International Workshop on Hadron Structure and Spectroscopy
March 30-April 1, 2009- Mainz, Germany

Recent Highlights from the HERMES Collaboration

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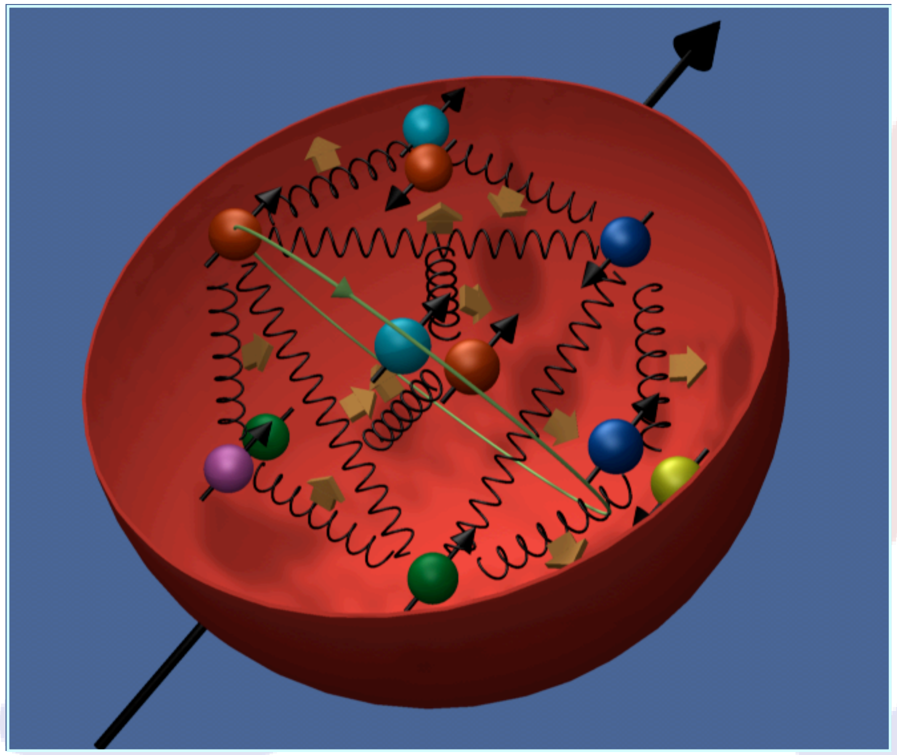
The Quest: Spin Structure of the Proton



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- $\frac{1}{2}\Delta\Sigma$ ← quark spin
- ΔG ← gluon spin
- $L_q + L_g$ ← orbital angular momentum

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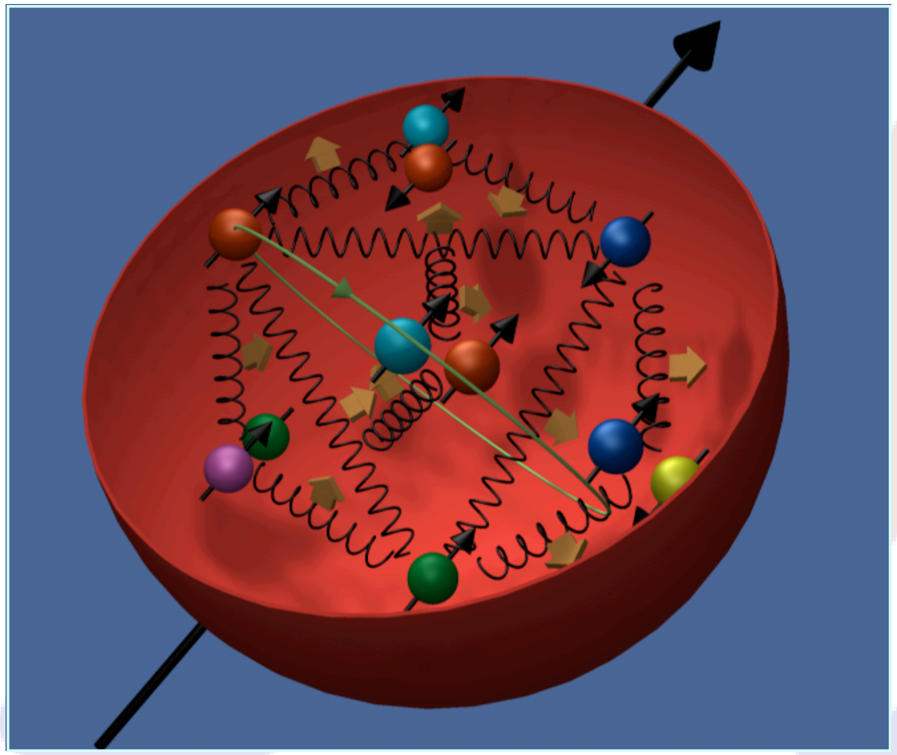

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- Inclusive DIS from longitudinally polarized Deuterium target:

$\Delta\Sigma = 0{,}330 \pm 0{,}025^{\text{(exp.)}} \pm 0{,}011^{\text{(theory)}} \pm 0{,}028^{\text{(evol.)}}$

PRD 75 (2007) 012007

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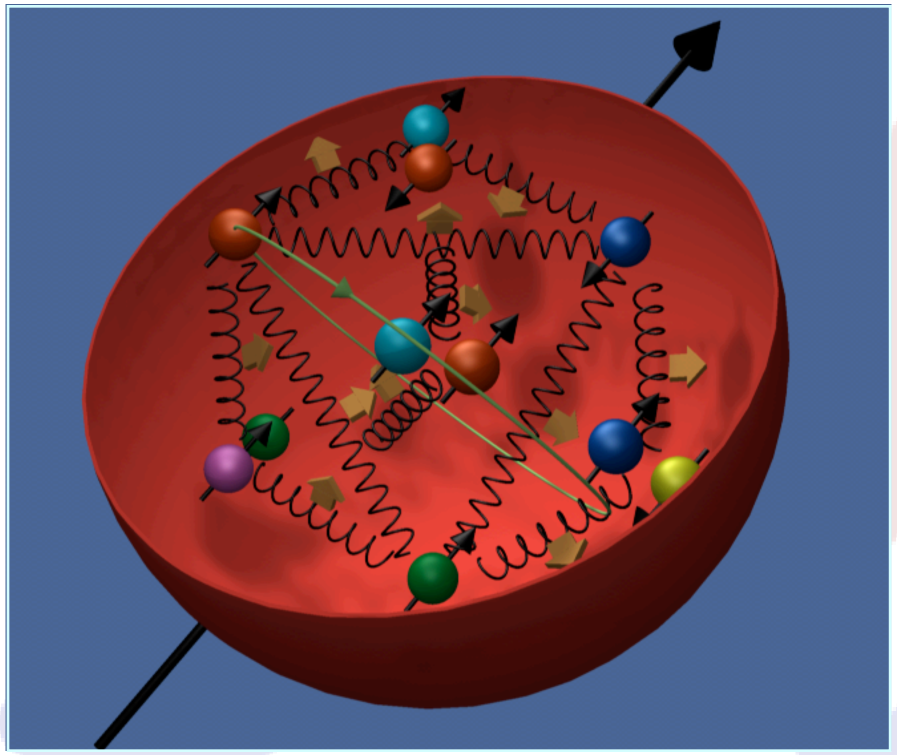

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- High-p_T hadrons at HERMES:

$\Delta G/G = 0.071 \pm 0.034^{(stat)} \pm 0.010^{\,(sys\text{-}exp)}\,{}^{+0.127}_{-0.105}\,(sys\text{-}model)$

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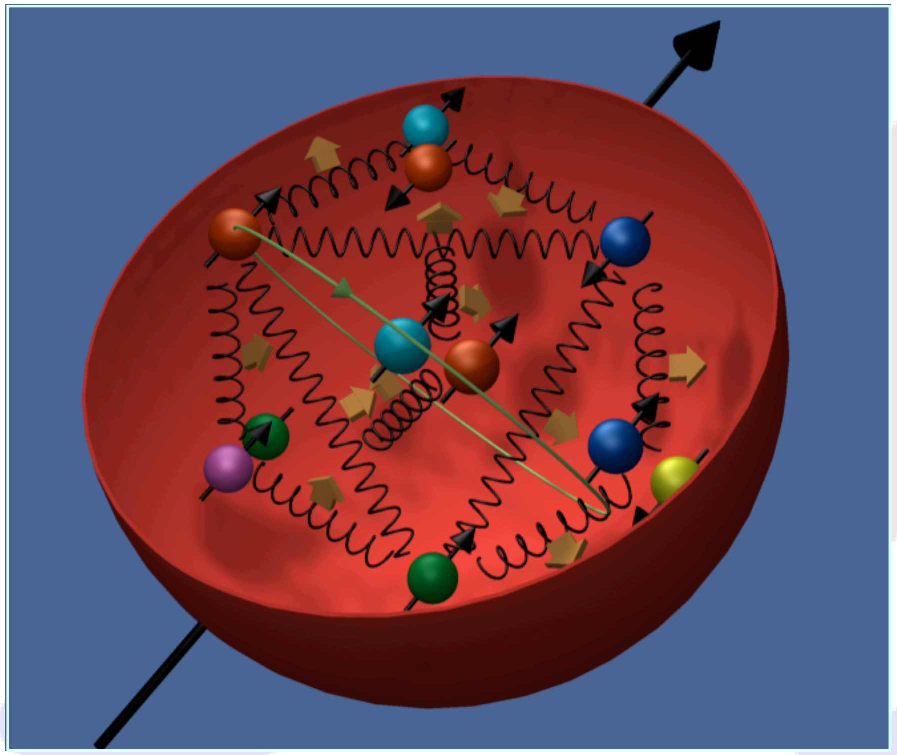

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- spin-orbit correlations
- hard exclusive reactions

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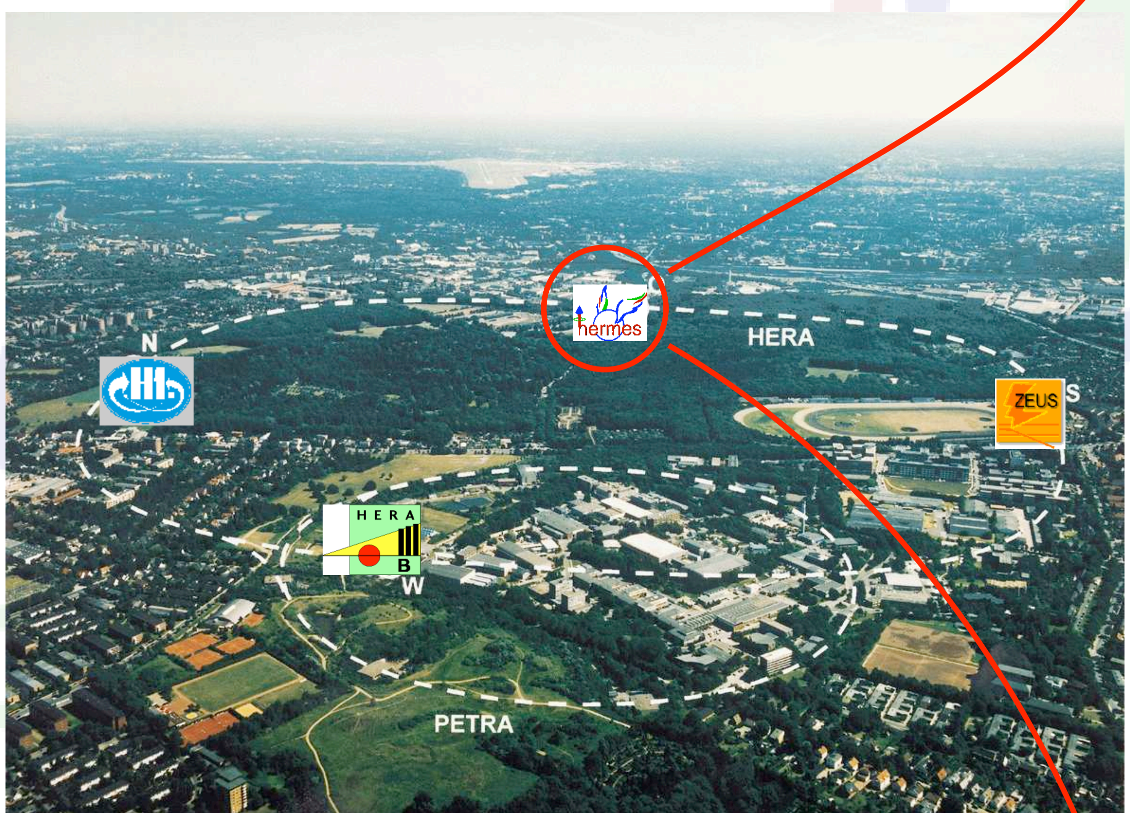
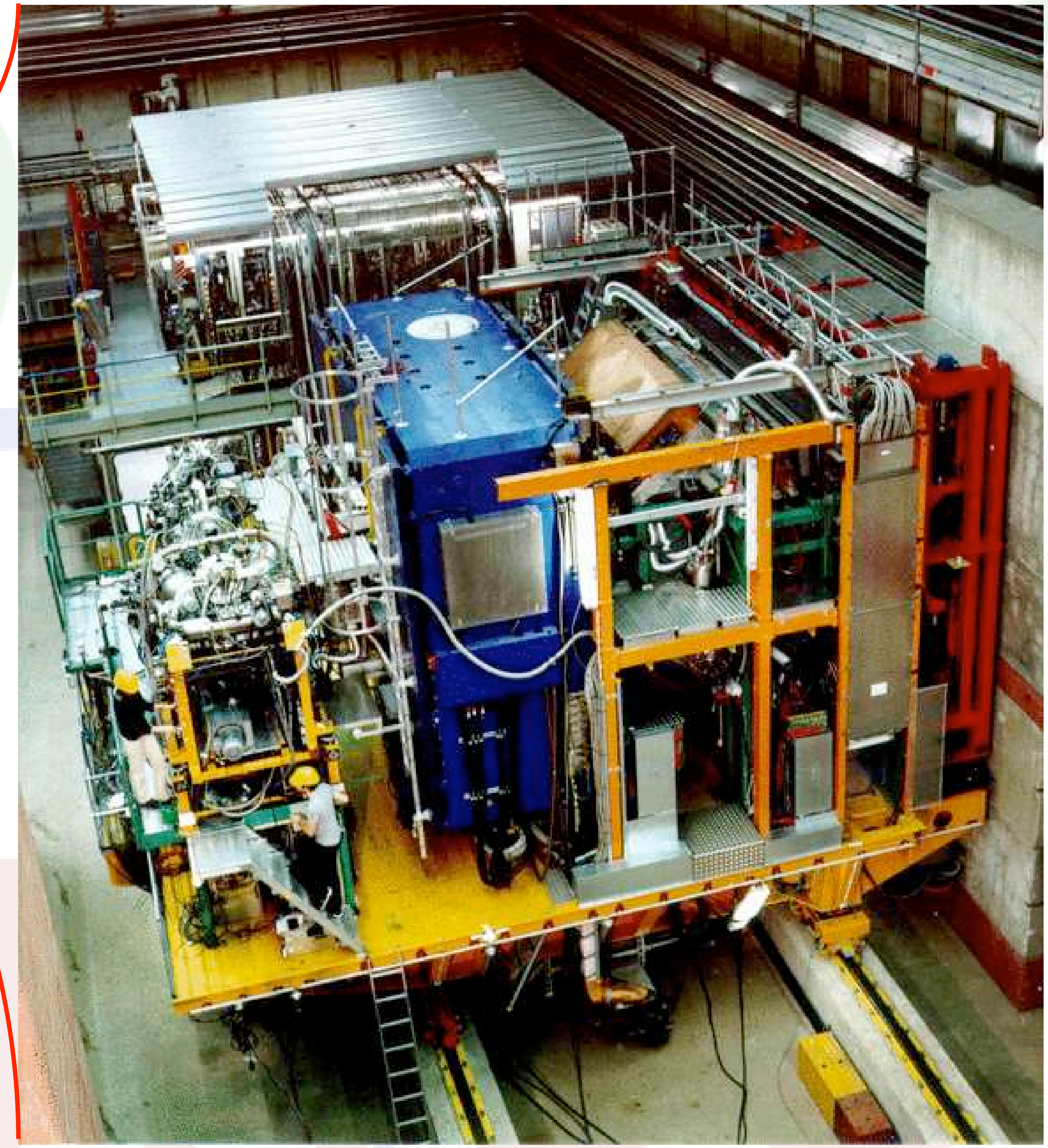
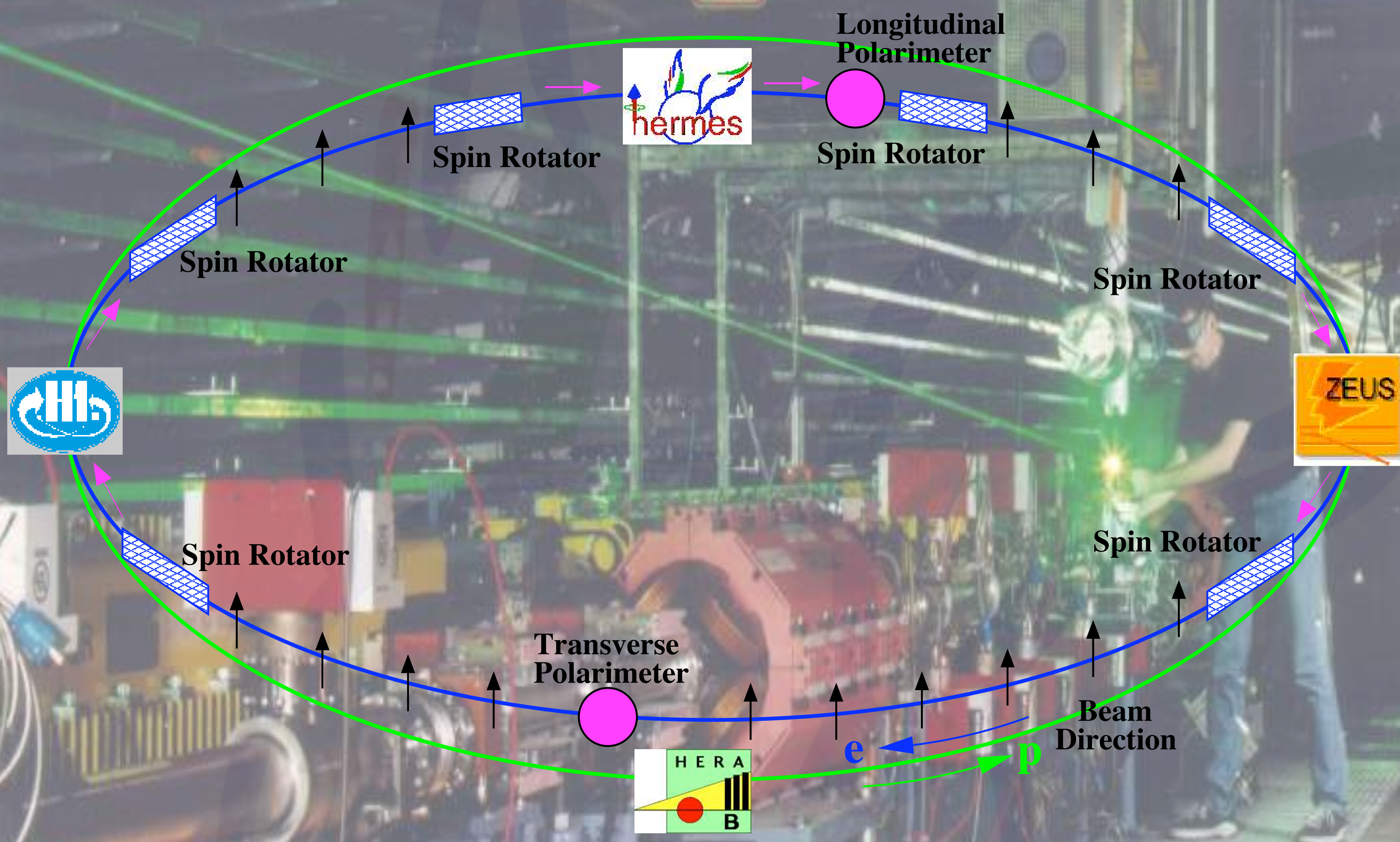
The HERMES Experiment

27.5 GeV e^+/e^- beam of HERA





Beam Polarization at HERA



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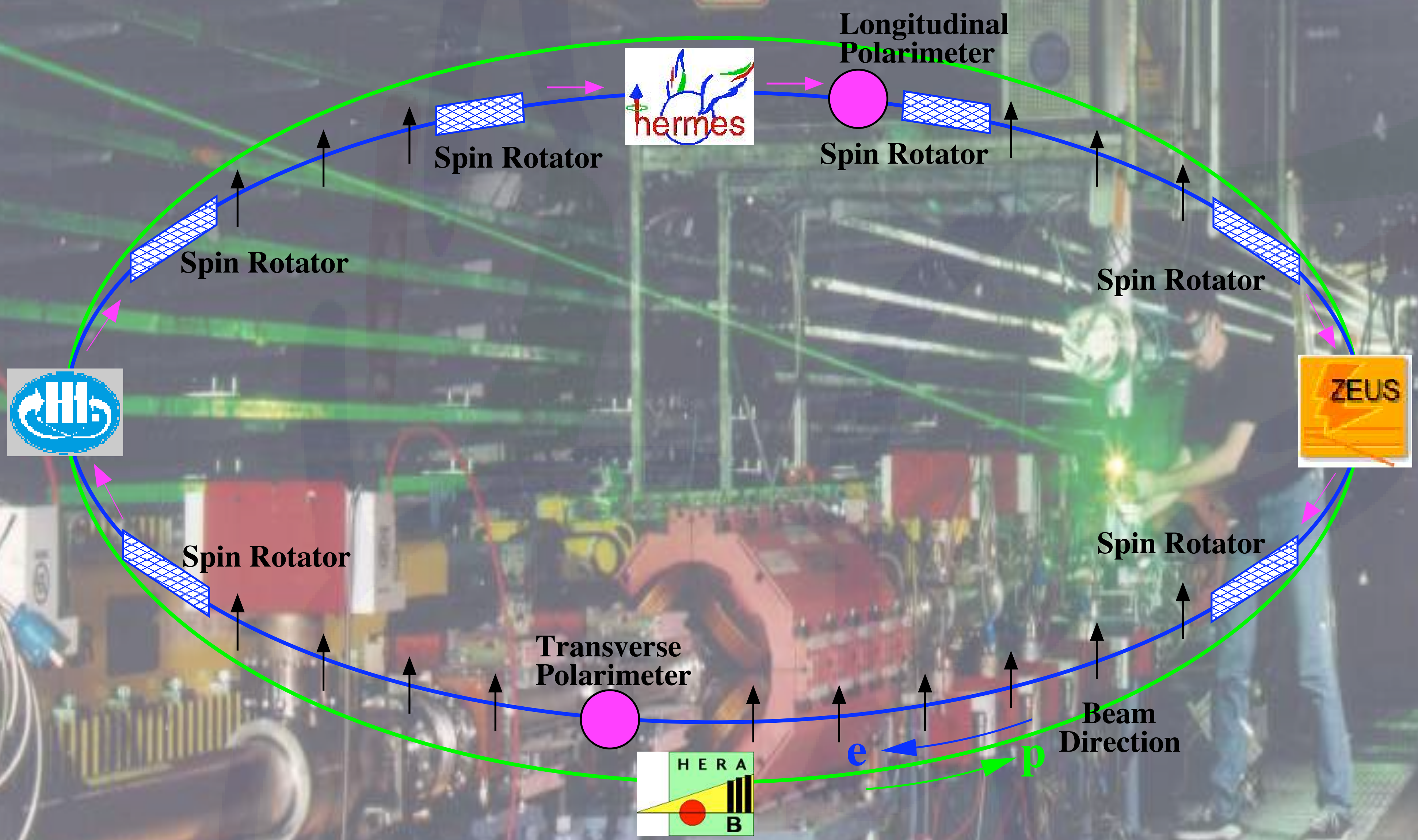

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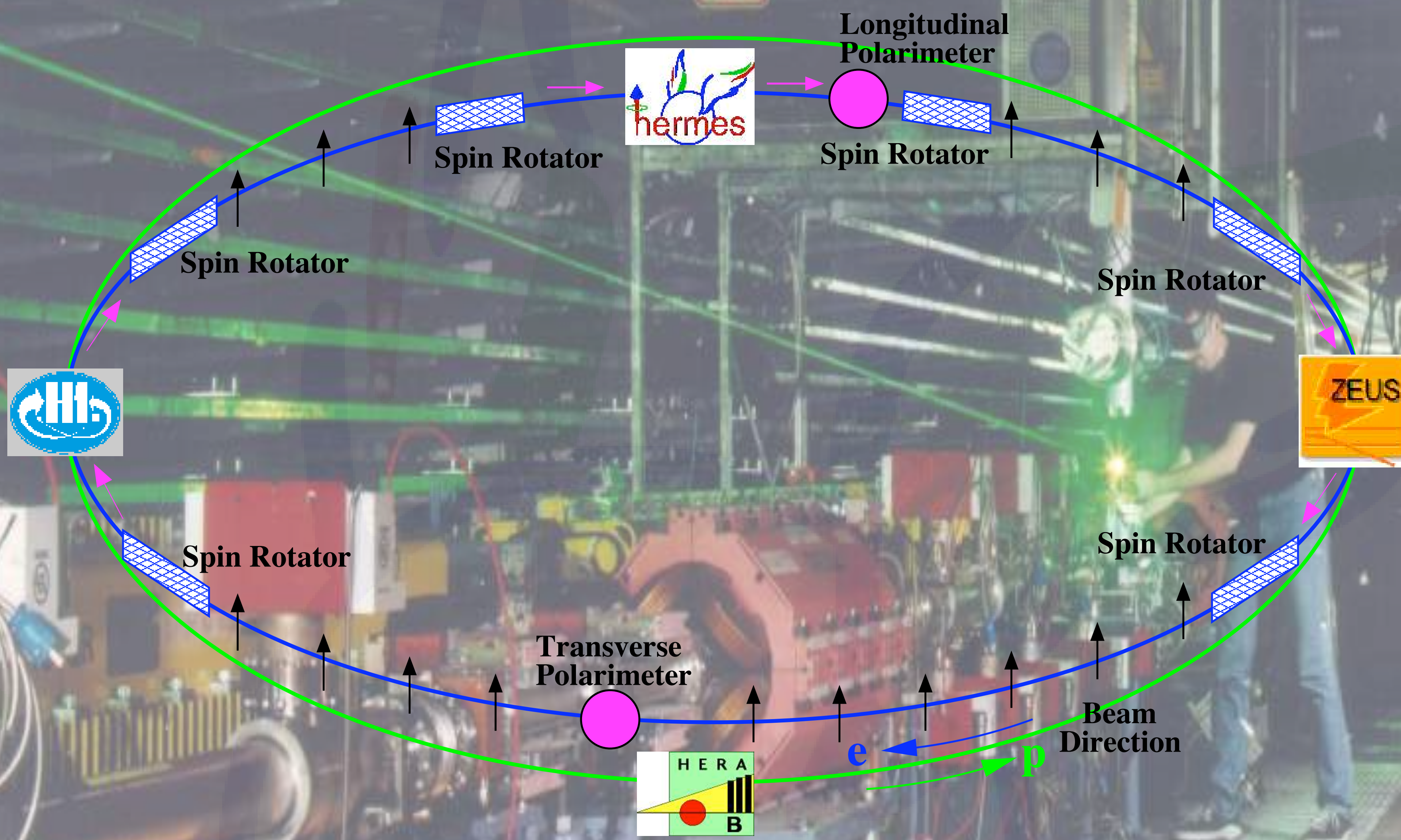

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- transversely polarized through Sokolov-Ternov effect

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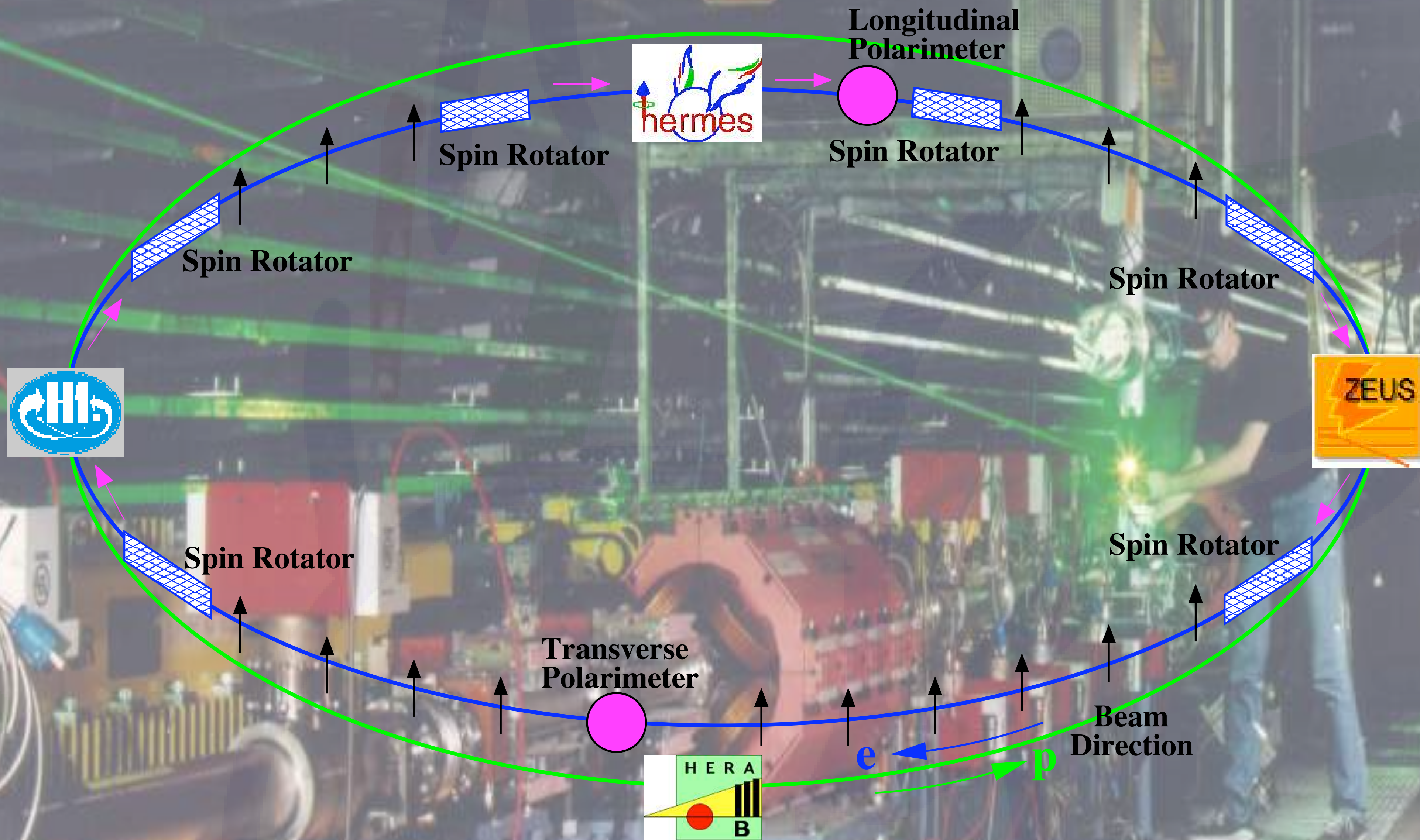
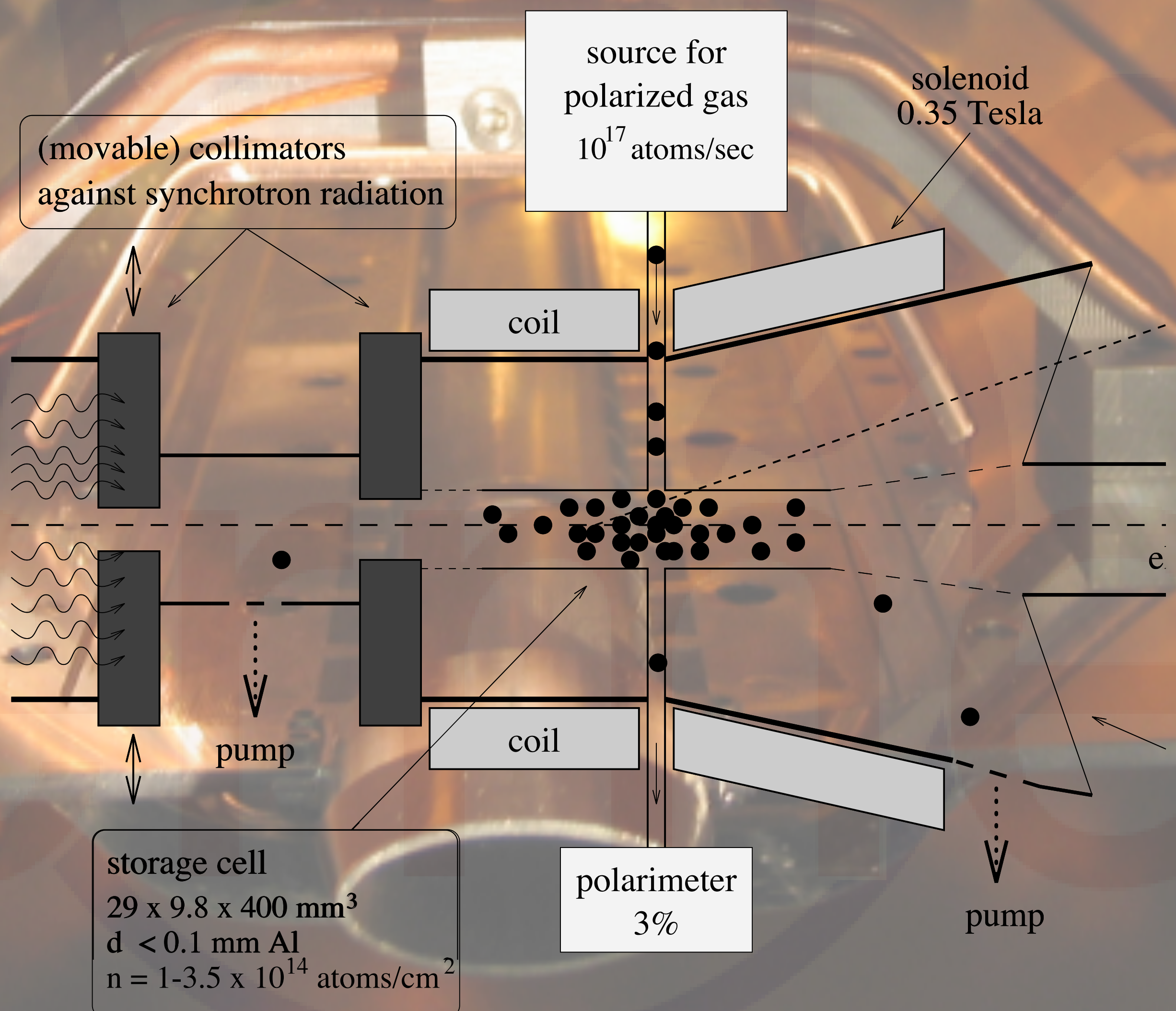


- 27.5 GeV electron/positron beam
- transversely polarized through Sokolov-Ternov effect
- average beam polarization up to 55%

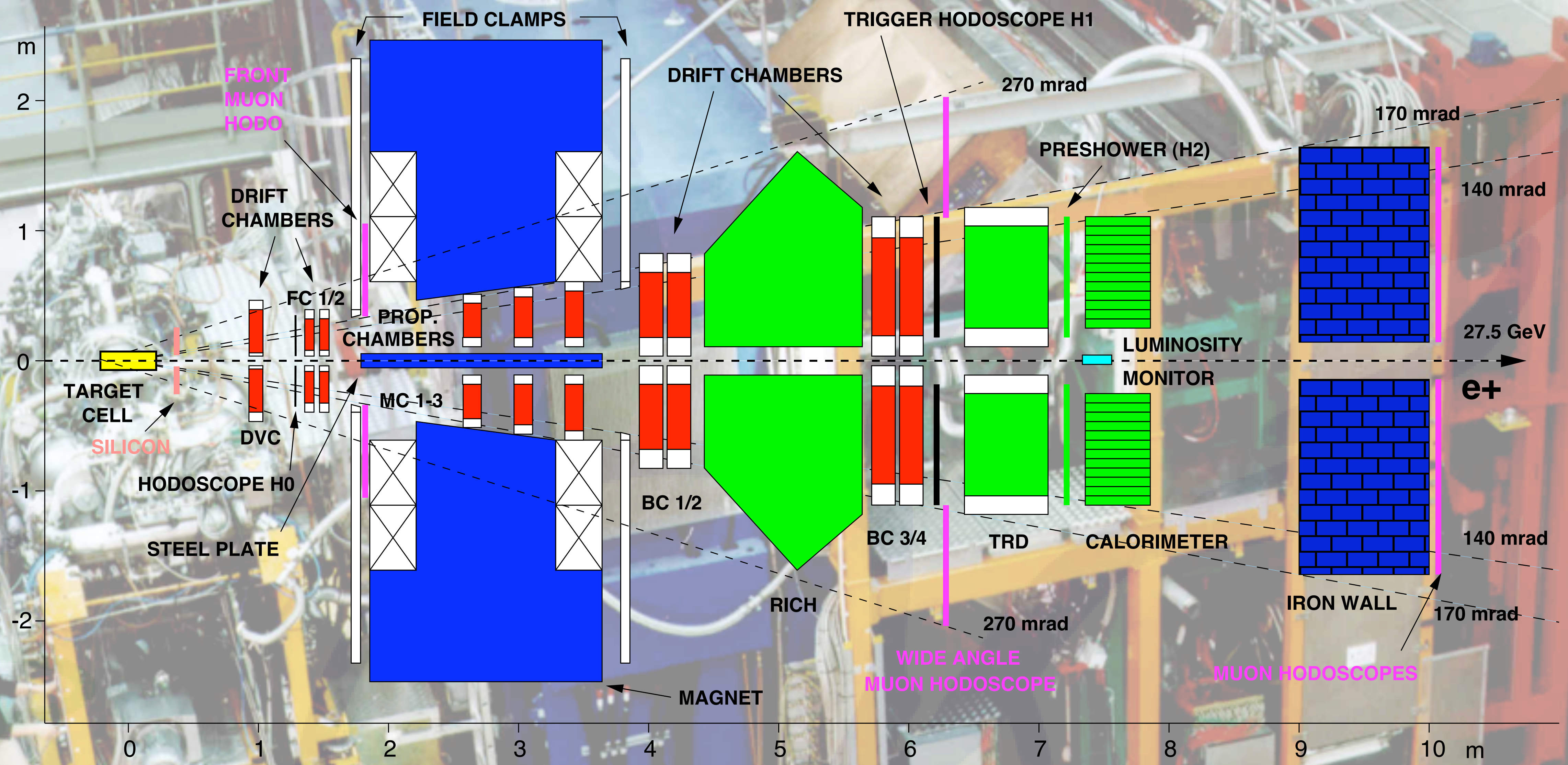
HERMES Polarized Target

- Storage cell with atomic beam source
- Pure target (NO dilution)
- Polarized or unpolarized targets possible
- Different gas targets available (H, D, He, N, Kr ...)

Polarization:
longitudinal: ~85%
transversal: ~75%

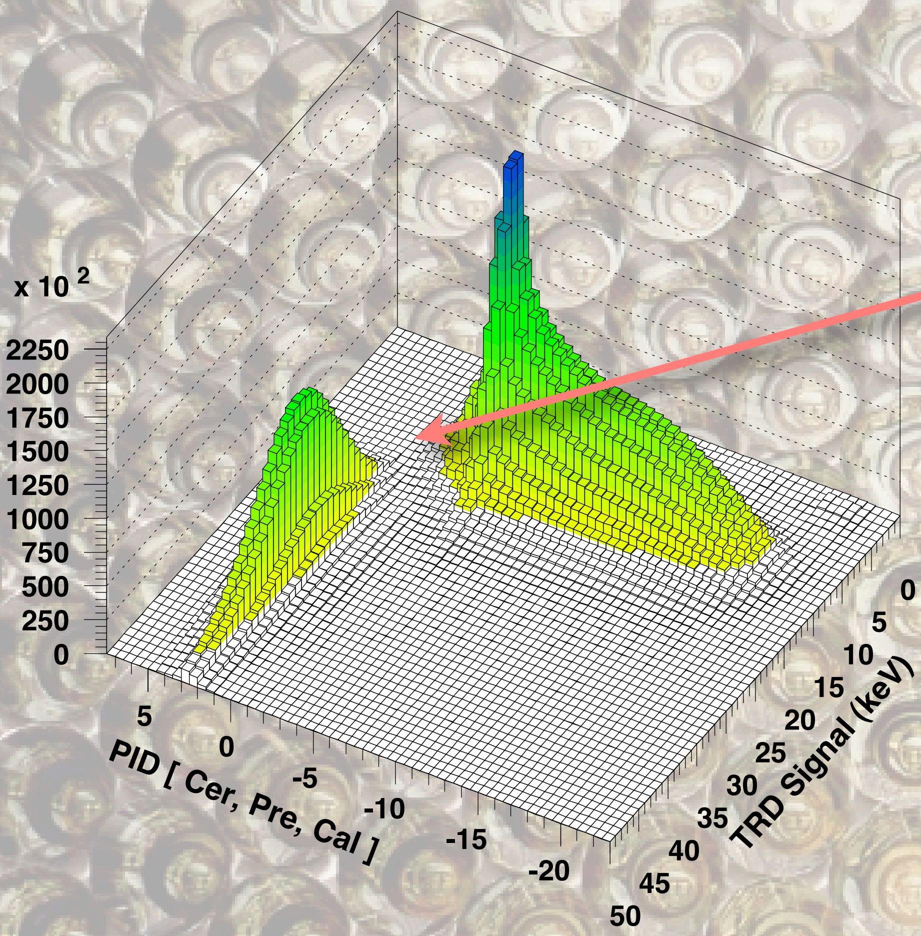


HERMES Spectrometer



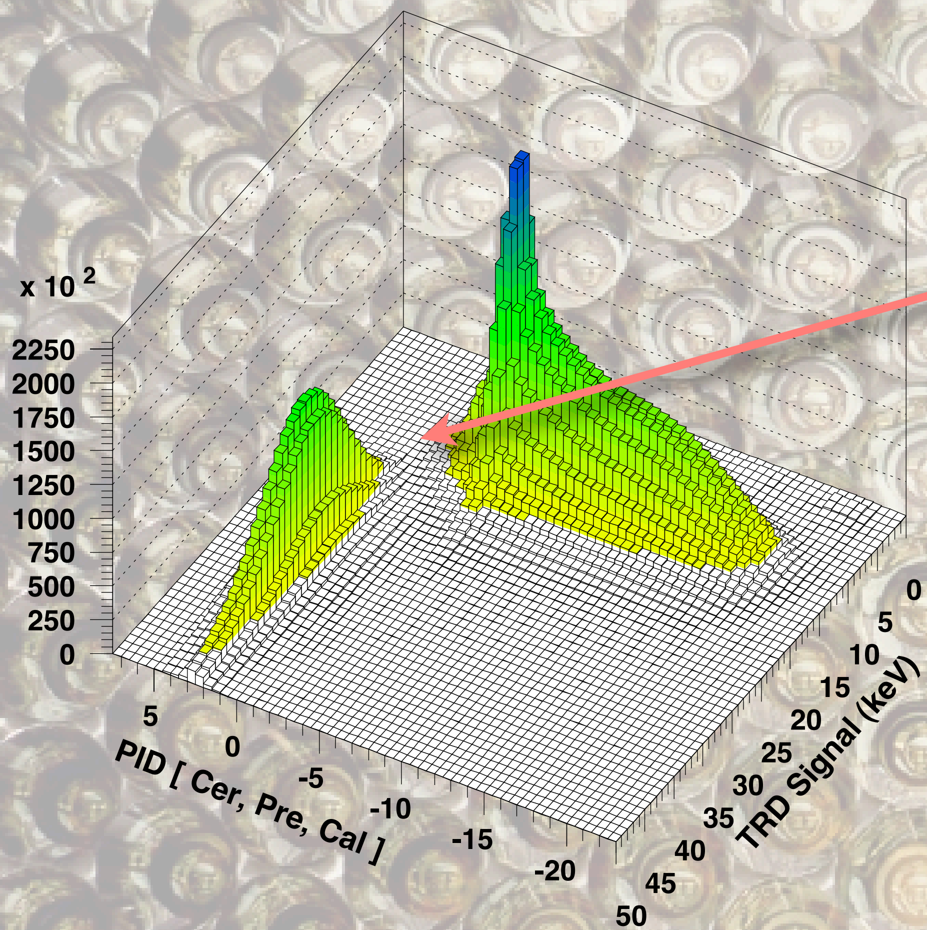
- Forward acceptance spectrometer: 40 mrad $\leq \Theta \leq$ 220 mrad
- Kinematic coverage: $0.02 \leq x \leq 0.8$ for $Q^2 > 1$ GeV^2 and $W > 2$ GeV
- Tracking: 57 tracking planes: $\delta P/P = (0.7-2.5)\%$, $\delta\Theta \leq 1$ mrad
- PID: Cherenkov (RICH after 1997), TRD, Preshower, Calorimeter

Particle Identification



excellent lepton/hadron separation

Particle Identification



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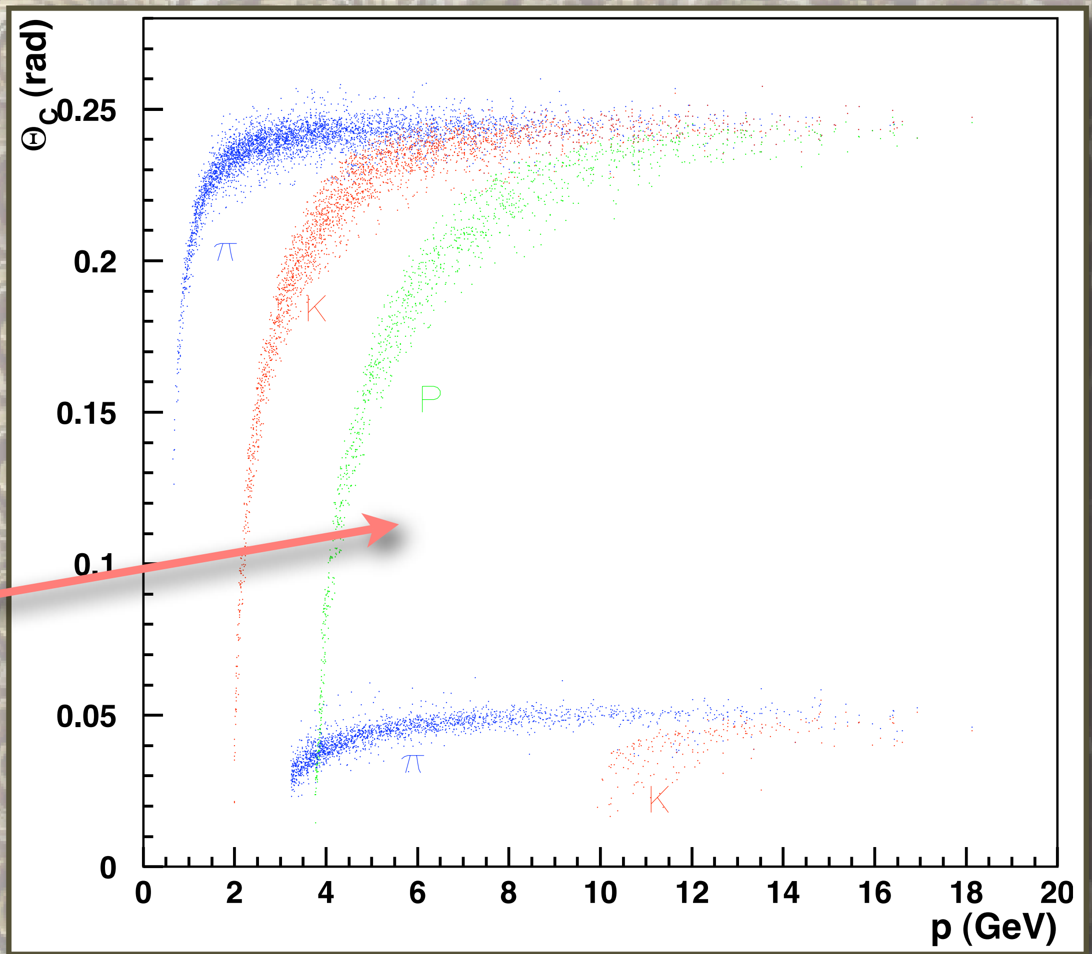
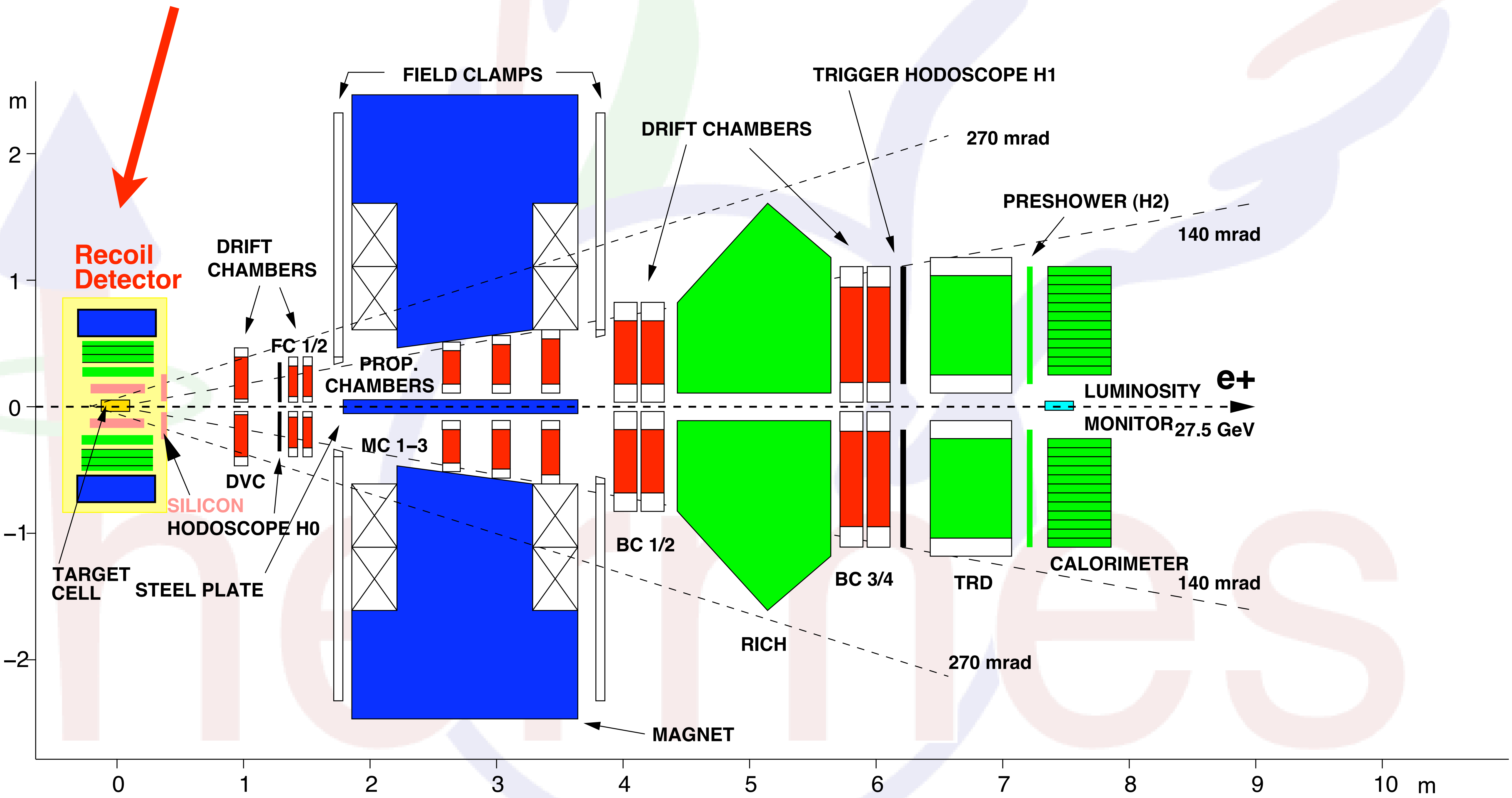
Dual-Radiator RICH hadron ID for momenta 2-15 GeV



HERMES Detector (2006/07)

detection of recoiling proton



Longitudinal Momentum & Spin Structure

Strange-Quark Distributions

- use isoscalar probe and target to extract strange-quark distributions
- only need inclusive asymmetries and K⁺+K⁻ asymmetries, i.e., $A_{\|,d}(x,Q^2)$ and $A_{\|,d}^{K^++K^-}(x,z,Q^2)$, as well as K⁺+K⁻ multiplicities on deuteron

$$S(x)\int \mathcal{D}_S^K(z)\,\mathrm{d}z \simeq Q(x)\left[5\frac{\mathrm{d}^2N^K(x)}{\mathrm{d}^2N^{\mathrm{DIS}}(x)} - \int \mathcal{D}_Q^K(z)\,\mathrm{d}z\right]$$

$$A_{\|,d}(x)\frac{\mathrm{d}^2N^{\mathrm{DIS}}(x)}{\mathrm{d}x\,\mathrm{d}Q^2} = \mathcal{K}_{LL}(x,Q^2)[5\Delta Q(x) + 2\Delta S(x)]$$

$$A_{\|,d}^{K^\pm}(x)\frac{\mathrm{d}^2N^K(x)}{\mathrm{d}x\,\mathrm{d}Q^2}$$

$$= \mathcal{K}_{LL}(x,Q^2)\left[\Delta Q(x)\int \mathcal{D}_Q^K(z)\,\mathrm{d}z + \Delta S(x)\int \mathcal{D}_S^K(z)\,\mathrm{d}z\right]$$

A. Airapetian et al., PLB 666, 446 (2008)

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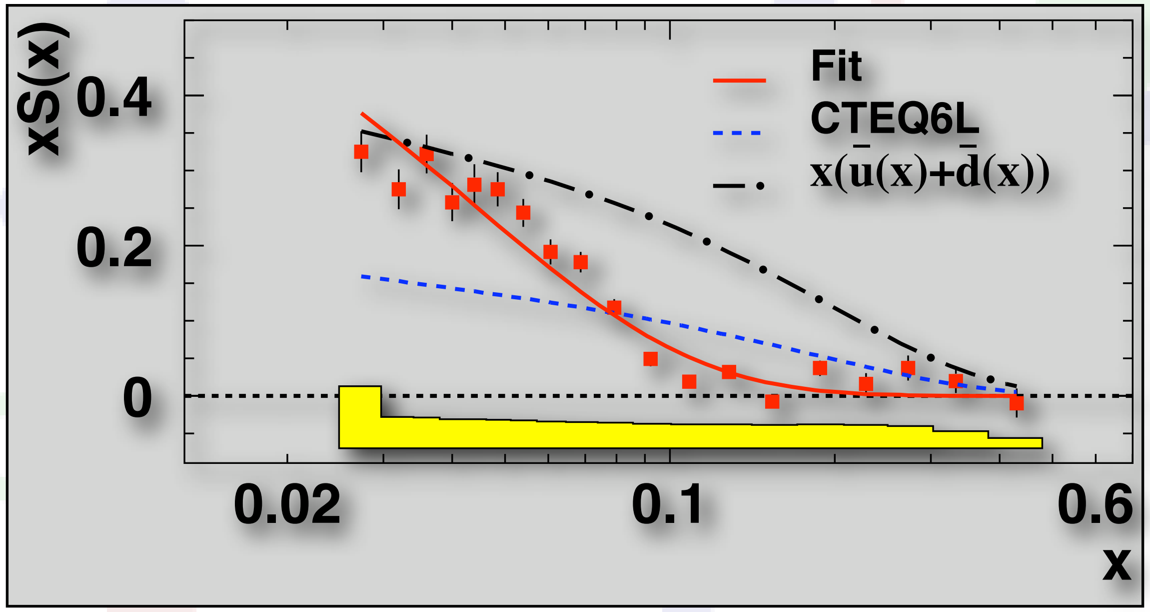

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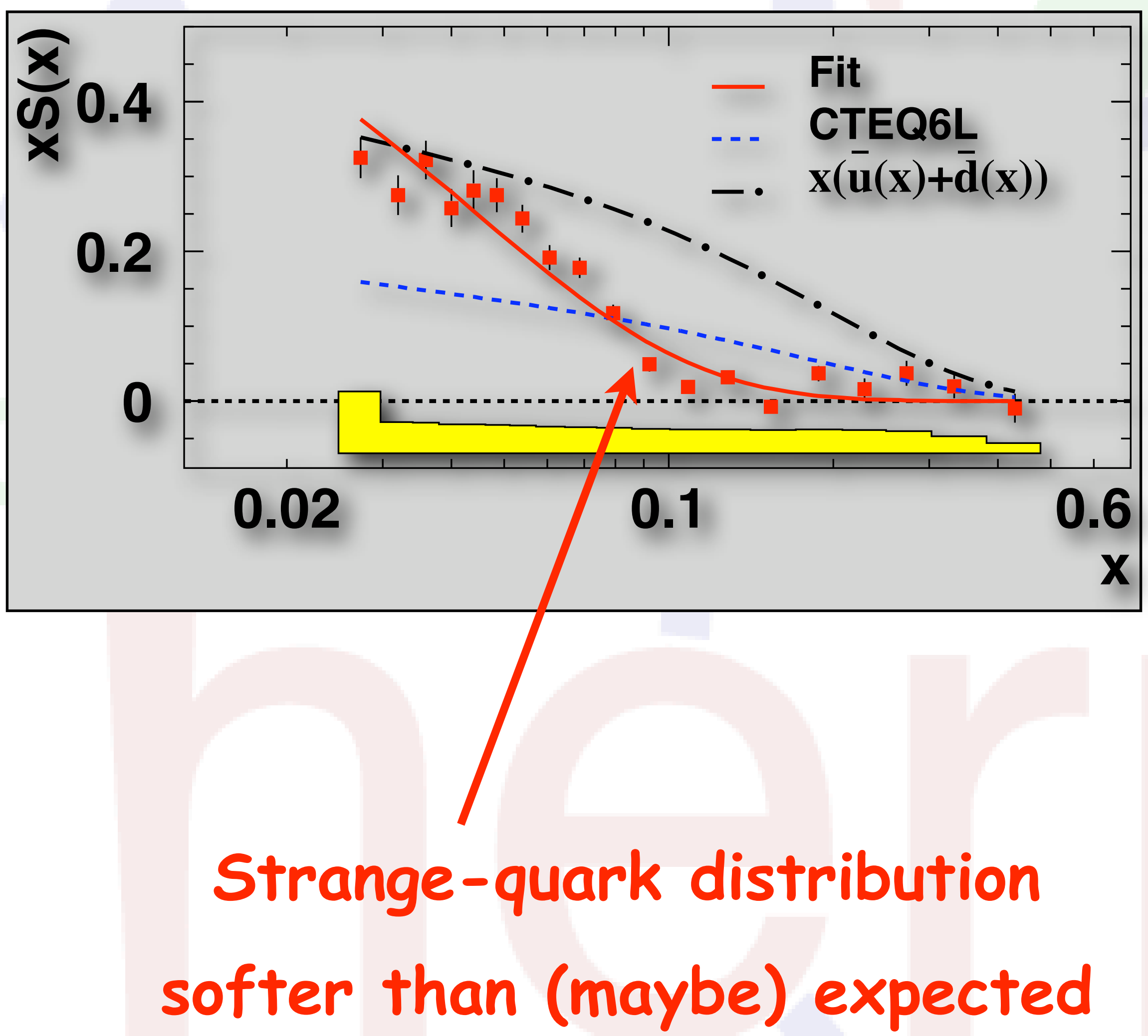

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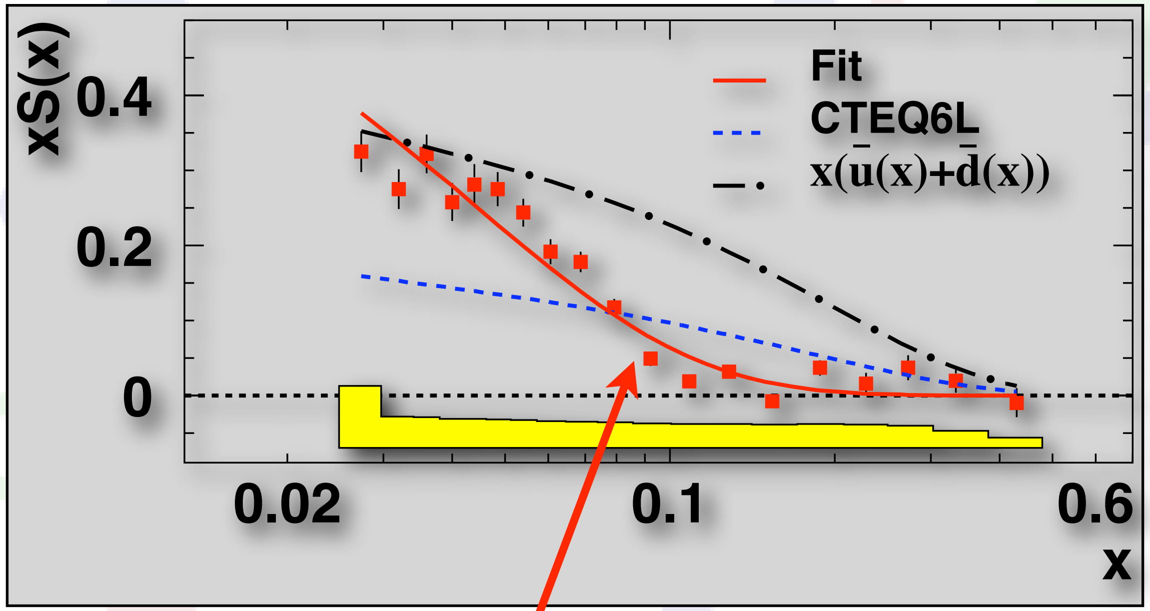

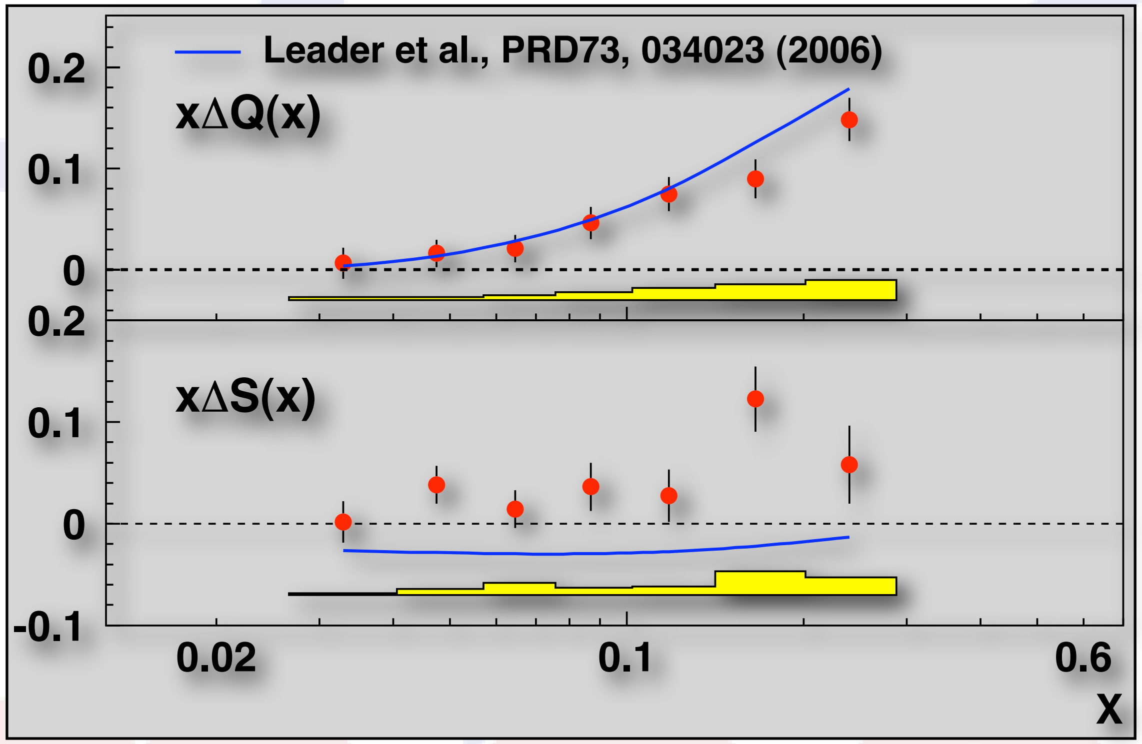

Strange-quark distribution softer than (maybe) expected

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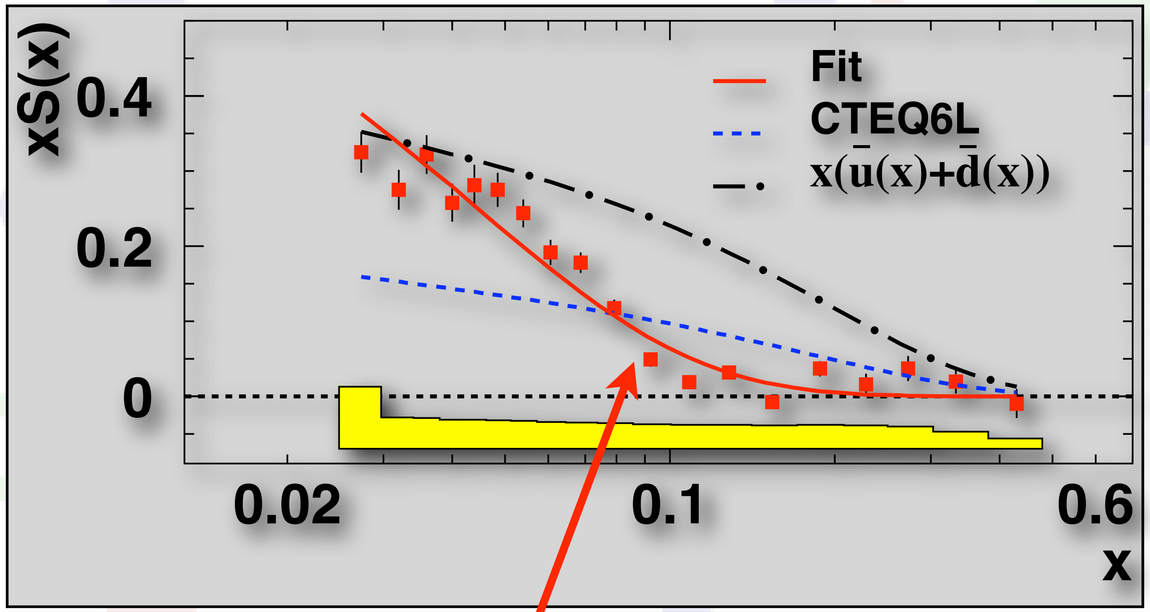
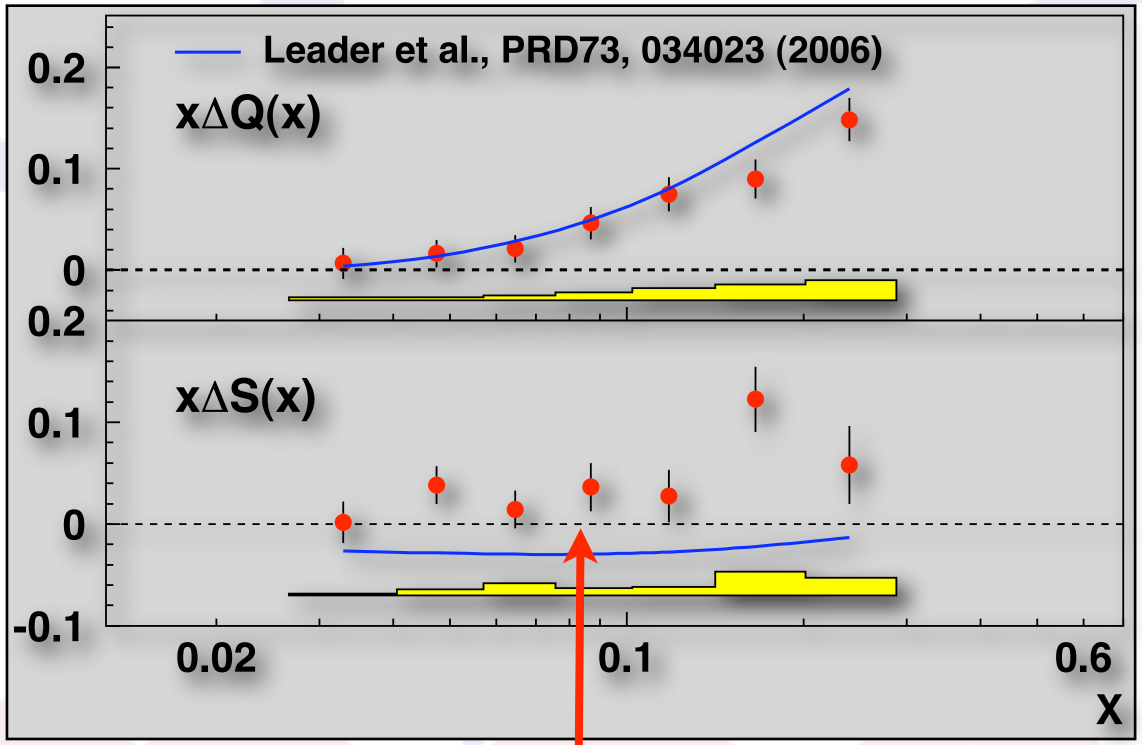




Strange-quark distribution softer than (maybe) expected

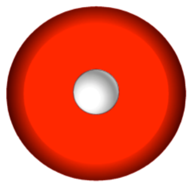
Strange-quark helicity distribution consistent with zero or slightly positive in contrast to inclusive DIS analyses

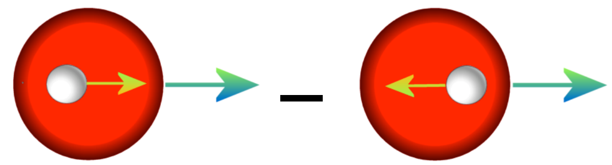
A. Airapetian et al., PLB 666, 446 (2008)

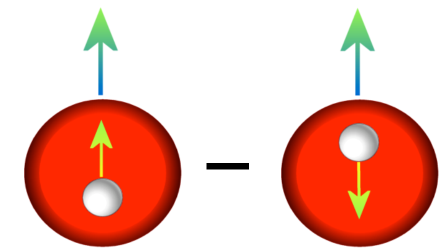
Transverse-Spin/Momentum Effects

Quark Structure of the Nucleon

(integrated over quark transverse momentum)

f_1^q = 

g_1^q = 

h_1^q = 

$\Downarrow$

Unpolarized quarks and nucleons

$f_1^q(x)$: spin averaged (well known)

$\Rightarrow$ Vector Charge

$\langle PS|\bar{\Psi}\gamma^\mu\Psi|PS\rangle = \int dx (f_1^q(x) - f_1^{\bar{q}}(x))$

$\Downarrow$

Longitudinally polarized quarks and nucleons

$g_1^q(x)$: helicity difference (known)

$\Rightarrow$ Axial Charge

$\langle PS|\bar{\Psi}\gamma^\mu\gamma_5\Psi|PS\rangle = \int dx (g_1^q(x) + g_1^{\bar{q}}(x))$

$\Downarrow$

Transversely polarized quarks and nucleons

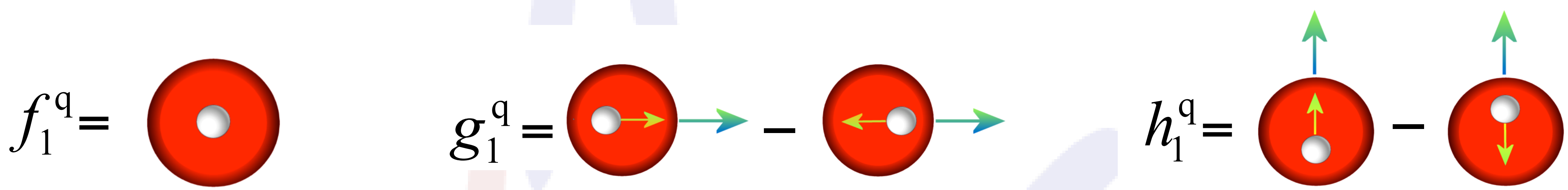
$h_1^q(x)$: transversity (hardly known!)

$\Rightarrow$ Tensor Charge

$\langle PS|\bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi|PS\rangle = \int dx (h_1^q(x) - h_1^{\bar{q}}(x))$

Quark Structure of the Nucleon

(integrated over quark transverse momentum)



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$h_1^q(x)$: transv… (hardly kn…)

$\Rightarrow$ Tens… …arge

$\langle PS|\bar{\Psi}\sigma$ … $\gamma_5\Psi|PS\rangle = \int dx(h_1^q(x) - h_1^{\bar{q}}(x))$

Chiral-odd!

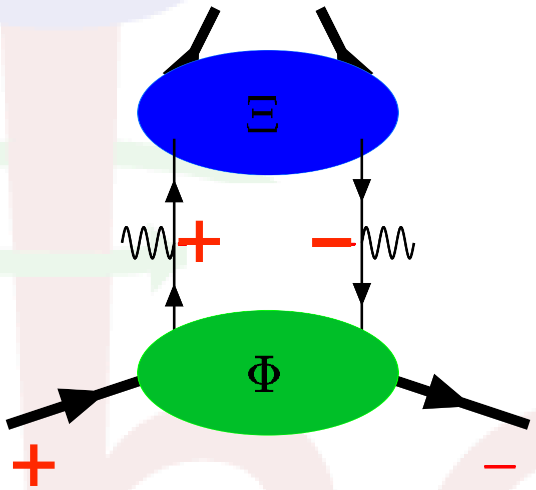
Transvershy Measurement

How can one measure transversity?

Need another chiral-odd object!

$\Rightarrow$ Semi-Inclusive DIS

$$\sigma^{ep\to ehX} = \sum_q h_1^q \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}$$



h_1^q $\Downarrow$ **chiral-odd** DF

$FF^{q\to h}$ $\Downarrow$ **chiral-odd** FF

CHIRAL EVEN

$\rightarrow$ chiral-odd FF as a polarimeter of transv. quark polarization

2-Hadron Fragmentation

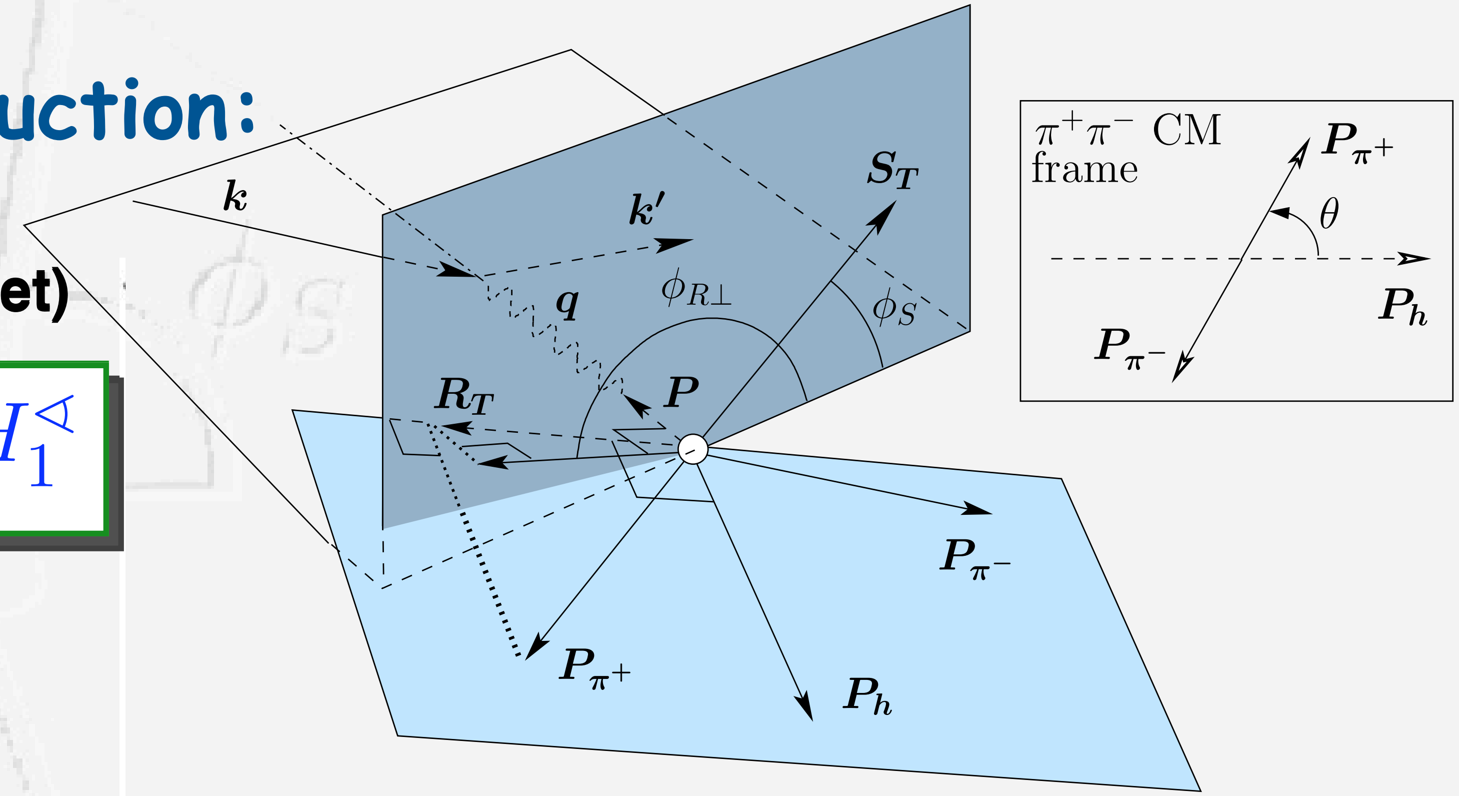
spin-dependent 2-hadron production:

(Unpolarized beam, Transversely pol. target)

$$\sigma_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sum e_q^2 \, h_1^q \, H_1^{\sphericalangle}$$

$$H_1^{\sphericalangle} = H_1^{\sphericalangle}(z, \zeta, M_{\pi\pi}^2)$$

$(\zeta \sim z_1/(z_1 + z_2))$



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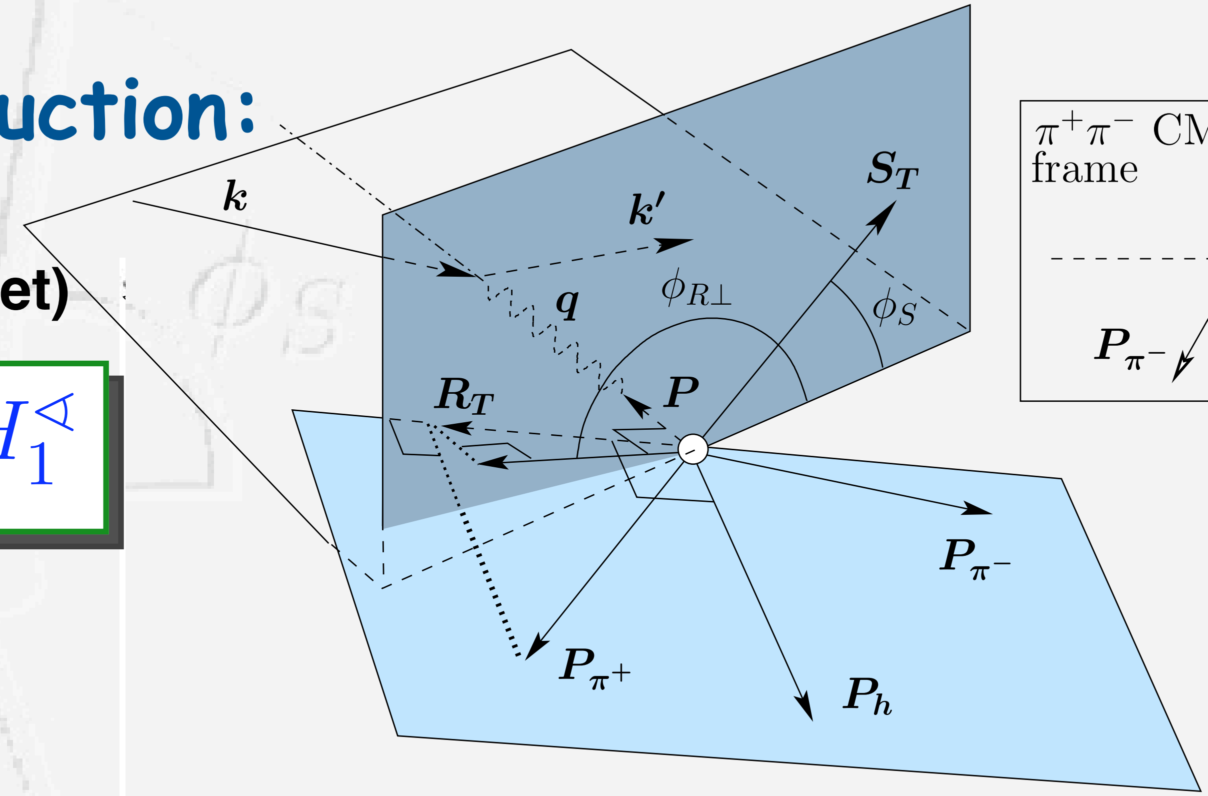

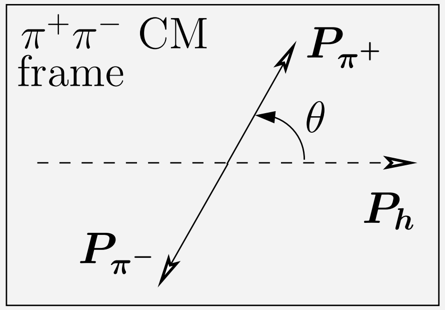

☺ only relative momentum of hadron pair relevant

⇒ integration over transverse momentum of hadron pair simplifies factorization and Q^2 evolution

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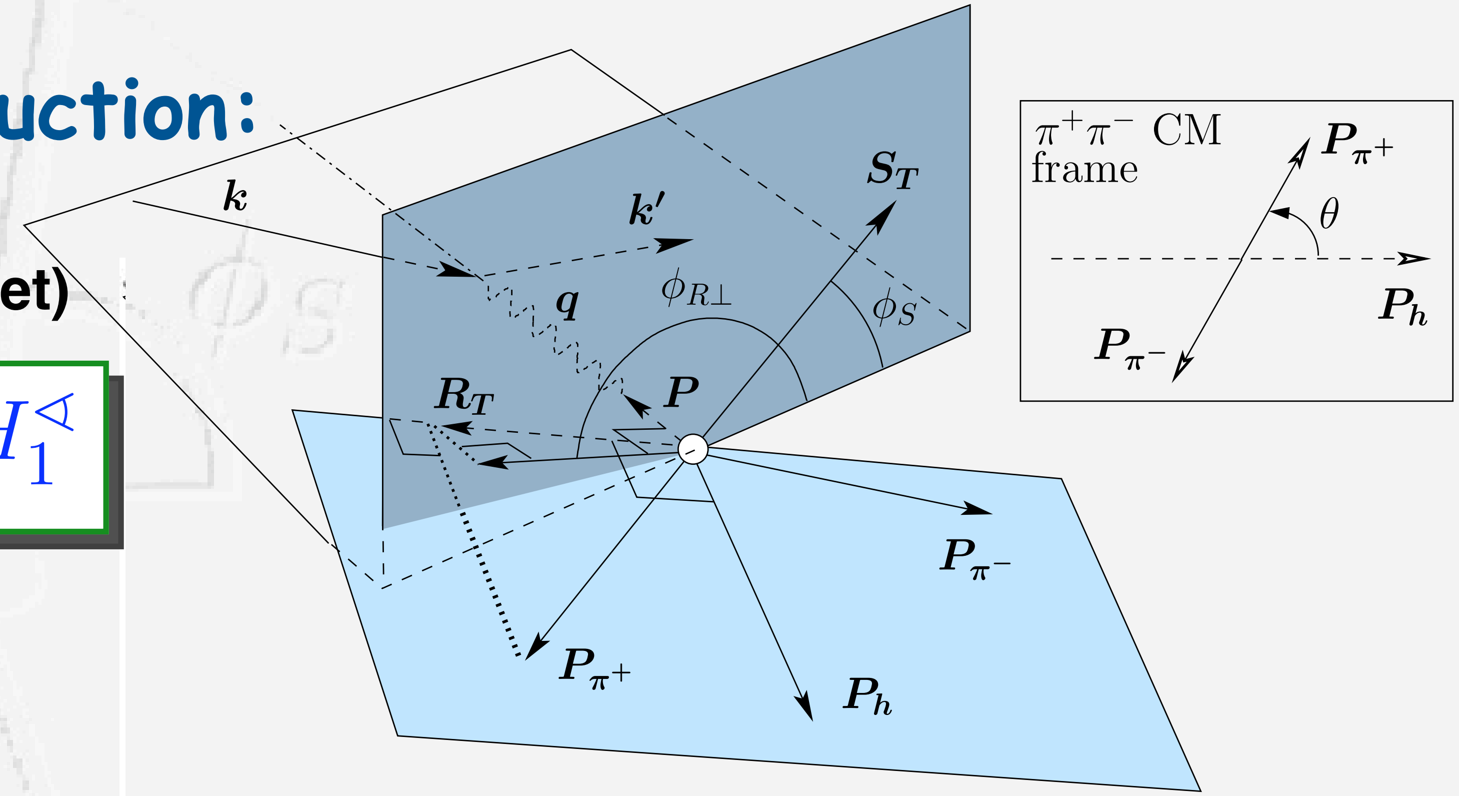


- only relative momentum of hadron pair relevant

  ⇒ integration over transverse momentum of hadron pair simplifies factorization and Q^2 evolution

- however, cross section becomes quite complex (differential in 9 variables)

Model for Dihadron Fragmentation

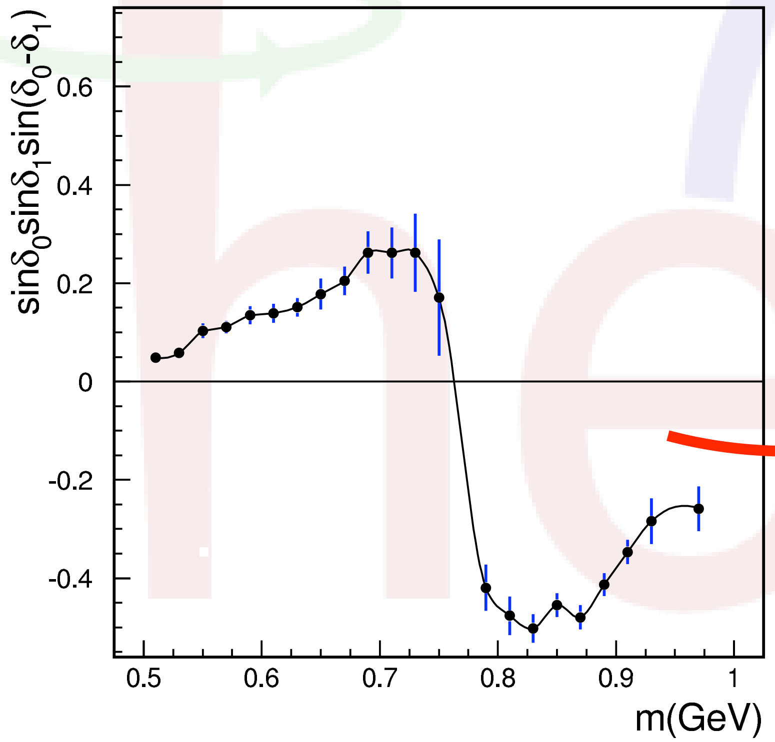
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin\theta h_1 H_1^{\sphericalangle}$$

Expansion of $H_1^{\sphericalangle}$ in Legendre moments:

$$H_1^{\sphericalangle}(z, \cos\theta, M_{\pi\pi}^2) = H_1{}^{\sphericalangle,sp}(z, M_{\pi\pi}^2) + \cos\theta H_1{}^{\sphericalangle,pp}(z, M_{\pi\pi}^2)$$

describe interference between 2 pion pairs coming from different production channels.

about $H_1^{\sphericalangle,sp}$:



Jaffe et al. [**hep-ph/9709322**]:

$$H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) = \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1) H_1^{\sphericalangle,sp'}(z)$$

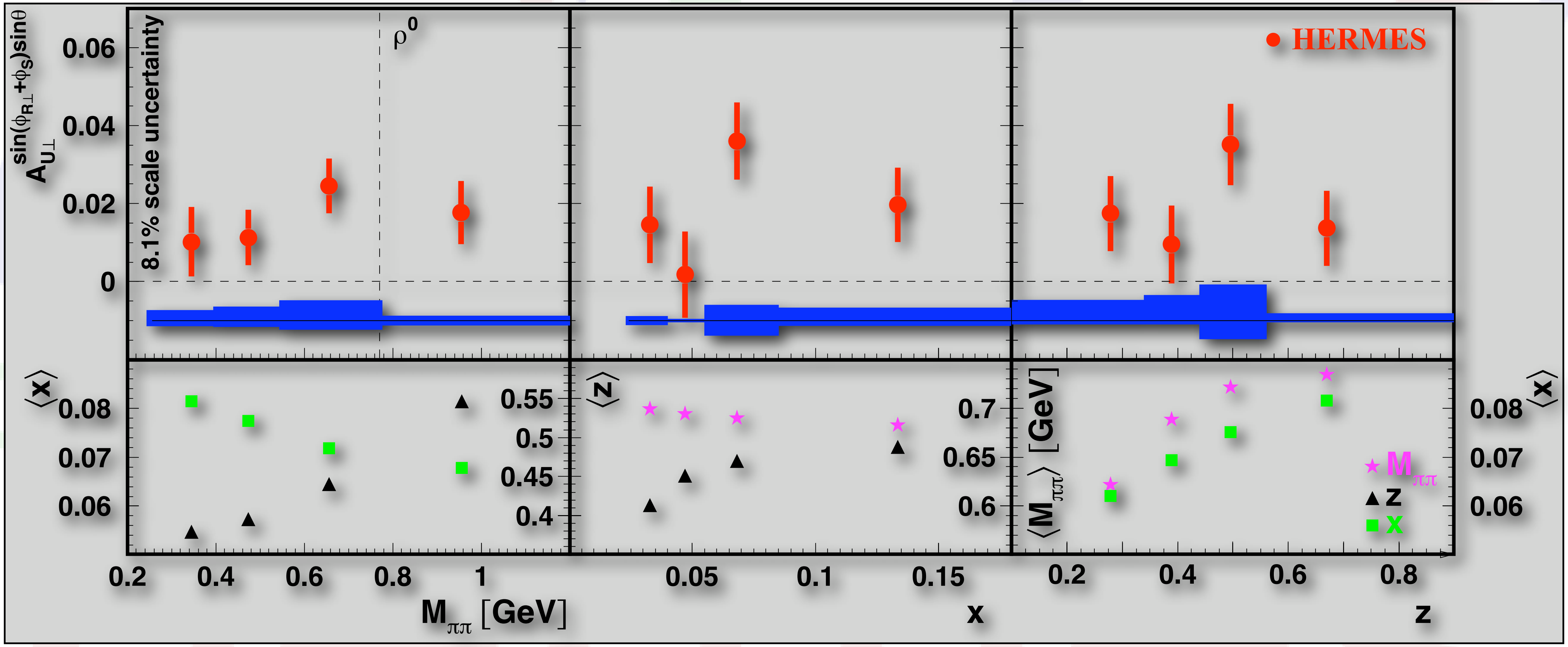
δ_0 (δ_1) → S(P)-wave phase shifts

$$= \mathcal{P}(M_{\pi\pi}^2) H_1^{\sphericalangle,sp'}(z)$$

⇒ A_{UT} might depend strongly on $M_{\pi\pi}$

2-Hadron Fragmentation @ HERMES

- First measurement of spin-dependent two-hadron fragmentation JHEP 06, 017 (2008).



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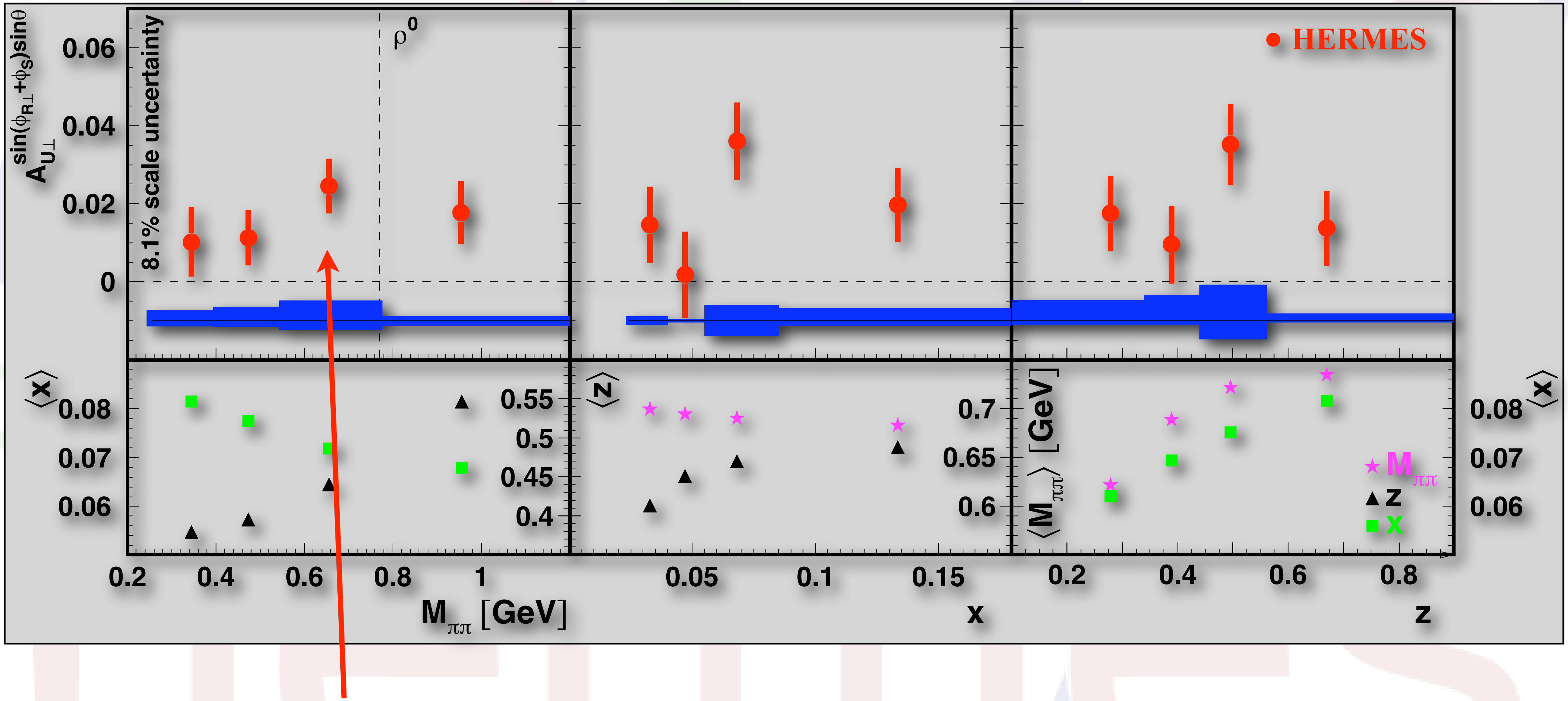

First evidence for (transversity and) naive-T-odd, chiral-odd, spin-dependent dihadron fragmentation function

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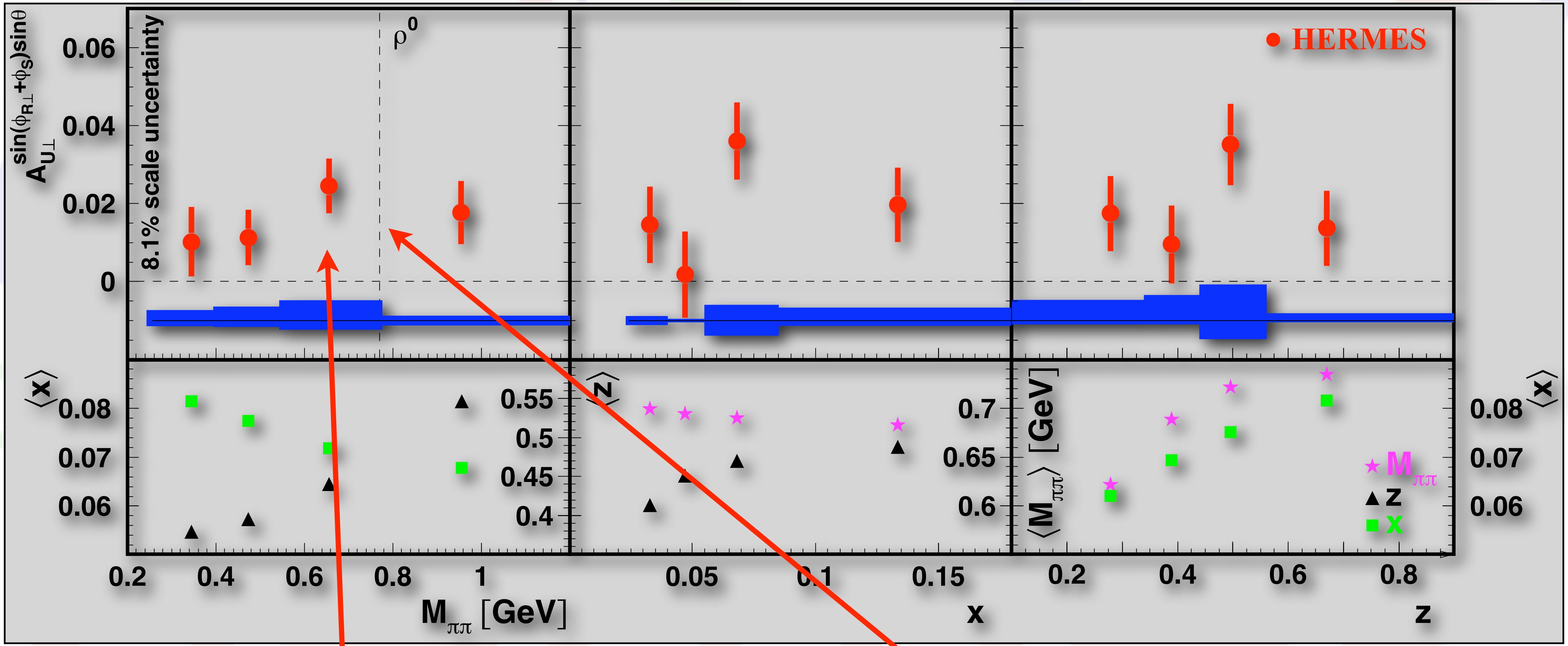


First evidence for (transversity and) naive-T-odd, chiral-odd, spin-dependent dihadron fragmentation function

No sign change as (maybe) expected around ρ^0 mass

Consistent in shape with later models (Radici et al.)

1-Hadron Production (ep→ehX)

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

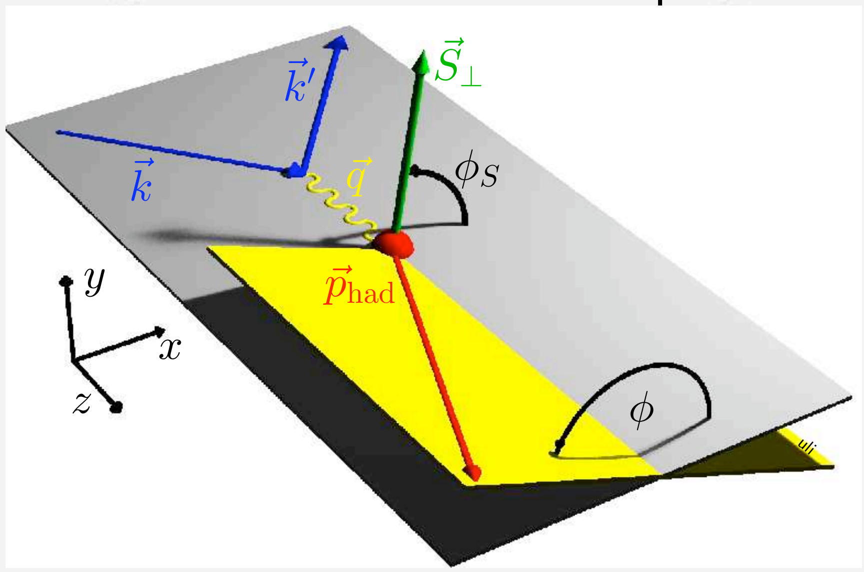
$$+S_L \left\{ \sin 2\phi\, d\sigma^4_{UL} + \frac{1}{Q}\sin\phi\, d\sigma^5_{UL} + \lambda_e \left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^7_{LL} \right] \right\}$$

$$+S_T \left\{ \sin(\phi - \phi_S)\, d\sigma^8_{UT} + \sin(\phi + \phi_S)\, d\sigma^9_{UT} + \sin(3\phi - \phi_S)\, d\sigma^{10}_{UT} \frac{1}{Q} \right.$$

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

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

σ_{XY}: X → **Beam**, Y → **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

Bacchetta et al., JHEP 0702 (2007) 093

“Trento Conventions”, Phys. Rev. D 70 (2004) 117504

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

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

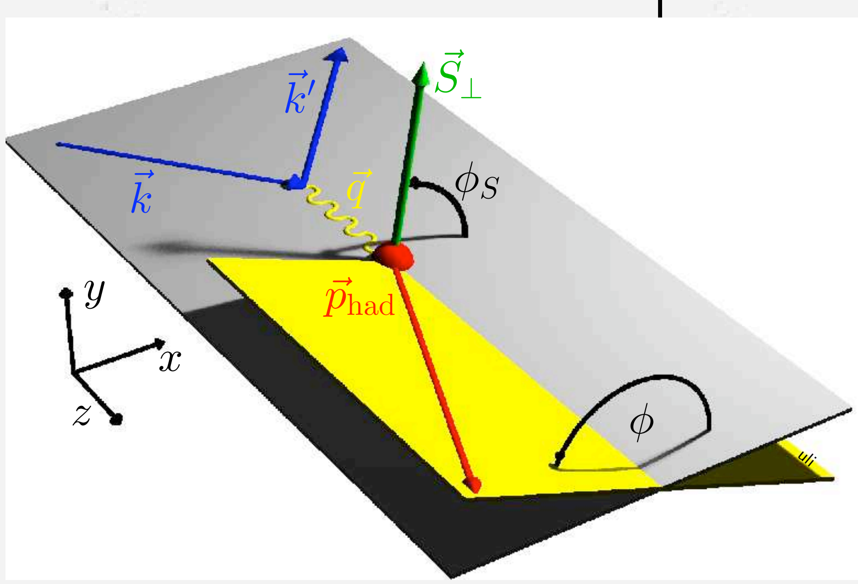
$$+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^{8} + \sin(\phi + \phi_S) \, d\sigma_{UT}^{9} + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \frac{1}{Q} \right.$$

$$+\frac{1}{Q}$$

$$+\lambda_e \left[\cos(\phi - \right.$$

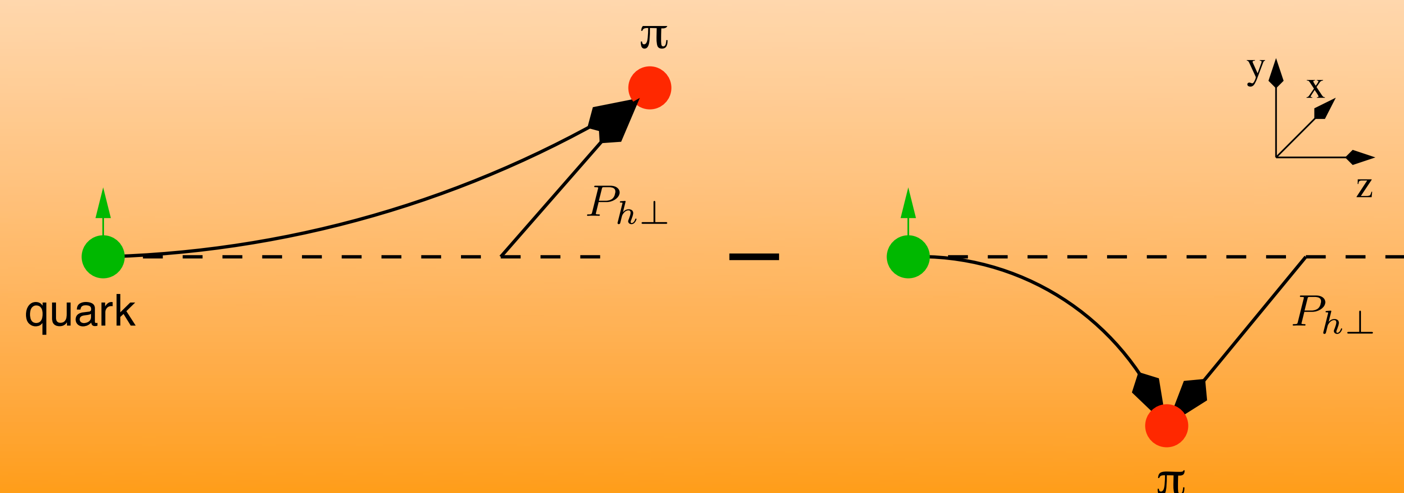
σ_{XY}

Beam **Target**
Polarization



Collins Effect:

sensitive to quark transverse spin



1-Hadron Production (ep→ehX)

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

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

$$+S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \, \frac{1}{Q} \right.$$

$$\ldots \, d\sigma^{12}_{UT})$$

$$\ldots + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT}) \Big] \Big\}$$

Sivers Effect:

- correlates hadron's transverse momentum with nucleon spin
- requires orbital angular momentum

…. Phys. B 461 (1996) 197

… 57 (1998) 5780

… 95 (2004) 309

Bacchetta et al., JHEP 0702 (2007) 093

"Trento Conventions", Phys. Rev. D 70 (2004) 117504

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

$$+S_L \Big\{ \sin 2\phi \, d\sigma^{4}_{U} \ldots$$

$$+S_T \Big\{ \sin(\phi - \phi_S) \, d \ldots$$

Cahn Effect:

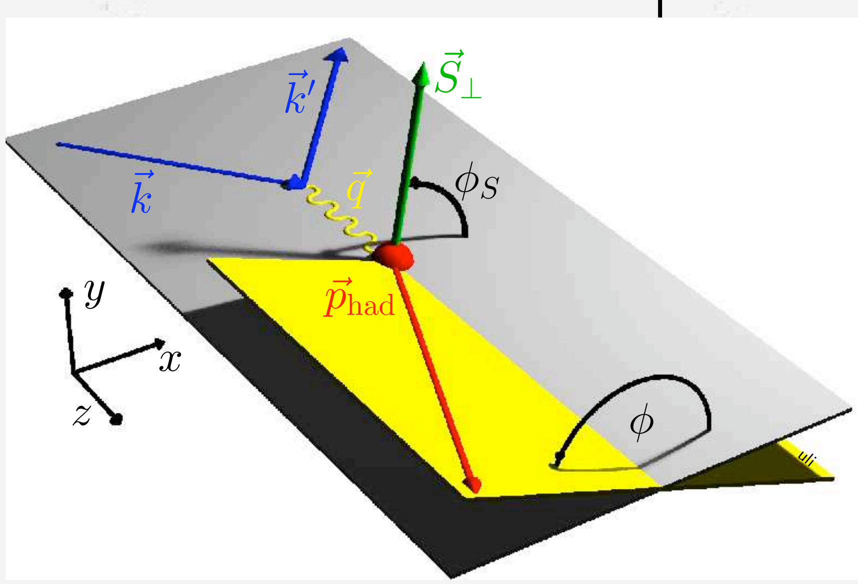
sensitive to quark transverse momentum

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

σ_{XY}

Beam Target
Polarization

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



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1-Hadron Production (ep→ehX)

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

Boer-Mulders Effect:

transversity in unpolarized nucleons

$$\ldots d\sigma^6_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^7_{LL} \Big]\Big\}$$

$$\ldots \sin(3\phi - \phi_S)\, d\sigma^{10}_{UT} \ldots$$

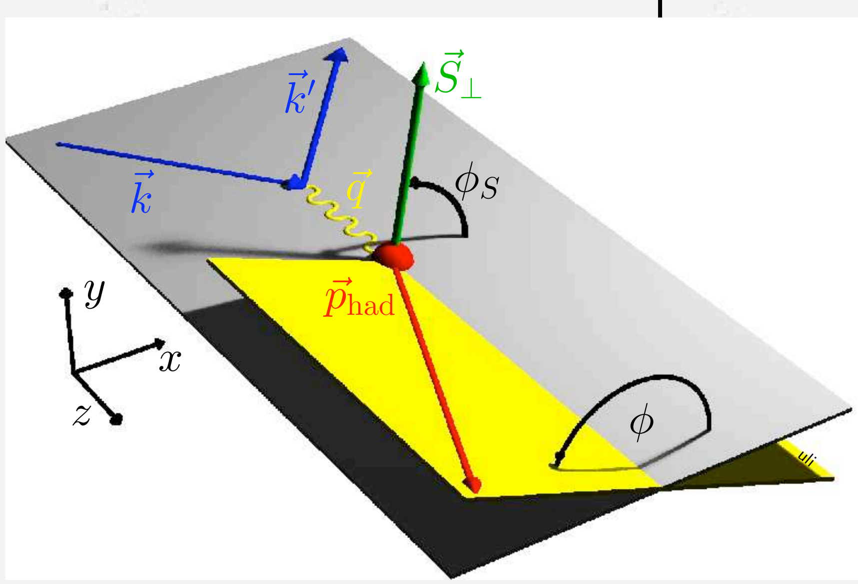
$$+ \frac{1}{Q}\left(\sin(2\phi - \phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma^{12}_{UT}\right)$$

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

σ_{XY}

Beam Target

Polarization



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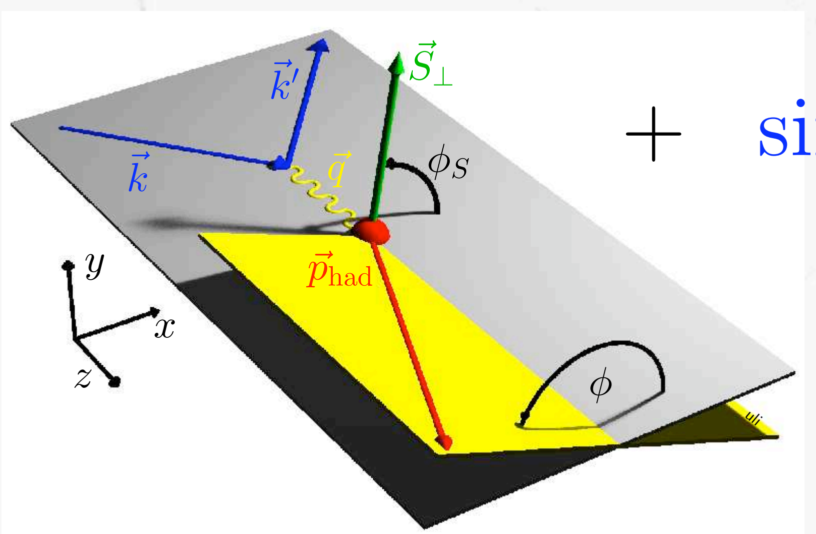
Measuring Azimuthal SSA

$$A_{UT}(\phi,\phi_S) = \frac{1}{\langle|S_\perp|\rangle}\frac{N_h^\uparrow(\phi,\phi_S)-N_h^\downarrow(\phi,\phi_S)}{N_h^\uparrow(\phi,\phi_S)+N_h^\downarrow(\phi,\phi_S)}$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{k_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M_h}h_1^q(x,p_T^2)H_1^{\perp,q}(z,k_T^2)\right]$$

$$+ \sin(\phi-\phi_S)\sum_q e_q^2\,\mathcal{I}\left[\frac{\boldsymbol{p_T}\hat{\boldsymbol{P}}_{\boldsymbol{h}\perp}}{M}f_{1T}^{\perp,q}(x,p_T^2)D_1^q(z,k_T^2)\right]$$

$$+ \quad \cdots$$

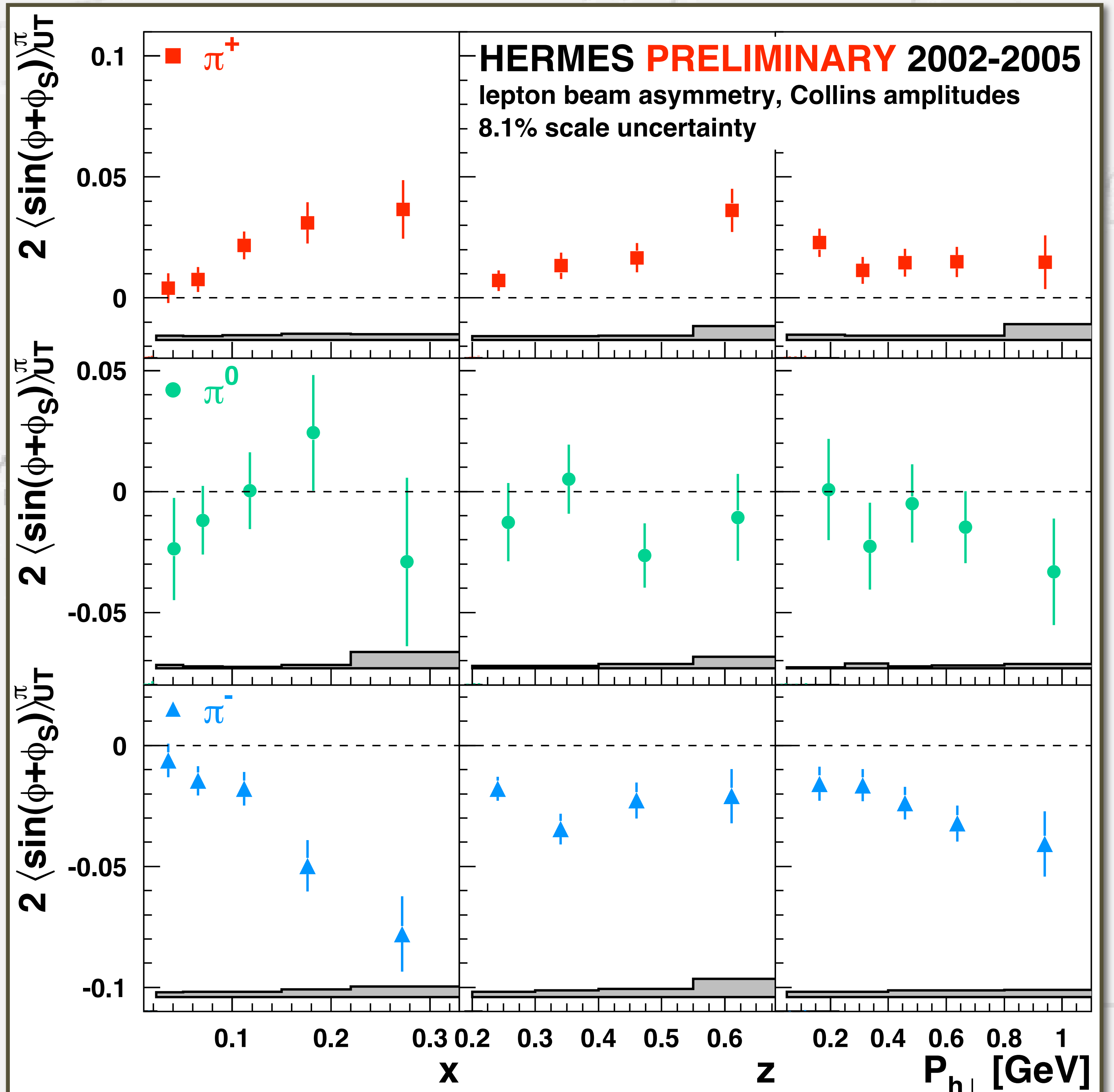


$\mathcal{I}[\ldots]$: **convolution integral over initial (p_T) and final (k_T) quark transverse momenta**

$\Rightarrow$ 2D Max.Likelihd. fit of to get Collins and Sivers amplitudes:

$$PDF(2\langle\sin(\phi\pm\phi_S)\rangle_{UT},\ldots,\phi,\phi_S) = \tfrac{1}{2}\{1+P_T(2\langle\sin(\phi\pm\phi_S)\rangle_{UT}\,\sin(\phi\pm\phi_s)+\ldots)\}$$

The HERMES Collins Results



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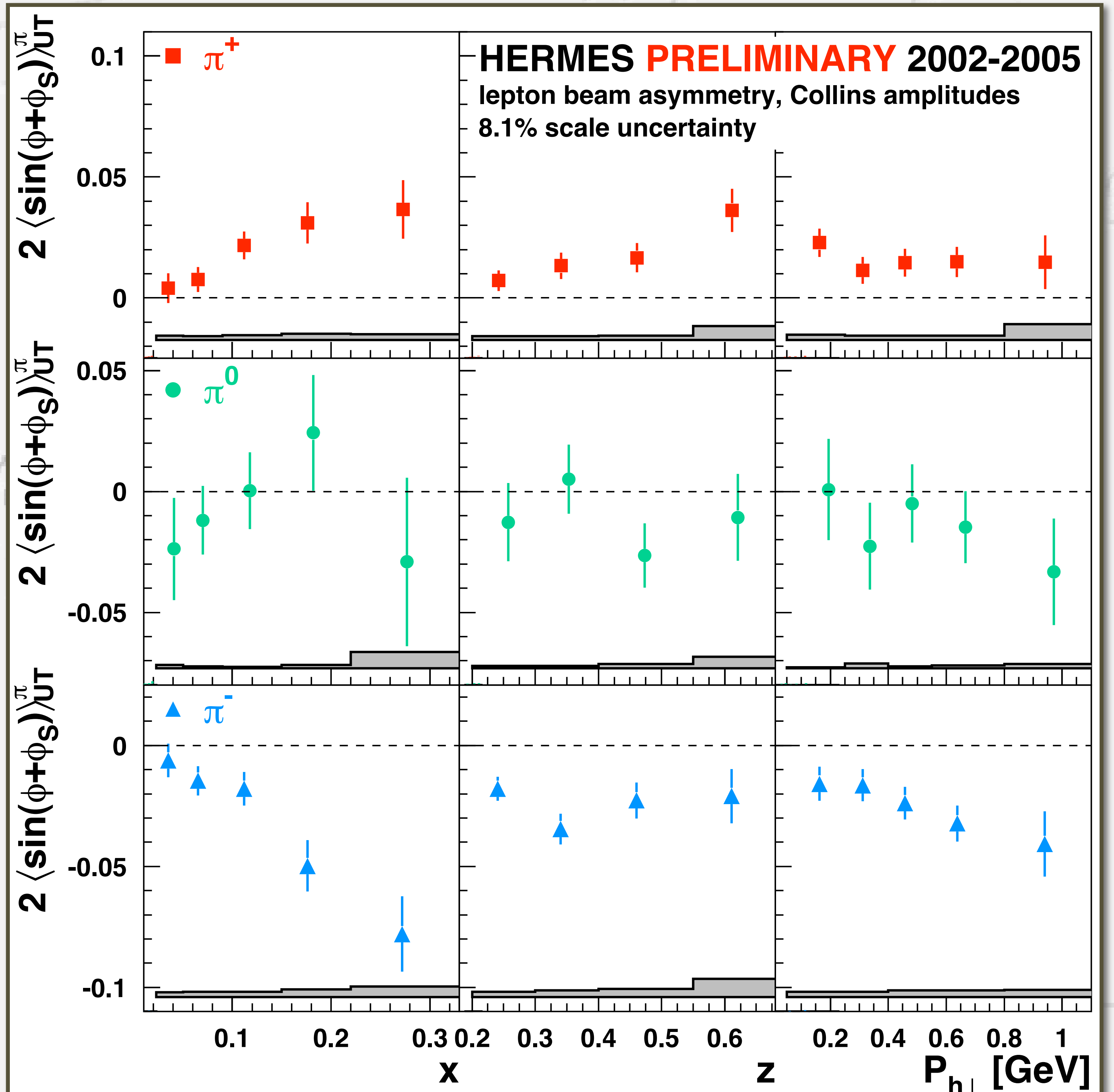

☑ non-zero Collins effect observed!

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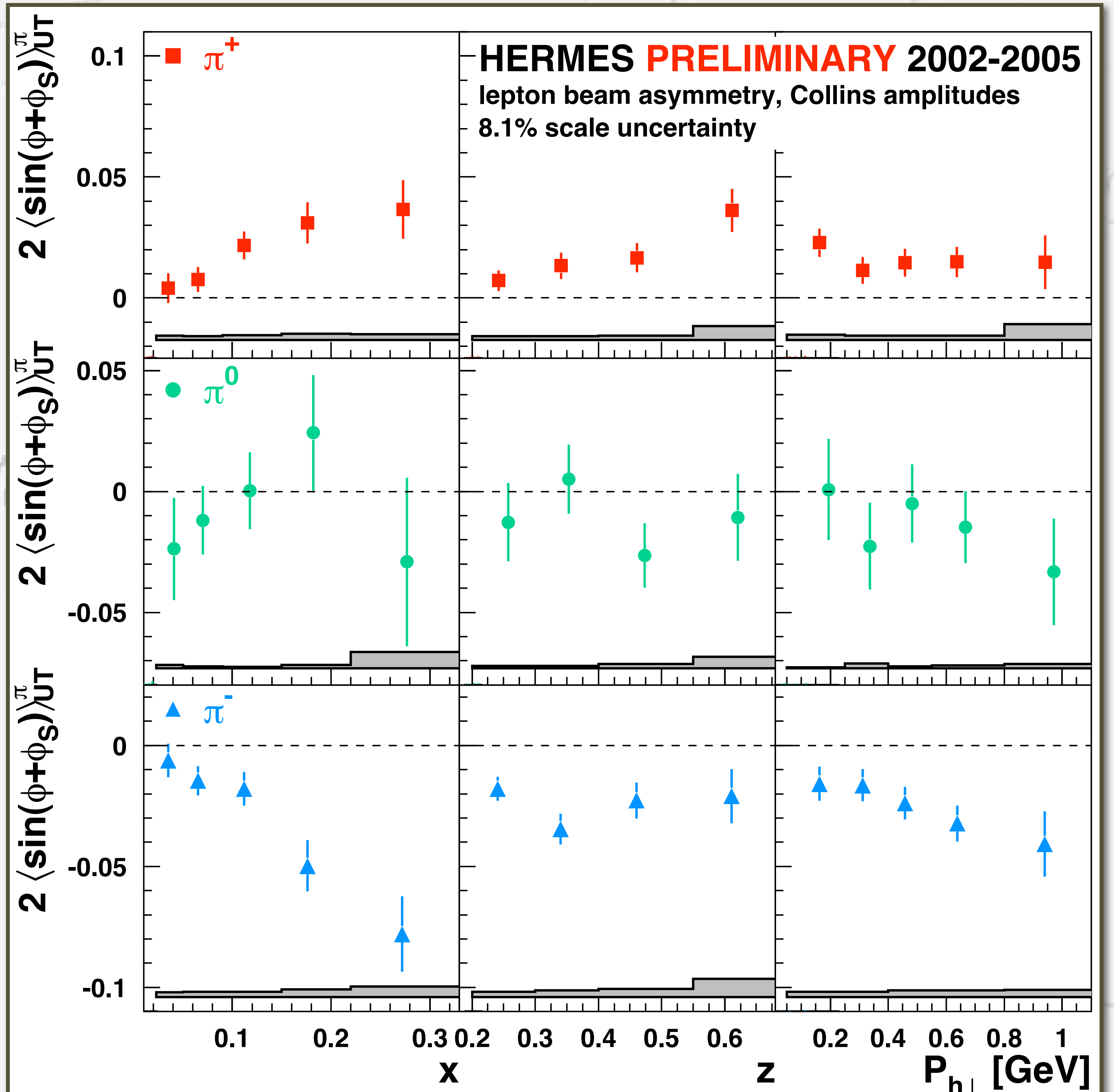
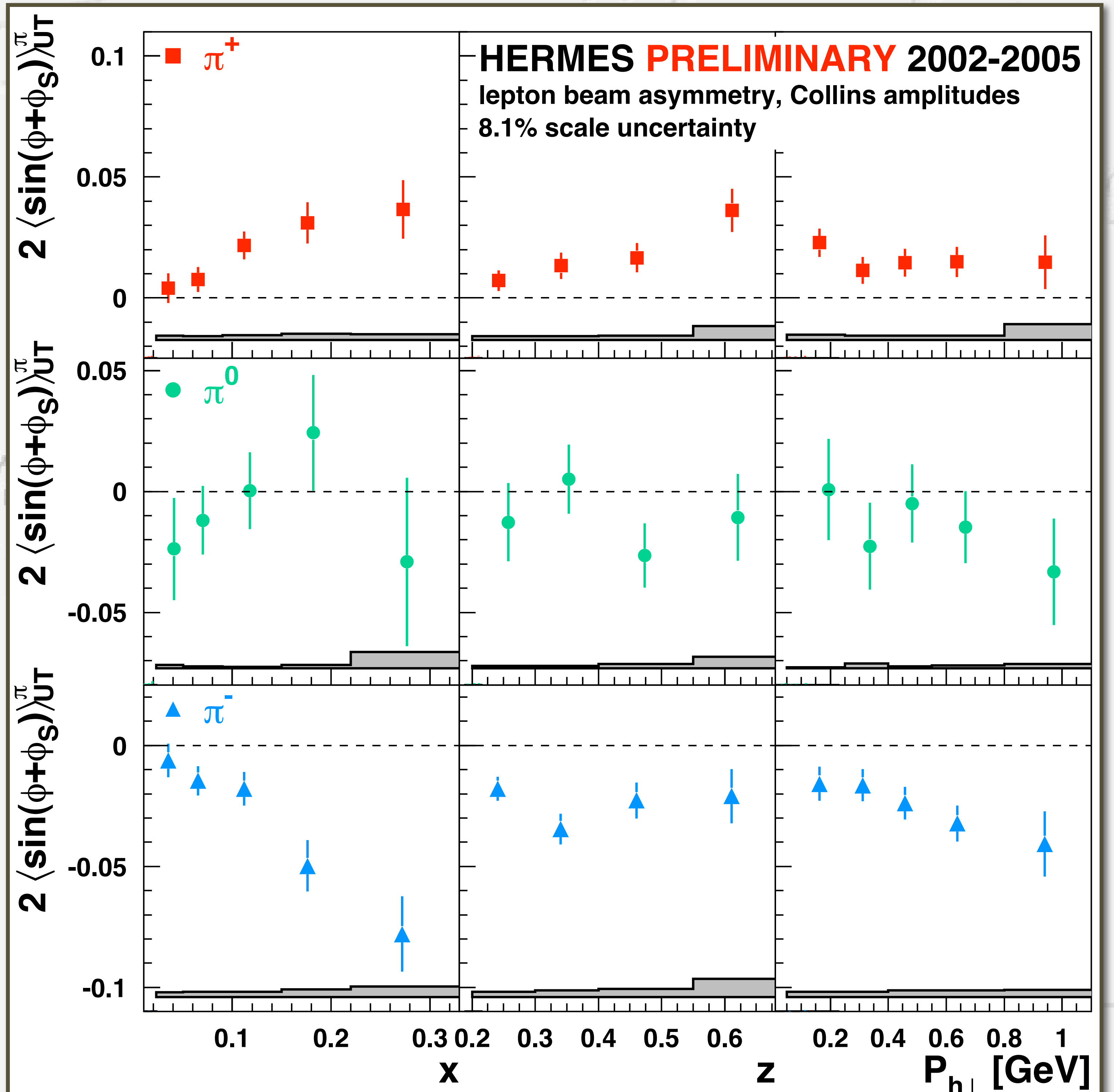


- ☑ non-zero Collins effect observed!
- ☑ both Collins FF and transversity sizeable

The HERMES Collins Results



- published† results confirmed with much higher statistical precission
- overall scale uncertainty of 8.1%
- positive for π^+ and negative for π^- as maybe expected ($\delta u \equiv h_1^u > 0$

  maybe expected ($\delta d \equiv h_1^d < 0$)
- unexpected large π^- asymmetry

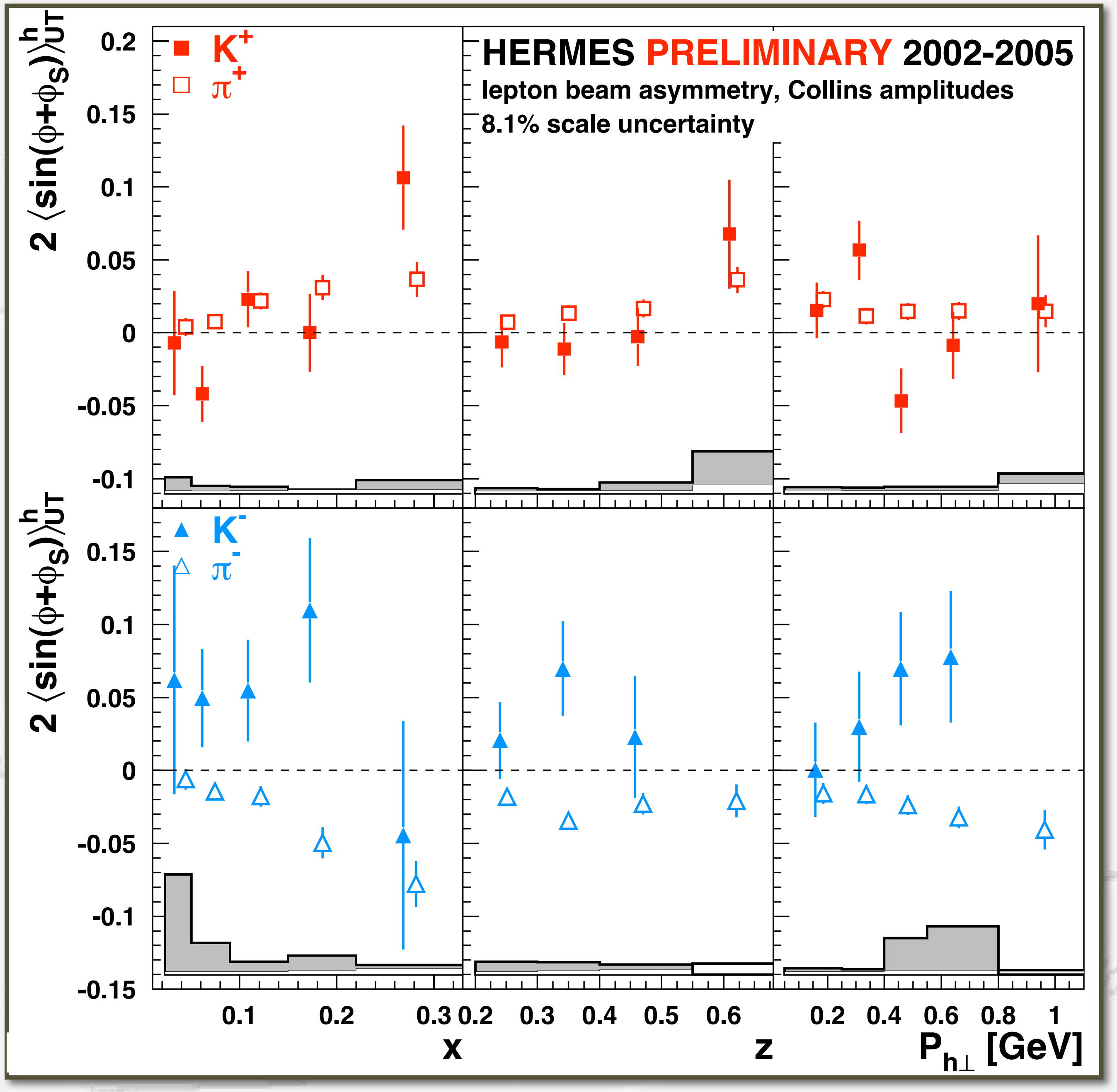
  $\Rightarrow$ role of disfavored Collins FF

  most likely: $H_1^{\perp,disf} \approx -H_1^{\perp,fav}$
- isospin symmetry among charged and neutral pions fulfilled

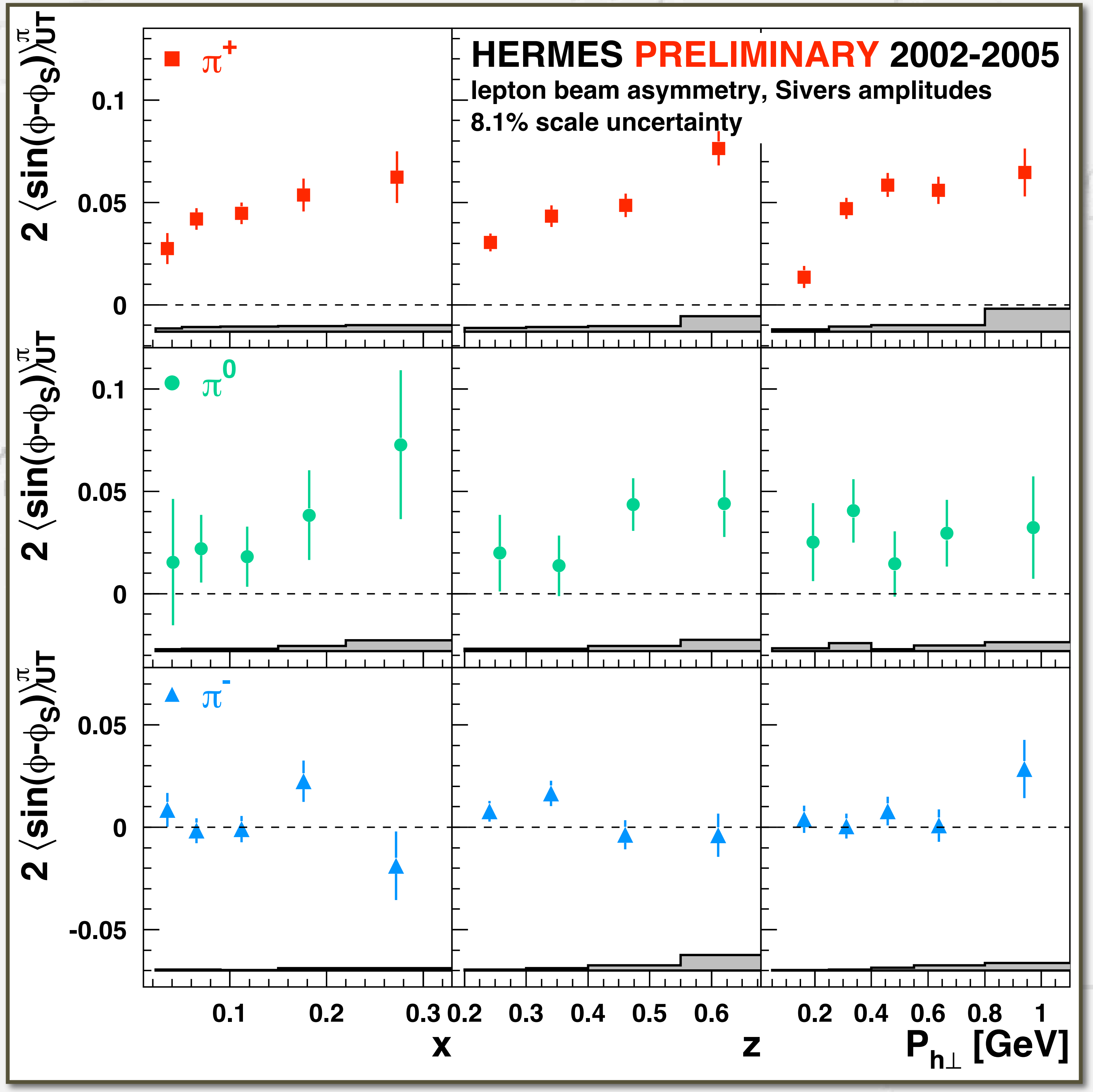
† [*A. Airapetian et al*, Phys. Rev. Lett. 94 (2005) 012002]

Collins Amplitudes for Kaons

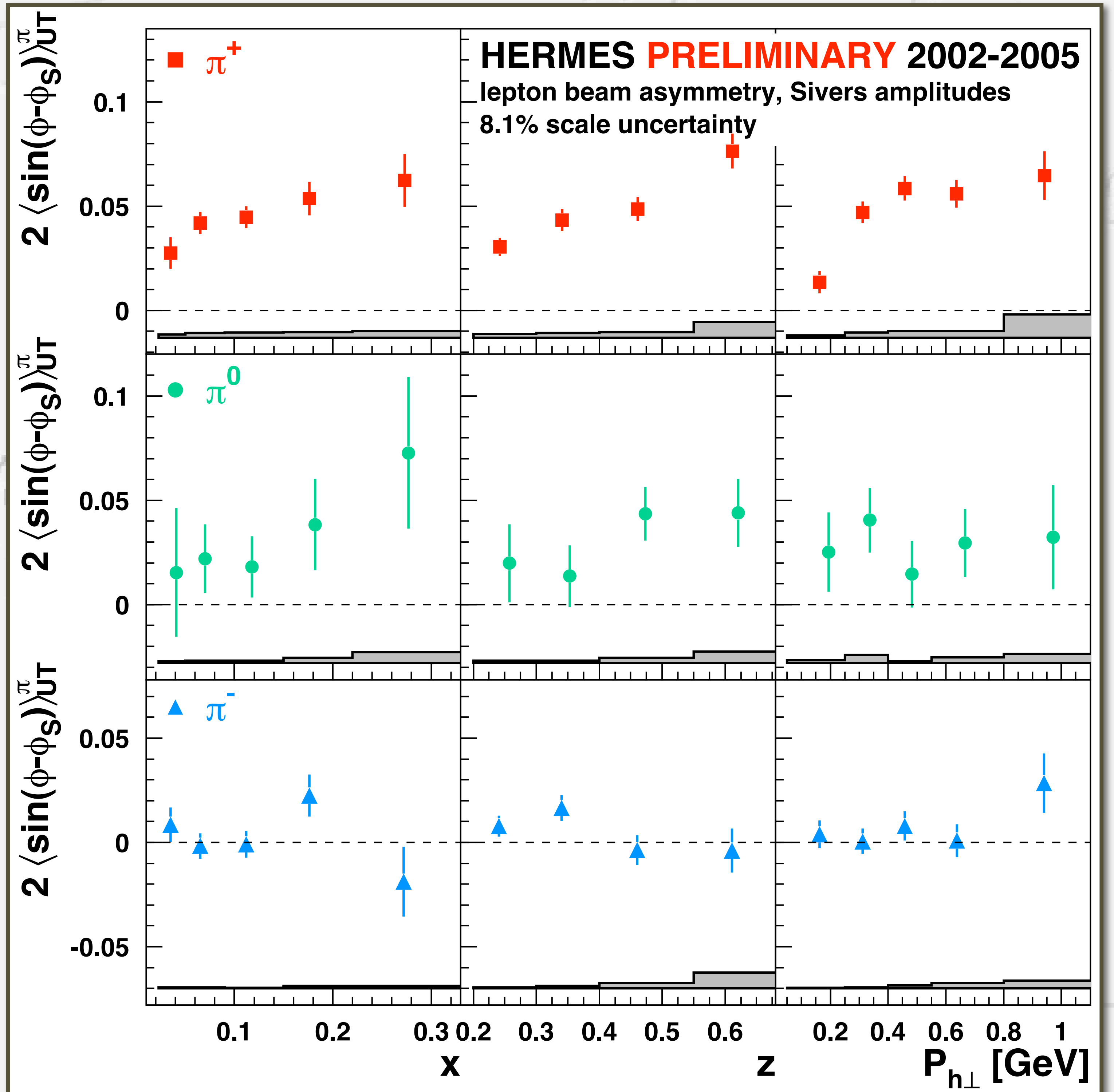
- none of the kaon amplitudes significantly nonzero
- K^+ amplitudes not really different from π^+ amplitudes
- K^- amplitudes slightly positive, contrary to large negative π^- amplitudes
- K^- is pure "sea object"



HERMES Sivers Results

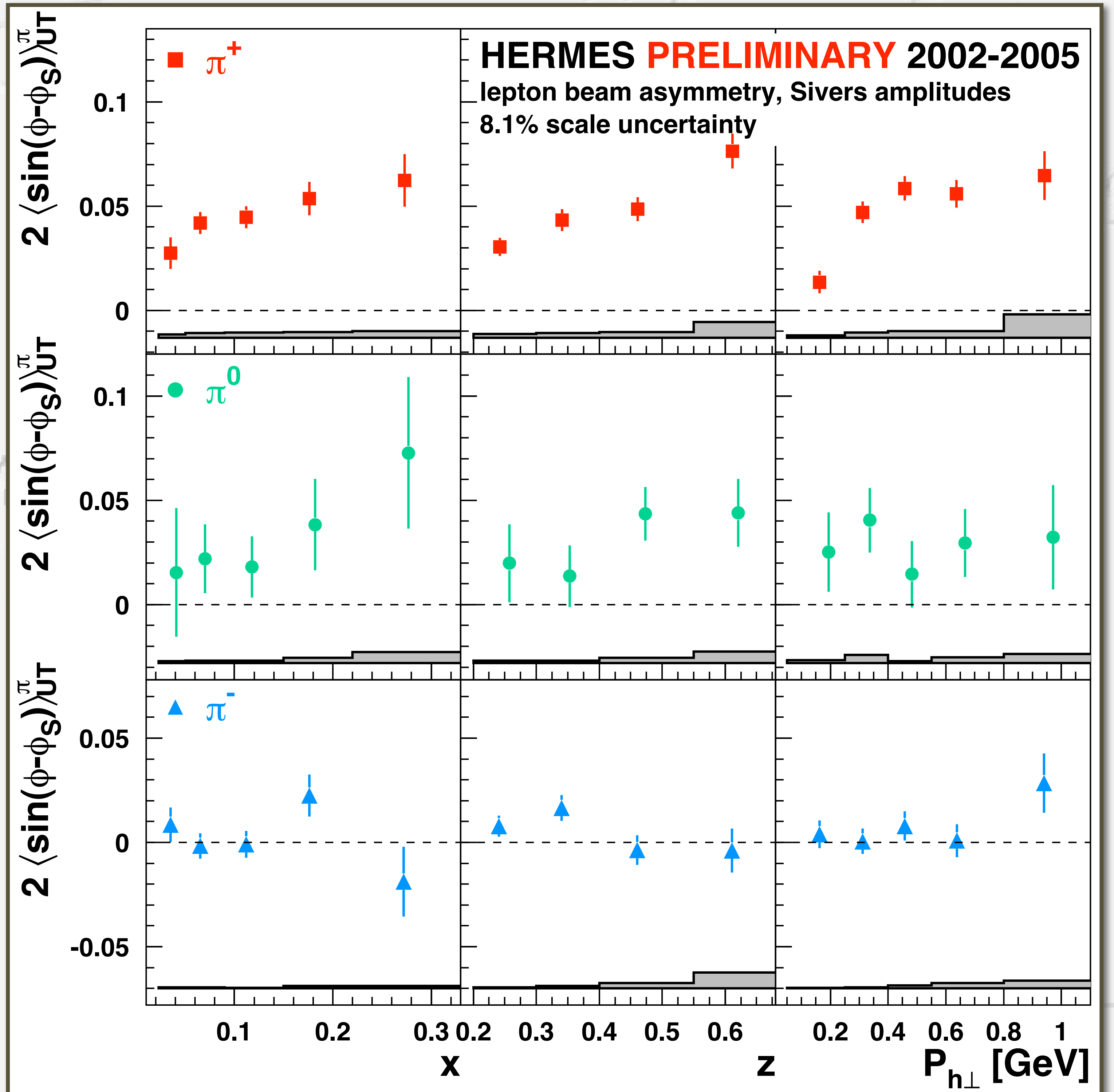


HERMES Sivers Results



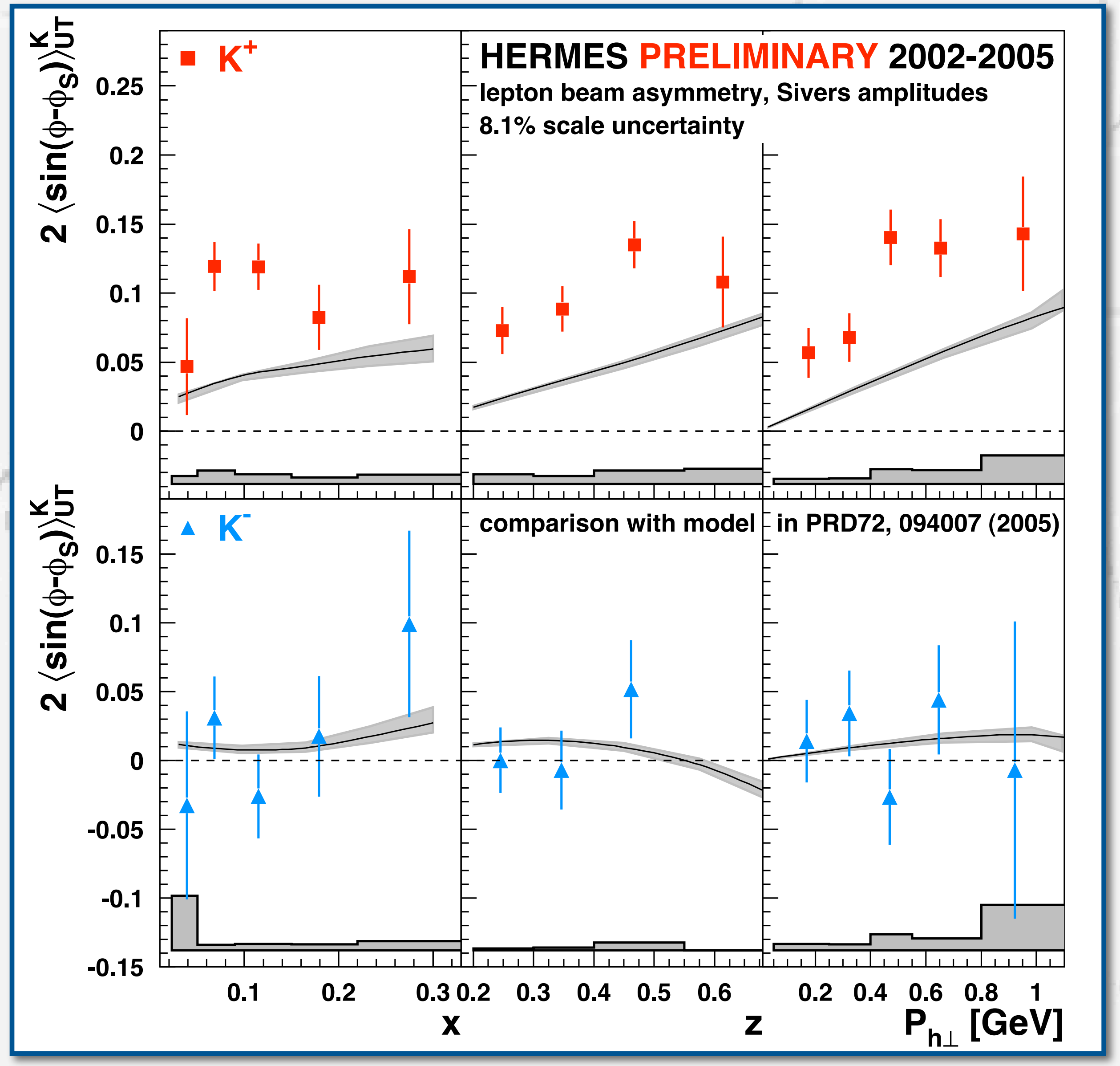
☑ first observation of T-odd Sivers effect in SIDIS!

HERMES Sivers Results



- ☑ first observation of T-odd Sivers effect in SIDIS!
- ☑ u-quark dominance suggests sizeable u-quark orbital motion

The Intriguing Kaon Amplitudes



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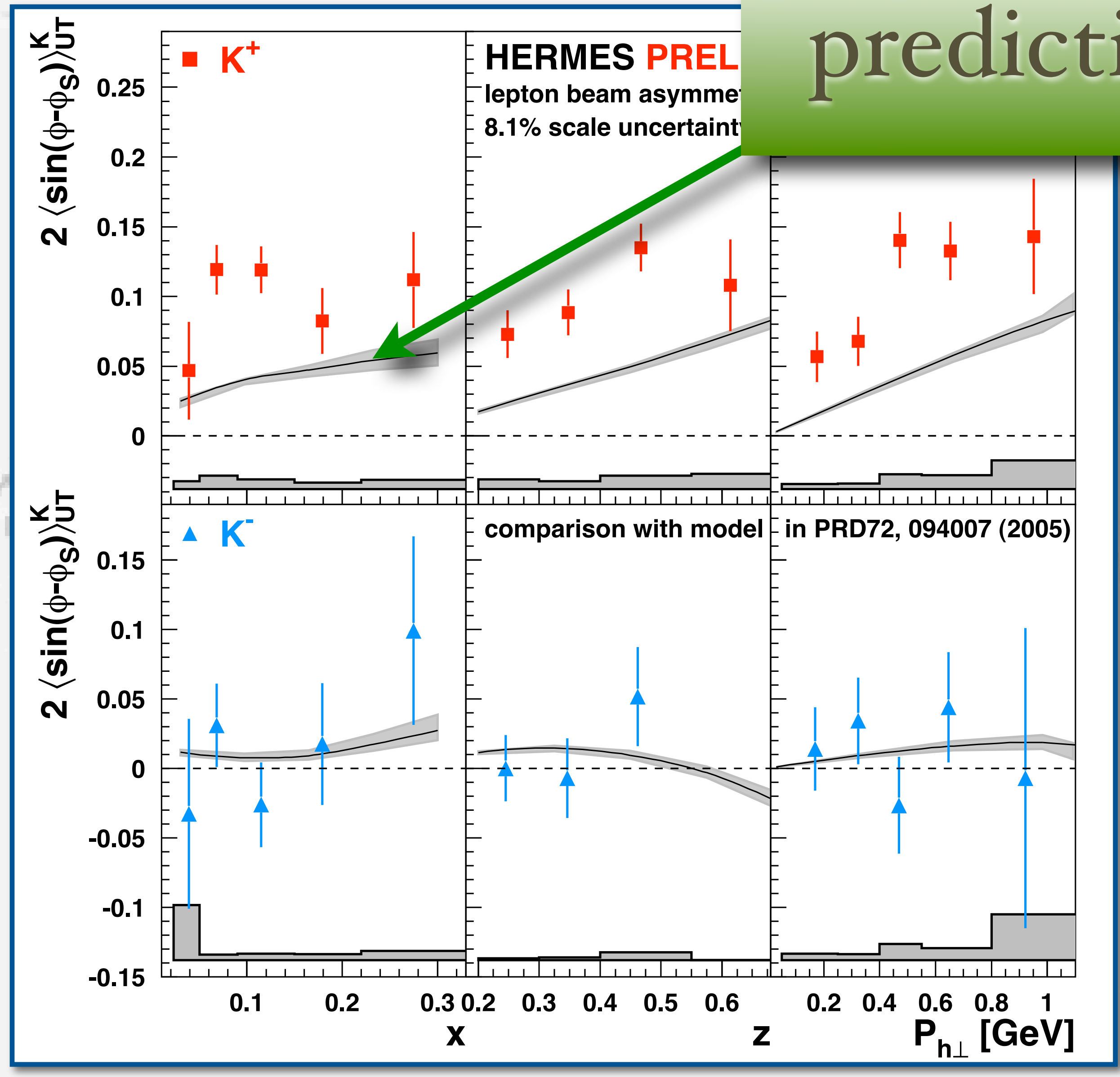
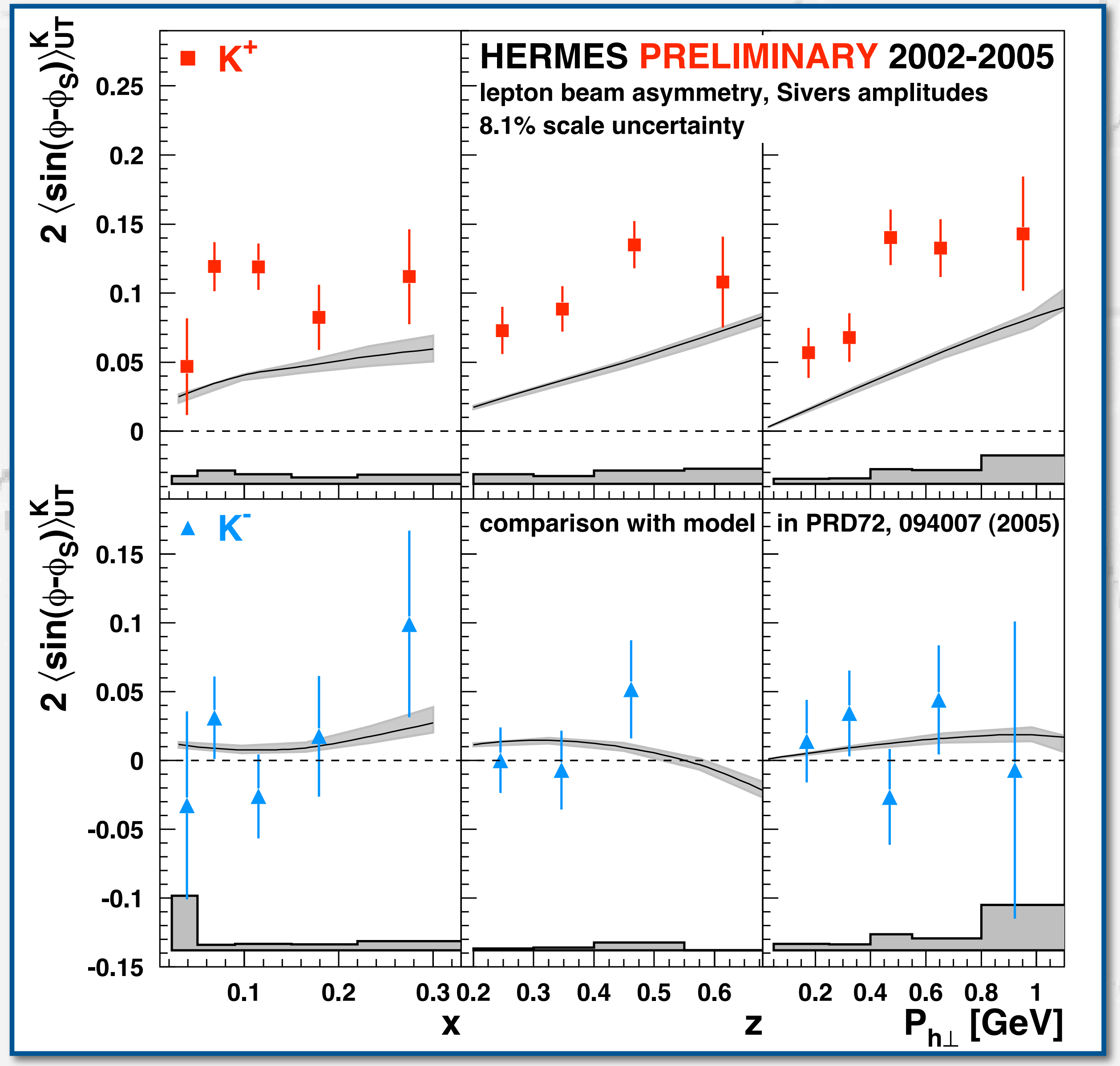
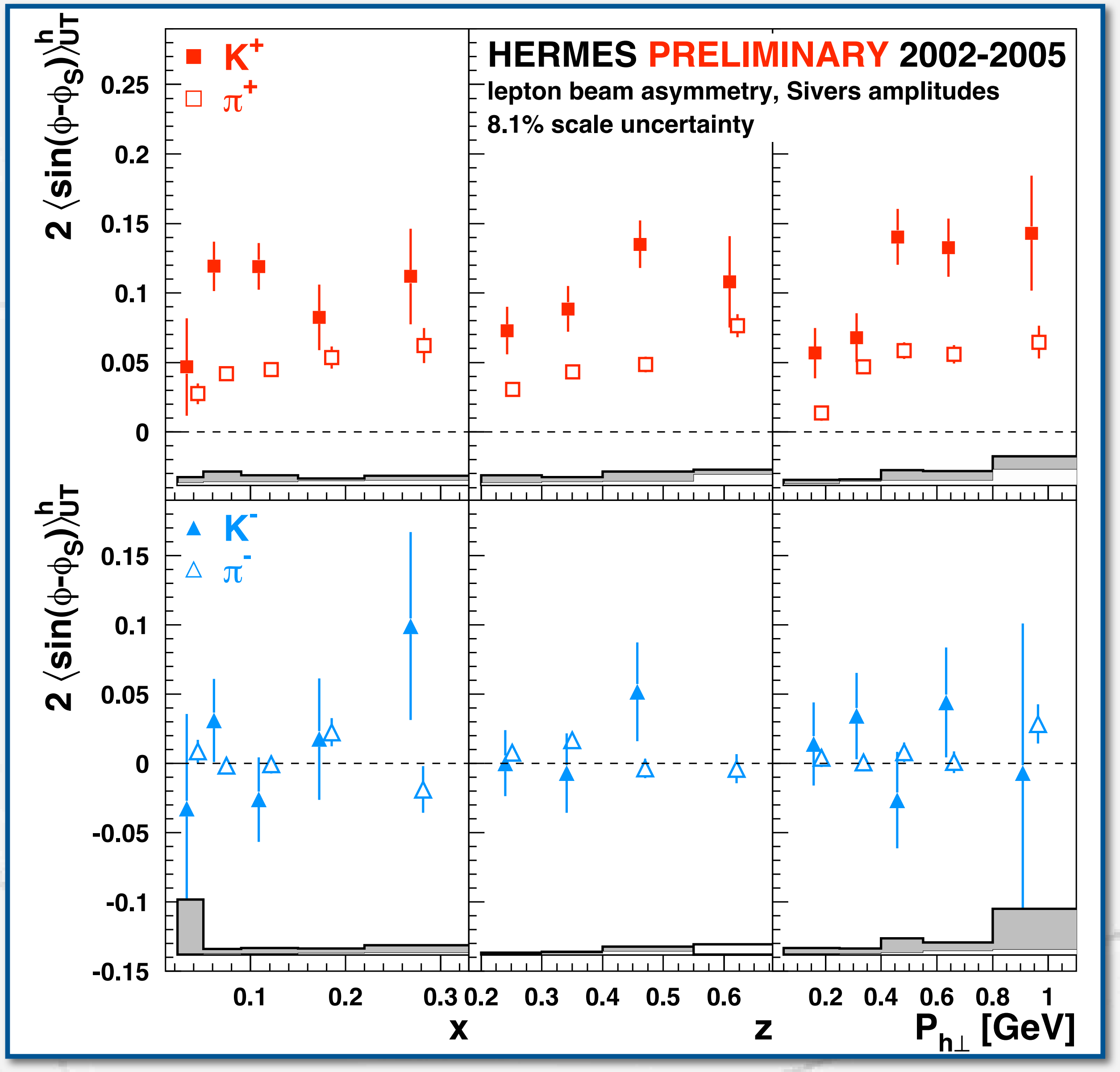


prediction using fit to pion data

The Intriguing Kaon Amplitudes





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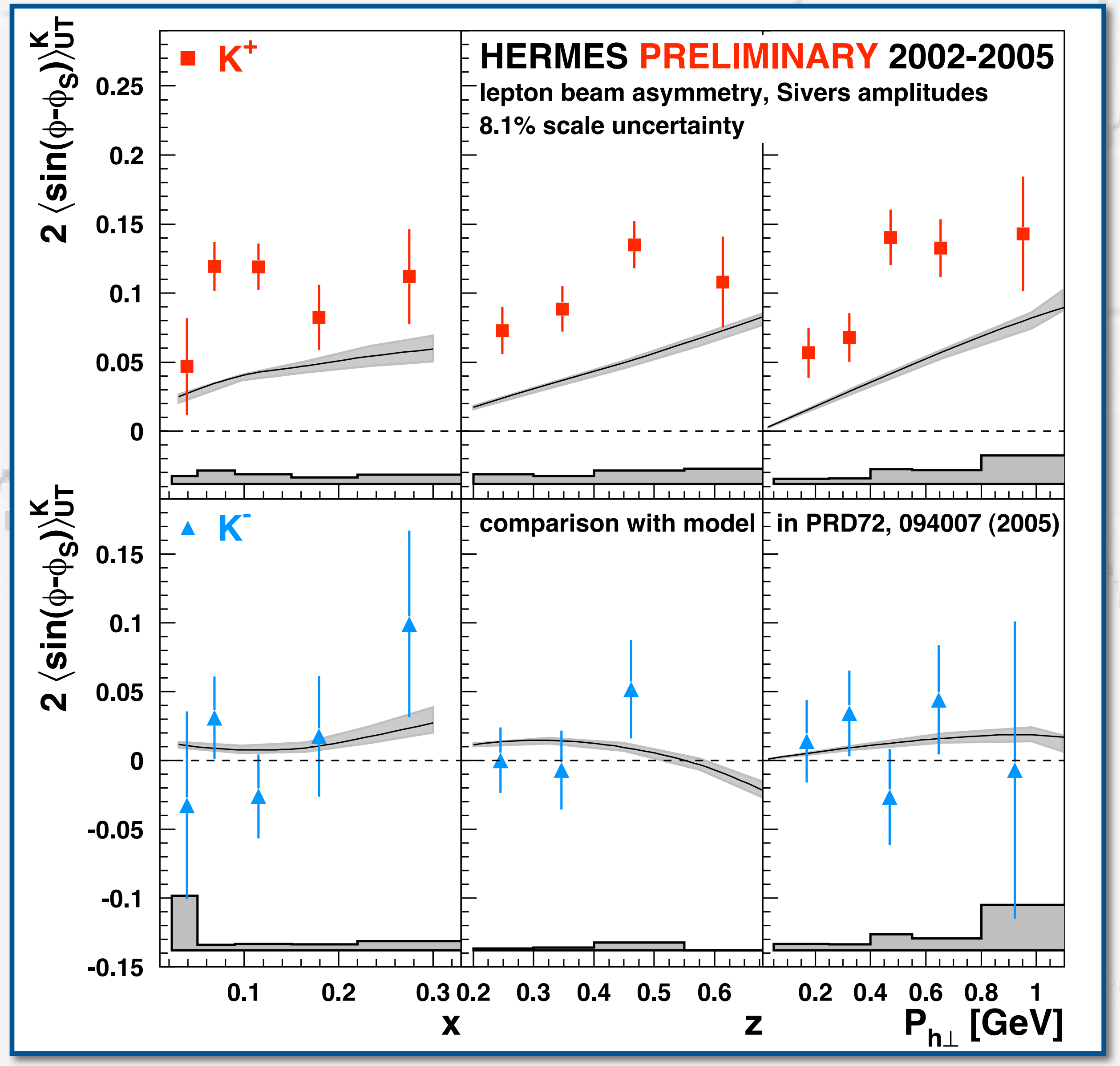

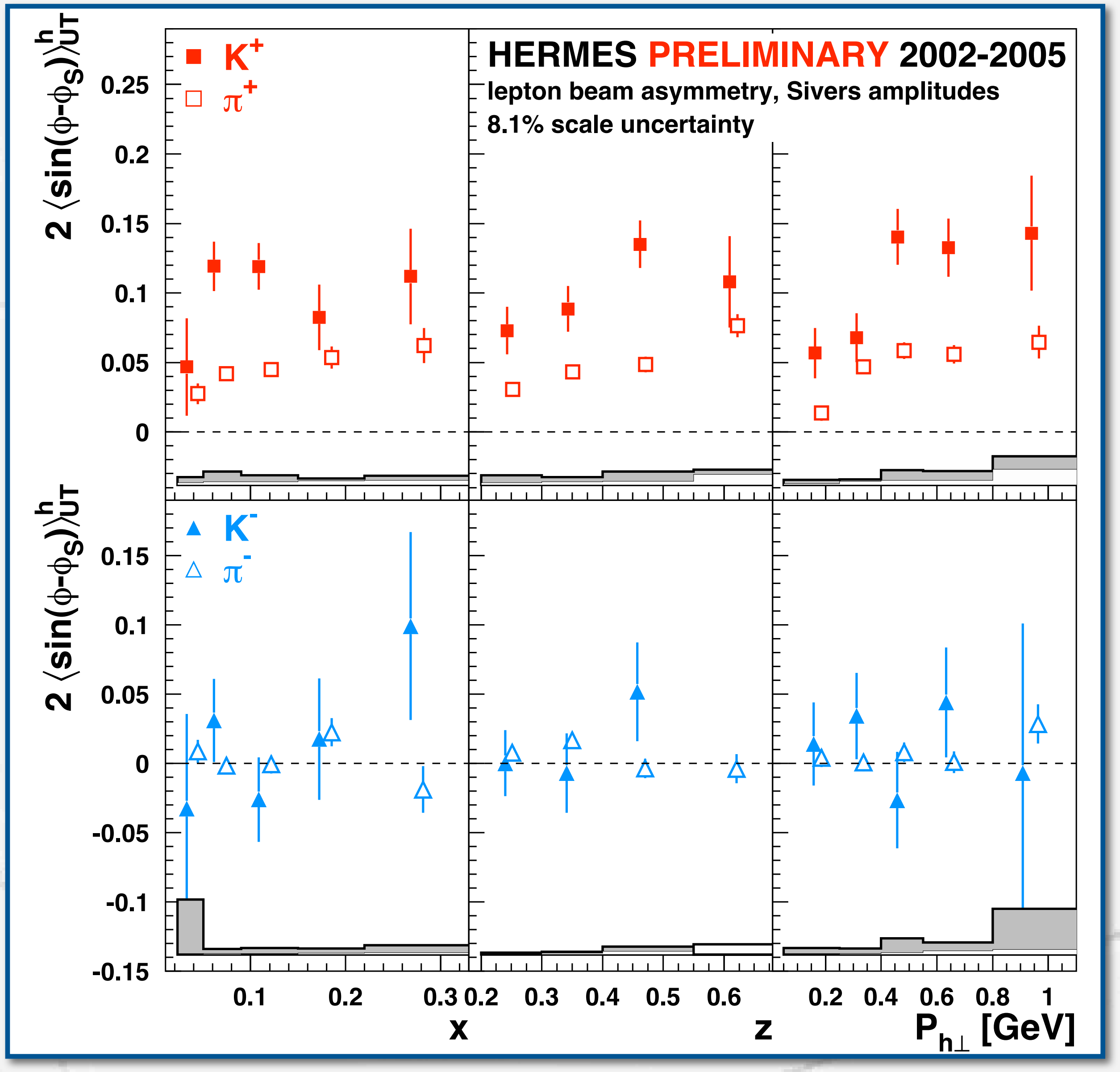

non-trivial role of sea quarks!

Sivers "Difference Asymmetry"

- Transverse single-spin asymmetry of pion cross-section difference

$$A_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) \equiv \frac{1}{S_T}\frac{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})-(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-})+(\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}$$

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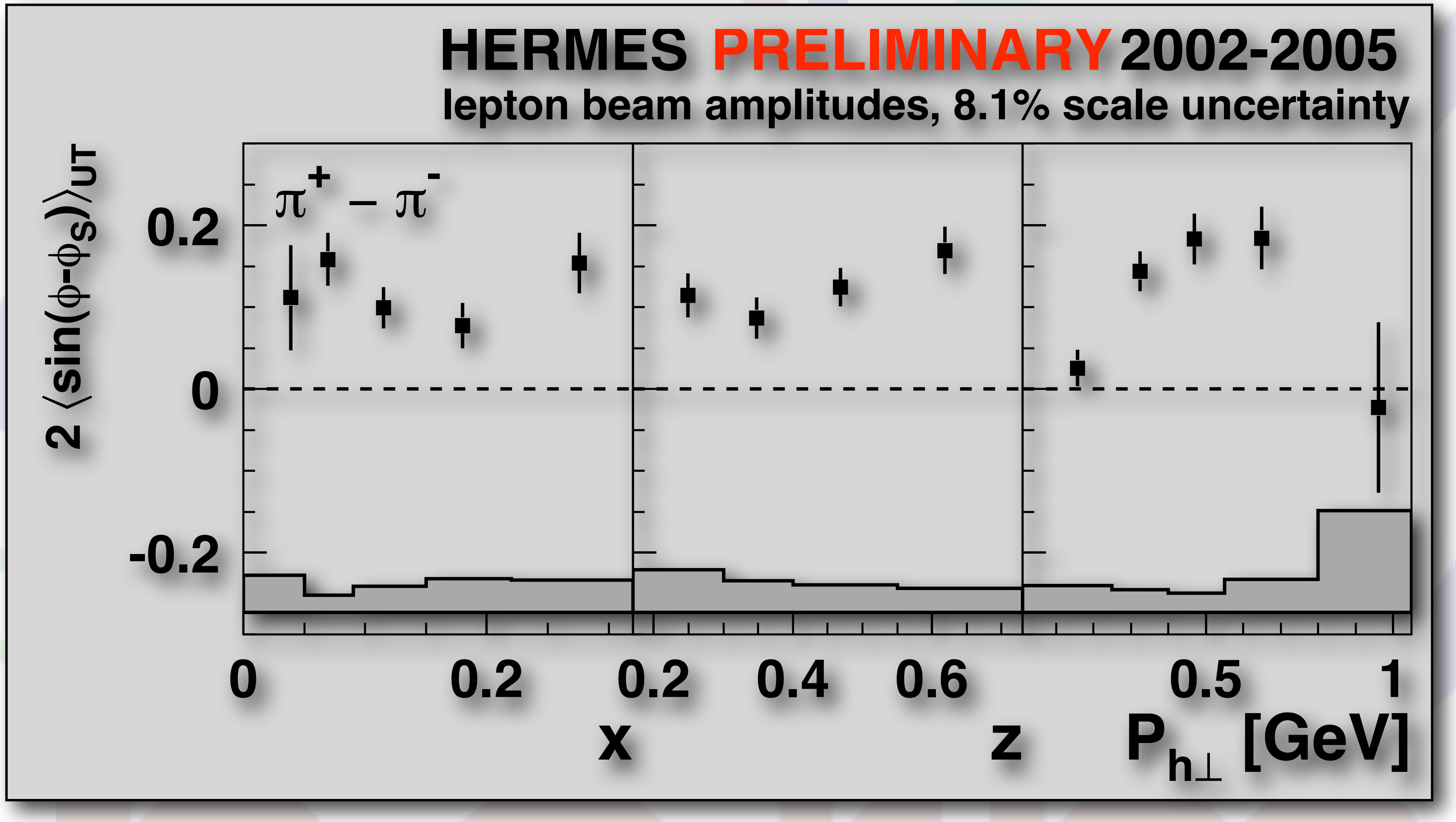

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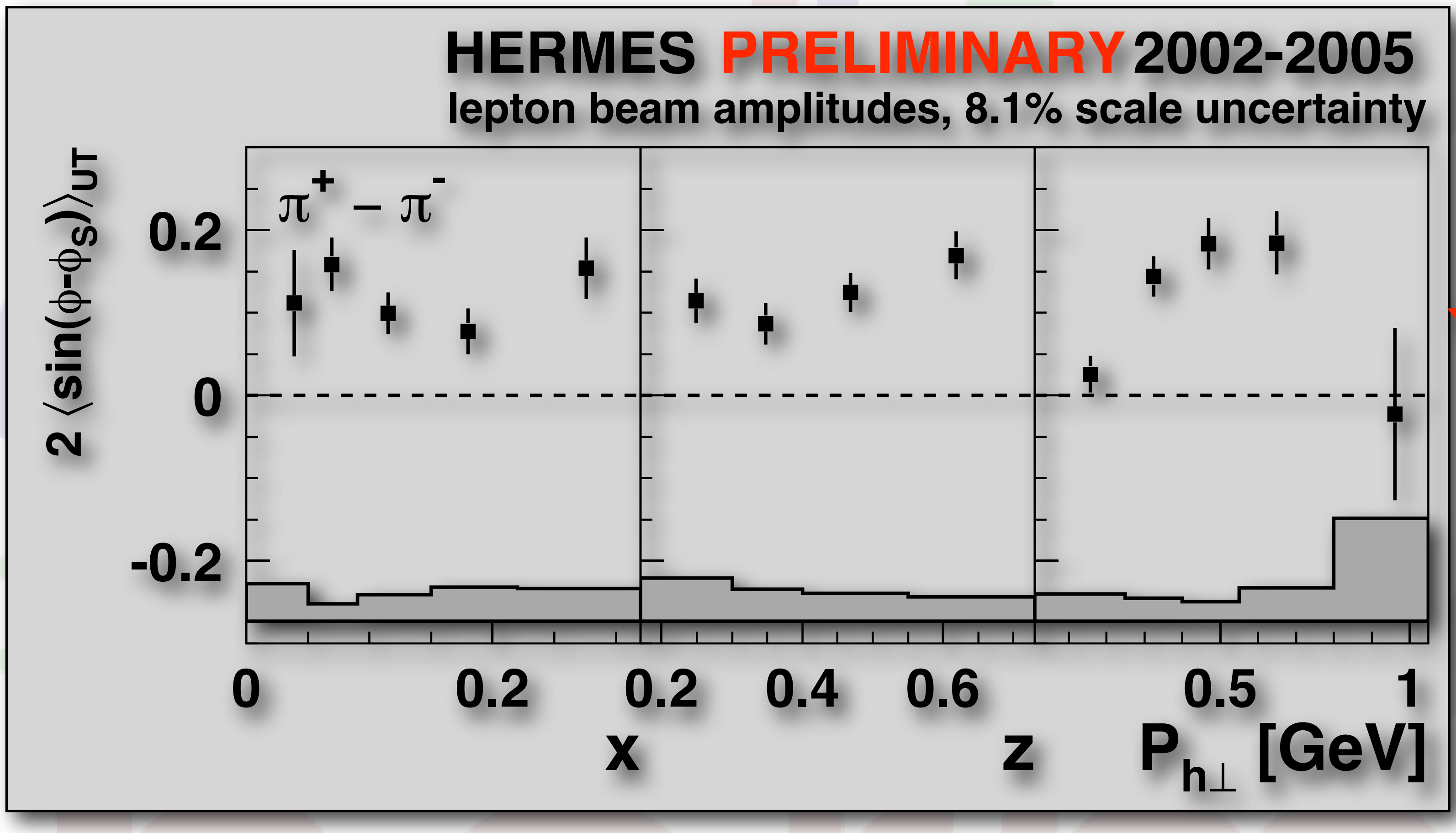
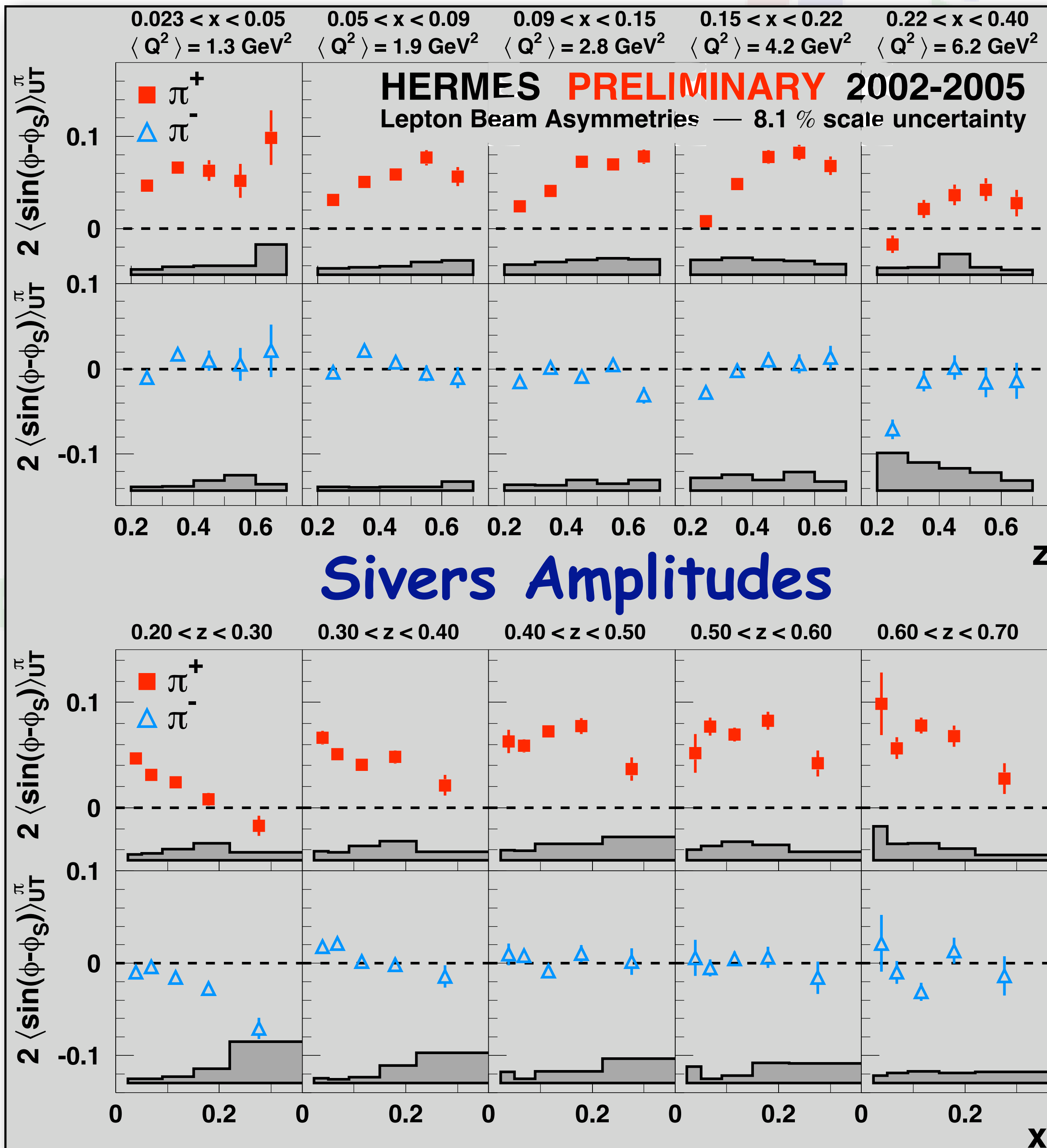


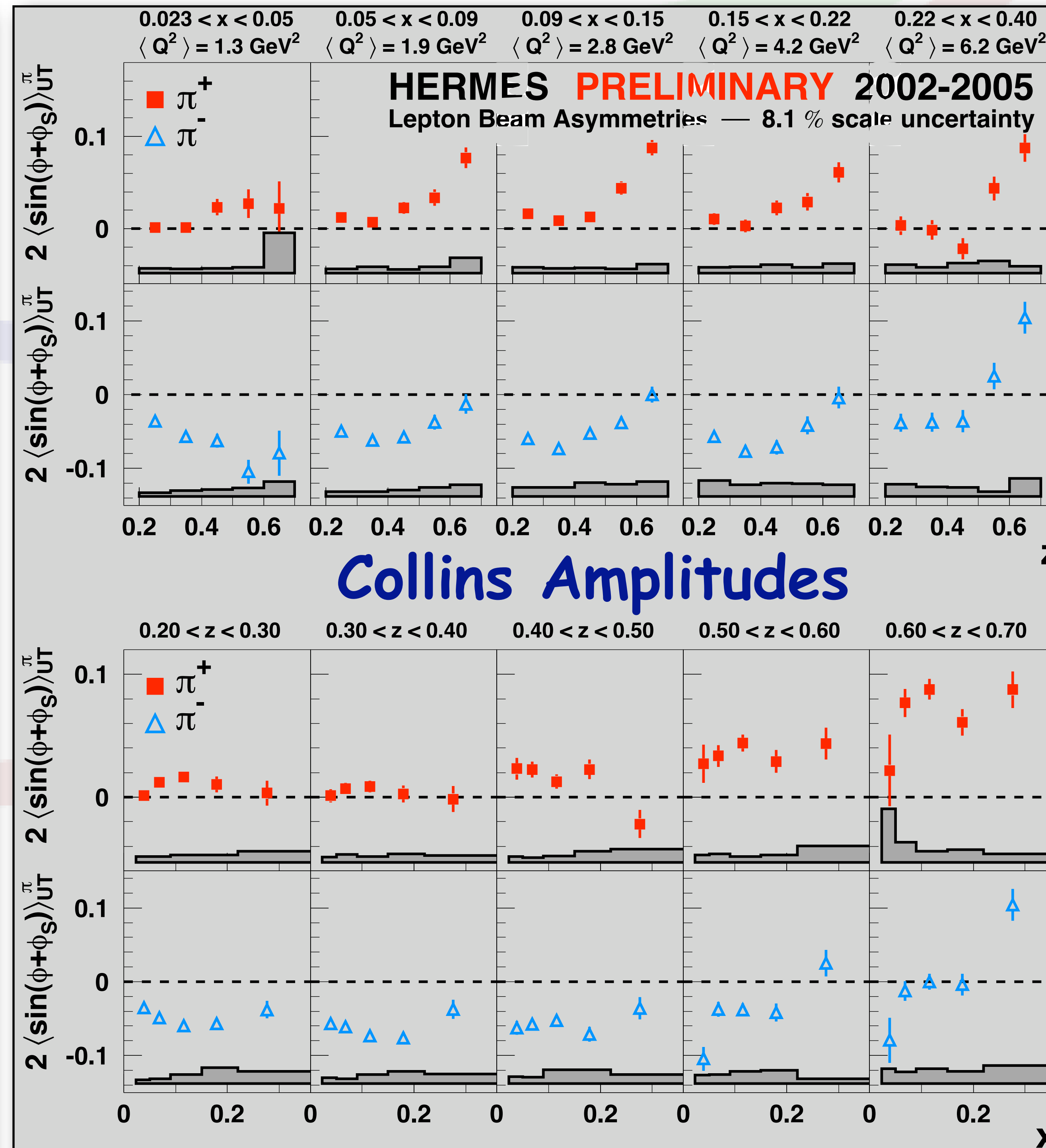
access to Sivers valence distribution

$$\langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+ - \pi^-}(\phi, \phi_S) \simeq -\frac{4 f_{1T}^{\perp, u_v} - f_{1T}^{\perp, d_v}}{4 f_1^{u_v} - f_1^{d_v}}$$

2D Binning of Sivers and Collins Amplitudes

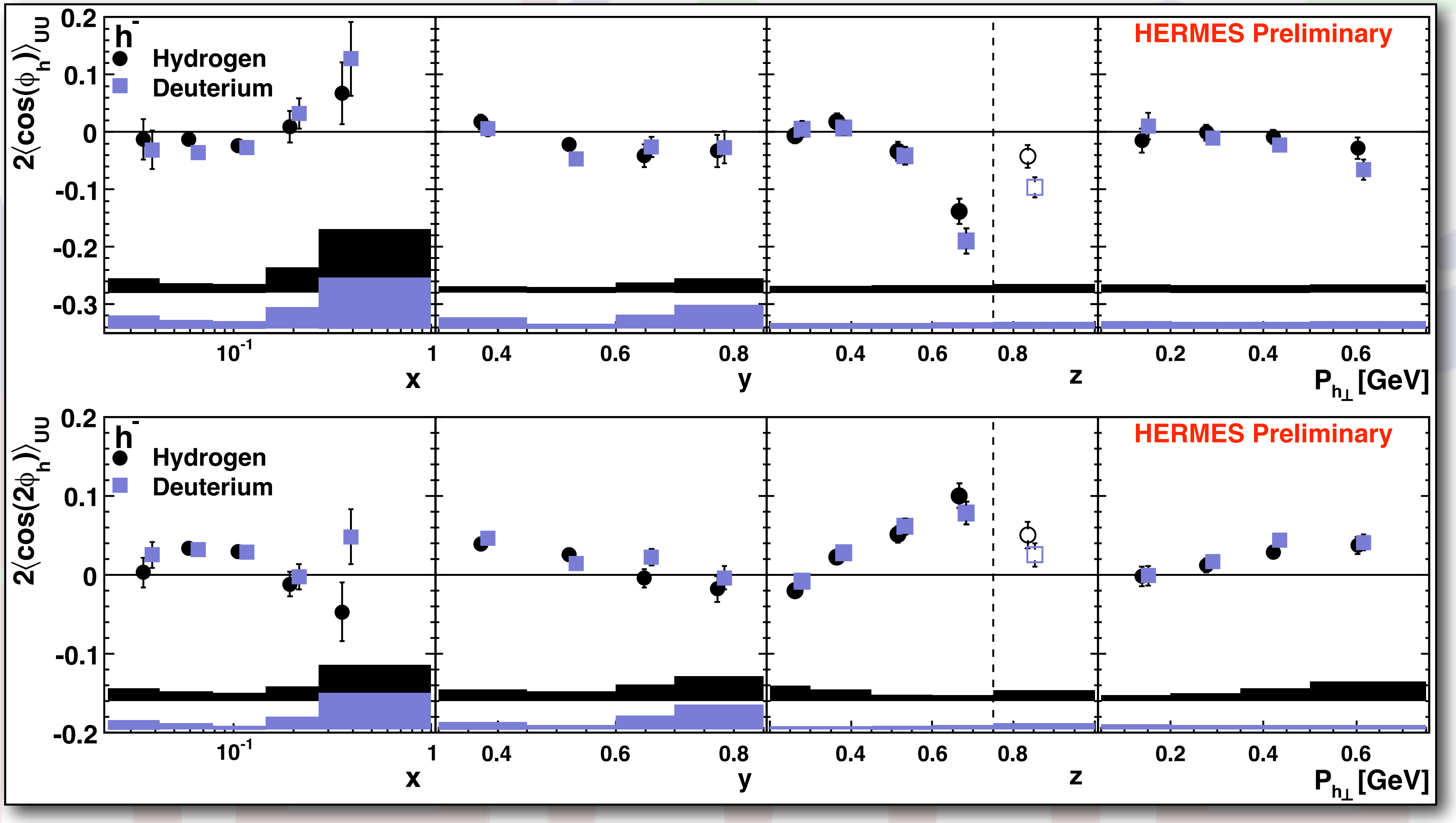
- Observed kinematics often strongly correlated in experiment
  bin in as many independent variables as possible, e.g.:





Cahn & Boer-Mulders Effects

- Azimuthal asymmetries in the spin-independent semi-inclusive XSec'n
- Extracted using 5D unfolding



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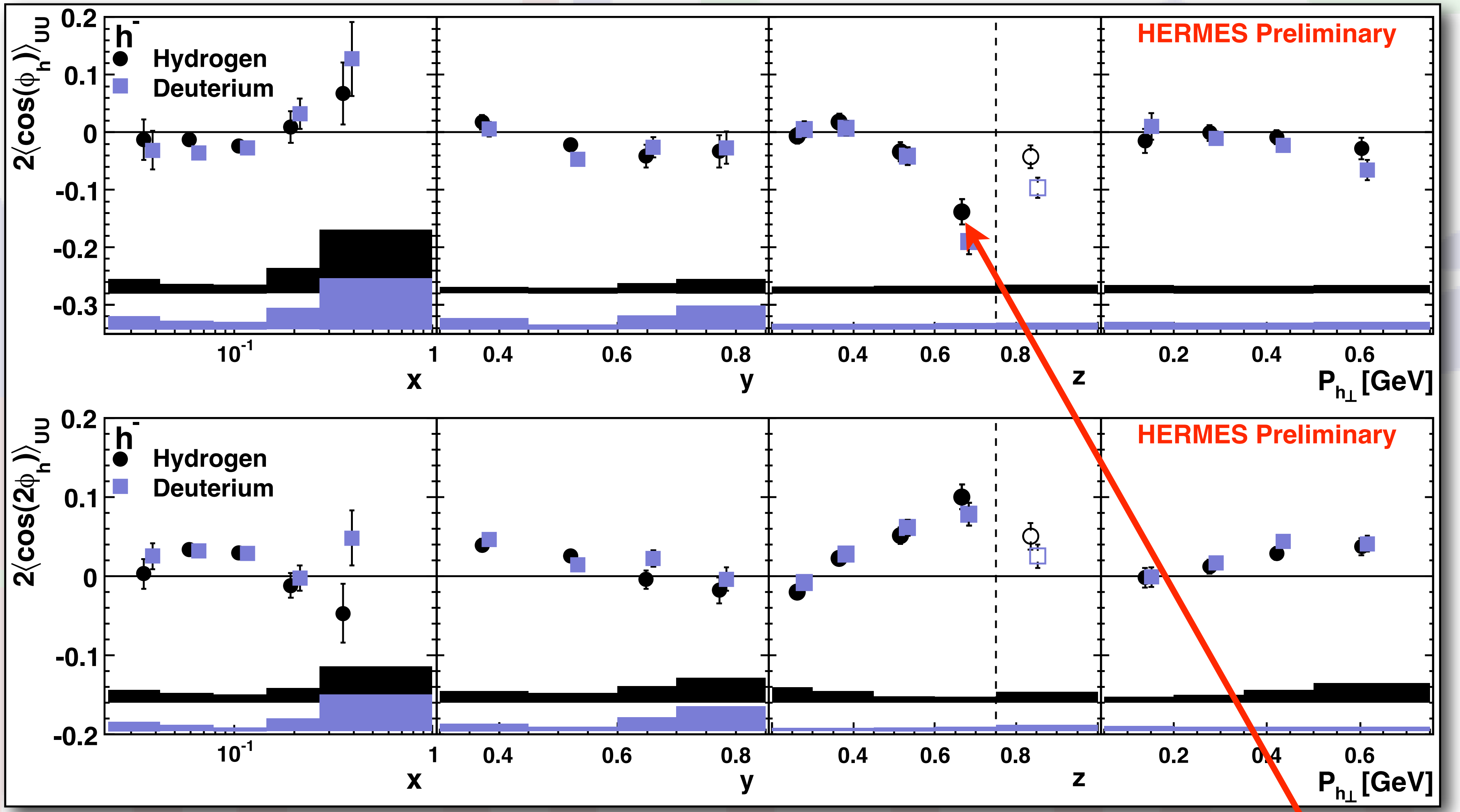

Cahn effect as manifest of intrinsic transverse quark momentum

Cahn & Boer-Mulders Effects

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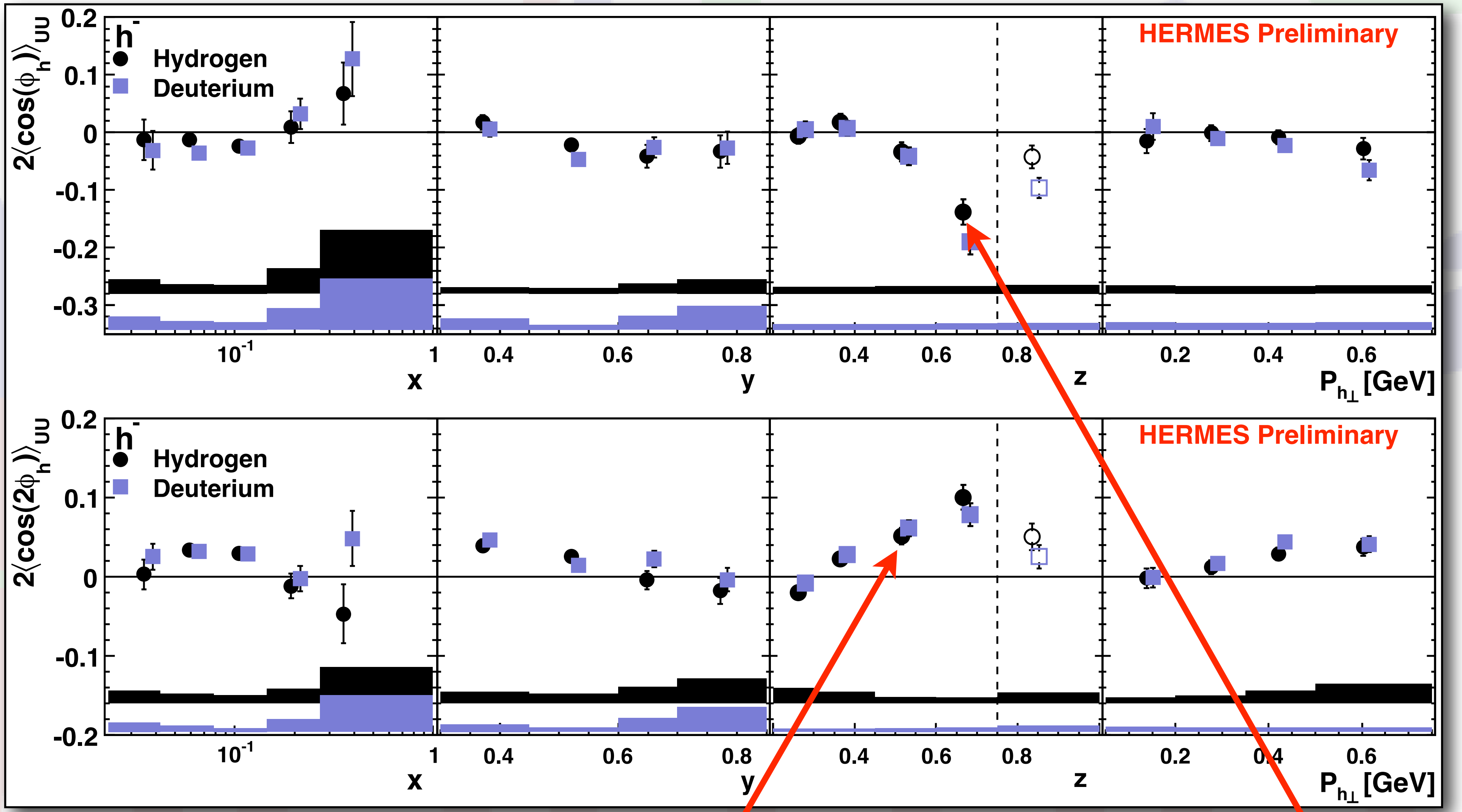
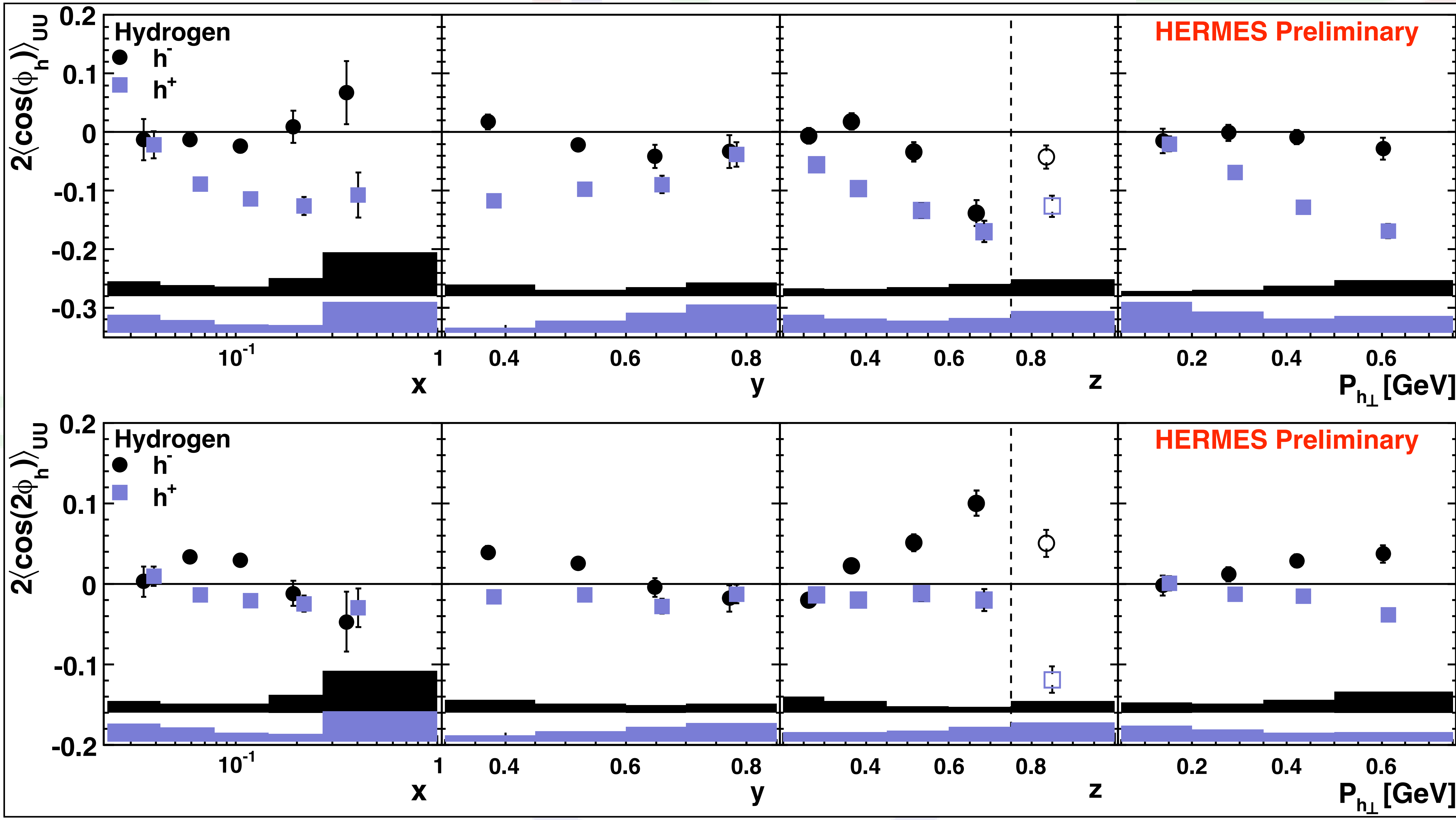


Signature of Boer-Mulders effect: transversely polarized quarks in unpolarized nucleons

Cahn effect as manifest of intrinsic transverse quark momentum

… Cahn & Boer-Mulders

- **hadron-charge comparison:**



… Cahn & Boer-Mulders

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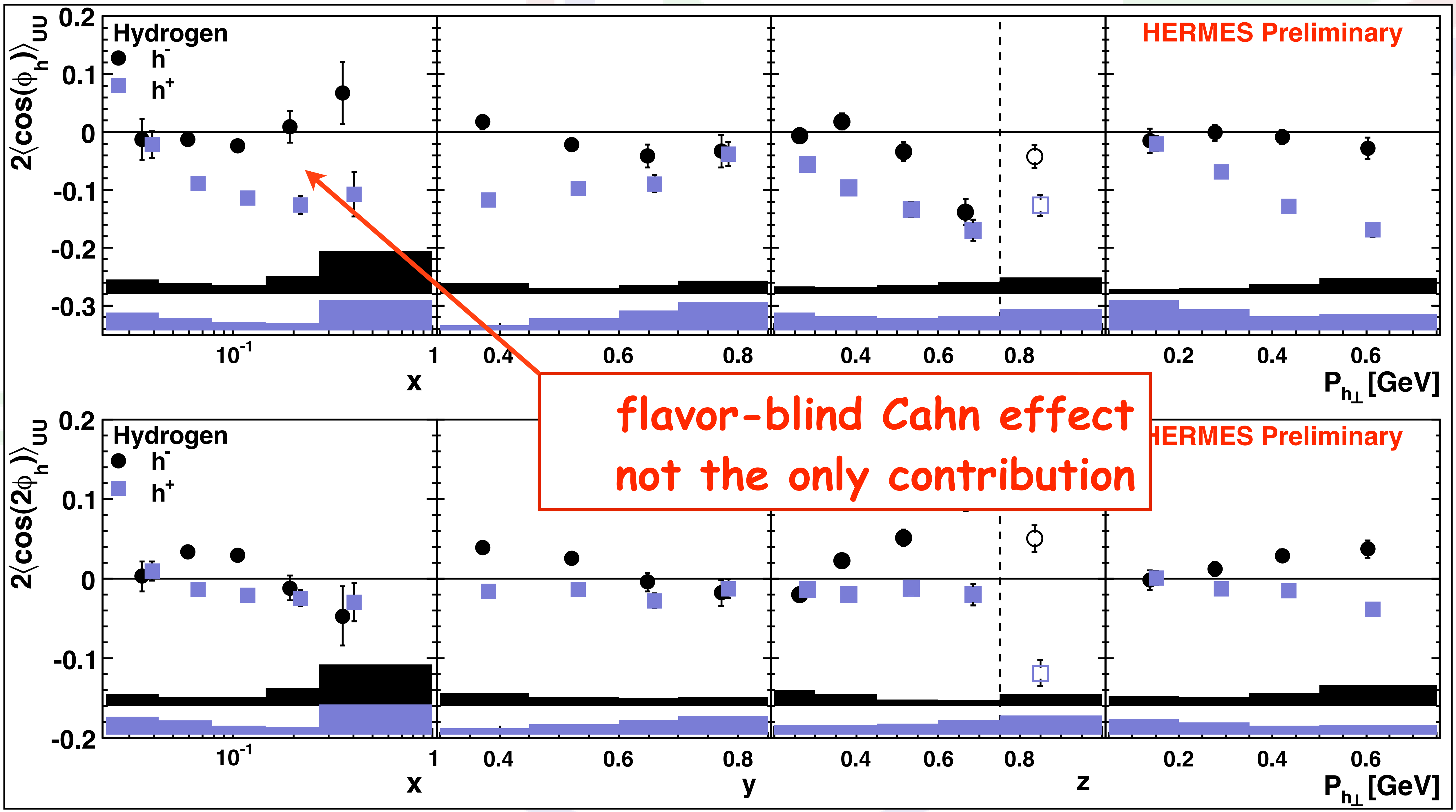
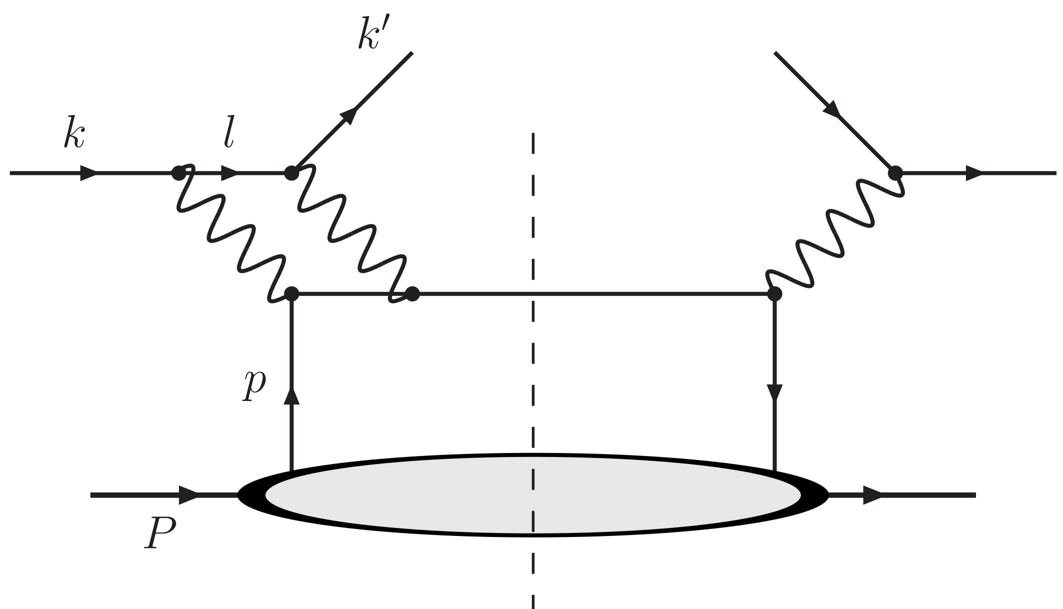


SSA in Inclusive DIS

Two-Photon Exchange

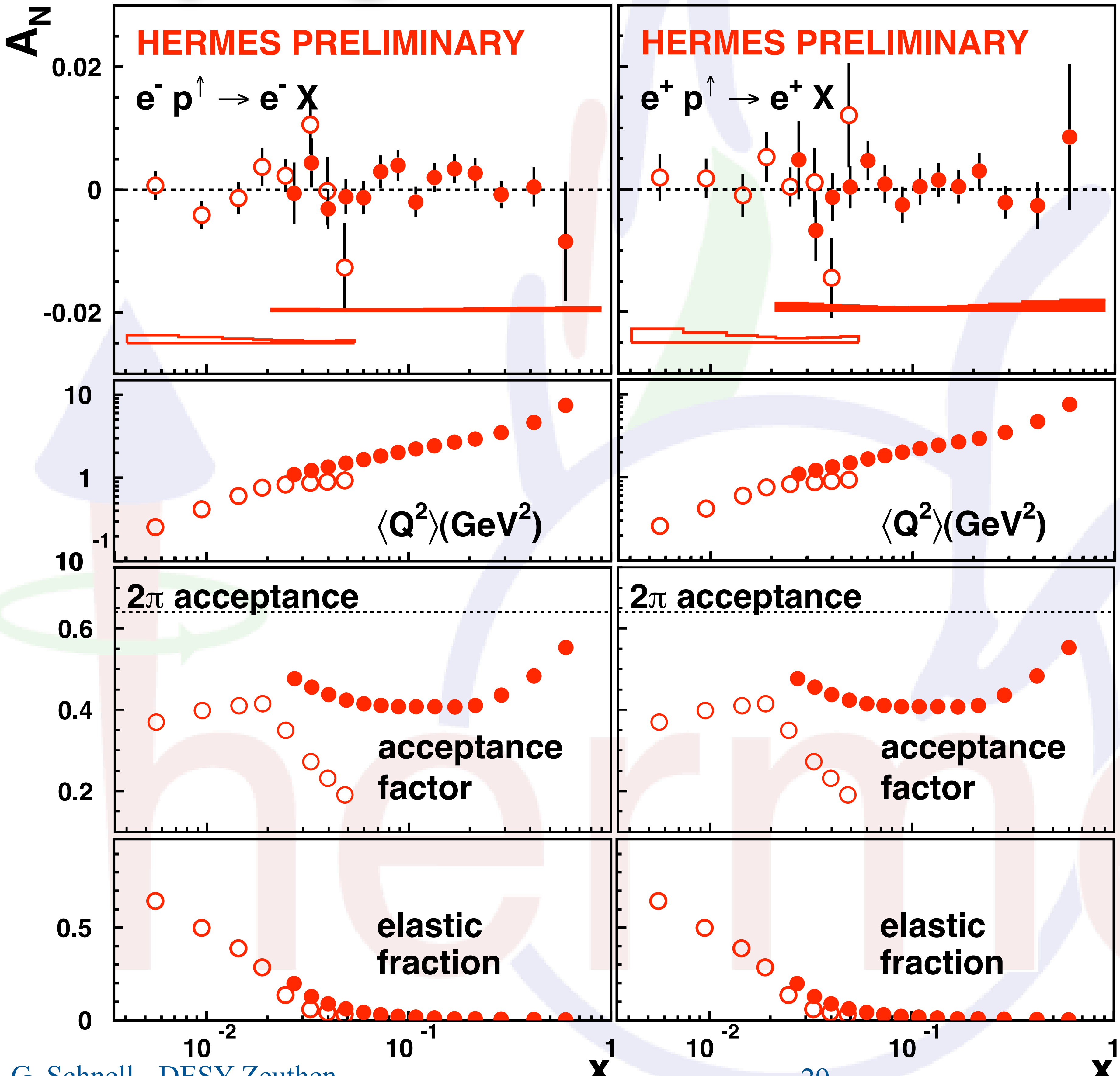
- Candidate to explain discrepancy in form-factor measurements
- Interference between one- and two-photon exchange amplitudes leads to SSAs



in inclusive DIS off transversely polarized targets

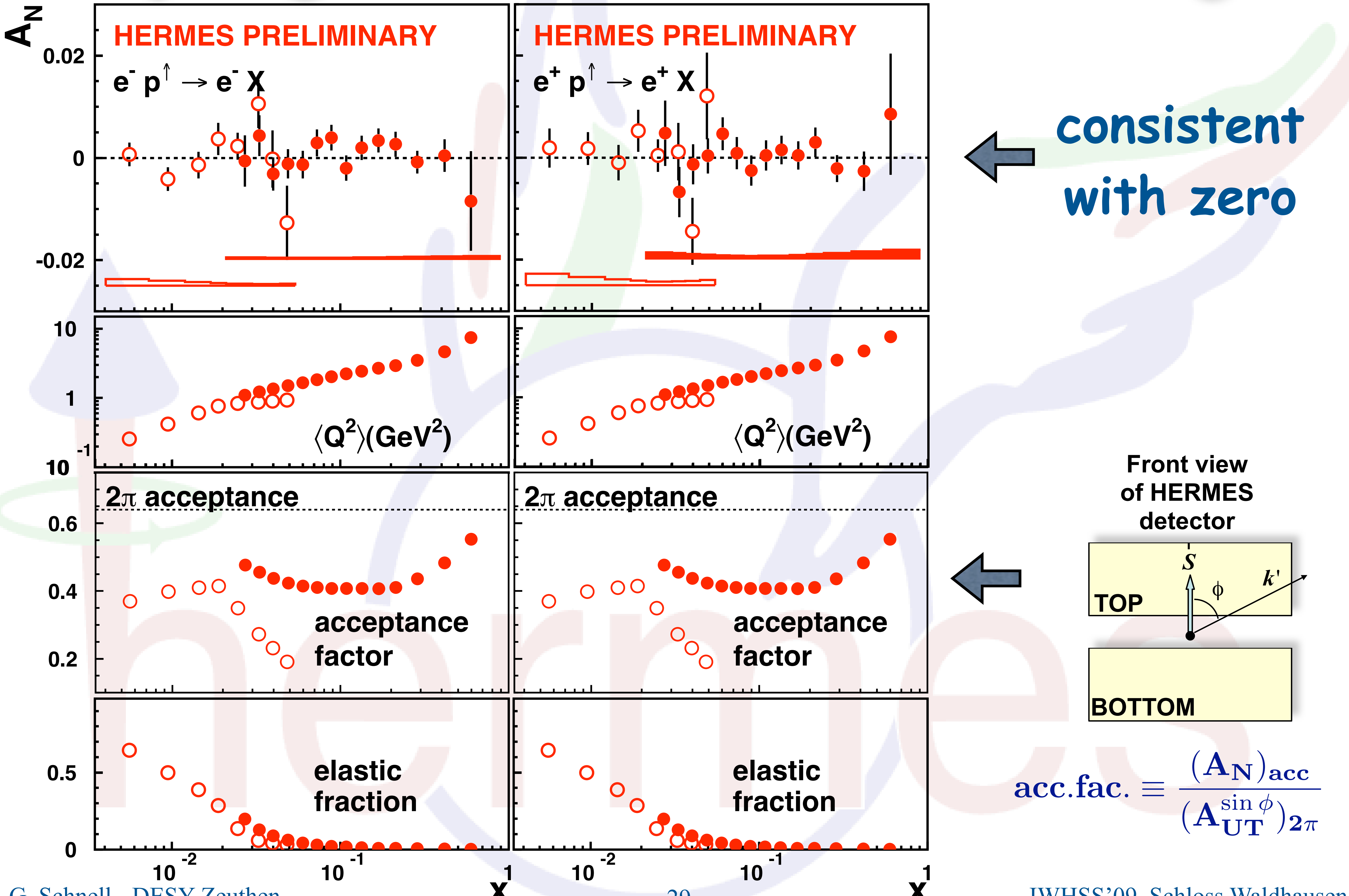
- sensitive to beam charge due to odd number of e.m. couplings to beam
- cross section proportional to S(kxk') - either measure left-right asymmetries or sine modulation

Any Sign of Two-Photon Exchange?



consistent with zero

Any Sign of Two-Photon Exchange?



$$\text{acc.fac.} \equiv \frac{(A_N)_{acc}}{(A_{UT}^{\sin\phi})_{2\pi}}$$

Exclusive Reactions

Accessing Generalized Parton Distributions

Angular Momentum and GPDs

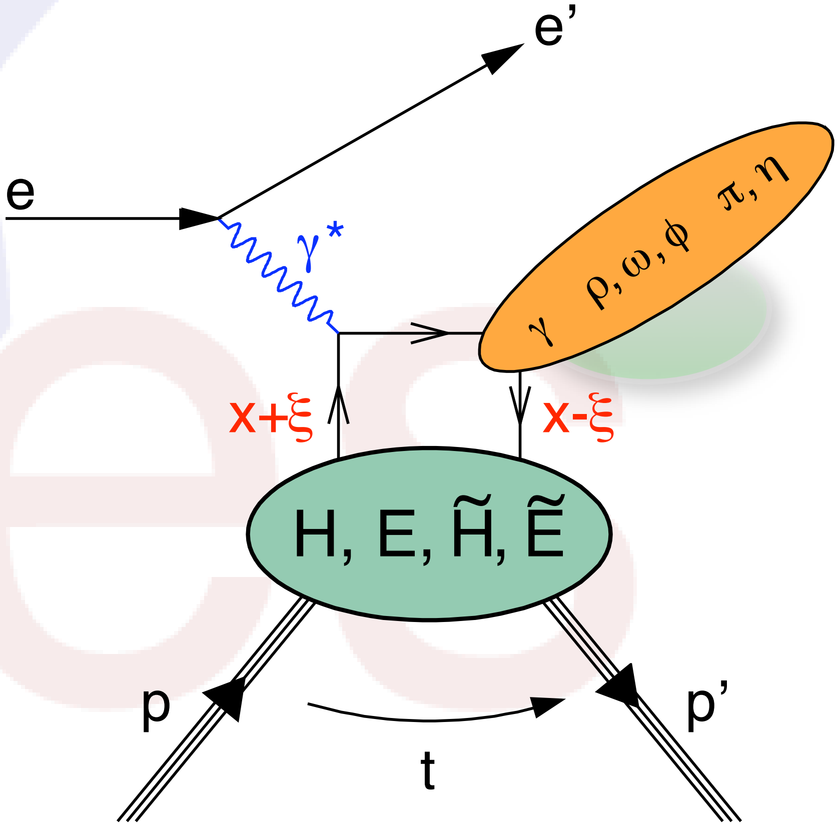
1997: Ji Relation for Nucleon Spin

$$\frac{1}{2}\hbar = \underbrace{\lim_{t\to 0}\sum_q \int dx\, x\, [H^q(x,\xi,t) + E^q(x,\xi,t)]}_{J^q} + \underbrace{\lim_{t\to 0}\int dx\, [H^g(x,\xi,t) + E^g(x,\xi,t)]}_{J^g}$$

- **"Ji's Recipe" provides way to measure angular momenta**
- **involves moment over new class of PDFs: Generalized PDs**
- **at leading twist there are 8 GPDs:** $E, H, \tilde{E}, \tilde{H}, E_T, H_T, \tilde{E}_T, \tilde{H}_T$
- **provide info about transverse position and long. mom.**
- **only two needed for Ji's recipe:** E, H

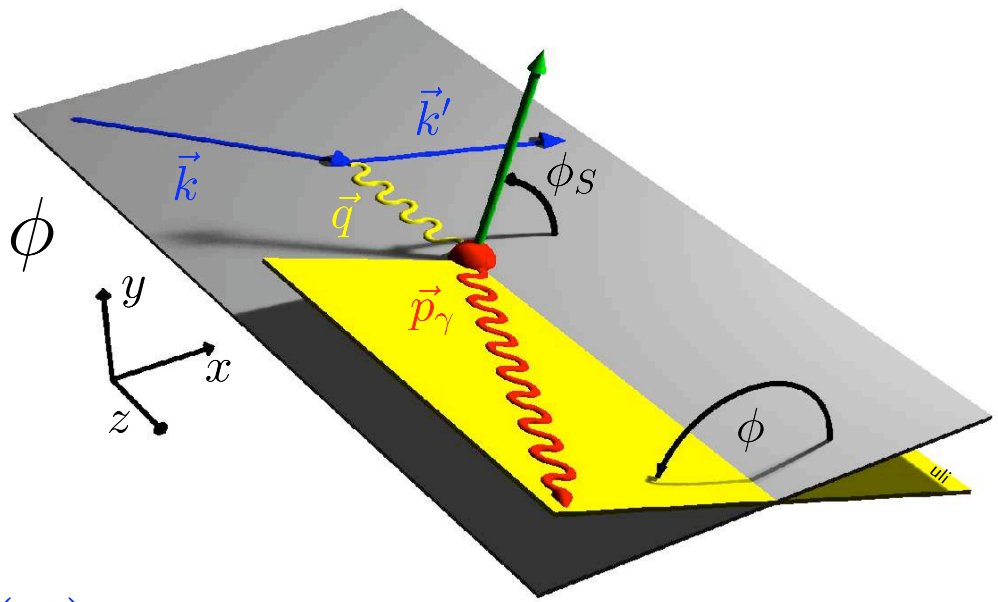
GPDs in Exclusive Reactions

- **GPDs involve off-forward matrix elements**
- **Moments give Form Factors, e.g.,** $\int dx H^q(x,\xi,t) = F_1^q(t)$
- **Forward limit give ordinary PDFs, e.g.,** $H^q(x,0,0) = f_1^q(x)$
- **at HERMES accessed in exclusive reactions:**
  - **Exclusive Vector-Meson Production**
  - **Exclusive Pseudoscalar-Meson Production**
  - **Deeply Virtual Compton Scattering (at HERMES mainly via Interference with Bethe-Heitler)**



Azimuthal Asymmetries in DVCS

Interference DVCS & BH cause azimuthal asymmetries in cross-section:



- Beam-charge asymmetry $A_C(\phi)$:
  $d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$
- Beam-spin asymmetry $A_{LU}(\phi)$:
  $d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi$
- Long. target-spin asymmetry $A_{UL}(\phi)$:
  $d\sigma(\overset{\Leftarrow}{P},\phi) - d\sigma(\overset{\Rightarrow}{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$
- Transverse target-spin asymmetry $A_{UT}(\phi,\phi_s)$ [TTSA]:

$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$$

(F_1, F_2 are the Dirac and Pauli form factors, calculable in QED)
($\widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}, \ldots$ Compton form factors involving GPDs $H, E, \ldots$)

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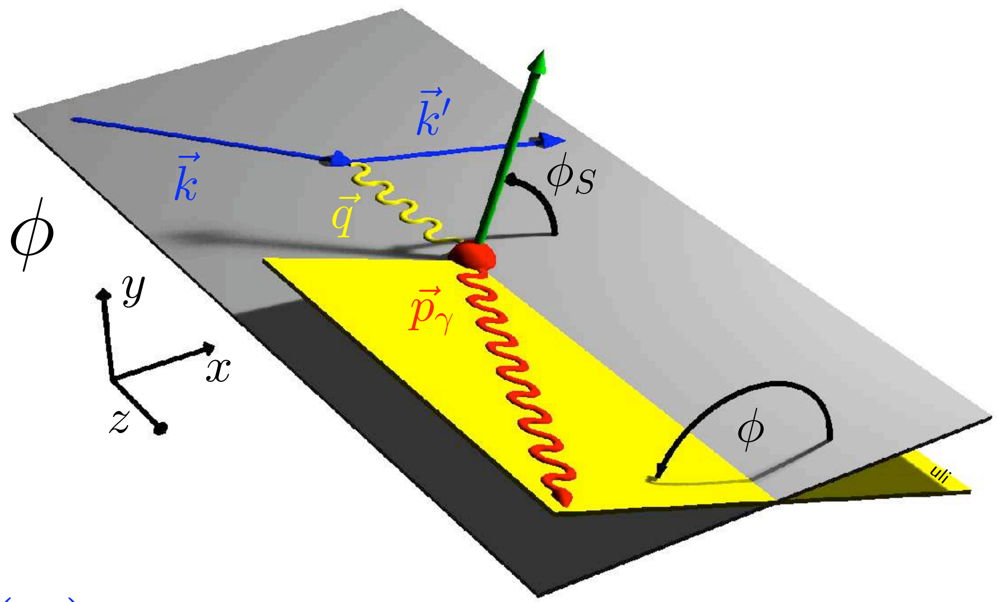

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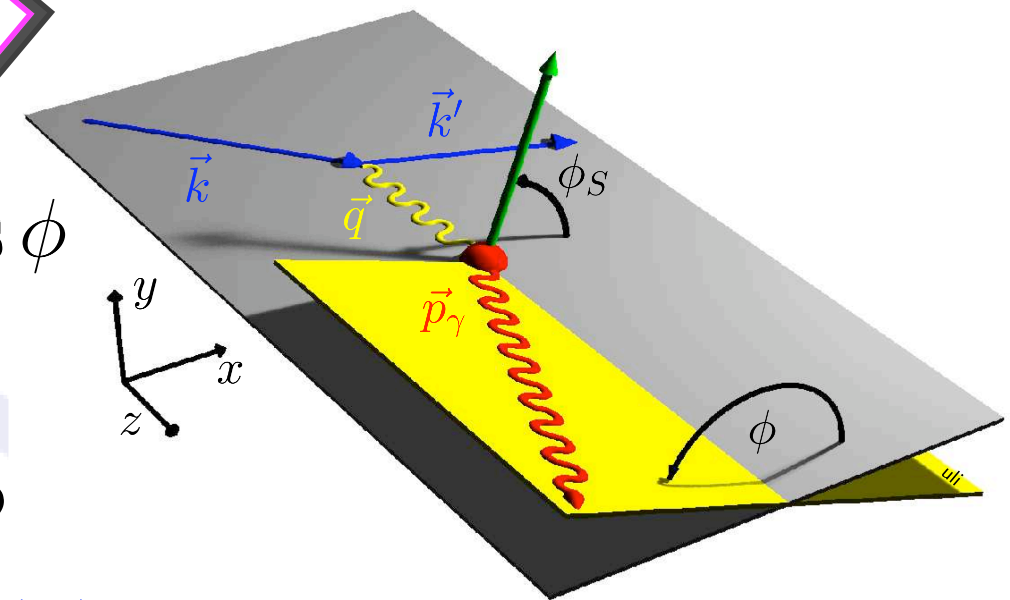

- Beam-charge asymmetry ... :
  $d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto$ Re ... $\cos\phi$
- Beam-spin asymmetr... (ϕ) :
  $d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi)$ ... $_1\mathcal{H}] \cdot \sin\phi$
- Long. target-sp... ...mmetry $A_{UL}(\phi)$:
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- Transvers... ...et-spin asymmetry $A_{UT}(\phi,\phi_s)$ [TTSA]:

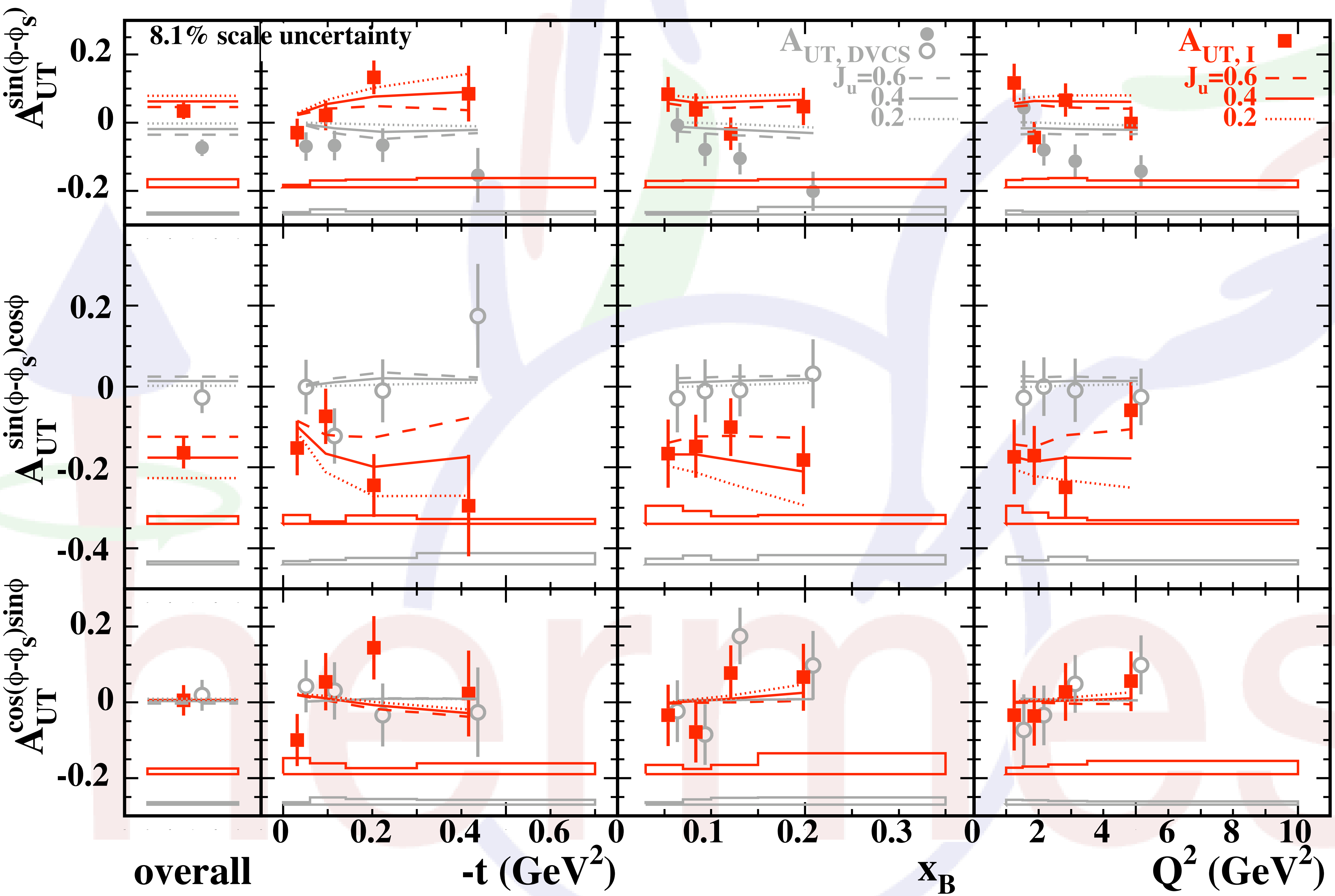
$$d\sigma(\phi,\phi \ldots (\phi,\phi_S+\pi) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi$$
$$+ \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$$

Only TTSA sensitive to E!

(F_1, F_2 a... ...e Dirac and Pauli form factors, calculable in QED)
($\widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}, \ldots$ Compton form factors involving GPDs $H, E, \ldots$)

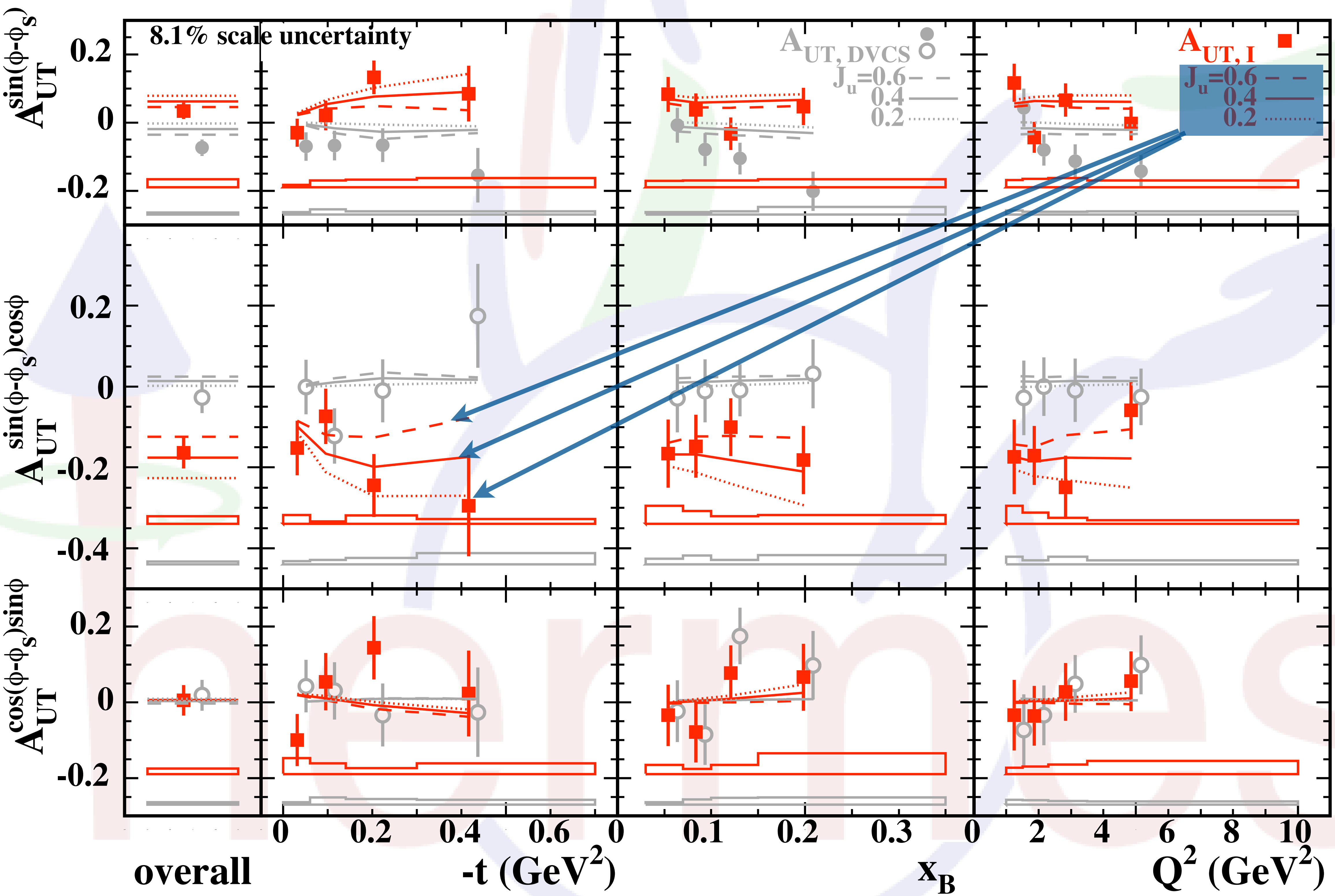
Amplitudes of TTSA

A. Airapetian et al., JHEP 0806:066,2008



Amplitudes of TTSA

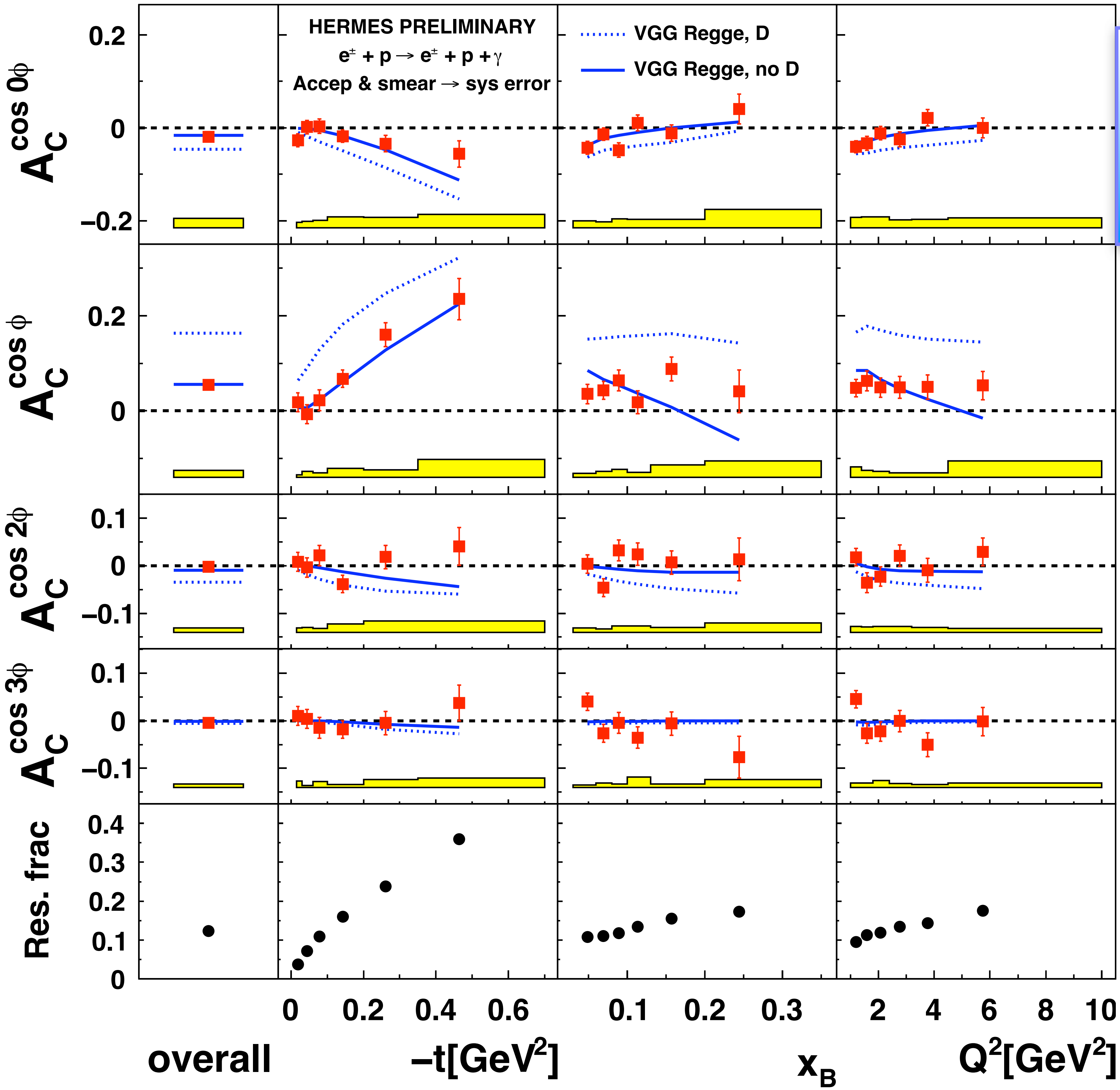
A. Airapetian et al., JHEP 0806:066,2008



Constraints on GPD Models

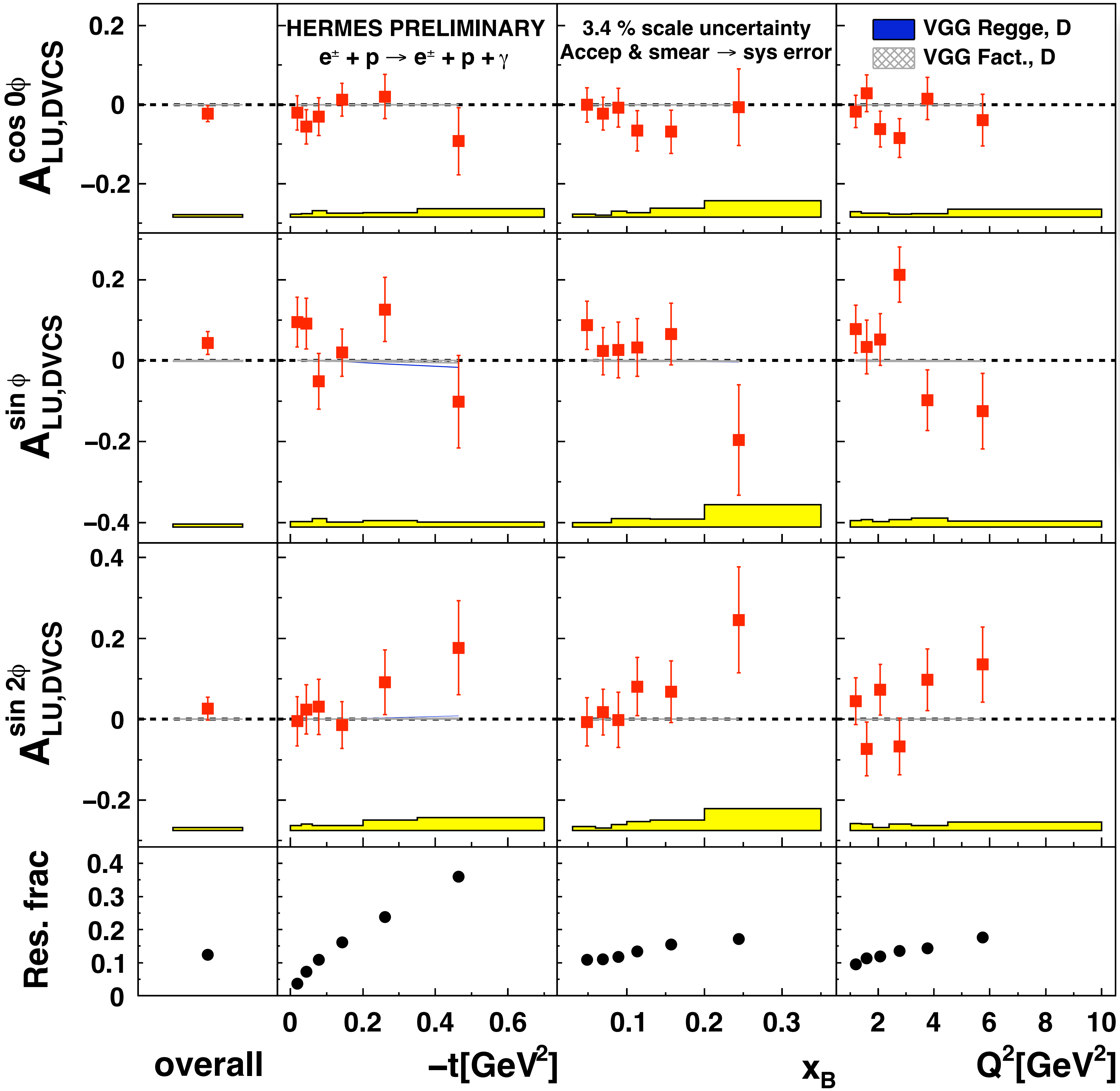
- several pioneering DVCS results on H, D, and nuclear targets
- provide important constraints on GPD models

Constraints on GPD Models



Beam-Charge asymmetry on H

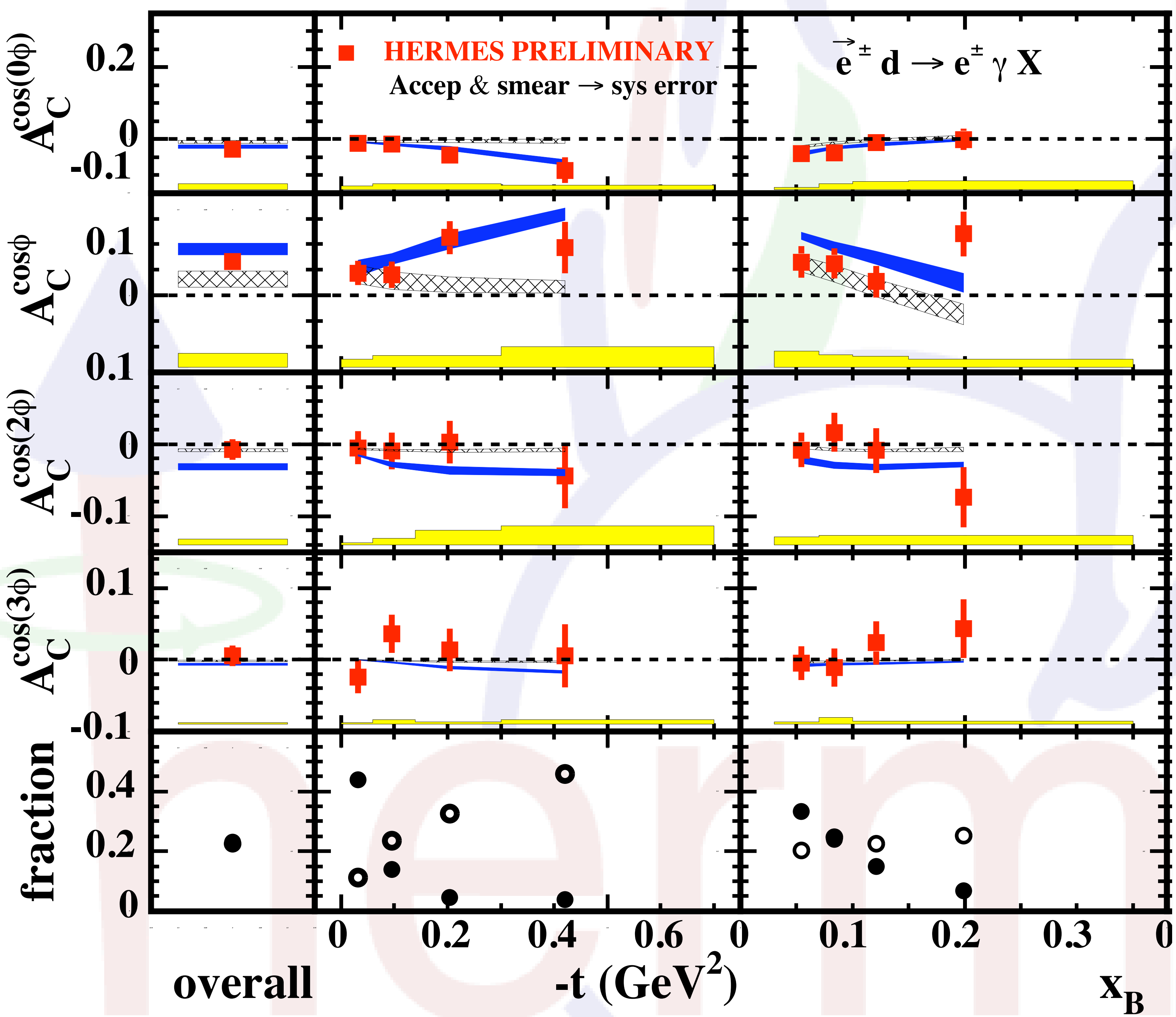
Constraints on GPD Models



Beam-Charge asymmetry on H

Beam-Spin asymmetry on H

Constraints on GPD Models

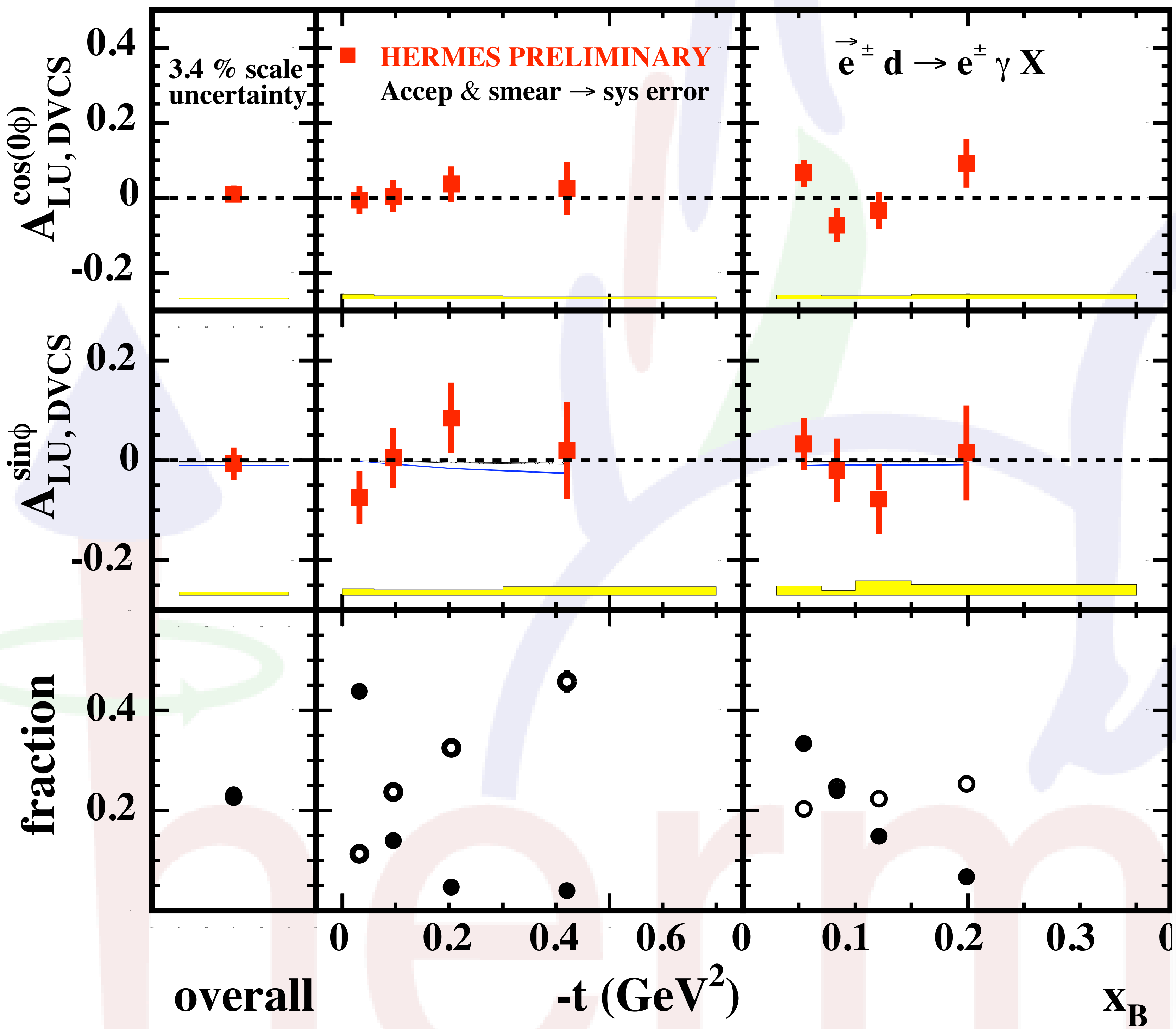


Beam-Charge asymmetry on H

Beam-Spin asymmetry on H

Beam-Charge asymmetry on D

Constraints on GPD Models



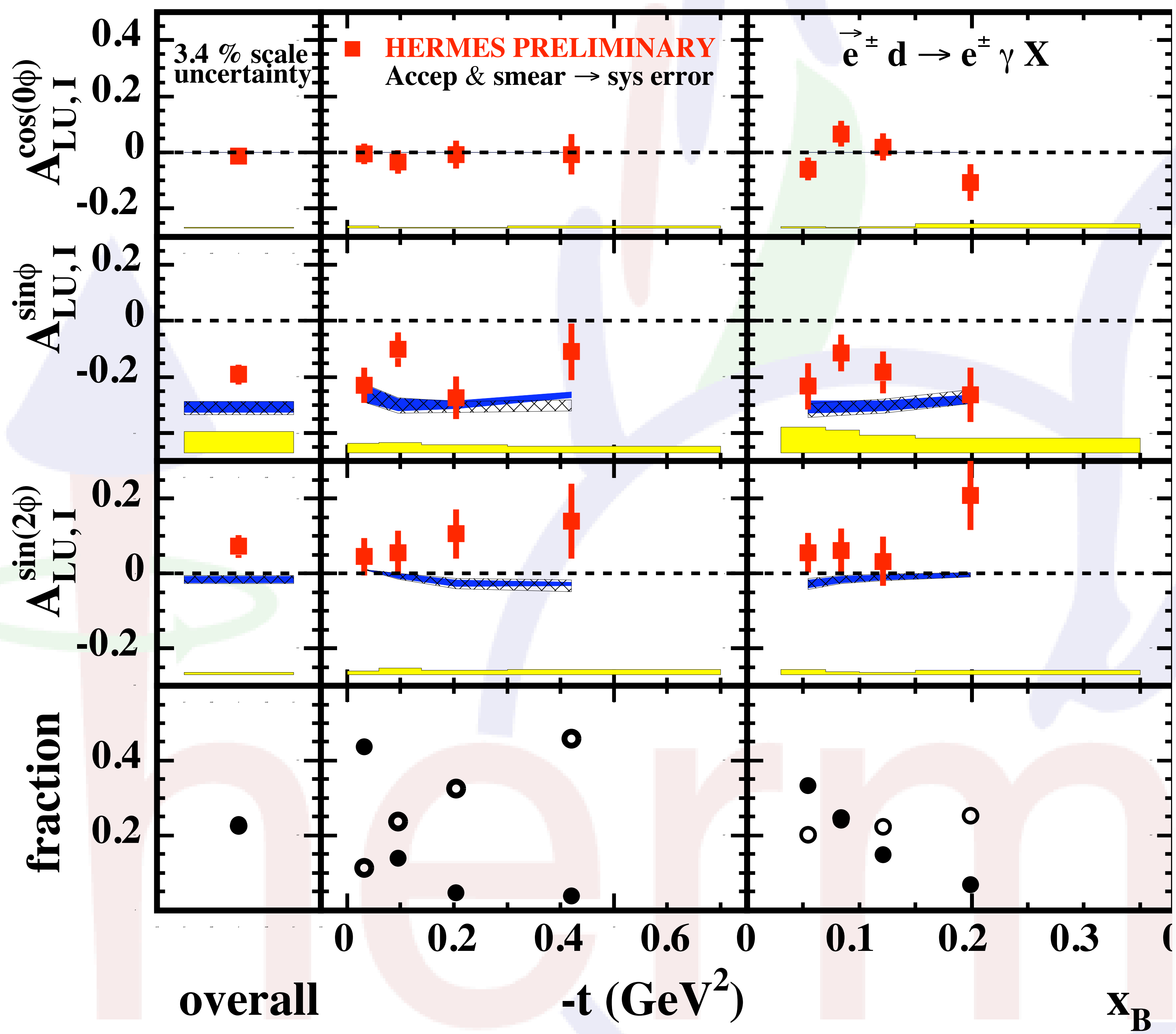
Beam-Charge asymmetry on H

Beam-Spin asymmetry on H

Beam-Charge asymmetry on D

Beam-Spin asymmetry on D

Constraints on GPD Models



Beam-Charge asymmetry on H

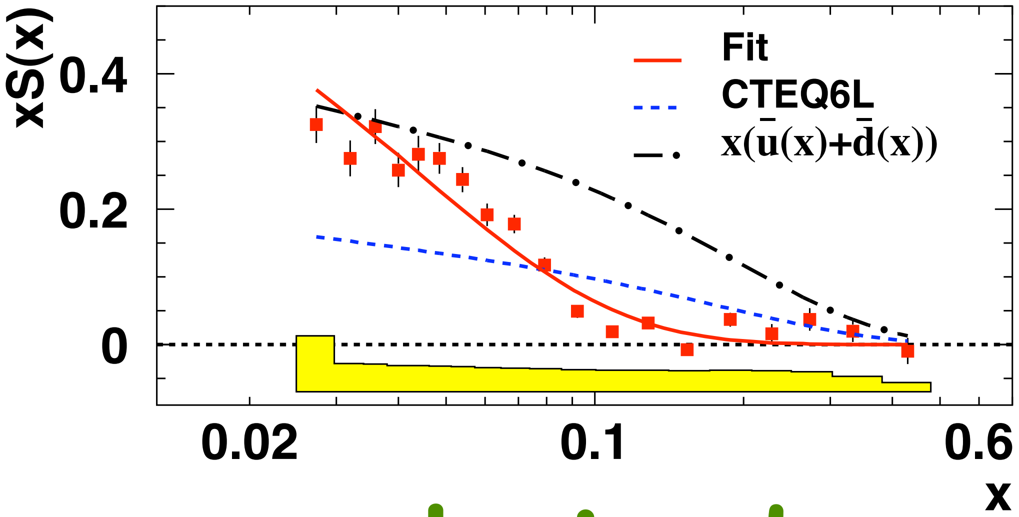
Beam-Spin asymmetry on H

Beam-Charge asymmetry on D

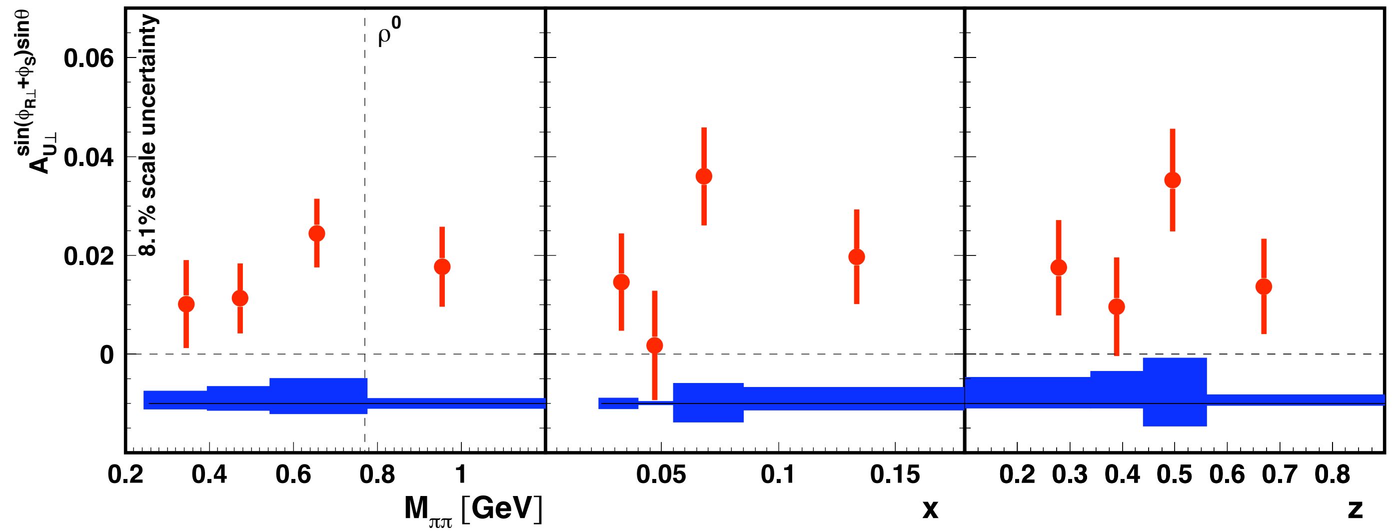
Beam-Spin asymmetry on D

no model so far able to describe all data!

hermes

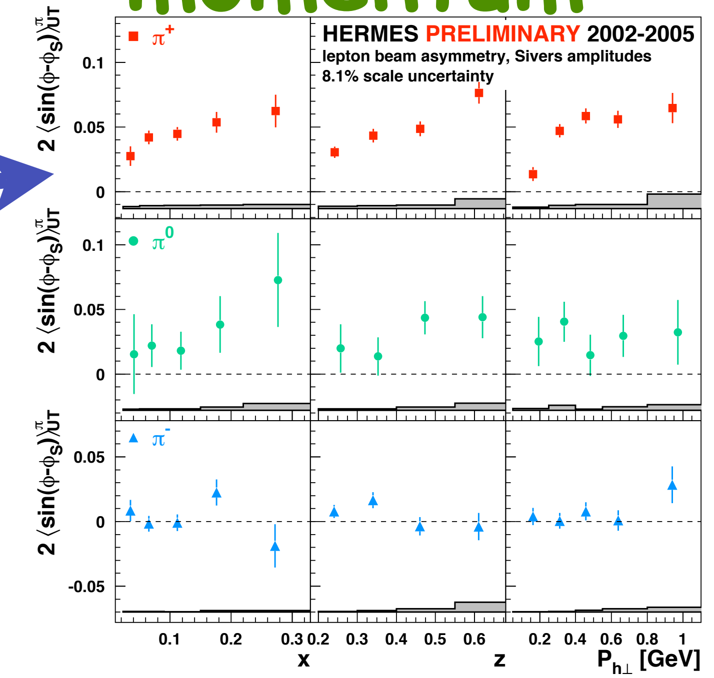


unpolarized quarks

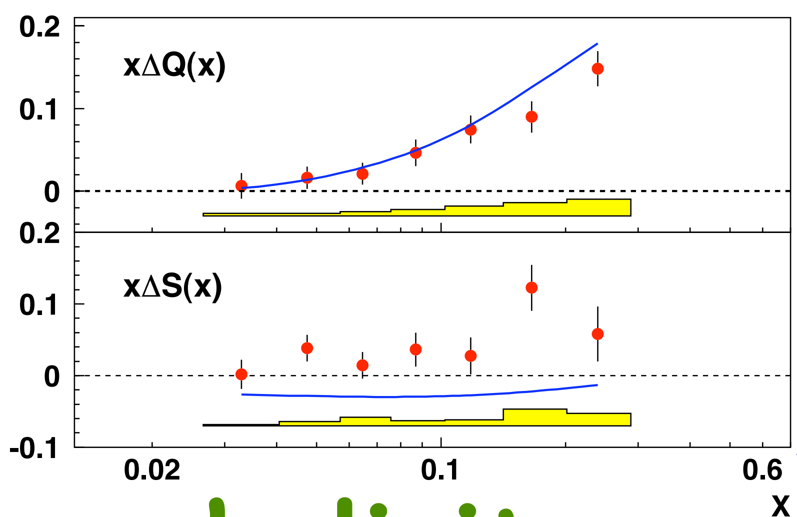


transversity

orbital angular momentum

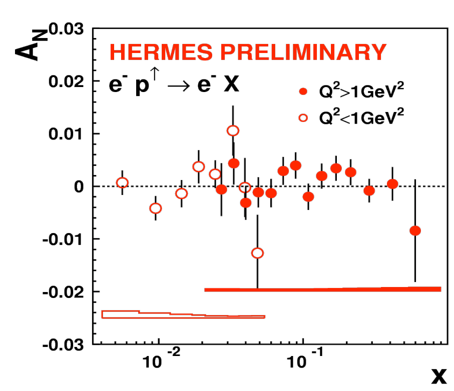


hermes



helicity distributions

2-Photon Exchange



GPDs