HERA end of data taking

2^{nd} anniversary symposium - July 7^{th}, 2009 - DESY

from solving the spin "crisis" to 3-D pictures of the nucleon

selected highlights from the hermes collaboration

Gunar.Schnell @ desy.de

DESY Zeuthen

June 30th, 2007 (around midnight)

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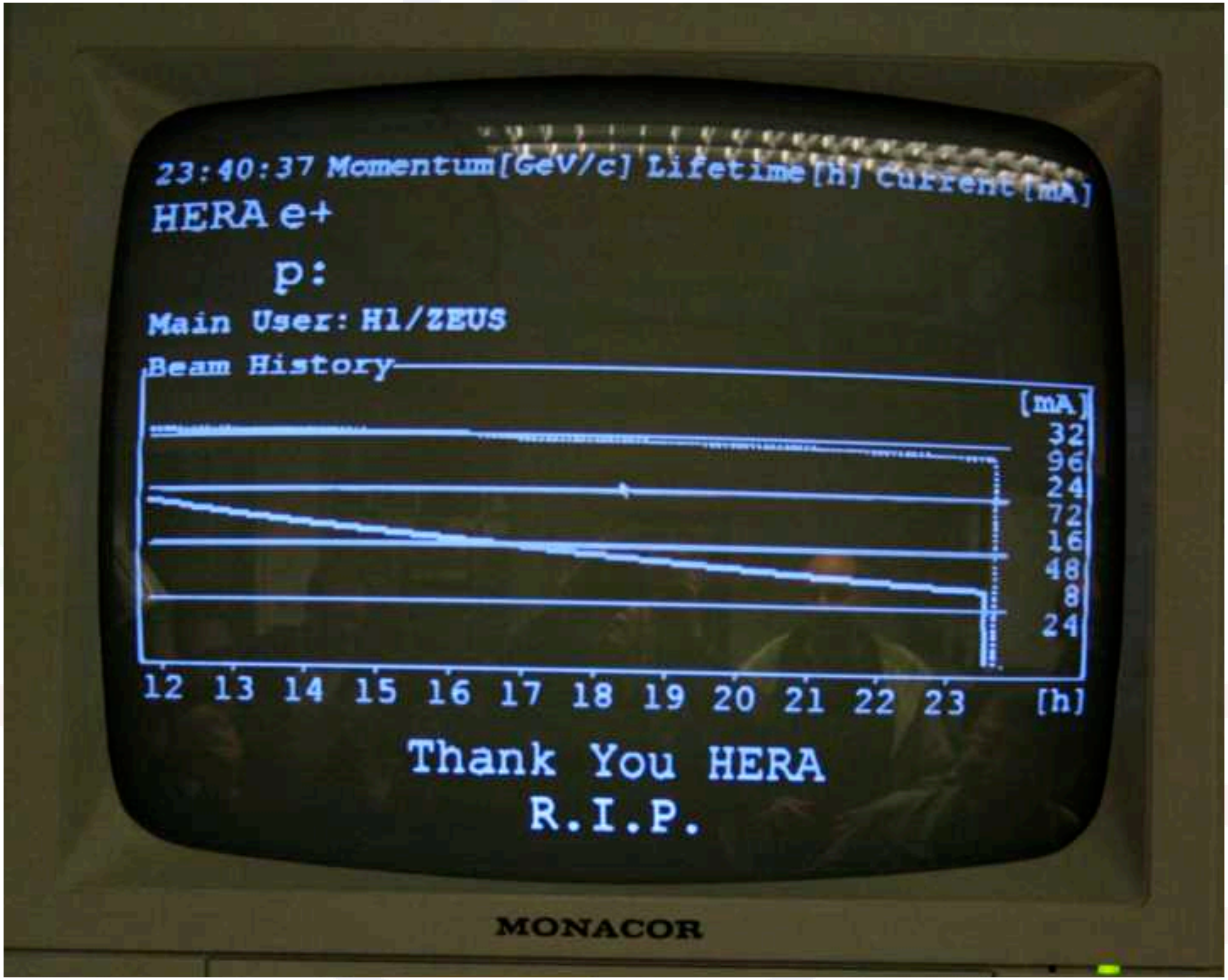
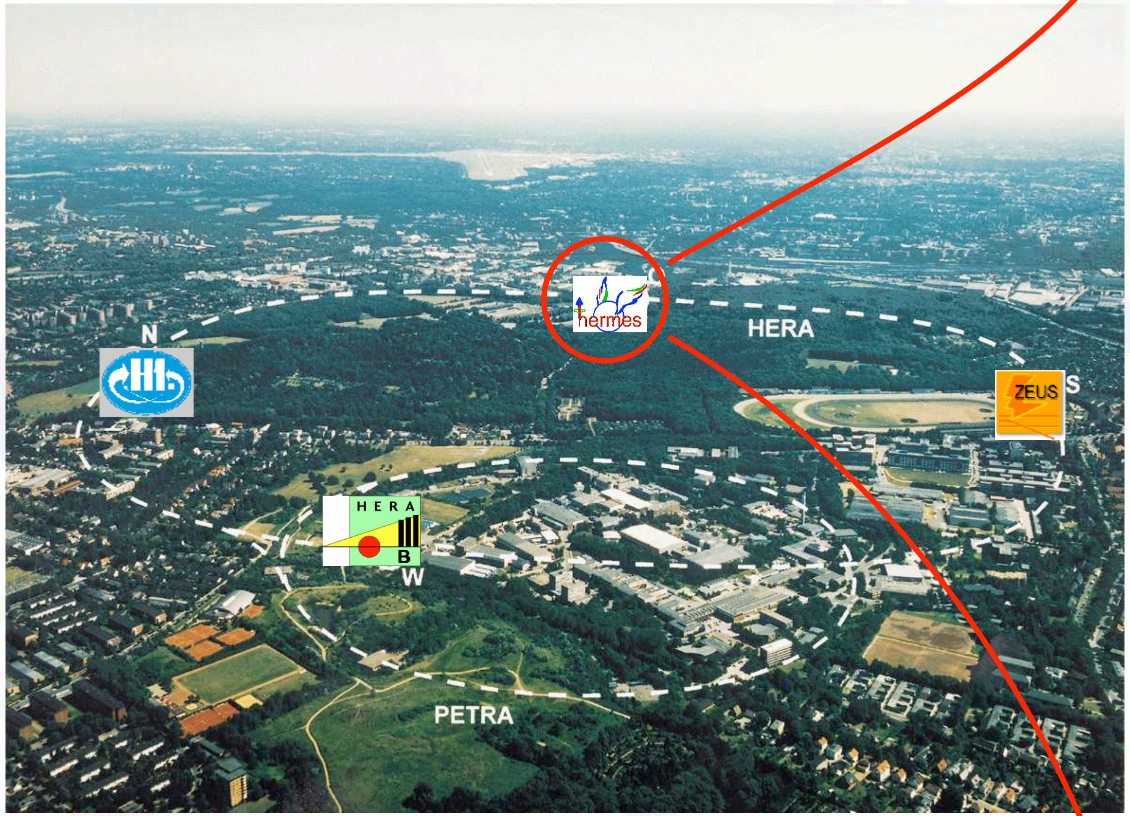
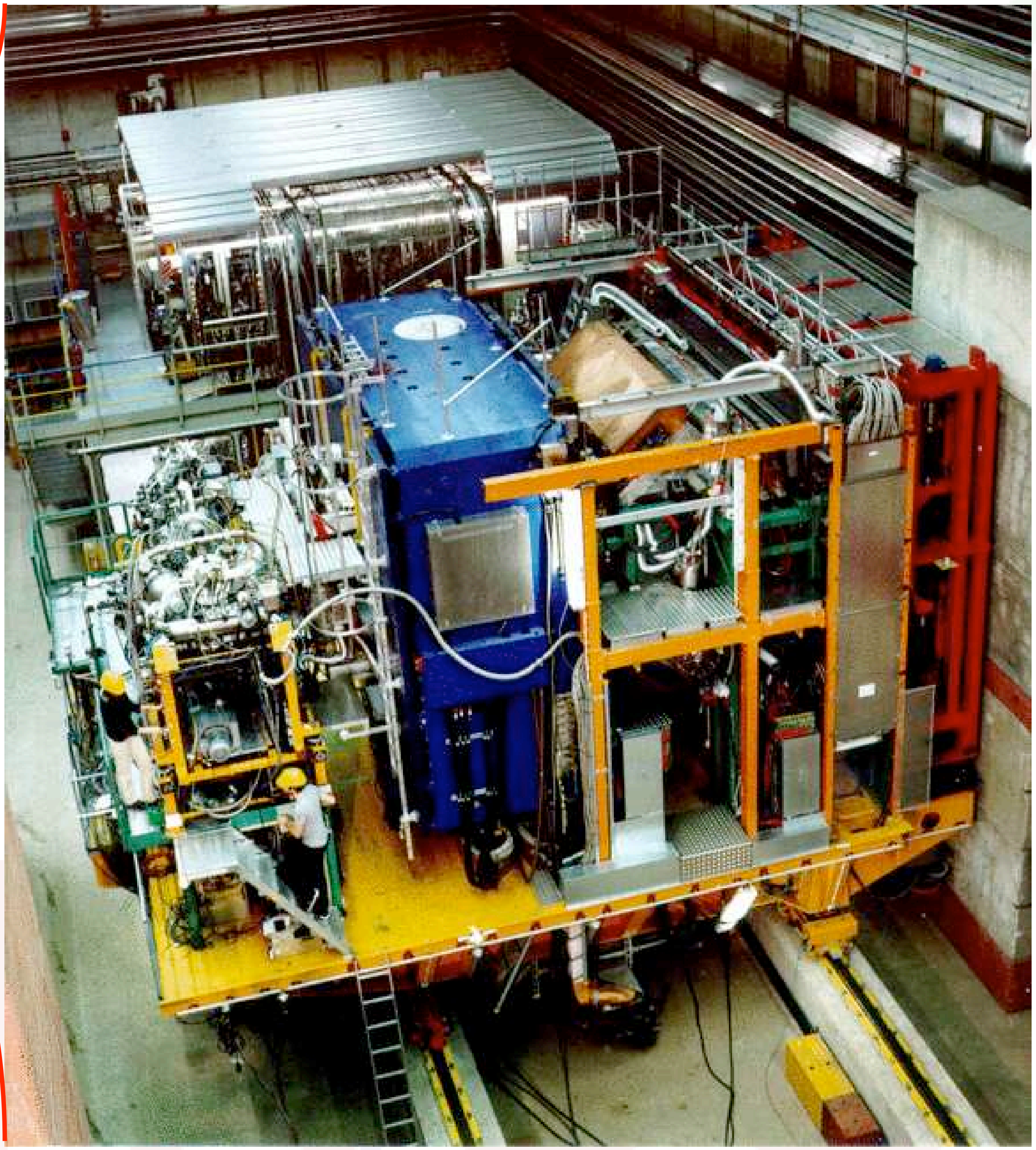


The HERMES experiment

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

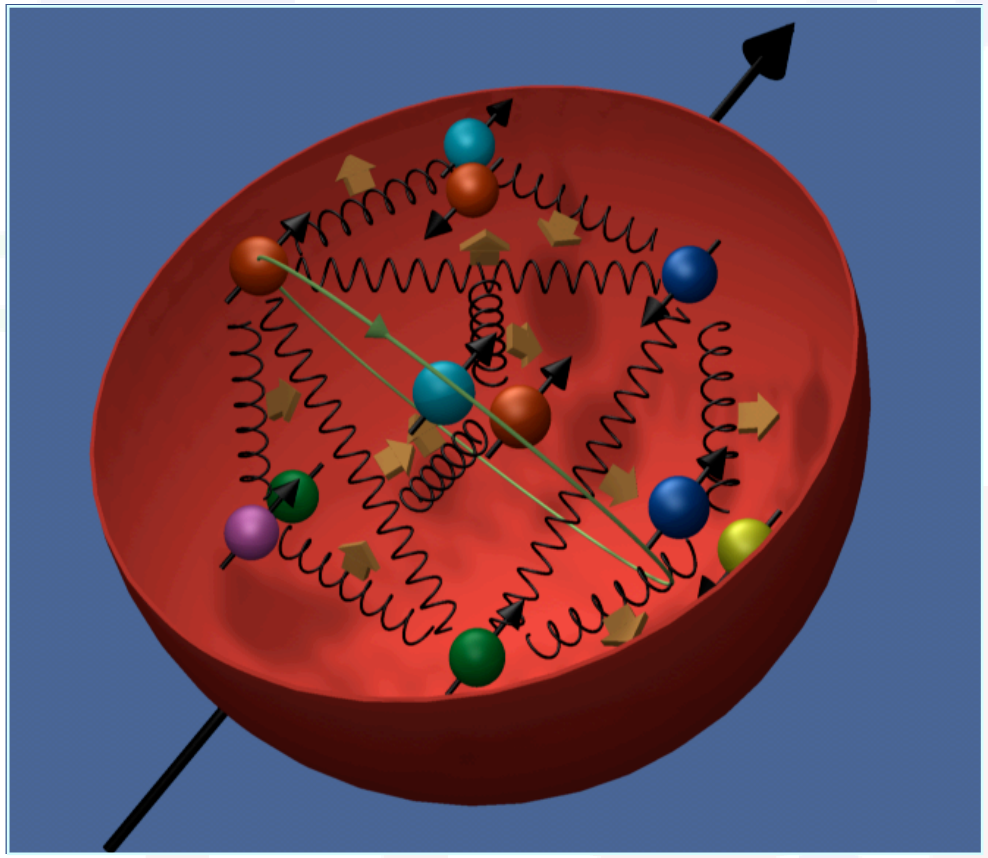




transversely/longitudinally polarized as well as unpolarized internal gas targets (H, D, He, N, …, Xe)

The (original) quest: proton spin

our understanding of the proton changed dramatically with the finding of EMC that the proton spin hardly comes from spin of quarks

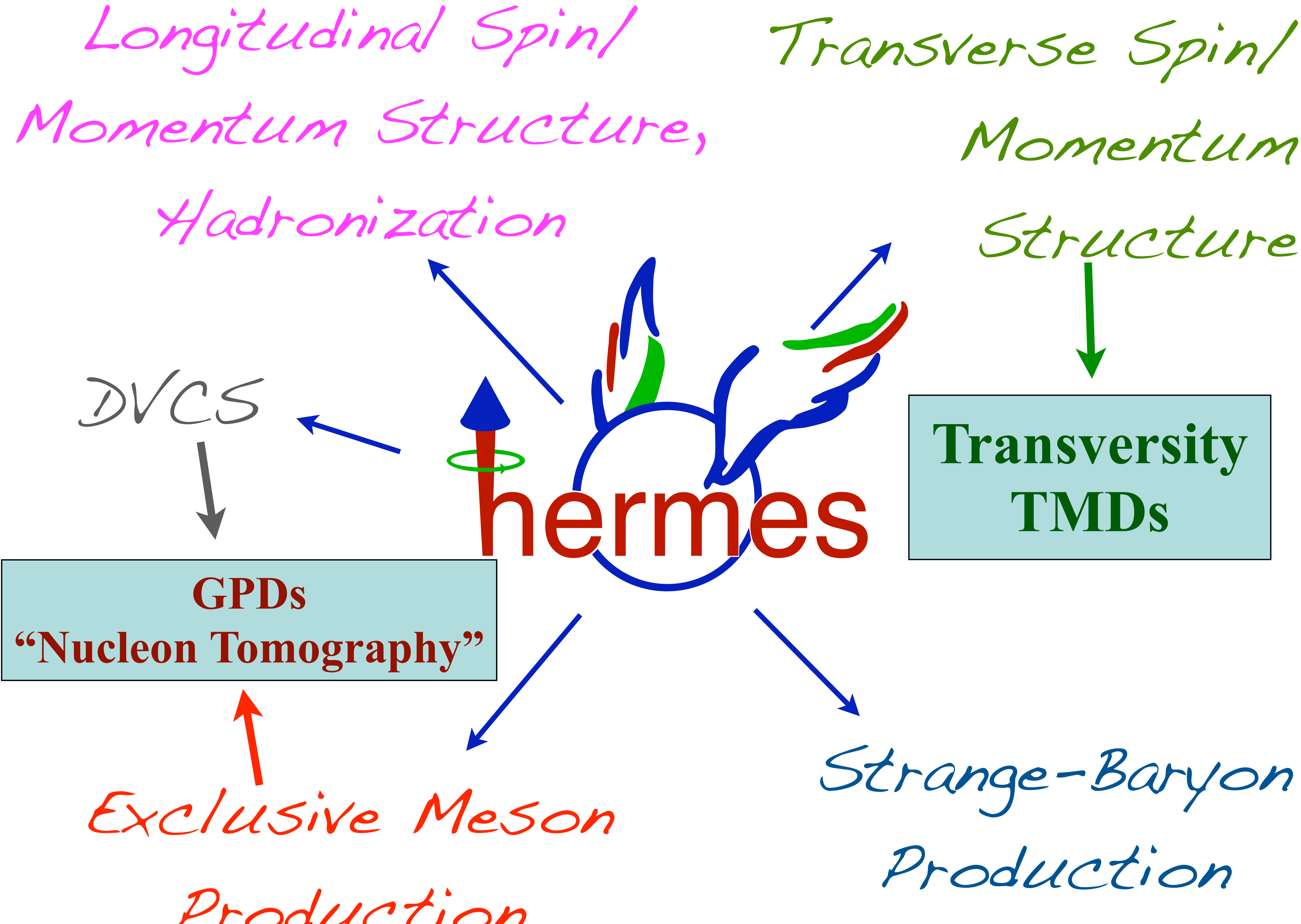


$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$\frac{1}{2}\Delta\Sigma$ ← quark spin

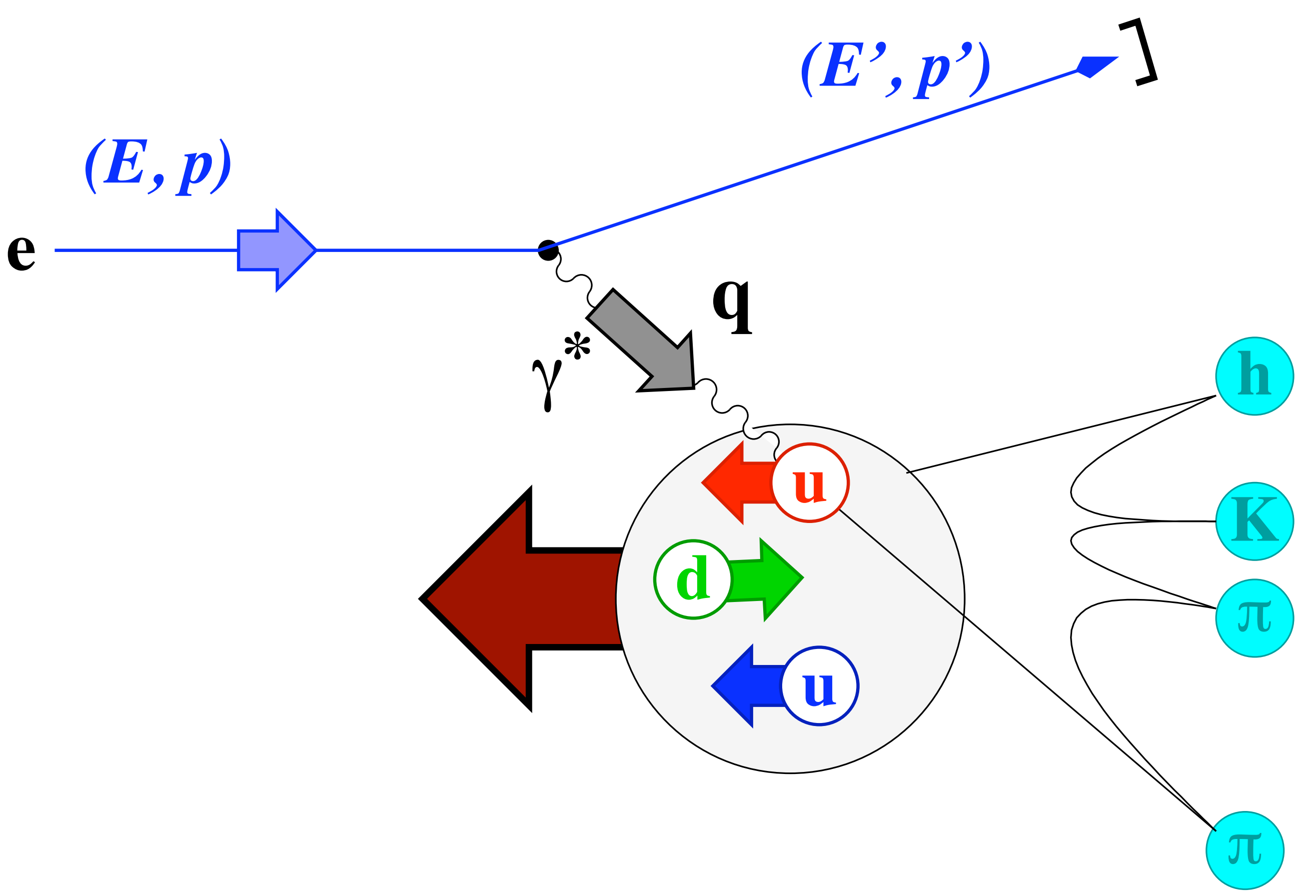
ΔG ← gluon spin

$L_q + L_g$ ← orbital angular momentum


Longitudinal Spin/
Momentum Structure,
Hadronization
Transverse Spin/
Momentum
Structure
DVCS
hermes
Transversity
TMDs
GPDs
“Nucleon Tomography”
Exclusive Meson
Production
Strange-Baryon
Production

Deep-Inelastic Scattering

use well-known probe to study hadronic structure:



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

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

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

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

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

inclusive DIS: detect scattered lepton

Deep-Inelastic Scattering

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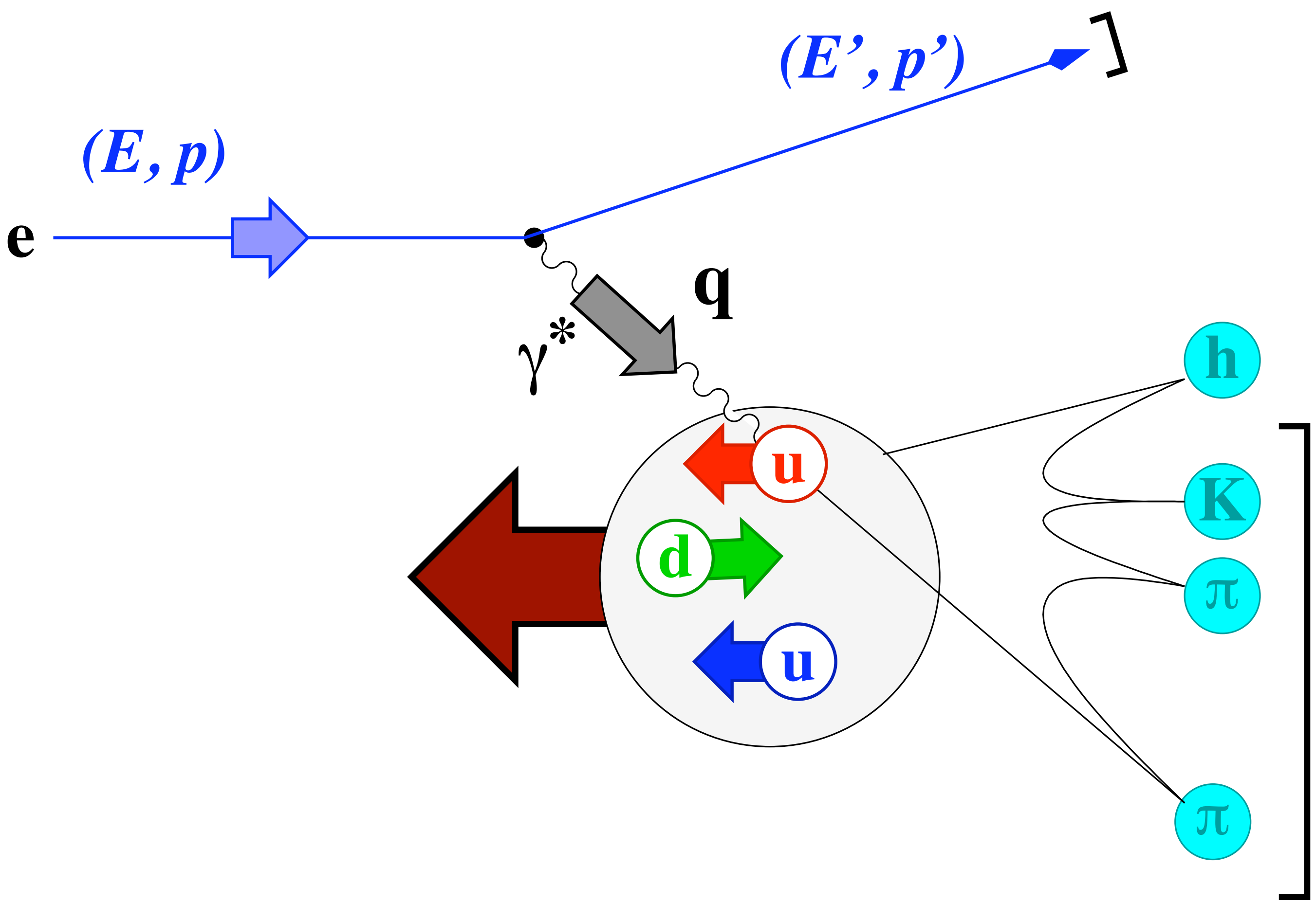

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$$y \overset{\text{lab}}{=} \frac{\nu}{E}$$

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

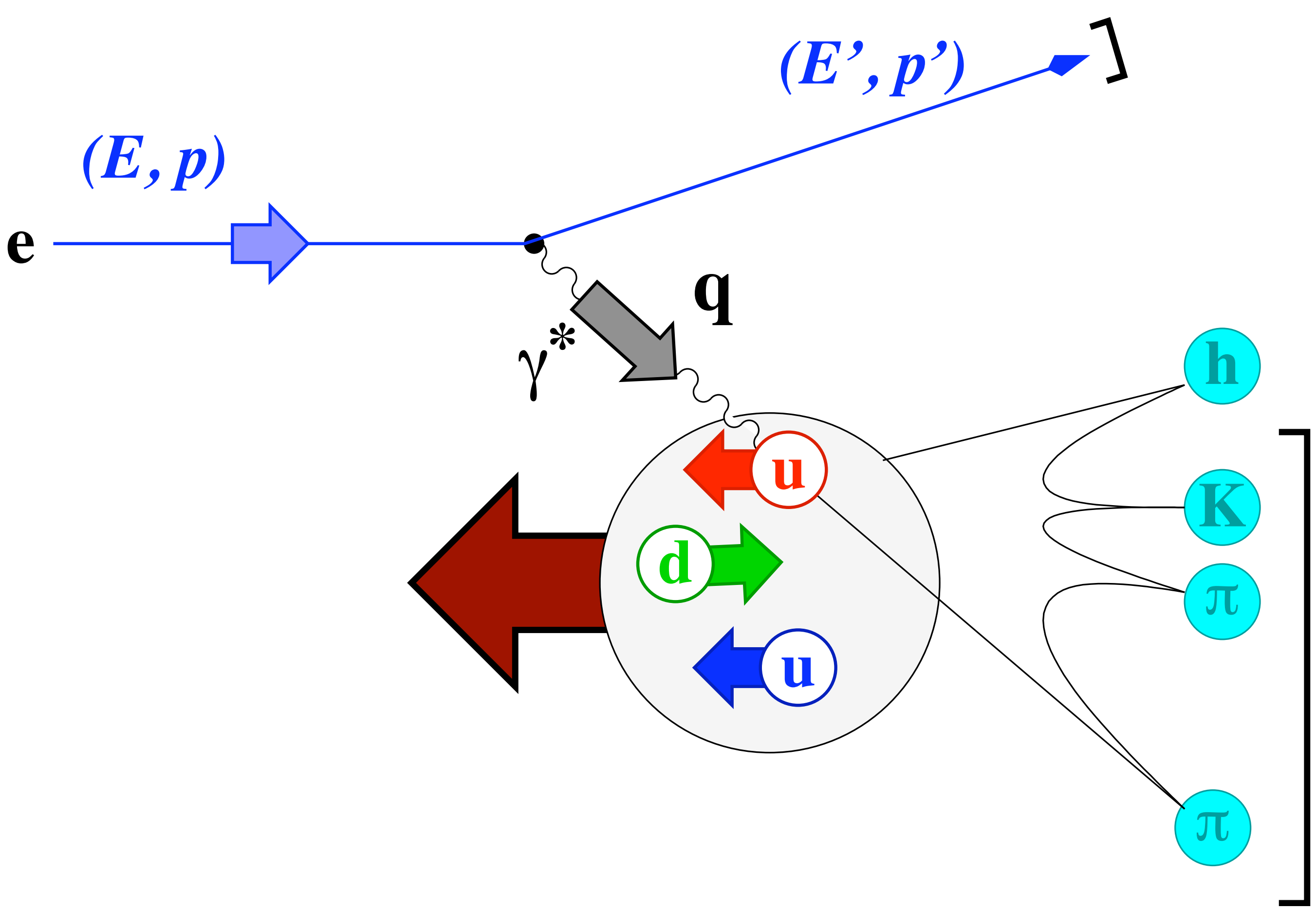
$$z \overset{\text{lab}}{=} \frac{E_h}{\nu}$$

inclusive DIS: detect scattered lepton

semi-inclusive DIS: detect scattered lepton and some fragments

Deep-Inelastic Scattering

use well-known probe to study hadronic structure:



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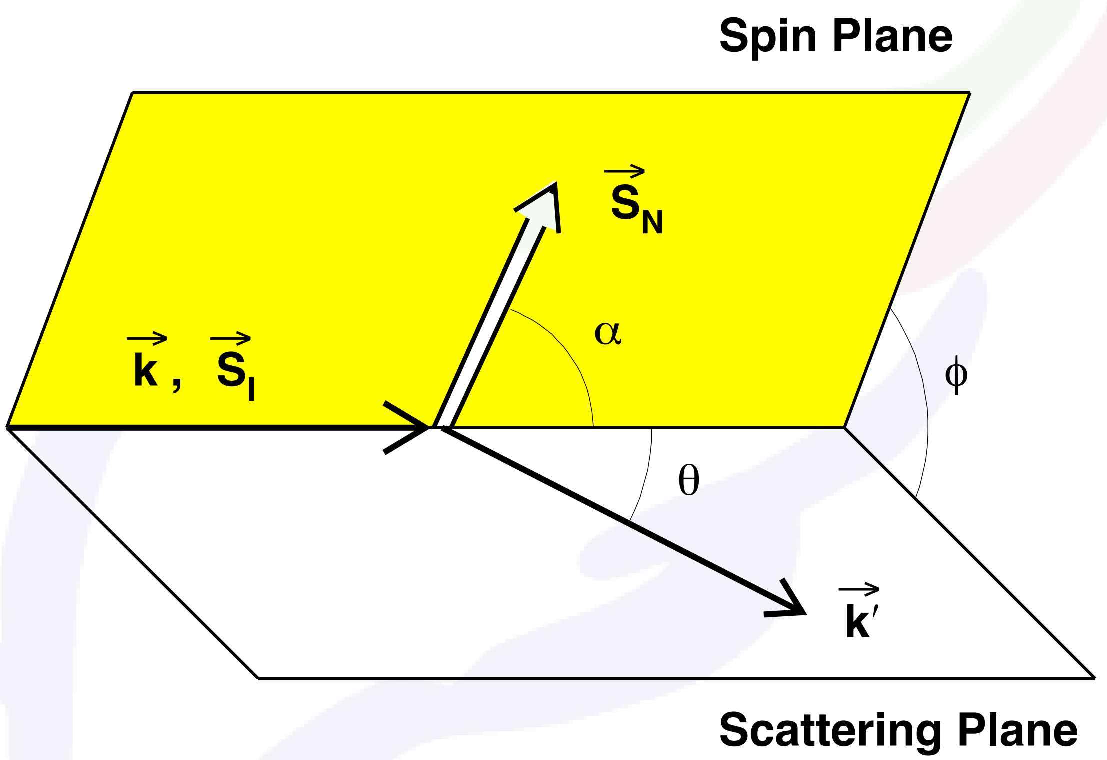
Factorization $\Rightarrow \sigma^{ep\to ehX} = \sum_q DF^{p\to q} \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}$

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

Inclusive DIS

Inclusive DIS

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



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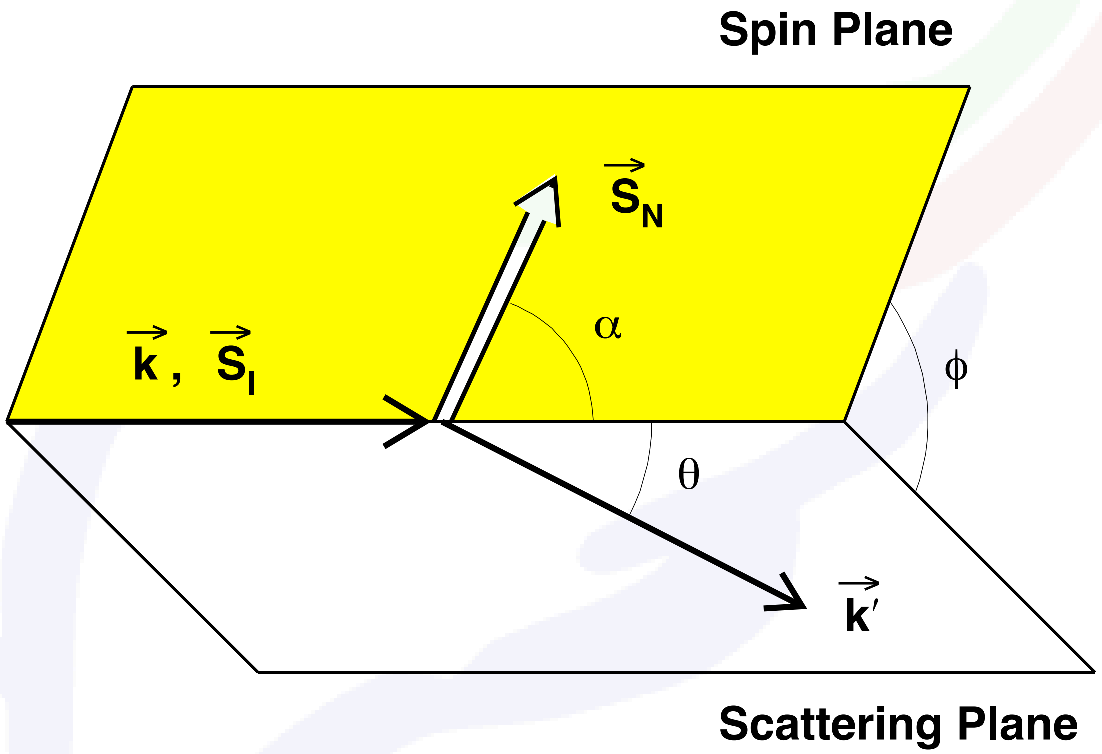
Lepton Tensor



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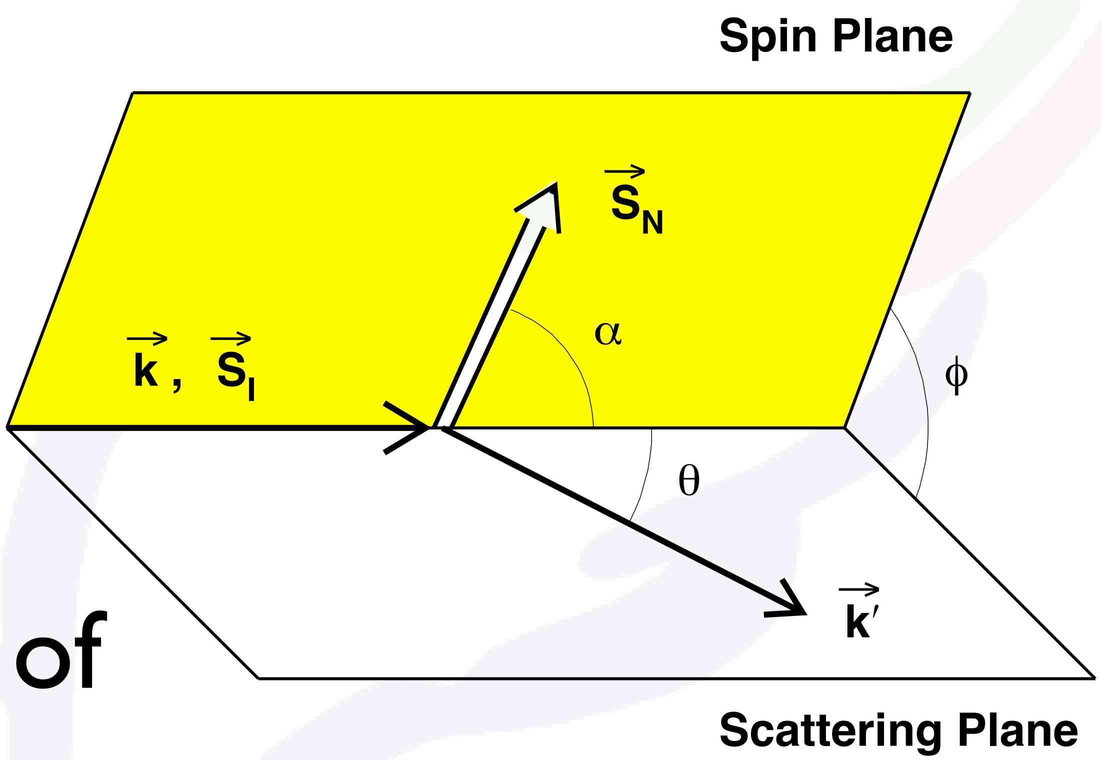
Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions



Inclusive DIS

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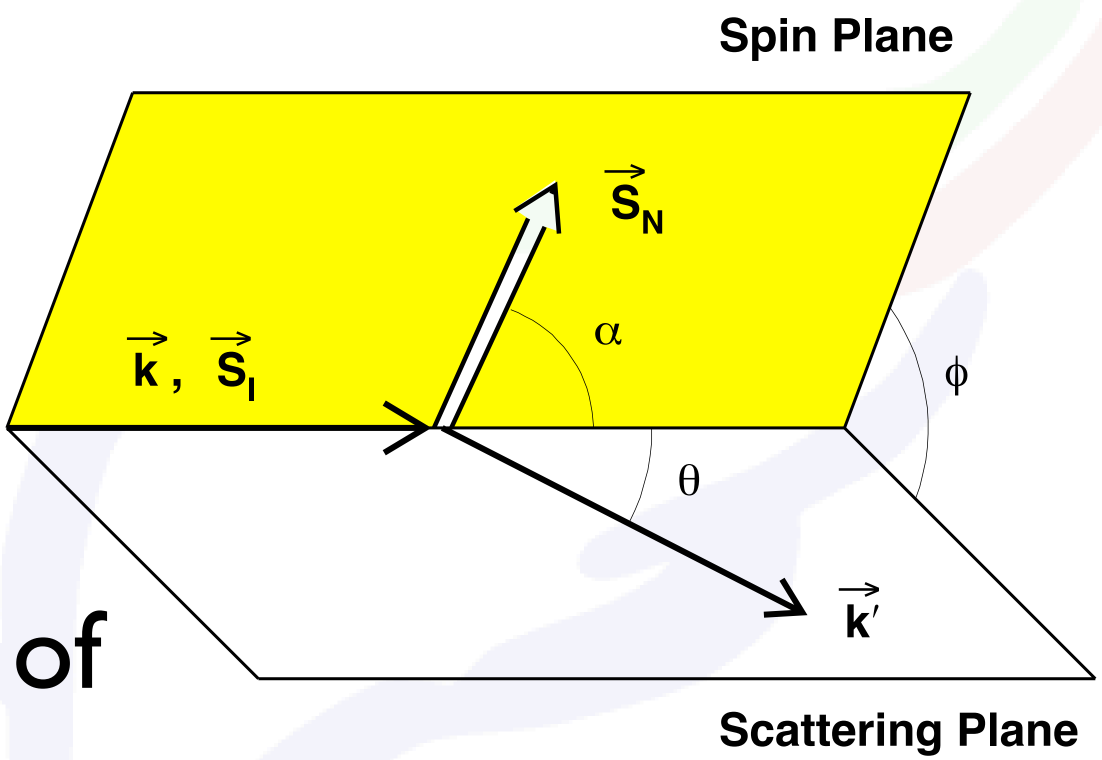


$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}\boxed{F_1(x,Q^2)} + \frac{1-y-\gamma^2y^2/4}{2xy}\boxed{F_2(x,Q^2)}$$
$$-P_l P_T \cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)\boxed{g_1(x,Q^2)} - \frac{\gamma^2 y}{2}\boxed{g_2(x,Q^2)}\right]$$
$$+P_l P_T \sin\alpha\cos\phi\,\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}\boxed{g_1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

Parton-Model Interpretation of Structure

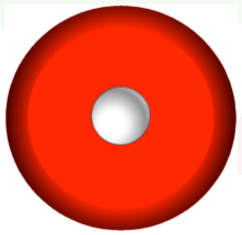
<u>structure function</u> $\leftrightarrow$ <u>parton distribution</u>

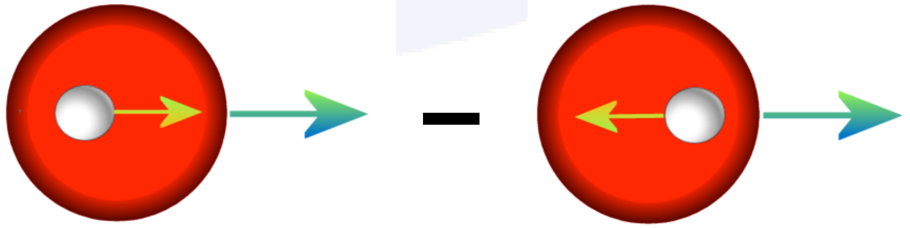
$$F_1(x) = \frac{1}{2}\sum_q e_q^2 f_1^q(x)$$

$$F_2(x) = x\sum_q e_q^2 f_1^q(x)$$

$$g_1(x) = \frac{1}{2}\sum_q e_q^2 g_1^q(x)$$

$$g_2(x) = 0$$

$f_1^q =$ 

$g_1^q =$ 

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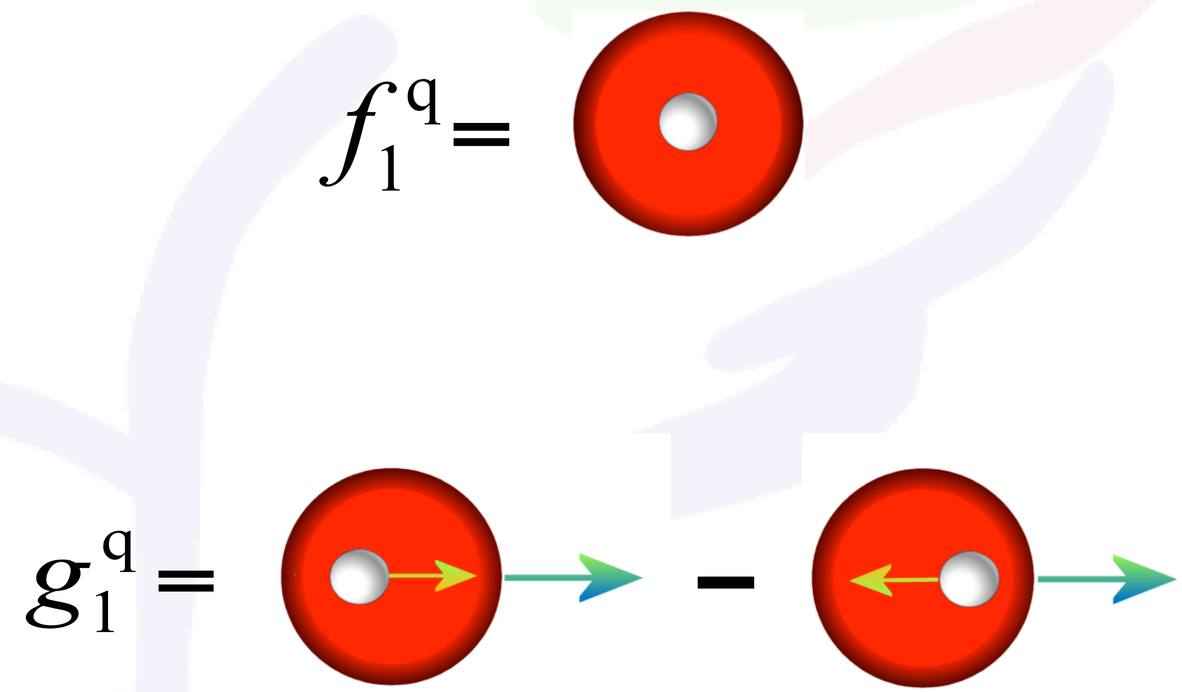

quark-spin contribution to nucleon spin

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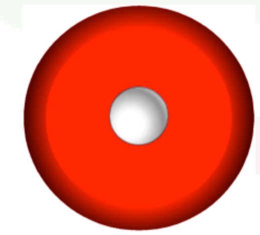
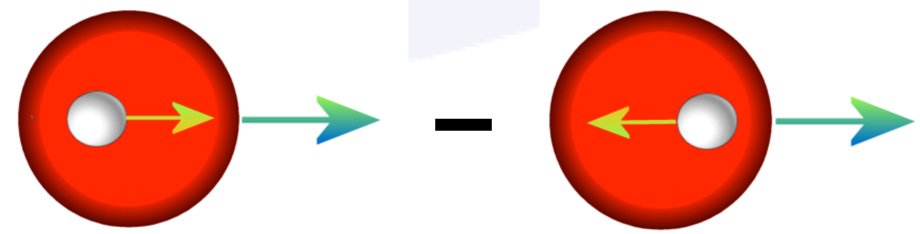
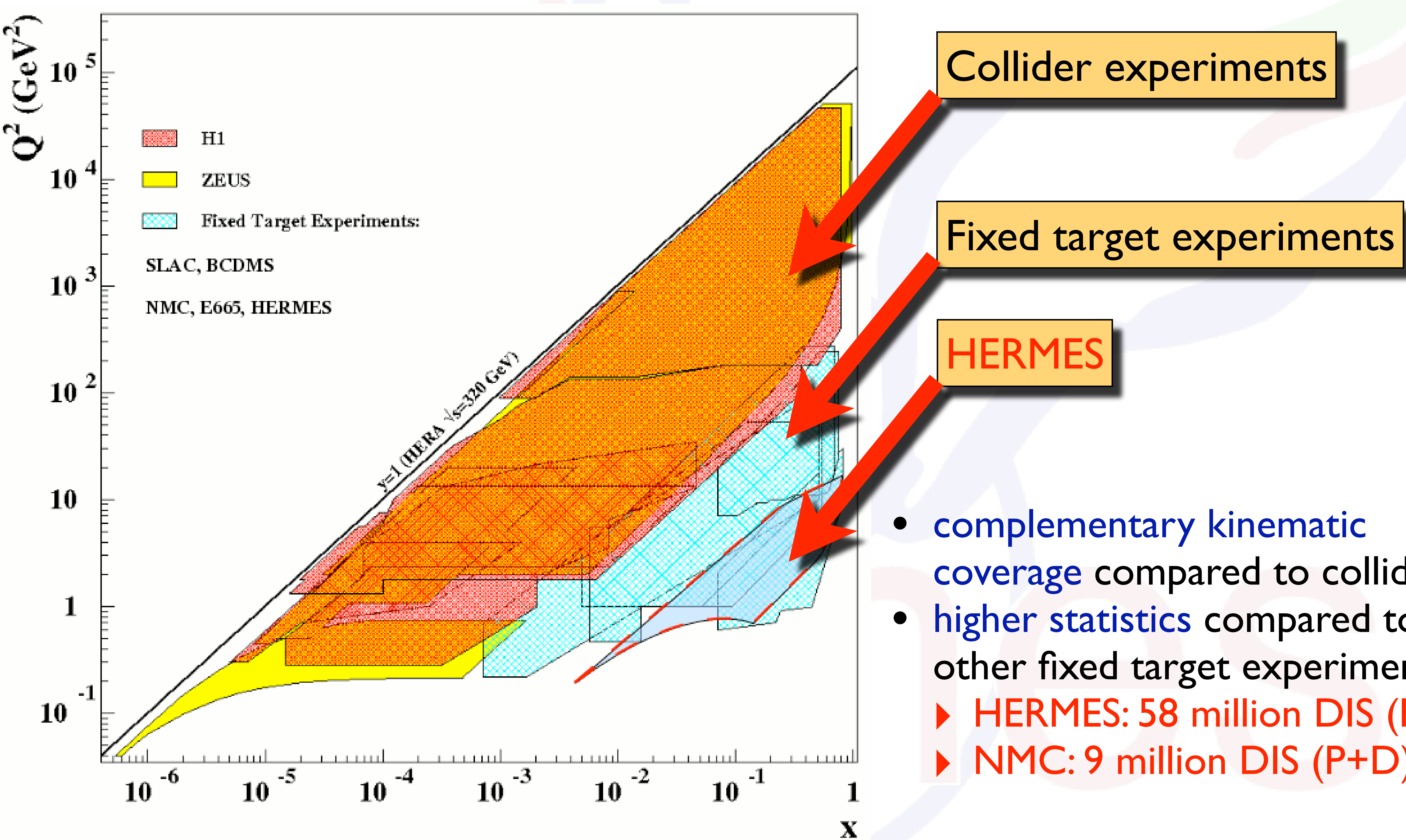
$f_1^q =$ 

$g_1^q =$ 

quark-spin contribution to nucleon spin

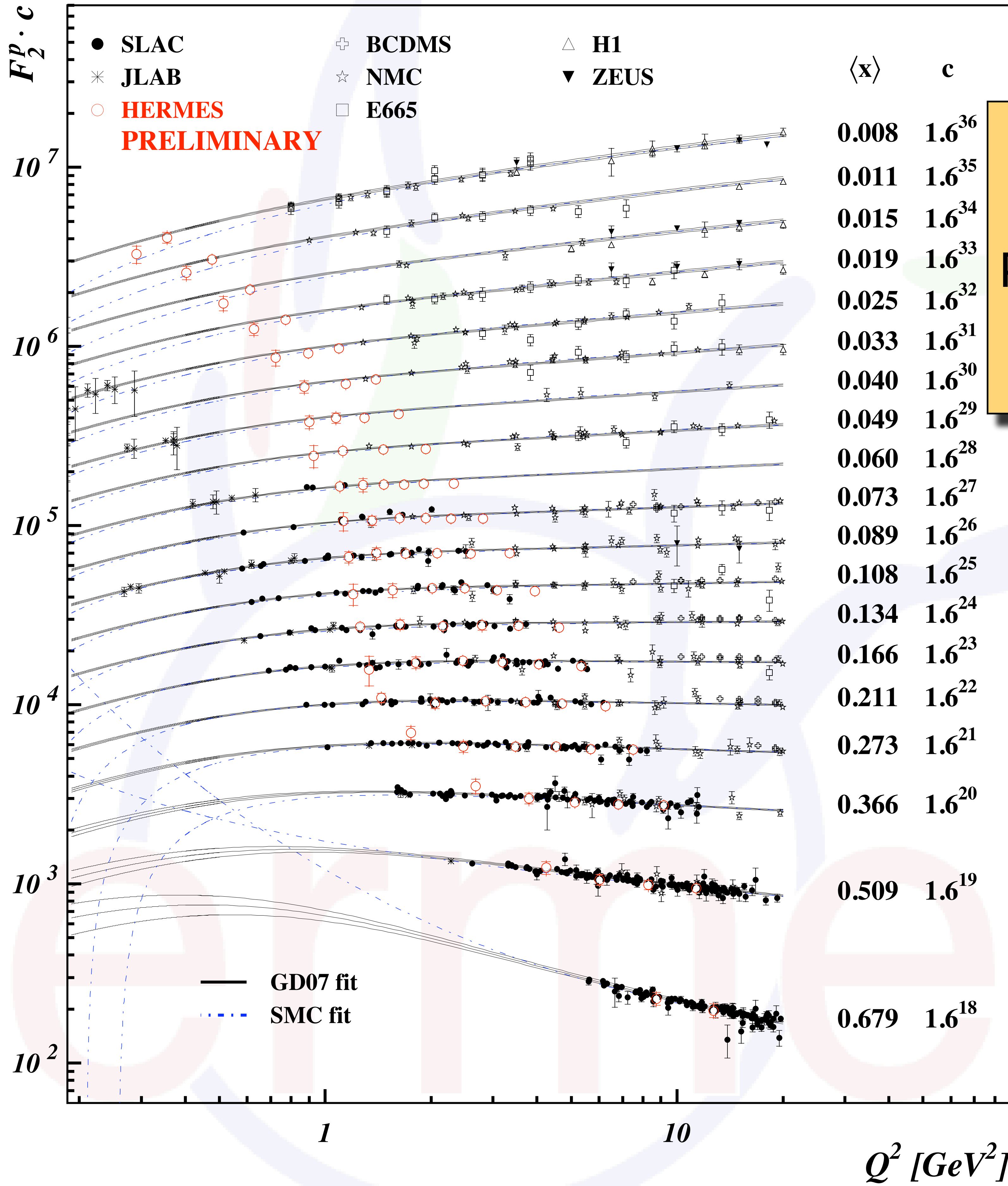
related to transverse force on struck quark

Why measure F_2 at HERMES?



- complementary kinematic coverage compared to colliders
- higher statistics compared to other fixed target experiments:
  - HERMES: 58 million DIS (P+D)
  - NMC: 9 million DIS (P+D)

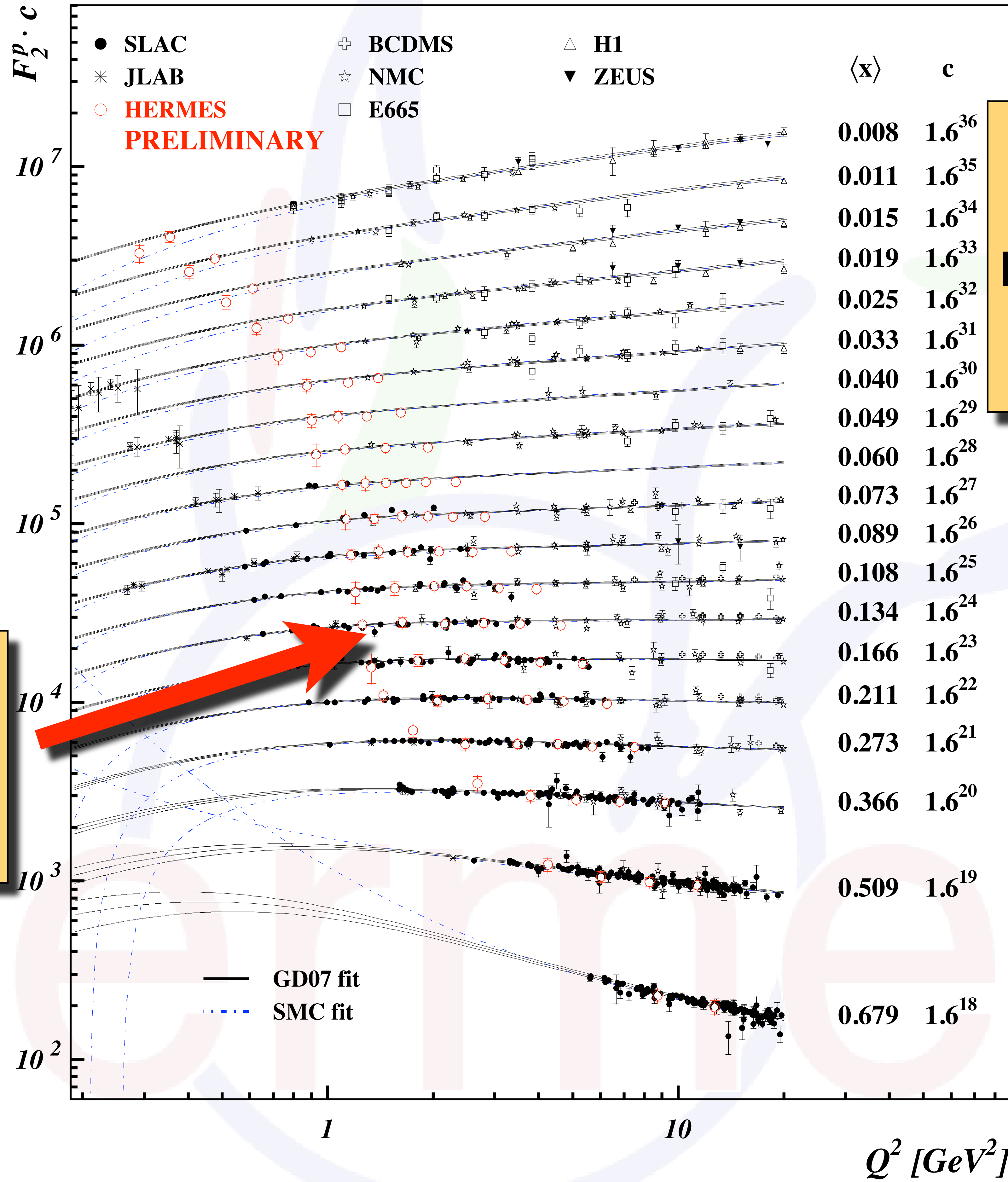
F_2 proton



Comparison with parameterization by SMC and GD07

GD07: hep-ph0708.3196
SMC: Phys. Rev. D, Vol. 58, 112001

F2
proton



Comparison with parameterization by SMC and GD07

Agreement with world data in the overlap region

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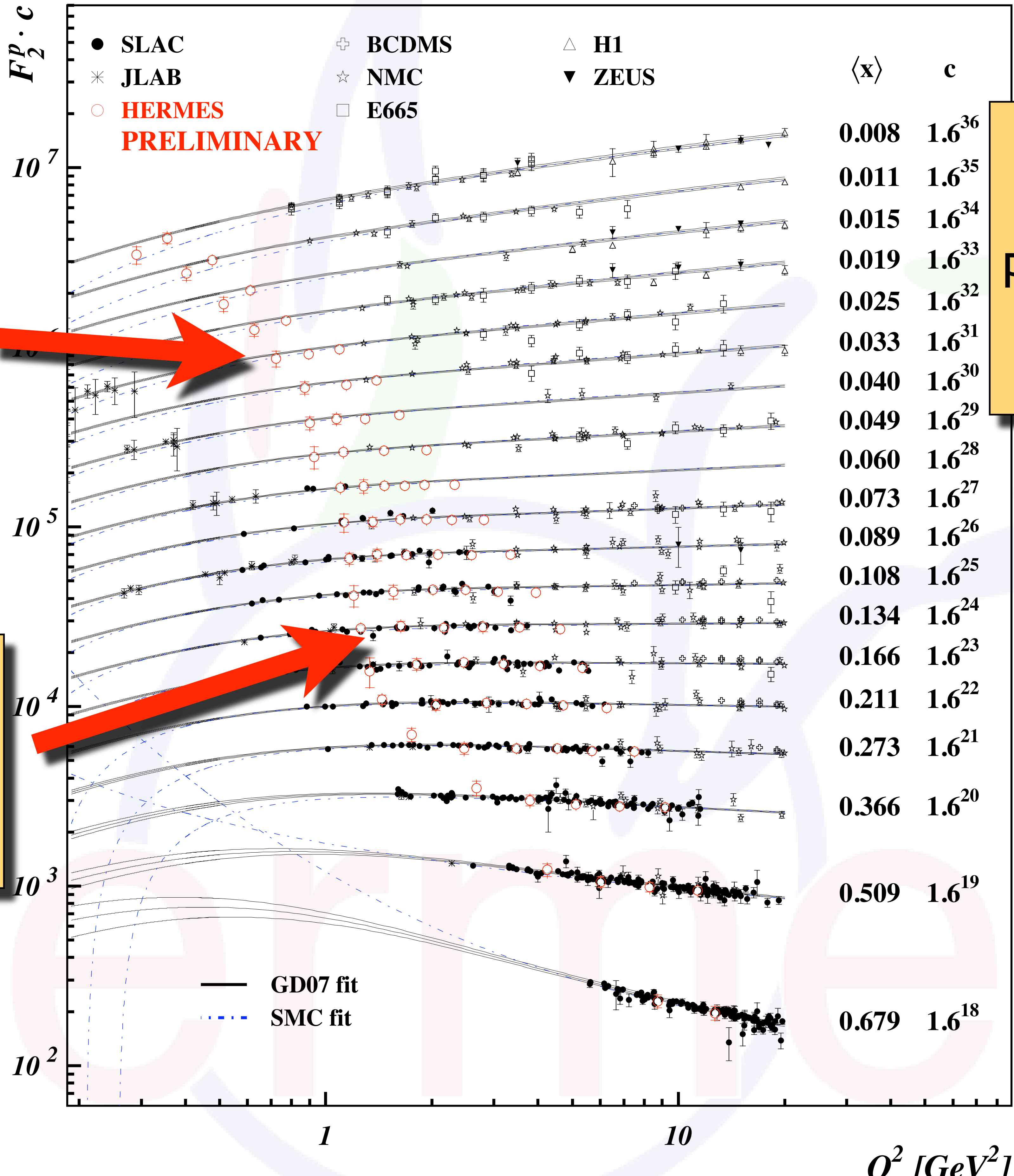
F_2 proton

New region covered by HERMES

Agreement with world data in the overlap region



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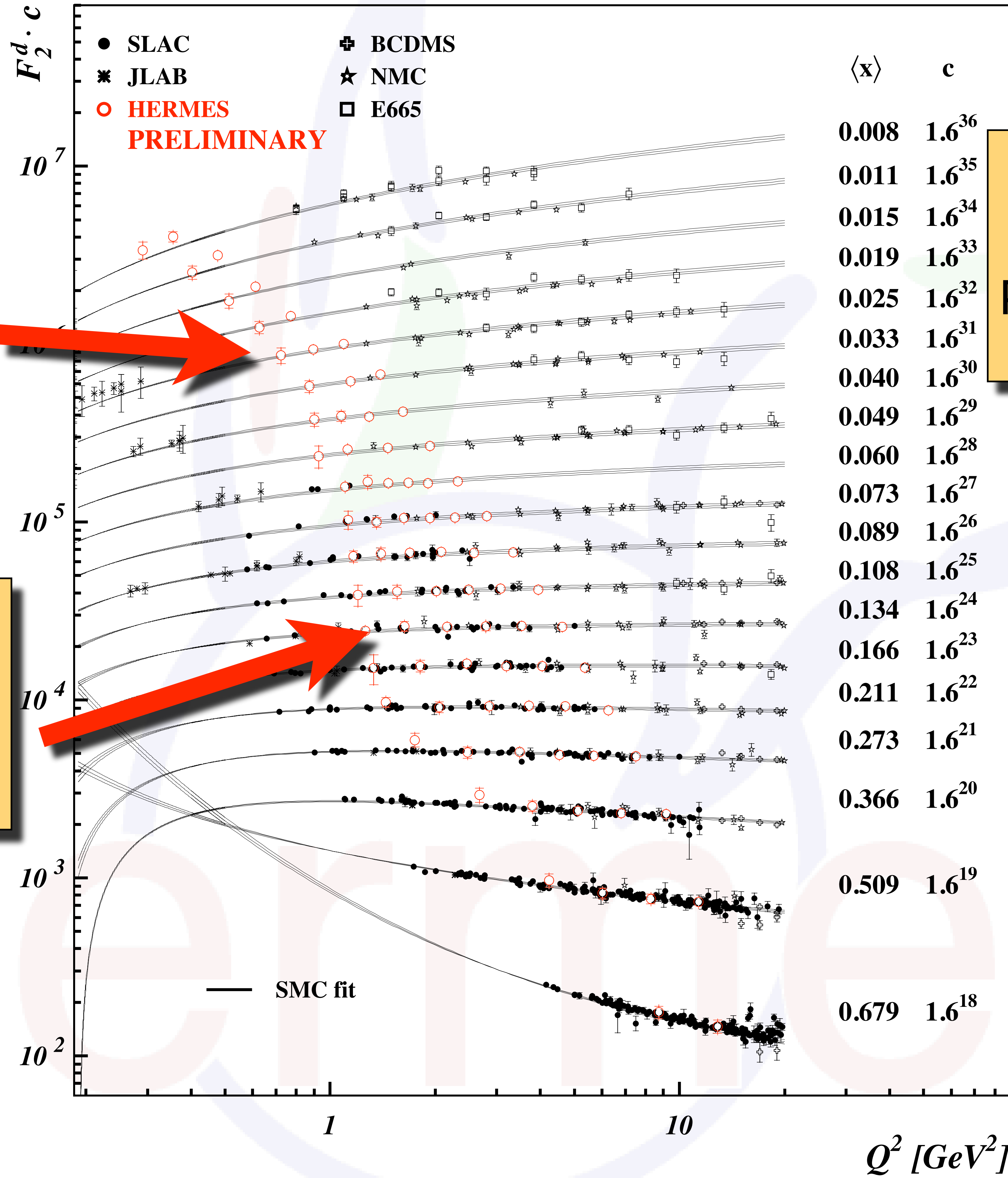
F_2 deuteron

New region covered by HERMES

Agreement with world data in the overlap region



Comparison with parameterization by SMC

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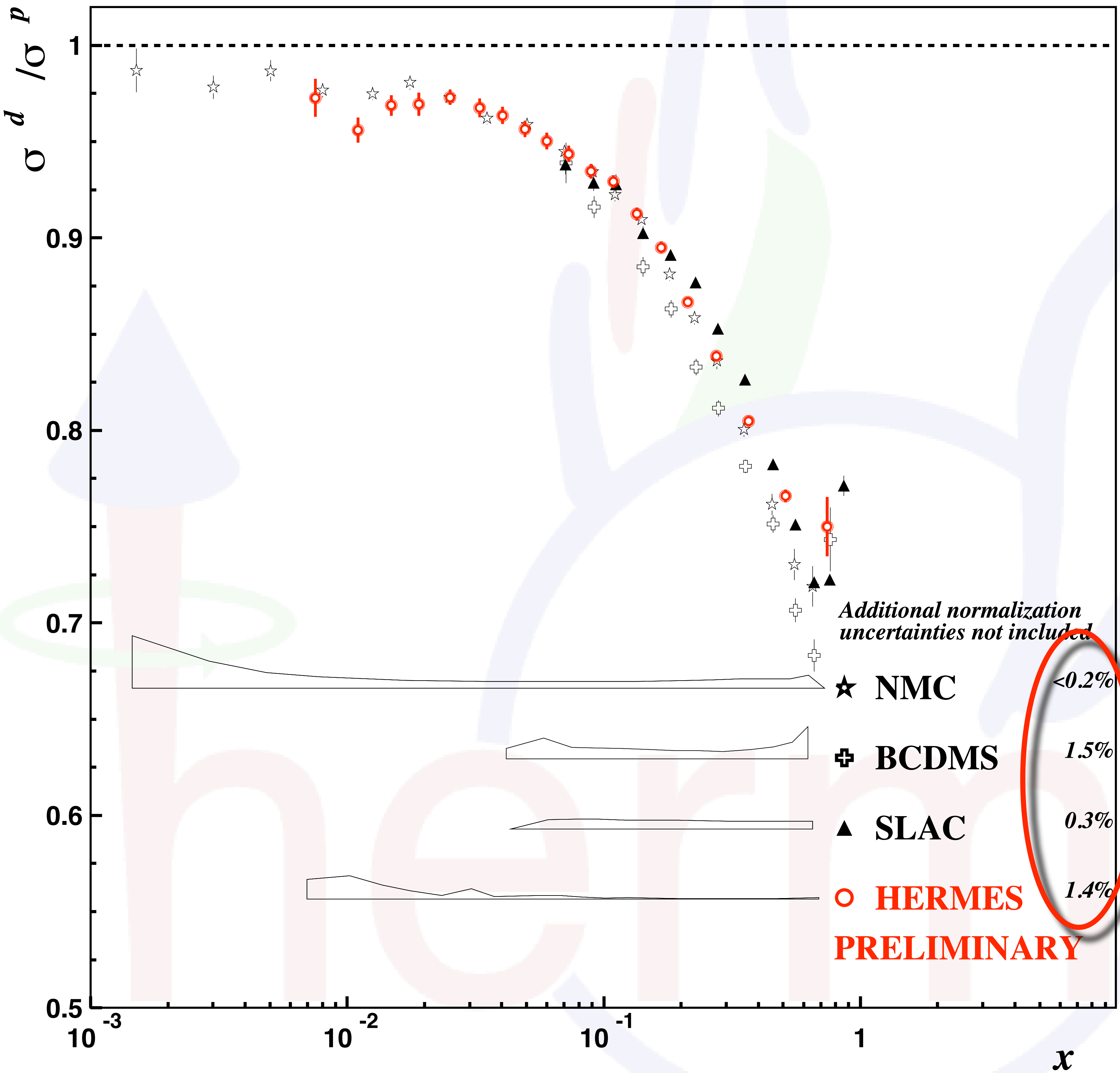
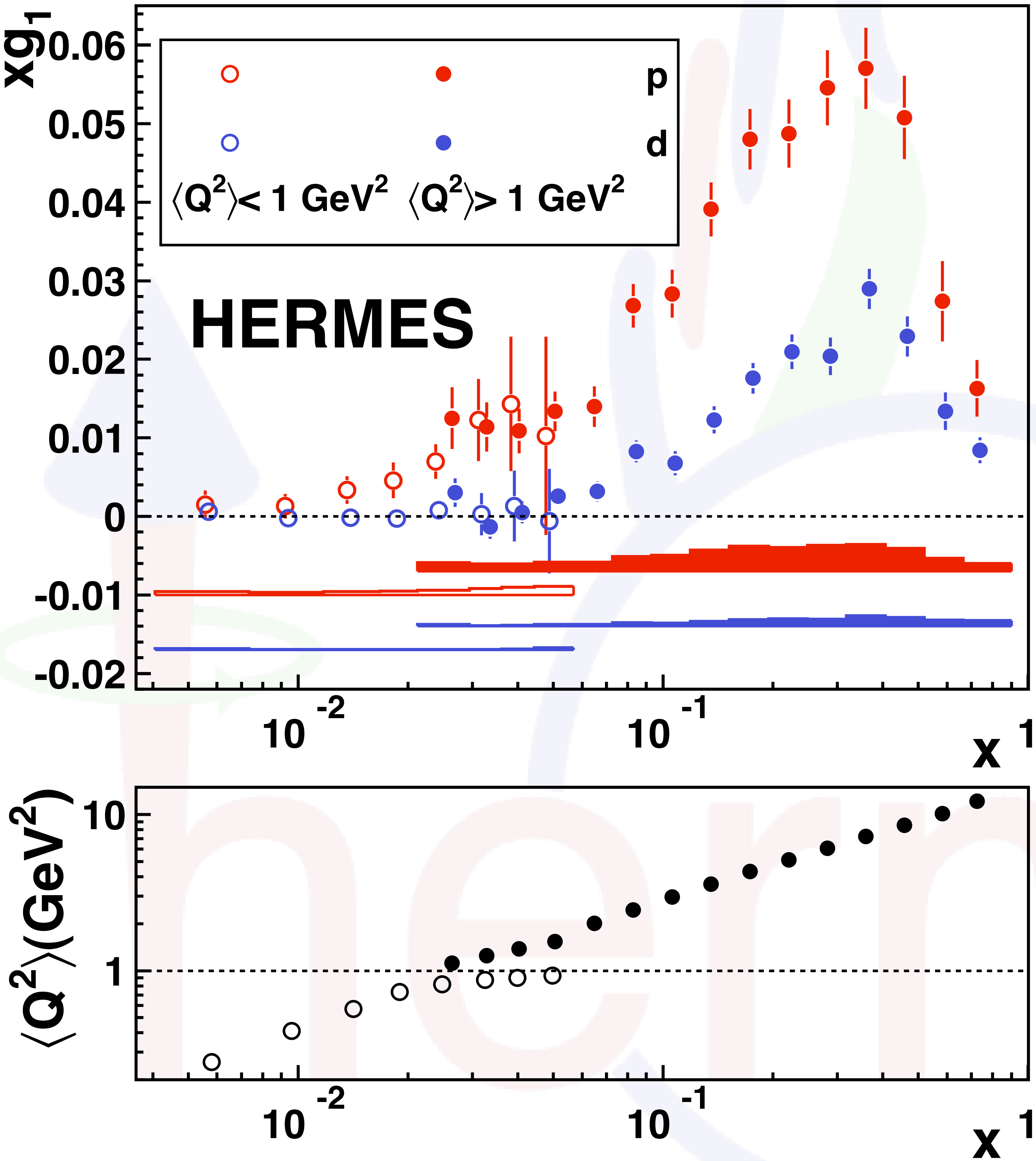
World data on σ^d / σ^p



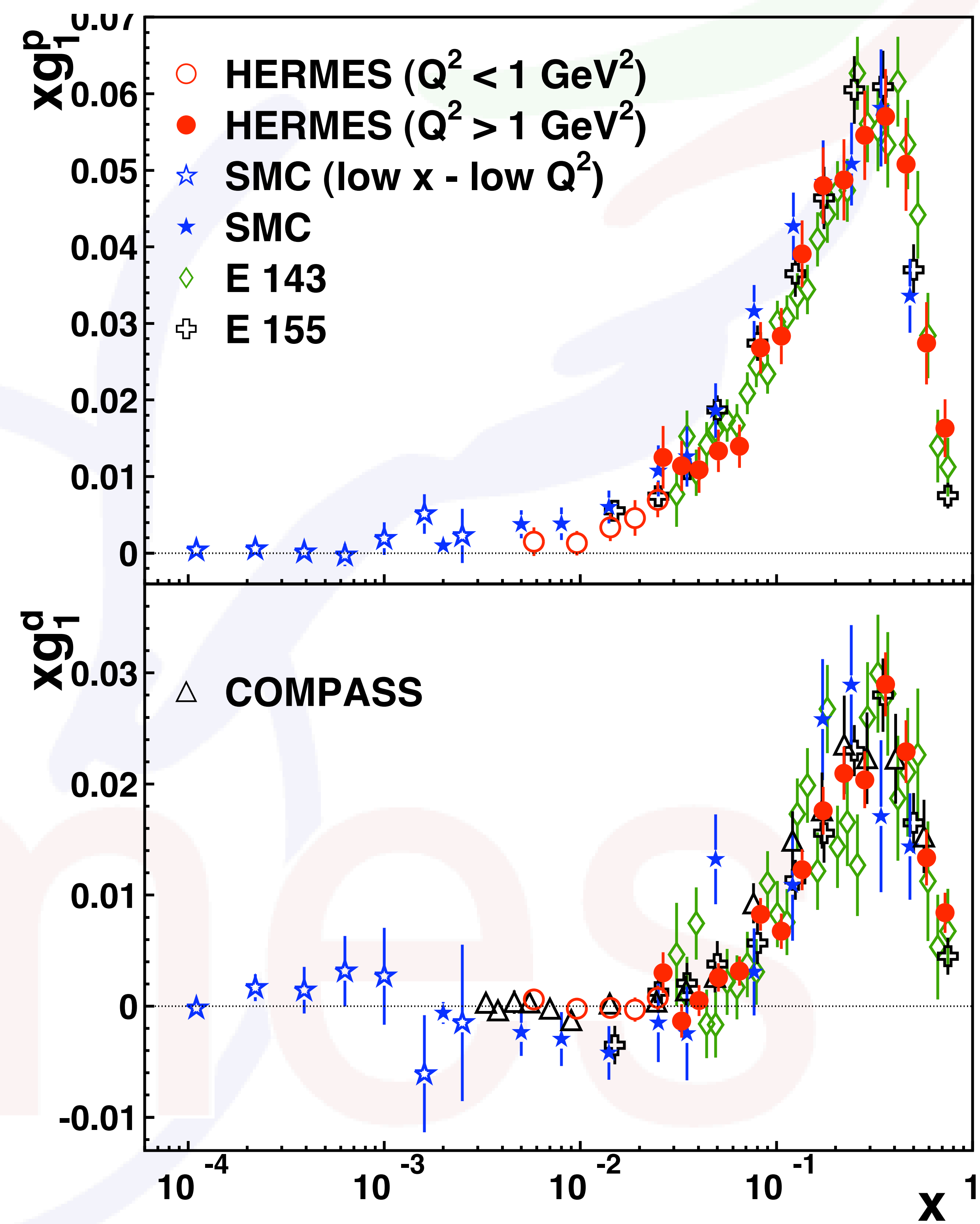
Many systematic errors common to proton and deuteron cross sections cancel in ratio

Normalization uncertainties

Polarized Structure Function g_1



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



Integral of $g_1(x)$

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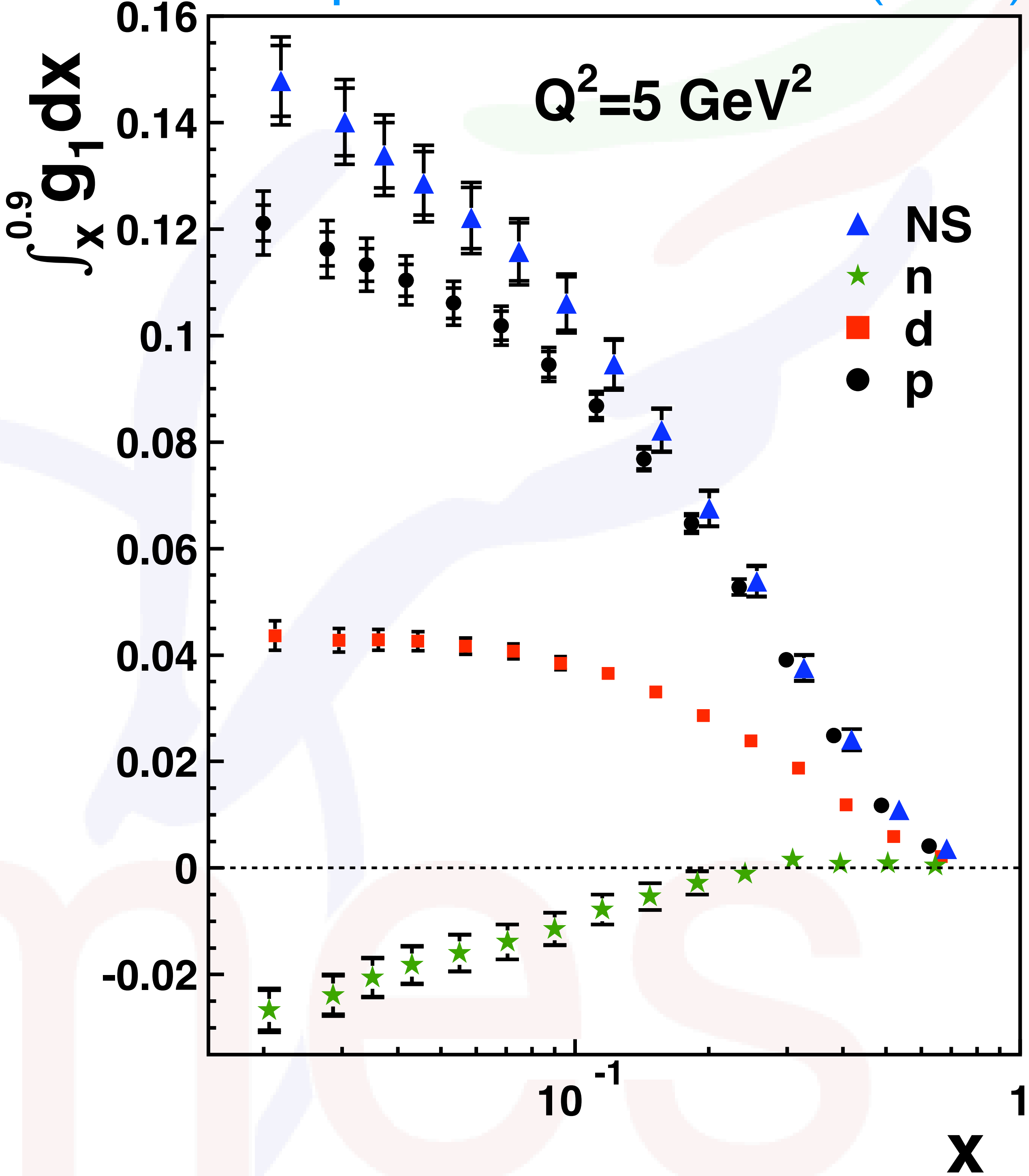


Integral of $g_1(x)$

Saturation

➠ close to full integral?

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

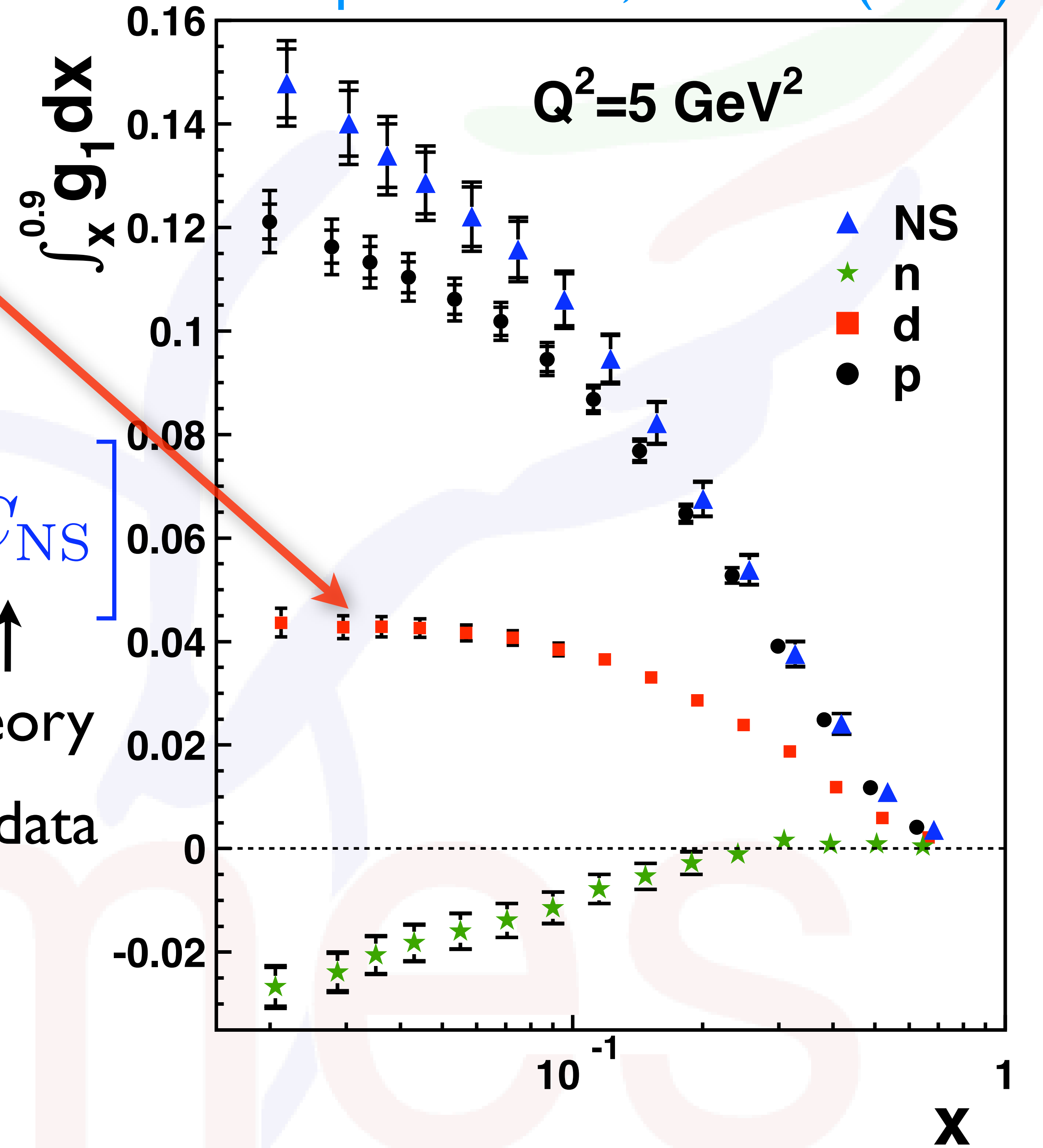
theory

0.05±0.05

hyperon-decay data

theory

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



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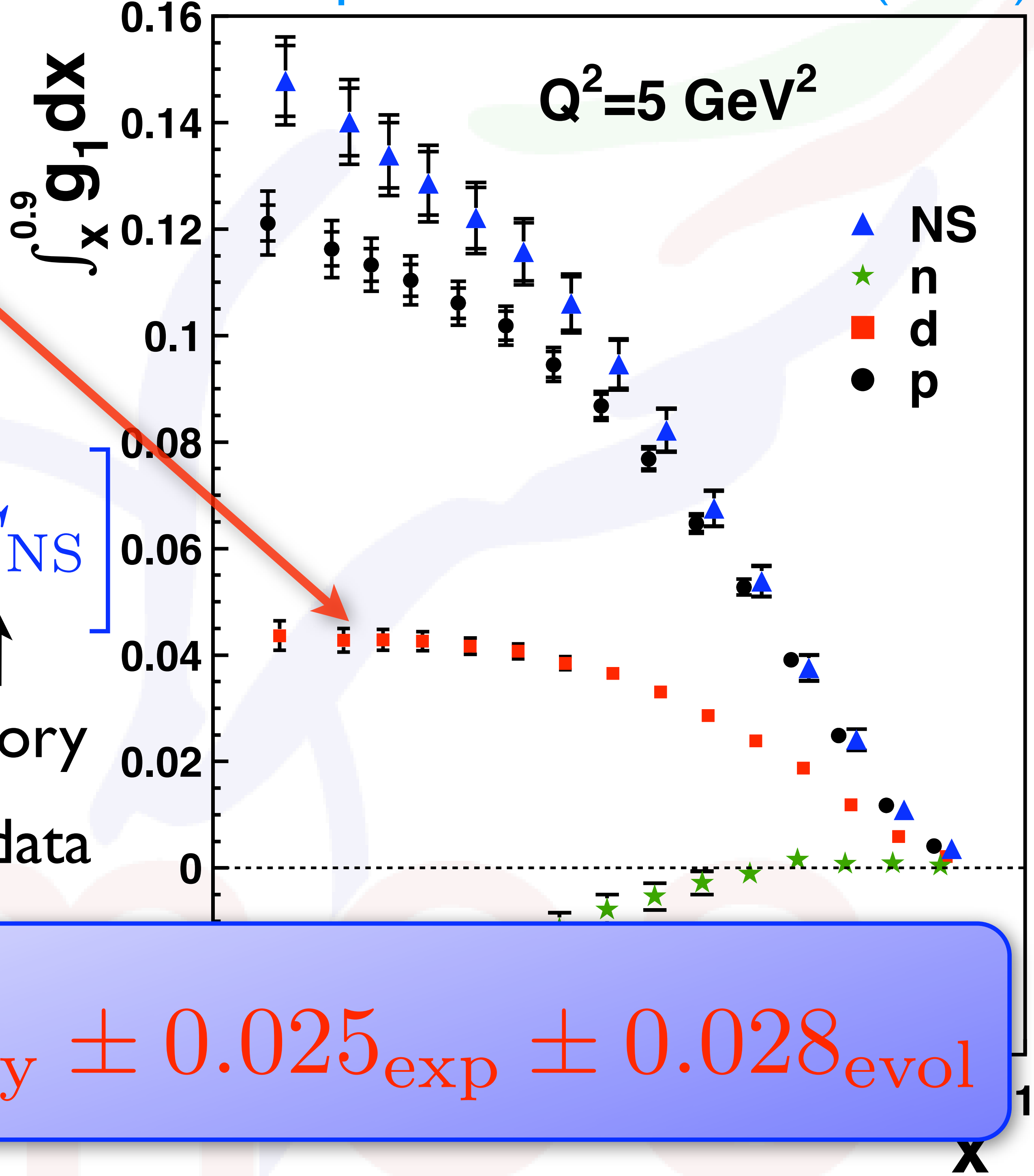

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theory

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

Integral of $g_1(x)$

Saturation

➠ close to full integral?

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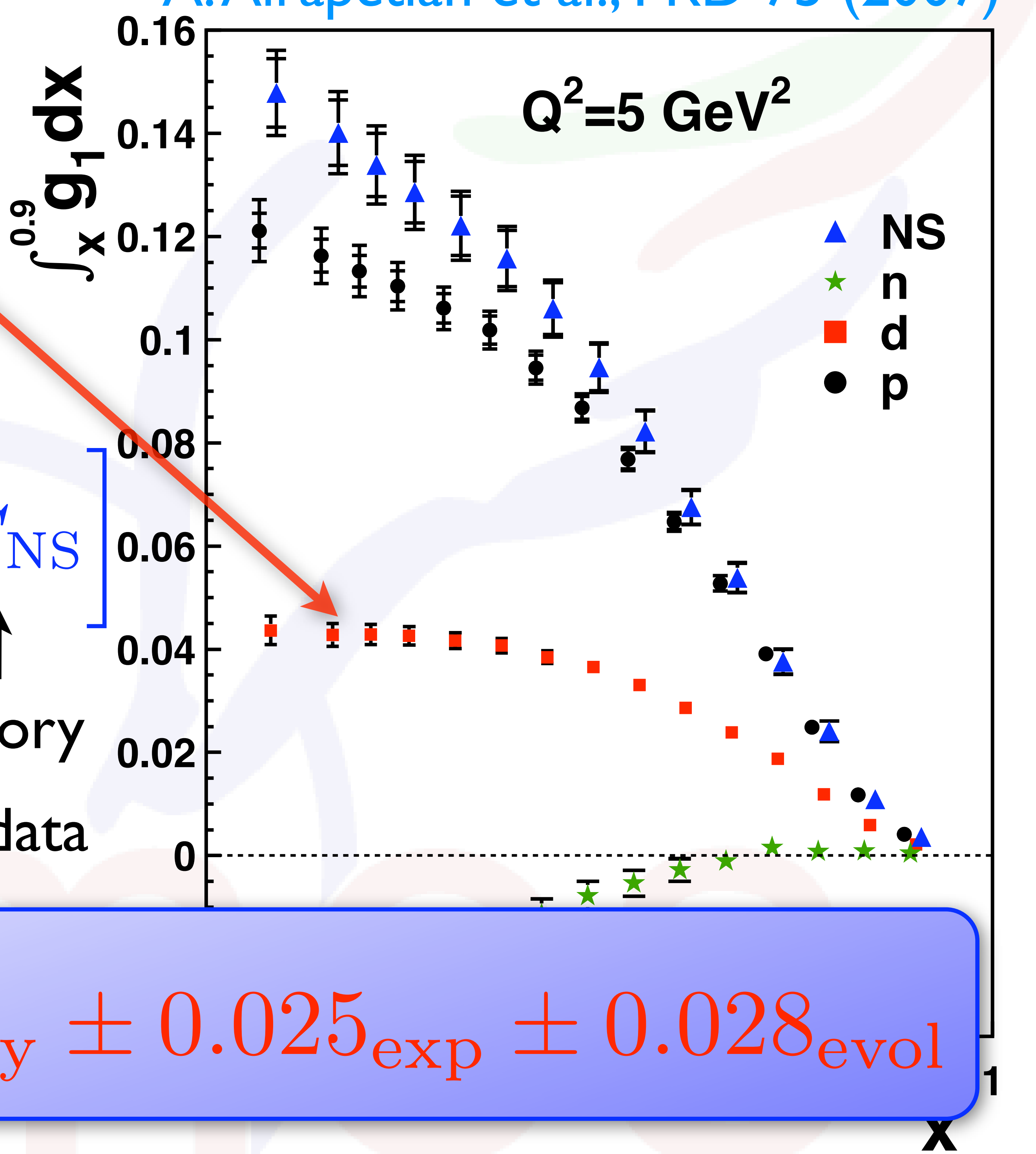
$\Delta C_{\rm S}$: theory; ω_D: 0.05±0.05; a_8: hyperon-decay data; $\Delta C_{\rm NS}$: theory

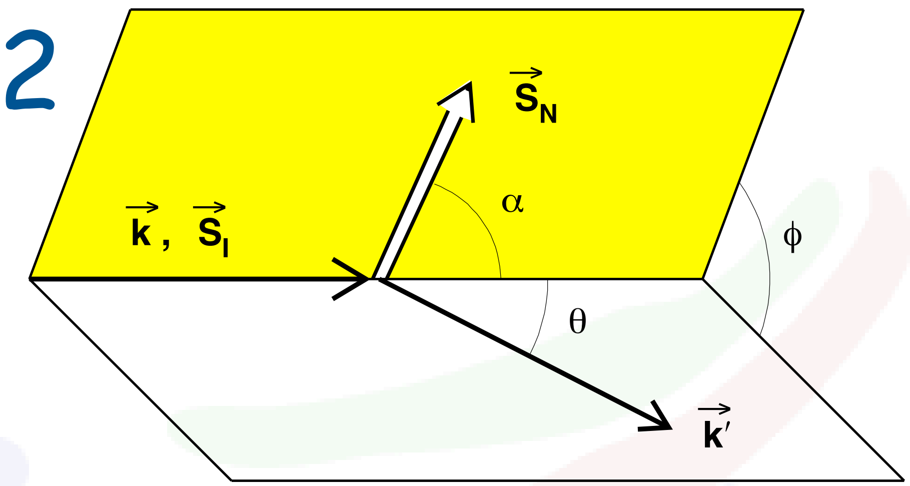
A. Airapetian et al., PRD 75 (2007)



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

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

Extraction of g_2



$$\frac{\sigma^{\rightarrow\Downarrow}(\phi) - \sigma^{\rightarrow\Uparrow}(\phi)}{\sigma^{\rightarrow\Downarrow}(\phi) + \sigma^{\rightarrow\Uparrow}(\phi)} = \frac{\Delta\sigma_T}{\overline{\sigma}} =$$

$$= \underbrace{\frac{-\gamma\sqrt{1-y-\frac{\gamma^2 y^2}{4}}\left(\frac{y}{2}g_1(x,Q^2)+g_2(x,Q^2)\right)}{\left[\frac{y}{2}F_1(x,Q^2)+\frac{1}{2xy}\left(1-y-\frac{\gamma^2y^2}{4}\right)F_2(x,Q^2)\right]}}_{A_T} \cos\phi$$

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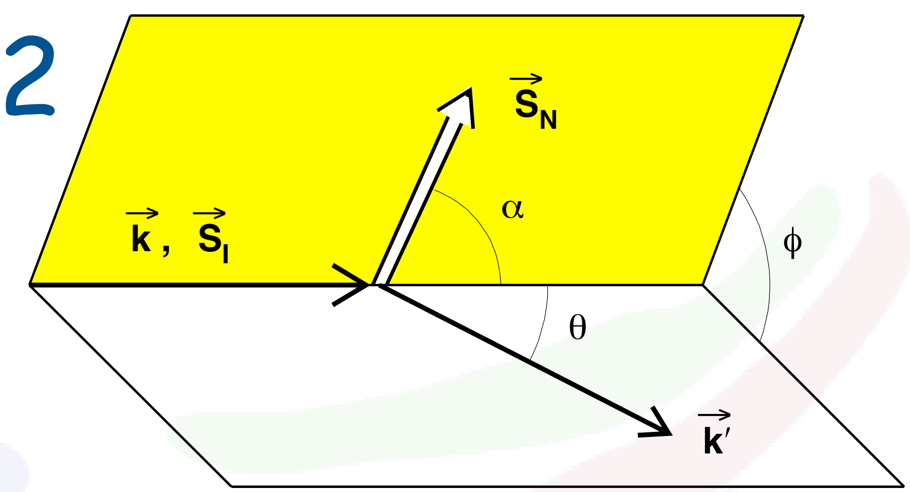

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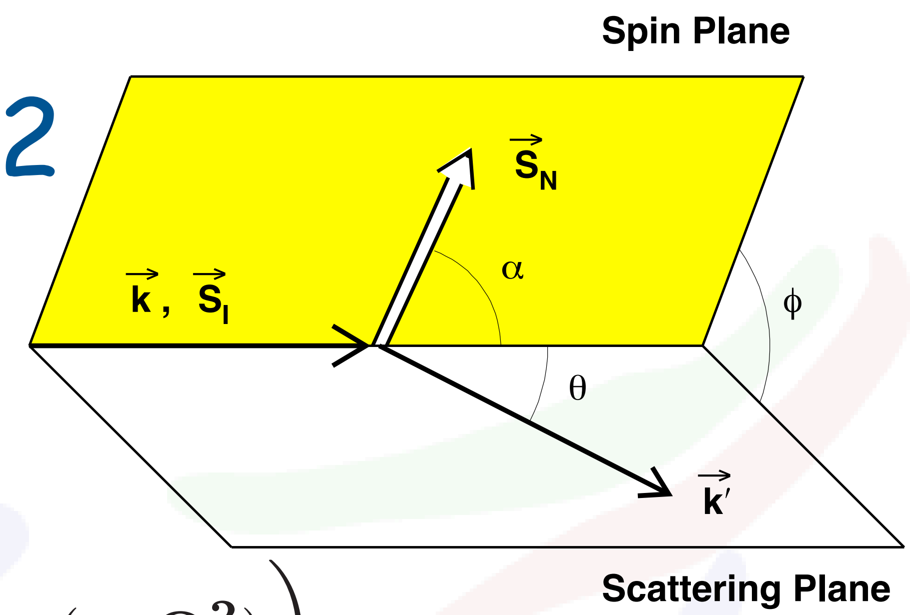
fit to double-spin asymmetry

$$A_2 = \frac{1}{d(1+\gamma\xi)}\, A_T + \frac{\xi(1+\gamma^2)}{1+\gamma\xi}\,\frac{g_1}{F_1}$$

$$g_2 = \frac{F_1}{\gamma d(1+\gamma\xi)}\, A_T - \frac{F_1(\gamma - \xi)}{\gamma(1+\gamma\xi)}\,\frac{g_1}{F_1}$$

Extraction of g_2



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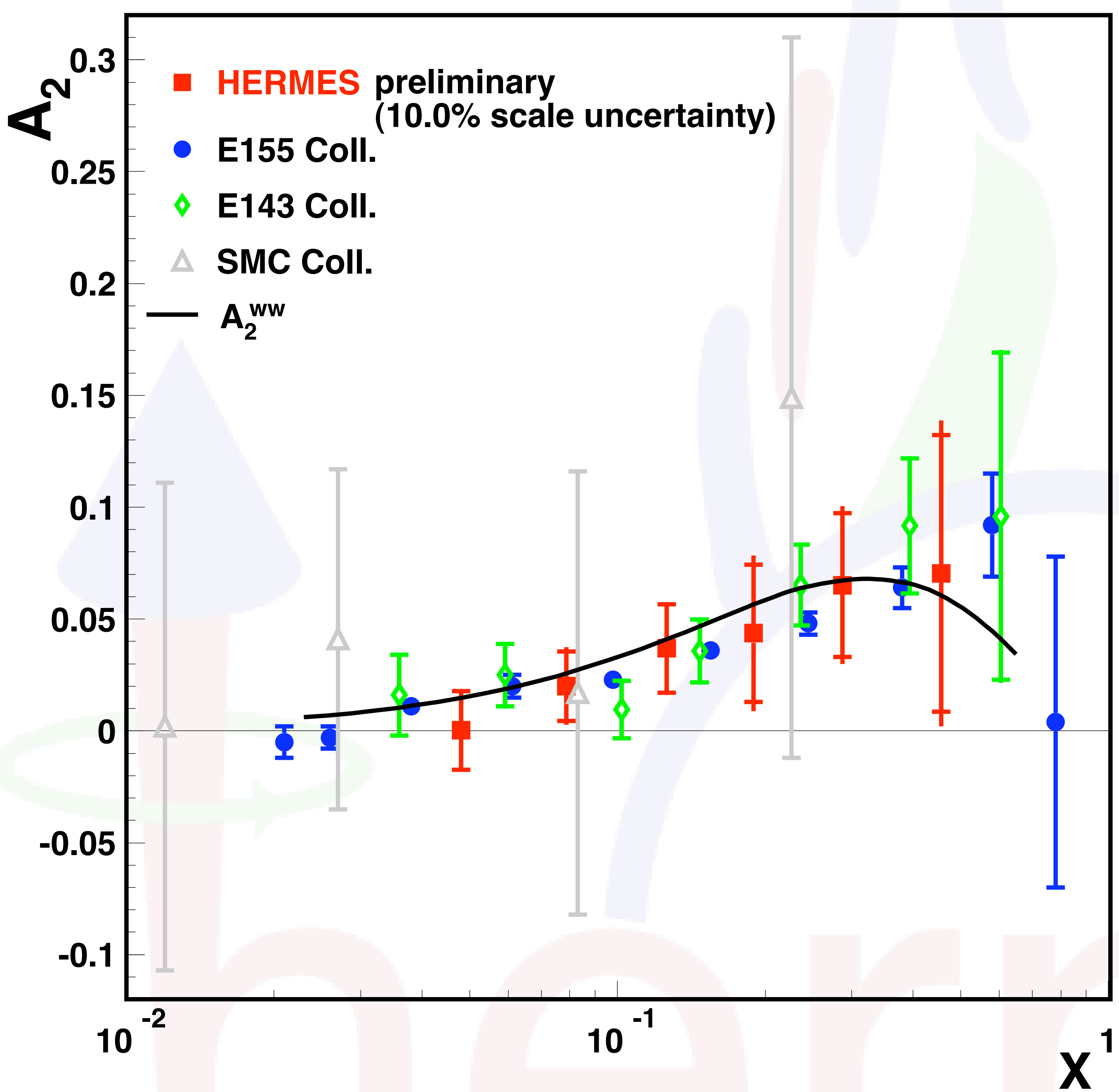
fit to double-spin asymmetry

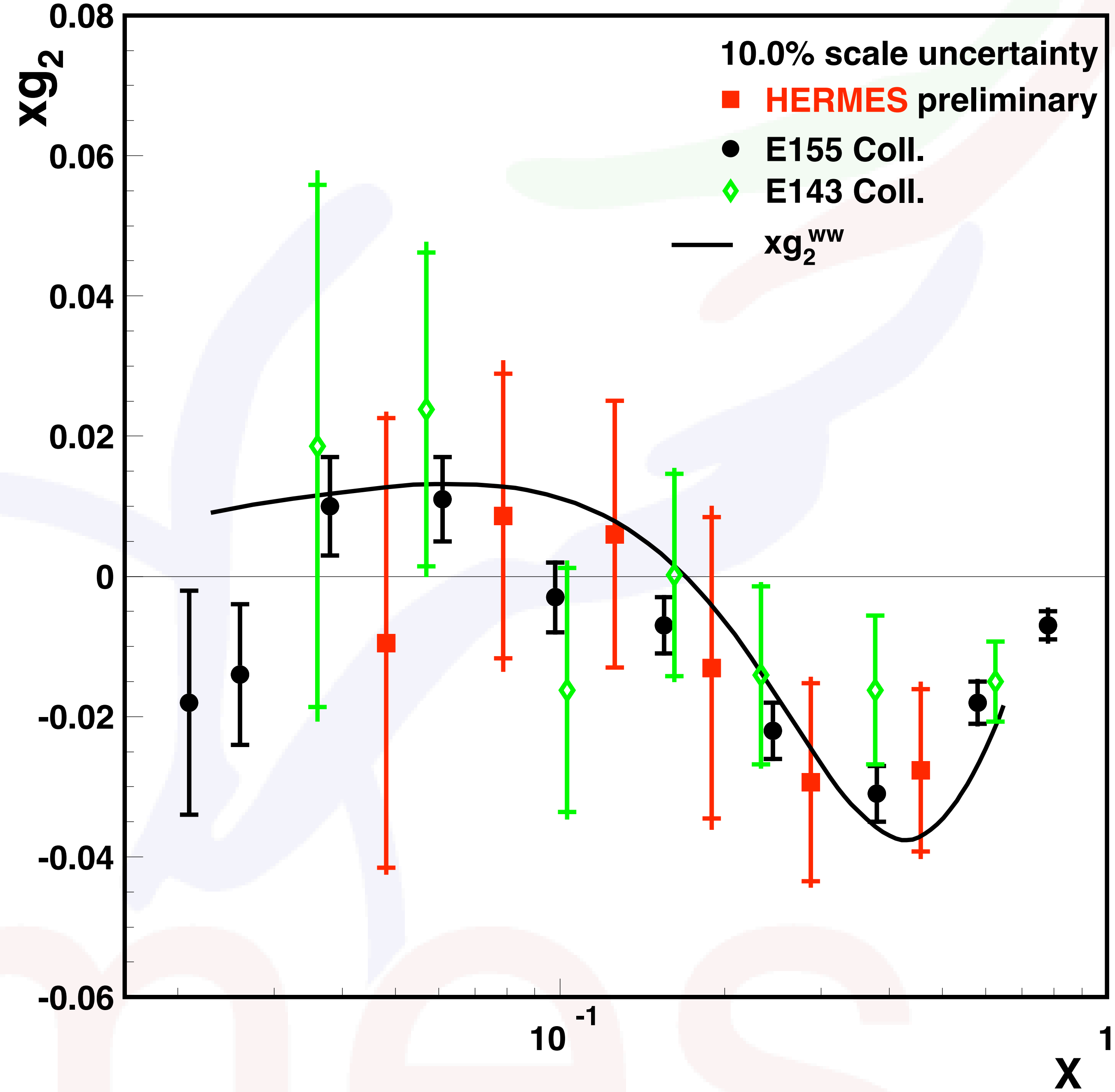
parameterizations

$$A_2 = \frac{1}{d(1+\gamma\xi)}\,A_T + \frac{\xi(1+\gamma^2)}{1+\gamma\xi}\,\frac{g_1}{F_1}$$

$$g_2 = \frac{F_1}{\gamma d(1+\gamma\xi)}\,A_T - \frac{F_1(\gamma - \xi)}{\gamma(1+\gamma\xi)}\,\frac{g_1}{F_1}$$

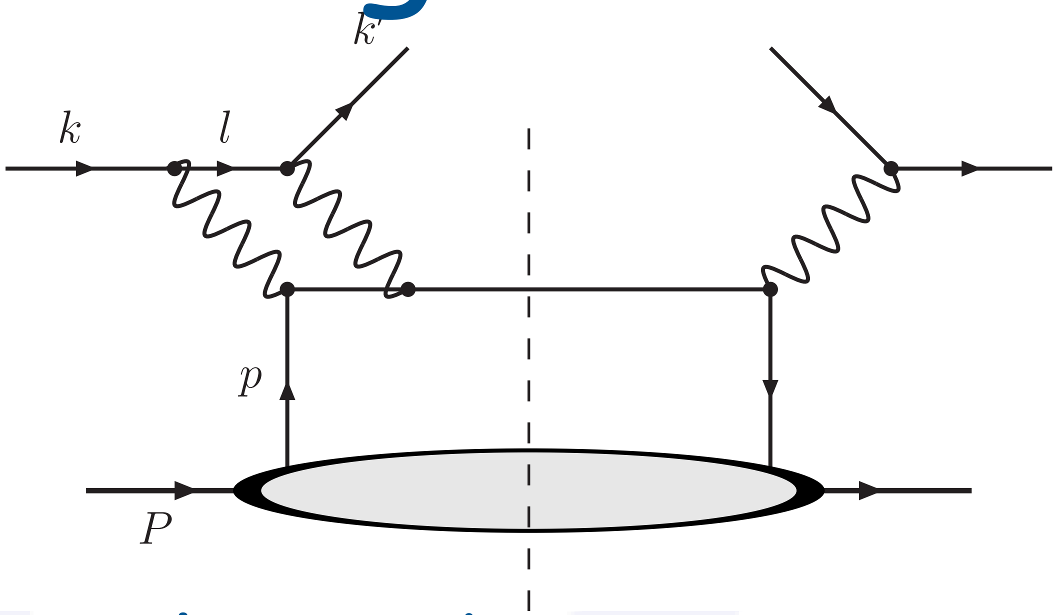
Results on A_2 and xg_2





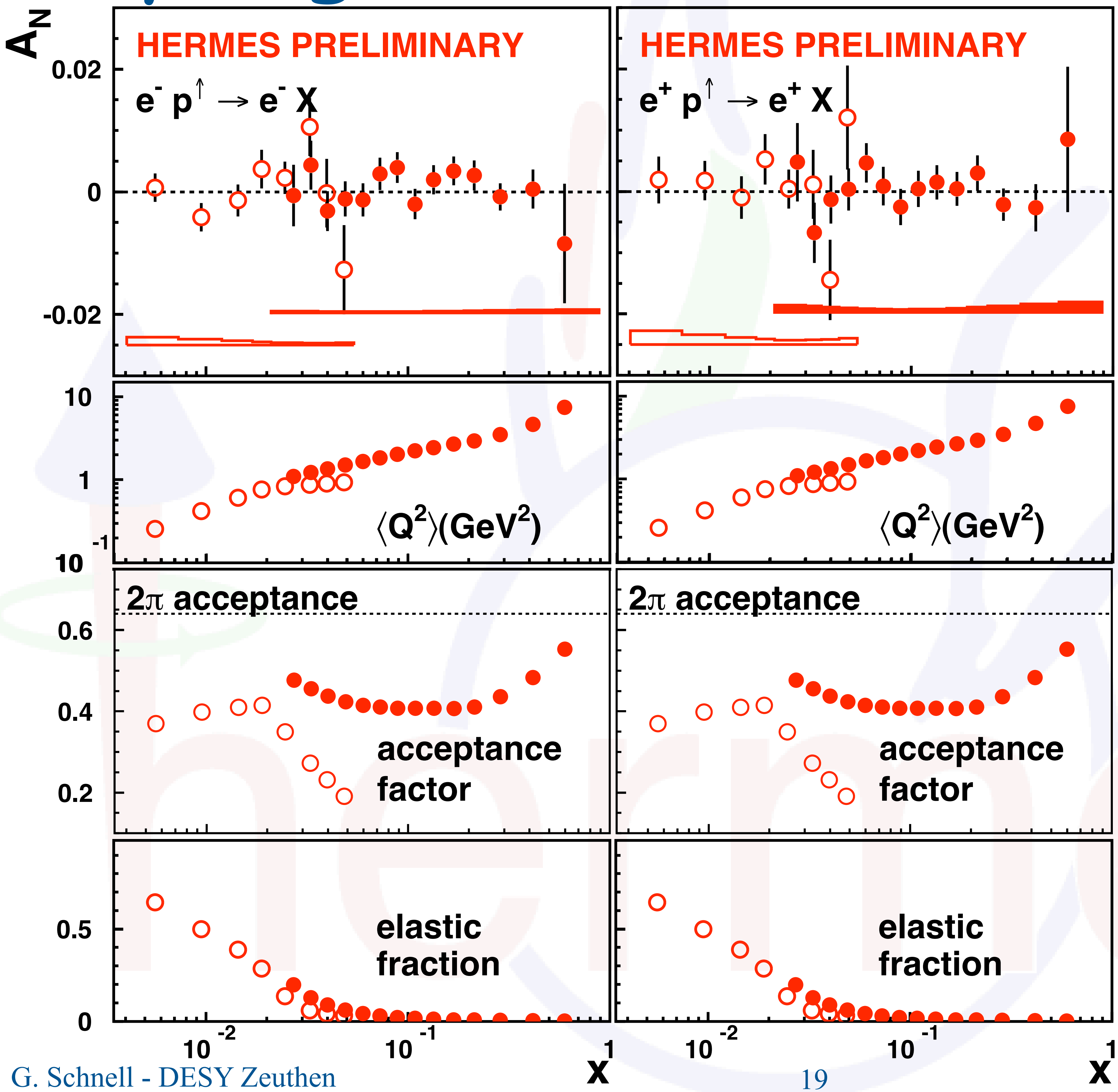
- consistent with (sparse) world data
- low beam polarization during HERA II ➡ small f.o.m.

Two-Photon Exchange



- interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets
- interference sensitive to beam charge due to odd number of e.m. couplings to beam
- proportional to S(kxk') - either measure left-right asymmetries or sine modulation
- two-photon exchange best candidate to explain discrepancy in form-factor measurements

Any Sign of Two-Photon Exchange?



consistent with zero at 10^{-3} level

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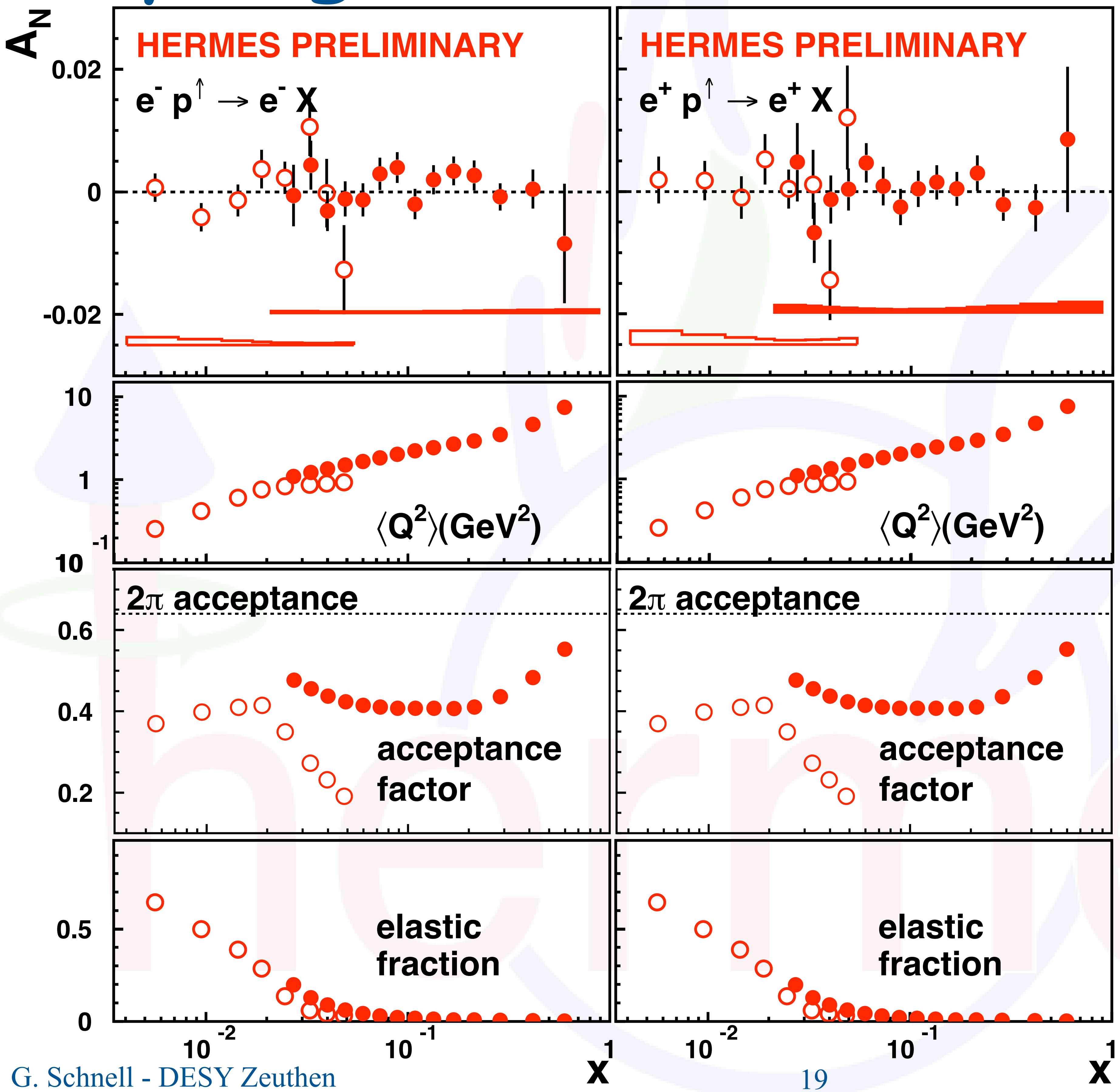

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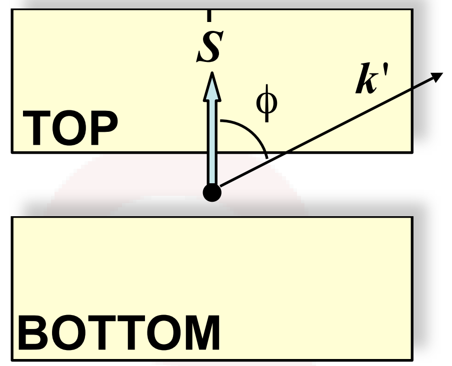
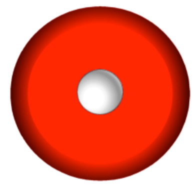


$$\mathrm{acc.fac.} \equiv \frac{(A_N)_{acc}}{(A_{UT}^{\sin\phi})_{2\pi}}$$

Semi-Inclusive DIS

Quark Structure of the Nucleon

(integrated over transverse momentum)

$f_1^q =$ 

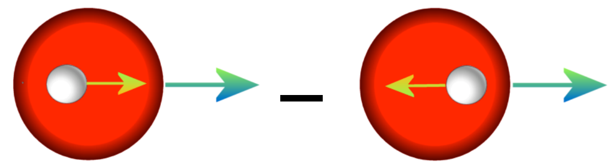
$\Downarrow$

Unpolarized quarks and nucleons

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

$\Rightarrow$ Vector Charge

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

$g_1^q =$ 

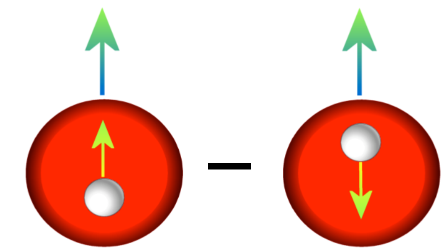
$\Downarrow$

Longitudinally polarized quarks and nucleons

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

$\Rightarrow$ Axial Charge

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

$h_1^q =$ 

$\Downarrow$

Transversely polarized quarks and nucleons

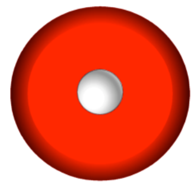
$h_1^q(x)$: transversity (hardly known!)

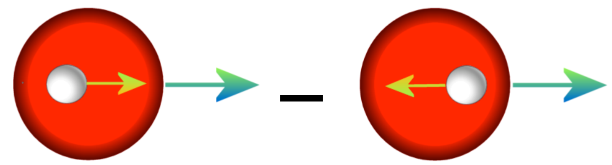
$\Rightarrow$ Tensor Charge

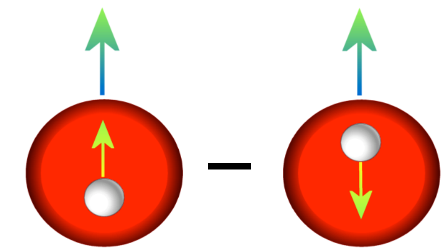
$\langle PS|\bar{\Psi}\sigma^{\mu\nu}\gamma_5\Psi|PS\rangle = \int dx (h_1^q(x) - h_1^{\bar{q}}(x))$

Quark Structure of the Nucleon

(integrated over transverse momentum)

f_1^q = 

g_1^q = 

h_1^q = 

$\Downarrow$ Unpolarized quarks and nucleons

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

$\Rightarrow$ Vector Charge

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

$\Downarrow$ Longitudinally polarized quarks and nucleons

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Chiral-odd!

Strange-quark distributions

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

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

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

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

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

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

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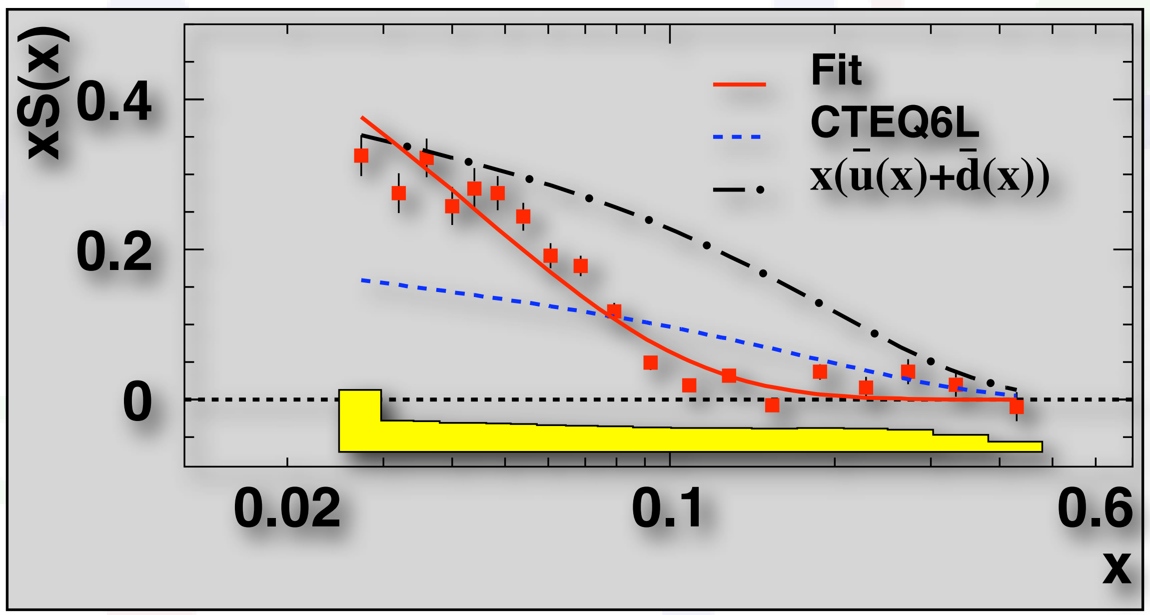

A. Airapetian et al., PLB 666, 446 (2008)

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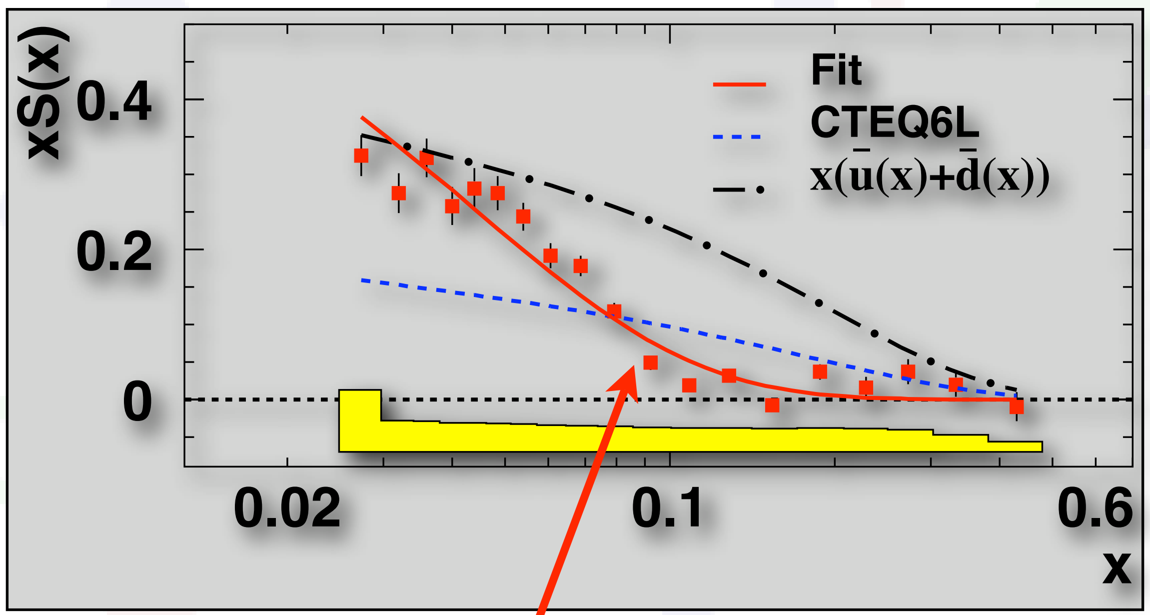

Strange-quark distribution softer than (maybe) expected

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

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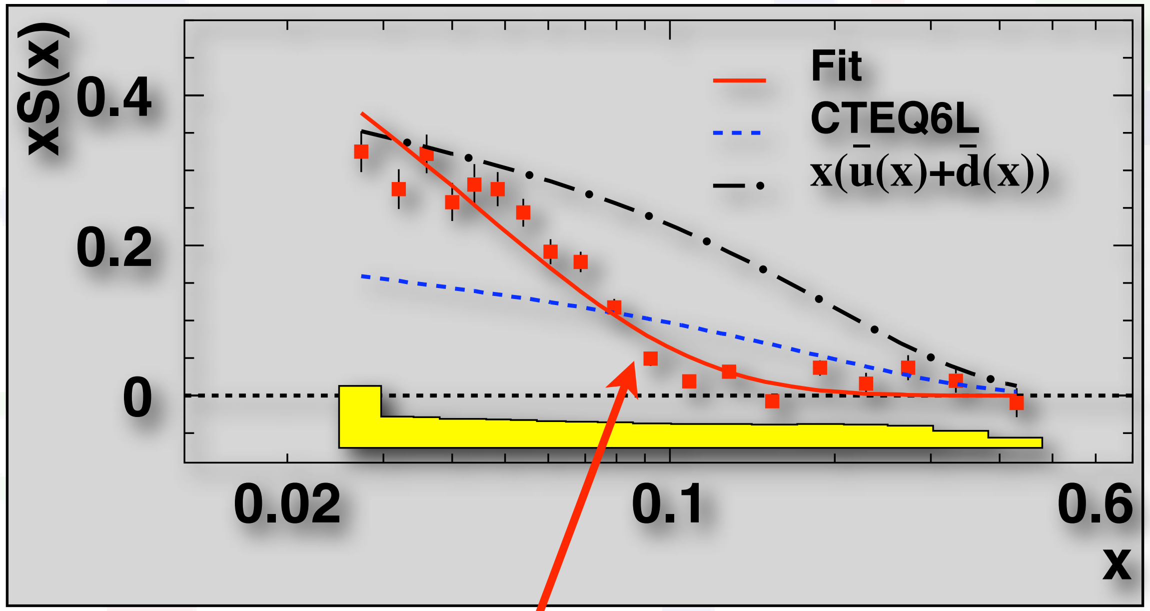

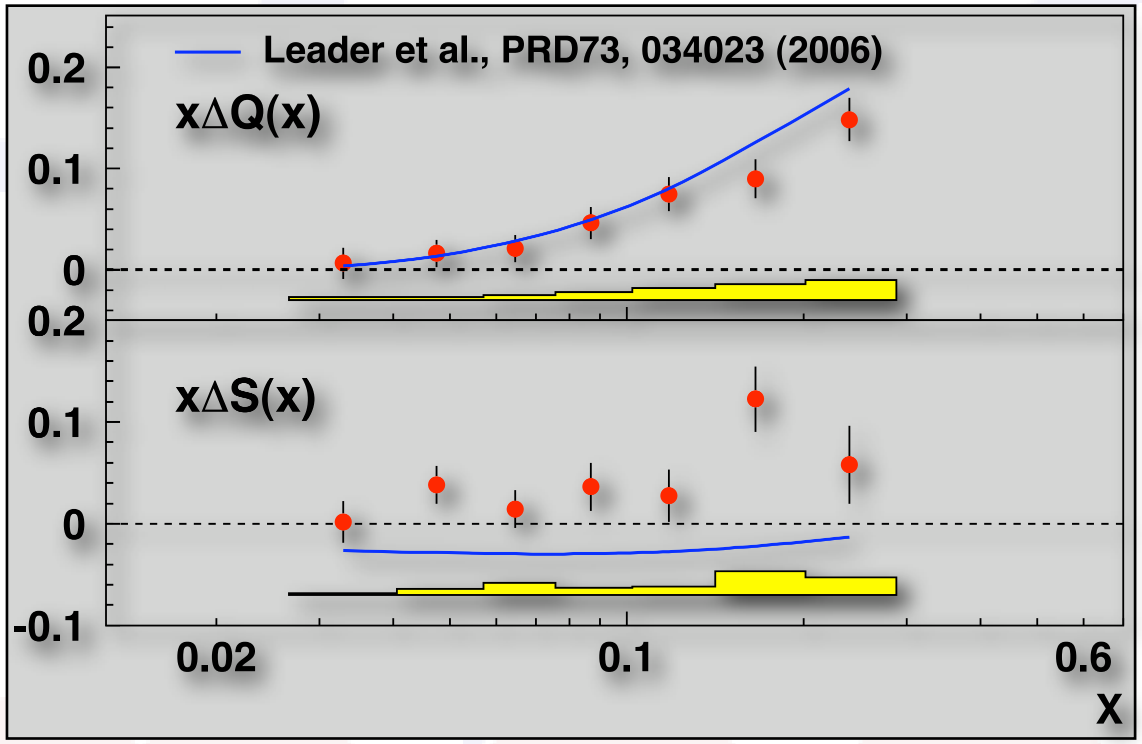

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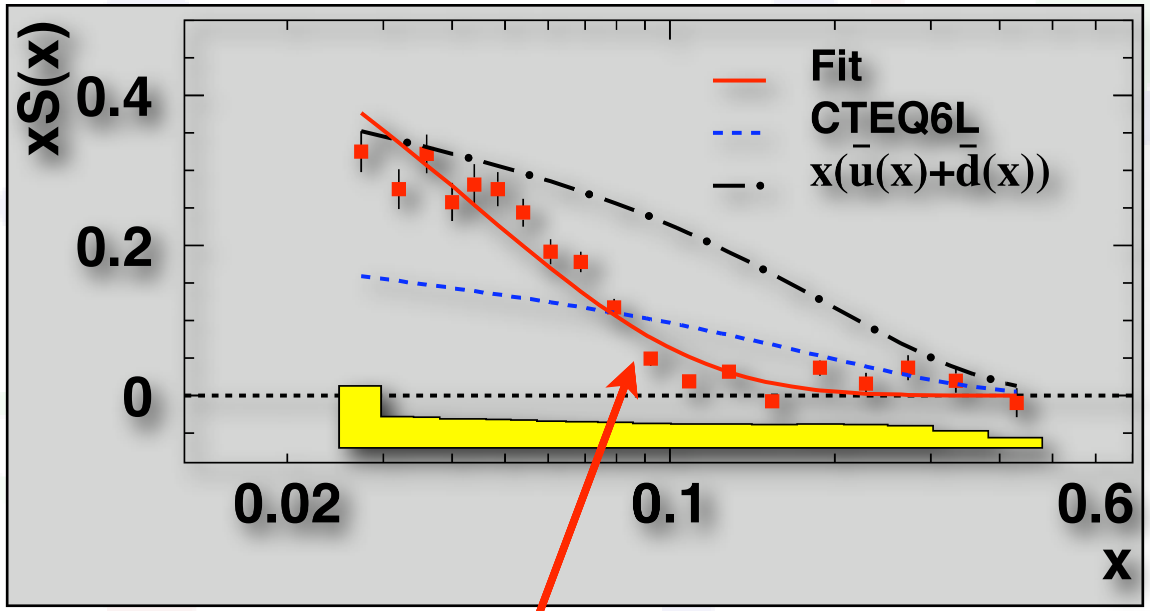
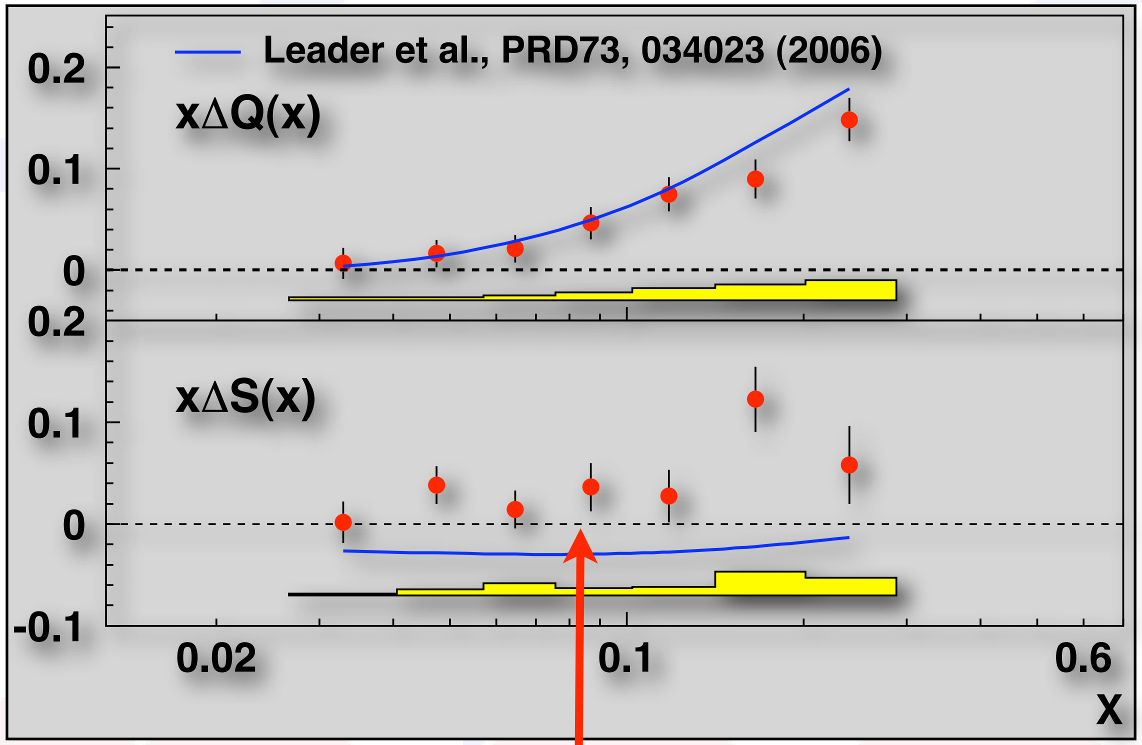




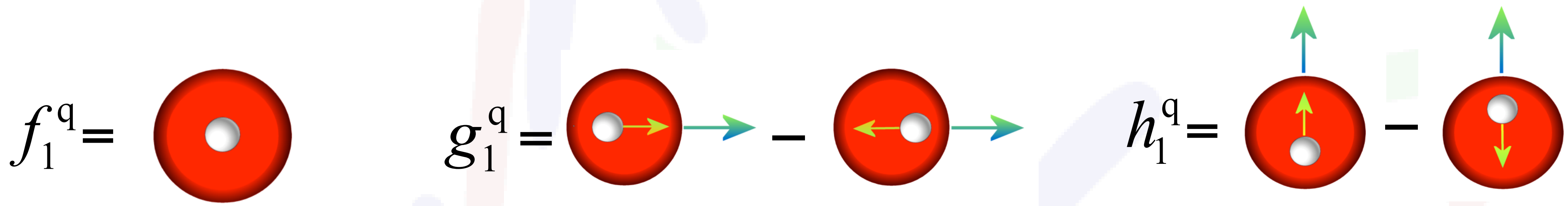
Strange-quark distribution softer than (maybe) expected

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

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

The "Trouble" with Transversity

chiral-odd transversity involves quark helicity flip



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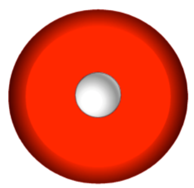
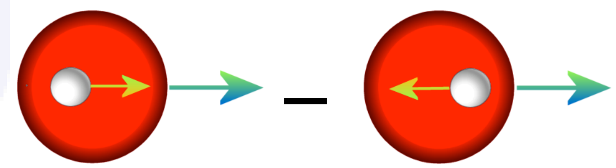
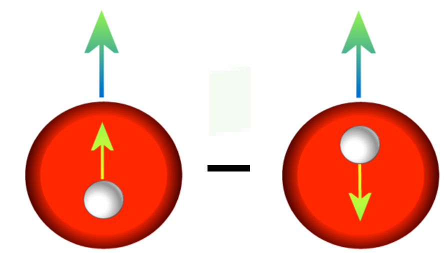
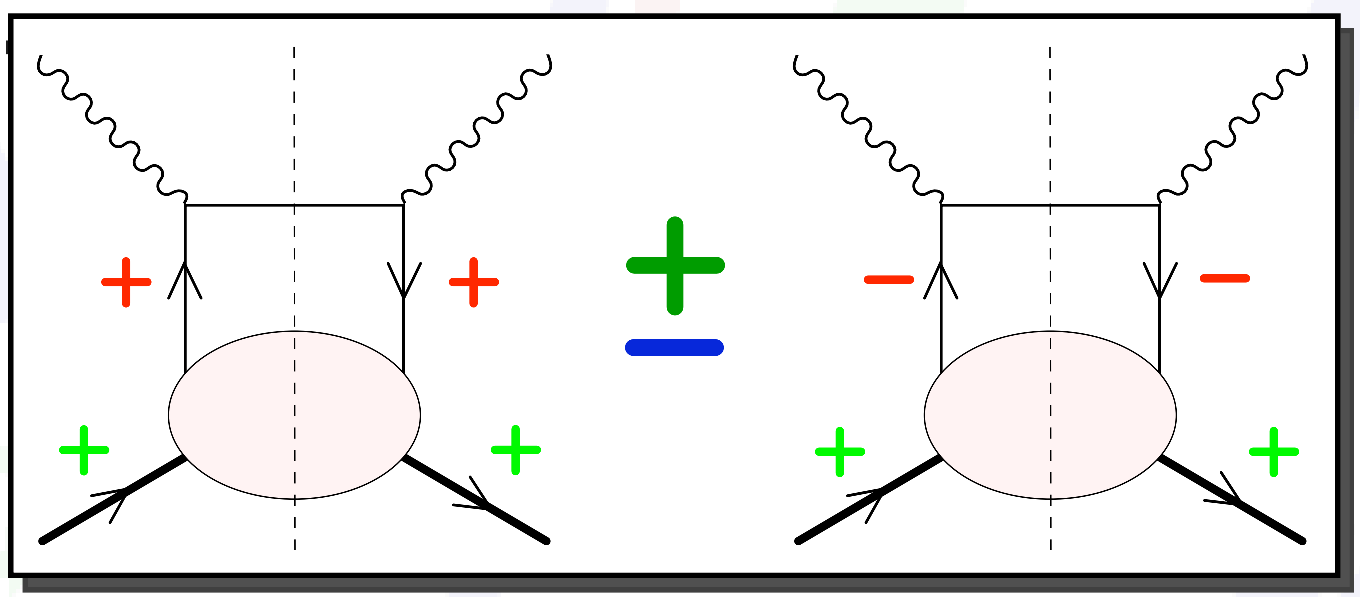
$f_1^q =$ 

$g_1^q =$ 

$h_1^q =$ 



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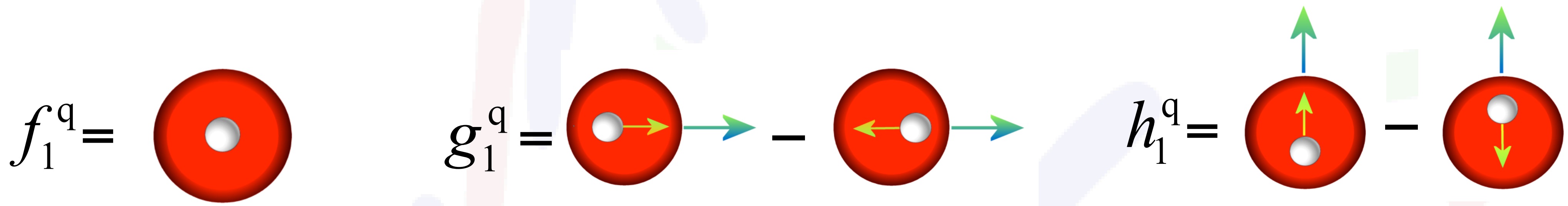

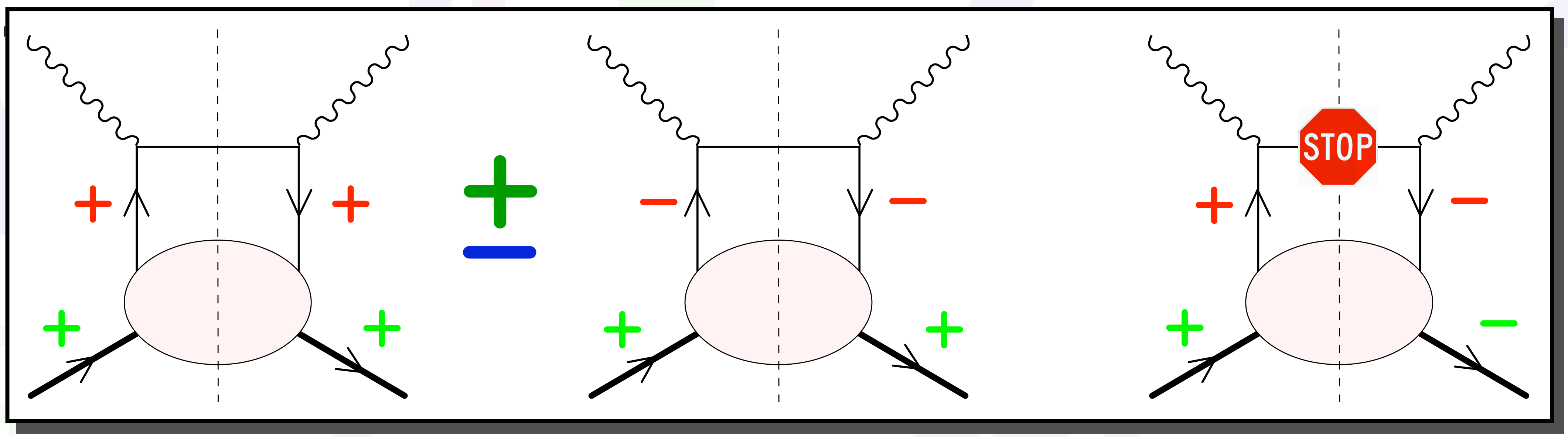

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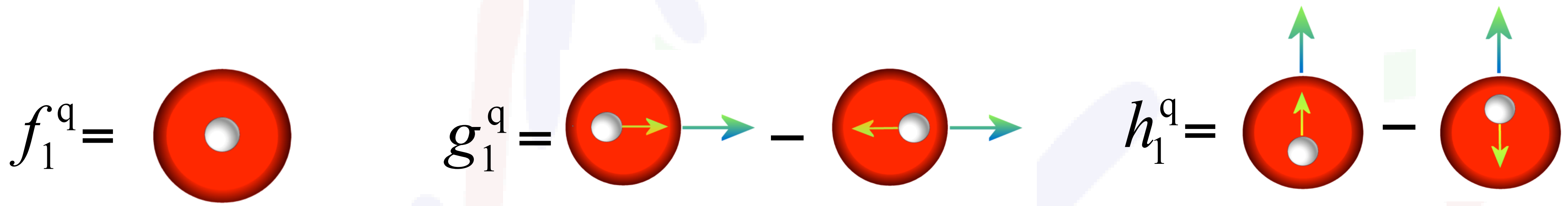

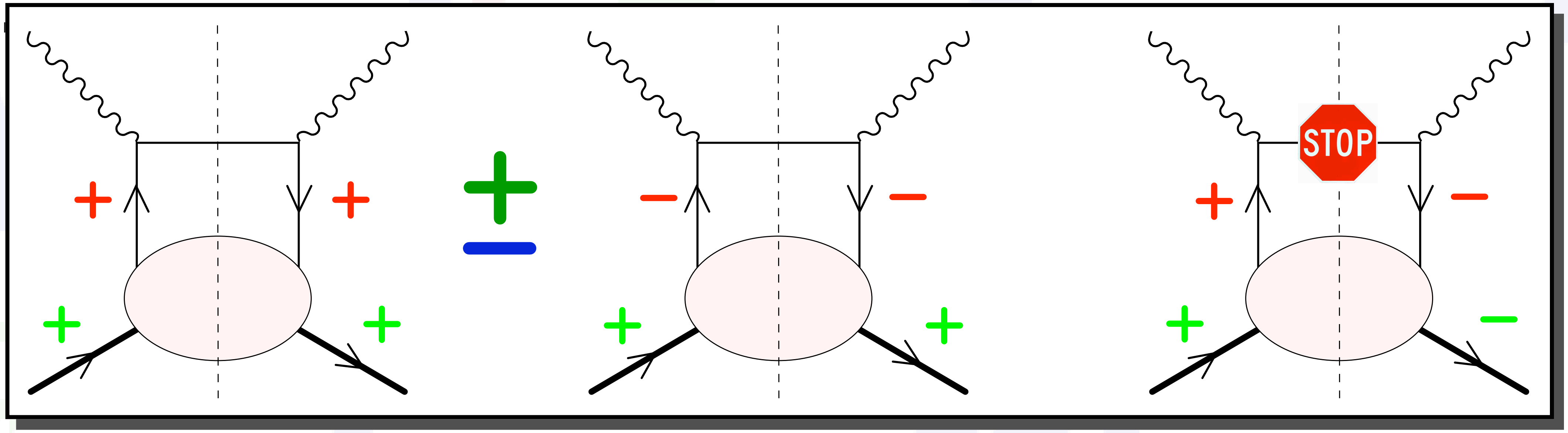

need to couple to chiral-odd fragmentation function:

The "Trouble" with Transversity

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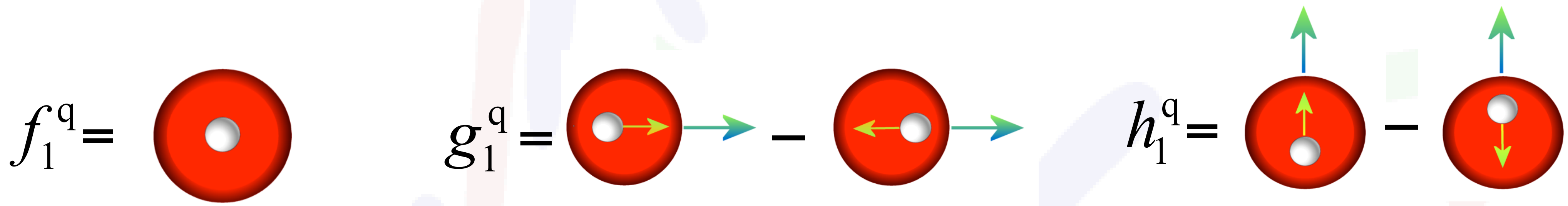

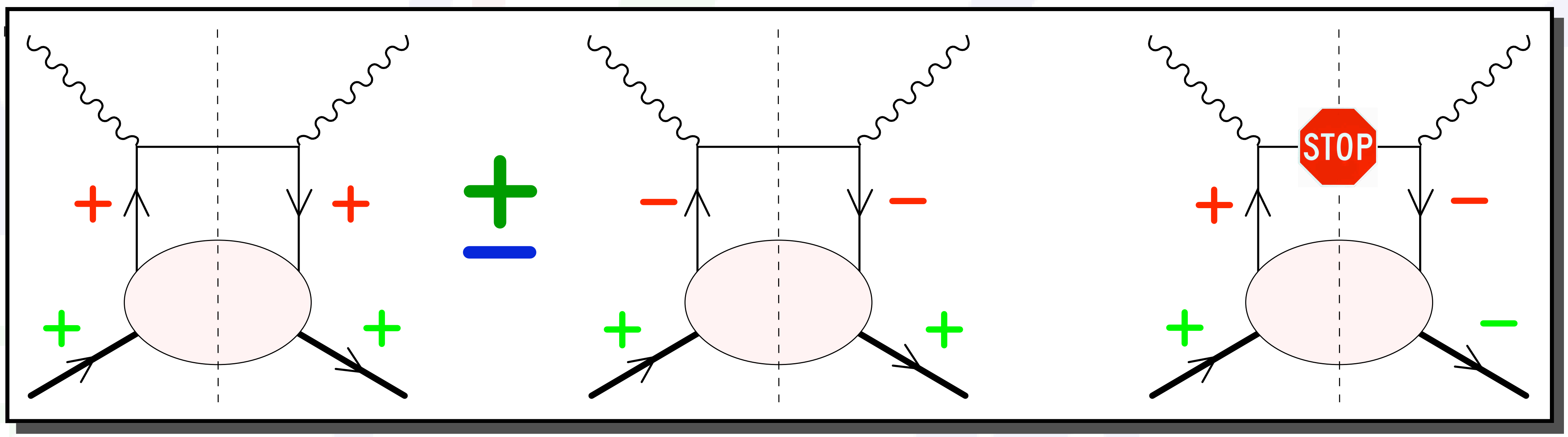

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- transverse spin transfer (polarized final-state hadron)

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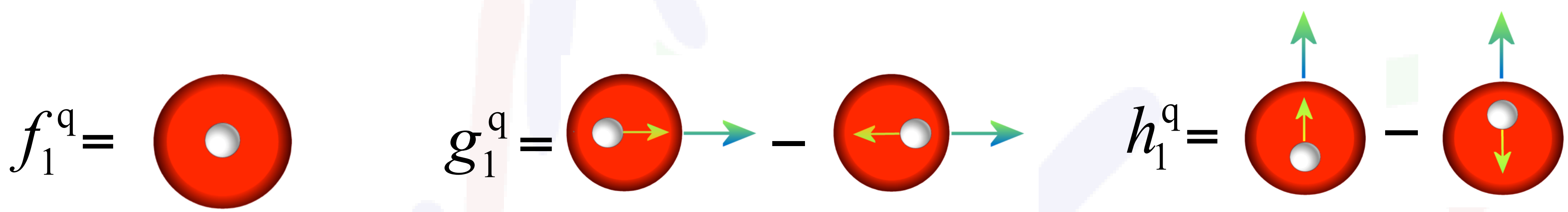

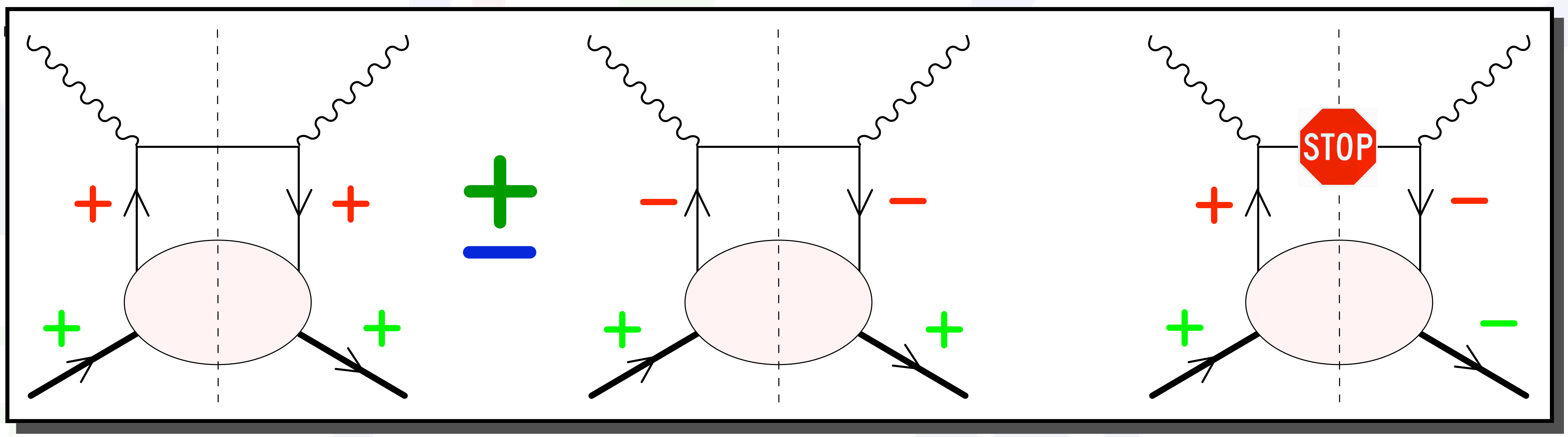

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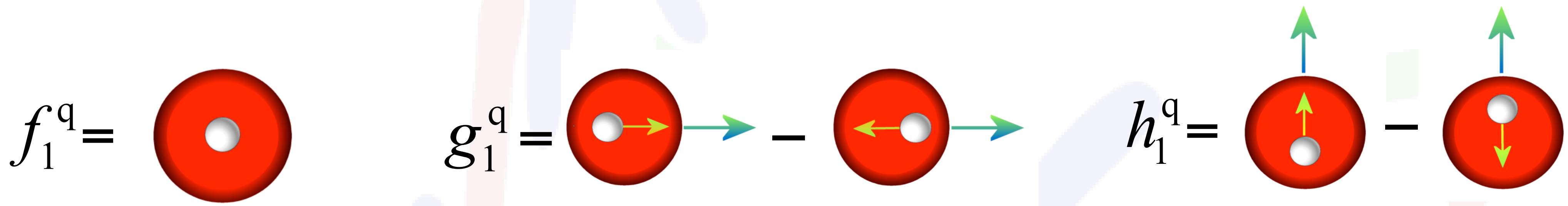
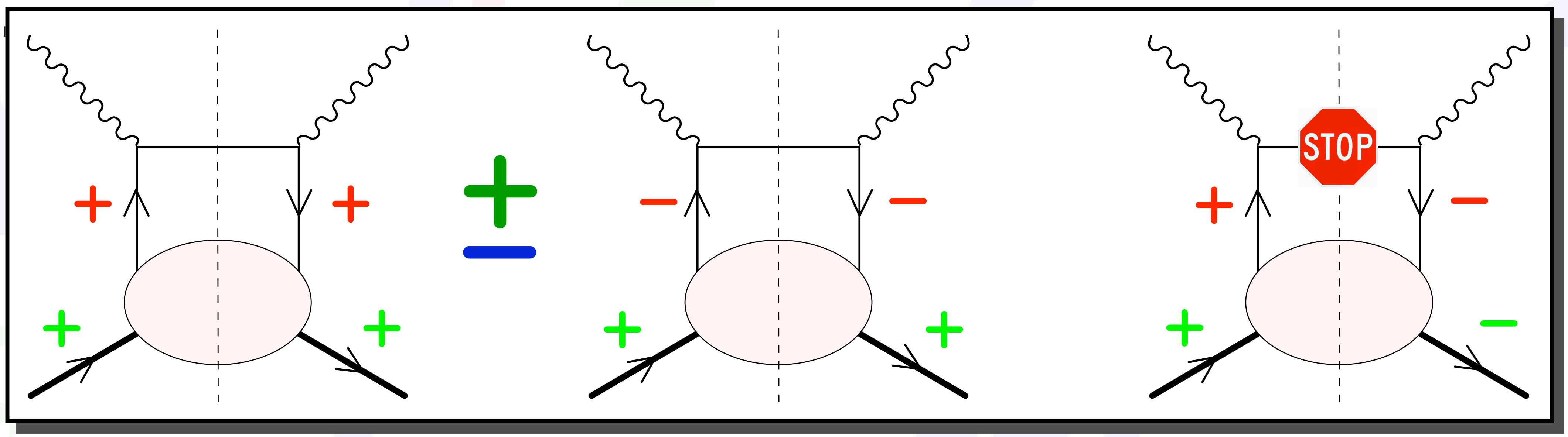




need to couple to chiral-odd fragmentation function:

- transverse spin transfer (polarized final-state hadron)
- **2-hadron fragmentation**
- **Collins fragmentation**

2-hadron fragmentation

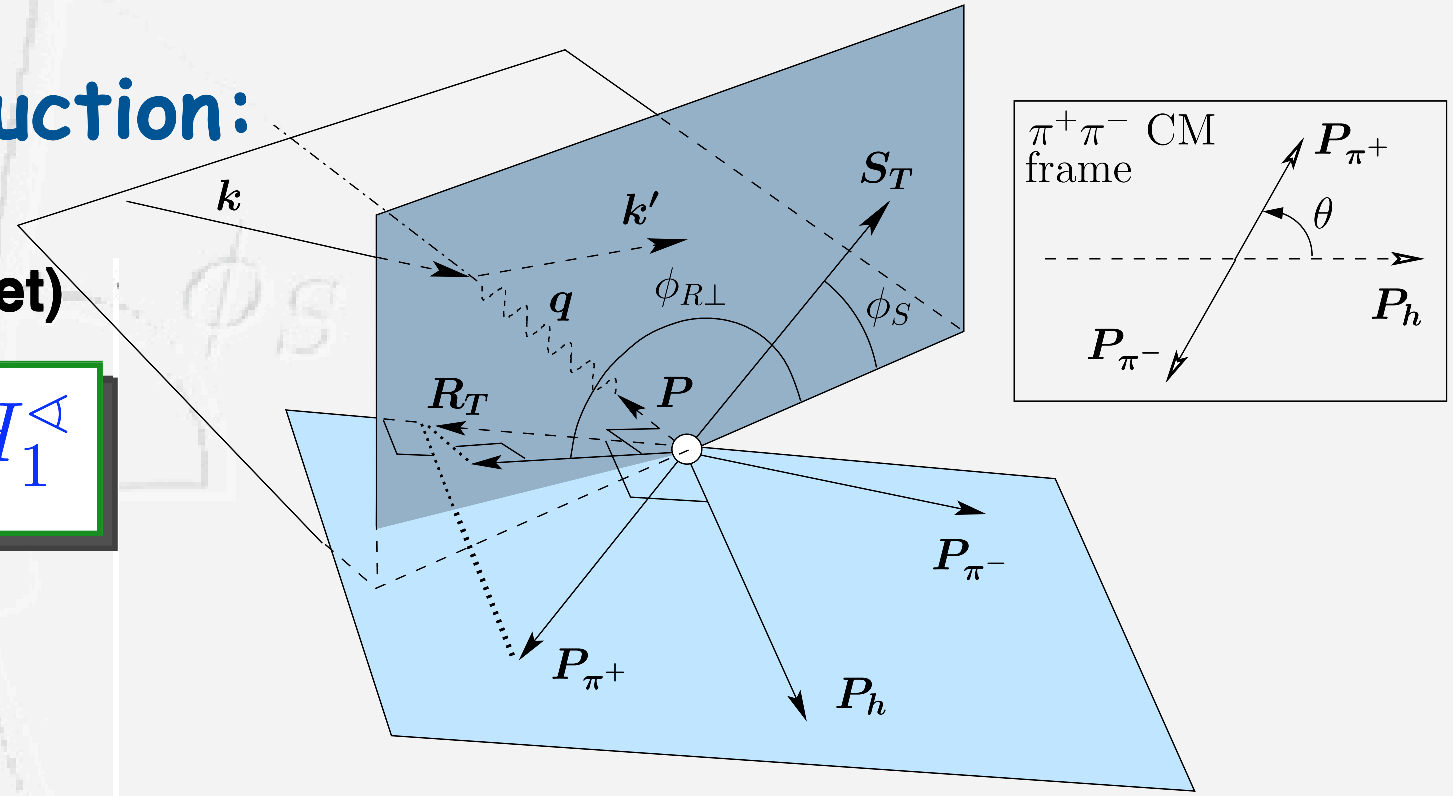
spin-dependent 2-hadron production:

(Unpolarized beam, Transversely pol. target)

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

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

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



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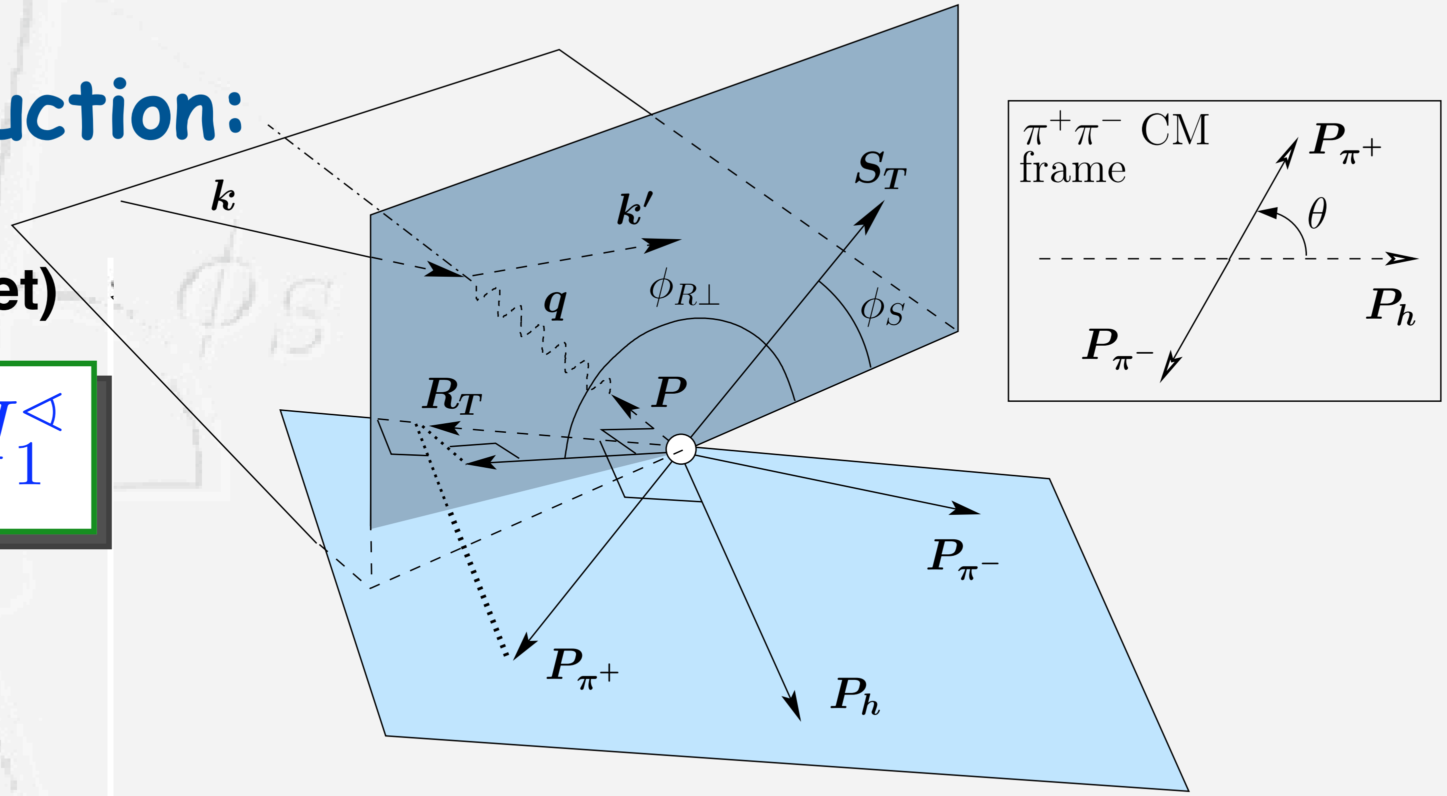

 only relative momentum of hadron pair relevant

$\Rightarrow$ integration over transverse momentum of hadron pair simplifies factorization and Q^2 evolution

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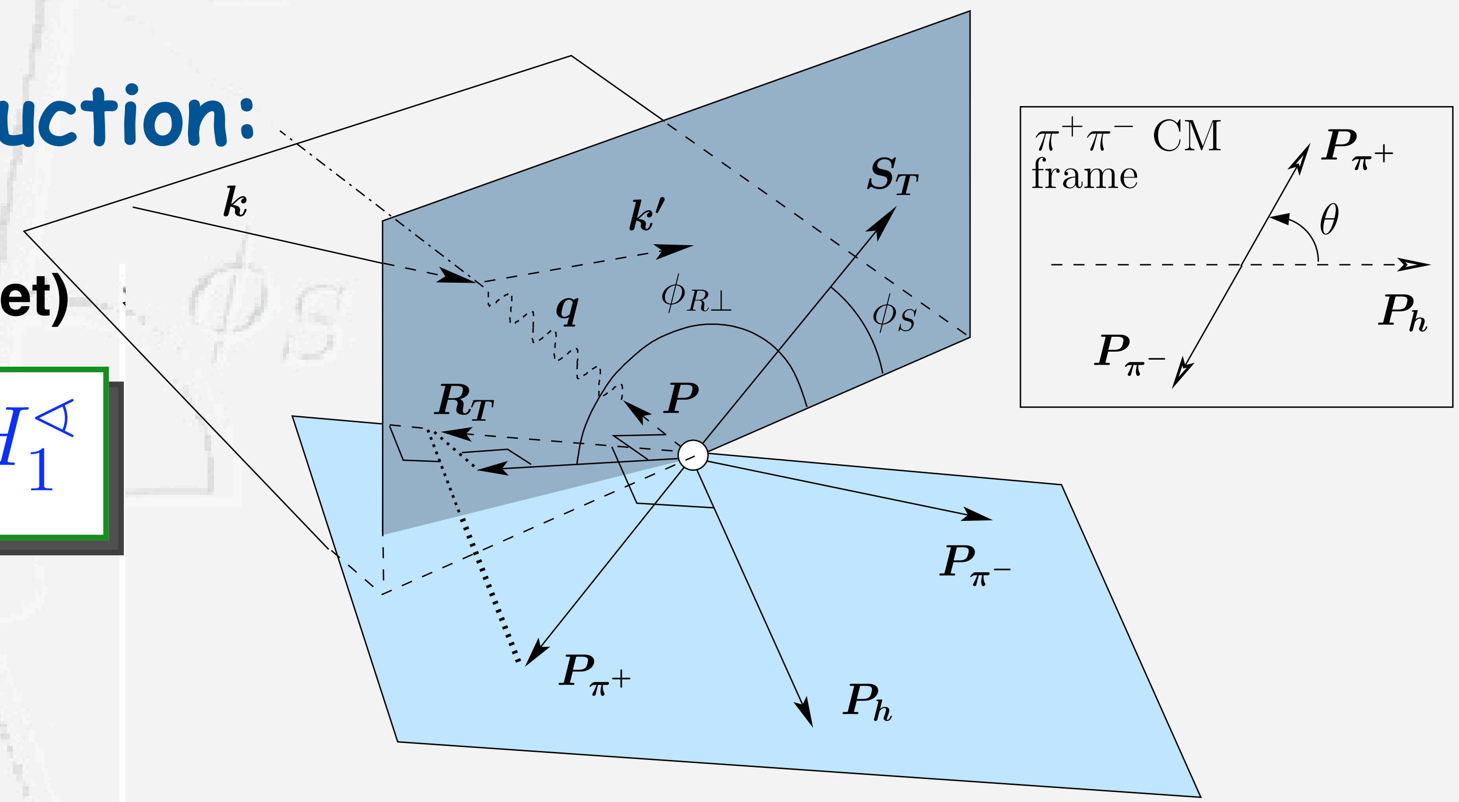


- only relative momentum of hadron pair relevant

  $\Rightarrow$ 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 two-pion fragmentation

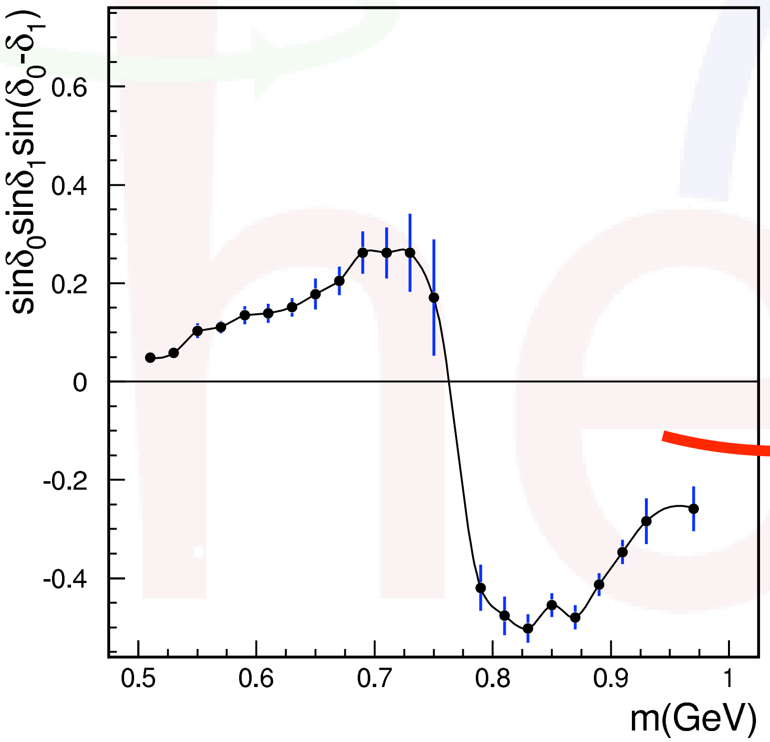
$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin\theta h_1 H_1^{\sphericalangle}$$

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**]:

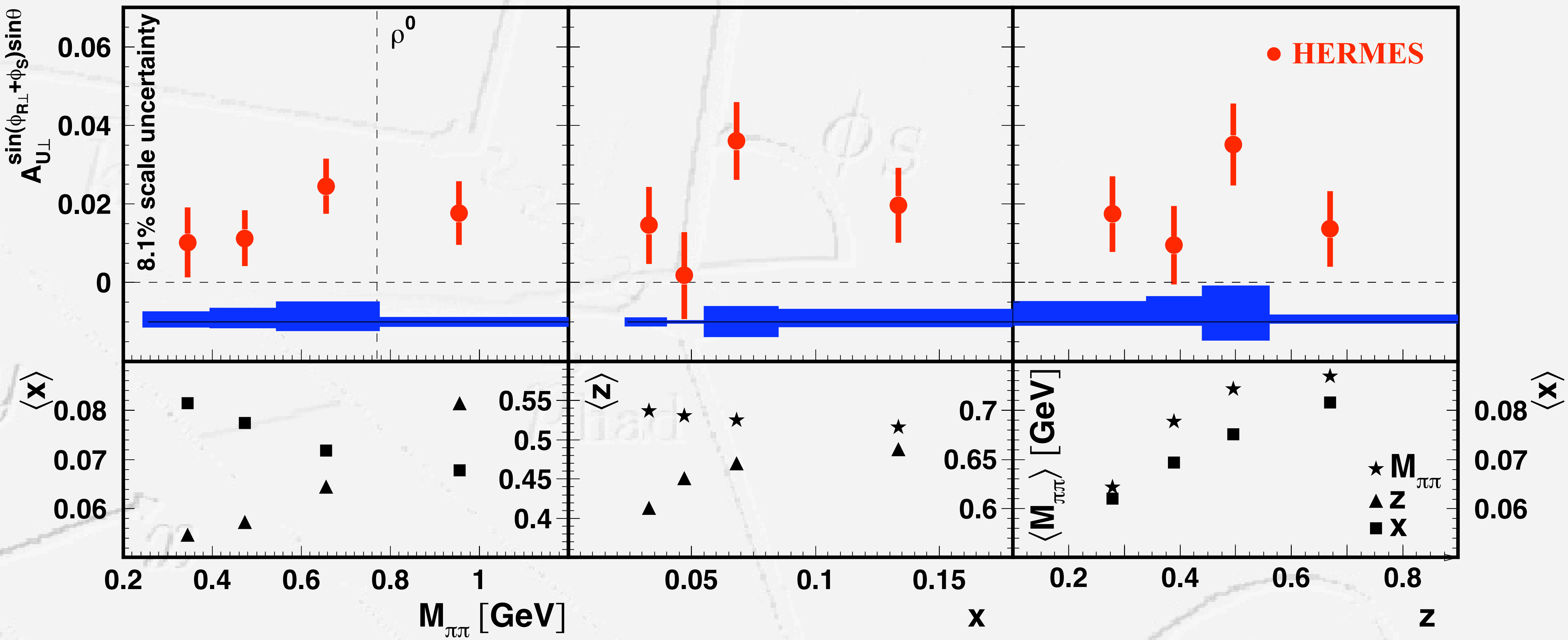
$$H_1^{\sphericalangle,sp}(z, M_{\pi\pi}^2) = \sin\delta_0 \sin\delta_1 \sin(\delta_0 - \delta_1) H_1^{\sphericalangle,sp'}(z)$$

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 $M_{\pi\pi}$

HERMES results (complete data)



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

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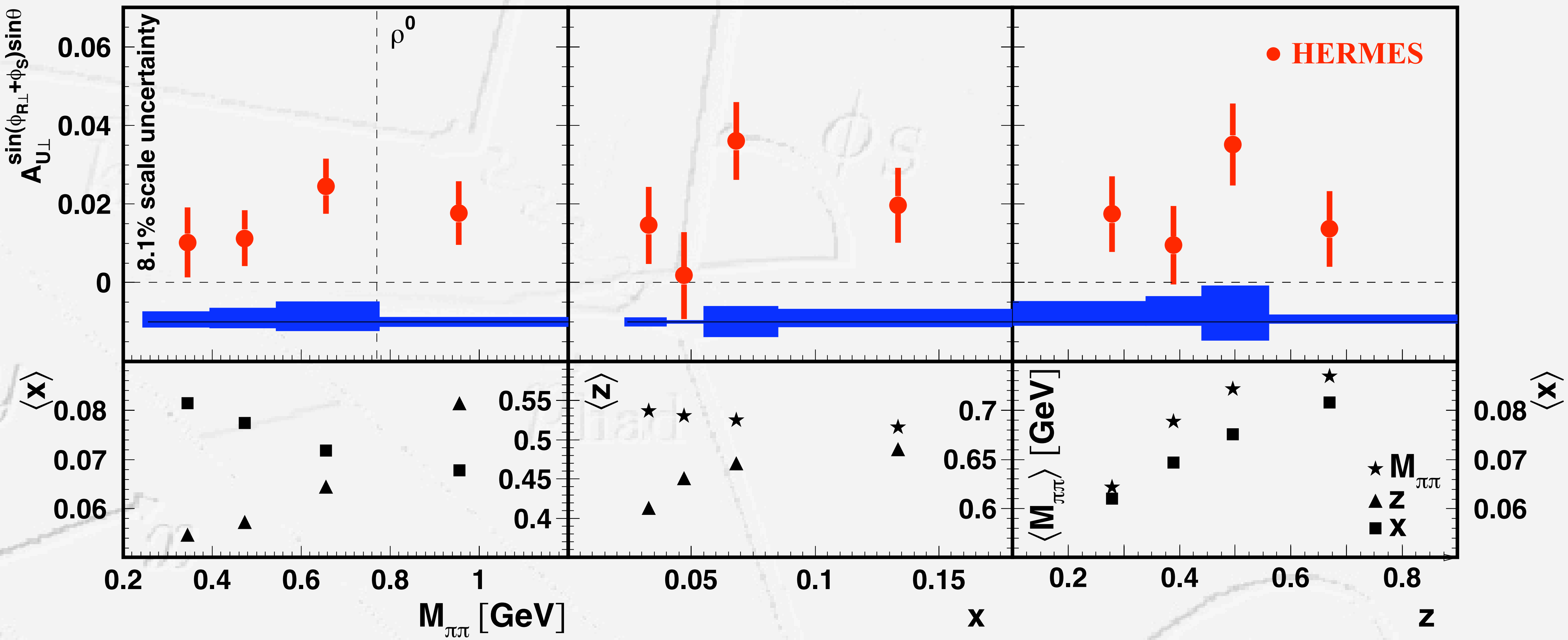

☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!

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

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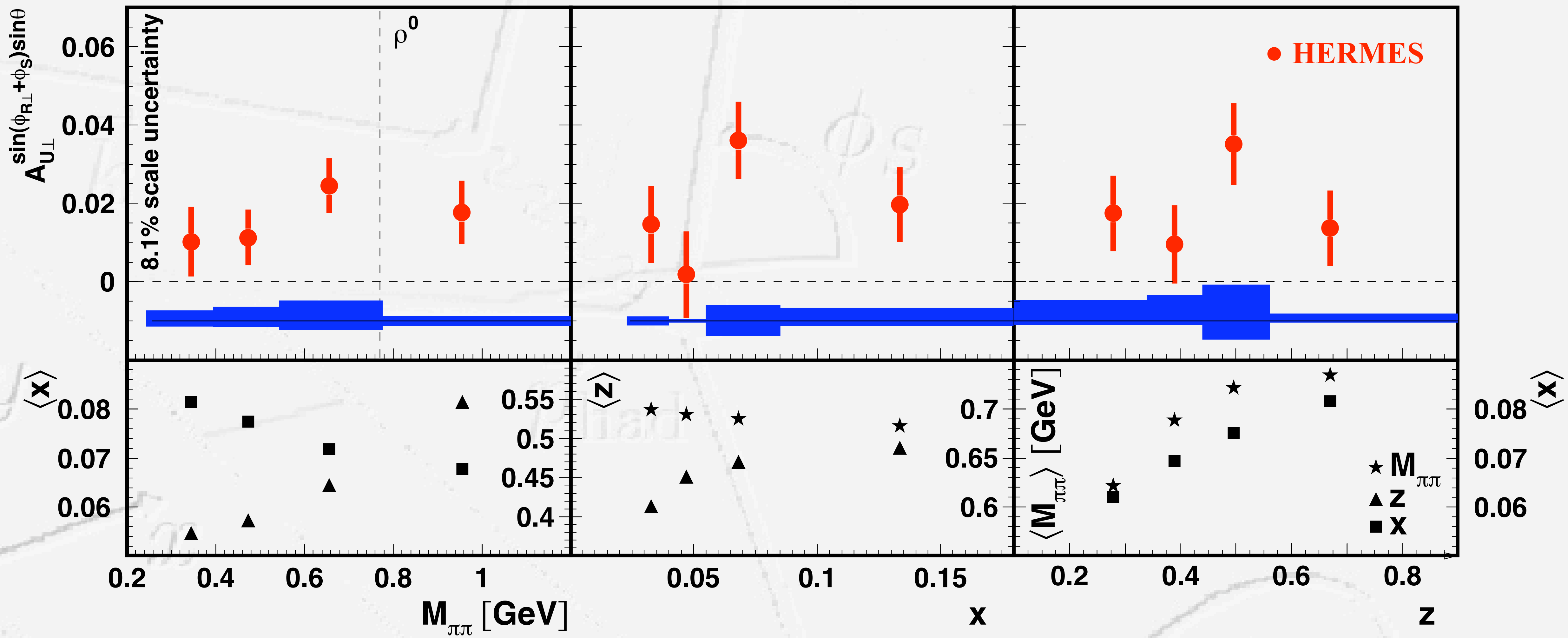
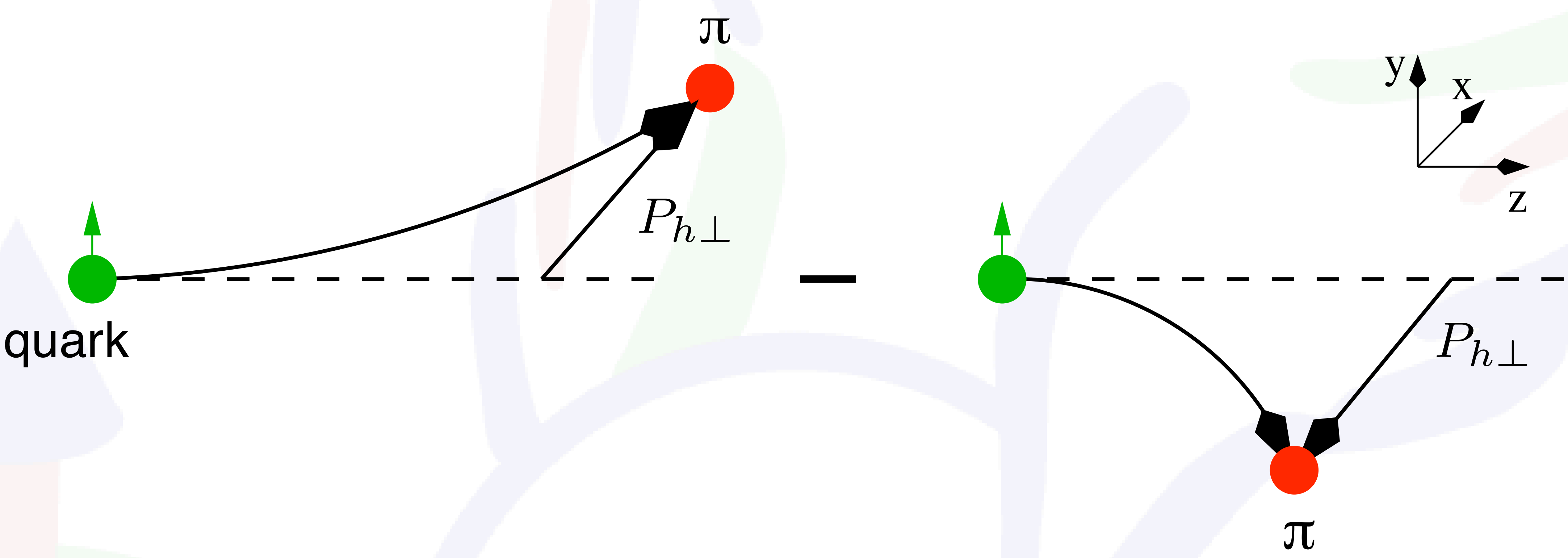


- first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!
- invariant-mass dependence rules out Jaffe model

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

Collins fragmentation function



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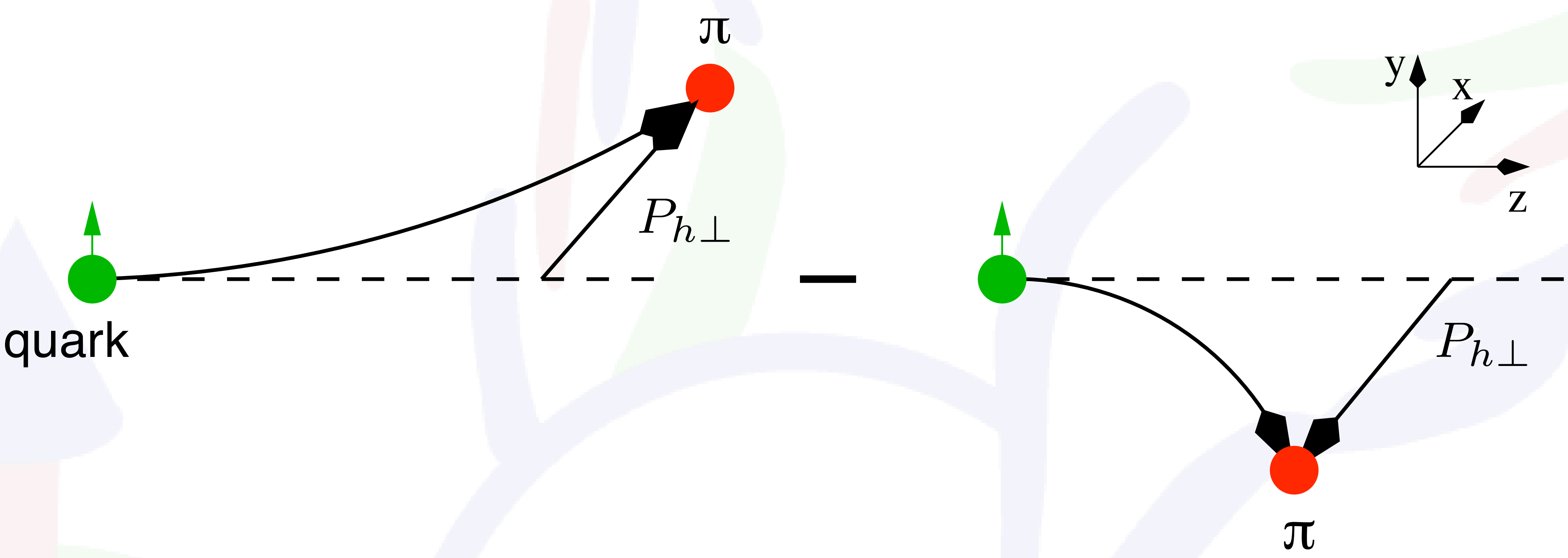
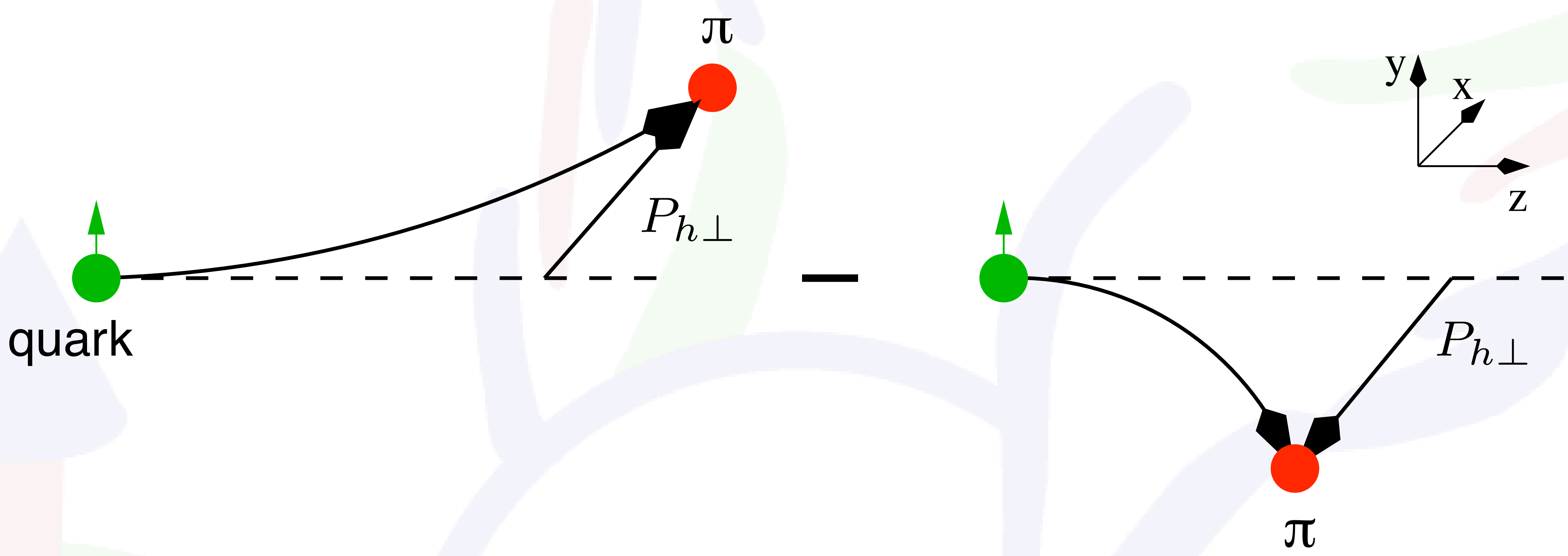


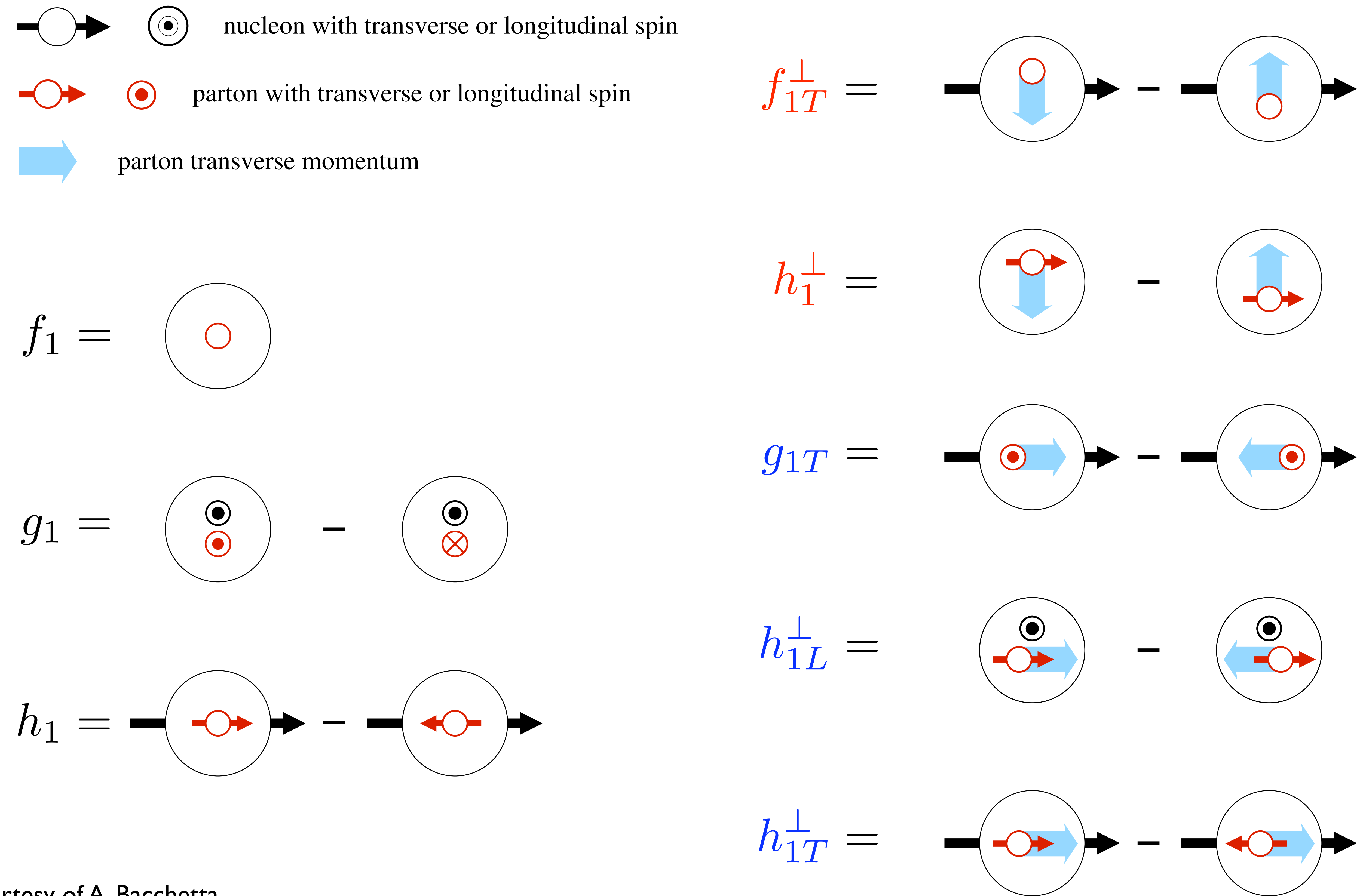
- provides a correlation between spin of quark and transverse momentum of produced hadron

Collins fragmentation function



- provides a correlation between spin of quark and transverse momentum of produced hadron
- example of transverse-momentum-dependent ("unintegrated") parton distribution/fragmentation functions

Unintegrated PDFs



Courtesy of A. Bacchetta

1-hadron production (ep→ehX)

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

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

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

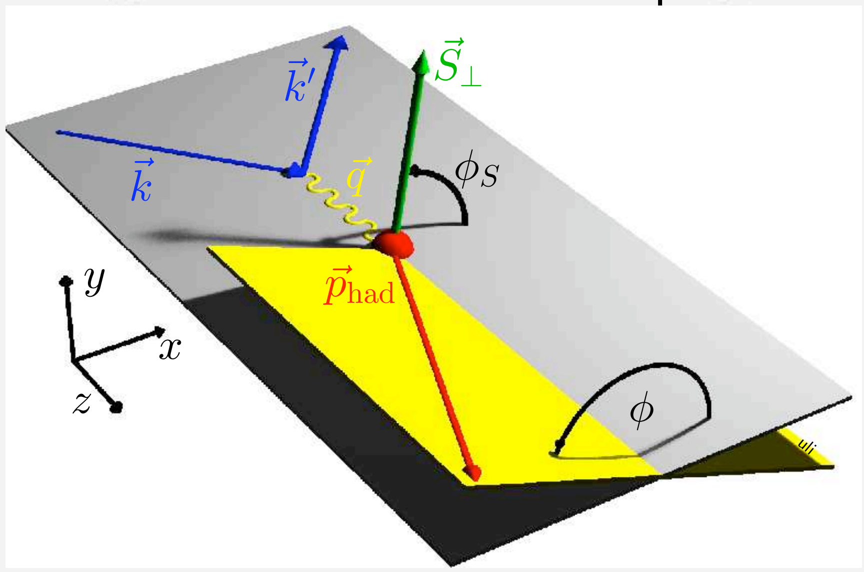
$$+\frac{1}{Q}\left(\sin(2\phi-\phi_S)\, d\sigma^{11}_{UT} + \sin\phi_S\, d\sigma^{12}_{UT} \right)$$

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

σ_{XY}

Beam Target

Polarization



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

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

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

Bacchetta et al., JHEP 0702 (2007) 093

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

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

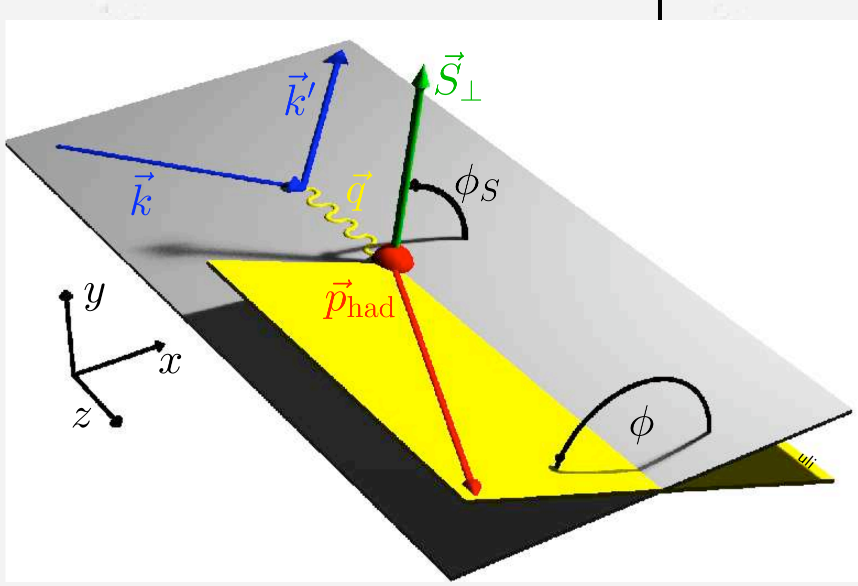
$$+\frac{1}{Q}$$

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

σ_{XY}

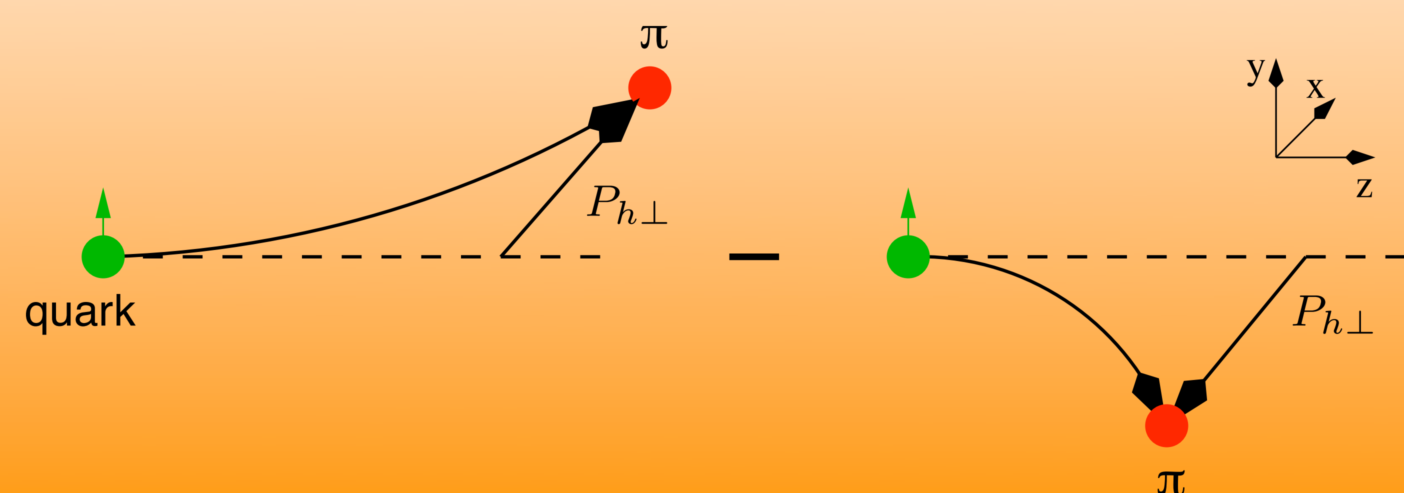
Beam Target

Polarization



Collins Effect:

sensitive to quark transverse spin



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

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

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

Sivers Effect:

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

. Phys. B 461 (1996) 197

) 57 (1998) 5780

95 (2004) 309

Bacchetta et al., JHEP 0702 (2007) 093

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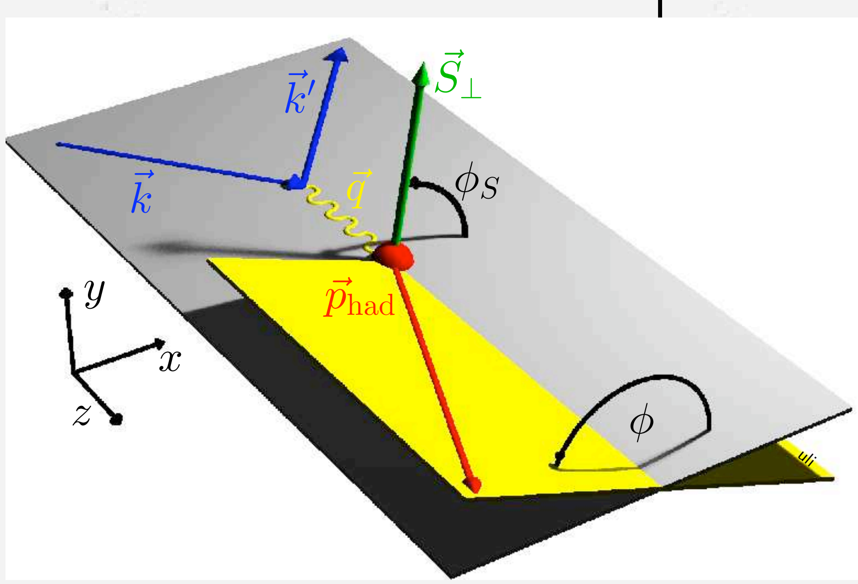
1-hadron production (ep→ehX)

$$
\begin{aligned}
d\sigma = \;& d\sigma^0_{UU} + \cos 2\phi \, d\sigma^1_{UU} + \frac{1}{Q}\cos\phi \, d\sigma^2_{UU} + \lambda_e \frac{1}{Q}\sin\phi \, d\sigma^3_{LU} \\
&+ S_L \left\{ \sin 2\phi \, d\sigma^4_{UL} + \frac{1}{Q}\sin\phi \, d\sigma^5_{UL} + \lambda_e \left[d\sigma^6_{LL} + \frac{1}{Q}\cos\phi \, d\sigma^7_{LL} \right] \right\} \\
&+ S_T \Bigg\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \frac{1}{Q} \\
&\qquad + \frac{1}{Q}\left(\sin(2\phi - \phi_S) \, d\sigma^{11}_{UT} + \sin\phi_S \, d\sigma^{12}_{UT} \right) \\
&\qquad + \lambda_e \left[\cos(\phi - \phi_S) \, d\sigma^{13}_{LT} + \frac{1}{Q}\left(\cos\phi_S \, d\sigma^{14}_{LT} + \cos(2\phi - \phi_S) \, d\sigma^{15}_{LT} \right) \right] \Bigg\}
\end{aligned}
$$

σ_{XY}

Beam Target
Polarization



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

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

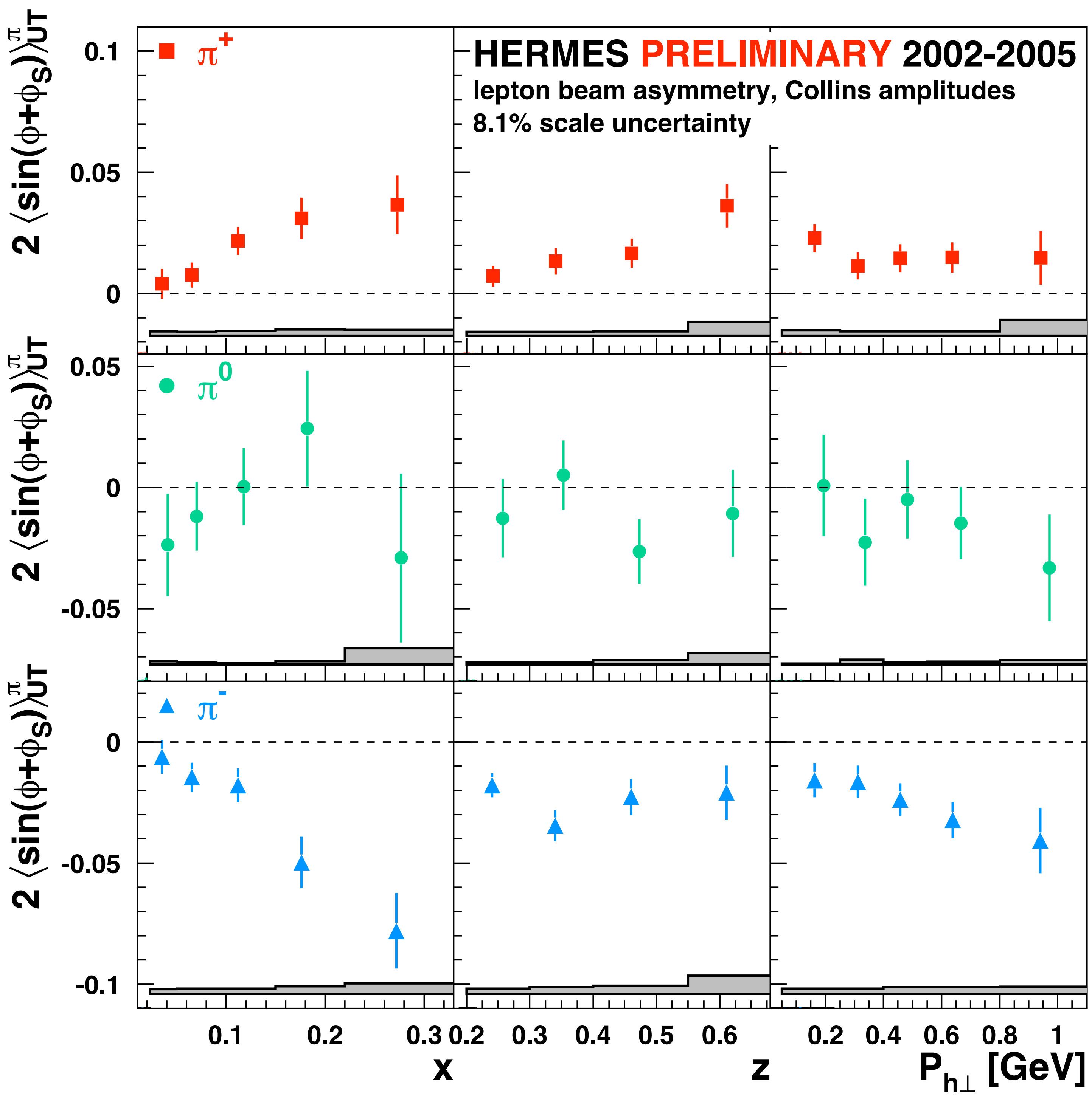
Bacchetta et al., Phys. Lett. B 595 (2004) 309

Bacchetta et al., JHEP 0702 (2007) 093

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

The HERMES Collins amplitudes

$$2\langle\sin(\phi+\phi_S)\rangle_{\mathrm{UT}} = -\frac{\sum_q e_q^2 h_1^q(x,p_T^2)\otimes H_1^{\perp,q}(z,K_T^2)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$



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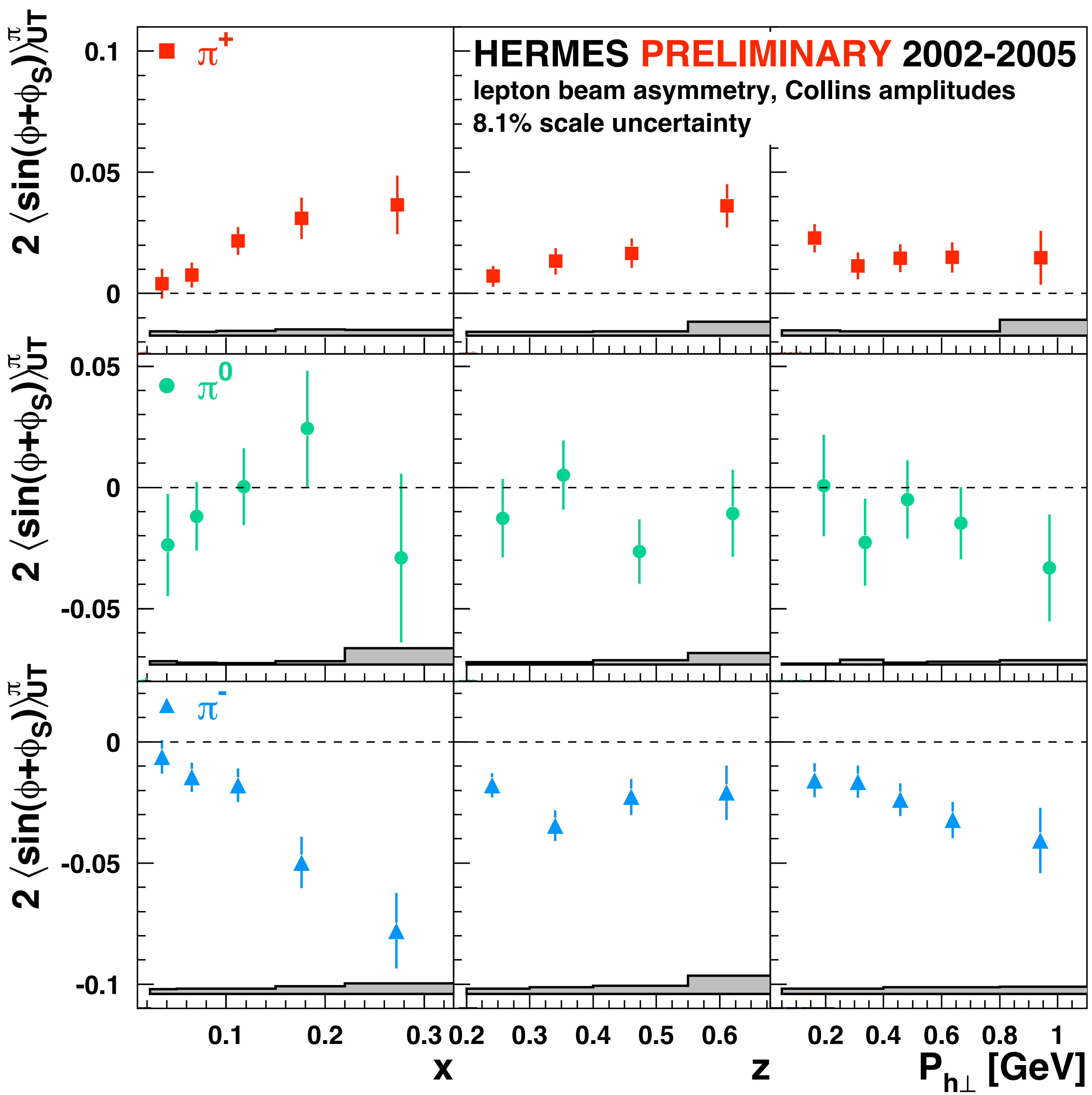

☑ non-zero Collins effect observed!

The HERMES Collins amplitudes

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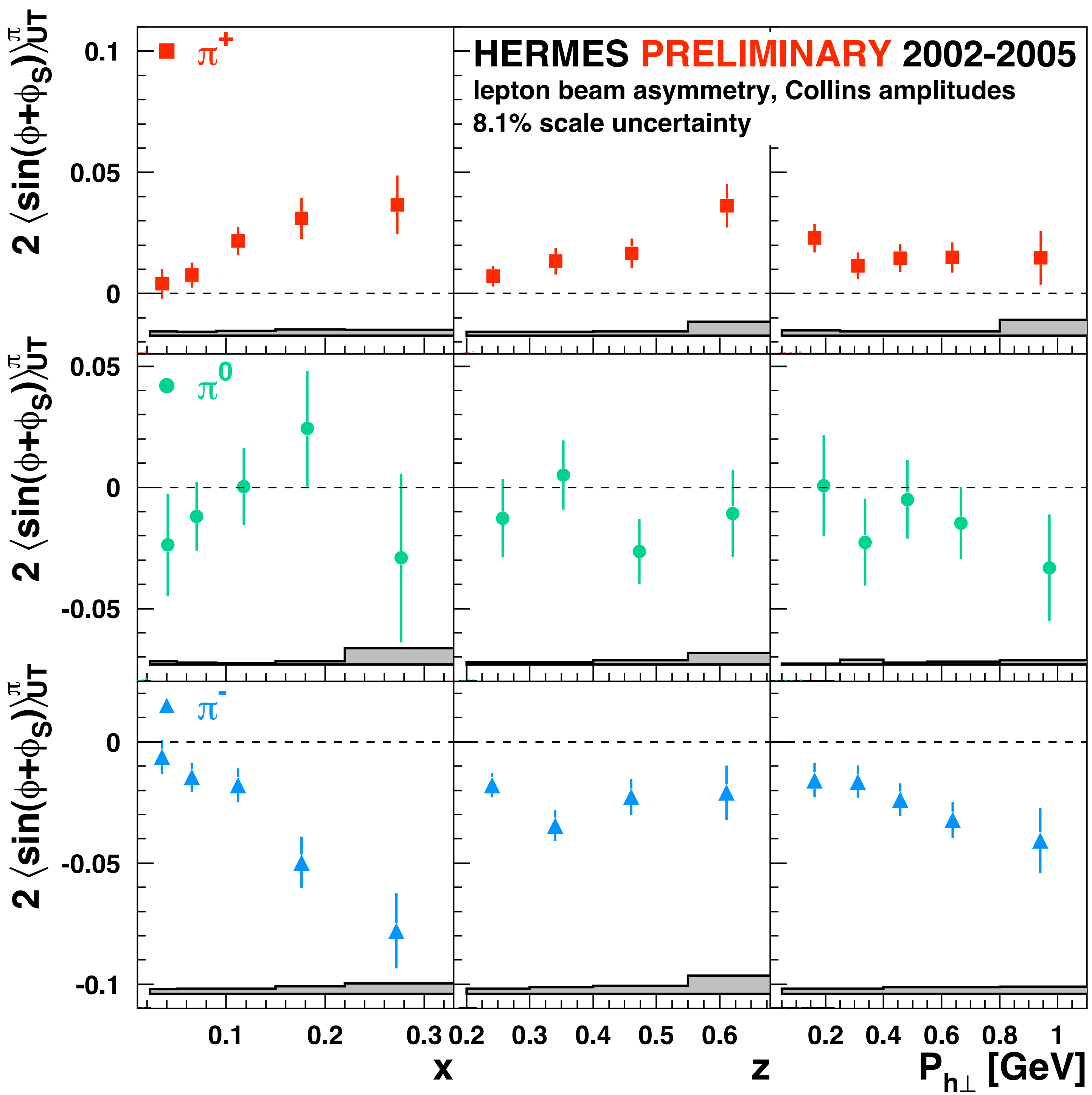

- ☑ non-zero Collins effect observed!
- ☑ both Collins FF and transversity sizeable

The HERMES Collins amplitudes

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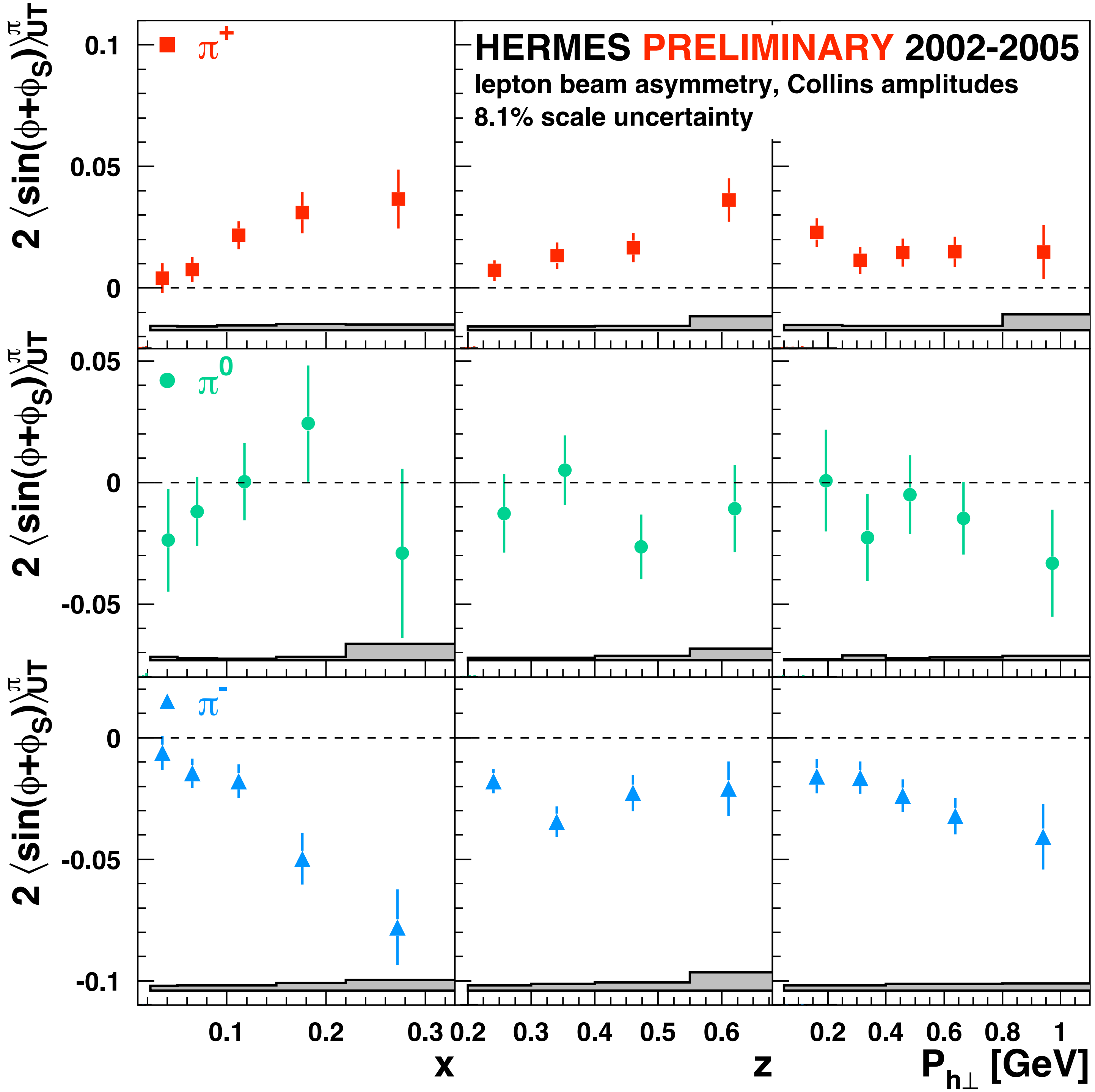
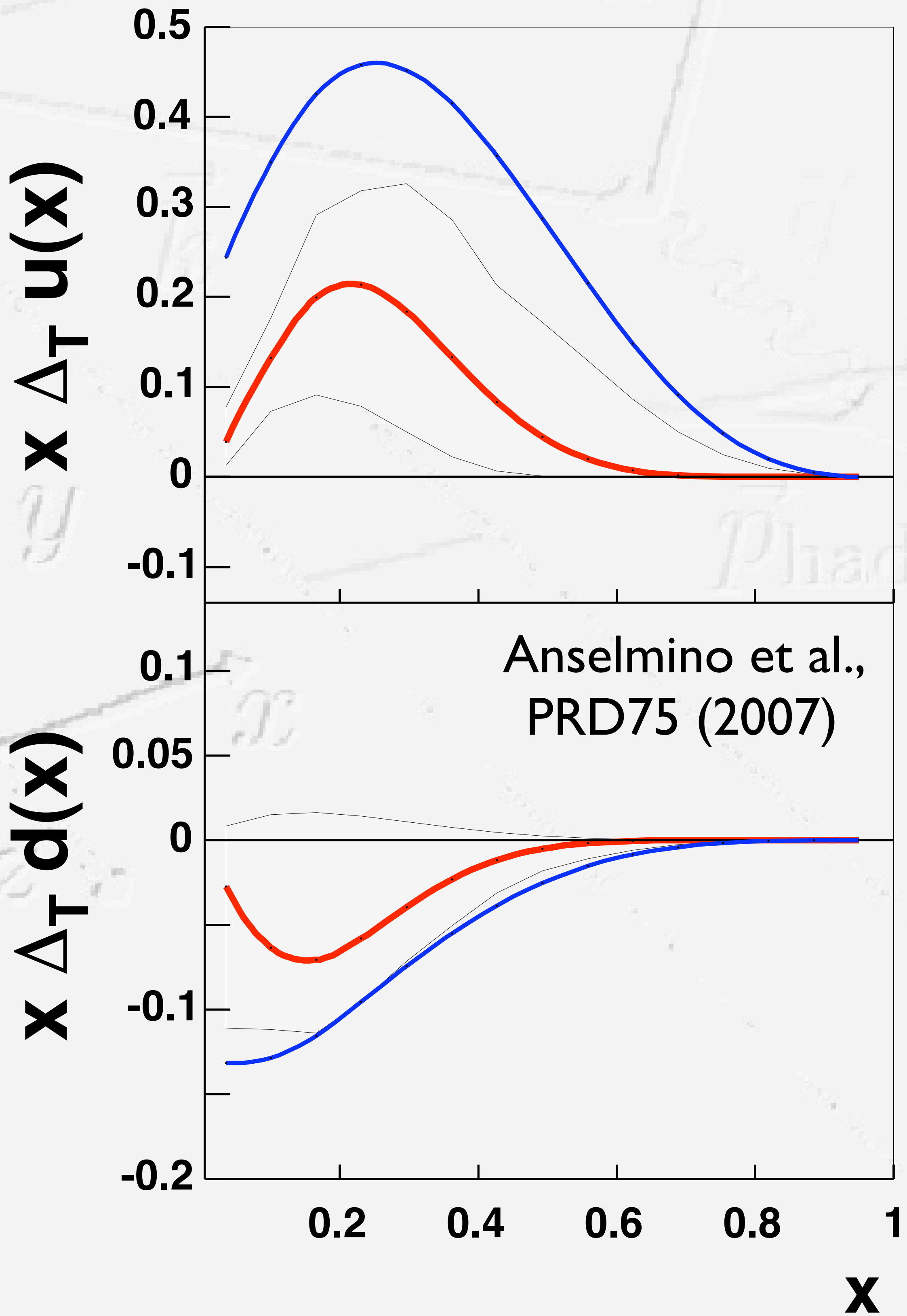


- published† results **confirmed** with much higher statistical precission
- overall scale uncertainty of 8.1%
- positive for π^+ and negative for π^- as maybe expected ($\delta u \equiv h_1^u > 0$
  $\delta d \equiv h_1^d < 0$)
- unexpected **large π^- asymmetry**
  $\Rightarrow$ role of **disfavored** 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]

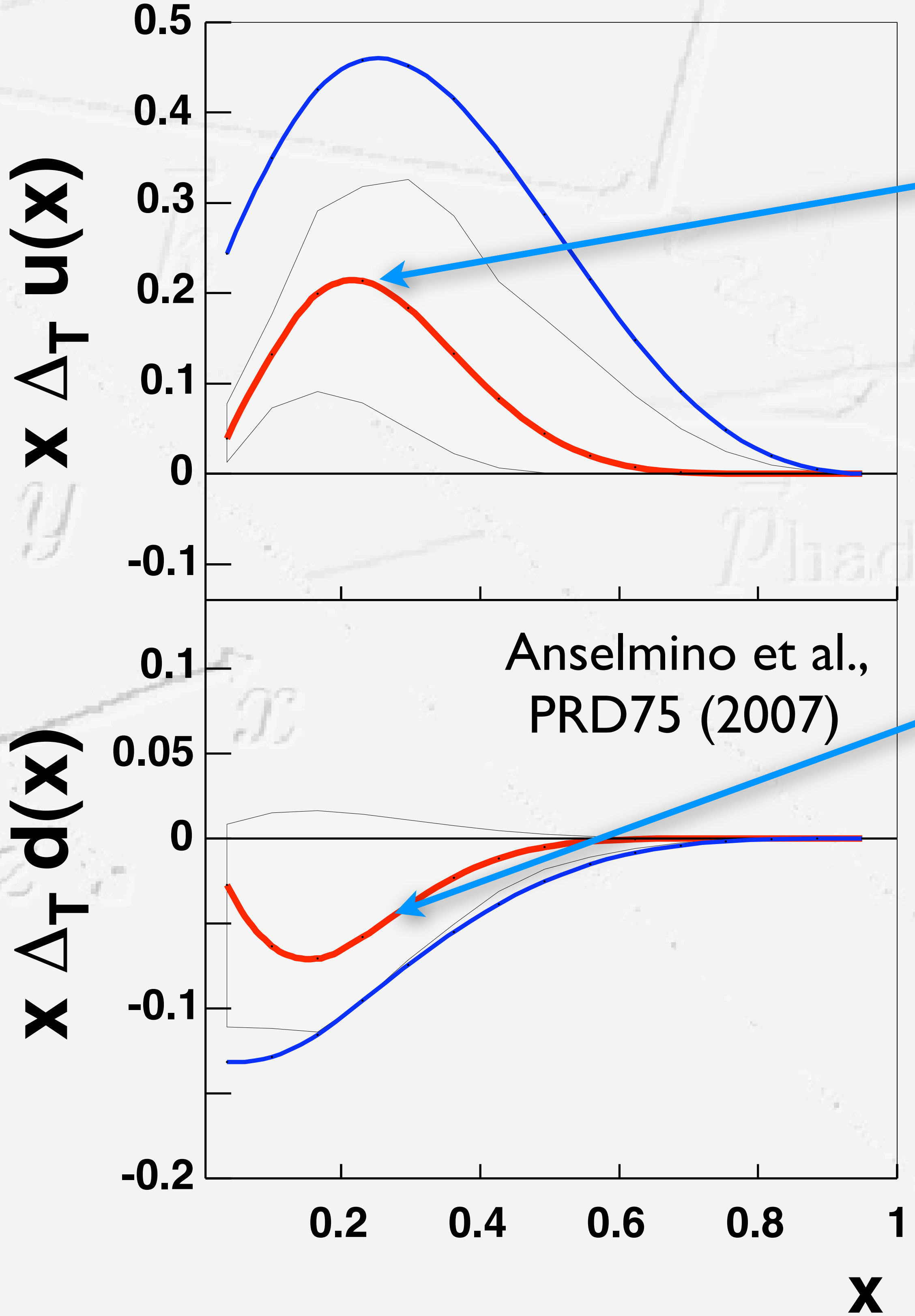
First glimpse at transversity

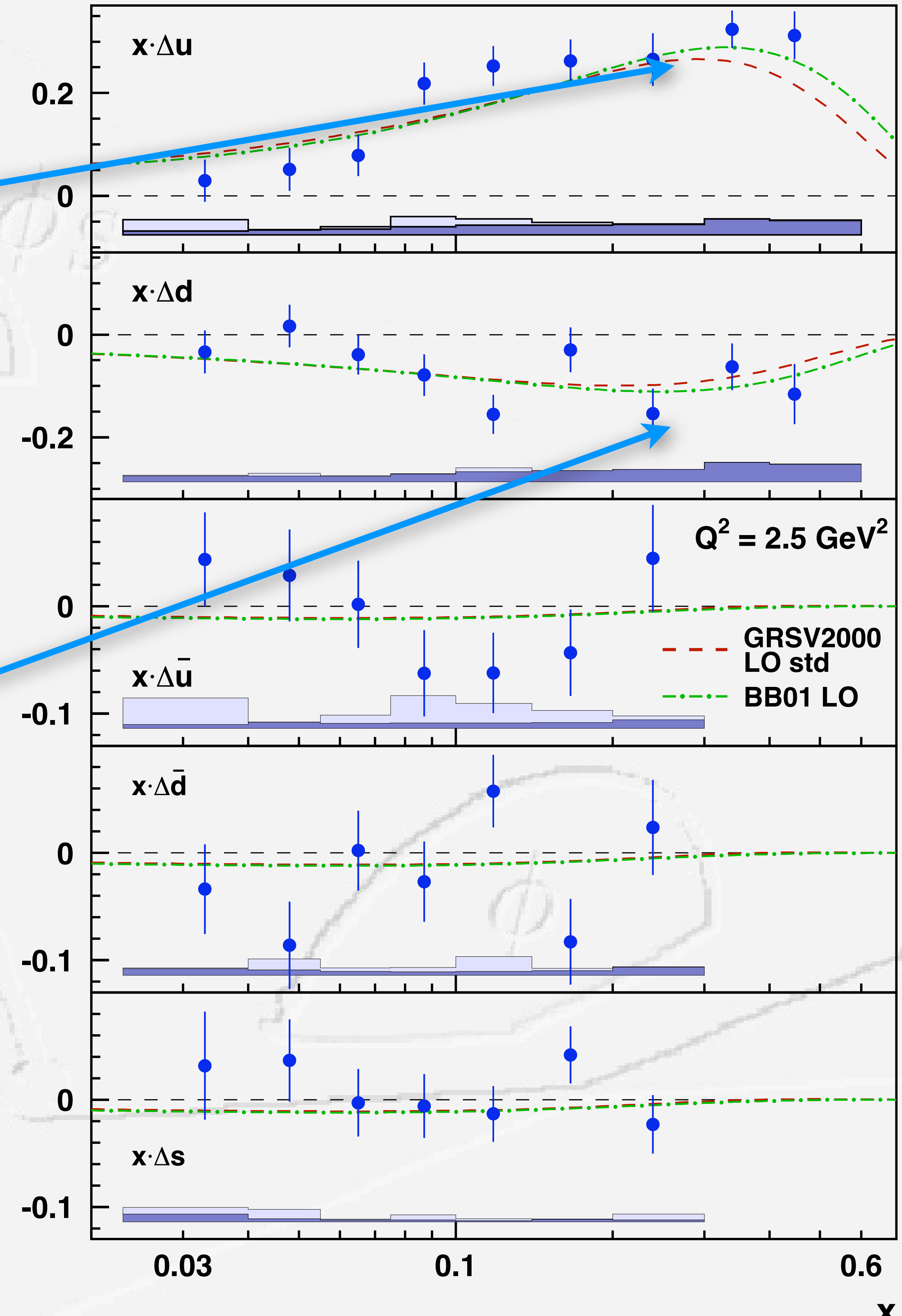


Combined analysis of data from:

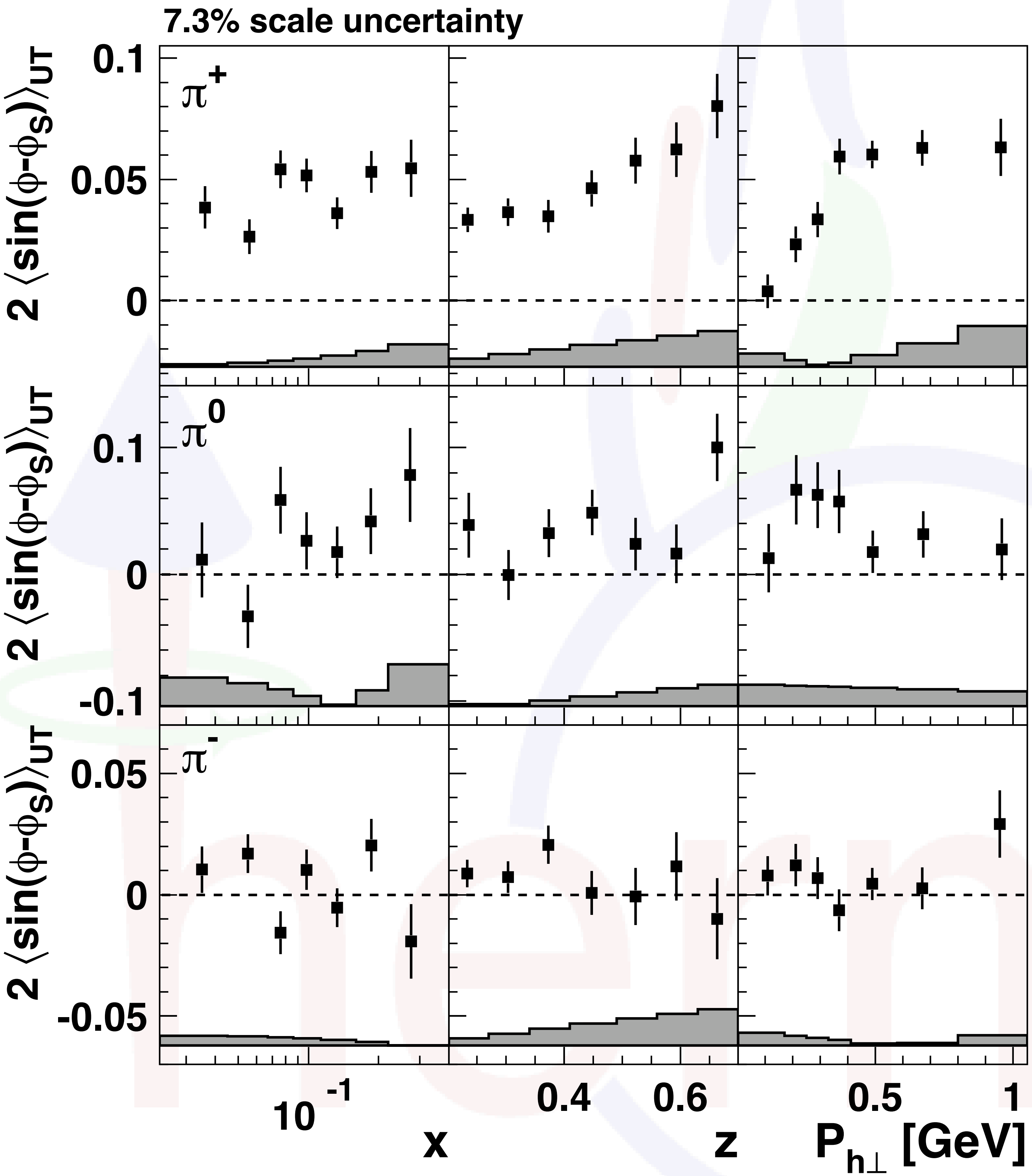
- HERMES
- COMPASS
- BELLE

First glimpse at transversity





Sivers amplitudes for pions



[*A. Airapetian et al.*, arXiv:0906.3918]

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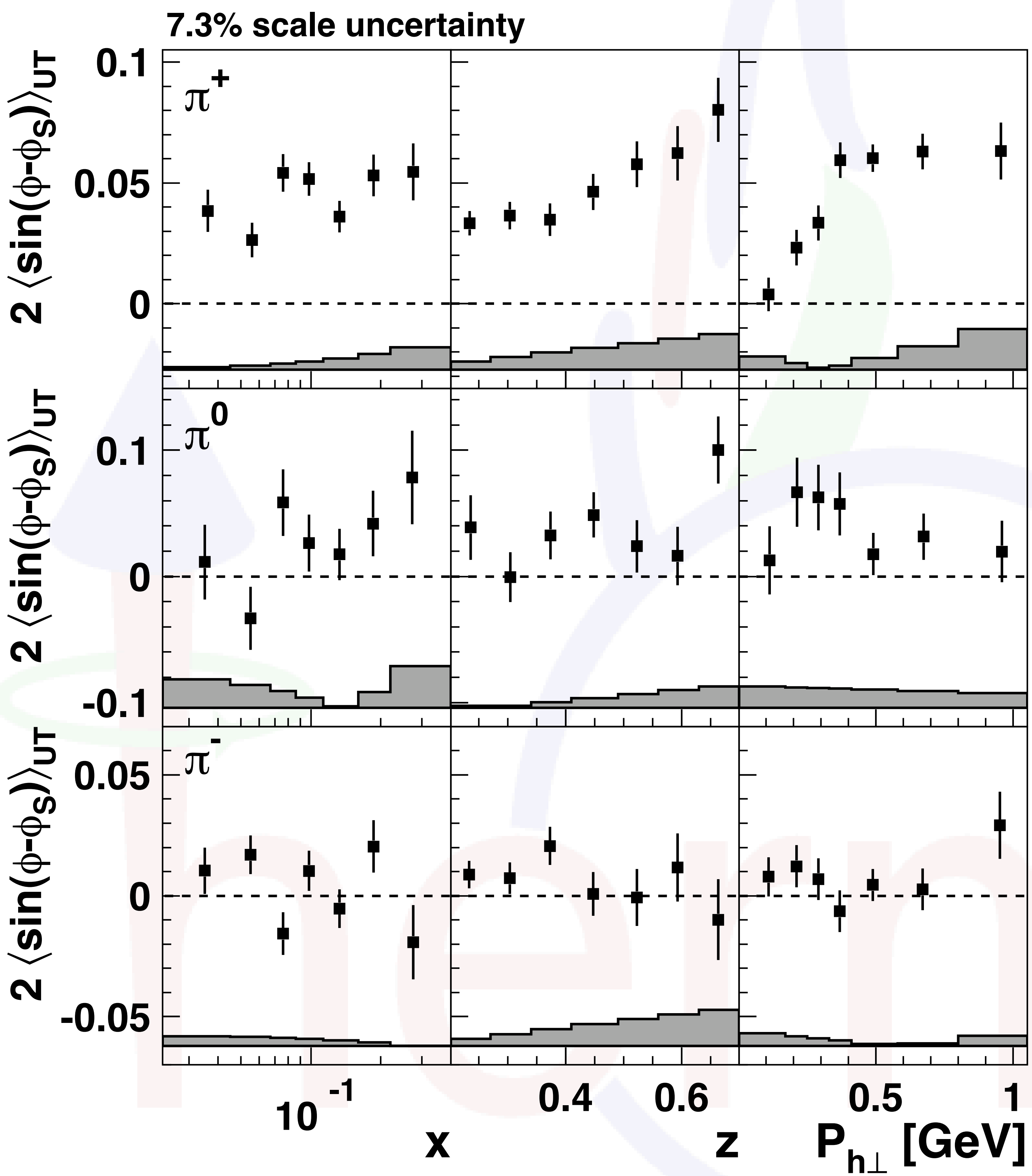


[*A. Airapetian et al.*, arXiv:0906.3918]

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

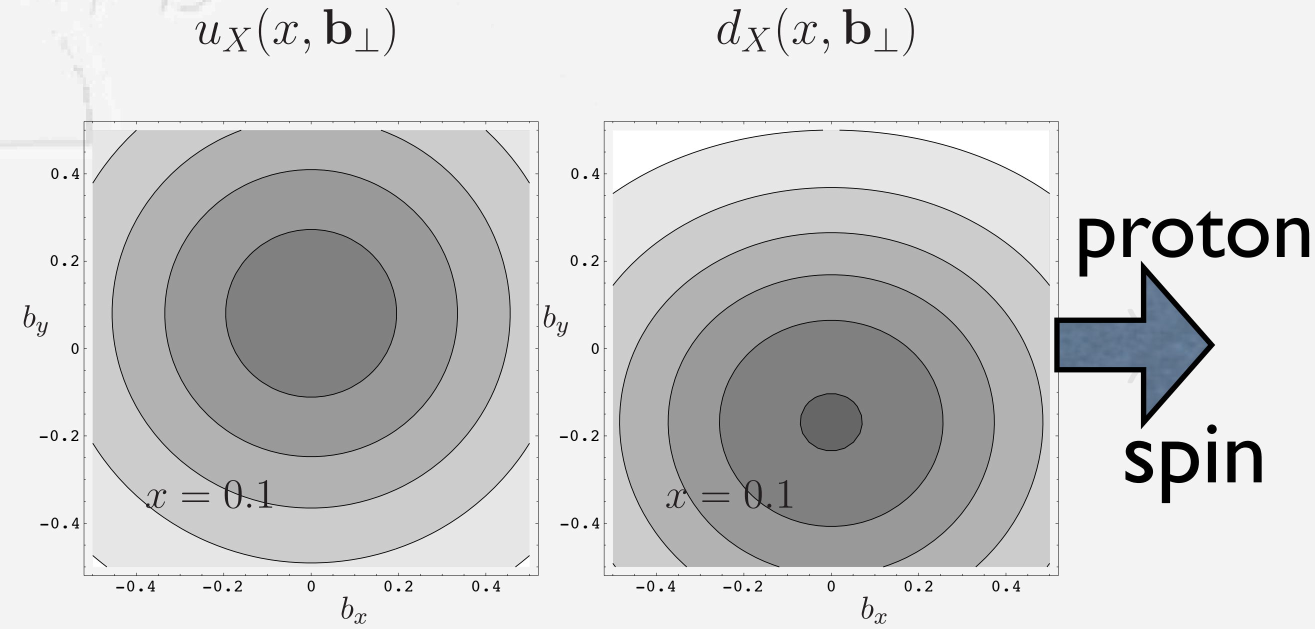
"Chromodynamic Lensing"

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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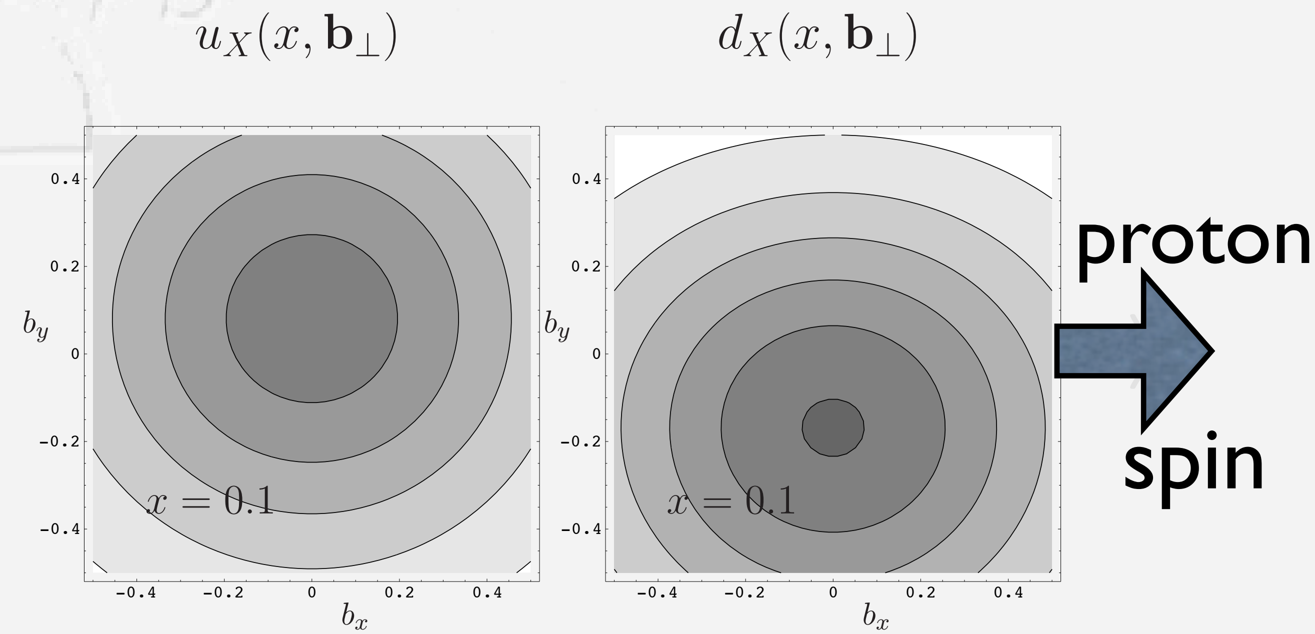
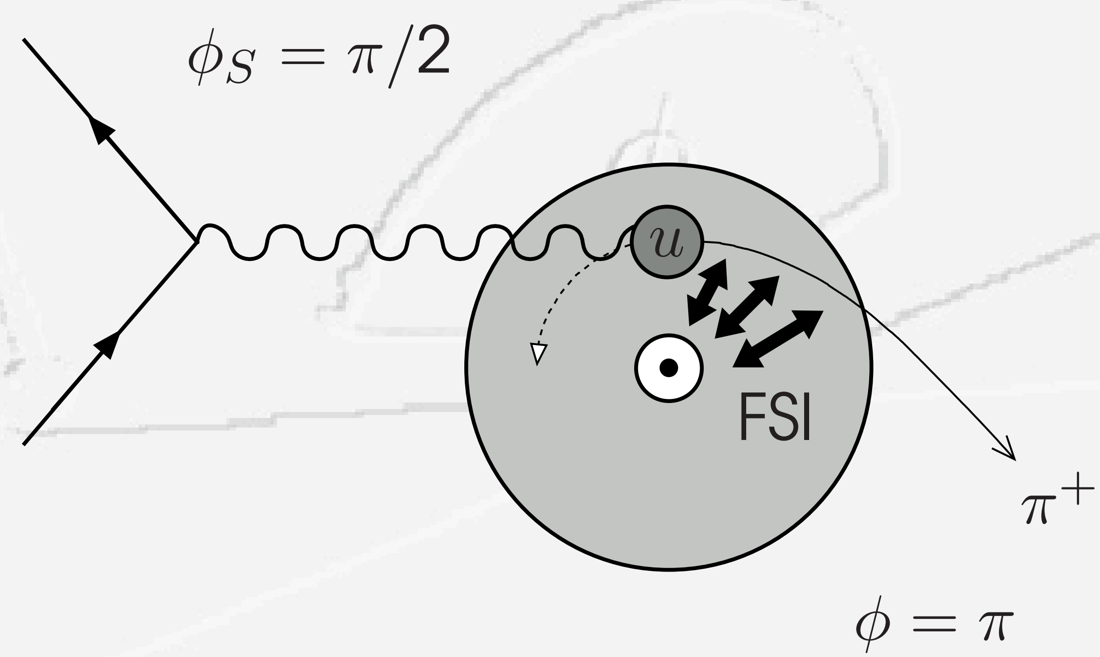
+ attractive QCD potential

(gluon exchange)

$\Rightarrow$ transverse asymmetries





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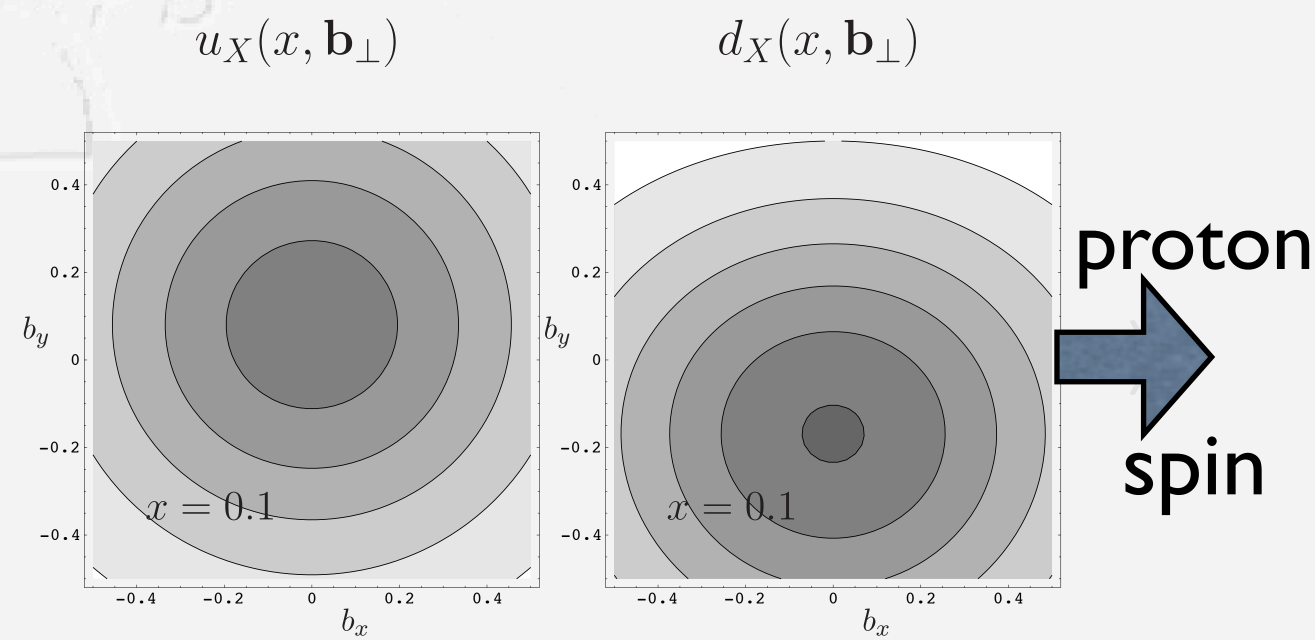

+ attractive QCD potential
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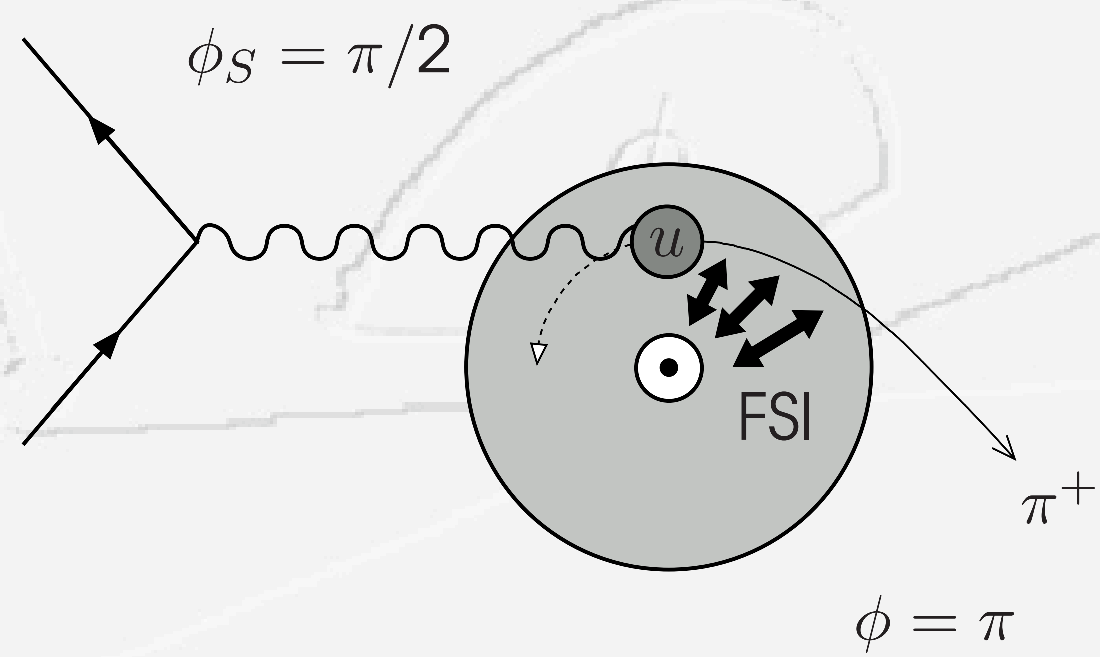
$$\boxed{L_z^u > 0}$$



Sivers amplitudes for pions

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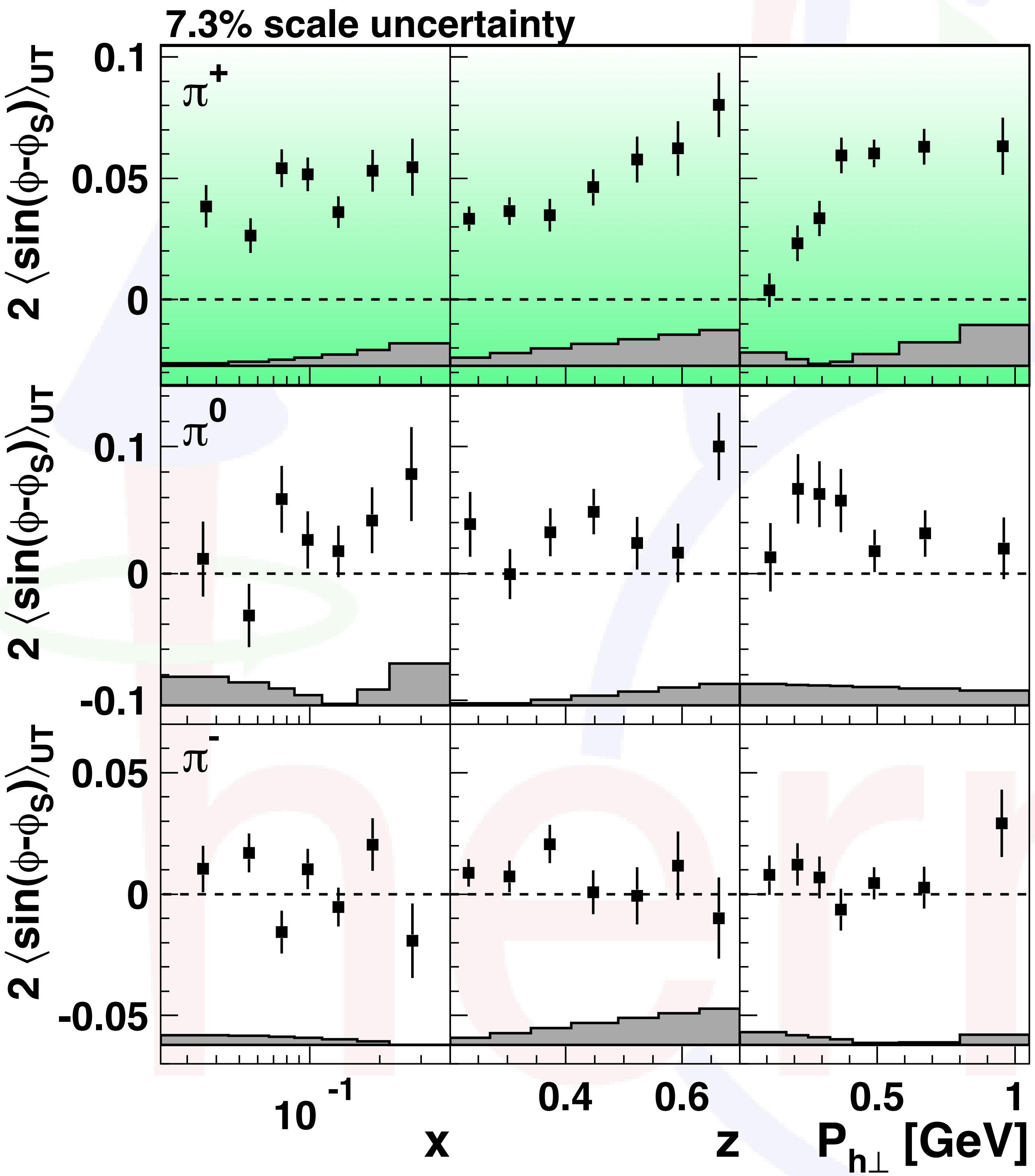

$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,K_T^2)}{f_1^u(x)\; D_1^{u\to\pi^+}(z)}$$

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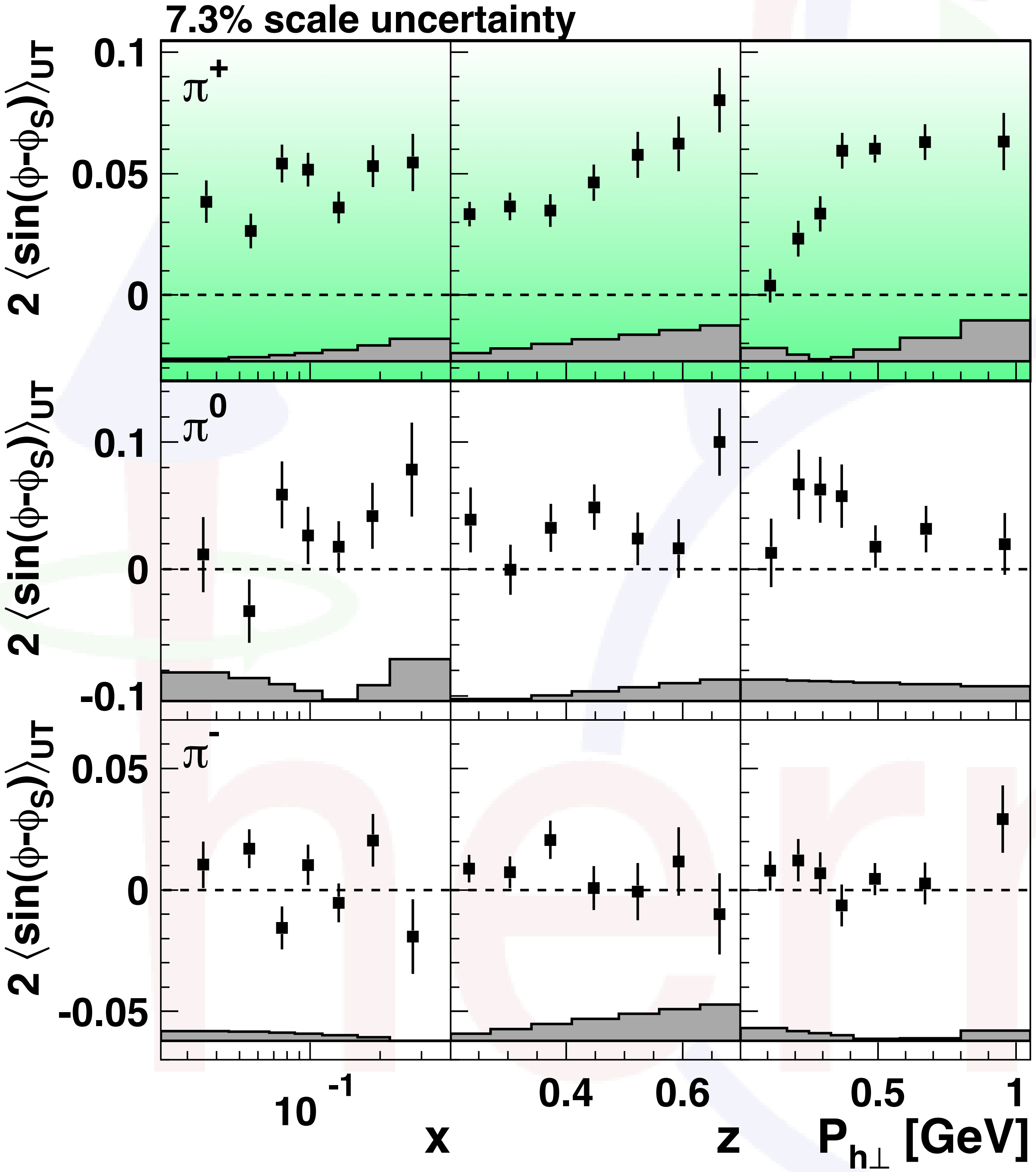

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☛ **u-quark Sivers DF < 0**

[*A. Airapetian et al.*, arXiv:0906.3918]

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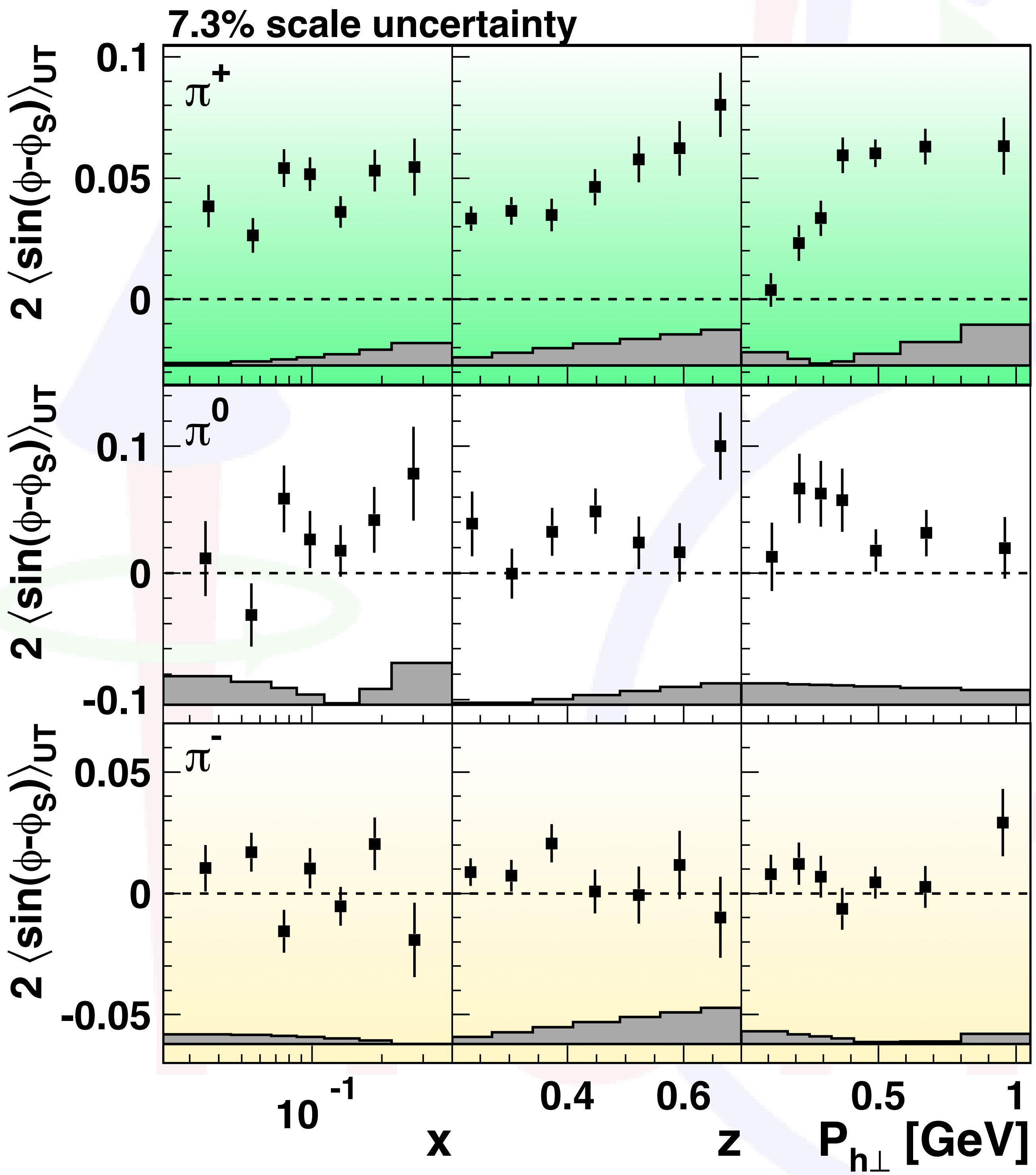

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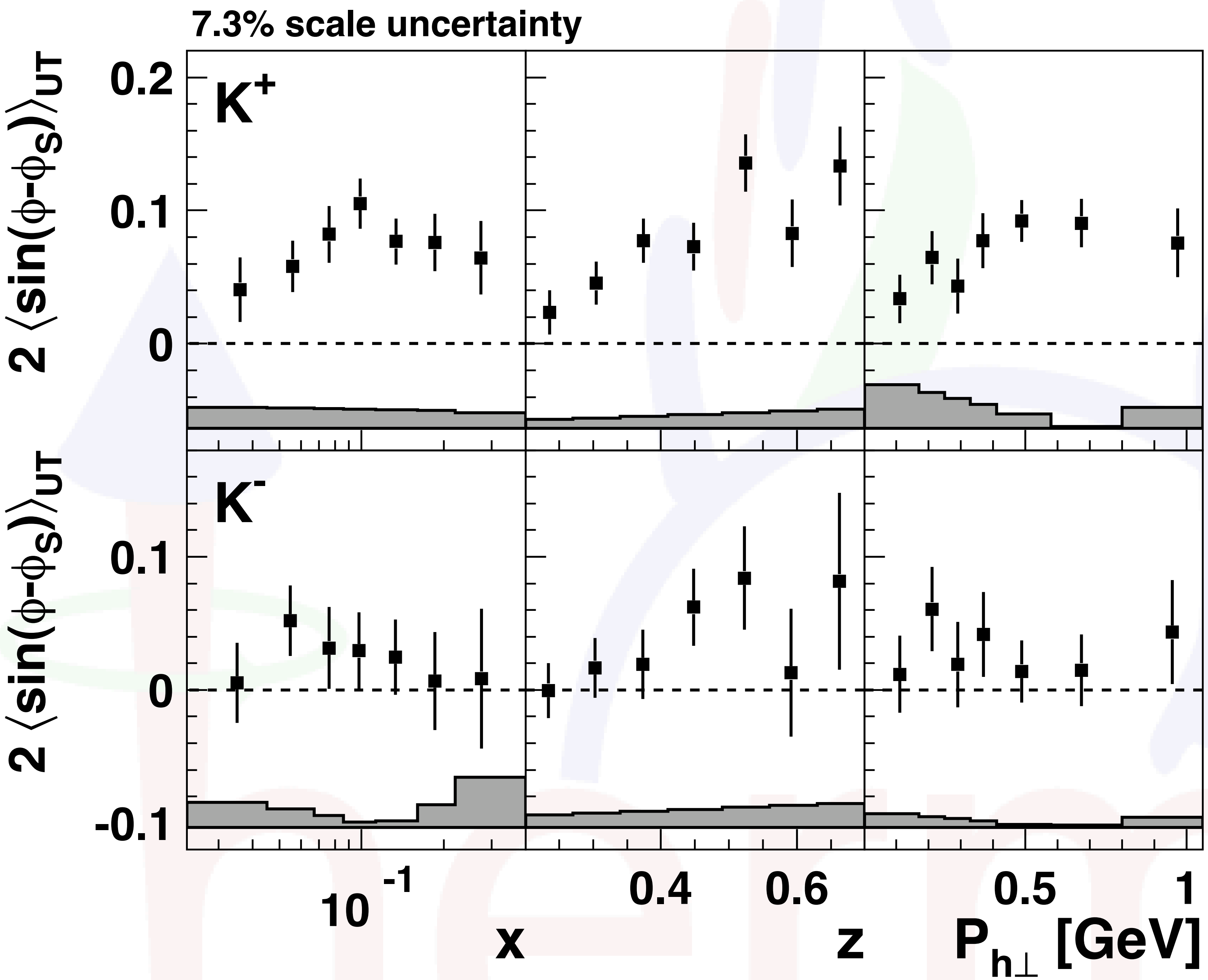
☛ **u-quark Sivers DF < 0**

☛ **d-quark Sivers DF > 0 (cancelation for π^-)**

[*A. Airapetian et al.*, arXiv:0906.3918]

Sivers amplitudes for kaons



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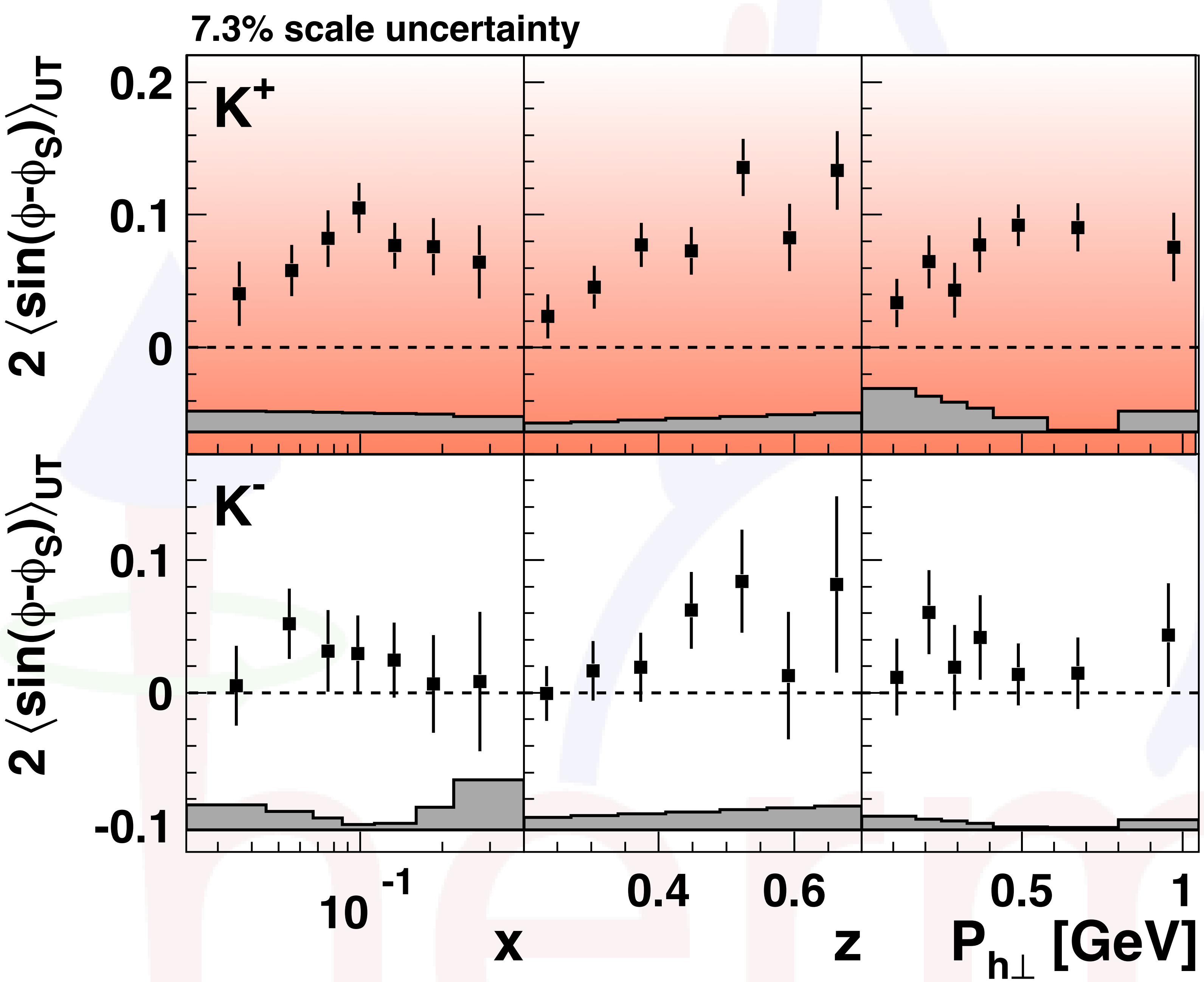
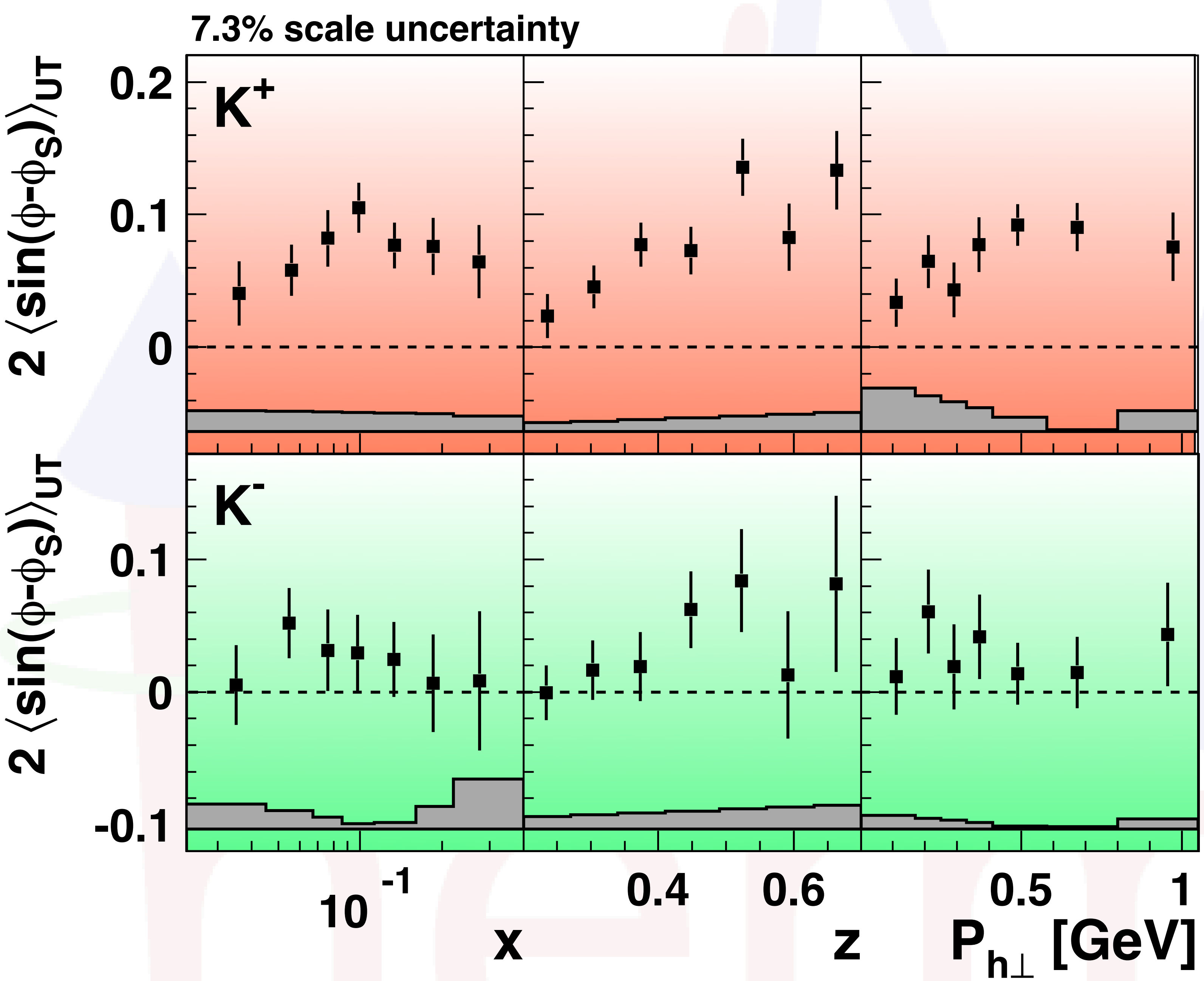


☛ large & positive

[*A. Airapetian et al.*, arXiv:0906.3918]

Sivers amplitudes for kaons

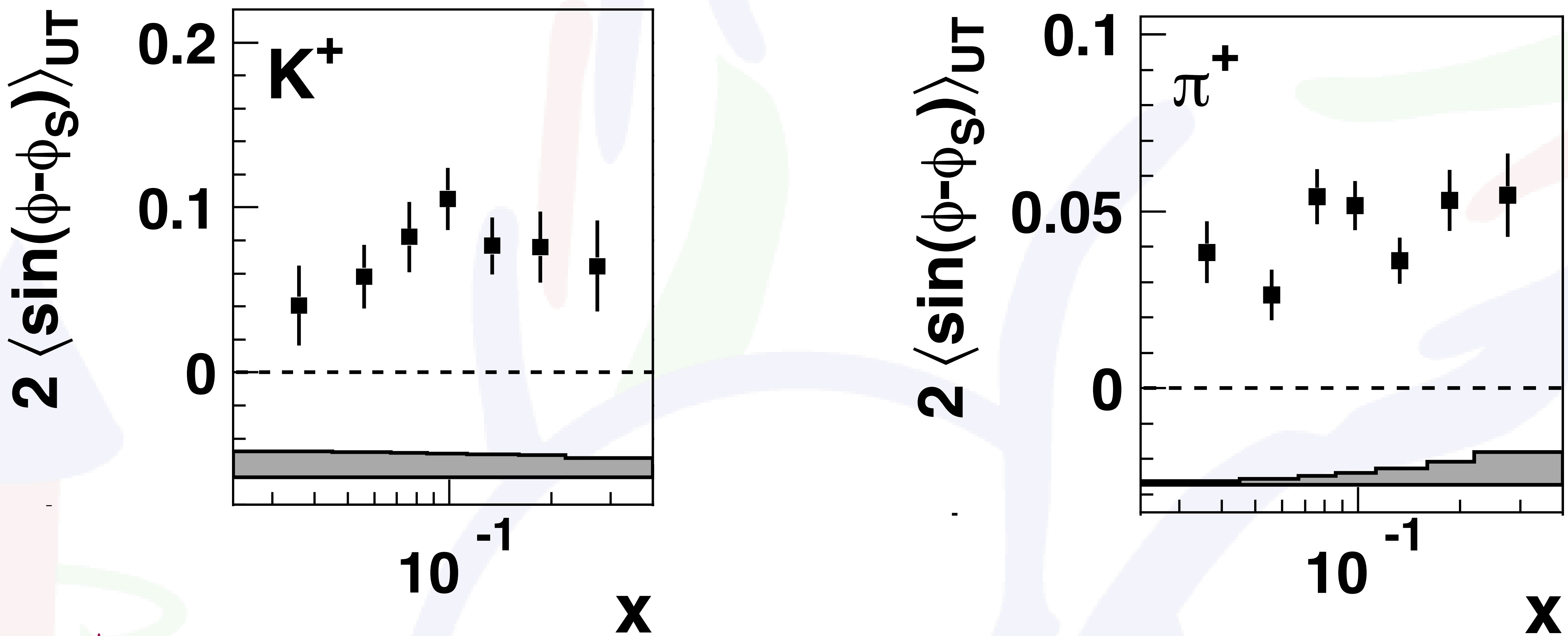


☛ large & positive

☛ slightly positive

[*A. Airapetian et al.*, arXiv:0906.3918]

The "Kaon Challenge"



π^+/K^+ production dominated by scattering off u-quarks: $\simeq -\dfrac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\to\pi^+/K^+}(z,K_T^2)}{f_1^u(x)\;D_1^{u\to\pi^+/K^+}(z)}$

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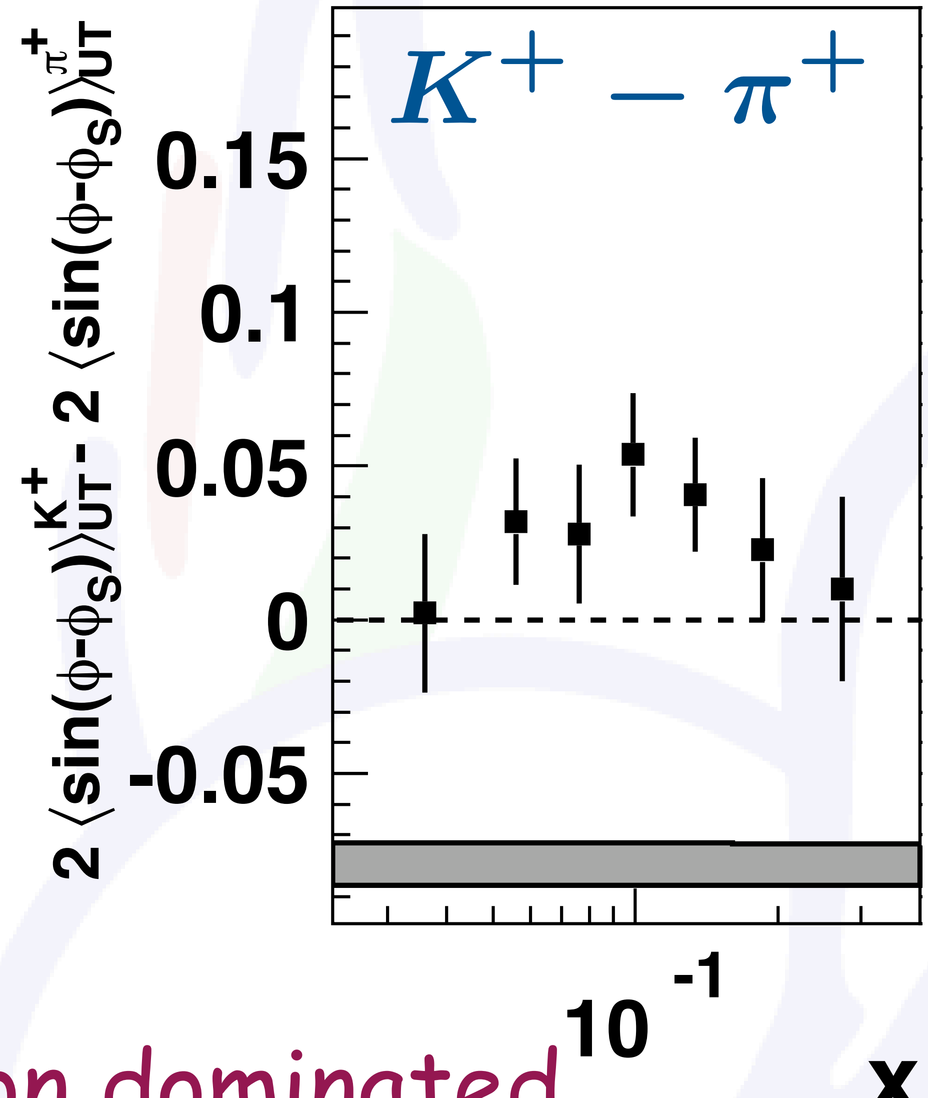

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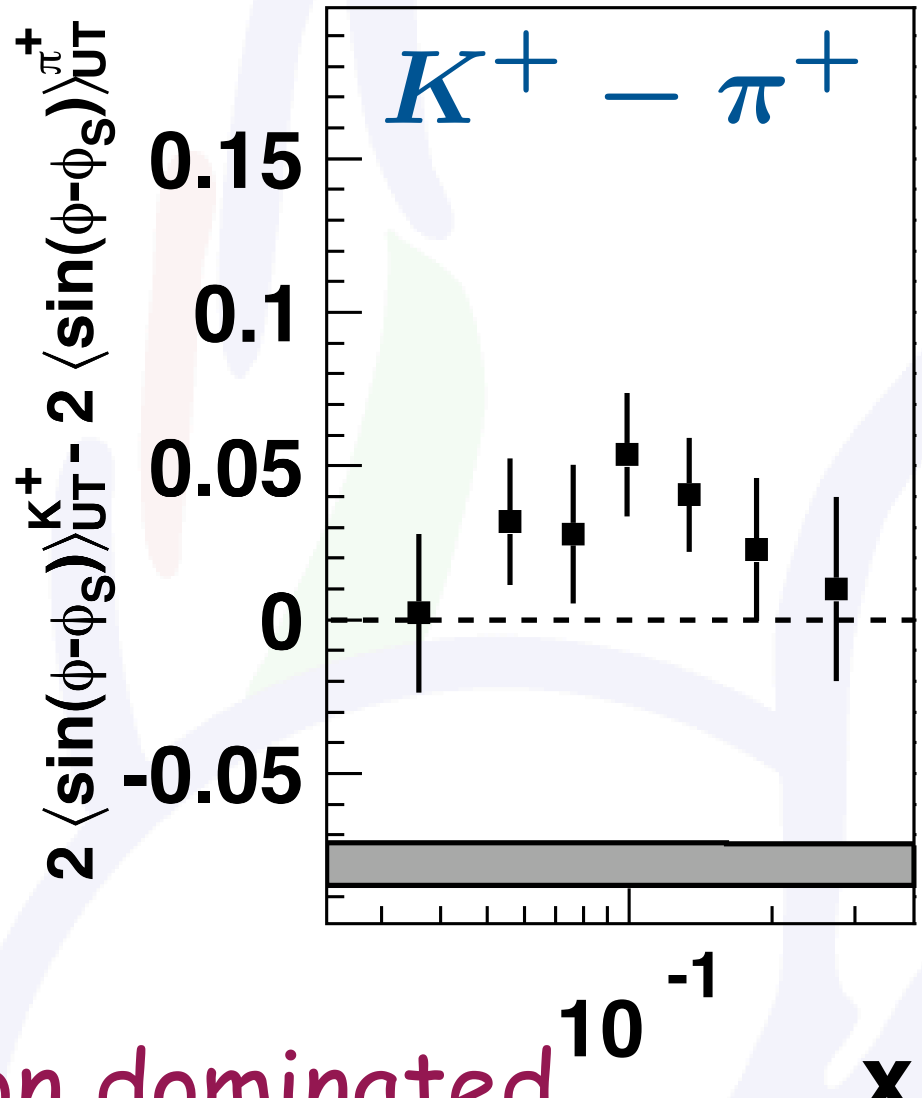

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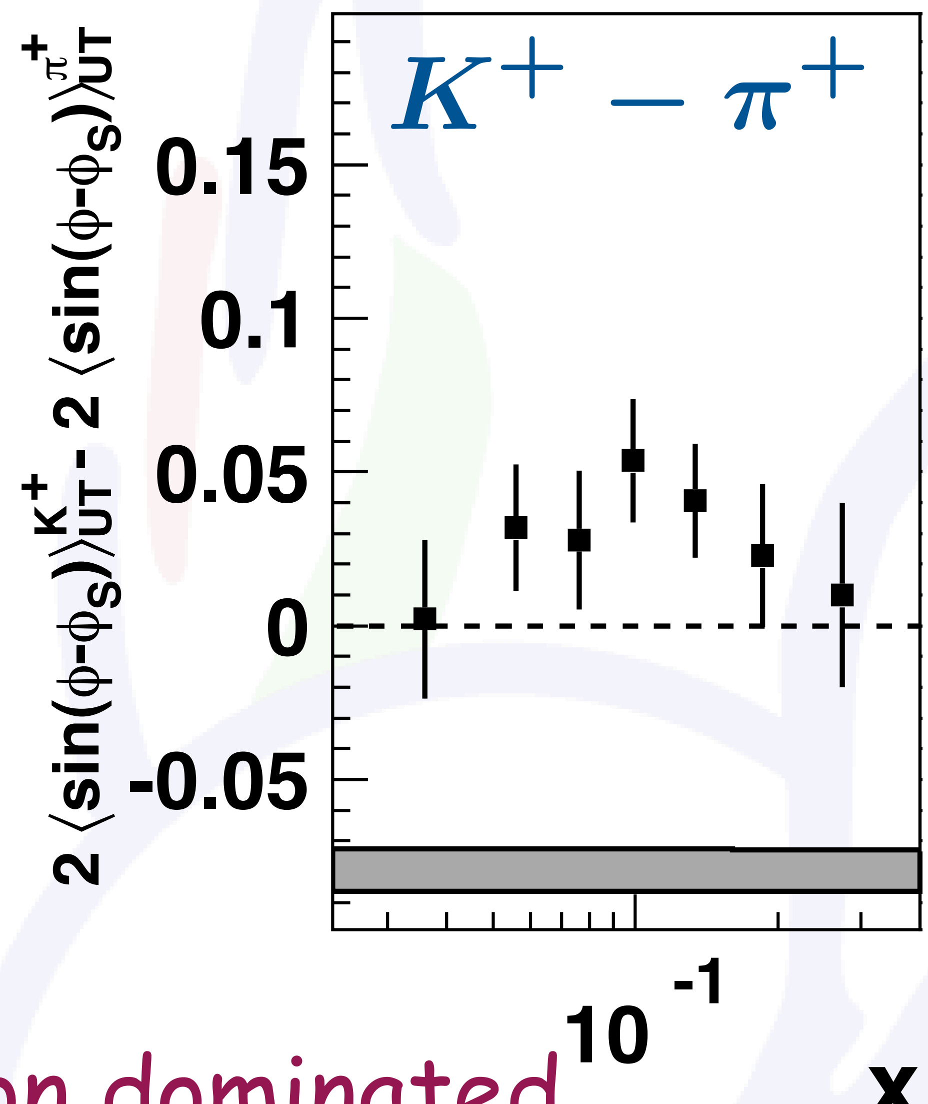
- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ **non-trivial role of sea quarks**

The "Kaon Challenge"



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- convolution integral in numerator depends on K_T dependence of FFs

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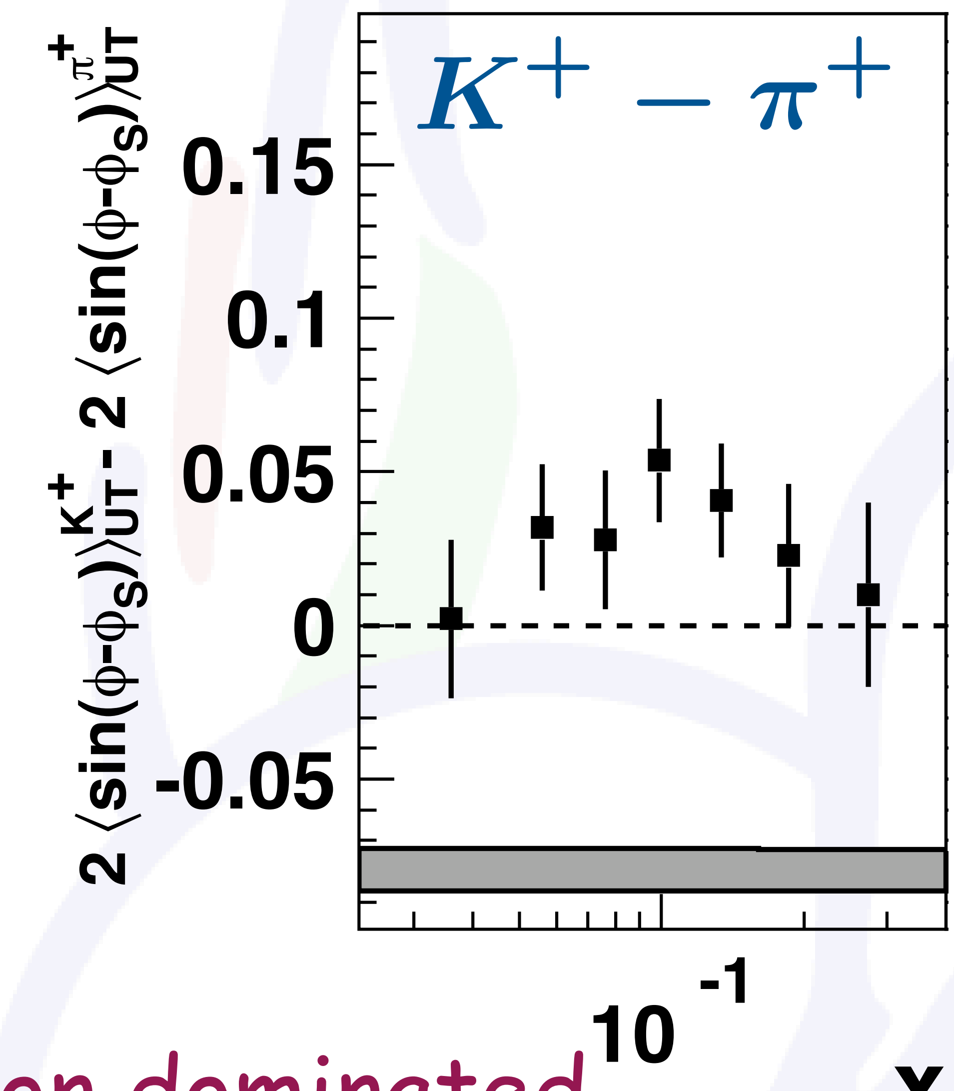

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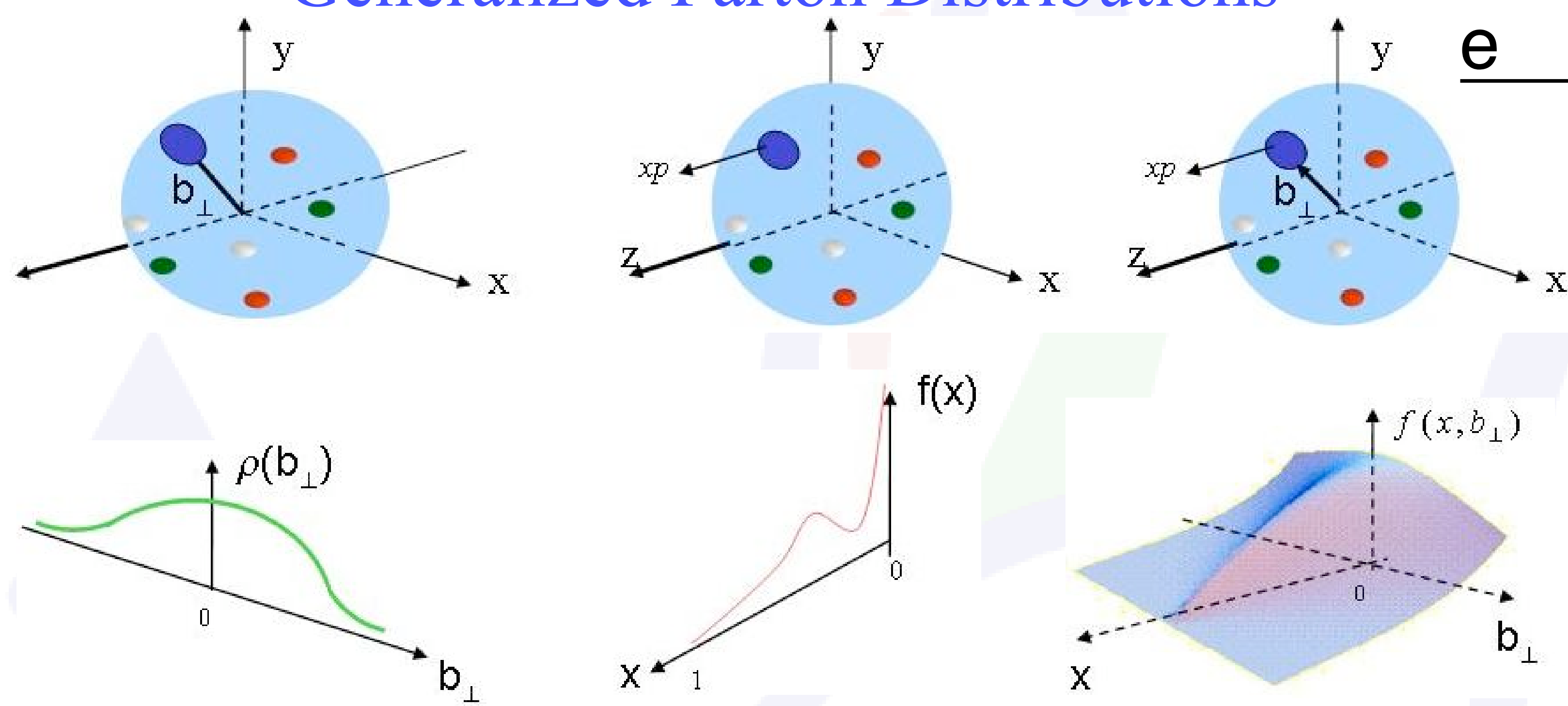
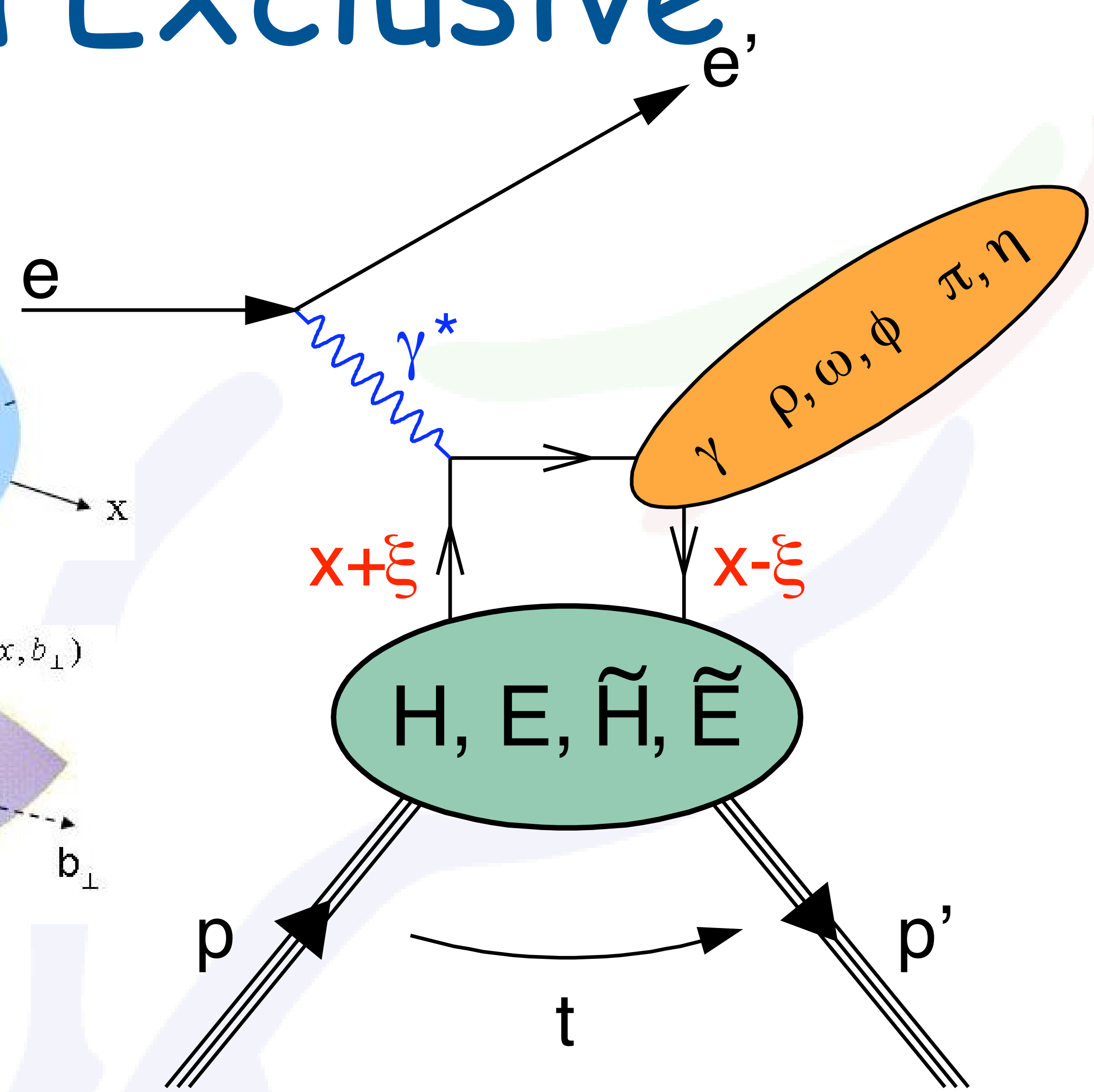
- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks
- convolution integral in numerator depends on K_T dependence of FFs
- difference in dependences on kinematics integrated over

Exclusive Reactions

Probing GPDs in Exclusive

Generalized Parton Distributions





Form factors	Parton Distribution Functions	GPDs
Transverse distribution of quarks in space coordinates	Quark longitudinal momentum fraction distribution in the nucleon	Correlation between transverse position and longitudinal momentum fraction of quark in the nucleon

$$\int dx H^q(x, \xi, t) = F_1^q(t)$$

$$\int dx E^q(x, \xi, t) = F_2^q(t)$$

$$H^q(x, \xi = 0, t = 0) = q(x)$$

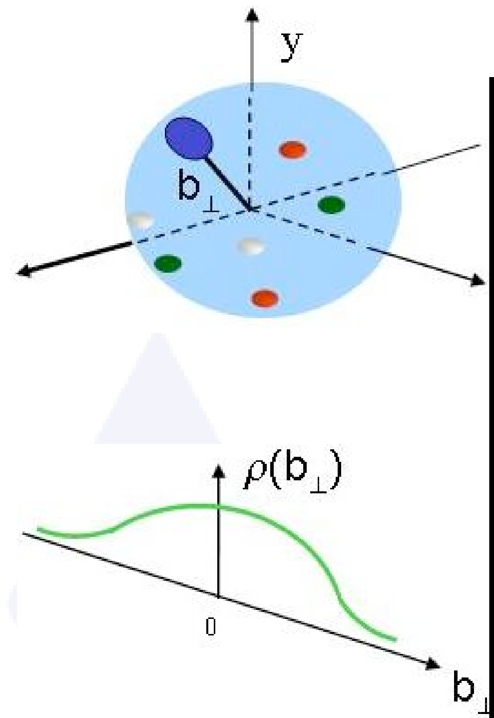
$$\widetilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)$$

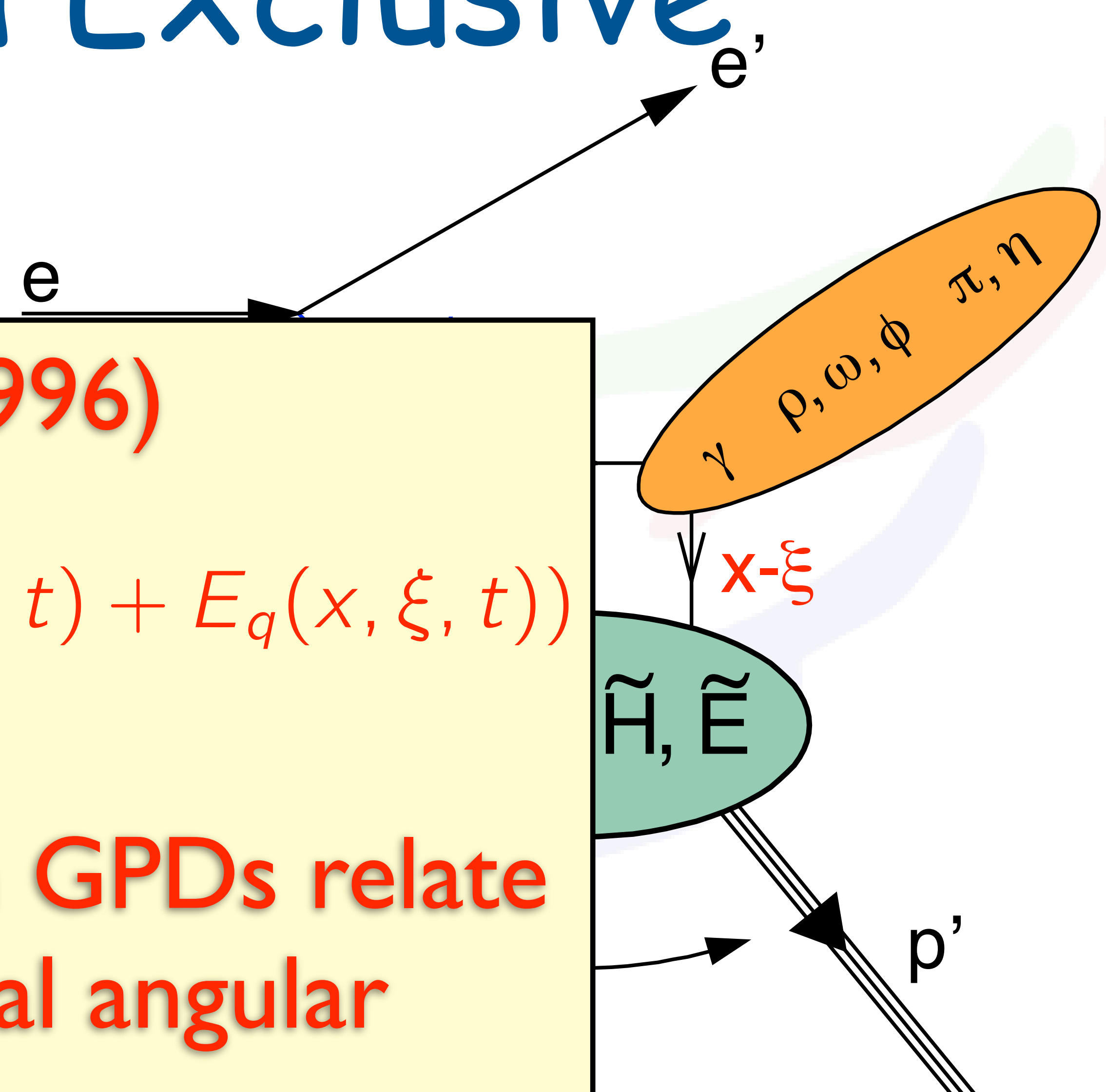
	unpolarized	polarized
no nucleon hel. flip	H	$\widetilde{H}$
nucleon hel. flip	E	$\widetilde{E}$

(+ 4 more chiral-odd functions)

Probing GPDs in Exclusive

Generalized Parton Distributions





Ji relation (1996)

$$J_q = \lim_{t \to 0} \int_{-1}^{1} \mathrm{d}x \, x \, (H_q(x,\xi,t) + E_q(x,\xi,t))$$

➜Moments of certain GPDs relate directly to the total angular

Form factors

Transverse distribution of quarks in space coordinates

Quark longitudinal momentum fraction distribution in the nucleon

Correlation between transverse position and longitudinal momentum fraction of quark in the nucleon

$$\int \mathrm{d}x H^q(x,\xi,t) = F_1^q(t)$$

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$$\widetilde{H}^q(x,\xi=0,t=0) = \Delta q(x)$$

	unpolarized	polarized
no nucleon hel. flip	H	$\widetilde{H}$
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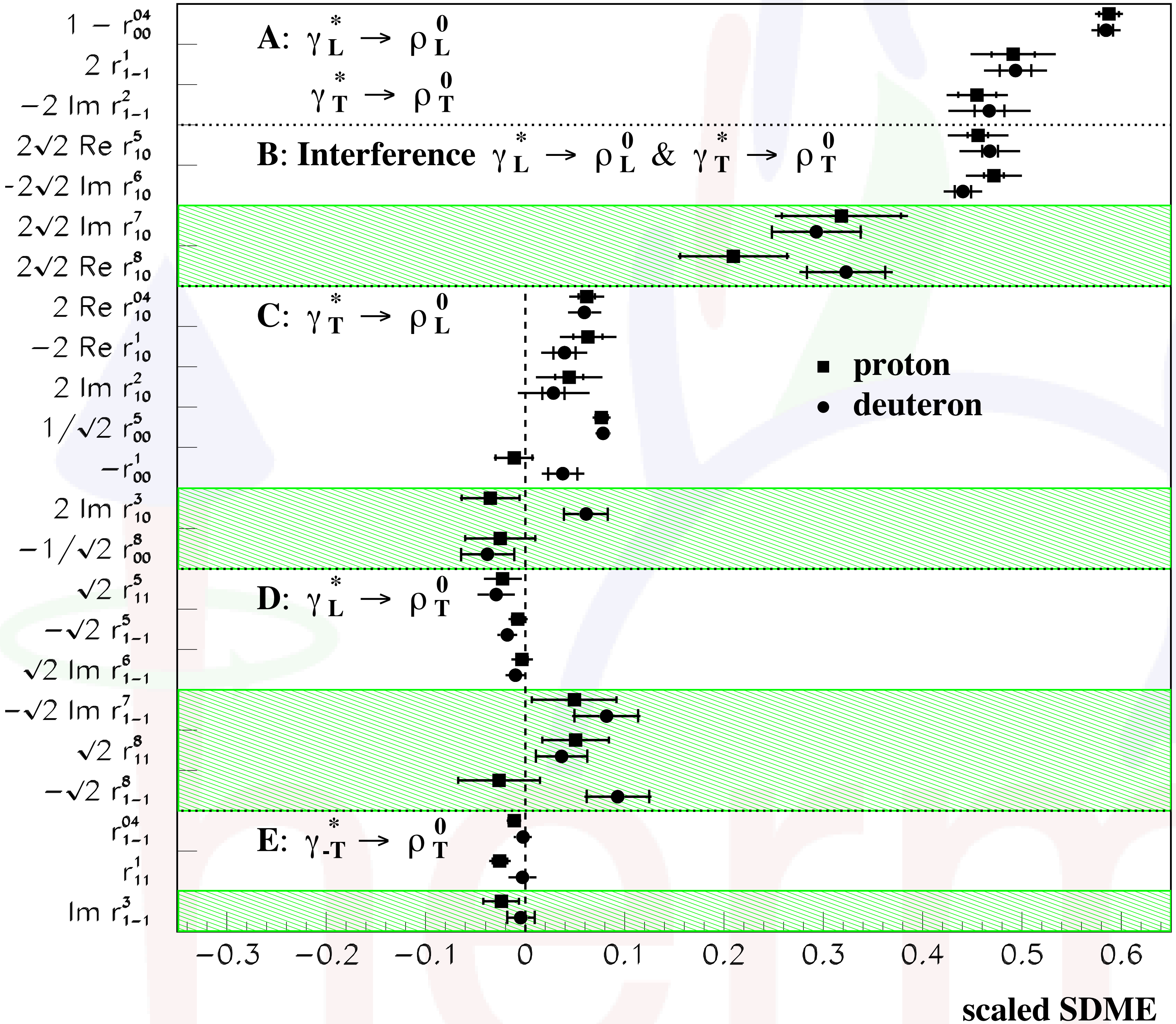
(+ 4 more chiral-odd functions)

ρ^0 SDMEs from HERMES

[*A. Airapetian et al.*, arXiv:0901.0701]



target-polarization independent SDMEs

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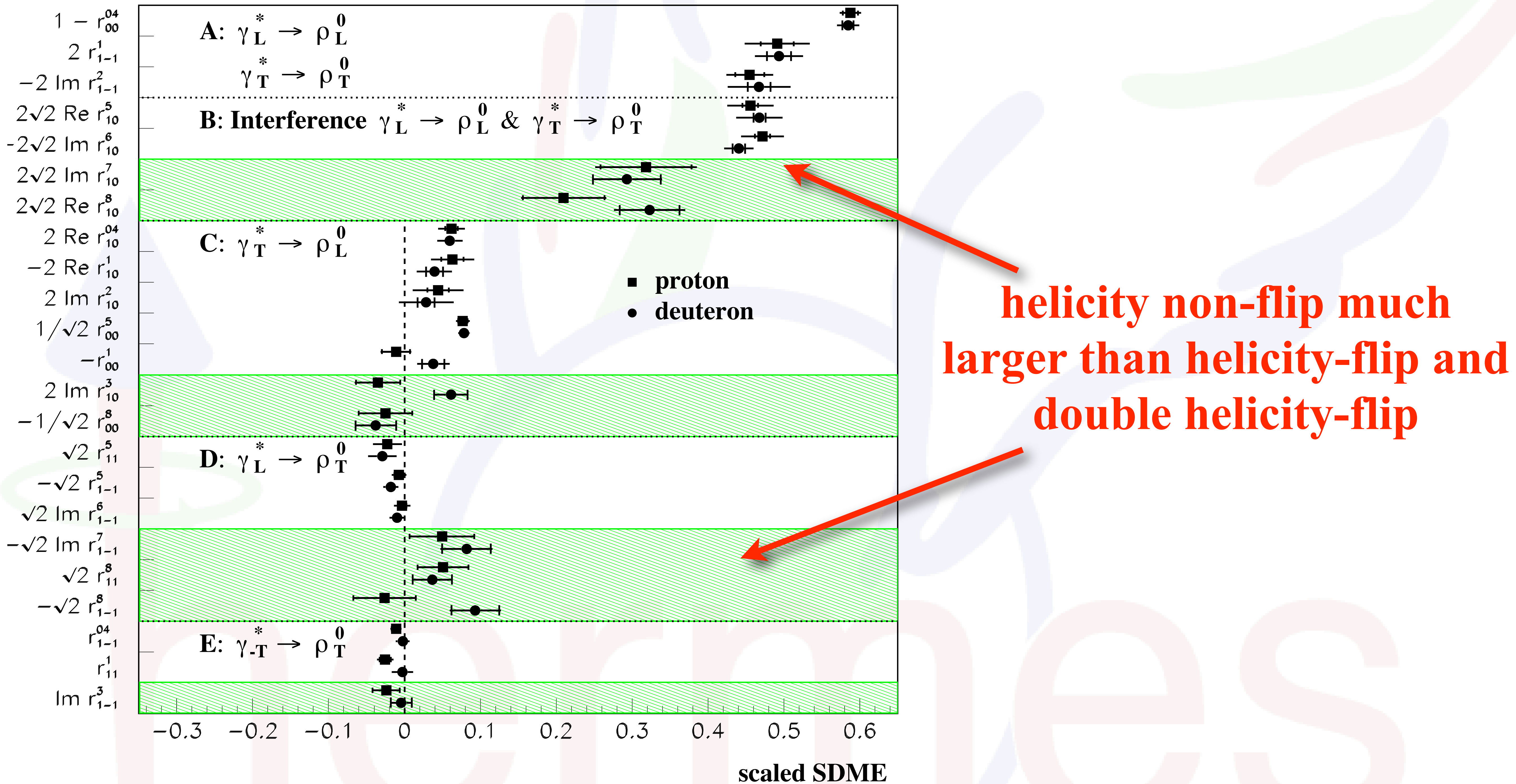

target-polarization independent SDMEs

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[*A. Airapetian et al.*, arXiv:0906.5160]

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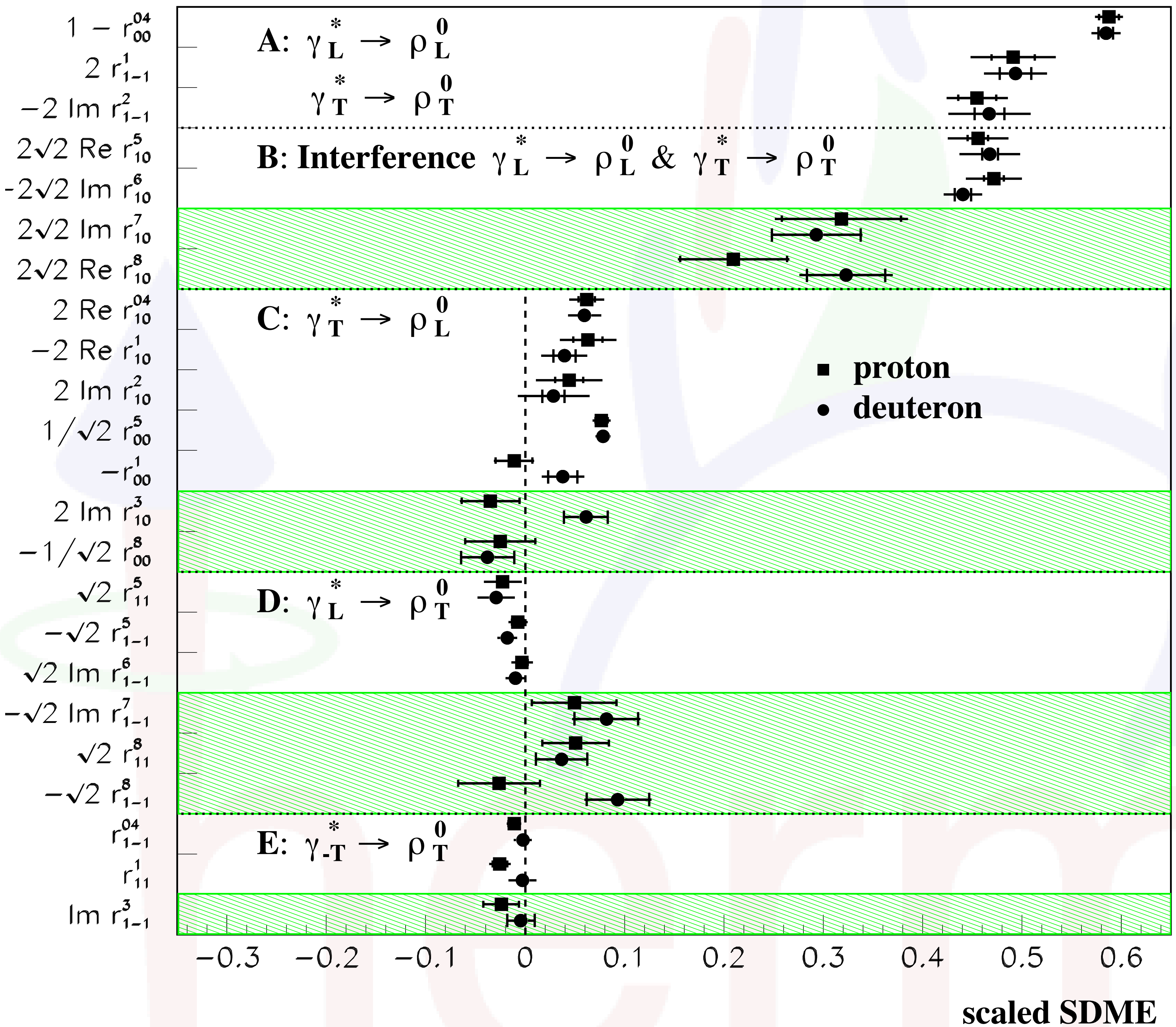
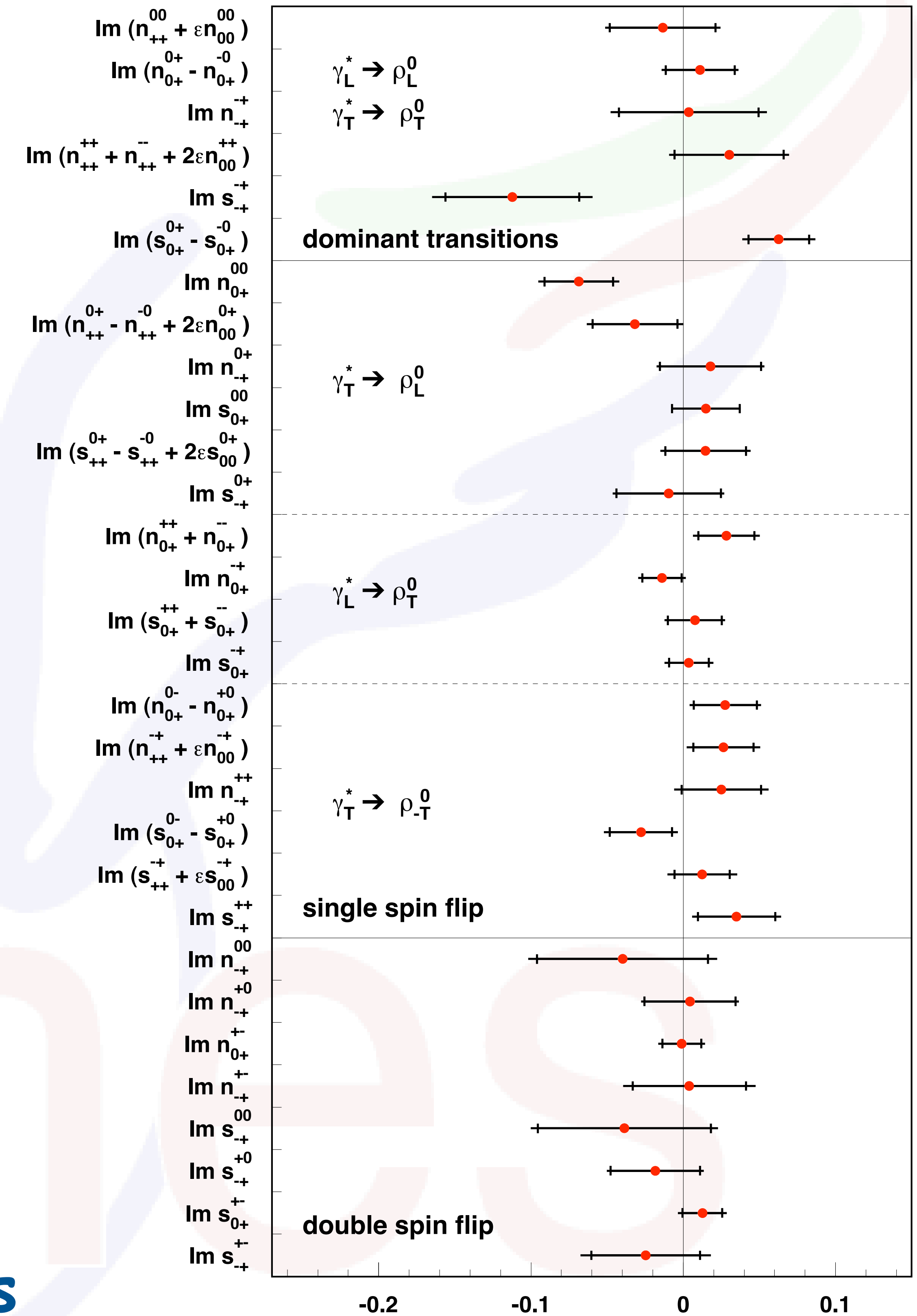


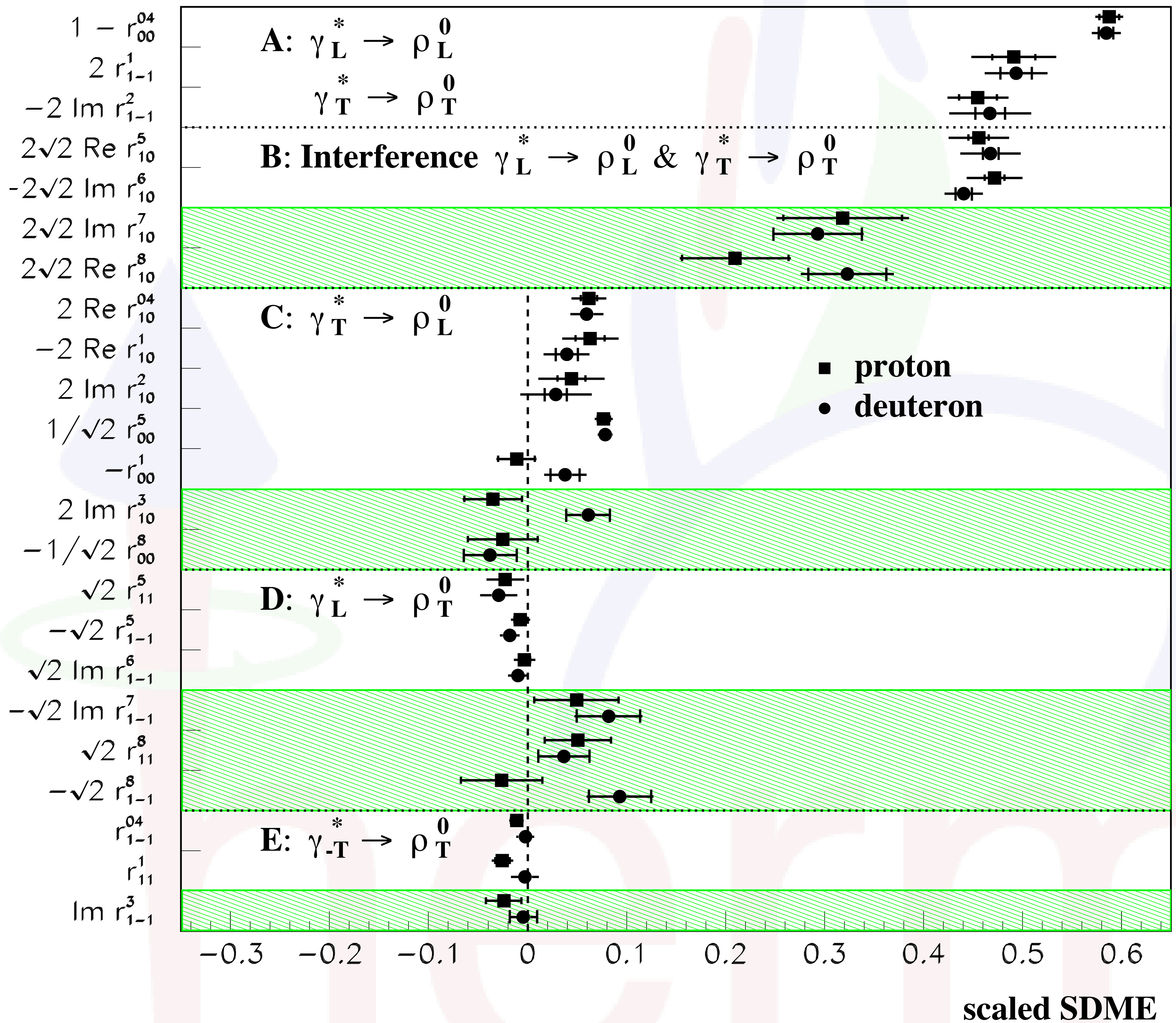


target-polarization independent SDMEs

"transverse" SDMEs

ρ^0 SDMEs from HERMES

[*A. Airapetian et al.*, arXiv:0901.0701]



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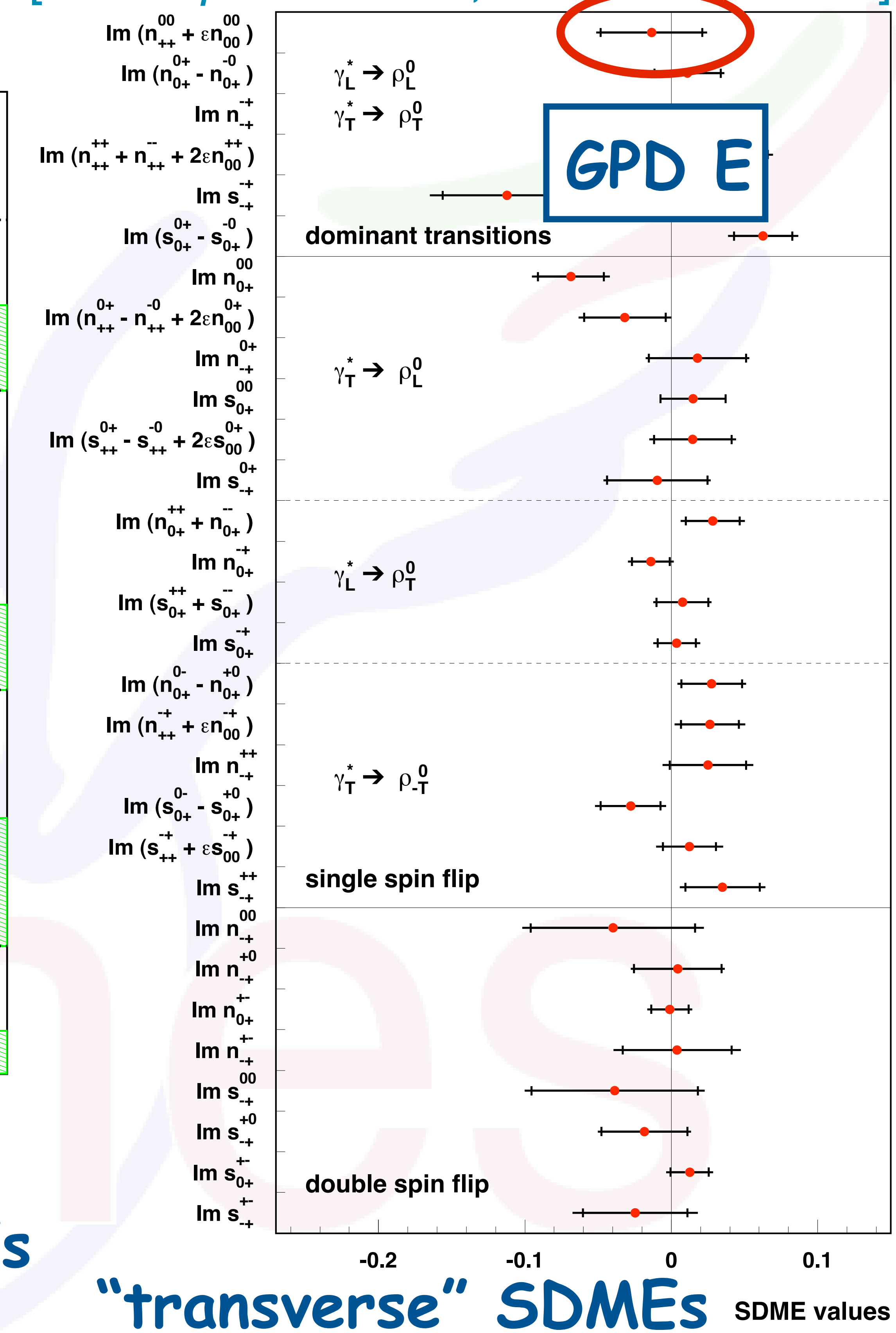

"transverse" SDMEs

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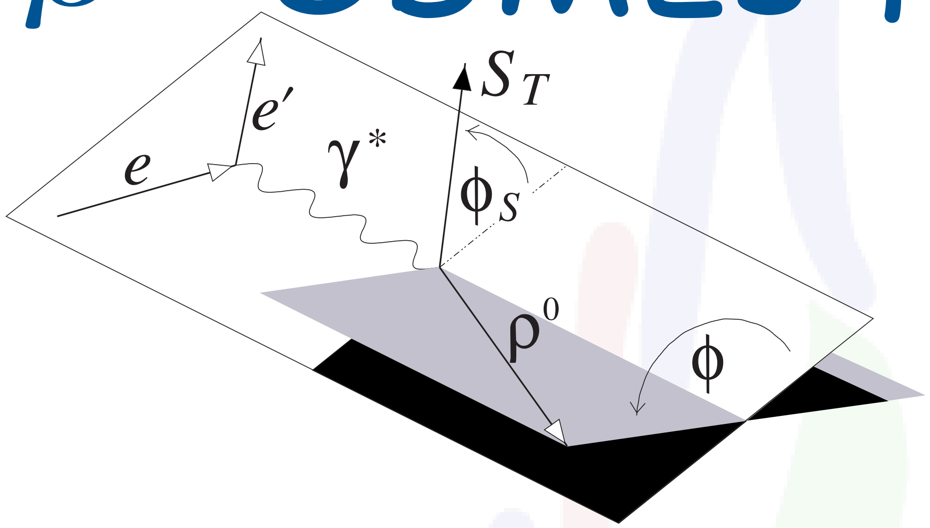

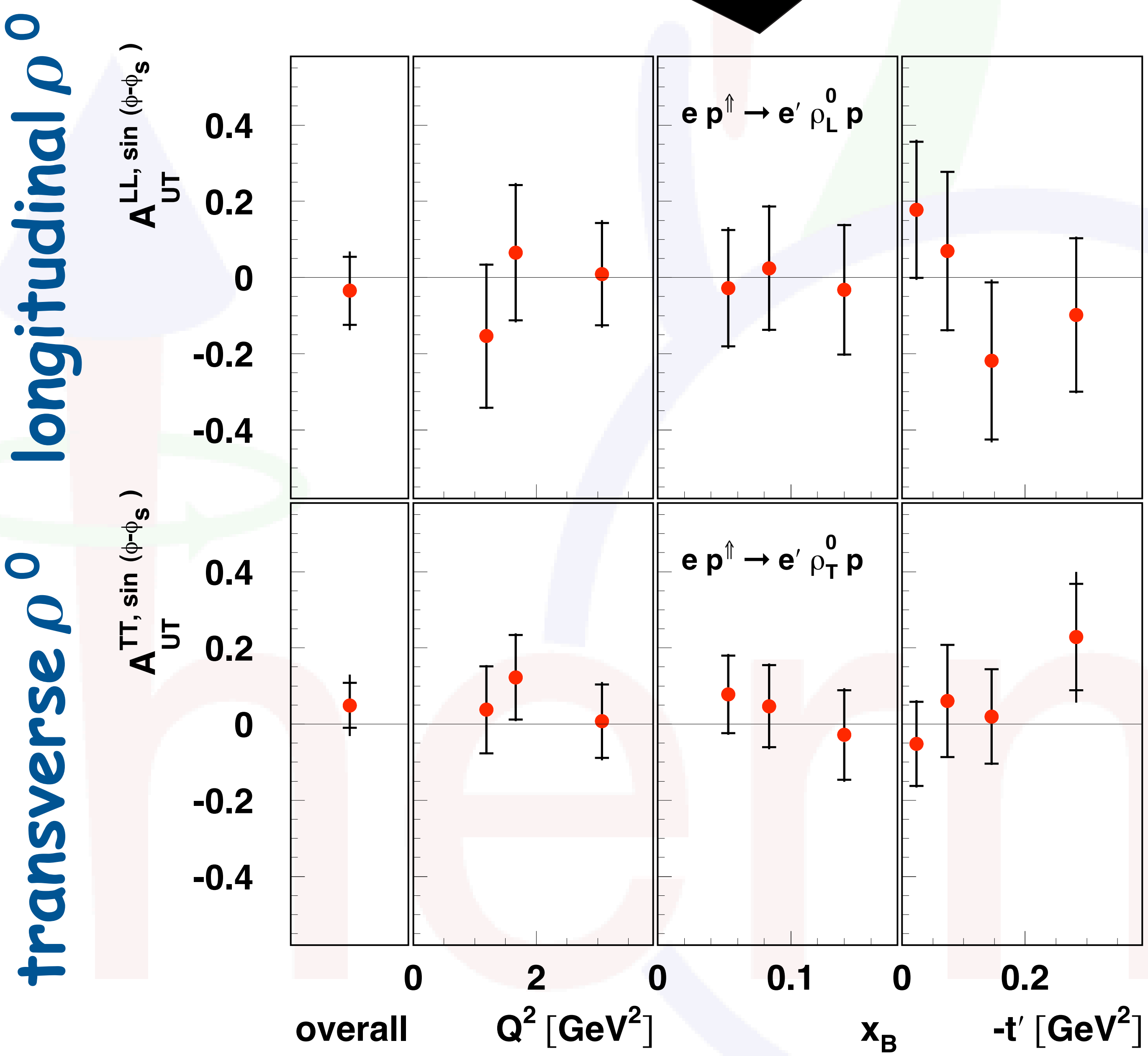

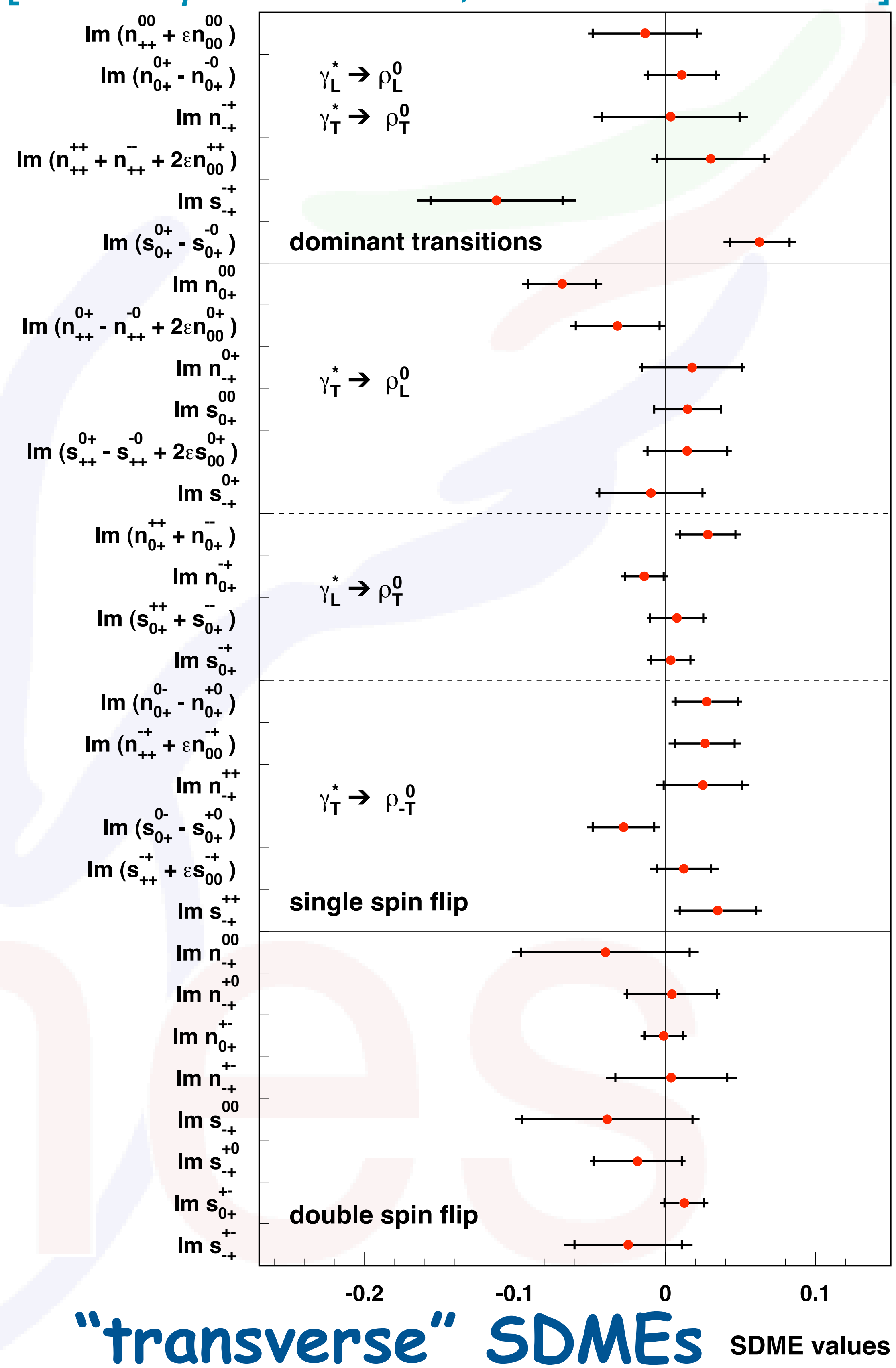

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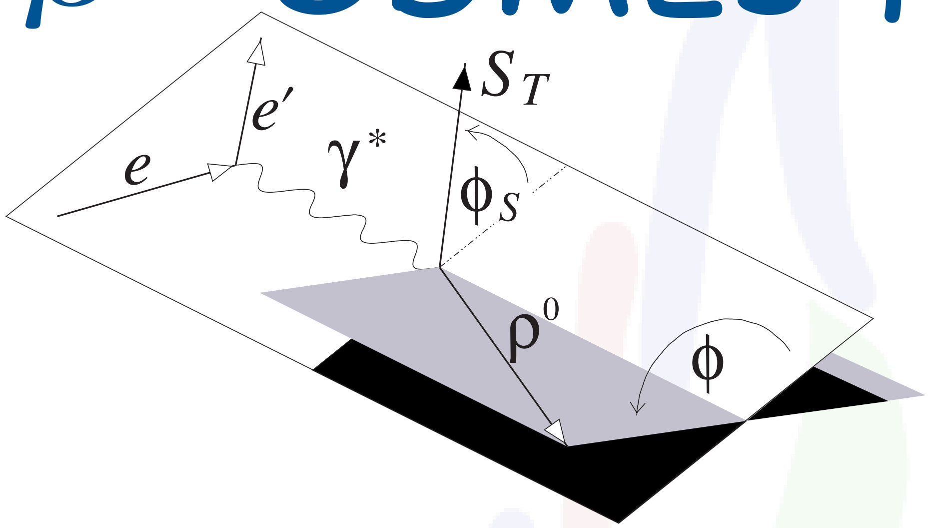

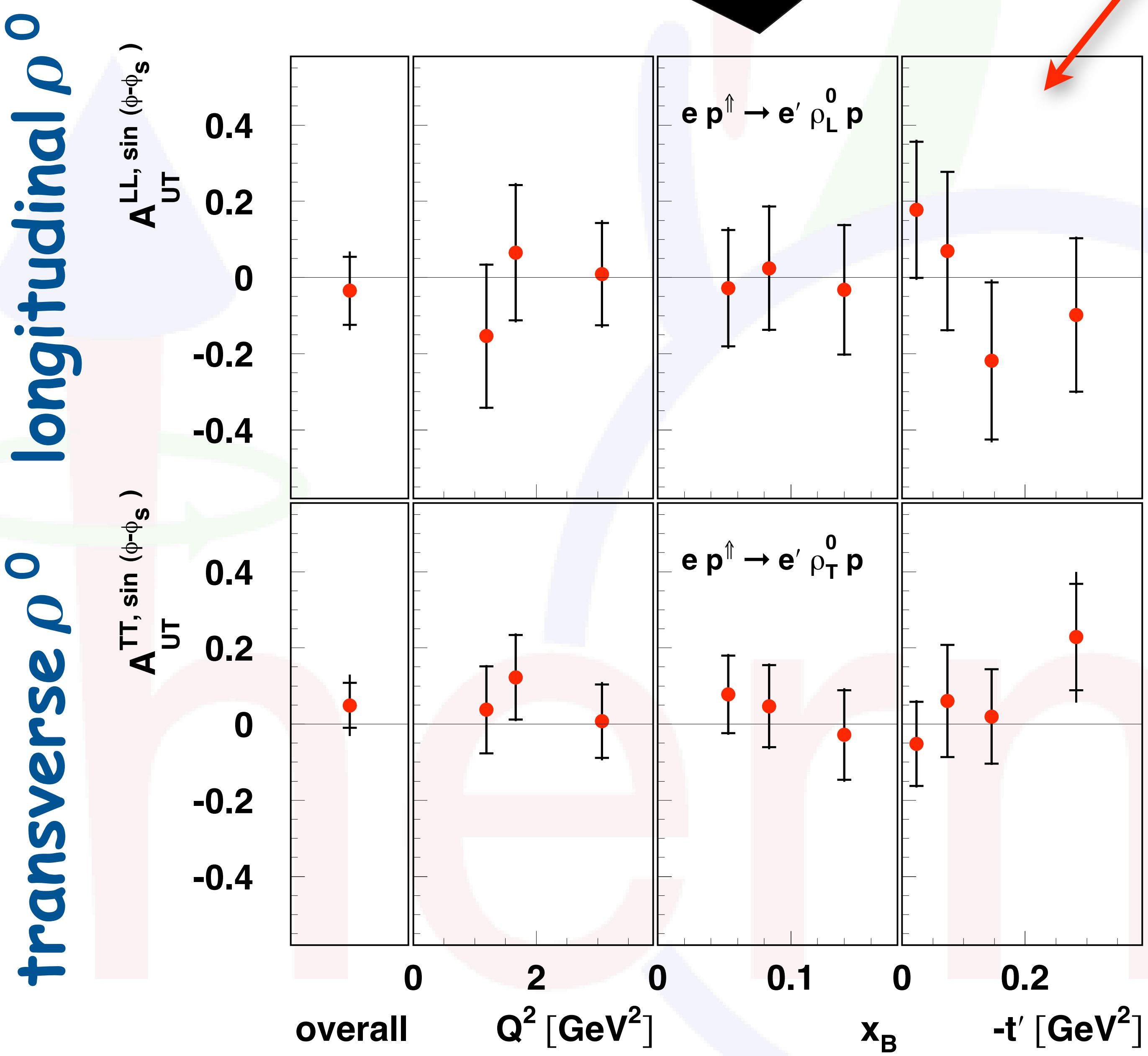

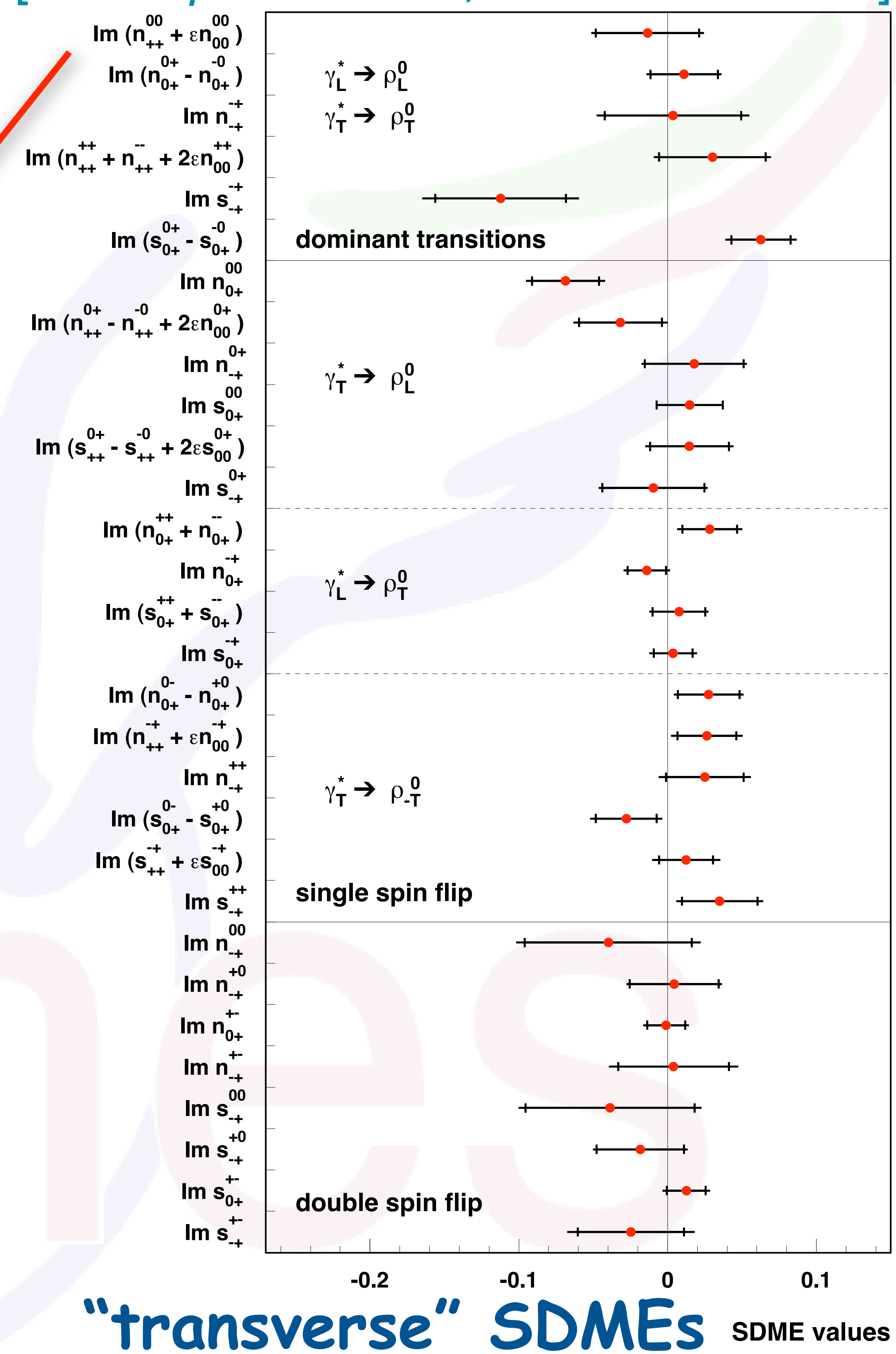

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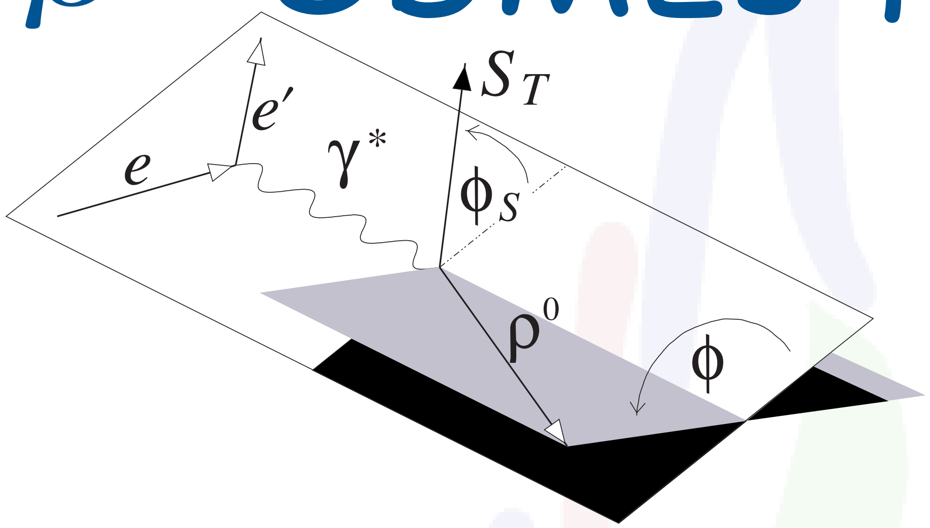
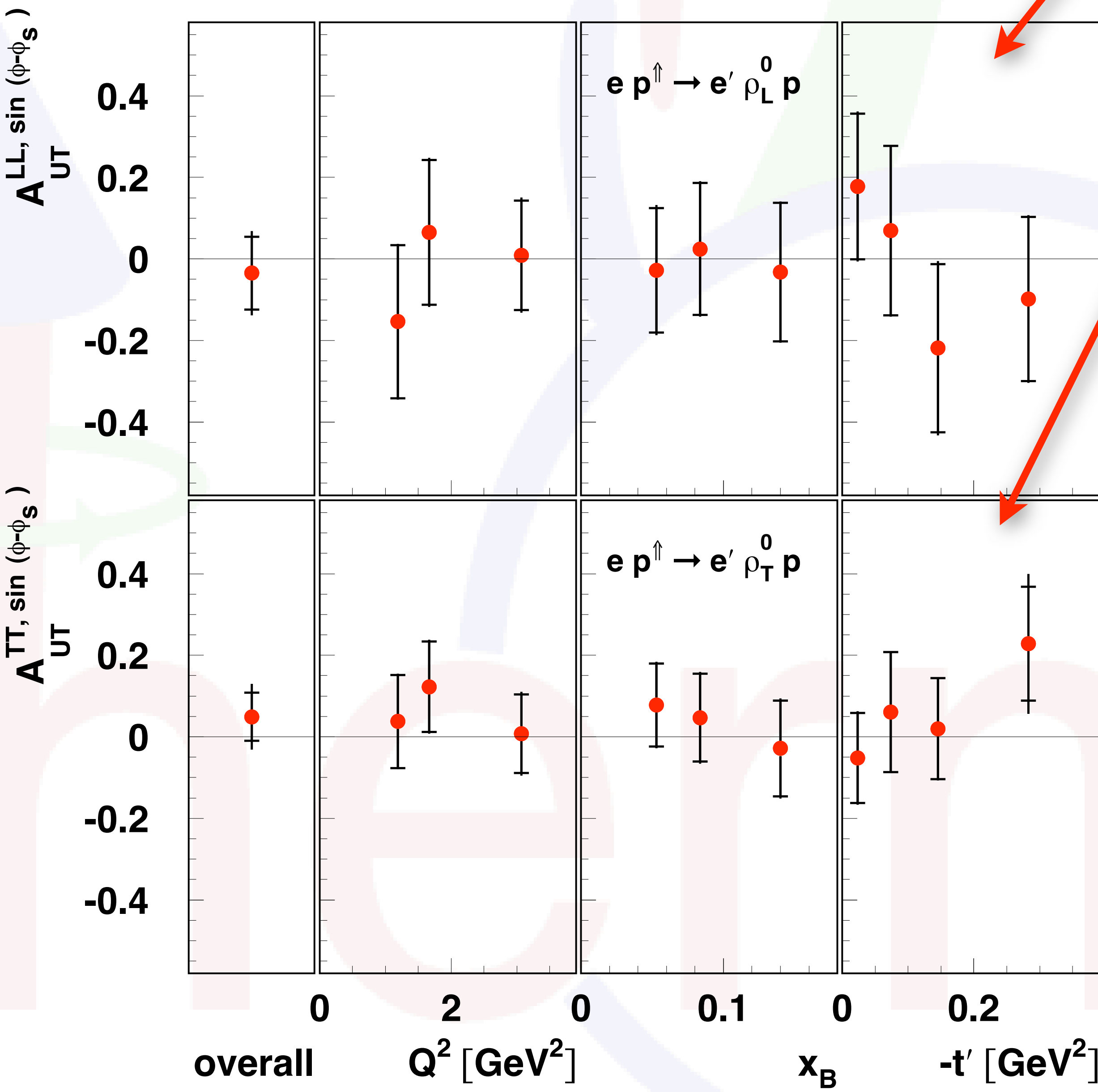
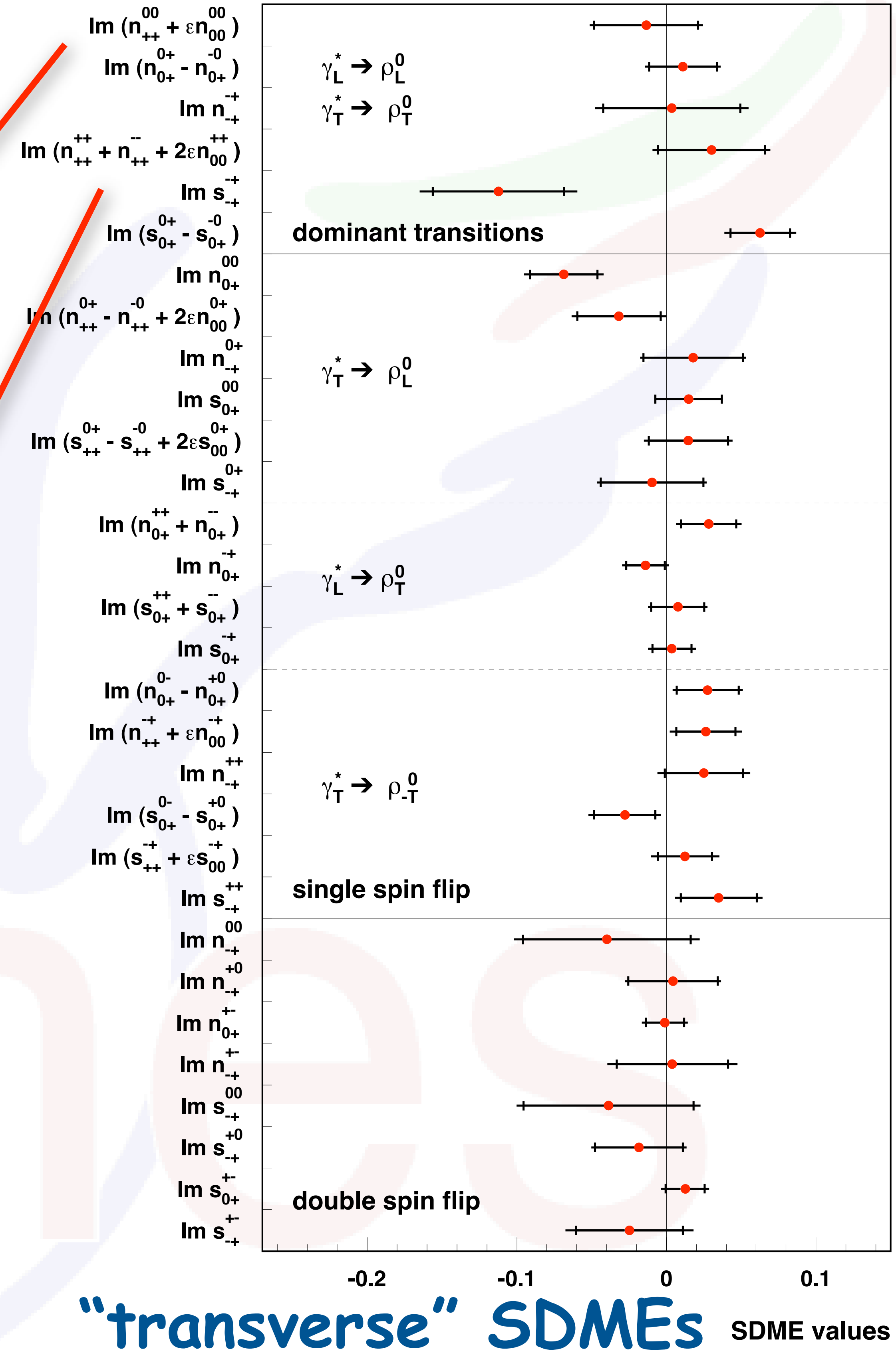


longitudinal ρ^0

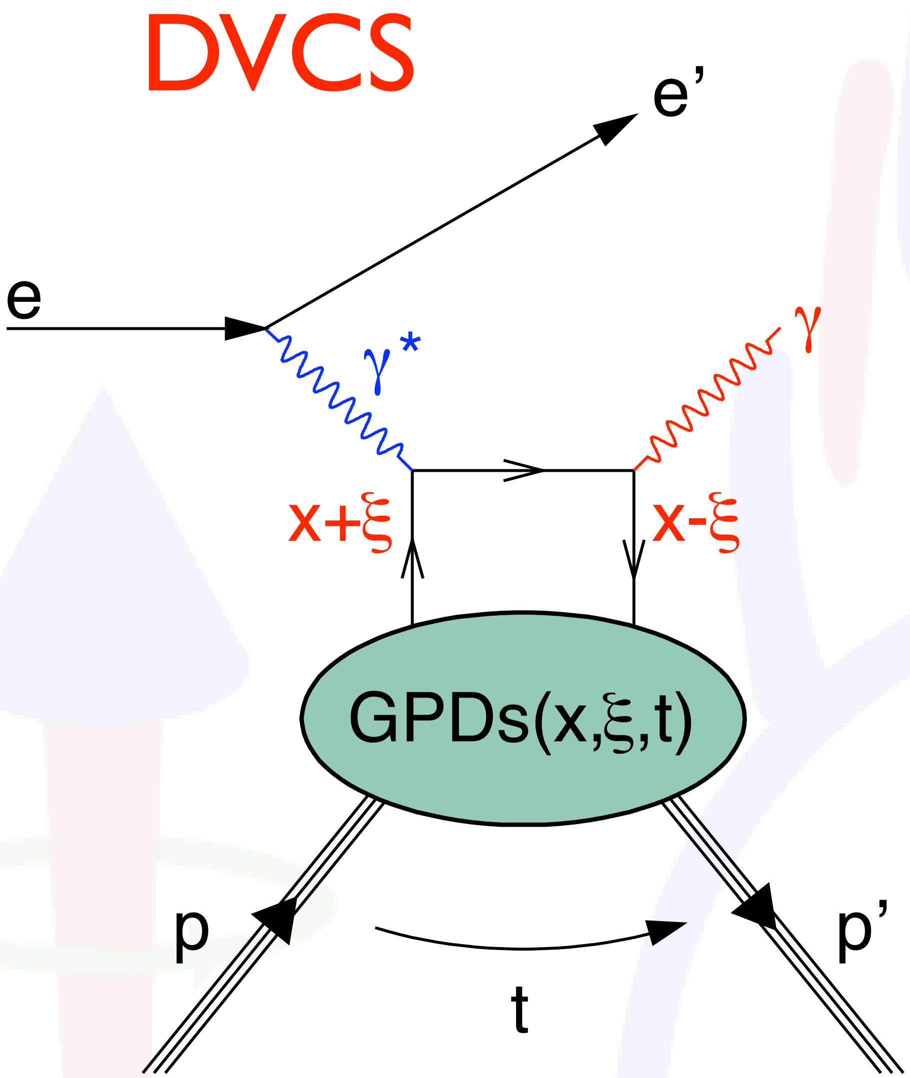
transverse ρ^0

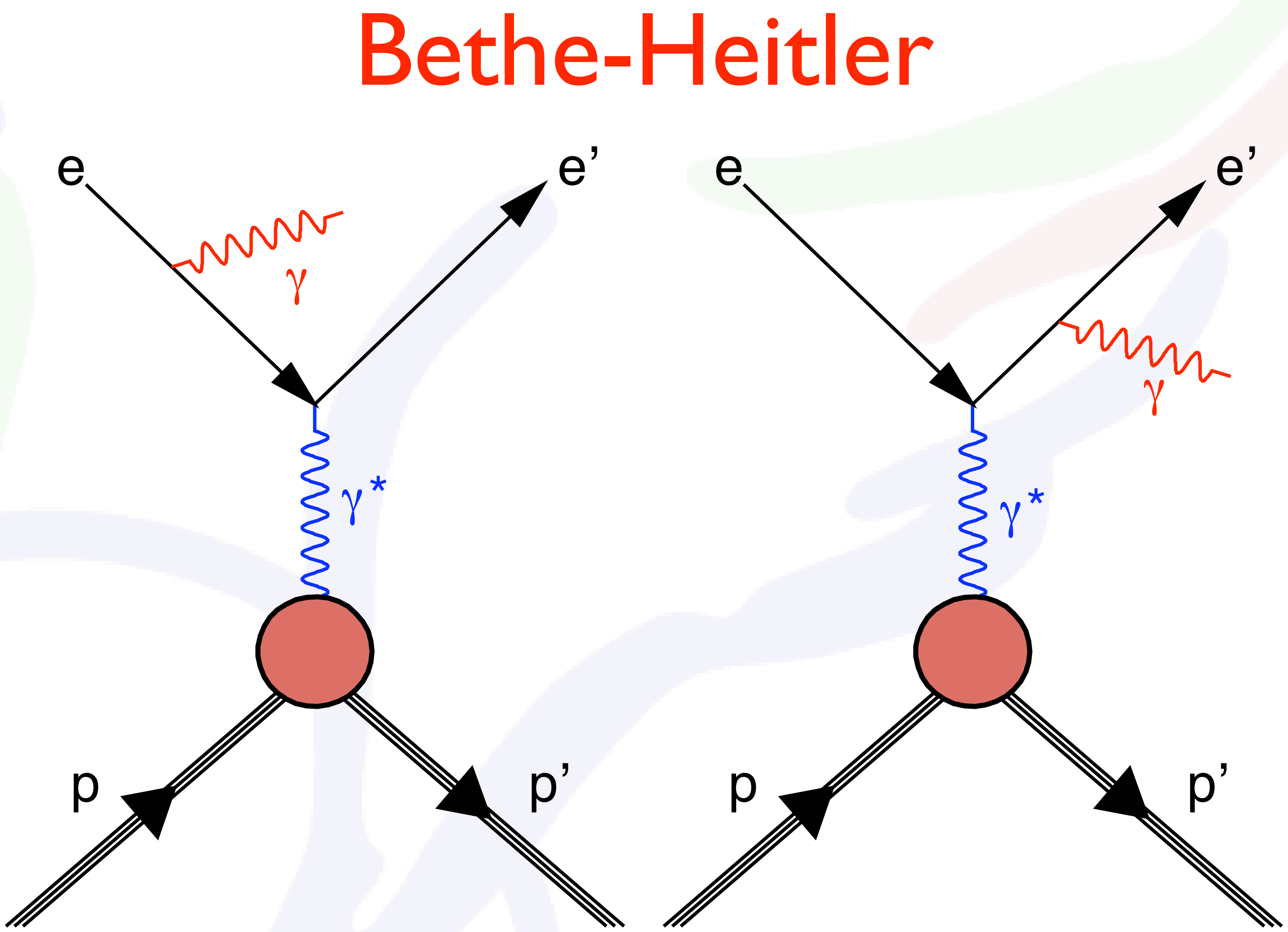




"transverse" SDMEs

DVCS/Bethe-Heitler interference





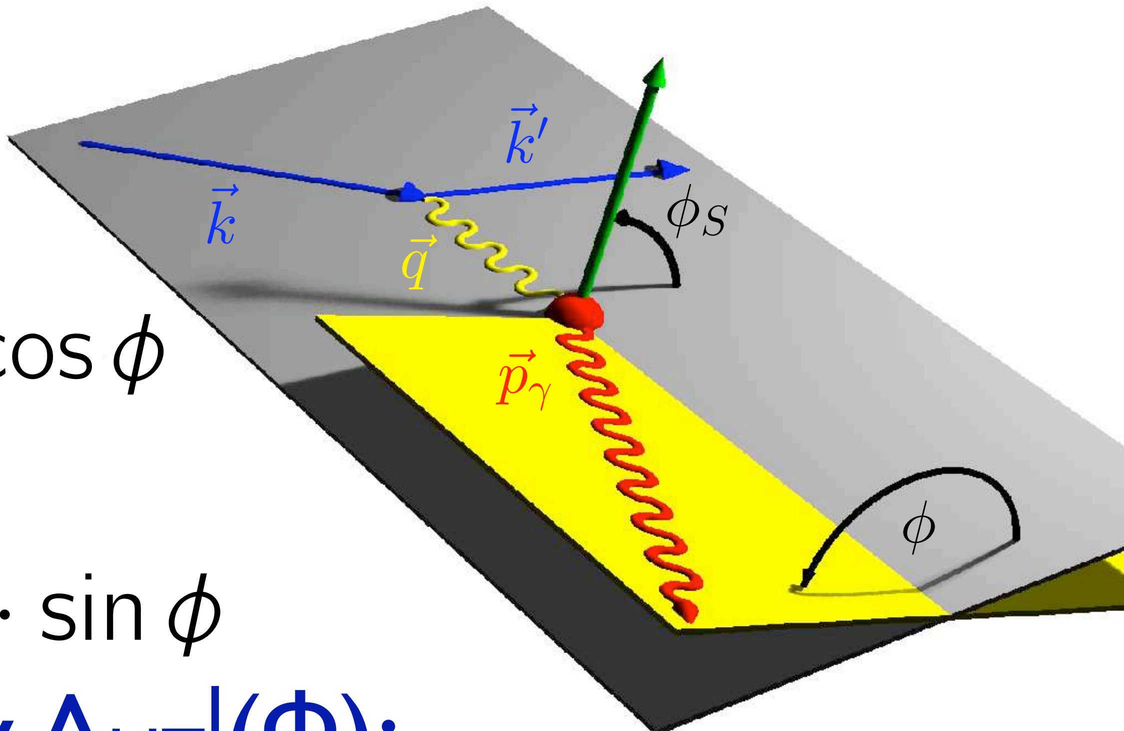
$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} = \frac{y^2}{32(2\pi))^4 \sqrt{1+\frac{4M^2x_B^2}{Q^2}}} \left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$

Azimuthal asymmetries in DVCS

Cross section:

$$\sigma(\phi,\phi_S,P_B,C_B,P_T) = \sigma_{\mathrm{UU}}(\phi)\cdot\Big[1 + P_B\mathcal{A}_{\mathrm{LU}}^{\mathrm{DVCS}}(\phi) + C_B P_B \mathcal{A}_{\mathrm{LU}}^{\mathcal{I}}(\phi) + C_B\mathcal{A}_{\mathrm{C}}(\phi) + P_T\mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi,\phi_S) + C_B P_T \mathcal{A}_{\mathrm{UT}}^{\mathcal{I}}(\phi,\phi_S)\Big]$$

Azimuthal asymmetries:



- **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-helicity asymmetry $A_{LU}^{I}(\Phi)$:**

  $$d\sigma(e^{\rightarrow},\phi) - d\sigma(e^{\leftarrow},\phi) \propto \mathrm{Im}[F_1\mathcal{H}]\cdot\sin\phi$$

- **Transverse target-spin asymmetry $A_{UT}^{I}(\Phi)$:**

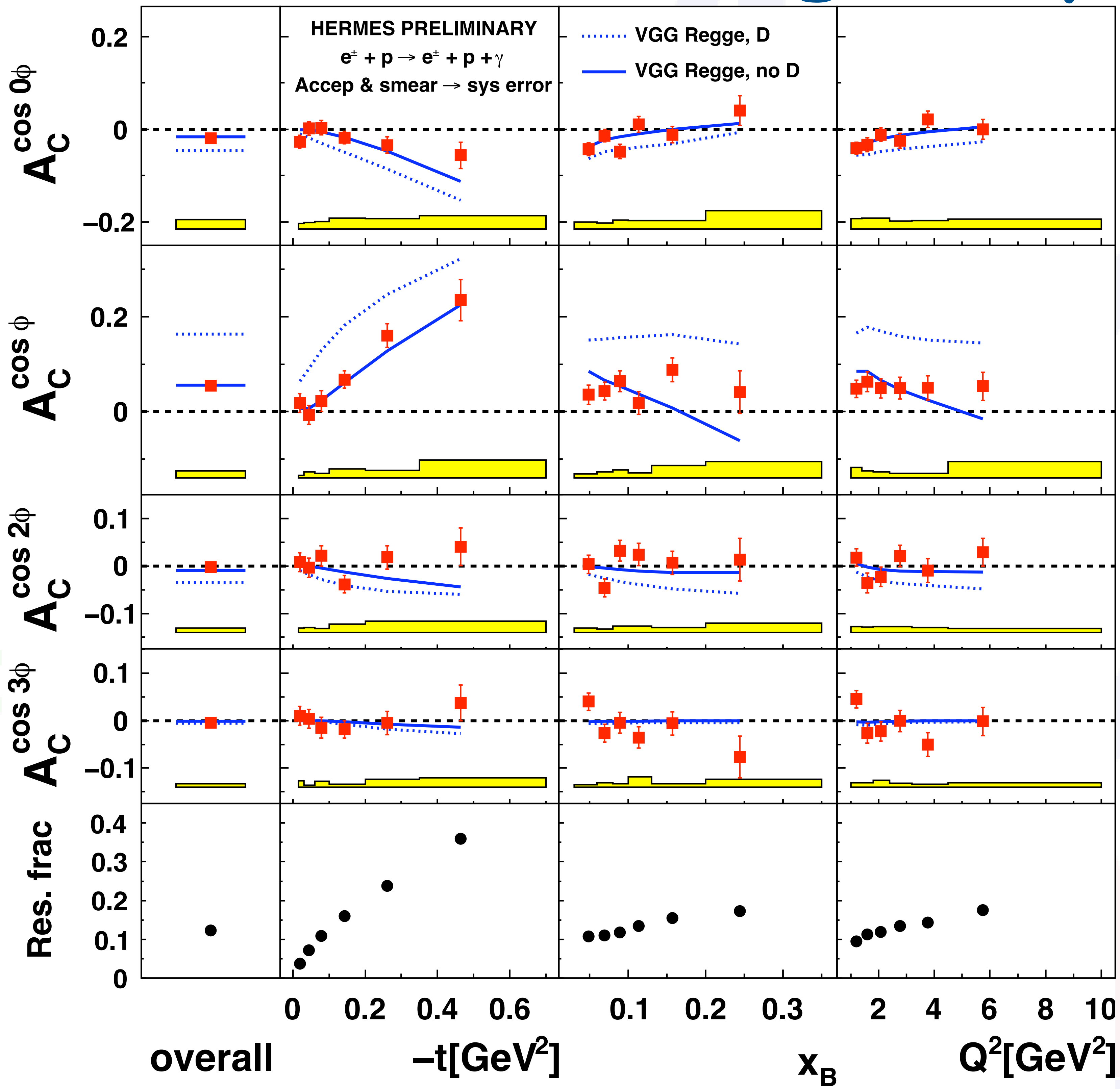
  $$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]\cdot\sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}]\cdot\cos(\phi-\phi_S)\sin\phi$$

(F_1, F_2 are the Dirac and Pauli form factors)

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

Beam-charge asymmetry

All data
1996-2005



constant term

$\propto -A_C^{\cos\phi}$

$\propto \mathrm{Re}[F_1\mathcal{H}]$

[higher twist]

[gluon leading twist]

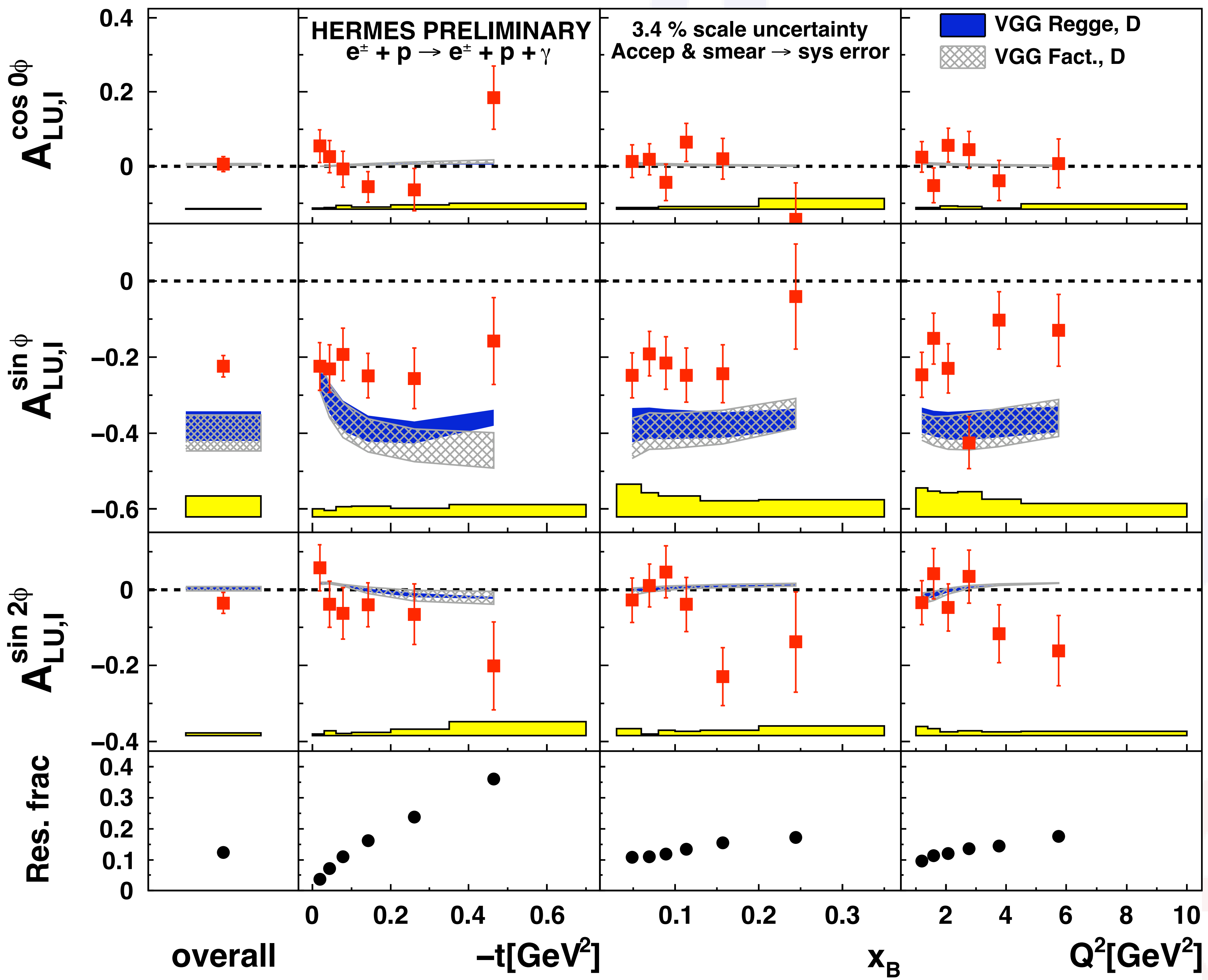
Resonant fraction:

$ep \to e\Delta^+\gamma$

GPD model: "VGG" Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

Beam-spin asymmetry

All data 1996-2005



$\propto \mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

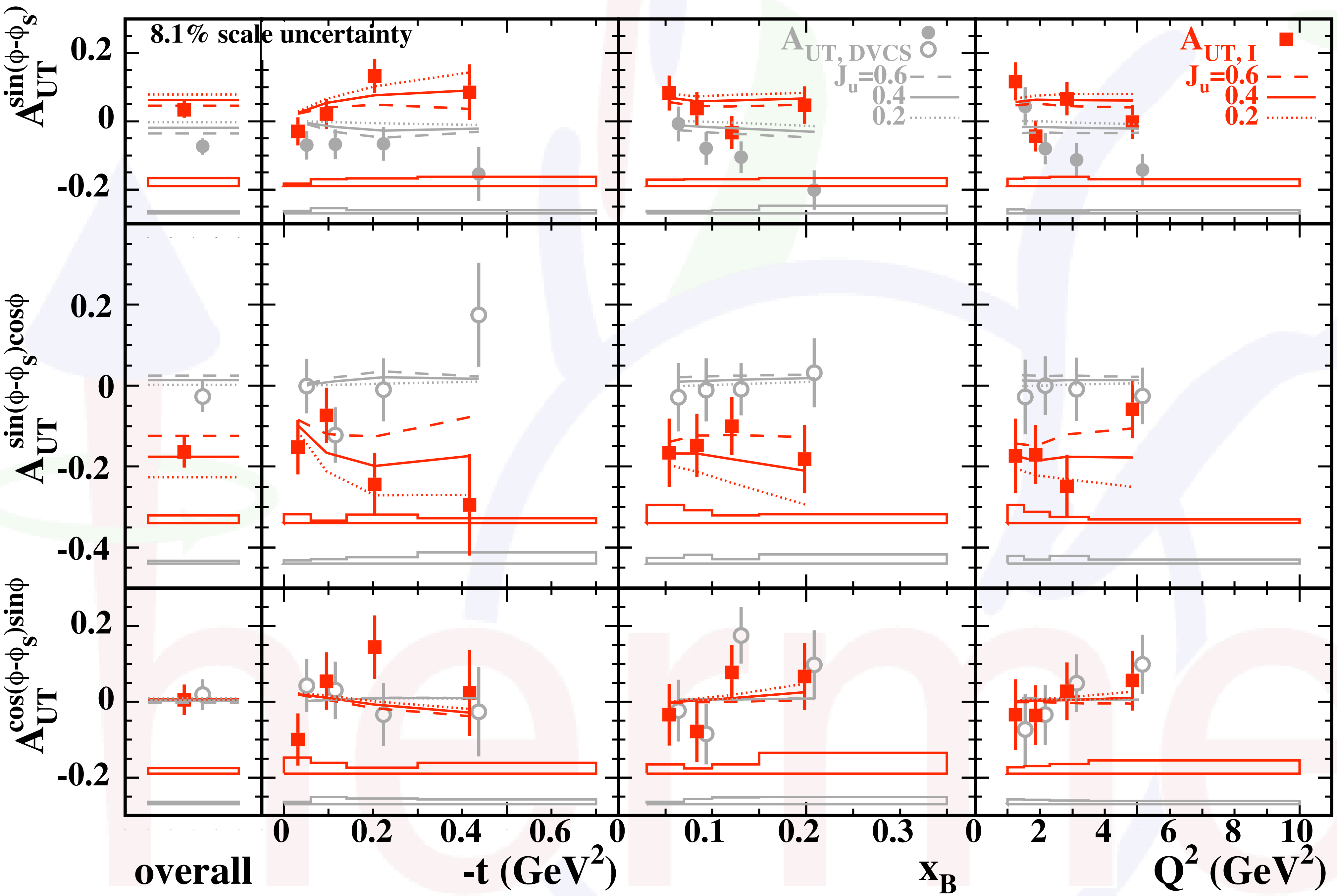
Resonant fraction:

$ep \to e\Delta^+\gamma$

GPD model: "VGG" Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

Transverse target-spin asymmetry

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



$\propto -A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$

$\propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]$

$\propto \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}]$

GPD model: "VGG" Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

Transverse target-spin asymmetry

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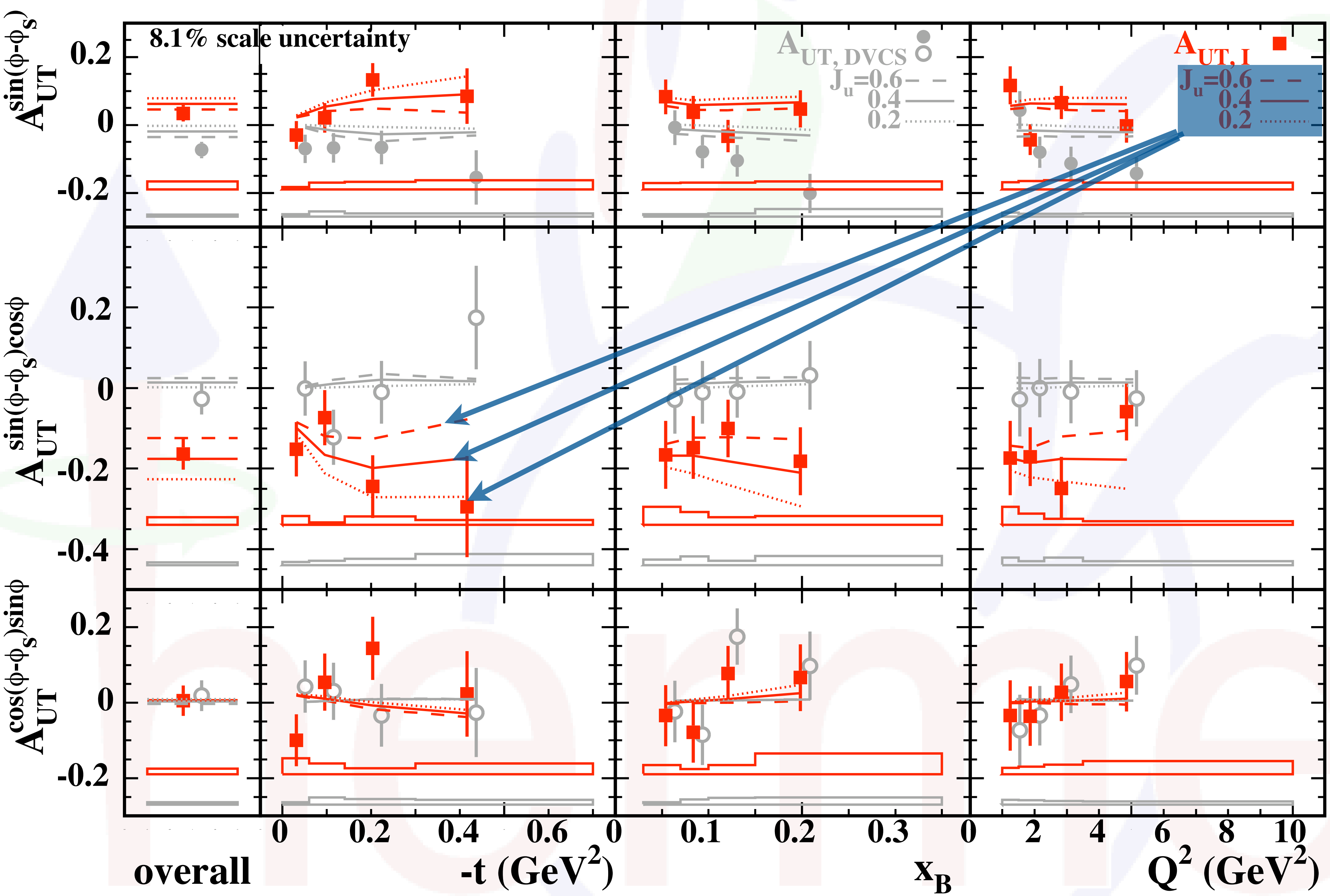


$\propto -A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$

$\propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}]$

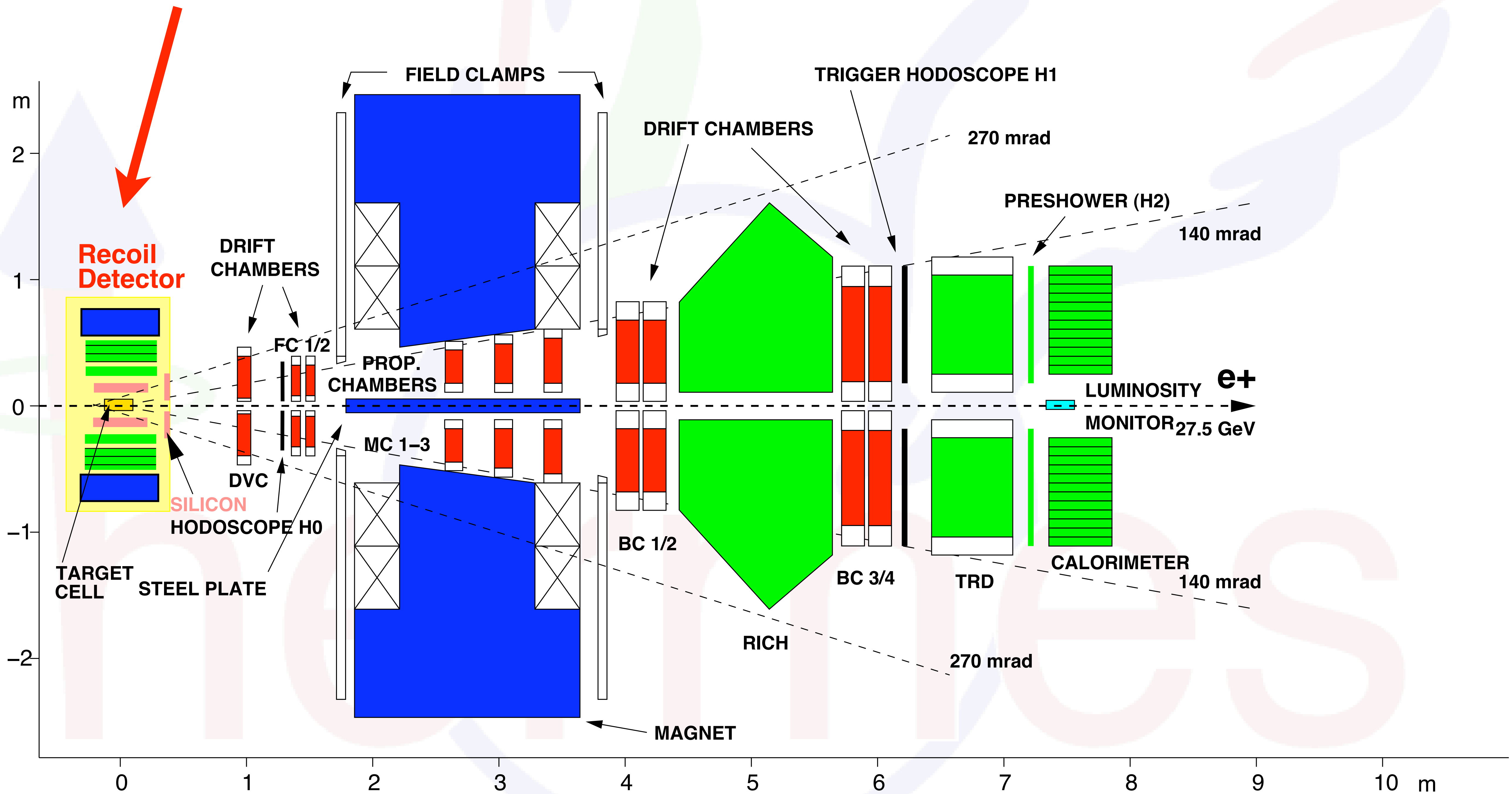
$\propto \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}]$

GPD model: "VGG" Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

Outlook

HERMES detector (2006/07)

detection of recoiling proton



DVCS event selection

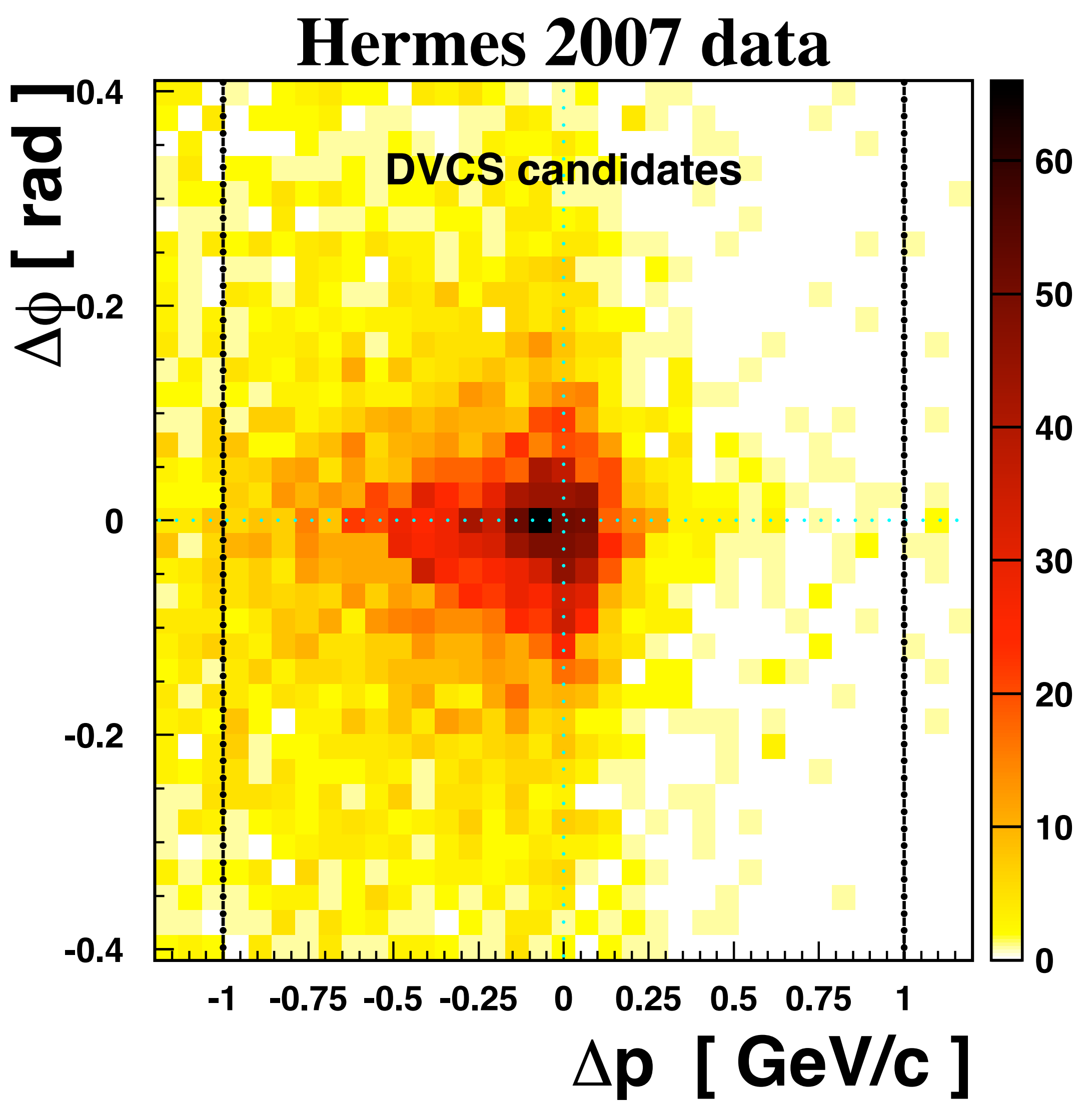
measured with RD

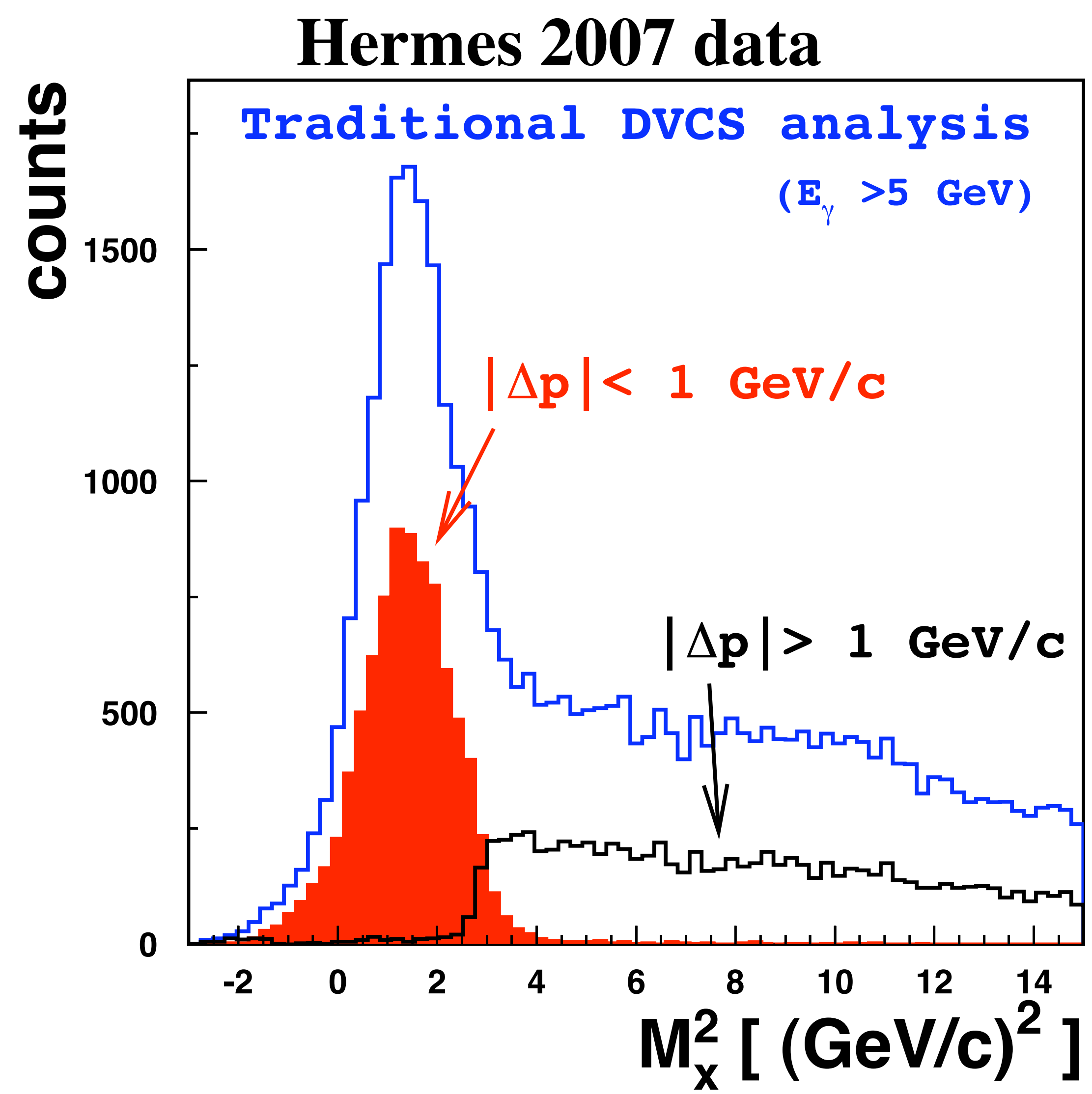
inferred from forward spectrometer

- **Missing** ϕ**:** $\Delta\phi = \phi_{\rm meas} - \phi_{\rm calc}$
- **Missing** p**:** $\Delta p = p_{\rm meas} - p_{\rm calc}$

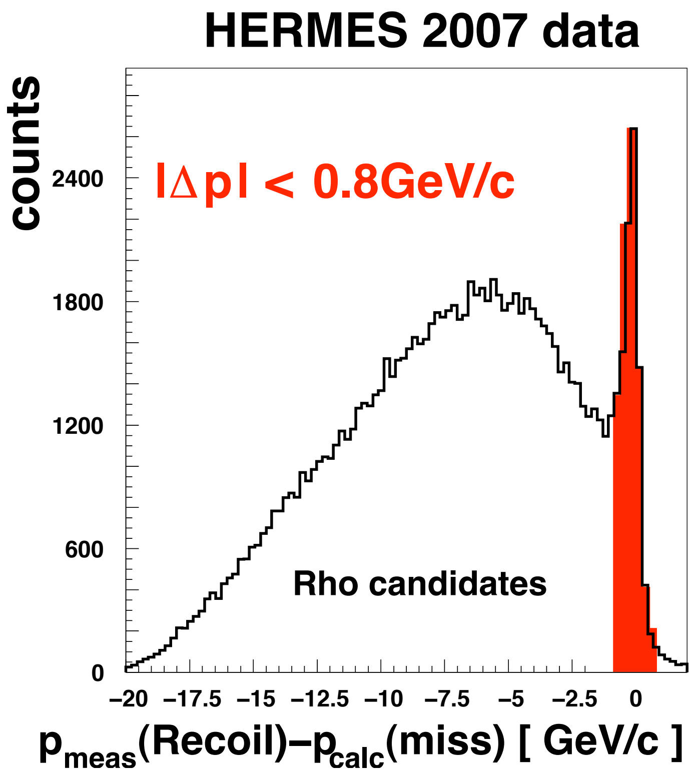
Missing Mass ($\approx M_P^2$)**:**

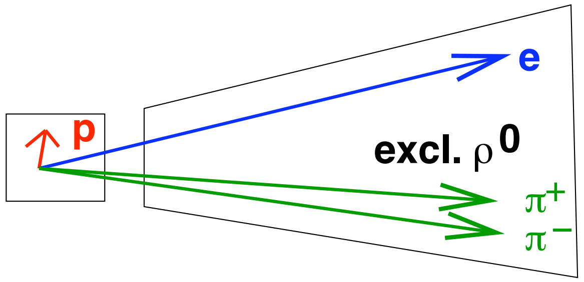
$$M_X^2 = (p + p_{\gamma^*} - p_\gamma)^2$$

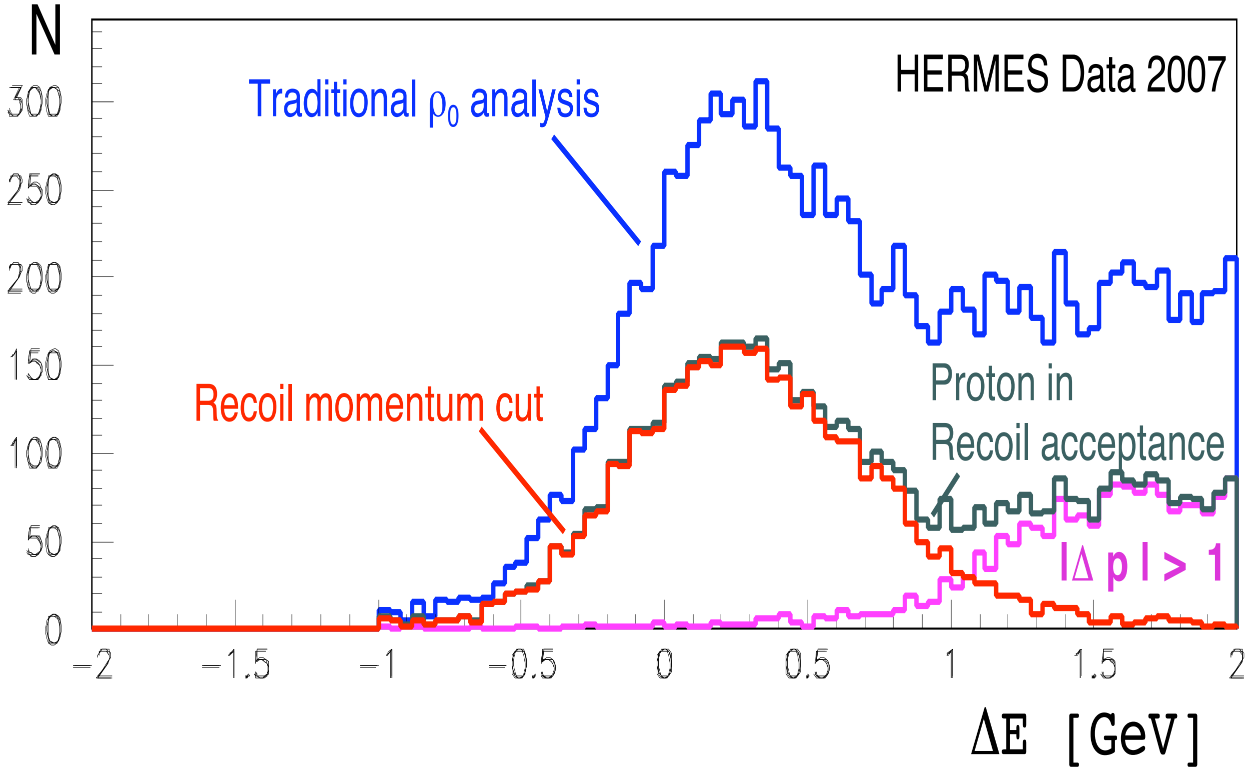


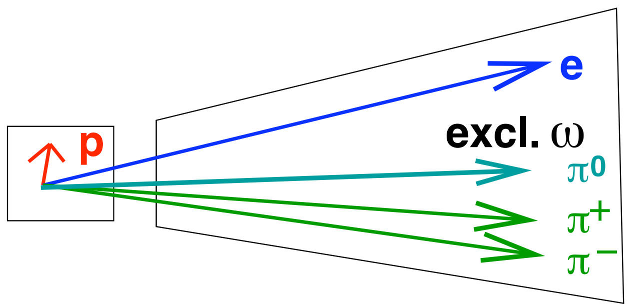


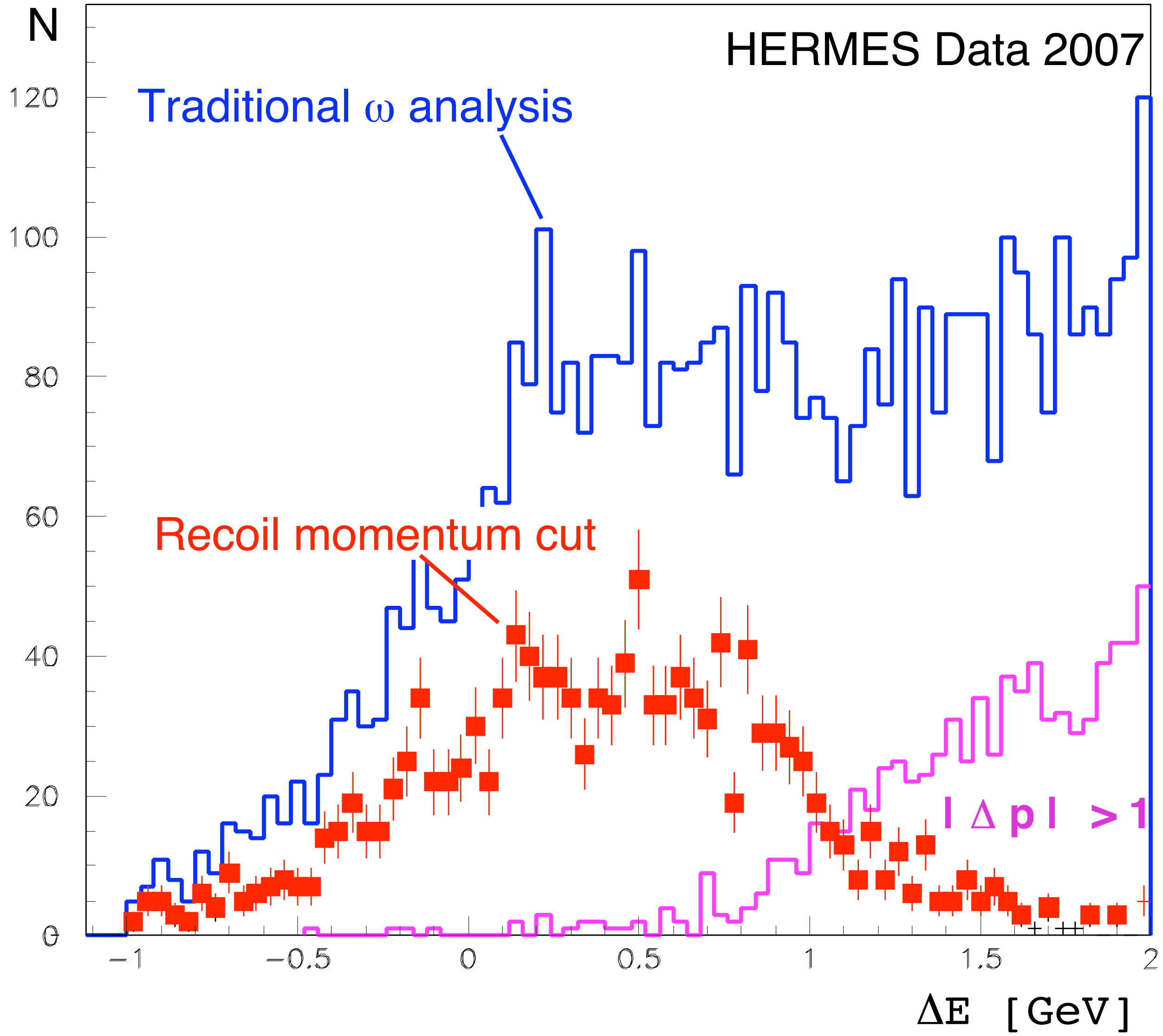
Exclusive VM event selection



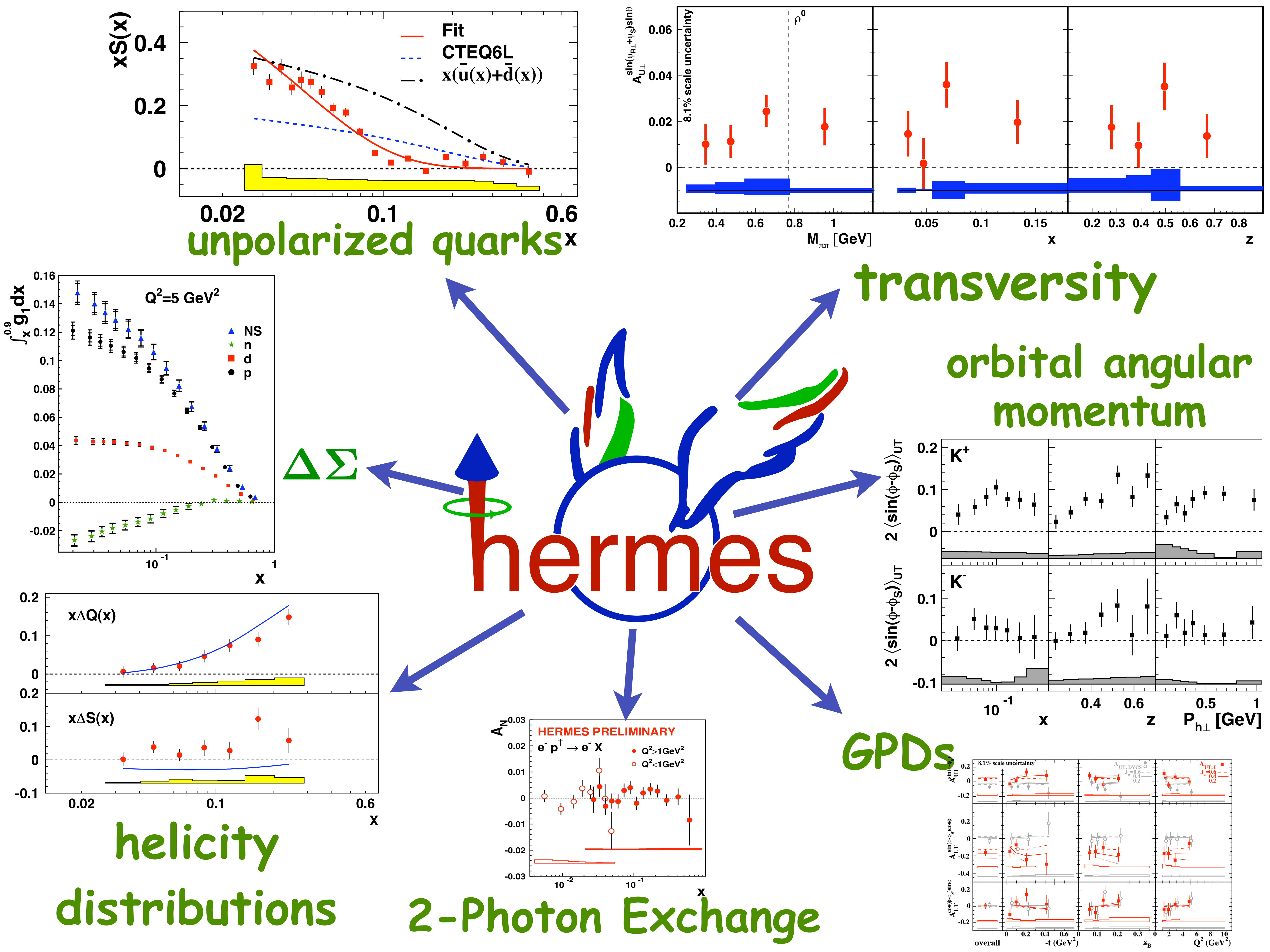








hermes



unpolarized quarks
Fit
CTEQ6L
x(ū(x)+d̄(x))
xS(x)
transversity
8.1% scale uncertainty
M_ππ [GeV]
orbital angular momentum
K+
K-
2 ⟨sin(φ-φ_S)⟩_UT
P_h⊥ [GeV]
Q²=5 GeV²
NS
n
d
p
ΔΣ
hermes
xΔQ(x)
xΔS(x)
helicity distributions
HERMES PRELIMINARY
e⁻ p↑ → e⁻ X
Q²>1GeV²
Q²<1GeV²
2-Photon Exchange
GPDs
8.1% scale uncertainty
overall
-t (GeV²)
x_B
Q² (GeV²)