Spin Structure of the Proton and Neutron studied with Electron DIS

Recent HERMES Results on the Quark Structure of the Nucleon

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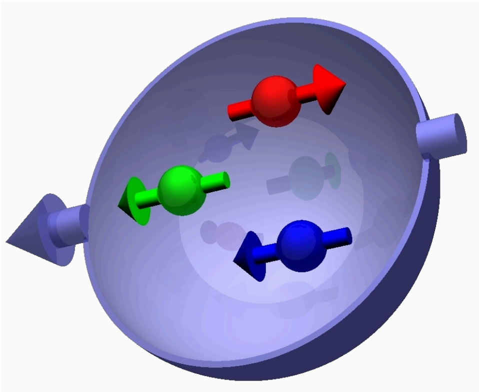
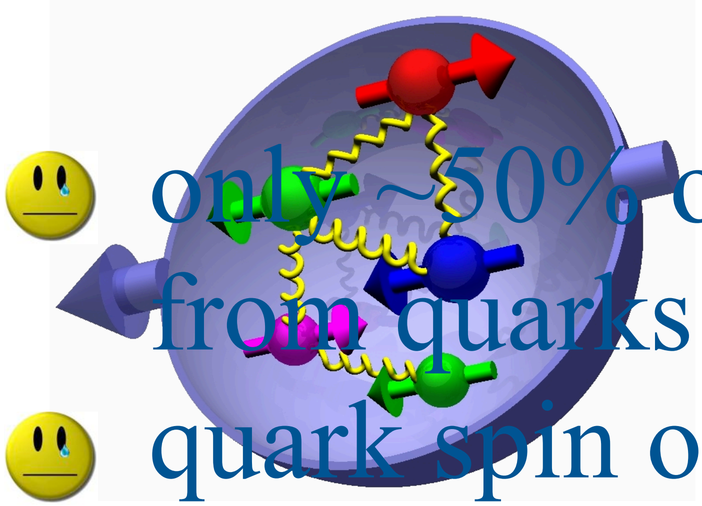
Evolution of our Nucleon Picture



1960/70’s : Nucleon consists of three (up and down) quarks whose spins add up to 1/2)

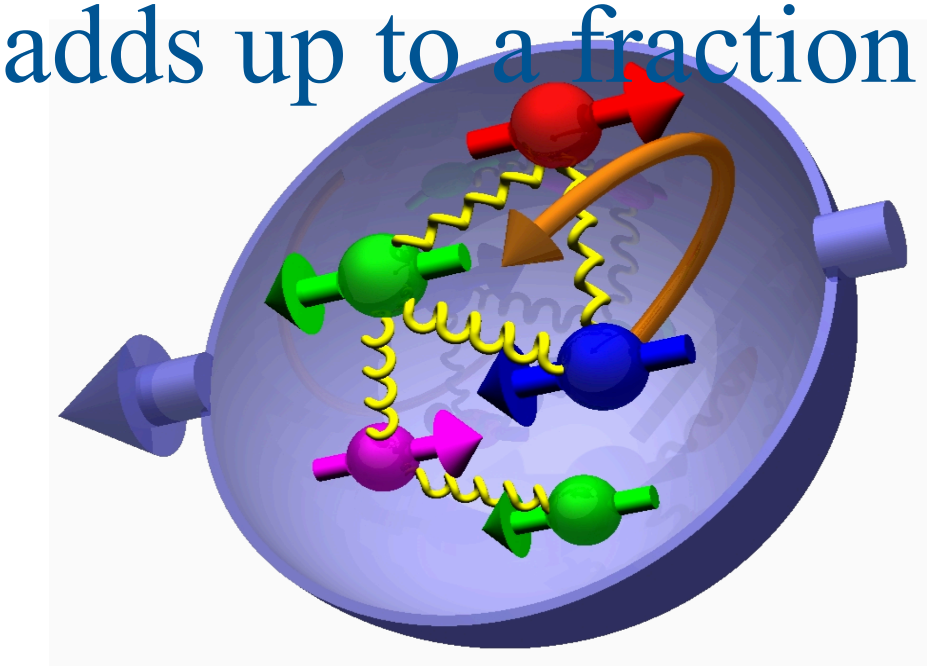


1970/80’s :

- 😐 only ~50% of proton mass is from quarks
- 😐 quark spin only adds up to a fraction of 1/2

Gluons are important as well!

1990/2000’s : Don’t forget orbital angular momentum!!

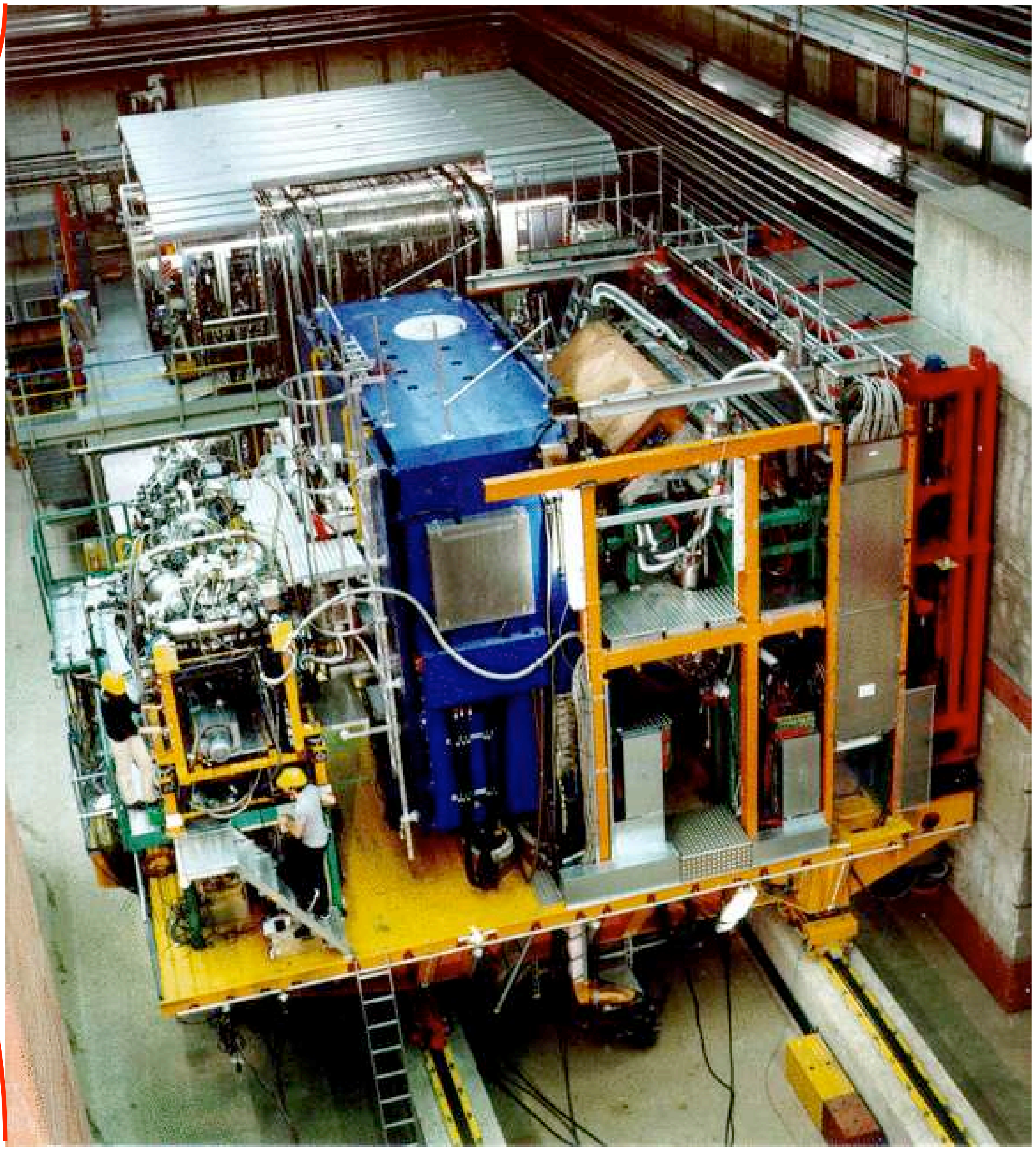


hermes

- **proposed in 1988 to solve the "spin crisis"**
    - **commissioned in 1995 at HERA**
        - **data taking ended in 2007 because of closing of HERA**
            - **however, many more exciting results to be expected from data on discs**

The HERMES Experiment

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

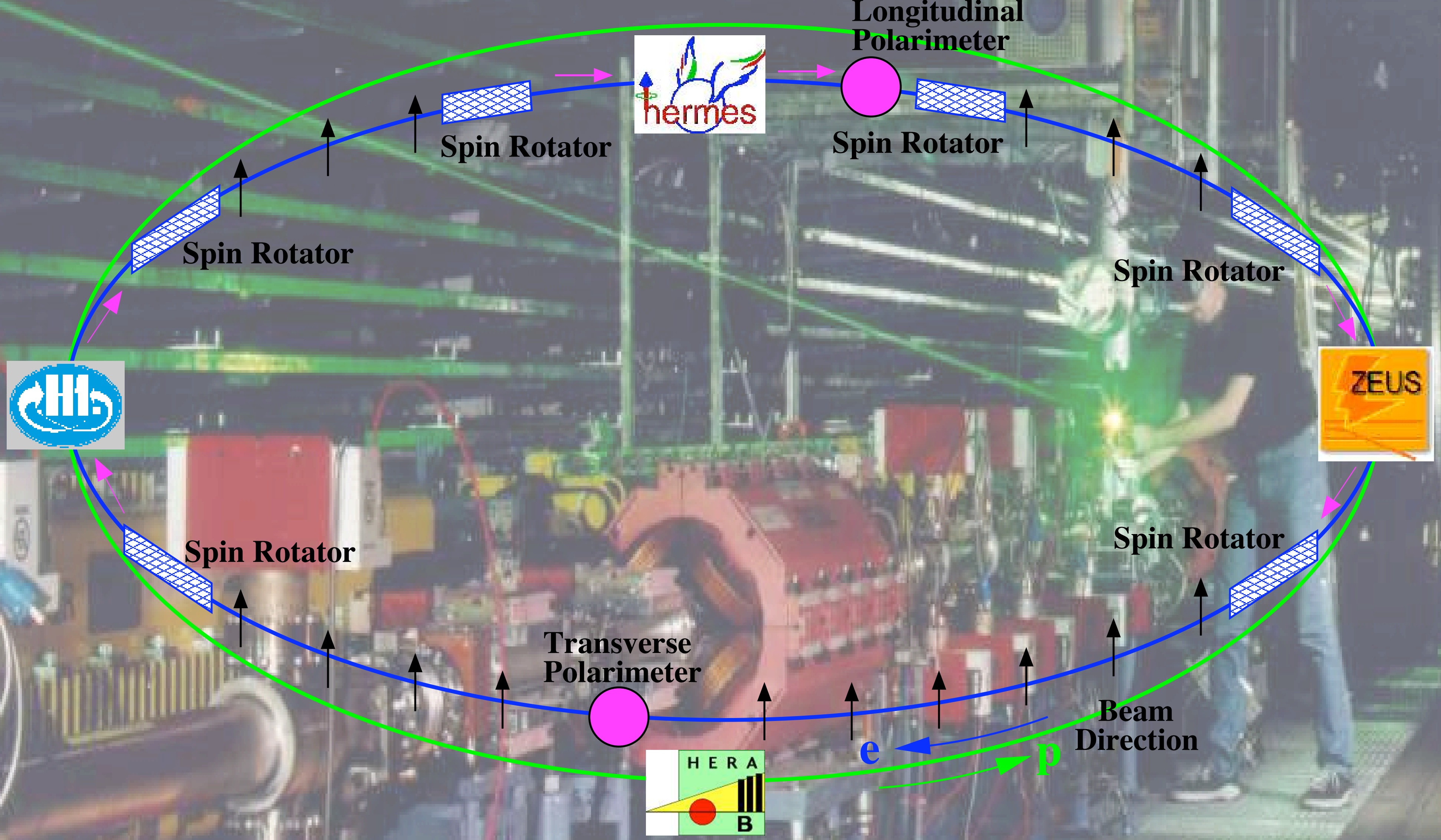


- **forward-acceptance spectrometer**

$\Rightarrow$ **40mrad$< \theta <$220mrad**

- **high lepton ID efficiency and purity**
- **excellent hadron ID thanks to dual-radiator RICH**

Beam Polarization at HERA

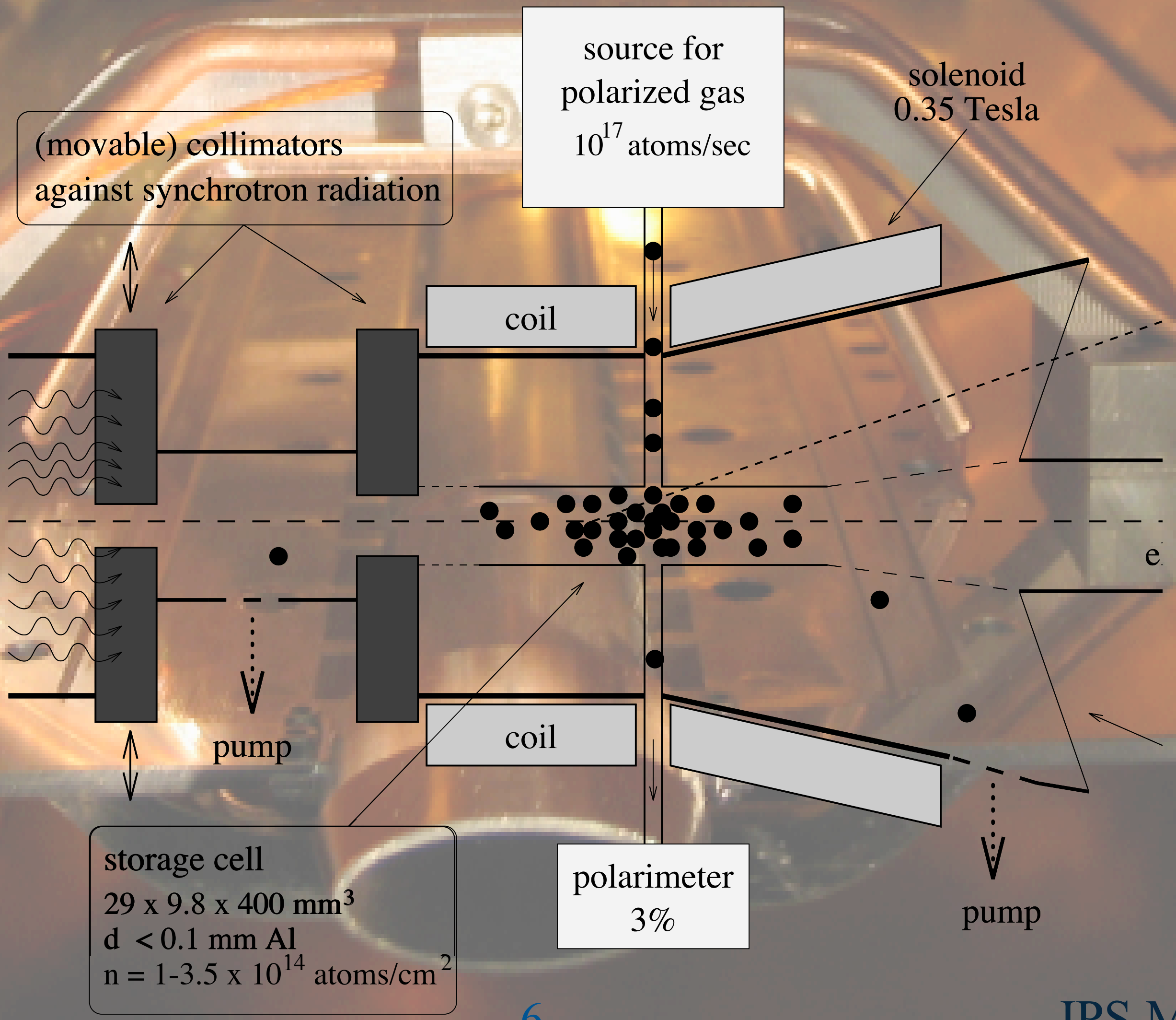


- 27.5 GeV e^+/e^- beam
- Self-polarizing through Sokolov-Ternov-Effect
- Average beam polarization of about 55%

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%

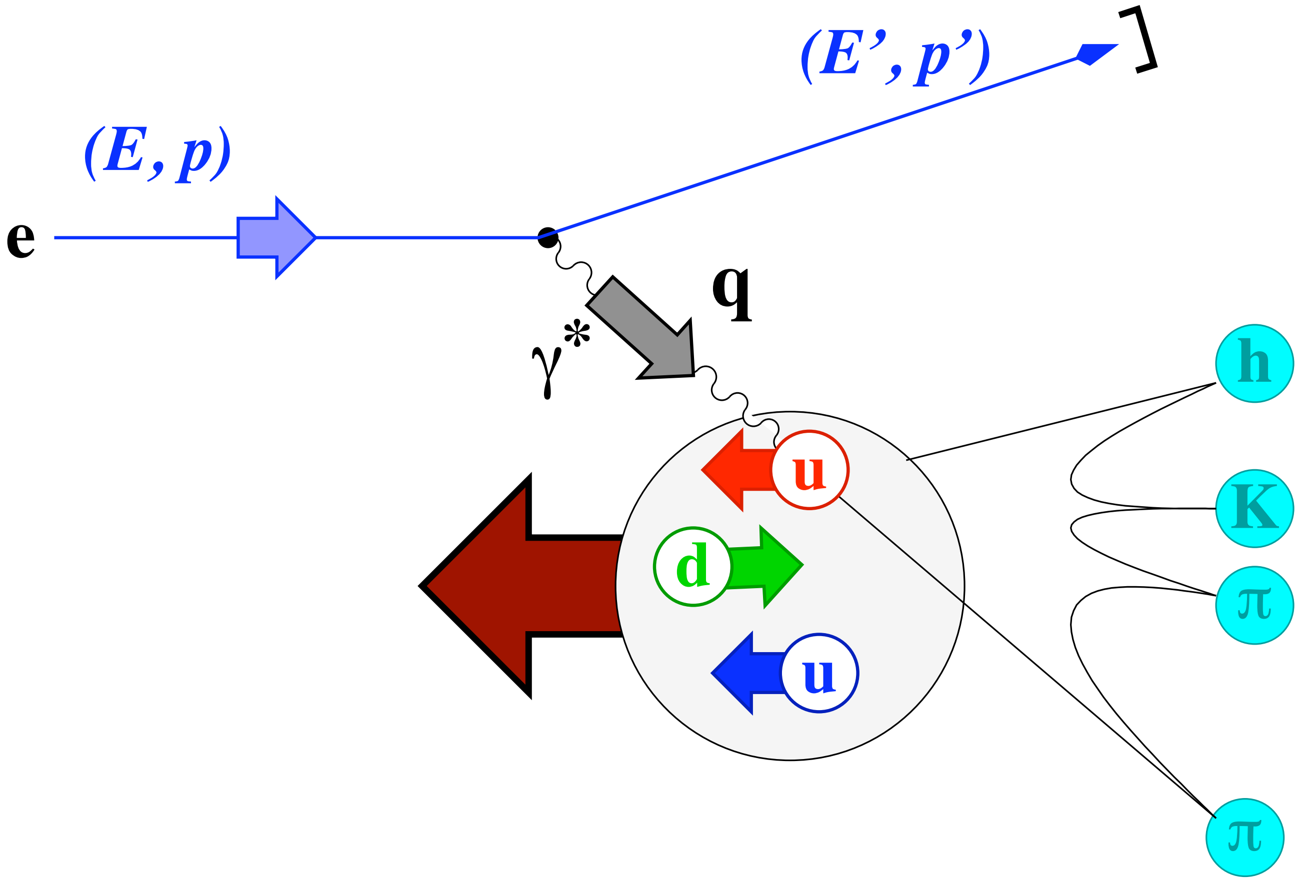


Deep-Inelastic Scattering

Probing the Structure of the Nucleon

Deep-Inelastic Scattering

use well-known probe to study hadronic structure:



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

$$\nu \overset{\text{lab}}{=} E - E'$$

$$W^2 \overset{\text{lab}}{=} M^2 + 2M\nu - Q^2$$

$$y \overset{\text{lab}}{=} \frac{\nu}{E}$$

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

inclusive DIS: detect scattered lepton

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

semi-inclusive DIS: detect scattered lepton and some fragments

exploit strong correlation between flavor structure of leading hadron and struck quark

Inclusive DIS

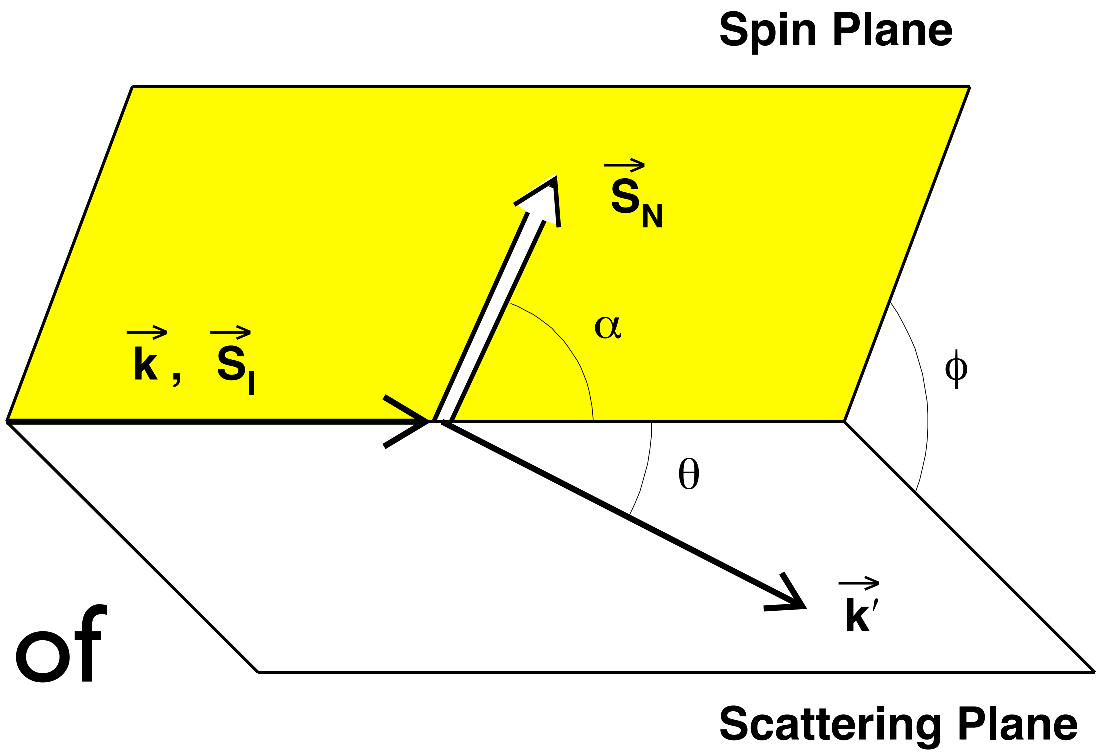
$$\frac{\mathrm{d}^2\sigma(s,S)}{\mathrm{d}x\ \mathrm{d}Q^2} = \frac{2\pi\alpha^2 y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$

Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions

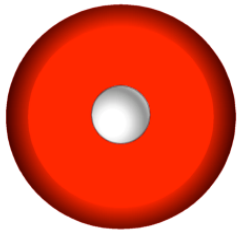


$$\frac{d^3\sigma}{dx dy d\phi} \propto \frac{y}{2}\boxed{F_1(x,Q^2)} + \frac{1-y-\gamma^2y^2/4}{2xy}\boxed{F_2(x,Q^2)}$$
$$-P_l P_T \cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\boxed{g_1(x,Q^2)}-\frac{\gamma^2 y}{2}\boxed{g_2(x,Q^2)}\right)\right]$$
$$+P_l P_T \sin\alpha\cos\phi\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}\boxed{g_1(x,Q^2)}+\boxed{g_2(x,Q^2)}\right)$$

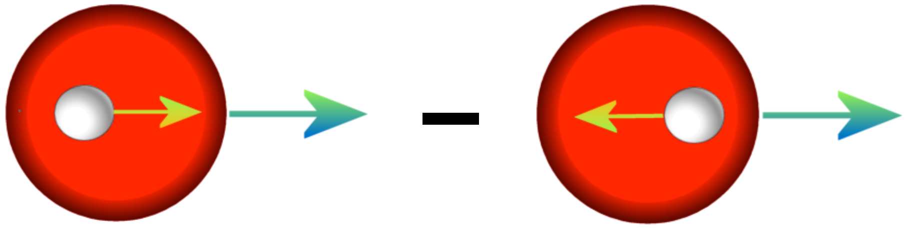
Parton-Model Interpretation of Structure Functions

$$
\begin{aligned}
F_1(x) &= \frac{1}{2}\sum_q e_q^2 f_1^q(x) \\
F_2(x) &= x\sum_q e_q^2 f_1^q(x) \\
g_1(x) &= \frac{1}{2}\sum_q e_q^2 g_1^q(x) \\
g_2(x) &= 0
\end{aligned}
$$

$f_1^q =$



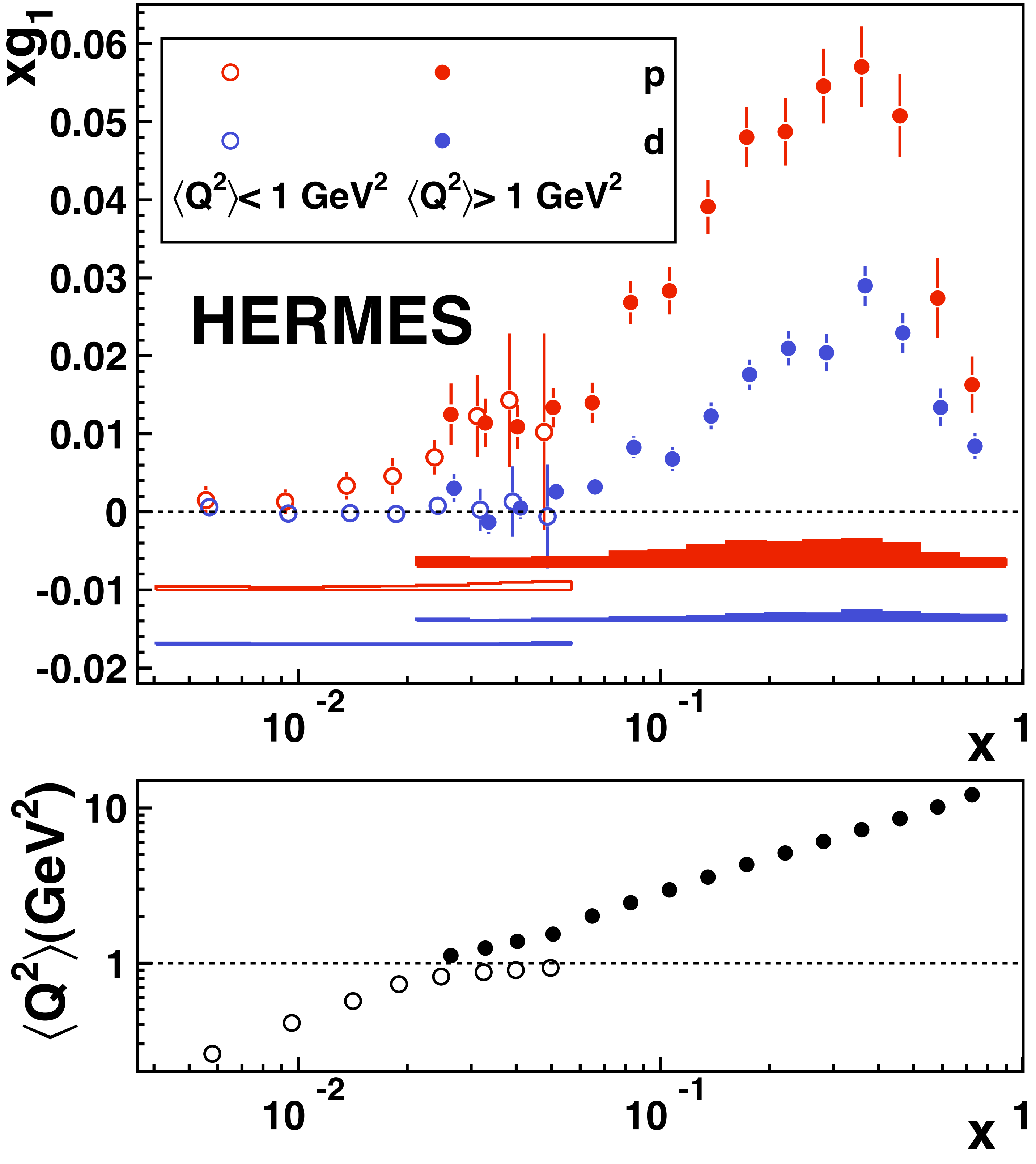
$g_1^q =$

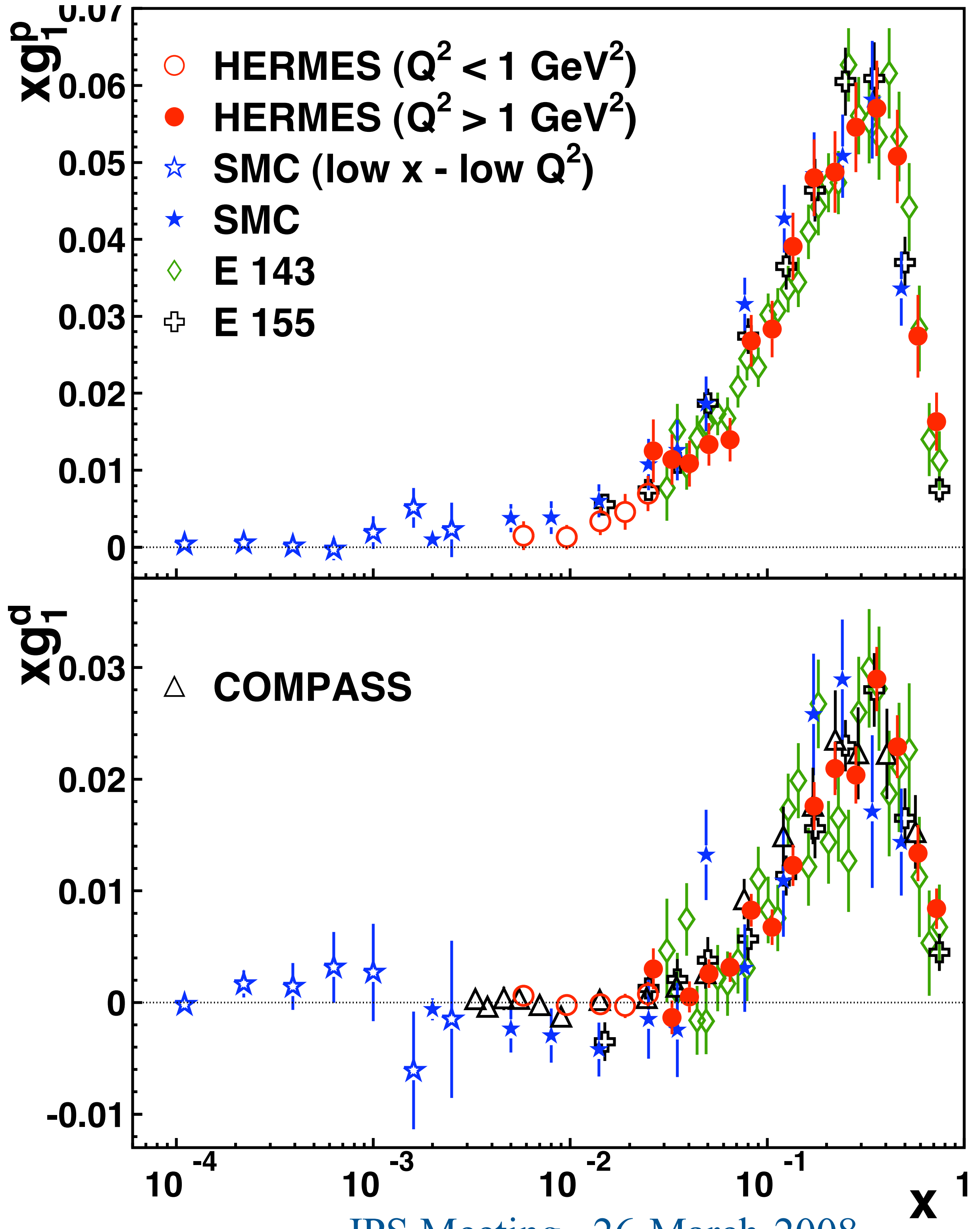


quark-spin constribution to nucleon helicity

Polarized Structure Function g_1

A. Airapetian et al., PRD 75 (2007)

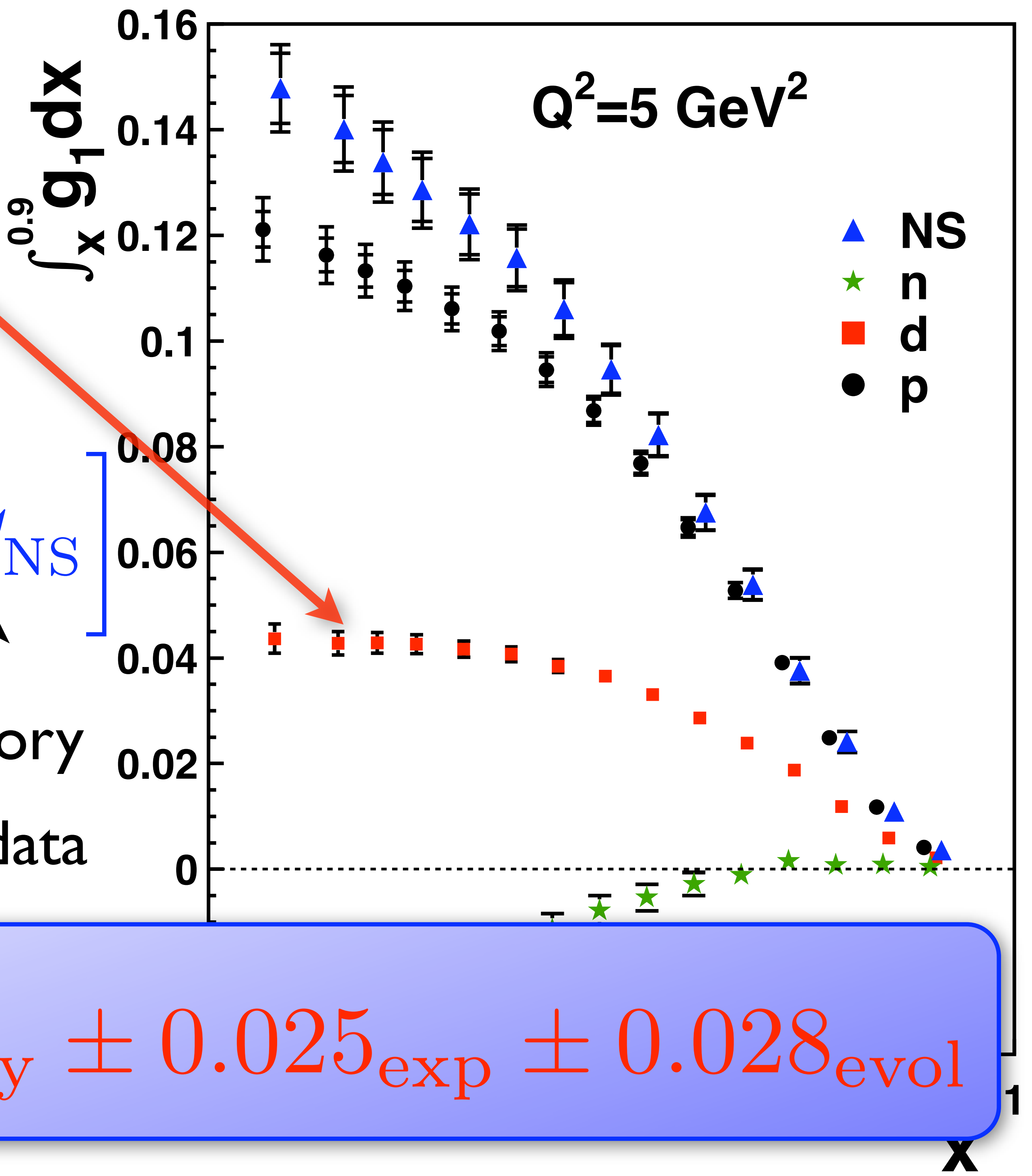




Integral of g_1(x)

Saturation

➠ close to full integral?



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

↑ theory

↑ *0.05±0.05*

↑ hyperon-decay data

↑ theory

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

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

Flavor Separation using SIDIS

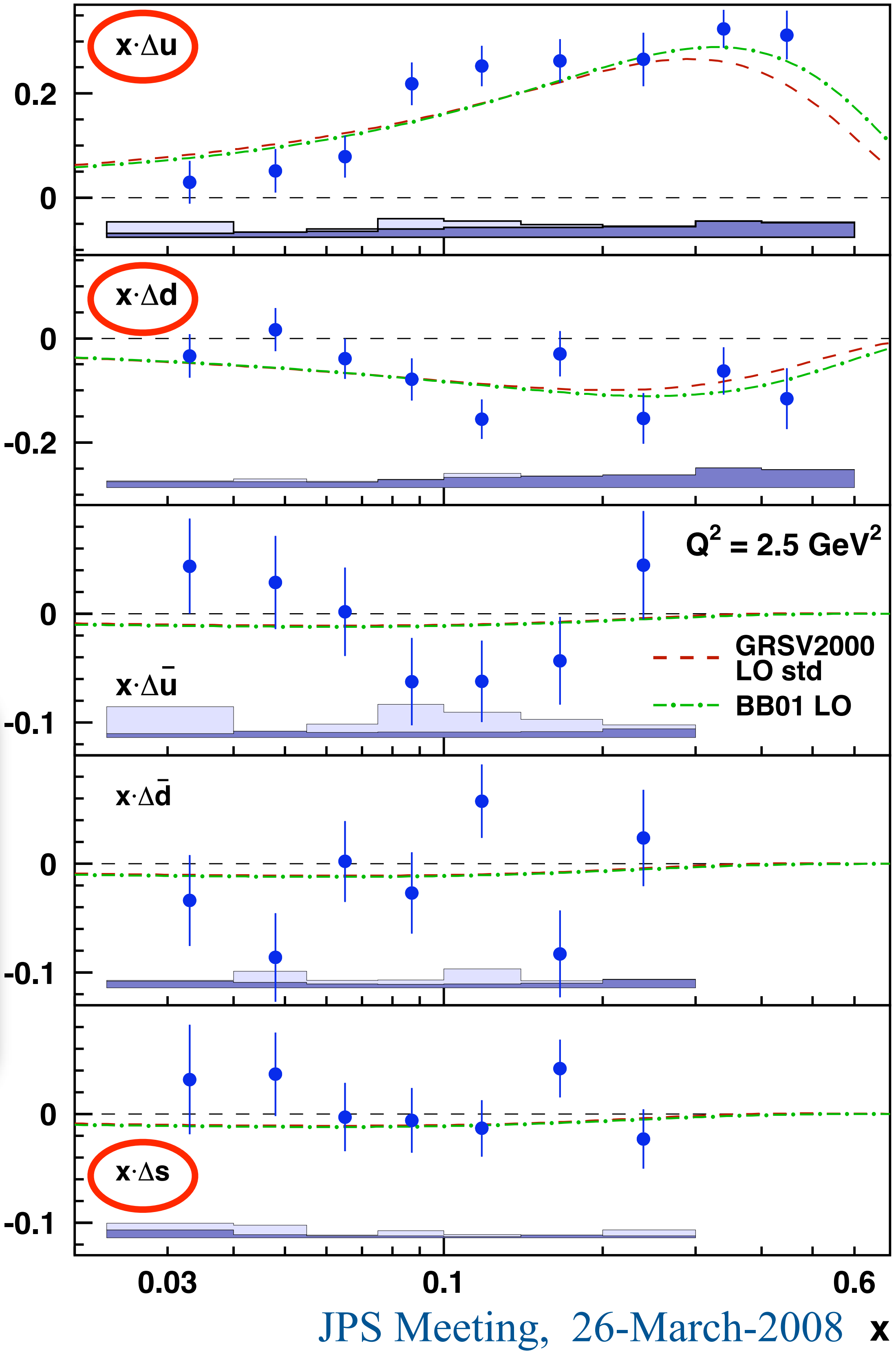
- **Remember:**

$$\Delta\Sigma = \sum_q \int dx\, g_1^q(x) \approx 1/3$$

- **use different hadron flavors in final state to *tag* quark flavor**

$$\begin{aligned} g_1^u(x) \equiv \Delta u &> 0 \text{ and large} \\ g_1^d(x) \equiv \Delta d &< 0 \text{ and smaller} \\ g_1^s(x) \equiv \Delta s &\approx 0 \end{aligned}$$

A. Airapetian et al., PRL 92 (2004)
A. Airapetian et al., PRD 71 (2005)

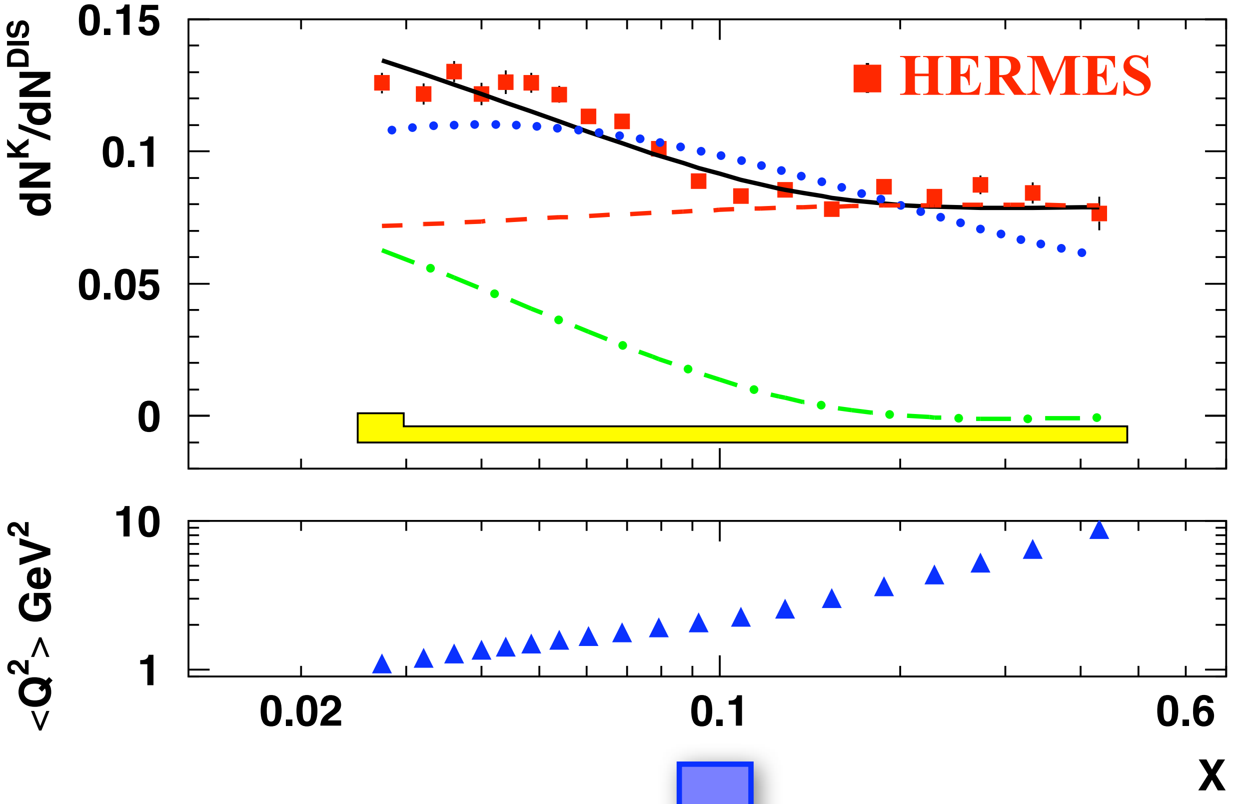


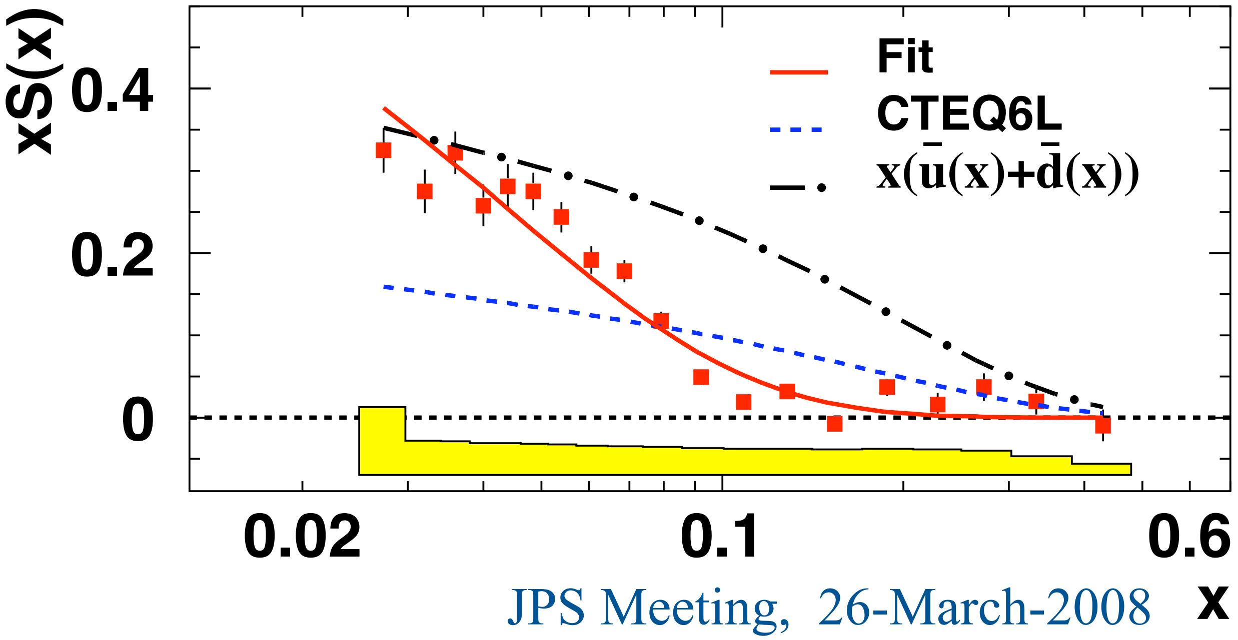
Distribution of Strange Quark

- strange quarks carry no isospin, thus the same in proton and neutron
- use isoscalar probe and target to extract strange-quark distributions
- only need inclusive asymmetries and K^{+}+K^{-} asymmetries, i.e., $A_{1,d}(x, Q^2)$ and $A_{1,d}^{K^+ + K^-}(x, z, Q^2)$, as well as K^{+}+K^{-} multiplicities
- strange-quark fragmentation function either directly from data or from parametrizations

Unpolarized Strange Quarks

- **S(x) non-zero for x<0.1**
- **vanishes for x>0.1**
- **apparent discrepancy with CTEQ6L**
- **S(x) not an average of an isoscalar non-strange sea**
  ➠ violation of SU(3) symmetry
- **HERMES data provides extremely valuable input to extraction of unpolarized PDFs**

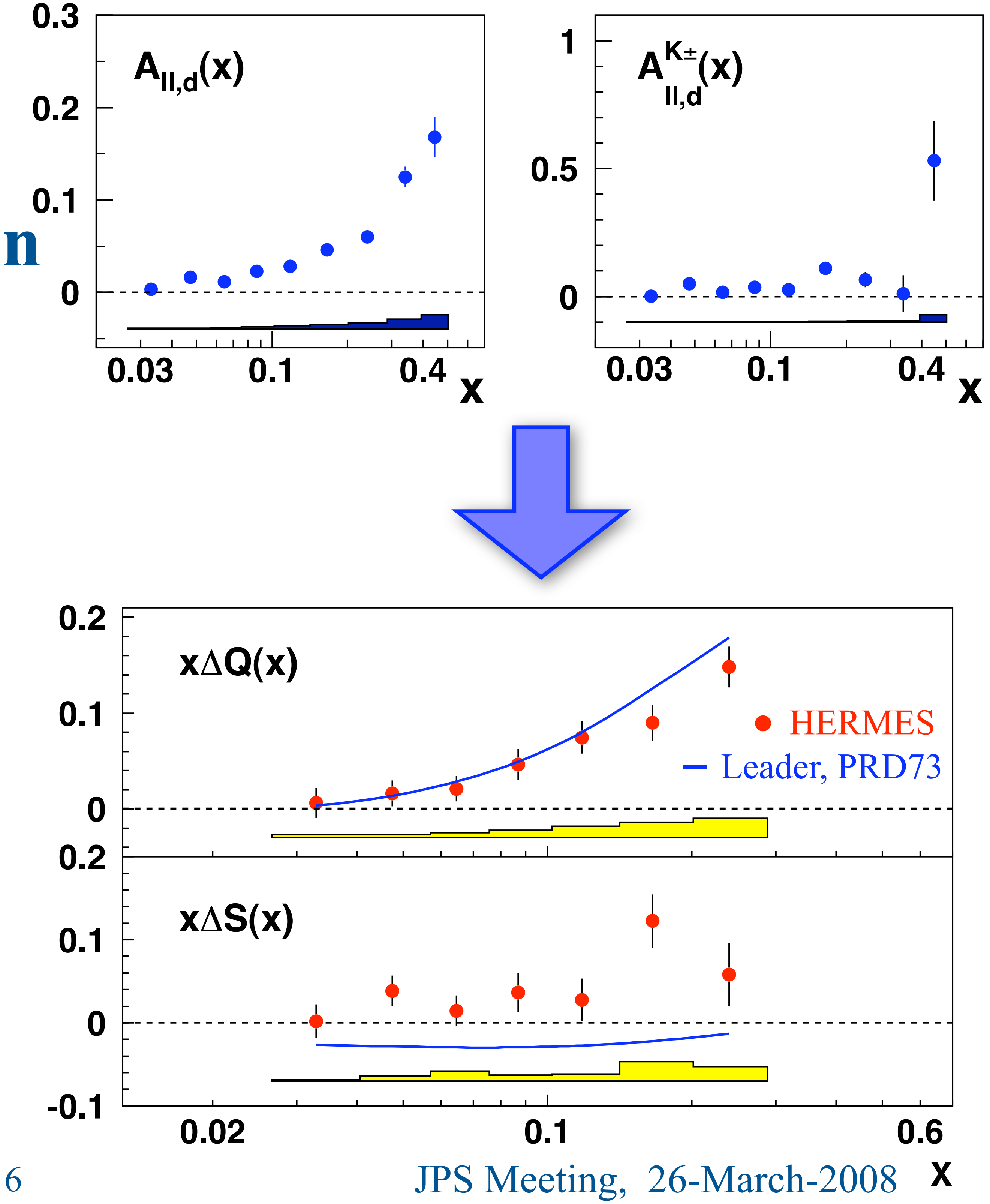




A. Airapetian et al., arXiv:0803.2993

Polarized Strange Quarks

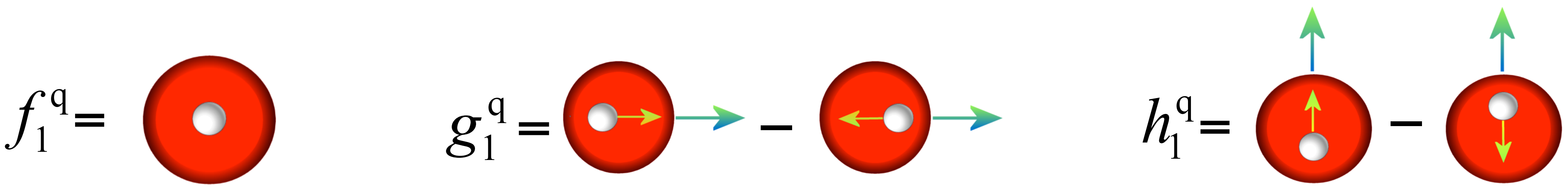
- results consistent with previous flavor decomposition
- no sizeable negatively polarized strange sea as expected from inclusive DIS results
- ➠ sign of violation of SU(3) symmetry or of substantial contributions from low-x region!



A. Airapetian et al., arXiv:0803.2993

Transverse-Spin Effects

Quark Structure of the Nucleon



$f_1^q=$

$g_1^q=$ $-$

$h_1^q=$ $-$

⇓

Unpolarized quarks and nucleons

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

⇒ Vector Charge

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

⇓

Longitudinally polarized quarks and nucleons

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

⇒ Axial Charge

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

⇓

Transversely polarized quarks and nucleons

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

⇒ Tensor Charge

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

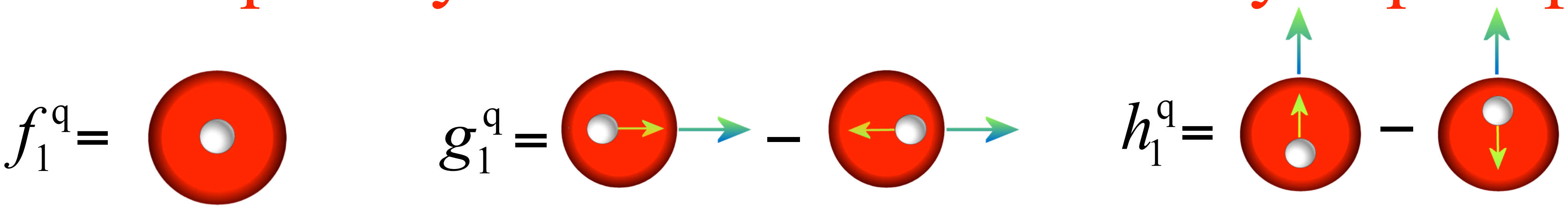
The “Trouble” with Transversity

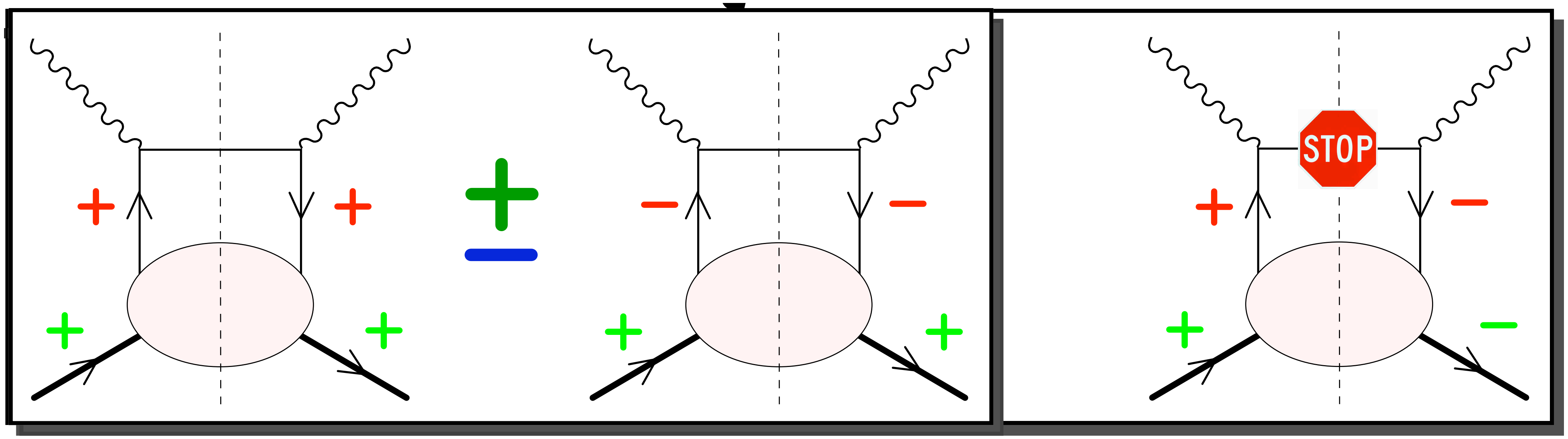
Transverse-spin states written in terms of helicity states:

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

$$|\downarrow\rangle = \frac{1}{\sqrt{2}}\Big[|+\rangle - \mathrm{i}|-\rangle\Big]$$

➠Transverse-spin asymmetries involve helicity-flip amplitudes





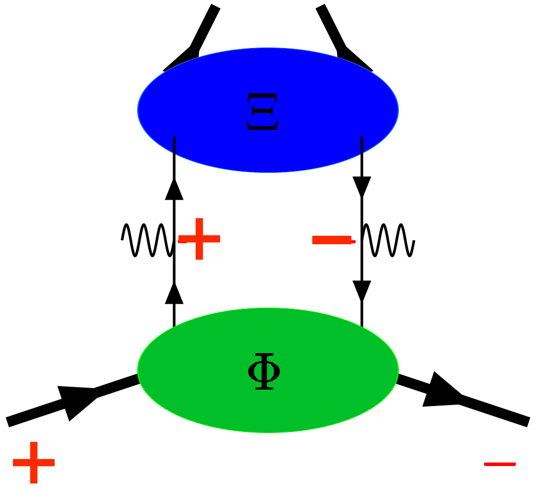
Transversity Measurement

How can one measure transversity?

Need another chiral-odd object!

$\Rightarrow$ Semi-Inclusive DIS

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



$\Downarrow$ **chiral-odd** DF

$\Downarrow$ **chiral-odd** FF

$$\underbrace{\text{DF} \qquad \text{FF}}_{\text{CHIRAL EVEN}}$$

→ chiral-odd FF as a polarimeter of transv. quark polarization

2-Hadron Fragmentation

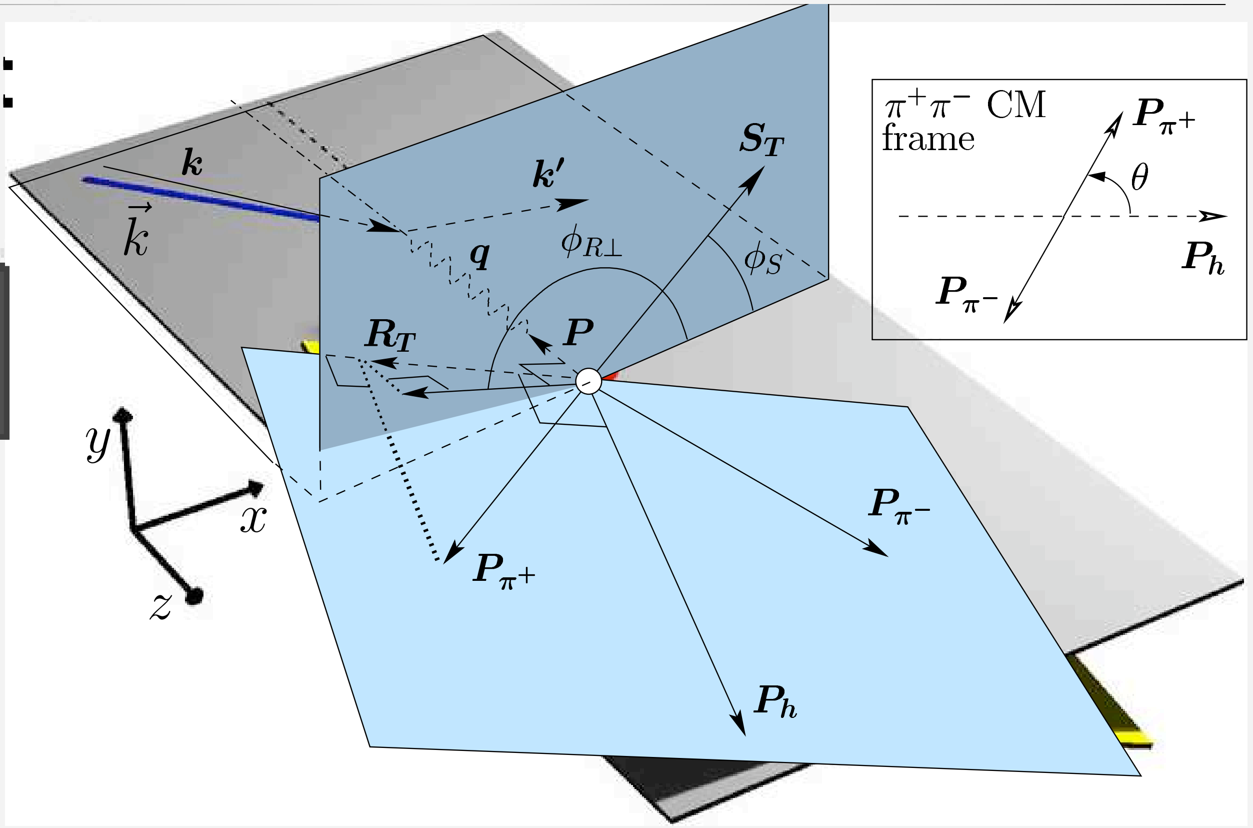
polarized 2-hadron cross section:

(**U**npolarized beam, **T**ransversely pol. target)

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

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

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



- 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

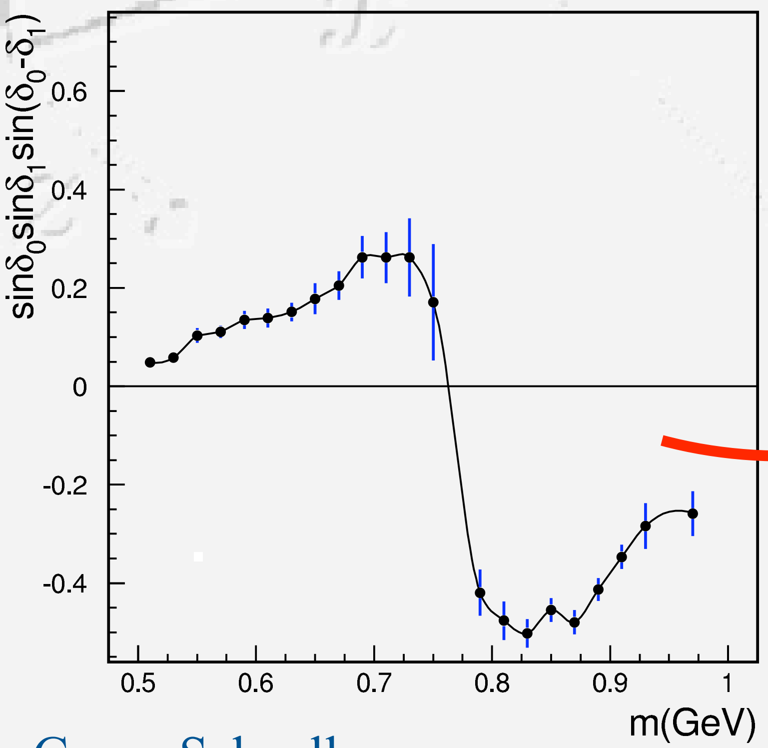
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S)\sin\theta h_1 H_1^{\sphericalangle}$$

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**]:

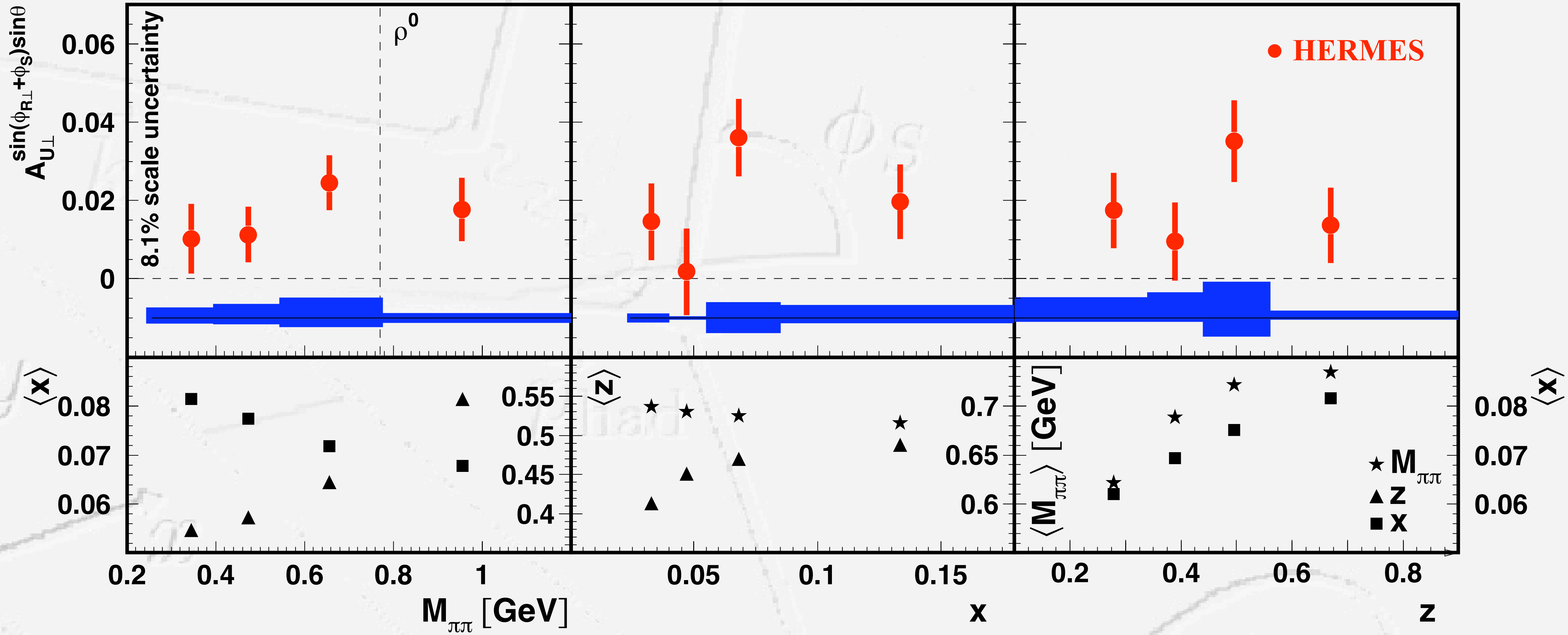
$$H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) = \underline{\sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1)} H_1^{\sphericalangle,sp'}(z)$$

δ_0 (δ_1) → S(P)-wave phase shifts

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

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

HERMES Results (complete data set)



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

A. Airapetian et al., arXiv:0803.2367

1-Hadron Production (ep→ehX)

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

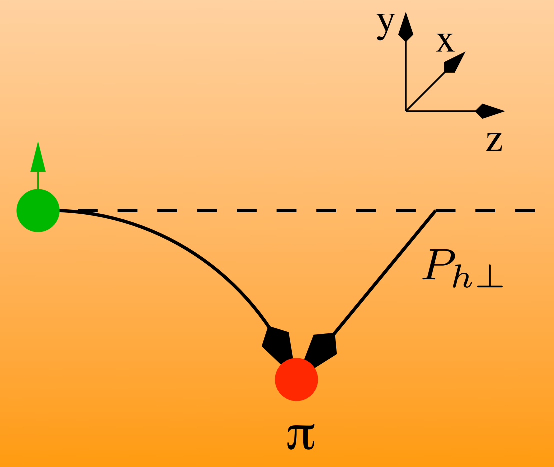
$$+S_L\left\{\sin 2\phi\, d\sigma^4_{UL} + \frac{1}{Q}\sin\phi\, d\sigma^5_{UL} + \lambda_e\left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi\, d\sigma^7_{LL}\right]\right\}$$

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

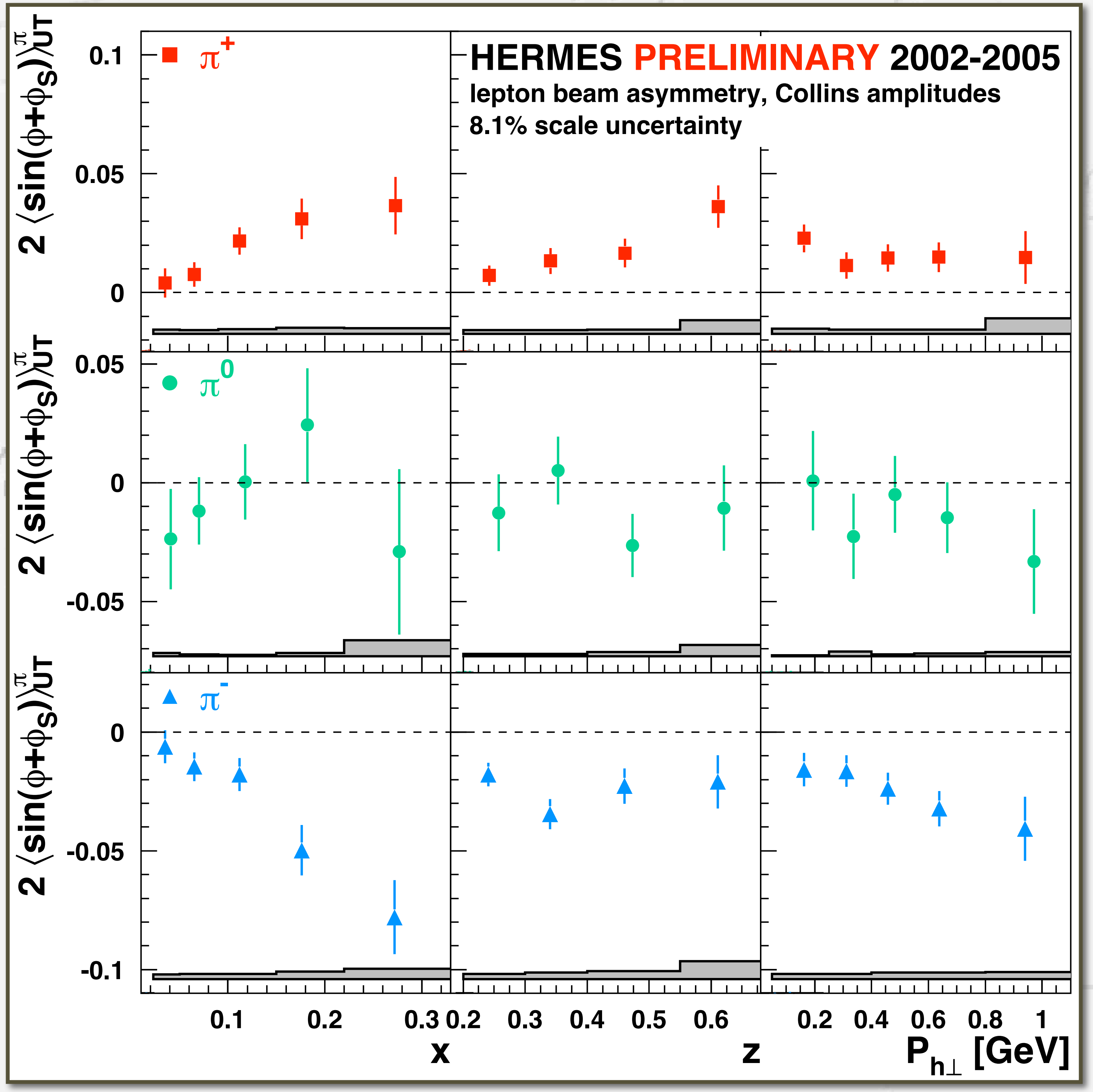
Sivers Effect:

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

k transverse spin



The HERMES Collins Results



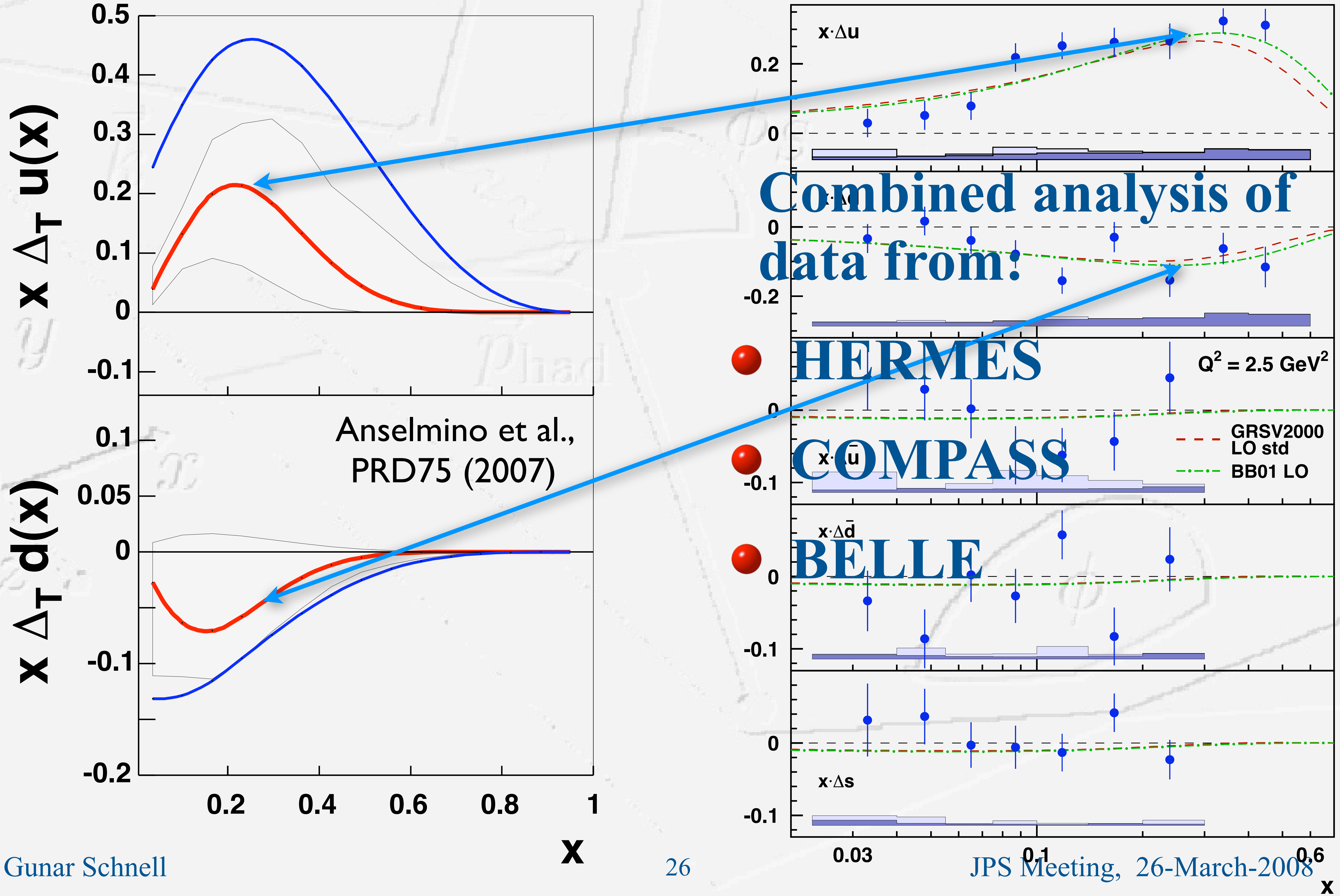
- published[†] results **confirmed** with much higher statistical precission
- overall scale uncertainty of 8.1%
- positive for π^+ and negative for π^- as maybe expected ($\delta u \equiv h_1^u > 0$ maybe expected ($\delta d \equiv h_1^d < 0$)
- unexpected **large π^- asymmetry**
  $\Rightarrow$ role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

☑ non-zero Collins effect observed!

☑ both Collins FF and transversity sizeable

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

First Glimpse at Transversity



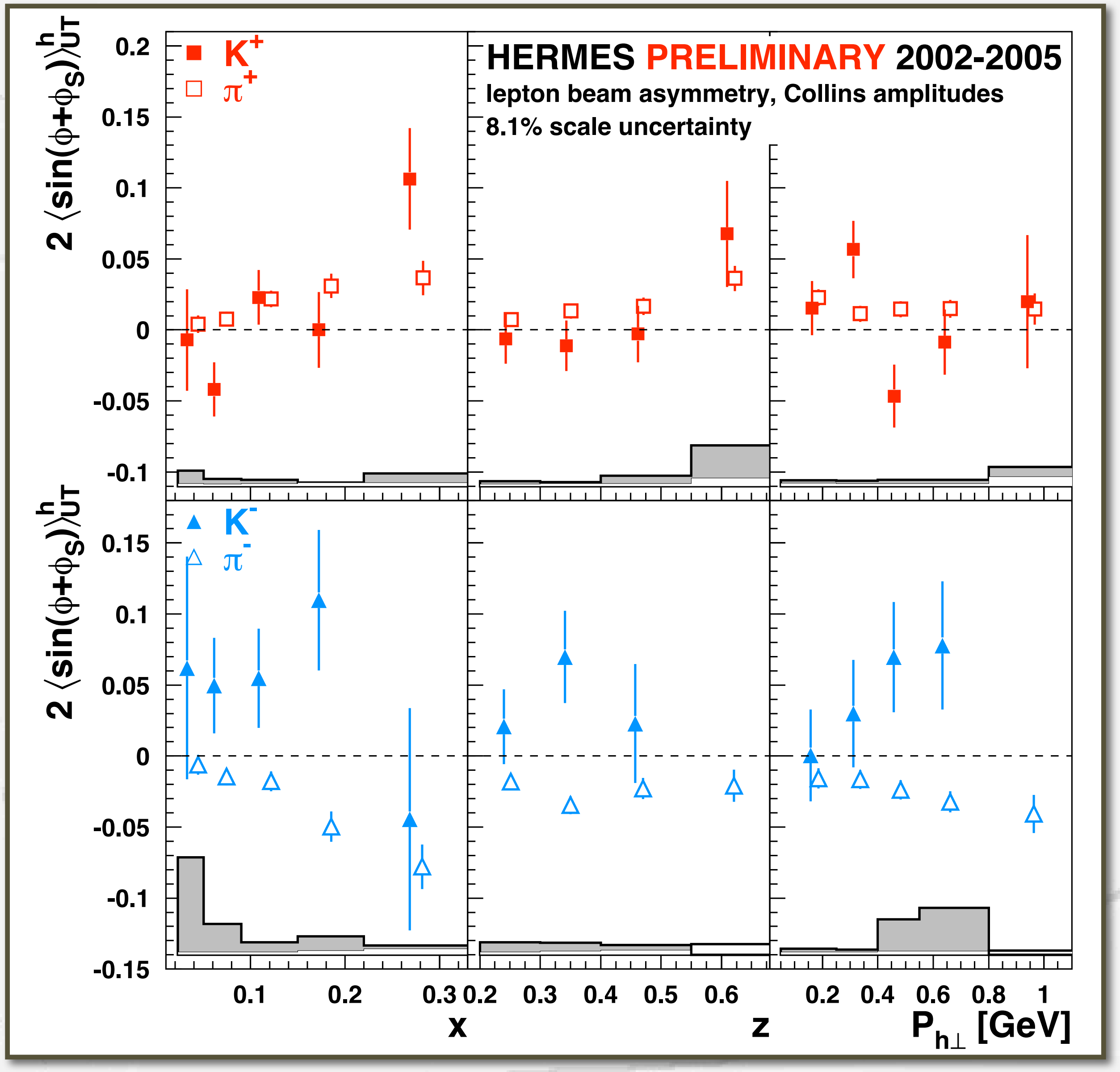
Anselmino et al., PRD75 (2007)

Combined analysis of data from:

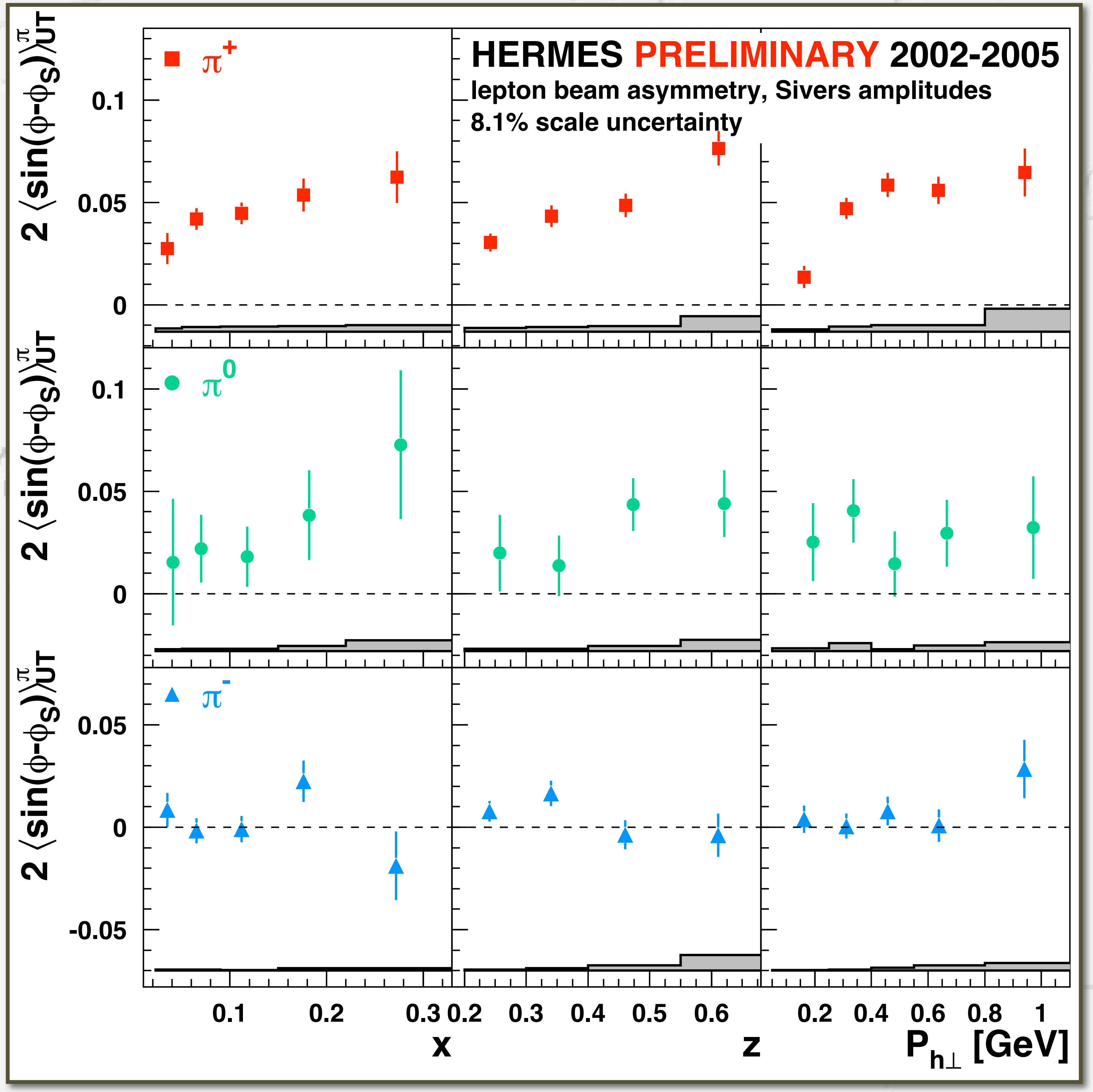
- HERMES
- COMPASS
- BELLE

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”



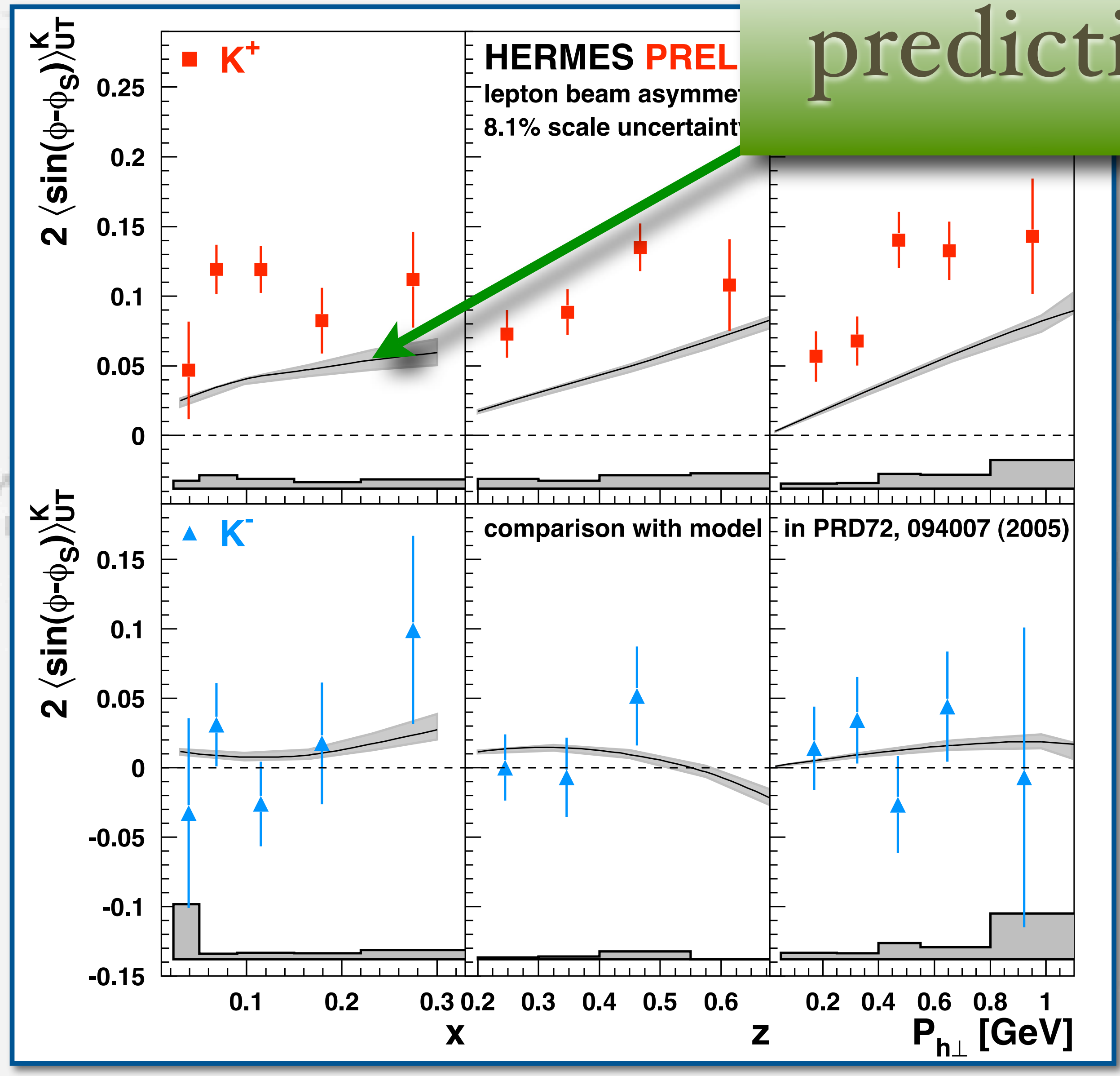
HERMES Sivers Results

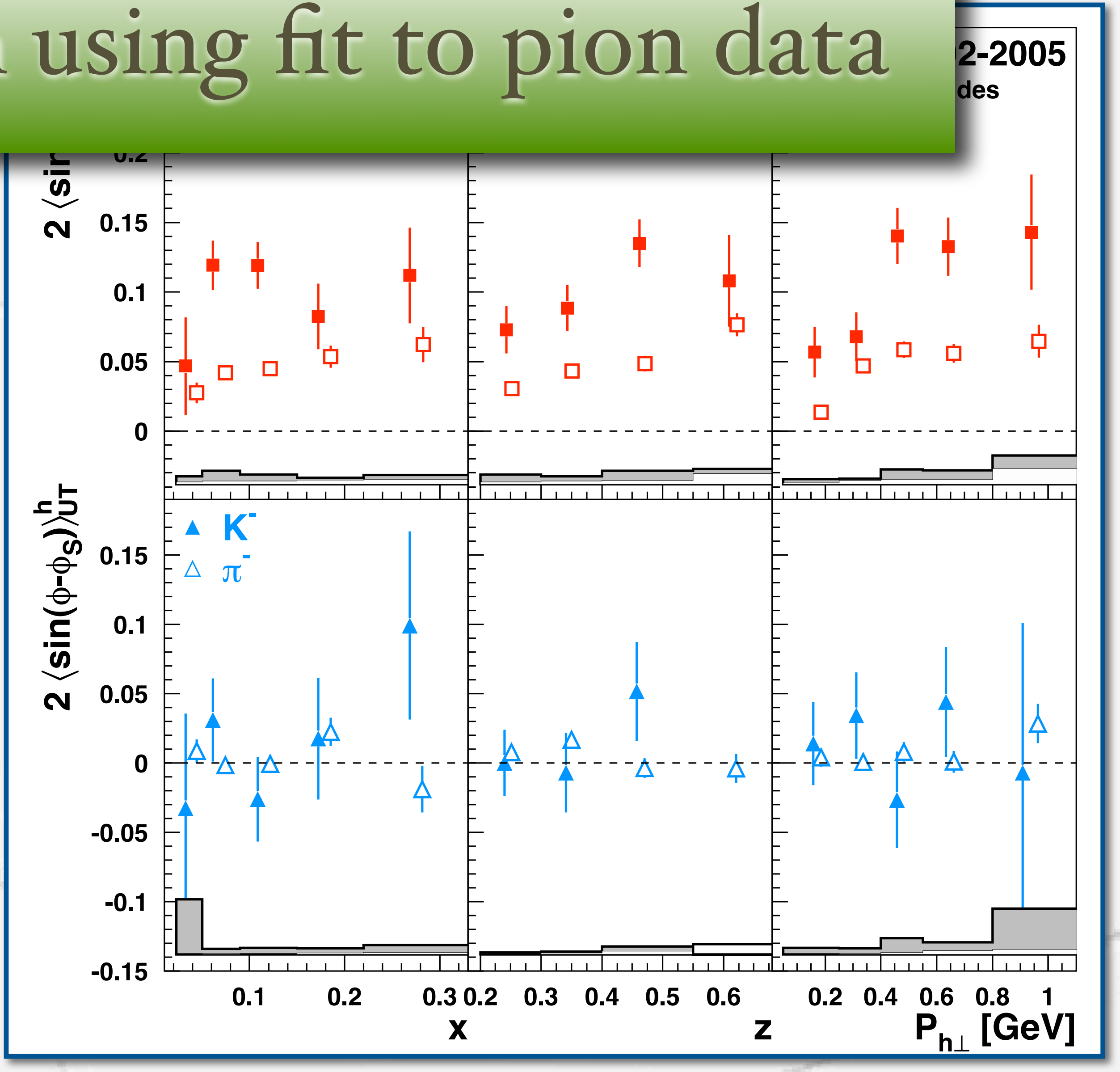


- ☑ first observation of T-odd Sivers effect in SIDIS!
- ☑ u-quark dominance suggests sizeable u-quark orbital motion

The Intriguing Kaon Amplitudes

prediction using fit to pion data





non-trivial role of sea quarks!

Exclusive Reactions

Accessing Generalized Parton Distributions

Angular Momentum and GPDs

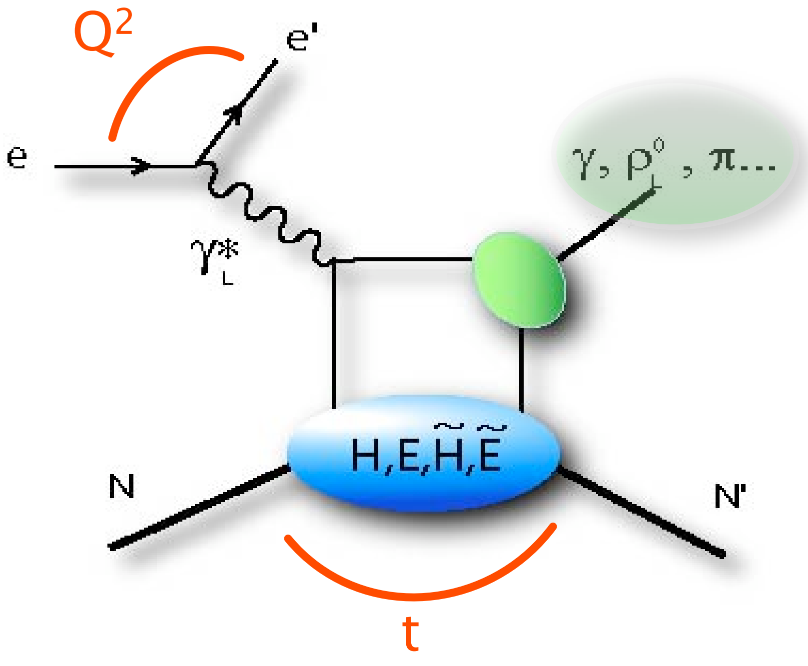
1997: Ji Relation for Nucleon Spin

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

- **"Ji's Recipe" provides way to measure angular momenta**
- **involves moment over new class of PDFs: Generalized 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 sum-rule recipe:** E, H
- **GPDs provide info about transverse position and long. mom.**

GPDs in Exclusive Reactions

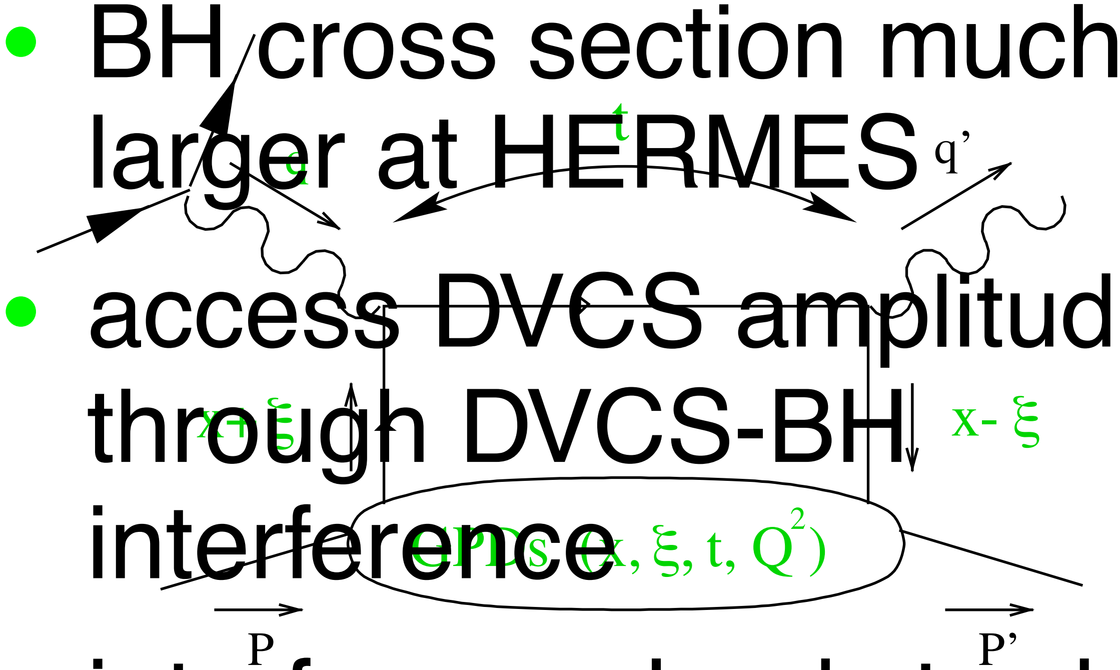
- **GPDs involve off-forward matrix elements**
- **moments give Form Factors, e.g.,** $\int dx H^q(x, \xi, t) = F_1^q(t)$
- **Forward limit give ordinary PDFs, e.g.,** $H^q(x, 0, 0) = f_1^q(x)$
- **at HERMES accessed in exclusive reactions:**
  - **Deeply Virtual Compton Scattering (DVCS)**
  - **Exclusive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



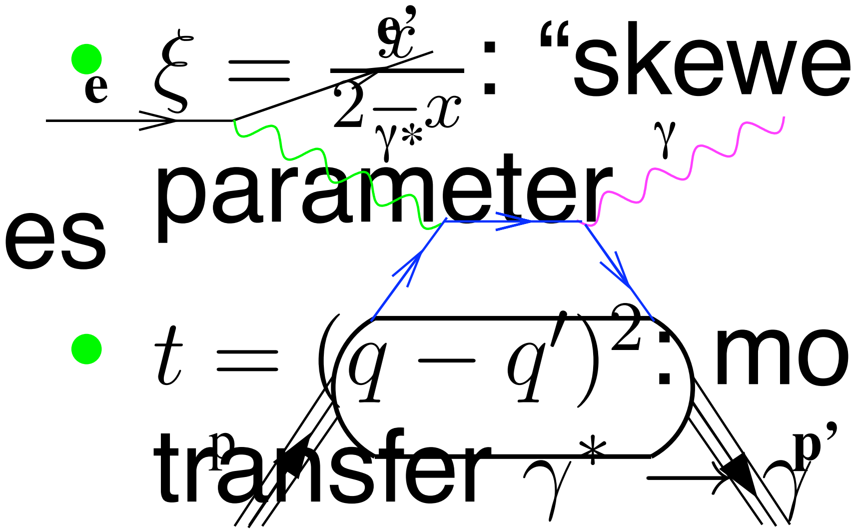
Deeply Virtual Compton Scattering

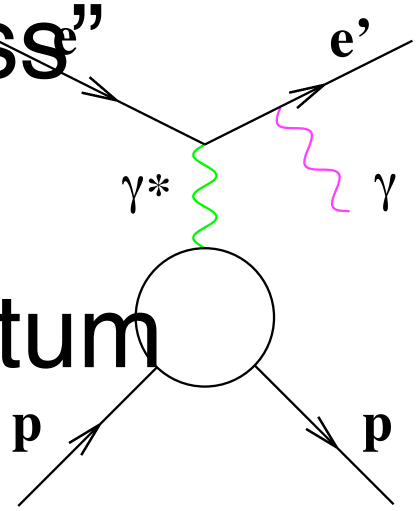
$e + p \rightarrow e' + p' + \gamma$ clean & simple exclusive process:

- DVCS and Bethe-Heitler (BH) indistinguishable
- BH cross section much larger at HERMES
- access DVCS amplitudes through DVCS-BH interference
- interference leads to characteristic azimuthal asymmetries



- x: long. momentum fraction
- $\xi = \frac{x}{2-x}$: "skewedness" parameter
- $t = (q - q')^2$: momentum transfer
- $Q^2 = -q^2$





Azimuthal Asymmetries in DVCS

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

Only TTSA sensitive to E!

- Beam-charge asymmetry :

  $d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{R}$ $\cdot \cos\phi$

- Beam-spin asymmet (ϕ) :

  $d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi)$ $_1\mathcal{H}] \cdot \sin\phi$

- Long. target-sp mmetry $A_{UL}(\phi)$:

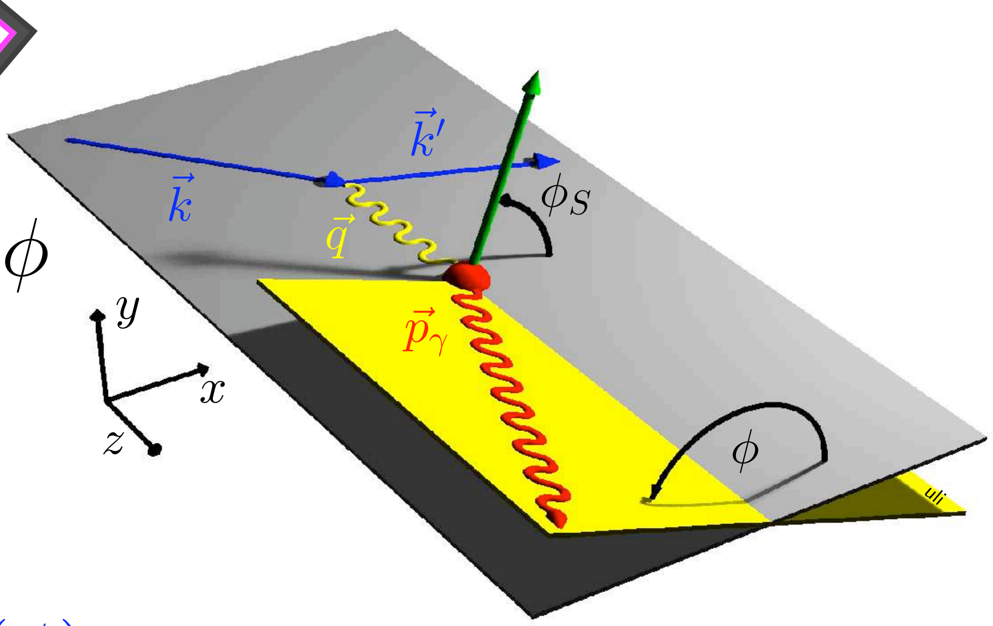
  $d\sigma(\overleftarrow{P},\phi) - d\sigma$ $\propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$

- Transvers et-spin asymmetry $A_{UT}(\phi,\phi_s)$ [TTSA]:

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

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

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



Constraining *E* - Transverse TSA

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

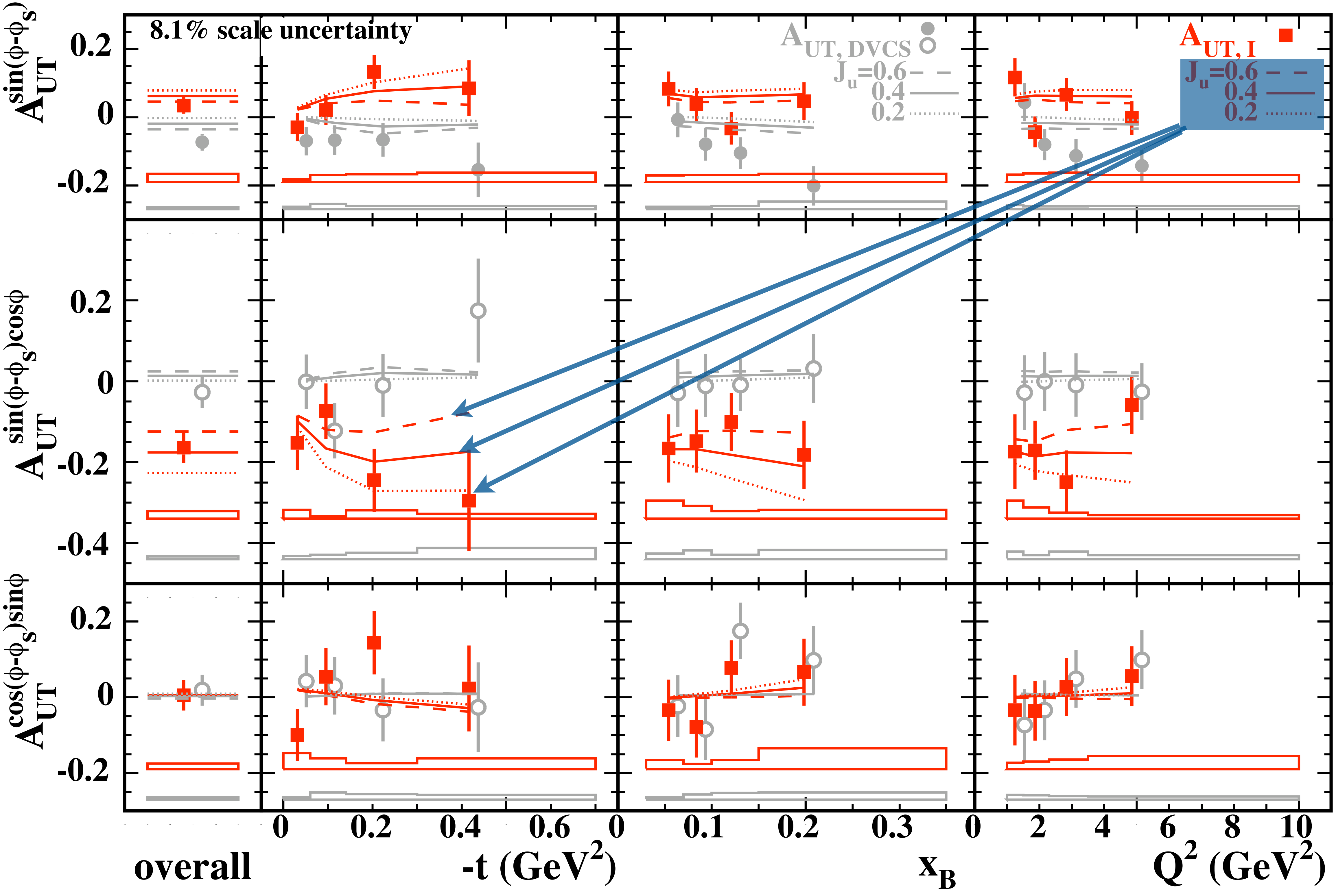
$$\boxed{A_{\mathrm{UT}}^{\mathcal{I}}(\phi,\phi_s) \propto \left[\mathrm{d}\sigma^{+}(\phi,\phi_s)-\mathrm{d}\sigma^{-}(\phi,\phi_s)\right] - \left[\mathrm{d}\sigma^{+}(\phi,\phi_s+\pi)-\mathrm{d}\sigma^{-}(\phi,\phi_s+\pi)\right]}$$

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

sensitive to *E*

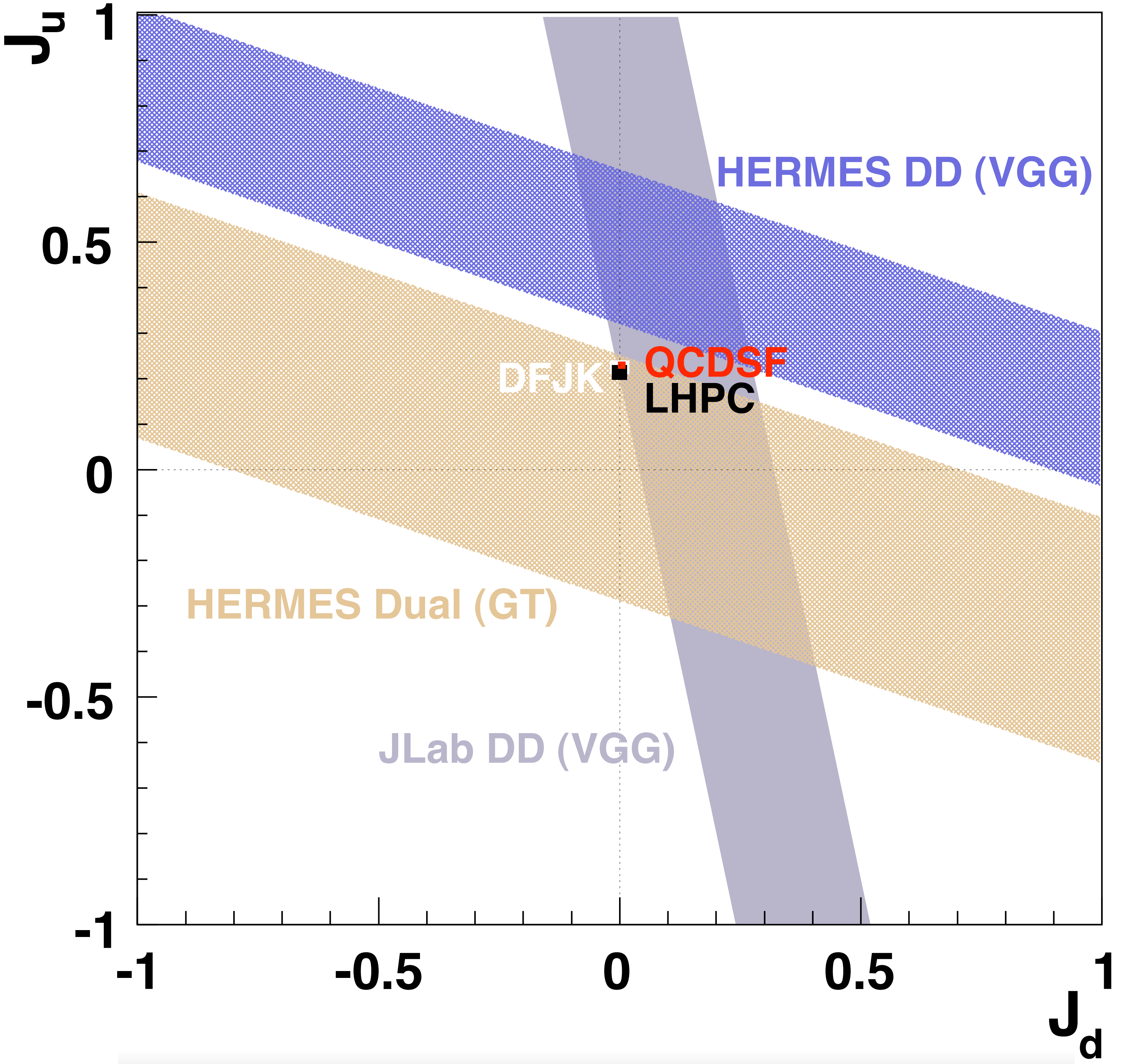
Amplitudes of TTSA

A. Airapetian et al., arXiv:0802.2499



Model-Dependent Extraction of J_{u} vs. J_{d}

$$\chi^2(J_{\mathrm{u}}, J_{\mathrm{d}}) = \left(A_{\mathrm{UT},I}^{\sin(\phi-\phi_s)\cos n\phi}\Big|_{\mathrm{exp}} - A_{\mathrm{UT},I}^{\sin(\phi-\phi_s)\cos n\phi}\Big|_{\mathrm{theo}} (J_{\mathrm{u}}, J_{\mathrm{d}}) \right)^2 / (\delta A_{\mathrm{stat}}^2 + \delta A_{\mathrm{sys}}^2)$$



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

- J_{u} and J_{d} are free param's in GPD models:
  - Double Distribution (DD): (Phys.Rev. D60 (1999) 094017)

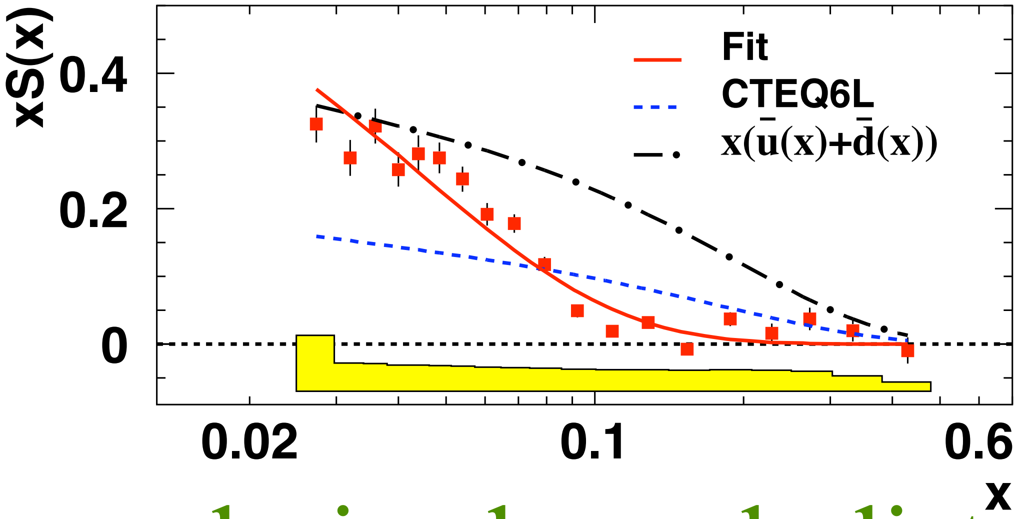
$$J_{\mathrm{u}} + J_{\mathrm{d}}/2.8 = 0.49 \pm 0.17$$

  - Dual Parameterization: (hep-ph/0207153 and Phys.Rev. D74 (2006) 054027)

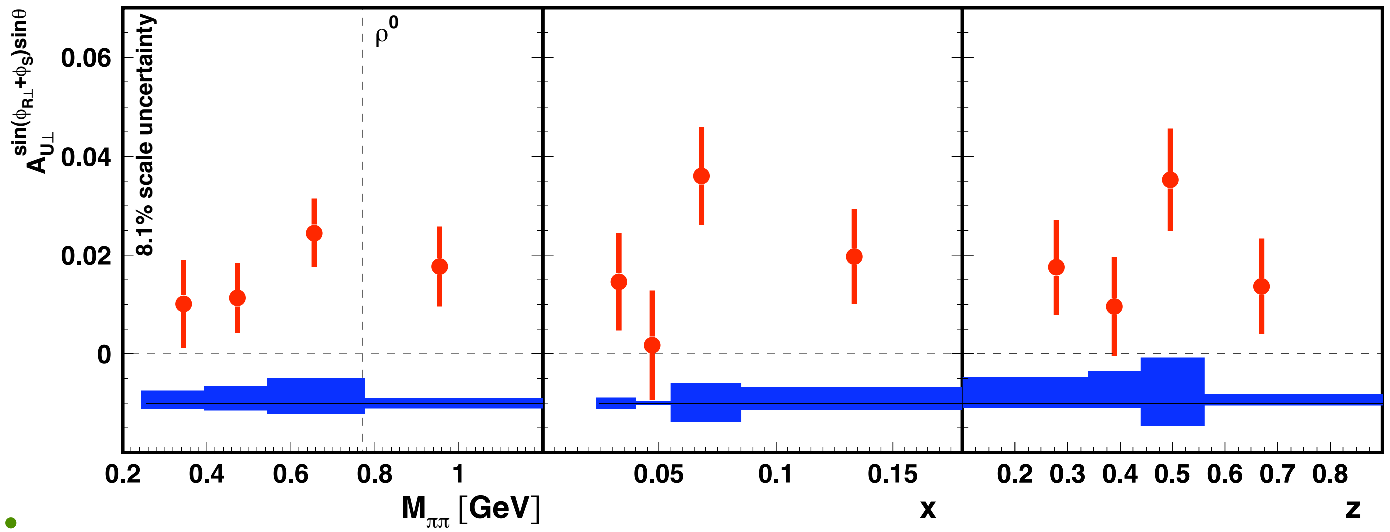
$$J_{\mathrm{u}} + J_{\mathrm{d}}/2.8 = -0.02 \pm 0.27$$

- Bands are 1σ constraint on J_{u} vs. J_{d}

Conclusions

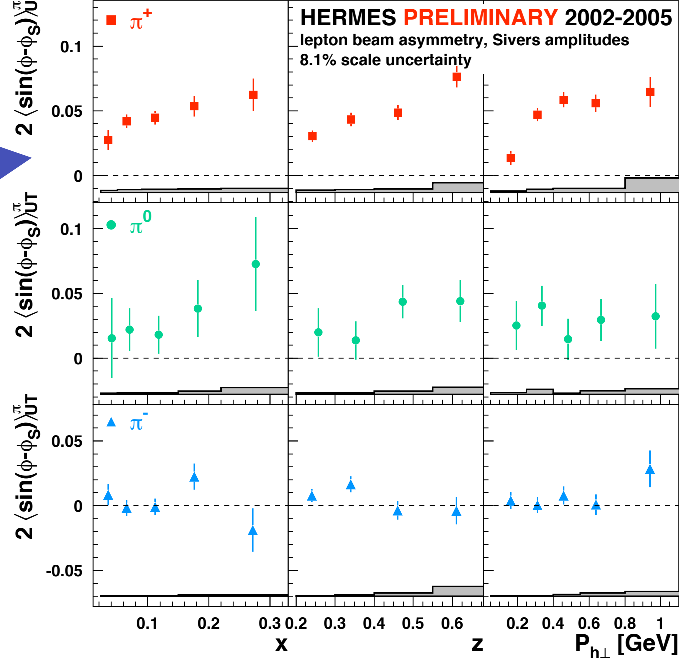


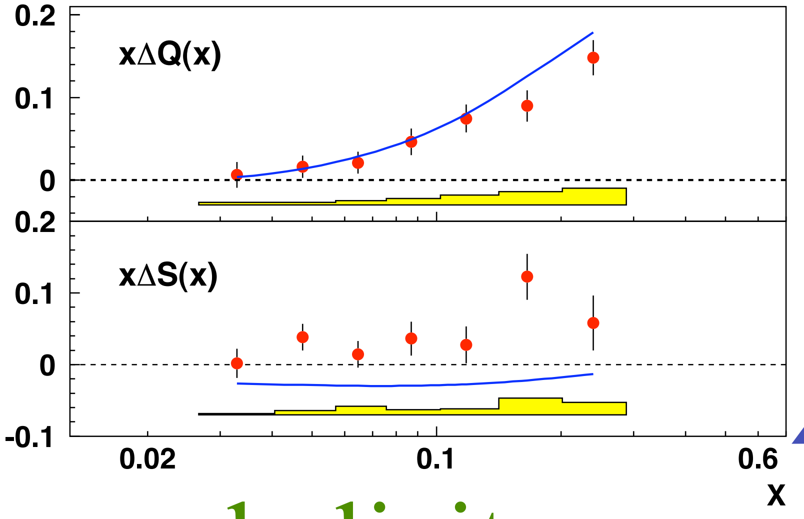
unpolarized quark distributions



transversity

orbital angular momentum

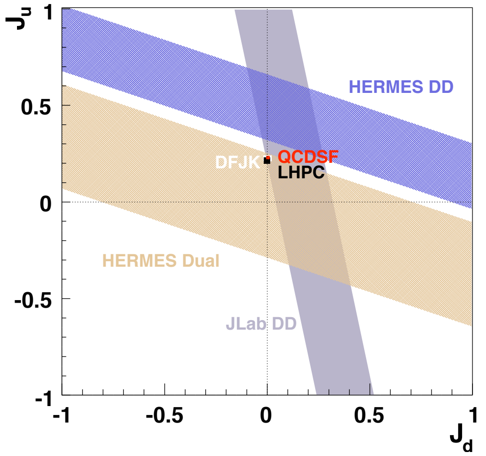




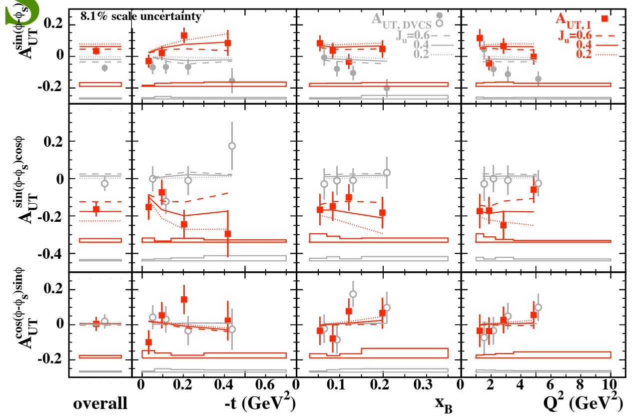
helicity distributions

hermes

angular momentum

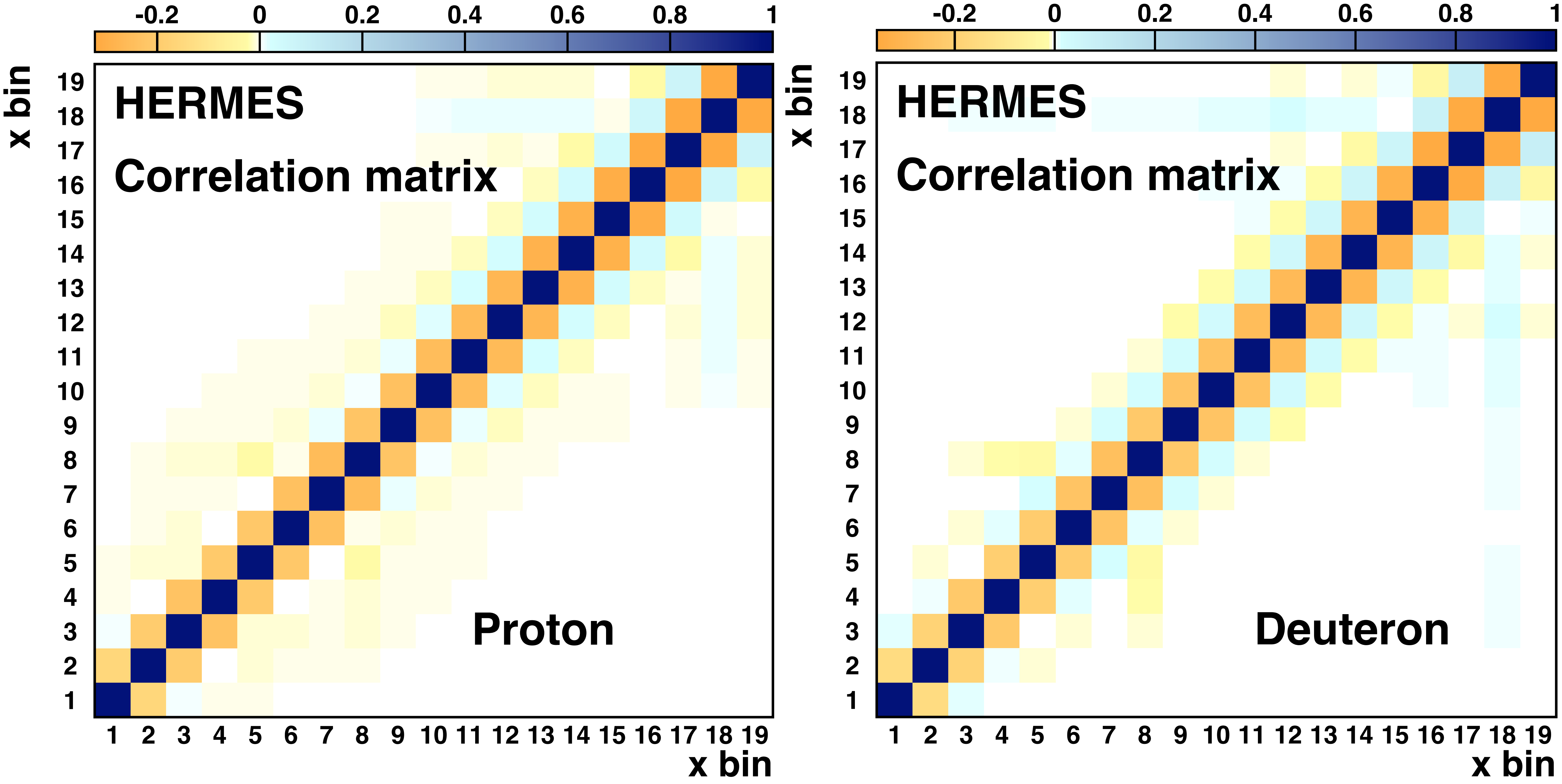


GPDs



Backup Slides

Statistical Correlations



Unknown systematic correlations replaced by known statistical correlations through *unfolding*

Partial Moments of Polarized Quark Distributions

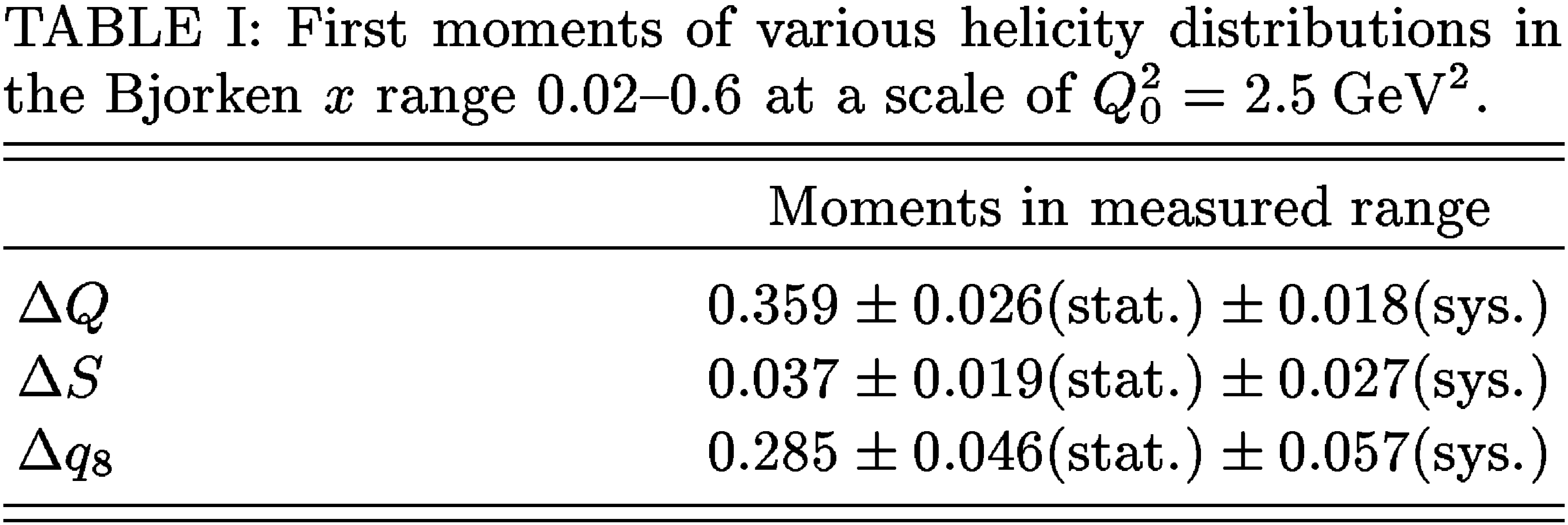
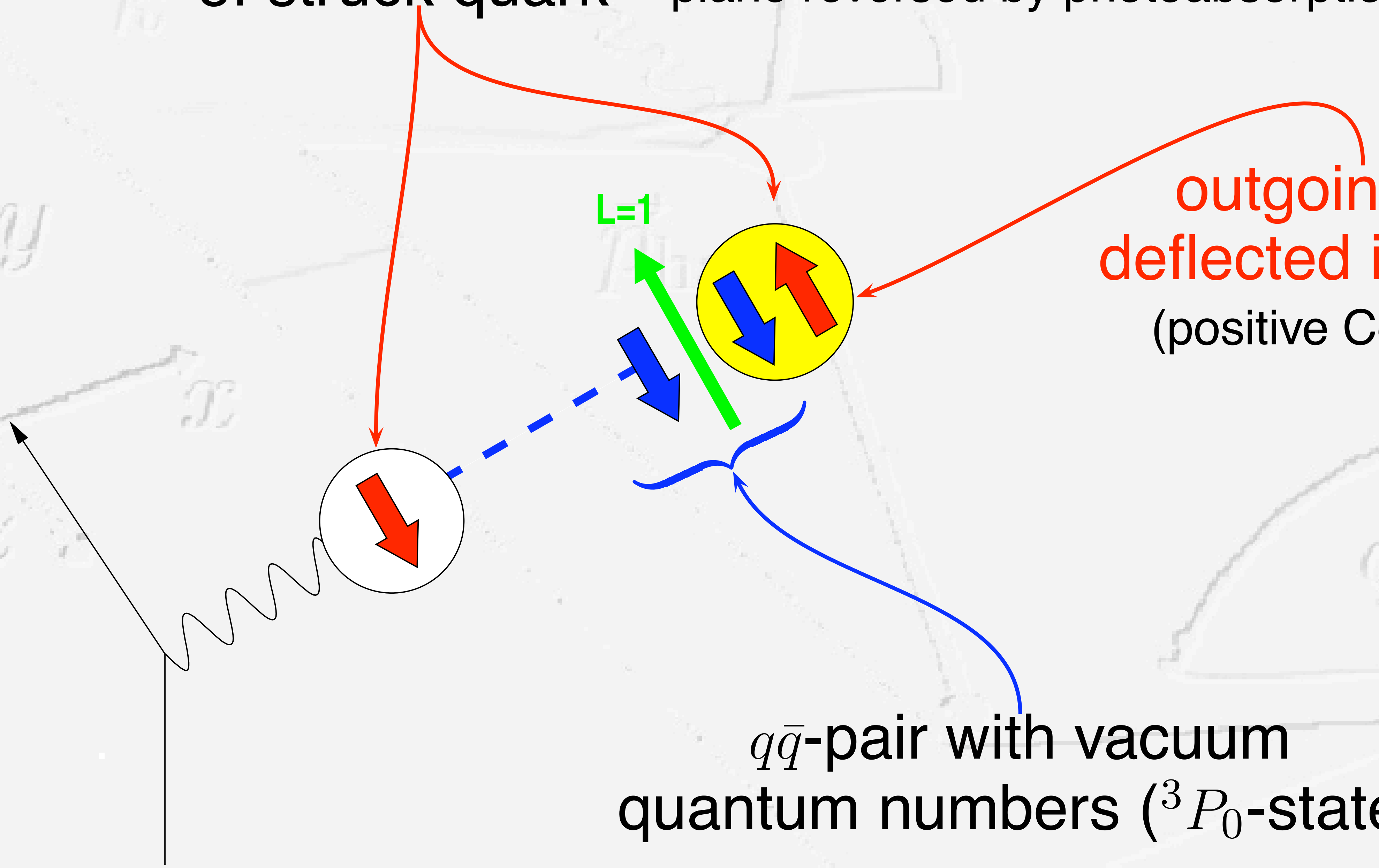


TABLE I: First moments of various helicity distributions in the Bjorken x range 0.02–0.6 at a scale of $Q_0^2 = 2.5\ \mathrm{GeV}^2$.

	Moments in measured range
ΔQ	$0.359 \pm 0.026(\mathrm{stat.}) \pm 0.018(\mathrm{sys.})$
ΔS	$0.037 \pm 0.019(\mathrm{stat.}) \pm 0.027(\mathrm{sys.})$
Δq_8	$0.285 \pm 0.046(\mathrm{stat.}) \pm 0.057(\mathrm{sys.})$

Artru Model for Collins Effect



transverse spin
of struck quark

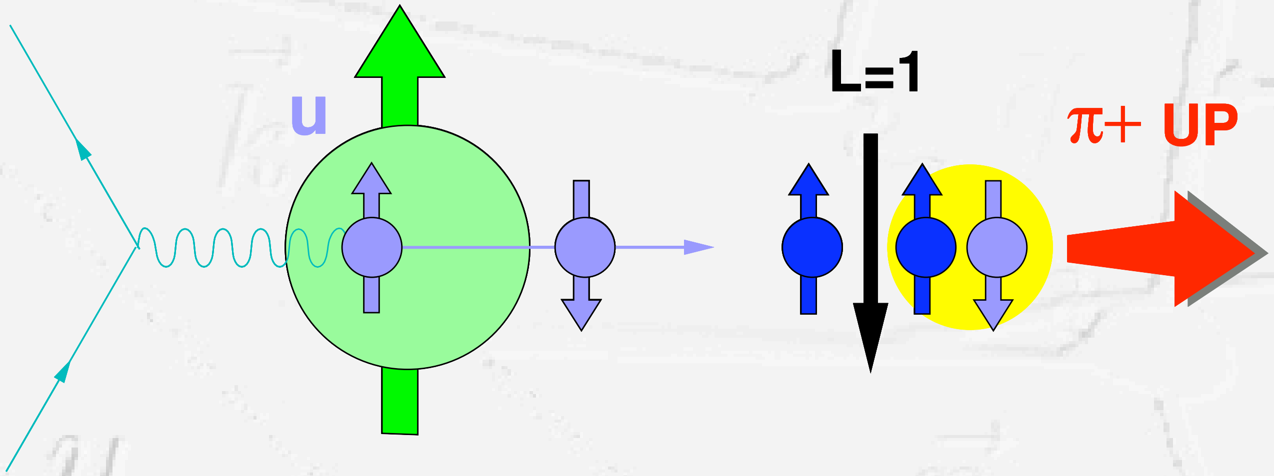
(polarization component in lepton scattering
plane reversed by photoabsorption)

outgoing pion
deflected into page

(positive Collins FF)

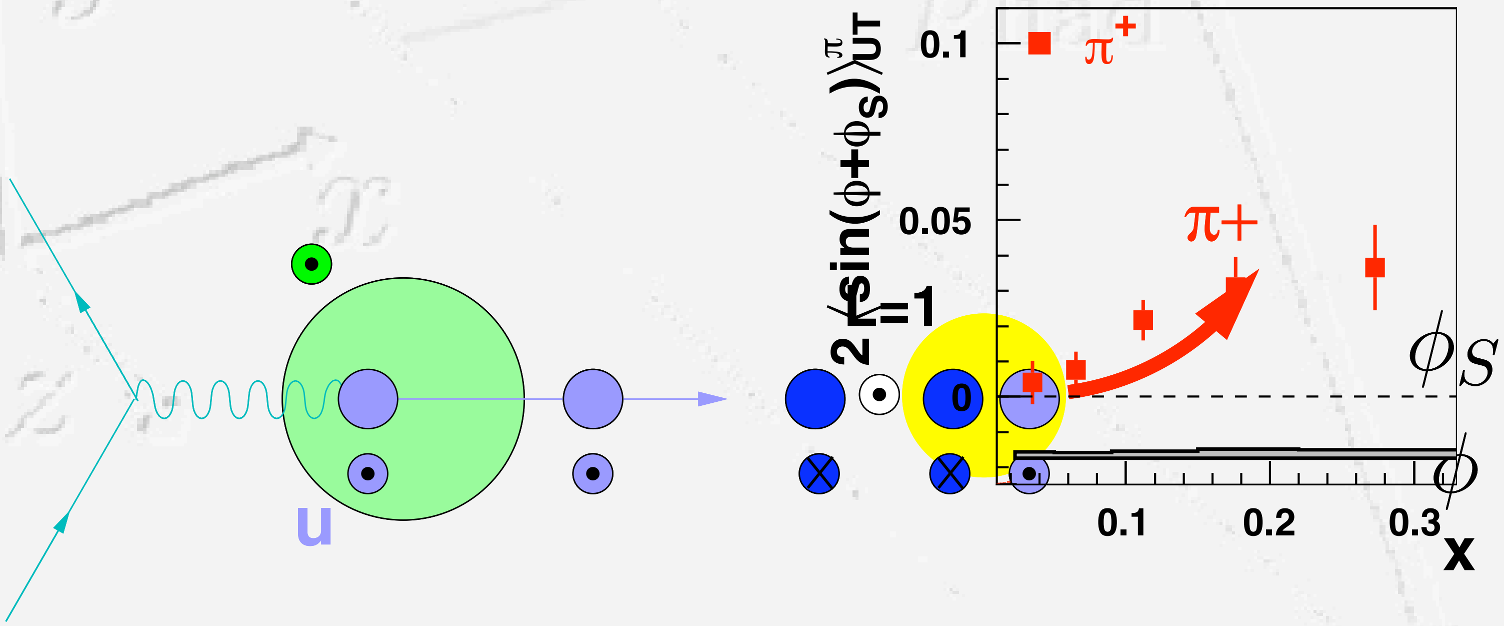
$q\bar{q}$-pair with vacuum
quantum numbers ($^3P_0$-state)

Artru Model vs. HERMES



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

✓



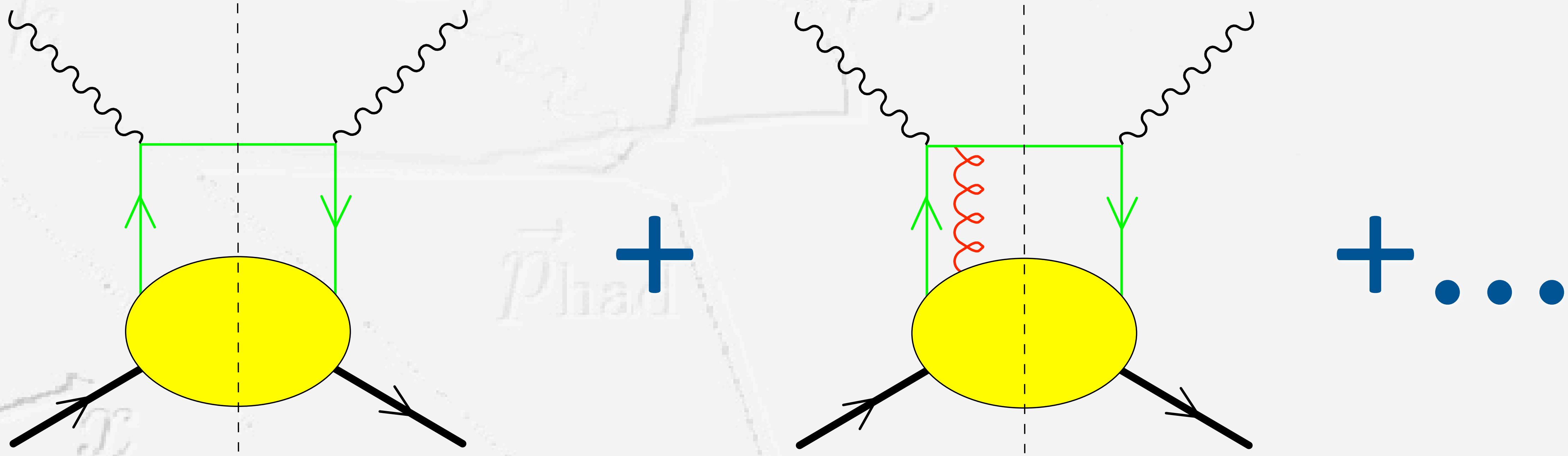
$$\left.\begin{aligned}\phi_S &= \pi/2\\ \phi &= 0\end{aligned}\right\} \sin(\phi+\phi_S) > 0$$

✓

Artru model and HERMES results in agreement!

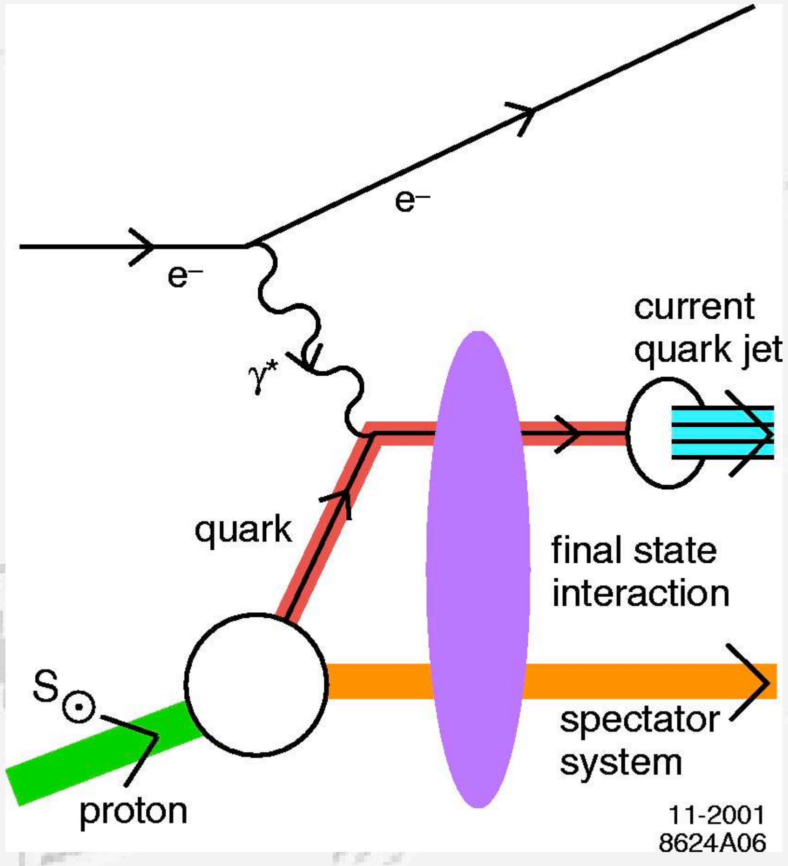
The Sivers Effect - A QCD Challenge?

- Distribution Function (DF) in handbag representation:



- Soft gluons needed for color gauge invariance
- Interference of amplitudes with different numbers of soft gluon exchanges possible
- represent color field of remnant seen by outgoing quark

The Sivers Effect



Thanks to Brodsky, Hwang & Schmidt:

- **quark rescattering via soft gluon exchange**
- **correlates transverse spin of nucleon with direction of struck quark**
- **requires orbital angular momentum!**
- **leading twist!**

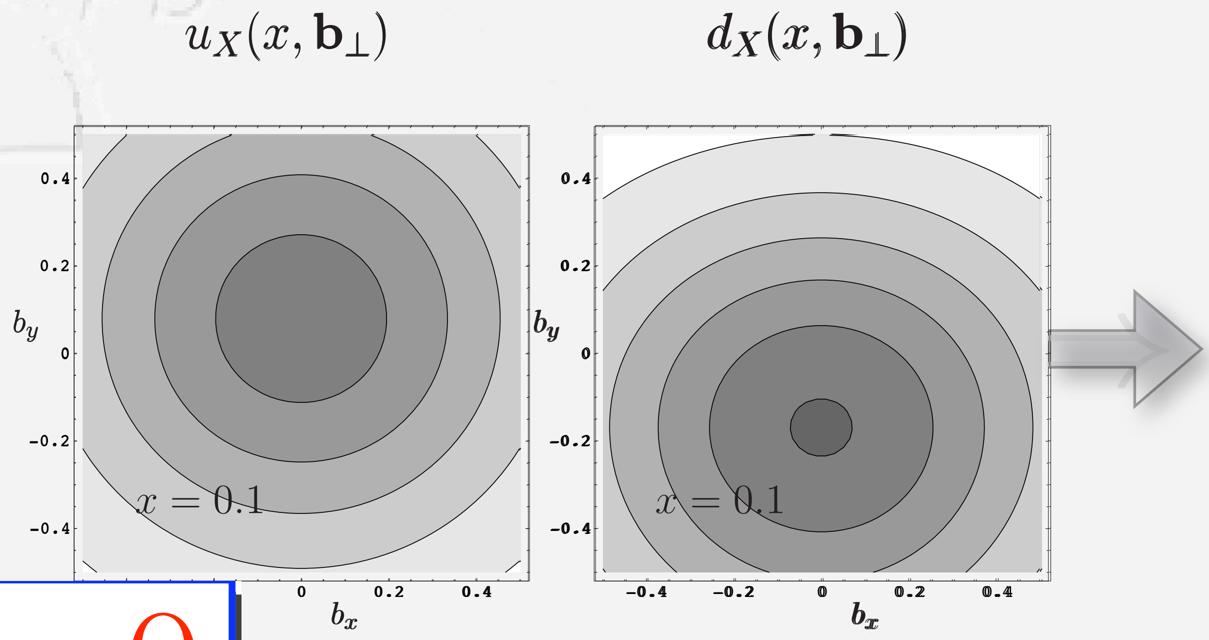
Thanks to Collins, Ji, Yuan, Belitzky ...:

- Soft gluon is model for gauge link needed for gauge invariance
- Gauge links provide necessary complex phase for interference
- T-Symmetry of QCD requires opposite sign of Sivers function in DIS and DY
- slightly different approach by Burkardt using impact parameter dependent PDF's ("chromodynamic lensing")

"Chromodynamic Lensing"

approach by M. Burkardt:

[hep-ph/0309269]



spatial distortion of q-distribution

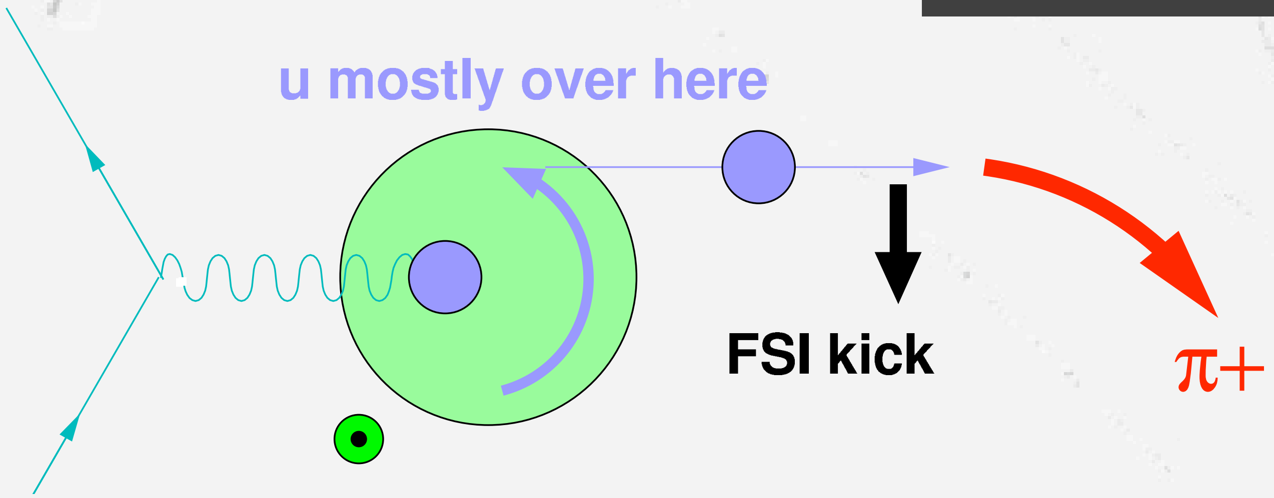
(obtained using anom. magn. moments
& impact parameter dependent PDFs)

+ attractive QCD potential

(gluon exchange)

⇒ transverse asymmetr

$$\boxed{L_z^u > 0}$$

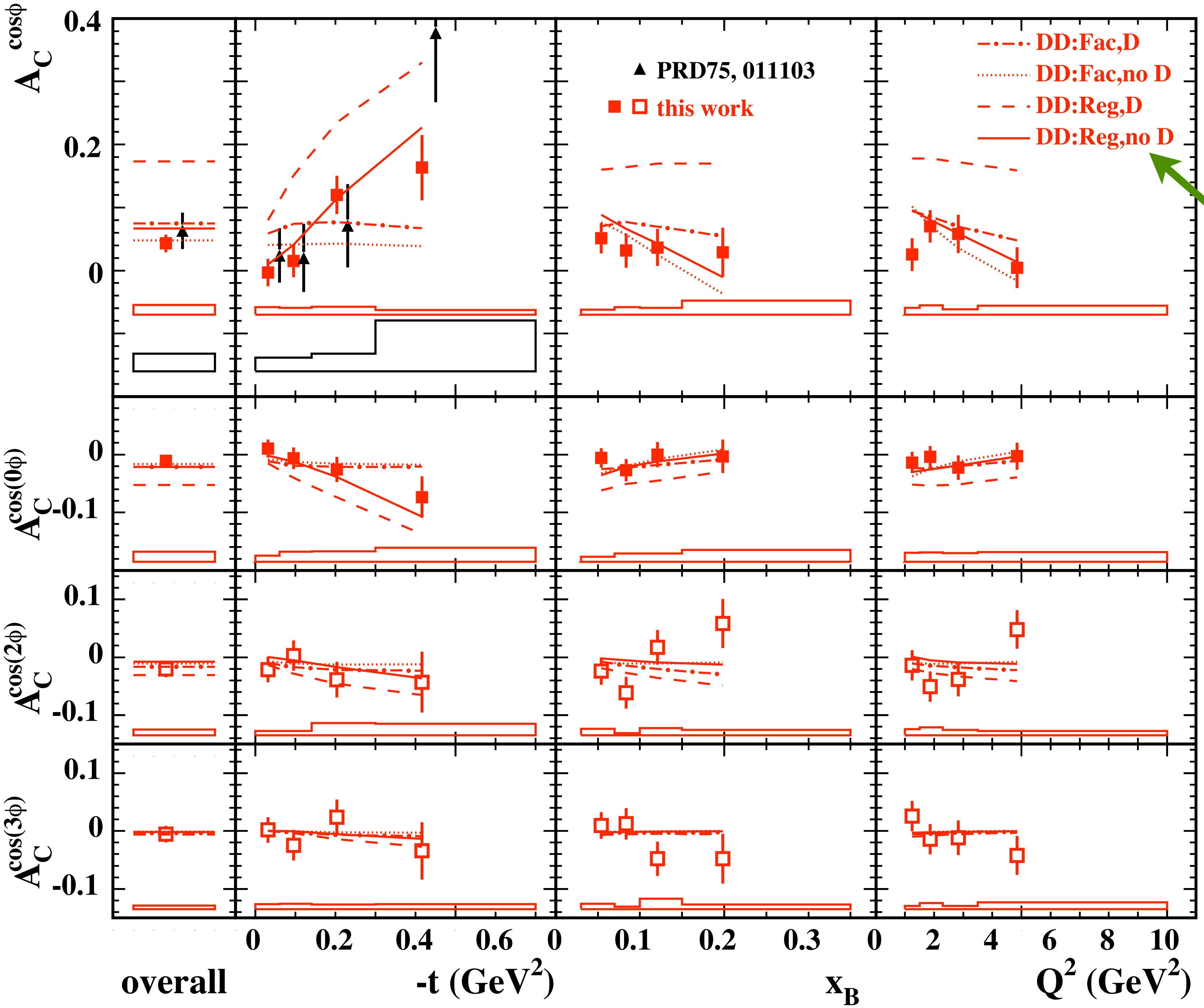


$$\left.\begin{array}{l}\phi_S = \pi/2\\ \phi \;=\; \pi\end{array}\right\} \sin(\phi-\phi_S) > 0$$

Constraining GPD *H*

Beam-charge asymmetry $A_C(\phi) \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$

(extracted from same data set as used for TTSA)



A. Airapetian et al.,
arXiv:0802.2499

clearly favored:

- double distribution
- factorized (Regge-inspired) Ansatz for t-independent part
- no "D-term"

(cf. PRD60 (1997))