Single Transverse-Spin Asymmetries in DIS off Transversely Polarized Protons

The Eighteenth Particles and Nuclei International Conference

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Gunar Schnell (DESY Zeuthen)

for the hermes Collaboration

Why transversely polarized nucleons?

- **vast information on spin-independent (f_1) and helicity (g_1) structure of nucleons available**
- **transverse polarization provides distinct view, e.g.**

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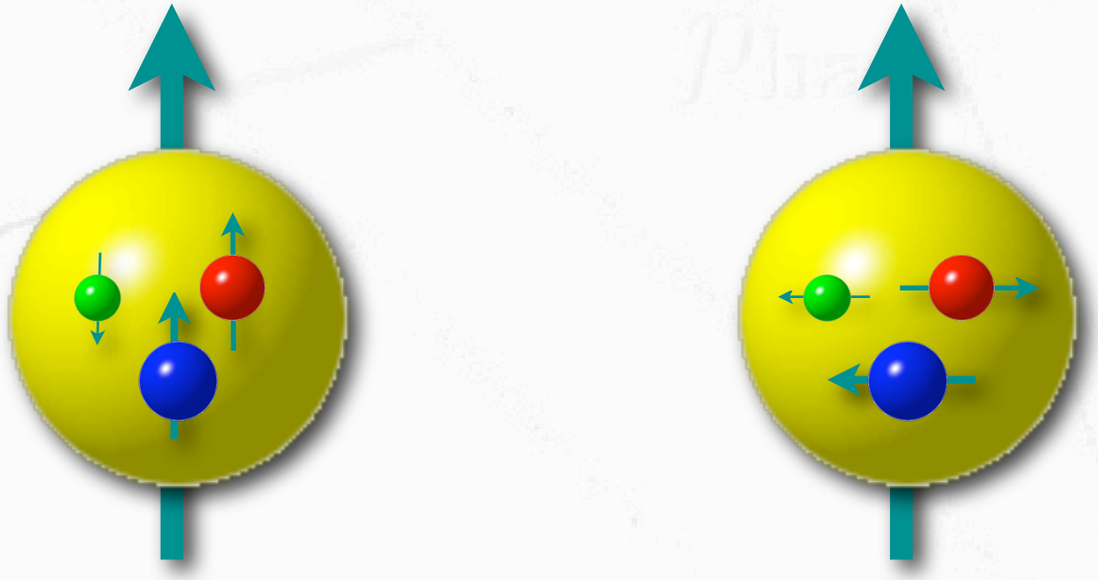

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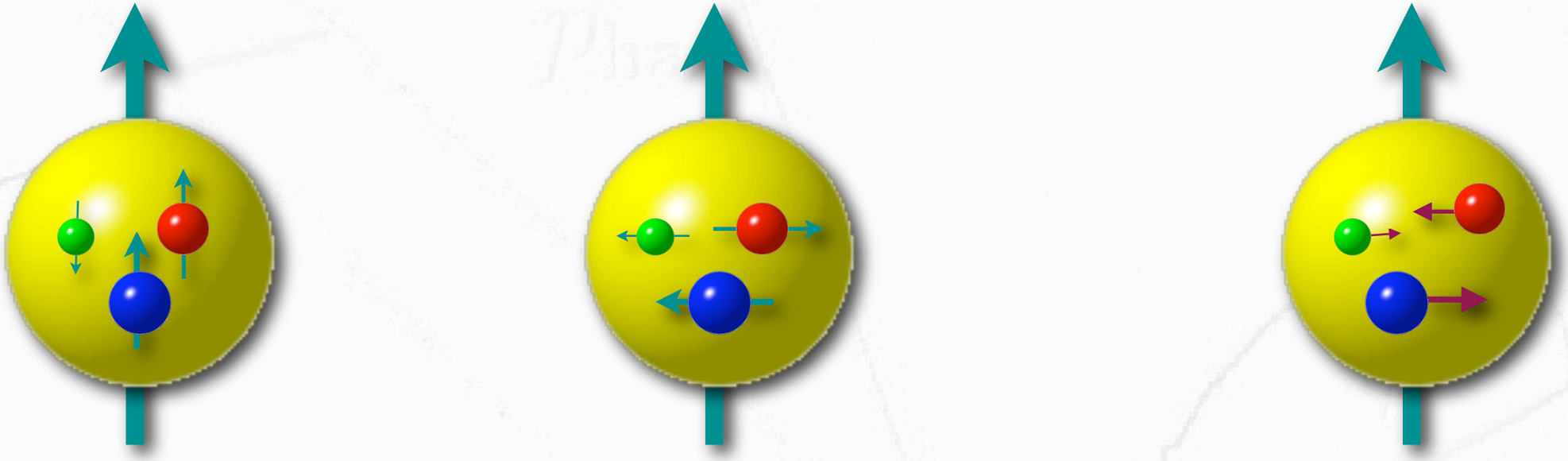

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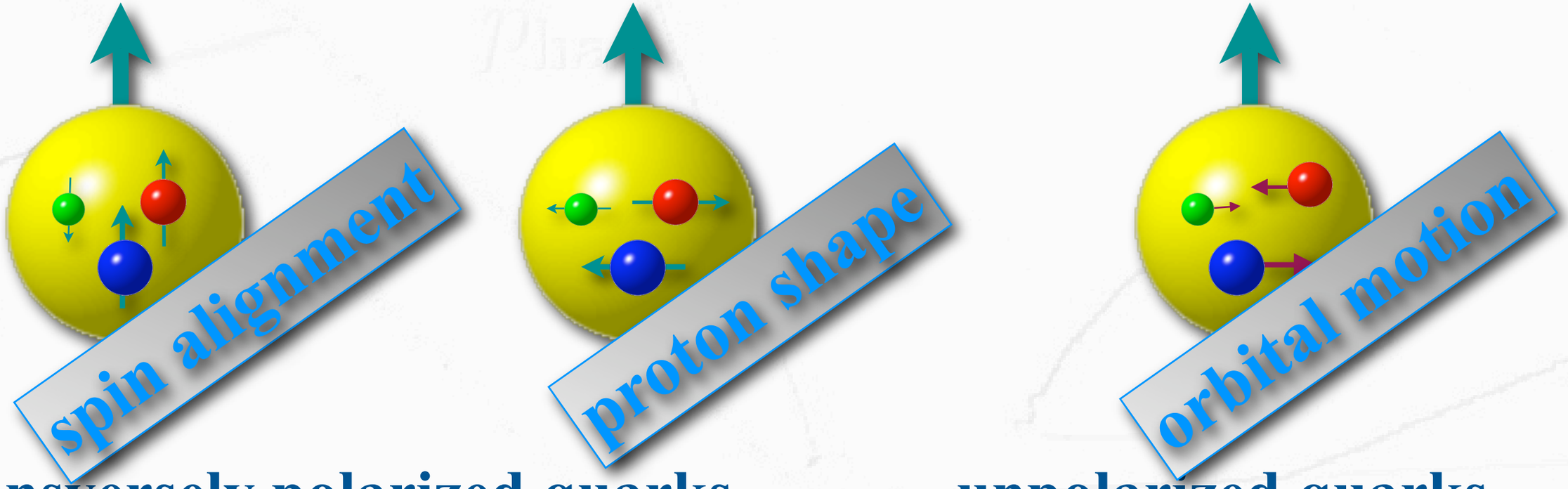

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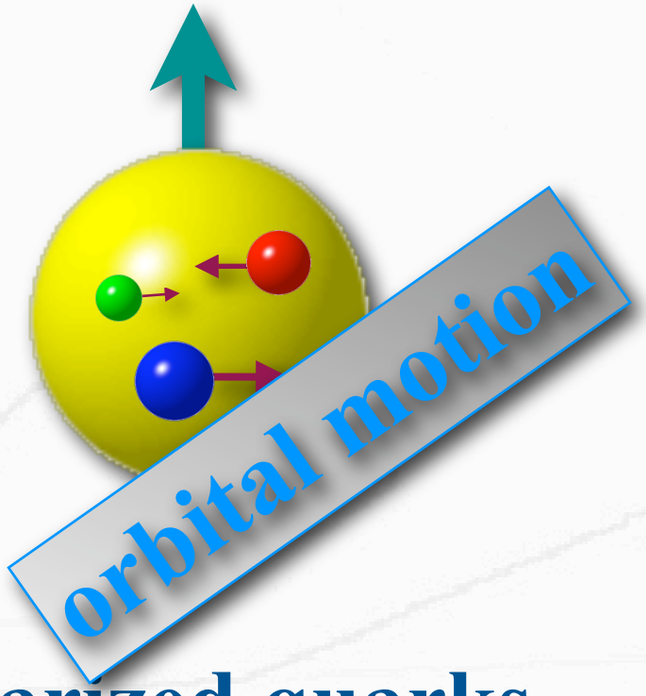

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The "Trouble" with Transversity

Transverse-spin states written in terms of helicity states:

$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\left[|+\rangle + \mathrm{i}|-\rangle\right]$$
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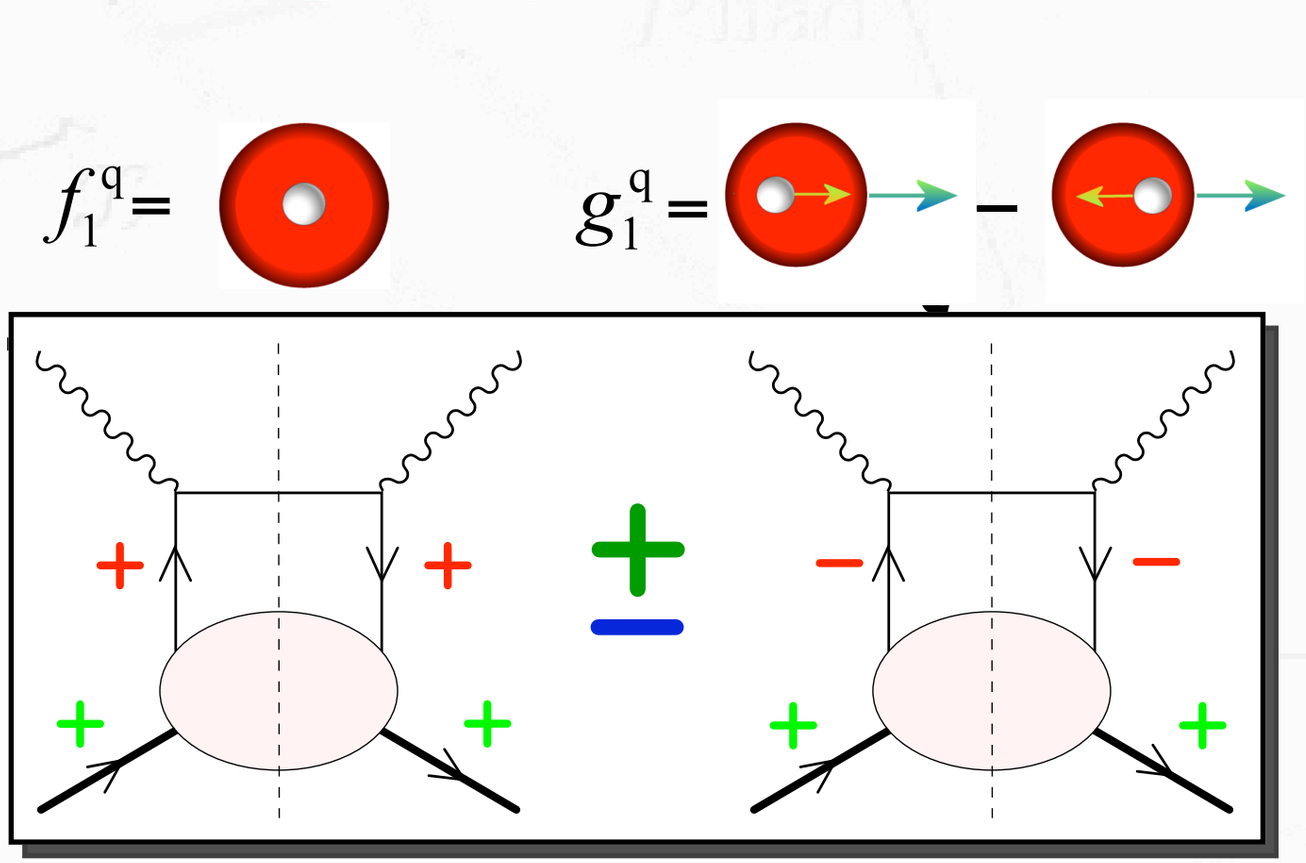

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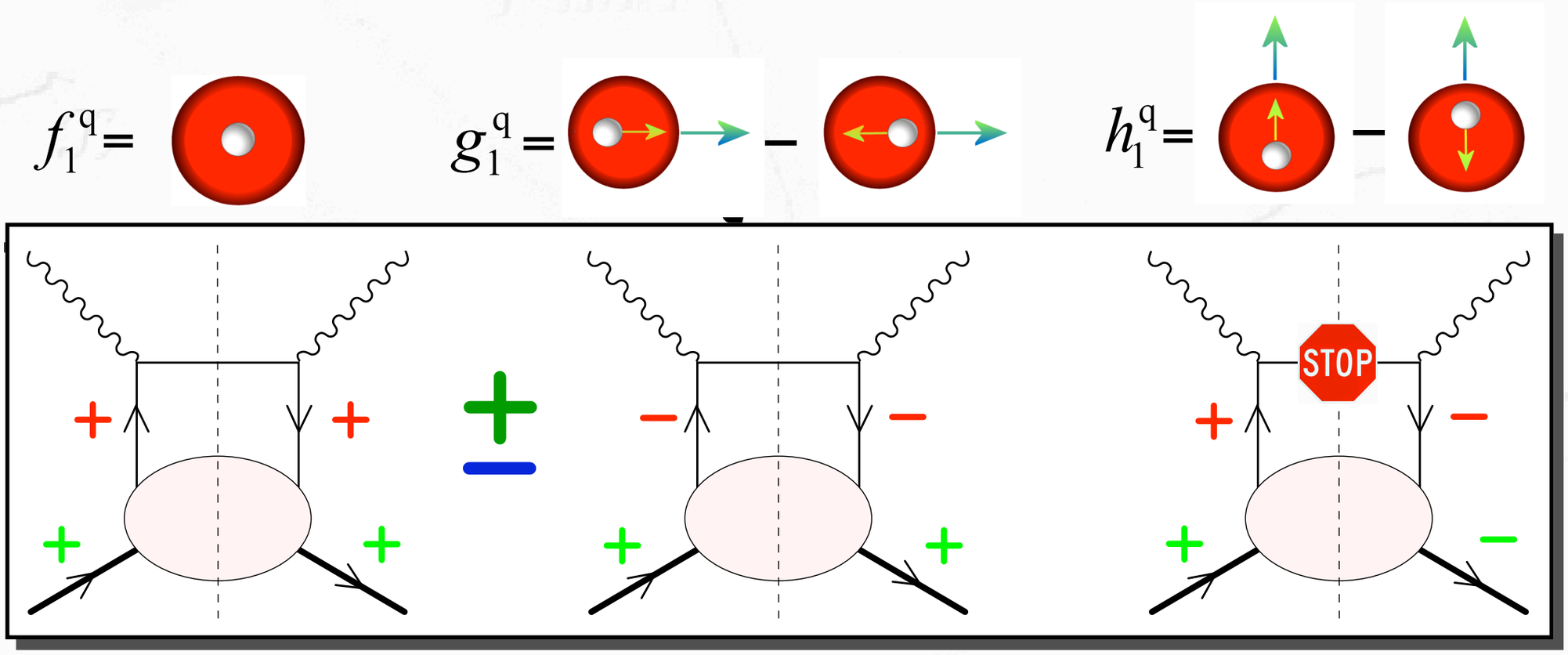

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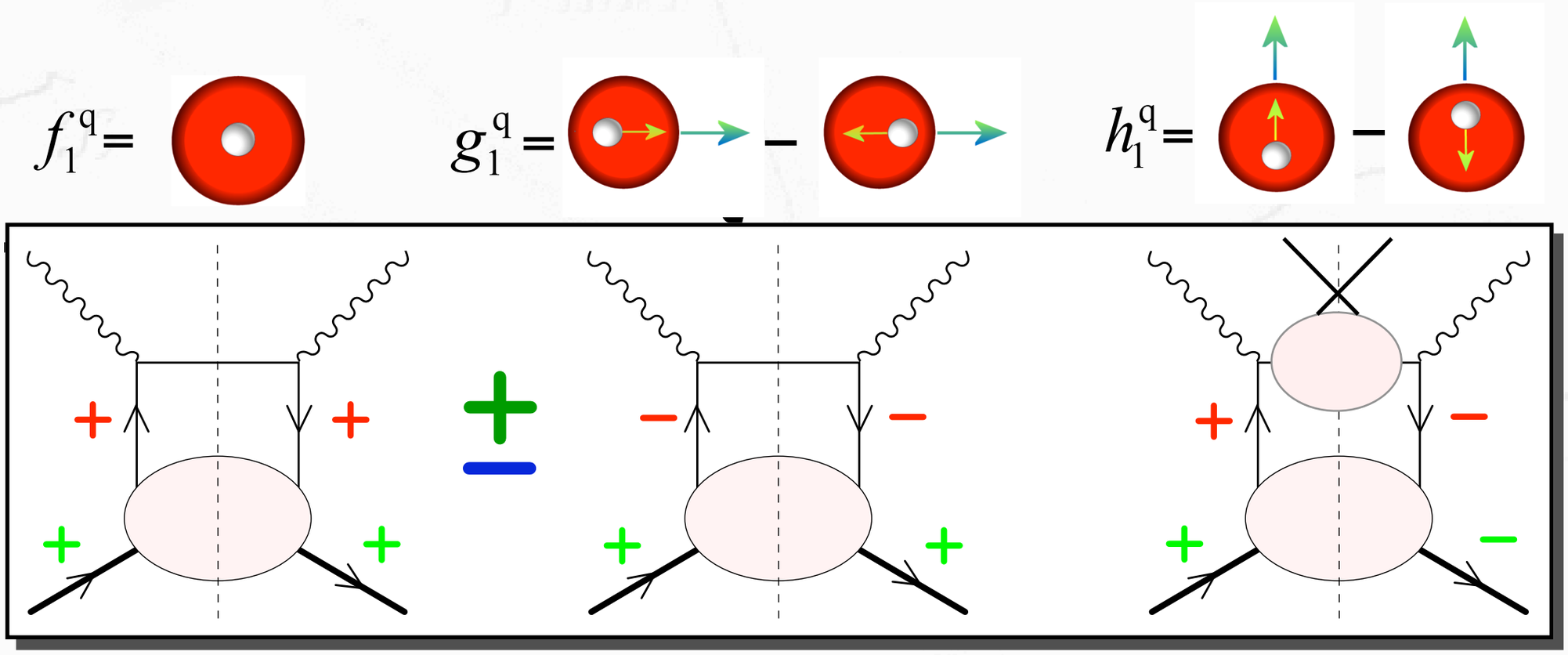


Semi-Inclusive Two-Hadron Production

2-Hadron Production ($ep \to e h_1 h_2 X$)

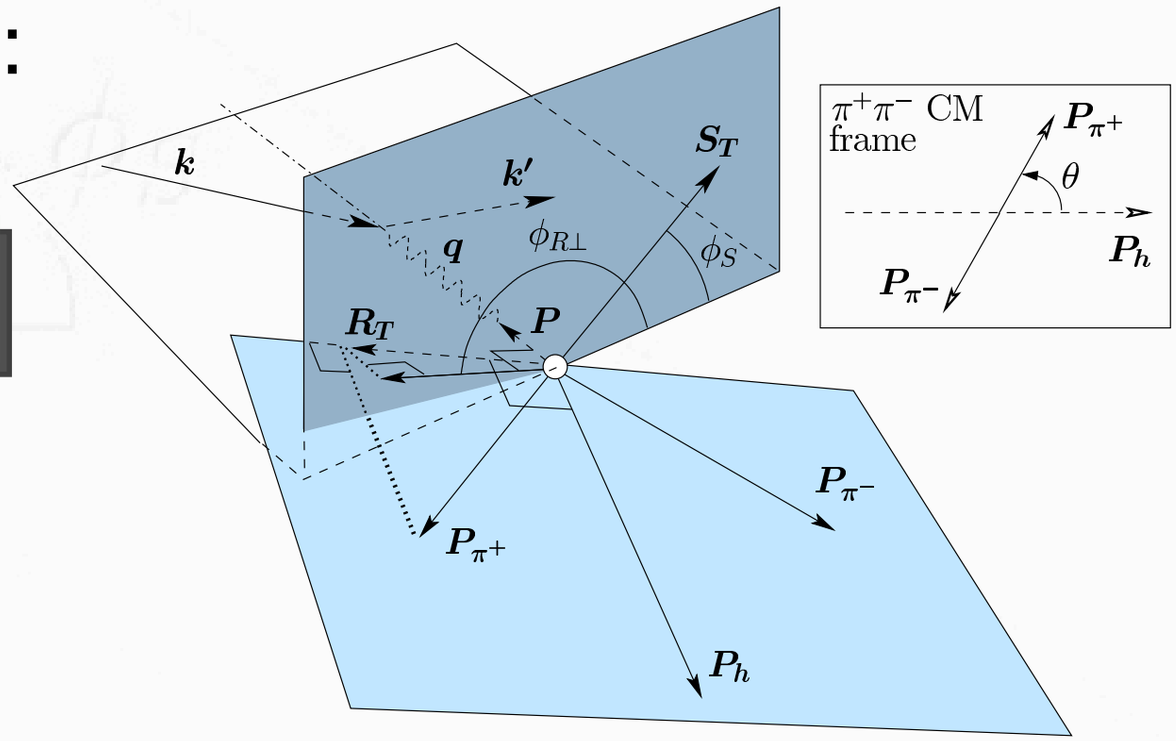
polarized 2-hadron cross section:

(**U**npolarized beam, **T**ransversely 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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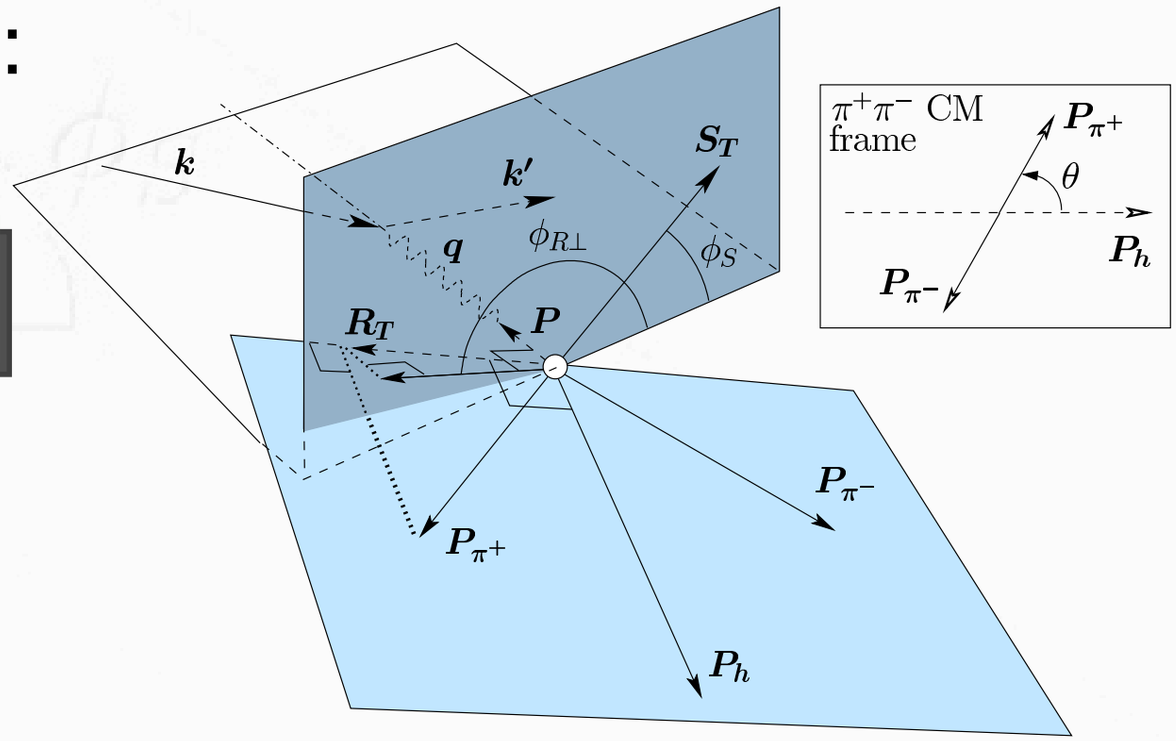

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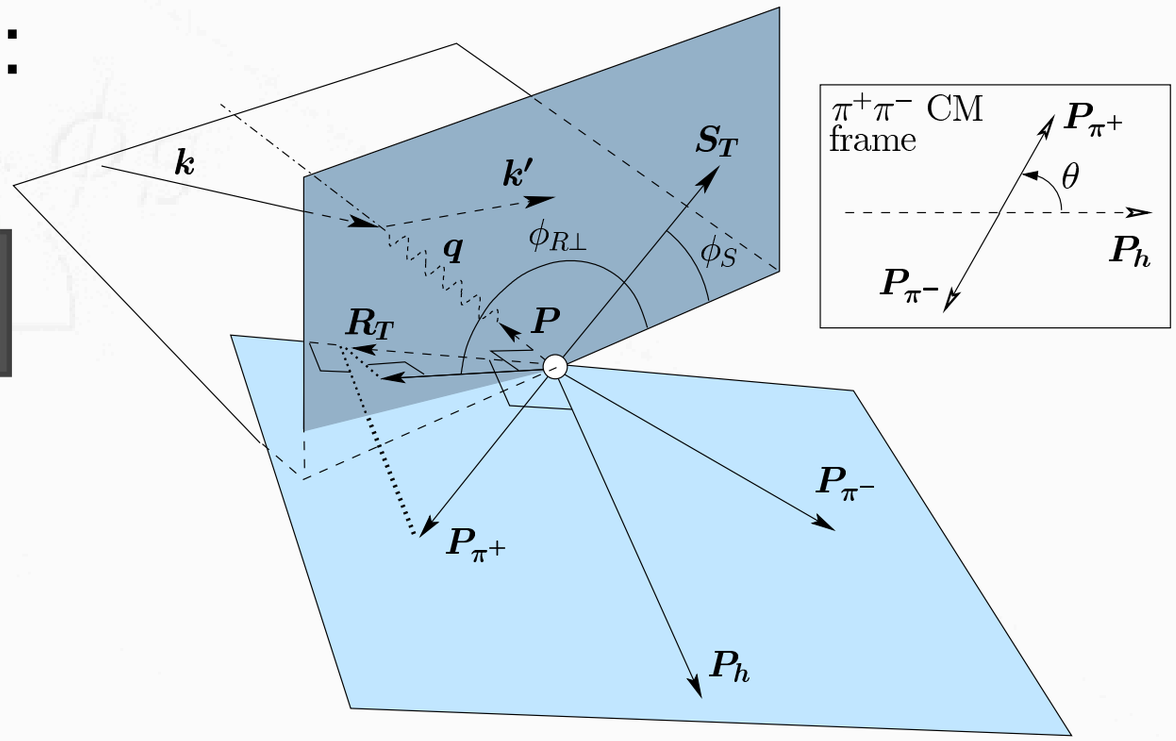


- only relative momentum of hadron pair relevant
  ⇒ integration over transverse momentum of hadron pair simplifies factorization and Q^2 evolution
- however, cross section becomes quite complex (differential in 9 variables)

Model for 2-Hadron Fragmentation

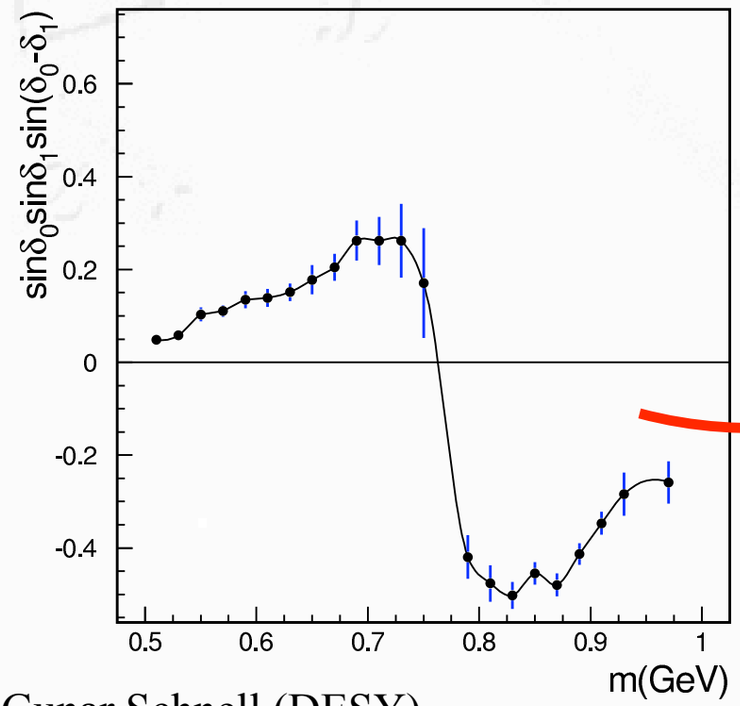
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin\theta h_1 H_1^{\sphericalangle}$$

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**]:

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

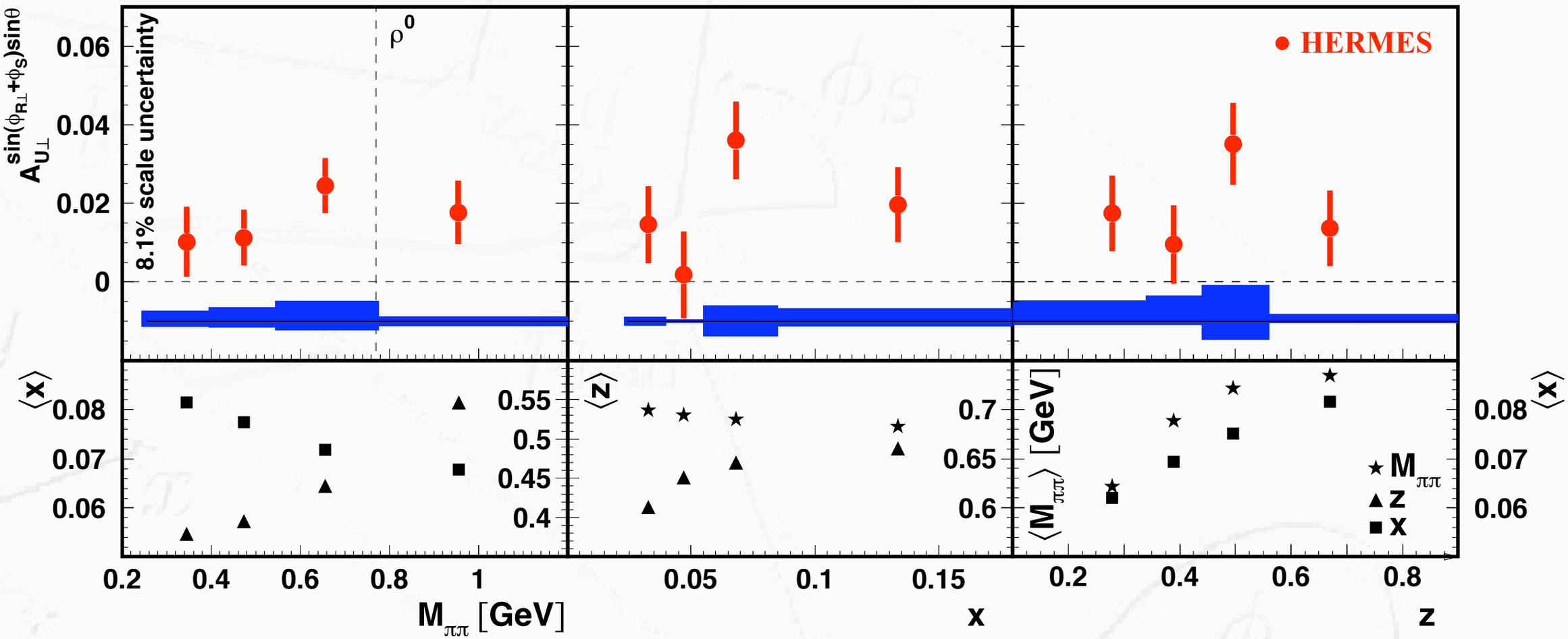
δ_0 (δ_1) $\rightarrow$ S(P)-wave phase shifts

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

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

Final HERMES Results

A. Airapetian et al., JHEP 0806:017,2008



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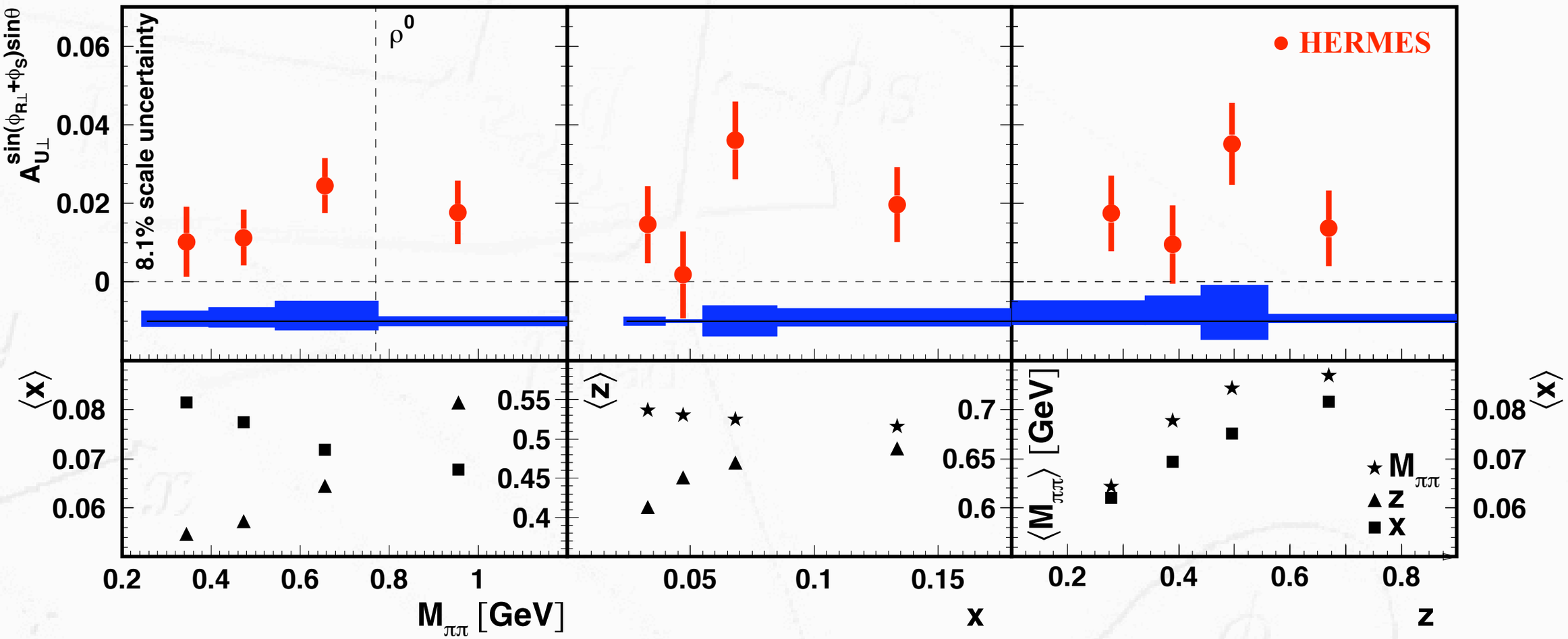

☑ first evidence for naive-T-odd 2-hadron fragmentation function in semi-inclusive DIS!

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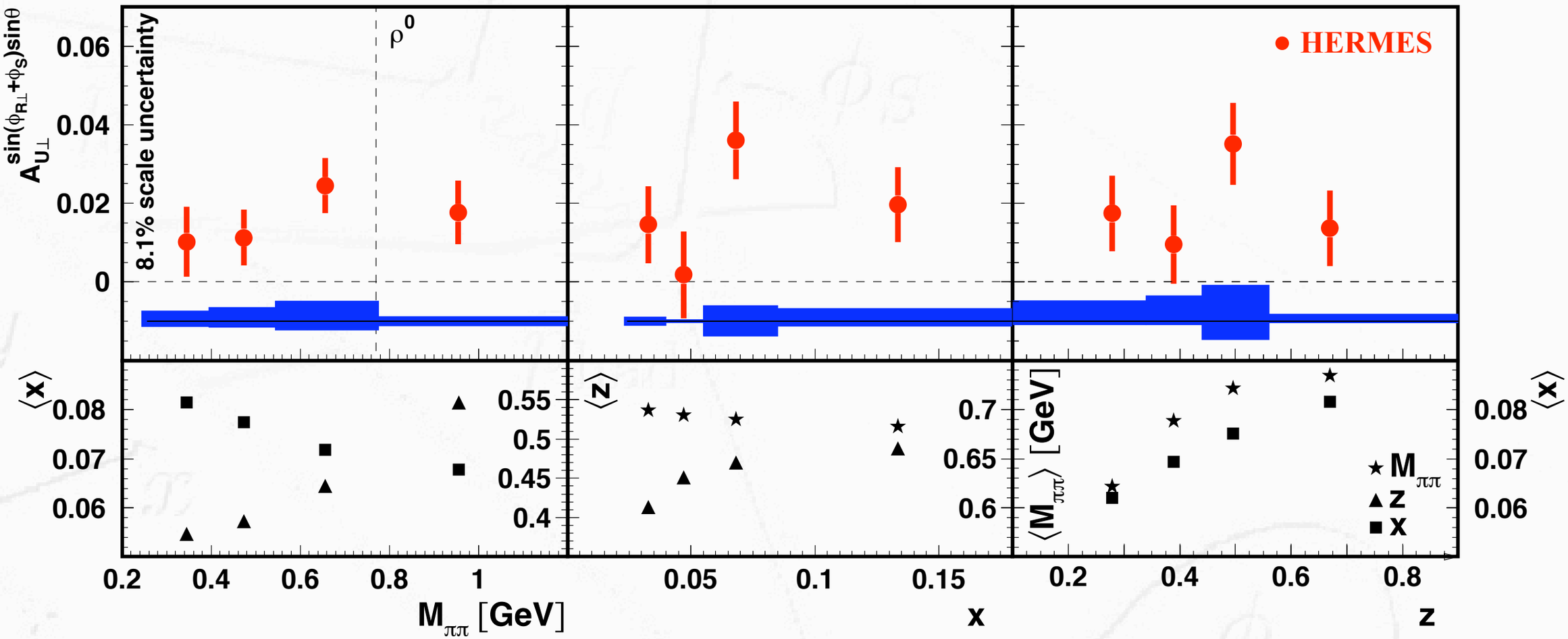


- ☑ first evidence for naive-T-odd 2-hadron fragmentation function in semi-inclusive DIS!
- ☑ invariant-mass dependence rules out Jaffe model

Semi-Inclusive One-Hadron Production

1-Hadron Production (ep → e h X)

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

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

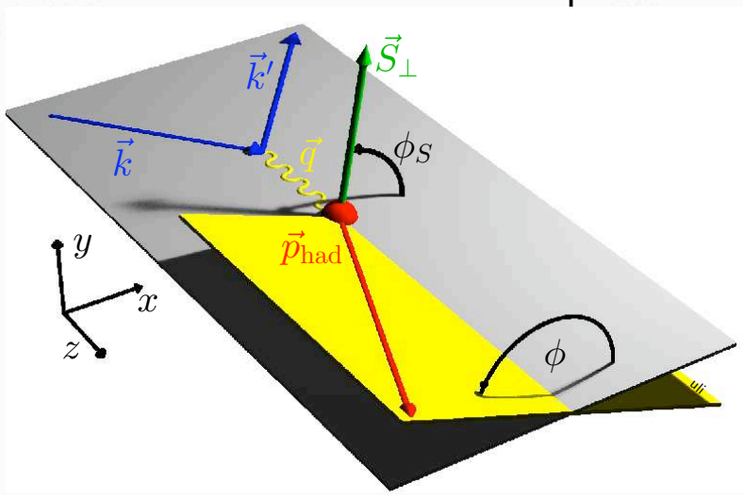
$$+S_T \left\{ \sin(\phi - \phi_S)\, d\sigma^8_{UT} + \sin(\phi + \phi_S)\, d\sigma^9_{UT} + \sin(3\phi - \phi_S)\, d\sigma^{10}_{UT} \right.$$

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

σ_{XY}

Beam Target Polarization

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



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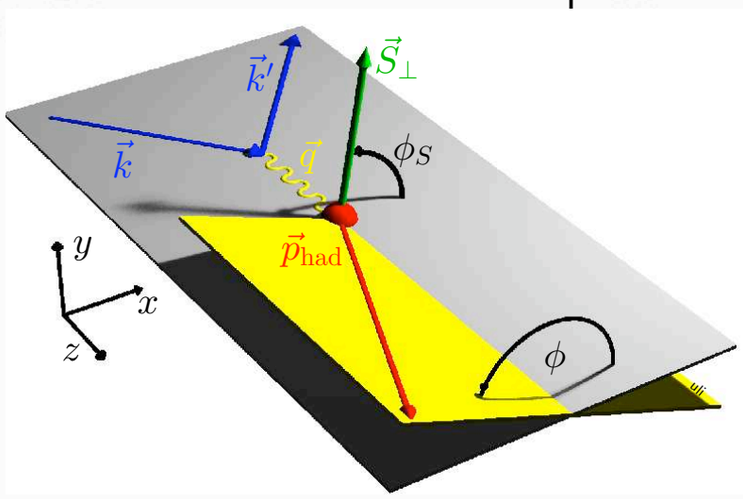
$$+\lambda_e \left[\cos(\phi$$

σ_{XY}

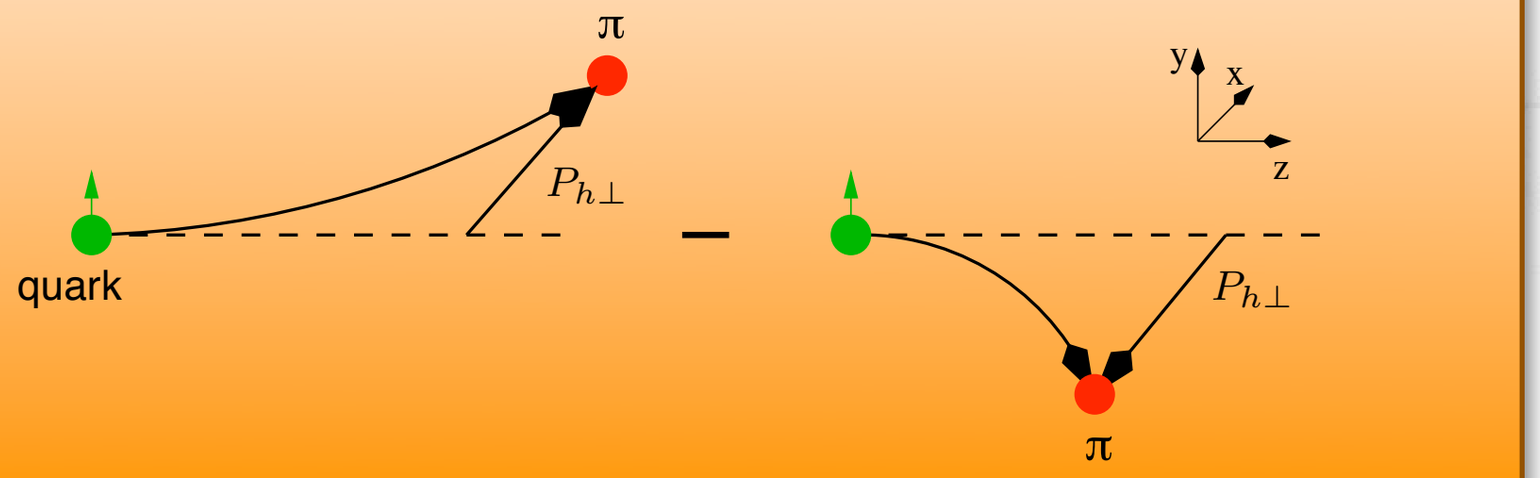
Beam Target

Polarization



Collins Effect:

sensitive to quark transverse spin



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Sivers Effect:

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

Phys. B 461 (1996) 197

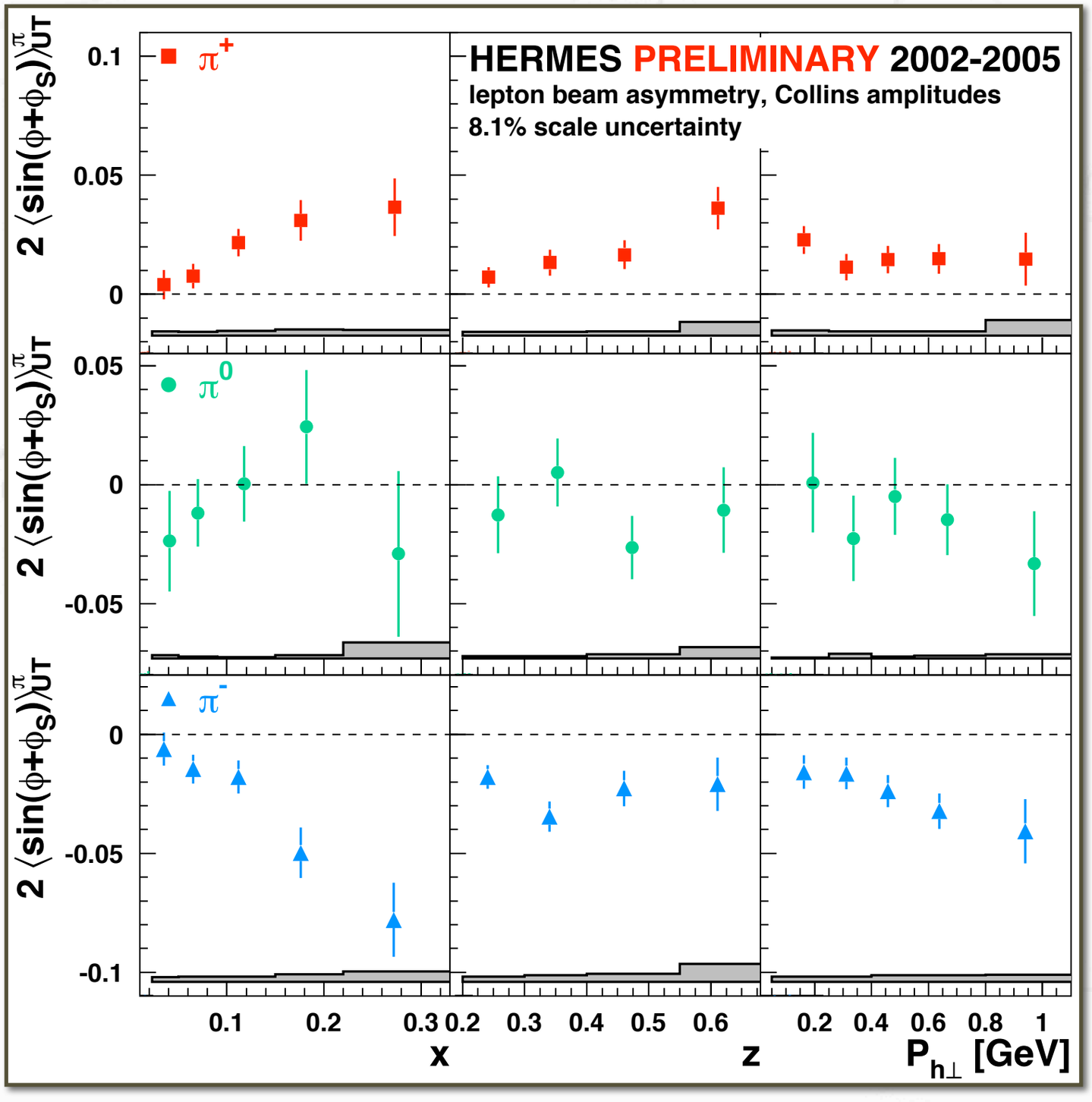
57 (1998) 5780

5 (2004) 309

7) 093

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

The HERMES Collins Results



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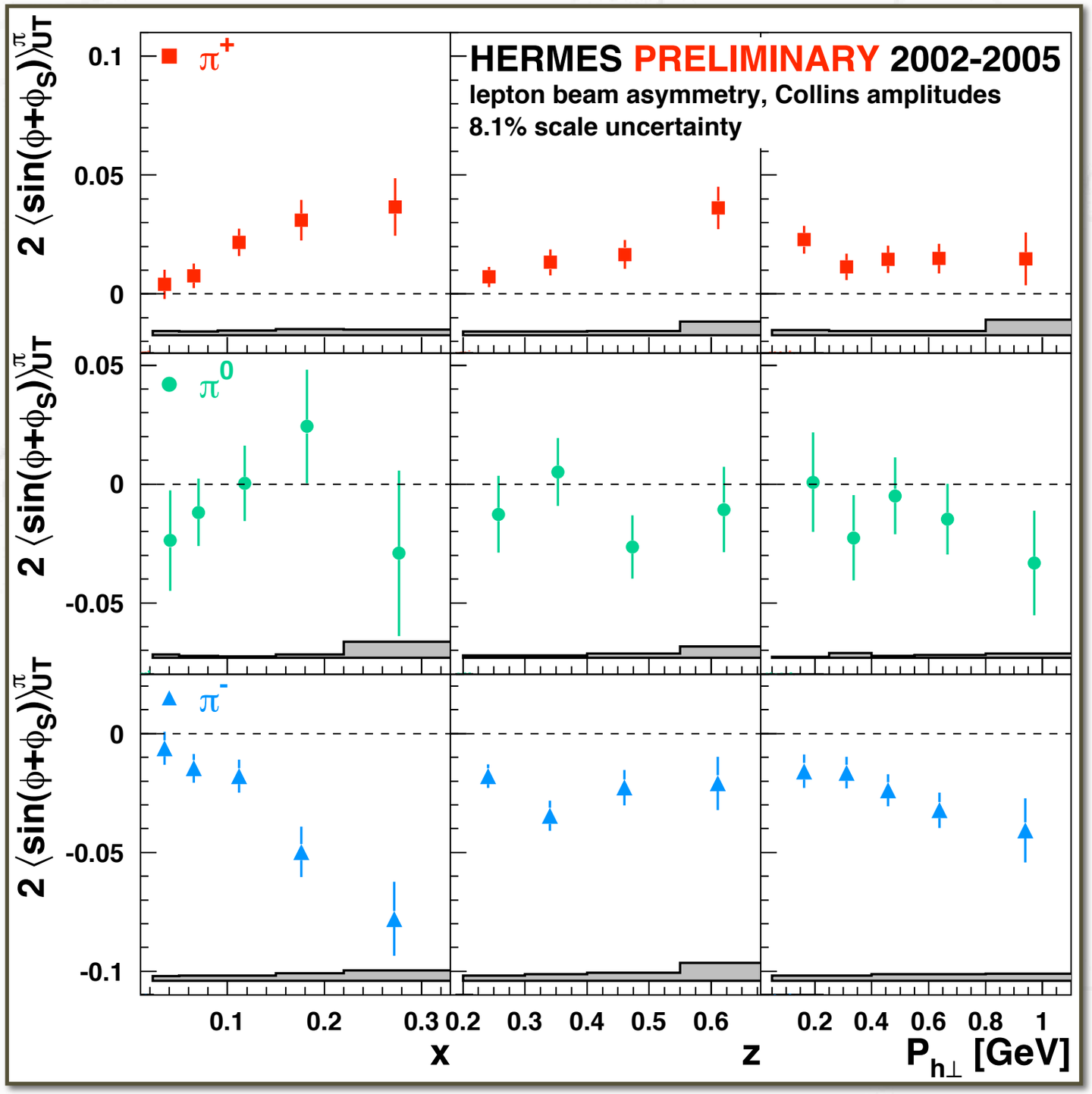

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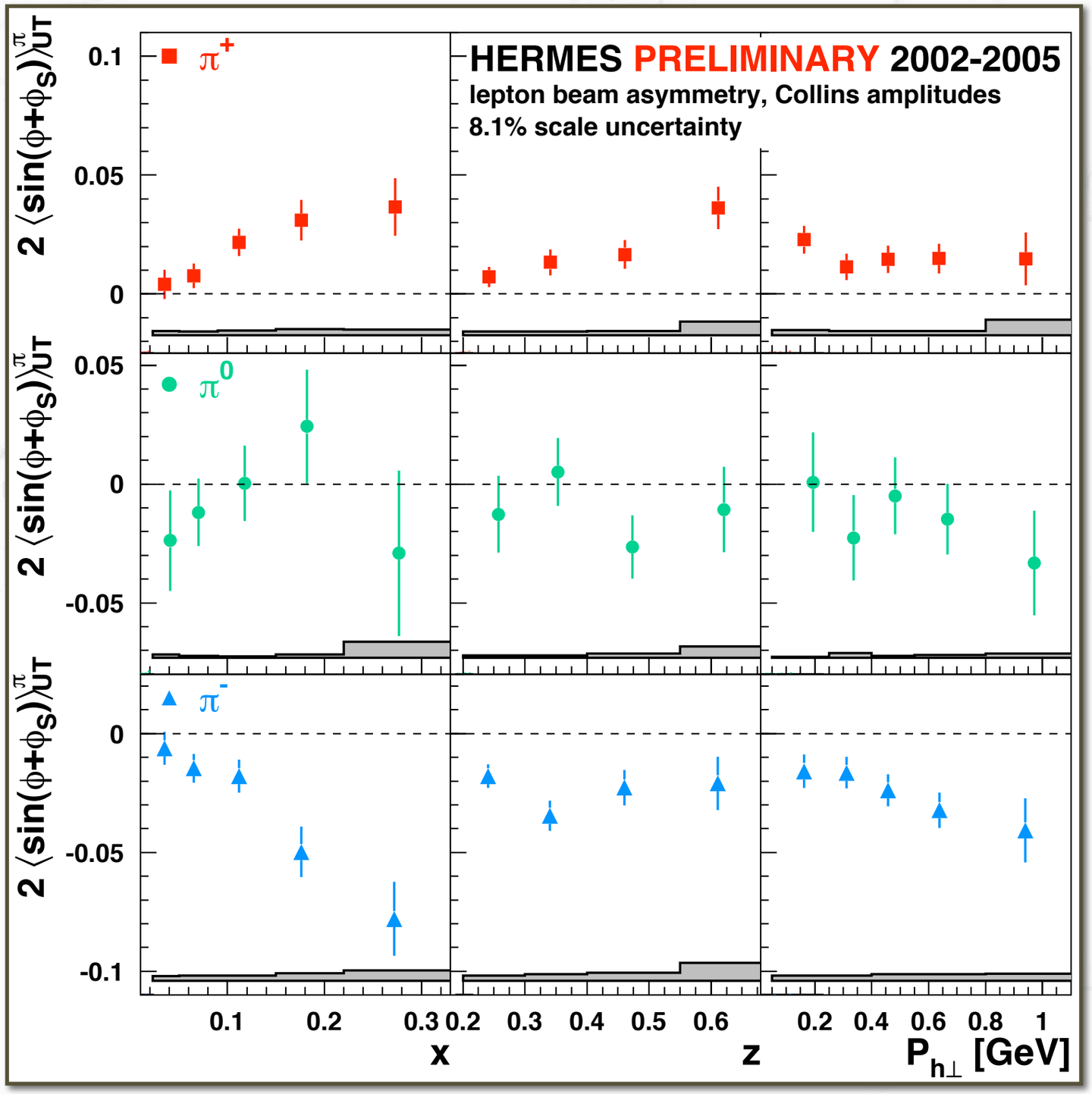
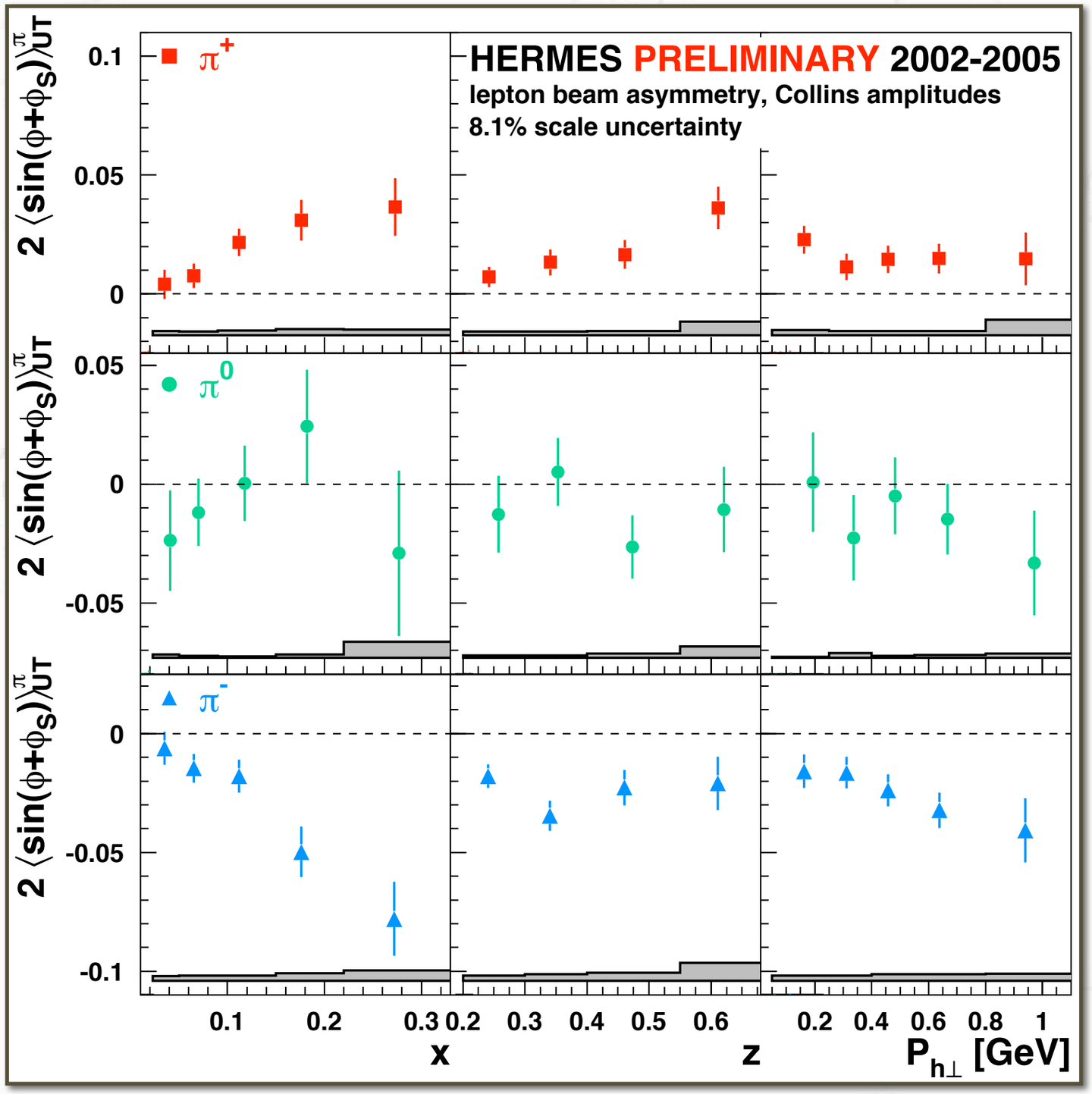


- ☑ non-zero Collins effect observed!
- ☑ both Collins FF and transversity sizeable

The HERMES Collins Results

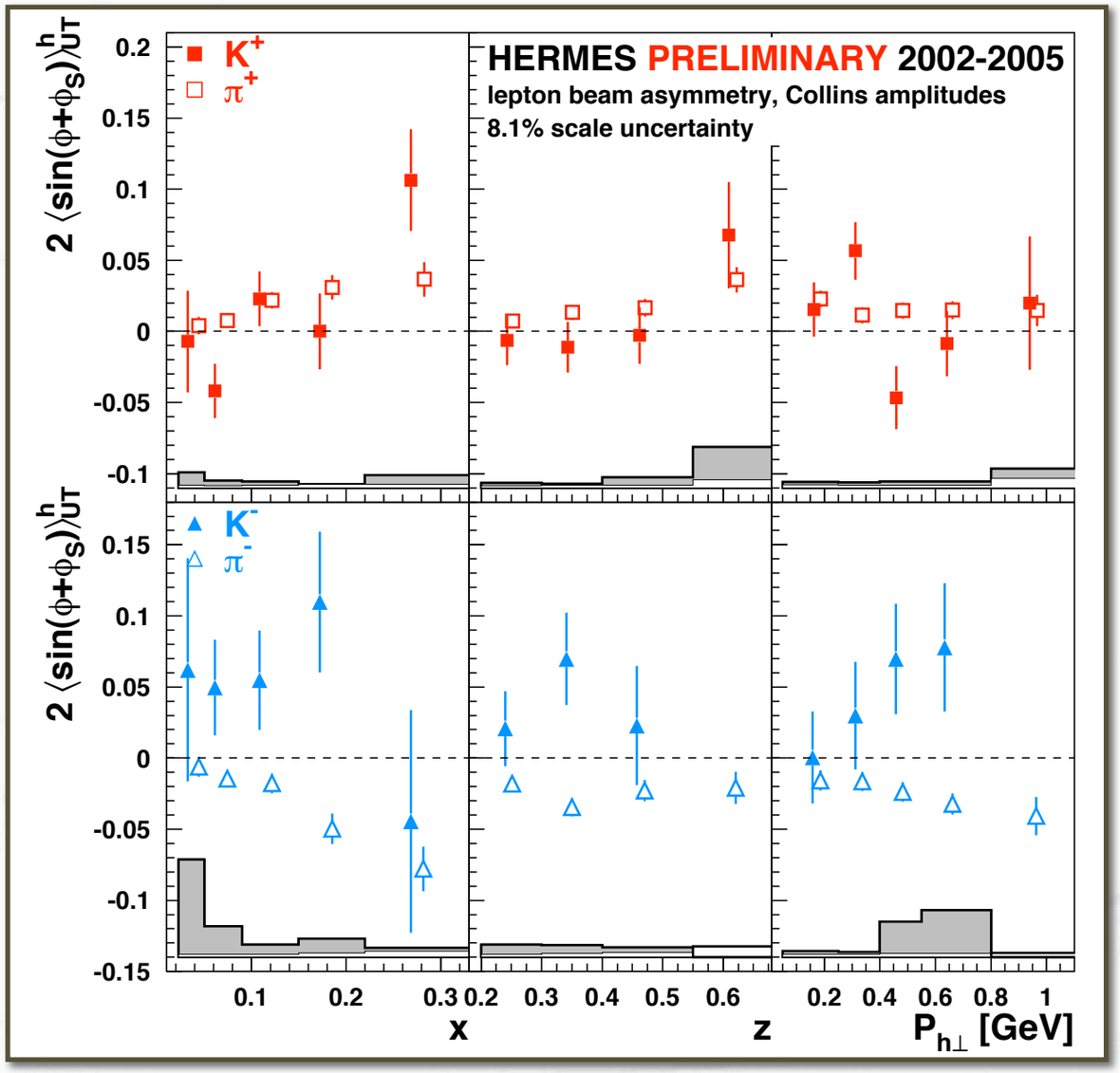


- published† results **confirmed** with much higher statistical precission
- overall scale uncertainty of 8.1%
- positive for π^+ and negative for π^- as maybe expected ($\delta u \equiv h_1^u > 0$ $\delta d \equiv h_1^d < 0$)
- unexpected large π^- asymmetry
  $\Rightarrow$ role of disfavored Collins 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 positive, contrary to large negative π^- amplitudes
- K^- is pure "sea object"



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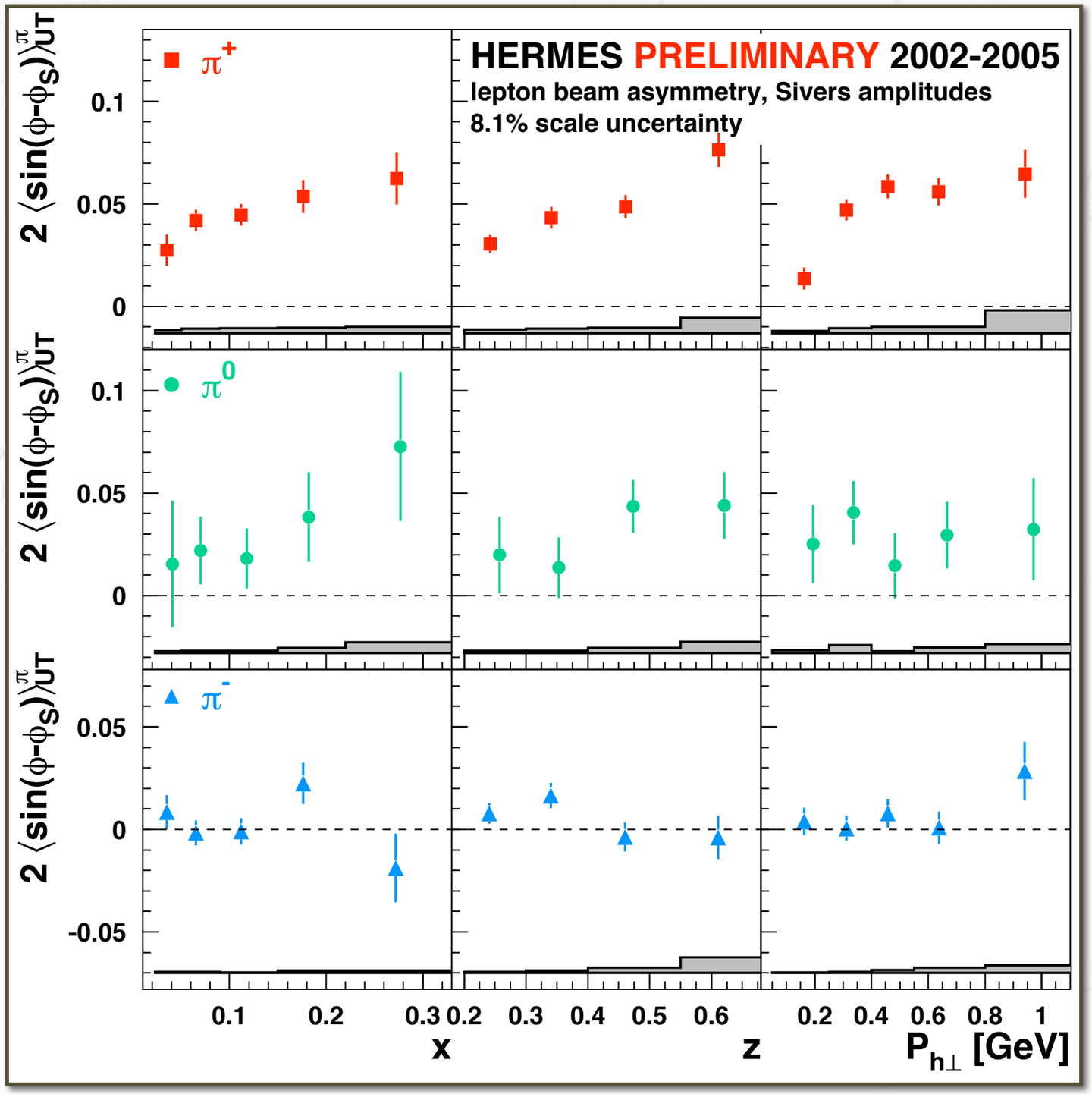

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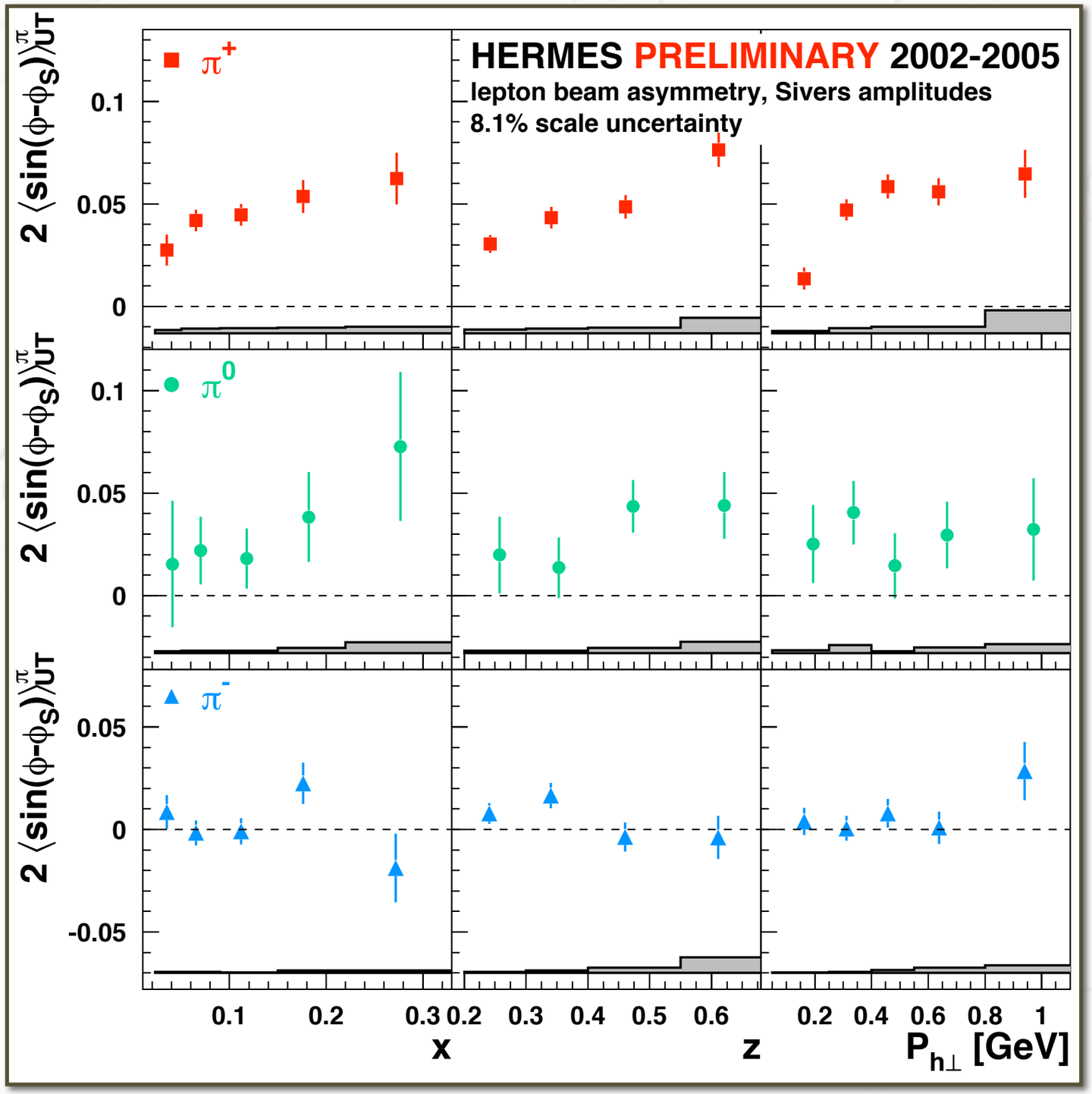

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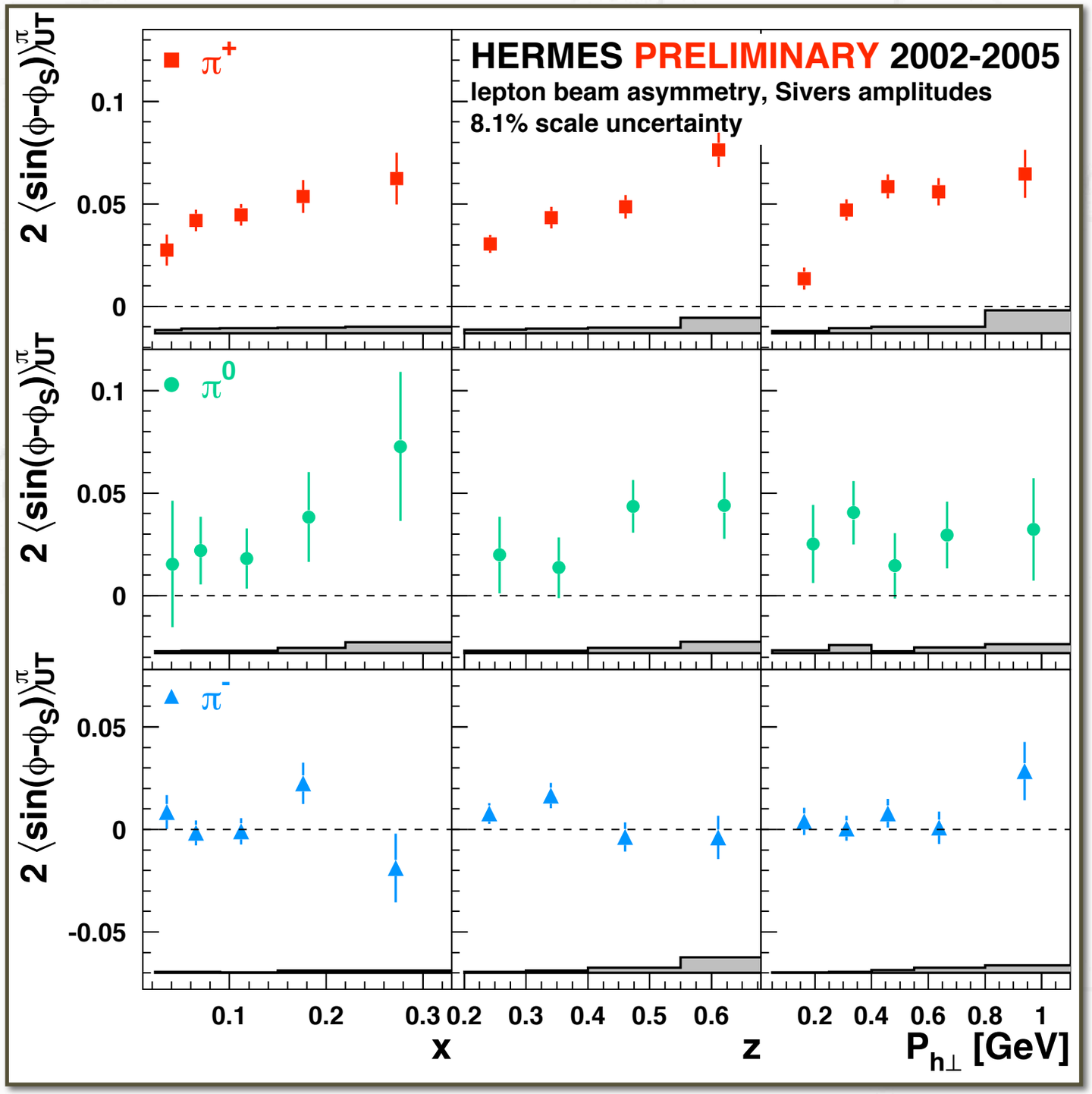

- ☑ first observation of T-odd Sivers effect in semi-inclusive DIS!
- ☑ u-quark dominance suggests sizeable u-quark orbital motion

Sivers Valence-Quark Distributions

look at charged-pions cross-section difference:

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

$$\rightarrow \quad \mathbf{2\,\langle \sin(\phi-\phi_S)\rangle_{UT}^{\pi^+-\pi^-}} = -\frac{\mathbf{4f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}}{\mathbf{4f_1^{u_v} - f_1^{d_v}}}$$

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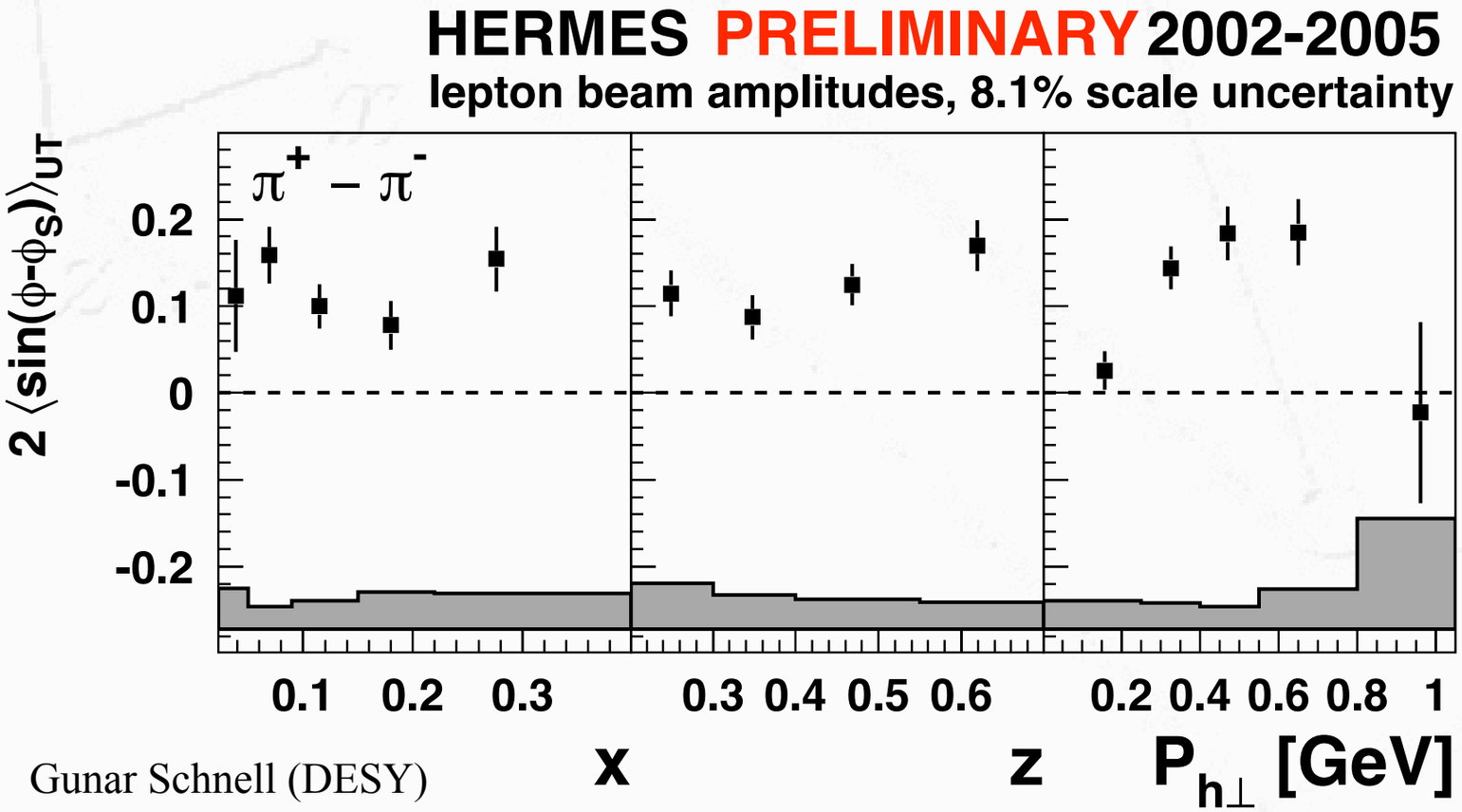
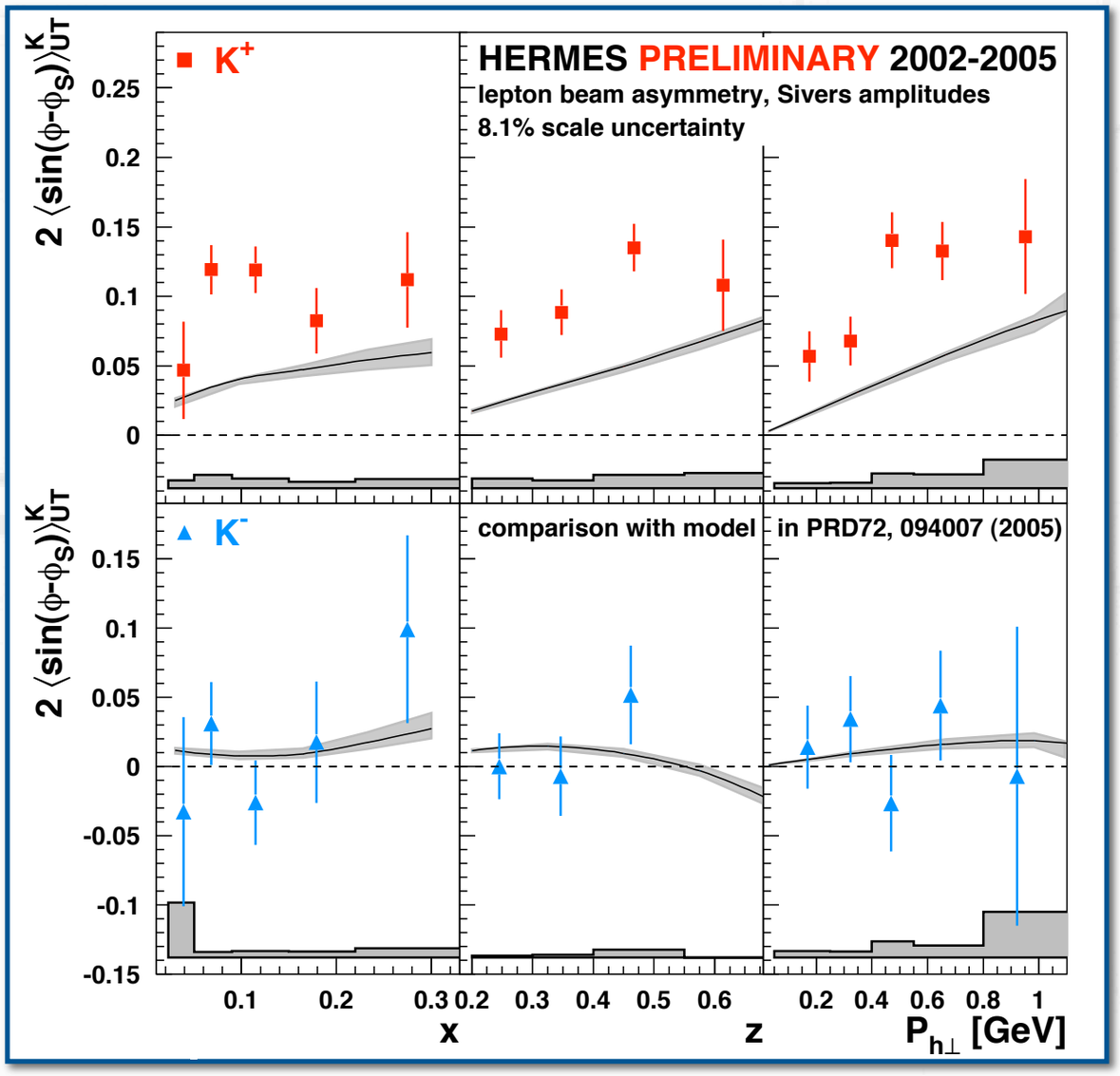


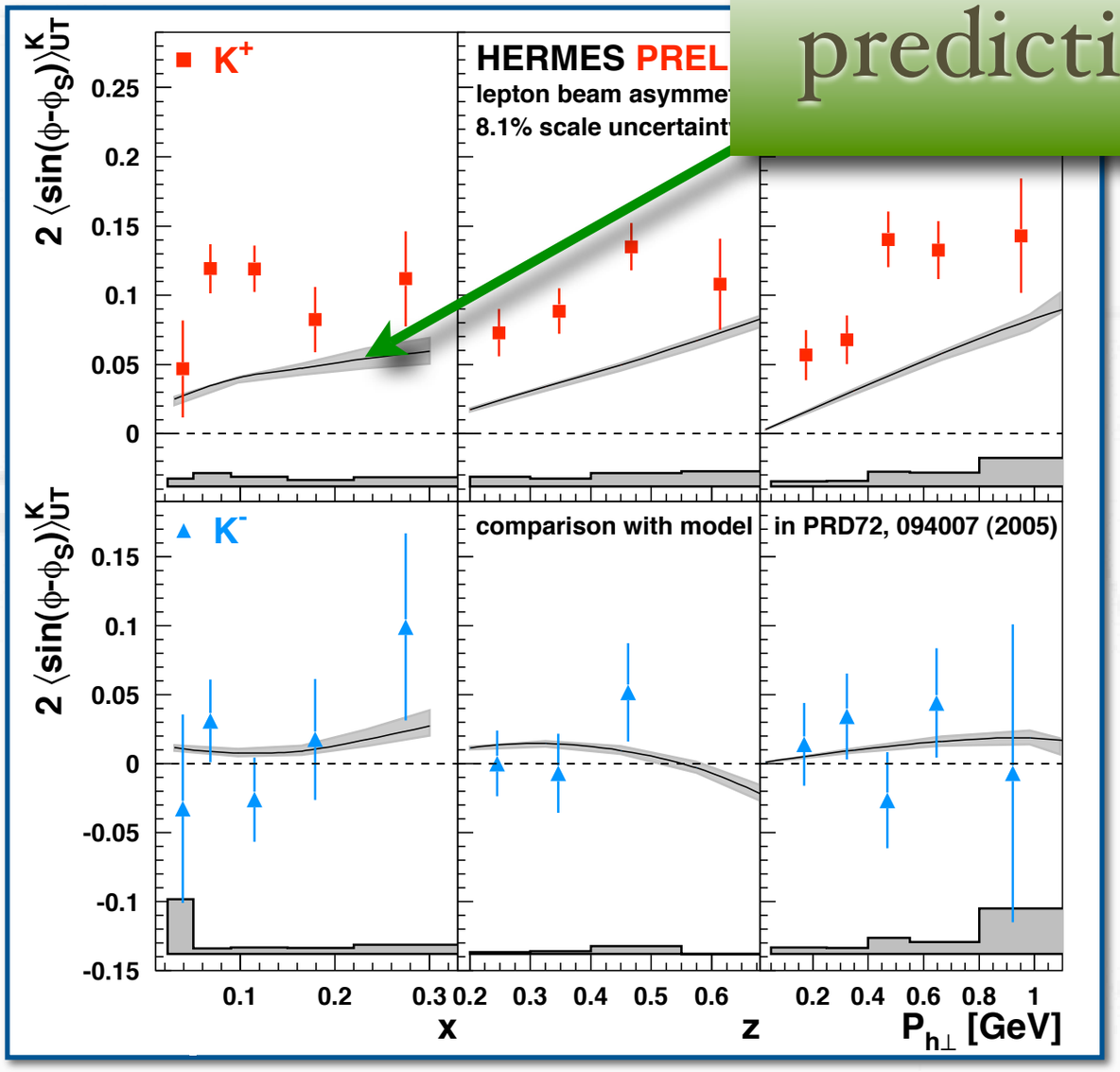
- **either Sivers distrib. for valence d-quarks much larger than for u-quarks**
- **or (more likely) Sivers distribution negative for valence u-quarks**

The Intriguing Kaon Amplitudes



The Intriguing Kaon Amplitudes

prediction using fit to pion data



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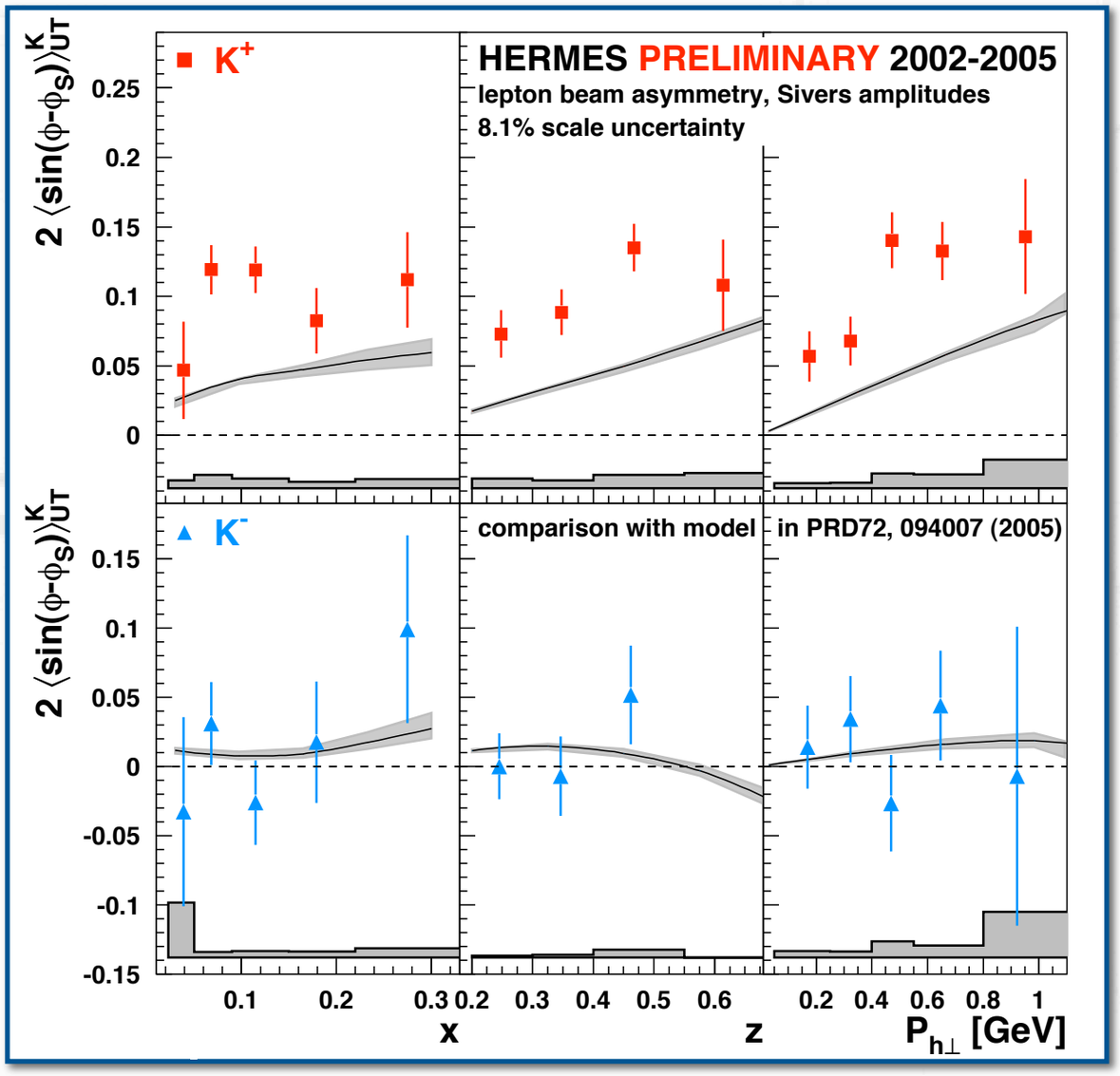
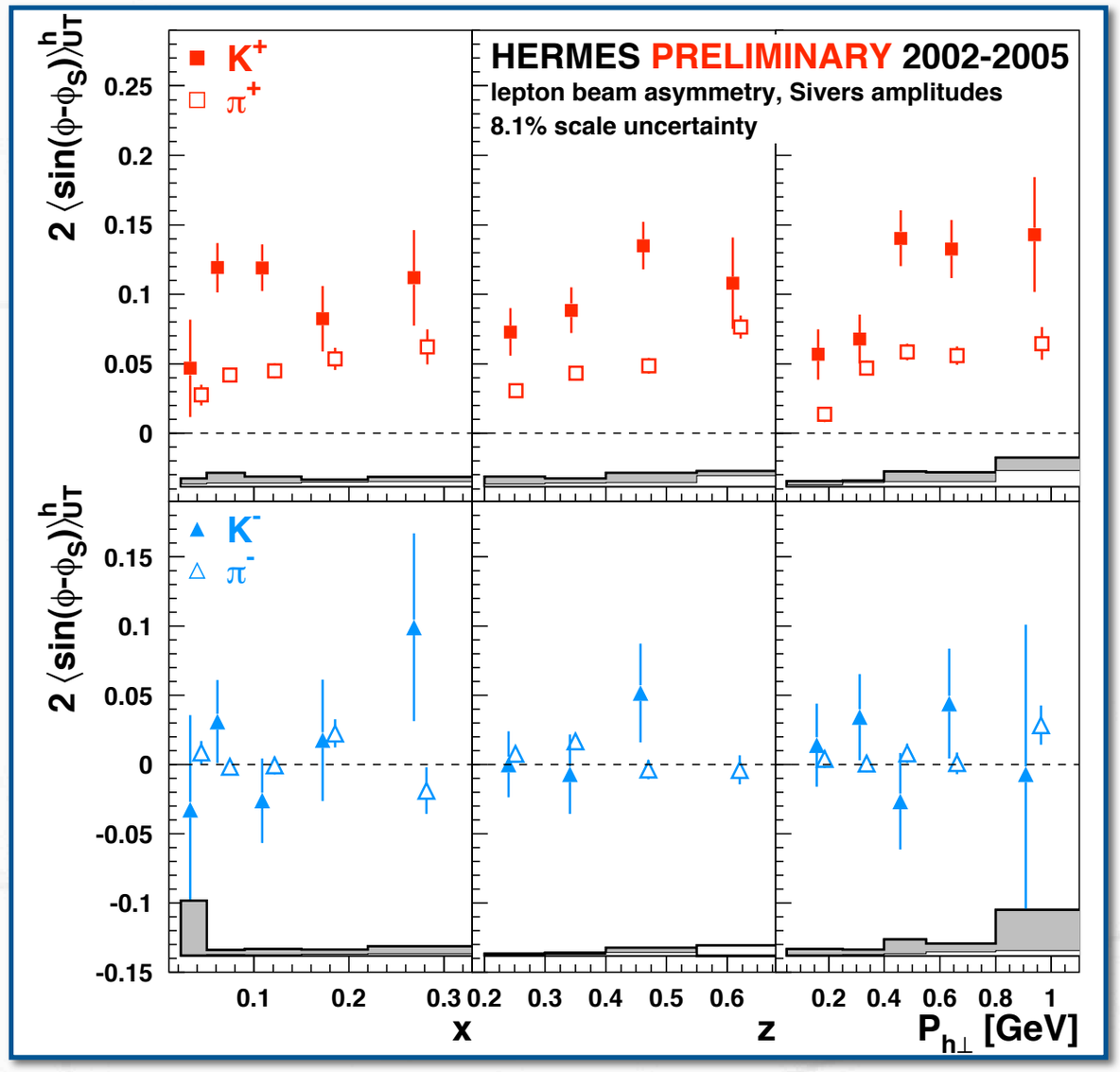
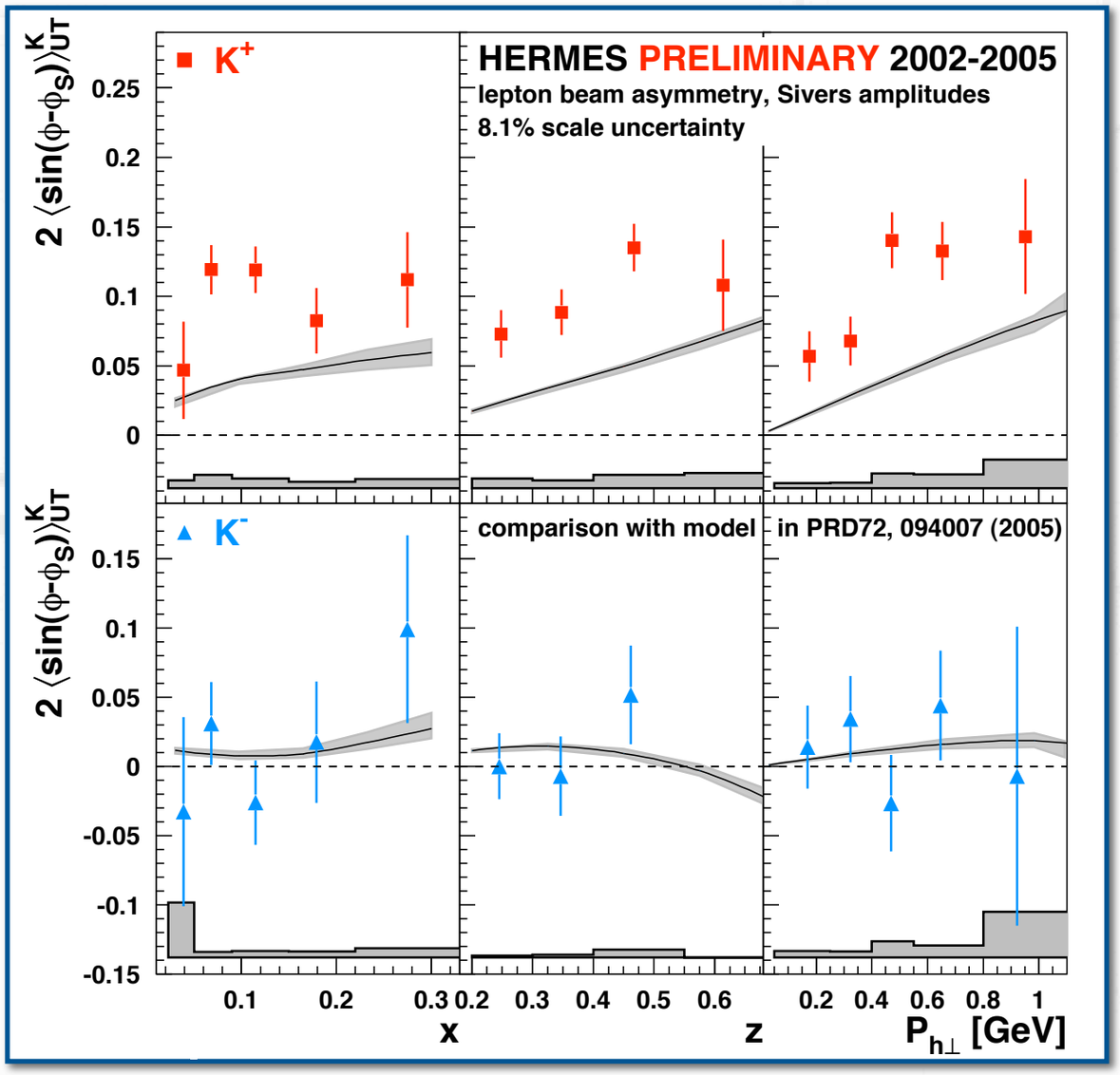
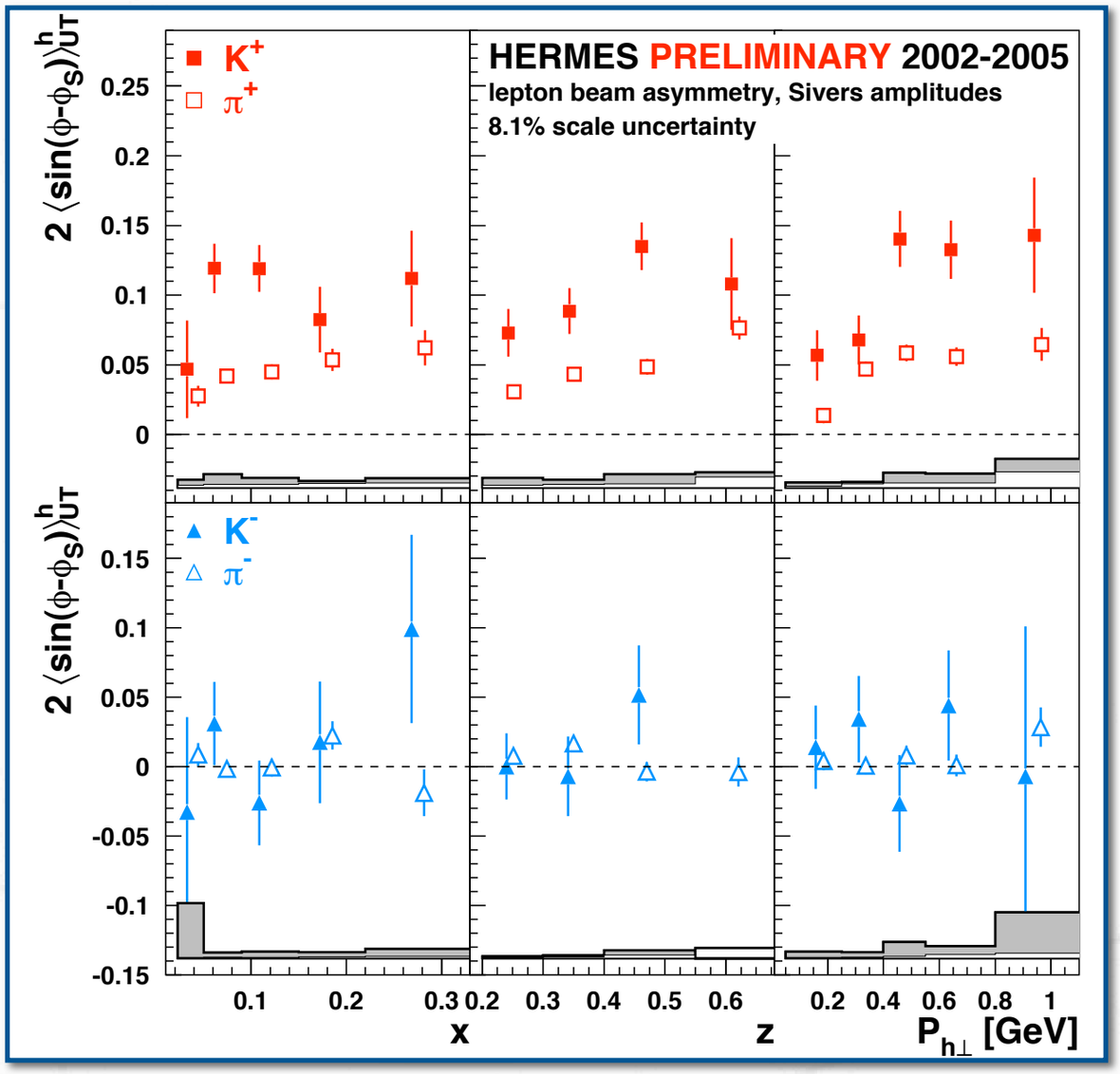




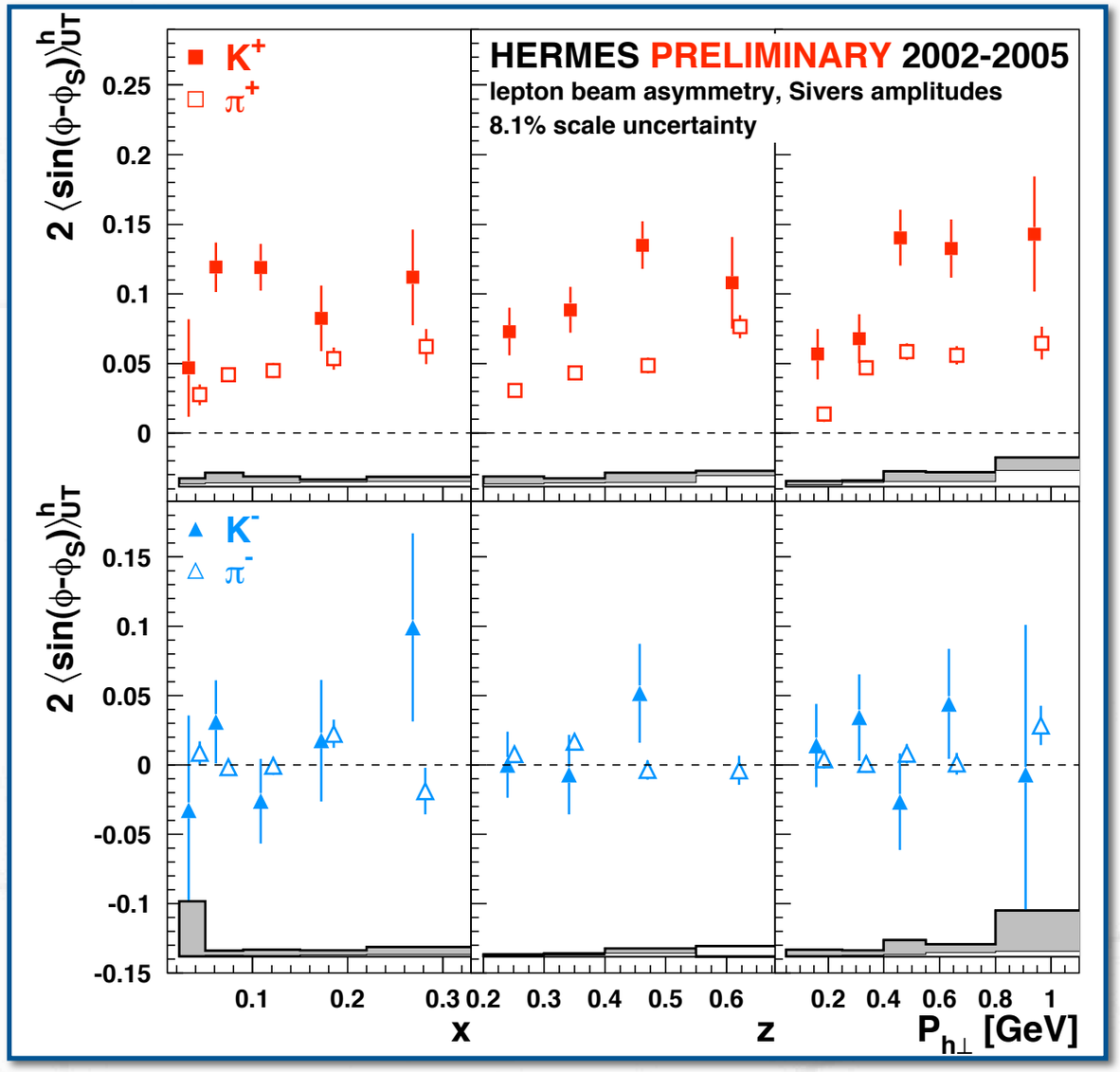
The Intriguing Kaon Amplitudes





non-trivial role of sea quarks!

(... let's speculate ...)



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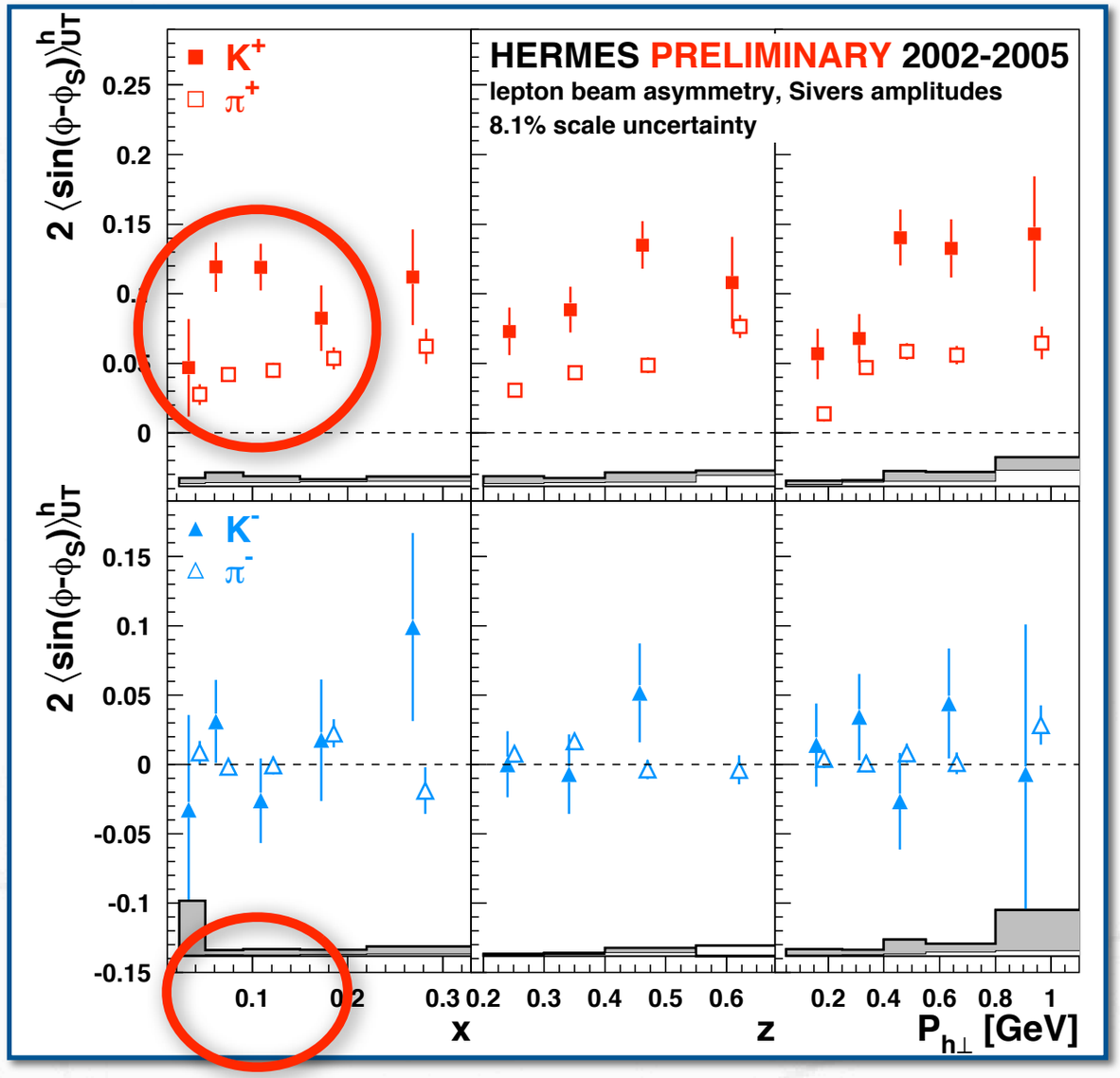
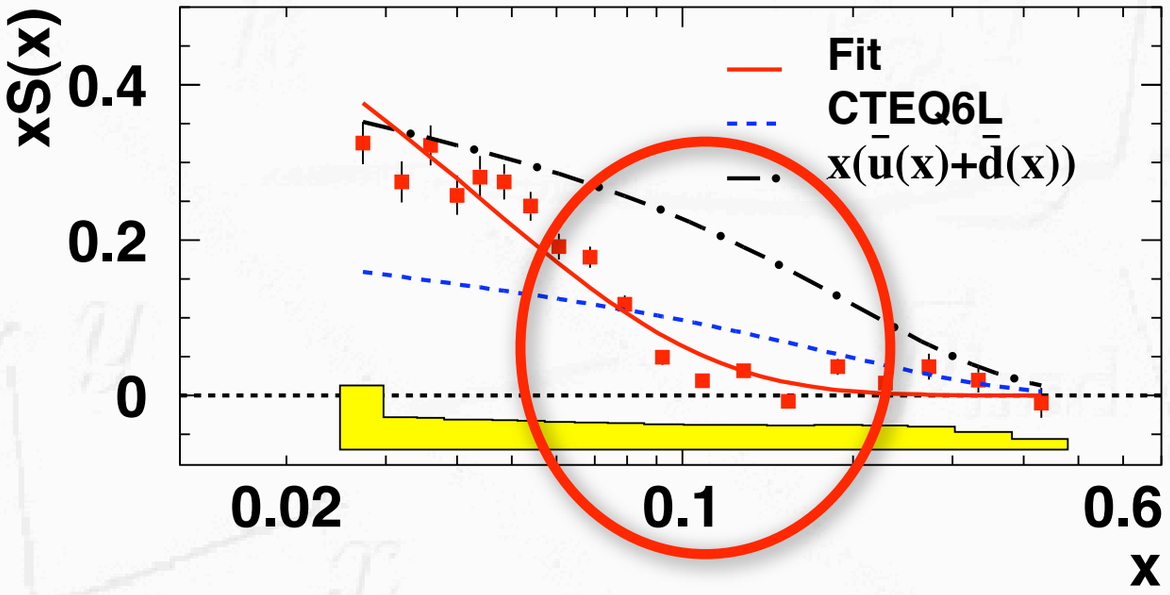
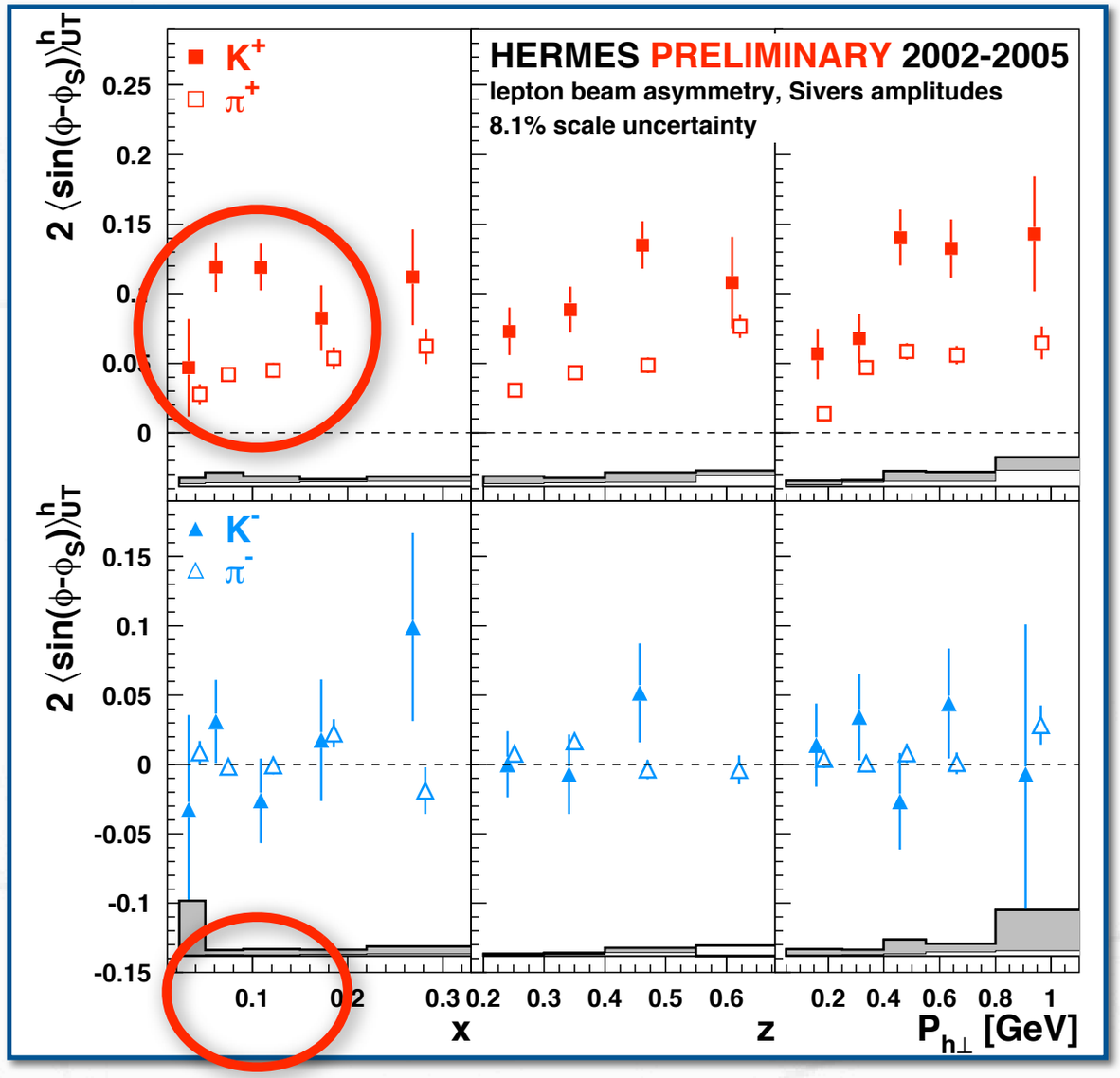


(... let's speculate ...)

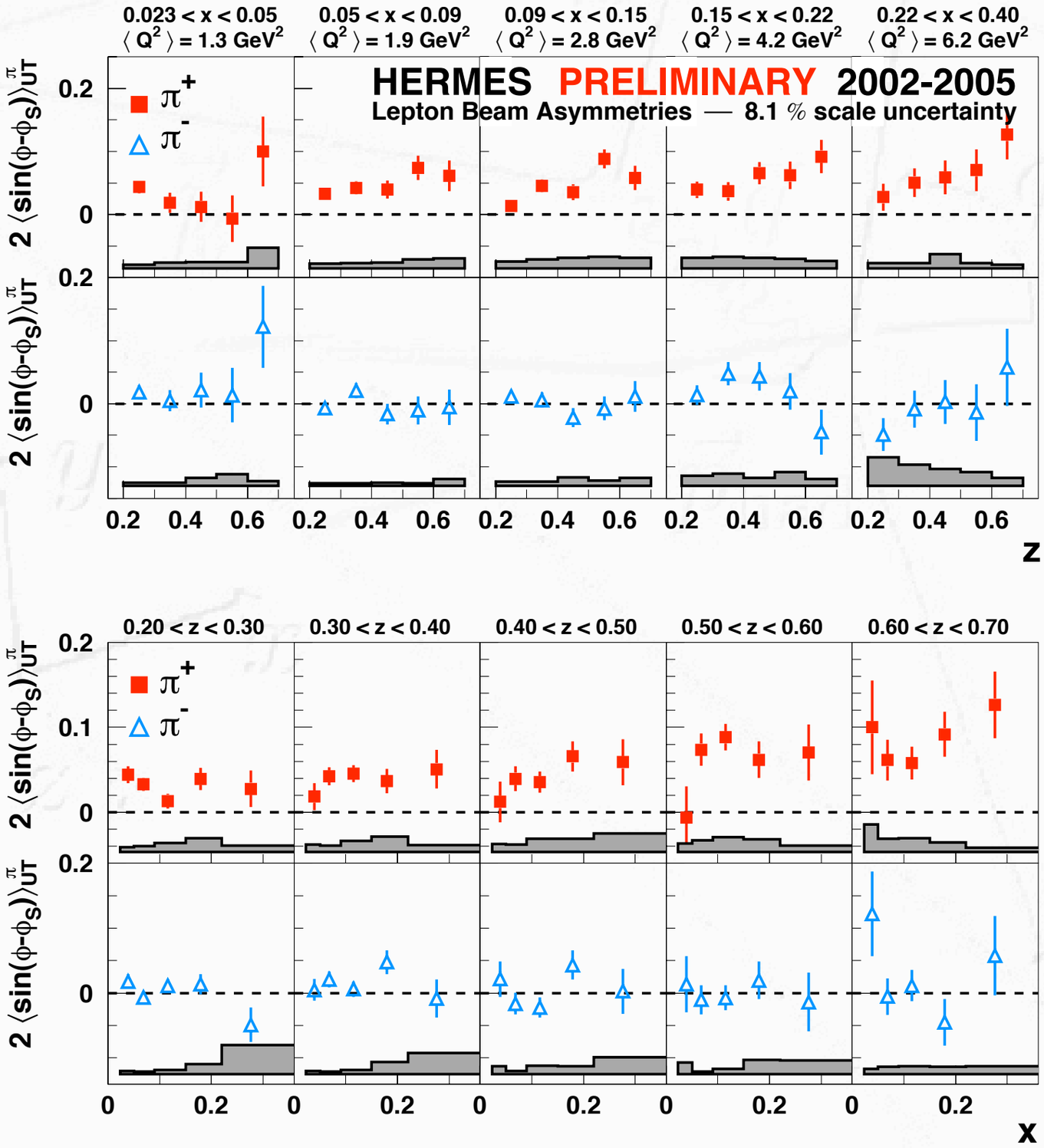
A. Airapetian et al., Phys.Lett.B **666**, 446 (2008)



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



2-Dimensional Binning



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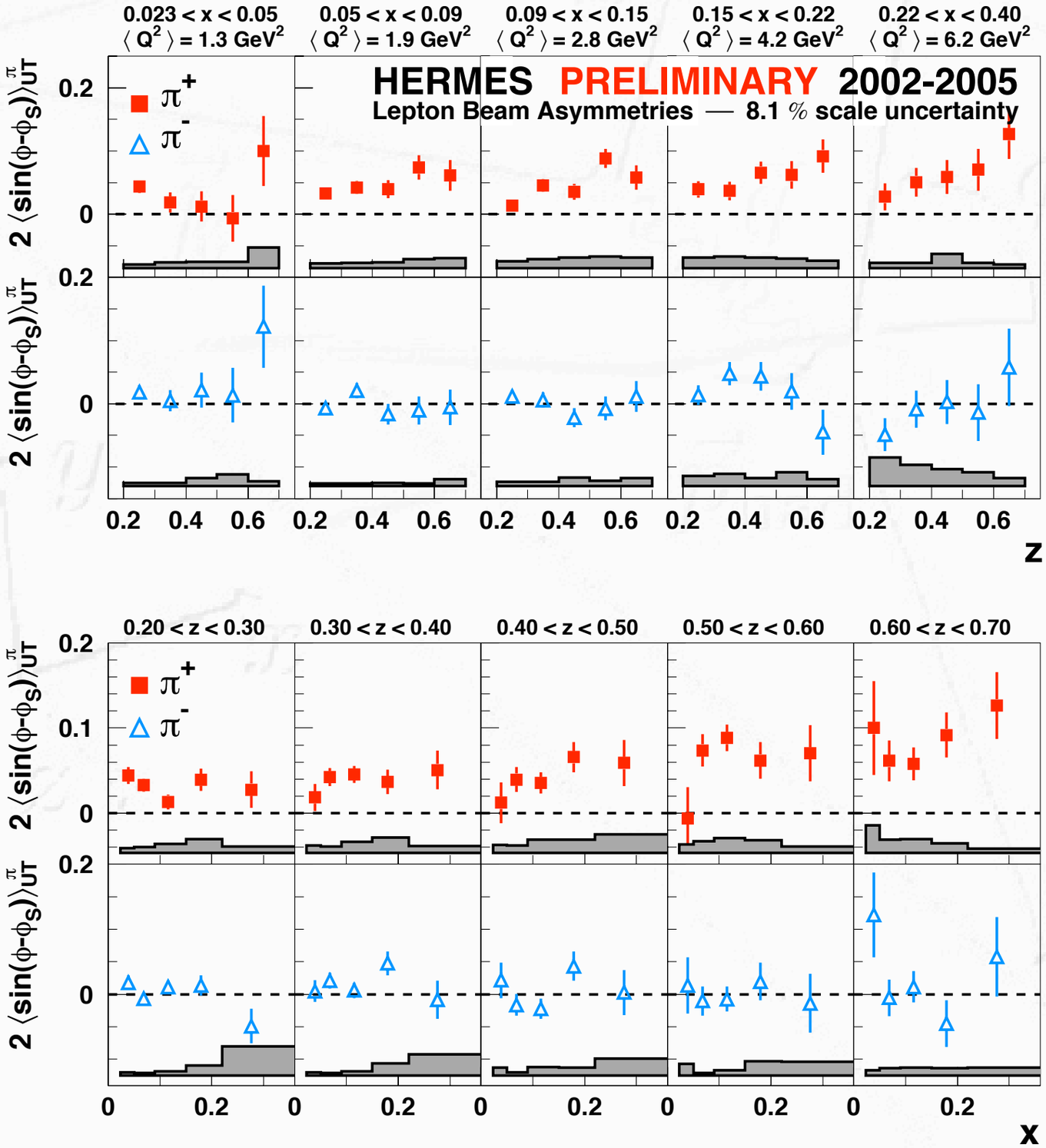
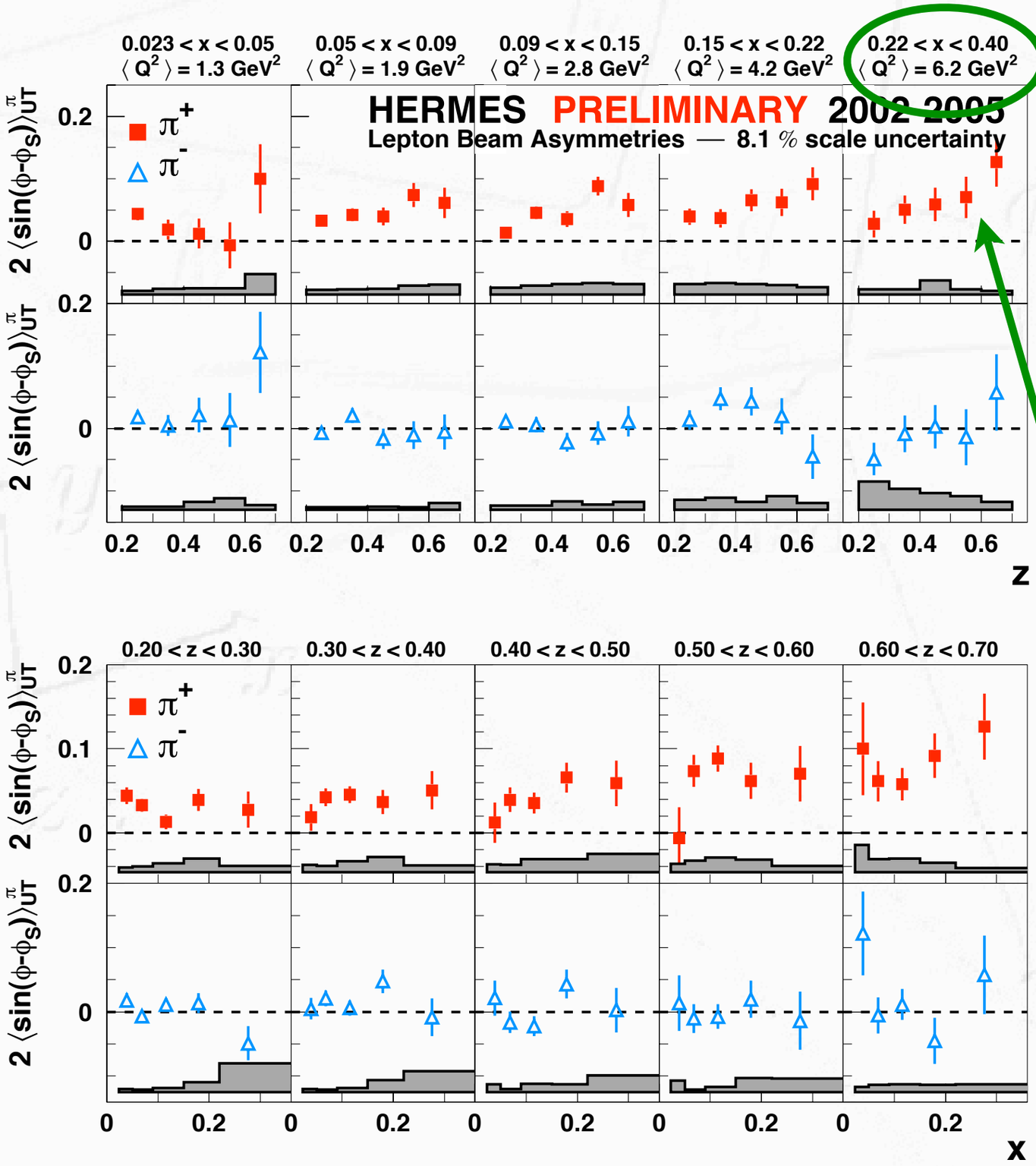


- ☑ high statistics of pion data allows binning in two kinematic variables simultaneously

2-Dimensional Binning



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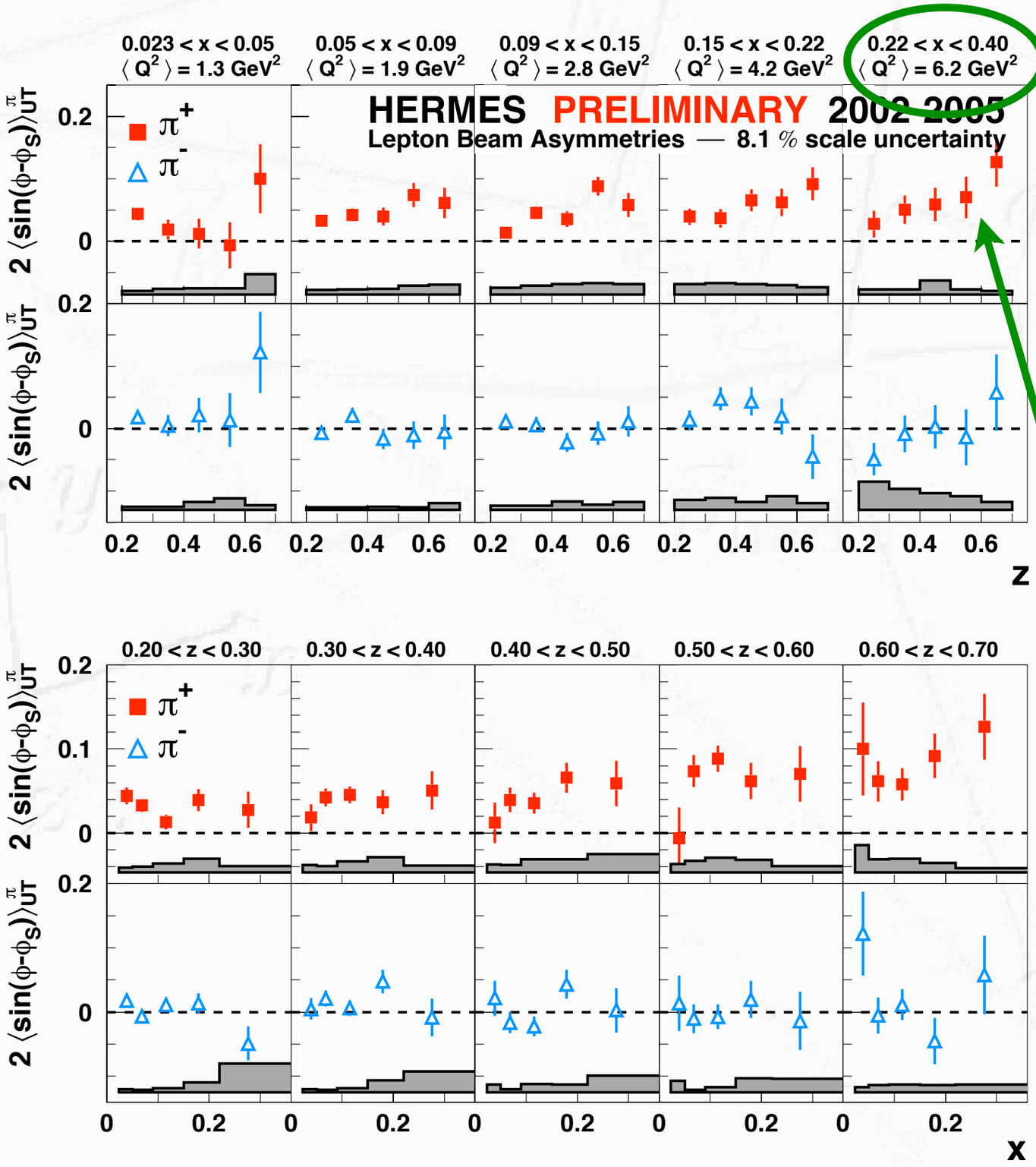
- ☑ amplitudes still non-zero at higher Q^2

2-Dimensional Binning



- ☑ high statistics of pion data allows binning in two kinematic variables simultaneously
- ☑ amplitudes still non-zero at higher Q^2

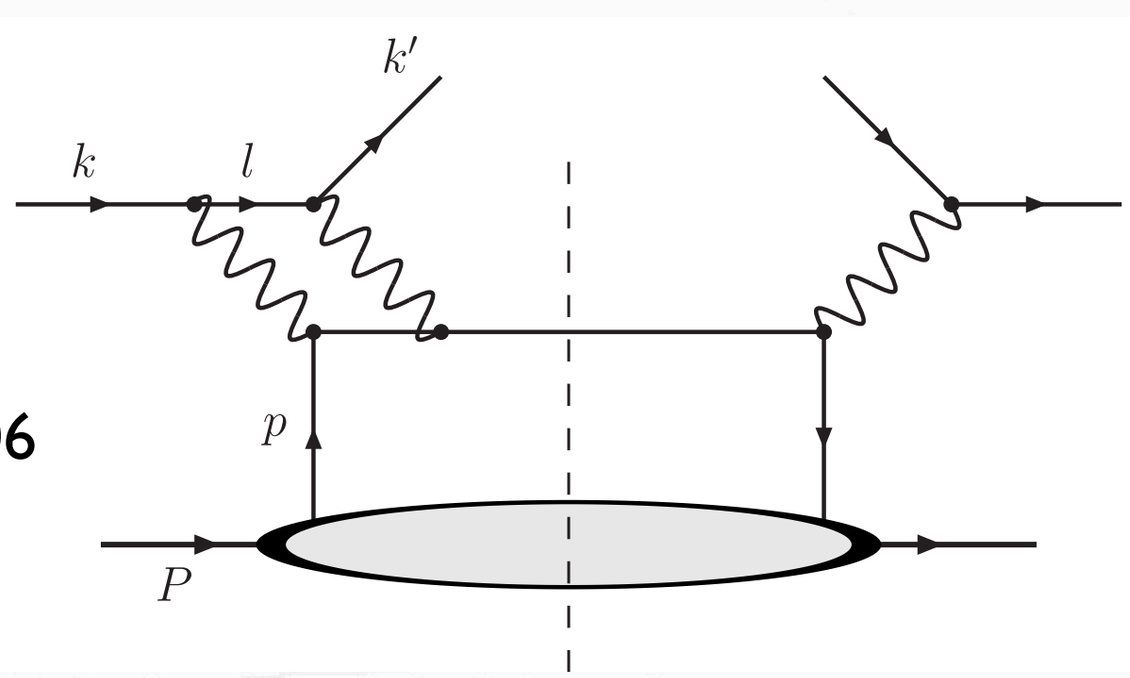
additional combination of kinematic variables available, e.g., for fitting models

Inclusive Deep-Inelastic Scattering

Transverse SSA in Inclusive DIS

- **transverse SSA require <u>interference</u> of amplitudes with different <u>phases</u>**
- **achievable via loop diagrams, e.g.**
  - **Sivers DF includes gauge link (soft gluon exchange)**
- **2-photon exchange could provide such mechanism in inclusive DIS**

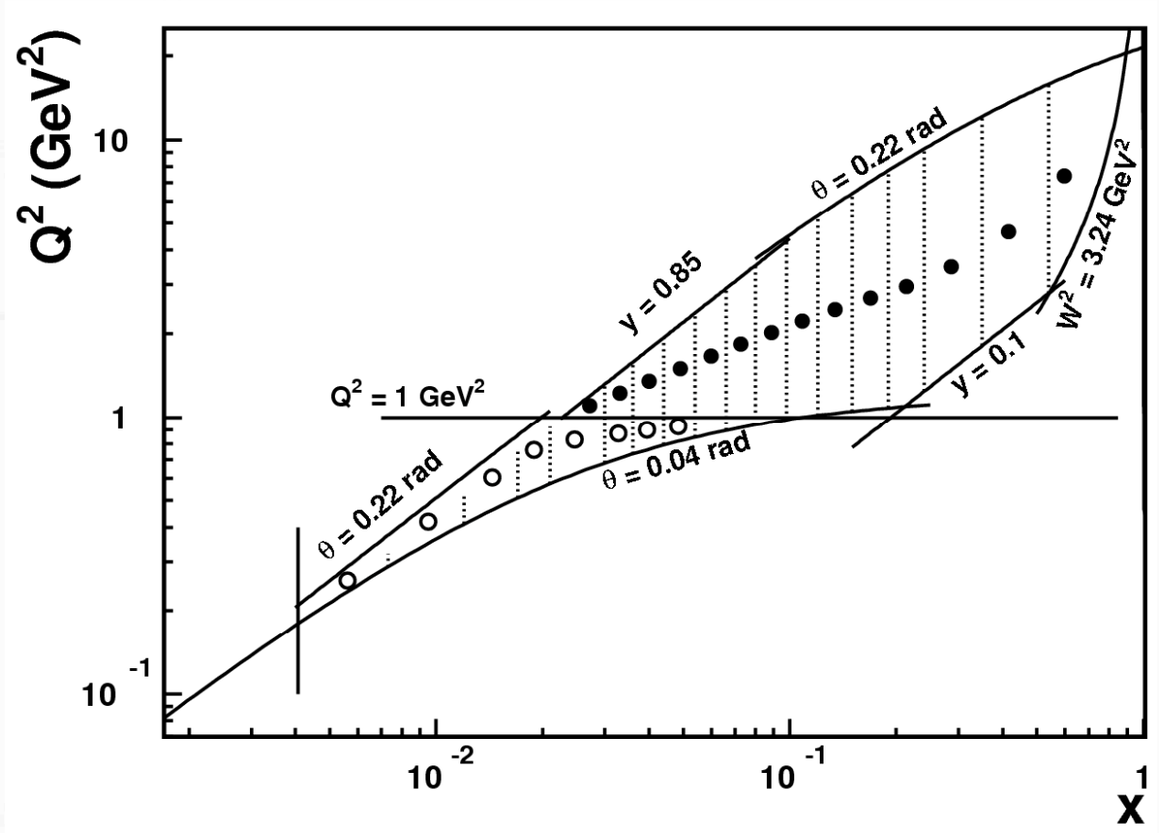
A. Metz et al., Phys.Lett.B **643**, 319-324, 2006



- **2-photon exchange: also candidate for explanation of discrepancy in form-factor measurements**

Inclusive Left-Right Asymmetry at HERMES

- **22 x bins separated into low- and high-Q^2 region**
- **to minimize systematic effects extract asymmetry as**



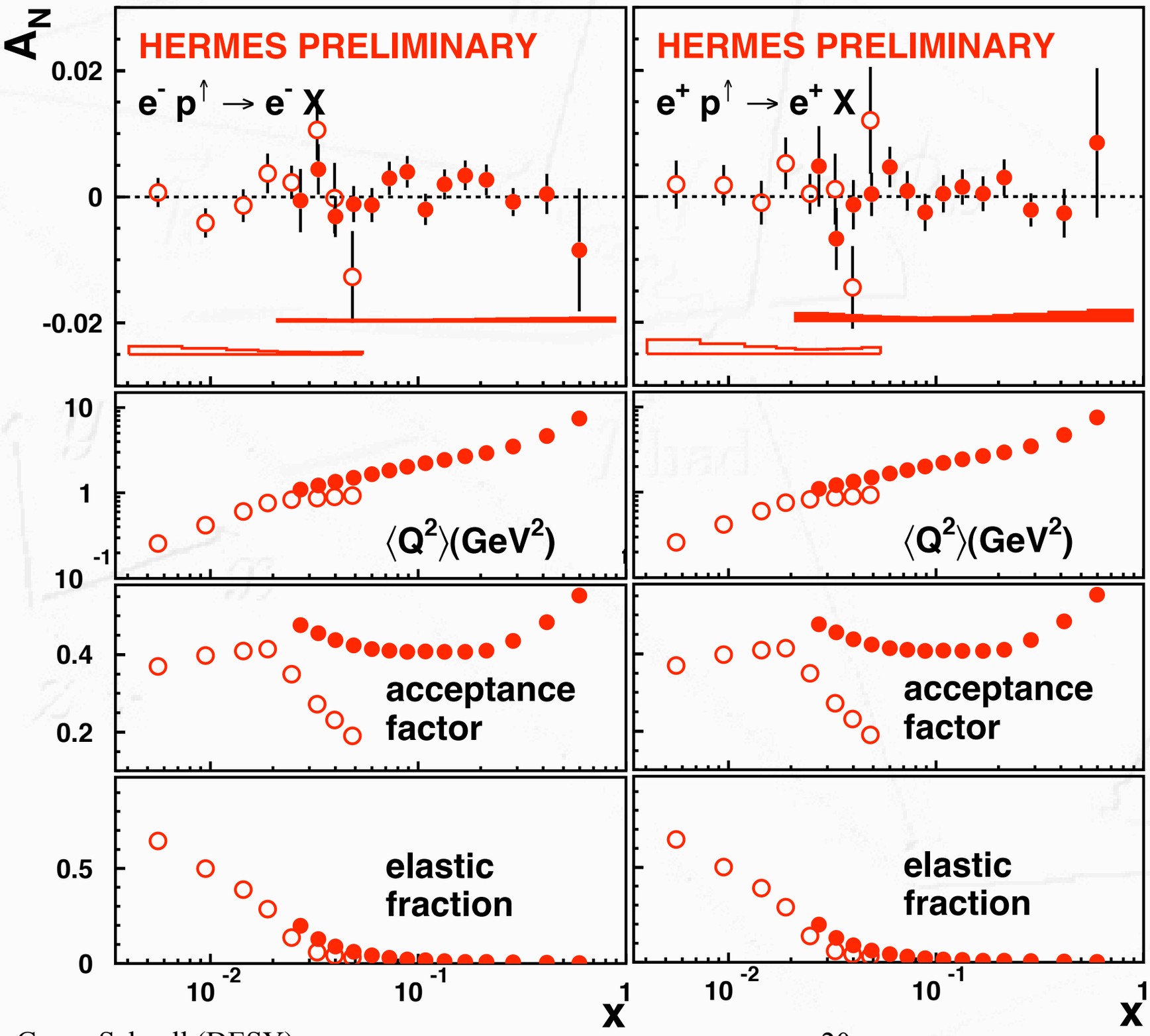
$$A_N = \frac{\sqrt{\frac{N_L^{\uparrow}}{L_P^{\uparrow}}\frac{N_R^{\downarrow}}{L_P^{\downarrow}}} - \sqrt{\frac{N_R^{\uparrow}}{L_P^{\uparrow}}\frac{N_L^{\downarrow}}{L_P^{\downarrow}}}}{\sqrt{\frac{N_L^{\uparrow}}{L_P^{\uparrow}}\frac{N_R^{\downarrow}}{L_P^{\downarrow}}} + \sqrt{\frac{N_R^{\uparrow}}{L_P^{\uparrow}}\frac{N_L^{\downarrow}}{L_P^{\downarrow}}}}$$

$$A_N = \frac{1}{\sqrt{P^{\uparrow}P^{\downarrow}}} \frac{\sqrt{(1-A_{true}P^{\uparrow})(1-A_{true}P^{\downarrow})} - \sqrt{(1+A_{true}P^{\uparrow})(1+A_{true}P^{\downarrow})}}{\sqrt{(1-A_{true}P^{\uparrow})(1-A_{true}P^{\downarrow})} + \sqrt{(1+A_{true}P^{\uparrow})(1+A_{true}P^{\downarrow})}}$$

$$\Rightarrow A_N \approx A_{true}\left(1+\frac{1}{2}\epsilon_P^2\right) \qquad \epsilon_P \equiv \frac{P^{\uparrow}-P^{\downarrow}}{P^{\uparrow}+P^{\downarrow}}$$

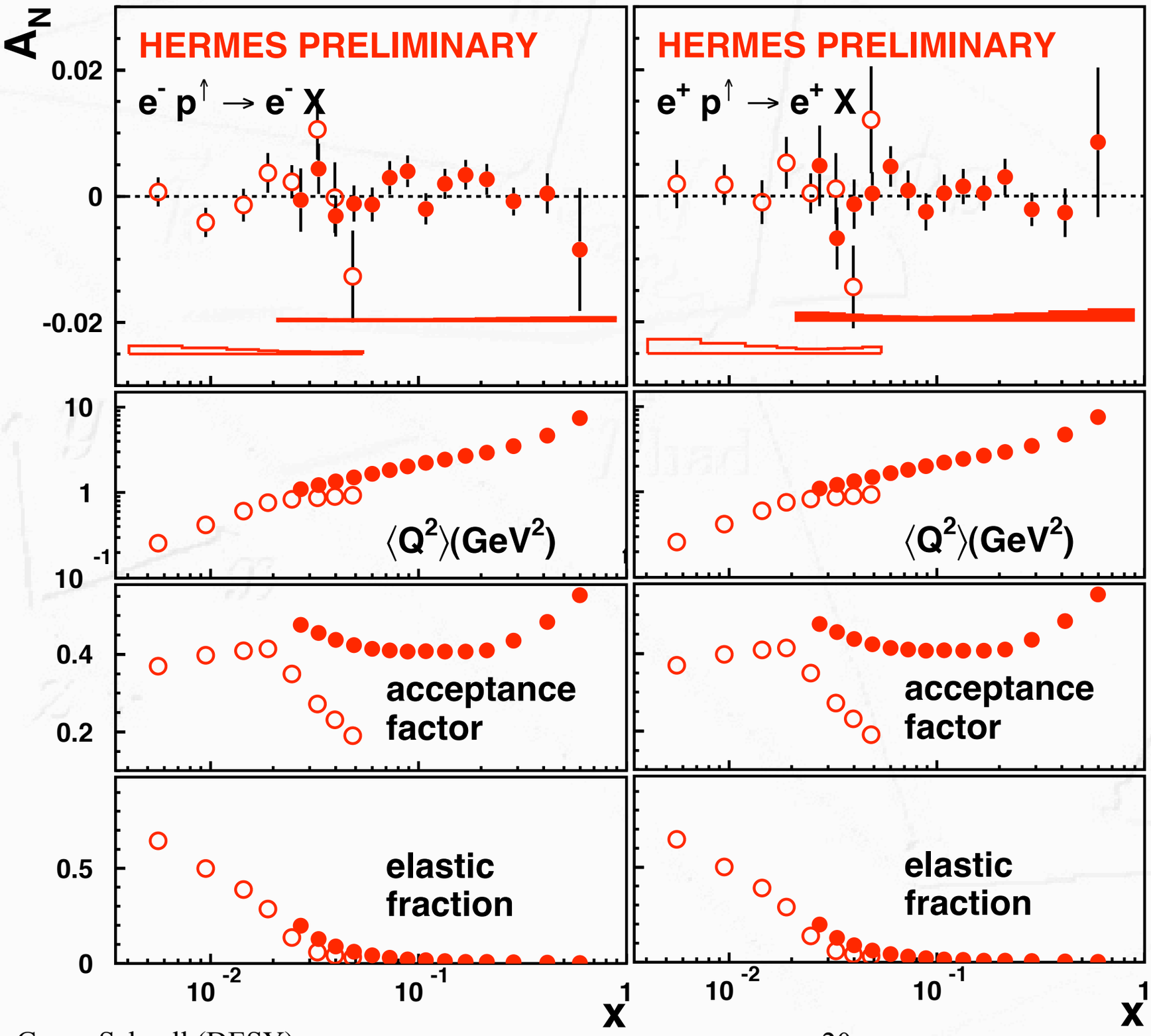
year	$P^{\uparrow}$	$P^{\downarrow}$
2002	0.795	0.795
2004	0.745	0.742
2005	0.705	0.705

Any Sign of 2-Photon Exchange?

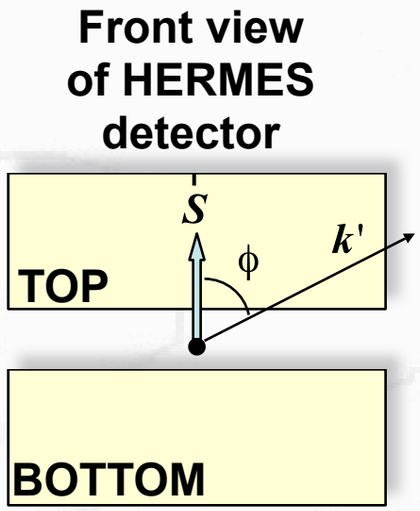


consistent with zero

Any Sign of 2-Photon Exchange?



consistent with zero



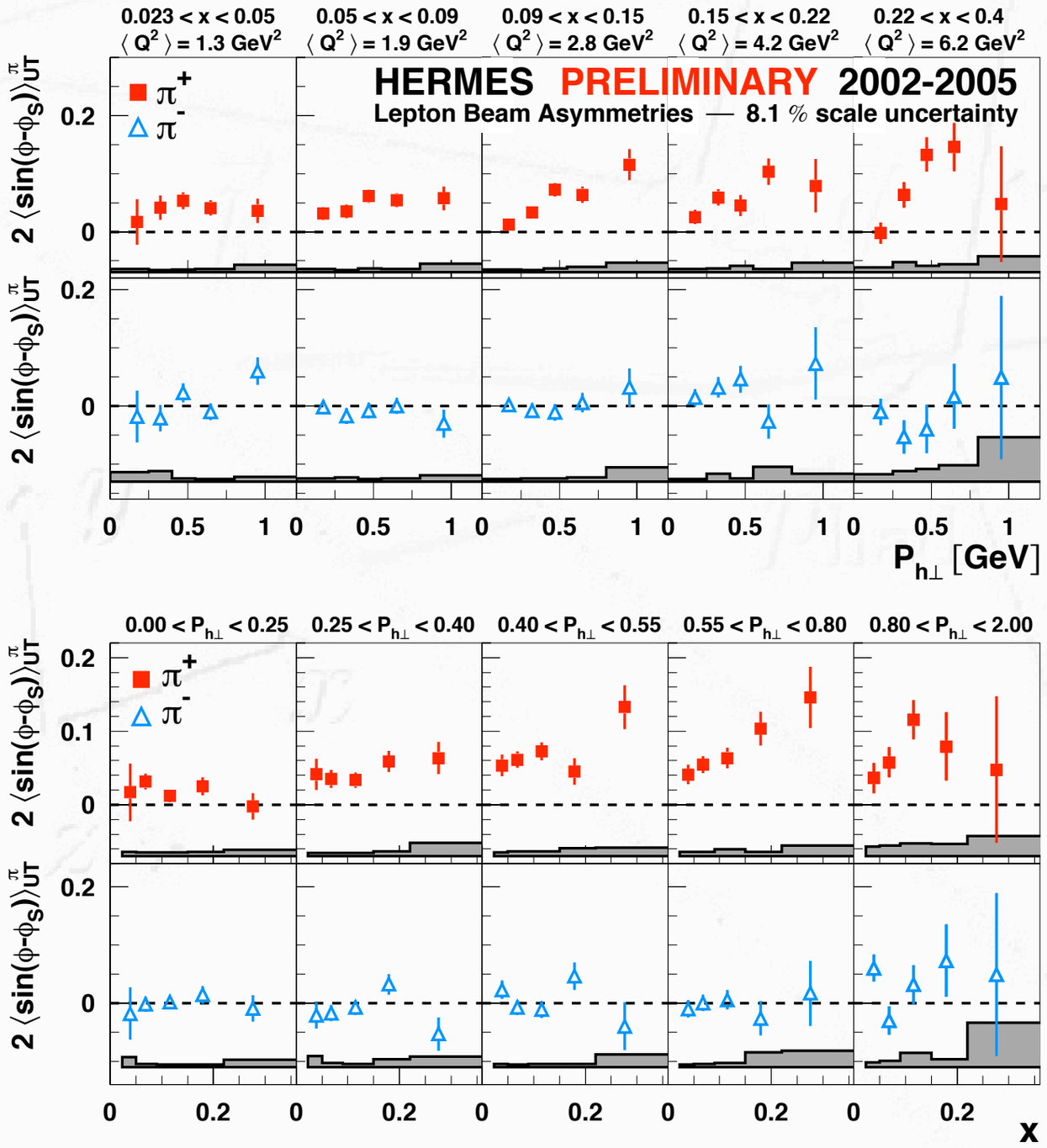
$$\text{acc.fac.} \equiv \frac{(A_N)_{acc}}{(A_{UT}^{\sin\phi})_{2\pi}}$$

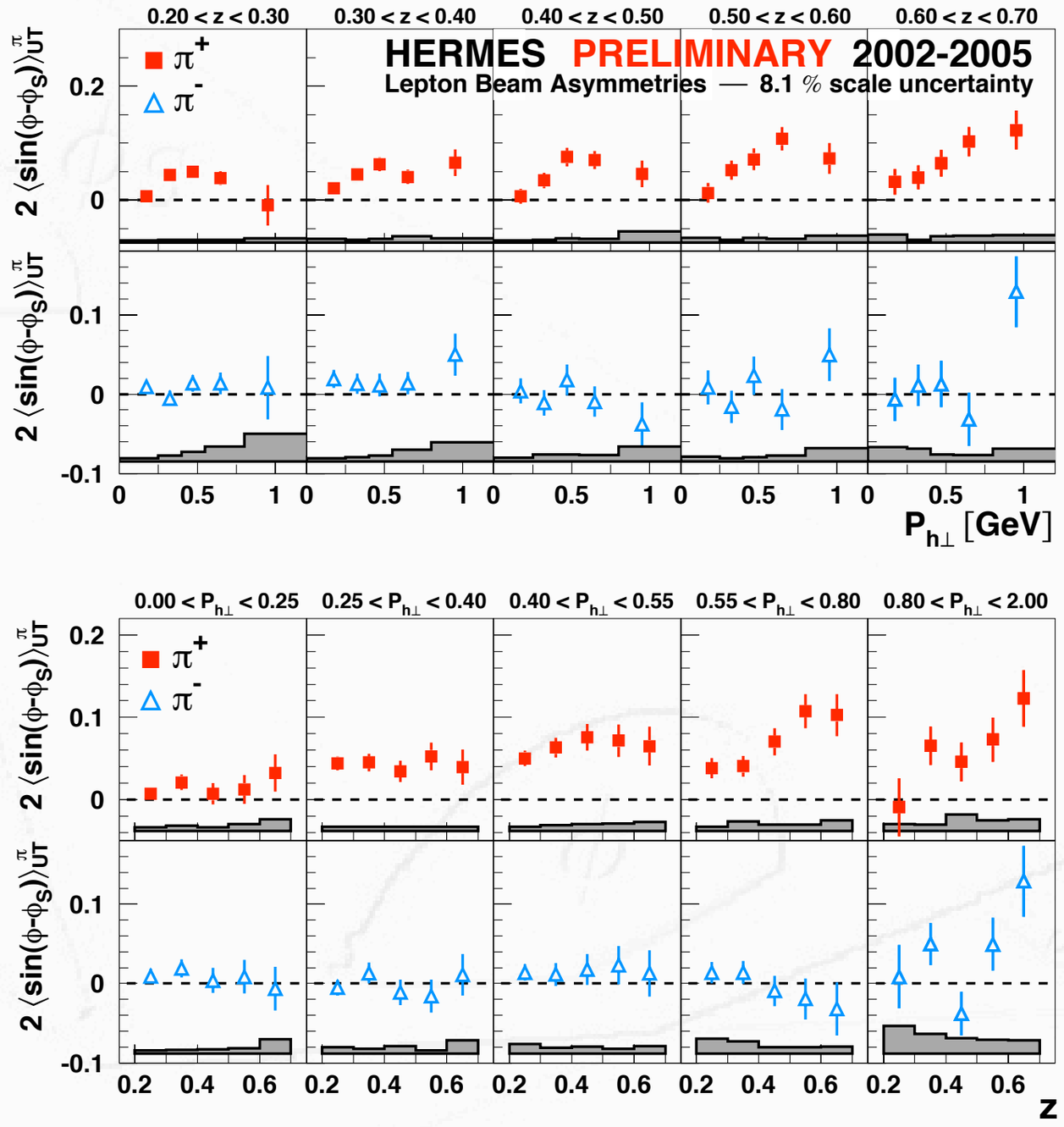
Conclusions

- **Clear evidence that transversity is non-zero and measurable through**
  - **2-hadron fragmentation (“*interference fragmentation*”)**
  - **Collins effect**
- **Observation of Sivers effect suggests sizeable orbital angular momentum of quarks**
- **vanishing left-right asymmetry in inclusive DIS does not support significant contribution from 2-photon exchange**

BACKUP

2D Binning Sivers





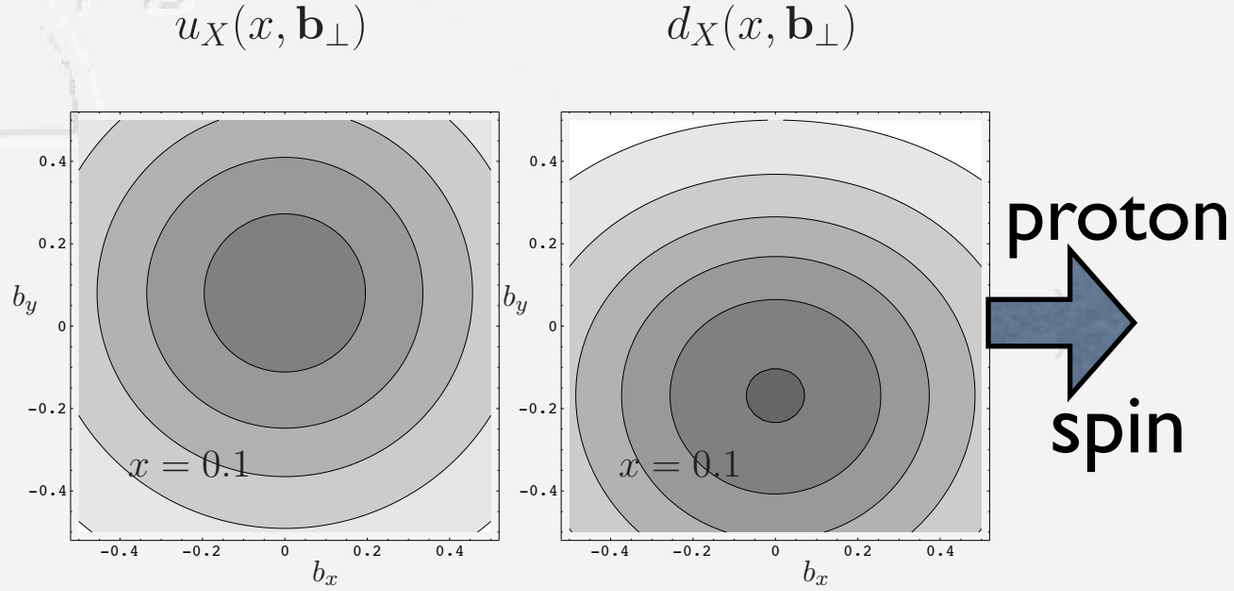
“Chromodynamic Lensing”

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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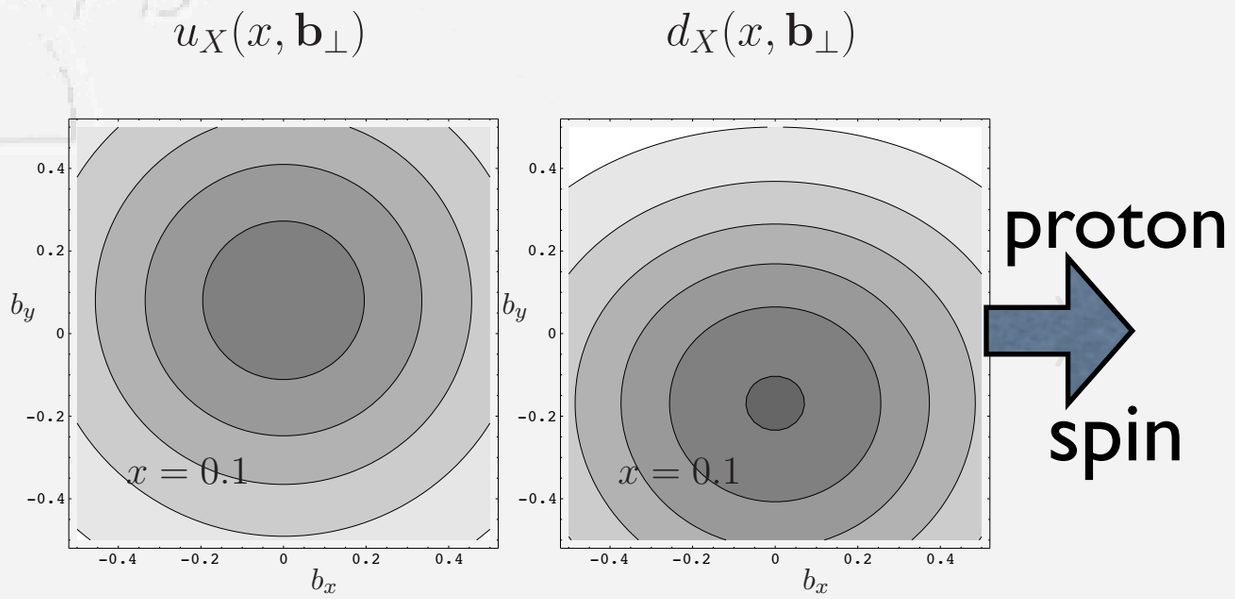
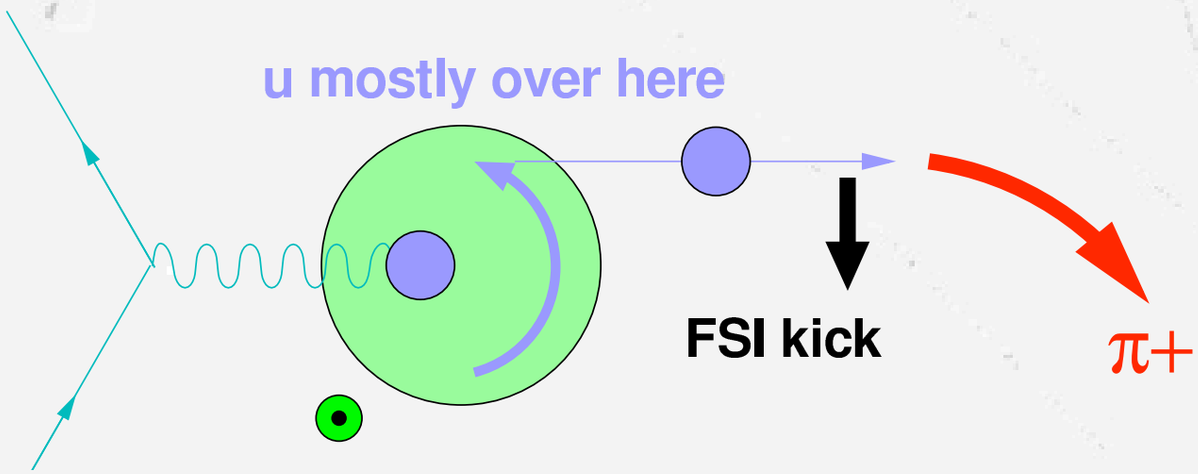
+ attractive QCD potential

(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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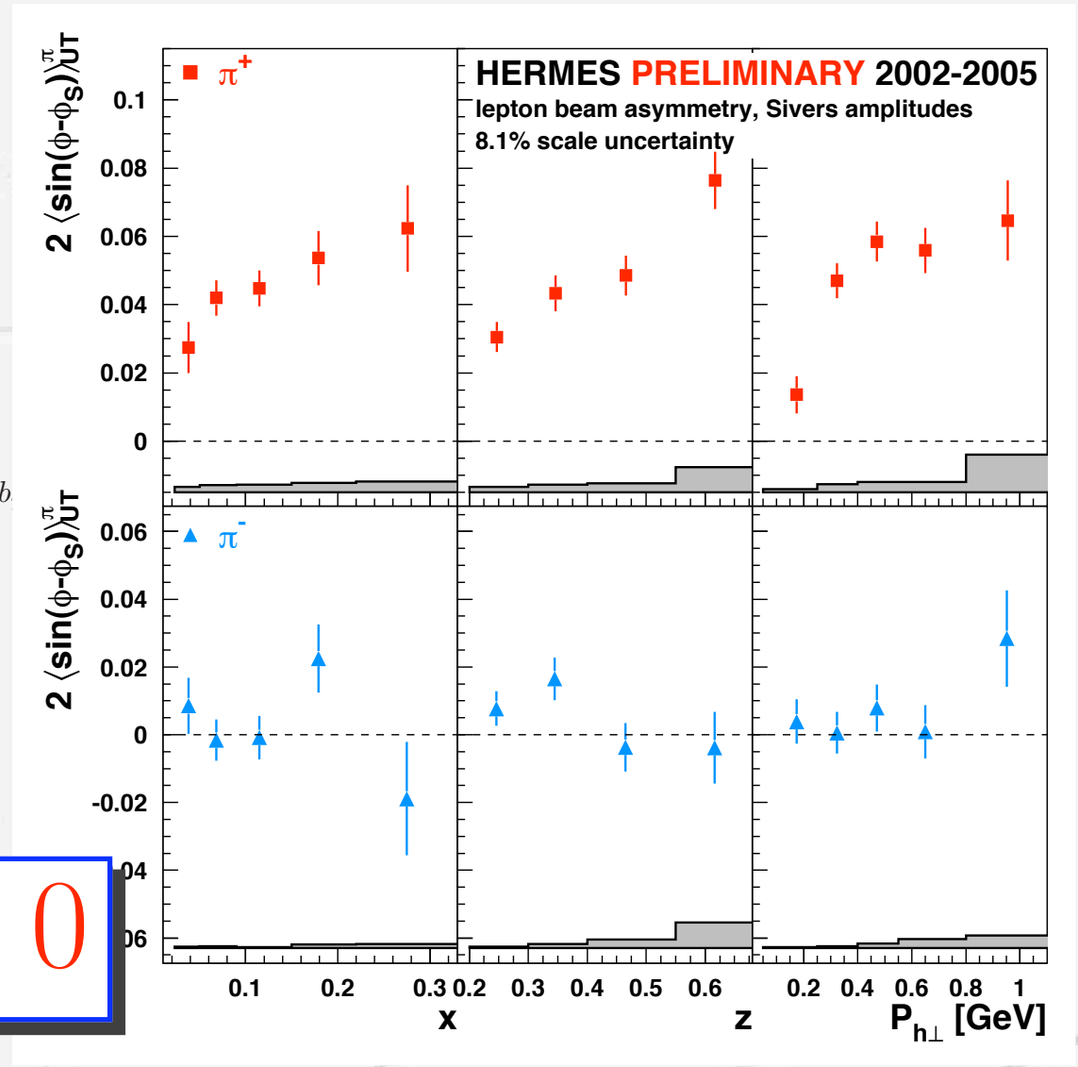
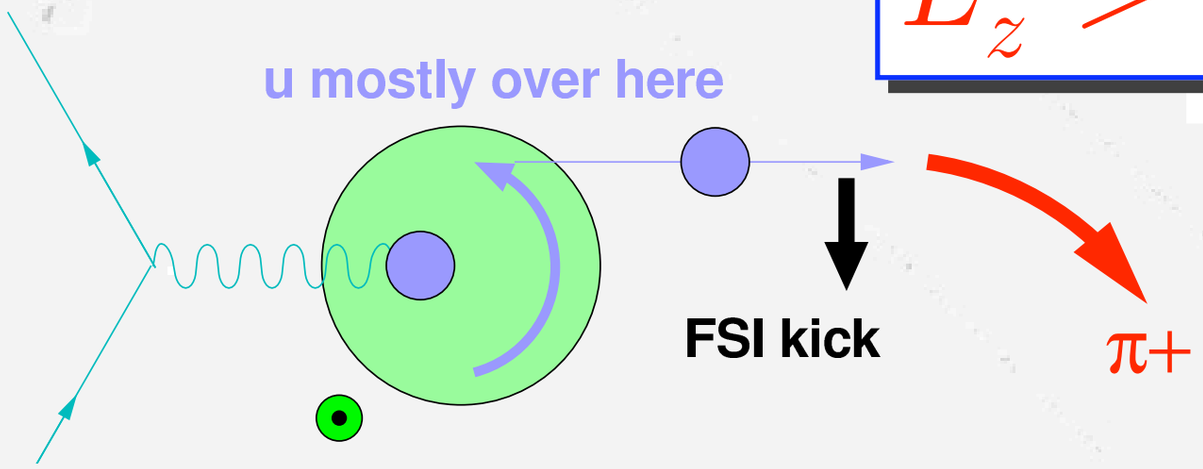
⇒ transverse asymmetries

$$L_z^u > 0$$





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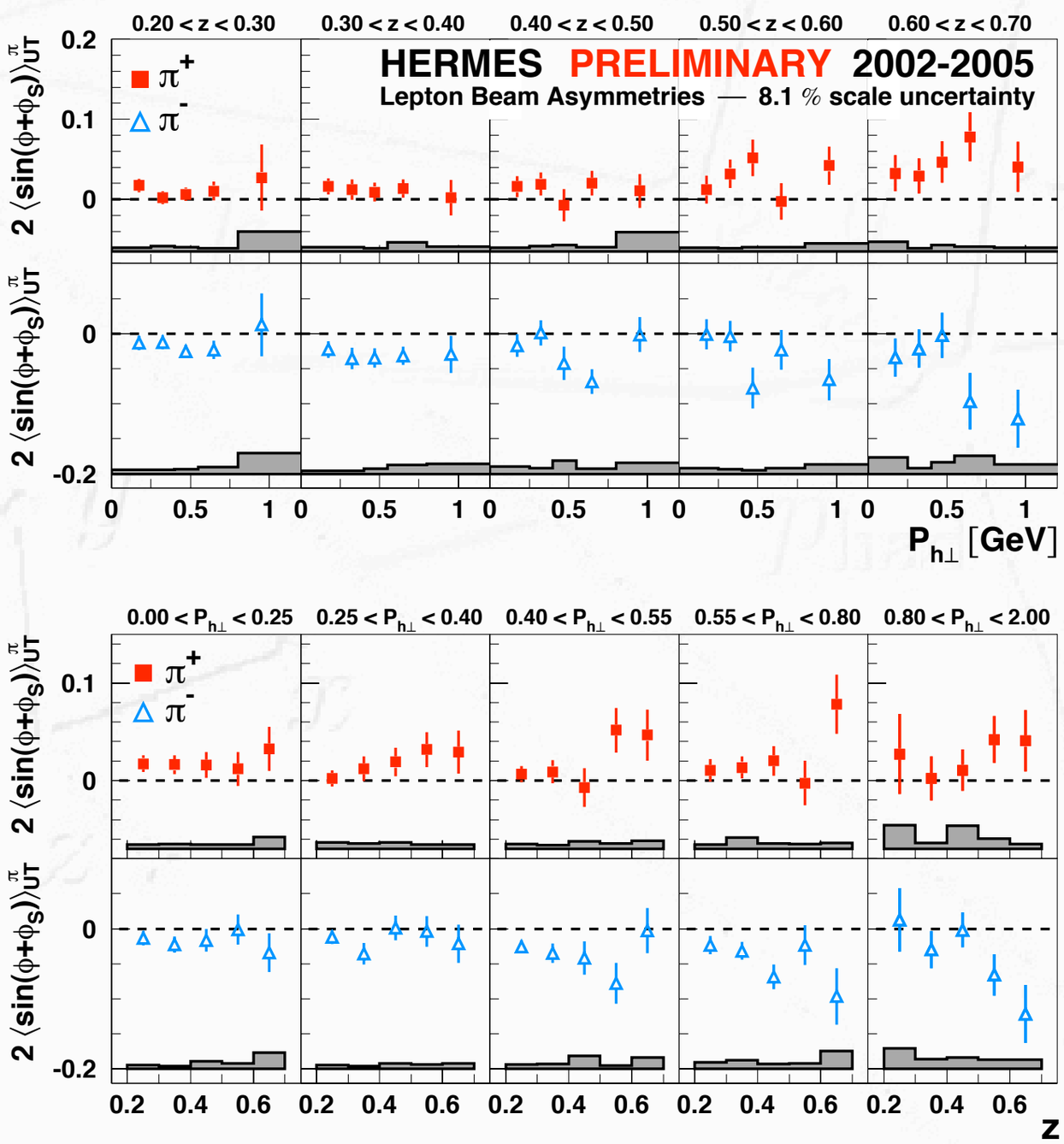
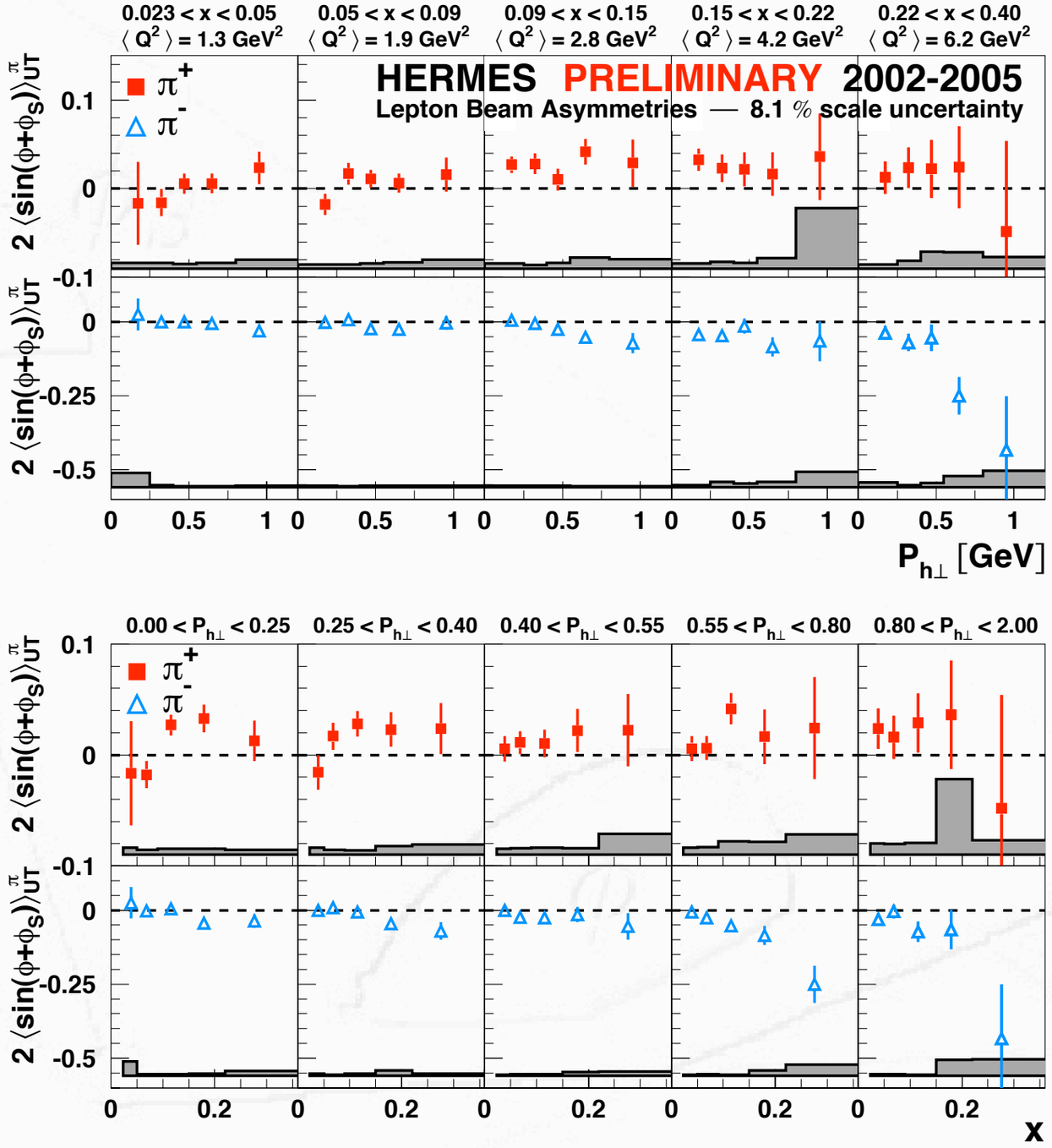
2D Collins


0.20 < z < 0.30
0.30 < z < 0.40
0.40 < z < 0.50
0.50 < z < 0.60
0.60 < z < 0.70
HERMES PRELIMINARY 2002-2005
Lepton Beam Asymmetries — 8.1 % scale uncertainty
π+
π-
2 ⟨sin(φ+φS)⟩UTπ
P h⊥ [GeV]
0.00 < P h⊥ < 0.25
0.25 < P h⊥ < 0.40
0.40 < P h⊥ < 0.55
0.55 < P h⊥ < 0.80
0.80 < P h⊥ < 2.00
z


0.023 < x < 0.05
⟨ Q2 ⟩ = 1.3 GeV2
0.05 < x < 0.09
⟨ Q2 ⟩ = 1.9 GeV2
0.09 < x < 0.15
⟨ Q2 ⟩ = 2.8 GeV2
0.15 < x < 0.22
⟨ Q2 ⟩ = 4.2 GeV2
0.22 < x < 0.40
⟨ Q2 ⟩ = 6.2 GeV2
HERMES PRELIMINARY 2002-2005
Lepton Beam Asymmetries — 8.1 % scale uncertainty
π+
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2 ⟨sin(φ+φS)⟩UTπ
P h⊥ [GeV]
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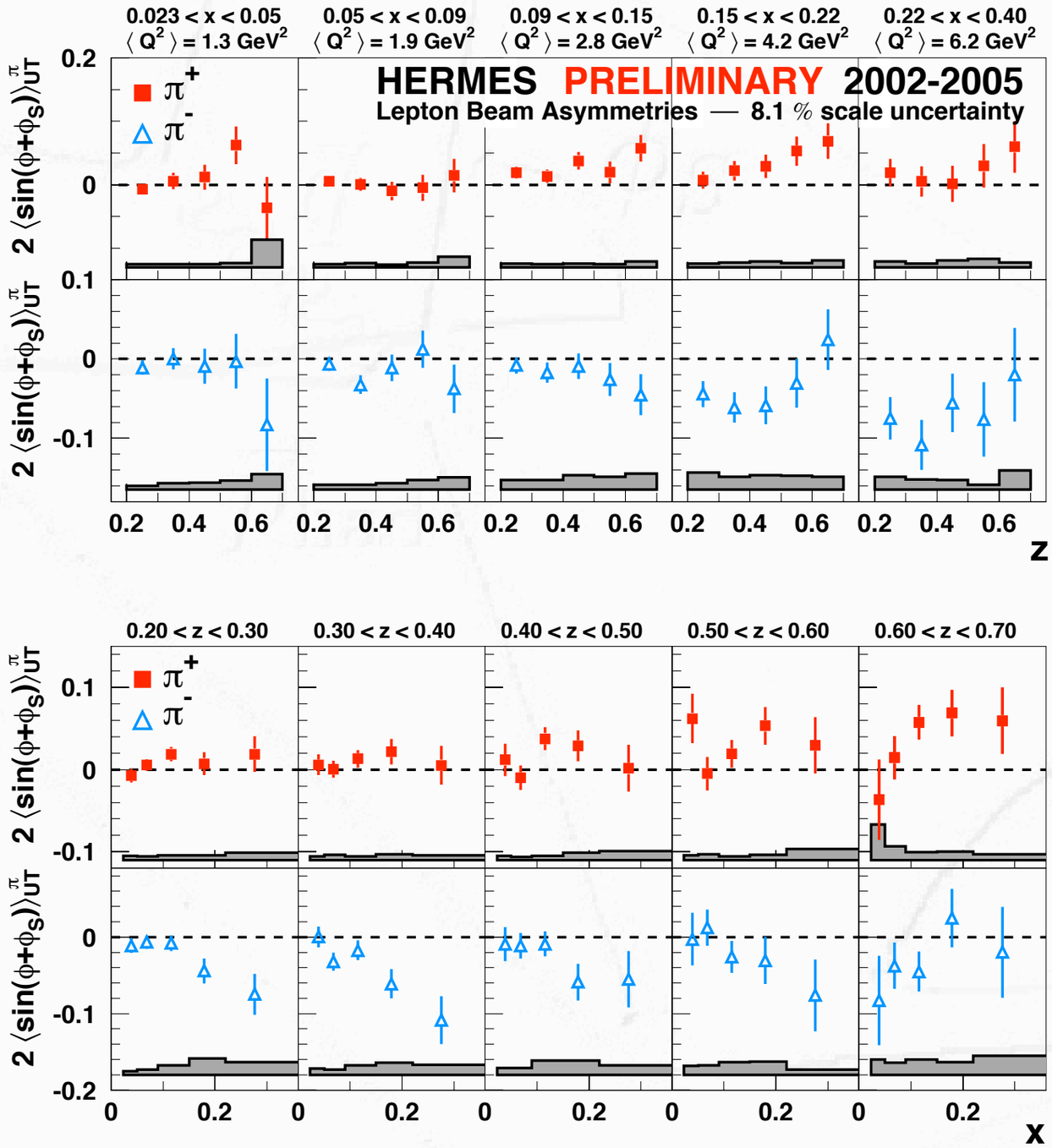
0.25 < P h⊥ < 0.40
0.40 < P h⊥ < 0.55
0.55 < P h⊥ < 0.80
0.80 < P h⊥ < 2.00
x

2D Collins


0.023 < x < 0.05
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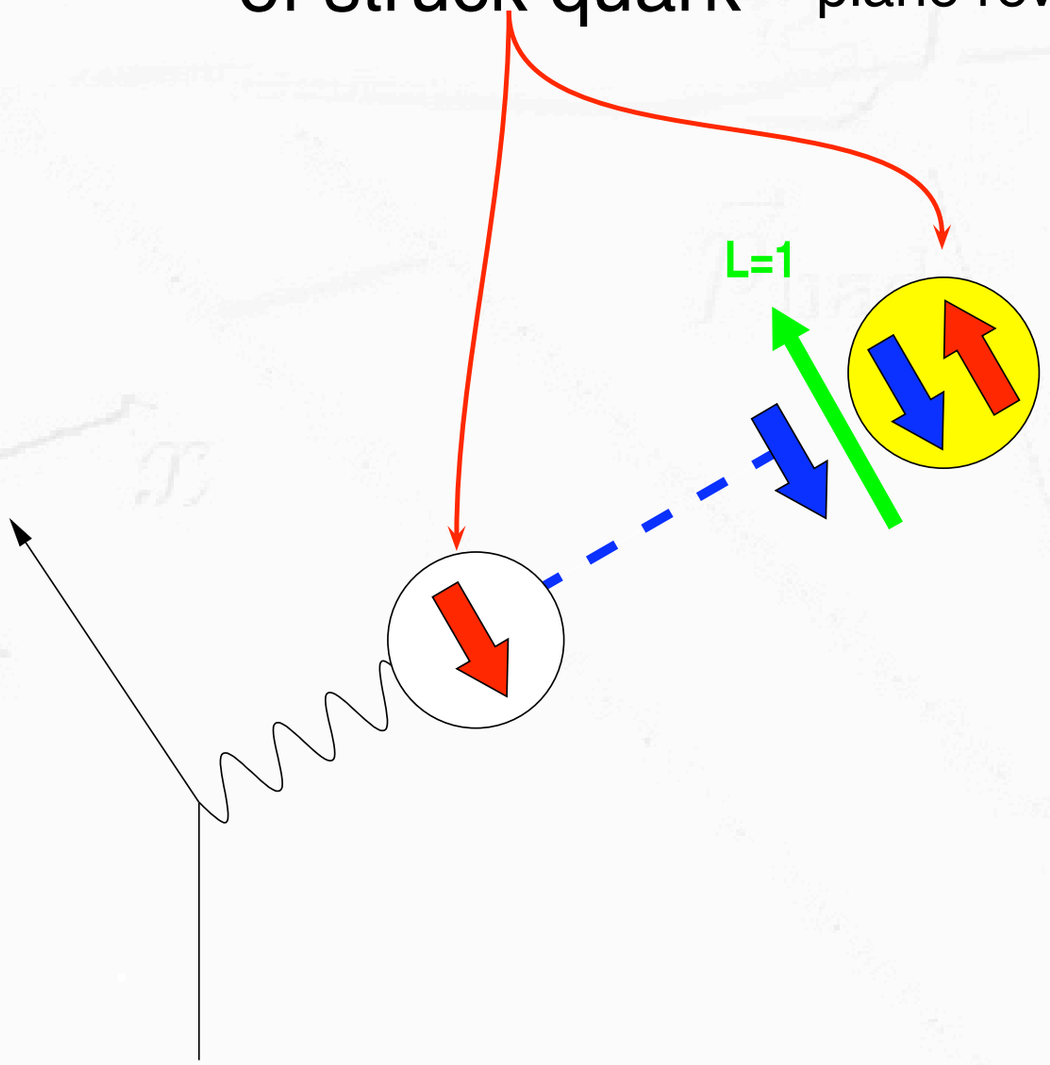
0.50 < z < 0.60
0.60 < z < 0.70
x

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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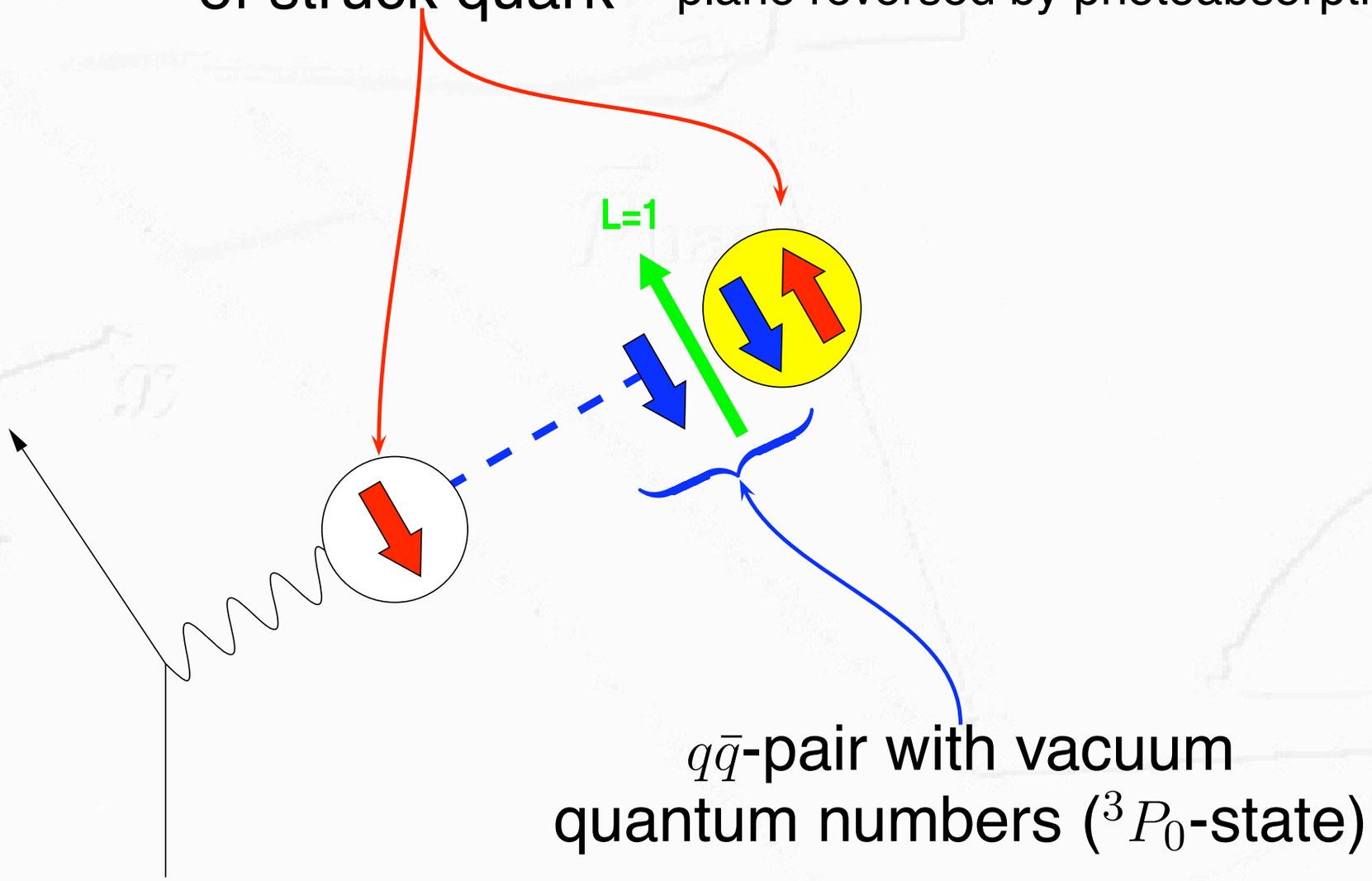

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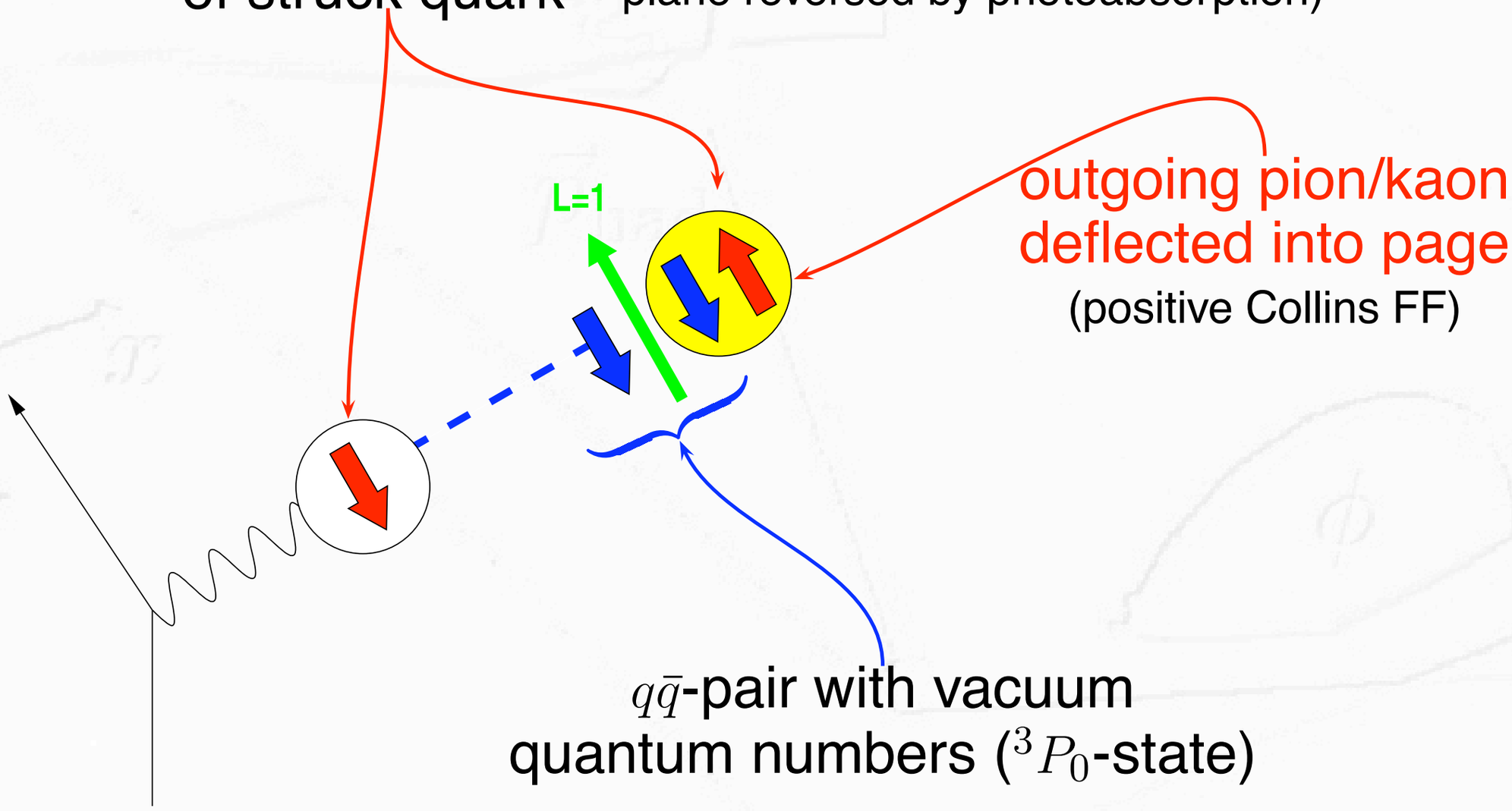

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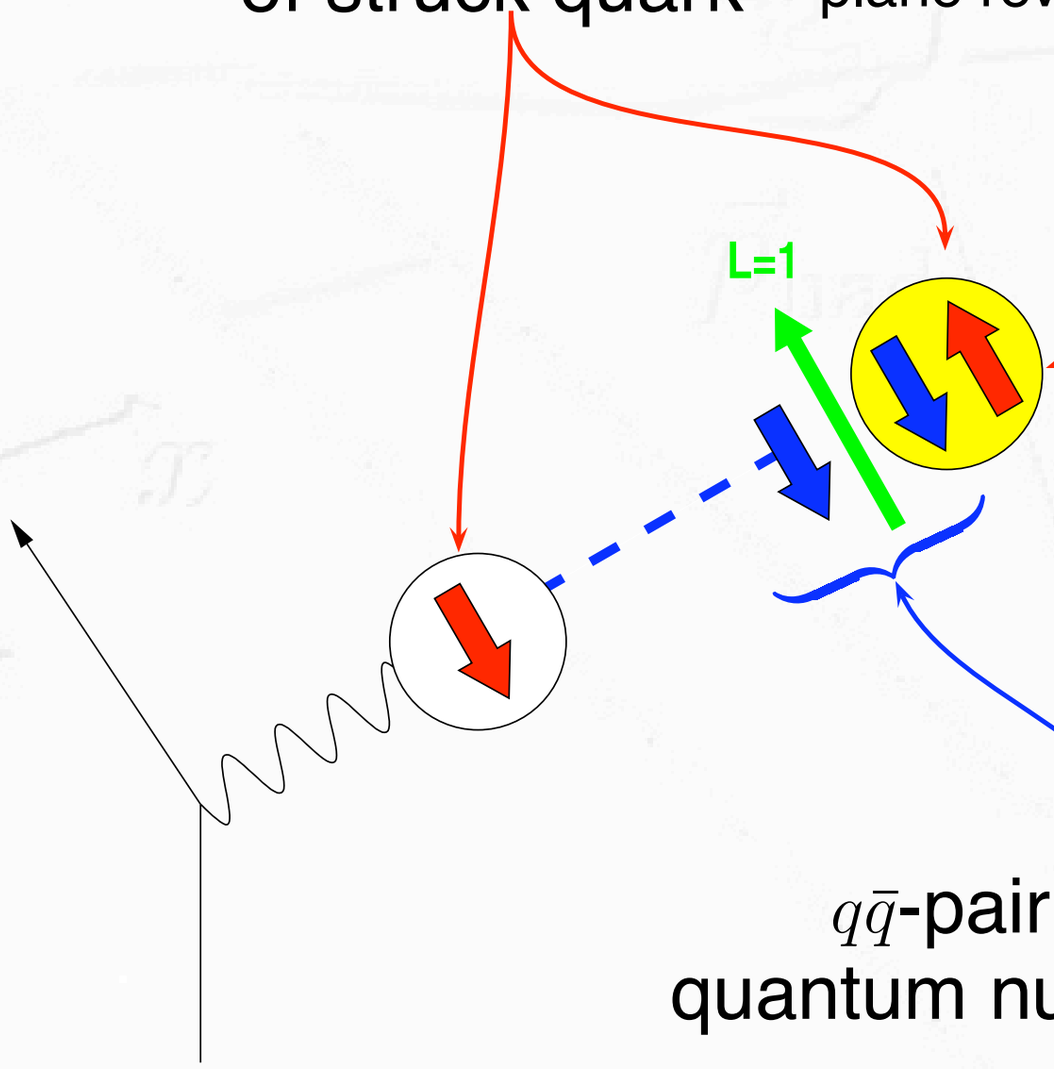


outgoing pion/kaon deflected into page

(positive Collins FF)

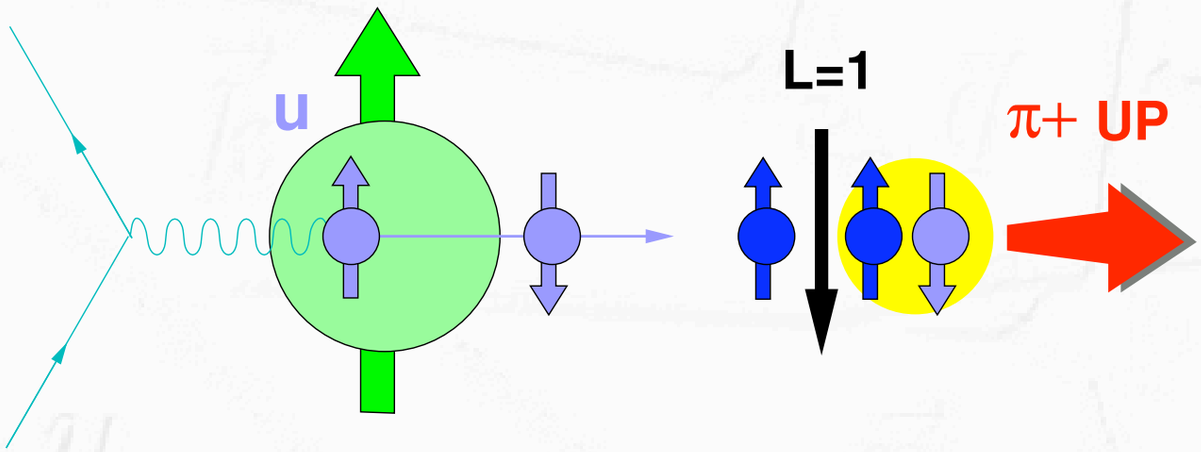
pion from next string break deflected out of page

(negative Collins FF)

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

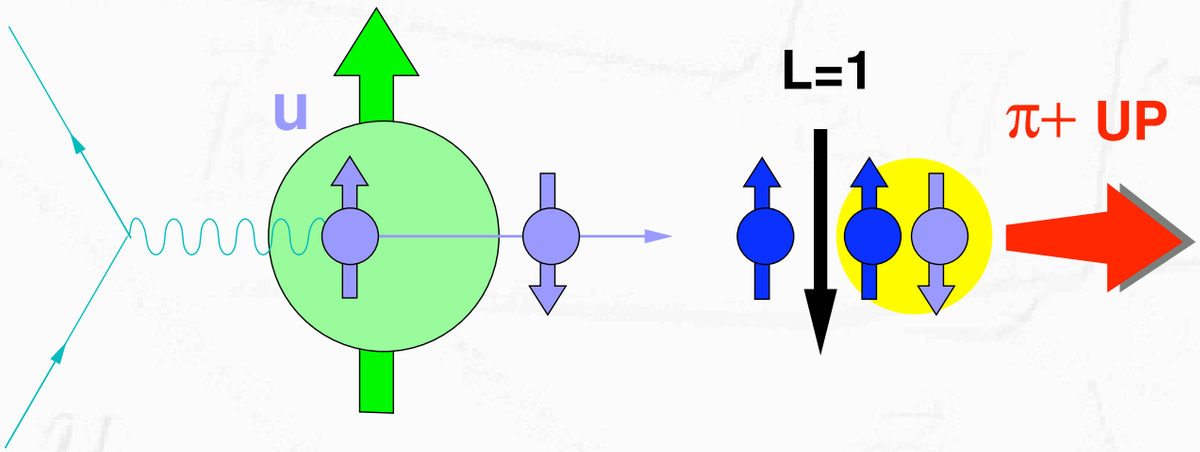
Artru Model vs. HERMES

Artru Model vs. HERMES



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

Artru Model vs. HERMES



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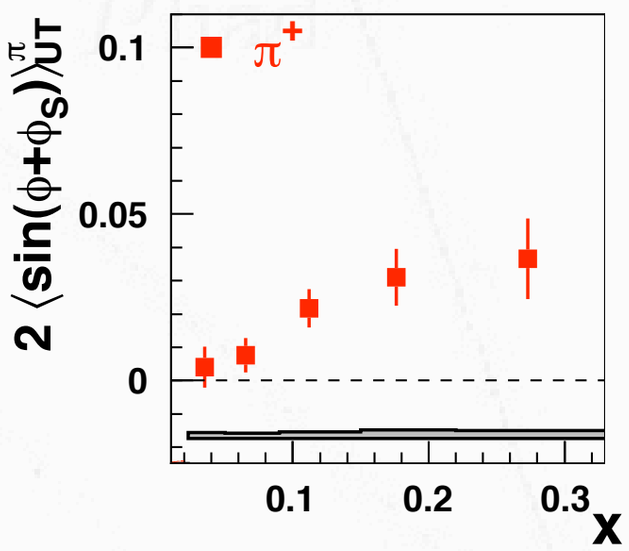
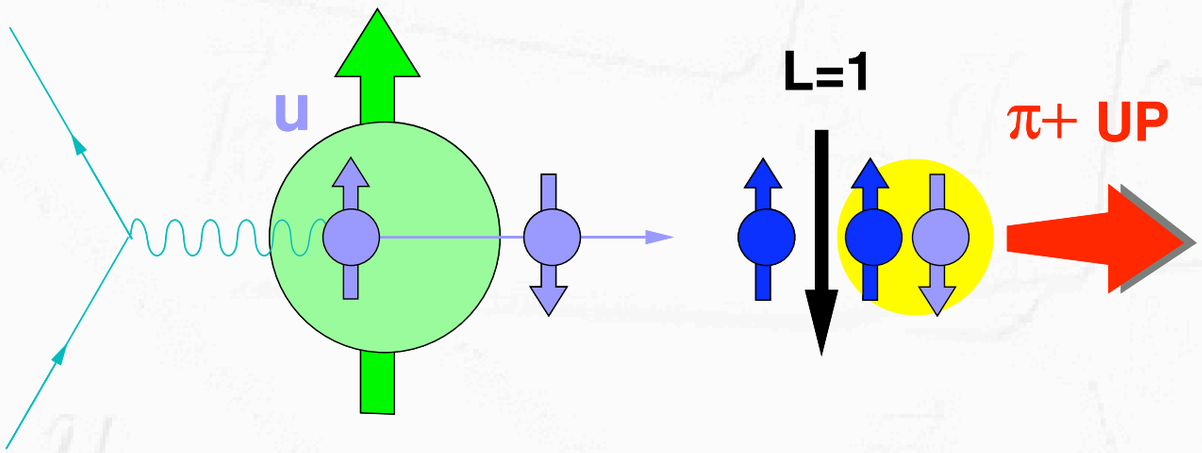


Artru Model vs. HERMES



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✓

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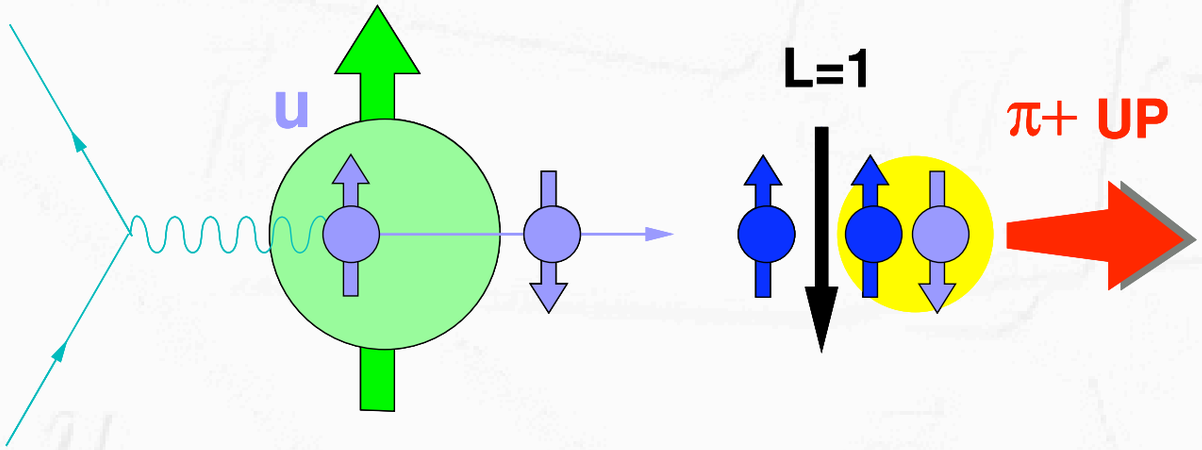

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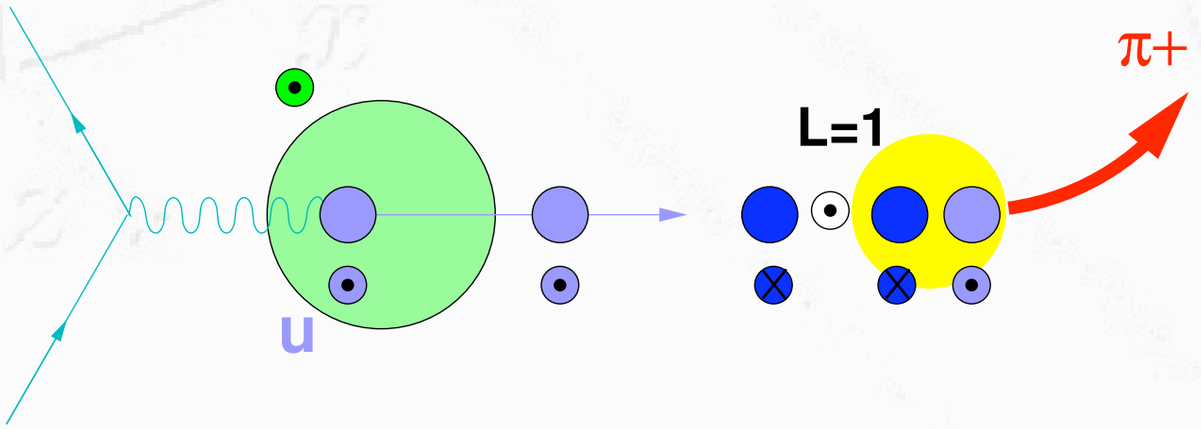

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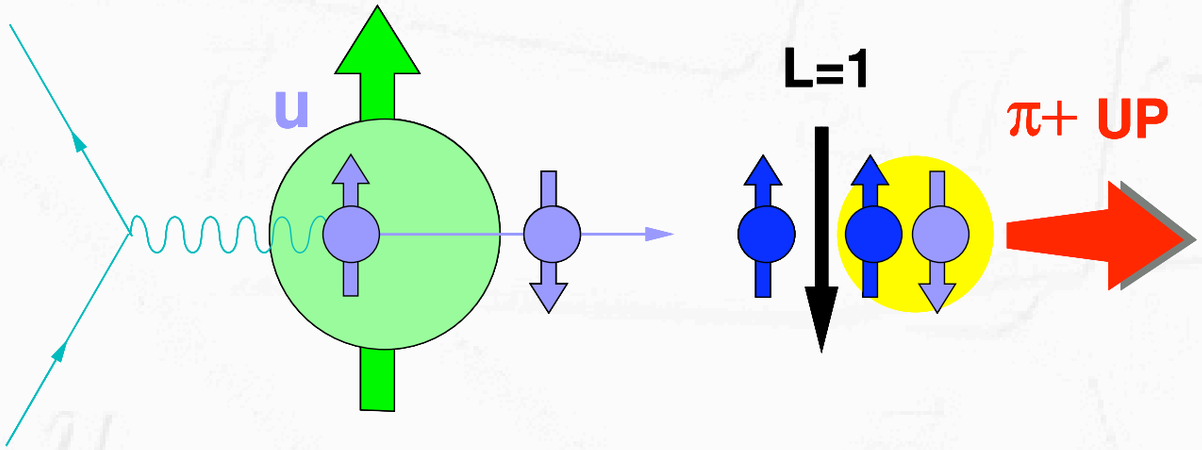

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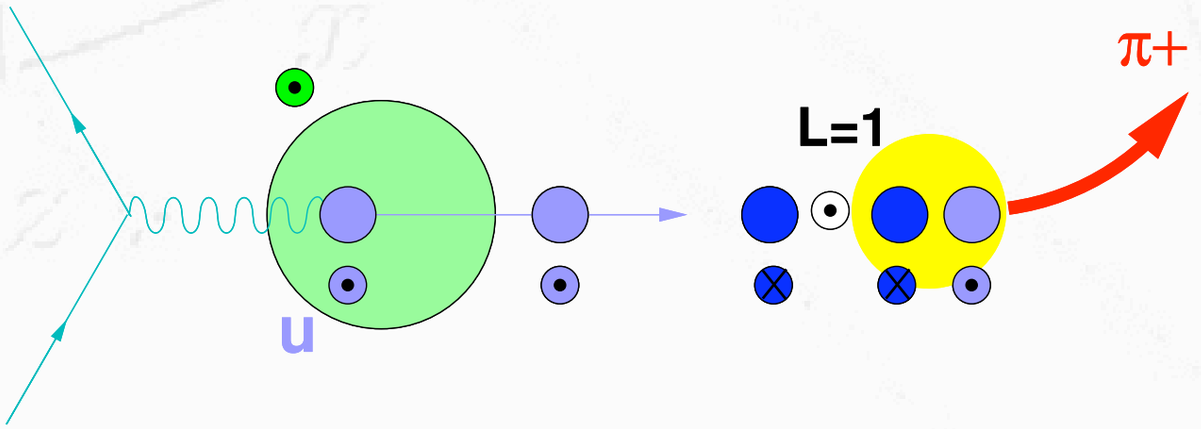

$$\left.\begin{array}{r}\phi_S = \pi/2 \\ \phi \ = \ 0\end{array}\right\} \sin(\phi + \phi_S) > 0$$

Artru model and HERMES results in agreement!

Inclusive A_N - No x-Binning

<x>=0.02, <Q^2>=0.6GeV^2

e+	$A_N = (\ 1.28 \pm 1.47_{stat} \pm 1.35_{syst}\ ) \times 10^{-3}$
e-	$A_N = (\ 1.35 \pm 1.29_{stat} \pm 0.73_{syst}\ ) \times 10^{-3}$

Acceptance factor:

0.37 ← **58% of full 2π acceptance**

<x>=0.14, <Q^2>=2.4GeV^2

e+	$A_N = (\ 0.21 \pm 0.90_{stat} \pm 0.74_{syst}\ ) \times 10^{-3}$
e-	$A_N = (\ 0.87 \pm 0.76_{stat} \pm 0.41_{syst}\ ) \times 10^{-3}$

Acceptance factor:

0.42 ← **66% of full 2π acceptance**

Expectation: $A_N \approx \alpha_{em} \frac{M}{Q} \approx 10^{-2}$