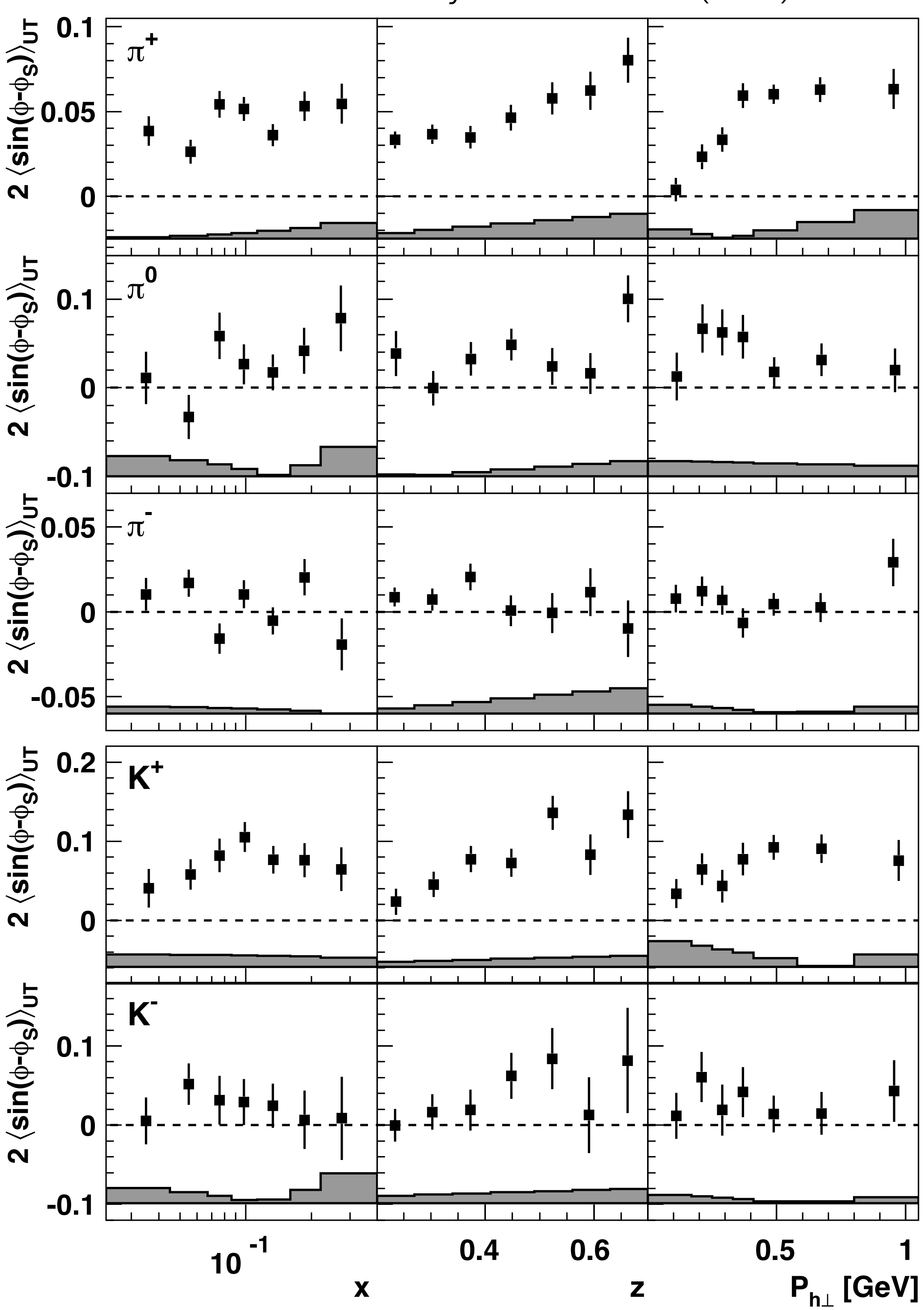
Largest at large x and z, where purest u-quark probe

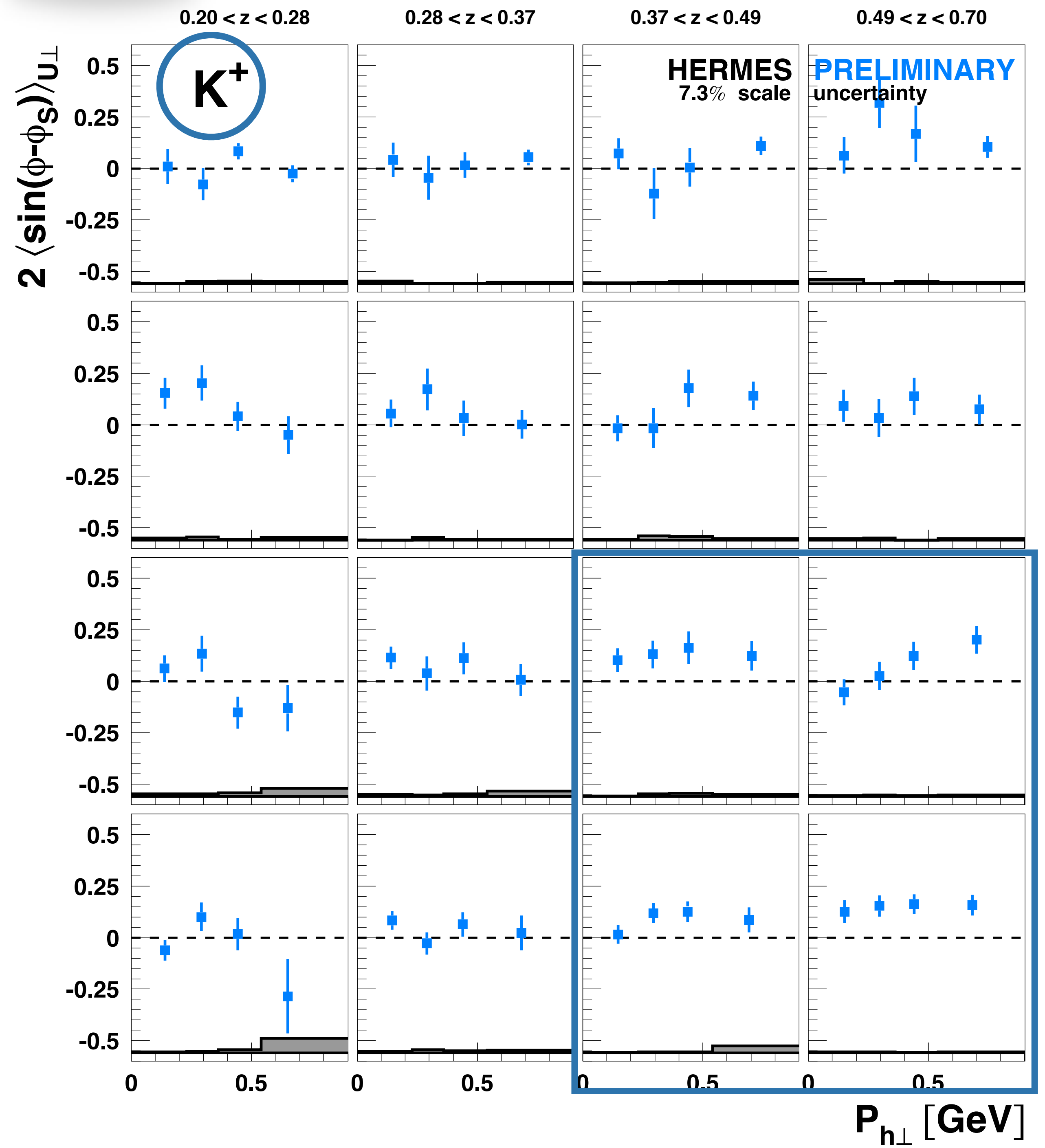


Sivers amplitudes

$$\mathcal{C}[f_{1T}^{\perp,q} \times D_1^q]$$

Phys. Rev. Lett. 103 (2009) 152002





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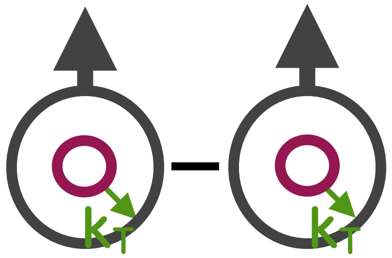

Sivers amplitudes

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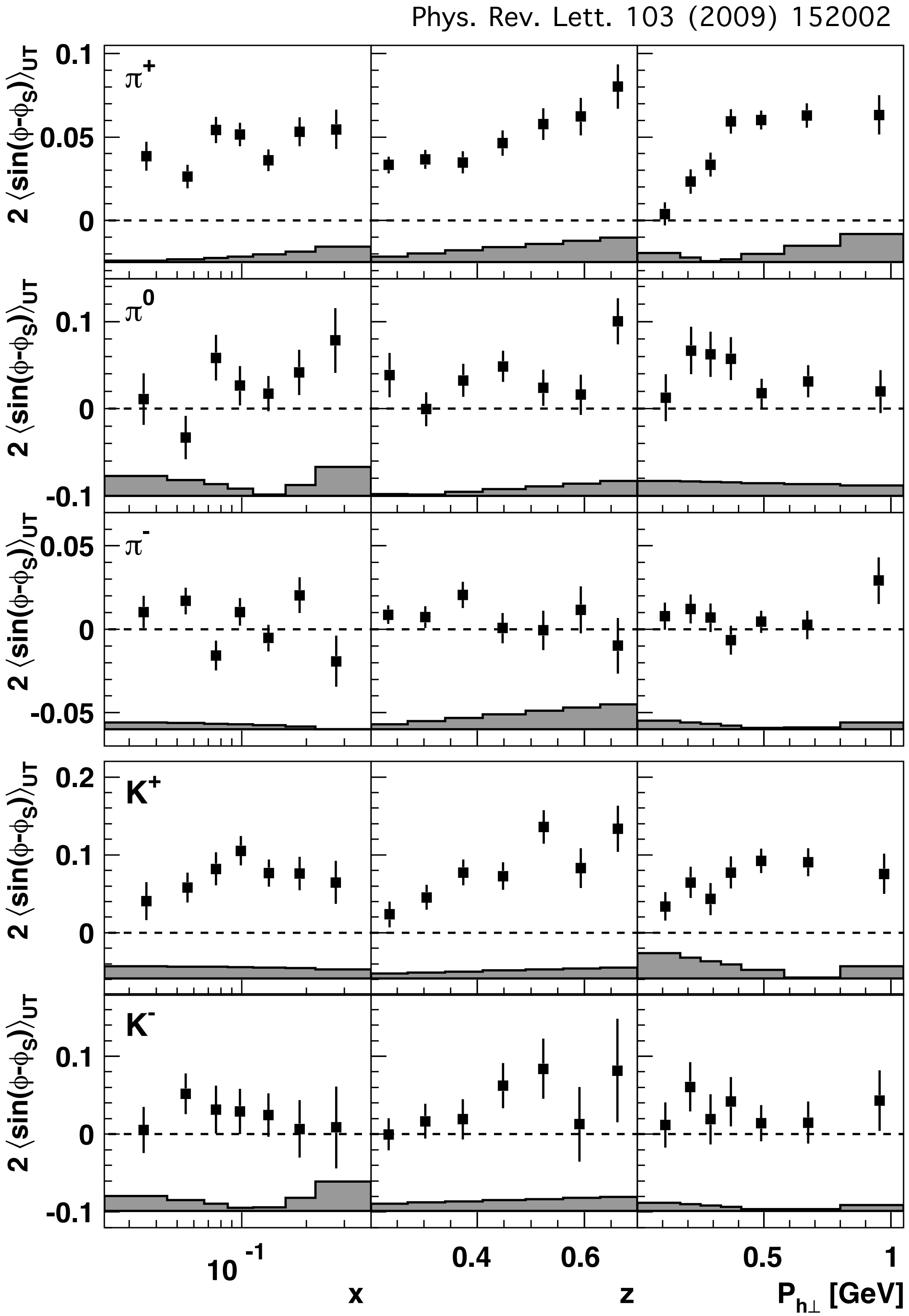
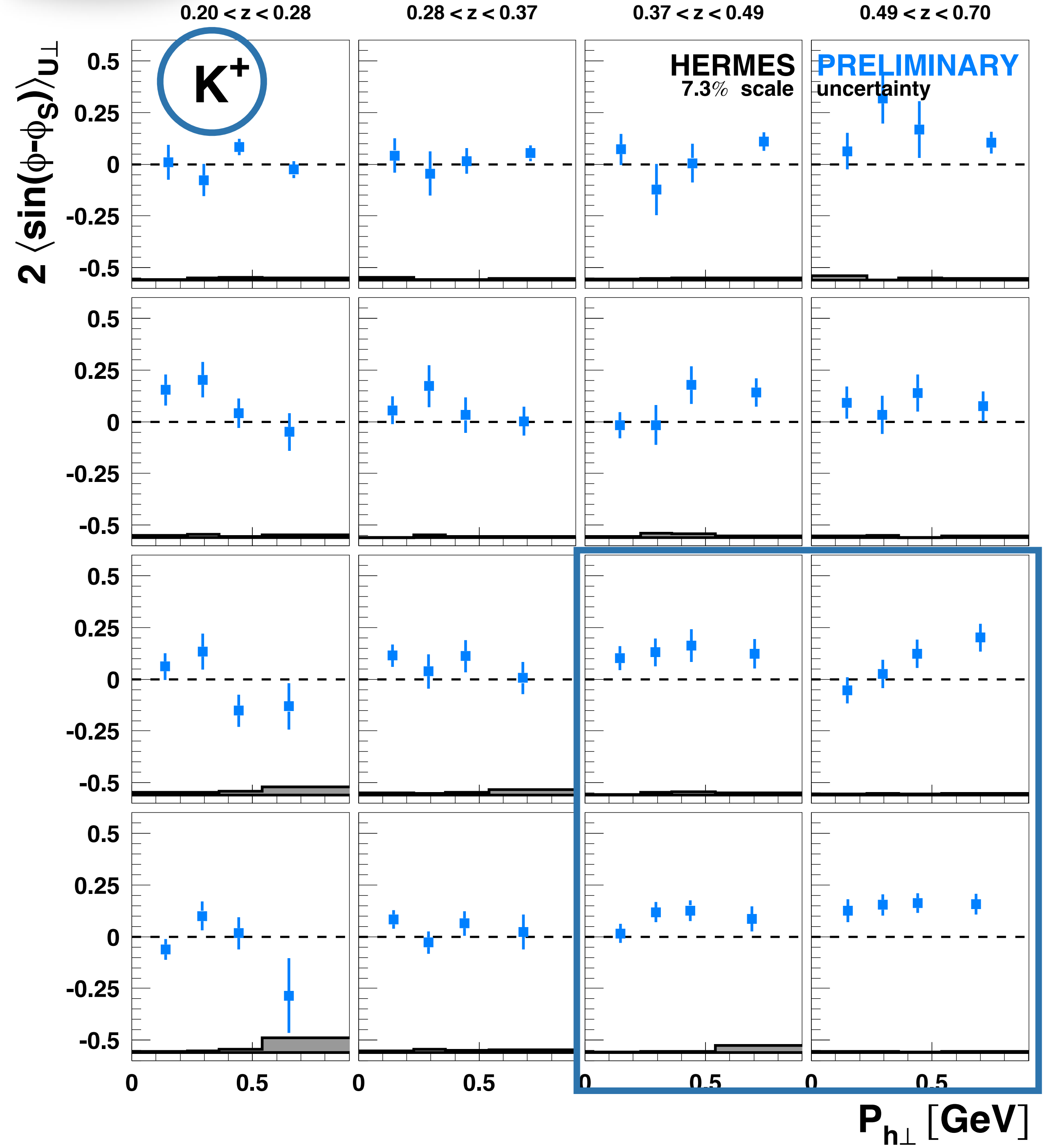




- Other hadrons, no clear kinematic dependencies in 3D
- No 3D for antiprotons

Twist-3: $\langle \sin(\phi_S) \rangle_{UT}$

$$\langle \sin(\phi_S) \rangle_{UT}$$
$$\propto \mathcal{C}[\boxed{f_T^q} \times D_1^q, h_{1T}^q \times \boxed{\tilde{H}^q}, \boxed{h_T^q} \times H_1^{\perp,q}, g_{1T}^{\perp,q} \times \boxed{\tilde{G}^{\perp,q}}, \boxed{h_T^{\perp,q}} \times H_1^{\perp,q}, f_{1T}^{\perp,q} \times \boxed{\tilde{D}^{\perp,q}}]$$

twist-3

Twist-3: $\langle \sin(\phi_S) \rangle_{UT}$

$$\langle \sin(\phi_S) \rangle_{UT} \propto \mathcal{C}[\boxed{f_T^q} \times D_1^q, h_{1T}^q \times \boxed{\tilde{H}^q}, \boxed{h_T^q} \times H_1^{\perp,q}, g_{1T}^{\perp,q} \times \boxed{\tilde{G}^{\perp,q}}, \boxed{h_T^{\perp,q}} \times H_1^{\perp,q}, f_{1T}^{\perp,q} \times \boxed{\tilde{D}^{\perp,q}}]$$

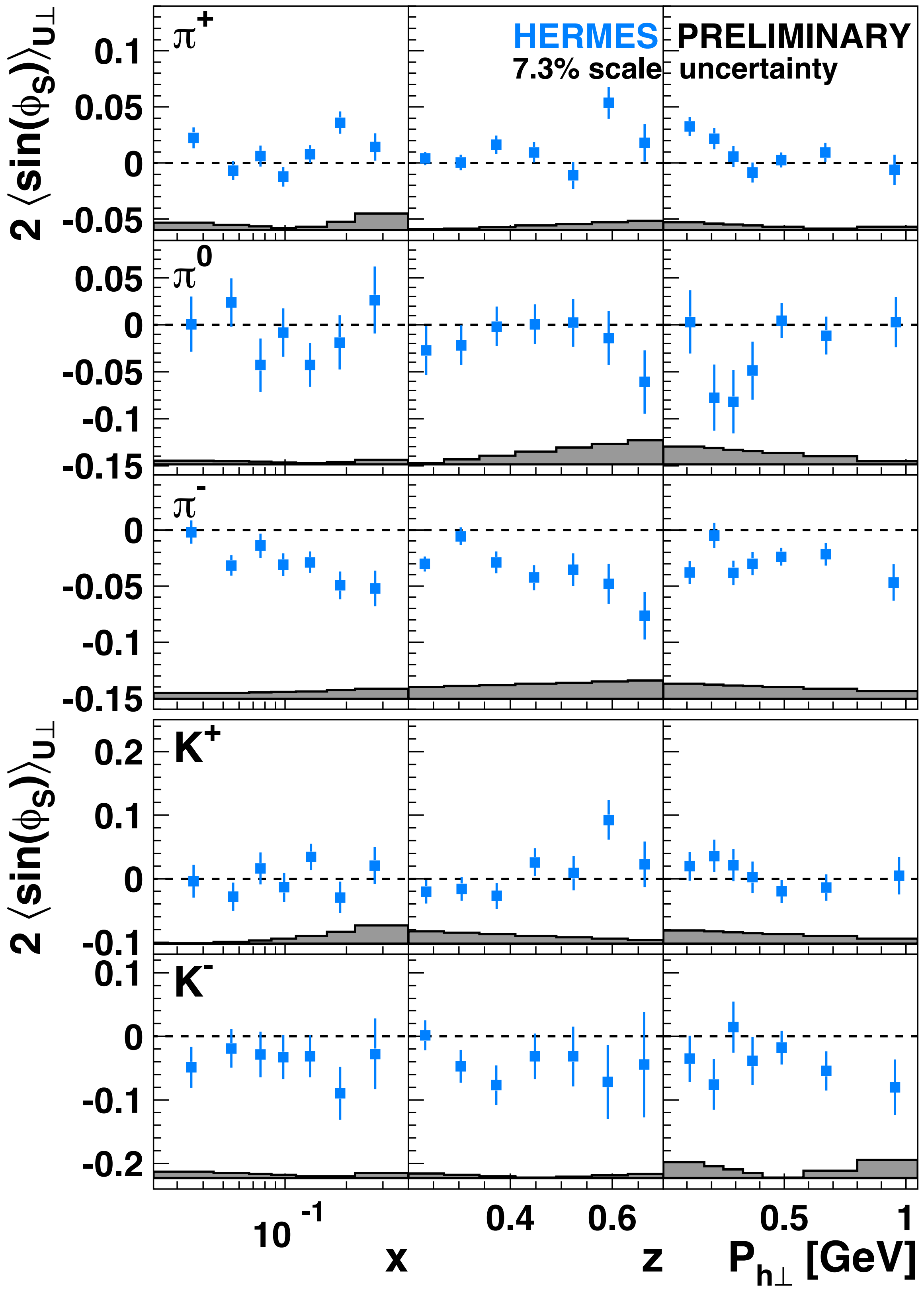
twist-3

integrate over hadron transverse momentum $P_{h\perp}$

$$\boxed{\langle \sin(\phi_S) \rangle_{UT} = -x \frac{2M_h}{Q} \sum_q e_q^2 h_{1T}^q \frac{\tilde{H}^q}{z}}$$

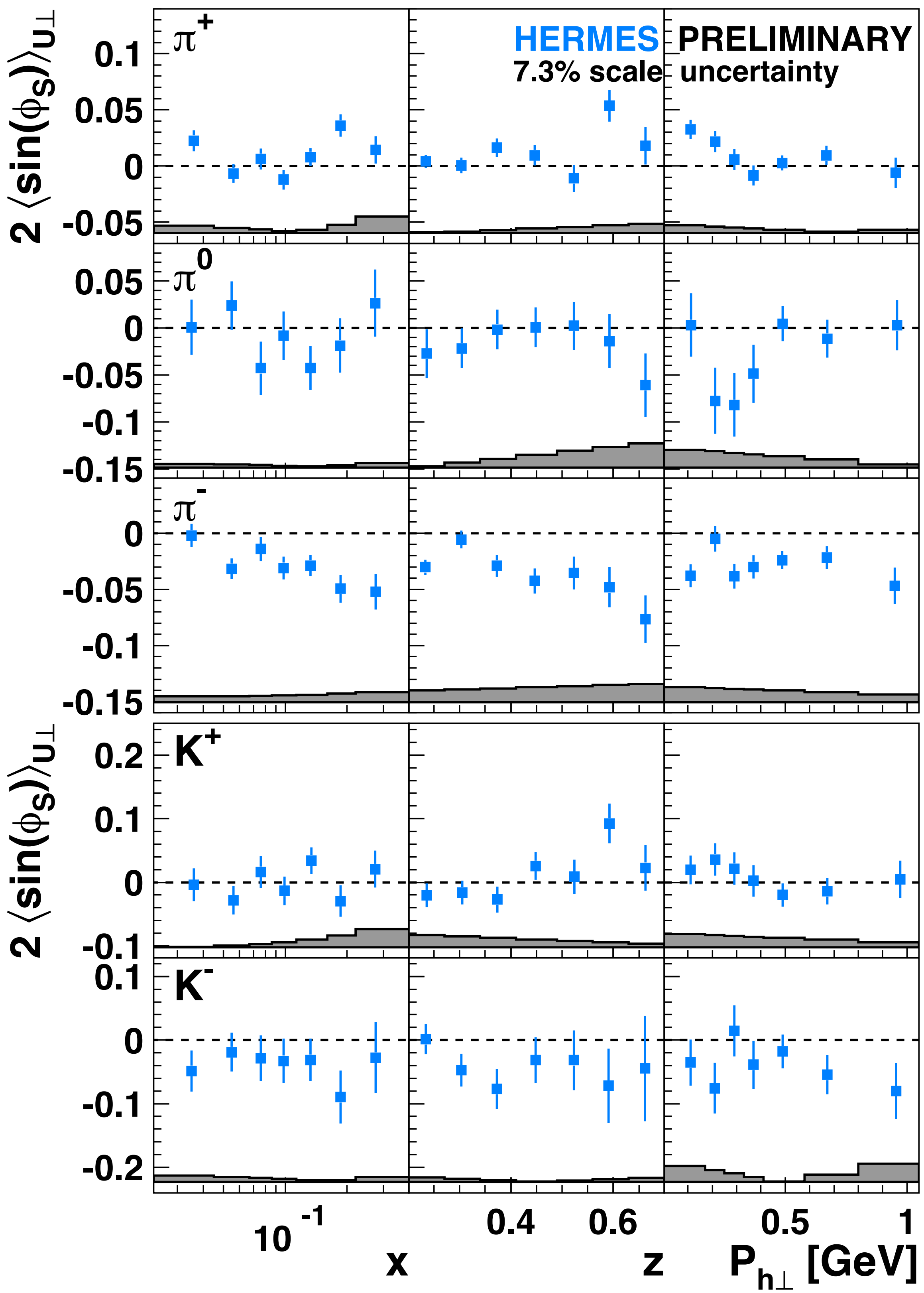
no convolution

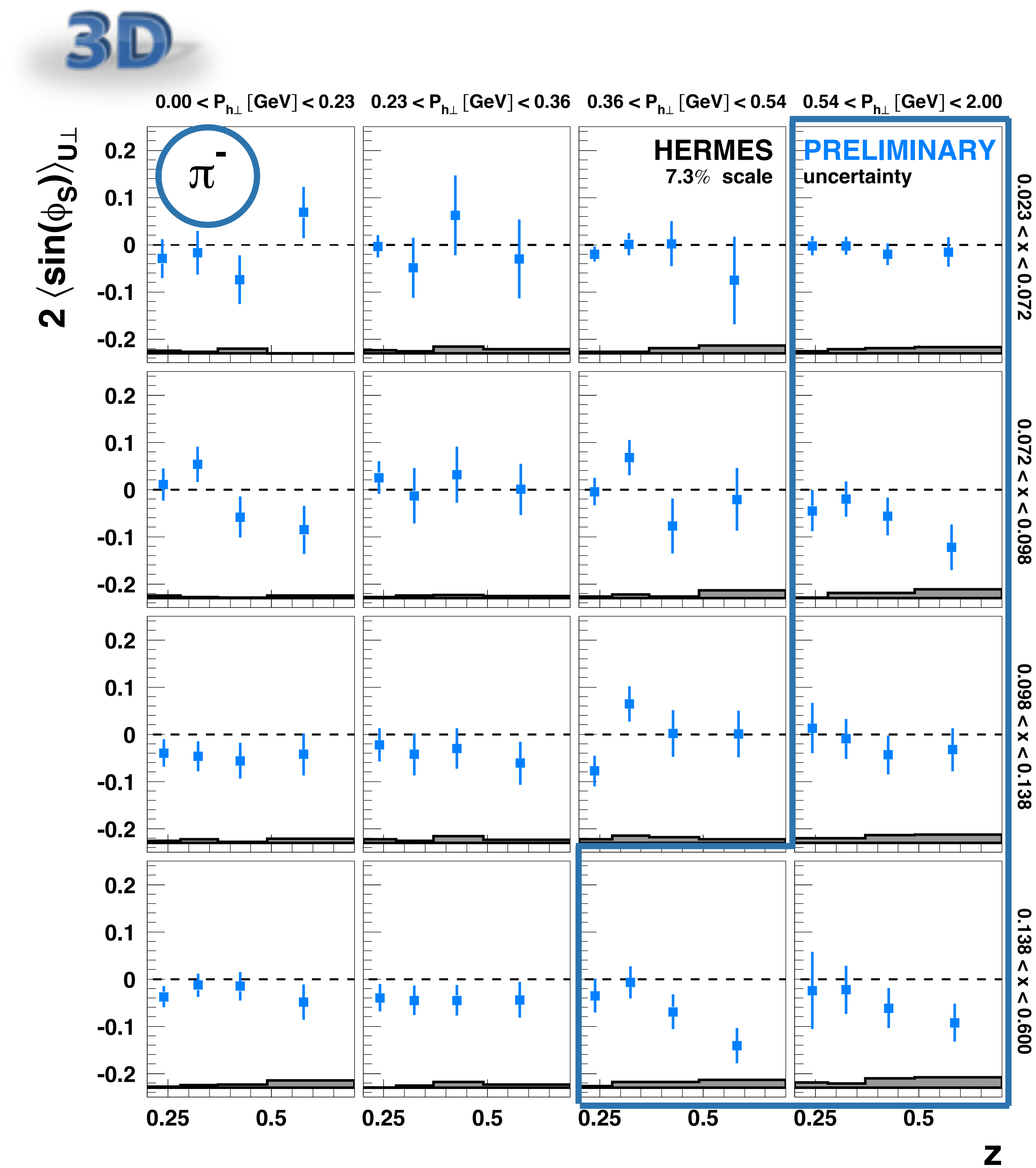
Twist-3: $\langle \sin(\phi_S) \rangle_{UT}$



- Significant non-zero signal for π^-, increasing with x, z

Twist-3: $\langle \sin(\phi_S) \rangle_{UT}$





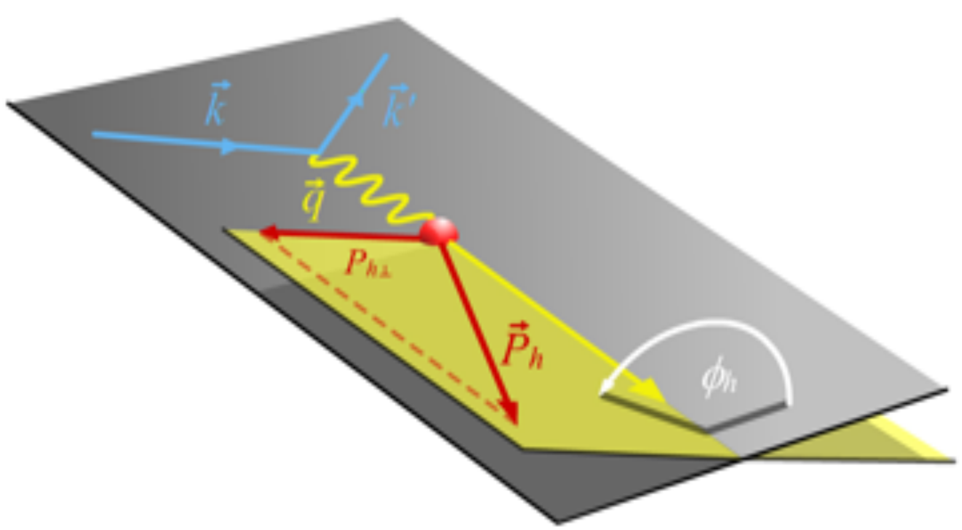
Increase with z, rather at larger x and $P_{h\perp}$

Presented amplitudes

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

- Longitudinally polarized e^+/e^- beam
- Unpolarized H and D target

$\longrightarrow$ Results for charged pions, kaons, (anti-)protons



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

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

Twist-3: $\langle \sin(\phi) \rangle^h_{LU}$

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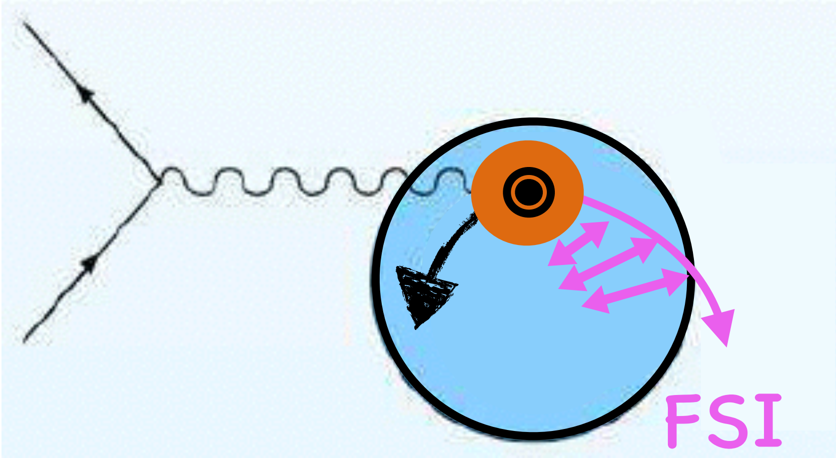
Boer-Mulders PDF

Chiral-odd T-even twist-3 FF

Boer-Mulders PDF



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

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

Chiral-odd T-even twist-3 PDF

Collins FF

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

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

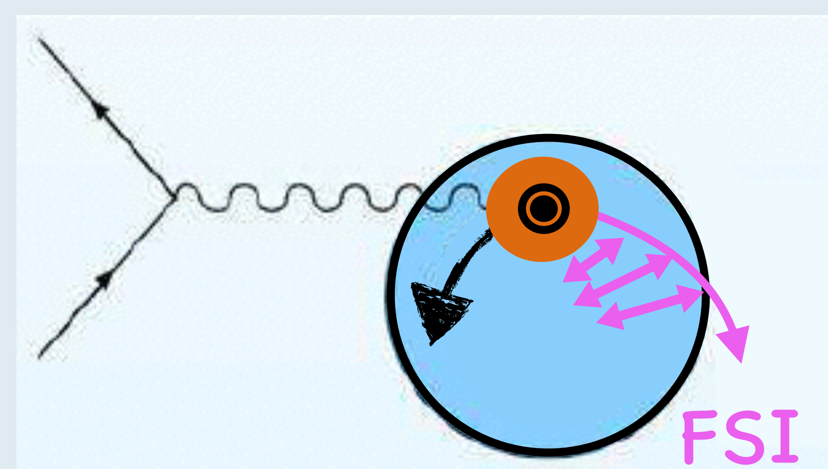
$$e(x) = e^{\mathrm{WW}}(x) + \bar{e}(x)$$

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

force on struck quark at t=0

M. Burkardt, arXiv:0810.3589

Boer-Mulders PDF



FSI: t=0→∞

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

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

Chiral-odd T-even twist-3 PDF

Collins FF

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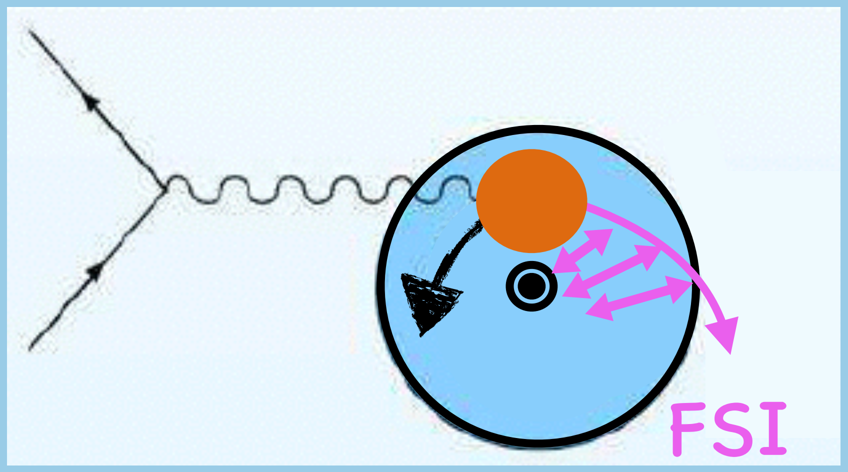
$e_2 \equiv \int_0^1 dx\, x^2 \bar{e}(x)$

force on struck qu

M. Burkardt,

$g_2(x) \Longleftrightarrow$ Sivers PDF

Sivers PDF



FSI: t=0→∞

M. Burkardt, arXiv:0810.3589

Twist-3: $\langle \sin(\phi) \rangle^h_{LU}$

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

Chiral-even T-odd twist-3 PDF

spin-independent FF

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

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

Chiral-even T-odd twist-3 PDF

spin-independent FF

Only term to survive in TMD single-jet inclusive DIS

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

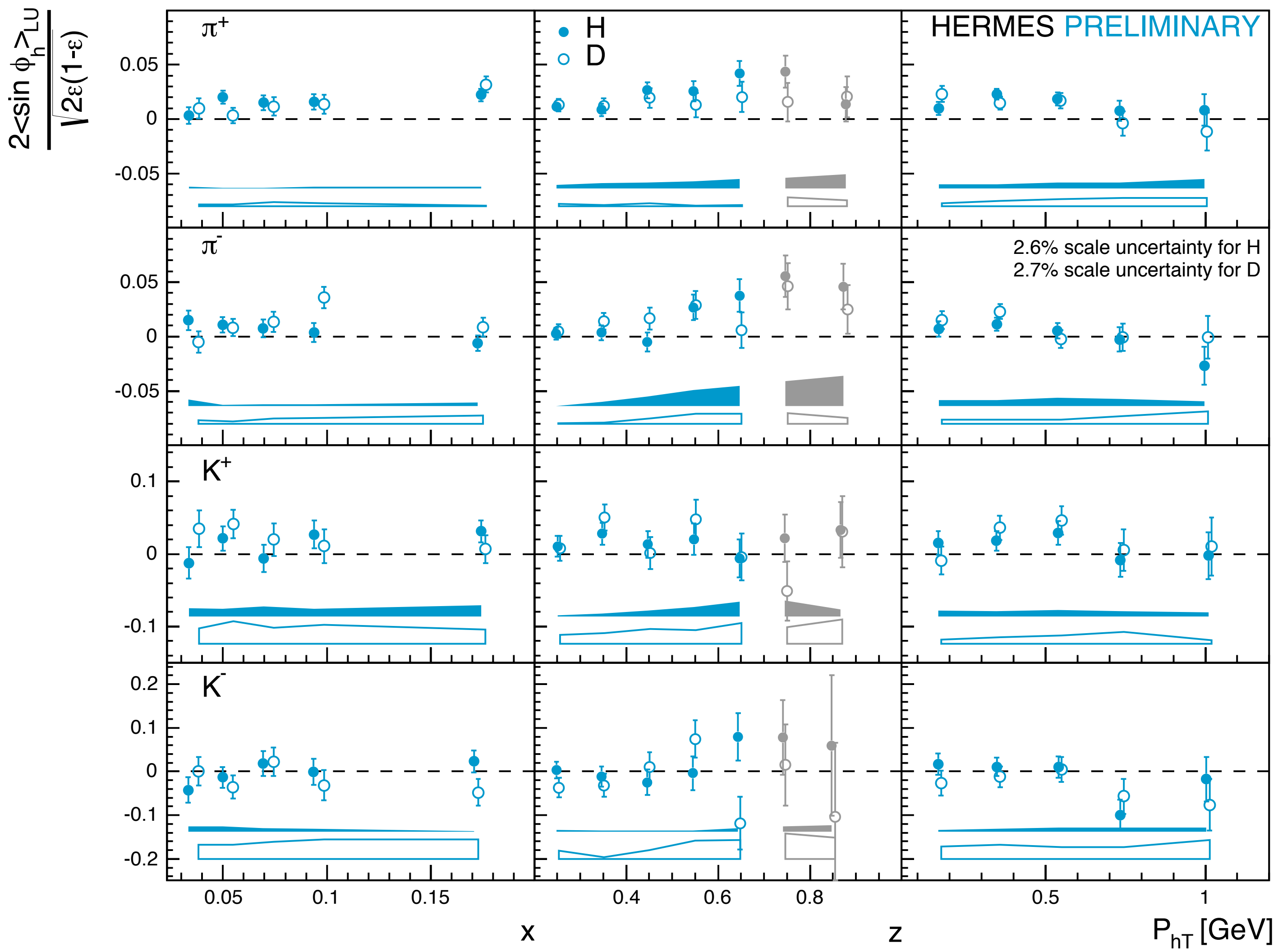
Twist-3: $\langle\sin(\phi)\rangle_{LU}^{h}$

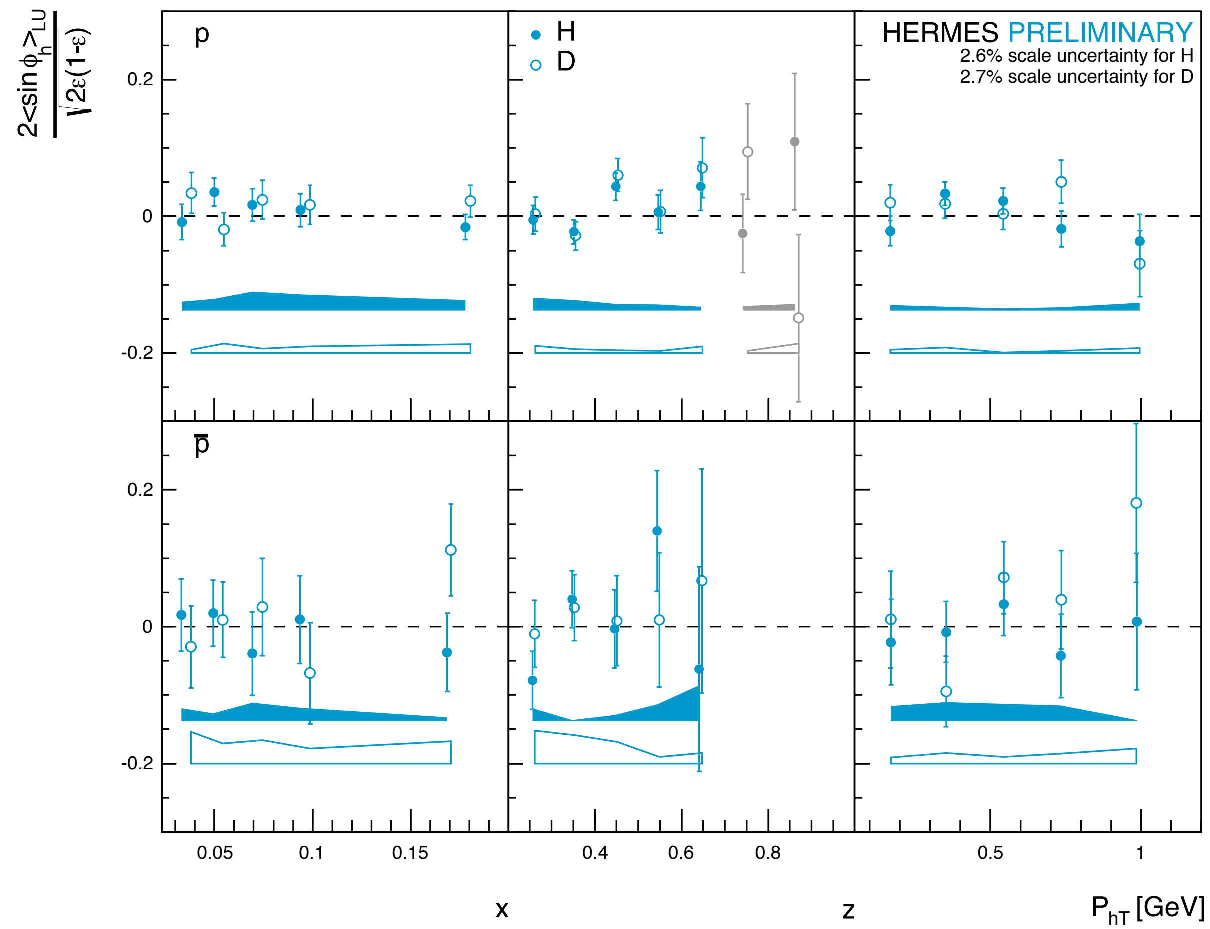
$$\langle\sin(\phi)\rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^{\perp}\times\tilde{E}, x\,e\times H_1^{\perp}, x\,g^{\perp}\times D_1, f_1\times\tilde{G}^{\perp}\right]$$

spin-independent PDF

chiral-even, T-odd twist-3 FF

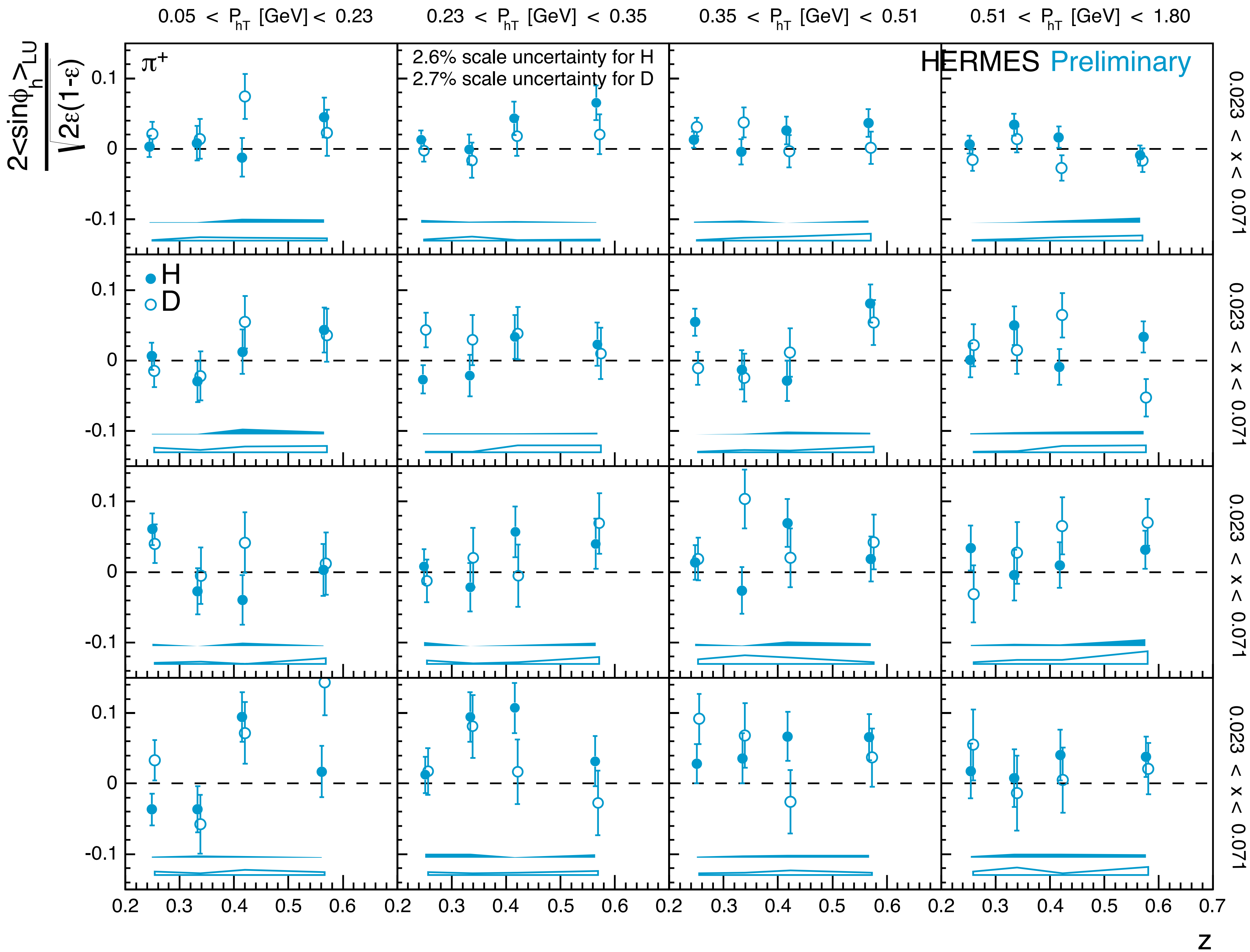
Twist-3: $\langle \sin(\phi) \rangle^{h}_{LU}$





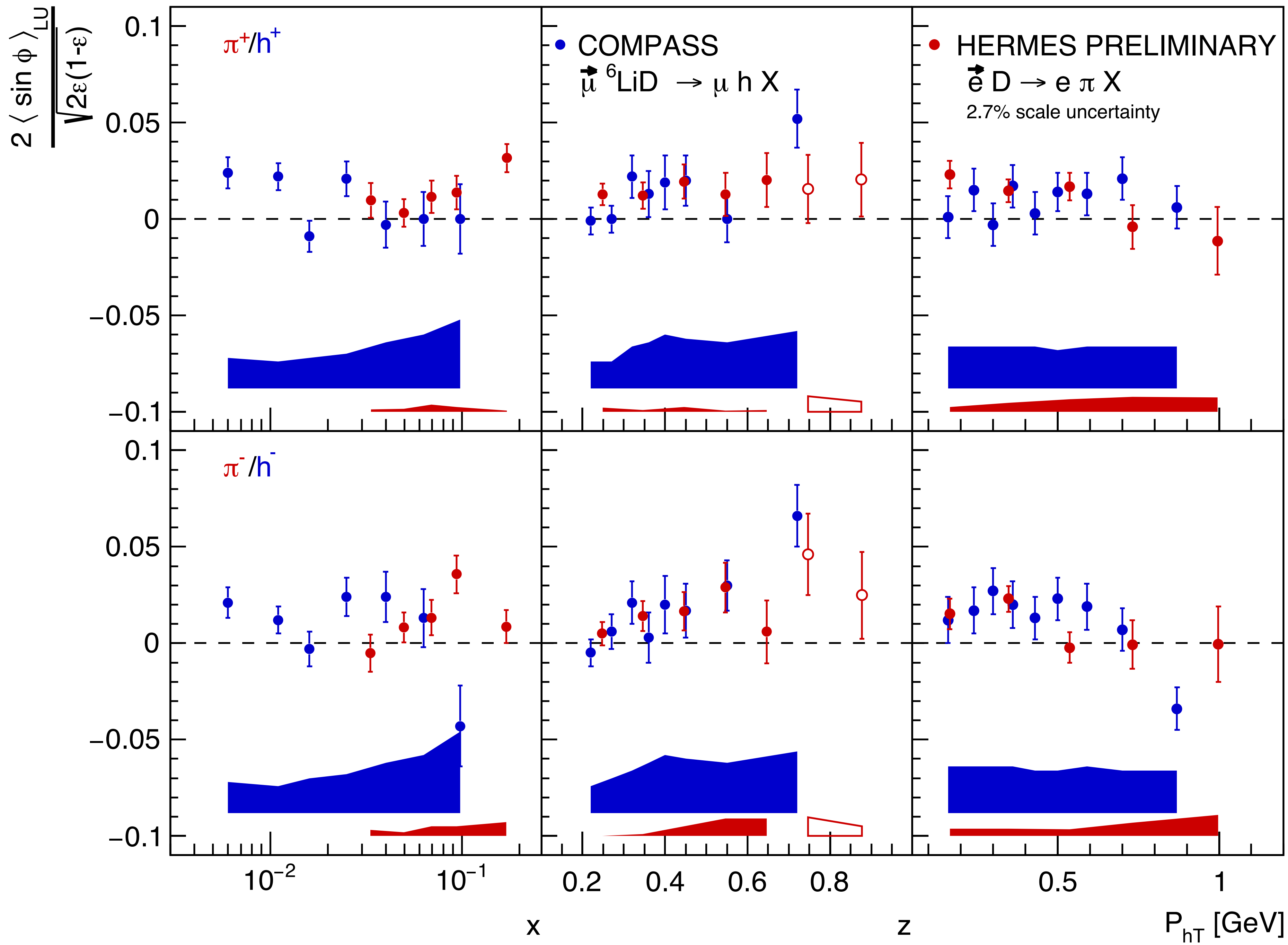
- Agreement H and D data
- Positive results for pions

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



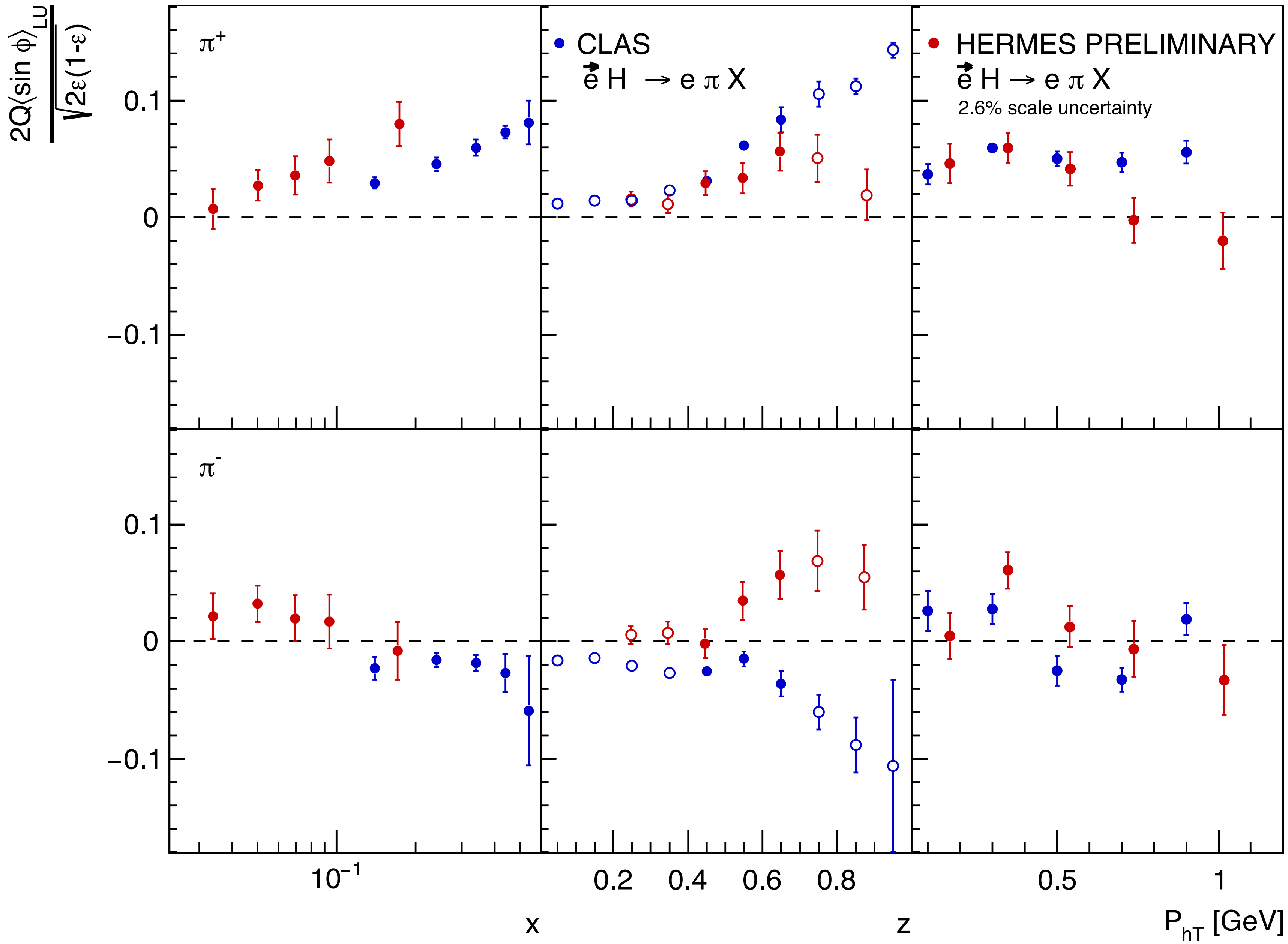
- No clear kinematic dependencies en 3D
- No 3D for anti-protons

Twist-3: $\langle \sin(\phi) \rangle^h_{LU}$



- Both measurements give compatible results

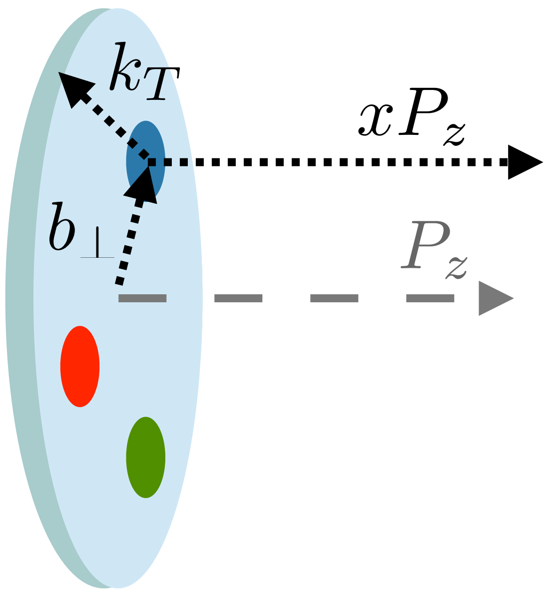
Twist-3: $\langle \sin(\phi) \rangle_{LU}^{h}$



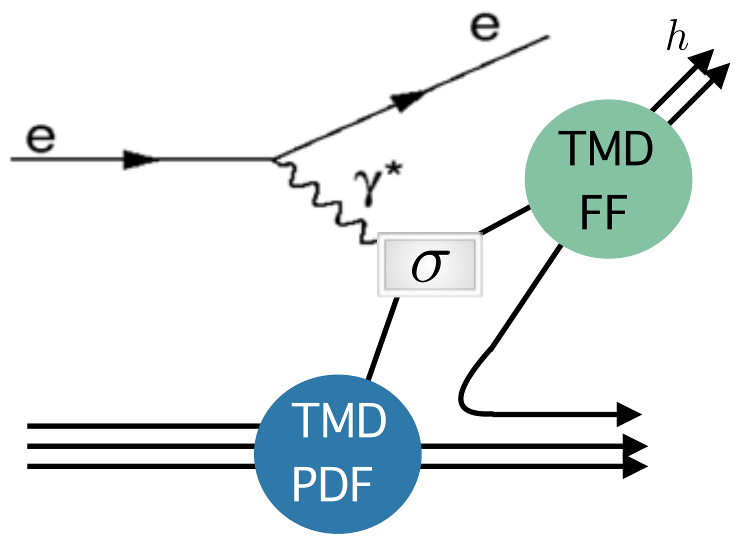
- Opposite behaviour for π^- z projection due to different x range probed
- CLAS probes higher x region: more sensitive to $e \times H_1^\perp$?

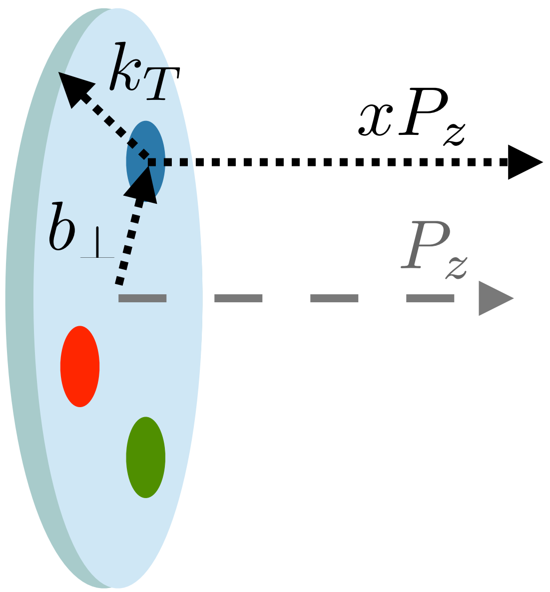
$$\langle \sin(\phi) \rangle_{LU}^{h} \propto \mathcal{C}\left[h_1^\perp \times \tilde{E}, \boxed{x\,e \times H_1^\perp}, x\,g^\perp \times D_1, f_1 \times \tilde{G}^\perp\right]$$

Summary

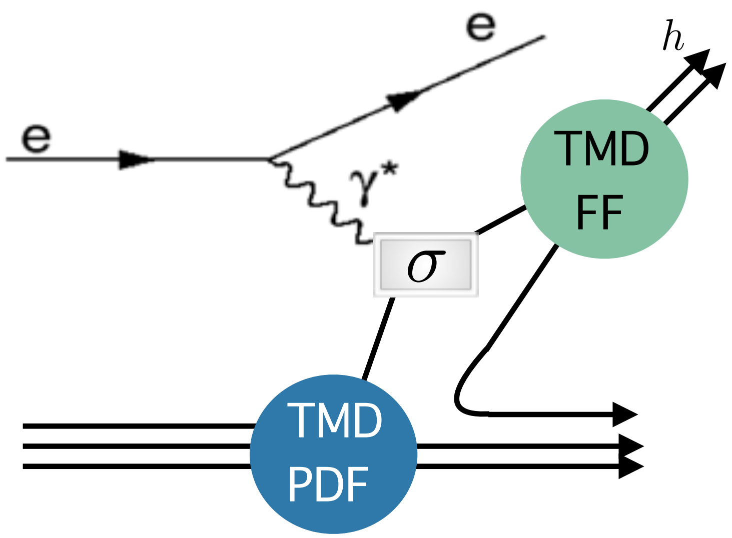


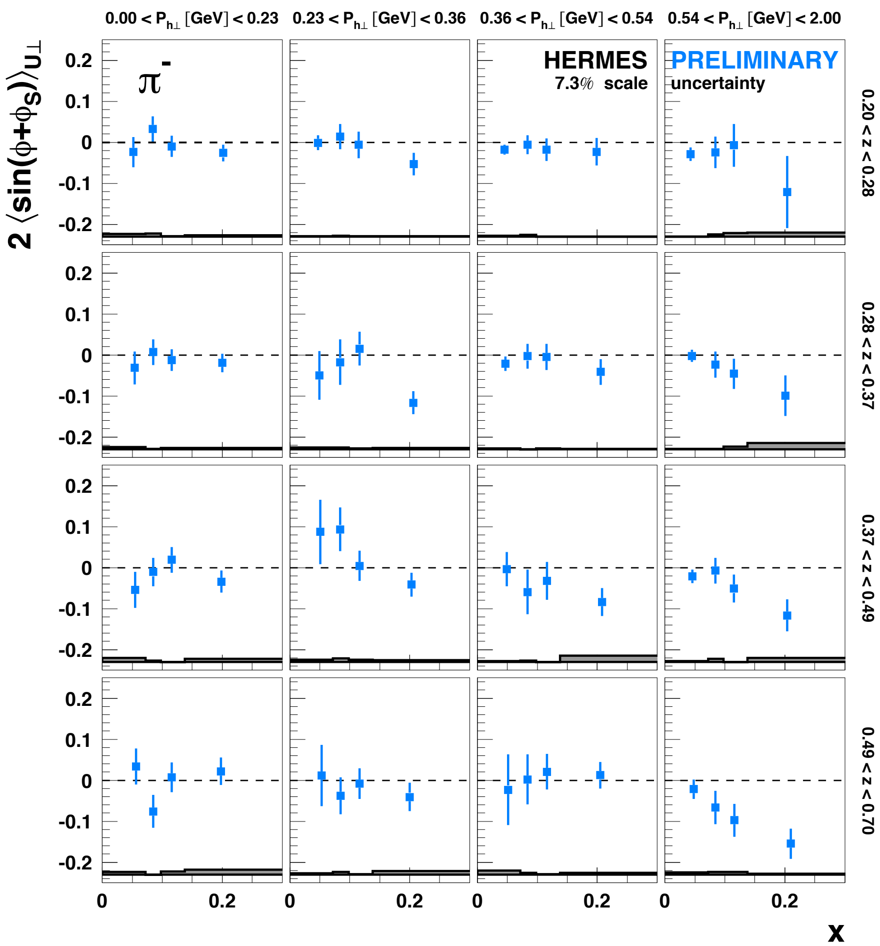
Summary

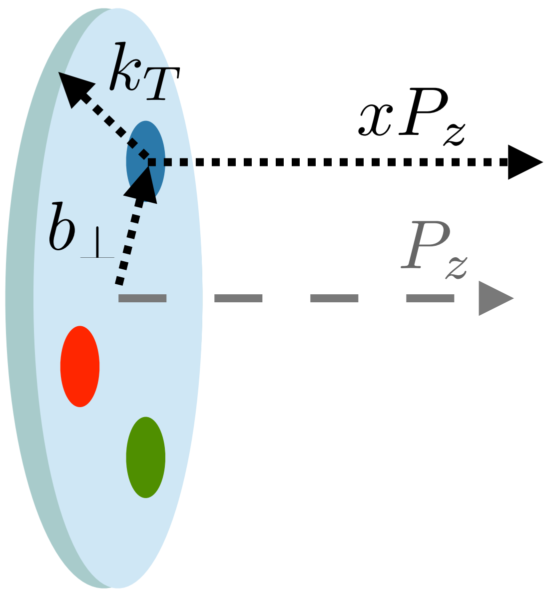




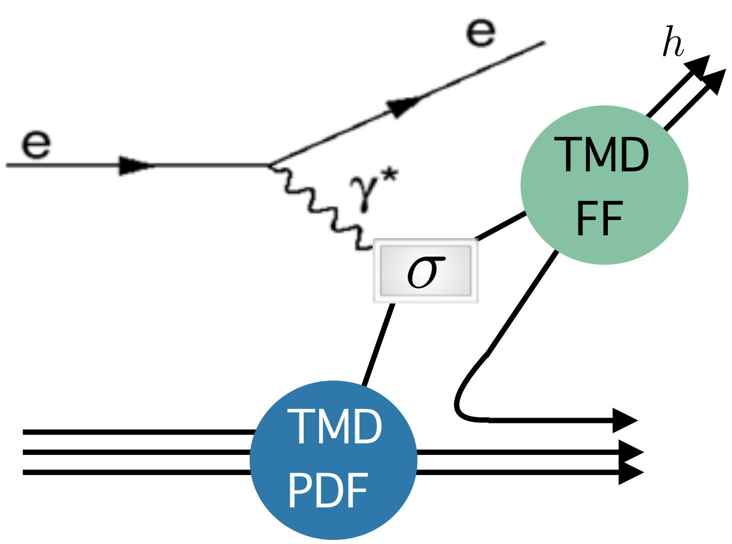
Summary


e
e
h
γ*
TMD
FF
σ
TMD
PDF

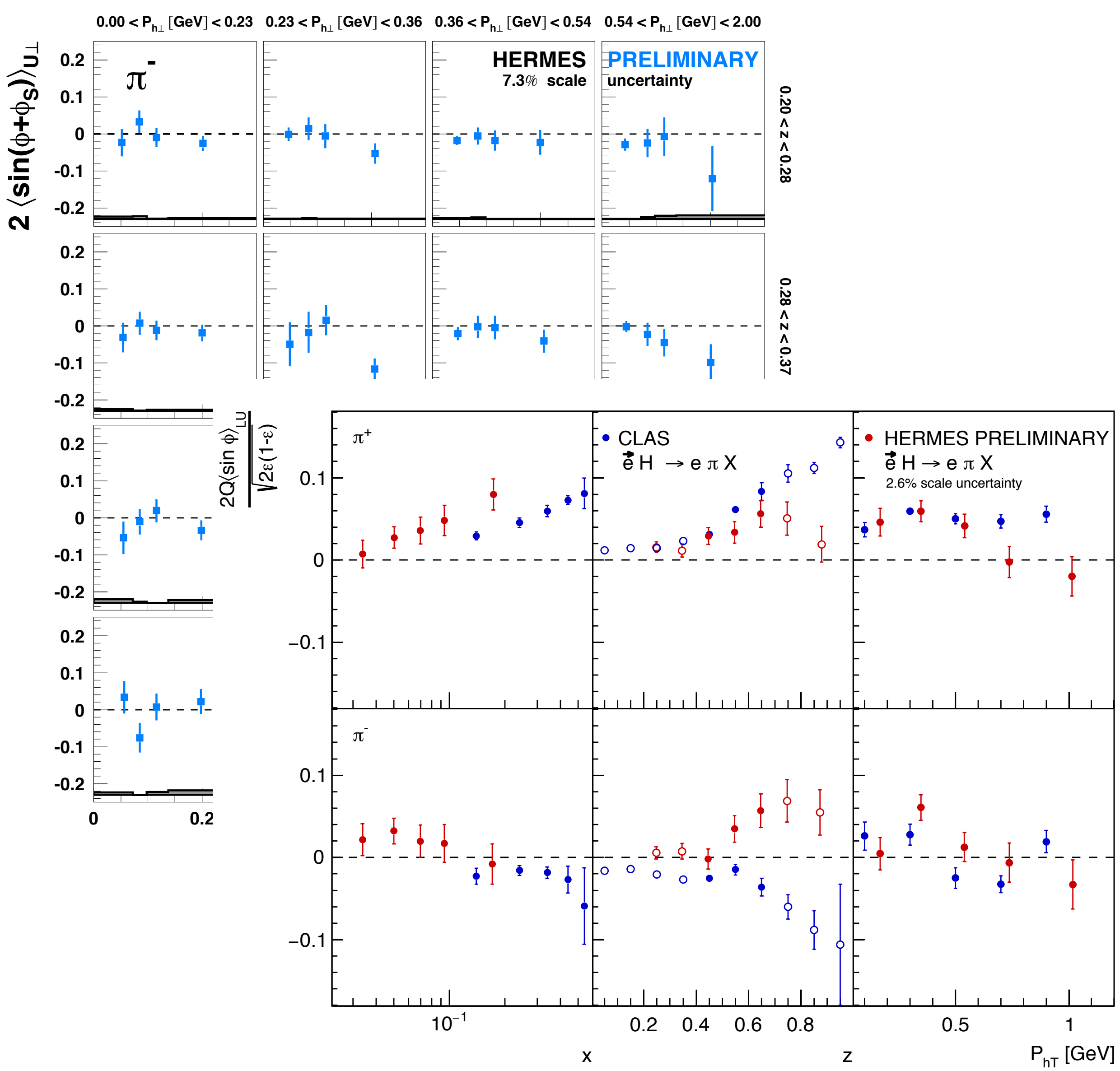

HERMES
7.3% scale
PRELIMINARY
uncertainty
0.00 < P_h⊥ [GeV] < 0.23
0.23 < P_h⊥ [GeV] < 0.36
0.36 < P_h⊥ [GeV] < 0.54
0.54 < P_h⊥ [GeV] < 2.00
0.20 < z < 0.28
0.28 < z < 0.37
0.37 < z < 0.49
0.49 < z < 0.70
2 ⟨sin(φ+φ_S)⟩_UT
x


k_T
xP_z
$b_\perp$
P_z

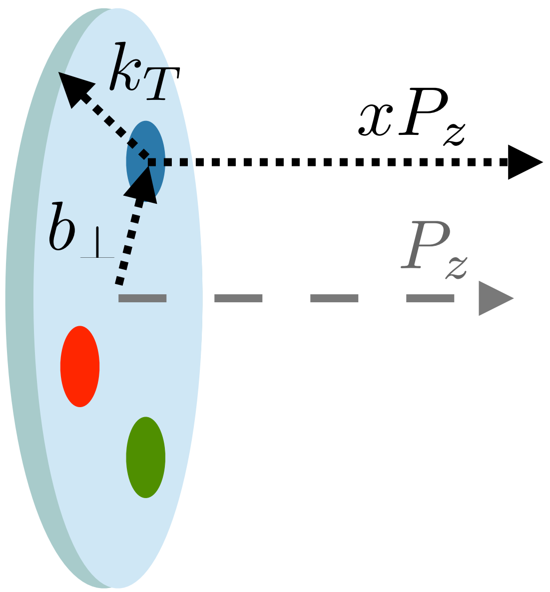
Summary



e
e
h
γ*
TMD
FF
σ
TMD
PDF

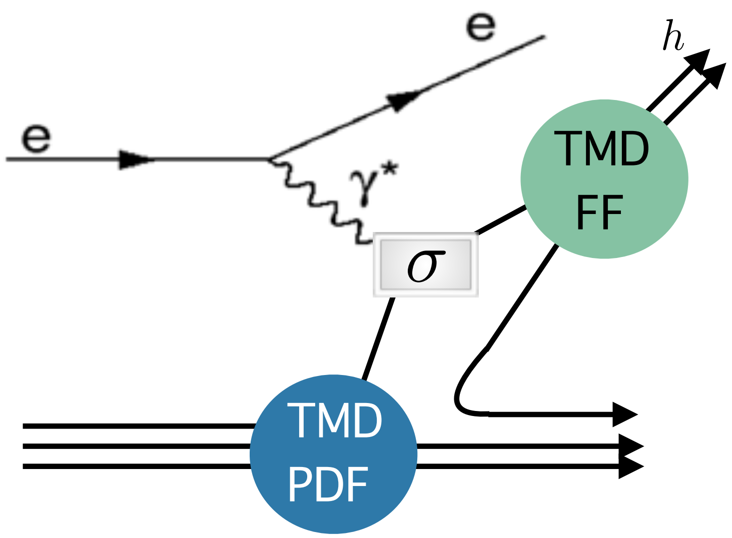


0.00 < P_h⊥ [GeV] < 0.23
0.23 < P_h⊥ [GeV] < 0.36
0.36 < P_h⊥ [GeV] < 0.54
0.54 < P_h⊥ [GeV] < 2.00
2 ⟨sin(ϕ+ϕ_S)⟩_UT
π-
HERMES
7.3% scale
PRELIMINARY
uncertainty
0.20 < z < 0.28
0.28 < z < 0.37
2Q⟨sin ϕ⟩_LU / √(2ε(1-ε))
π+
π-
CLAS
e H → e π X
HERMES PRELIMINARY
e H → e π X
2.6% scale uncertainty
x
z
P_hT [GeV]

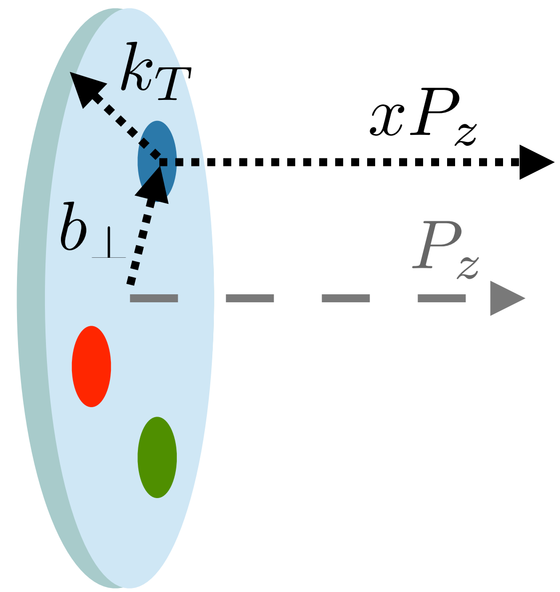


k_T
xP_z
$b_\perp$
P_z

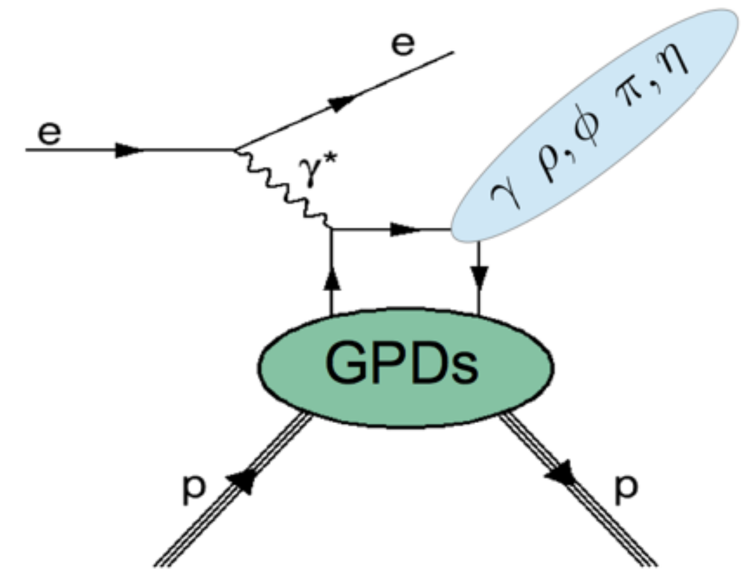
Summary



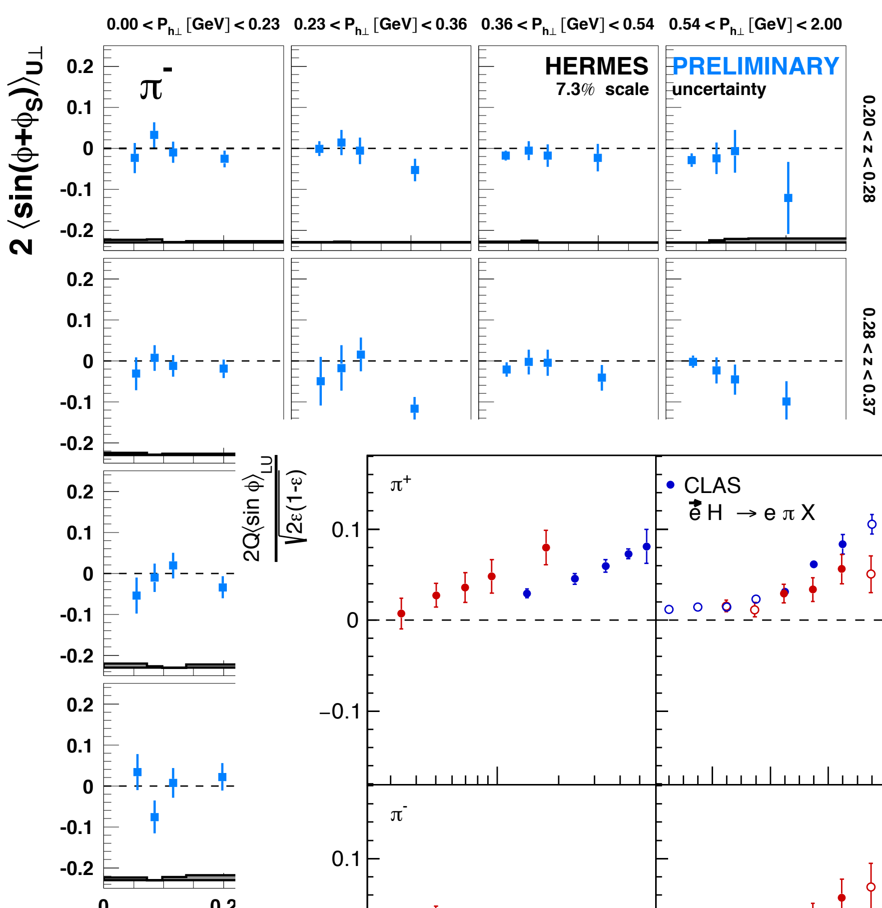
e
e
h
γ^*
σ
TMD FF
TMD PDF



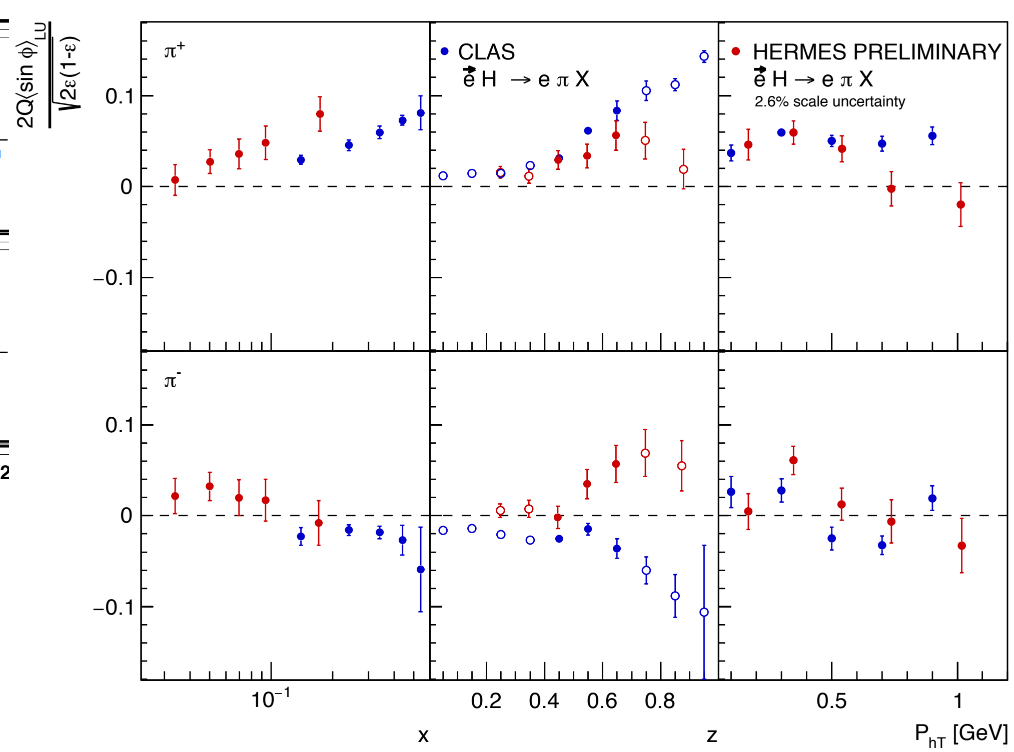
k_T
xP_z
$b_\perp$
P_z



e
e
γ^*
$\gamma\ \rho,\phi\ \pi,\eta$
GPDs
p
p

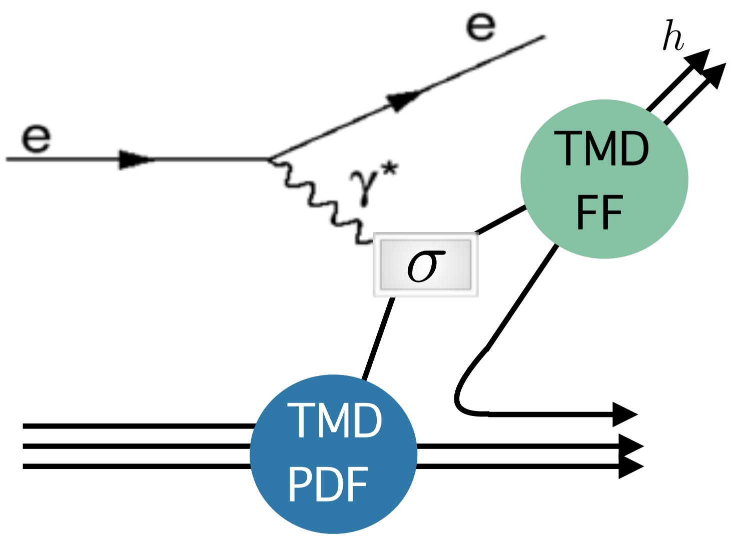


0.00 < $P_{h\perp}$ [GeV] < 0.23
0.23 < $P_{h\perp}$ [GeV] < 0.36
0.36 < $P_{h\perp}$ [GeV] < 0.54
0.54 < $P_{h\perp}$ [GeV] < 2.00
2 ⟨sin(φ+φ_S)⟩_UT
π⁻
HERMES
7.3% scale
PRELIMINARY
uncertainty
0.20 < z < 0.28
0.28 < z < 0.37

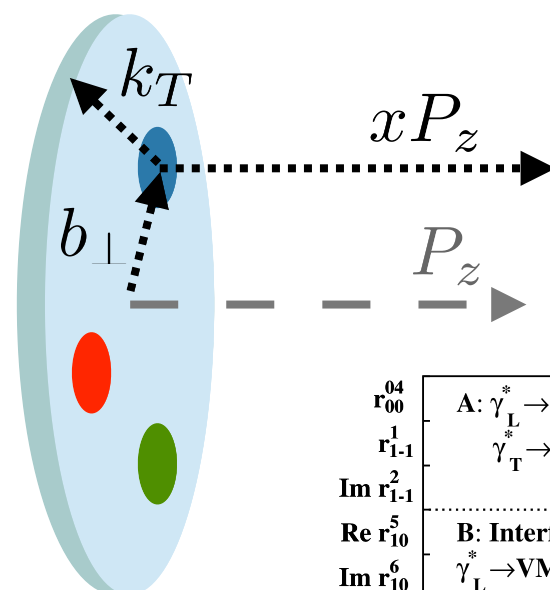


2Q⟨sin φ⟩_LU / √(2ε(1-ε))
π⁺
π⁻
CLAS
e⃗ H → e π X
HERMES PRELIMINARY
e⃗ H → e π X
2.6% scale uncertainty
x
z
P_hT [GeV]

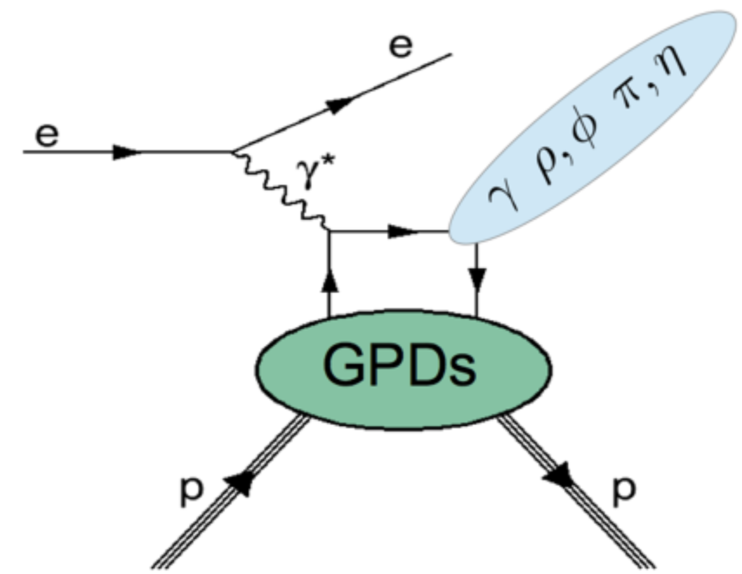
Summary



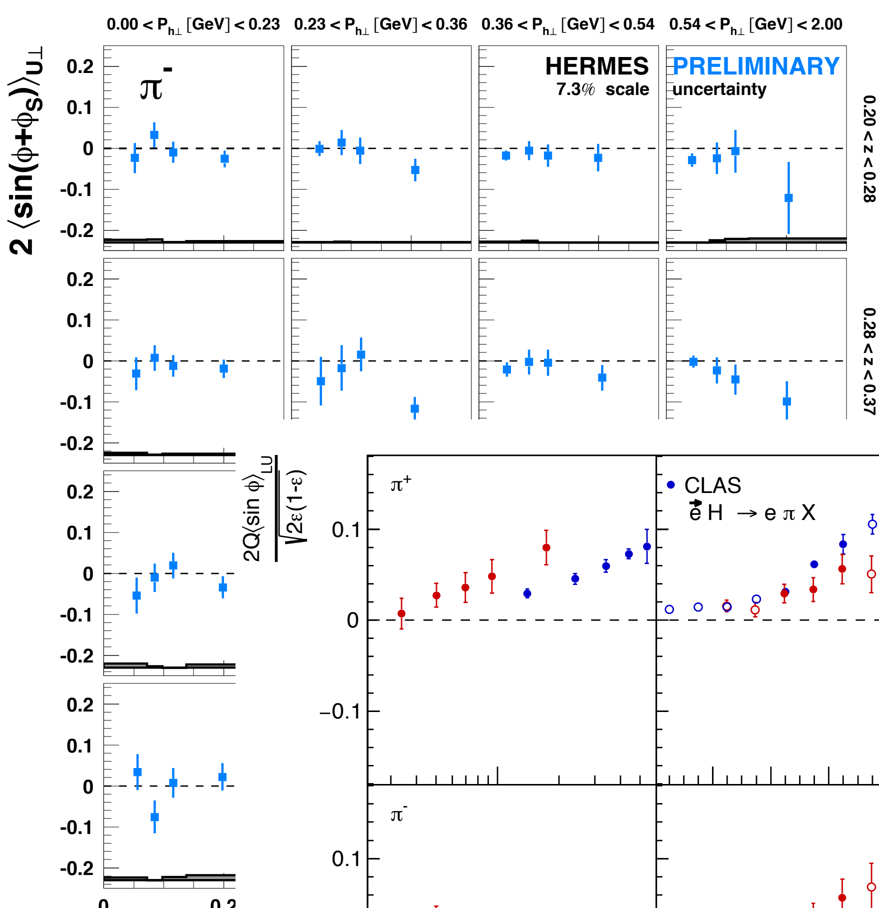
e
e
h
γ*
σ
TMD FF
TMD PDF



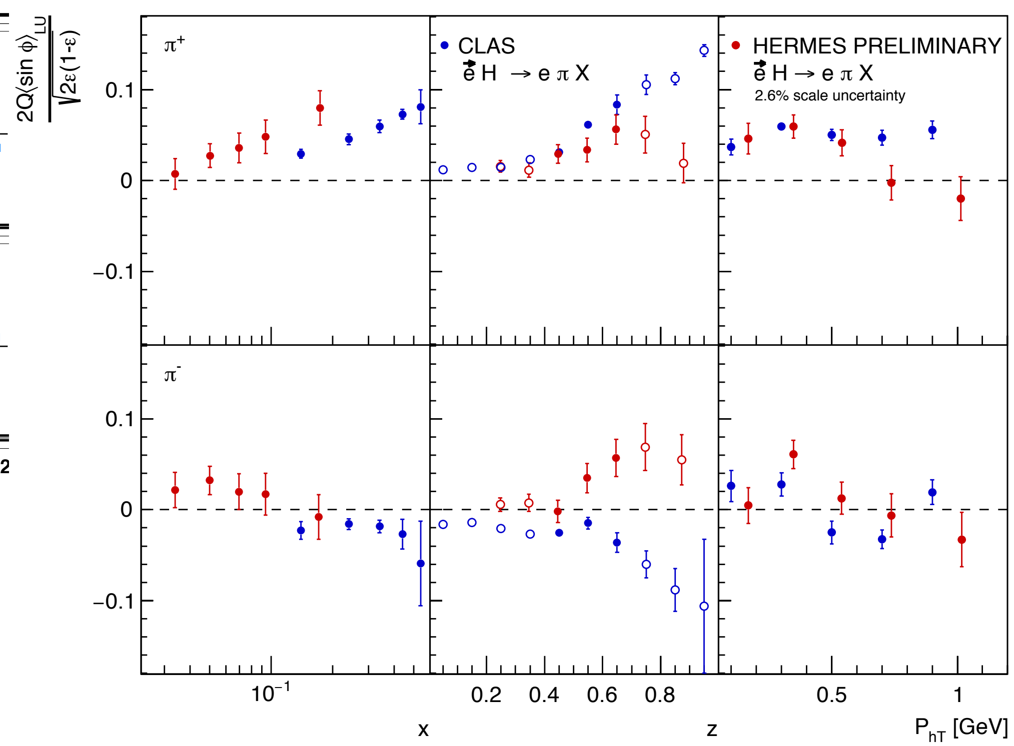
k_T
xP_z
$b_\perp$
P_z



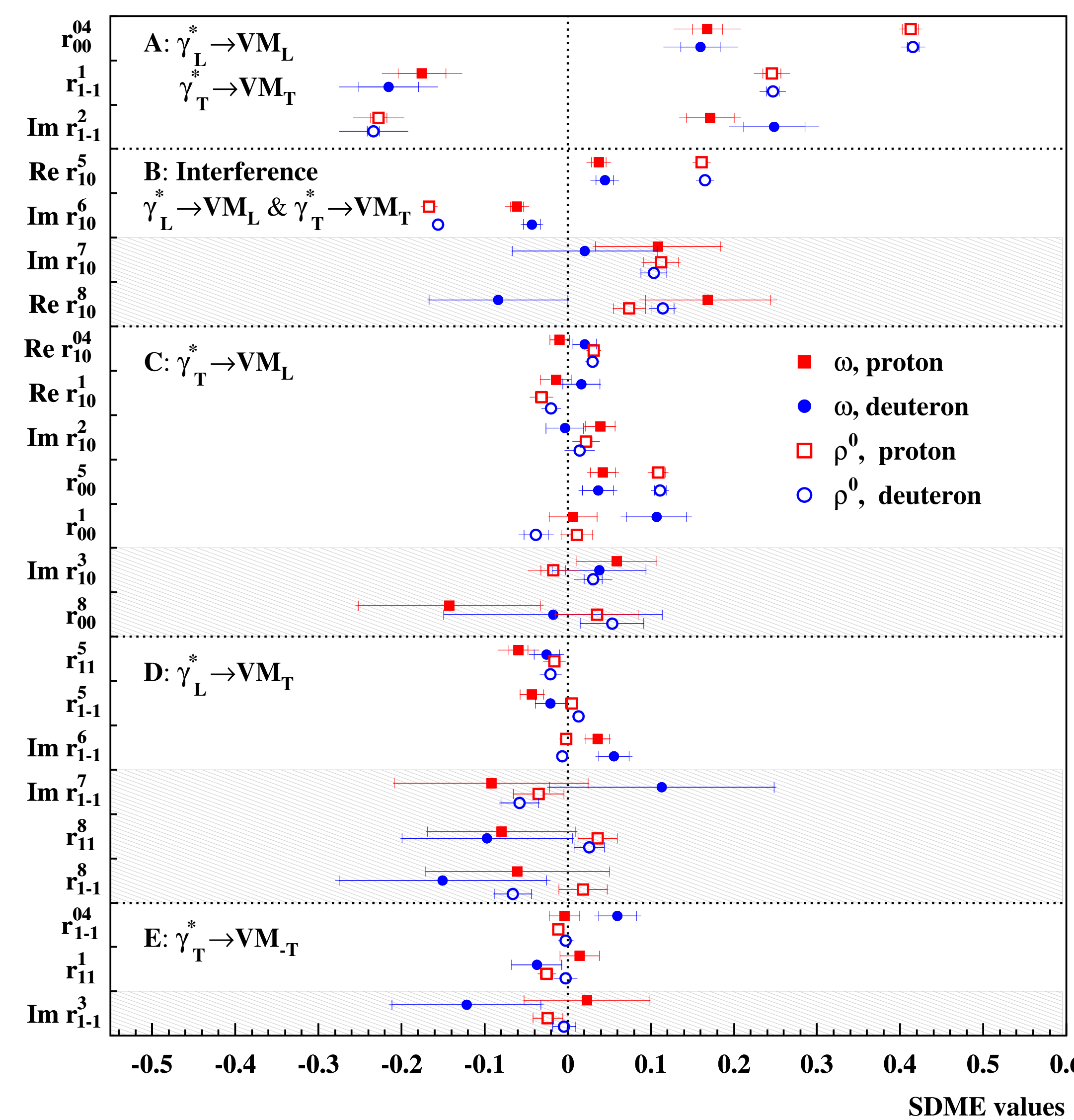
e
e
γ*
γ ρ,φ π,η
GPDs
p
p



HERMES
7.3% scale
PRELIMINARY
uncertainty
π⁻

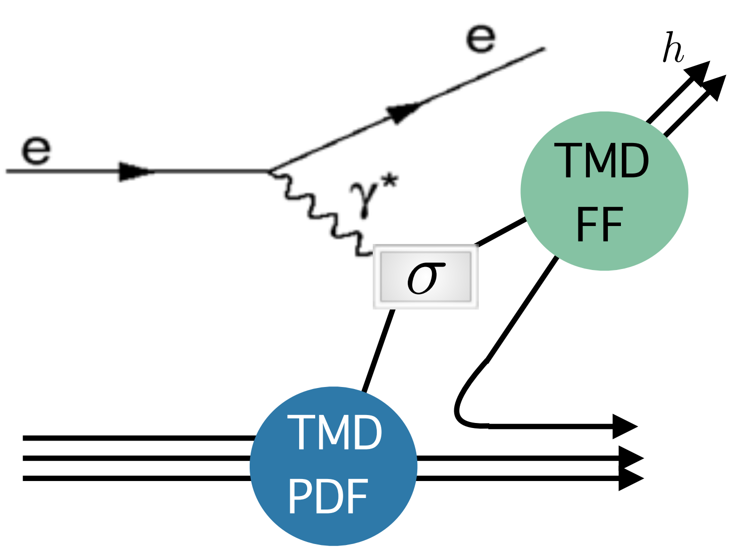


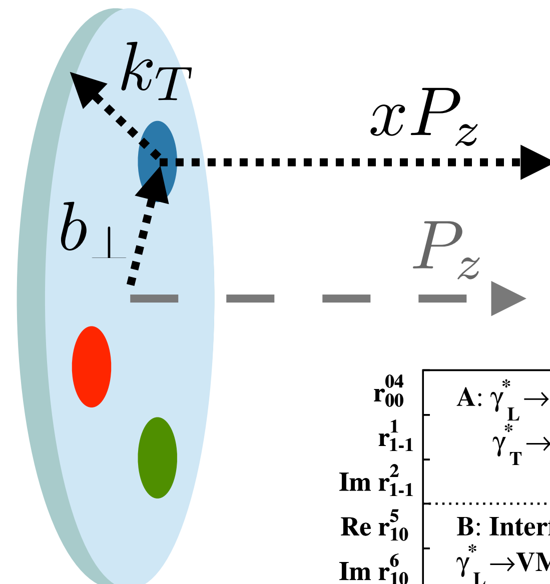
CLAS
HERMES PRELIMINARY
2.6% scale uncertainty
x
z
P_hT [GeV]

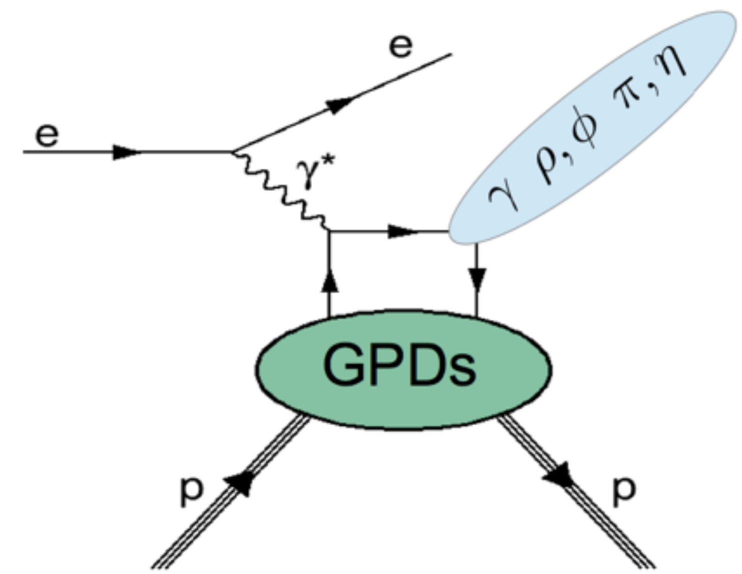


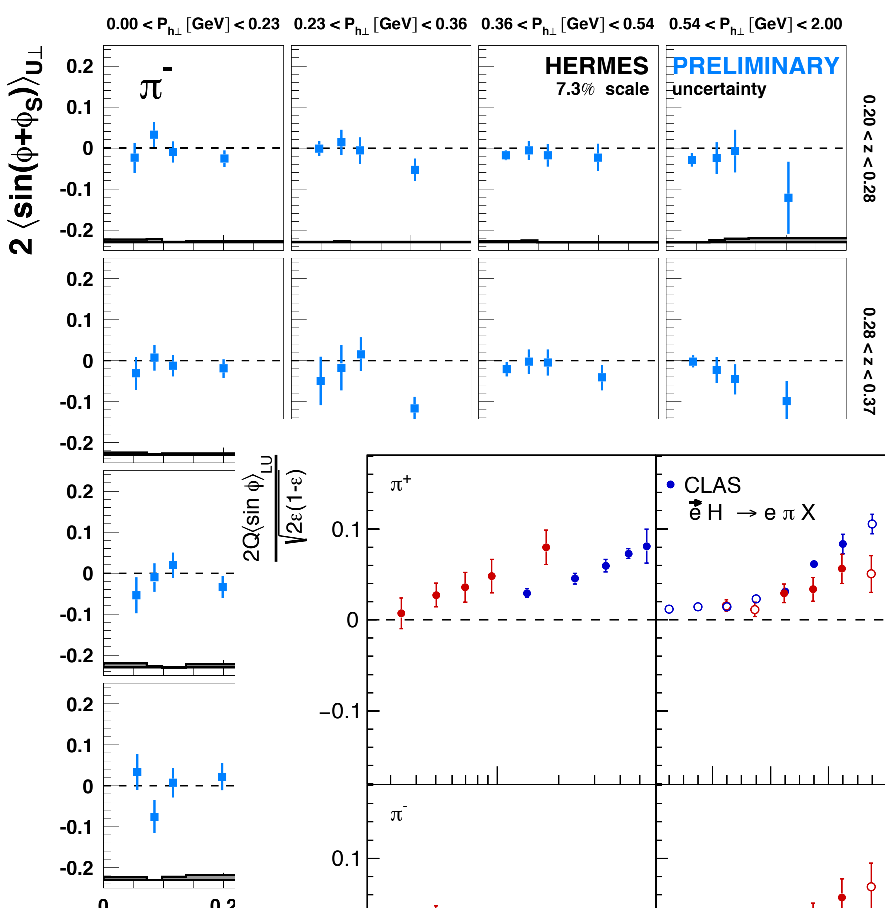
A: γ*_L→VM_L
γ*_T→VM_T
B: Interference
γ*_L→VM_L & γ*_T→VM_T
C: γ*_T→VM_L
D: γ*_L→VM_T
E: γ*_T→VM_-T
ω, proton
ω, deuteron
ρ⁰, proton
ρ⁰, deuteron
SDME values

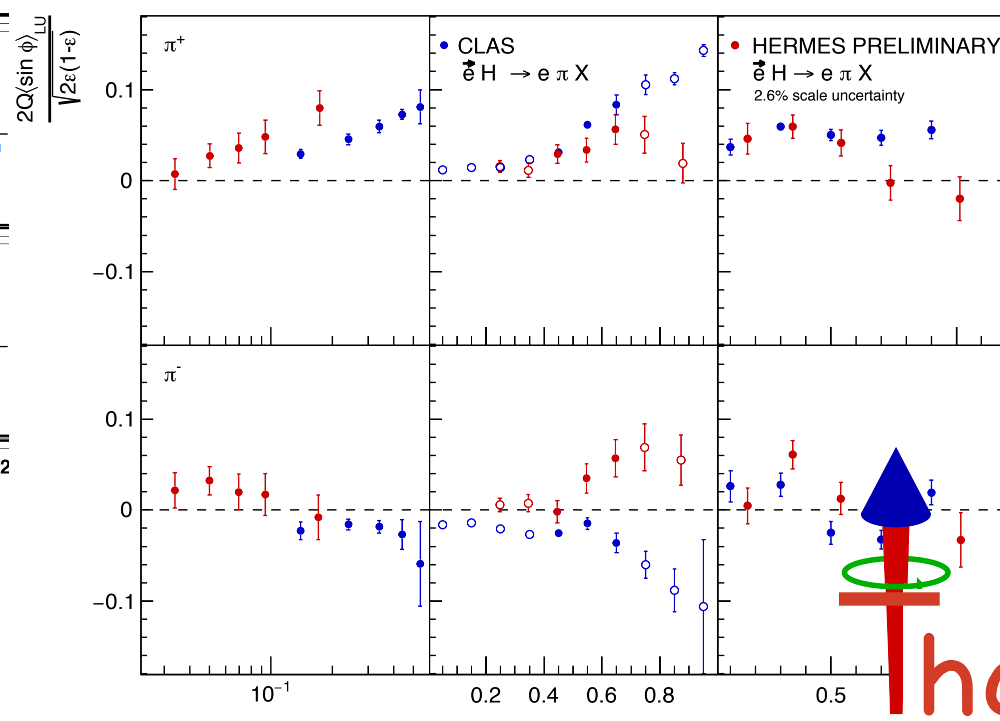
Summary

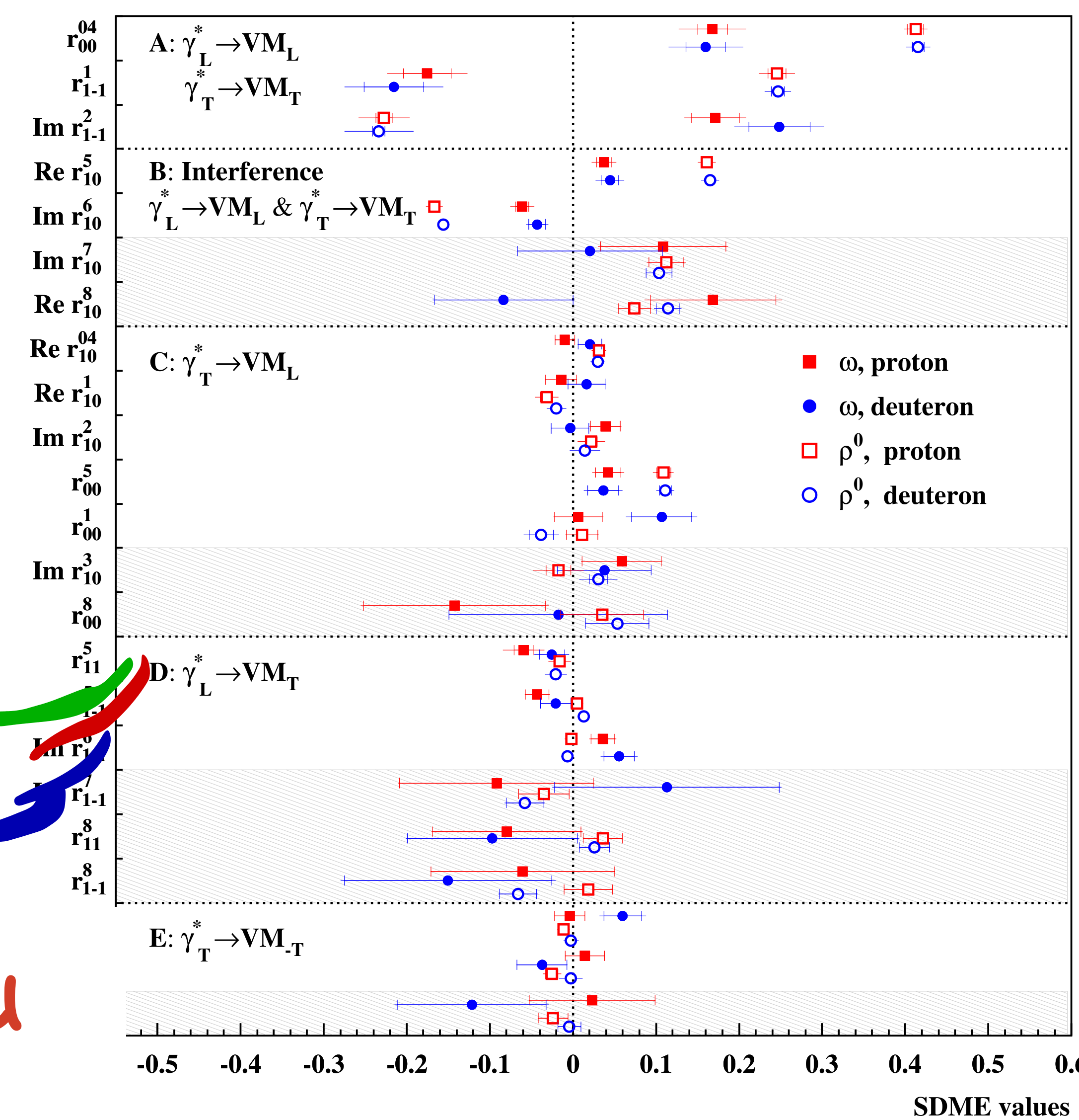

e
e
γ^*
h
σ
TMD FF
TMD PDF

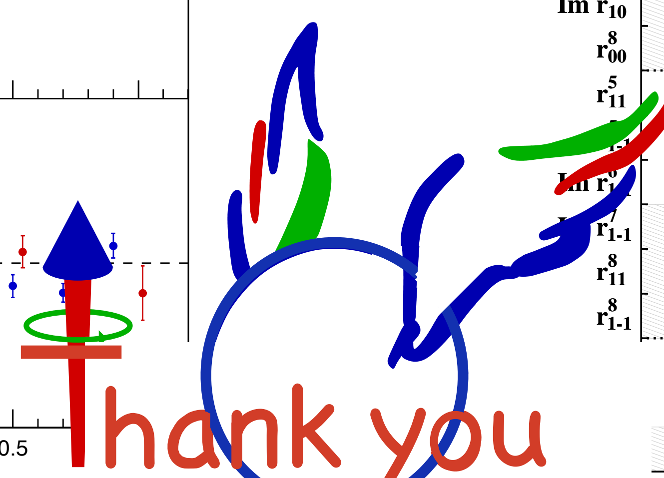

k_T
xP_z
$b_\perp$
P_z


e
e
γ^*
γ ρ,ϕ π,η
GPDs
p
p


$0.00 < P_{h\perp}$ [GeV] < 0.23
$0.23 < P_{h\perp}$ [GeV] < 0.36
$0.36 < P_{h\perp}$ [GeV] < 0.54
$0.54 < P_{h\perp}$ [GeV] < 2.00
$2\langle\sin(\phi+\phi_S)\rangle_{U\perp}$
π^-
HERMES
7.3% scale
PRELIMINARY
uncertainty
$0.20 < z < 0.28$
$0.28 < z < 0.37$


$\frac{2Q\langle\sin\phi\rangle_{LU}}{\sqrt{2\epsilon(1-\epsilon)}}$
π^+
π^-
CLAS
$\vec{e}$ H $\to$ e π X
HERMES PRELIMINARY
$\vec{e}$ H $\to$ e π X
2.6% scale uncertainty
x
z


A: $\gamma^*_L \to VM_L$
$\gamma^*_T \to VM_T$
B: Interference
$\gamma^*_L \to VM_L$ & $\gamma^*_T \to VM_T$
C: $\gamma^*_T \to VM_L$
D: $\gamma^*_L \to VM_T$
E: $\gamma^*_T \to VM_{-T}$
ω, proton
ω, deuteron
ρ^0, proton
ρ^0, deuteron
SDME values


Thank you