CLAS12 European Workshop
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Recent Highlights of the HERMES Experiment

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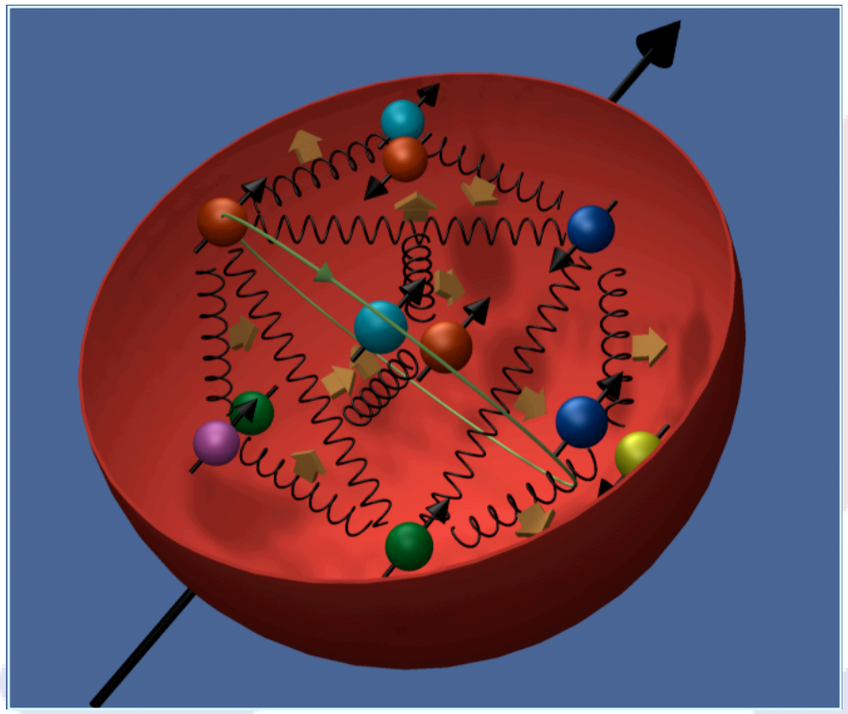
The Quest: Spin Structure of the Proton



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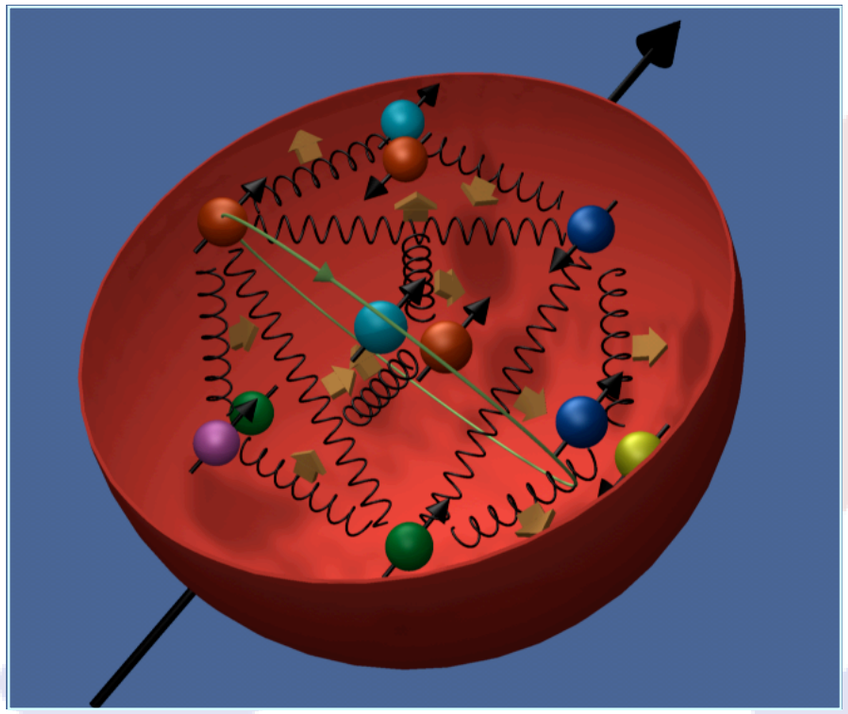

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PRD 75 (2007) 012007

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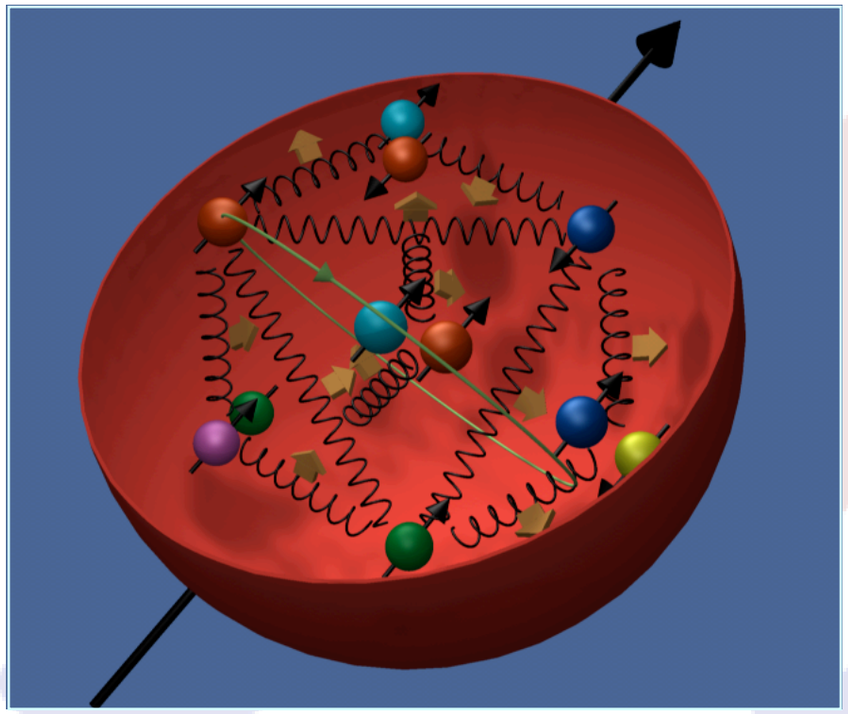

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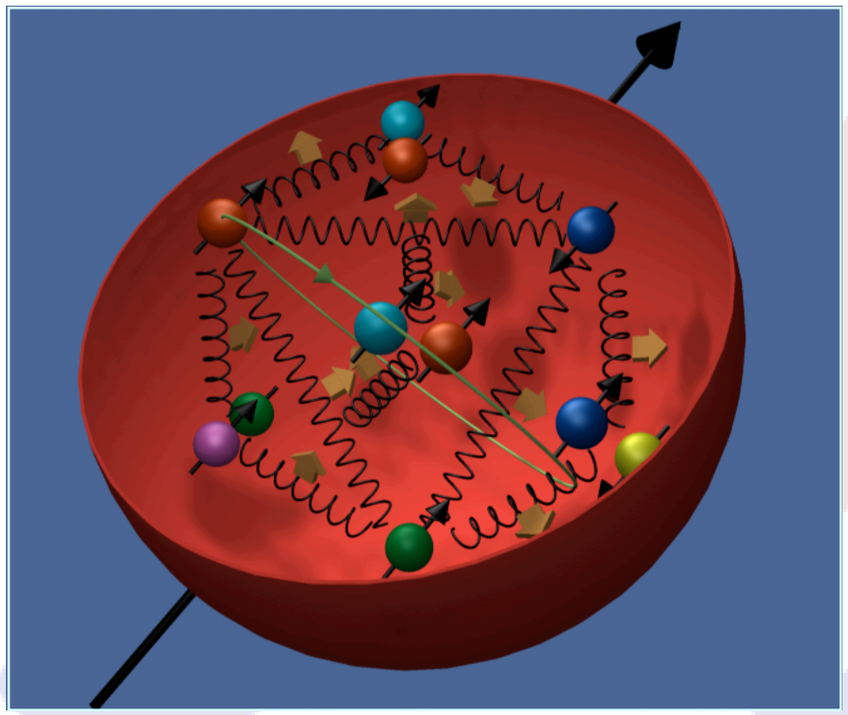

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- TMDs
- hard exclusive reactions

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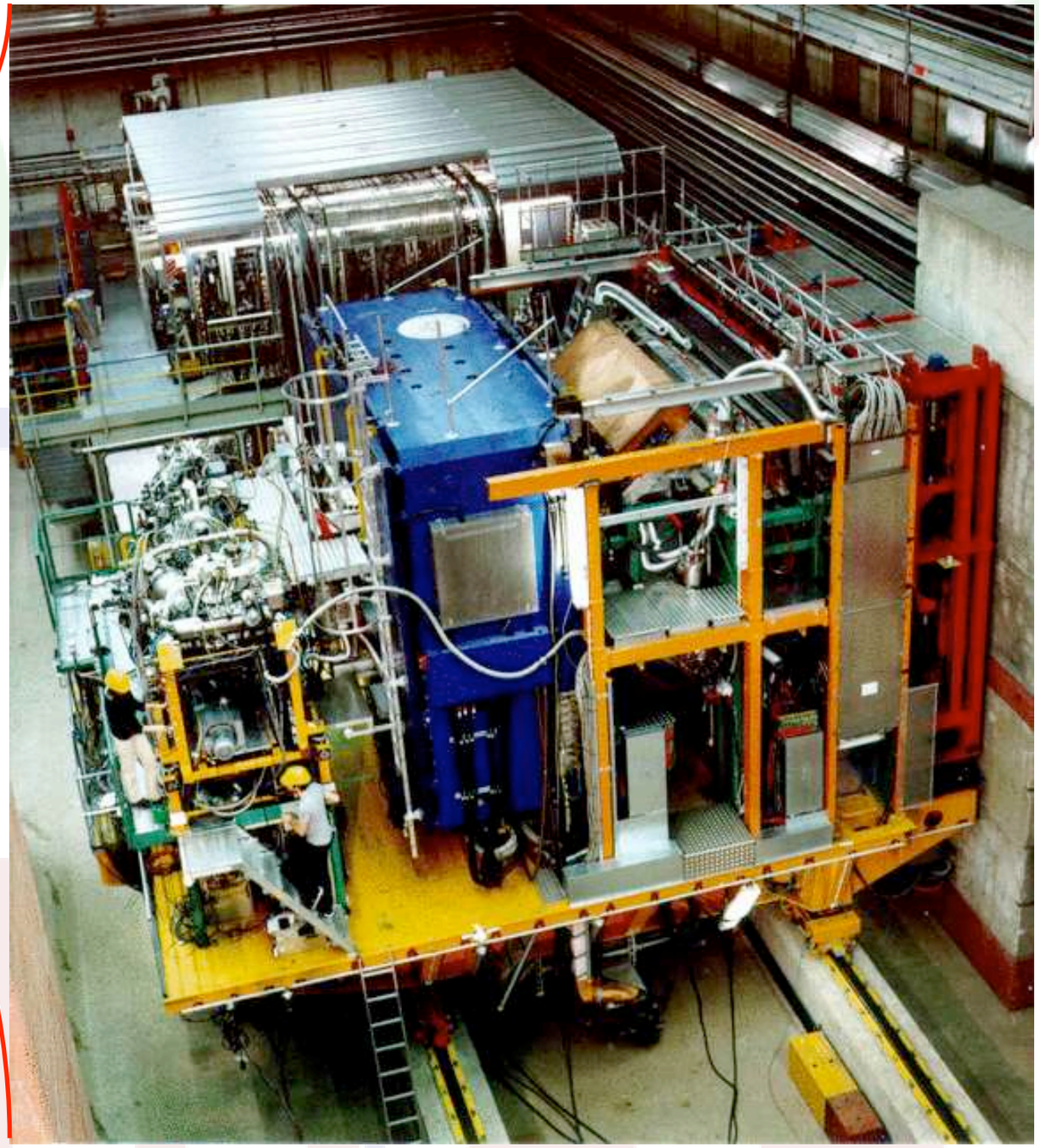
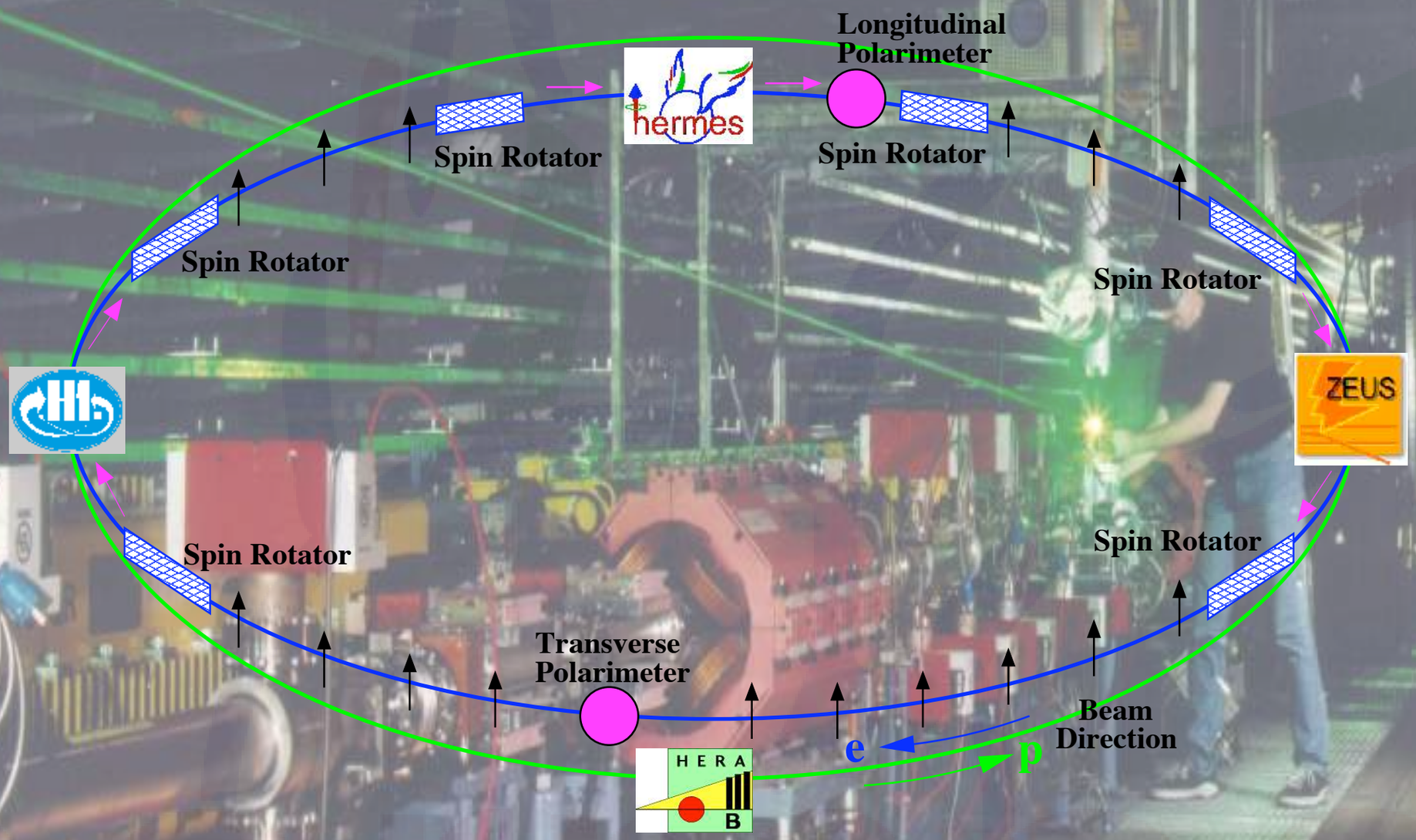
The HERMES Experiment

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



Beam Polarization at HERA

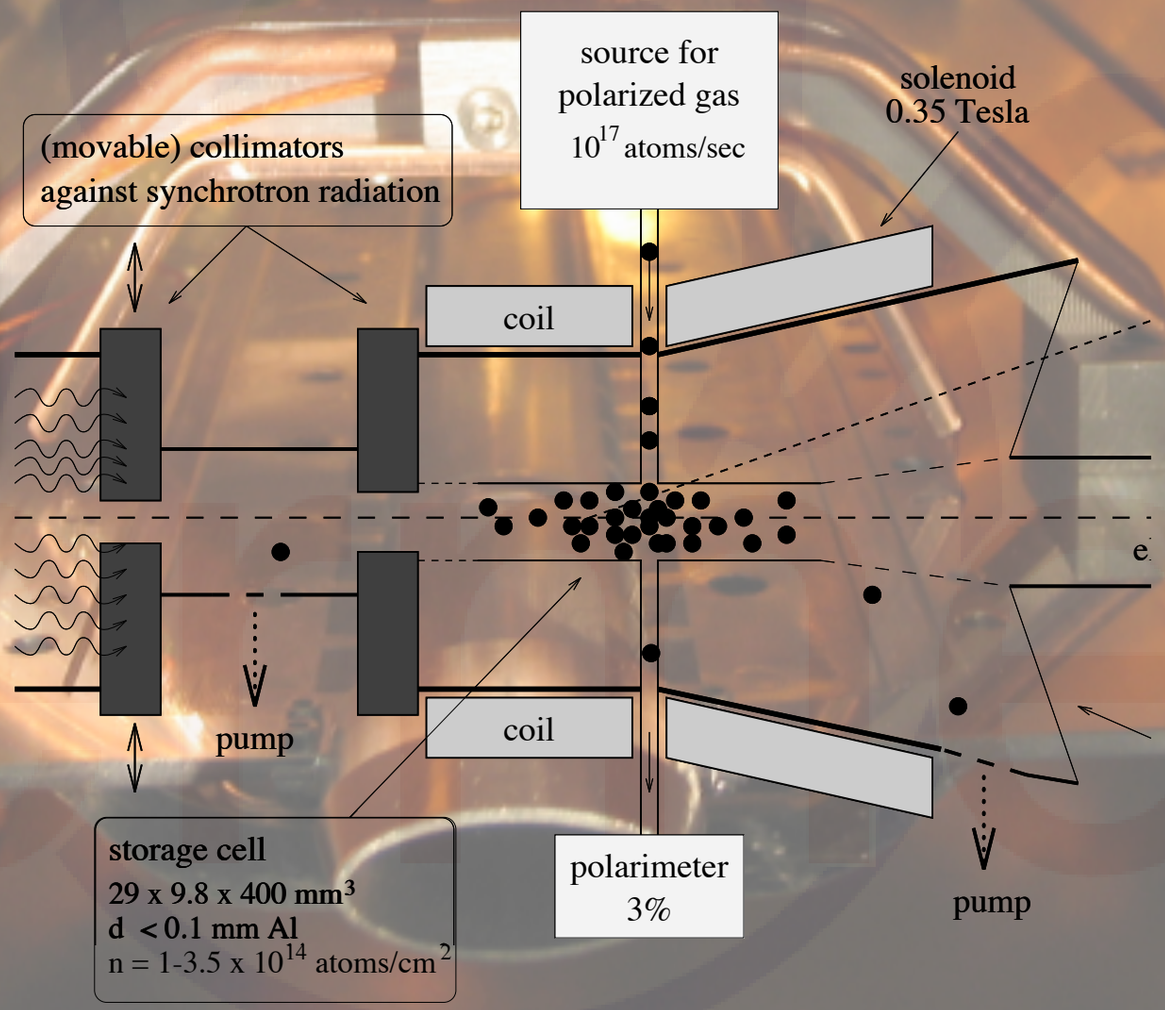


- 27.5 GeV e^+/e^- beam
- Self-polarizing through Sokolov-Ternov-Effect
- Average beam polarization of about 55%

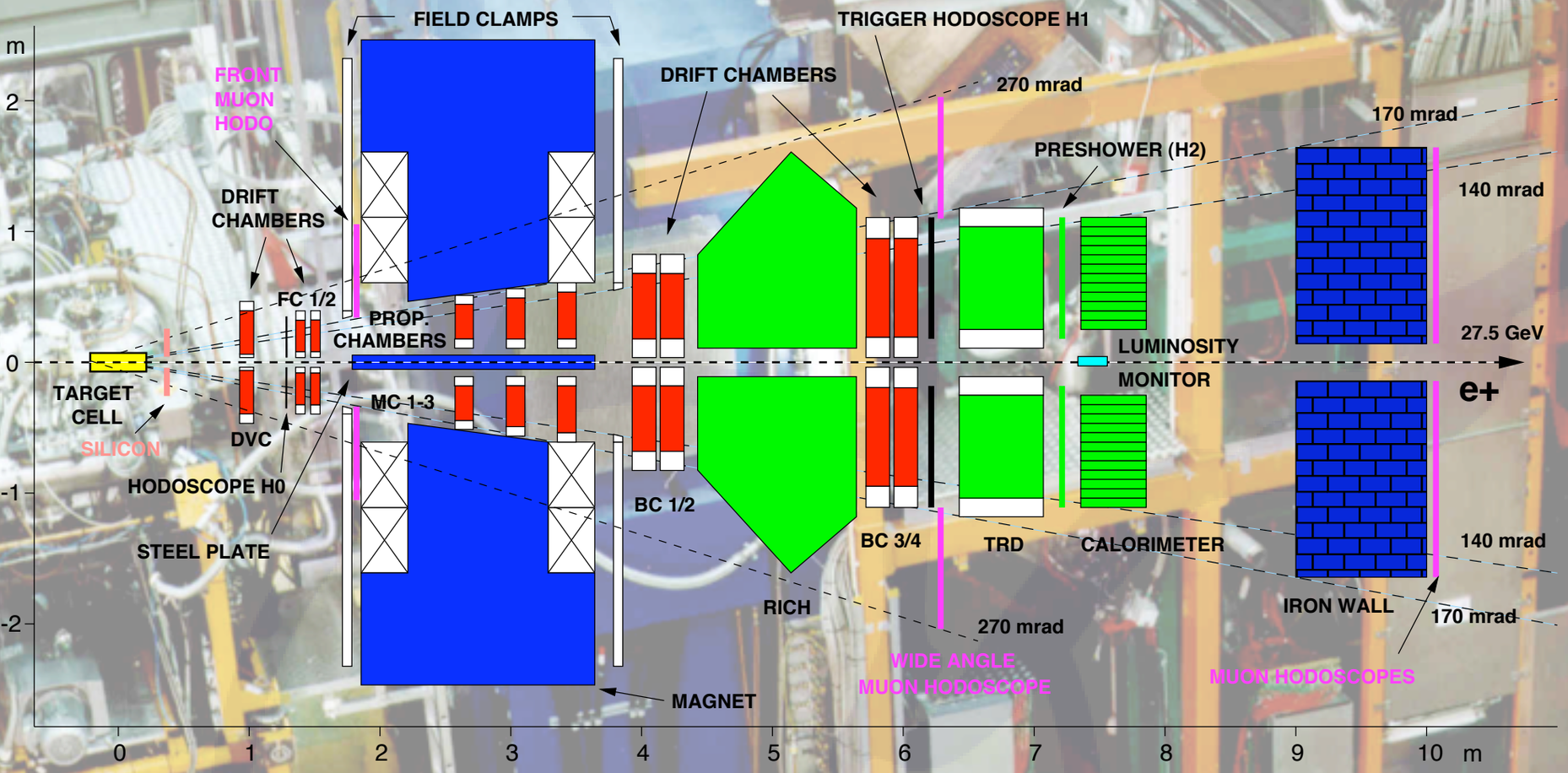
HERMES Polarized Target

- 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%

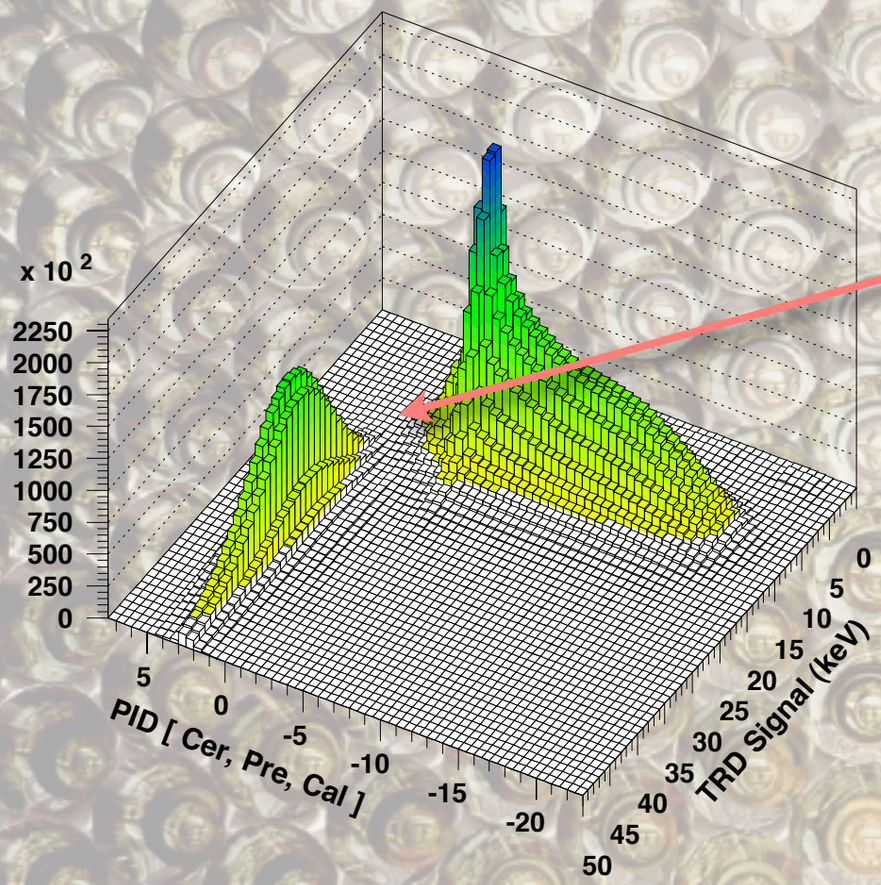


HERMES Spectrometer



- 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

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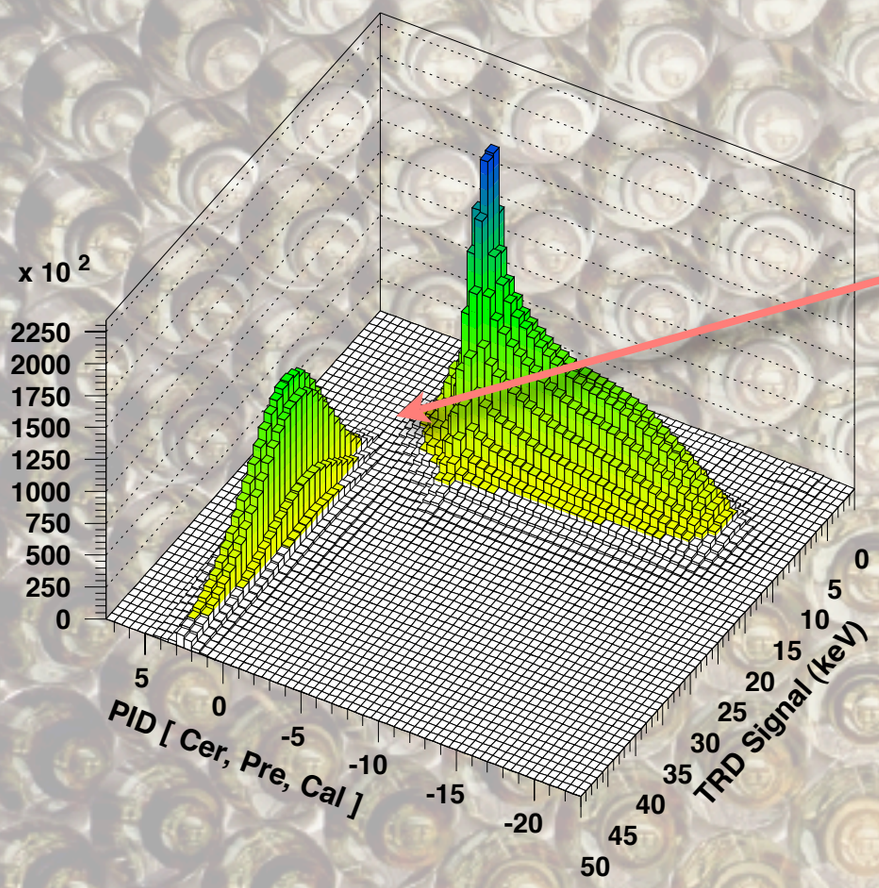
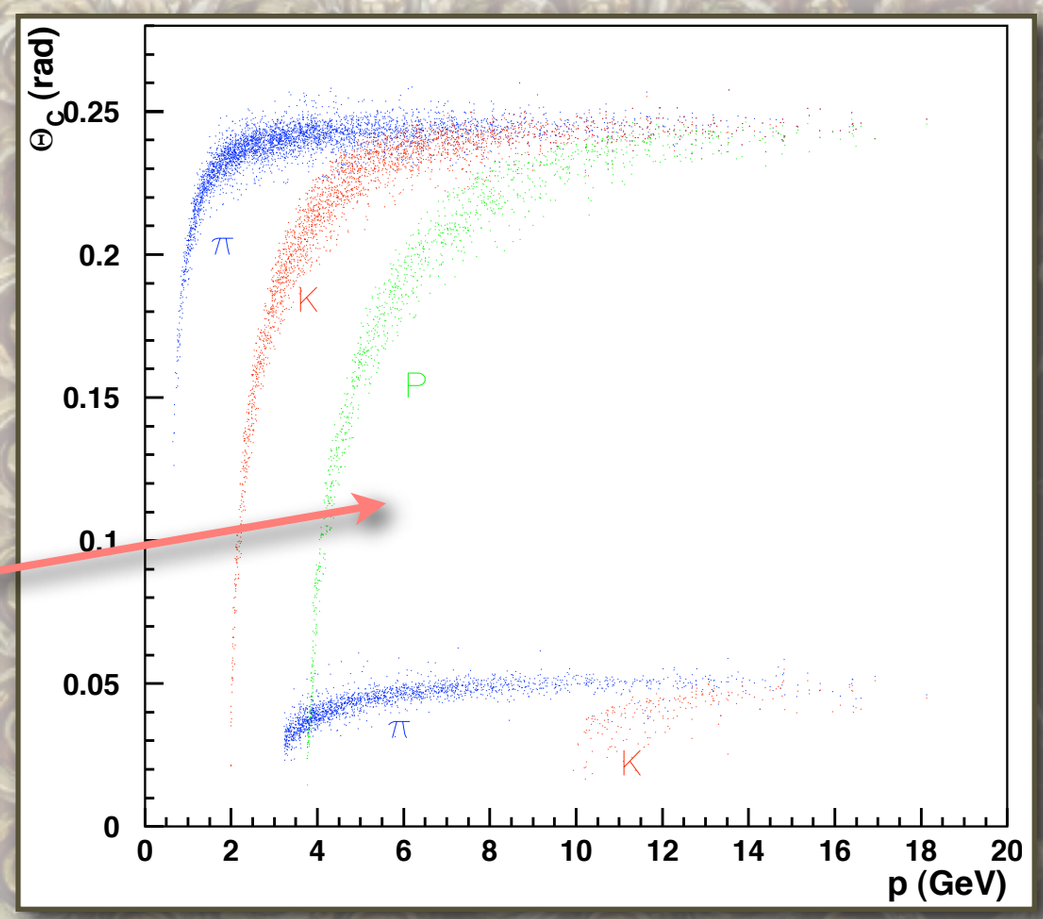
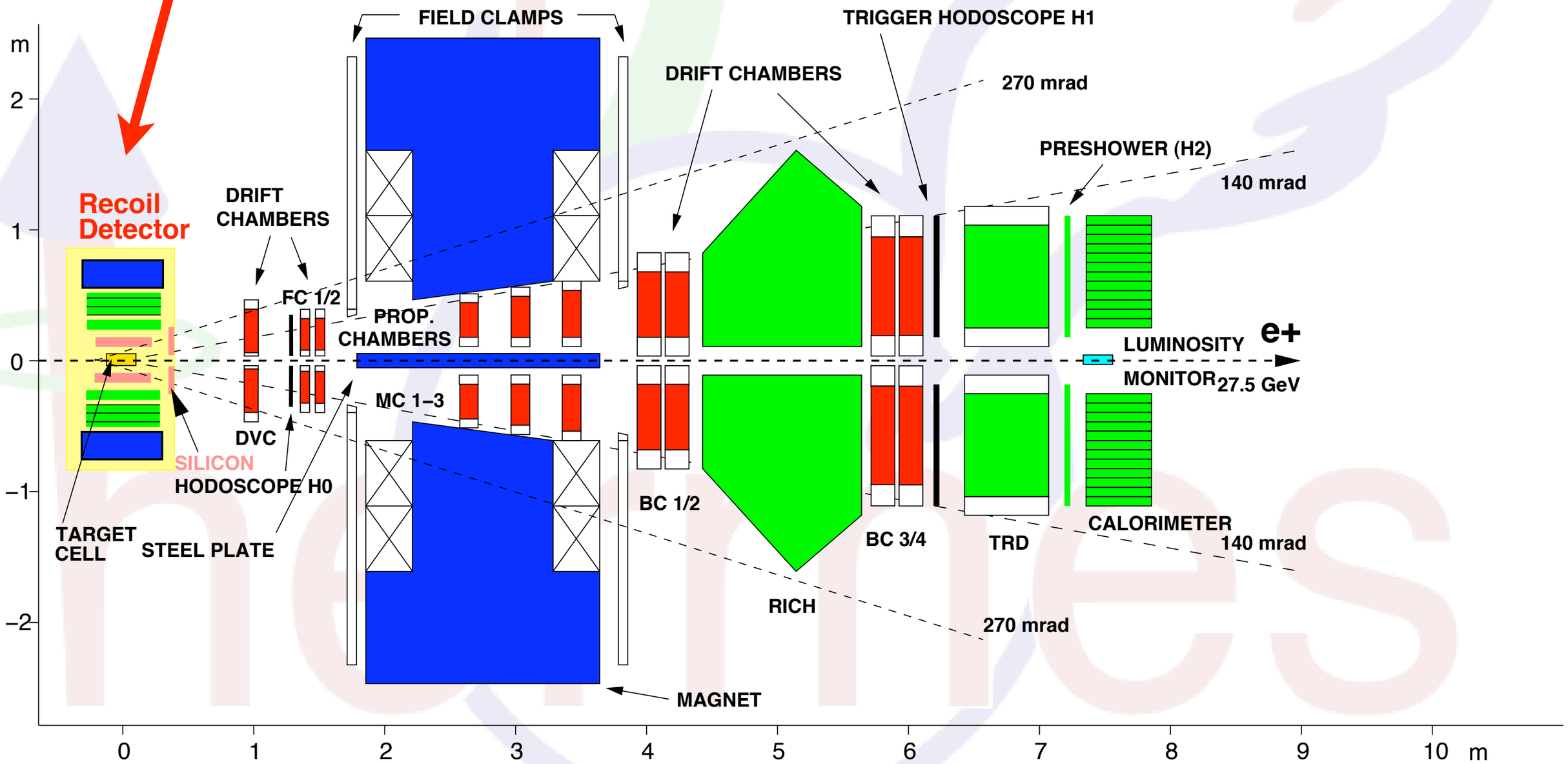


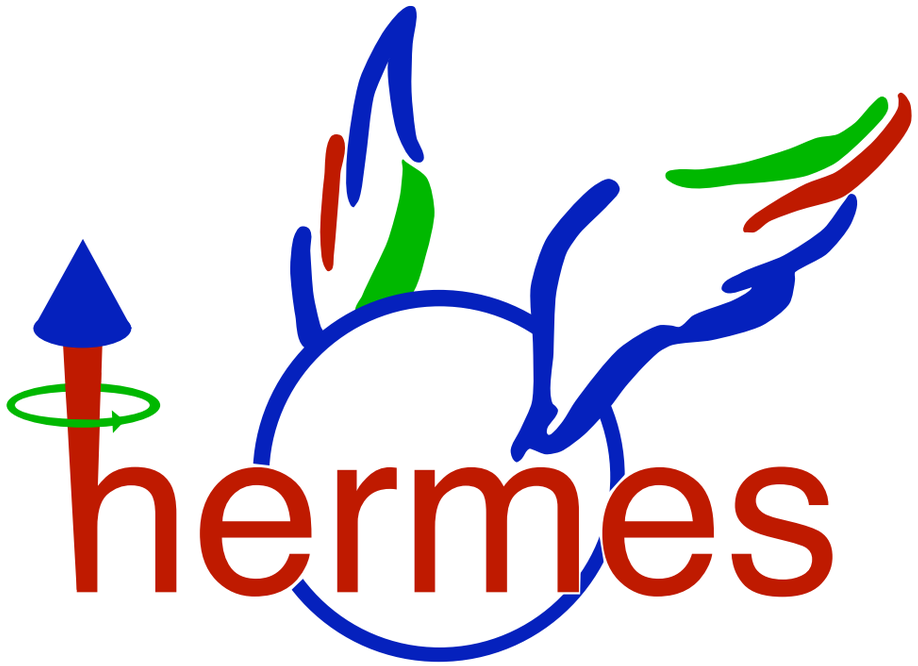
Dual-Radiator RICH hadron ID for momenta 2-15 GeV



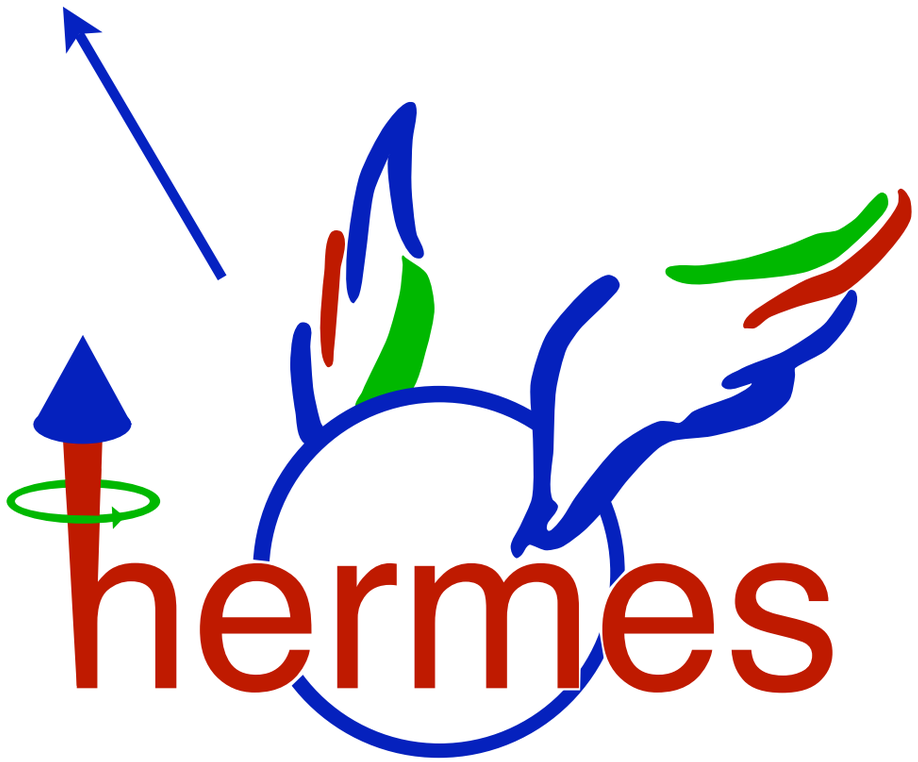
HERMES Detector (2006/07)

detection of
recoiling proton




hermes

Longitudinal-Spin Structure, Hadronization



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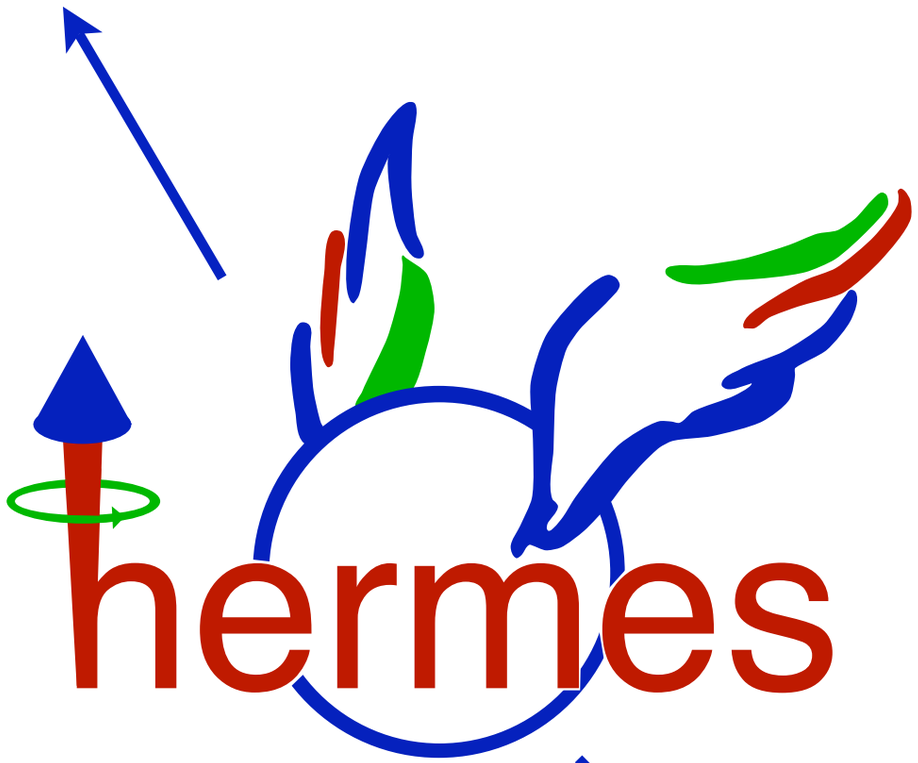
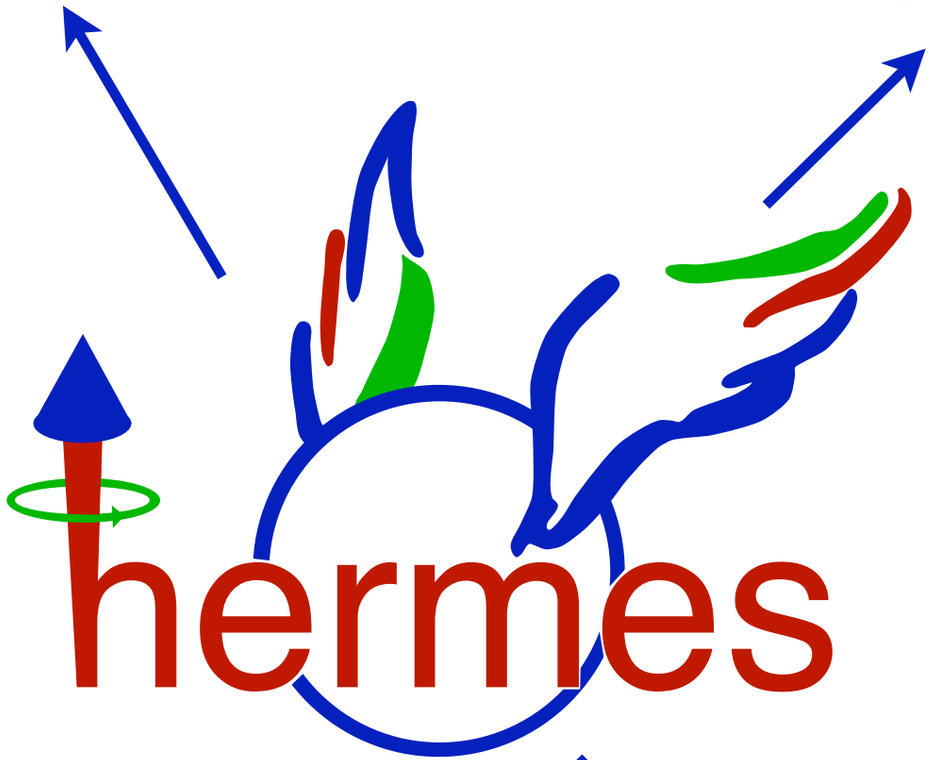


Strange-Baryon Production

Longitudinal-Spin Structure, Hadronization

Transverse-Spin Structure



Transversity TMDs

Strange-Baryon Production

Longitudinal-Spin Structure, Hadronization

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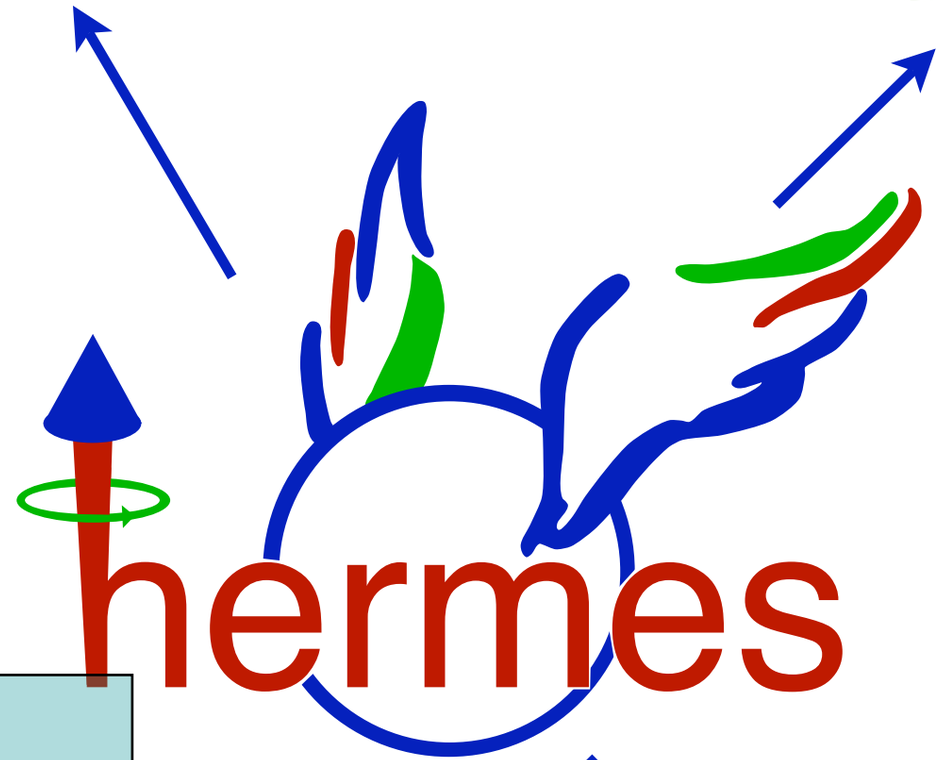
DVCS



Transversity TMDs

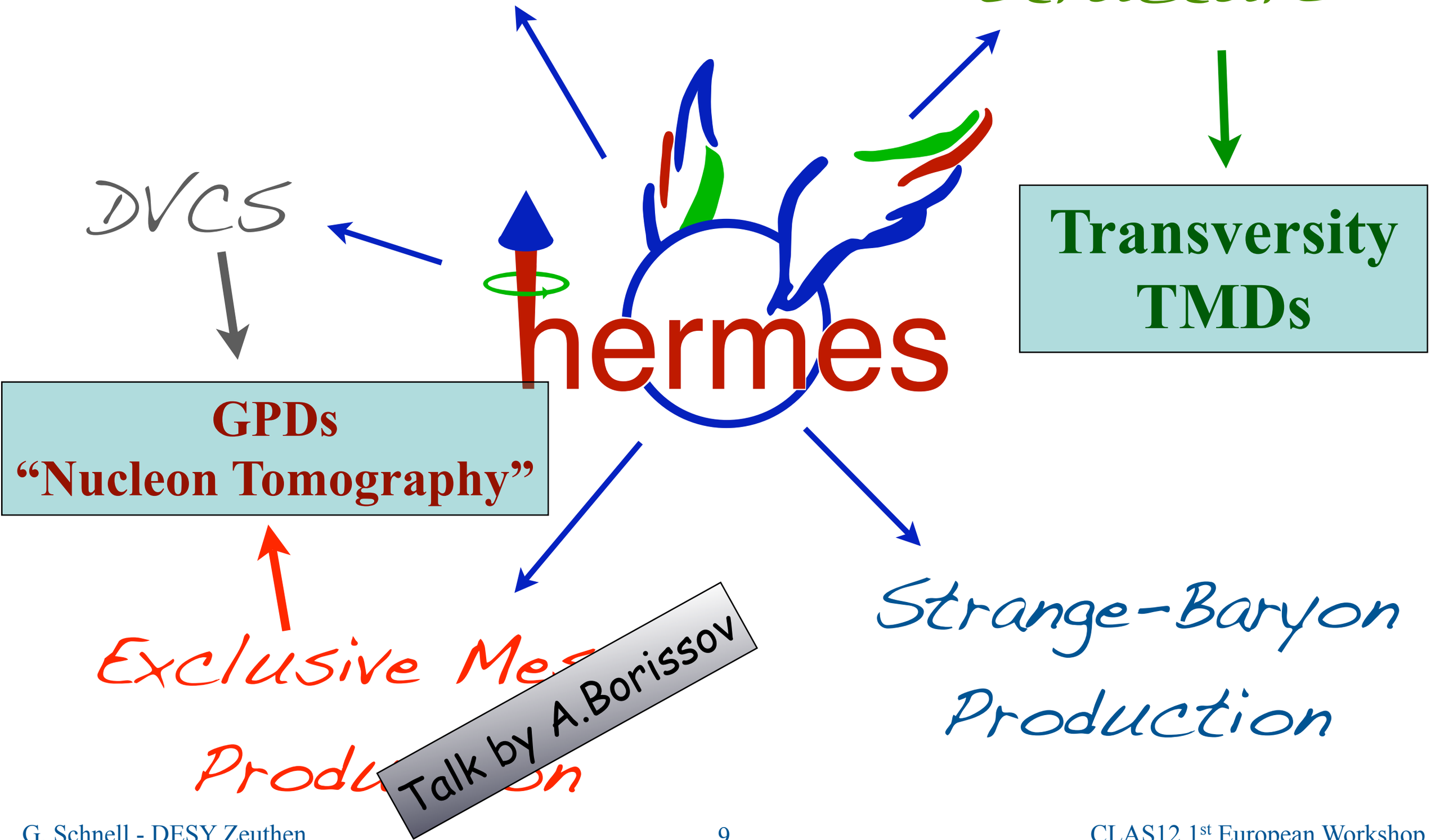
GPDs "Nucleon Tomography"

Exclusive Meson Production

Strange-Baryon Production

Longitudinal-Spin Structure, Hadronization

Transverse-Spin Structure



Transversity TMDs

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Longitudinal-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., $A_{\parallel,d}(x,Q^2)$ and $A_{\parallel,d}^{K^+ + K^-}(x,z,Q^2)$, as well as K⁺+K⁻ multiplicities on deuteron

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

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

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

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

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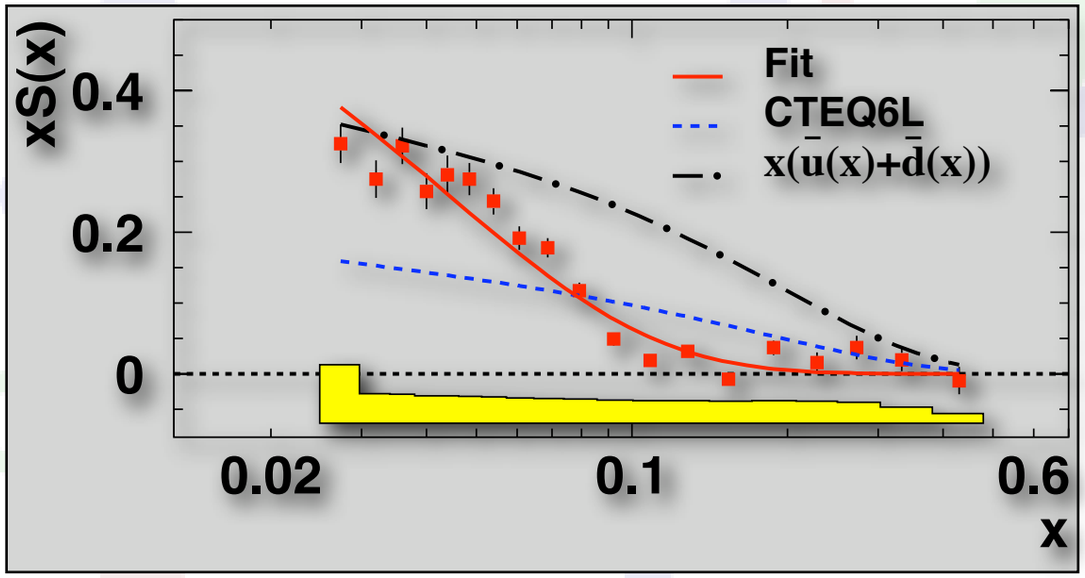

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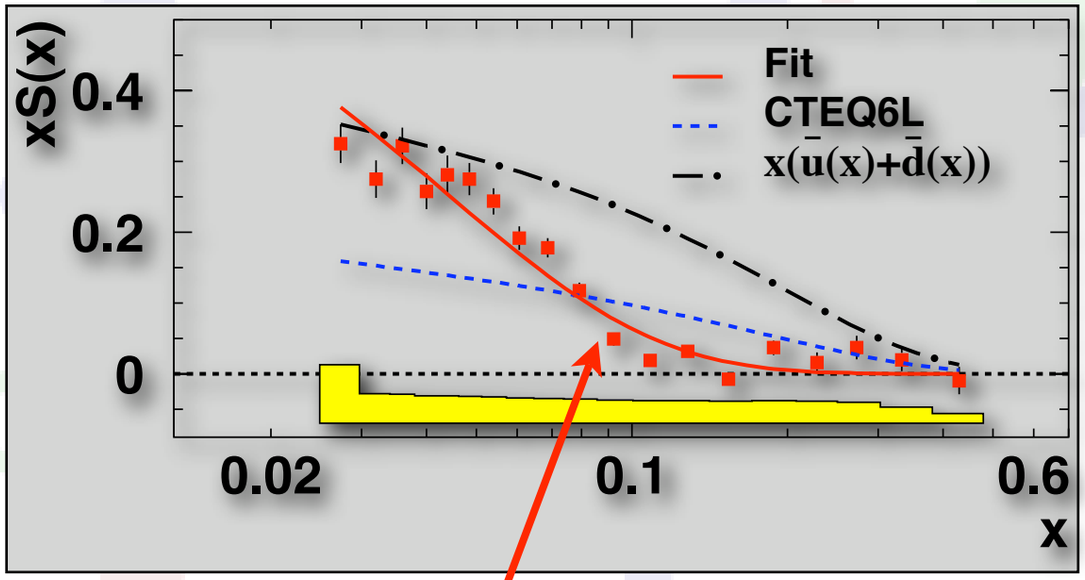

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softer than (maybe) expected

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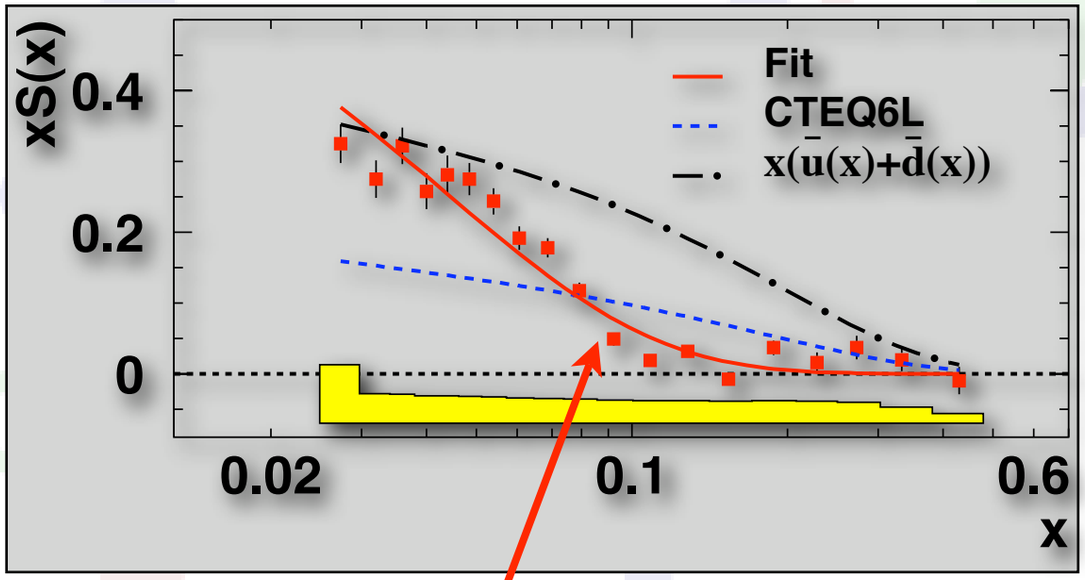

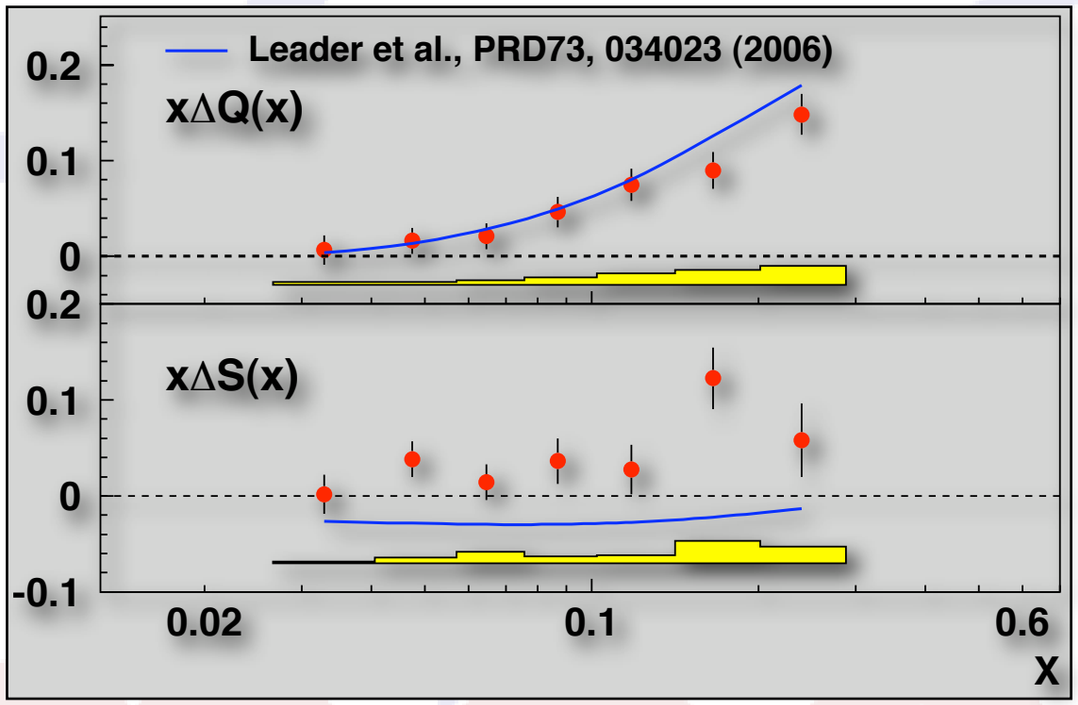

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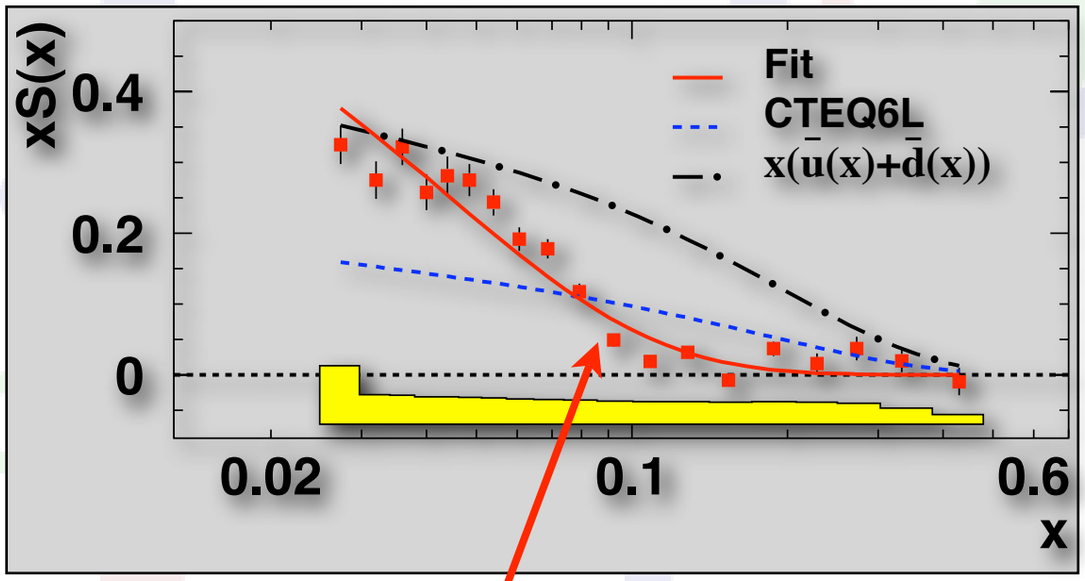

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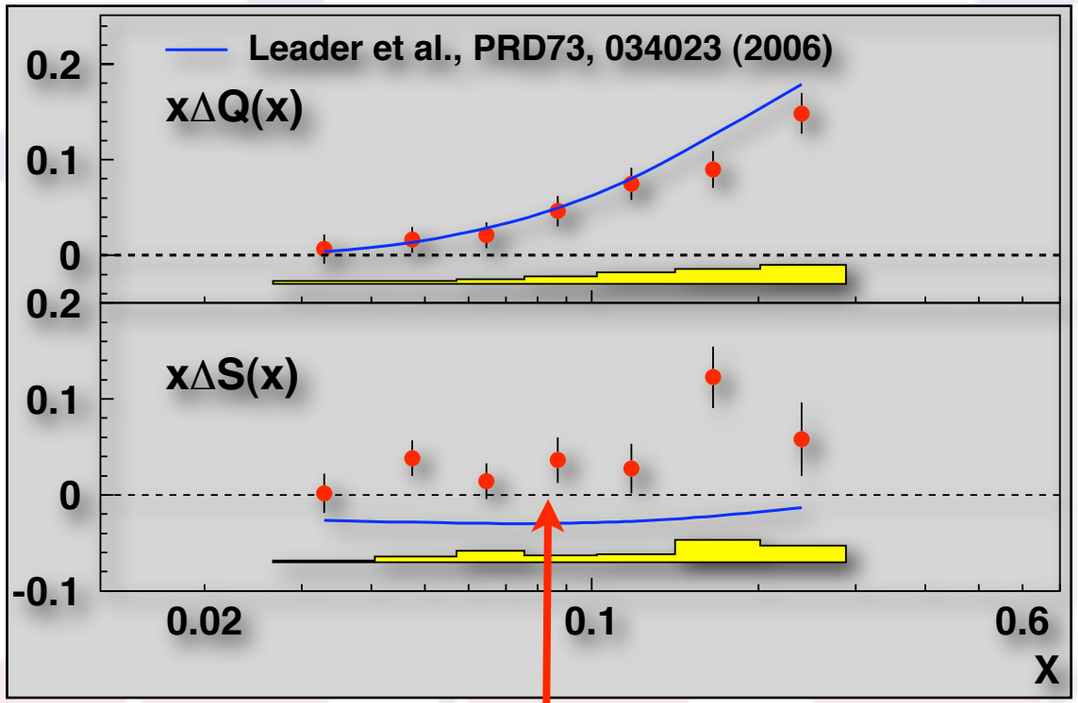
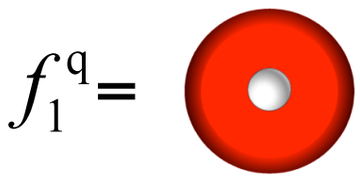


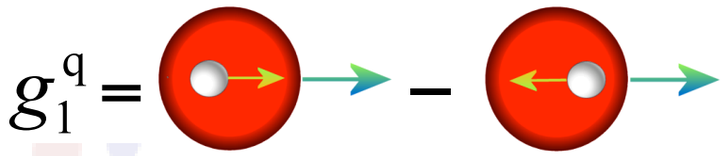
Strange-quark helicity distribution consistent with zero or slightly positive in contrast to inclusive DIS analyses

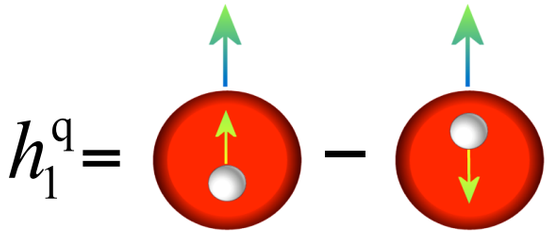
A. Airapetian et al., PLB 666, 446 (2008)

Transverse-Spin/Momentum Effects

Quark Structure of the Nucleon







Unpolarized quarks and nucleons

Longitudinally polarized quarks and nucleons

Transversely polarized quarks and nucleons

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

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

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

$\Rightarrow$ Vector Charge

$\Rightarrow$ Axial Charge

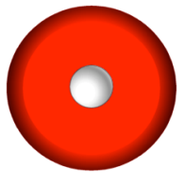
$\Rightarrow$ Tensor Charge

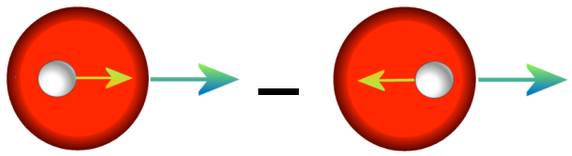
$$\langle PS|\bar{\Psi}\gamma^\mu\Psi|PS\rangle = \int dx(f_1^q(x) - f_1^{\bar{q}}(x))$$

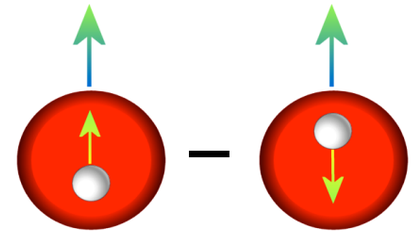
$$\langle PS|\bar{\Psi}\gamma^\mu\gamma_5\Psi|PS\rangle = \int dx(g_1^q(x) + g_1^{\bar{q}}(x))$$

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

Quark Structure of the Nucleon

$f_1^q =$ 

$g_1^q =$ 

$h_1^q =$ 

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Chiral-odd!

$\Rightarrow$ Vector Charge

$\Rightarrow$ Axial Charge

$\Rightarrow$ Tens… harge

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

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

Transversity Measurement

How can one measure transversity?

Need another chiral-odd object!

$\Rightarrow$ Semi-Inclusive DIS

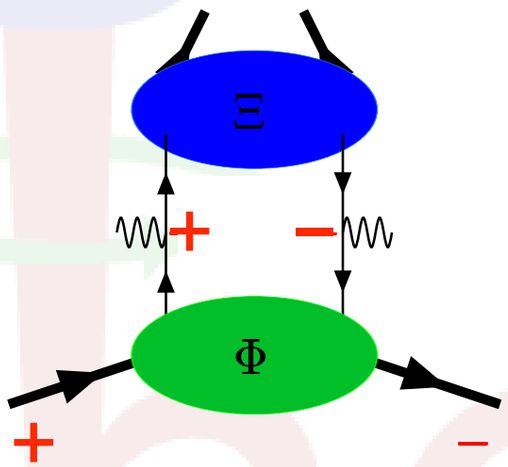
$$\sigma^{ep\to ehX} = \sum_q h_1^q \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}$$

$\Downarrow$ $\Downarrow$

chiral-odd **chiral-odd**

DF FF

CHIRAL EVEN



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

2-Hadron Fragmentation

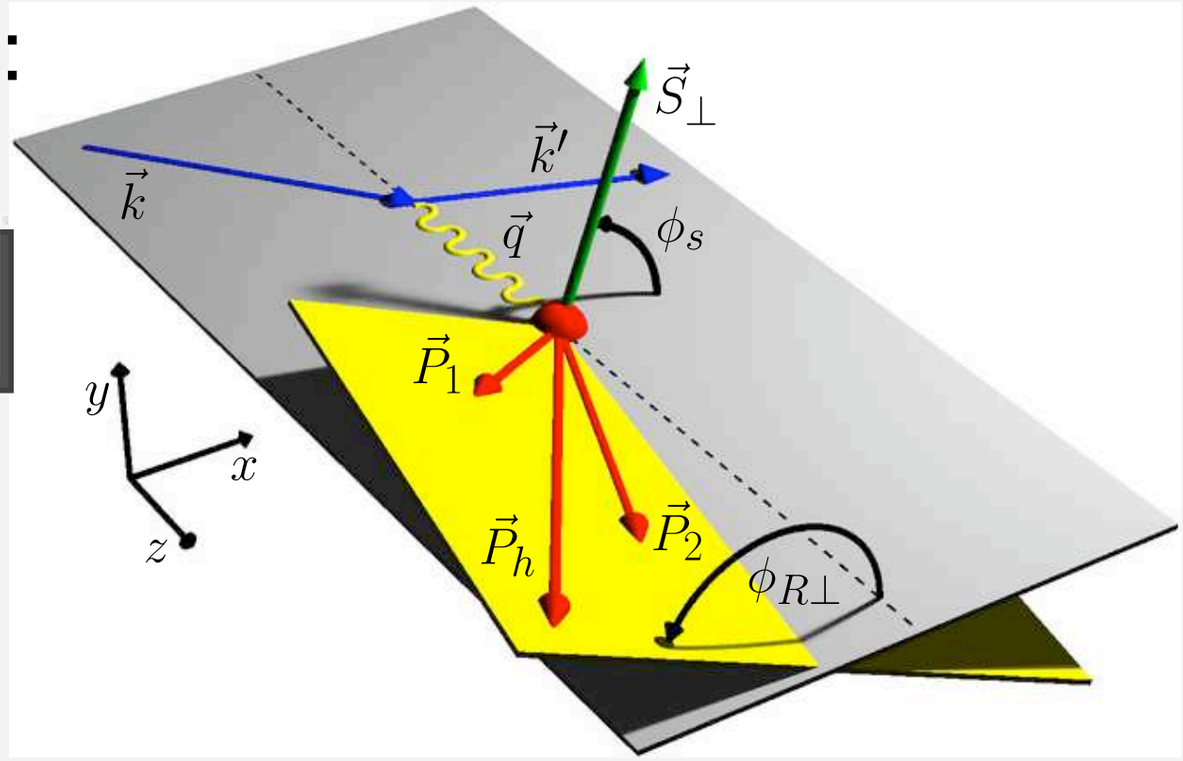
polarized 2-hadron cross section:

(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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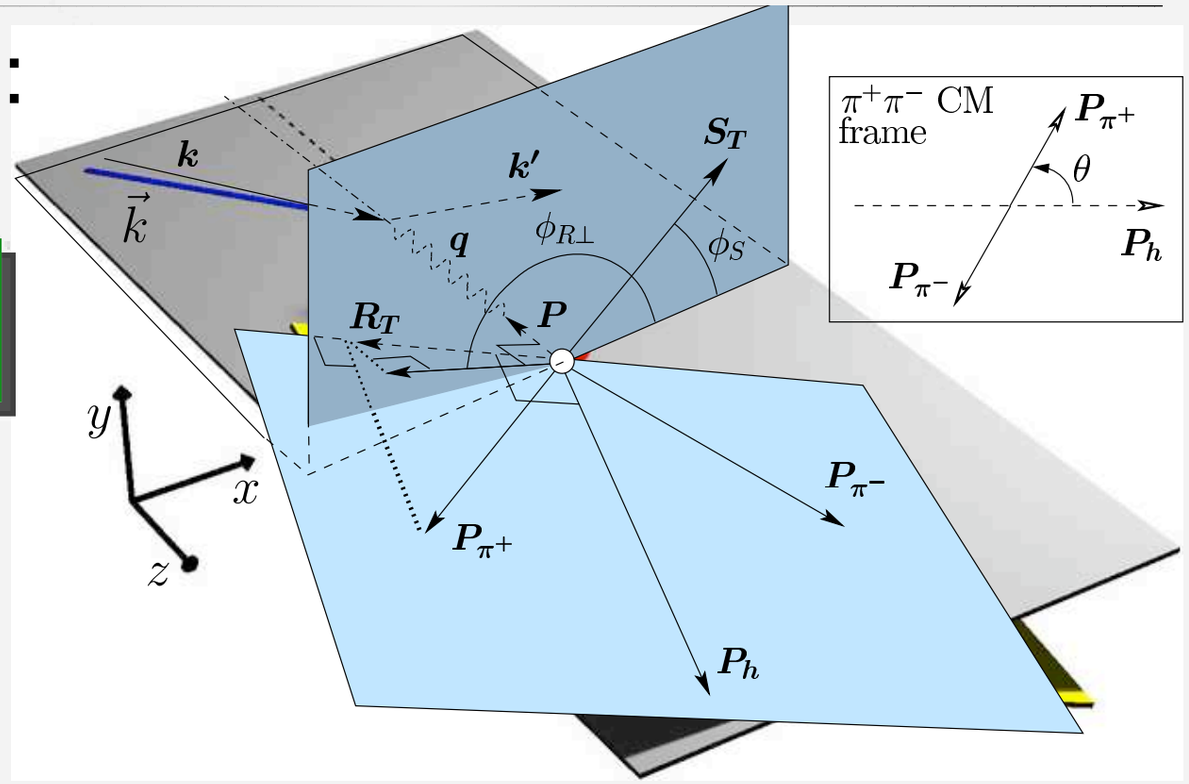

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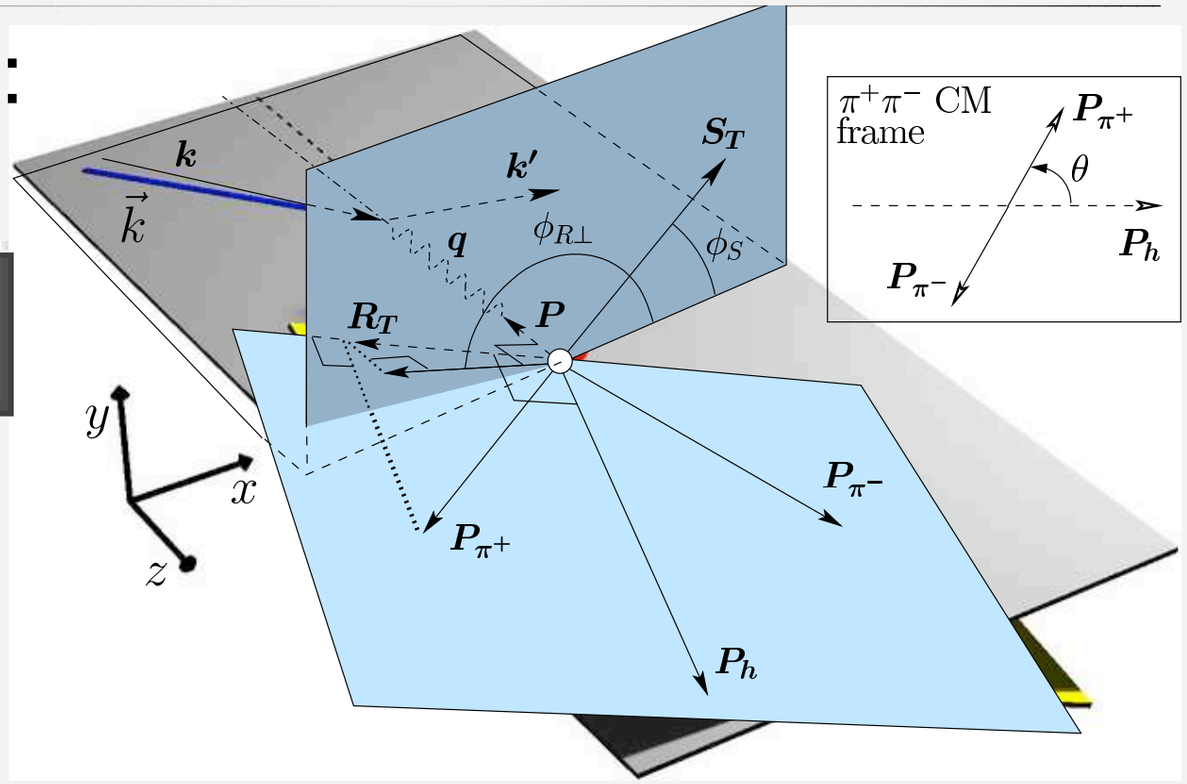

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  ⇒ integration over transverse momentum of hadron pair simplifies factorization and Q^2 evolution

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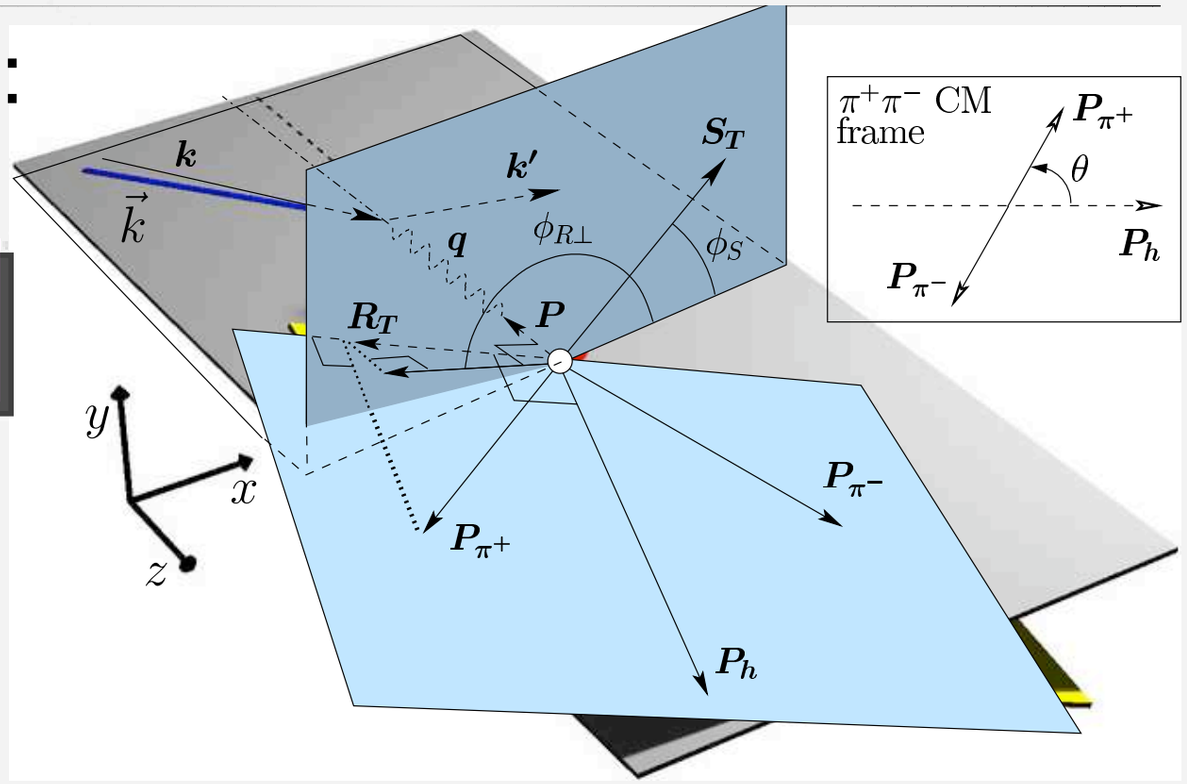

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- however, cross section becomes quite complex (differential in 9 variables)

Model for Dihadron Fragmentation

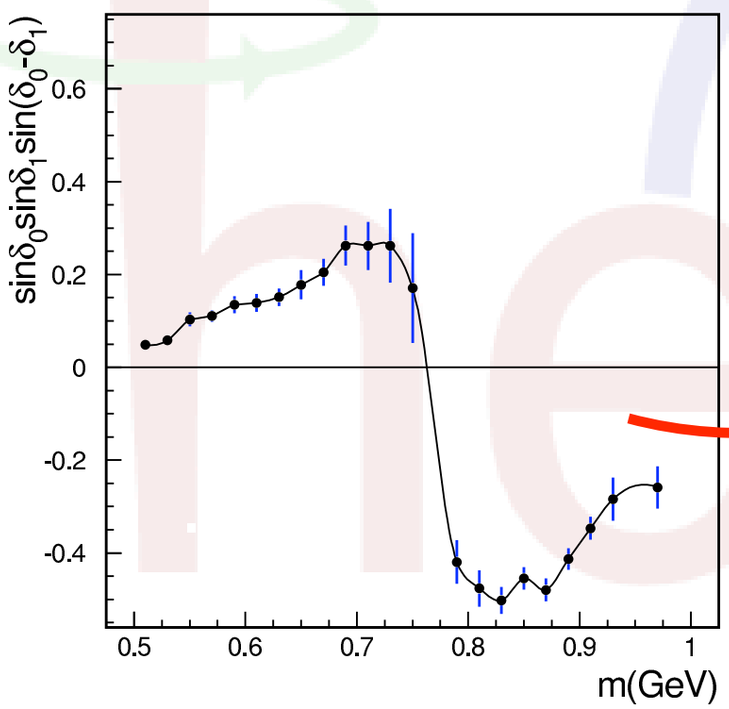
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin\theta h_1 H_1^{\sphericalangle}$$

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**]:

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

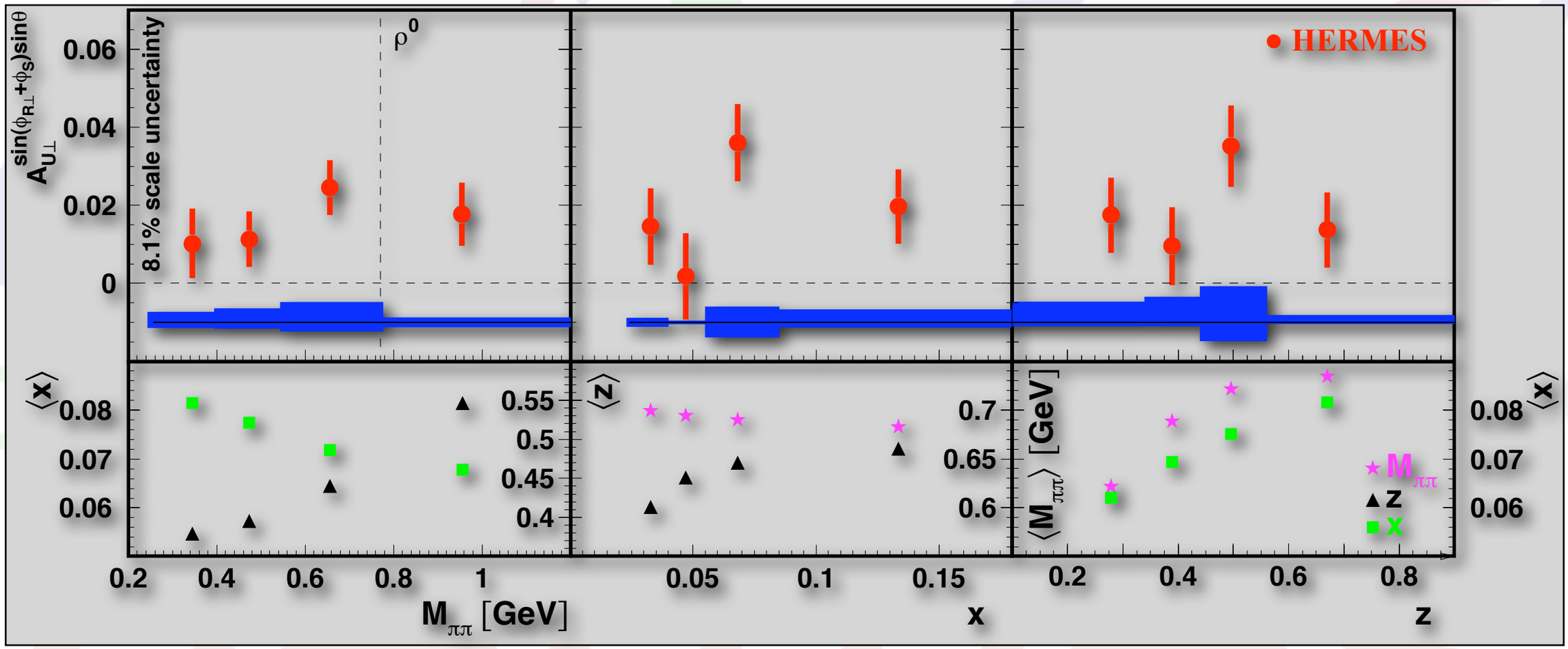
δ_0 (δ_1) $\rightarrow$ S(P)-wave phase shifts

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

$\Rightarrow$ 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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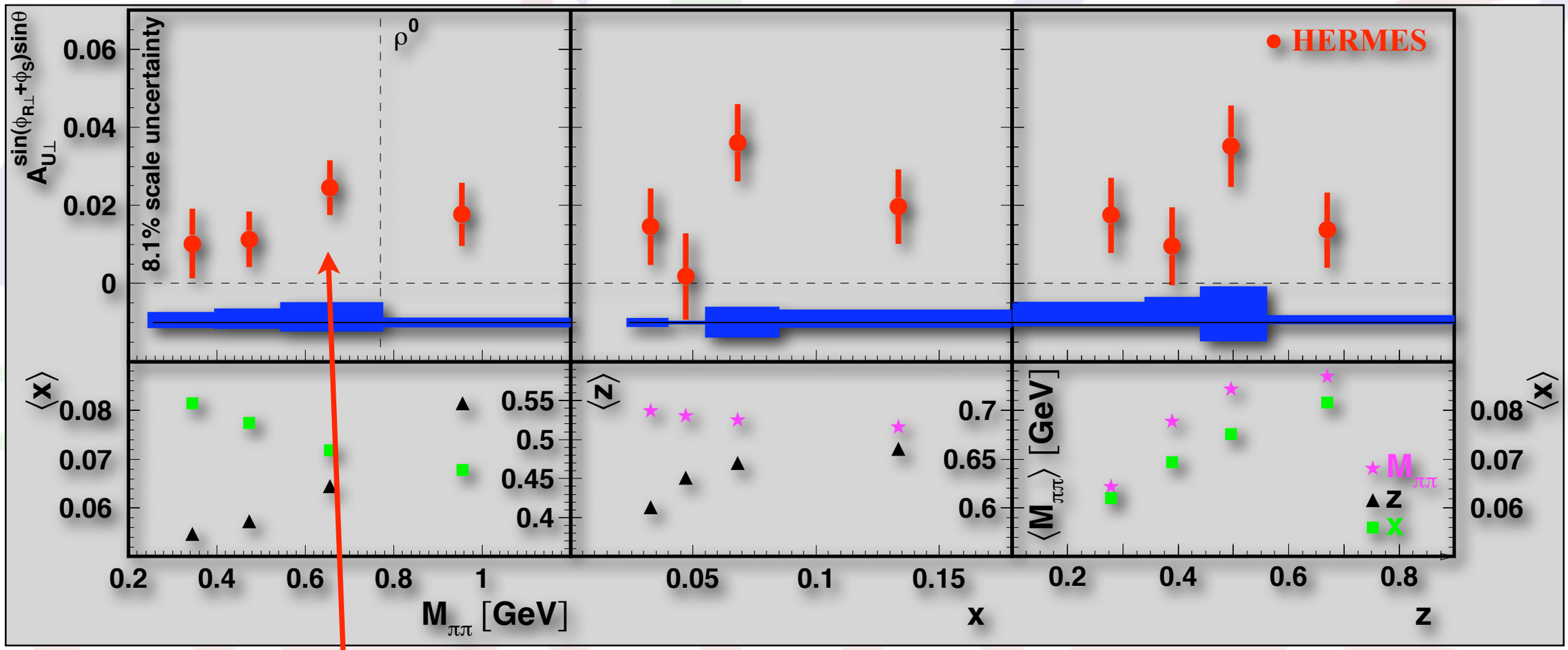

First evidence for (transversity and) naive-T-odd, chiral-odd, spin-dependent dihadron fragmentation function

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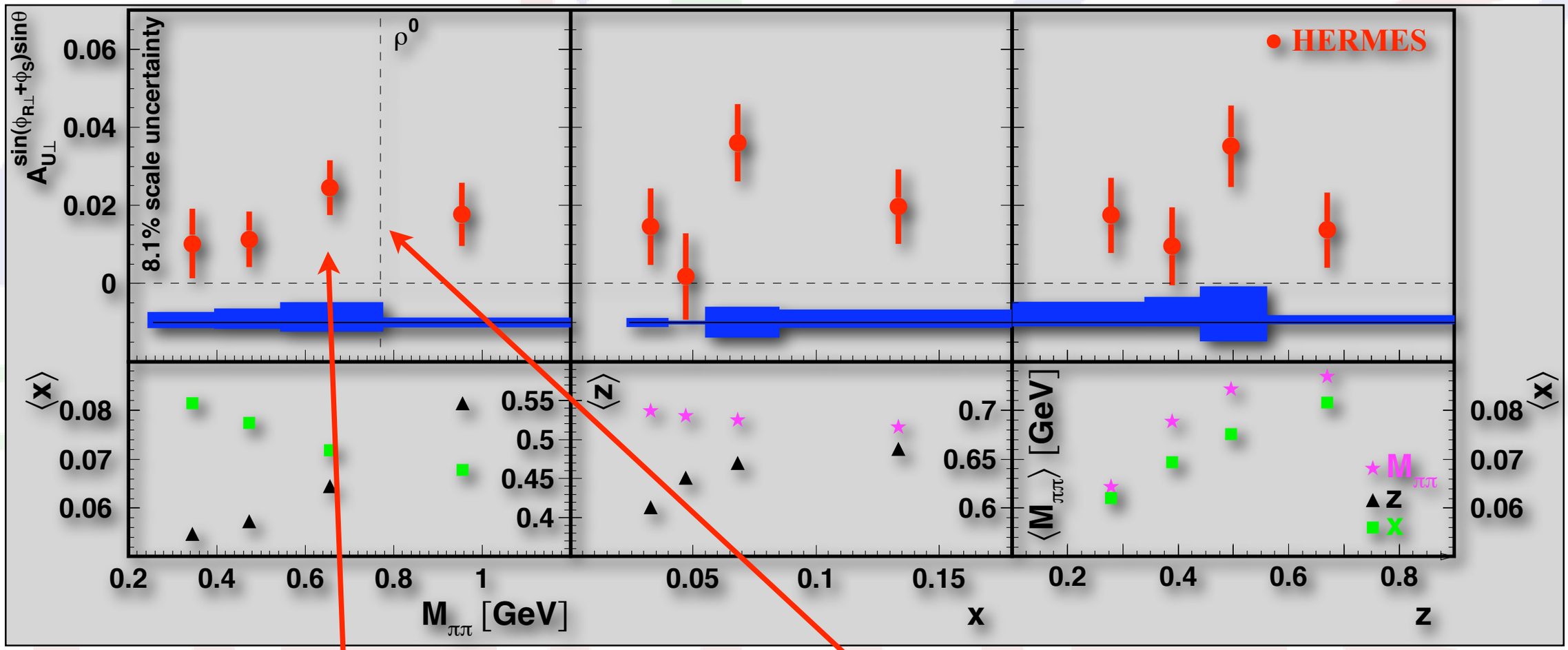


First evidence for (transversity and) naive-T-odd, chiral-odd, spin-dependent dihadron fragmentation function

No sign change as (maybe) expected around ρ^0 mass Consistent in shape with later models (Radici et al.)

1-Hadron Production (ep→ehX)

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

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

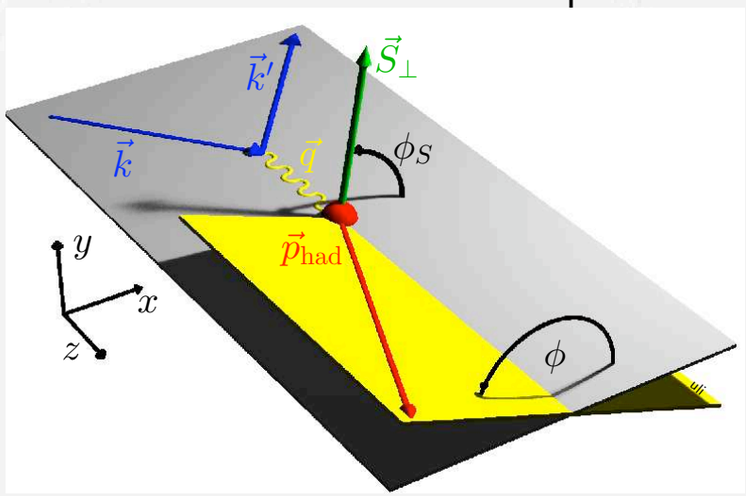
$$+S_T \left\{ \sin(\phi-\phi_S)\, d\sigma^8_{UT} + \sin(\phi+\phi_S)\, d\sigma^9_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{10}_{UT} \frac{1}{Q} \right.$$

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

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

σ_{XY}

Beam Target Polarization



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

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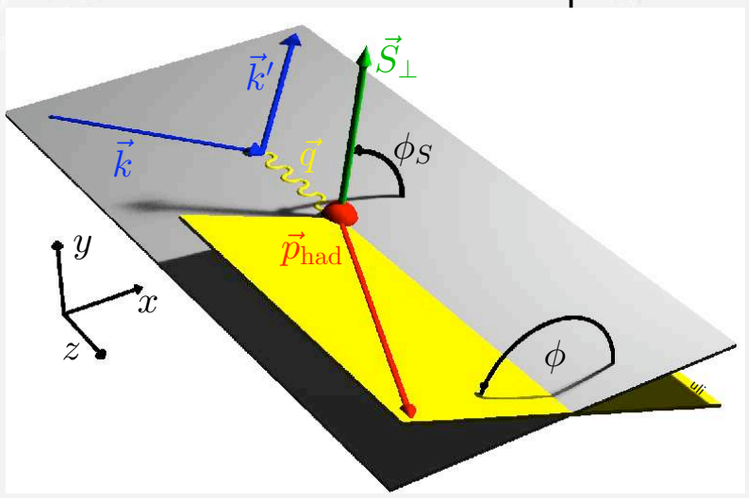
$$+S_T \left\{ \sin(\phi - \phi_S)\, d\sigma^8_{UT} + \sin(\phi + \phi_S)\, d\sigma^9_{UT} + \sin(3\phi - \phi_S)\, d\sigma^{10}_{UT} \frac{1}{Q} \right.$$

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

$$+\lambda_e \left[\cos(\phi$$

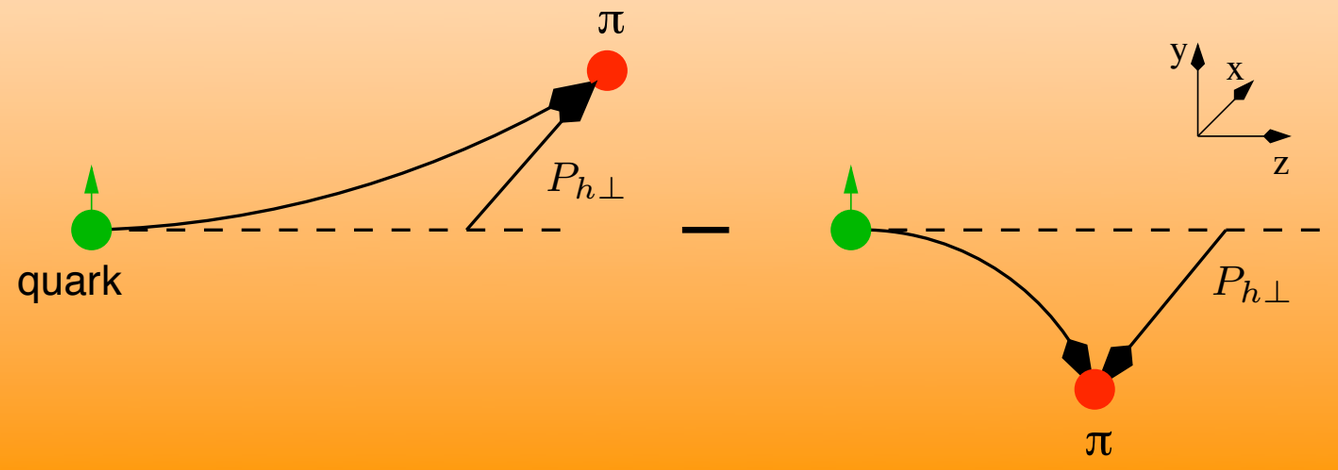
σ_{XY}

Beam Target Polarization



Collins Effect:

sensitive to quark transverse spin



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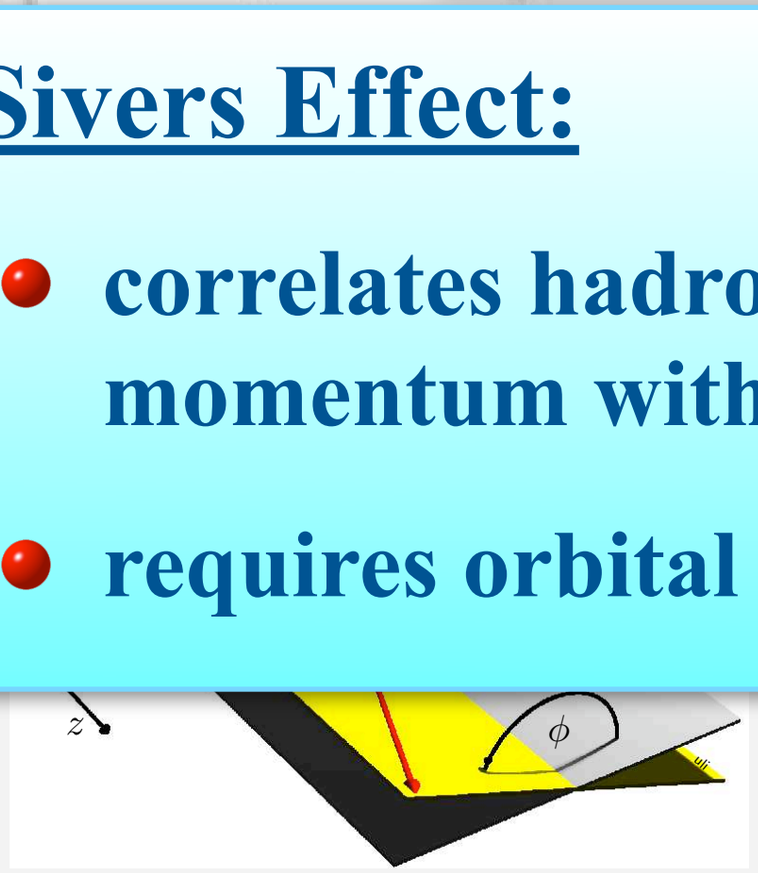
$$\left. \ldots + d\sigma^{12}_{UT} \right)$$

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

Sivers Effect:

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



Phys. B 461 (1996) 197

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σ_{XY}

Beam Target Polarization

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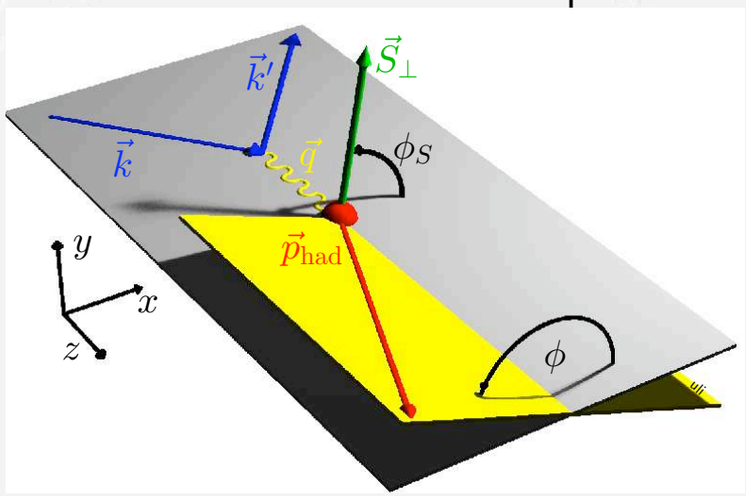

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Boer-Mulders Effect:

transversity in unpolarized nucleons

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$$\sin(3\phi - \phi_S)\, d\sigma^{10}_{UT}\, \frac{1}{Q}$$

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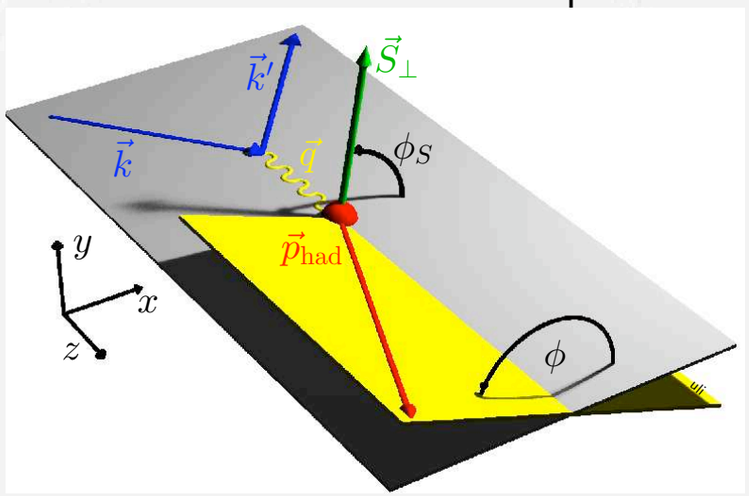

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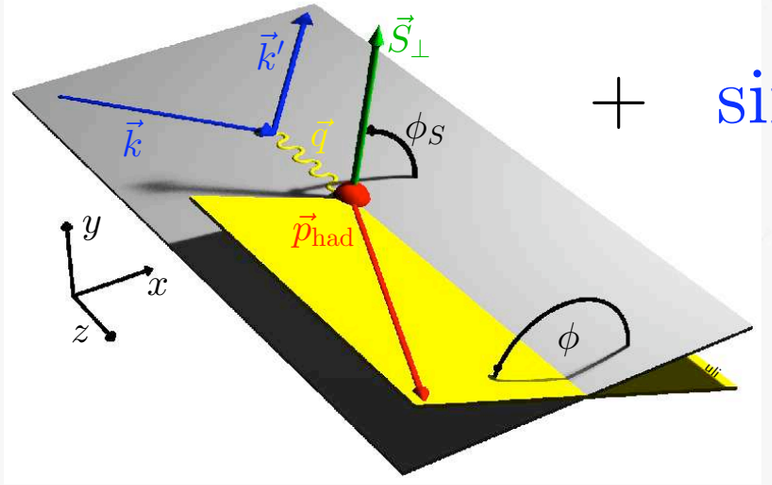
Measuring Azimuthal SSA

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

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



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

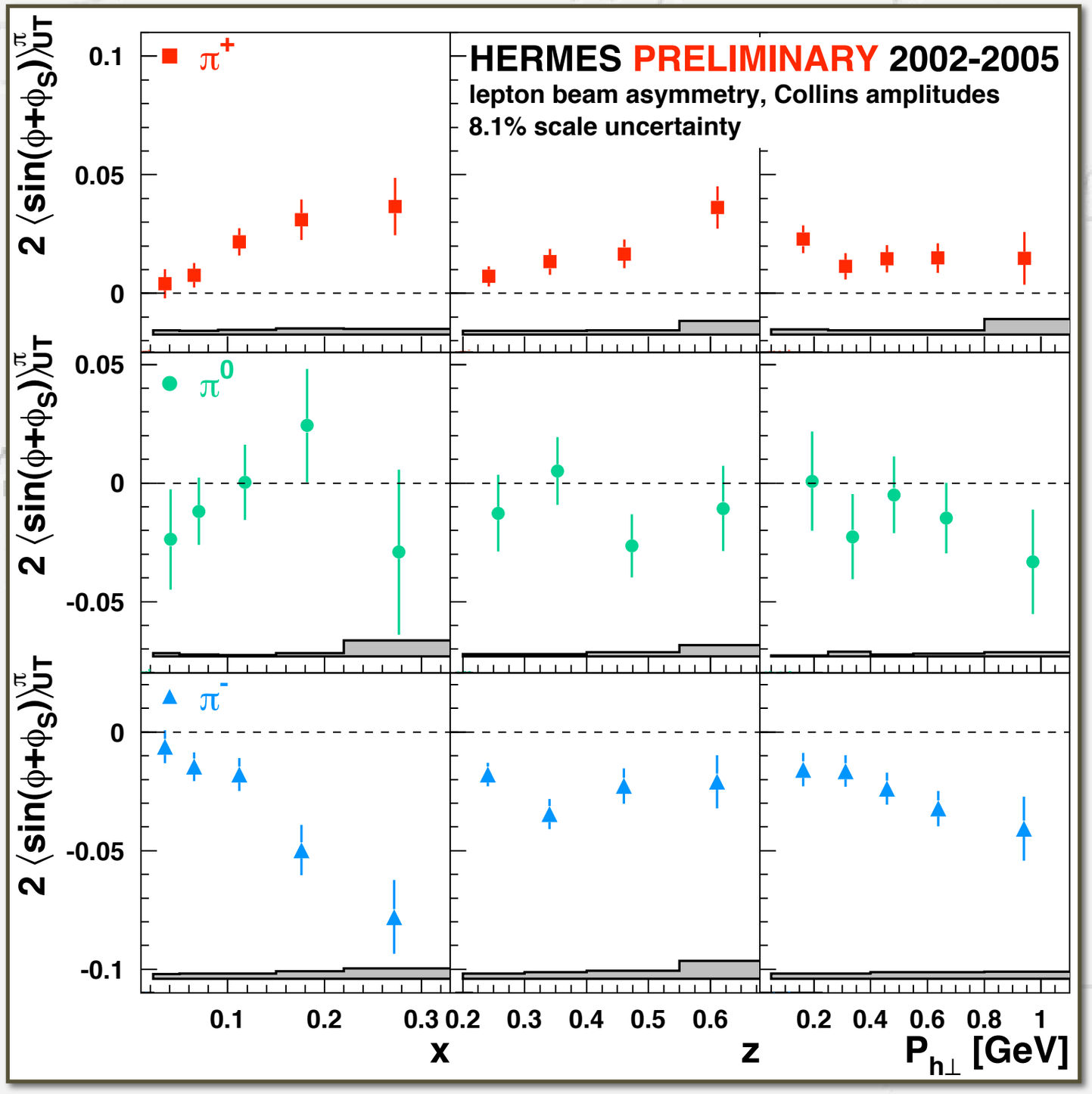
$$+ \cdots$$

$\mathcal{I}[\ldots]$: **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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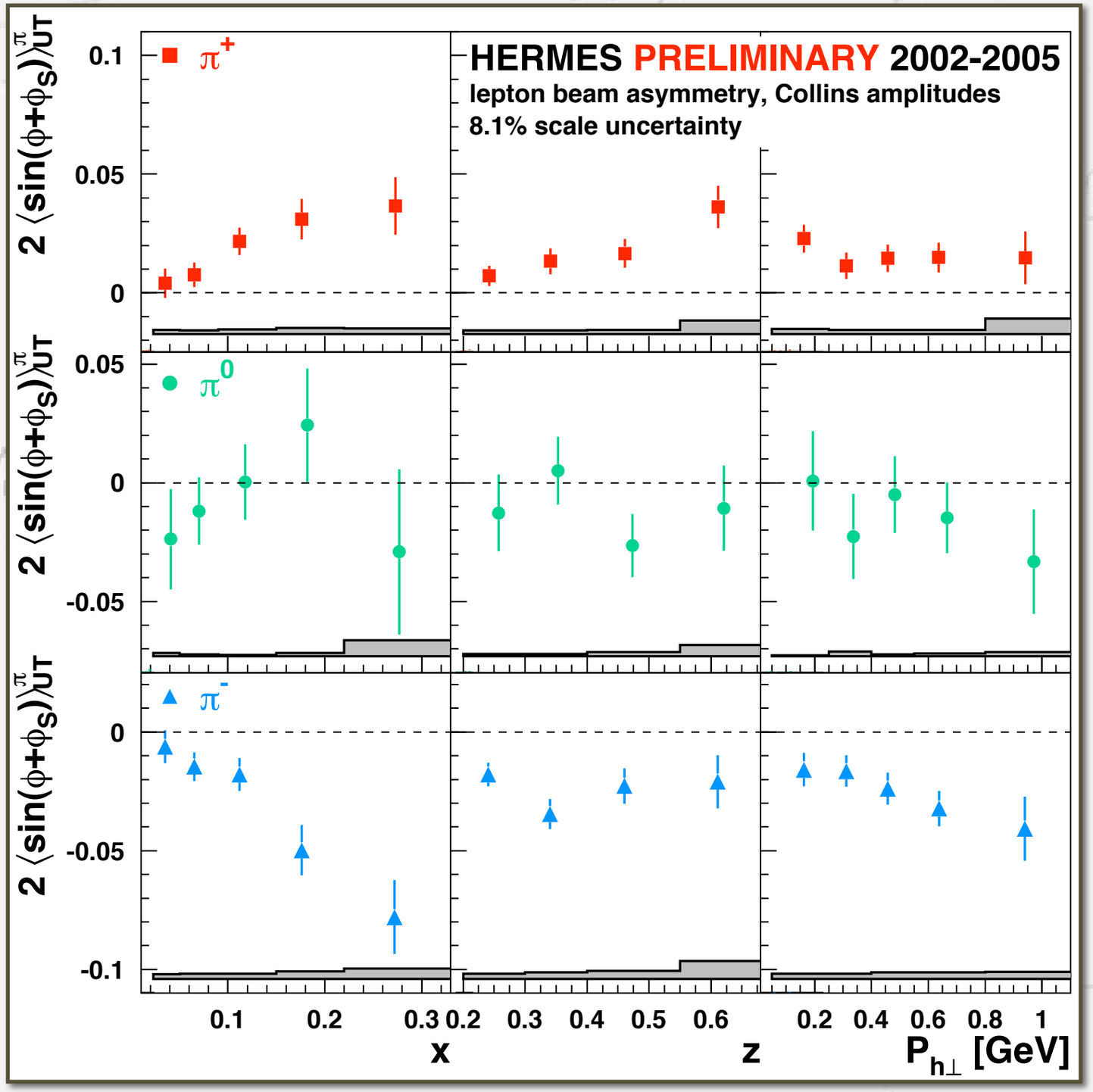

☑ non-zero Collins effect observed!

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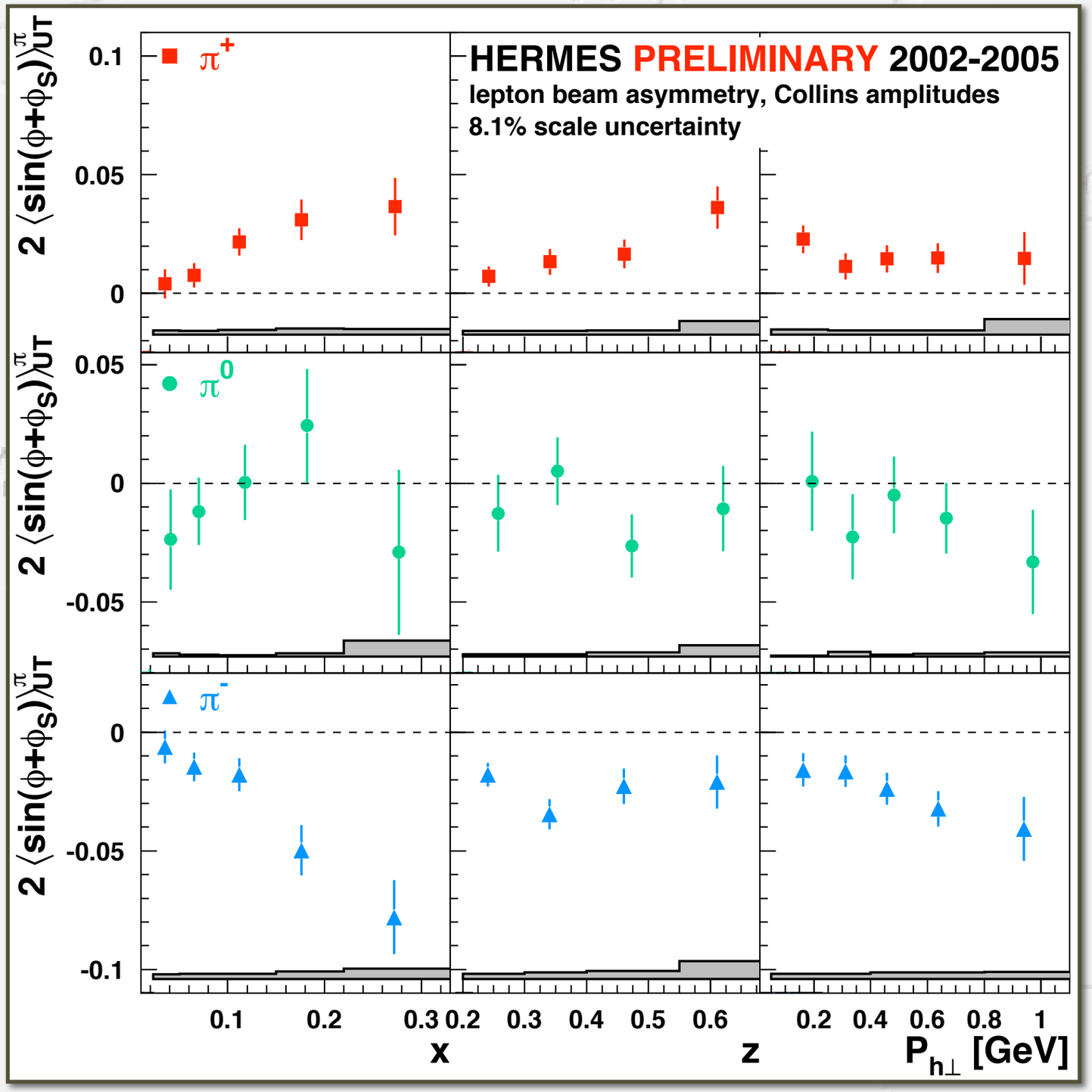
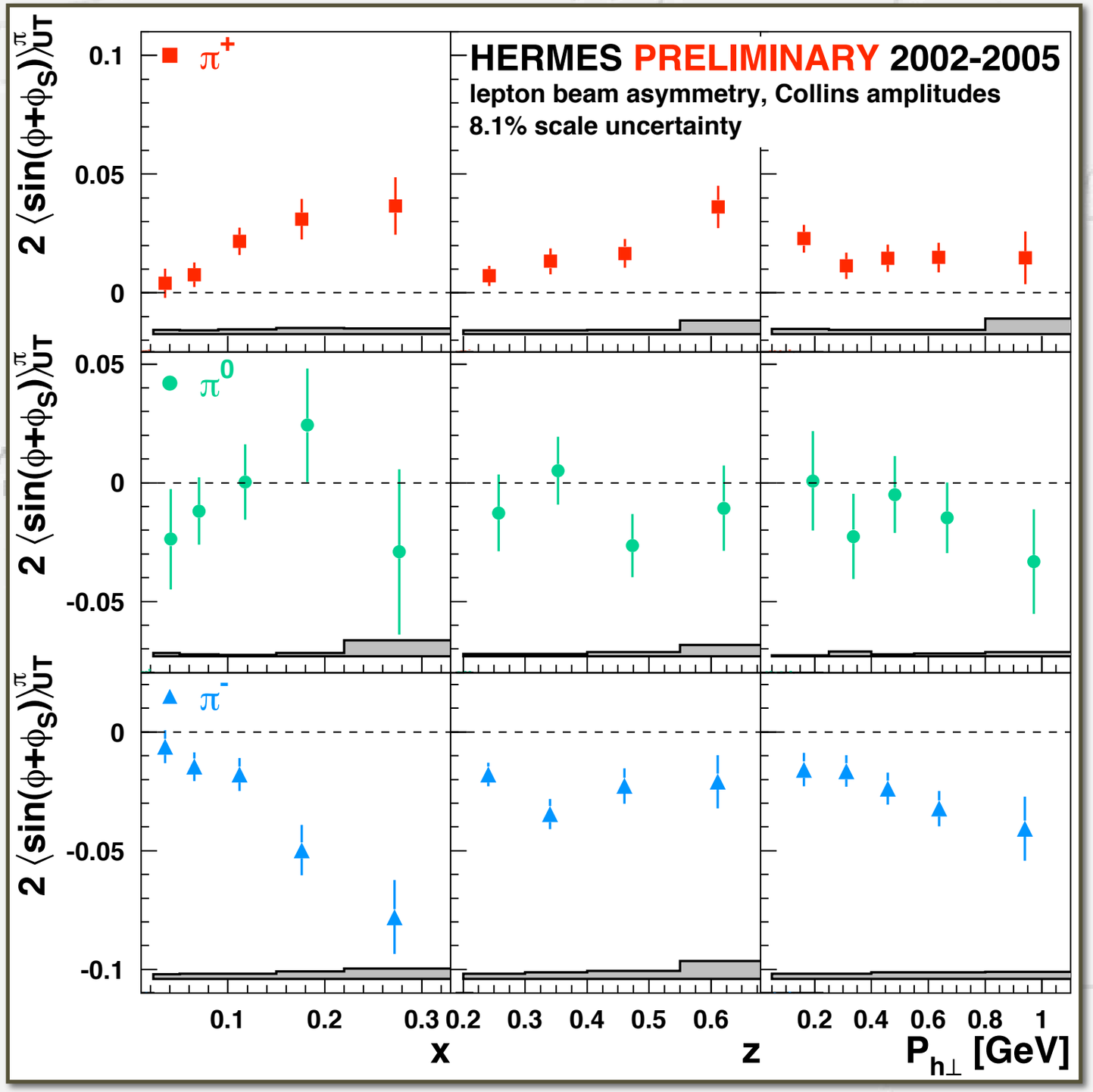


☑ non-zero Collins effect observed!

☑ both Collins FF and transversity sizeable

The HERMES Collins Results

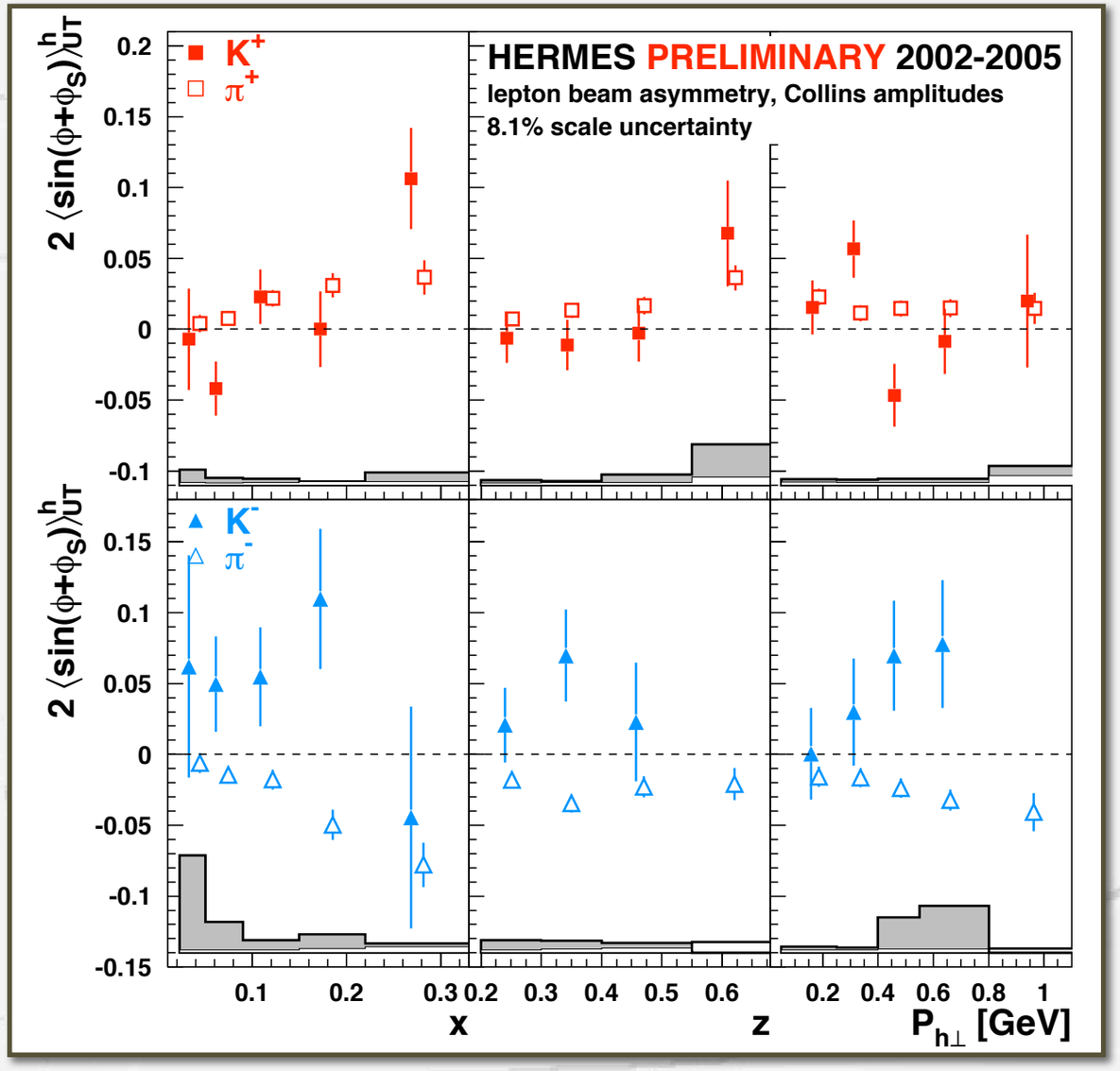


- published† results **confirmed** with much higher statistical precission
- overall scale uncertainty of 8.1%
- positive for π^+ and negative for π^- as maybe expected ($\delta u \equiv h_1^u > 0$ maybe expected ($\delta d \equiv h_1^d < 0$)
- unexpected large π^- asymmetry
  $\Rightarrow$ role of disfavored Collins FF
  most likely: $H_1^{\perp,disf} \approx -H_1^{\perp,fav}$
- isospin symmetry among charged and neutral pions fulfilled

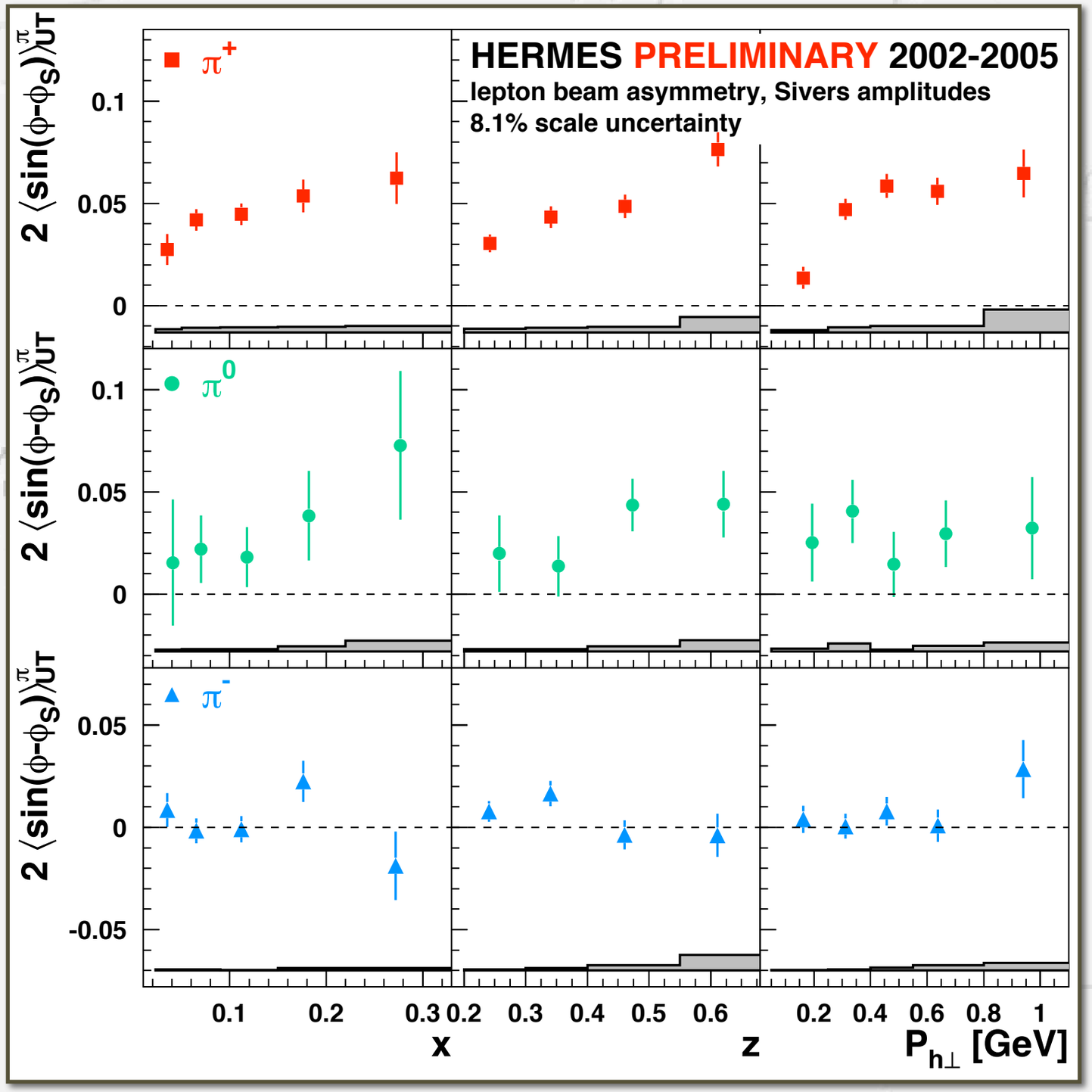
† [*A. Airapetian et al*, Phys. Rev. Lett. 94 (2005) 012002]

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



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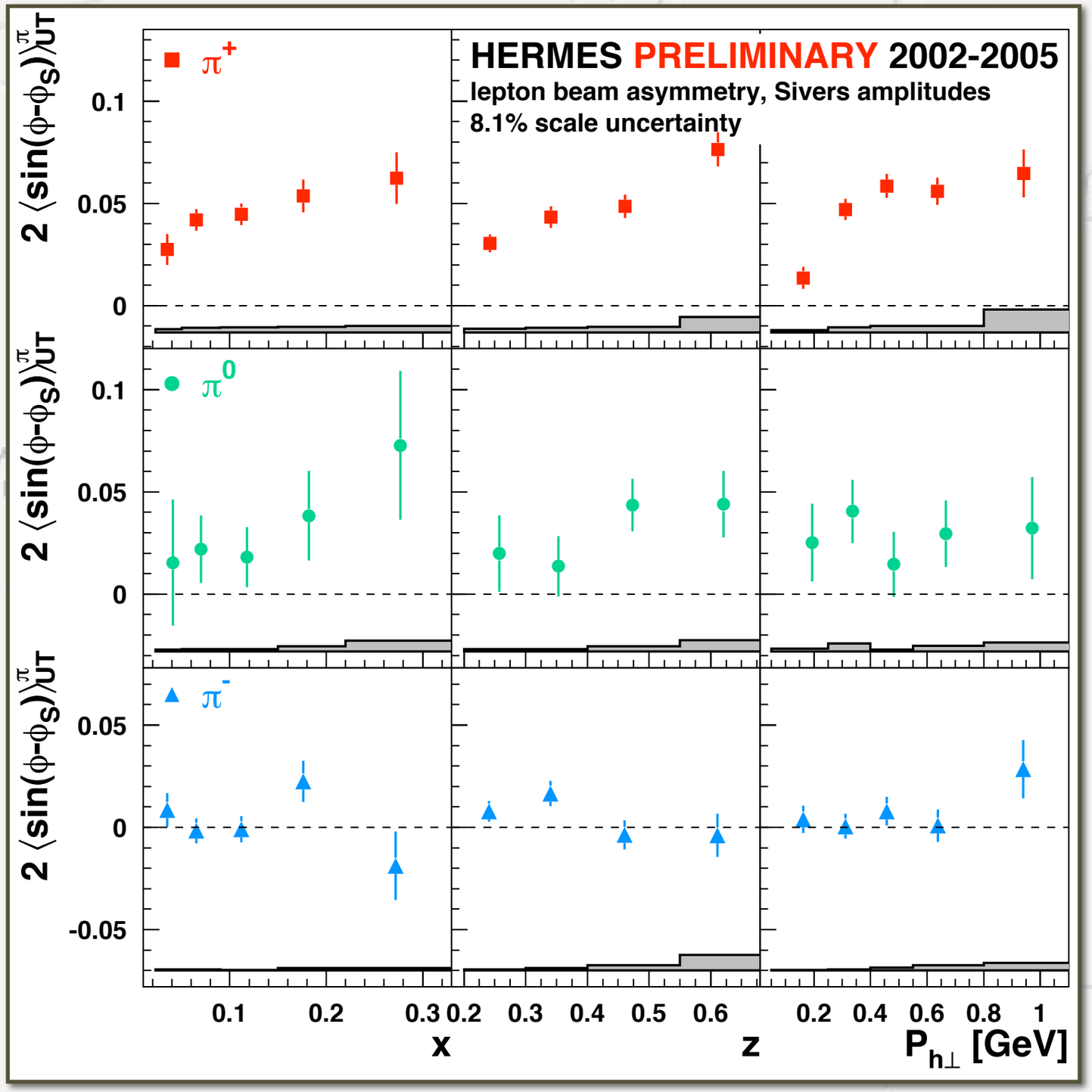

☑ first observation of T-odd Sivers effect in SIDIS!

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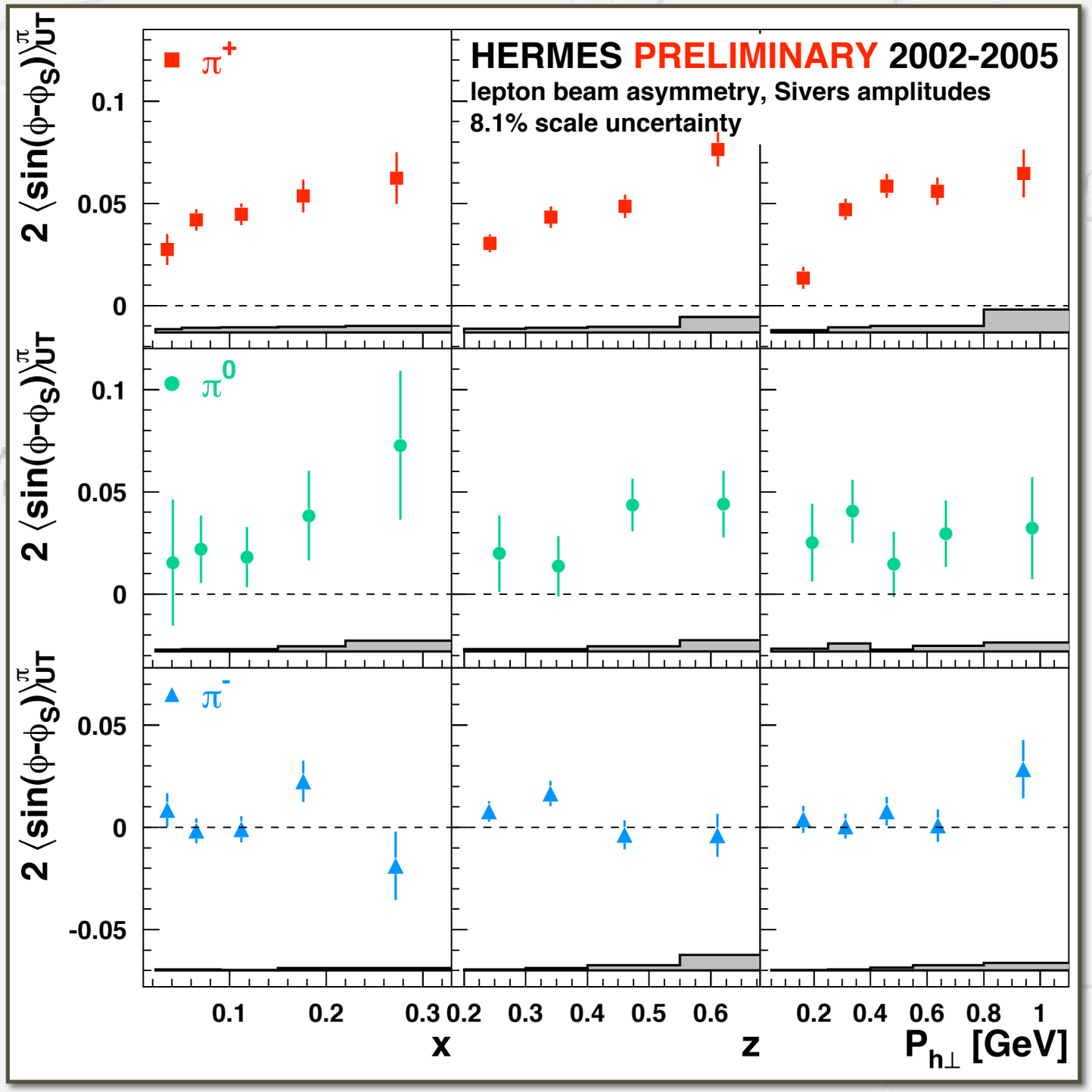
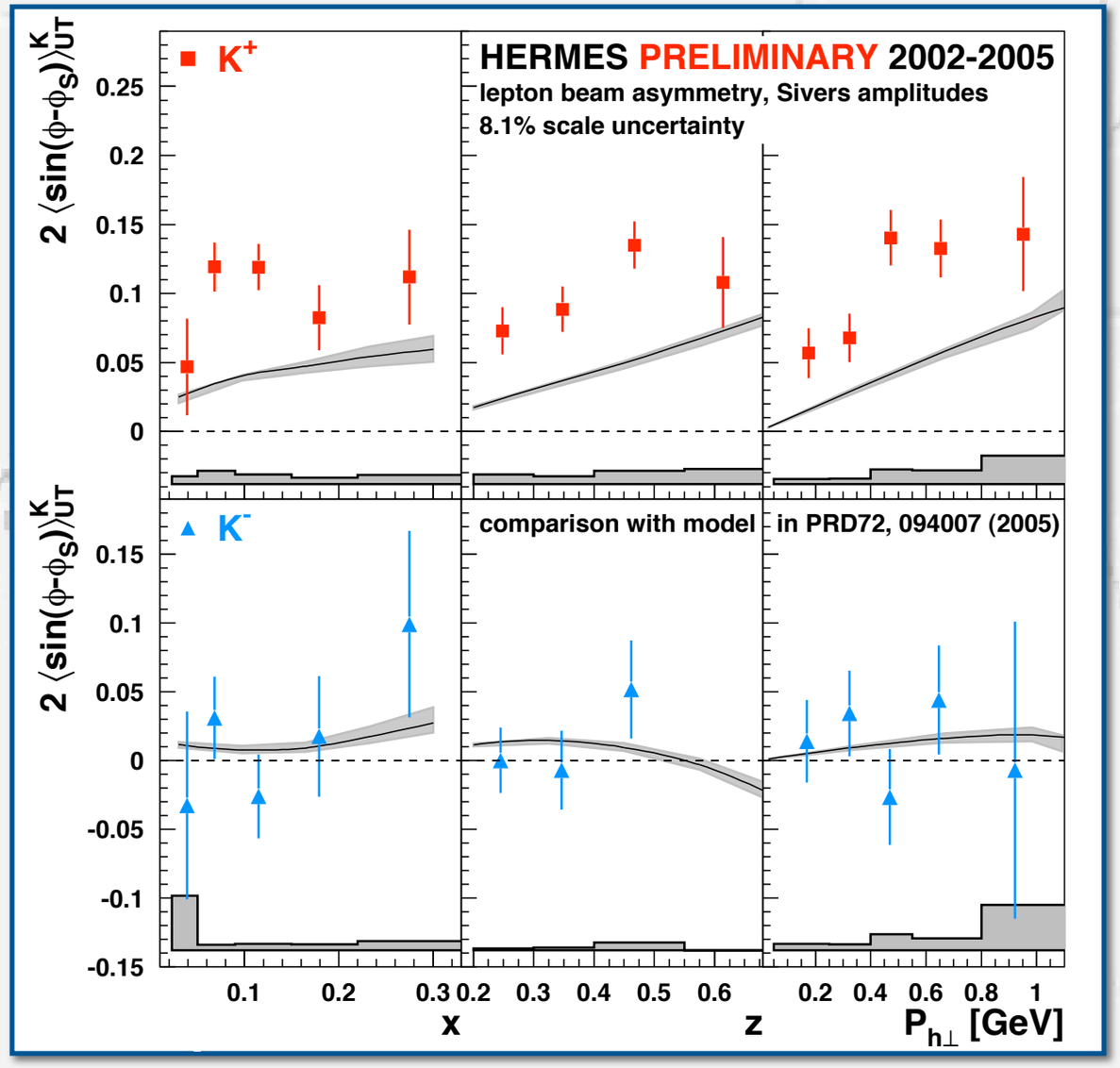


☑ first observation of T-odd Sivers effect in SIDIS!

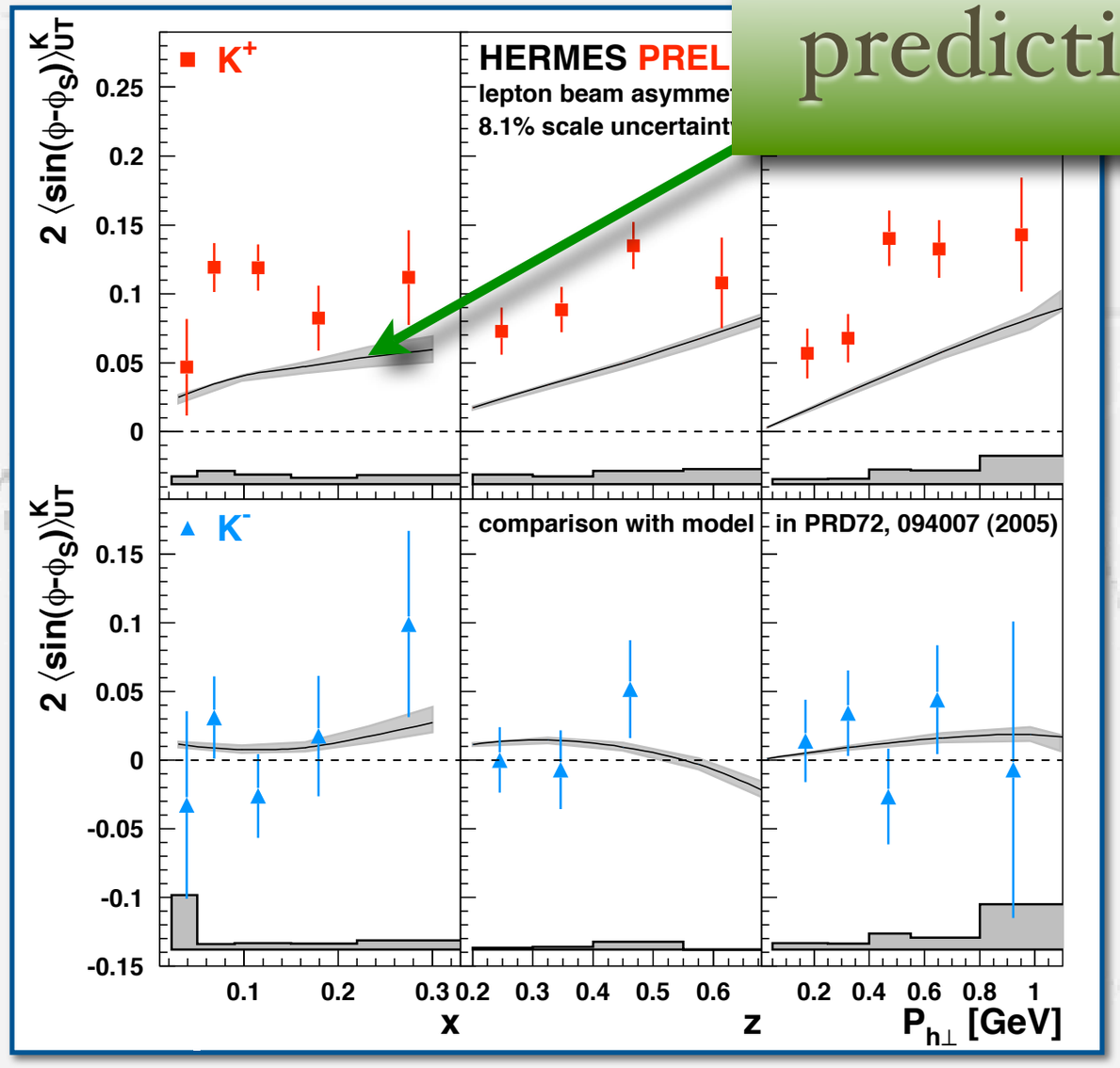
☑ u-quark dominance suggests sizeable u-quark orbital motion

The Intriguing Kaon Amplitudes



The Intriguing Kaon Amplitudes

prediction using fit to pion data



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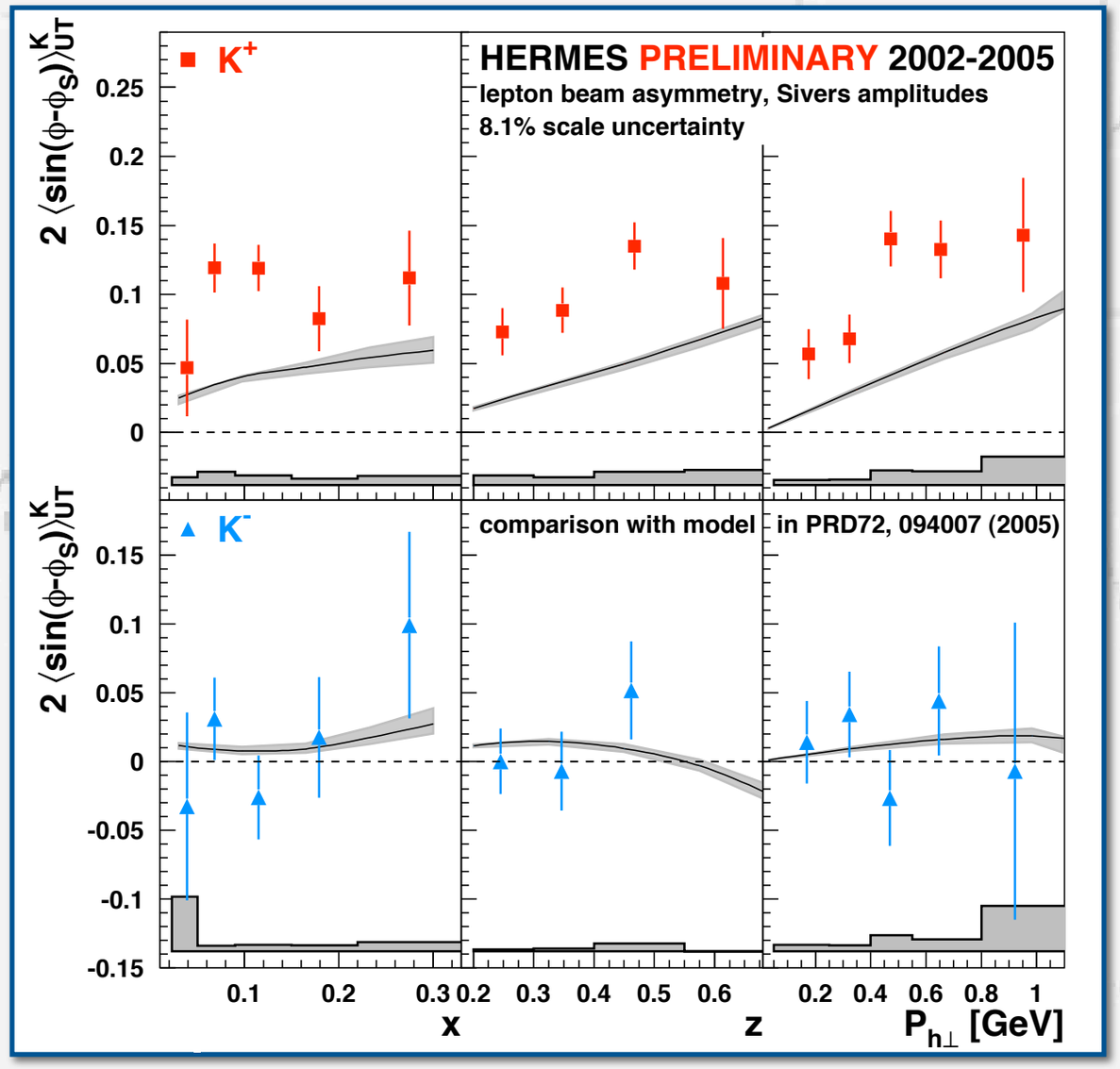

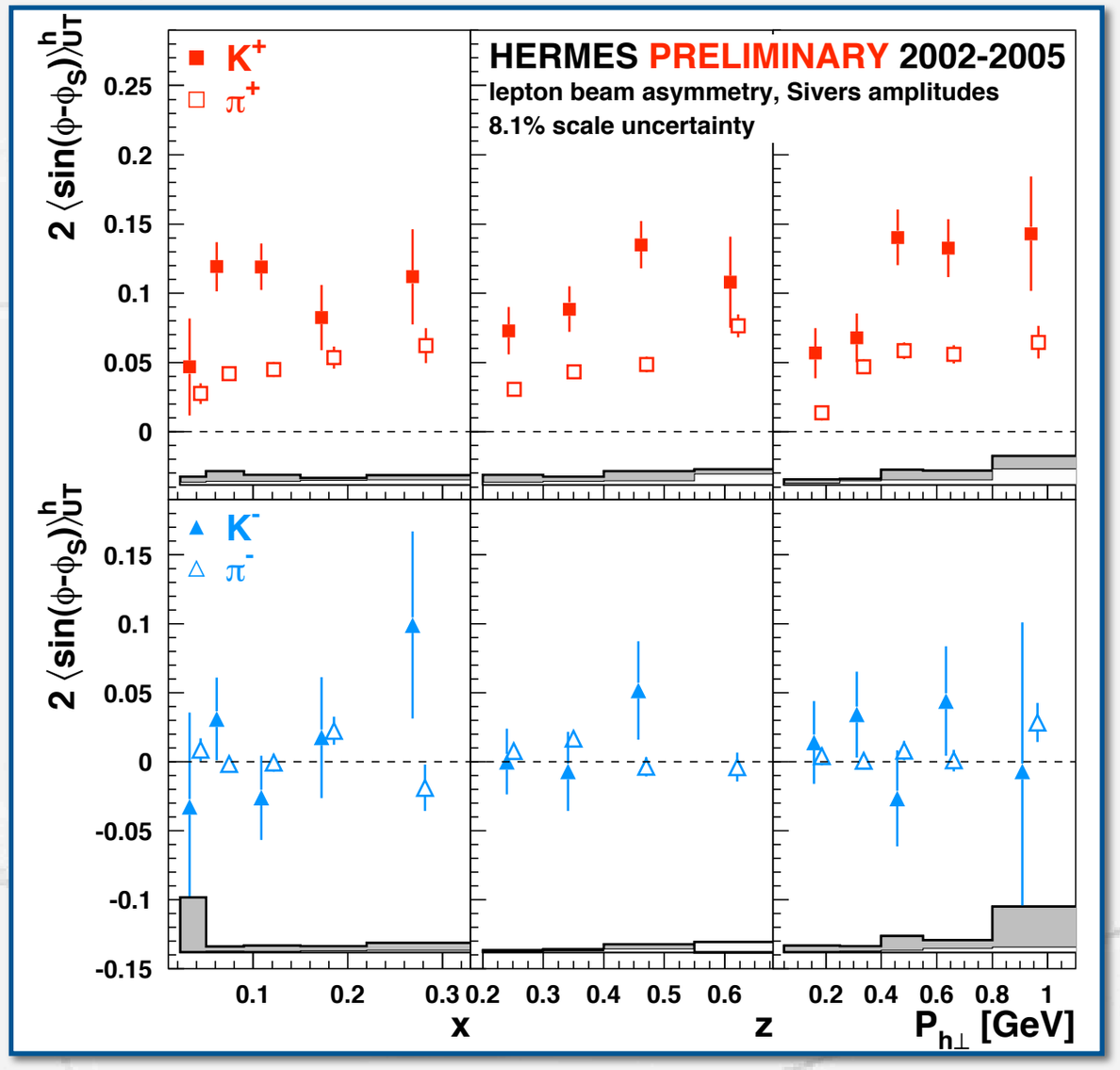

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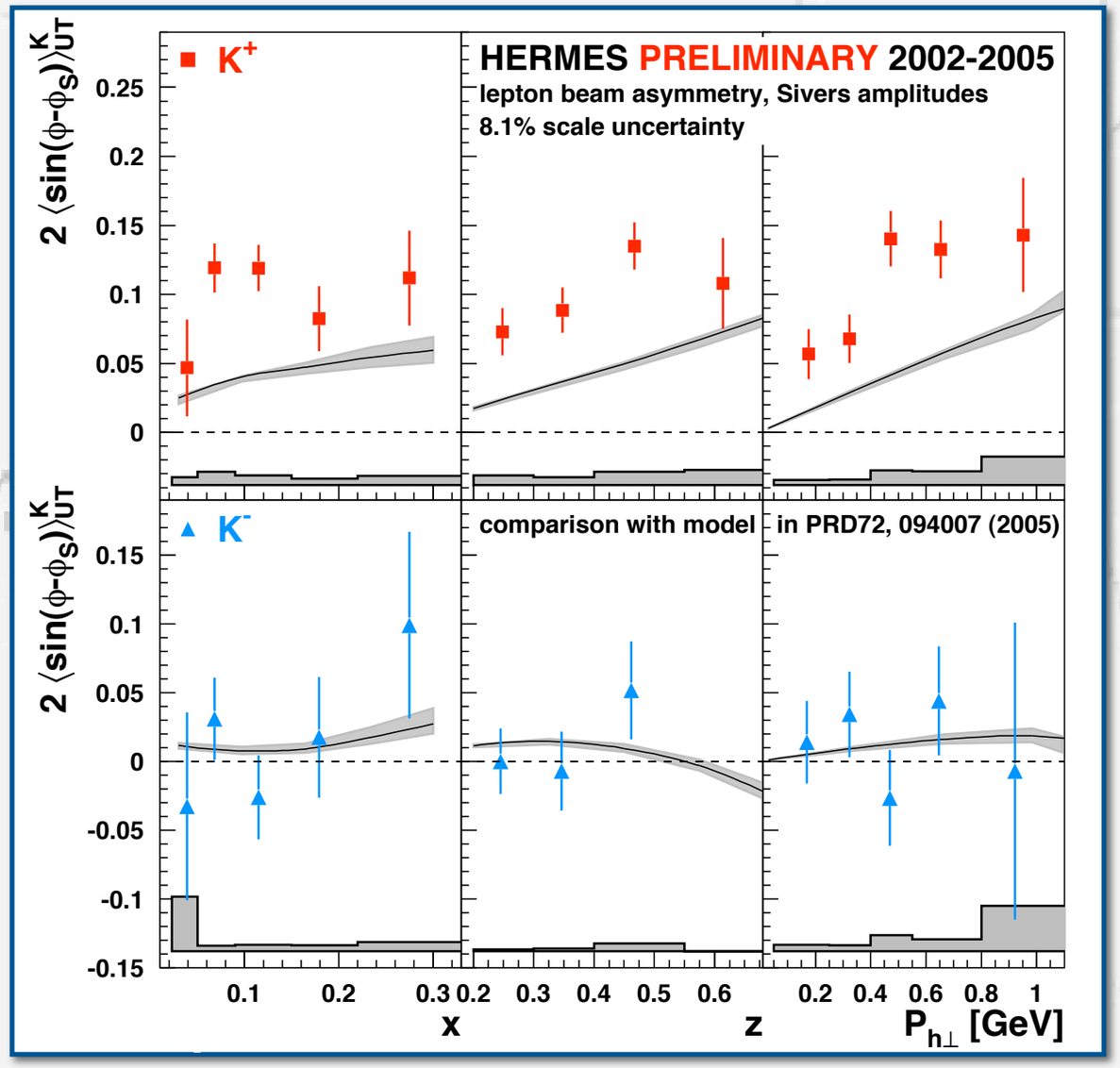

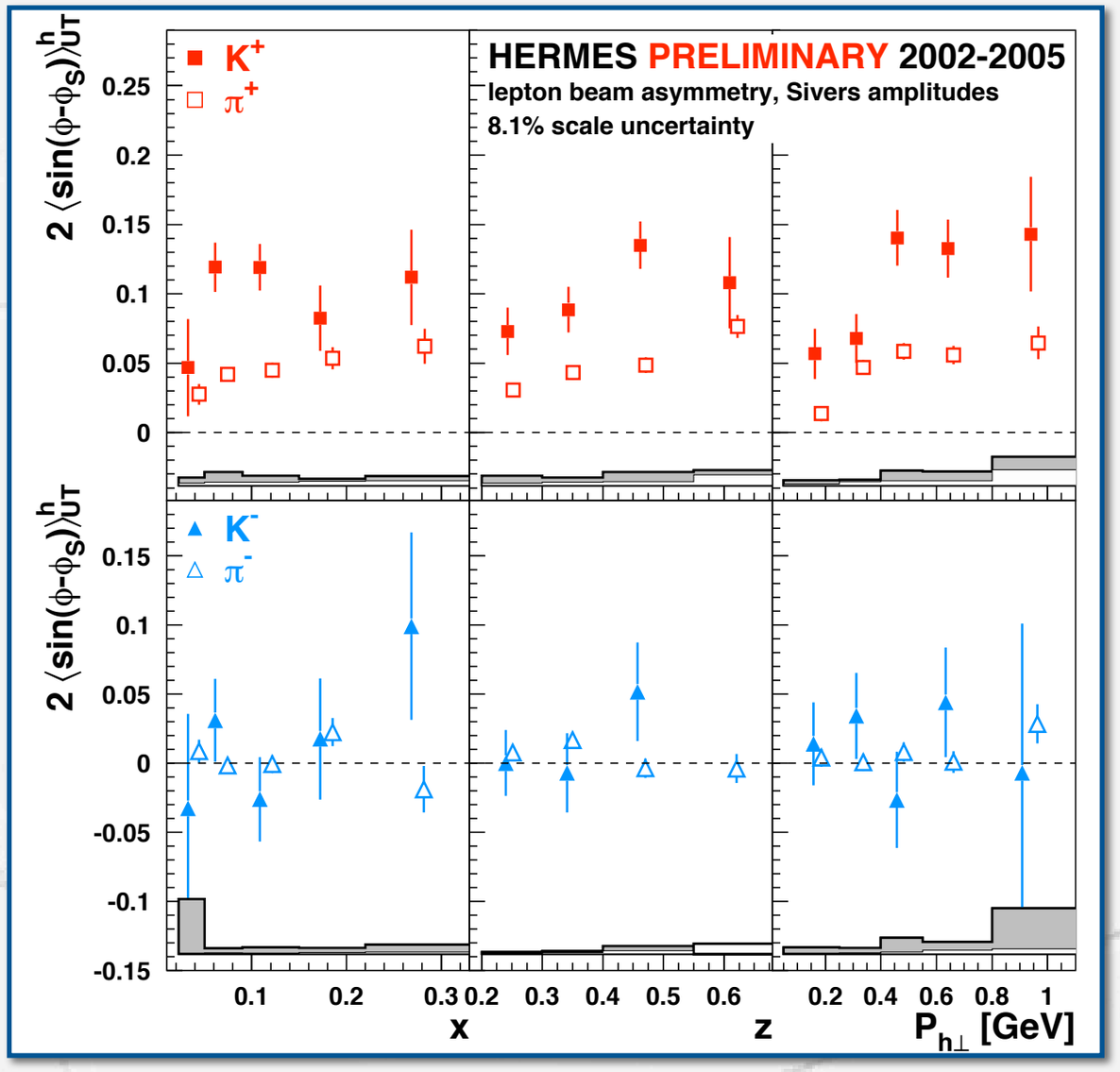

non-trivial role of sea quarks!

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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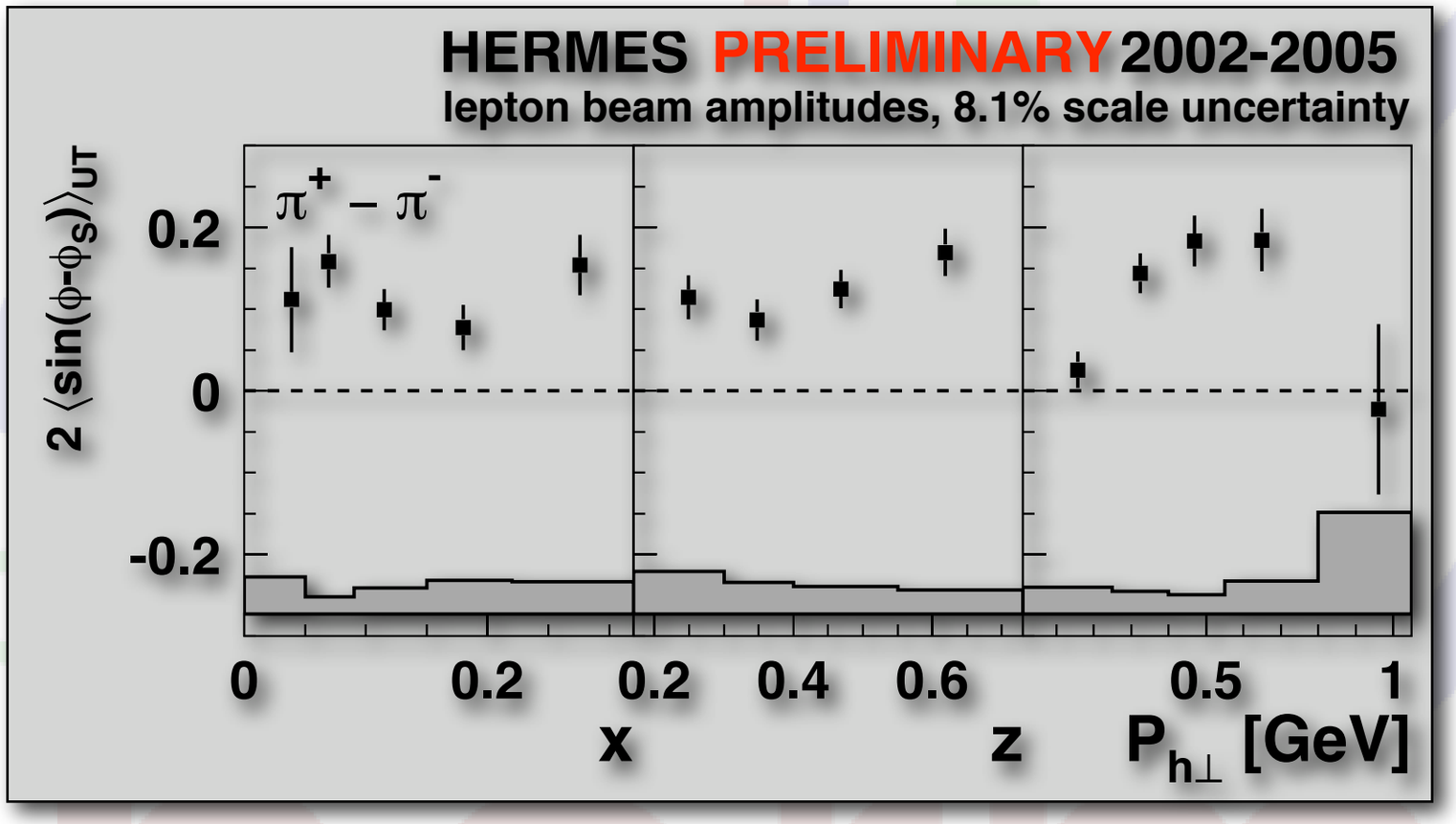

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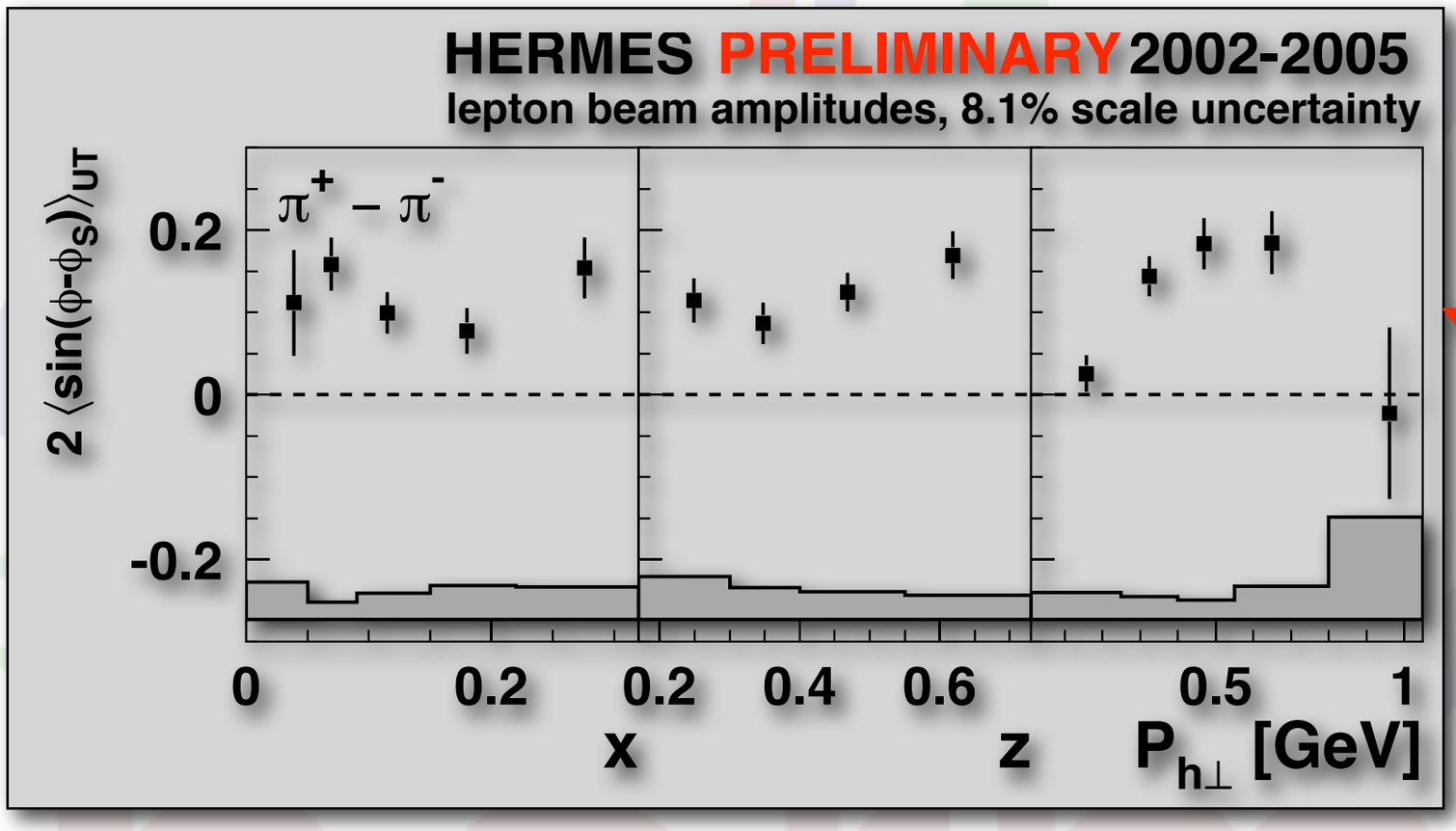
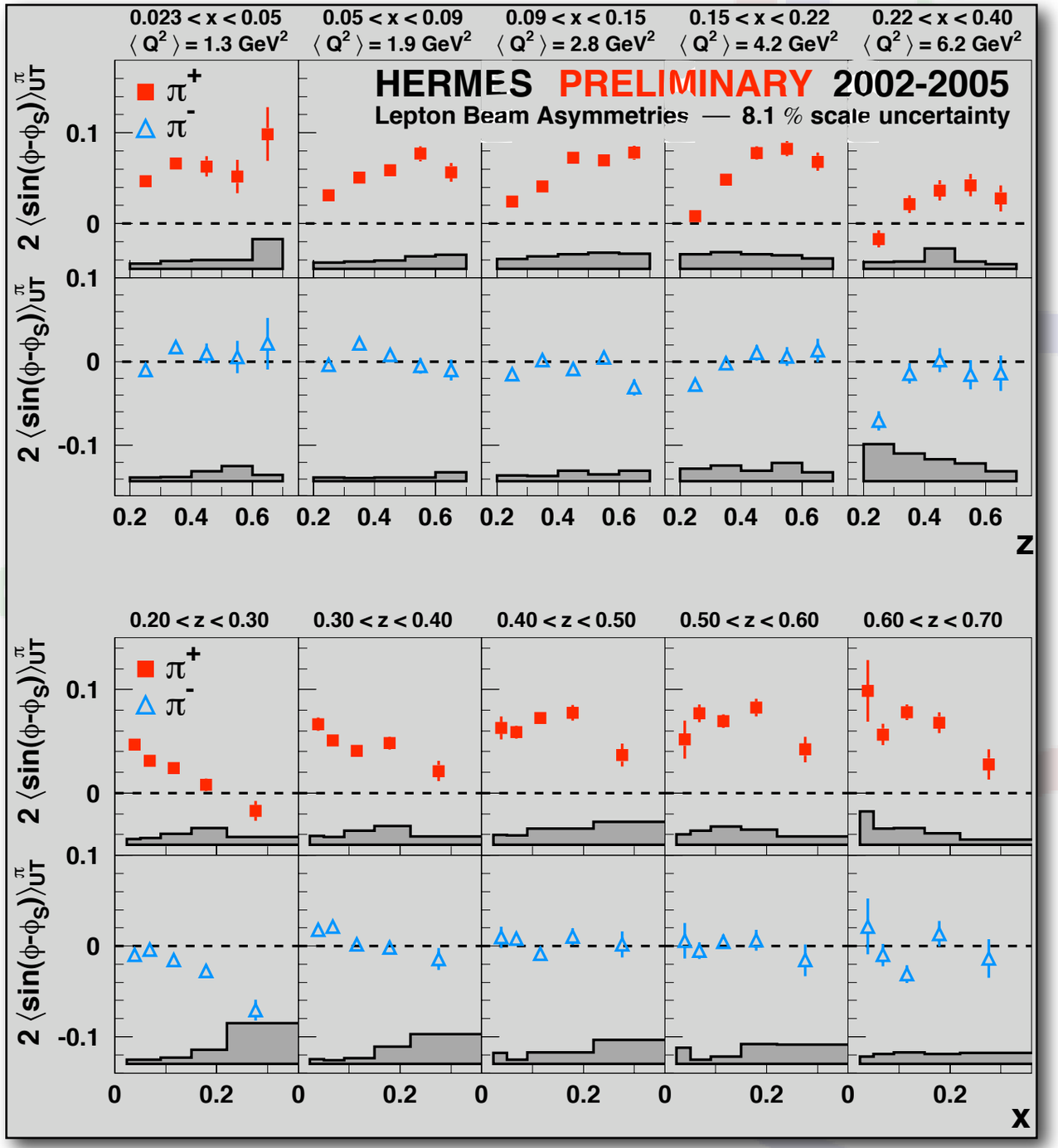


access to Sivers valence distribution

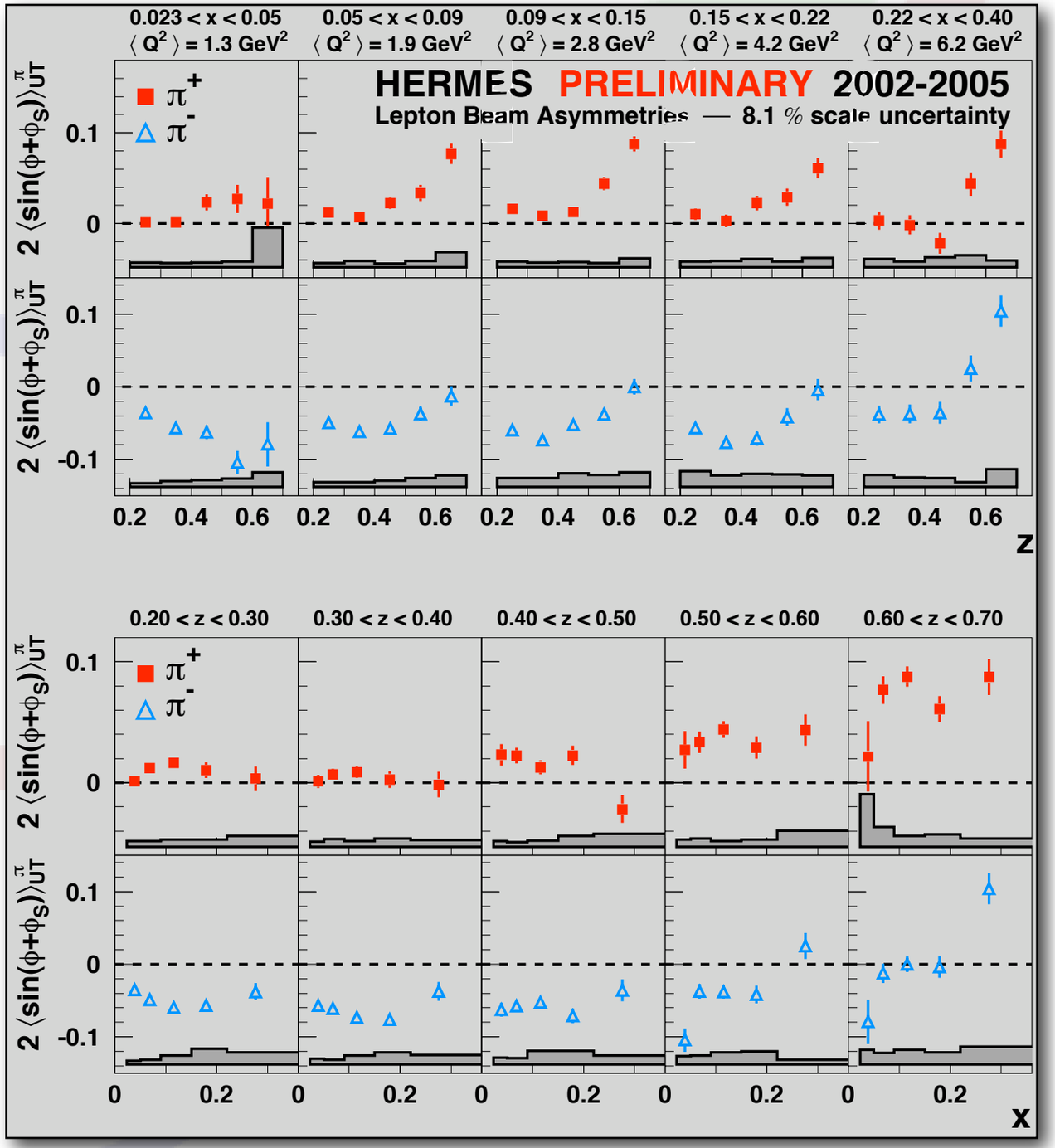
$$\langle \sin(\phi - \phi_S) \rangle_{UT}^{\pi^+ - \pi^-}(\phi, \phi_S) = -\frac{4f_T^{\perp, u_v} - f_T^{\perp, d_v}}{4f^{u_v} - f^{d_v}}$$

2D Binning of Sivers and Collins Amplitudes

- **Observed kinematics often strongly correlated in experiment**
  bin in as many independent variables as possible



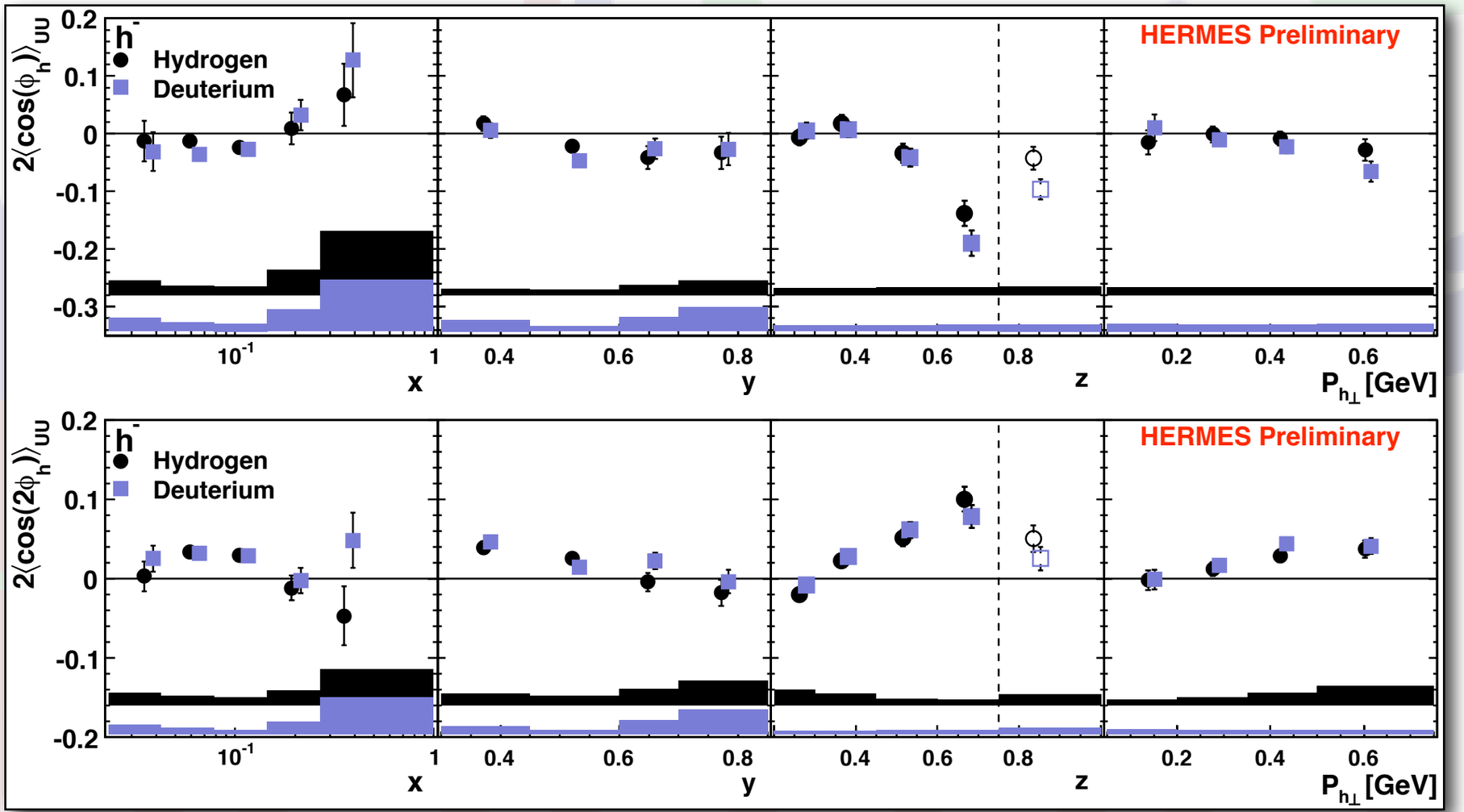
Sivers



Collins

Cahn & Boer-Mulders Effects

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



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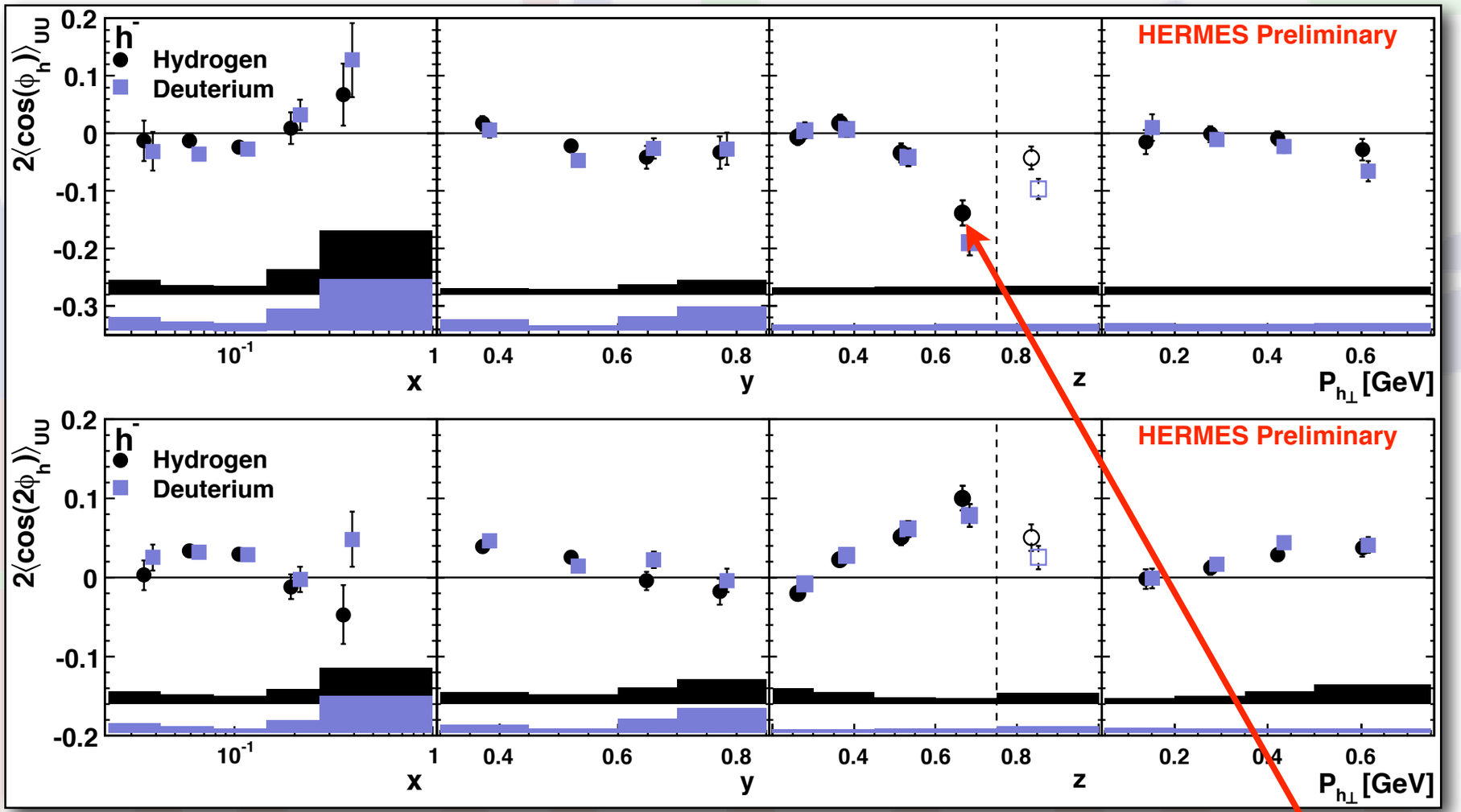

Cahn effect as manifest of intrinsic transverse quark momentum

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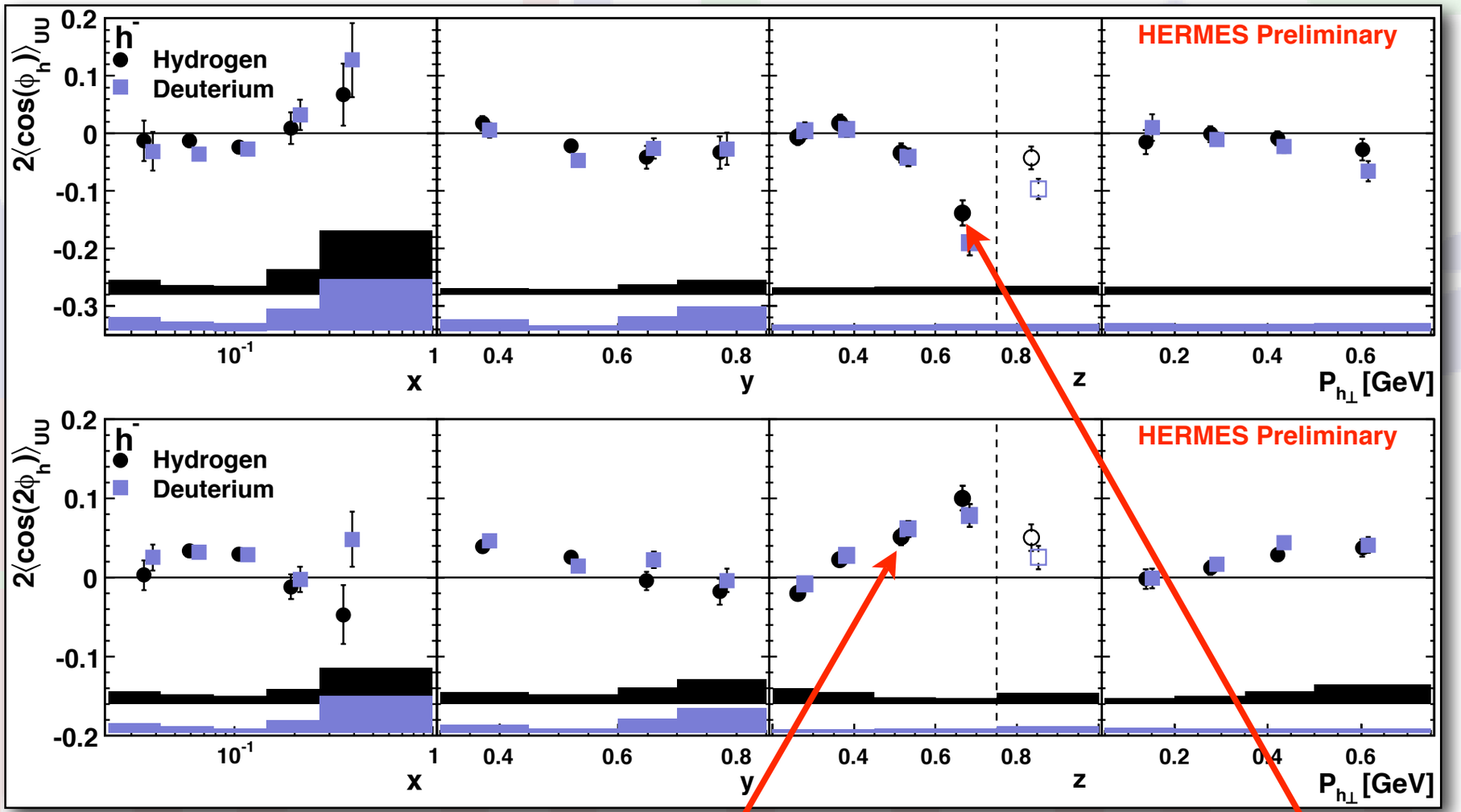


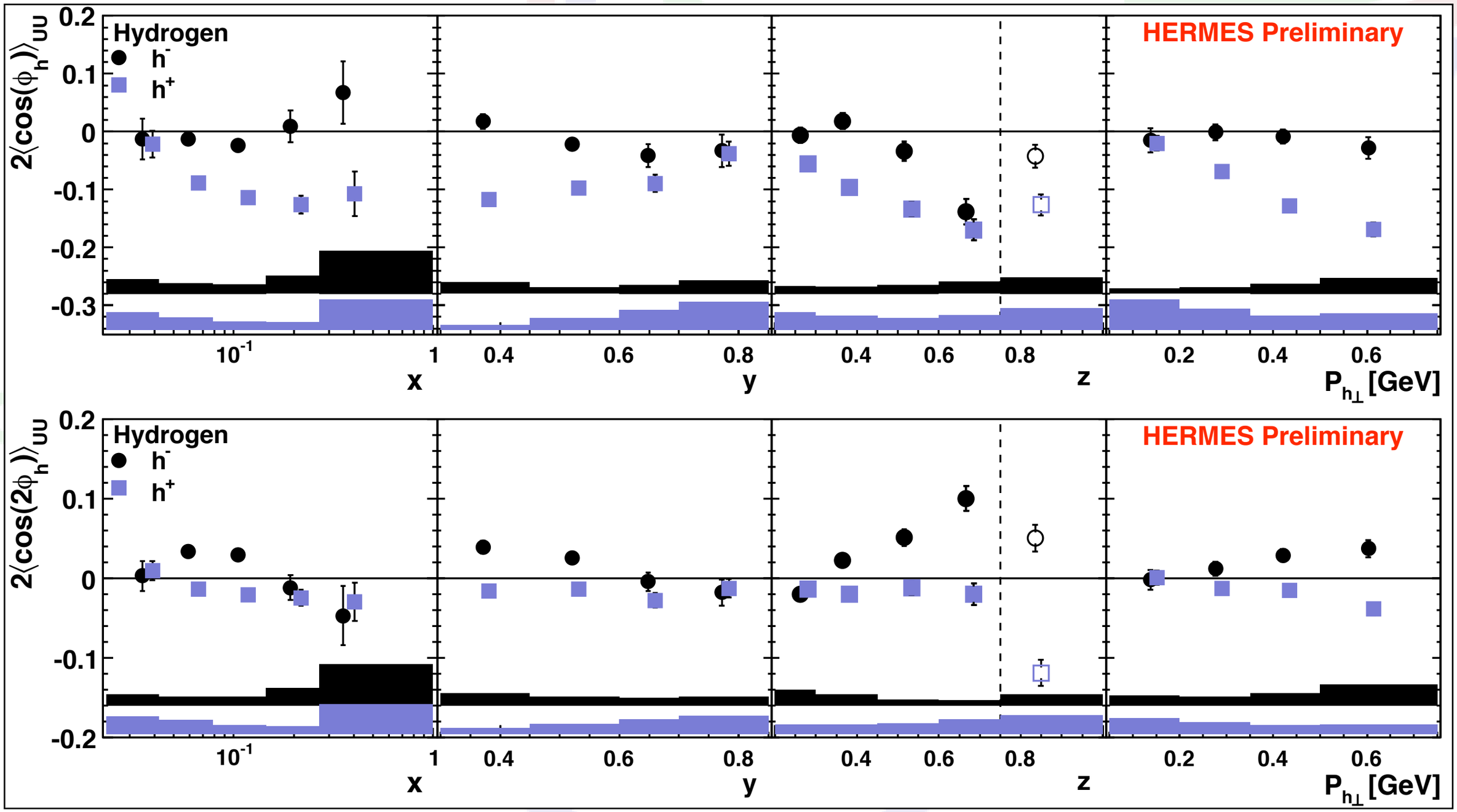
Signature of Boer-Mulders effect:

transversely polarized quarks in unpolarized nucleons

Cahn effect as manifest of intrinsic transverse quark momentum

… Cahn & Boer-Mulders

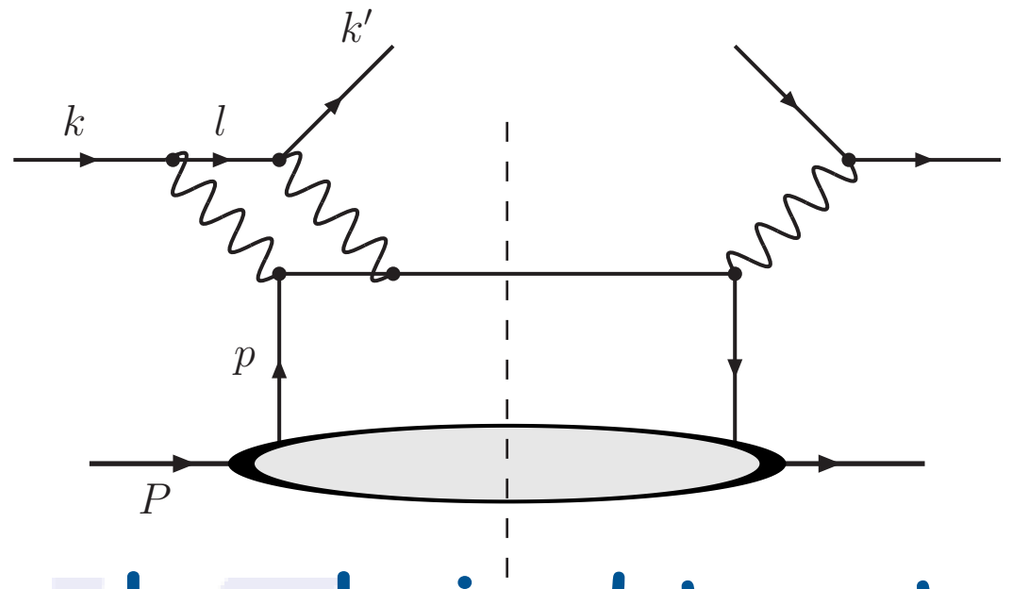
- hadron-charge comparison:



SSAs in Inclusive DIS

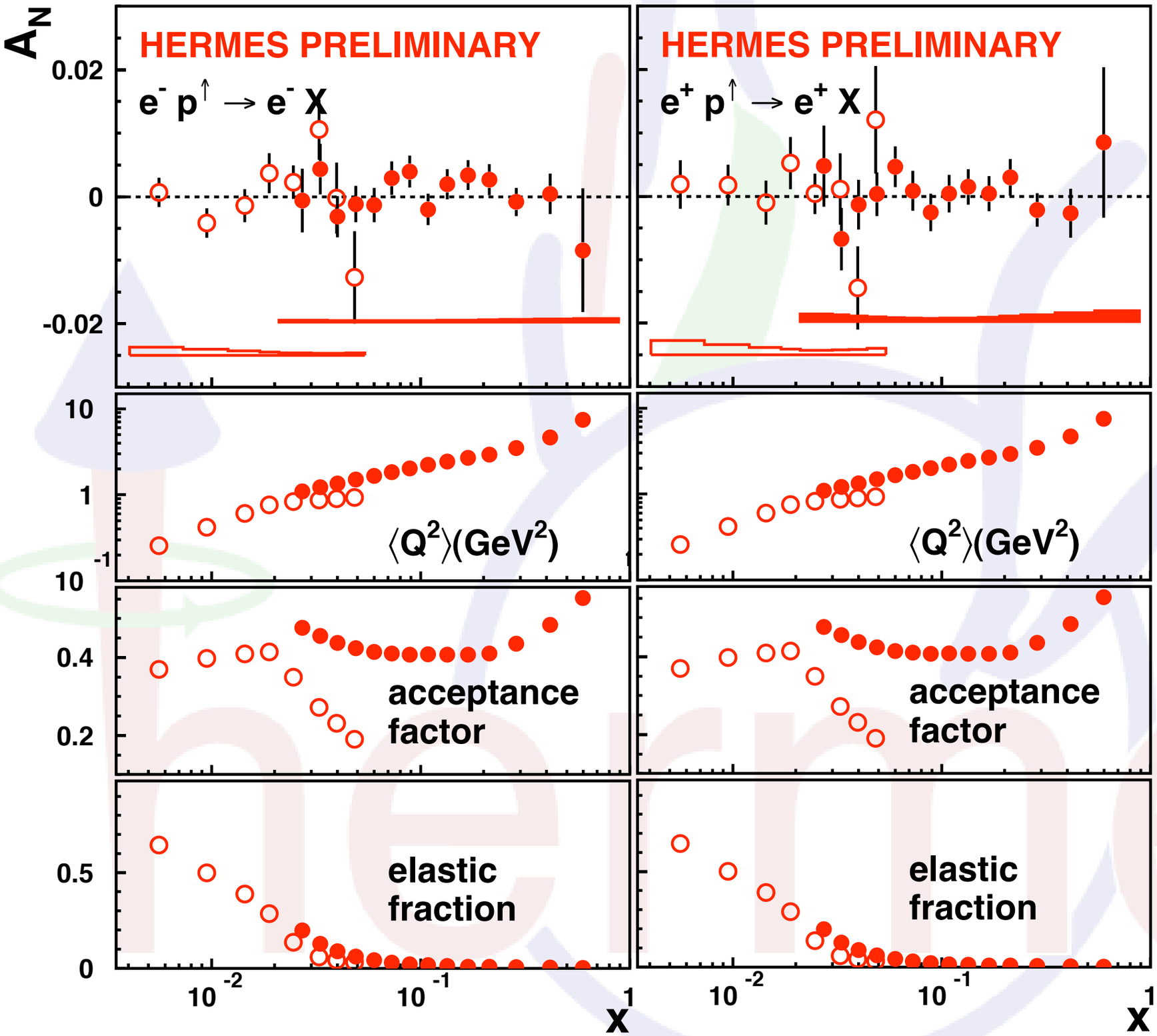
Two-Photon Exchange

- 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

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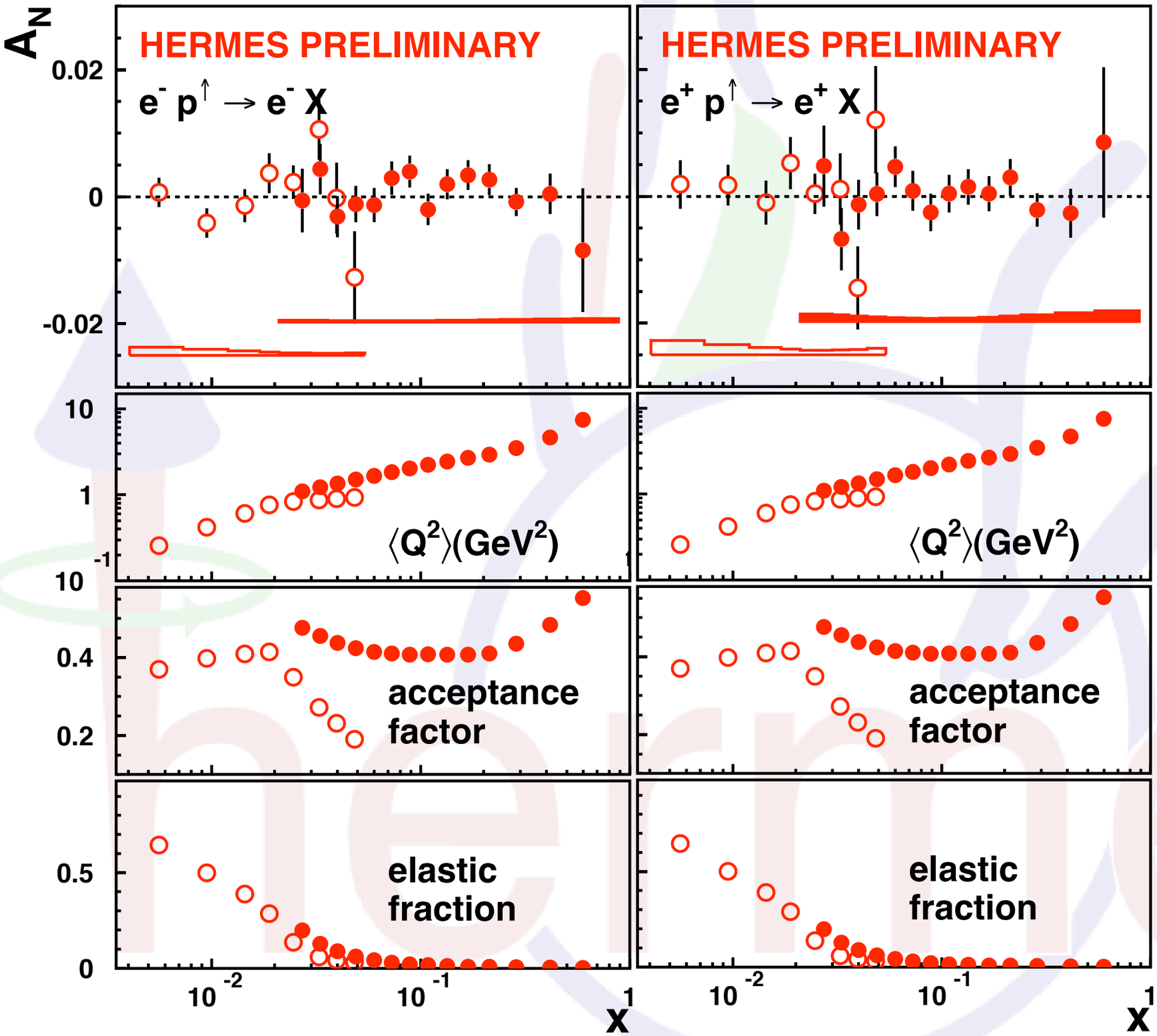
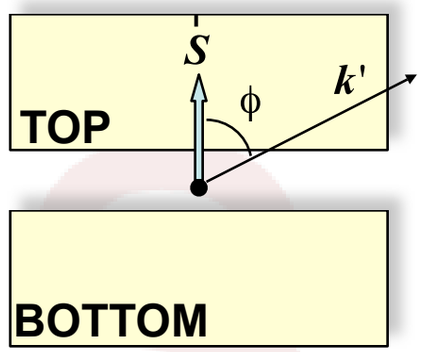


consistent with zero

Front view of HERMES detector



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

Exclusive Reactions

Accessing Generalized Parton Distributions

Angular Momentum and GPDs

1997: Ji Relation for Nucleon Spin

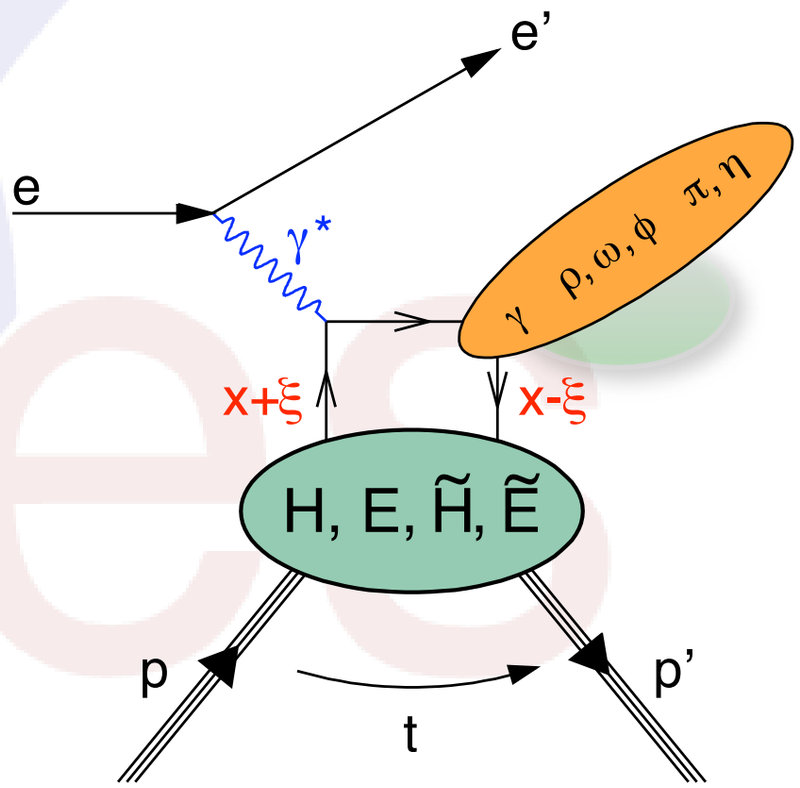
$$\frac{1}{2}\hbar = \lim_{t\to 0}\sum_q \int dx\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)] + \lim_{t\to 0}\int dx\,[H^g(x,\xi,t) + E^g(x,\xi,t)]$$

J^q J^g

- **"Ji's Recipe" provides way to measure angular momenta**
- **involves moment over new class of PDFs: Generalized PDFs**
- **at leading twist there are 8 GPDs:** $E, H, \tilde{E}, \tilde{H}, E_T, H_T, \tilde{E}_T, \tilde{H}_T$
- **but only 2 of them needed for Ji's recipe:** E, H
- **GPDs provide info about transverse position and long. mom.**

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

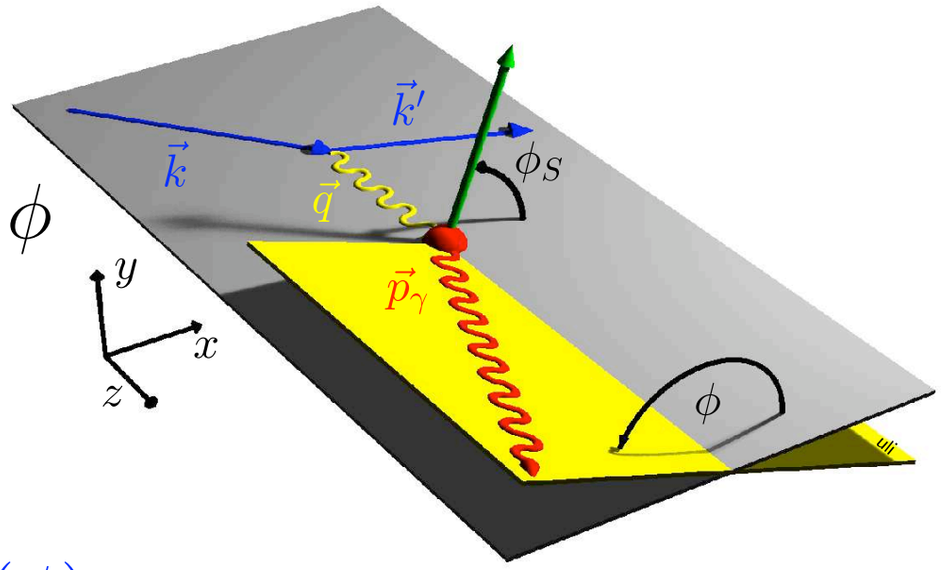
Interference DVCS & BH cause azimuthal asymmetries in cross-section:

- 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 $A_{UL}(\phi)$:

  $d\sigma(\overleftarrow{P},\phi) - d\sigma(\overrightarrow{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$

- 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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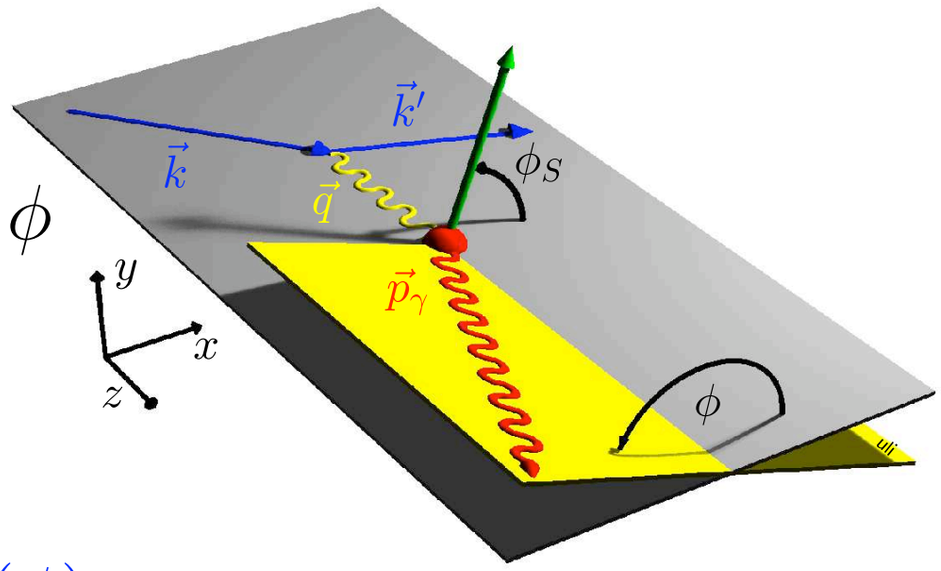

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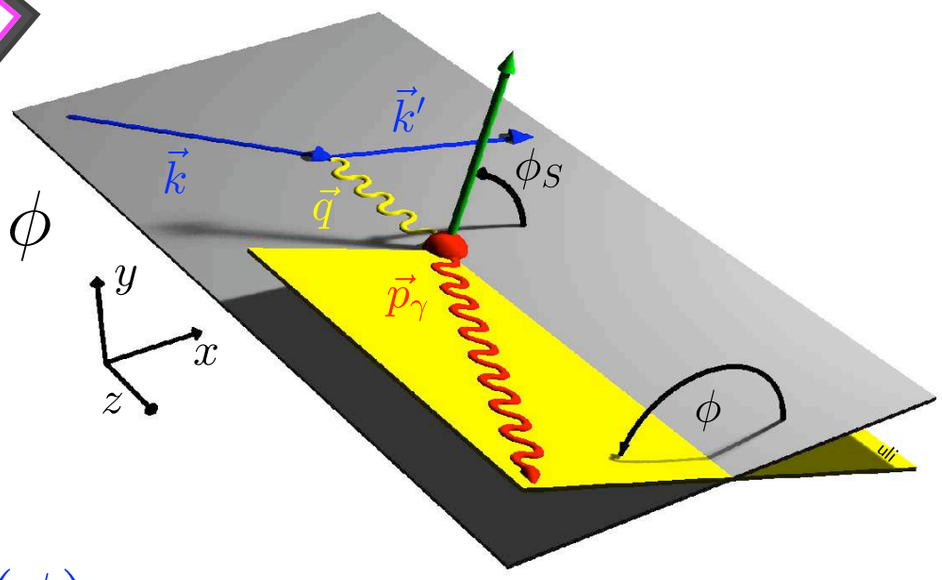
(F_1, F_2 are Dirac and Pauli form factors, calculable in QED)

($\widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}, \ldots$ Compton form factors involving GPDs $H, E, \ldots$)

Only TTSA sensitive to E!



Constraining E - Transverse TSA

$$e^{\pm}\, p^{\Uparrow} \longrightarrow e^{\pm}\, p\, \gamma$$

$$A_{\mathrm{UT}}^{\mathcal{I}}(\phi,\phi_s) \propto \left[\mathrm{d}\sigma^{+}(\phi,\phi_s) - \mathrm{d}\sigma^{-}(\phi,\phi_s)\right] - \left[\mathrm{d}\sigma^{+}(\phi,\phi_s+\pi) - \mathrm{d}\sigma^{-}(\phi,\phi_s+\pi)\right]$$

$$\begin{aligned} A_{\mathrm{UT}}^{\mathcal{I}}(\phi,\phi_s) \quad &\propto \quad \mathrm{Im}\left(F_2\mathcal{H} - F_1\mathcal{E}\right)\sin(\phi-\phi_s)\cos\phi \\ &+ \quad \mathrm{Im}\left(F_2\widetilde{\mathcal{H}} - (F_1+\xi F_2)\widetilde{\mathcal{E}}\right)\cos(\phi-\phi_s)\sin\phi \end{aligned}$$

Constraining E - Transverse TSA

$$e^{\pm}\, p^{\Uparrow} \longrightarrow e^{\pm}\, p\, \gamma$$

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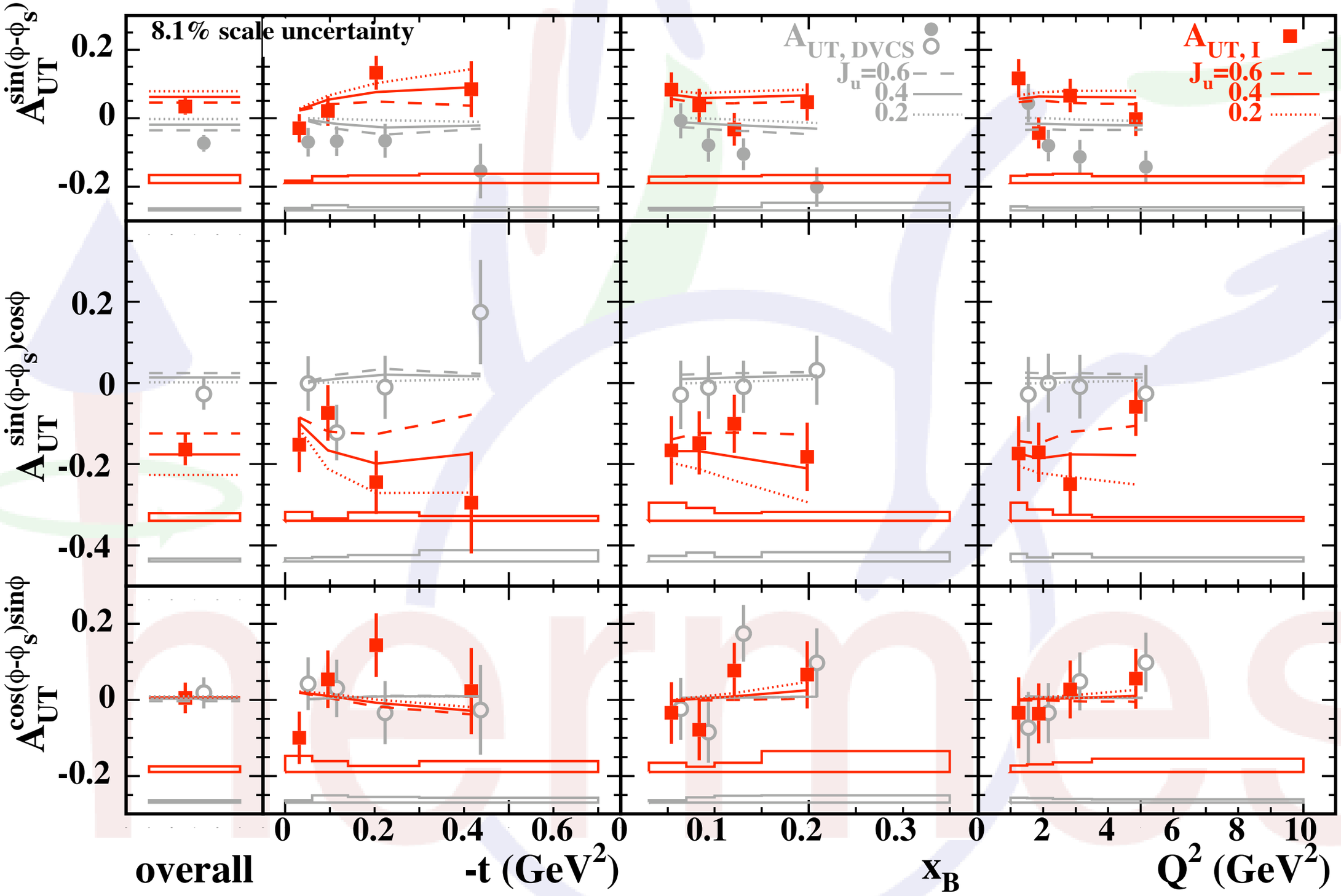
sensitive to E

Amplitudes of TTSA

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



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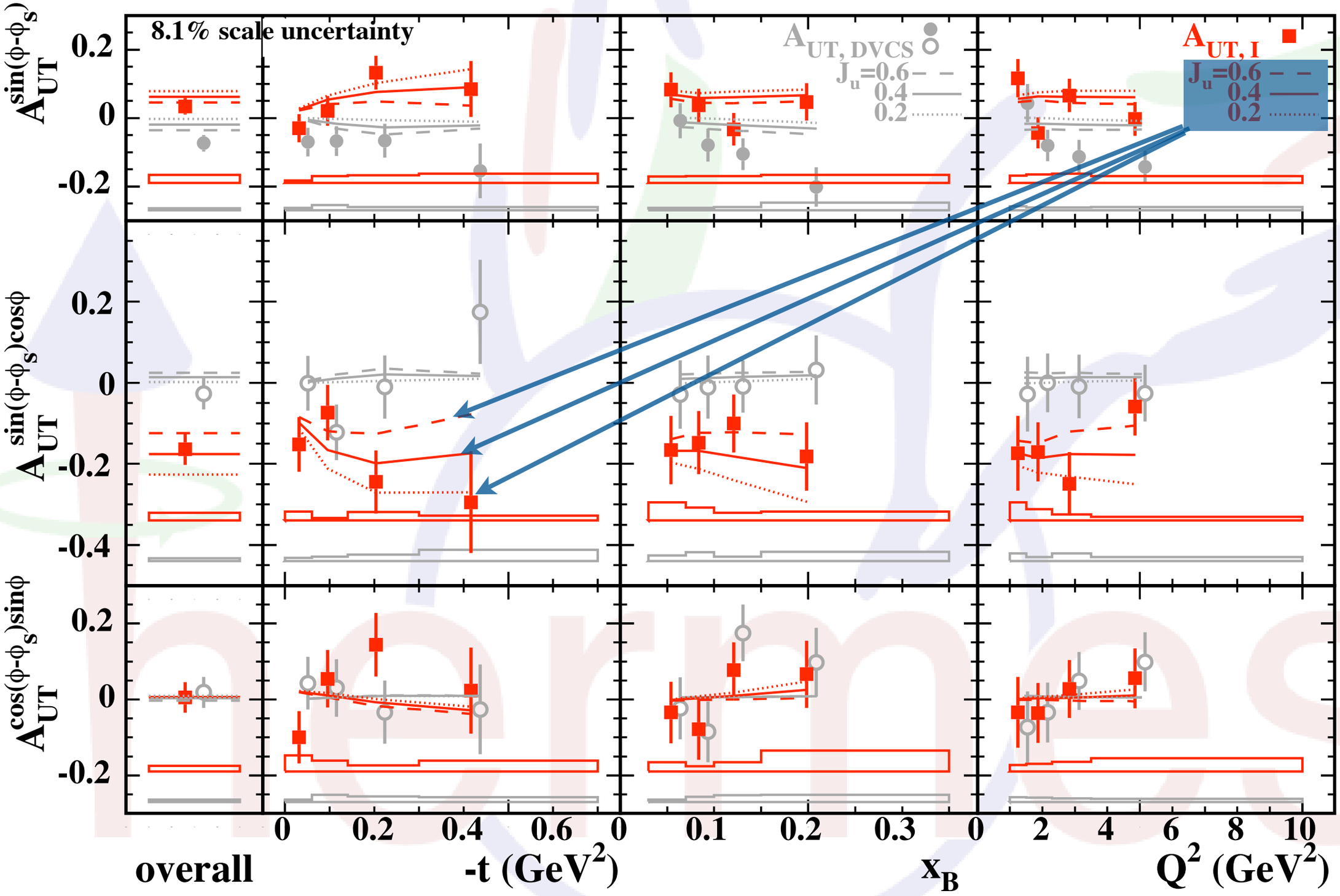
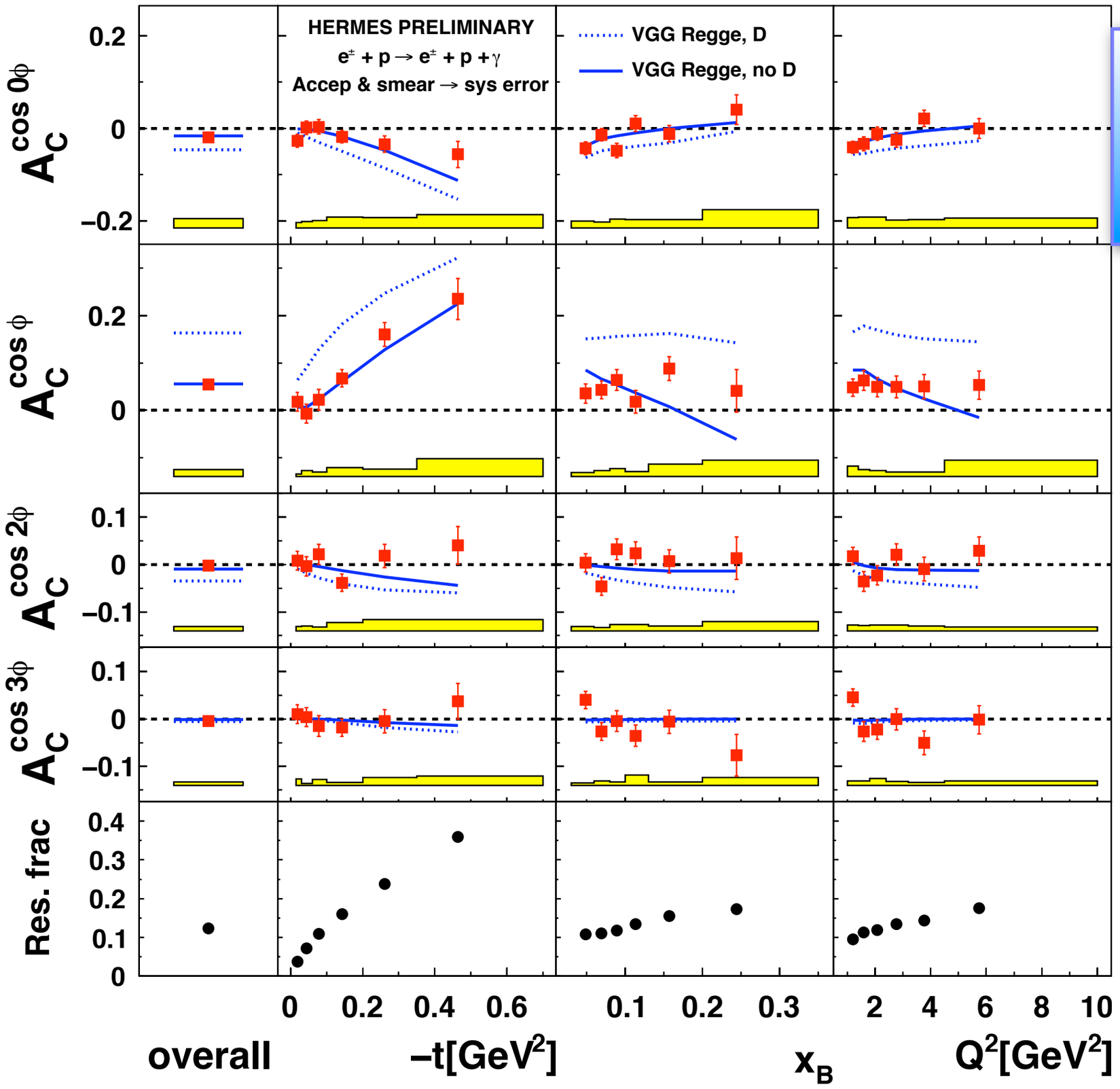


Constraints on GPD Models

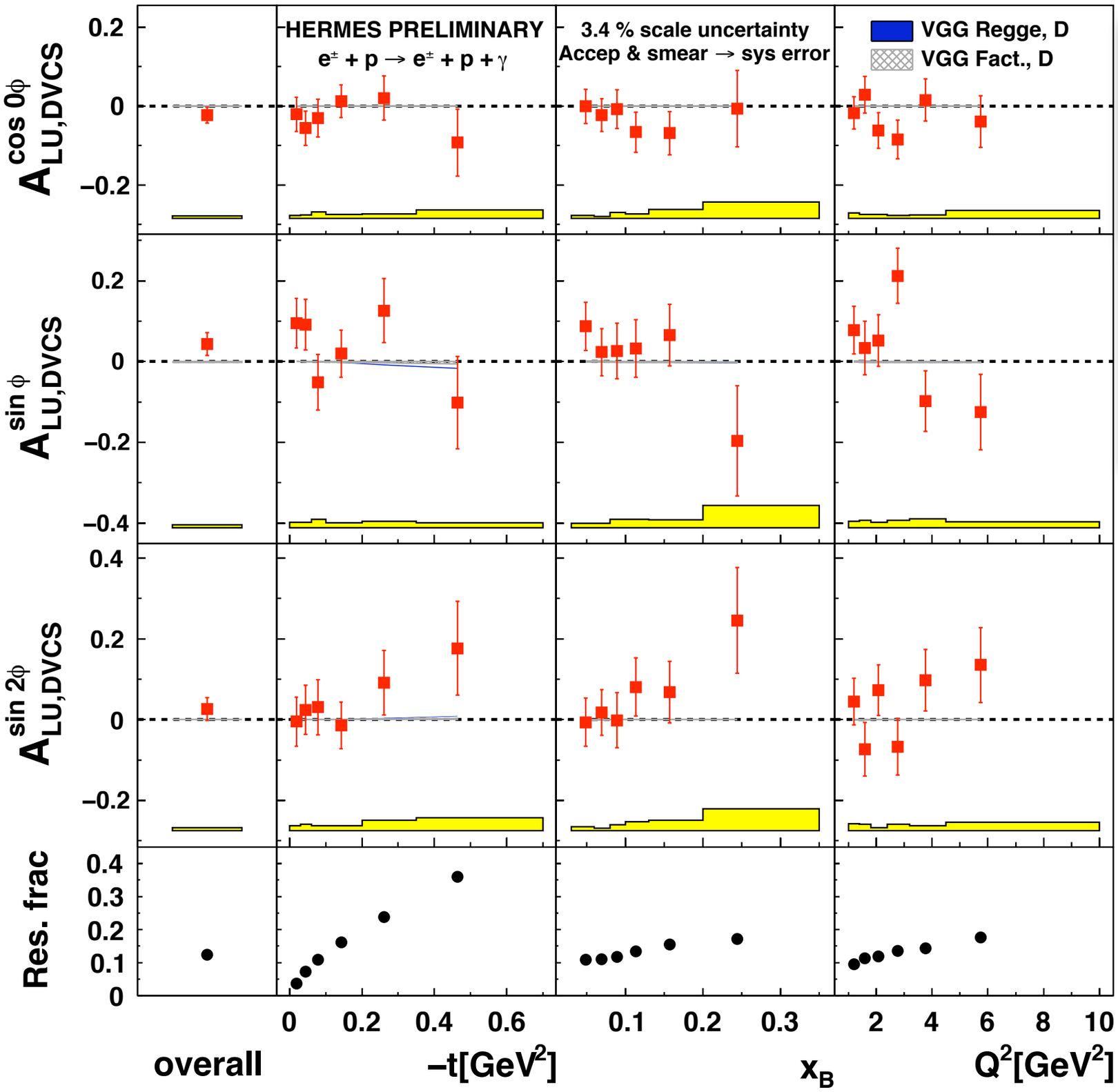
- **several pioneering DVCS results on H, D, and nuclear targets**
- **provide important constraints on GPD models**

Constraints on GPD Models



Beam-Charge asymmetry on H

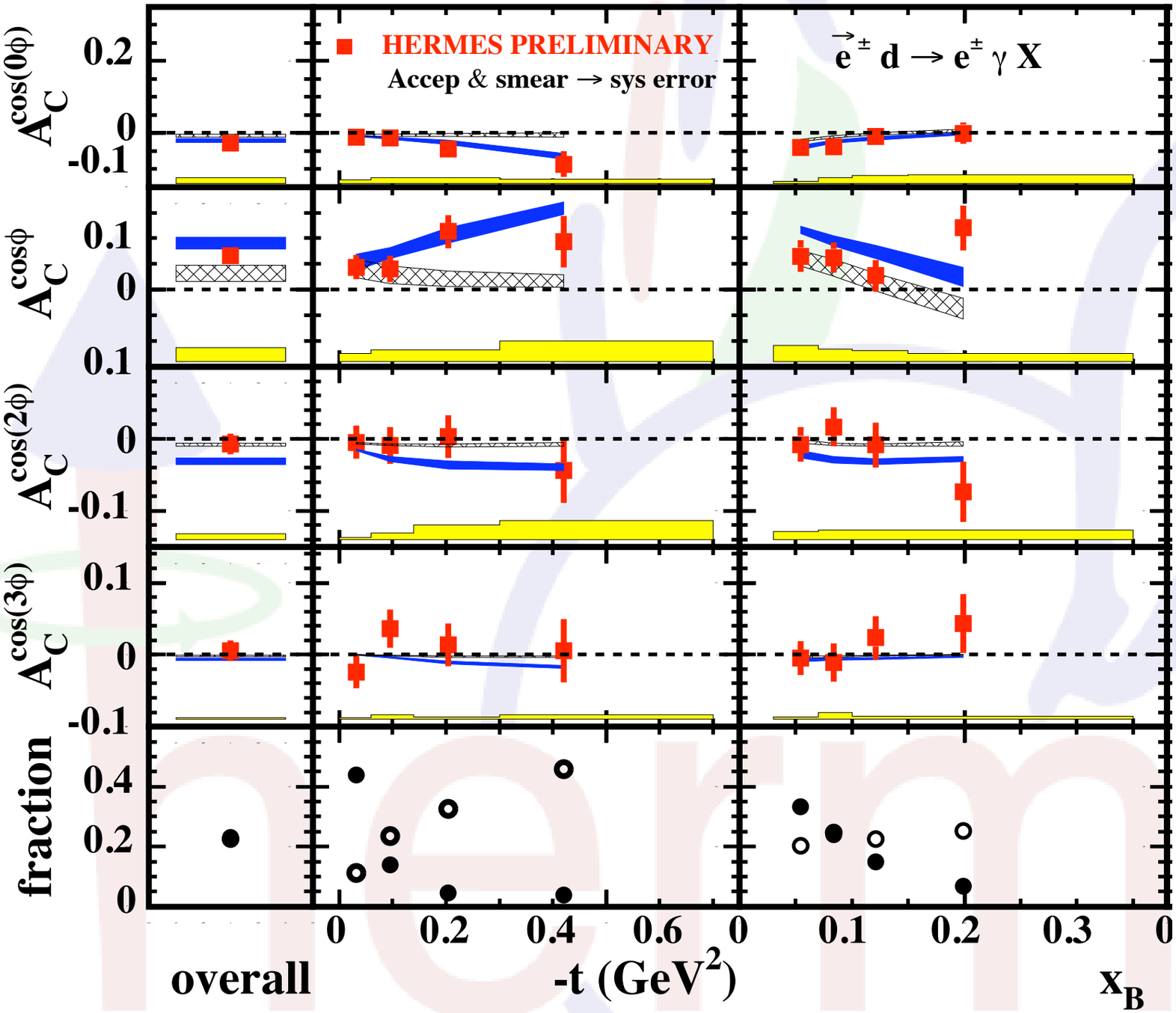
Constraints on GPD Models



Beam-Charge asymmetry on H

Beam-Spin asymmetry on H

Constraints on GPD Models

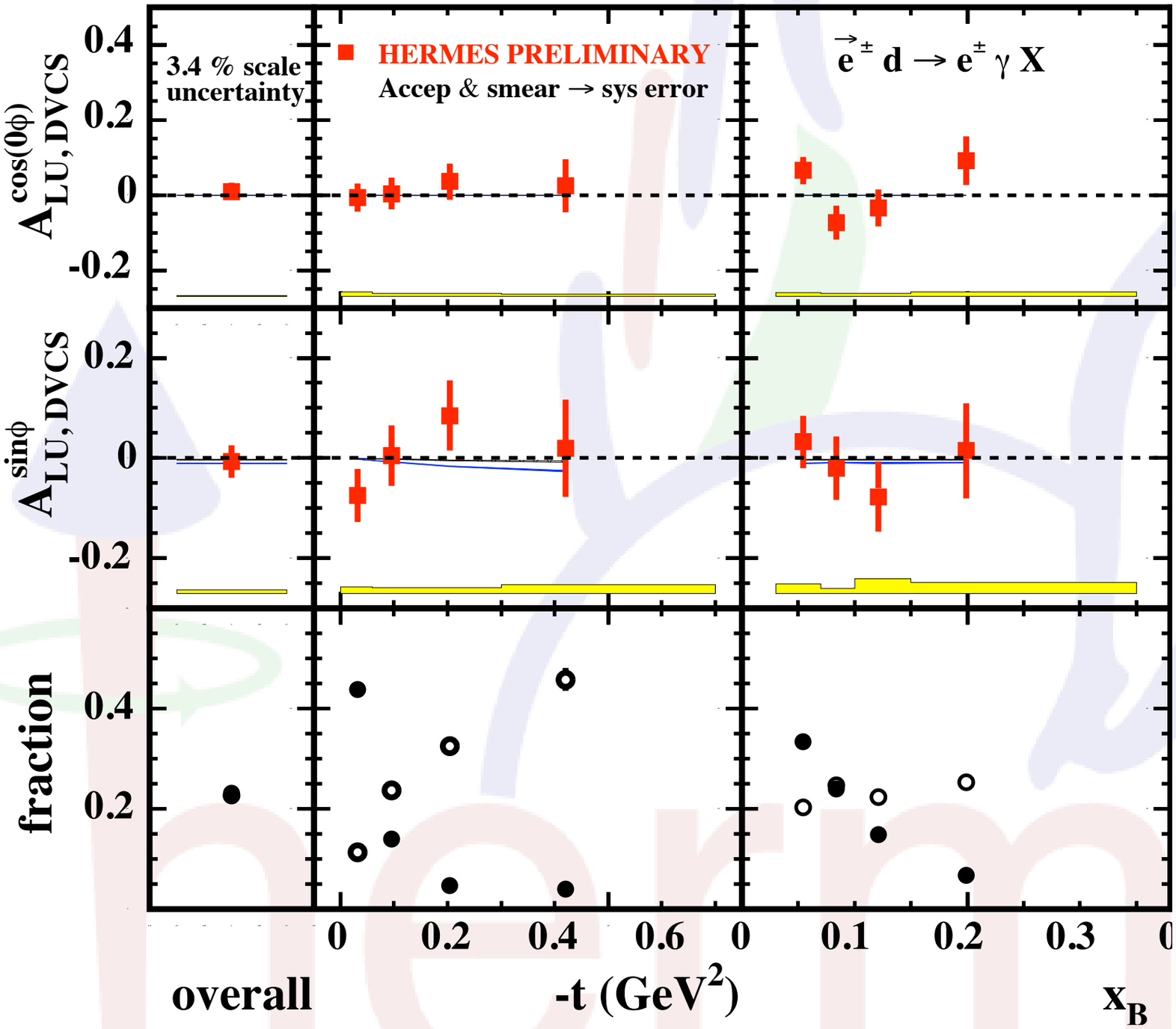


Beam-Charge asymmetry on H

Beam-Spin asymmetry on H

Beam-Charge asymmetry on D

Constraints on GPD Models



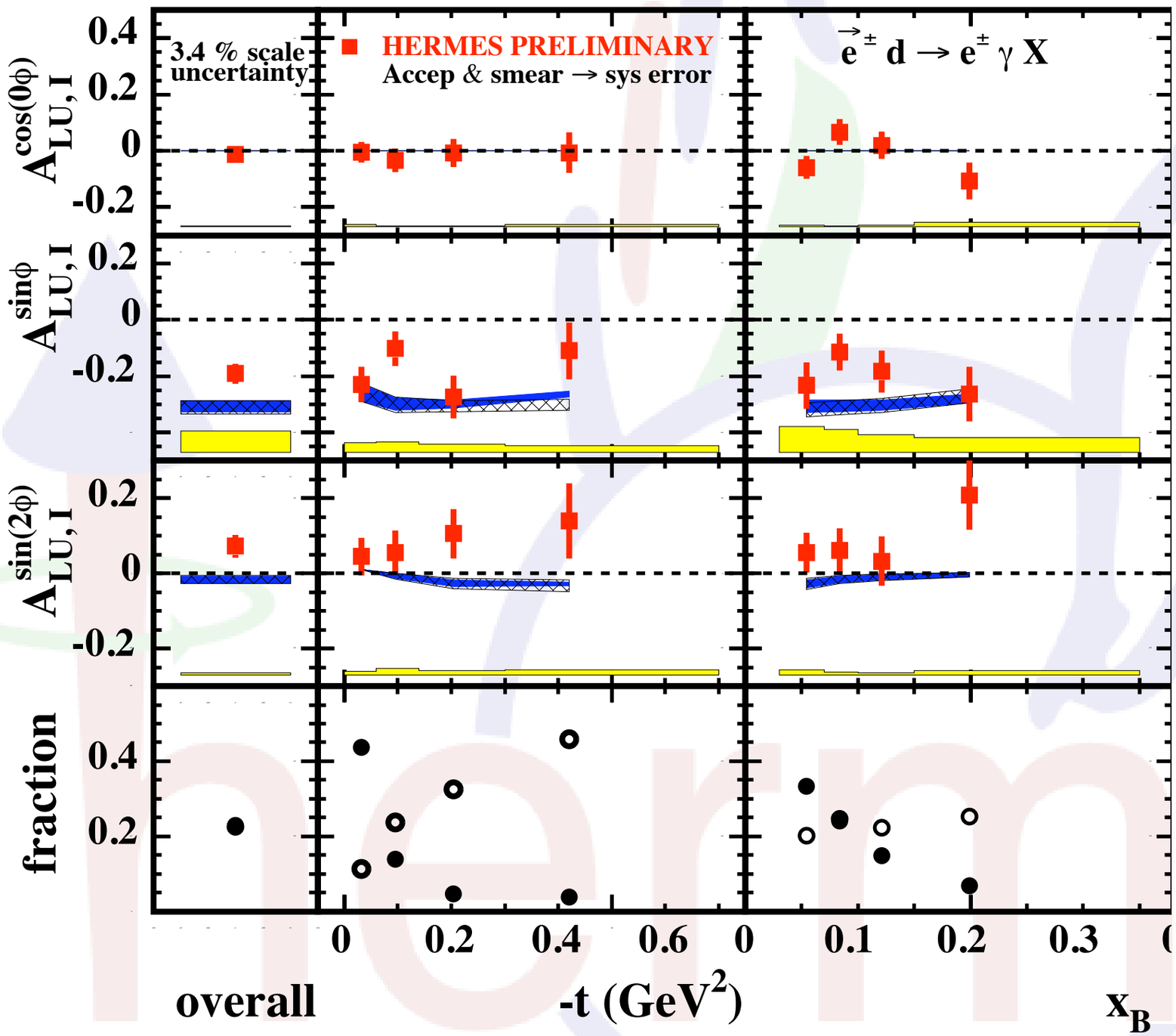
Beam-Charge asymmetry on H

Beam-Spin asymmetry on H

Beam-Charge asymmetry on D

Beam-Spin asymmetry on D

Constraints on GPD Models



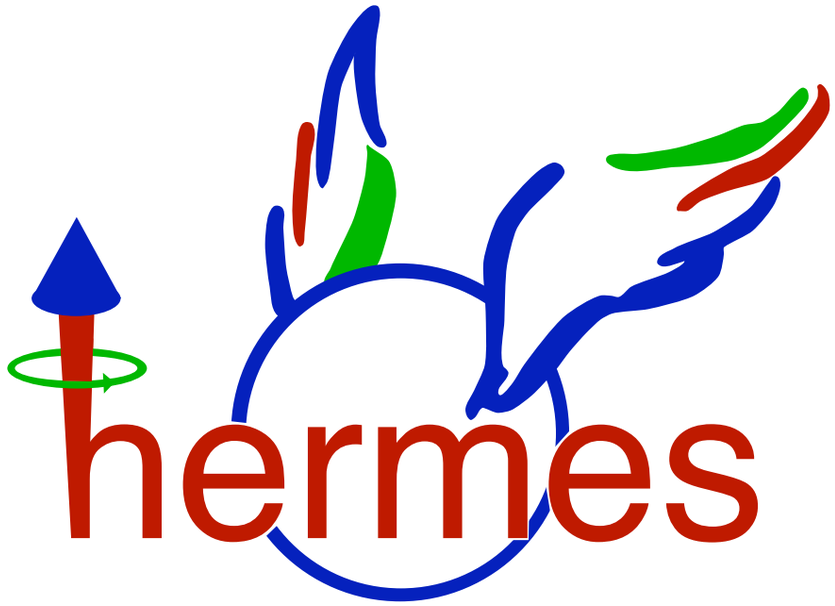
Beam-Charge asymmetry on H

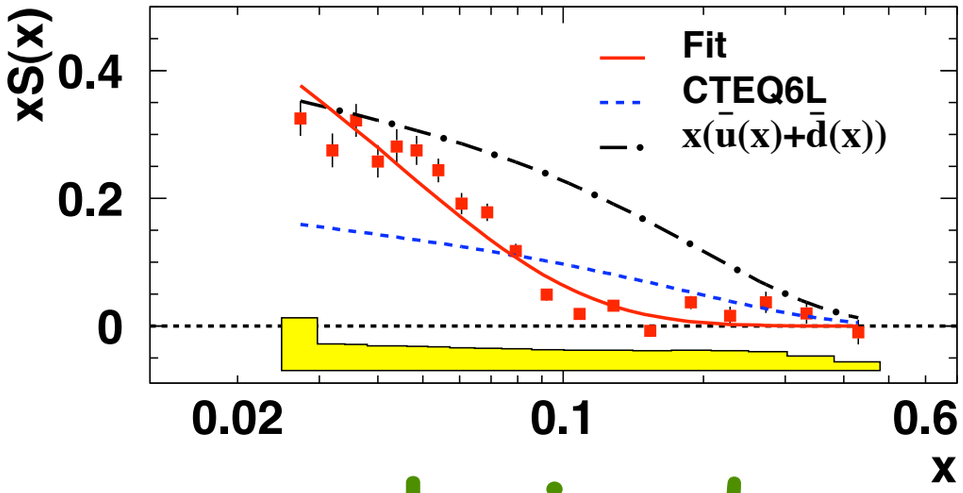
Beam-Spin asymmetry on H

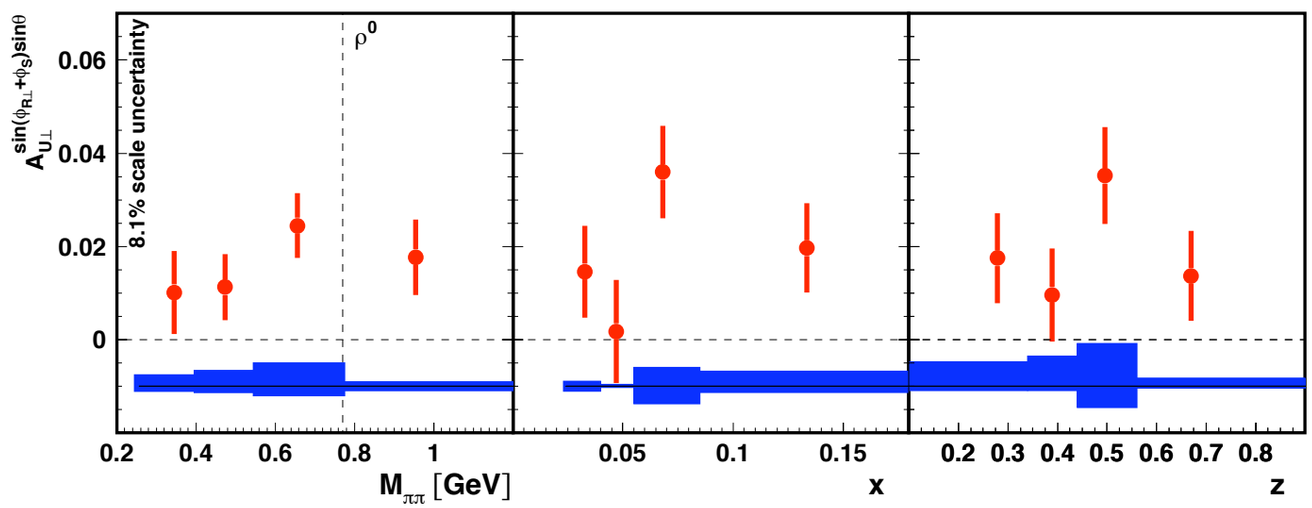
Beam-Charge asymmetry on D

Beam-Spin asymmetry on D

no model so far able to describe all data!


hermes

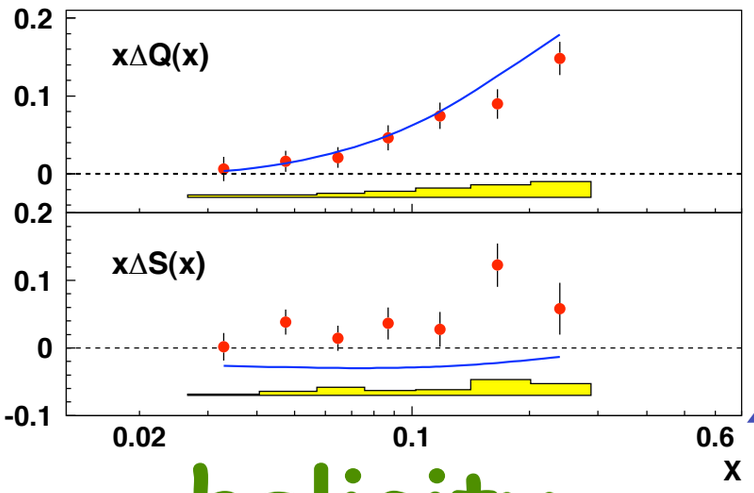




unpolarized quarks

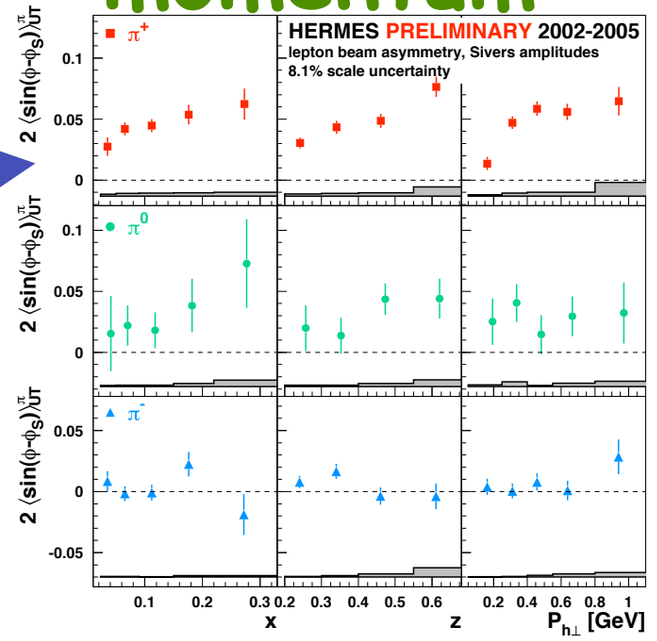
transversity

orbital angular momentum

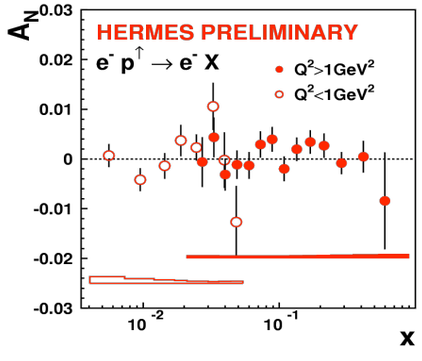


helicity distributions

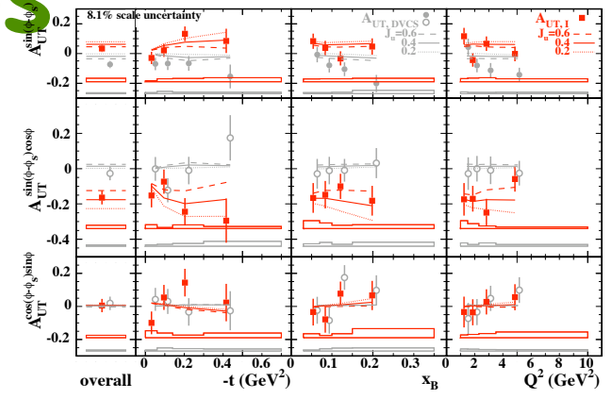
hermes



2-Photon Exchange

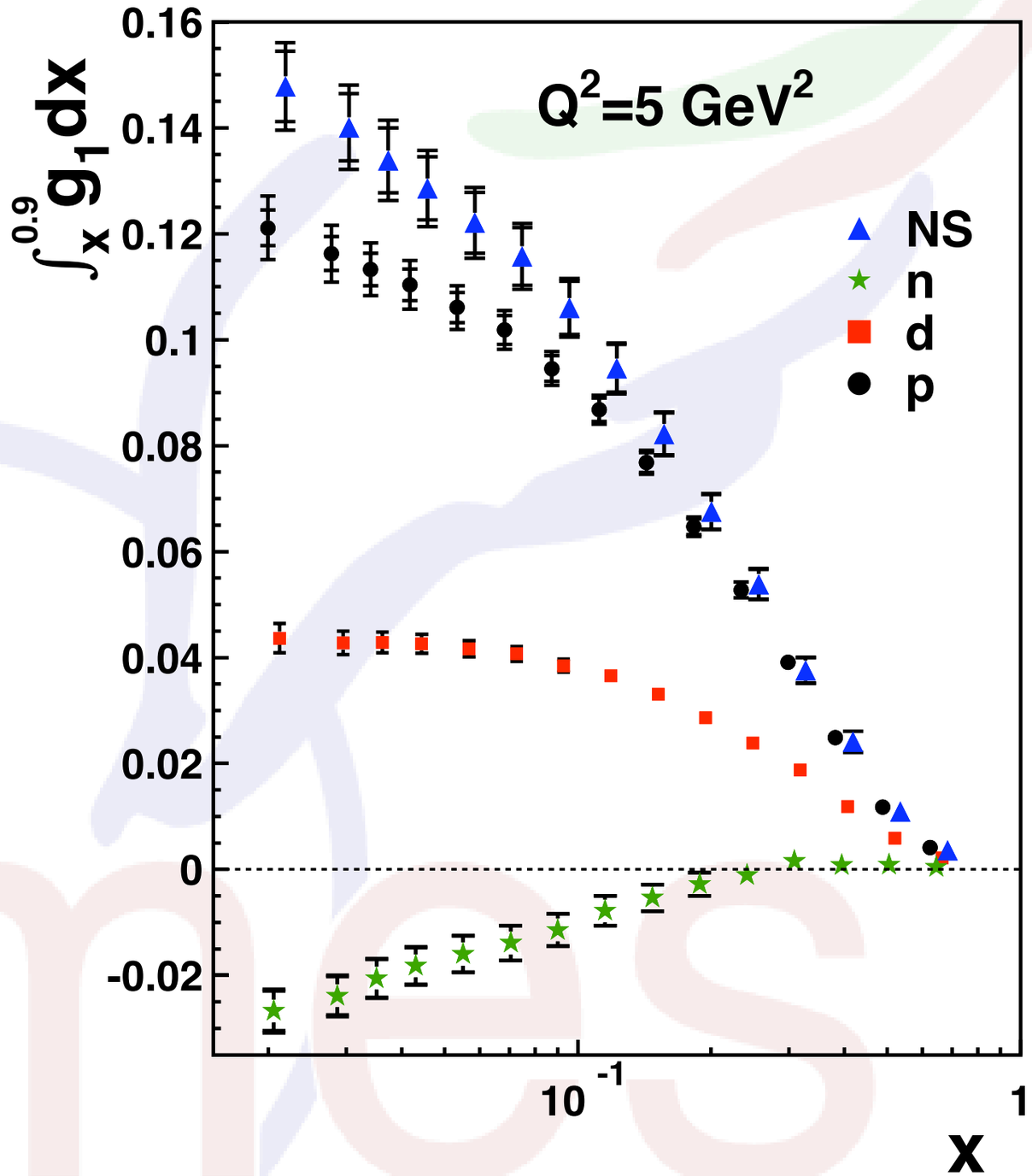


GPDs



Backup Slides

Integral of $g_1(x)$



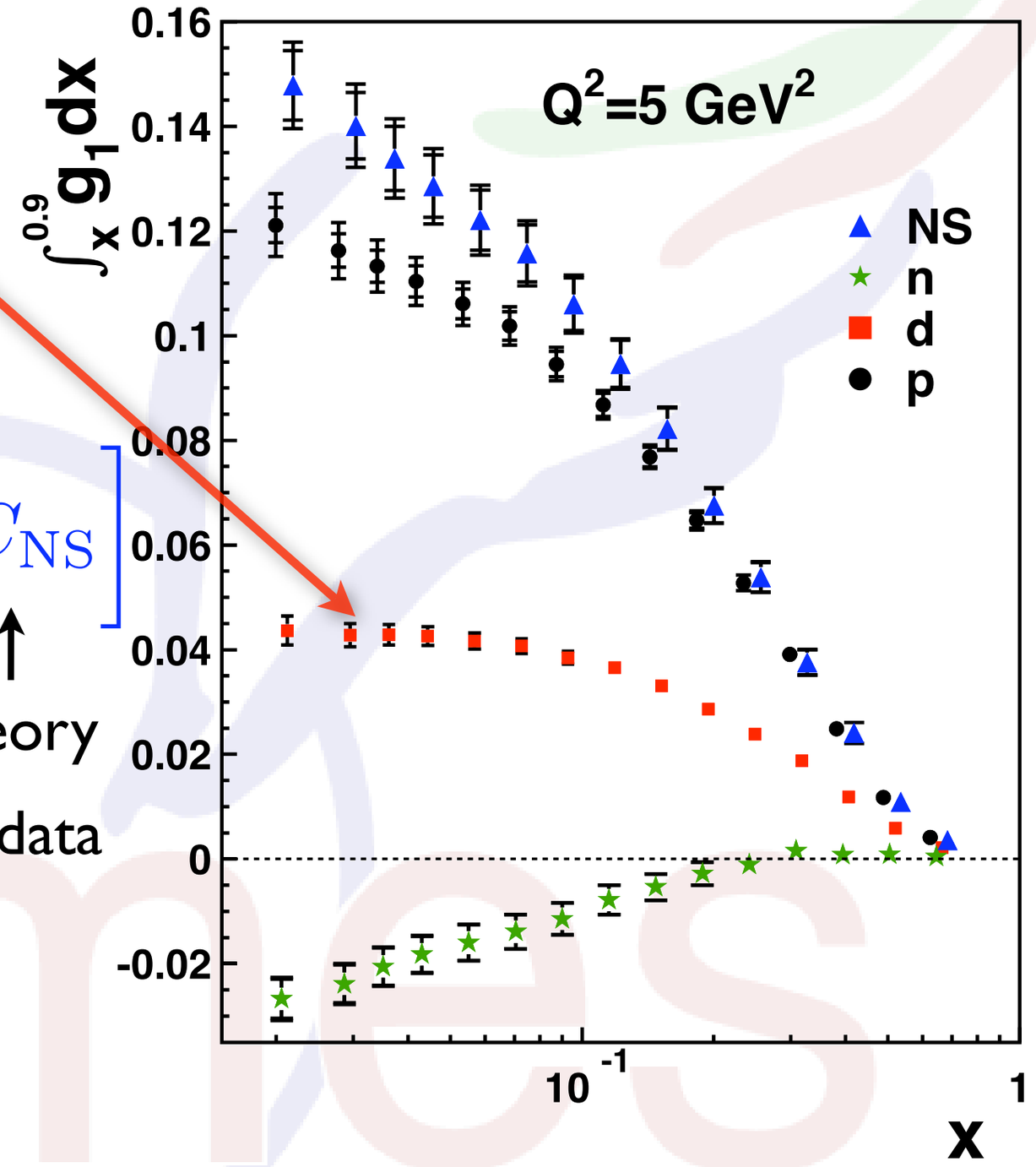
Integral of $g_1(x)$

Saturation

➠ **close to full integral?**

$$\Delta\Sigma \overset{\overline{\rm MS}}{=} \frac{1}{\Delta C_{\rm S}}\left[\frac{9\Gamma_1^d}{1-\frac{3}{2}\omega_D} - \frac{1}{4}a_8\Delta C_{\rm NS}\right]$$

theory ↑ — 0.05 ± 0.05 ↑ — hyperon-decay data ↑ — theory ↑



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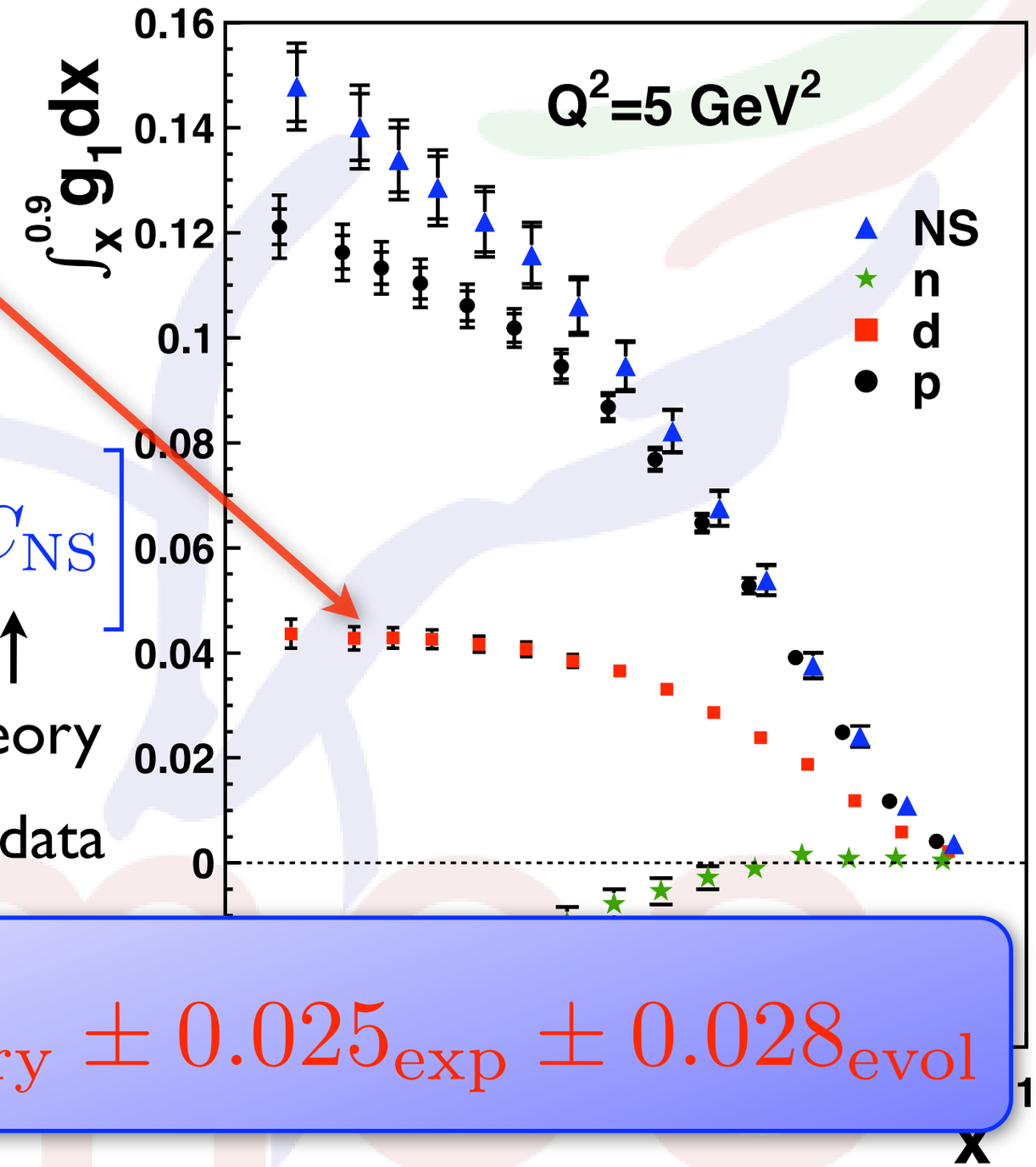
theory

0.05 ± 0.05

hyperon-decay data

theory



$$\Delta\Sigma \overset{\overline{\rm MS}}{=} 0.330 \pm 0.011_{\rm theory} \pm 0.025_{\rm exp} \pm 0.028_{\rm evol}$$

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- ω_D: 0.05±0.05
- Γ_1^d: hyperon-decay data
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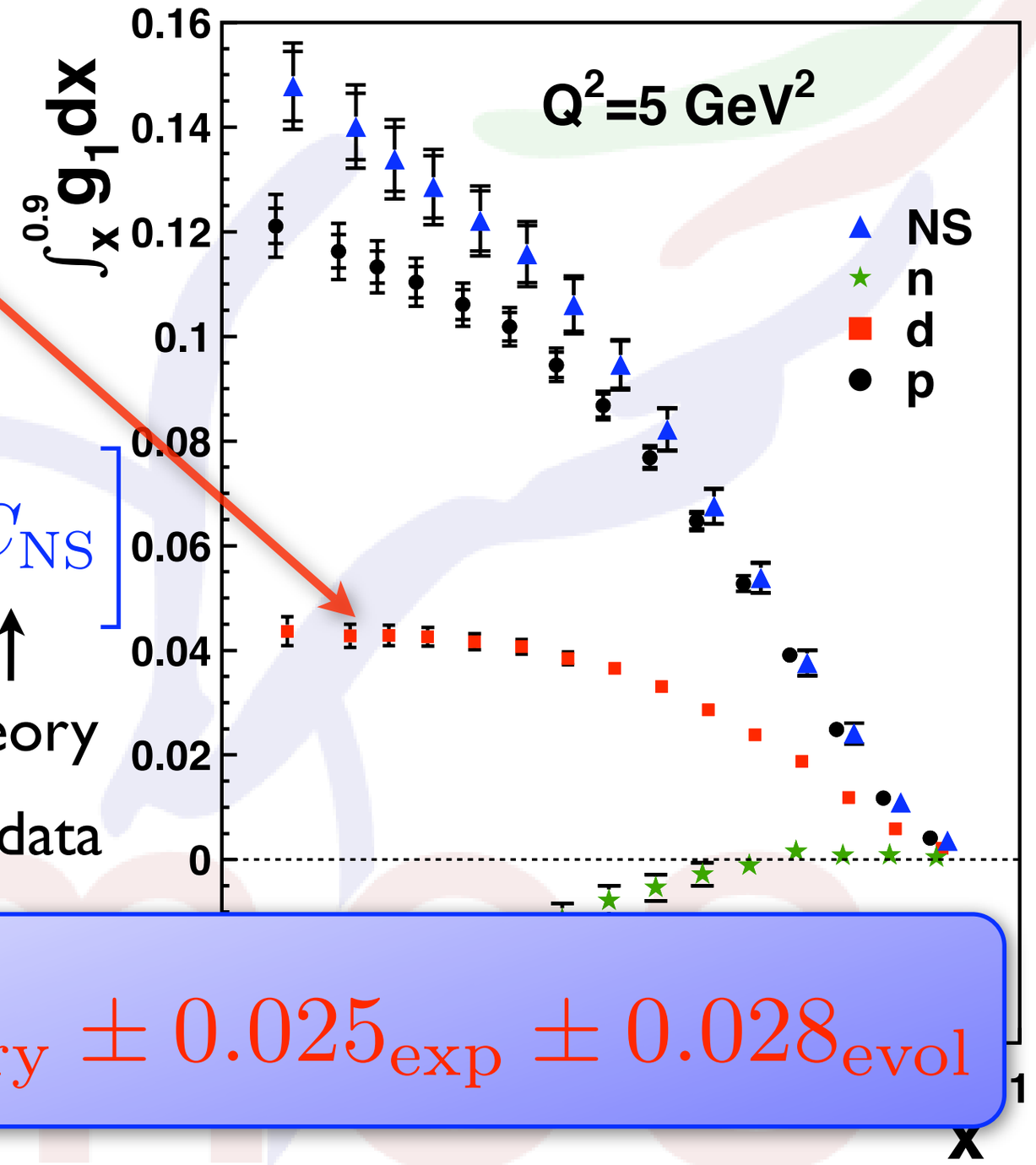


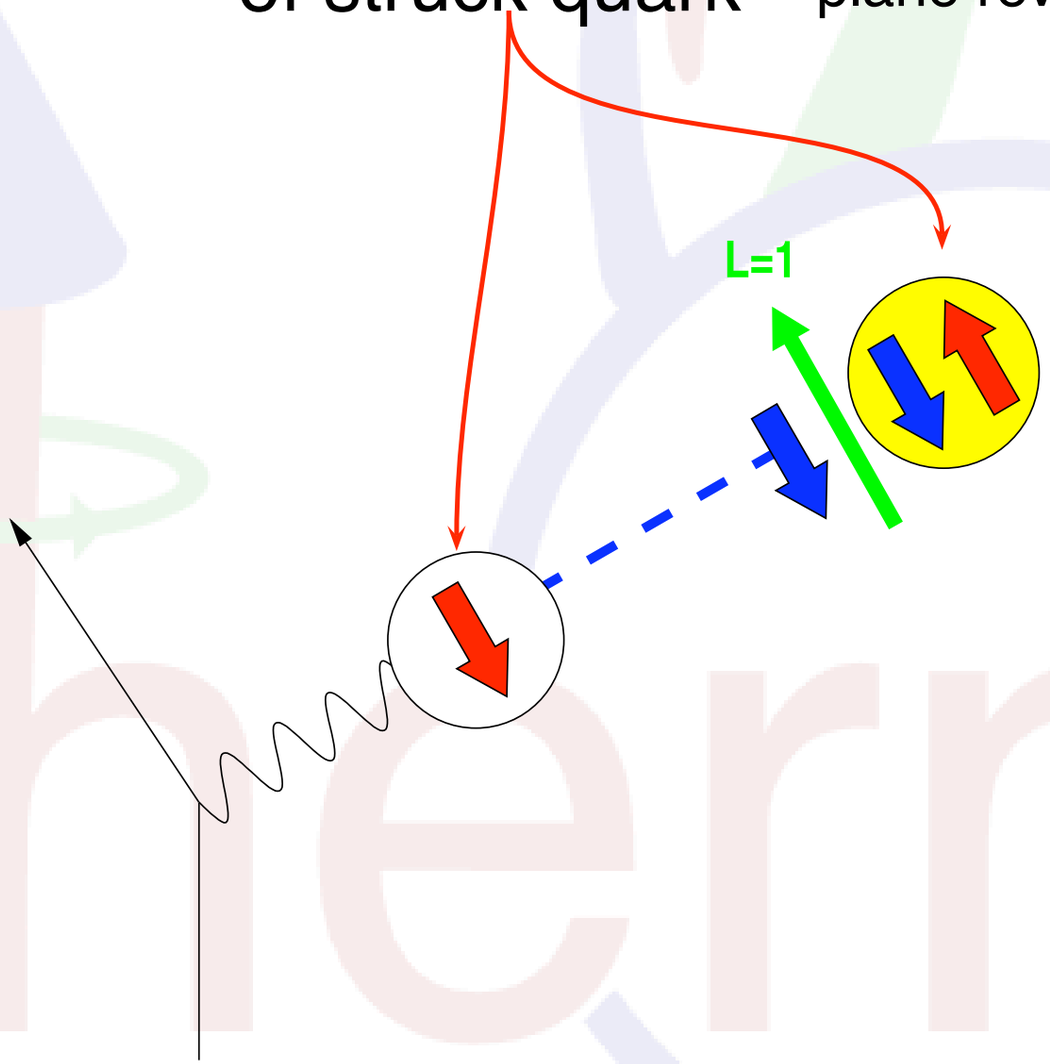
$$\Delta\Sigma \overset{\overline{\rm MS}}{=} 0.330 \pm 0.011_{\rm theory} \pm 0.025_{\rm exp} \pm 0.028_{\rm evol}$$

most precise result; only 1/3 of nucleon spin from quarks

Collins Fragmentation Function
String Model Interpretation (Artru)

transverse spin of struck quark

(polarization component in lepton scattering plane reversed by photoabsorption)



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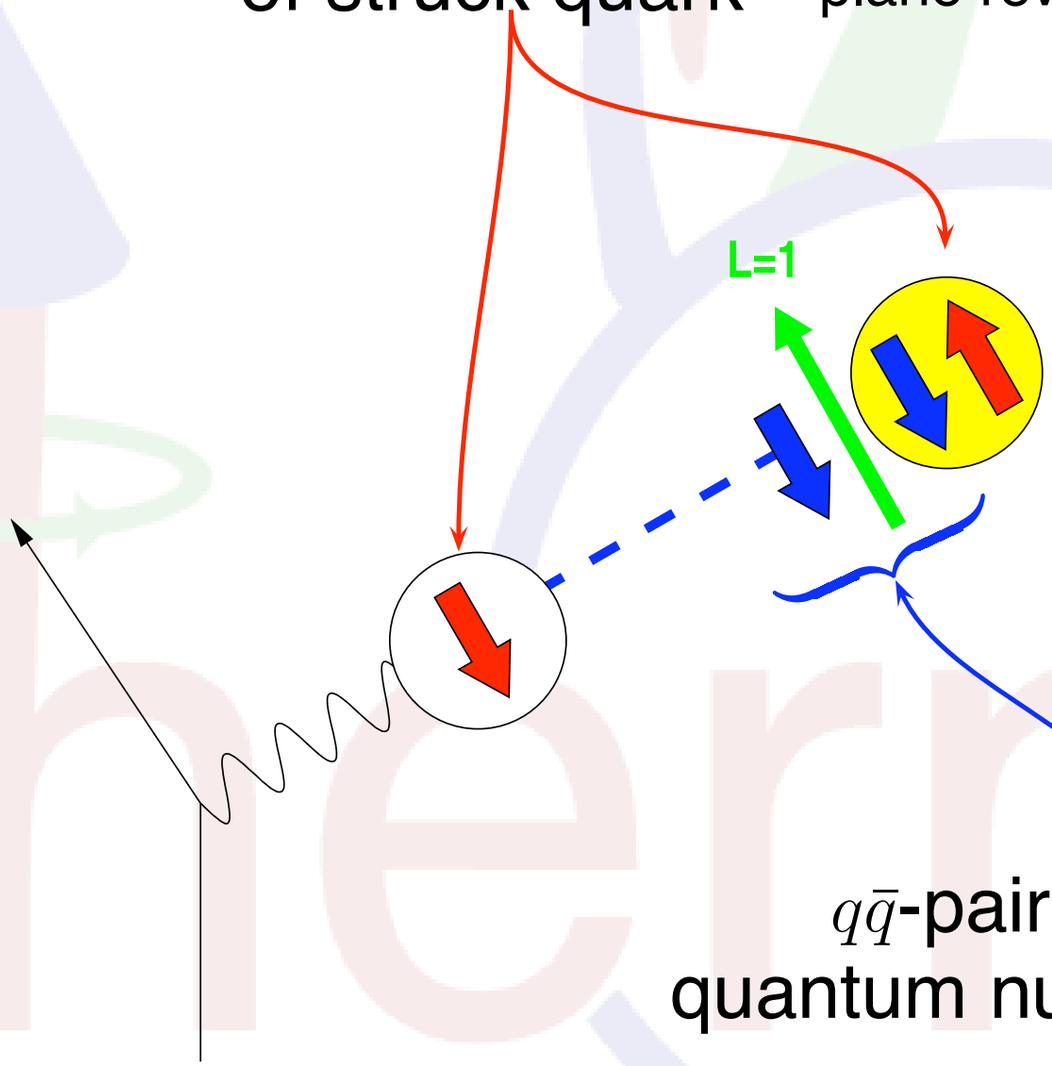

$q\bar{q}$-pair with vacuum quantum numbers ($^3P_0$-state)

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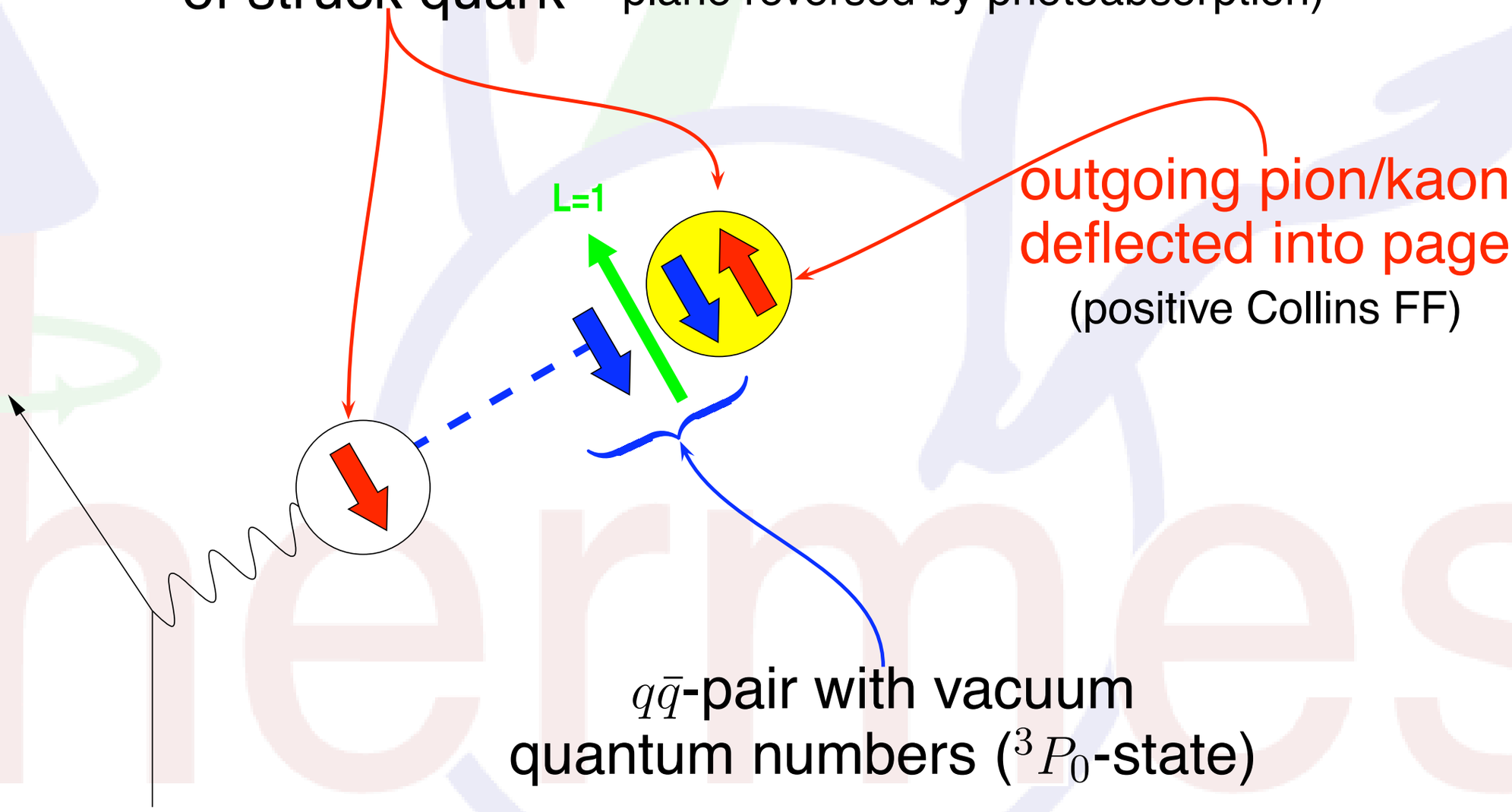


outgoing pion/kaon deflected into page

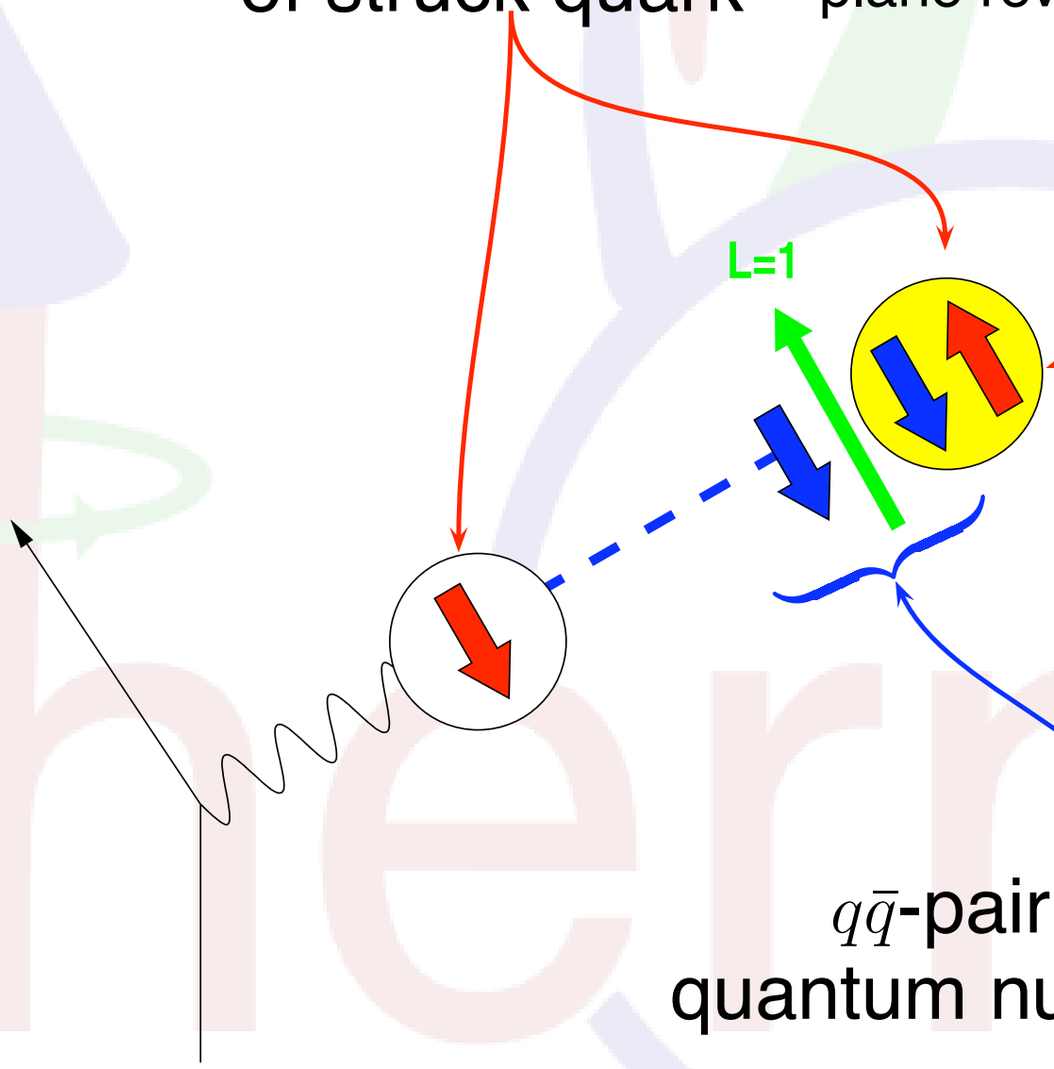
(positive Collins FF)

$q\bar{q}$-pair with vacuum quantum numbers ($^3P_0$-state)

Collins Fragmentation Function
String Model Interpretation (Artru)

transverse spin of struck quark

(polarization component in lepton scattering plane reversed by photoabsorption)



outgoing pion/kaon deflected into page

(positive Collins FF)

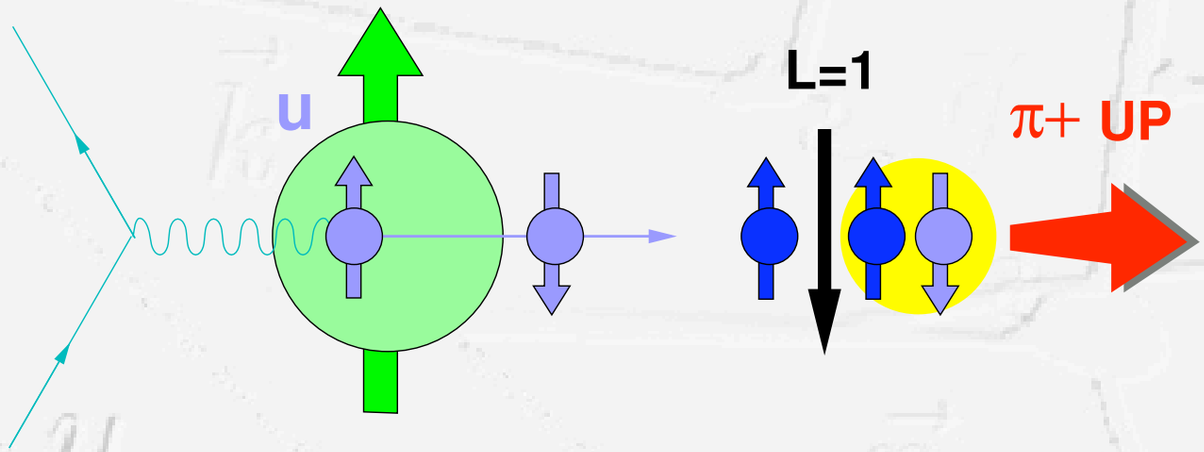
pion from next string break deflected out of page

(negative Collins FF)

$q\bar{q}$-pair with vacuum quantum numbers ($^3P_0$-state)

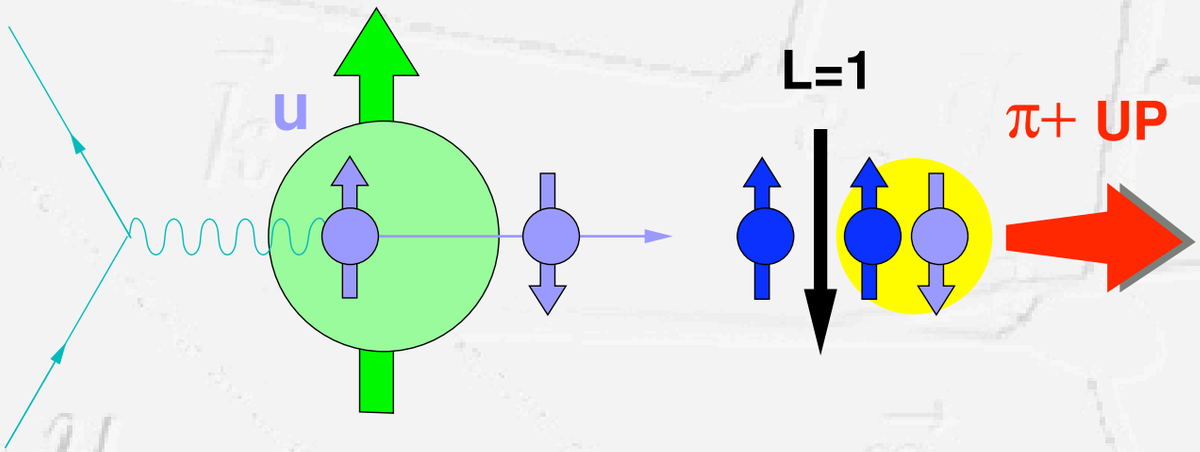
Artru Model vs. HERMES

Artru Model vs. HERMES



$$\left.\begin{array}{l}\phi_S = 0 \\ \phi = \pi/2\end{array}\right\} \sin(\phi + \phi_S) > 0$$

Artru Model vs. HERMES



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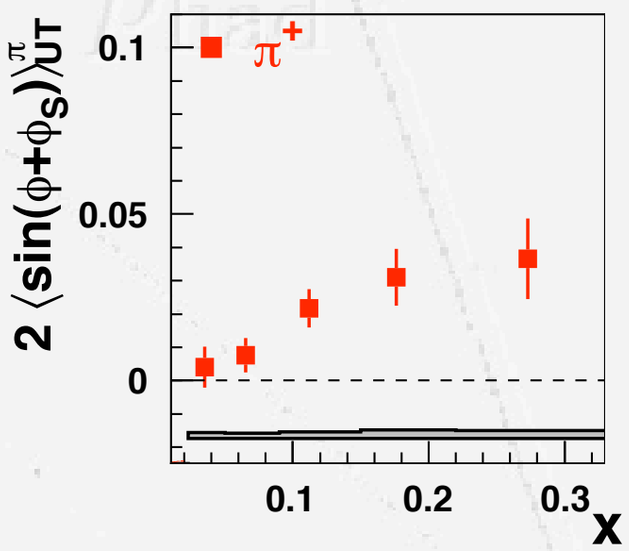
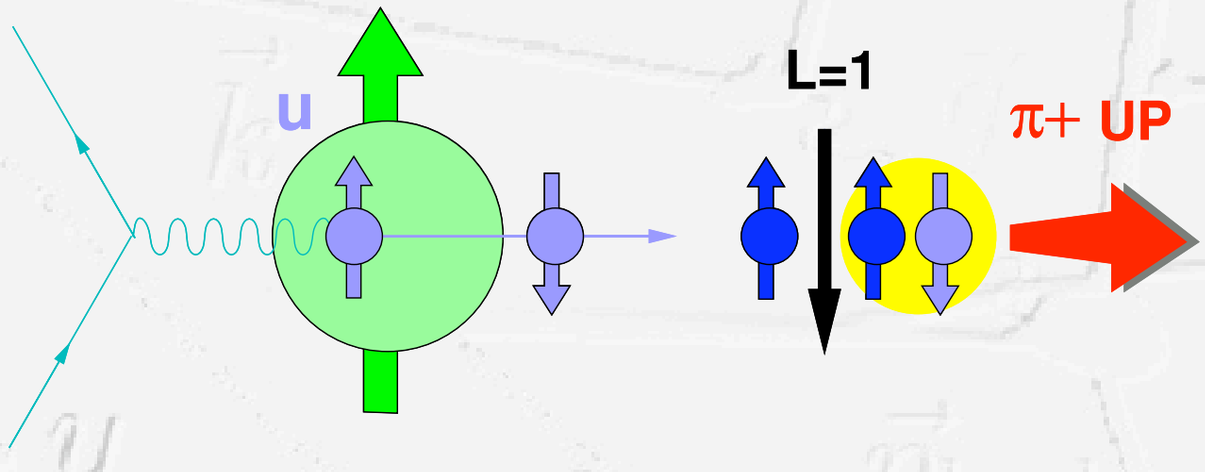


Artru Model vs. HERMES



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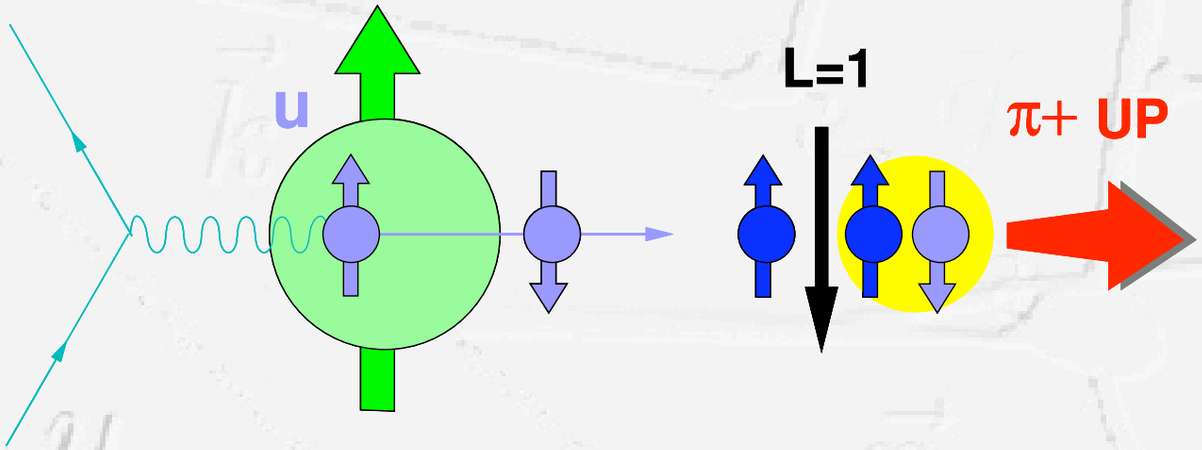
✓

Artru Model vs. HERMES



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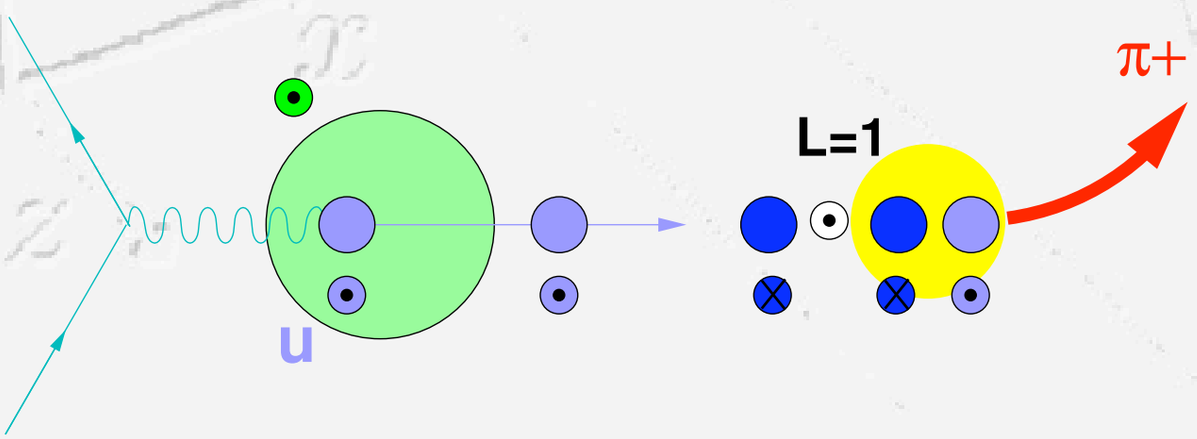
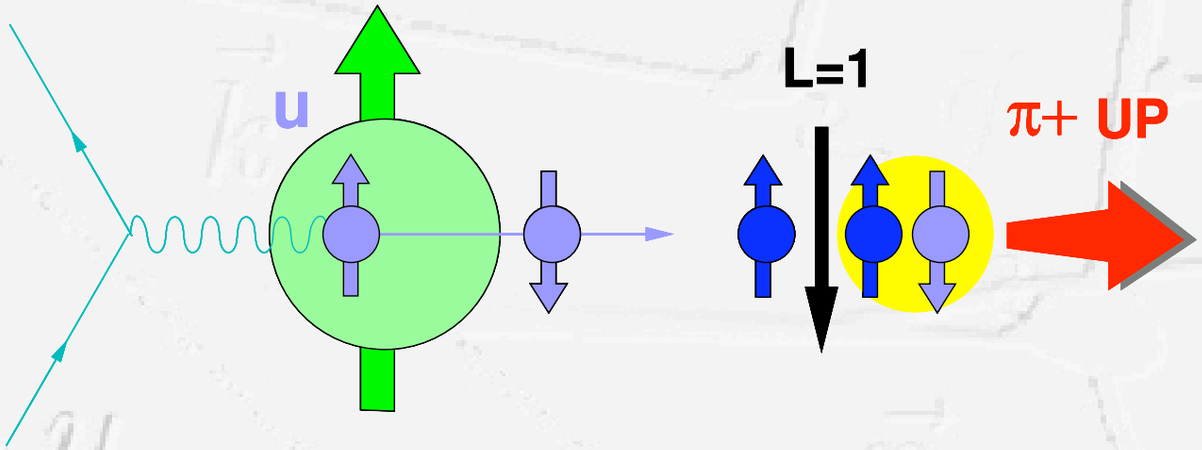
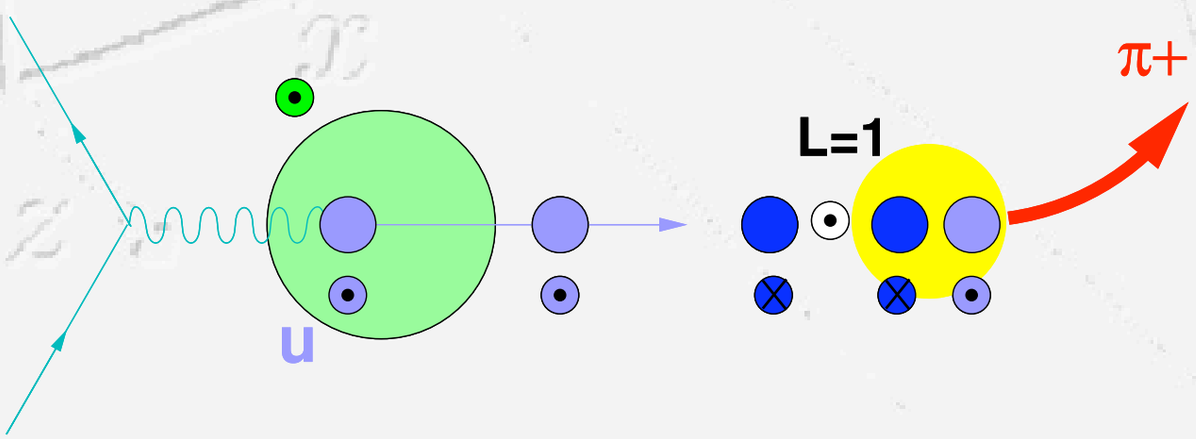


$$\left.\begin{array}{l}\phi_S = \pi/2 \\ \phi = 0\end{array}\right\} \sin(\phi + \phi_S) > 0$$

Artru Model vs. HERMES



$$\left.\begin{array}{l}\phi_S = 0 \\ \phi = \pi/2\end{array}\right\} \sin(\phi+\phi_S) > 0$$



$$\left.\begin{array}{l}\phi_S = \pi/2 \\ \phi = 0\end{array}\right\} \sin(\phi+\phi_S) > 0$$

Artru model and HERMES results in agreement!

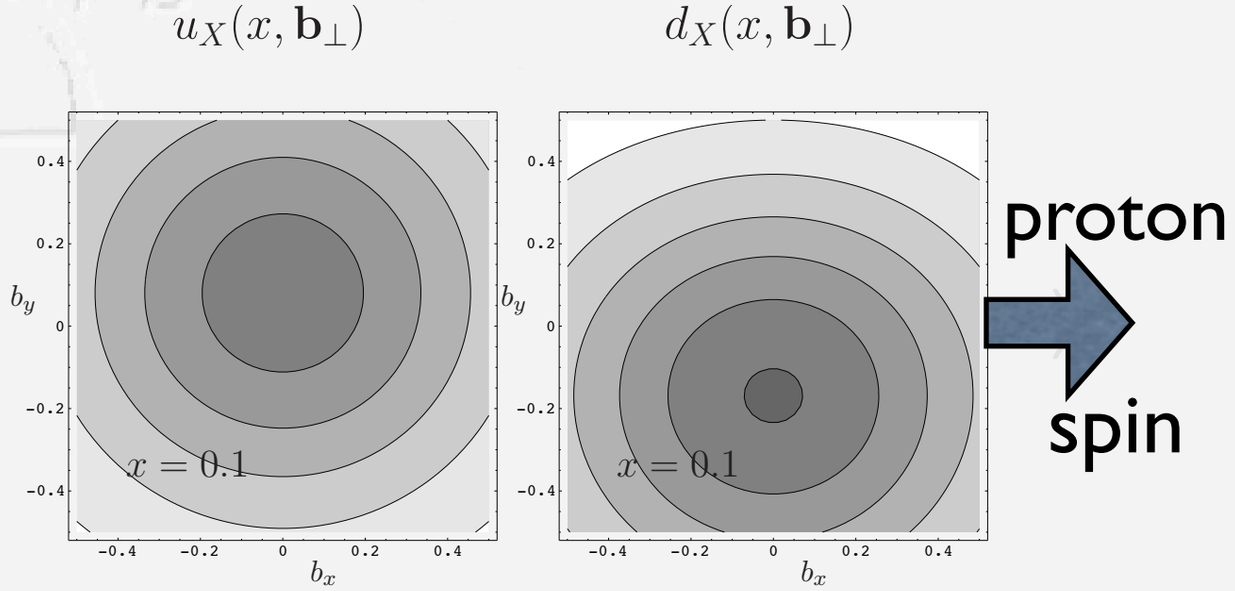
“Chromodynamic Lensing”

approach by M. Burkardt:

[hep-ph/0309269]

spatial distortion of q-distribution

(obtained using anom. magn. moments & impact parameter dependent PDFs)



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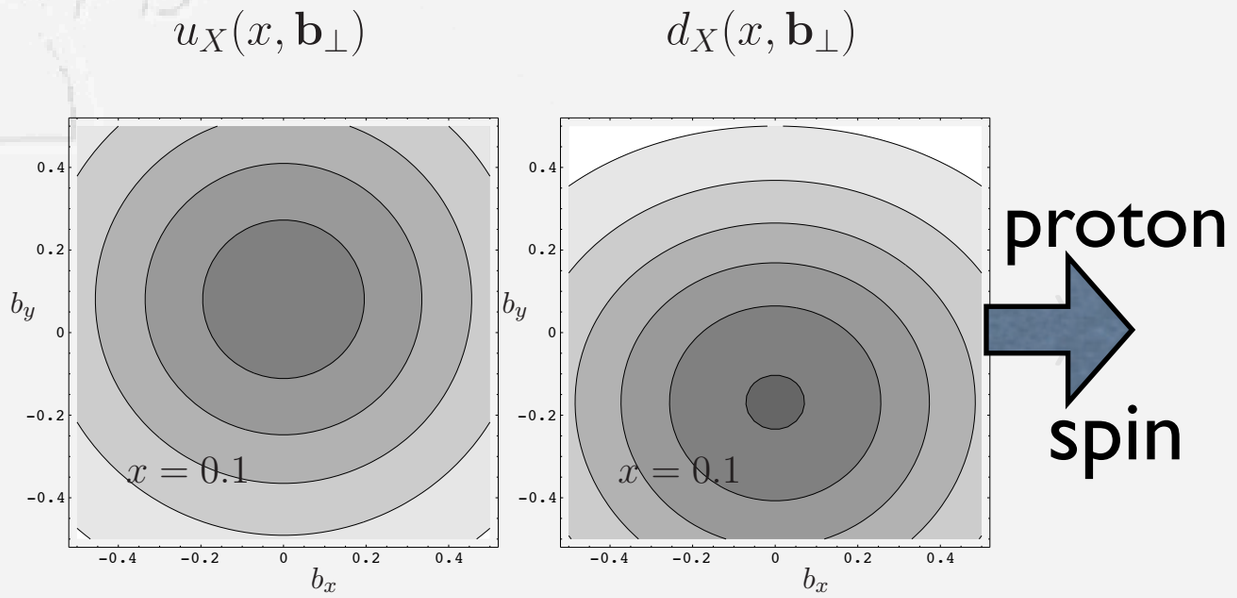
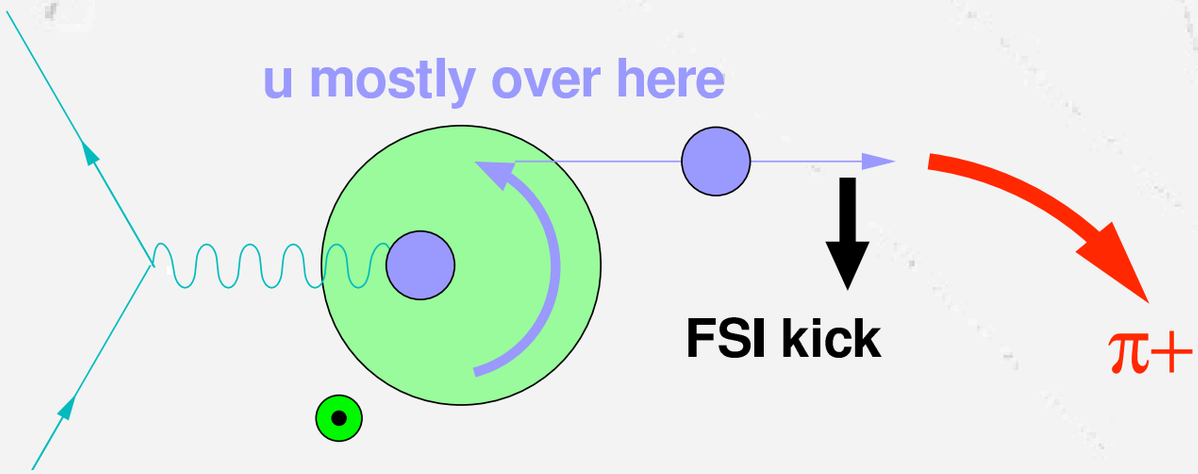
+ attractive QCD potential

(gluon exchange)

⇒ transverse asymmetries





$$\left.\begin{array}{l}\phi_S = \pi/2 \\ \phi = \pi\end{array}\right\} \sin(\phi - \phi_S) > 0$$

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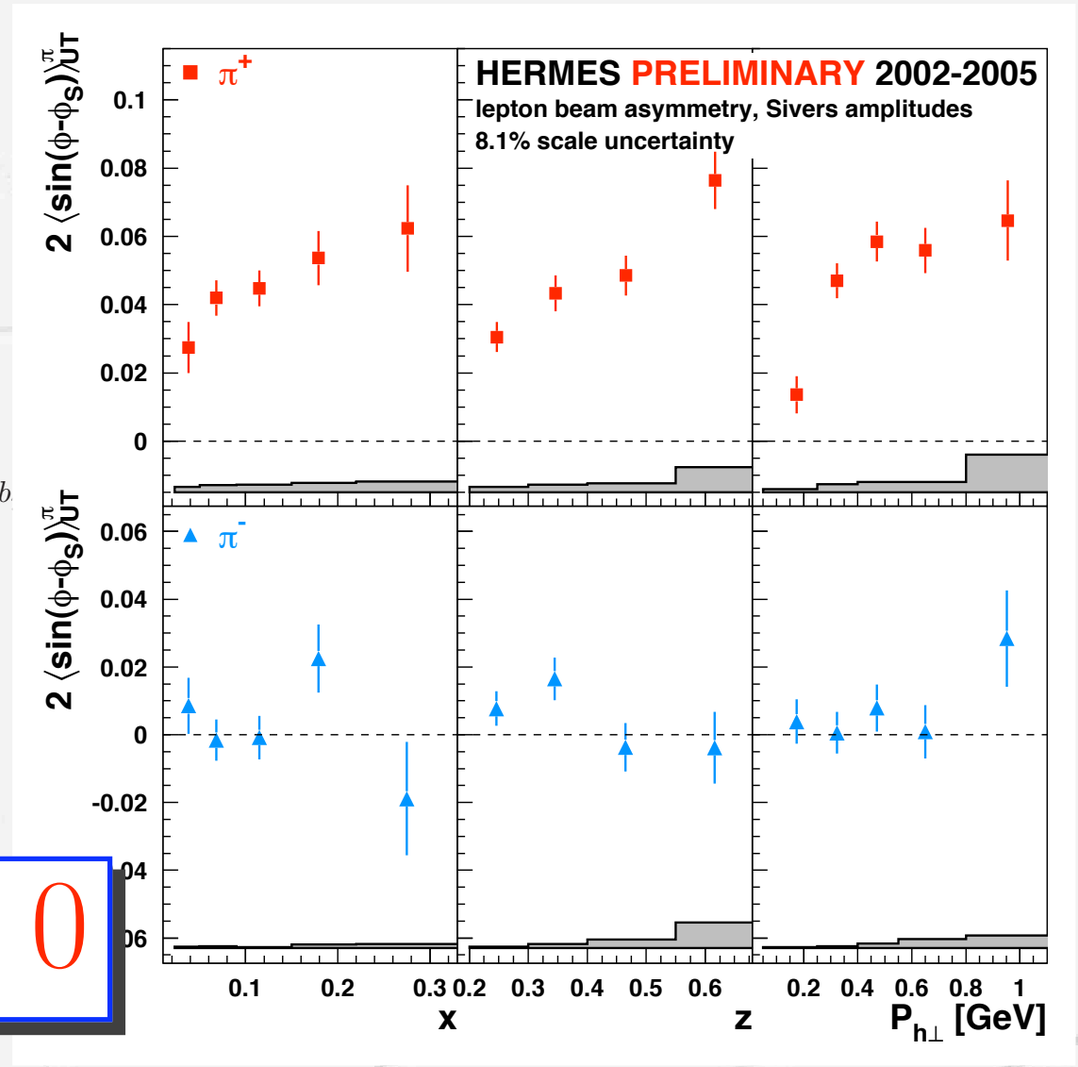
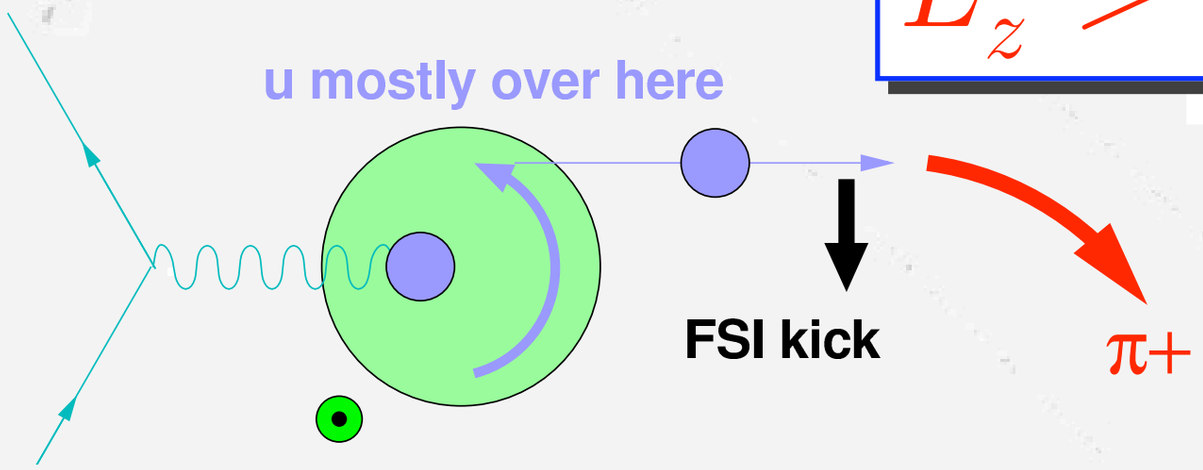
+ attractive QCD potential

(gluon exchange)

⇒ transverse asymmetries

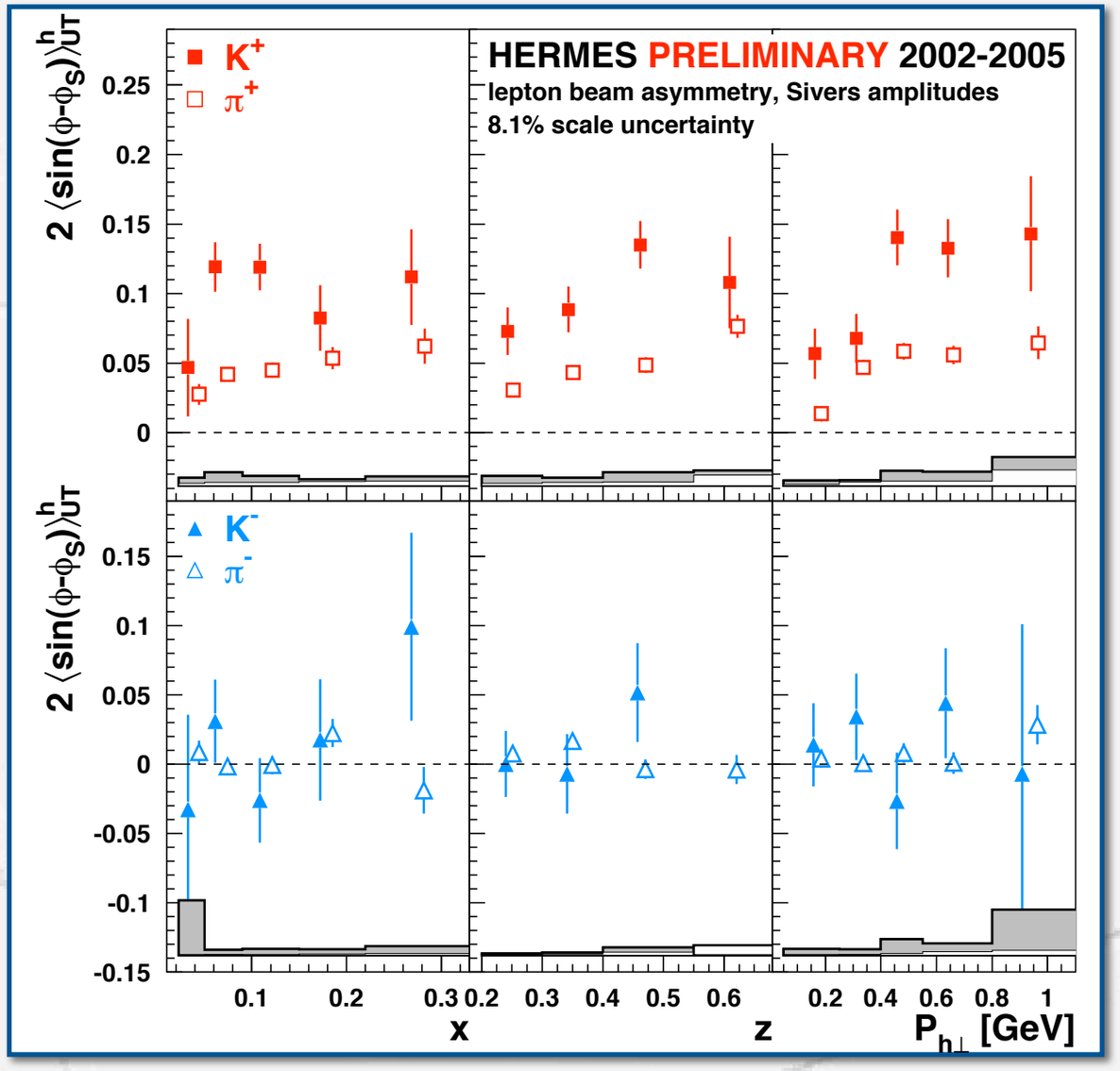
$$L_z^u > 0$$



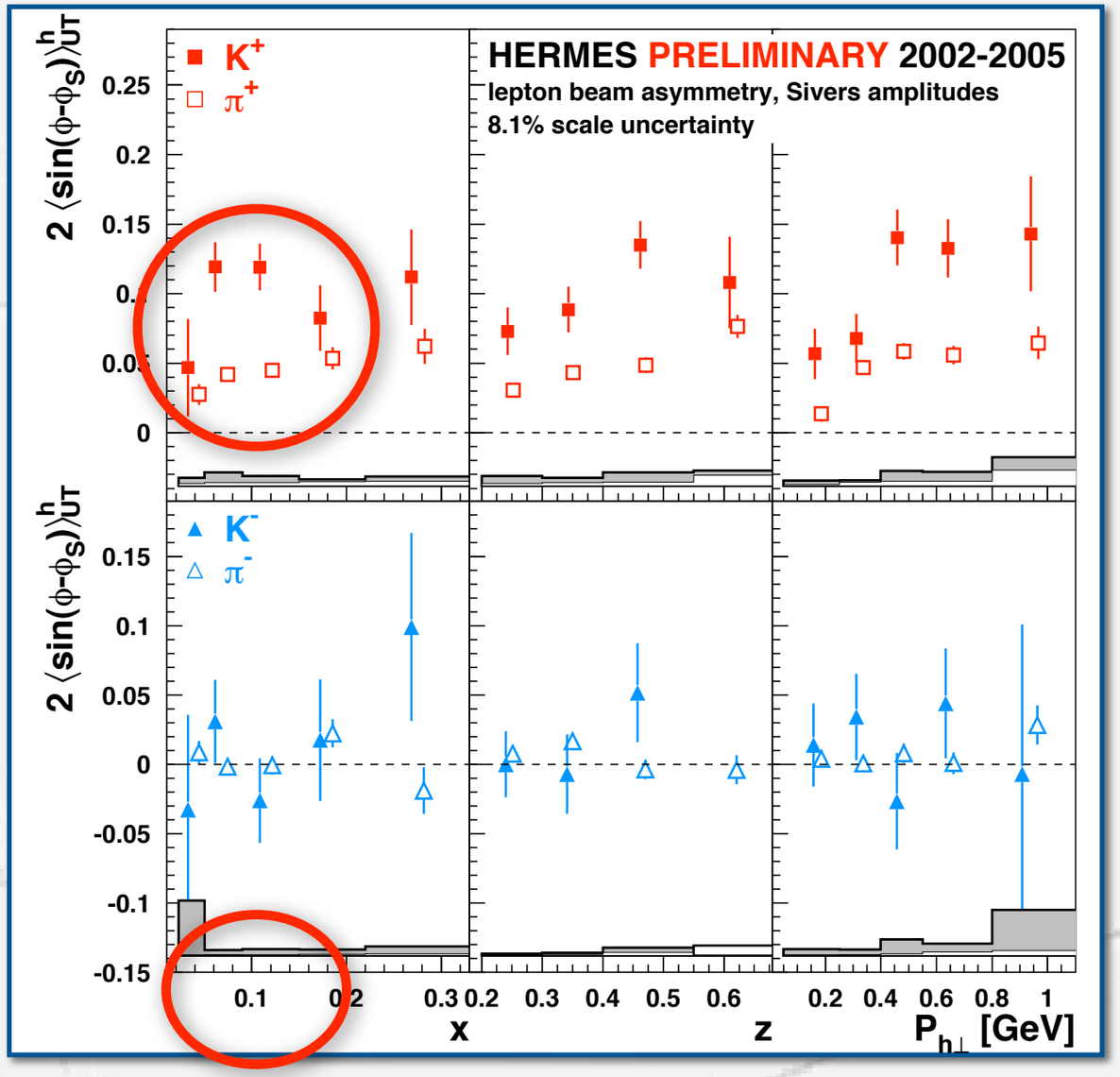


$$\left.\begin{array}{l}\phi_S = \pi/2 \\ \phi = \pi\end{array}\right\} \sin(\phi - \phi_S) > 0$$

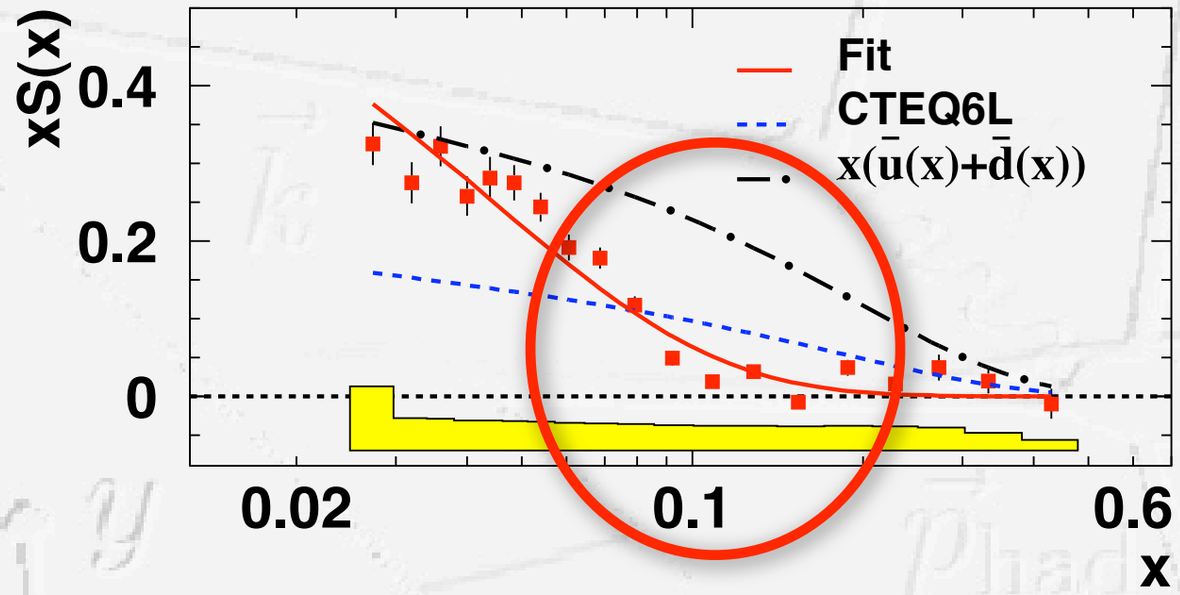
The “Kaon Challenge”

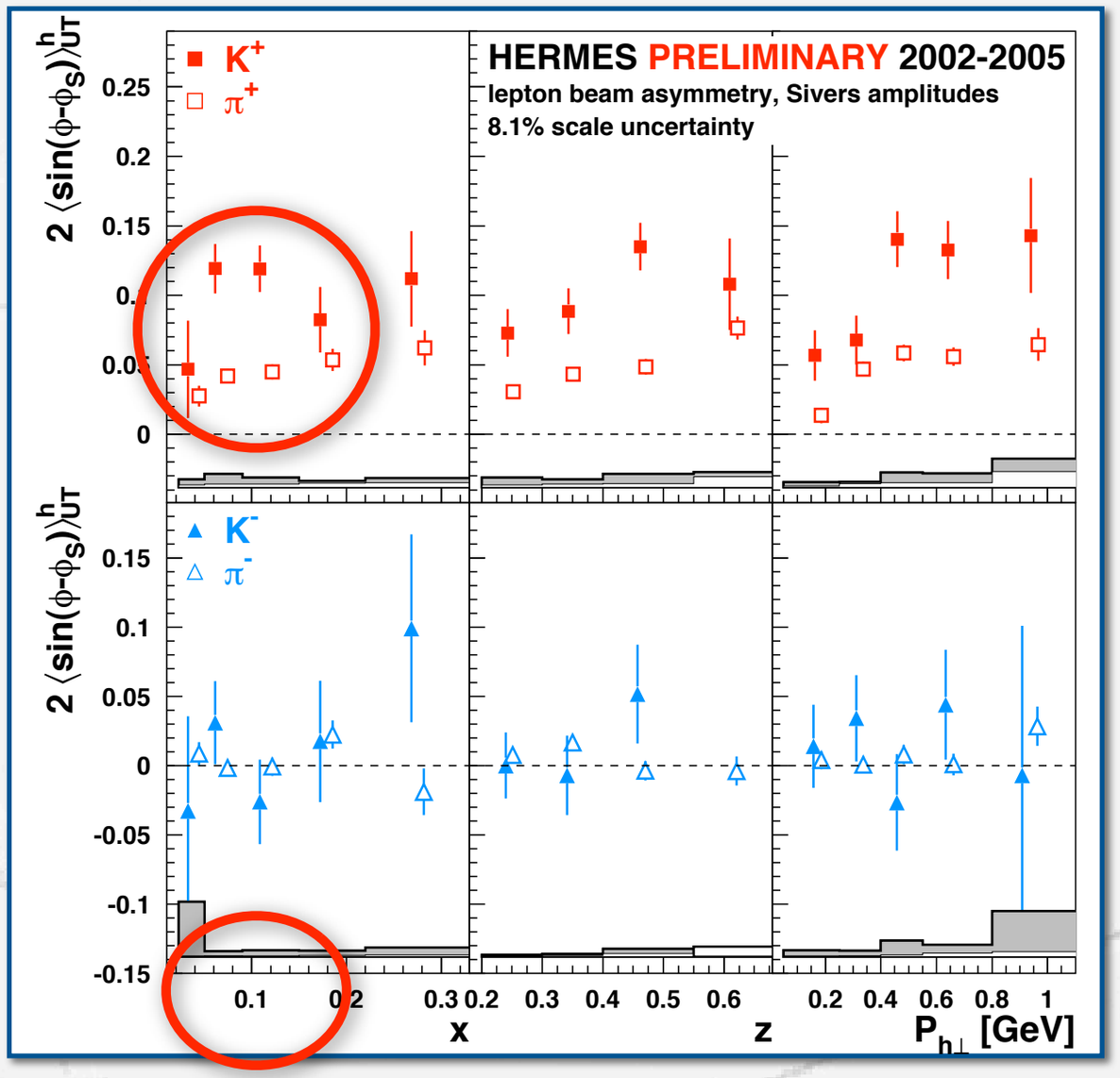


The “Kaon Challenge”

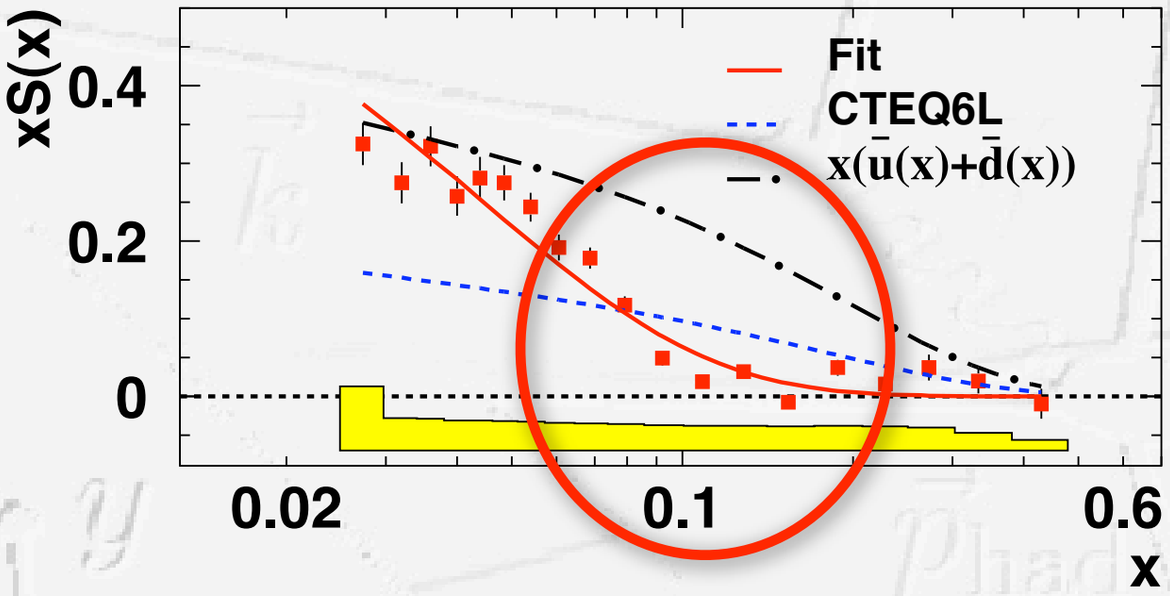


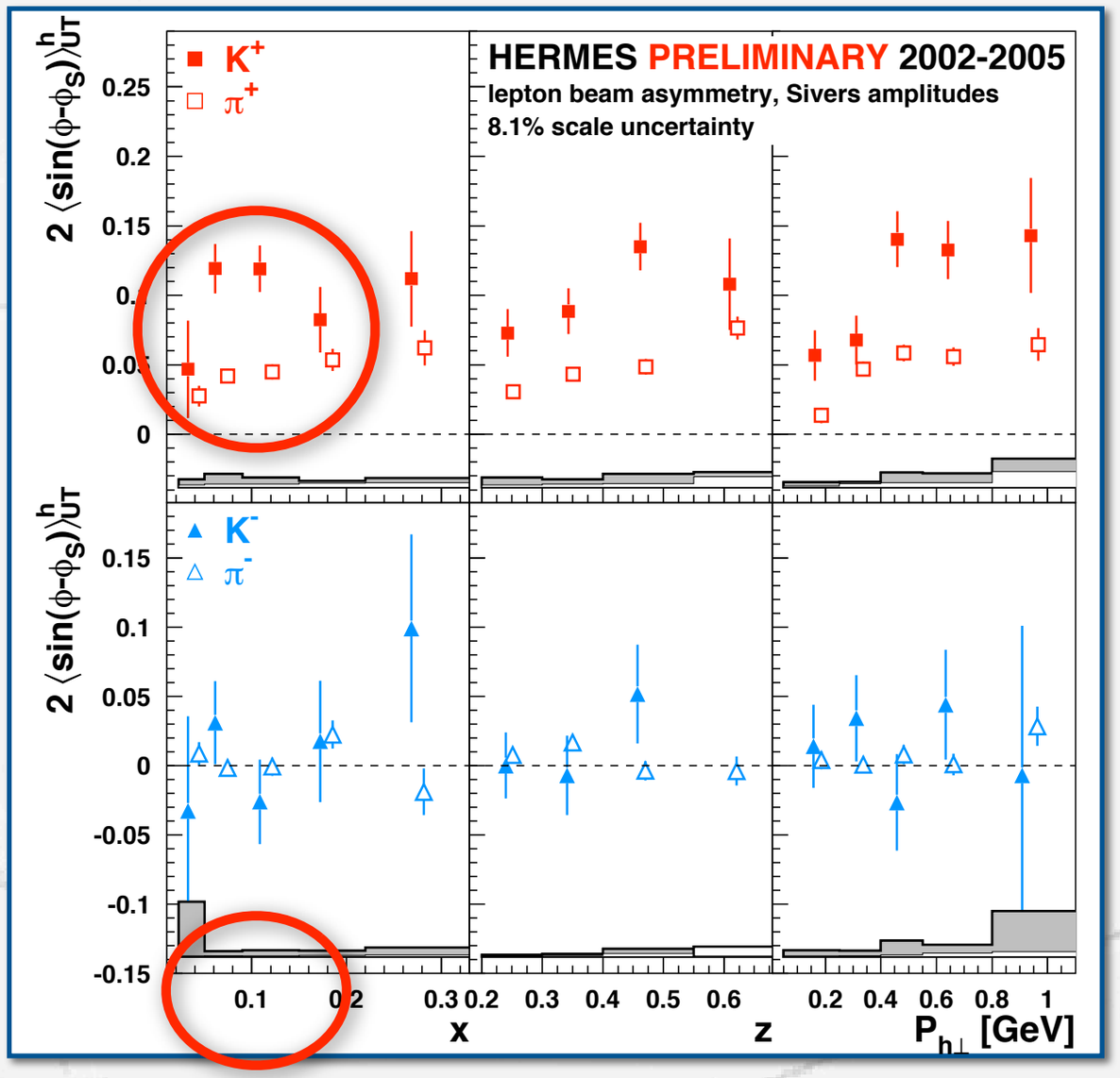
The “Kaon Challenge”





The “Kaon Challenge”





differences biggest in region where strange sea is most different from light sea

DVCS Asymmetries

$$\mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi,\phi_S) \equiv \frac{1}{S_\perp}\cdot\frac{d\sigma^+(\phi,\phi_S)-d\sigma^+(\phi,\phi_S+\pi)+d\sigma^-(\phi,\phi_S)-d\sigma^-(\phi,\phi_S+\pi)}{d\sigma^+(\phi,\phi_S)+d\sigma^+(\phi,\phi_S+\pi)+d\sigma^-(\phi,\phi_S)+d\sigma^-(\phi,\phi_S+\pi)}$$

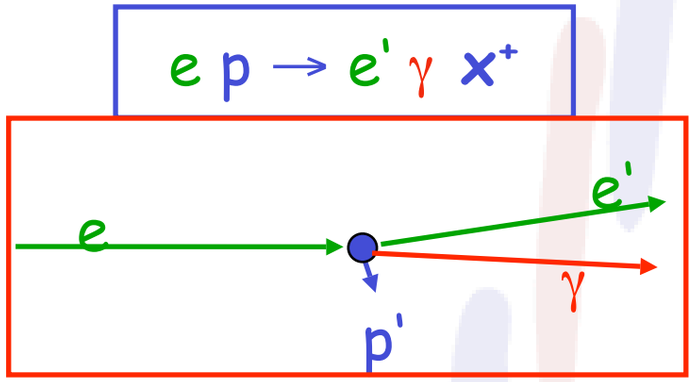
$$\mathcal{A}_{\mathrm{UT}}^{\mathrm{I}}(\phi,\phi_S) \equiv \frac{1}{S_\perp}\cdot\frac{d\sigma^+(\phi,\phi_S)-d\sigma^+(\phi,\phi_S+\pi)-d\sigma^-(\phi,\phi_S)+d\sigma^-(\phi,\phi_S+\pi)}{d\sigma^+(\phi,\phi_S)+d\sigma^+(\phi,\phi_S+\pi)+d\sigma^-(\phi,\phi_S)+d\sigma^-(\phi,\phi_S+\pi)}$$

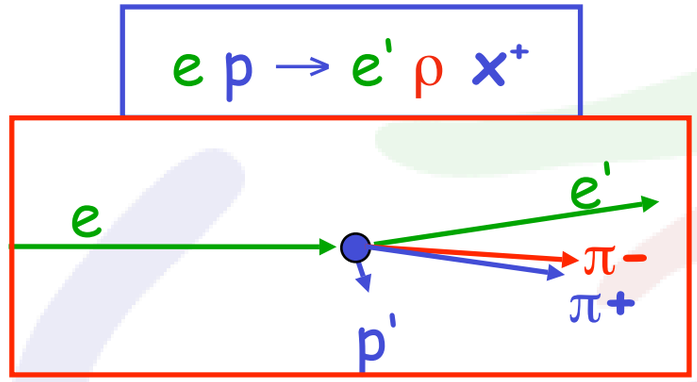
$$\begin{aligned}\mathcal{A}_{\mathrm{C}}(\phi) &= \frac{-\frac{K_{\mathrm{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{3} c_{n,\mathrm{UU}}^{I}\cos(n\phi)}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{2} c_{n,\mathrm{UU}}^{\mathrm{BH}}\cos(n\phi)+K_{\mathrm{DVCS}}\sum_{n=0}^{2} c_{n,\mathrm{UU}}^{\mathrm{DVCS}}\cos(n\phi)} \\ &\simeq \frac{-K_{\mathrm{I}}\left[c_{1,\mathrm{UU}}^{I}\cos(\phi)\right]}{K_{\mathrm{BH}}c_{0,\mathrm{UU}}^{\mathrm{BH}}},\end{aligned} \tag{4.4}$$

$$\begin{aligned}\mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi,\phi_S) &= \\ &\frac{K_{\mathrm{DVCS}}\left[\sum_{n=0}^{2} c_{n,\mathrm{UT}}^{\mathrm{DVCS}}\sin(\phi-\phi_S)\cos(n\phi)+\sum_{n=1}^{2} s_{n,\mathrm{UT}}^{\mathrm{DVCS}}\cos(\phi-\phi_S)\sin(n\phi)\right]}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{2} c_{n,\mathrm{UU}}^{\mathrm{BH}}\cos(n\phi)+K_{\mathrm{DVCS}}\sum_{n=0}^{2} c_{n,\mathrm{UU}}^{\mathrm{DVCS}}\cos(n\phi)}, \\ &\simeq \frac{K_{\mathrm{DVCS}}c_{0,\mathrm{UT}}^{\mathrm{DVCS}}\sin(\phi-\phi_S)}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}c_{0,\mathrm{UU}}^{\mathrm{BH}}}\end{aligned} \tag{4.5}$$

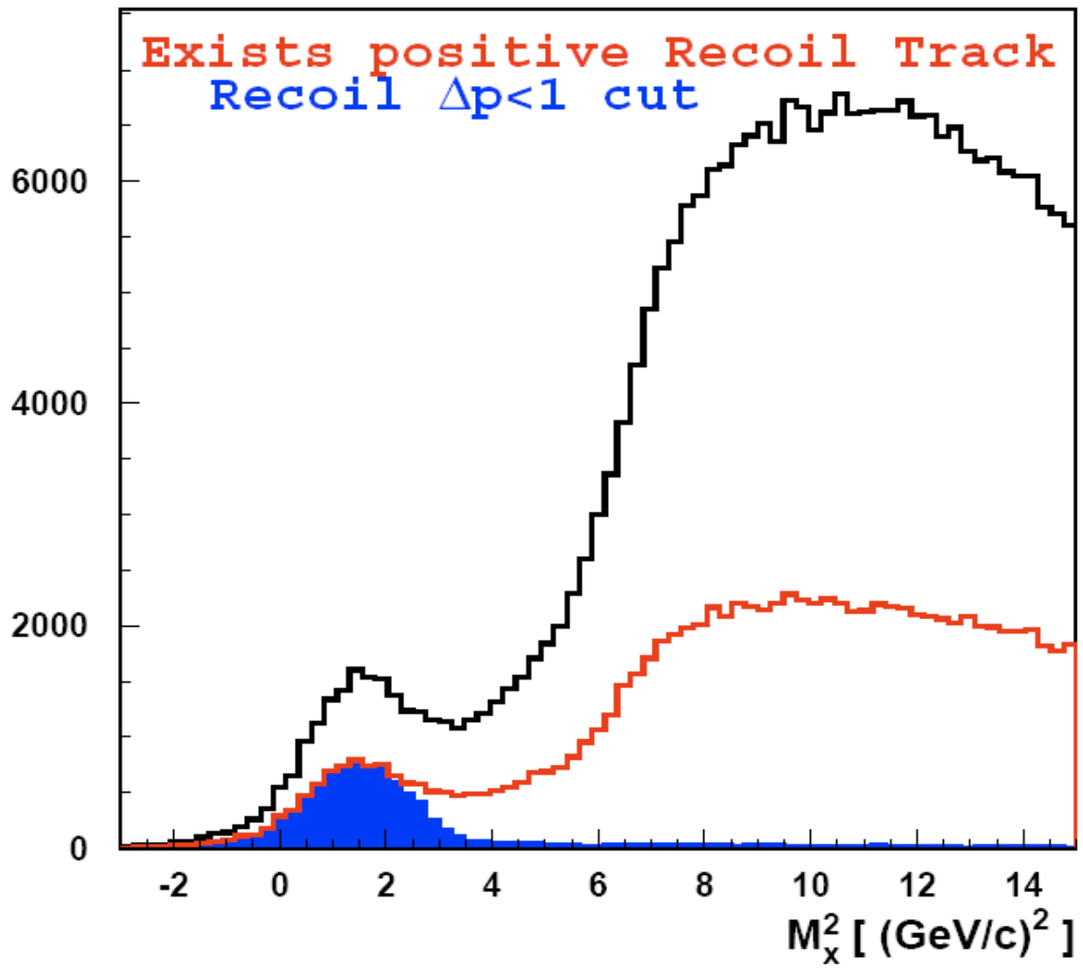
$$\begin{aligned}\mathcal{A}_{\mathrm{UT}}^{\mathrm{I}}(\phi,\phi_S) &= \\ &\frac{-\frac{K_{\mathrm{I}}e_l}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\left[\sum_{n=0}^{3} c_{n,\mathrm{UT}}^{\mathrm{I}}\sin(\phi-\phi_S)\cos(n\phi)+\sum_{n=1}^{3} s_{n,\mathrm{UT}}^{\mathrm{I}}\cos(\phi-\phi_S)\sin(n\phi)\right]}{\frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}\sum_{n=0}^{2} c_{n,\mathrm{UU}}^{\mathrm{BH}}\cos(n\phi)+K_{\mathrm{DVCS}}\sum_{n=0}^{2} c_{n,\mathrm{UU}}^{\mathrm{DVCS}}\cos(n\phi)} \\ &\simeq \frac{-K_{\mathrm{I}}e_l\left[c_{1,\mathrm{UT}}^{\mathrm{I}}\sin(\phi-\phi_S)\cos\phi+s_{1,\mathrm{UT}}^{\mathrm{I}}\cos(\phi-\phi_S)\sin(\phi)\right]}{K_{\mathrm{BH}}c_{0,\mathrm{UU}}^{\mathrm{BH}}}.\end{aligned} \tag{4.6}$$

Event Selection with Recoil Detector





DVCS event candidates



Rho event candidates