Single-Spin Asymmetries in Semi-Inclusive DIS on Polarized Hydrogen at HERMES

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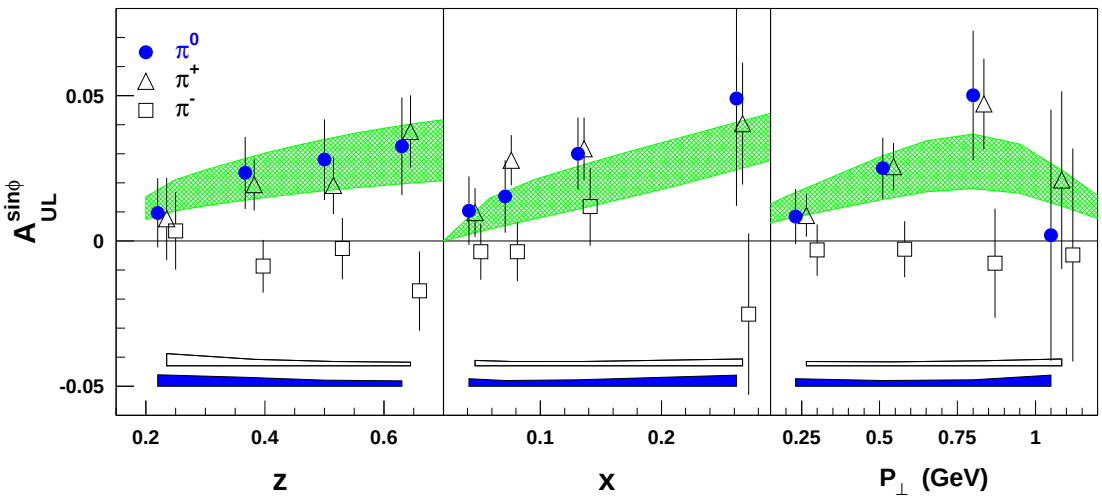
Single-Spin Asymmetries in DIS

$$e\vec{p} \rightarrow e'\pi X$$

HERMES

$$A_{UL}^{\sin\phi}(z, x, p_\perp)$$



Possible mechanisms:

- Collins effect (green band)

left-right-asymmetry w.r.t. lepton scattering plane

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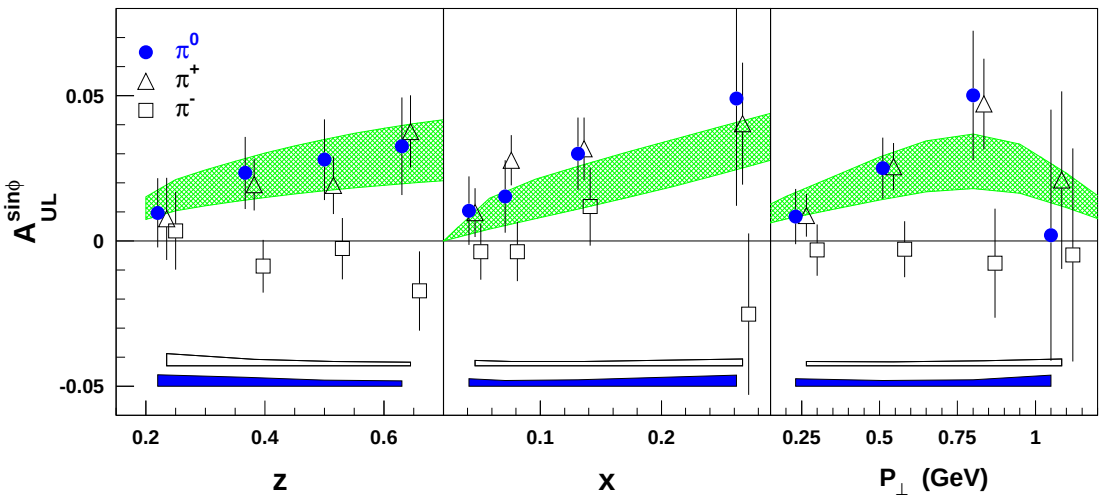

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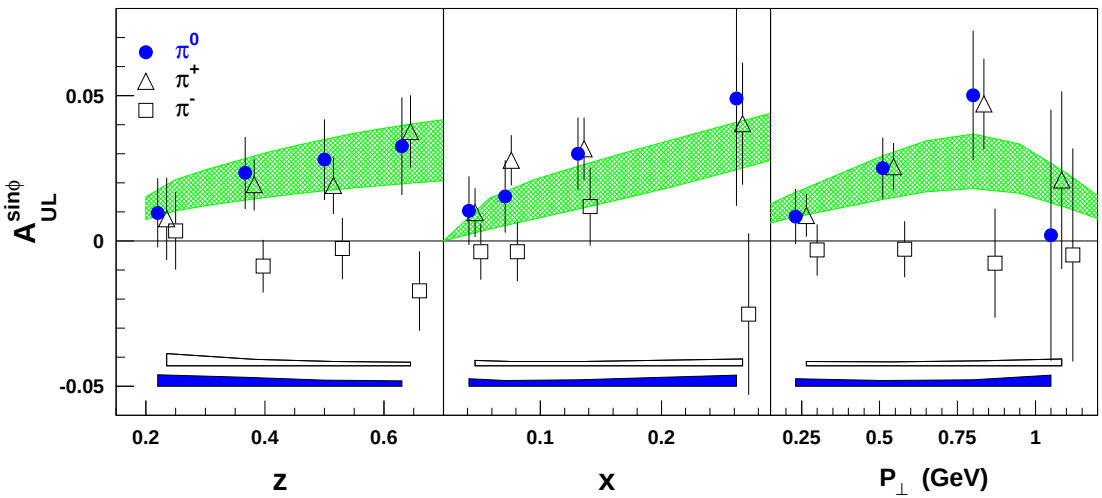
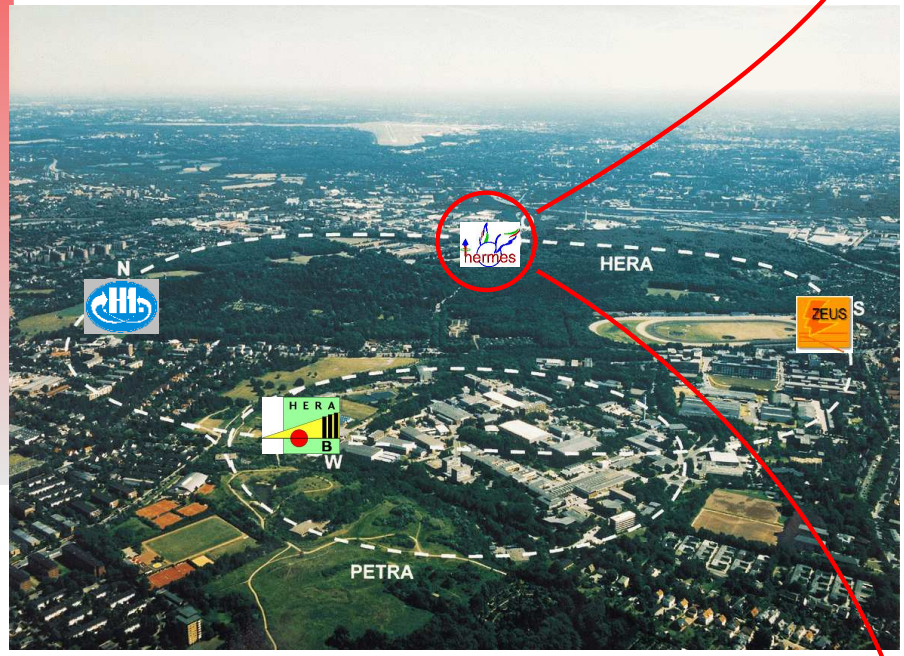


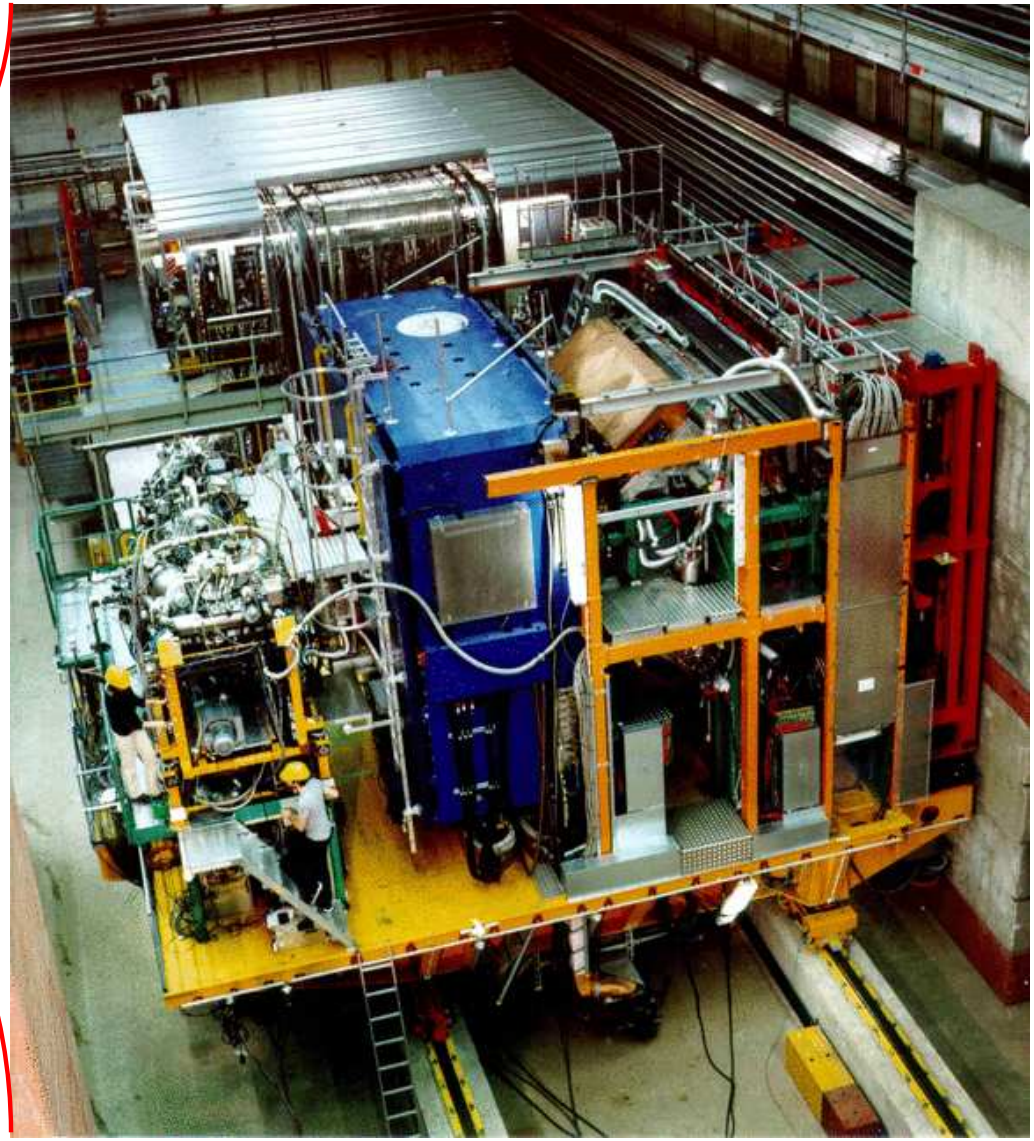
Possible mechanisms:

- Collins effect (green band)
- Sivers effect
- Subleading-twist effects

left-right-asymmetry w.r.t. lepton scattering plane

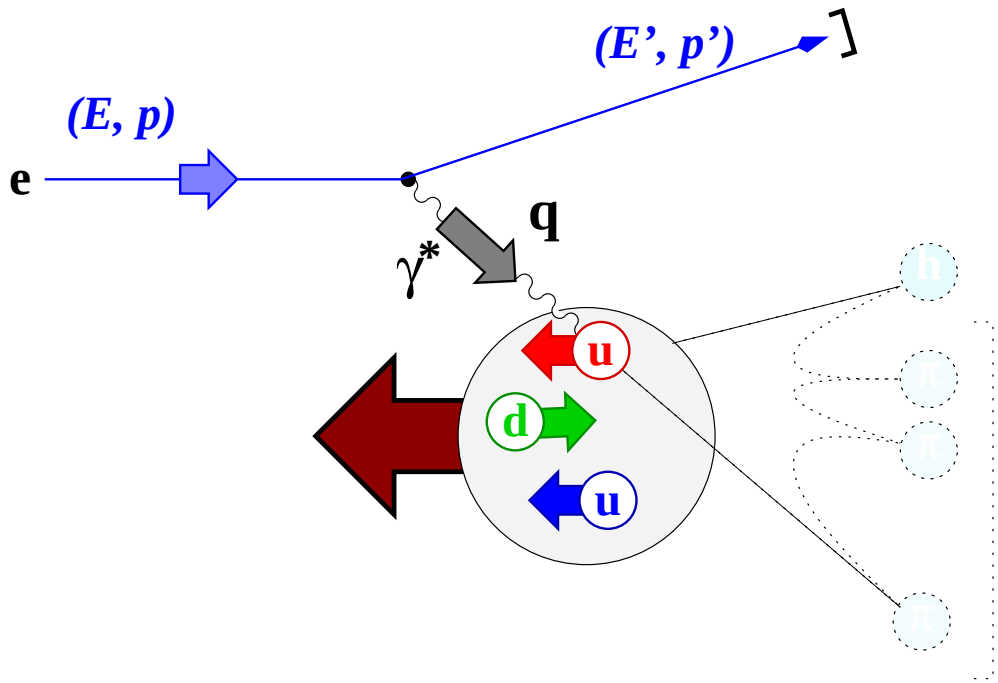
HERMES at DESY





Lepton Deep-Inelastic Scattering

use well-known probe to study hadronic structure:



$$Q^2 \overset{\text{lab}}{=} 4EE' \sin^2(\frac{\Theta}{2})$$

$$y \overset{\text{lab}}{=} \frac{E - E'}{E}$$

$$x \overset{\text{lab}}{=} \frac{Q^2}{2MEy}$$

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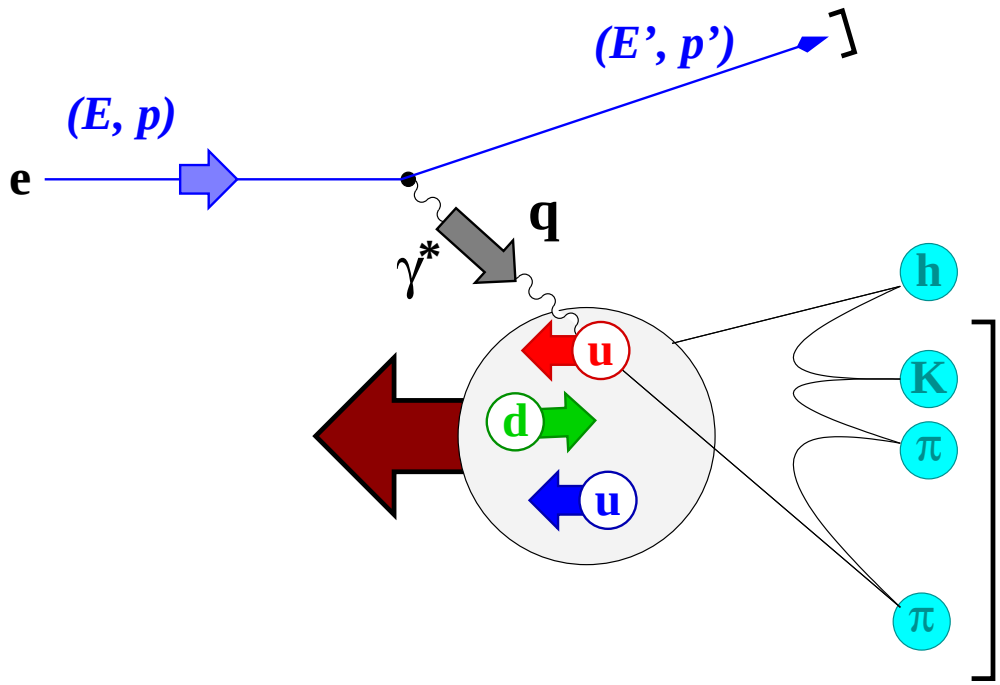

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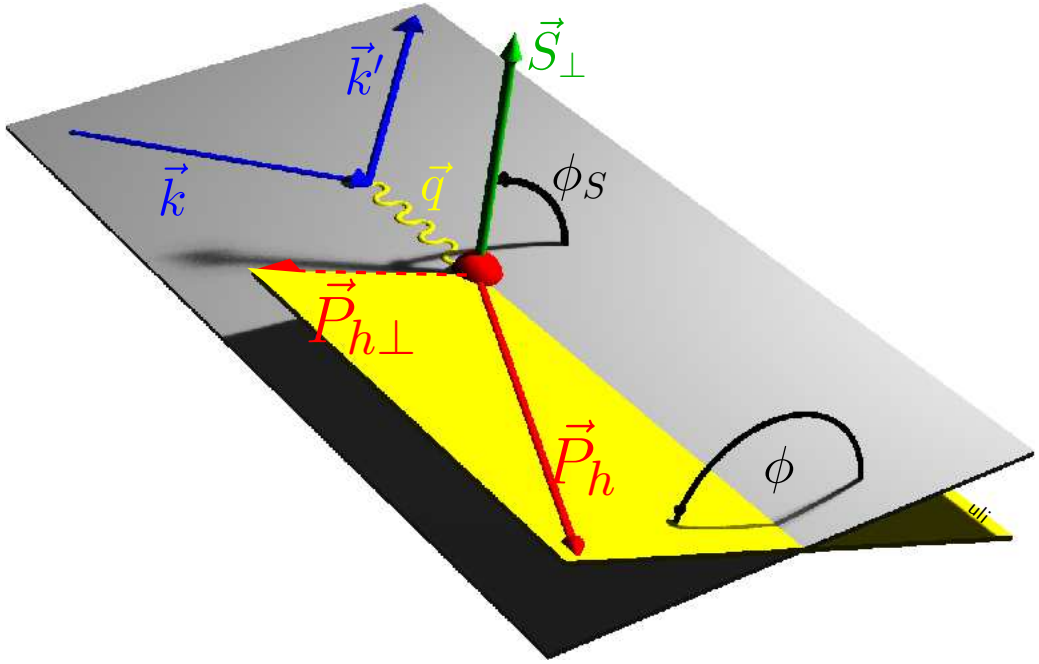
$$z \overset{\text{lab}}{=} \frac{E_h}{E - E'}$$

Factorization $\Rightarrow \sigma^{ep \to ehX} = \sum_q DF^{p \to q} \otimes \sigma^{eq \to eq} \otimes FF^{q \to h}$

(quark distribution $\otimes$ hard scattering $\otimes$ hadron formation)

Azimuthal Angles in SIDIS Cross Section

- SIDIS cross section depends on x, y (Q^2), and z
- add azimuthal distribution of produced hadrons:



- additional degrees of freedom: ϕ_S and $\vec{P}_{h\perp}$ (ϕ, $P_{h\perp}$)

SIDIS Cross Section (up to subleading order in 1/Q)

$$d\sigma = d\sigma^0_{UU} + \cos 2\phi\, d\sigma^1_{UU} + \frac{1}{Q}\cos\phi\, d\sigma^2_{UU} + \lambda_e \frac{1}{Q}\sin\phi\, d\sigma^3_{LU}$$

$$+S_L\left\{\sin 2\phi\, d\sigma^4_{UL} + \frac{1}{Q}\sin\phi\, d\sigma^5_{UL} + \lambda_e\left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^7_{LL}\right]\right\}$$

$$+S_T\left\{\sin(\phi+\phi_S)\, d\sigma^8_{UT} + \sin(\phi-\phi_S)\, d\sigma^9_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{10}_{UT}\right.$$

$$+\frac{1}{Q}\left(\sin(2\phi-\phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma^{12}_{UT}\right)$$

$$\left.+\lambda_e\left[\cos(\phi-\phi_S)\, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S\, d\sigma^{14}_{LT} + \cos(2\phi-\phi_S)\, d\sigma^{15}_{LT}\right)\right]\right\}$$

σ_{XY}

Beam Target
Polarization

Mulders and Tangermann, Nucl. Phys. B 461 (1996) 197

Boer and Mulders, Phys. Rev. D 57 (1998) 5780

Bacchetta et al., Phys. Lett. B 595 (2004) 309

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σ_{XY}

Beam Target

Polarization

Terms with 1/Q are 'subleading twist'

(Factorization for SIDIS (including transverse momentum) not yet proven)

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$$d\sigma = d\sigma^0_{UU} + \cos 2\phi\, d\sigma^1_{UU} + \frac{1}{Q}\cos\phi\, d\sigma^2_{UU} + \lambda_e \frac{1}{Q}\sin\phi\, d\sigma^3_{LU}$$

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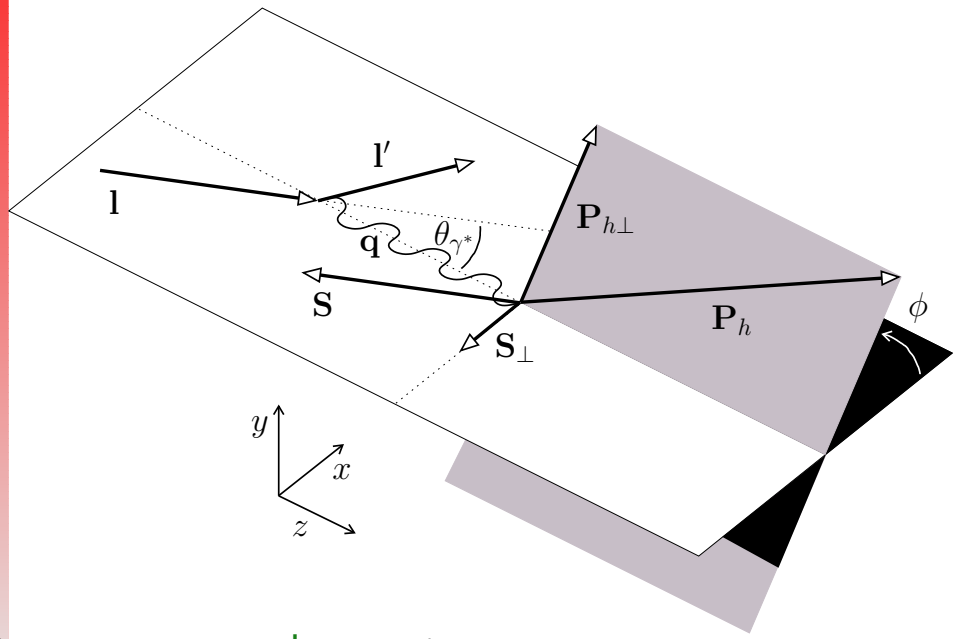
σ_{XY}

Beam Target
Polarization

$\sin\phi\, d\sigma^5_{UL}$	...	Subleading Twist
$\sin(\phi-\phi_S)\, d\sigma^9_{UT}$	...	Sivers Effect
$\sin(\phi+\phi_S)\, d\sigma^8_{UT}$	...	Collins Effect

Mixing of Azimuthal Moments



Experiment: Target Polarization w.r.t. Beam Direction!

$\Rightarrow$ **experimental asymmetries (which have polarization along beam) related to "theory" asymmetries (polarization along virtual photon direction) via:**

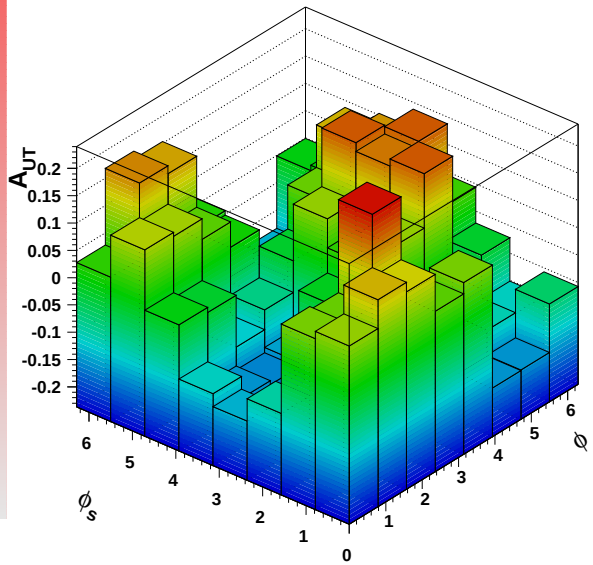
[**Diehl and Sapeta, hep-ph/0503023**]

$$\begin{pmatrix} \langle \sin\phi \rangle^{l}_{UL} \\ \langle \sin(\phi-\phi_S) \rangle^{l}_{UT} \\ \langle \sin(\phi+\phi_S) \rangle^{l}_{UT} \end{pmatrix} = \begin{pmatrix} \cos\theta_{\gamma^*} & -\sin\theta_{\gamma^*} & -\sin\theta_{\gamma^*} \\ \frac{1}{2}\sin\theta_{\gamma^*} & \cos\theta_{\gamma^*} & 0 \\ \frac{1}{2}\sin\theta_{\gamma^*} & 0 & \cos\theta_{\gamma^*} \end{pmatrix} \begin{pmatrix} \langle \sin\phi \rangle^{q}_{UL} \\ \langle \sin(\phi-\phi_S) \rangle^{q}_{UT} \\ \langle \sin(\phi+\phi_S) \rangle^{q}_{UT} \end{pmatrix}$$

(**$\cos\theta_{\gamma^*} \simeq 1$, $\sin\theta_{\gamma^*}$ up to 15% at HERMES energies)**

Extracting Collins and Sivers Asymmetries

$$A_{UT}(\phi,\phi_S) = \frac{1}{\langle S_\perp\rangle}\frac{N_\pi^+(\phi,\phi_S)-N_\pi^-(\phi,\phi_S)}{N_\pi^+(\phi,\phi_S)+N_\pi^-(\phi,\phi_S)}$$



$$\sim \sin(\phi-\phi_S)\sum_q e_q^2\,\mathcal{I}\left[f_{1T}^{\perp,q}(x,q_T^2)D_1^q(z,k_T^2)\right]$$

$$+ \sin(\phi+\phi_S)\sum_q e_q^2\,\mathcal{I}\left[h_{1T}^{q}(x,p_T^2)H_1^{\perp,q}(z,k_T^2)\right]$$

$$+ \ldots$$

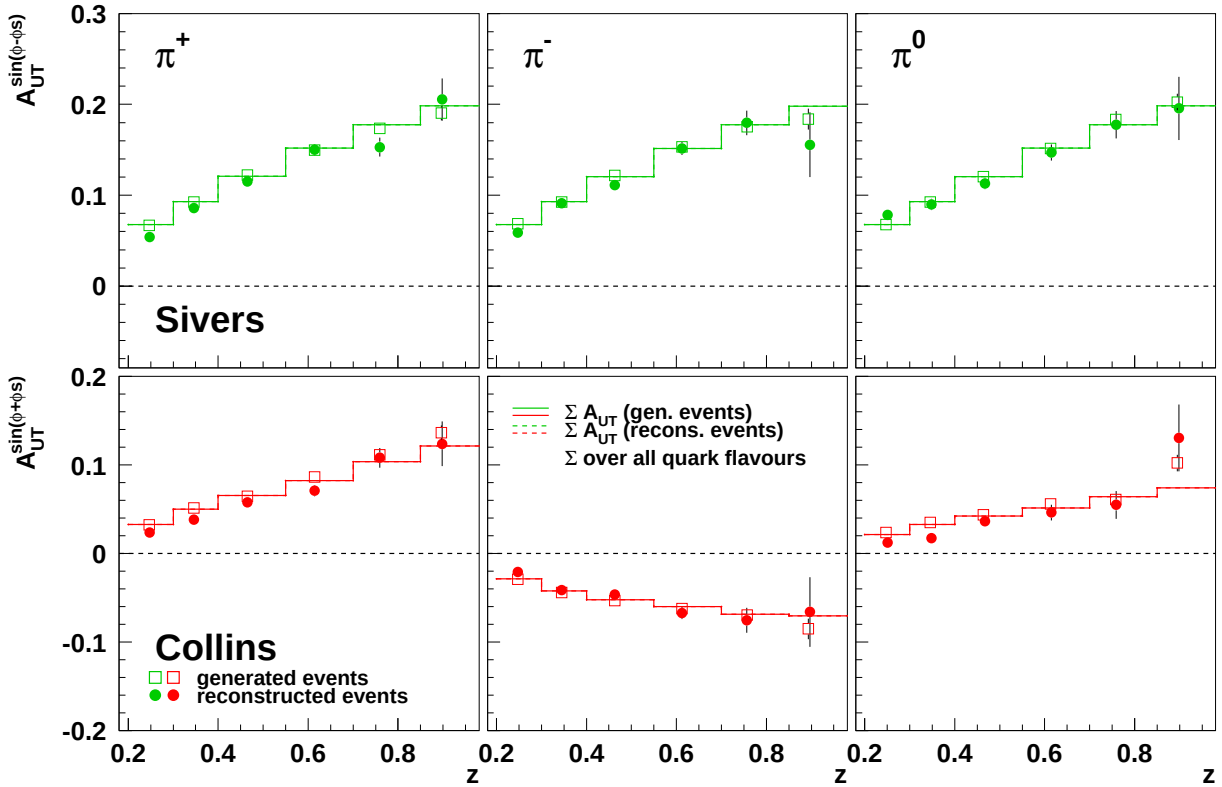
$\mathcal{I}[\ldots]$: **convolution integral over initial (p_T) and final (k_T) quark transverse momenta**

$\Rightarrow$ 2D-fit of A_{UT} to get Collins and Sivers asymmetries:

$$A_{UT}(\phi,\phi_S) = 2\left\langle \sin(\phi-\phi_S)\right\rangle_{UT}^{I}\sin(\phi-\phi_s) + 2\left\langle \sin(\phi+\phi_S)\right\rangle_{UT}^{I}\sin(\phi+\phi_s)$$

Monte Carlo Test of the Extraction Method

- generate Collins and Sivers asymmetries (Gaussian Ansatz in p_T^2)
- analyze MC data like experimental data and extract asymmetries:

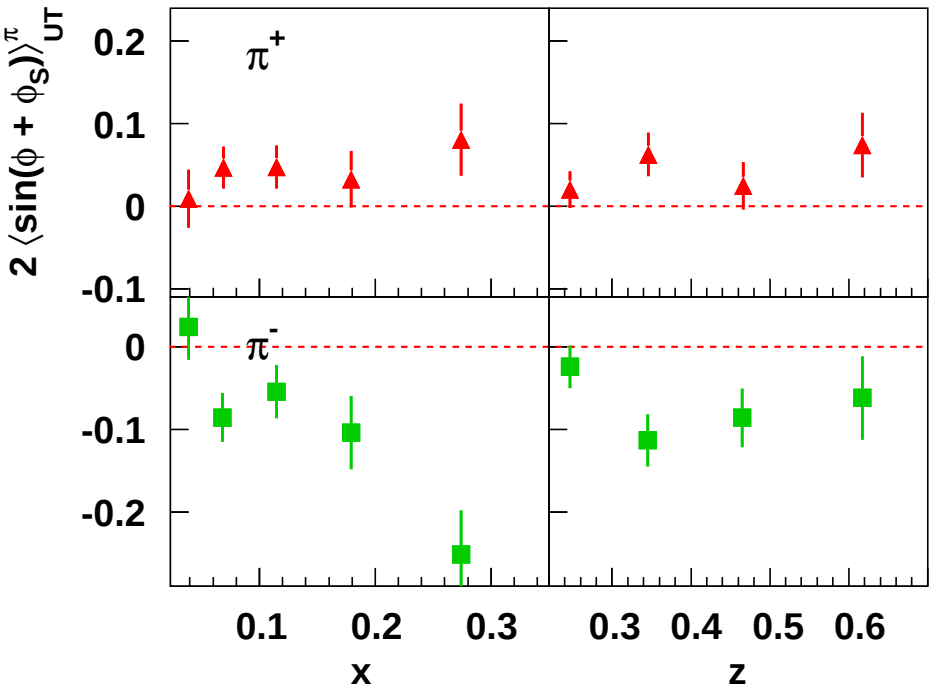


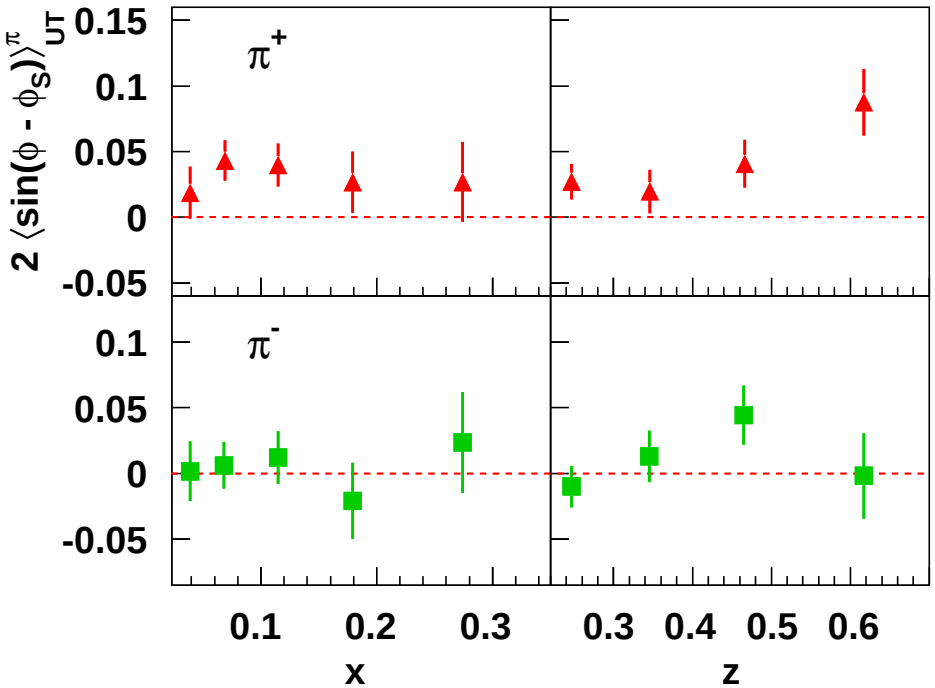
- Collins-Sivers cross contamination negligible
- insensitive to transverse target tracking corrections

Published Collins and Sivers Asymmetries

Fit $A(\phi, \phi_S) = A_C \frac{B(<y>)}{A(<x>,<y>)} \sin(\phi + \phi_S) + A_S \sin(\phi - \phi_S)$

(Virtual Photon Asymmetries)

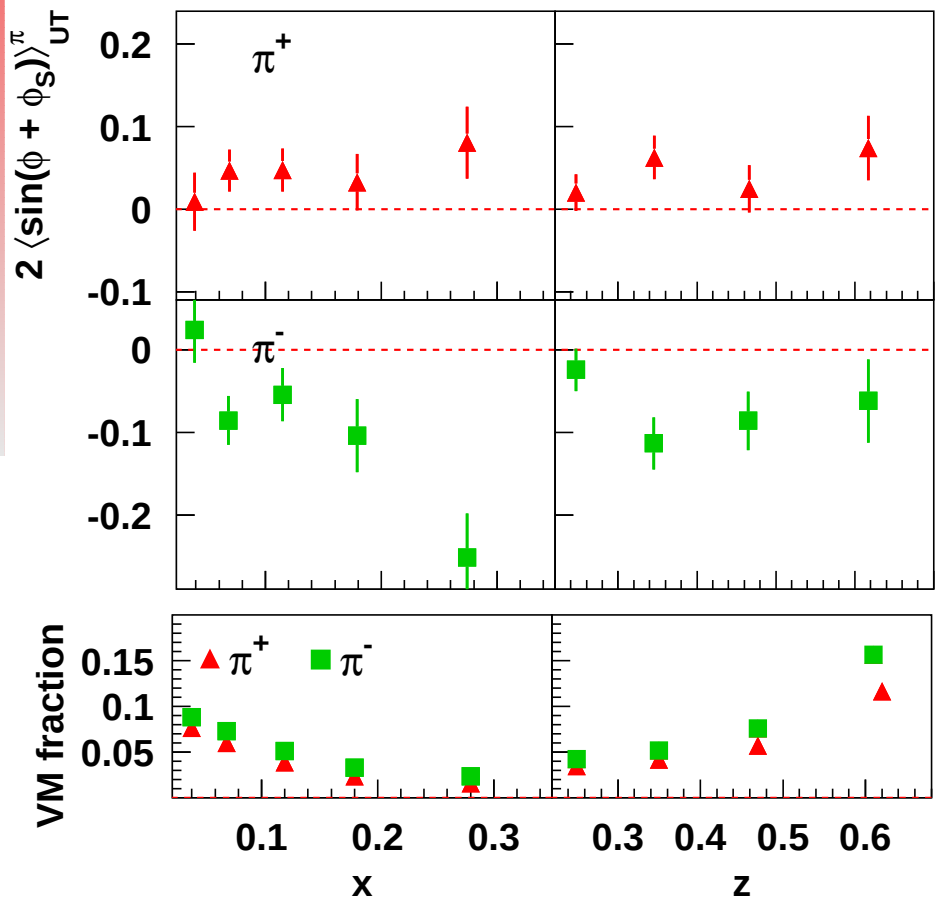




A. Airapetian et al, **Phys. Rev. Lett. 94 (2005) 012002**

Published Collins and Sivers Asymmetries

Collins Asymmetry: $A_C \propto -\mathcal{I}\left[h_1(x,p_T^2)H_1^\perp(z,z^2k_T^2)\right]$

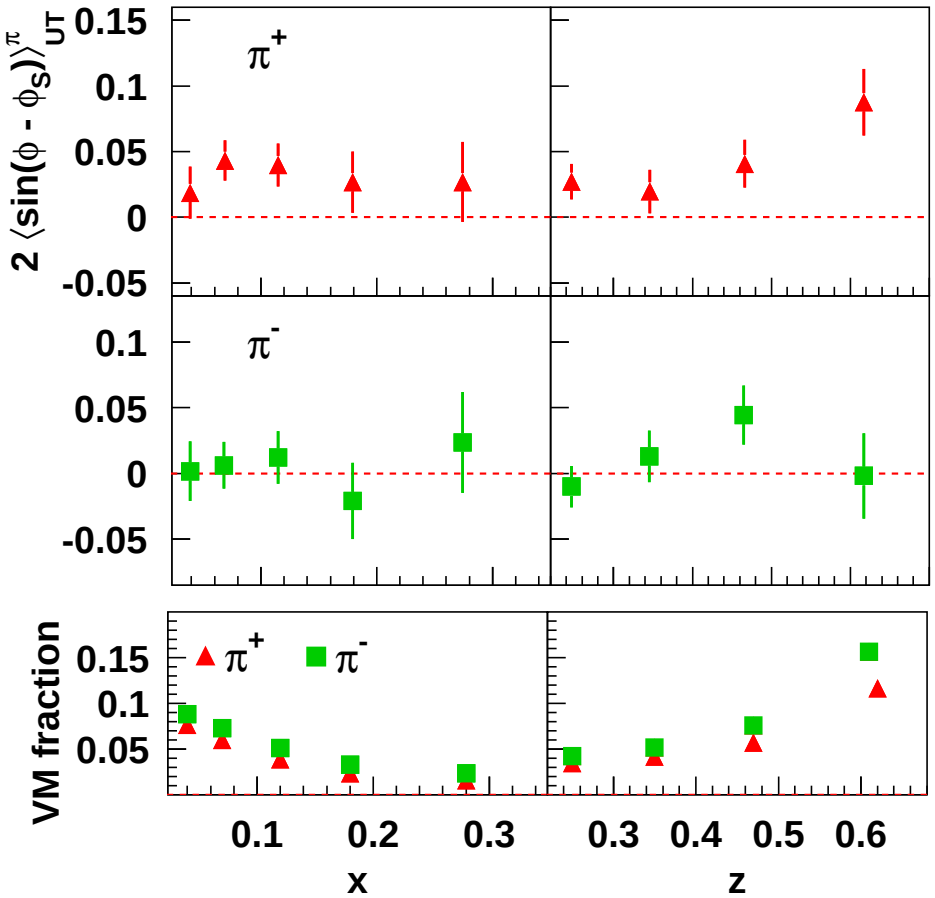


- positive for π^+ and negative for π^- as maybe expected (expectation for transversity gives positive δu and negative δd)
- unexpected large π^- asymmetry
- averaged over acceptance: $A_C^{\pi^+} = 0.042 \pm 0.014$ and $A_C^{\pi^-} = -0.076 \pm 0.016$
- overall scale uncertainty of 8%
- contribution to pion sample from exclusively produced vector mesons (VM) (from PYTHIA MC)

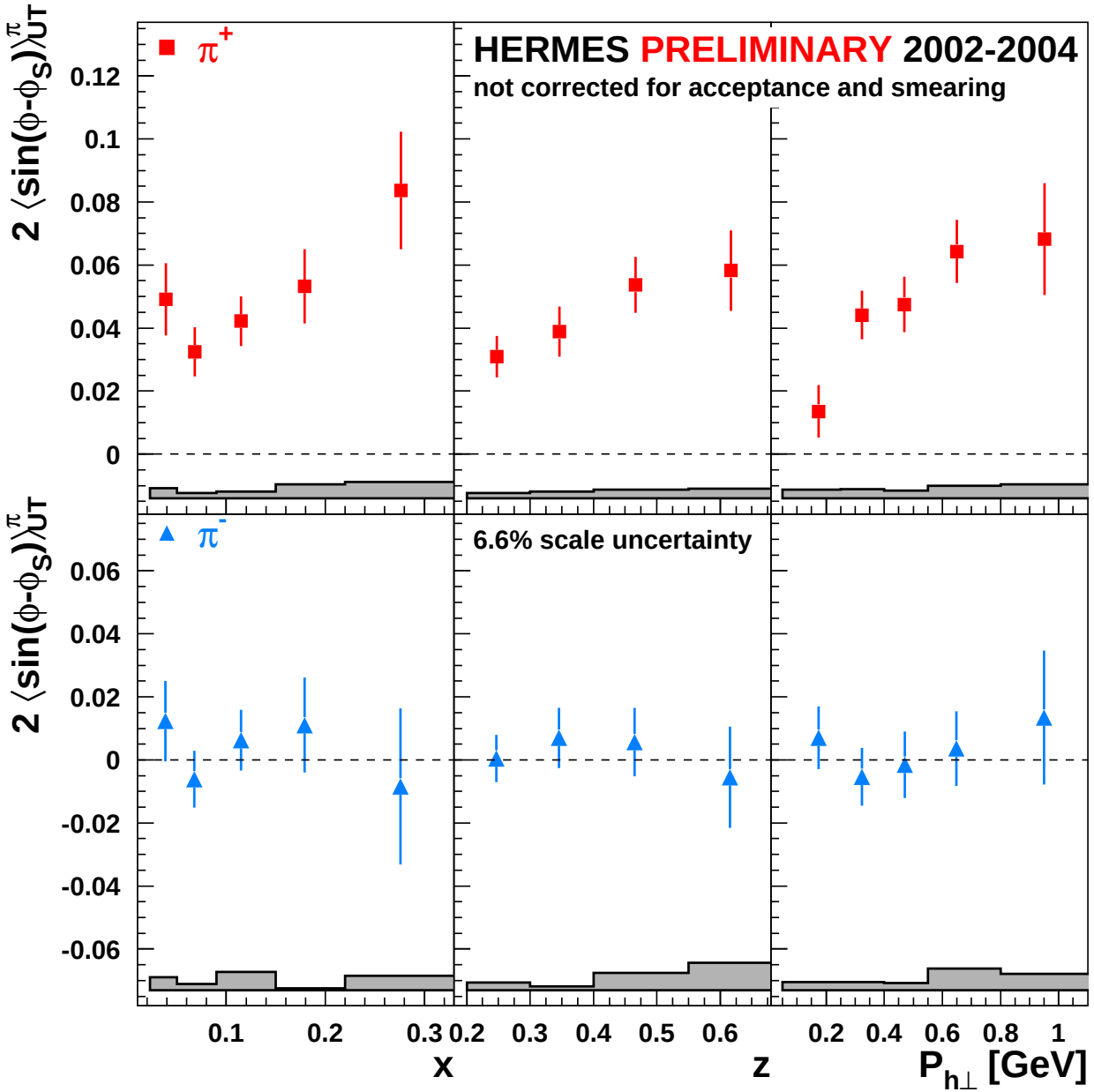
Published Collins and Sivers Asymmetries

Sivers Asymmetry: $A_S \propto -\mathcal{I}\left[f_{1T}^{\perp}(x, p_T^2) D_1(z, z^2 k_T^2)\right]$

- significantly positive for π^+
- first hint of T-odd distribution function from DIS
- π^- asymmetry consistent with zero
- averaged over acceptance:
  $A_S^{\pi^+} = 0.034 \pm 0.008$ and
  $A_S^{\pi^-} = 0.004 \pm 0.010$
- overall scale uncertainty of 8%
- systematic error due to VM contribution unknown because VM asymmetry itself unknown



Sivers Asymmetries 2002-2004 (Lepton-Beam Asymmetries)



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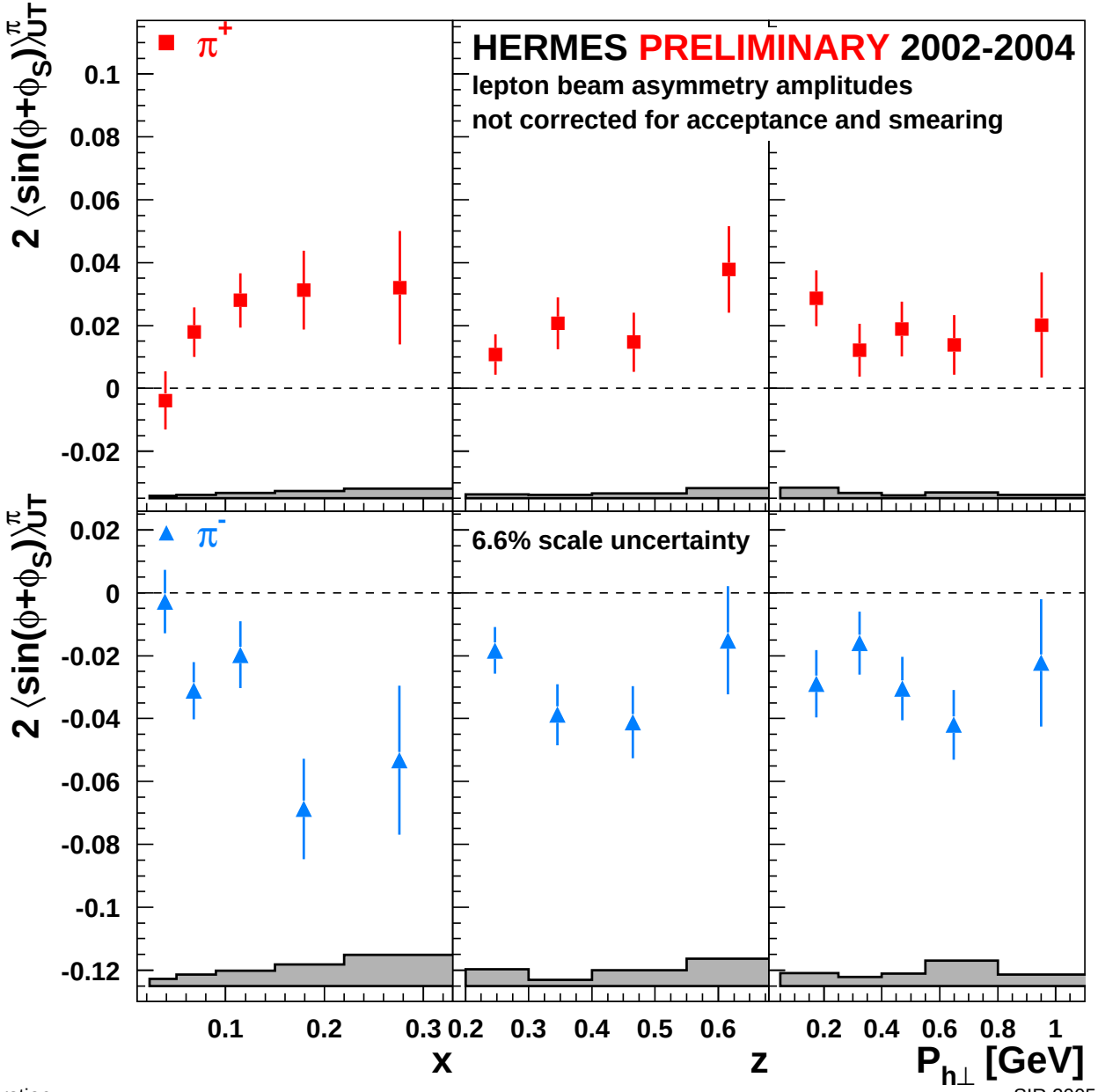

What About Longitudinally Polarized Targets?

$$\left\langle \sin\phi \right\rangle^{q}_{UL} = \left\langle \sin\phi \right\rangle^{I}_{UL} + \sin\theta_{\gamma^*} \left(\left\langle \sin(\phi+\phi_S) \right\rangle^{I}_{UT} + \left\langle \sin(\phi-\phi_S) \right\rangle^{I}_{UT} \right)$$

$$\left\langle \sin\phi \right\rangle^{q}_{UL} \propto \frac{M}{Q} \mathcal{I}\left[\frac{\hat{\boldsymbol{P}}_{h\perp}\boldsymbol{k_T}}{M_h} \left(\frac{M_h}{zM} g_1 G^{\perp} + x h_L H_1^{\perp} \right) + \frac{\hat{\boldsymbol{P}}_{h\perp}\boldsymbol{p_T}}{M} \left(\frac{M_h}{zM} h_{1L}^{\perp} \tilde{H} - x f_L^{\perp} D_1 \right) \right]$$

Bacchetta et al., Phys. Lett. B 595 (2004) 309

$\Rightarrow$ they are all subleading-twist expressions!

$\left\langle \sin\phi \right\rangle^{I}_{UL}$ . . . **Airapetian et al., Phys. Rev. Lett. 84 (2000) 4047**

$\left\langle \sin(\phi\pm\phi_S) \right\rangle^{I}_{UT}$ . . . **Airapetian et al., Phys. Rev. Lett. 94 (2005) 012002**

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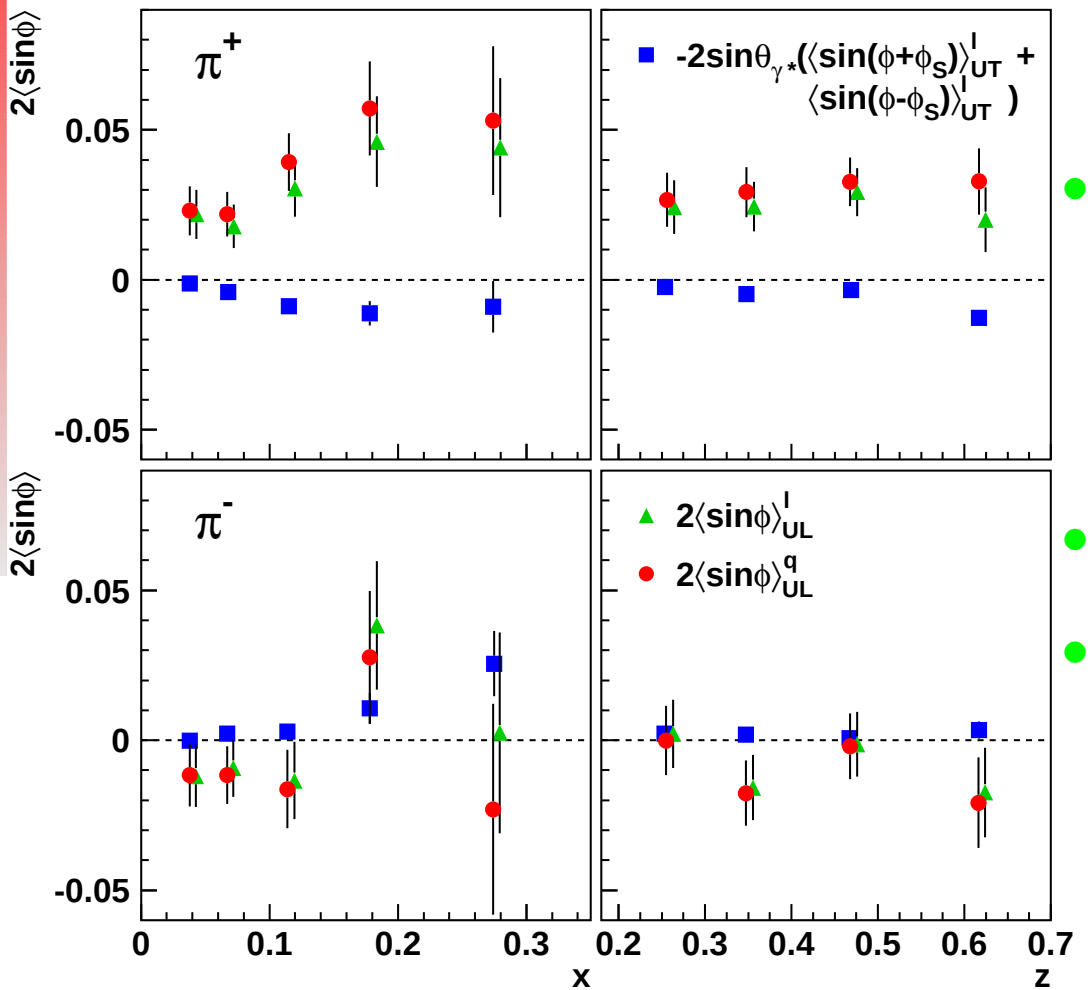

- twist-3 dominates measured asymmetries on longitudinally polarized targets!
- significantly positive for π^+
- consistent with zero for π^-

[Airapetian et al., hep-ex/0505042]

Summary and Outlook

- Non-vanishing Collins effect observed for $\pi^{\pm}$
- First evidence of T-odd Sivers distribution in DIS?
- Previous results confirmed with much better statistical precission
- $\left\langle \sin\phi \right\rangle_{UL}^{|}$ dominated by subleading twist

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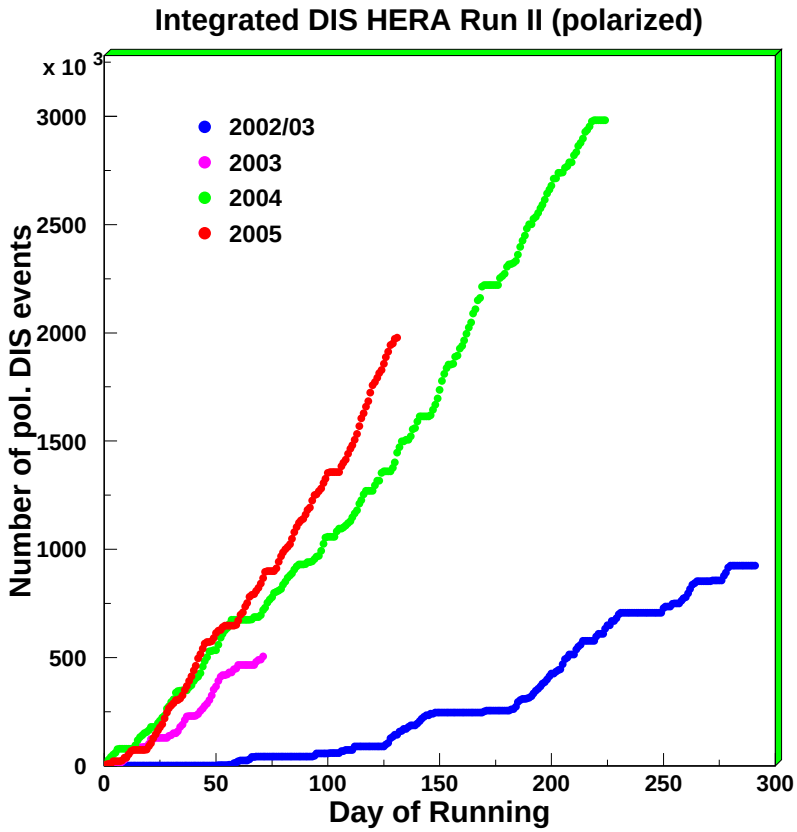

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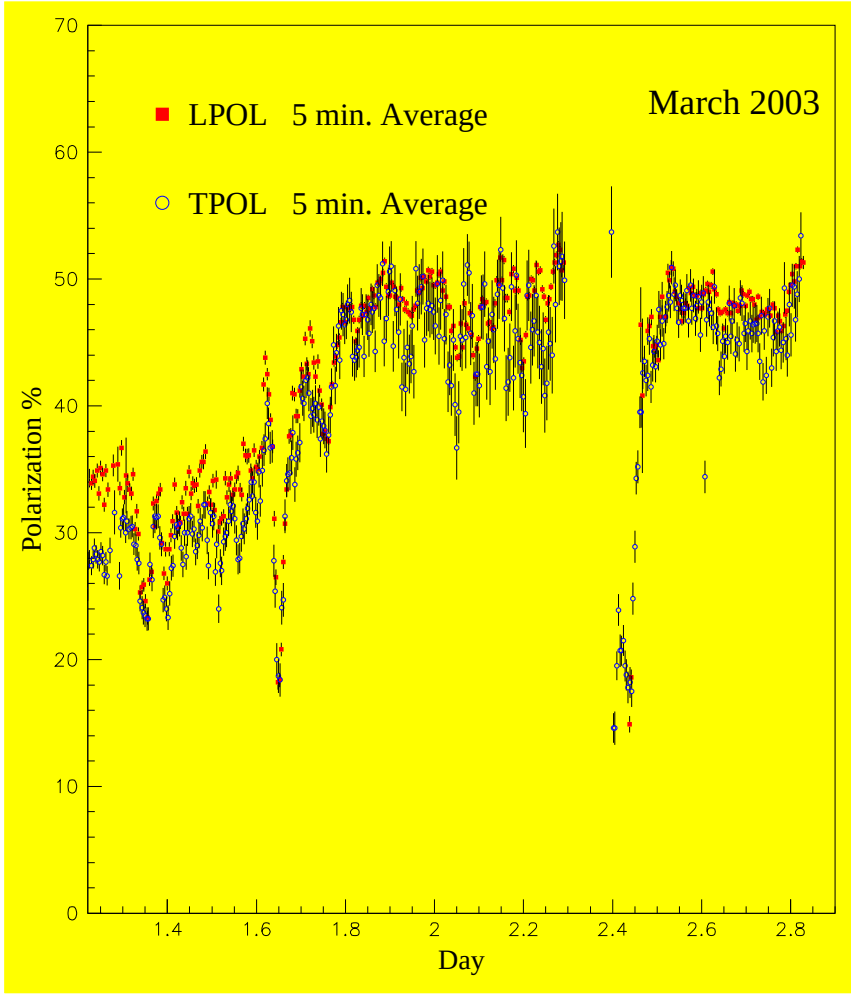

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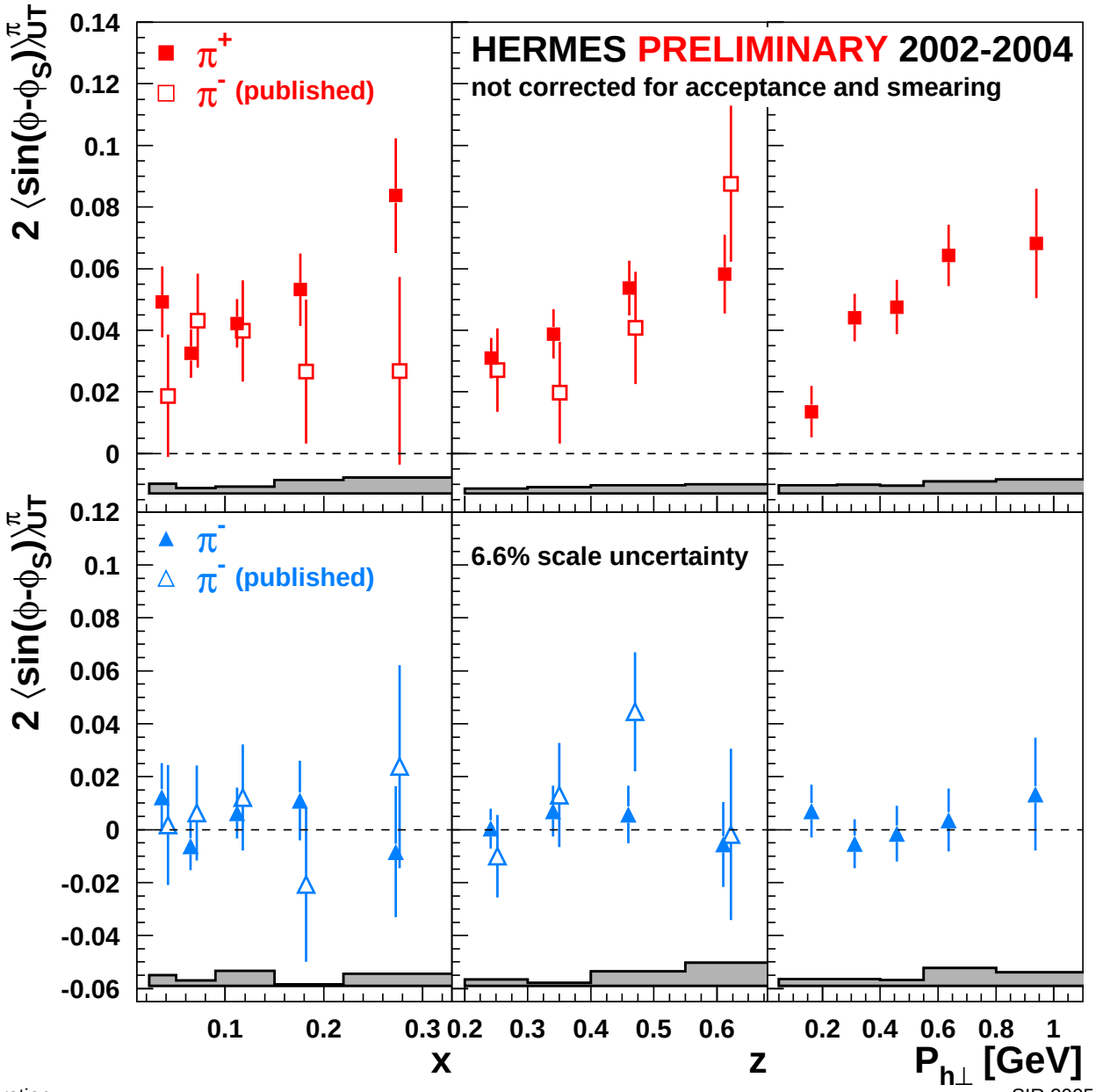
- 2-hadron fragmentation (talk by T. Kobayashi)
  beam-spin asymmetries (talk by E. Avetisyan)

Backup Slides

Sivers Asymmetries 2002-2004
Comparison with Publication



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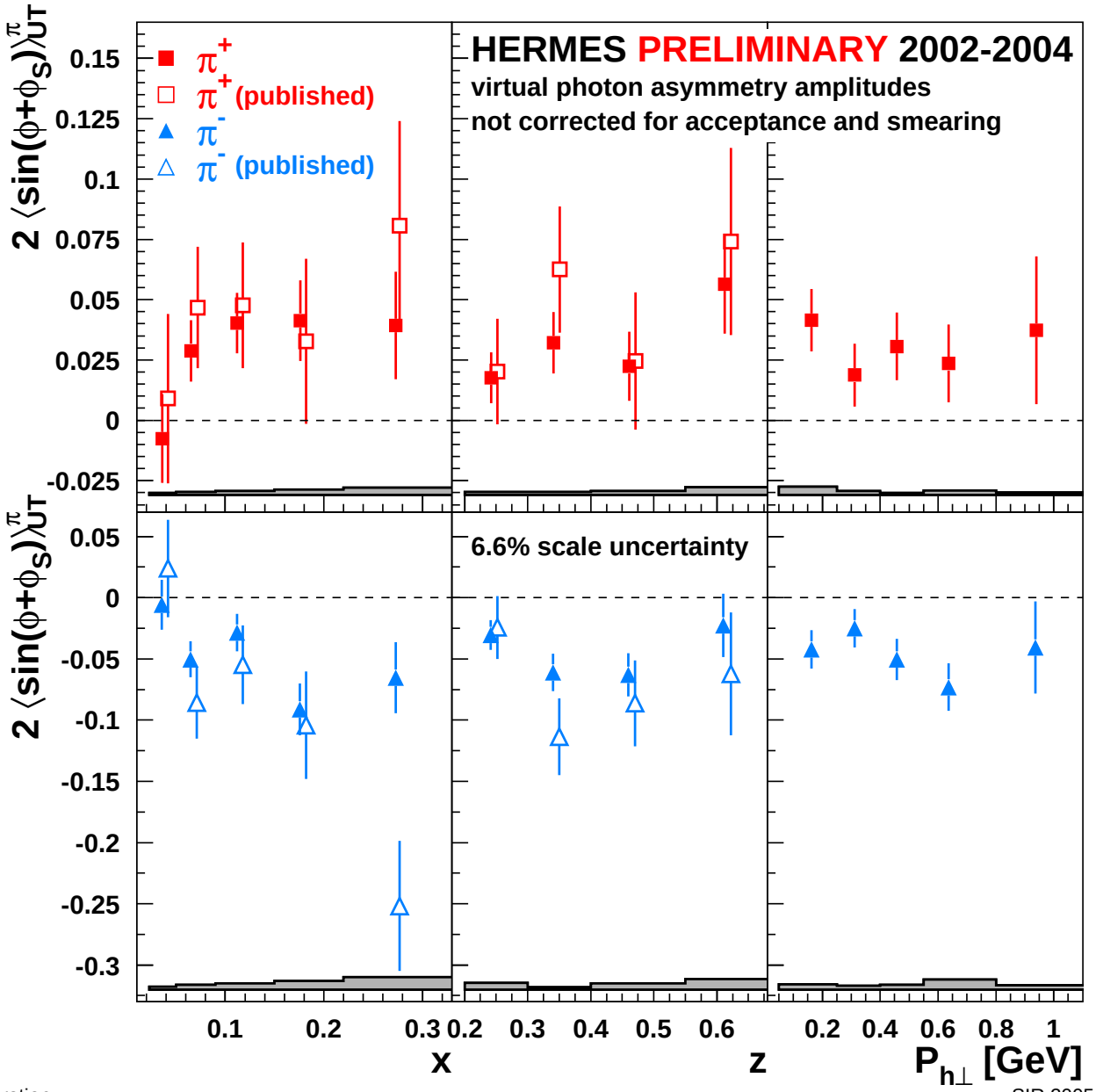
Comparison with Publication



Kinematic Cuts

$$
\begin{aligned}
1\ \text{GeV}^2 < \quad & Q^2 & \\
0.1 < \quad & y & < 0.85 \\
0.023 < \quad & x & < 0.4 \\
10\ \text{GeV}^2 < \quad & W^2 & \\
0.2 < \quad & z & < 0.7 \\
2\ \text{GeV} < \quad & P_h & < 15\ \text{GeV} \\
0.02\ \text{rad} < \quad & \theta_{\gamma^* h} &
\end{aligned}
$$