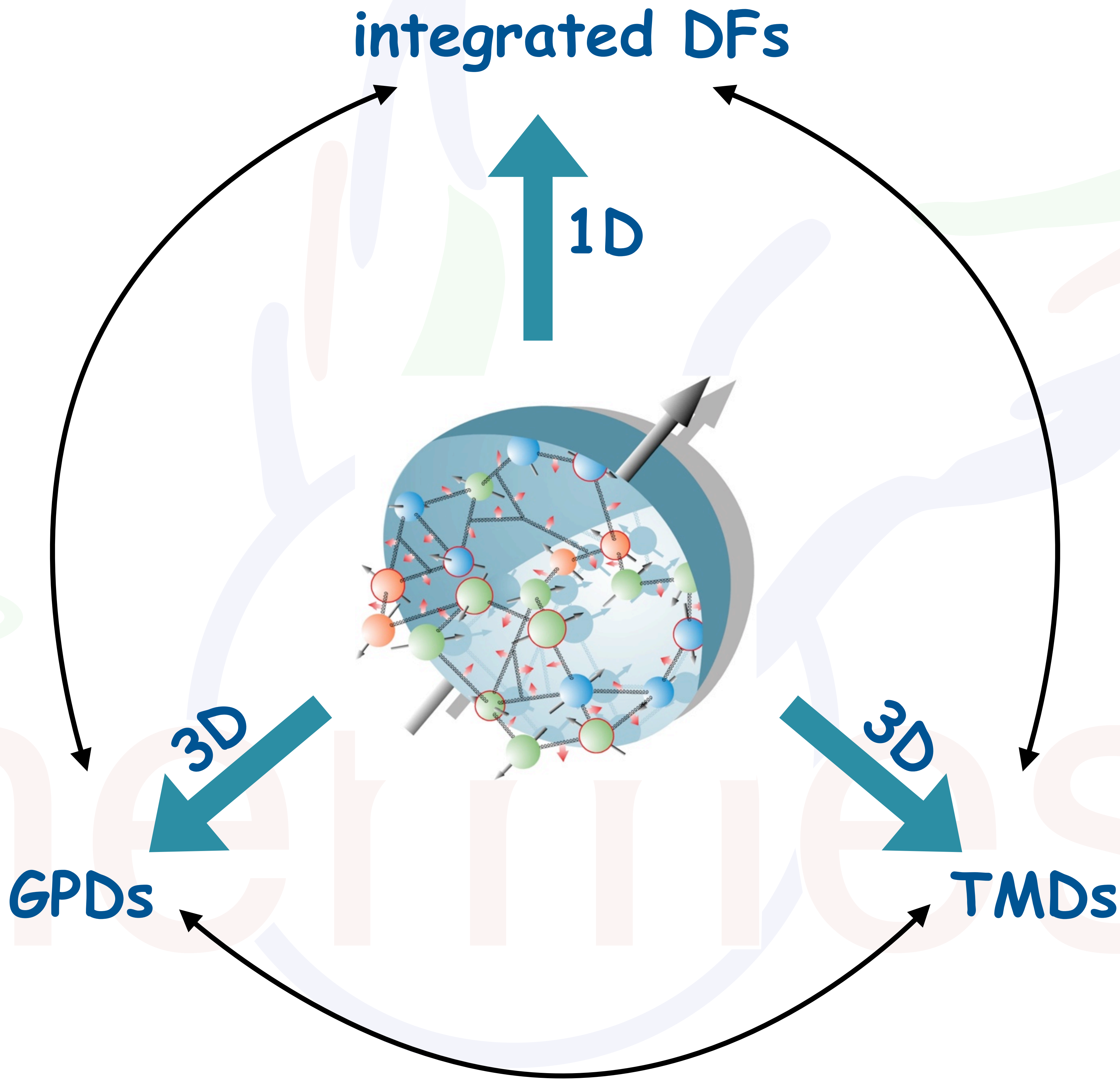
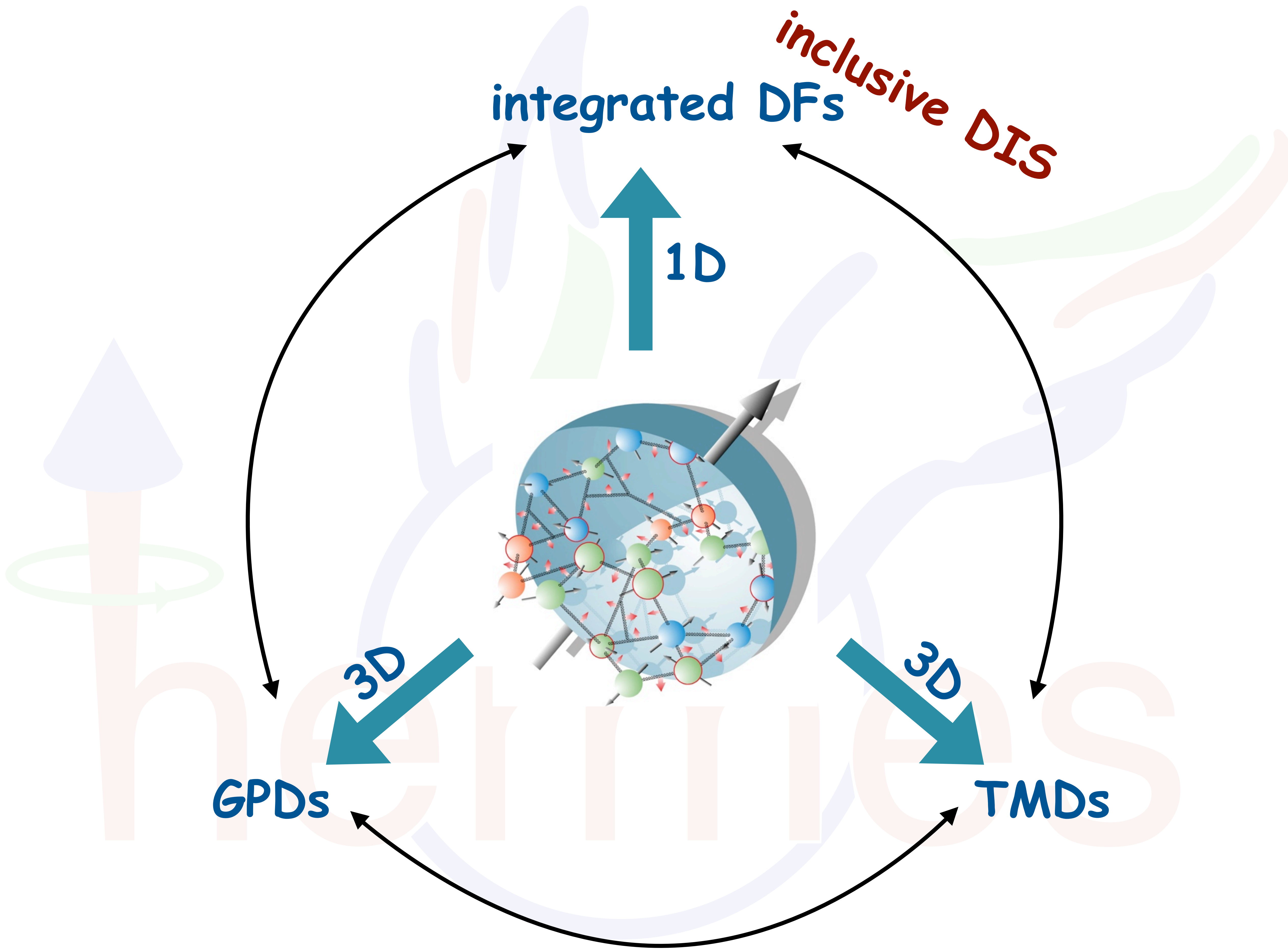
BNL/RBRC Summer Program on Nucleon Spin
July 14-27, 2010

# The structure of the nucleon

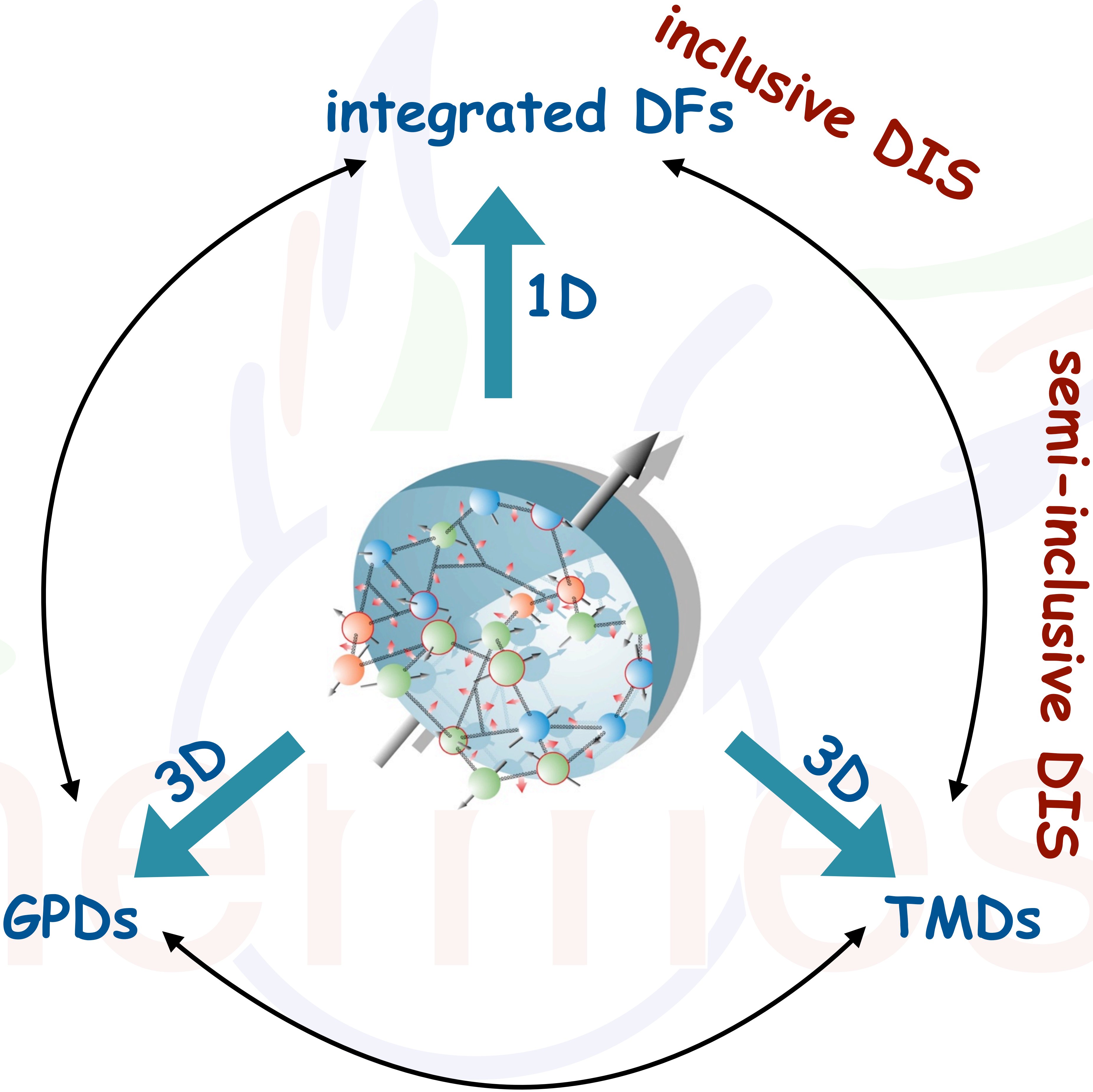
--the hermes perspective--

Gunar.Schnell @ desy.de


integrated DFs
1D
3D
3D
GPDs
TMDs



integrated DFs
inclusive DIS
1D
3D
3D
GPDs
TMDs


integrated DFs
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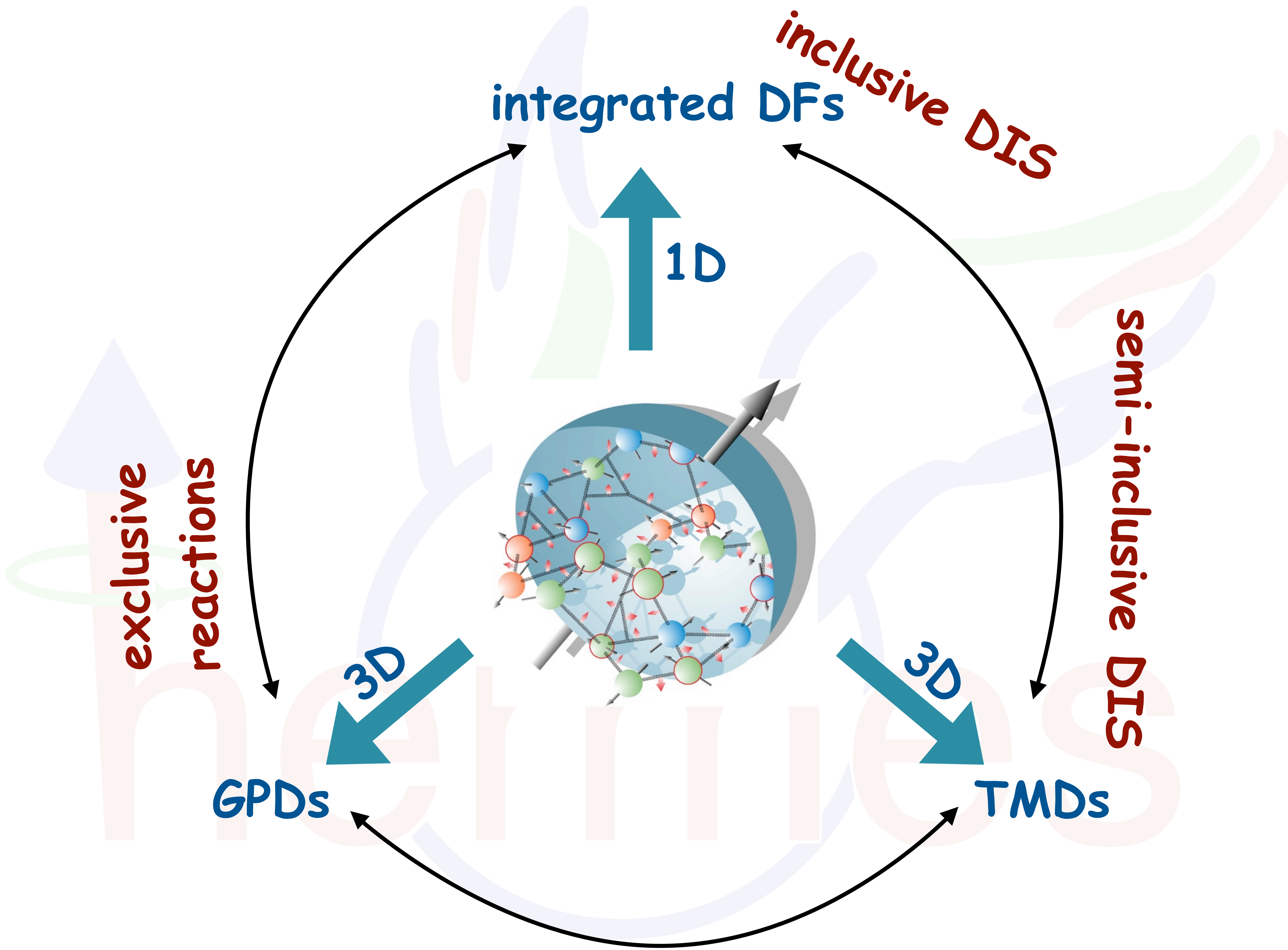
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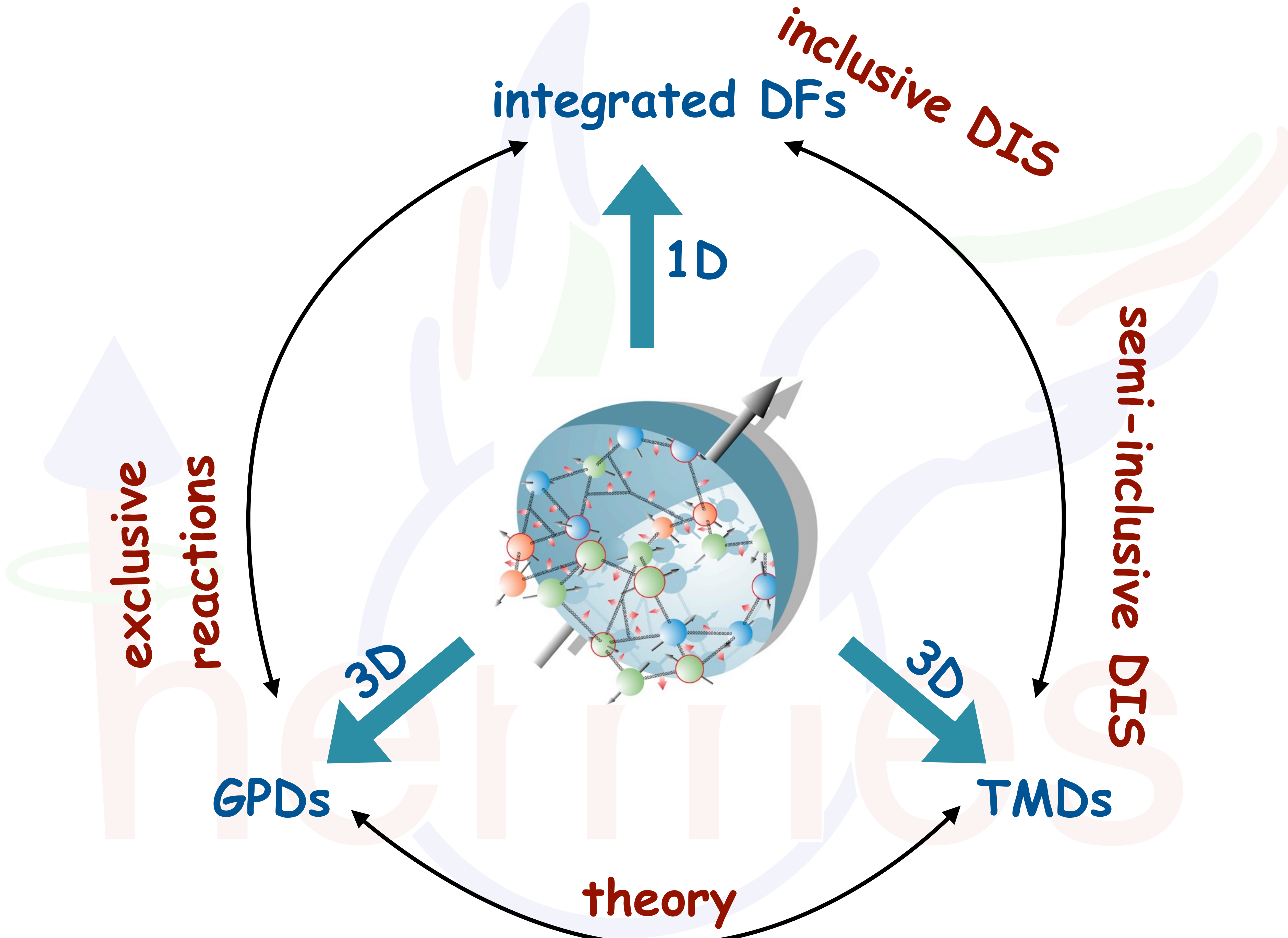
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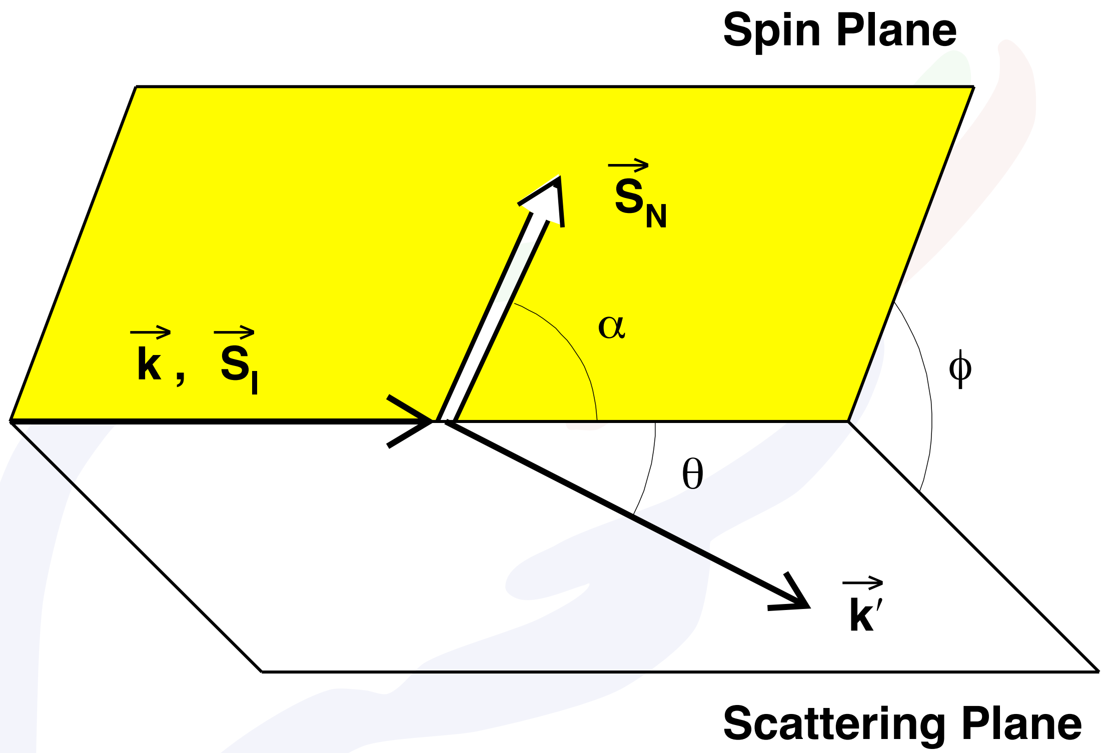
theory

# Inclusive DIS

# Inclusive DIS

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



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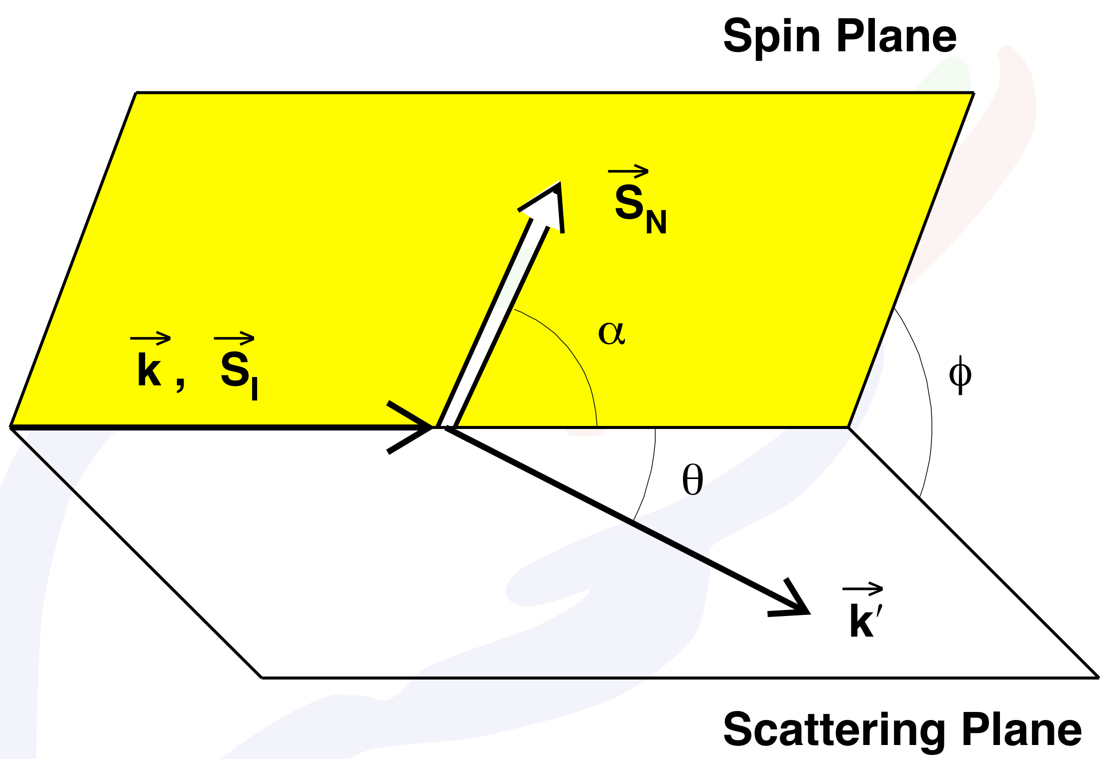
Lepton Tensor

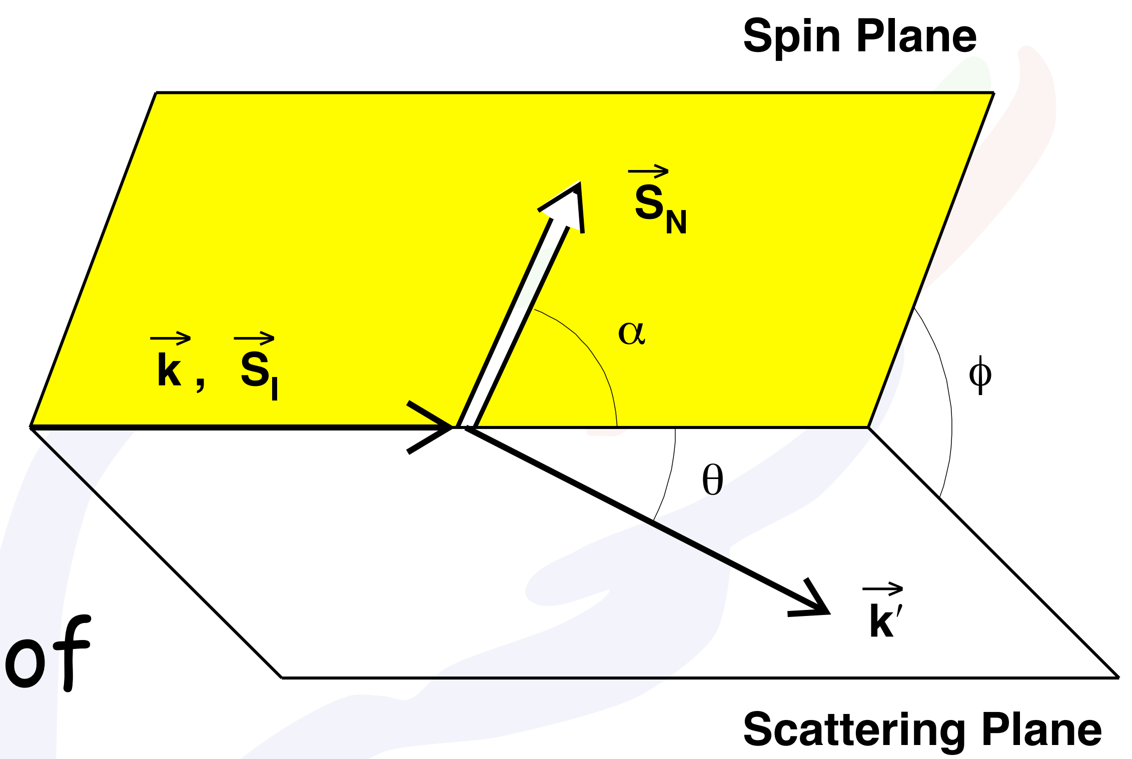


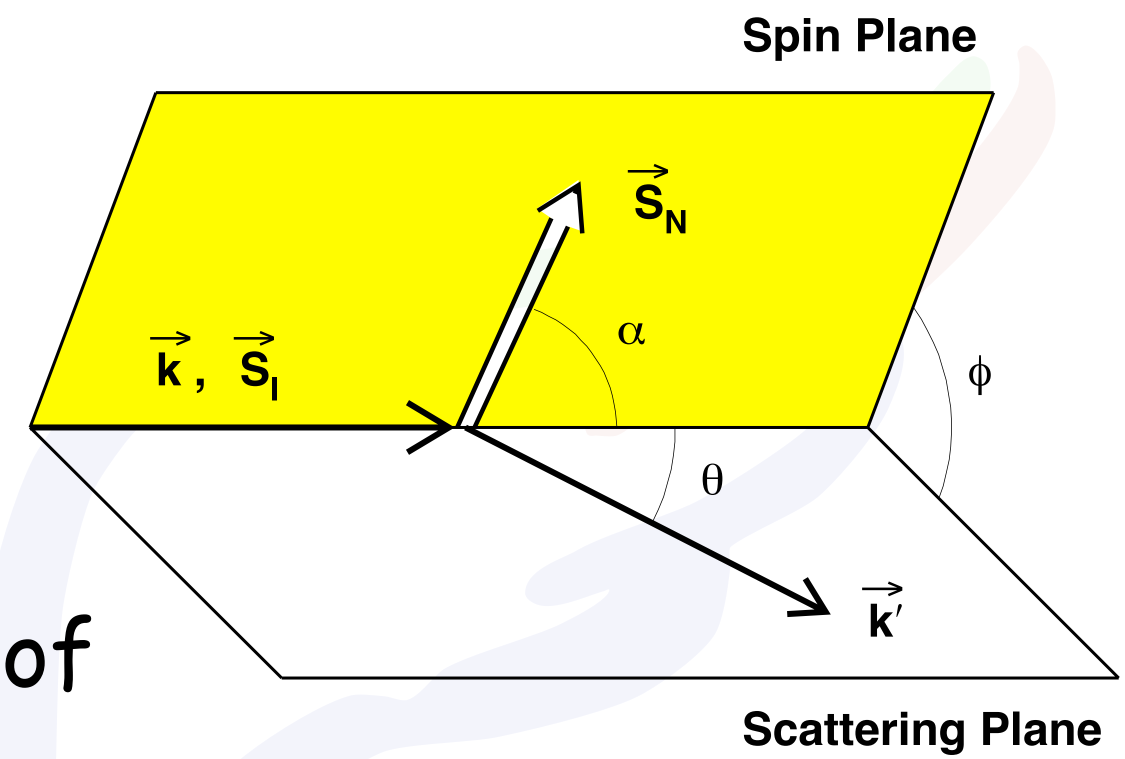
# Inclusive DIS

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

Lepton Tensor

Hadron Tensor
parametrized in terms of
Structure Functions






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

Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions

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

# Check the details!

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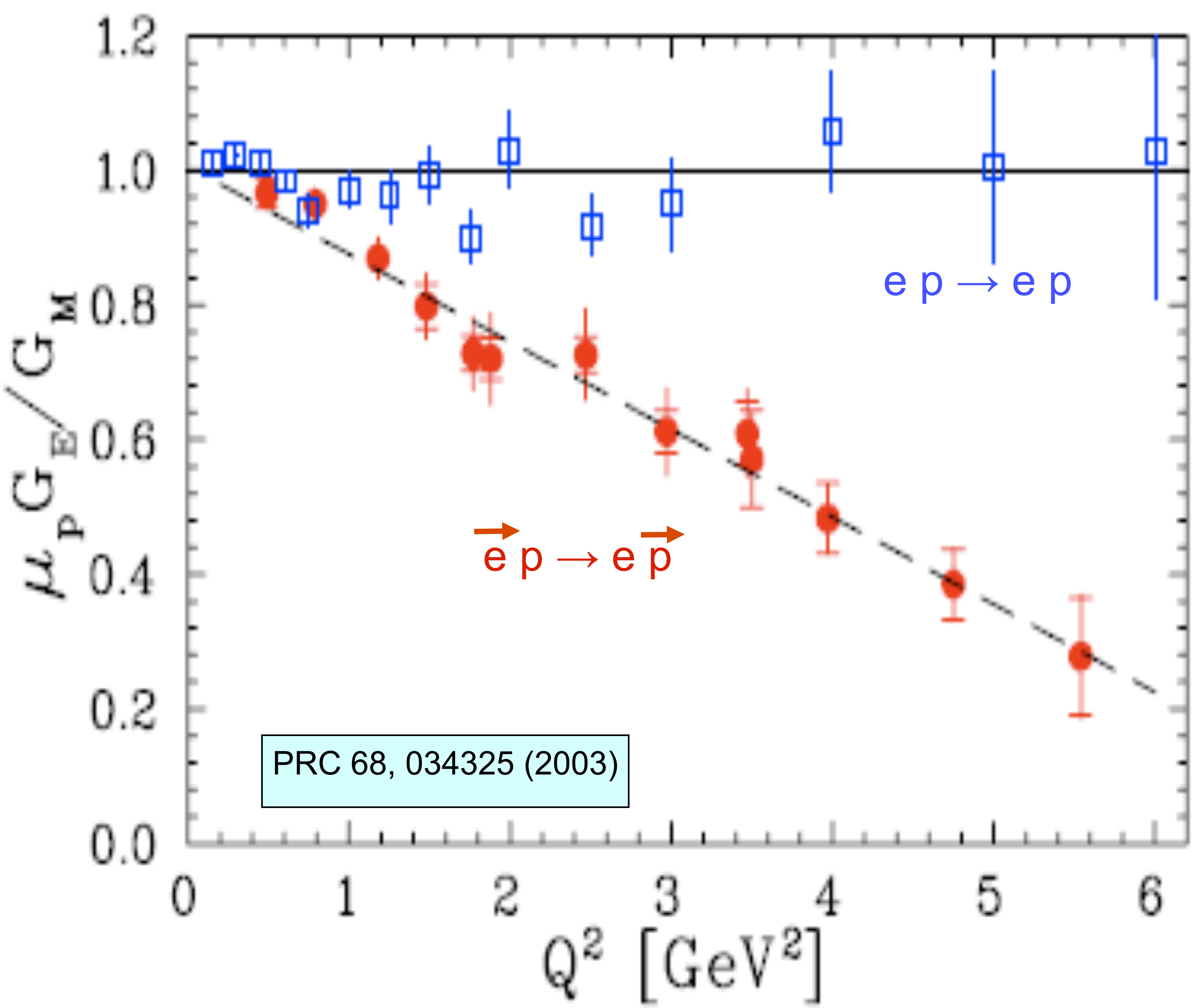
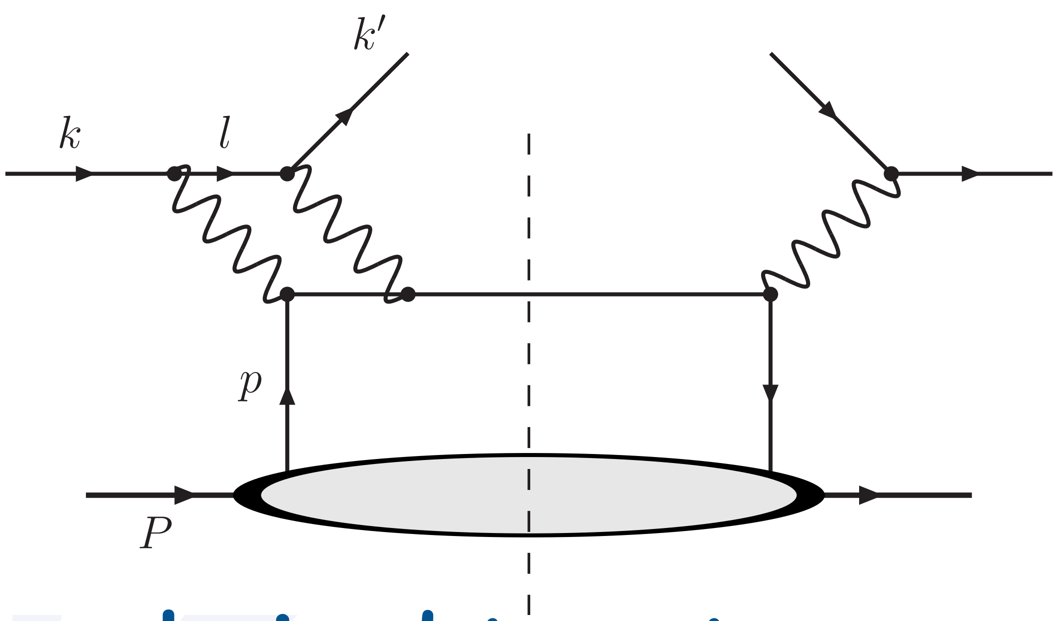



$x_F$

☛ **two-photon exchange important?!**

# Two-photon exchange

- Candidate to explain discrepancy in form-factor measurements

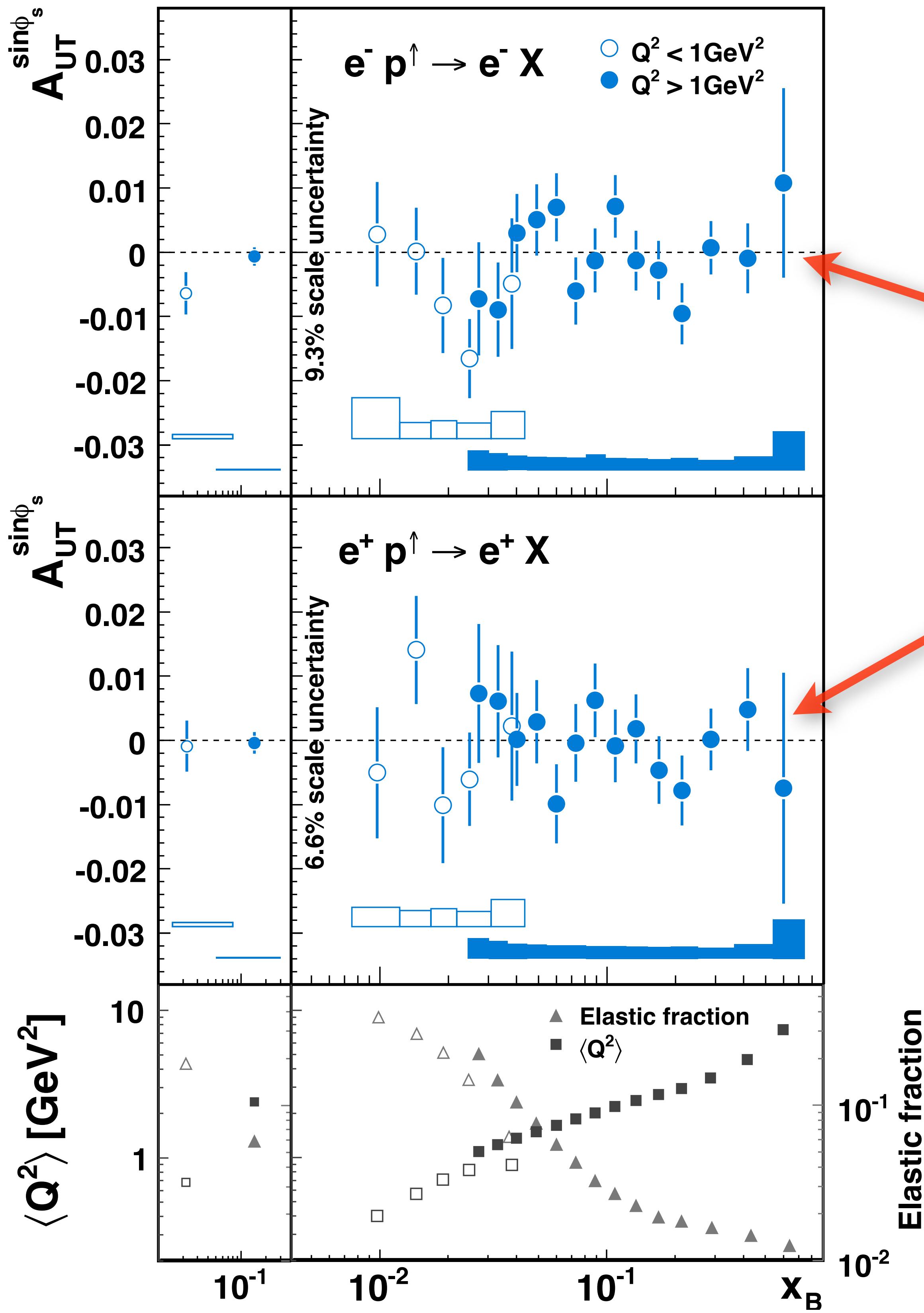



- Interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets

- sensitive to beam charge due to odd number of e.m. couplings to beam

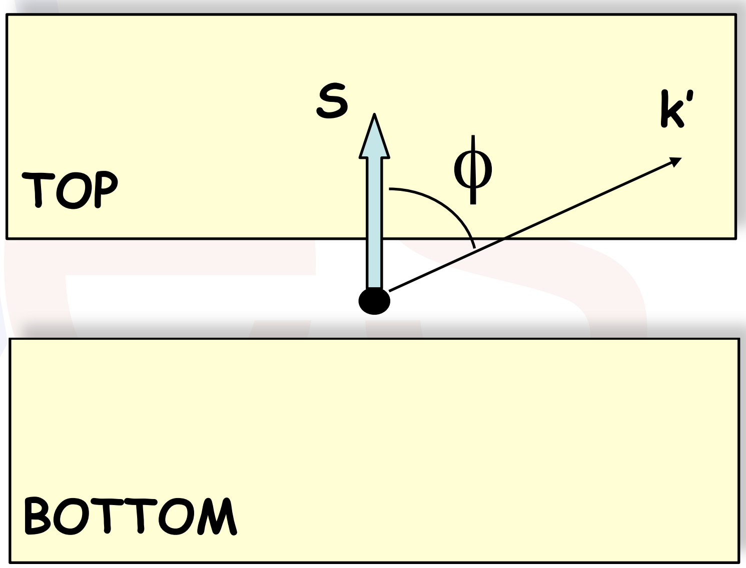
- cross section proportional to S(kxk') - either measure left-right asymmetries or sine modulation

# No sign of two-photon exchange

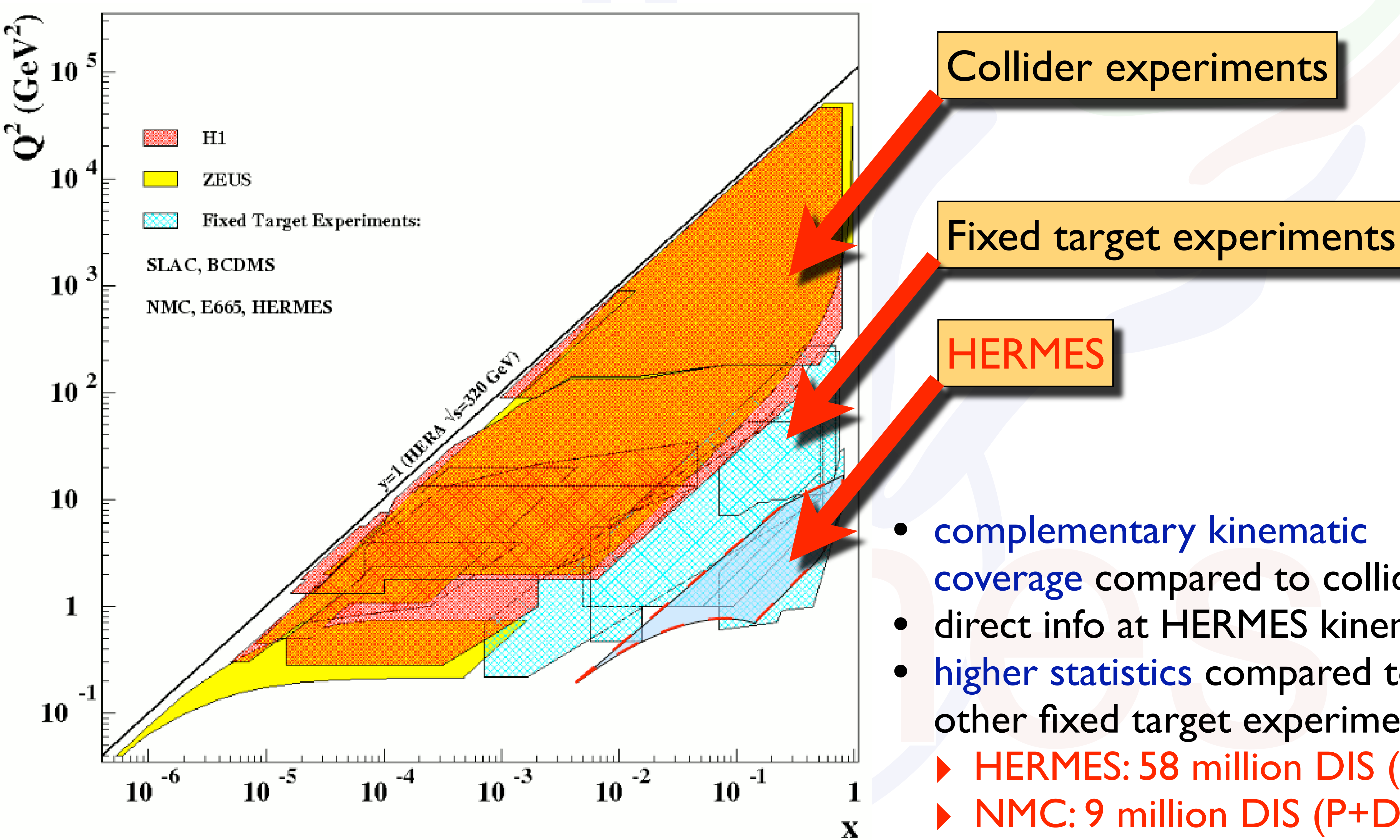



consistent with zero

Front view of HERMES detector

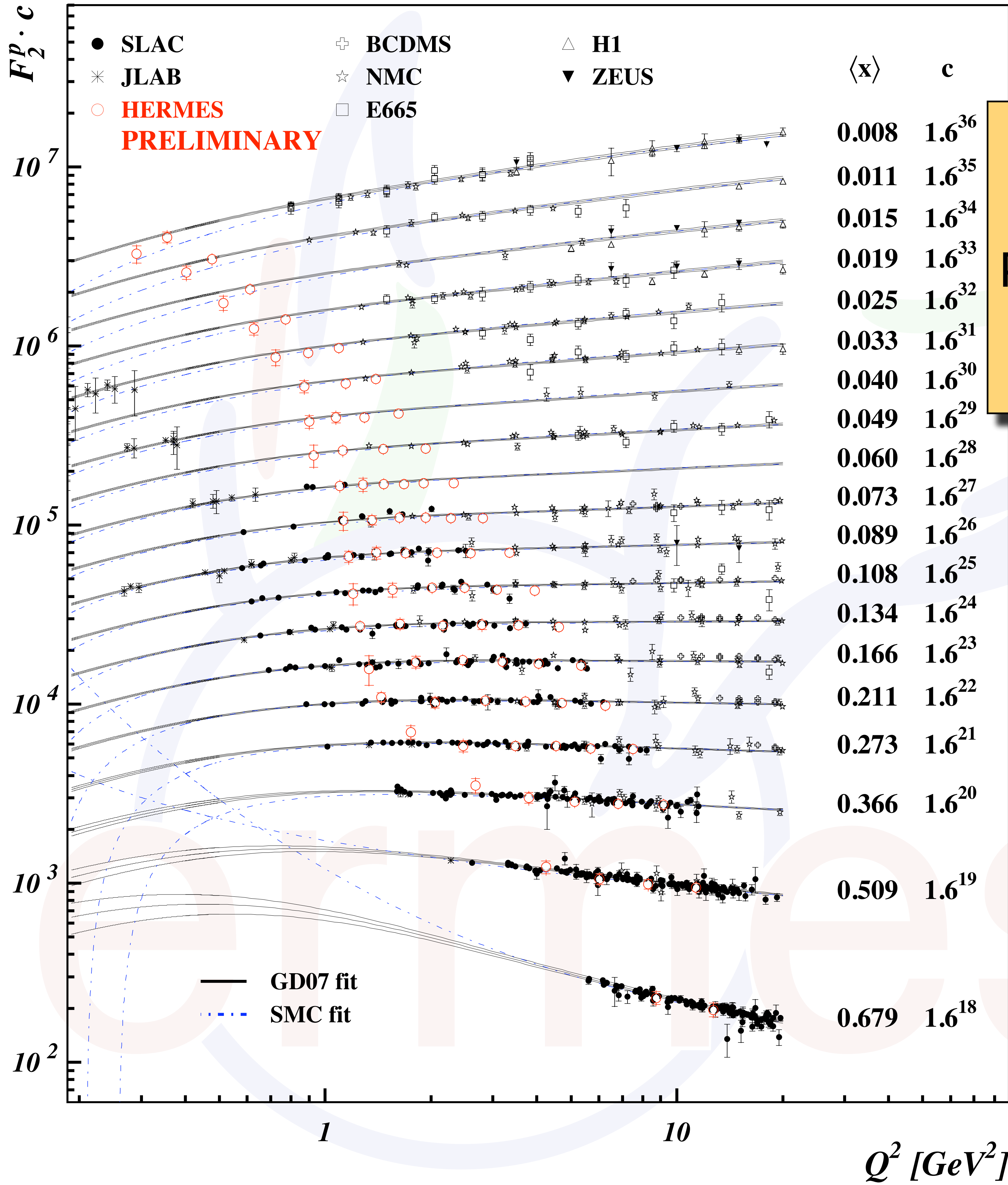


# Why measure $F_2$ at HERMES?




- complementary kinematic coverage compared to colliders
- direct info at HERMES kinematics
- 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

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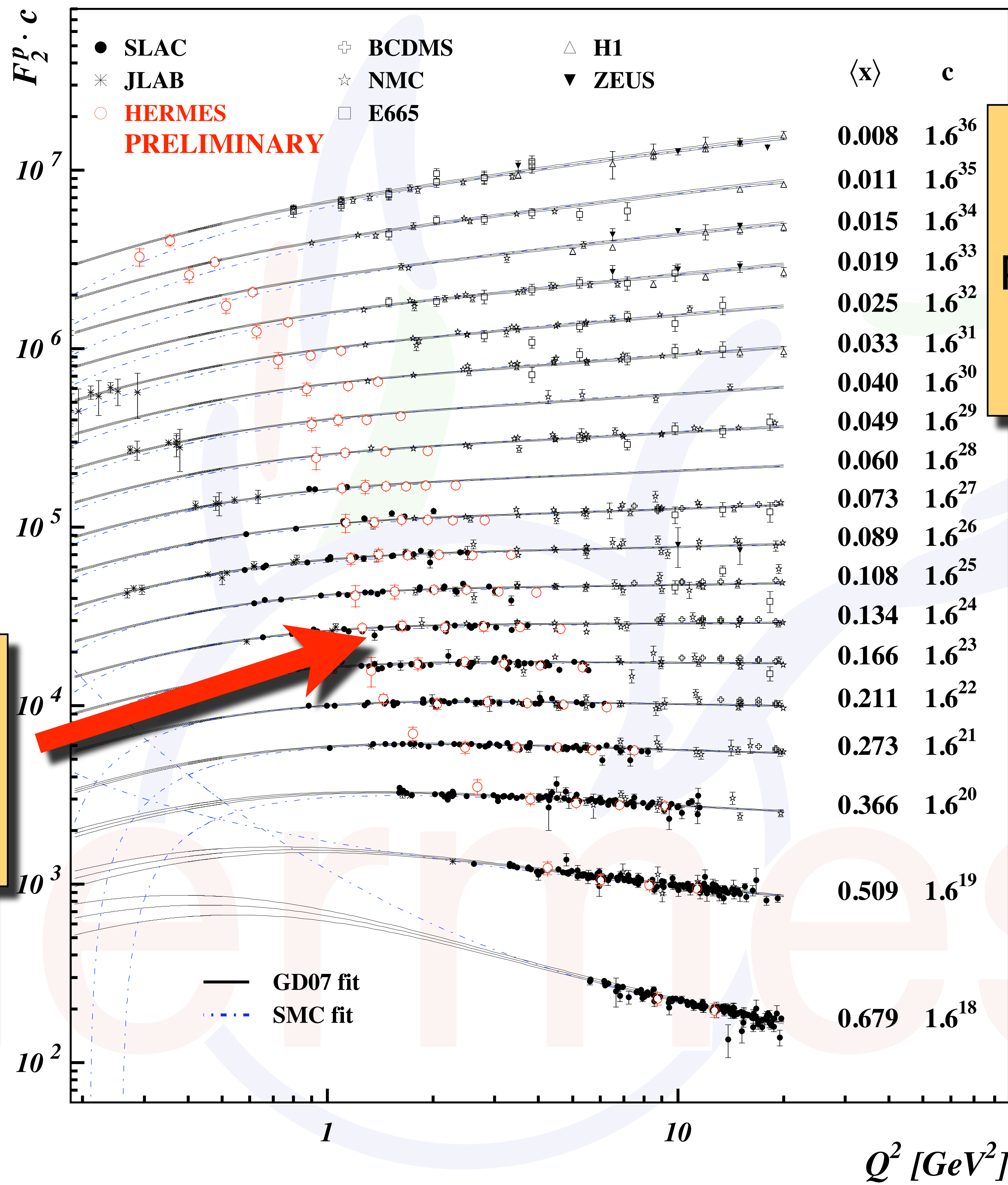


Comparison with parameterization by SMC and GD07

Agreement with world data in the overlap region

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New region covered by HERMES

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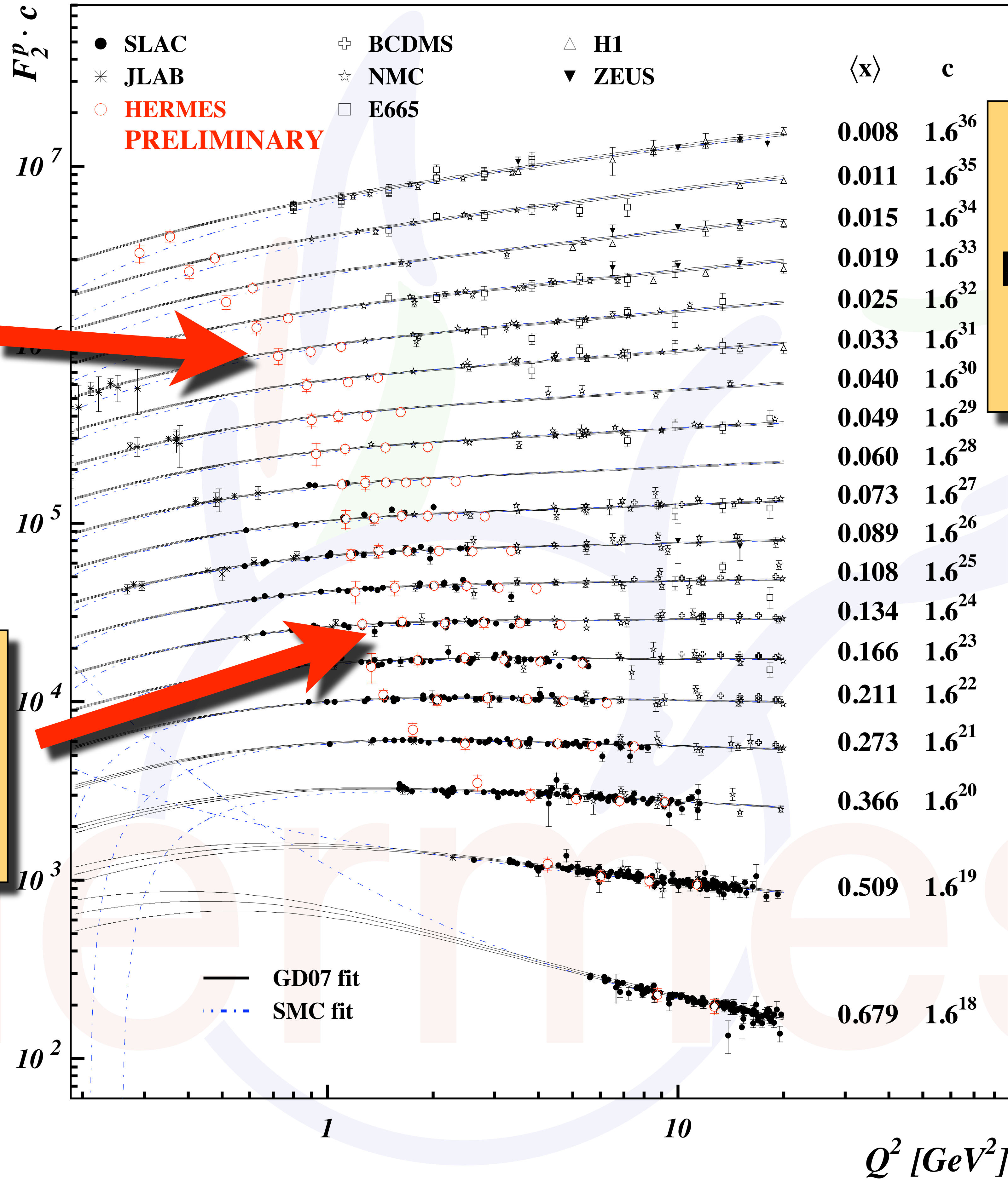


Comparison with parameterization by SMC and GD07

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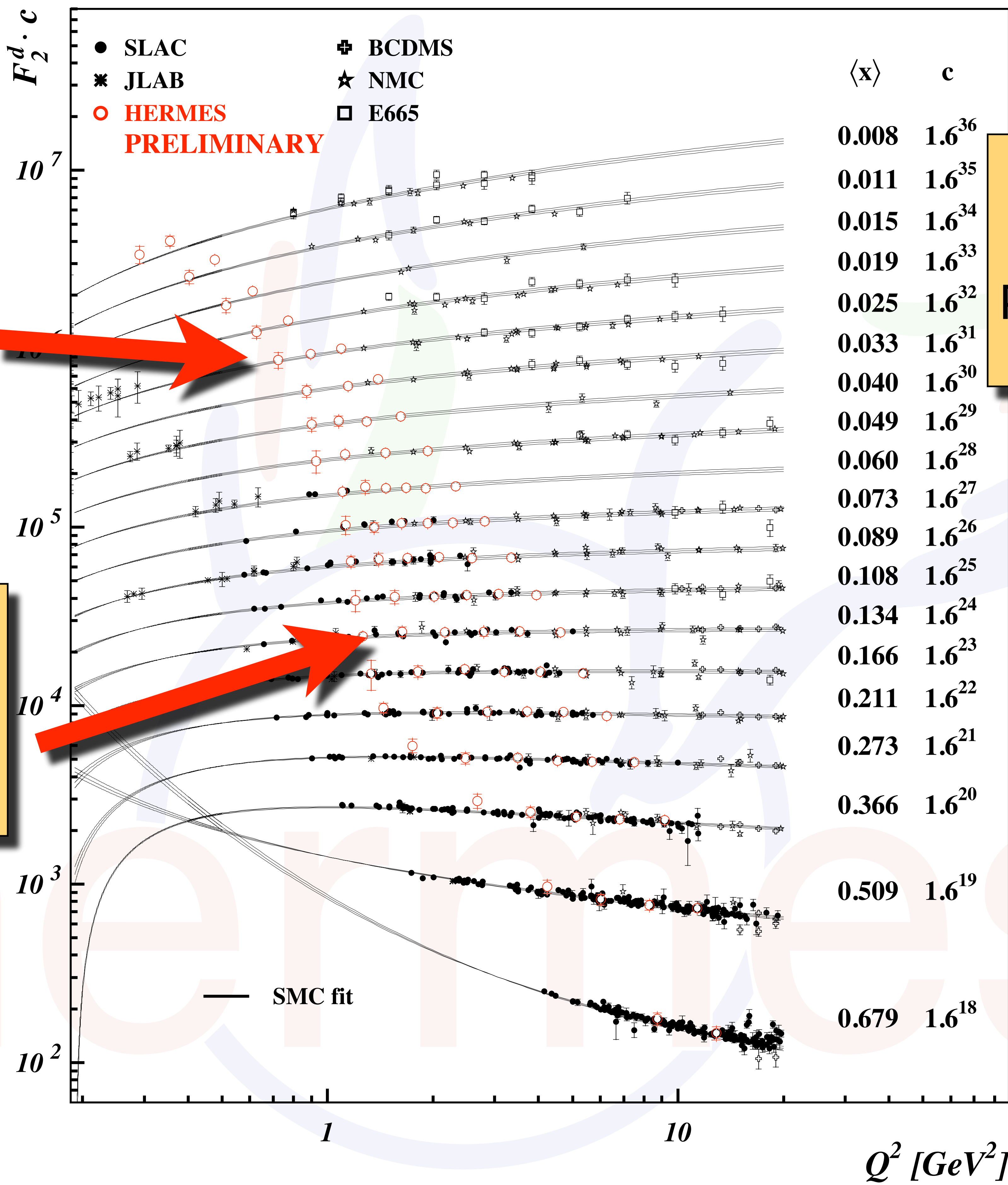
# $F_2$ deuteron

New region covered by HERMES

Agreement with world data in the overlap region

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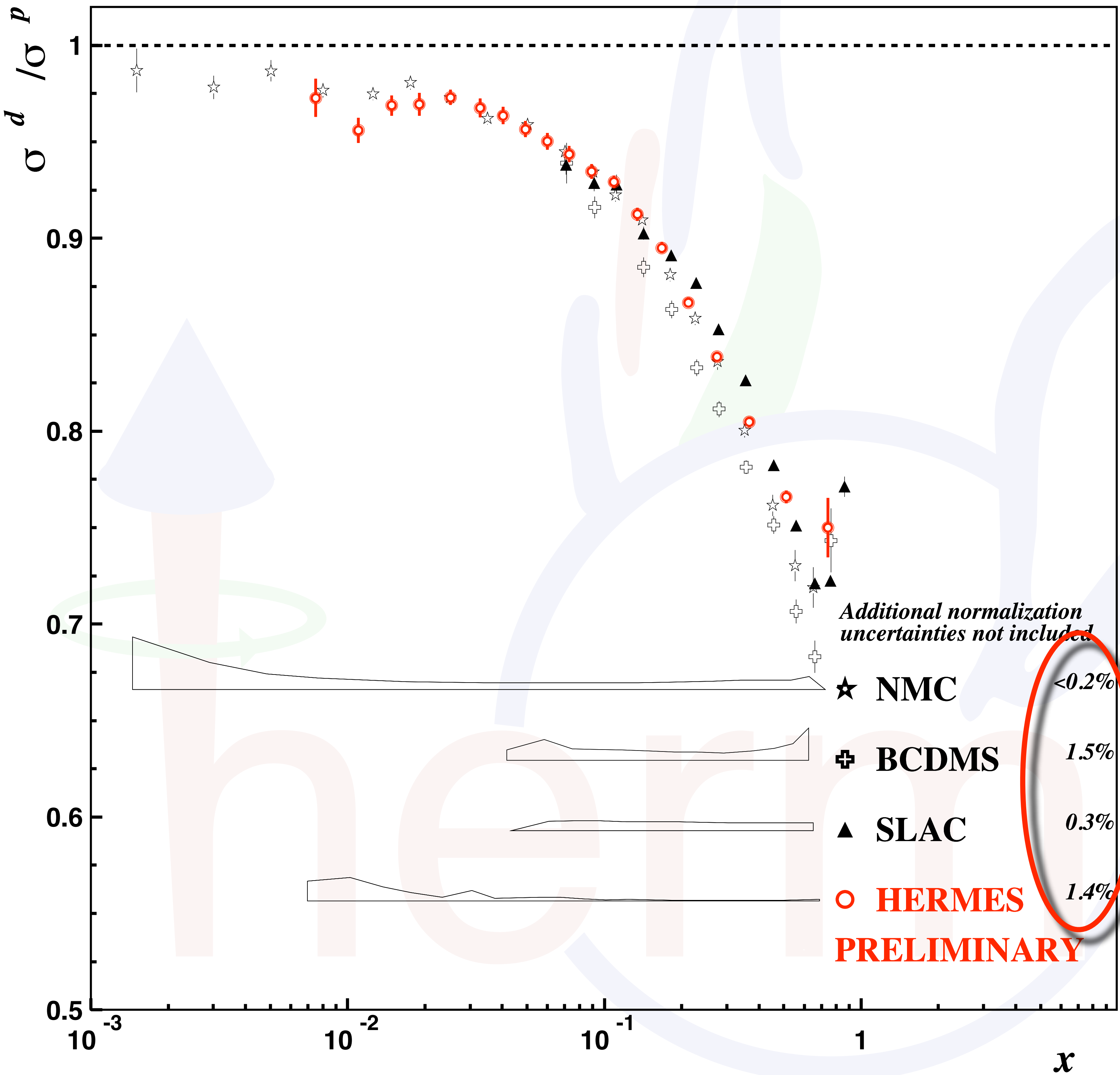
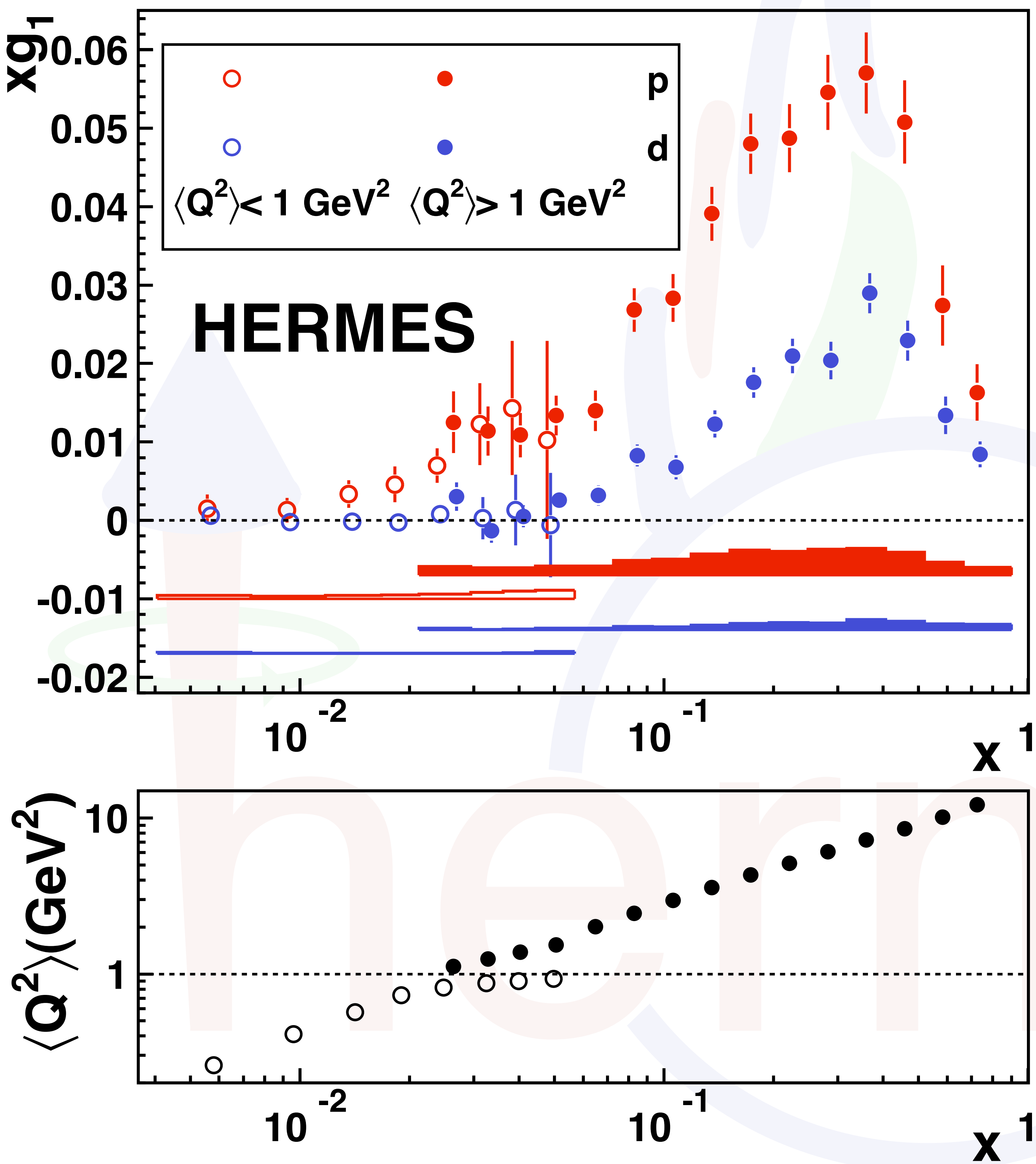
# World data on $\sigma^d/\sigma^p$



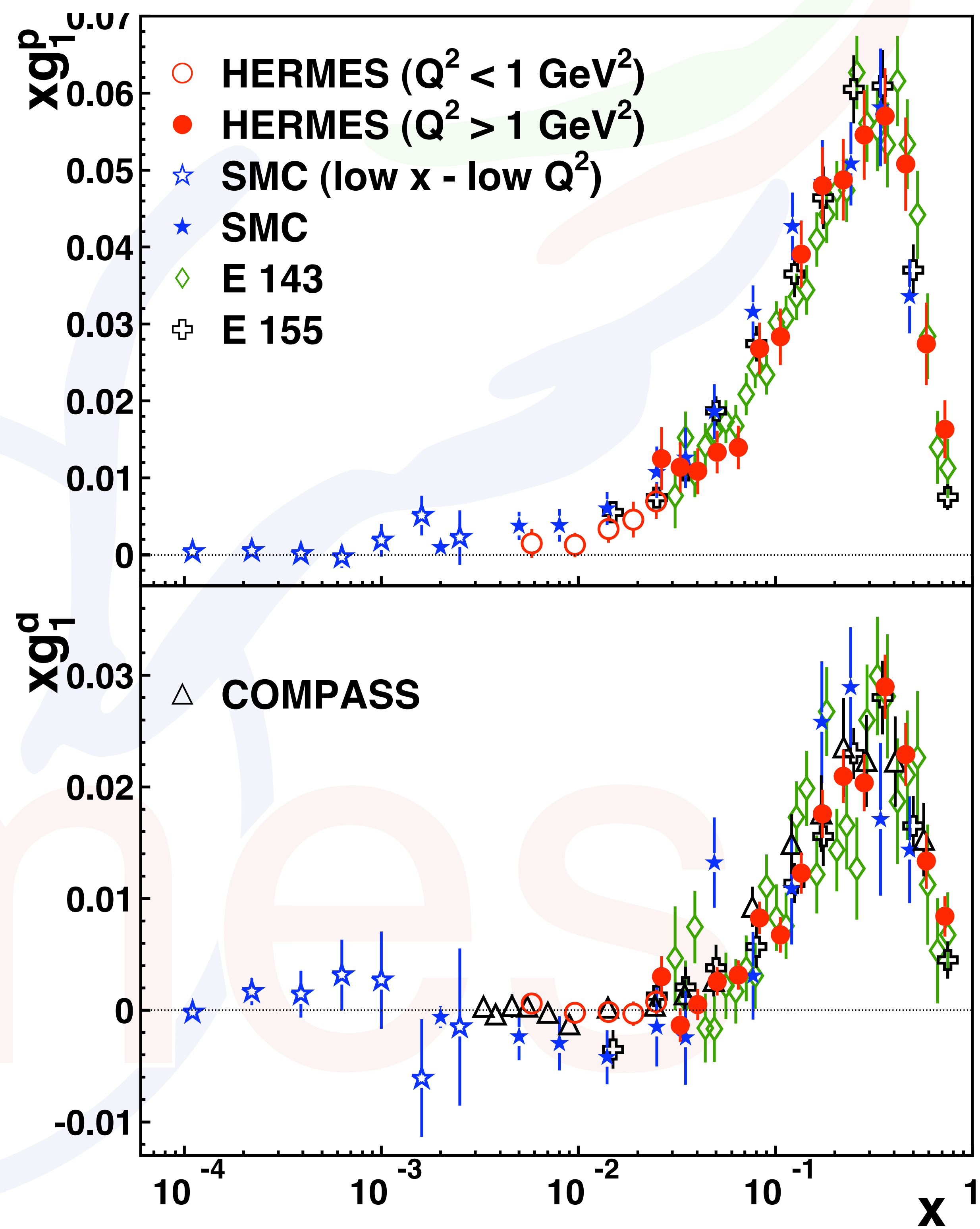

Many systematic errors common to proton and deuteron cross sections cancel in ratio

*Normalization uncertainties*

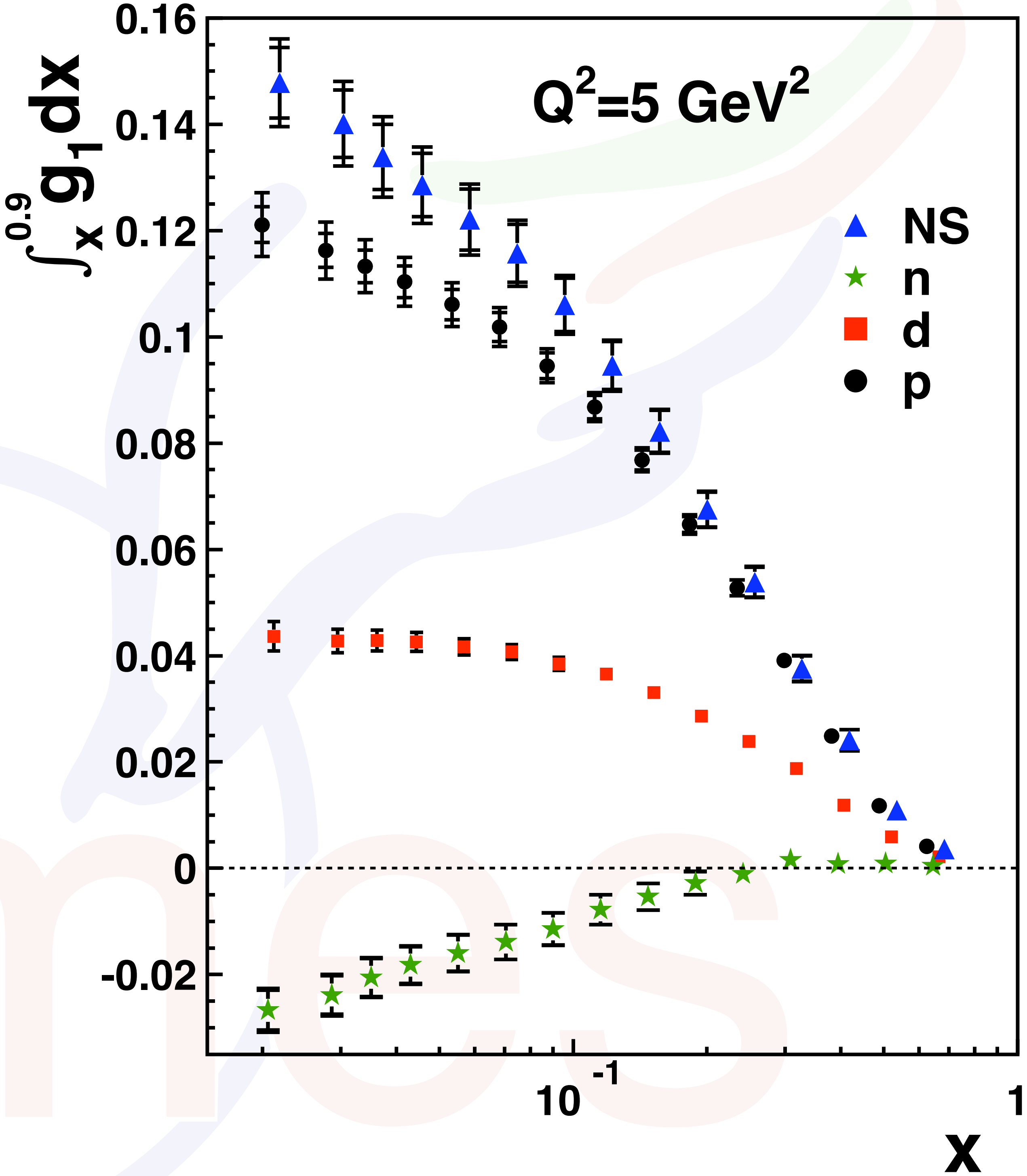
# Polarized Structure Function $g_1$




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



# Integral of $g_1(x)$



# Integral of $g_1(x)$

**Saturation**

➟ **close to full integral?**

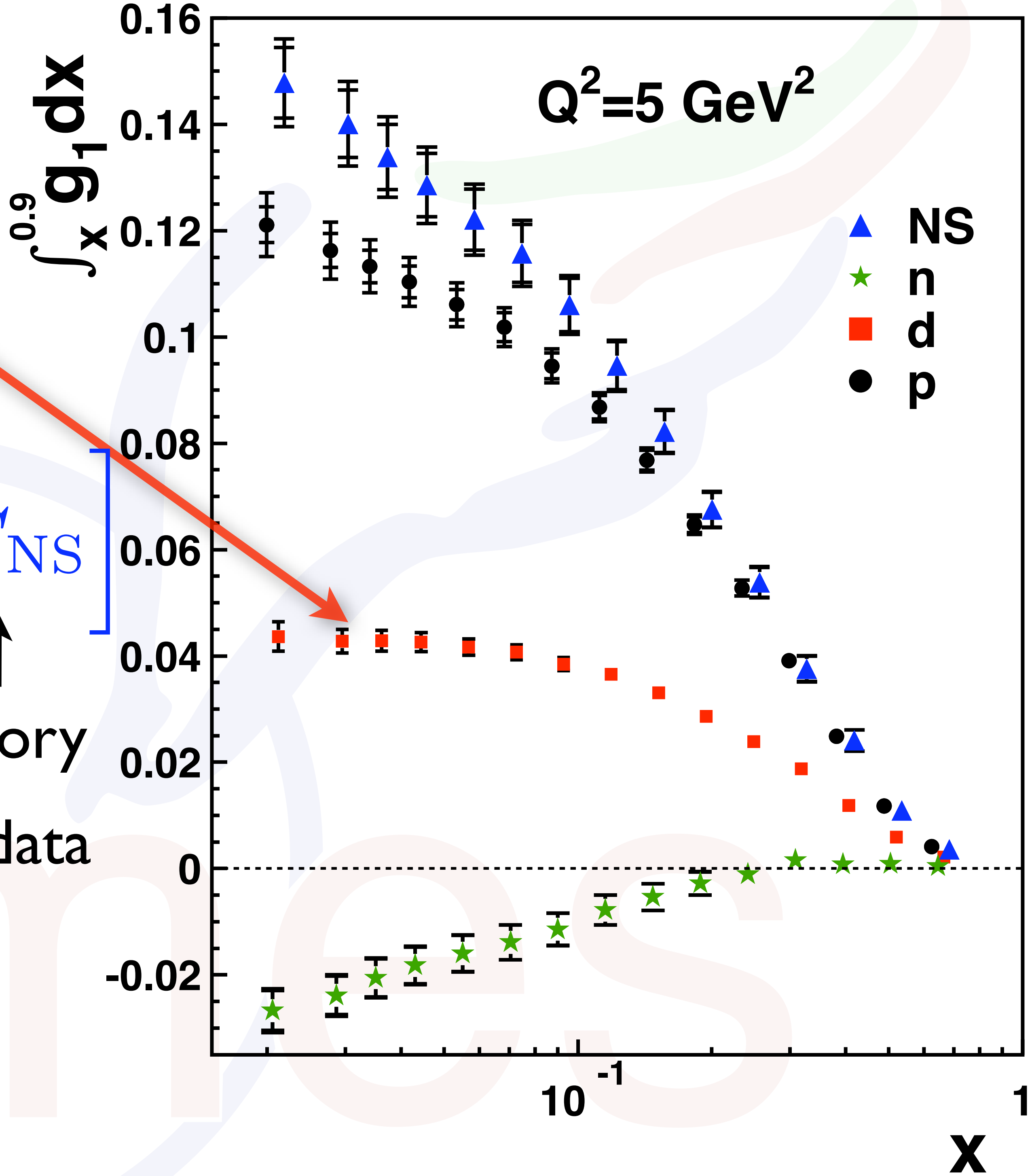
$$\Delta\Sigma \stackrel{\overline{\mathrm{MS}}}{=} \frac{1}{\Delta C_{\mathrm{S}}}\left[\frac{9\Gamma_1^d}{1-\frac{3}{2}\omega_D} - \frac{1}{4}a_8\Delta C_{\mathrm{NS}}\right]$$

theory

0.05±0.05

hyperon-decay data

theory



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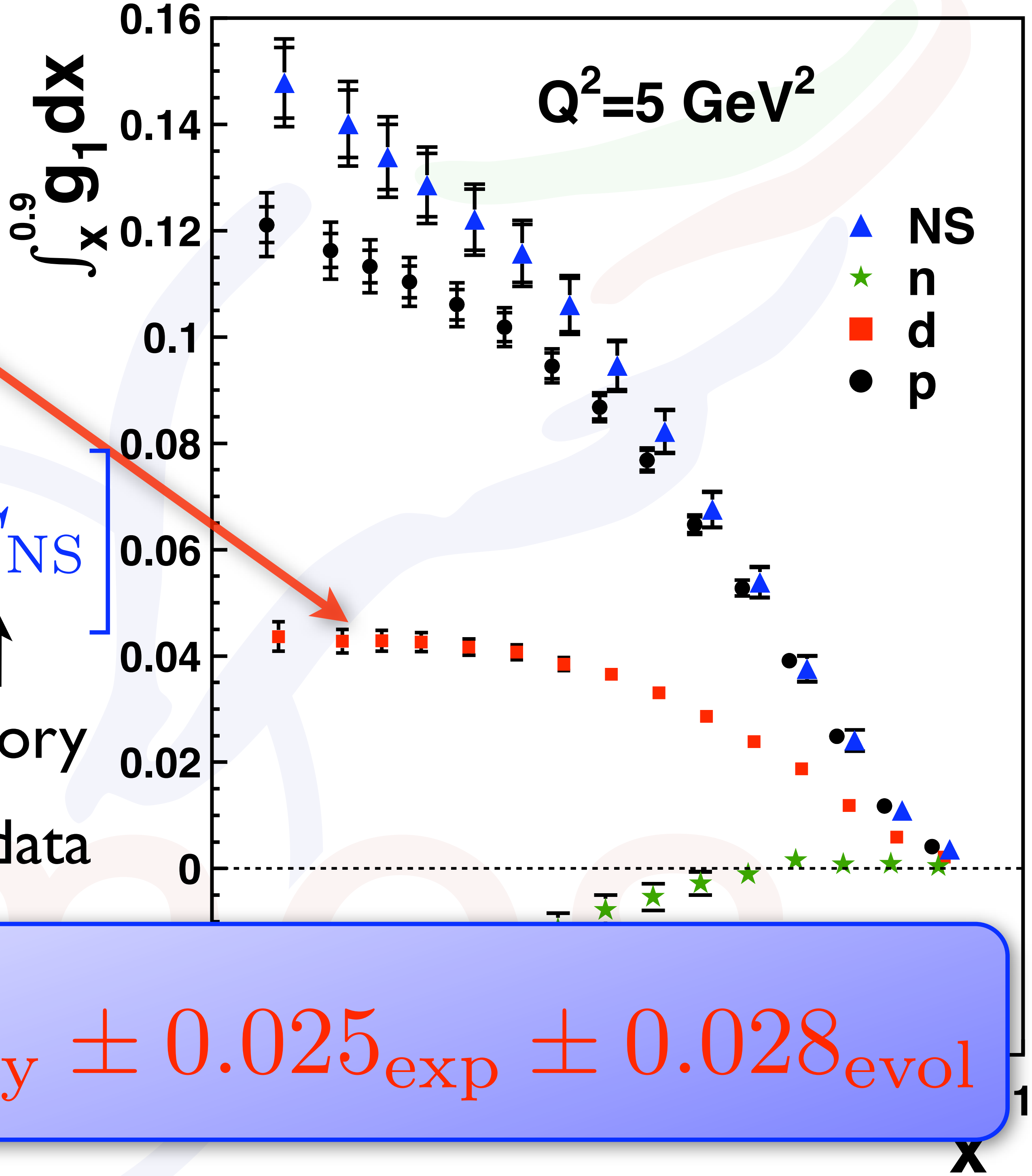


$$\Delta\Sigma \overset{\overline{\mathrm{MS}}}{=} 0.330 \pm 0.011_{\mathrm{theory}} \pm 0.025_{\mathrm{exp}} \pm 0.028_{\mathrm{evol}}$$

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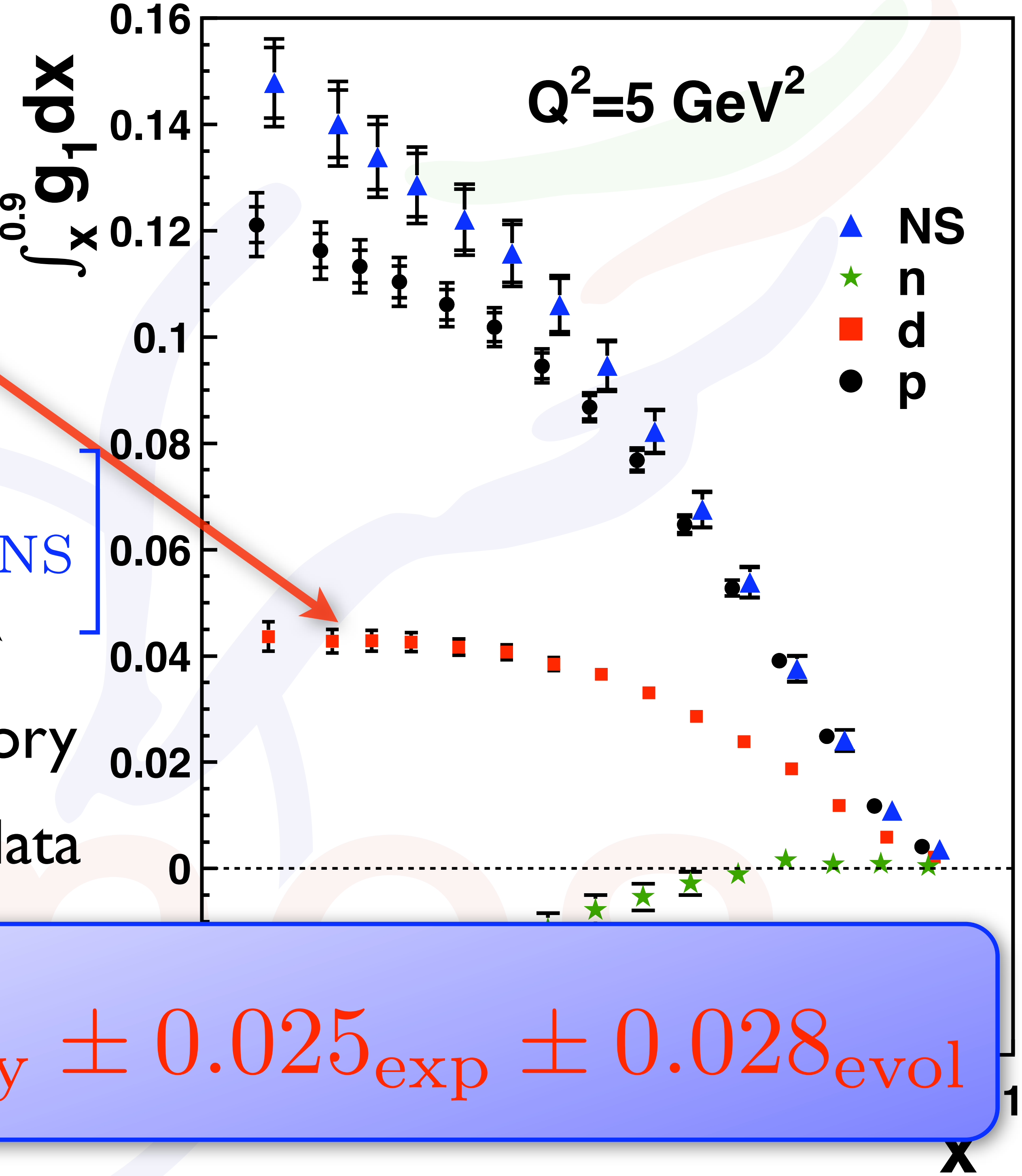
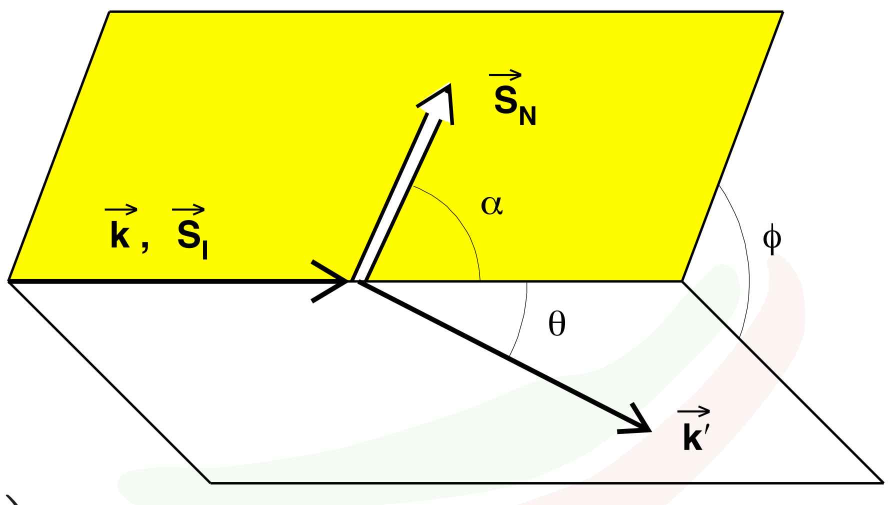



$$\Delta\Sigma \overset{\overline{\mathrm{MS}}}{=} 0.330 \pm 0.011_{\mathrm{theory}} \pm 0.025_{\mathrm{exp}} \pm 0.028_{\mathrm{evol}}$$

**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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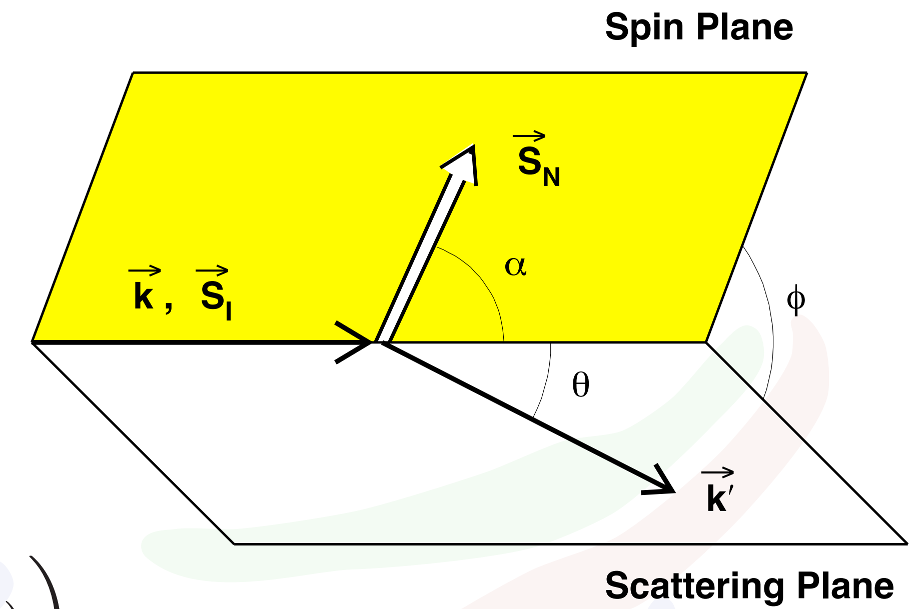


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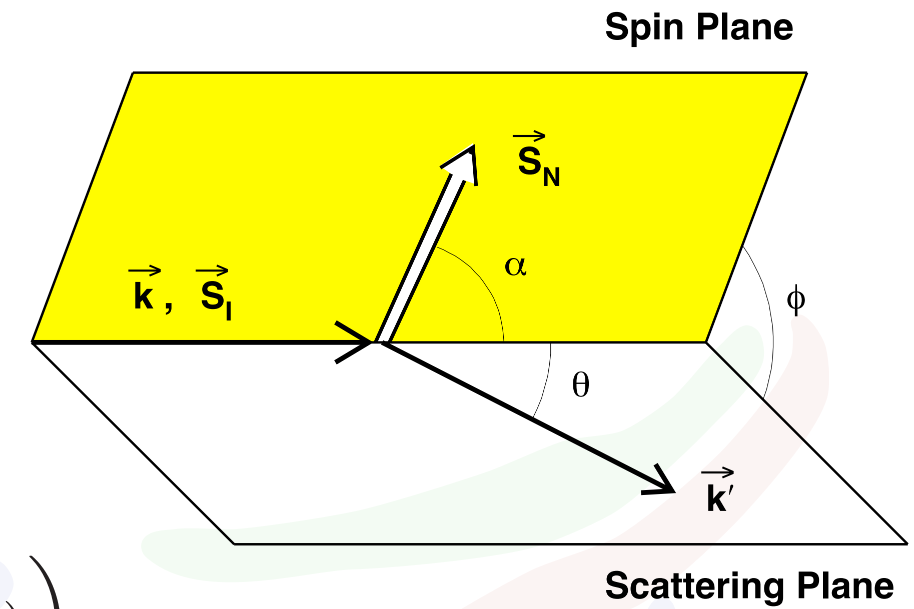
fit to double-spin asymmetry

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

# Extraction of $g_2$

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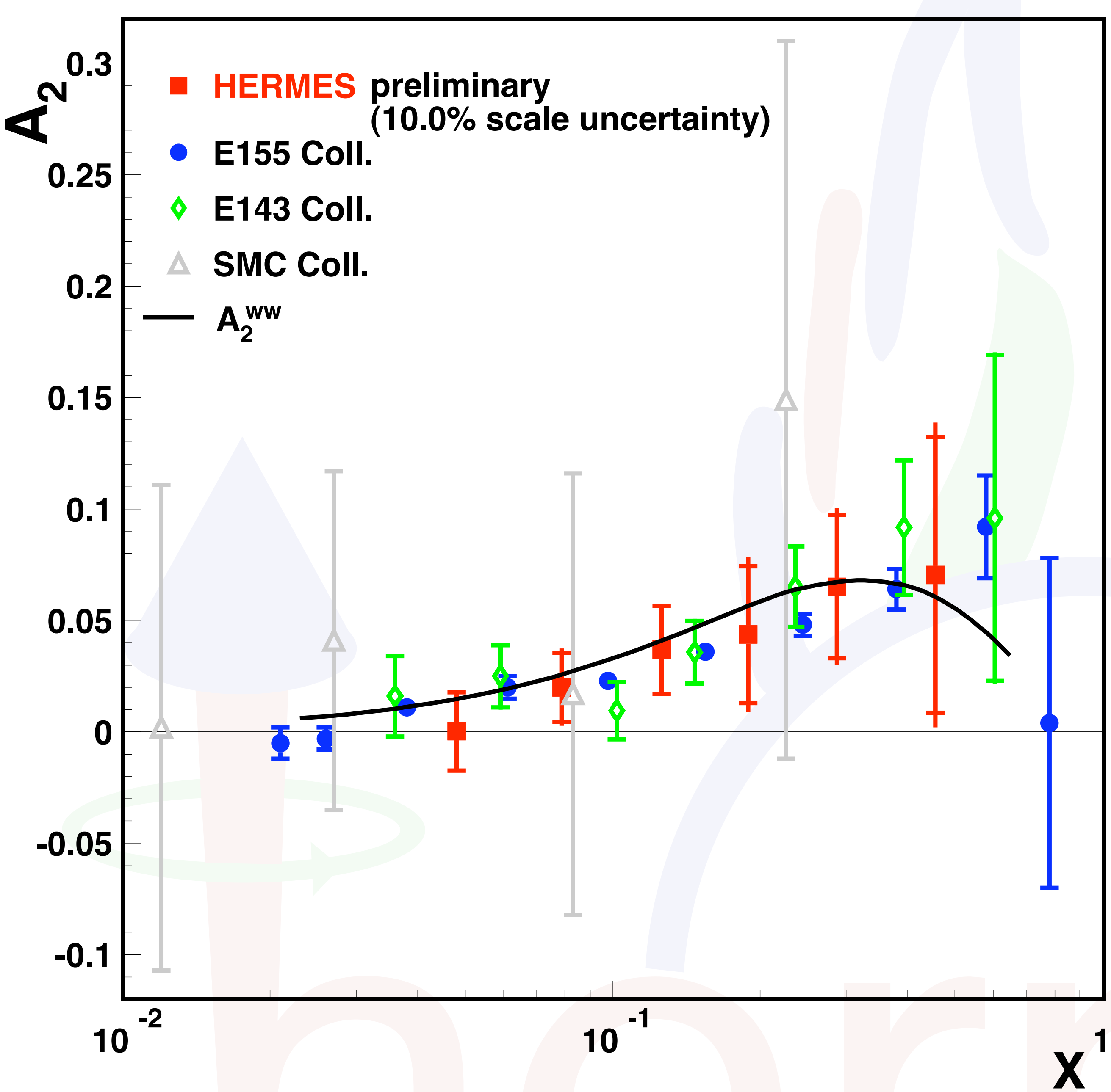
fit to double-spin asymmetry

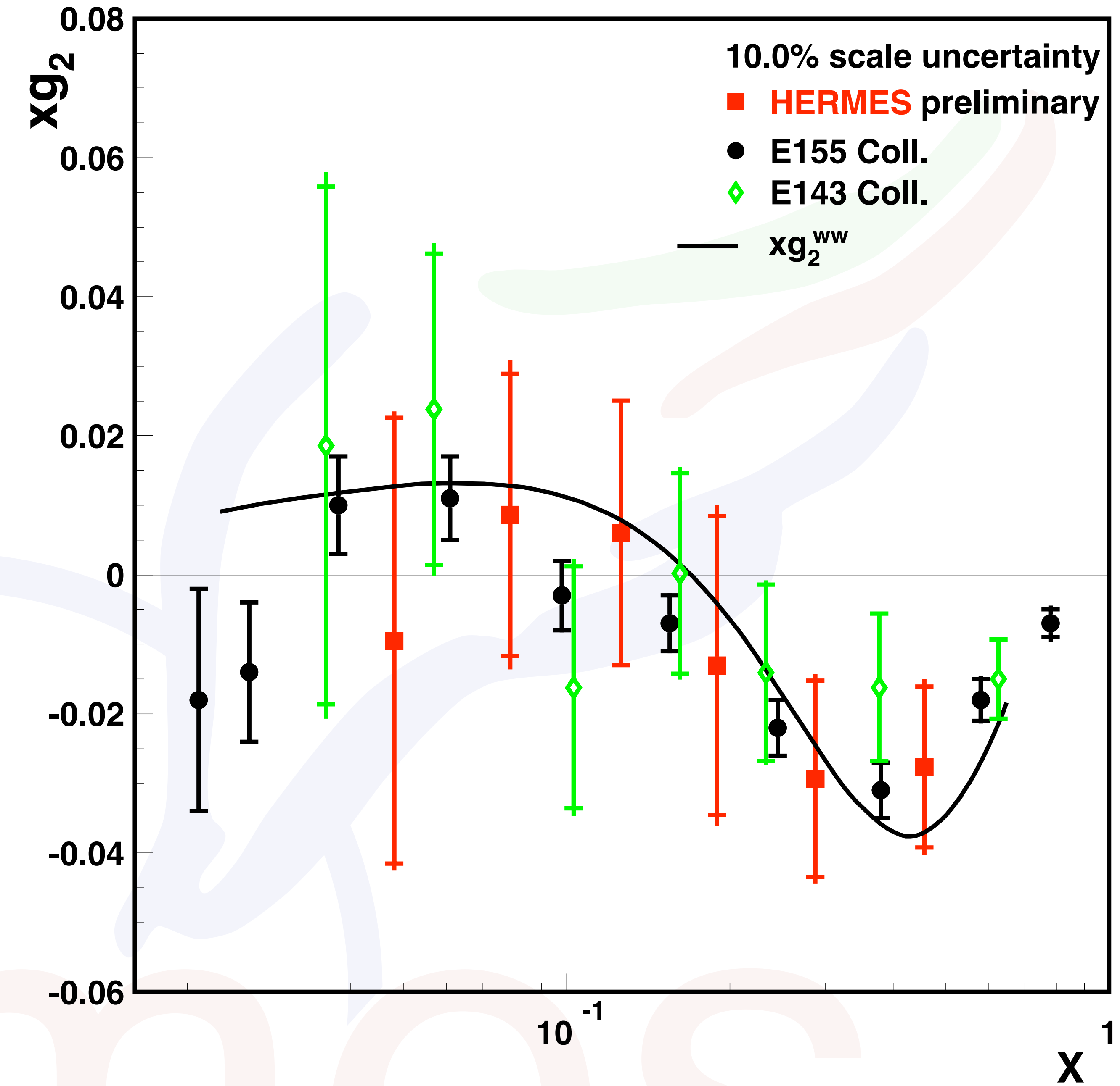
parameterizations

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

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

# Results on $A_2$ and $xg_2$




- consistent with (sparse) world data
- low beam polarization during HERA II ➥ small f.o.m.
- in analysis stage: low-$x/Q^2$ data

# Semi-Inclusive DIS

# Spin-Momentum Structure of the Nucleon

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ + \lambda\gamma^+\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + \lambda\Lambda\,g_1 + \lambda\,S^i k^i\,\frac{1}{m}\,g_{1T}\Big]$$

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^{\perp} + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_1^{\perp} + s^i S^i h_1 + s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^{\perp} + \Lambda\,s^i k^i\,\frac{1}{m}\,h_{1L}^{\perp}\Big]$$

quark pol.

| nucleon pol. | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^{\perp}$ |
| L | | $g_{1L}$ | $h_{1L}^{\perp}$ |
| T | $f_{1T}^{\perp}$ | $g_{1T}$ | $h_1,\ h_{1T}^{\perp}$ |

Twist-2 TMDs

- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

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$$+ s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^\perp\Big]$$

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| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

Twist-2 TMDs

helicity

Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

- functions in black survive integration over transverse momentum
- functions in green box are chirally odd
- functions in red are naive T-odd

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^{\perp}$ |
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# 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

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

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

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

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

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
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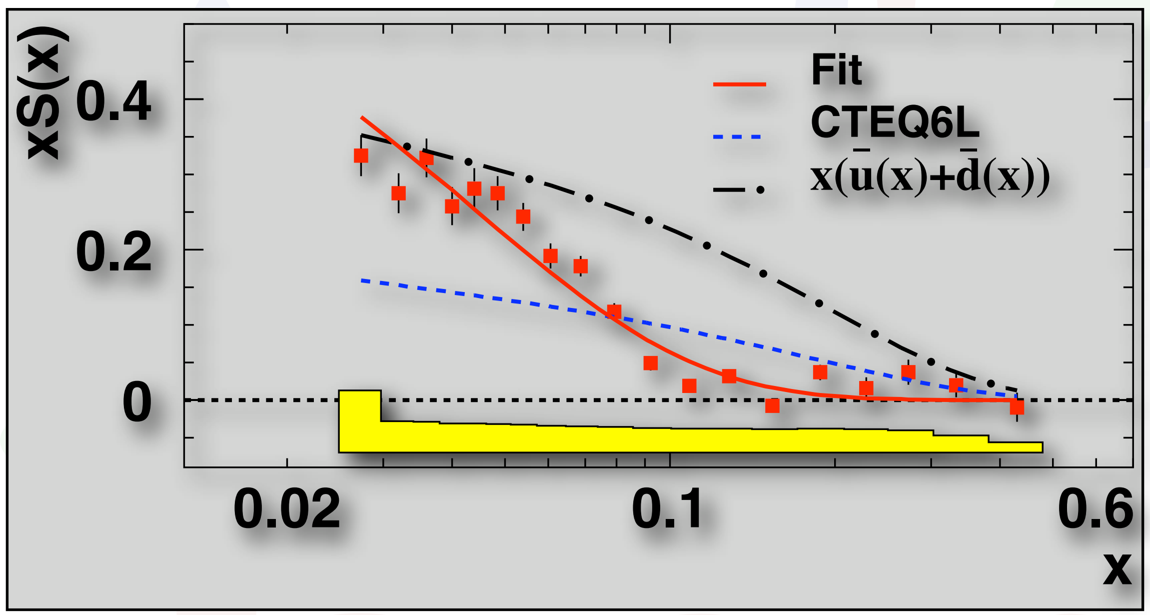


A. Airapetian et al., PLB 666, 446 (2008)

| | U | L | T |
|---|---|---|---|
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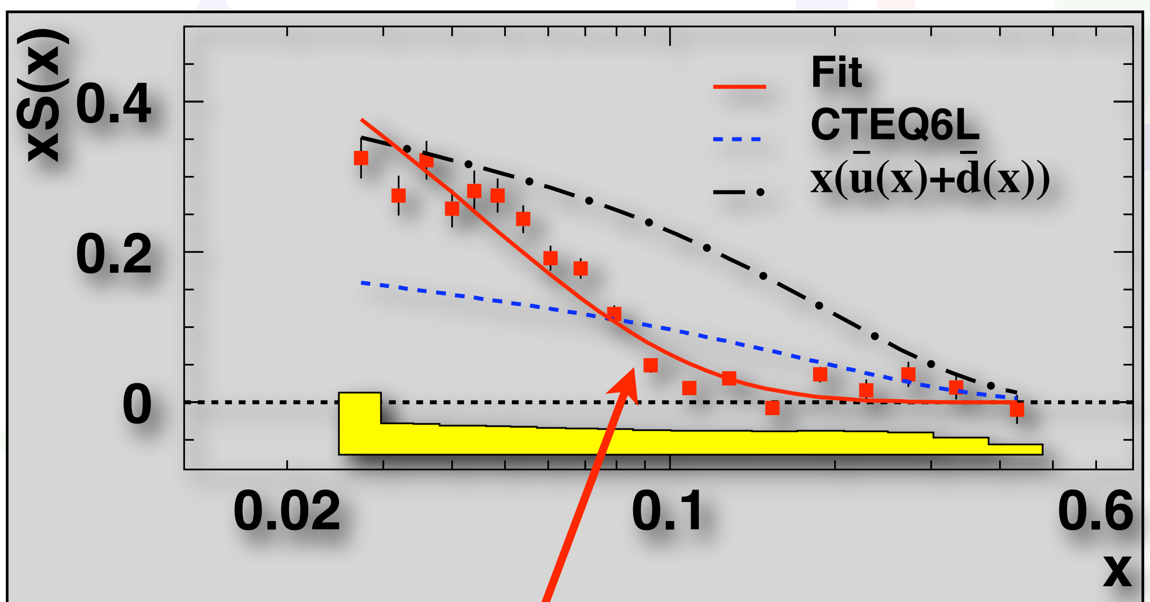


**Strange-quark distribution softer than (maybe) expected**

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

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
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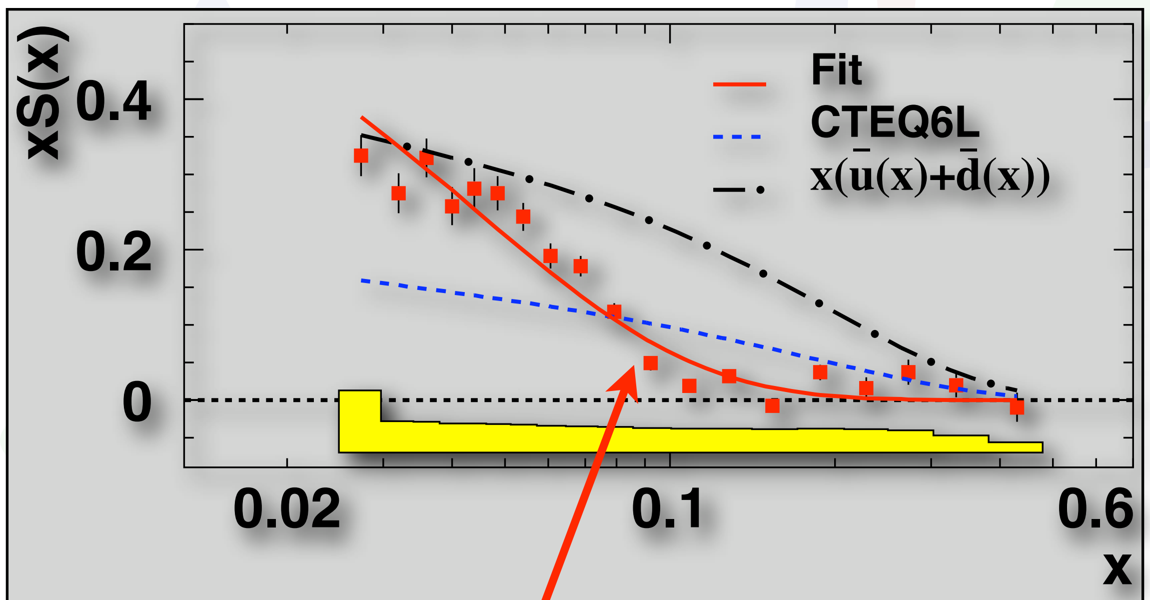
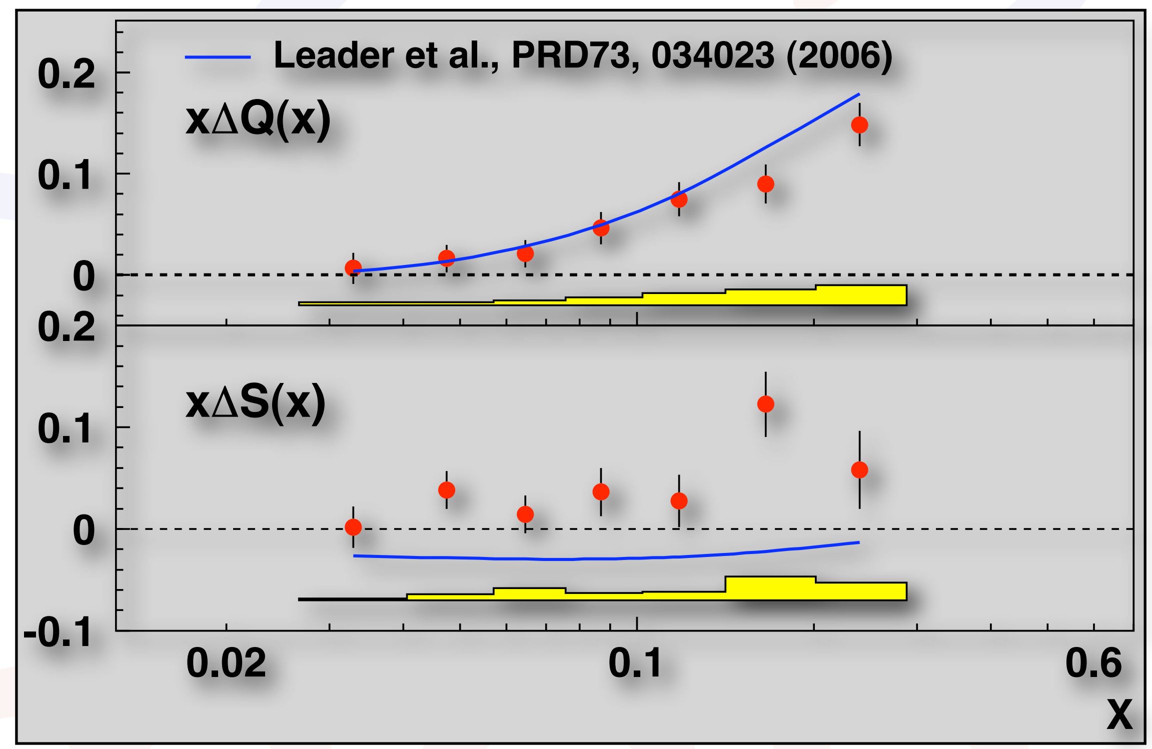
- only need inclusive asymmetries and K⁺+K⁻ asymmetries, i.e., $A_{\|,d}(x,Q^2)$ and $A_{\|,d}^{K^++K^-}(x,z,Q^2)$ , as well as K⁺+K⁻ multiplicities on deuteron



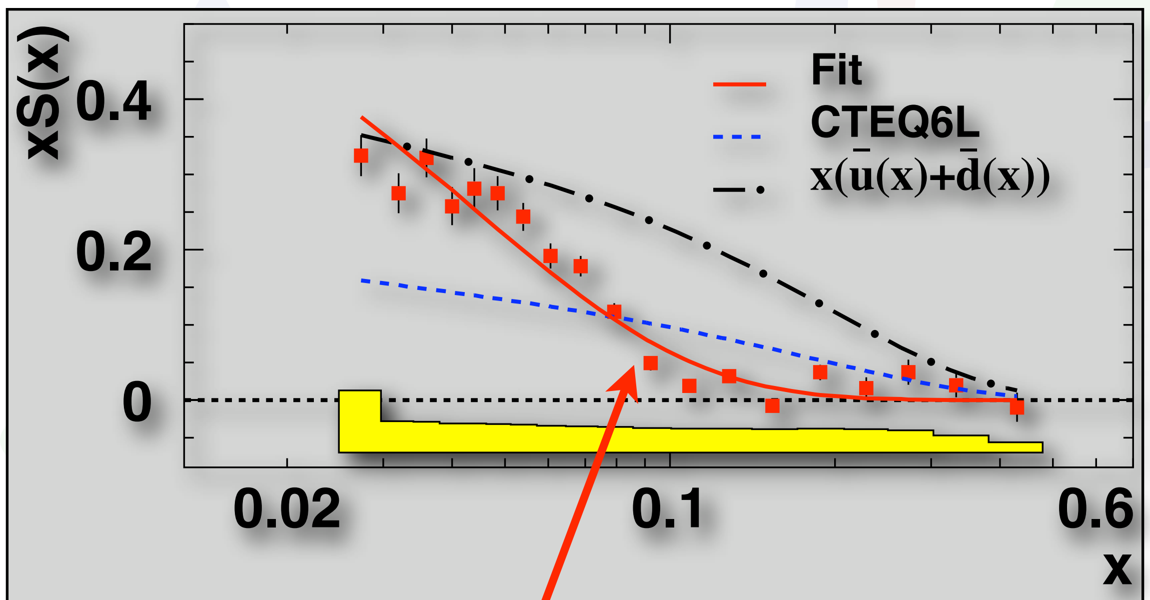

**Strange-quark distribution softer than (maybe) expected**

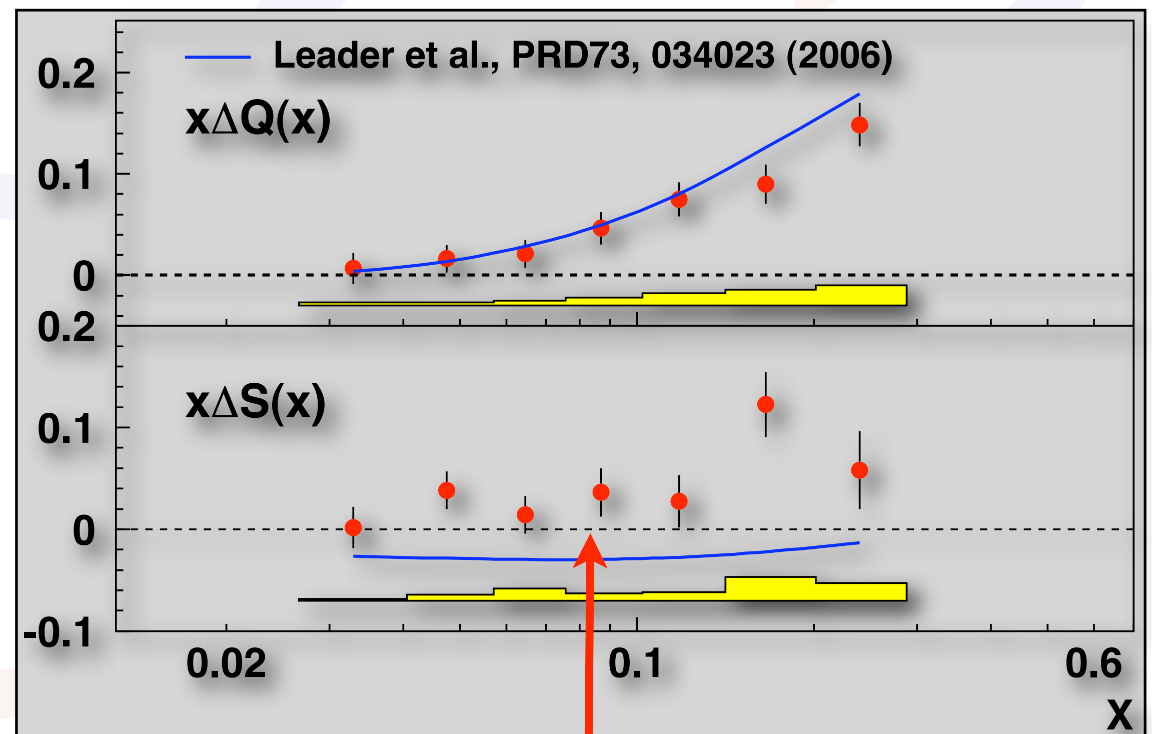
A. Airapetian et al., PLB 666, 446 (2008)

|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |  | $h_1^\perp$ |
| L |  | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# 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




Strange-quark distribution softer than (maybe) expected

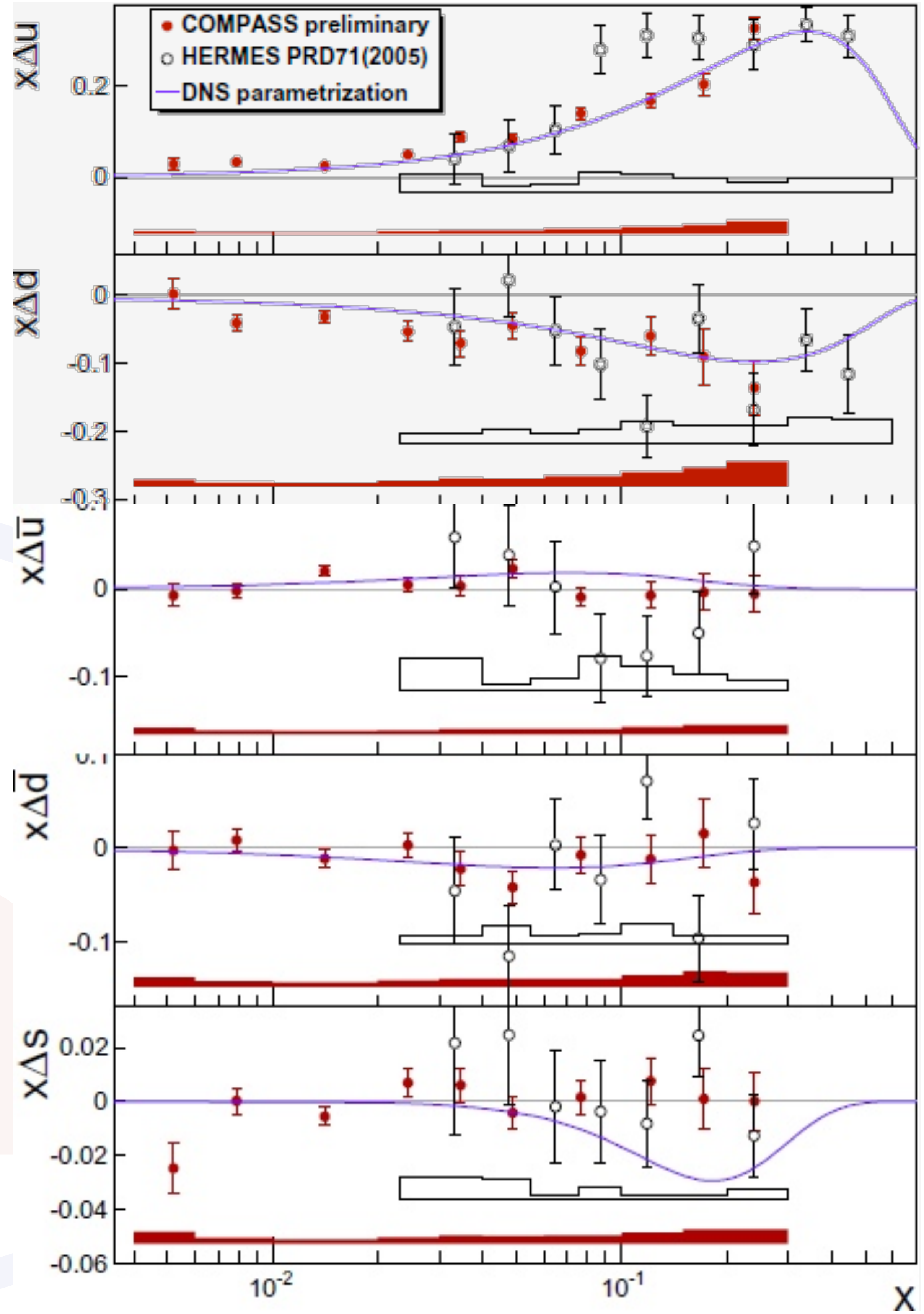
Strange-quark helicity distribution consistent with zero or slightly positive in contrast to inclusive DIS analyses

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

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Helicity density

- smaller range in $(x,Q^2)$ than for $f_1$
- data mainly for integrated version of $g_{1L}$
- need asymmetries not only binned in x but also in $P_{h\perp}$



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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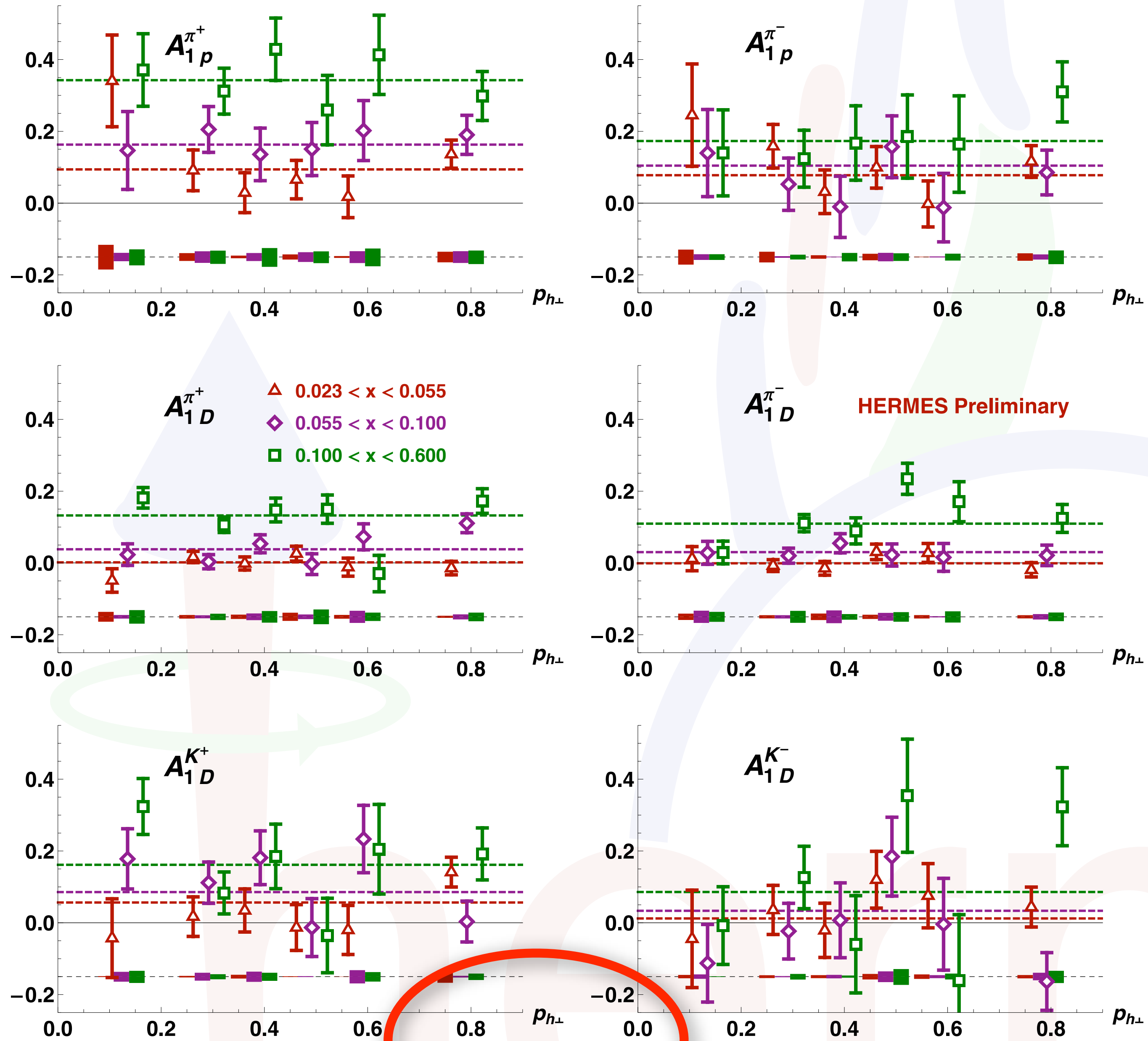
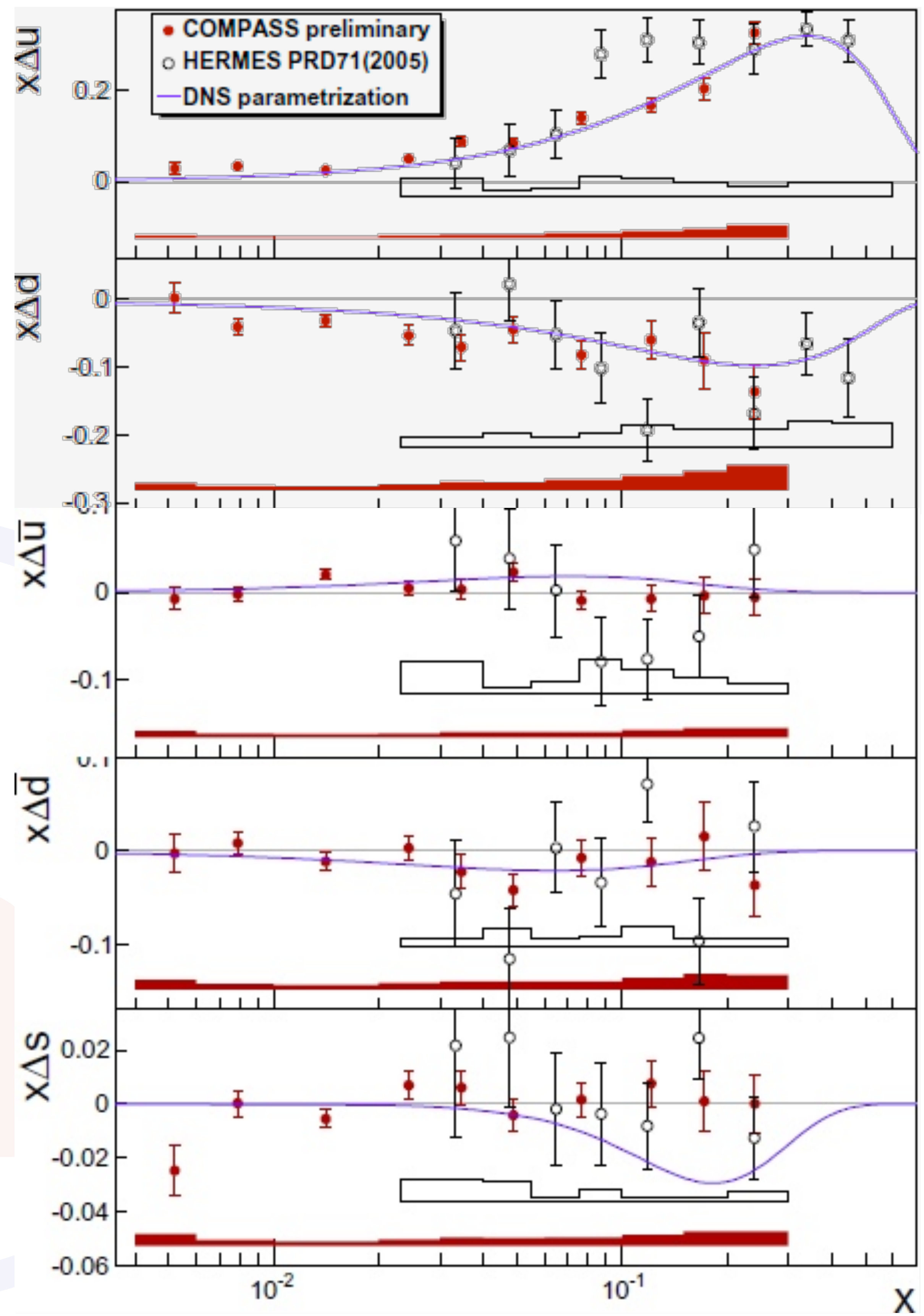
# Helicity density



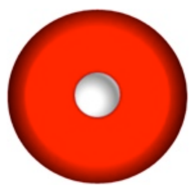



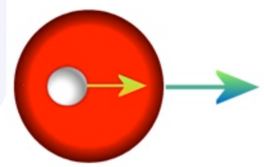
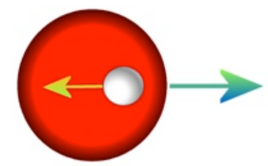

only weak if any dependence on $P_{h\perp}$ seen

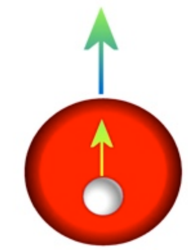
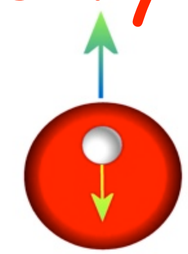
| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^{\perp}$ |
| L | | $g_{1L}$ | $h_{1L}^{\perp}$ |
| T | $f_{1T}^{\perp}$ | $g_{1T}$ | $h_1$, $h_{1T}^{\perp}$ |

# Transversity distribution

## chiral-odd transversity involves quark helicity flip

$f_1^q =$ 

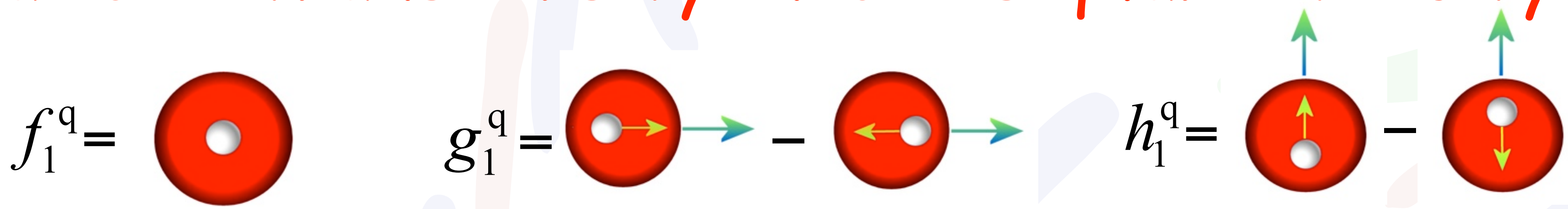
$g_1^q =$  $-$ 

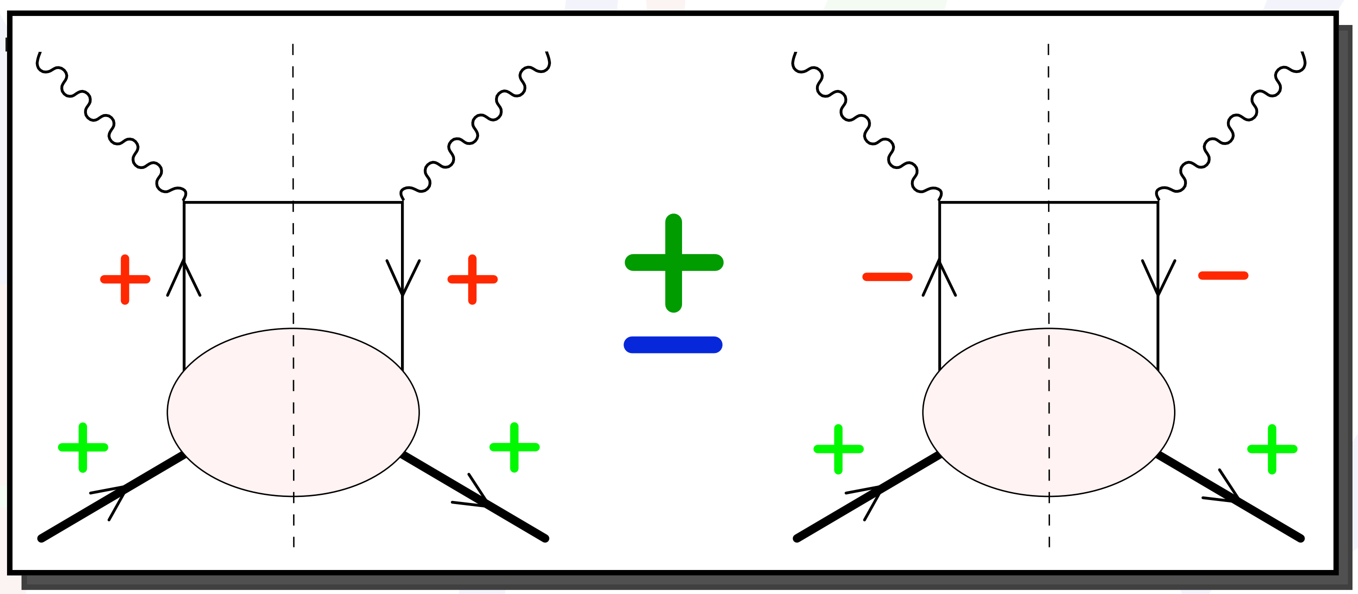
$h_1^q =$  $-$ 

|  | U | L | T |
|---|---|---|---|
| U | $f_1$ |  | $h_1^\perp$ |
| L |  | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1,\ h_{1T}^\perp$ |

# Transversity distribution

chiral-odd transversity involves quark helicity flip



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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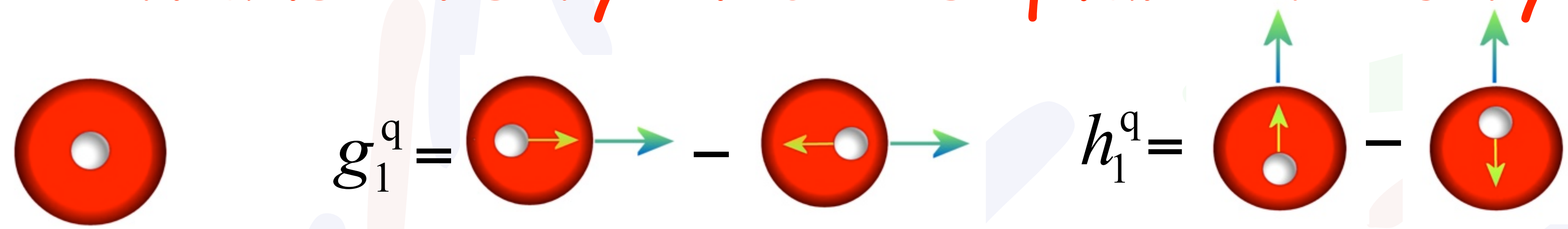
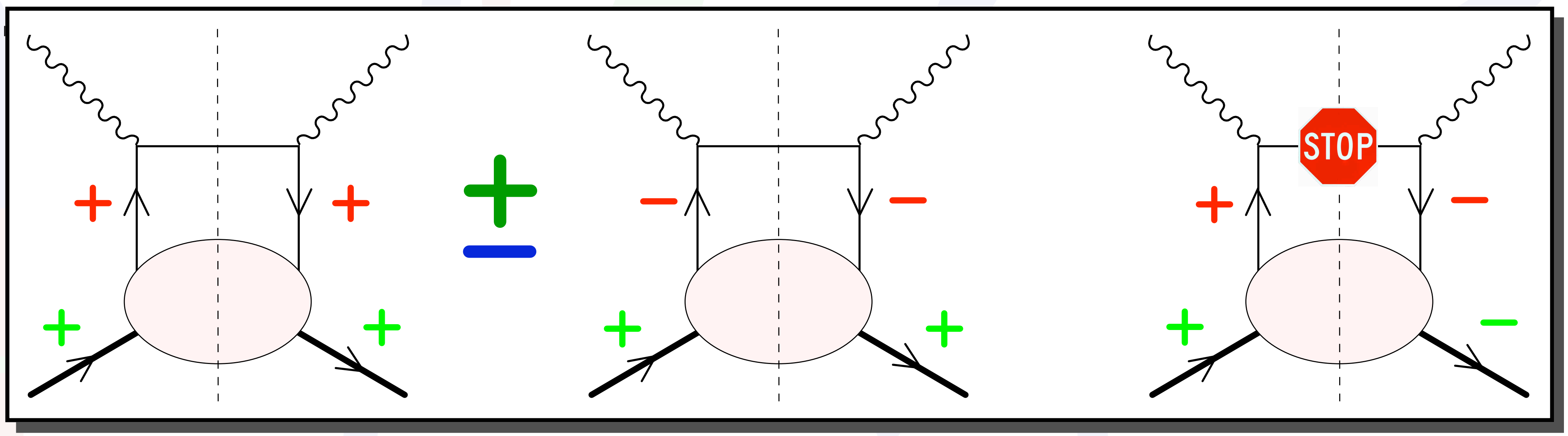
# Transversity distribution

## chiral-odd transversity involves quark helicity flip

$f_1^q =$ , $g_1^q = \ldots - \ldots$ , $h_1^q = \ldots - \ldots$





| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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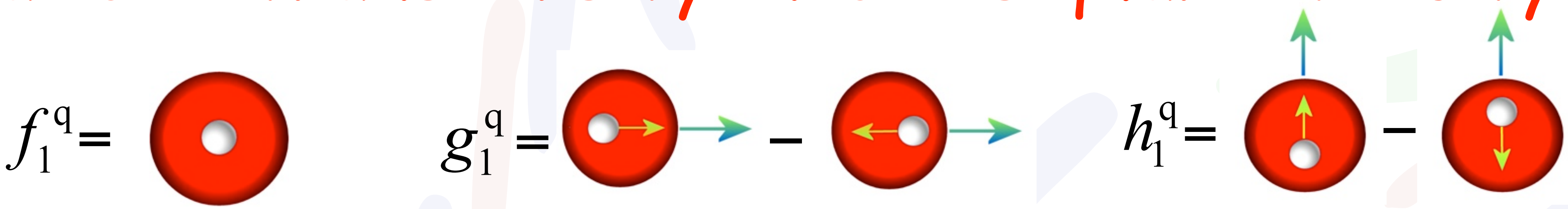
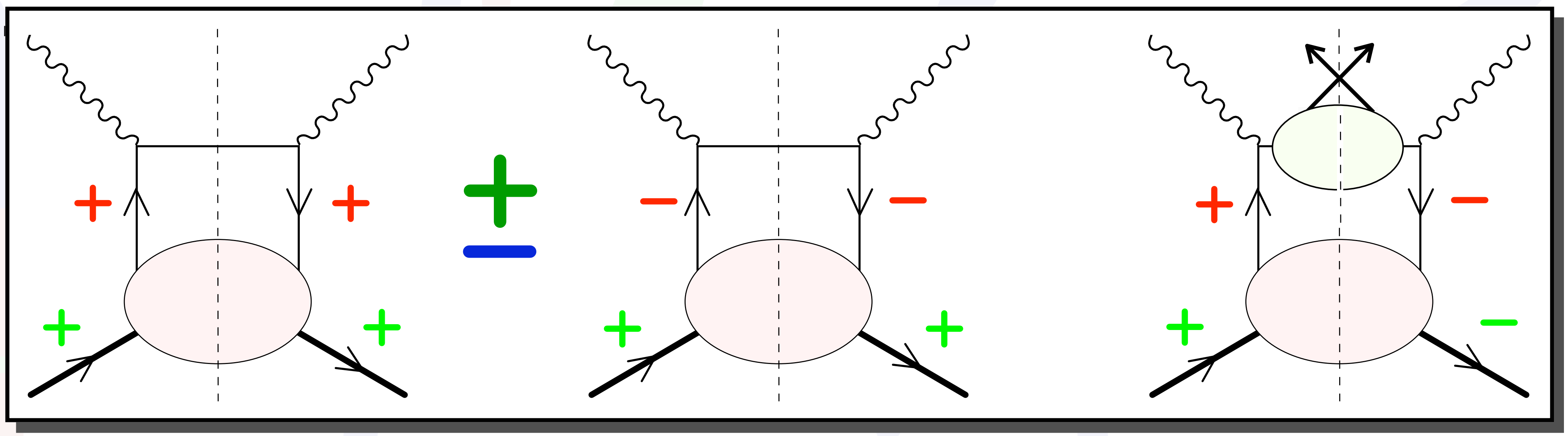
# Transversity distribution

chiral-odd transversity involves quark helicity flip



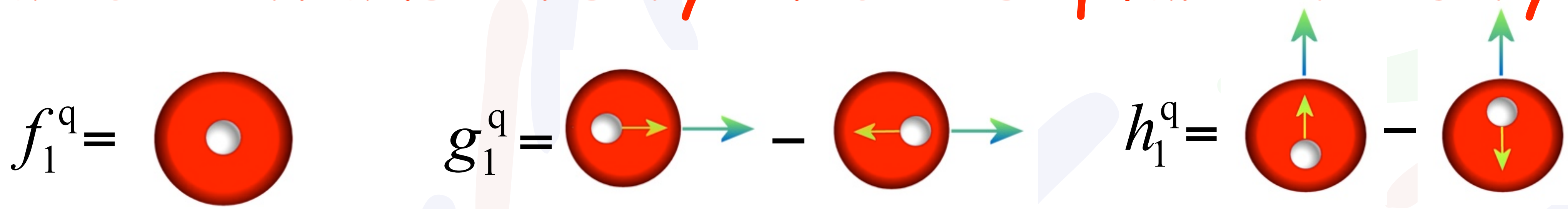



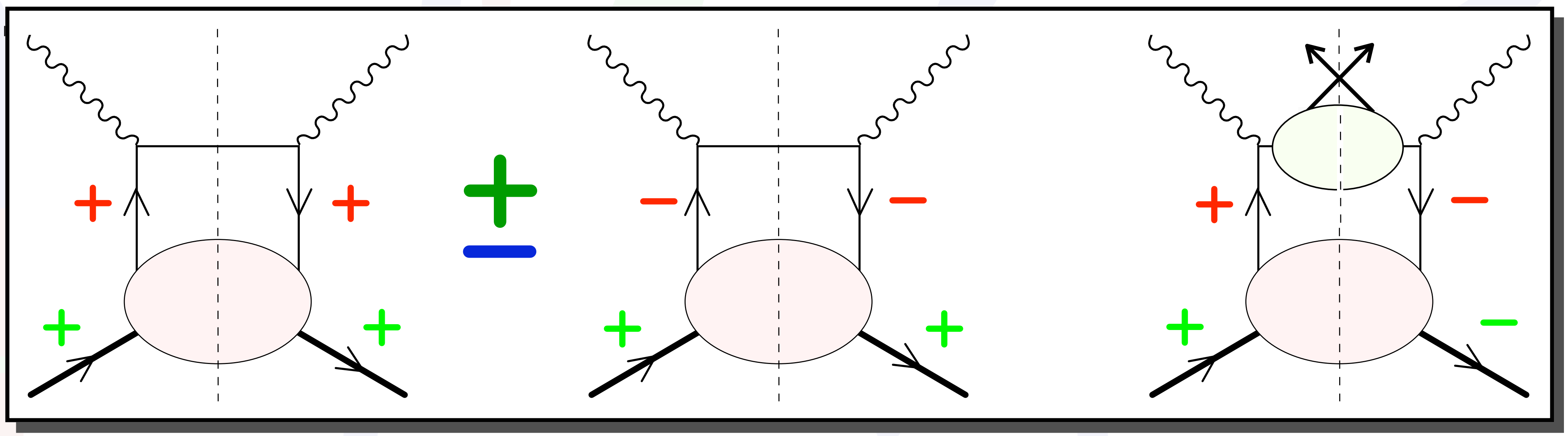
need to couple to chiral-odd fragmentation function:

|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |  | $h_1^\perp$ |
| L |  | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1,\ h_{1T}^\perp$ |

# Transversity distribution

chiral-odd transversity involves quark helicity flip



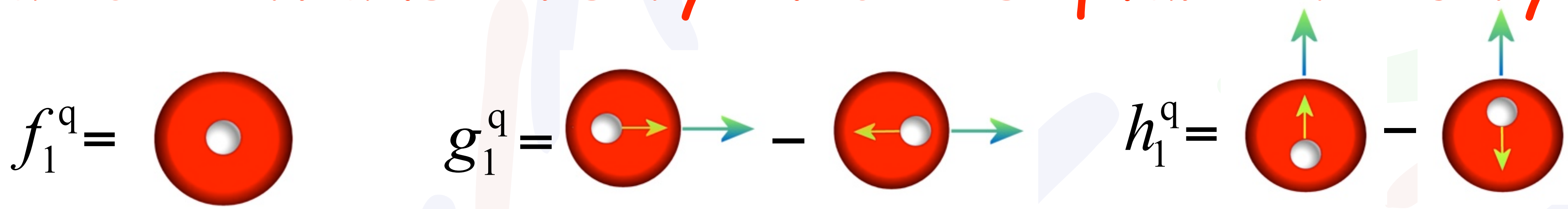
need to couple to chiral-odd fragmentation function:

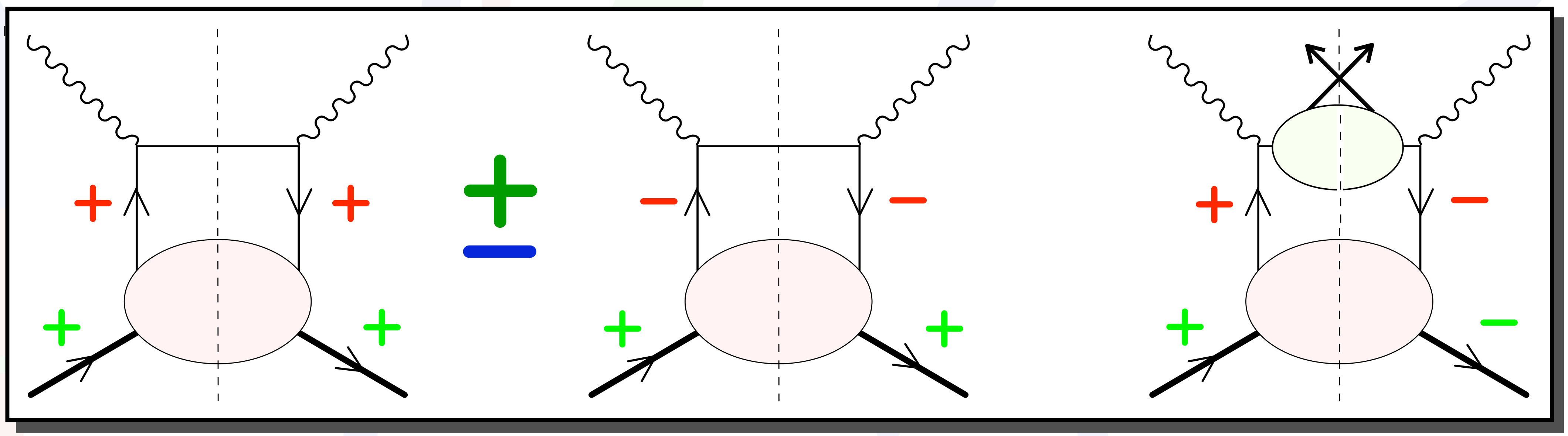
- **transverse spin transfer** (polarized final-state hadron)

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Transversity distribution

chiral-odd transversity involves quark helicity flip



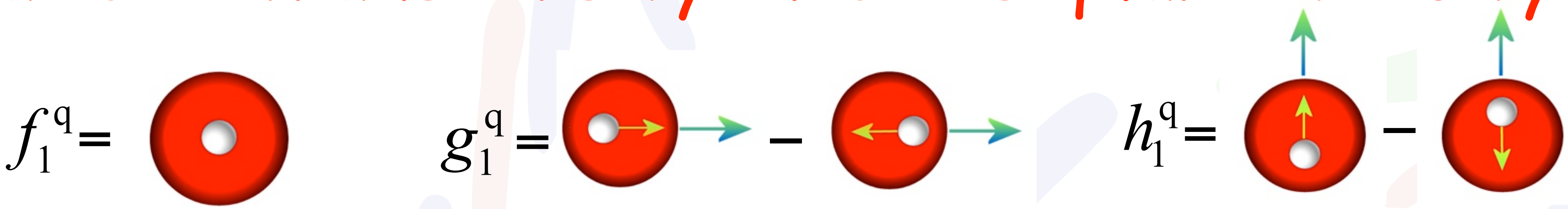

need to couple to chiral-odd fragmentation function:

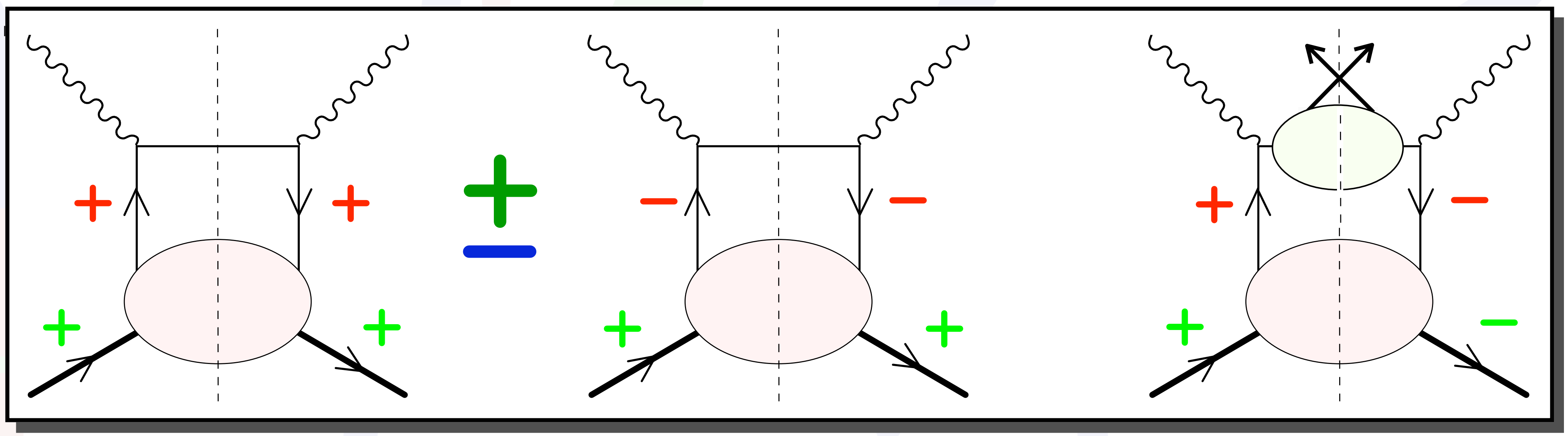
- **transverse spin transfer** (polarized final-state hadron)
- **2-hadron fragmentation**

|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |   | $h_1^\perp$ |
| L |   | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Transversity distribution

chiral-odd transversity involves quark helicity flip



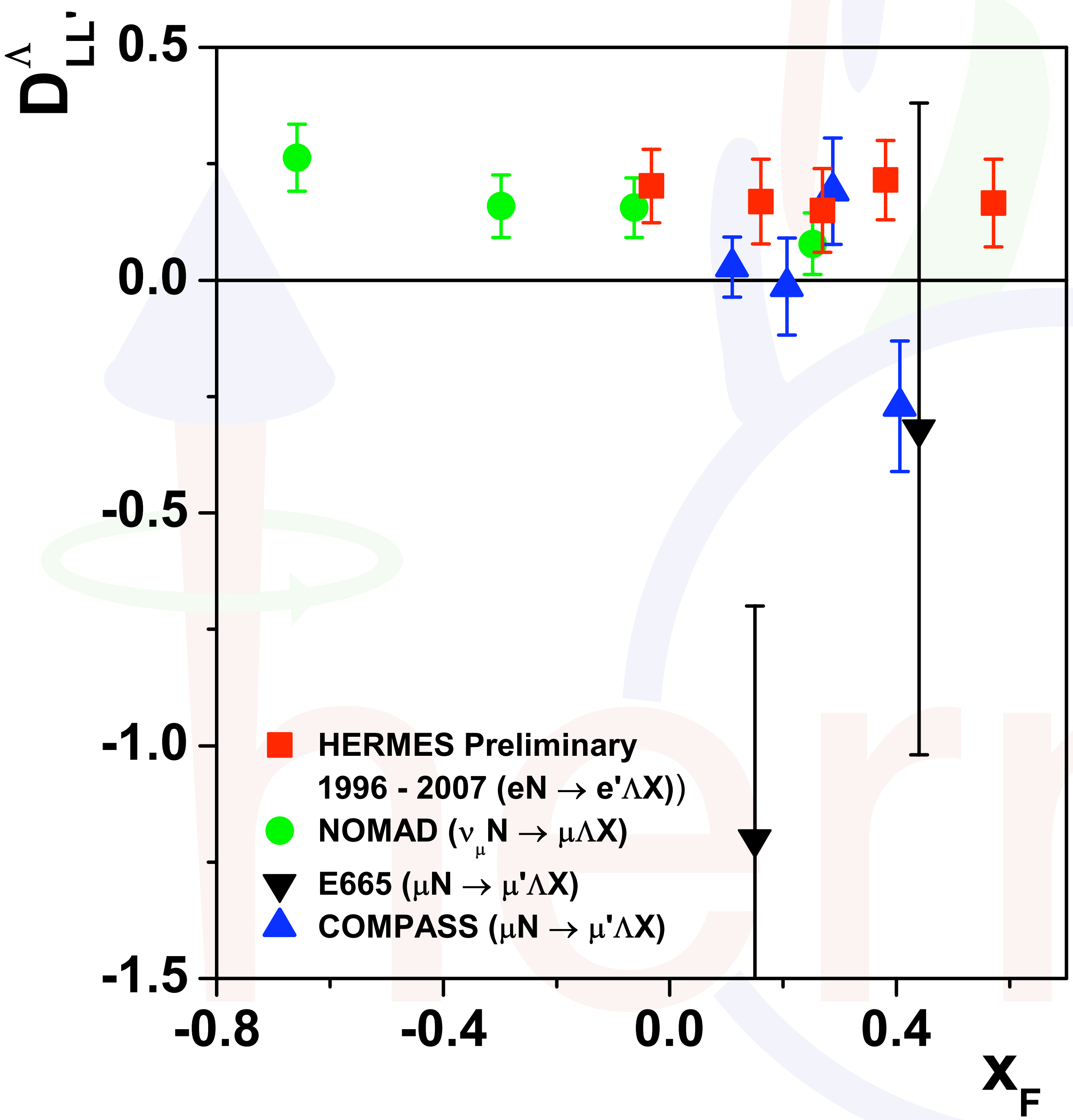




need to couple to chiral-odd fragmentation function:

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

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Transversity distribution (transverse-spin transfer)



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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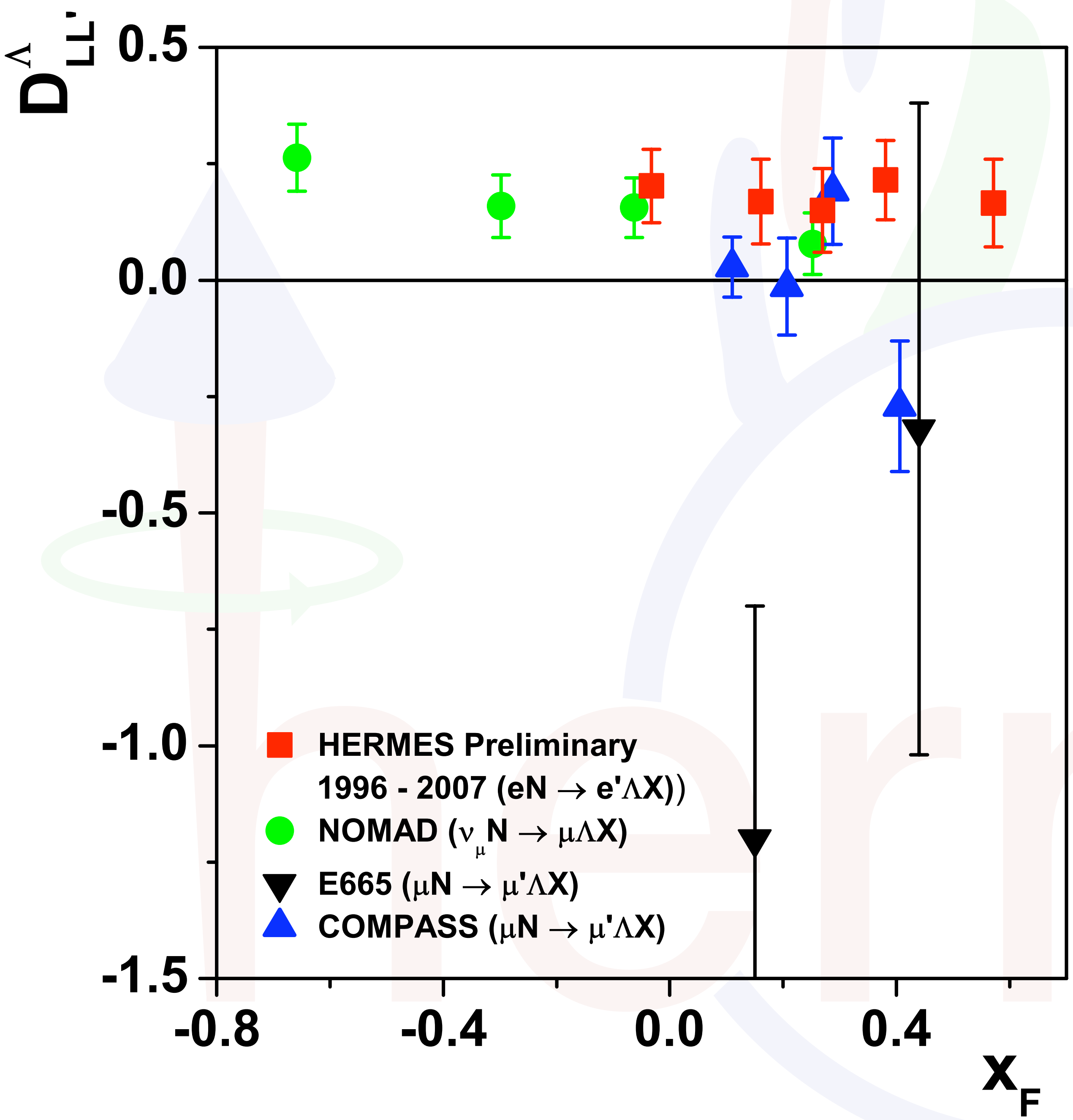
# Transversity distribution (transverse-spin transfer)




- non-zero longitudinal spin transfer (based on complete HERMES data set)
- statistics much lower for transverse-target data
- spin-transfer already puzzle for longitudinal case

➡ no real prospects at HERMES for measuring transversity via spin transfer

| | U | L | T |
|---|---|---|---|
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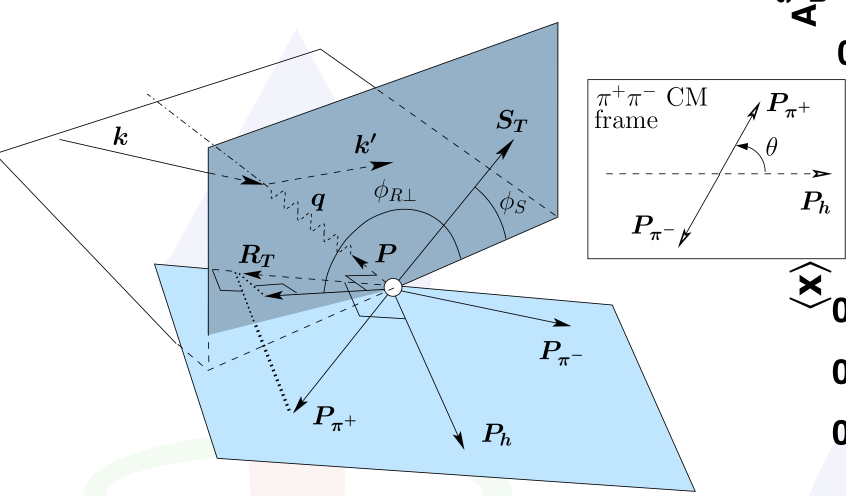
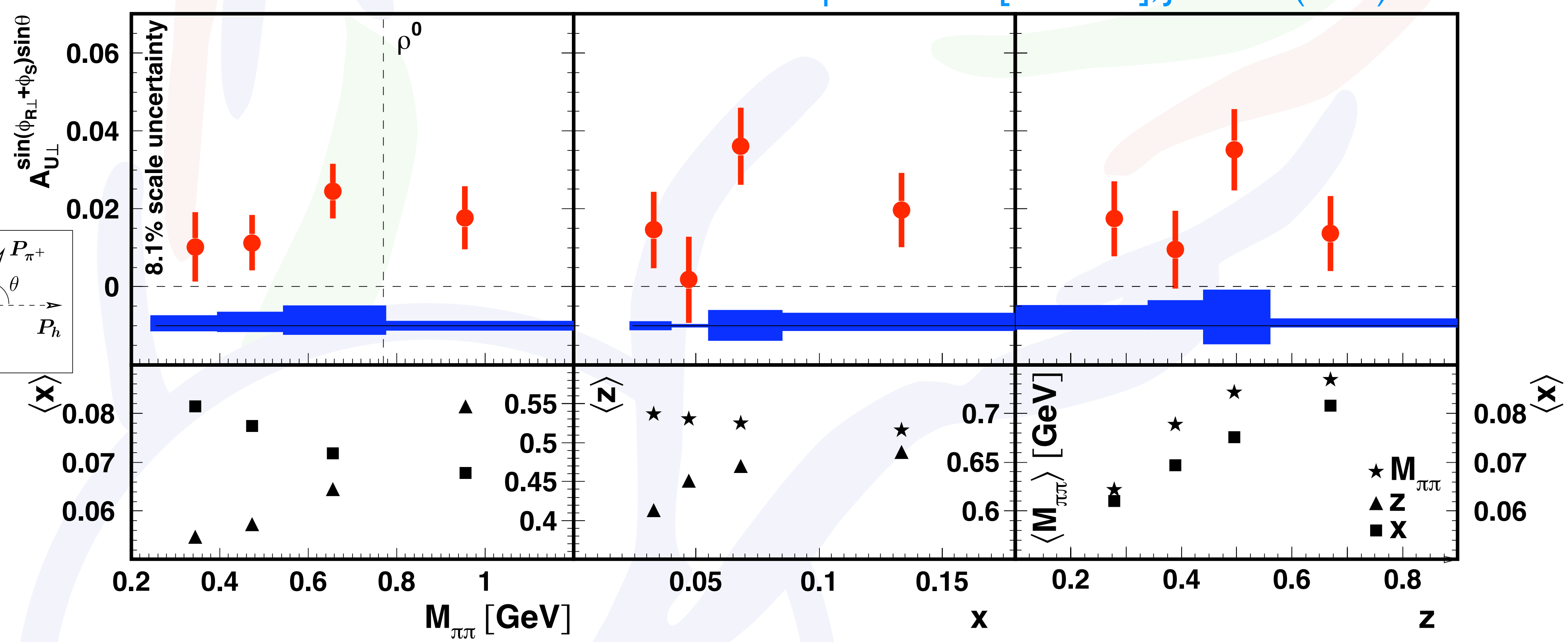
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Transversity distribution (2-hadron fragmentation)

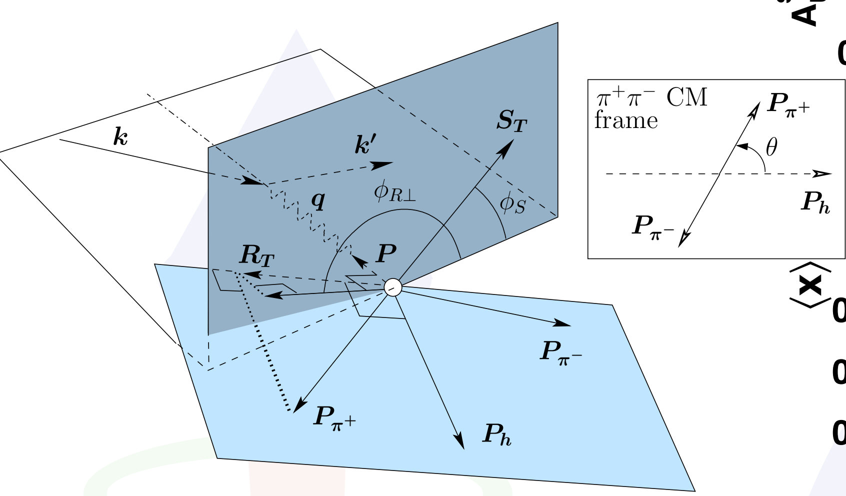



A. Airapetian et al. [HERMES], JHEP 06 (2008) 017



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Transversity distribution (2-hadron fragmentation)

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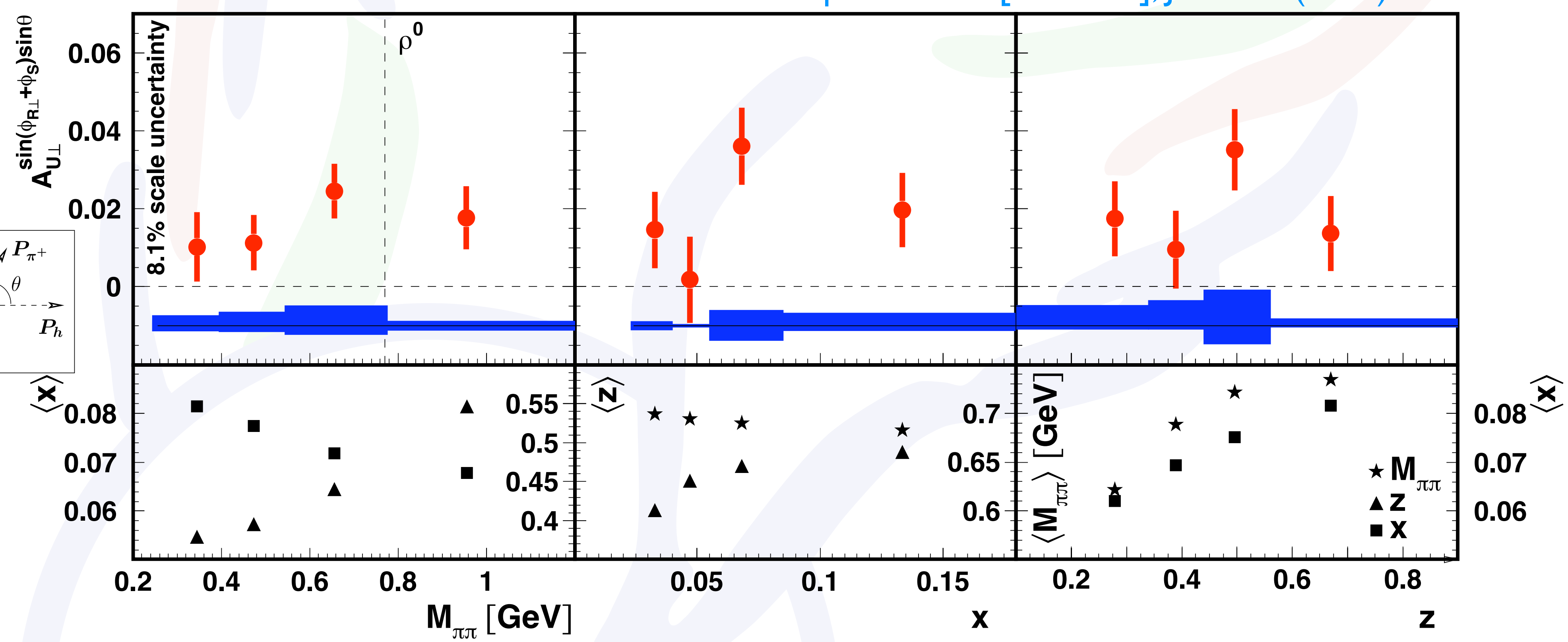


☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS

|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |   | $h_1^\perp$ |
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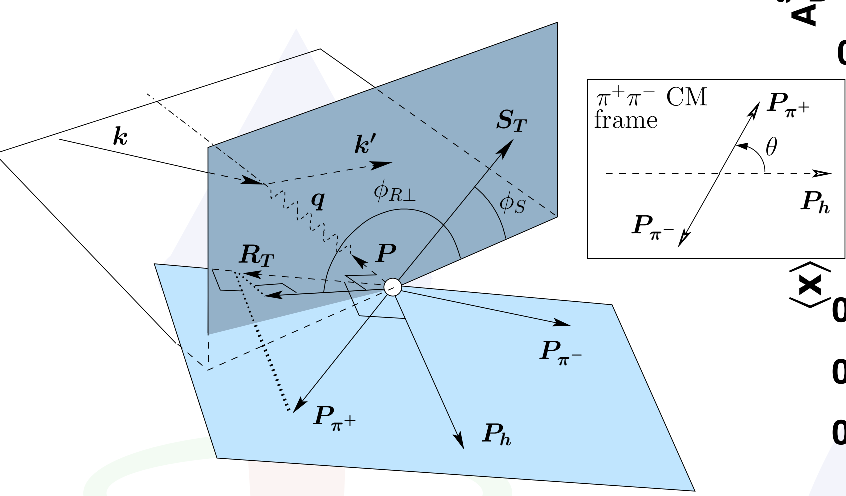


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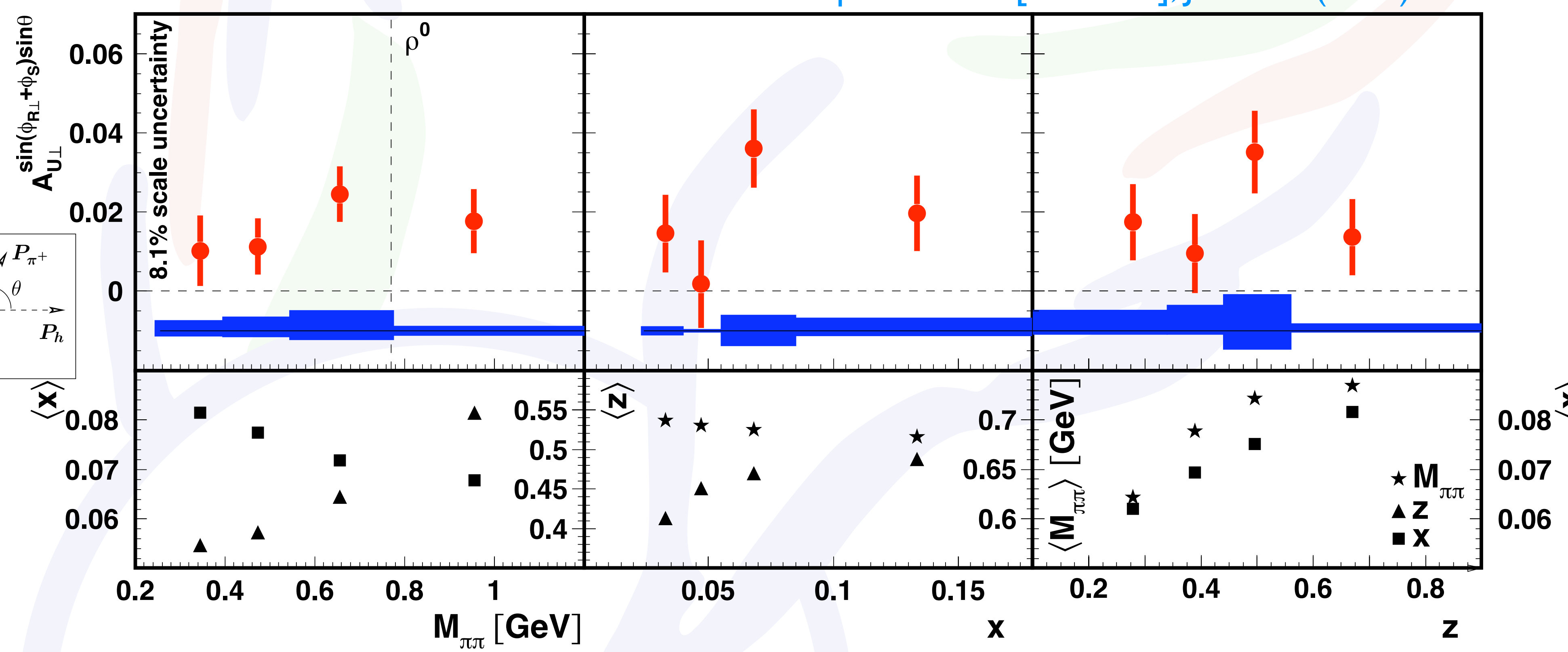


☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS

☑ invariant-mass dependence rules out Jaffe model

| | U | L | T |
|---|---|---|---|
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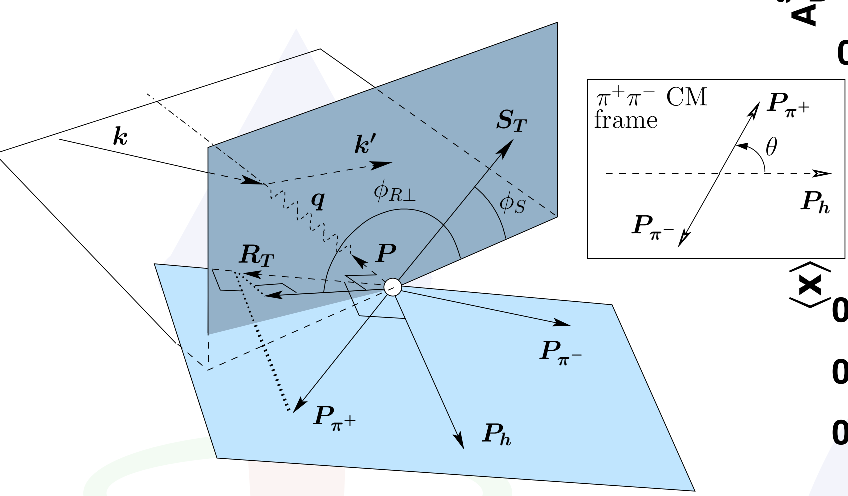
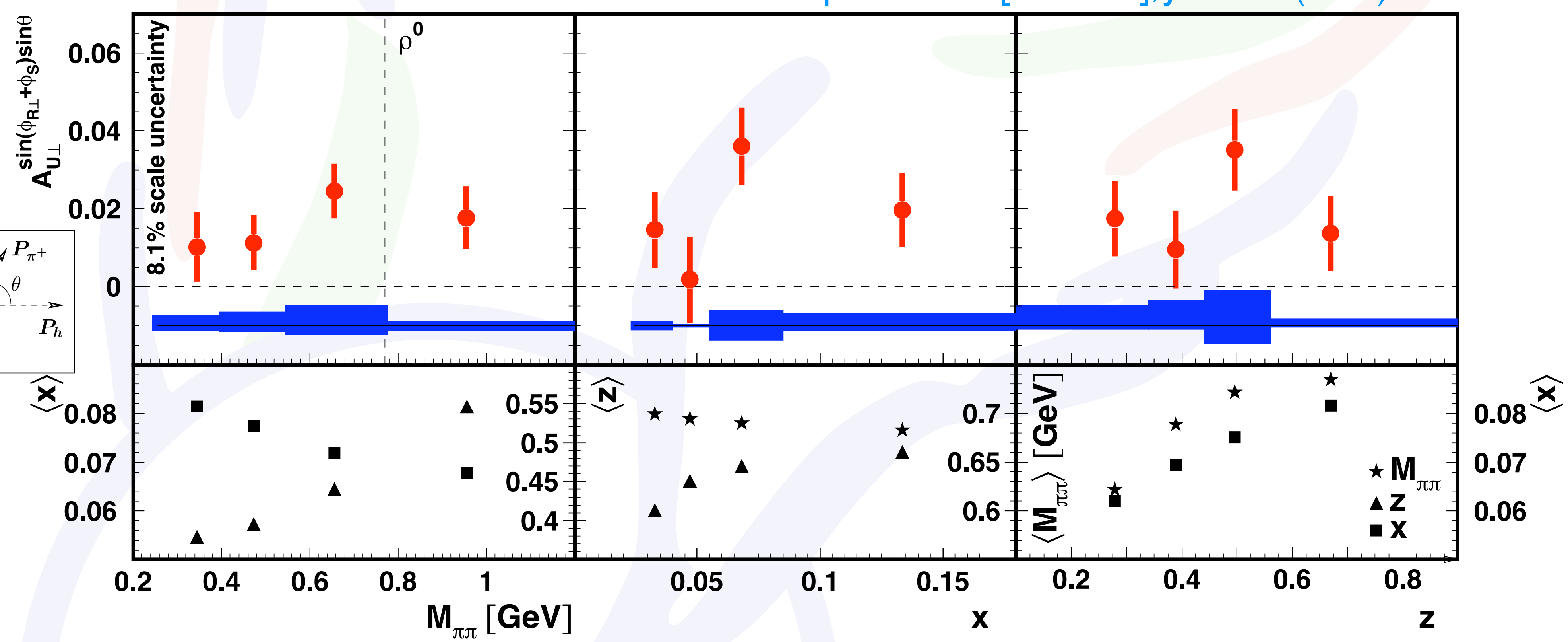
# Transversity distribution (2-hadron fragmentation)

A. Airapetian et al. [HERMES], JHEP 06 (2008) 017

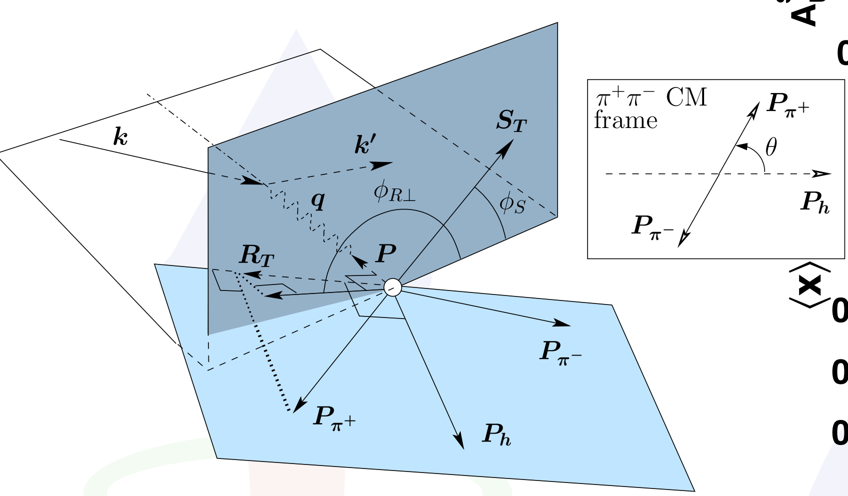



- ☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS
- ☑ invariant-mass dependence rules out Jaffe model
- ☐ difference in magnitude between COMPASS and HERMES

|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |   | $h_1^\perp$ |
| L |   | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Transversity distribution (2-hadron fragmentation)

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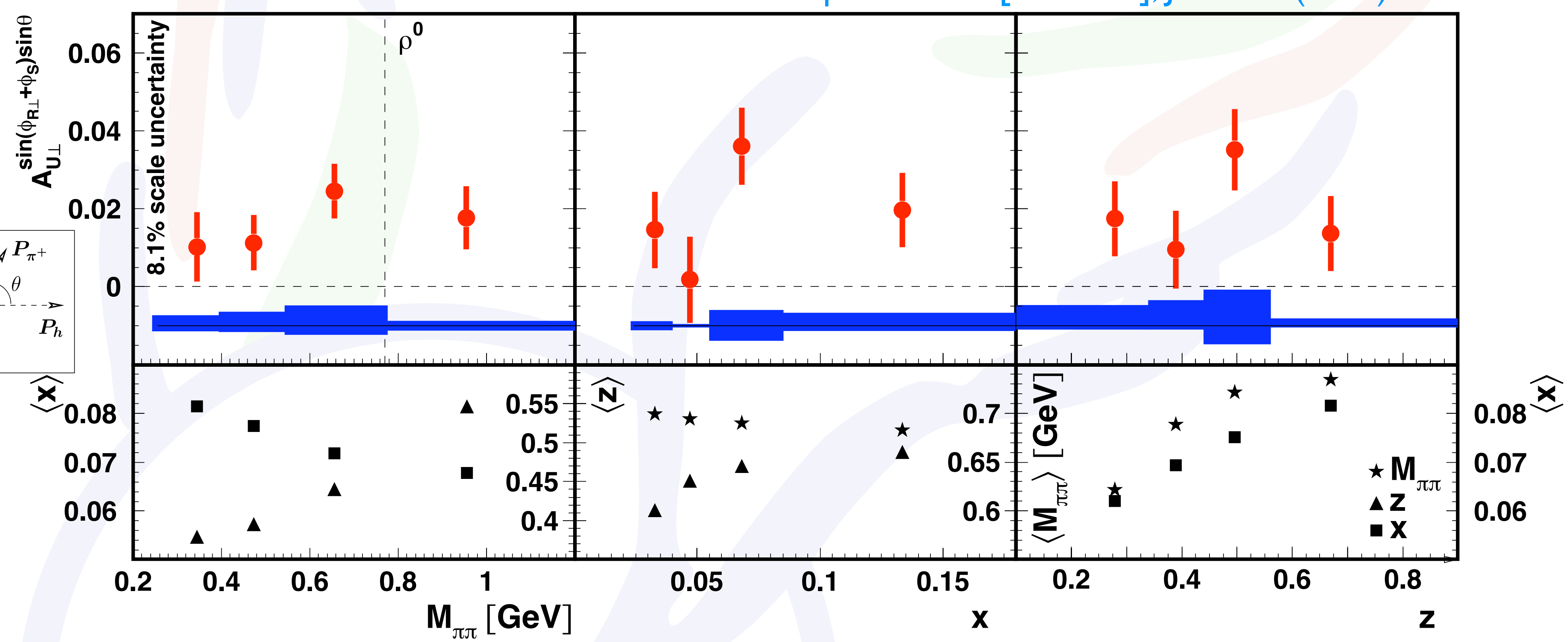



☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS

☑ invariant-mass dependence rules out Jaffe model

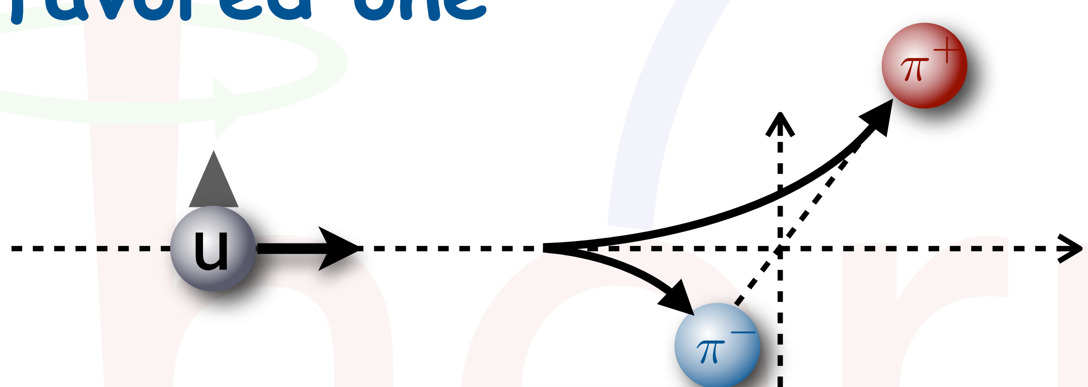
☐ difference in magnitude between COMPASS and HERMES

☐ more amplitudes coming out soon

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

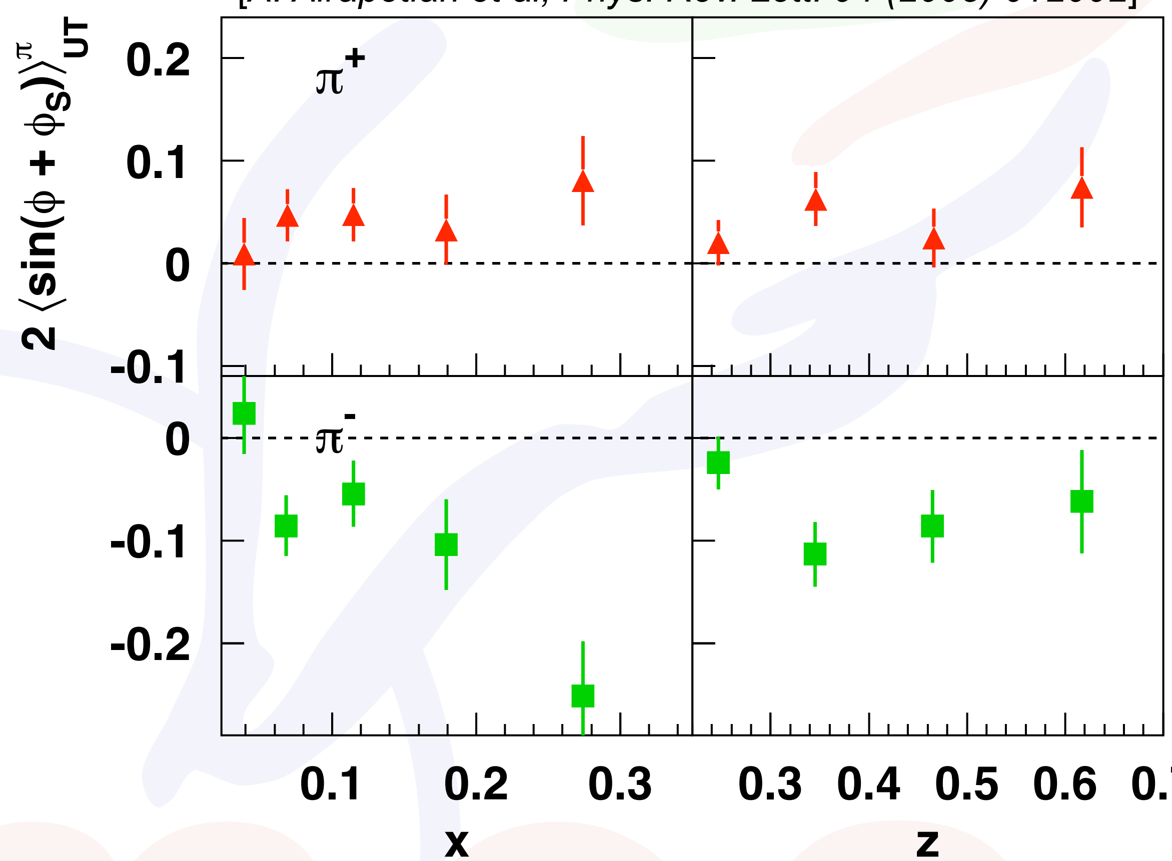
# Transversity distribution (Collins fragmentation)

- significant in size and opposite in sign for charged pions
- disfavored Collins FF large and opposite in sign to favored one




- leads to various cancellations in SSA observables

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




2005: First evidence from HERMES SIDIS on proton

Non-zero transversity
Non-zero Collins function

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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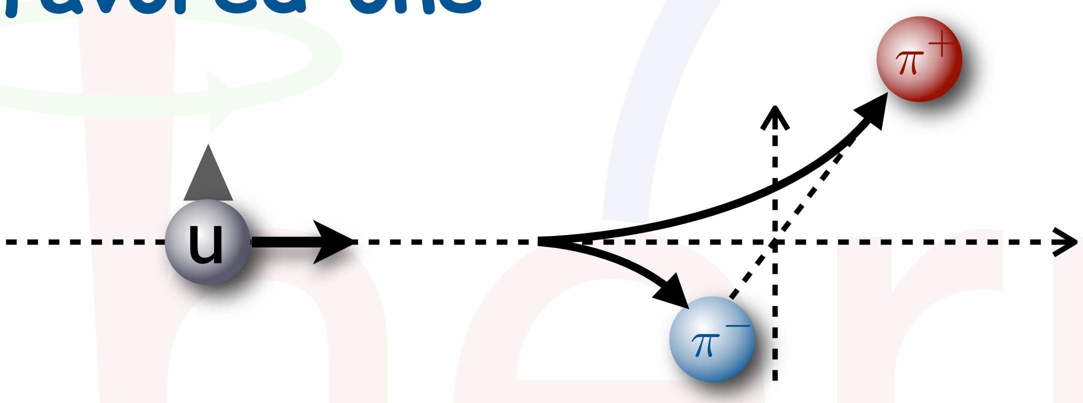
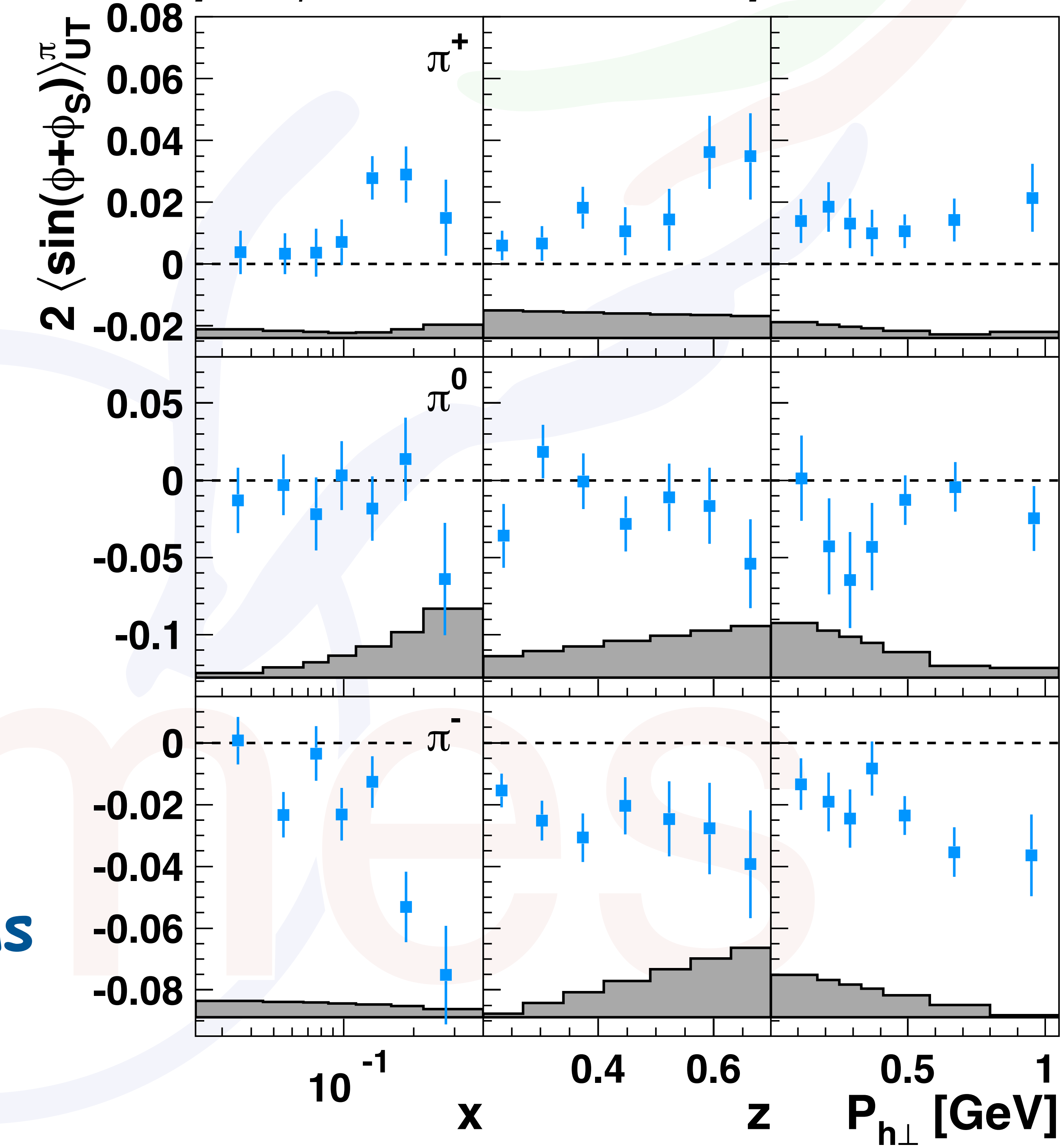



- leads to various cancellations in SSA observables

[A.Airapetian et al., arXiv:1006.4221]



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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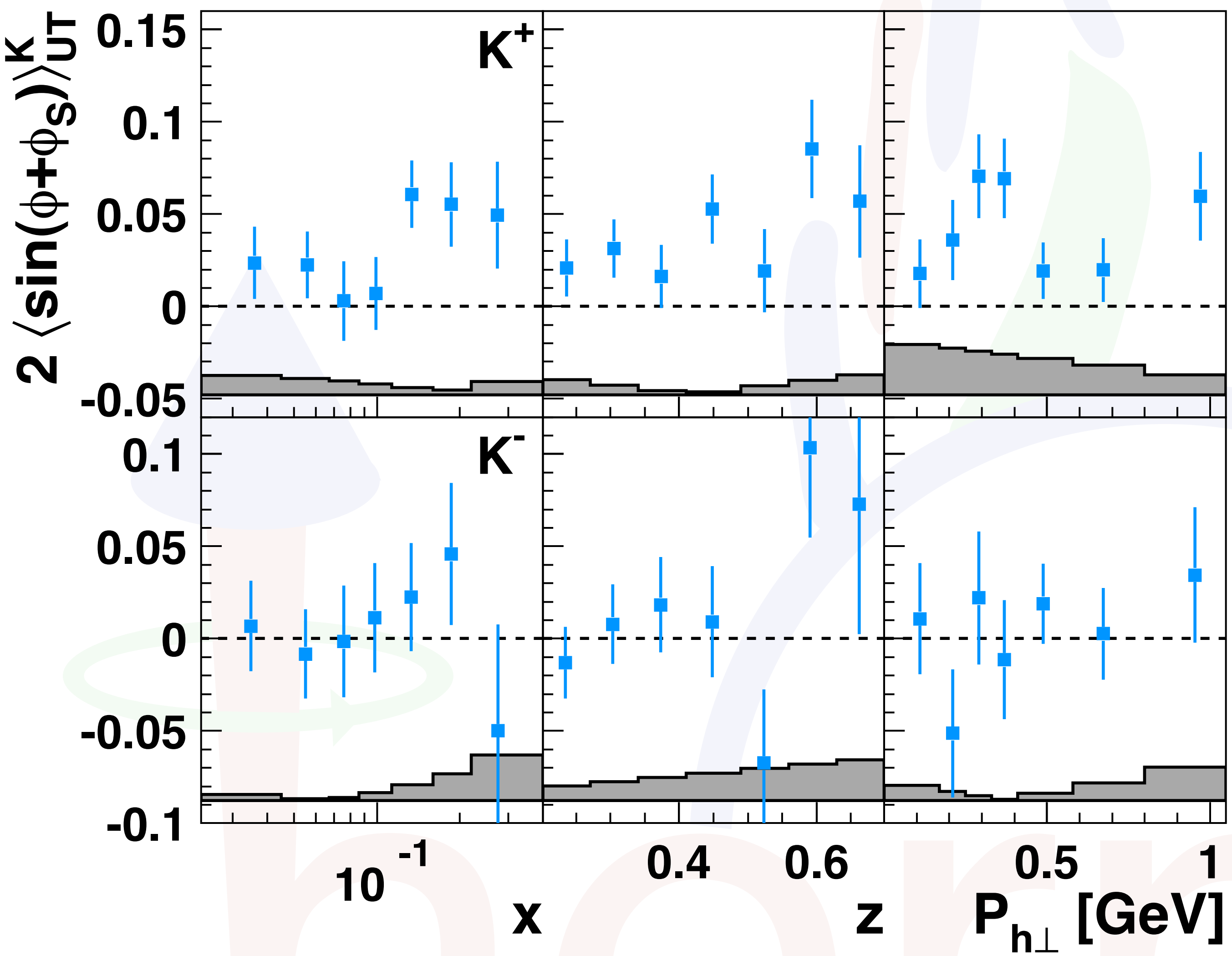
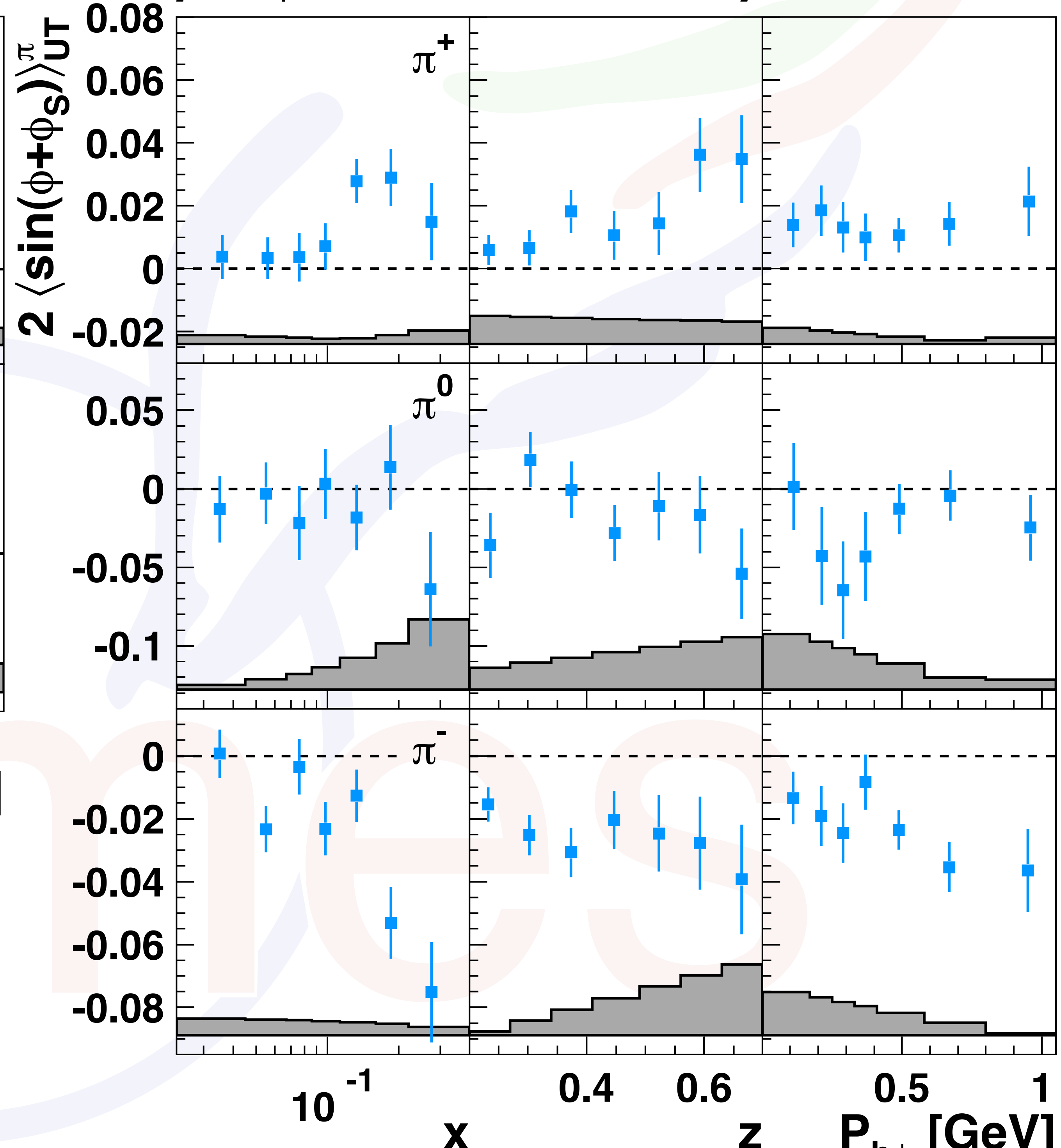
# Transversity distribution (Collins fragmentation)

[A.Airapetian et al., arXiv:1006.4221]



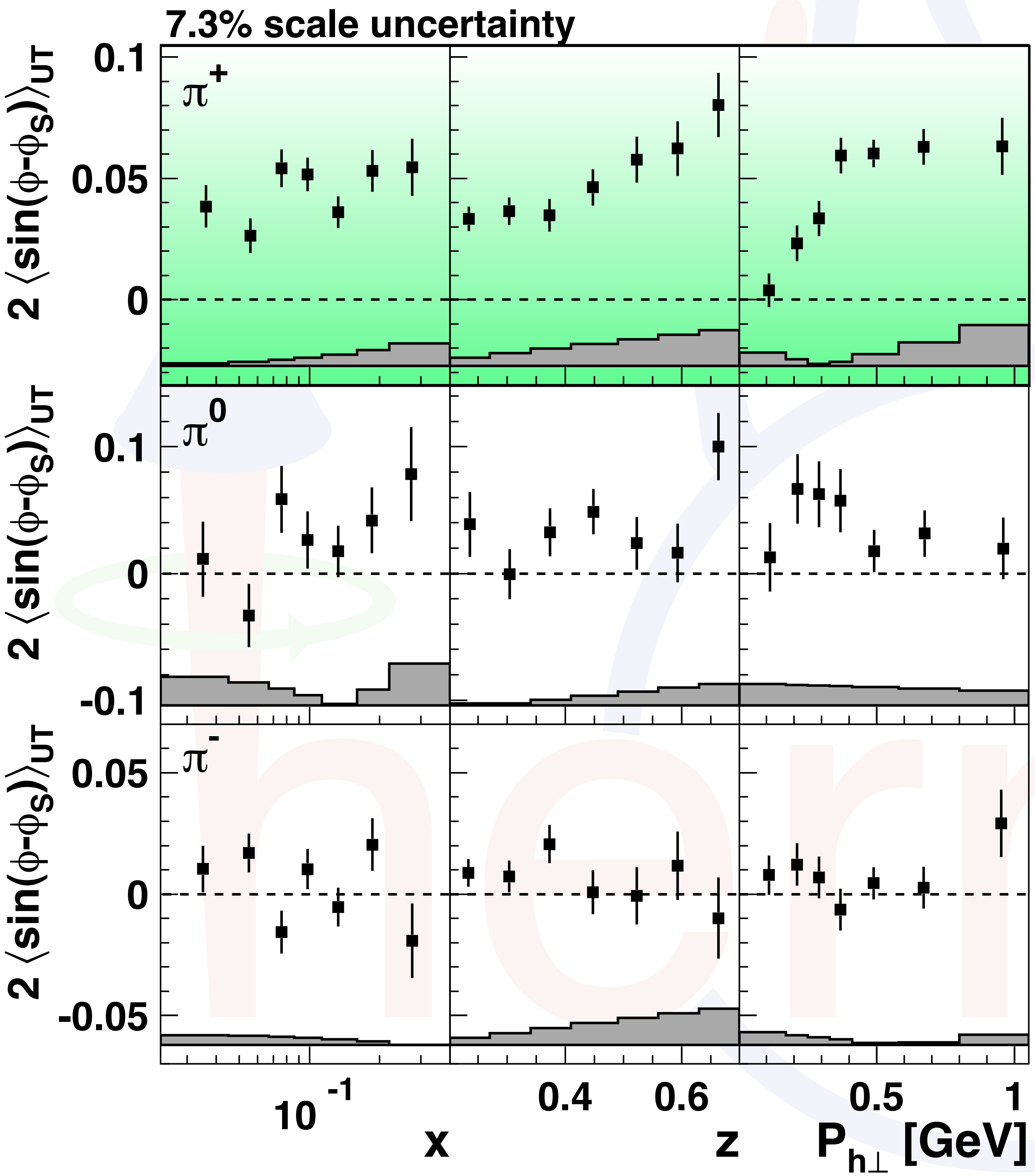




- significantly non-zero amplitudes also for $K^+$

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Sivers amplitudes for pions

$$2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}} = -\frac{\sum_q e_q^2 f_{1\mathrm{T}}^{\perp,q}(x,p_T^2)\otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2)\otimes D_1^q(z,k_T^2)}$$



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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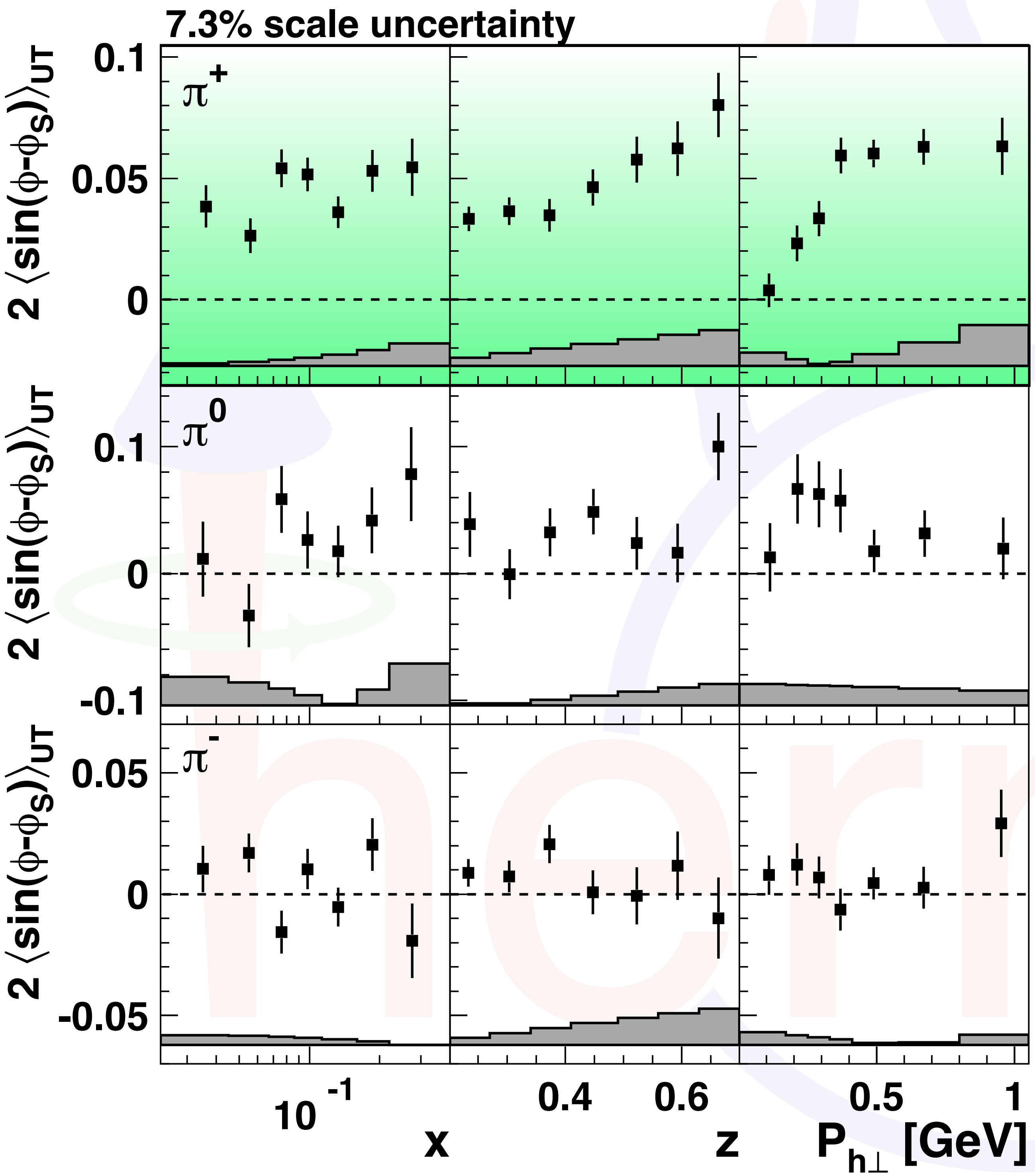
# Sivers amplitudes for pions

$$2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}} = -\frac{\sum_q e_q^2 f_{1\mathrm{T}}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$




$\pi^+$ dominated by u-quark scattering:

$$\simeq -\frac{f_{1\mathrm{T}}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

☛ u-quark Sivers DF < 0

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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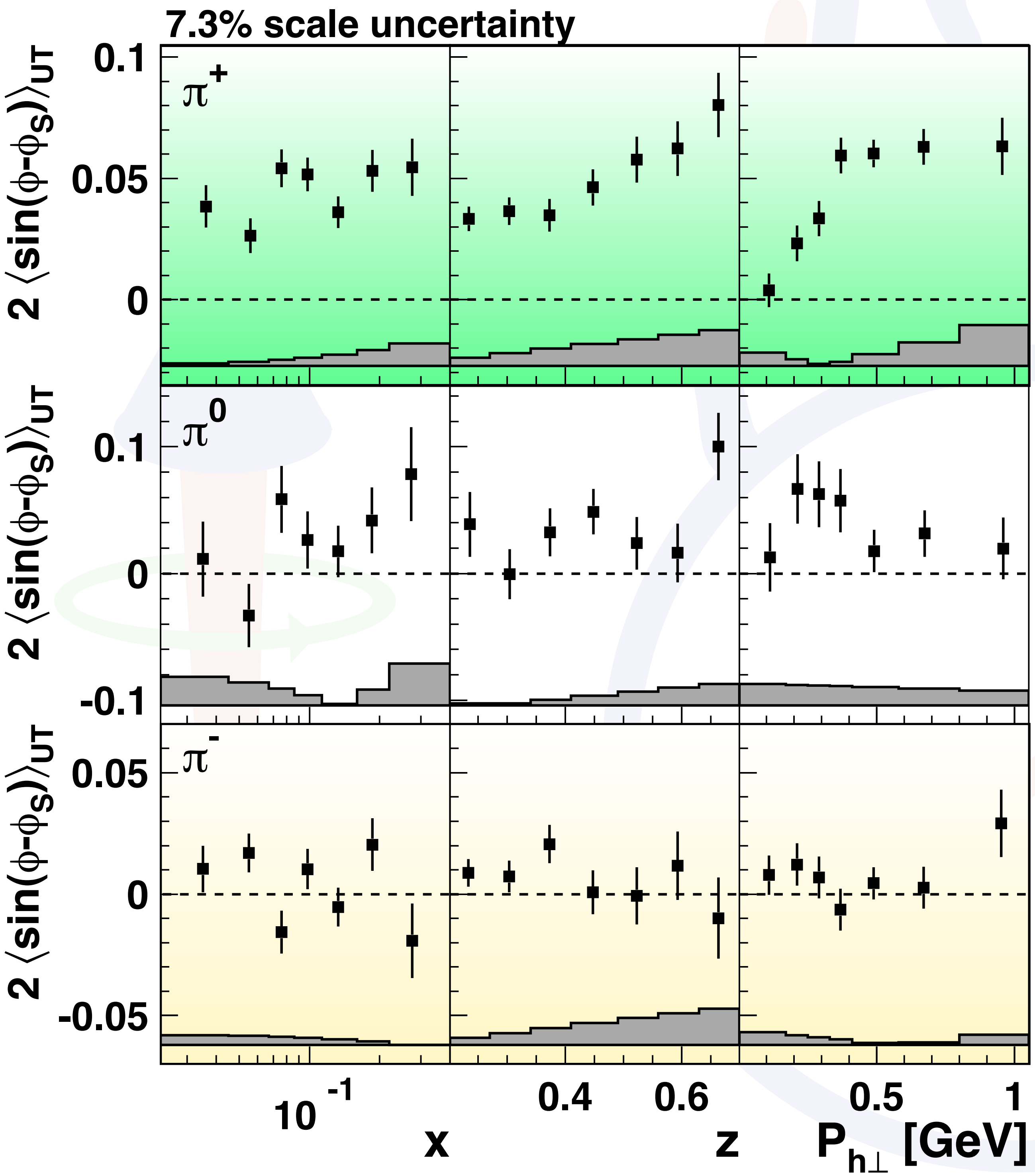


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☛ u-quark Sivers DF < 0

☛ d-quark Sivers DF > 0 (cancelation for $\pi^-$)

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1,\ h_{1T}^\perp$ |

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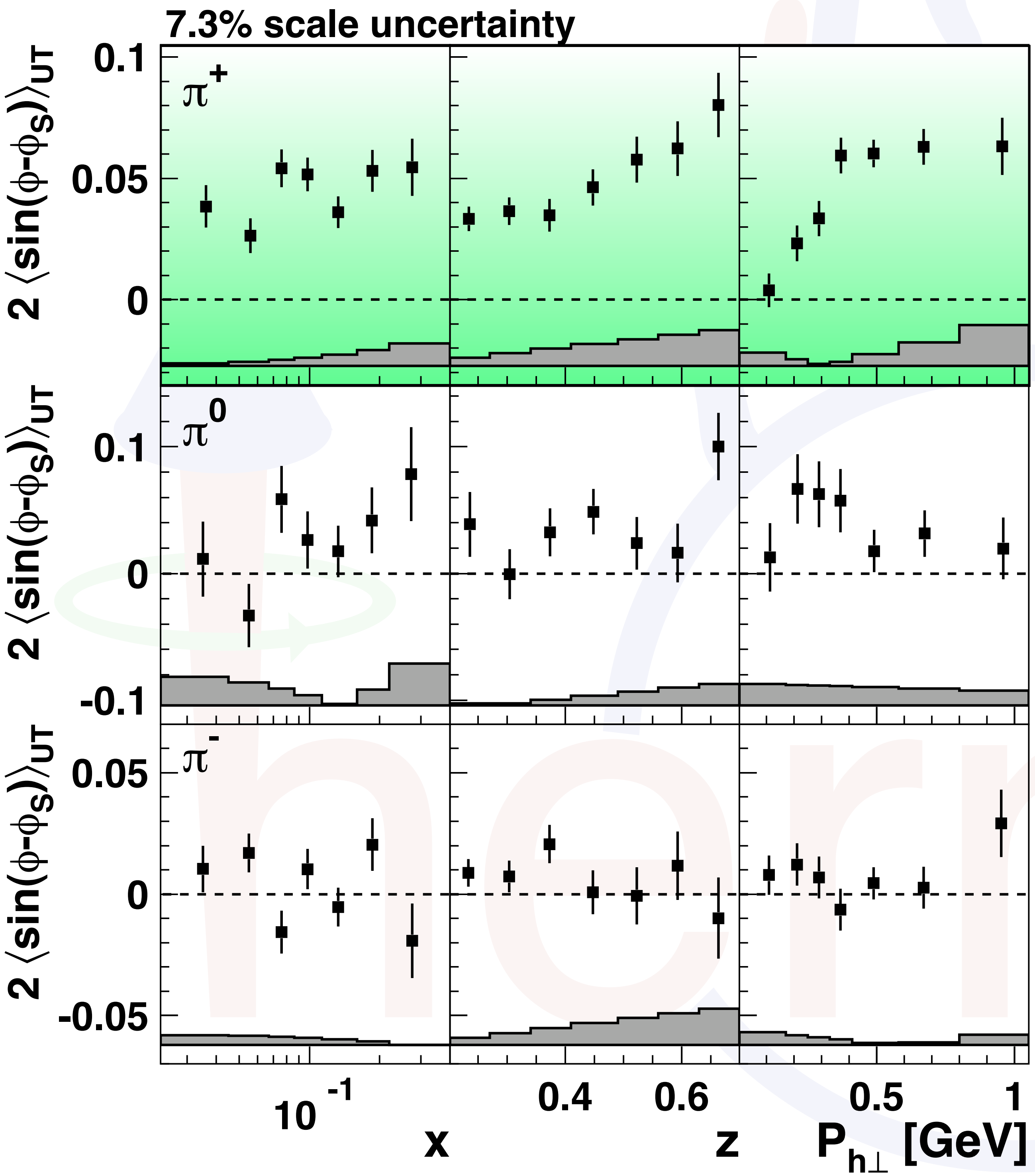
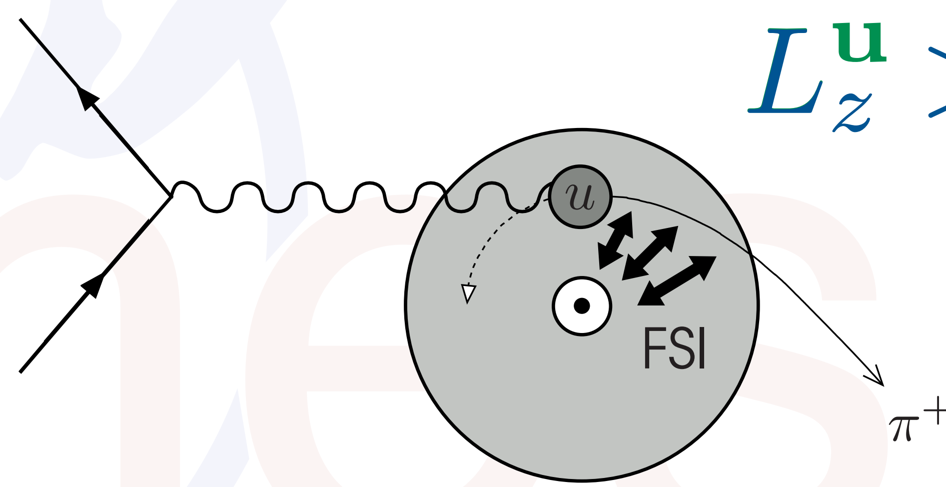
$$2\langle\sin(\phi-\phi_S)\rangle_{\mathrm{UT}} = -\frac{\sum_q e_q^2 f_{1\mathrm{T}}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$




**π⁺ dominated by u-quark scattering:**

$$\simeq -\frac{f_{1\mathrm{T}}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

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




[*M. Burkardt*, Phys. Rev. D66 (2002) 014005]

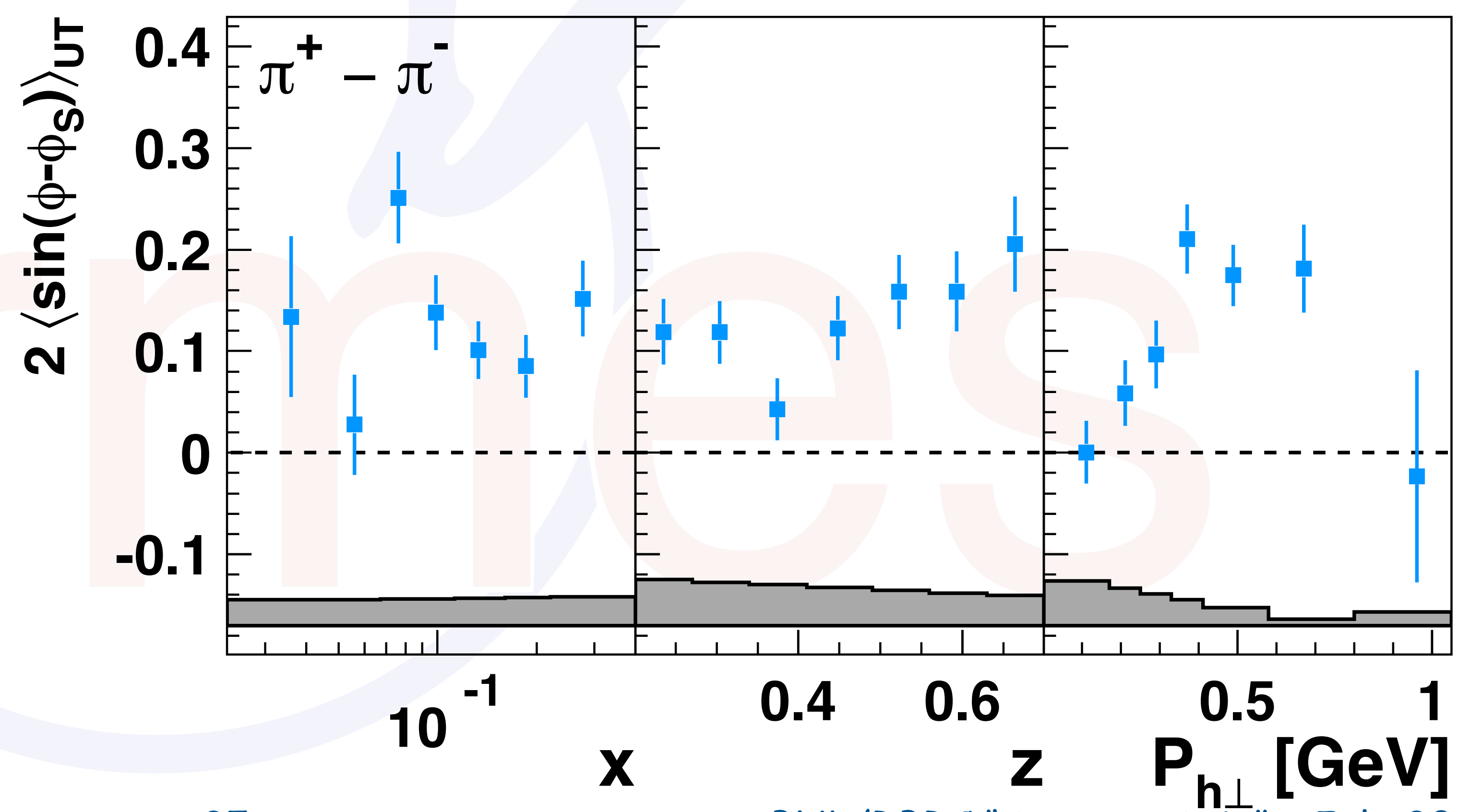
|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |   | $h_1^\perp$ |
| L |   | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Sivers "difference asymmetry"

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

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

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



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
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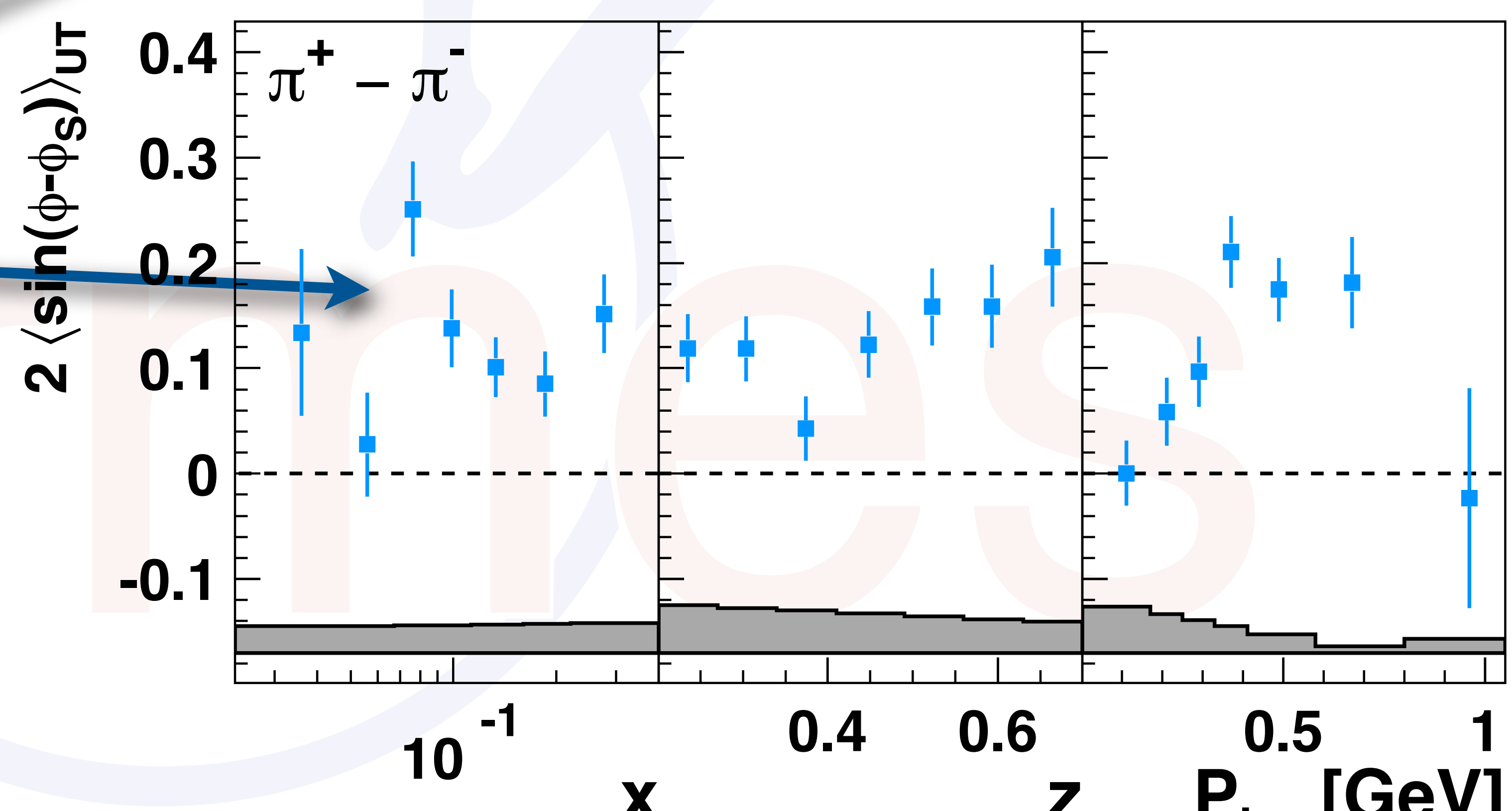
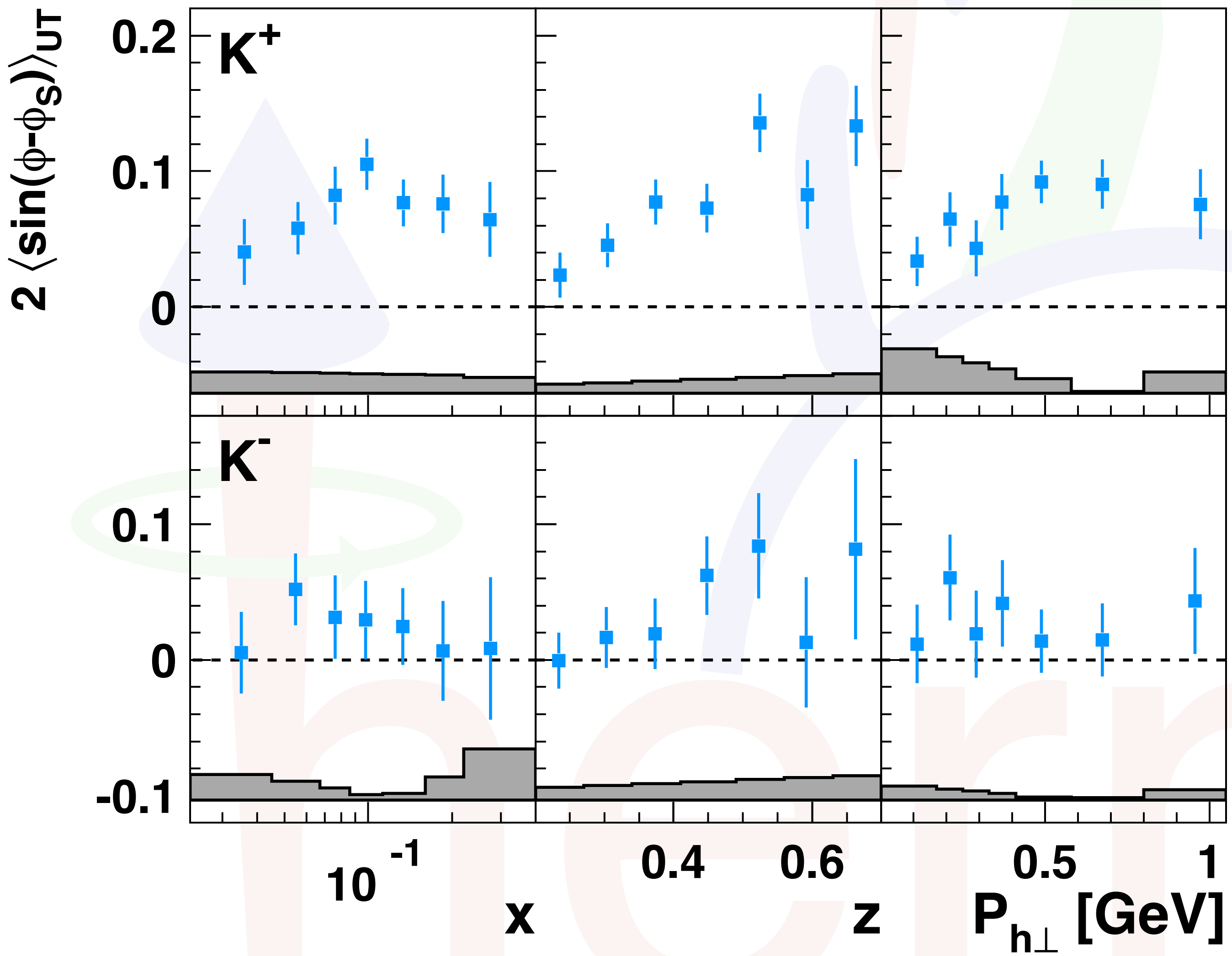
access to Sivers

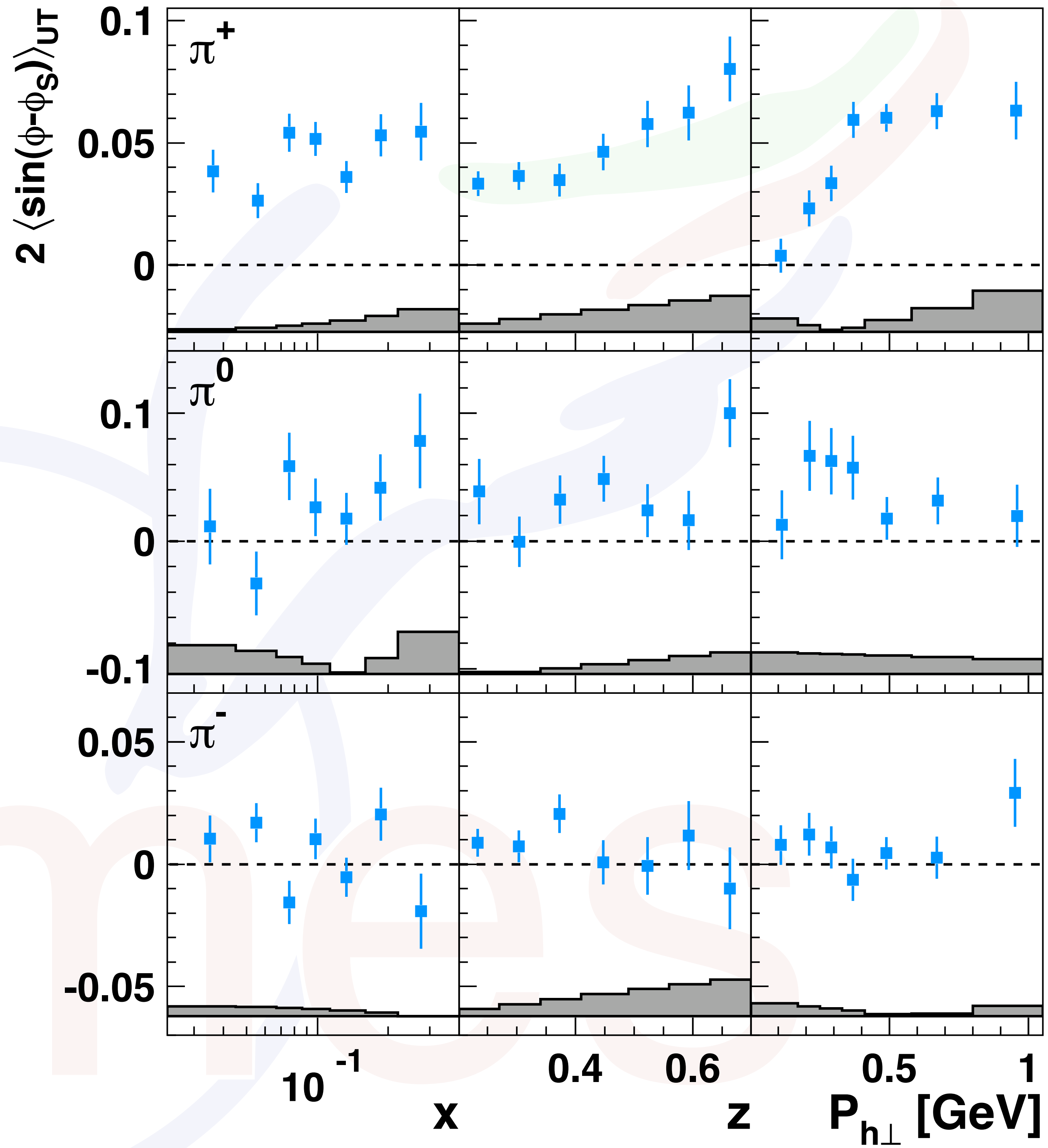
u-valence distribution



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# The kaon Sivers amplitudes



|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |   | $h_1^\perp$ |
| L |   | $g_{1L}$ | $h_{1L}^\perp$ |
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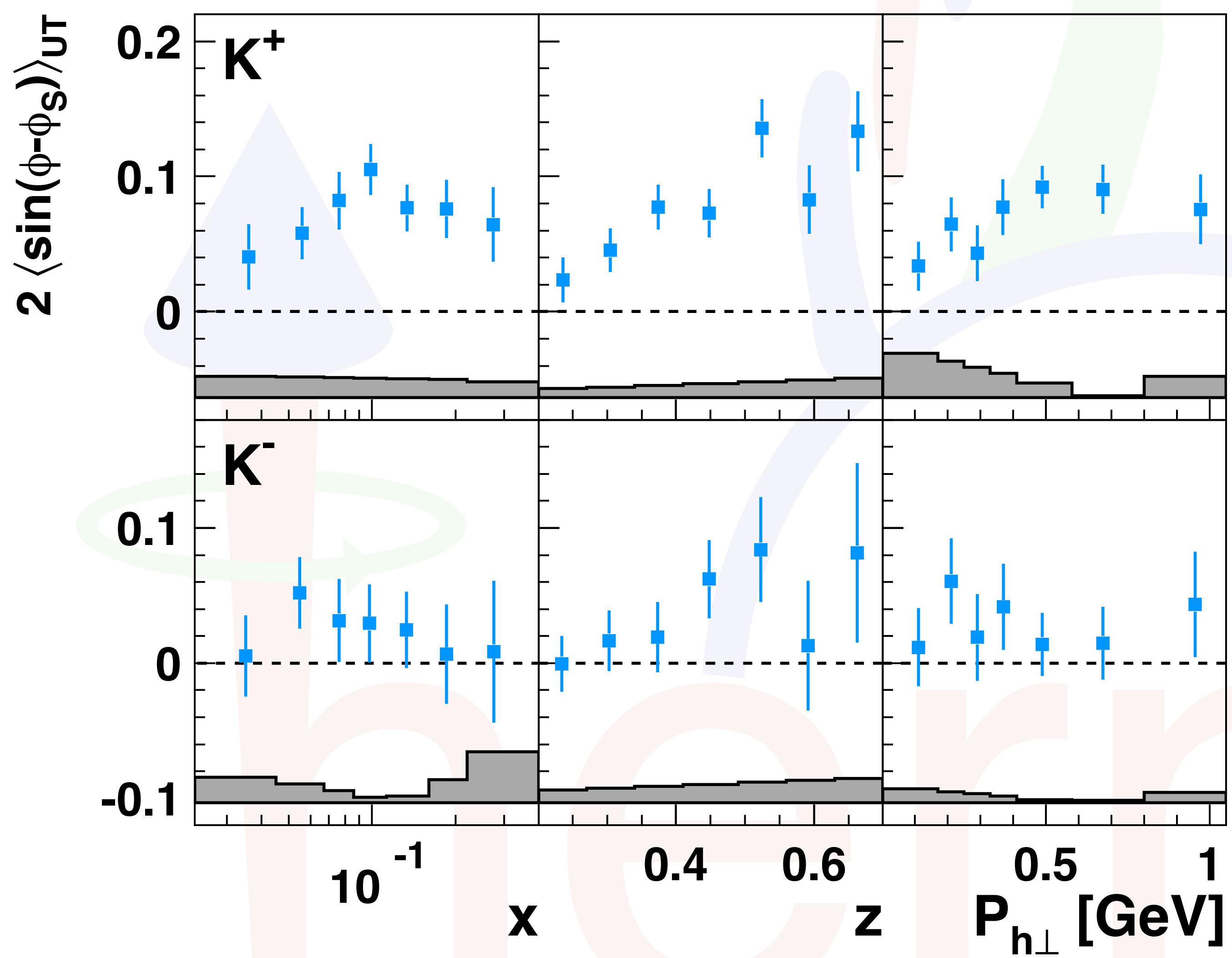
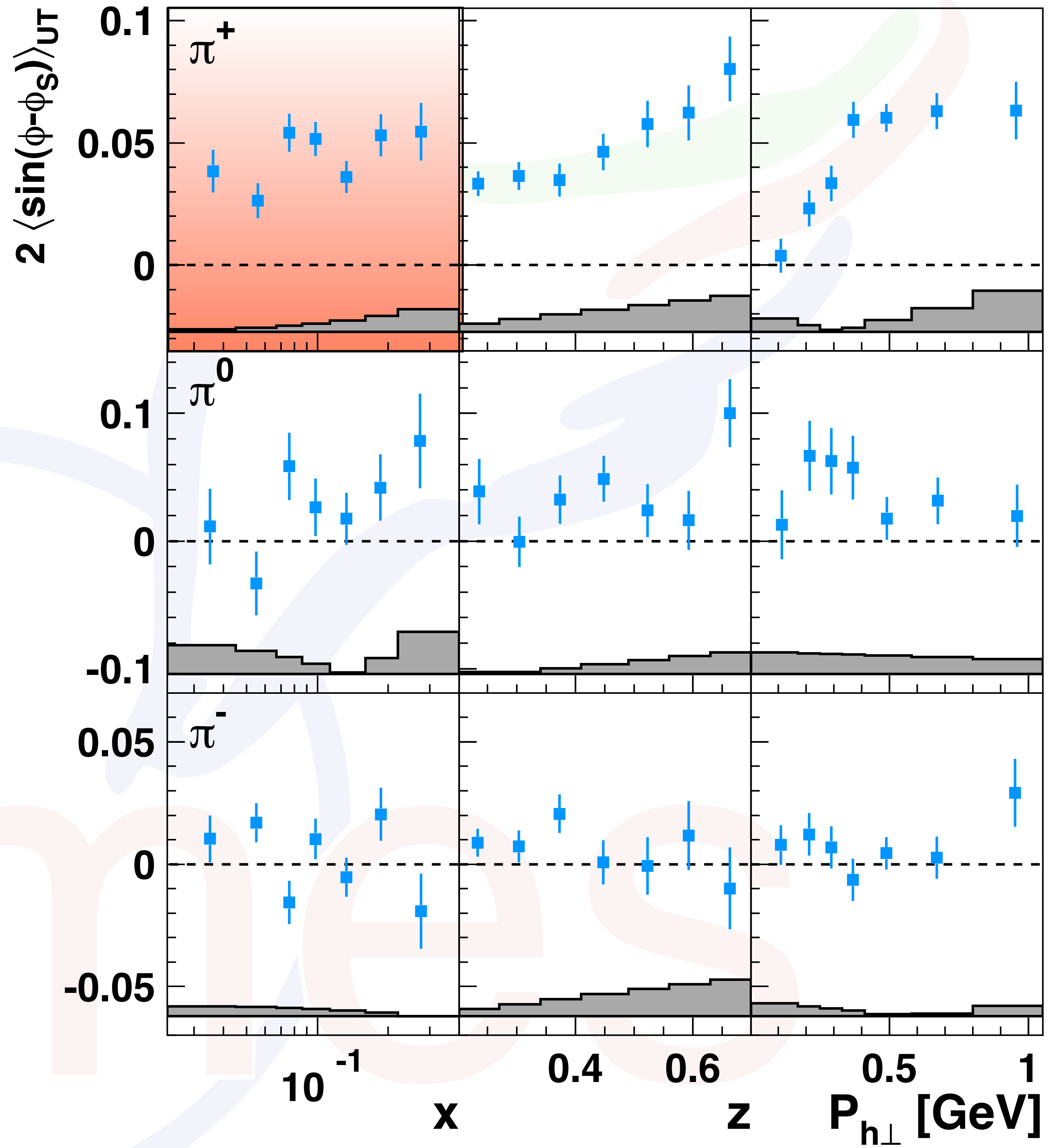
# The kaon Sivers amplitudes



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
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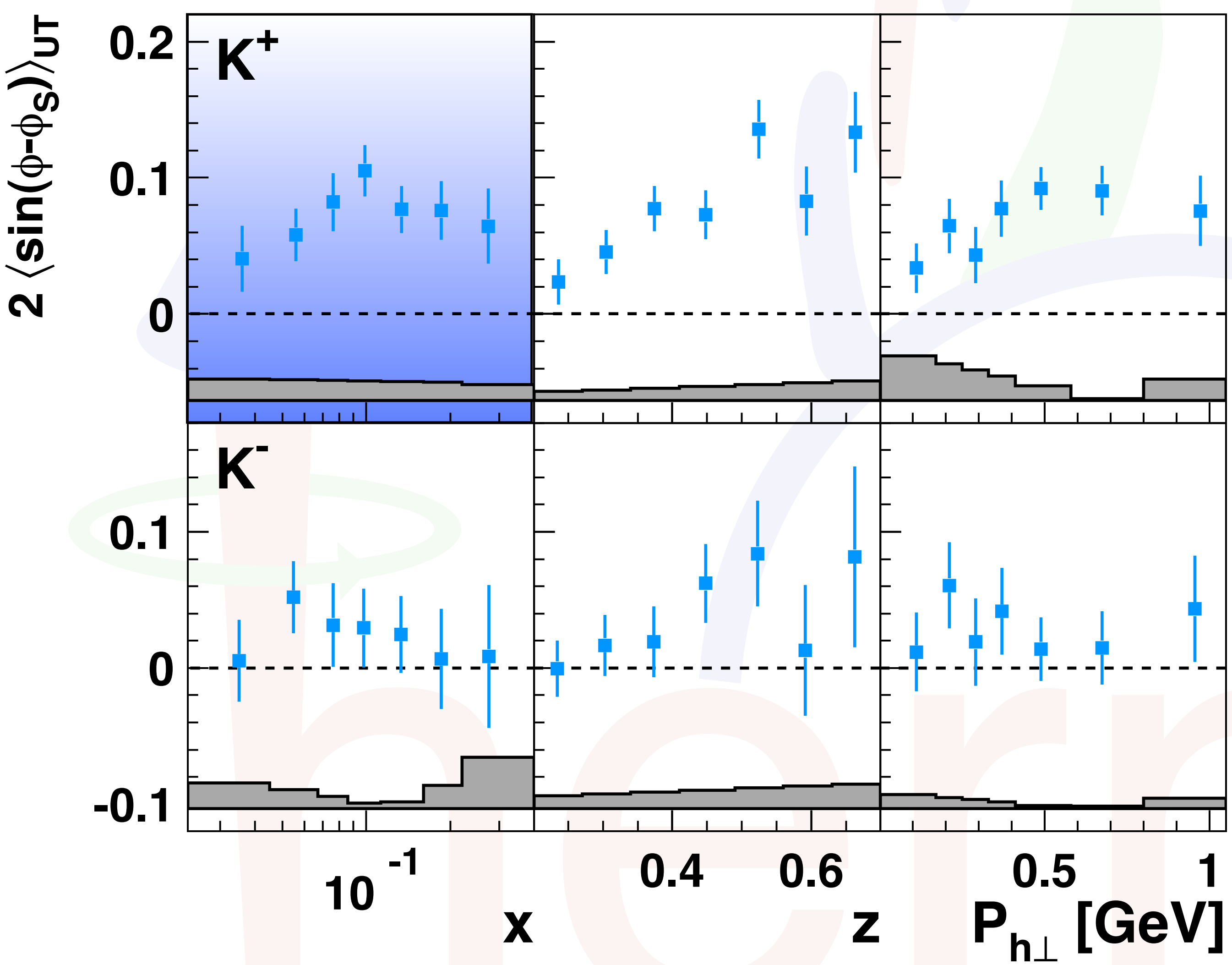


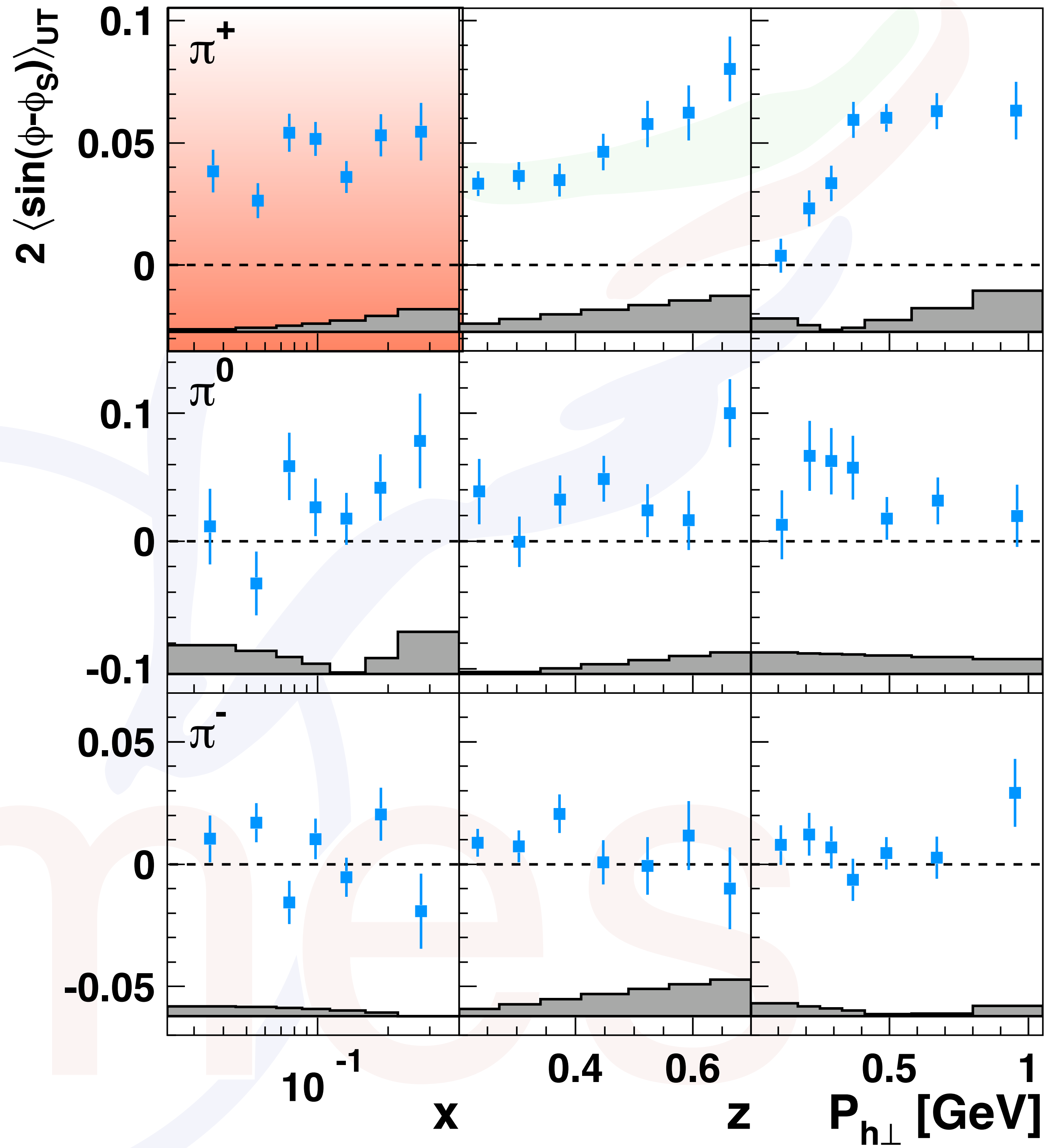

|  | U | L | T |
|---|---|---|---|
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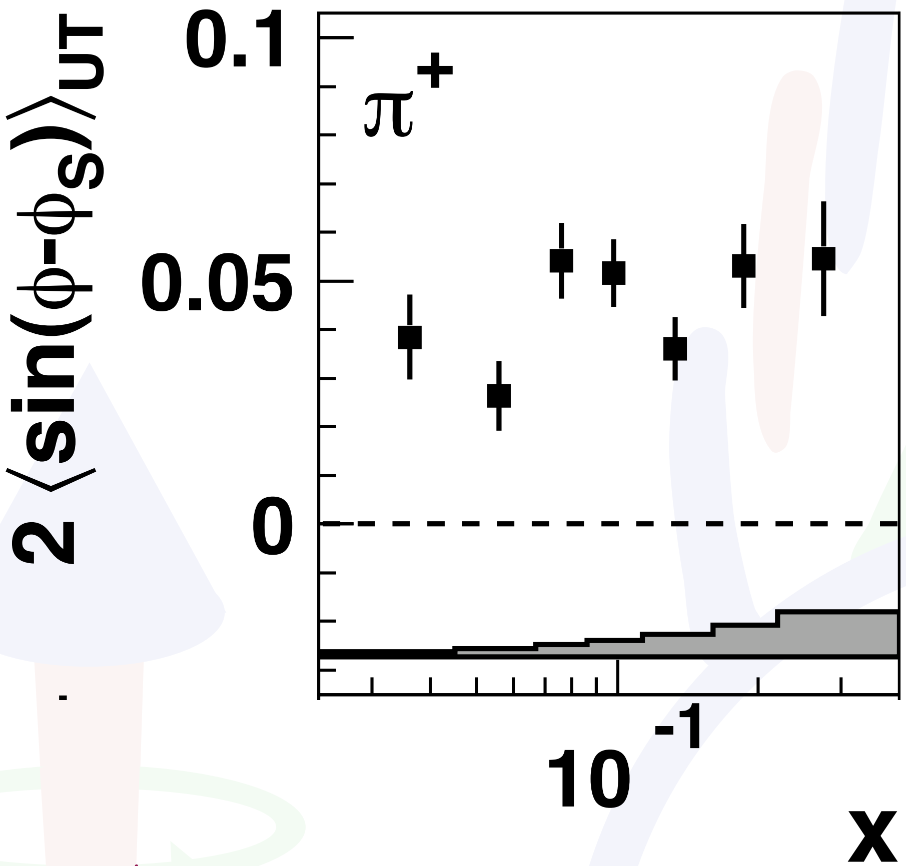
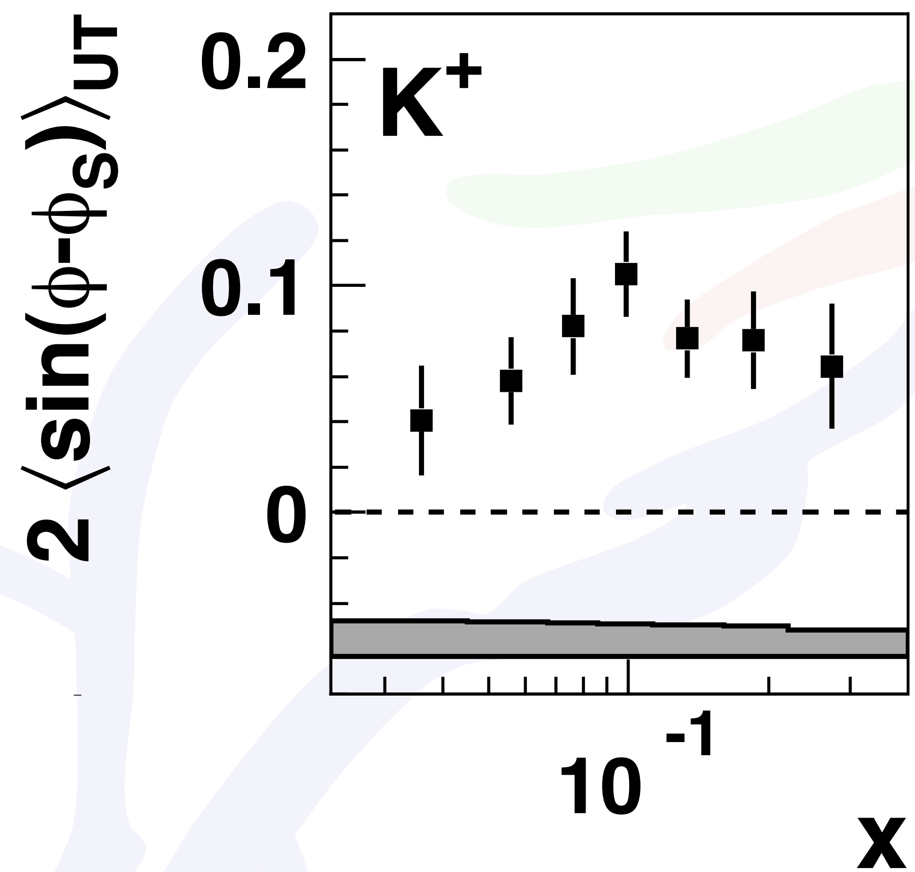
# The "Kaon Challenge"




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

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1,\ h_{1T}^\perp$ |

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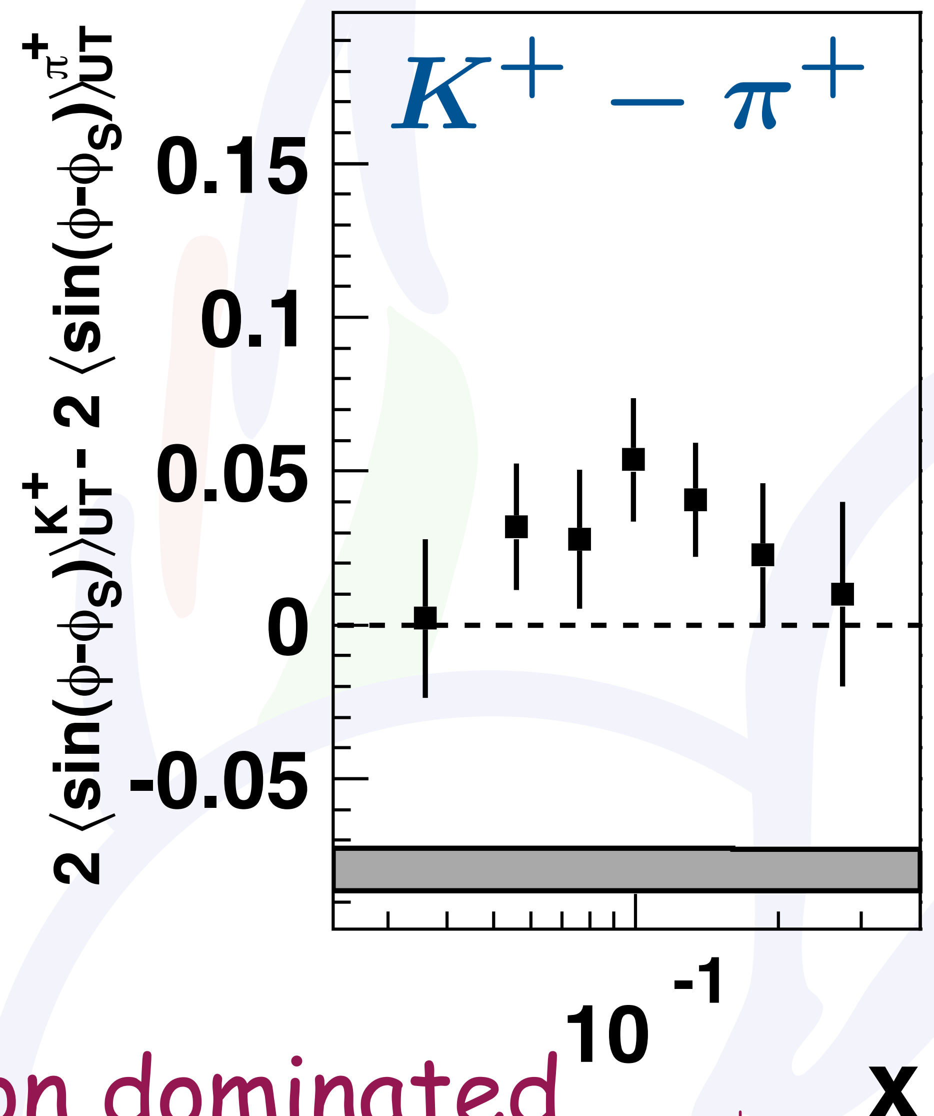


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| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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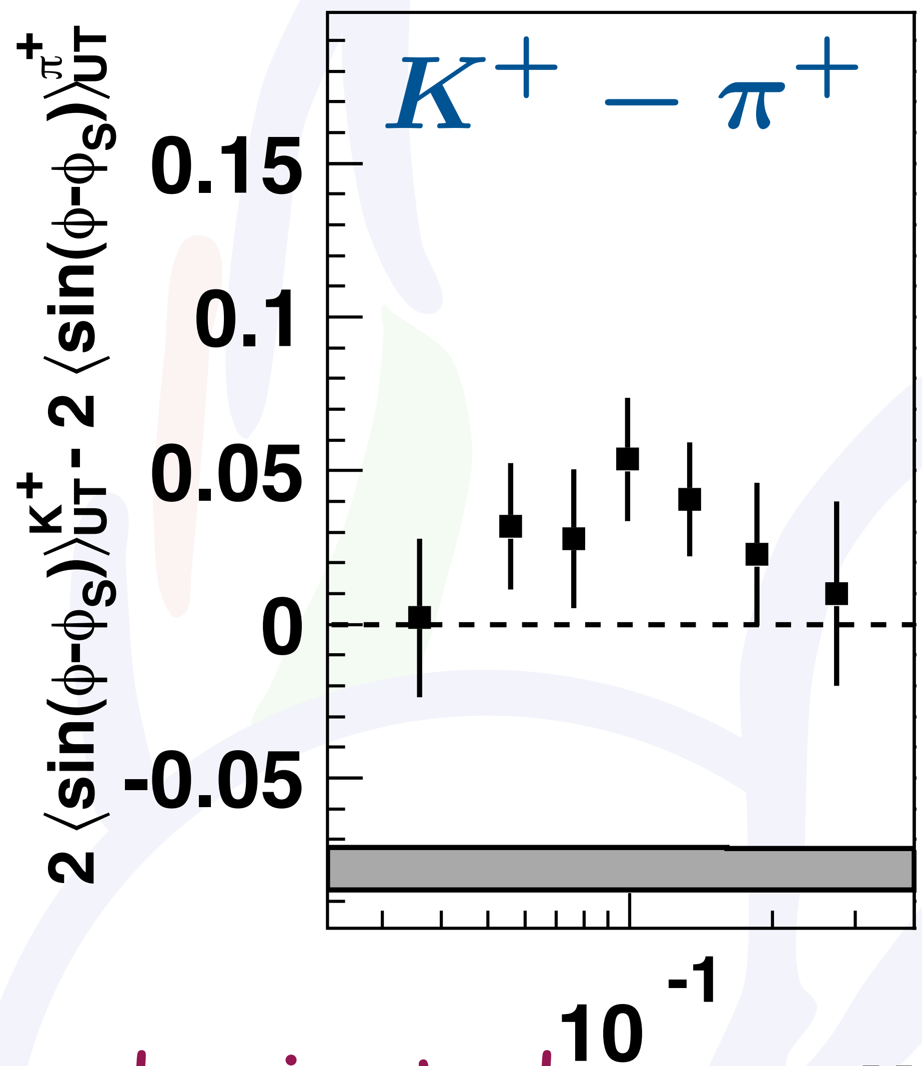


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- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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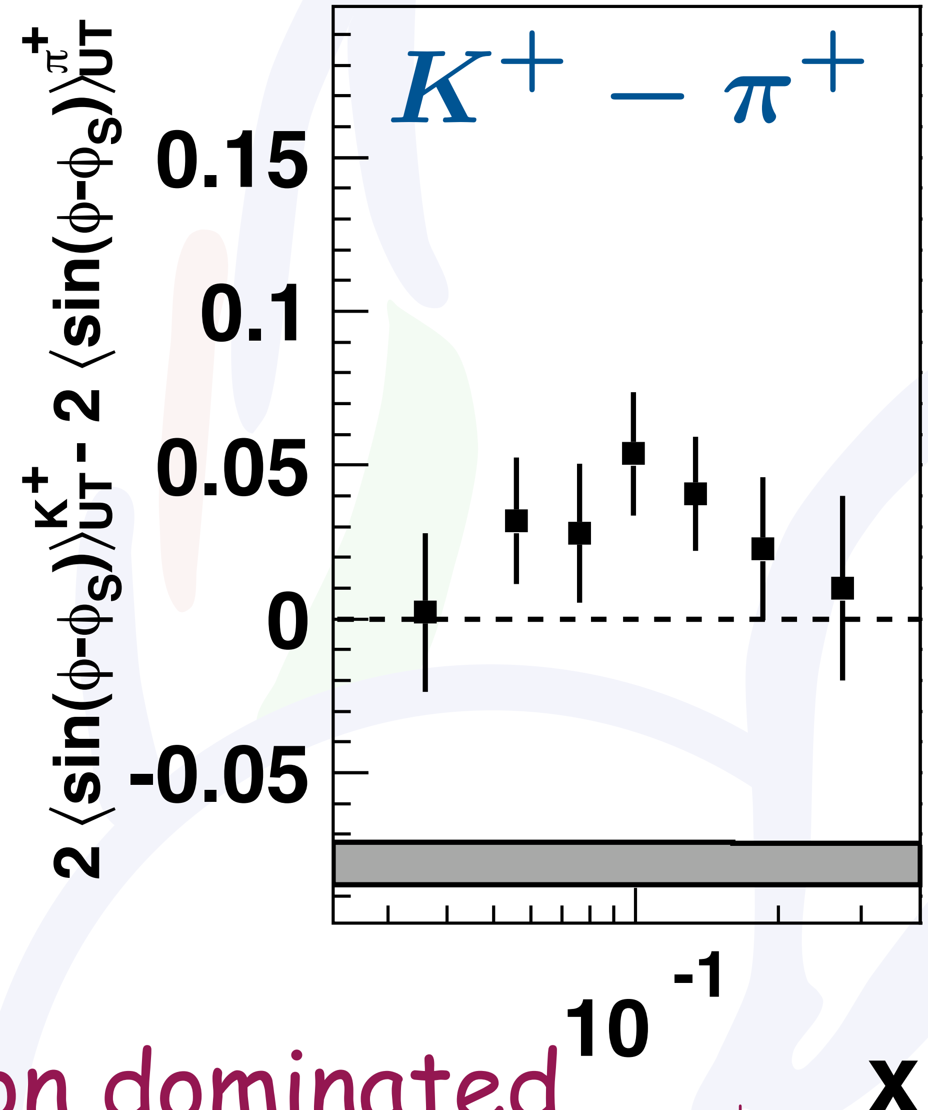


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- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?
- convolution integrals depend on $k_T$ dependence of fragmentation functions

| | U | L | T |
|---|---|---|---|
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| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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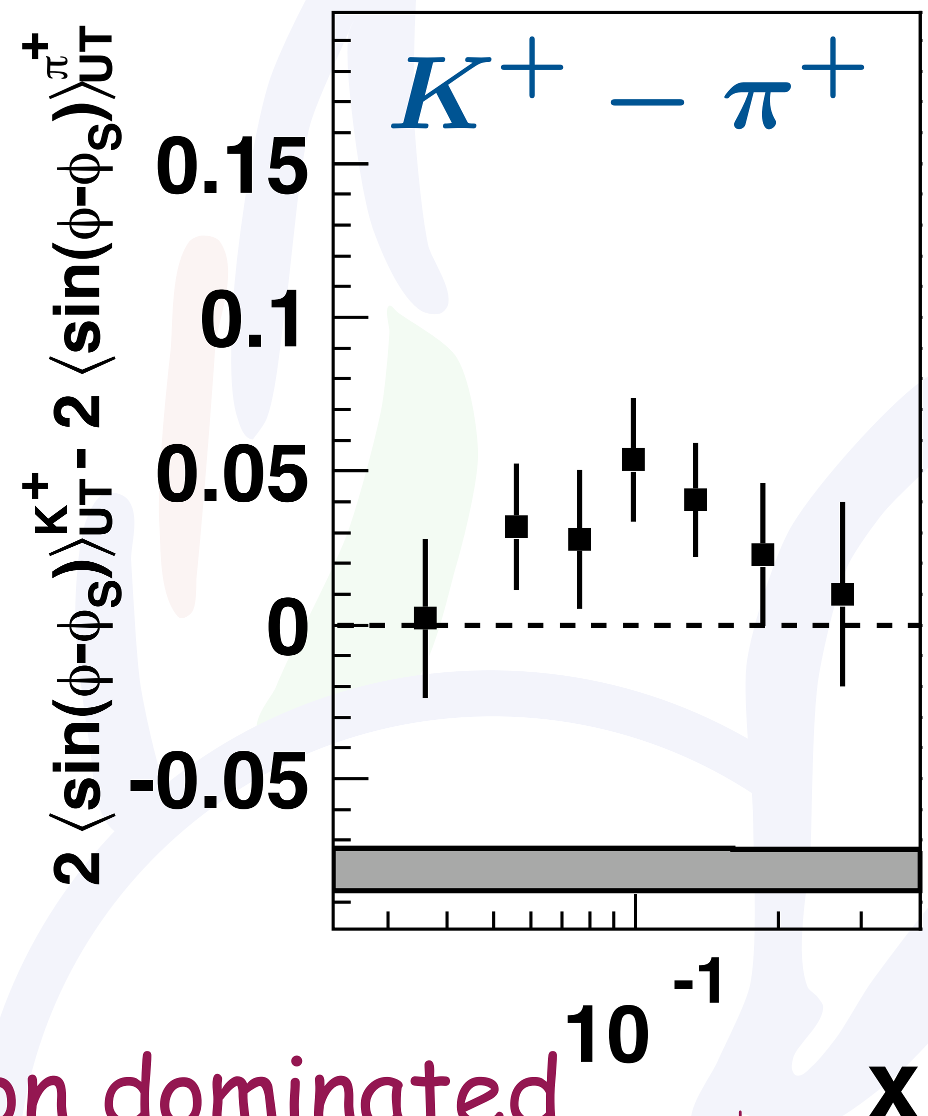
# The "Kaon Challenge"



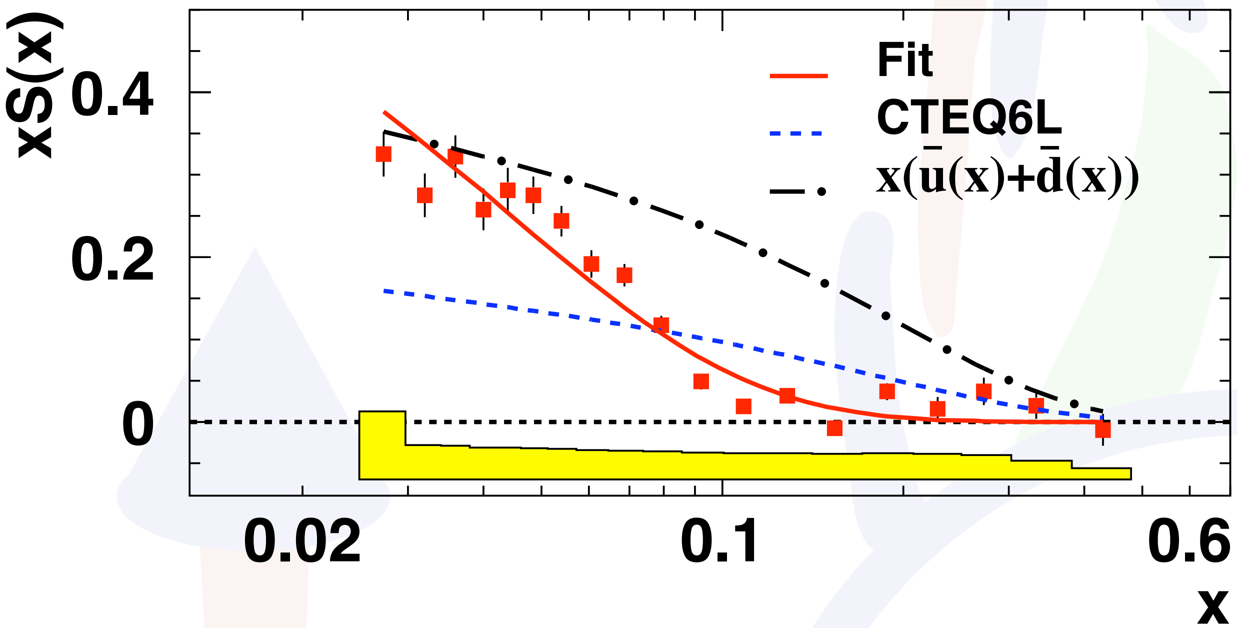

$\pi^+/K^+$ production dominated by scattering off u-quarks: $\simeq - \frac{f_{1T}^{\perp,u}(x,p_T^2) \otimes_{\mathcal{W}} D_1^{u\to\pi^+/K^+}(z,k_T^2)}{f_1^u(x,p_T^2) \otimes D_1^{u\to\pi^+/K^+}(z,k_T^2))}$

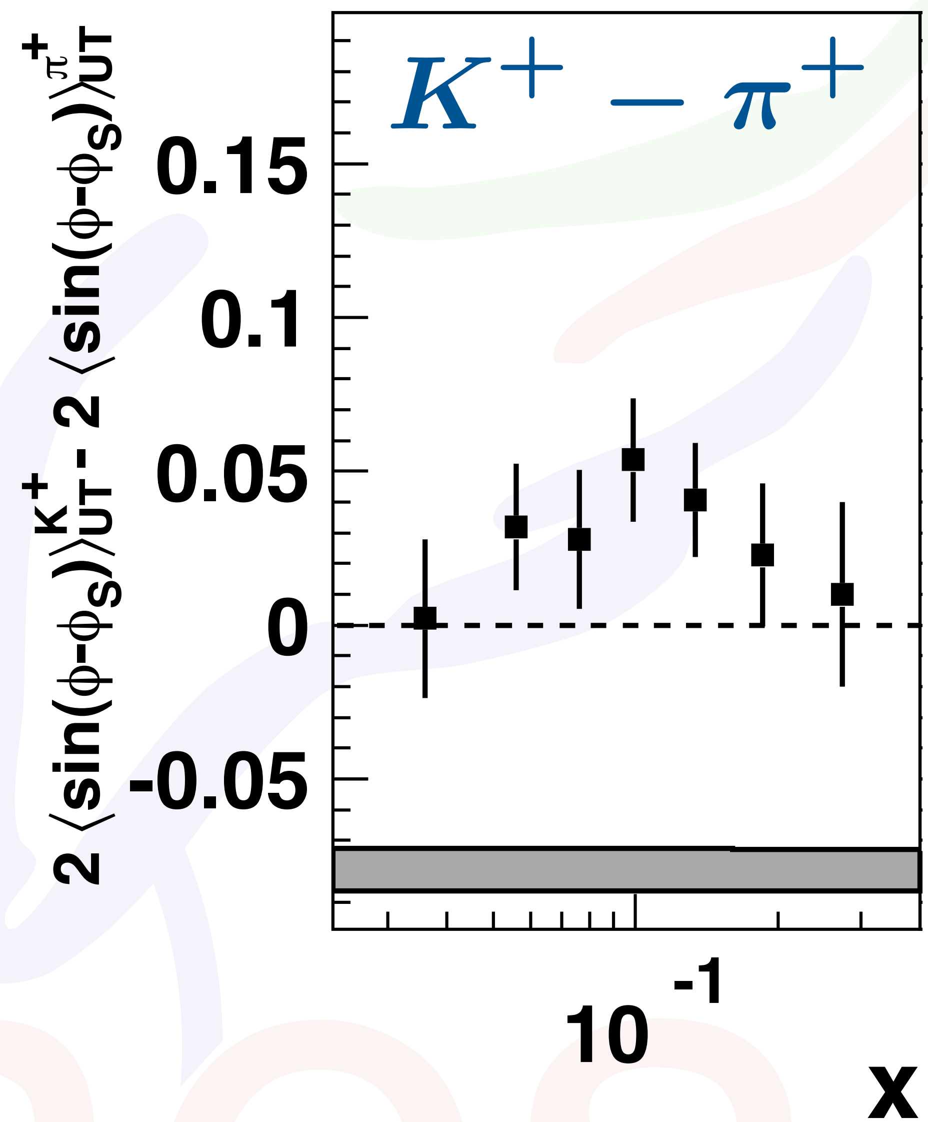
- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ ➥ non-trivial role of sea quarks?
- convolution integrals depend on $k_T$ dependence of fragmentation functions
- possible difference in dependences on the kinematics integrated over

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Role of sea quarks

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



| | U | L | T |
|---|---|---|---|
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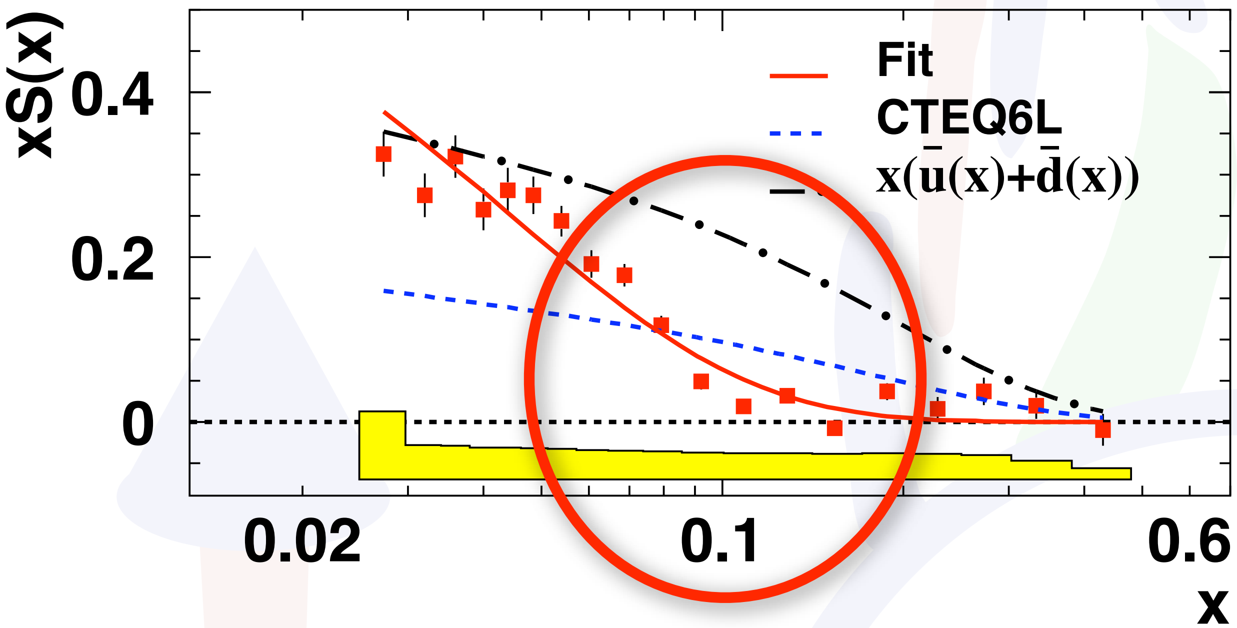
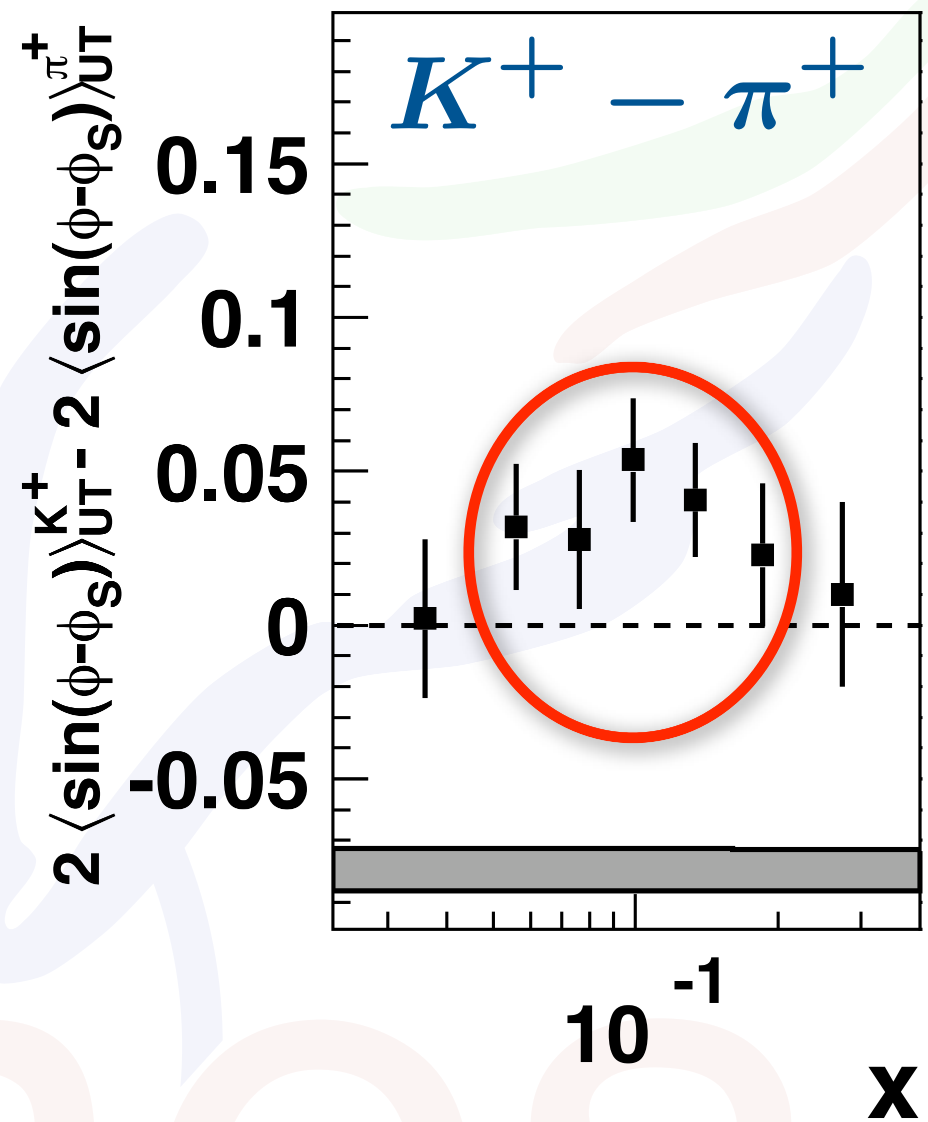


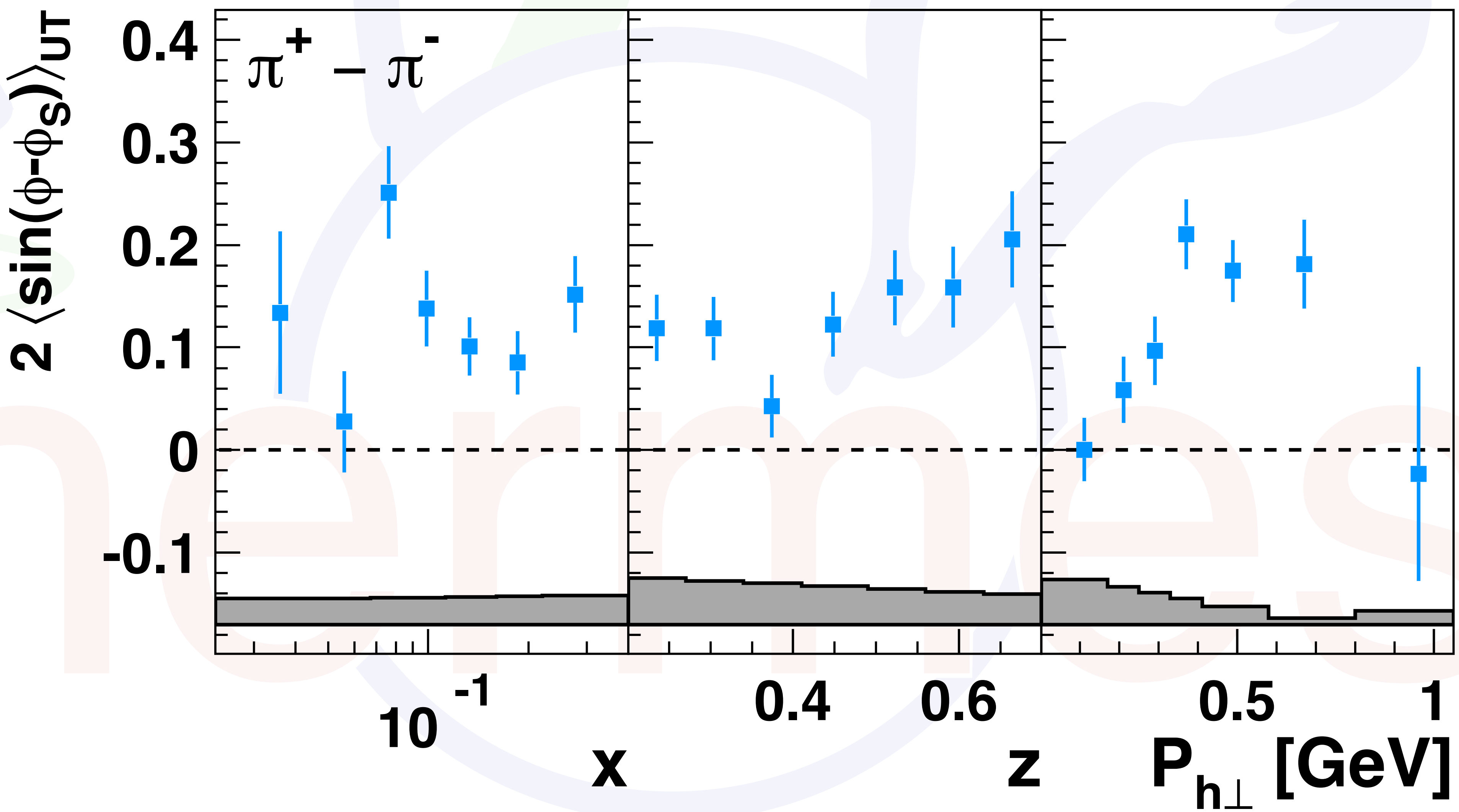




differences biggest in region where strange sea is most different from light sea

# Cancelation of FFs

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1,\, h_{1T}^\perp$ |

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



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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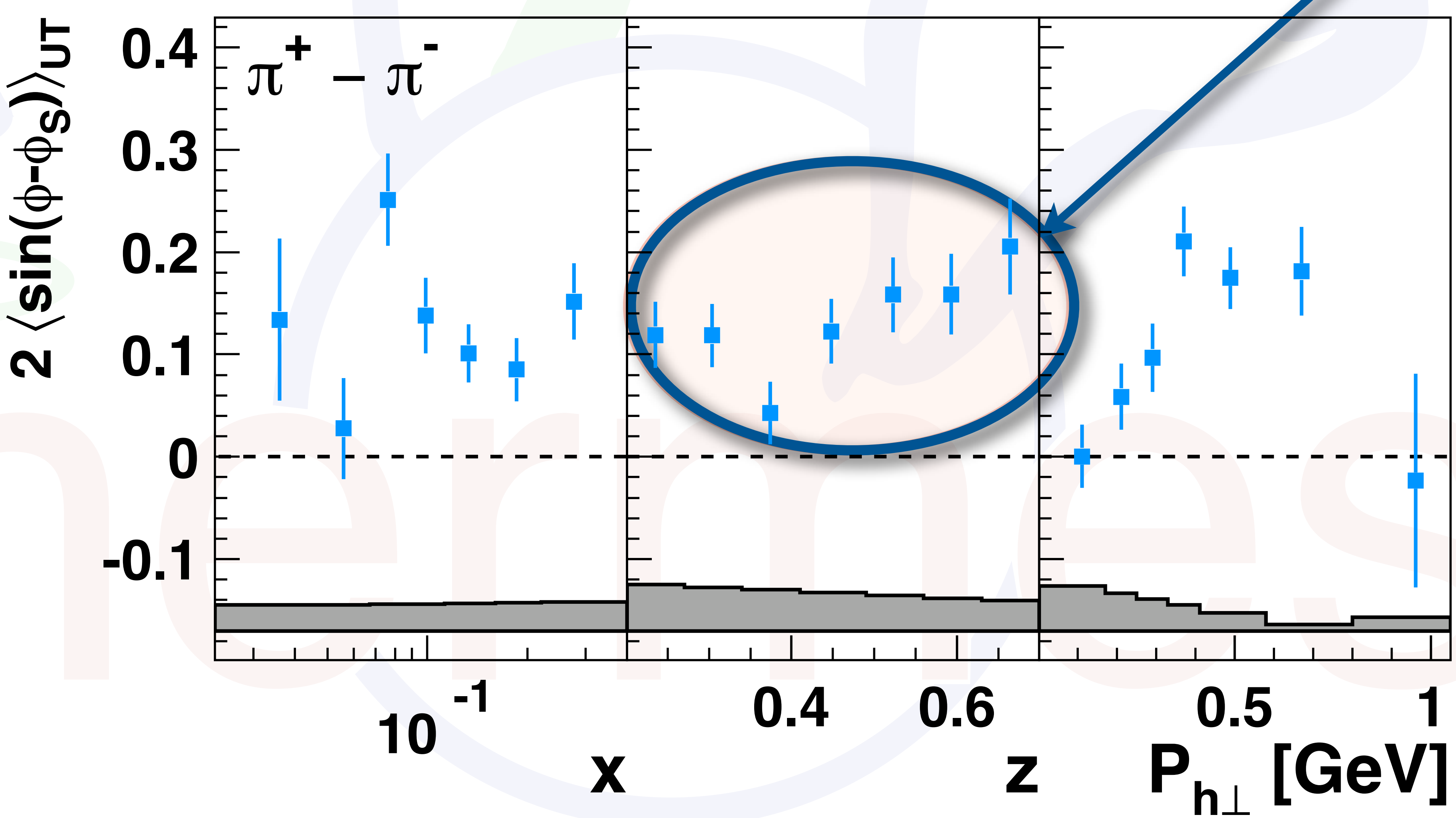
# Cancelation of FFs

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

should be flat



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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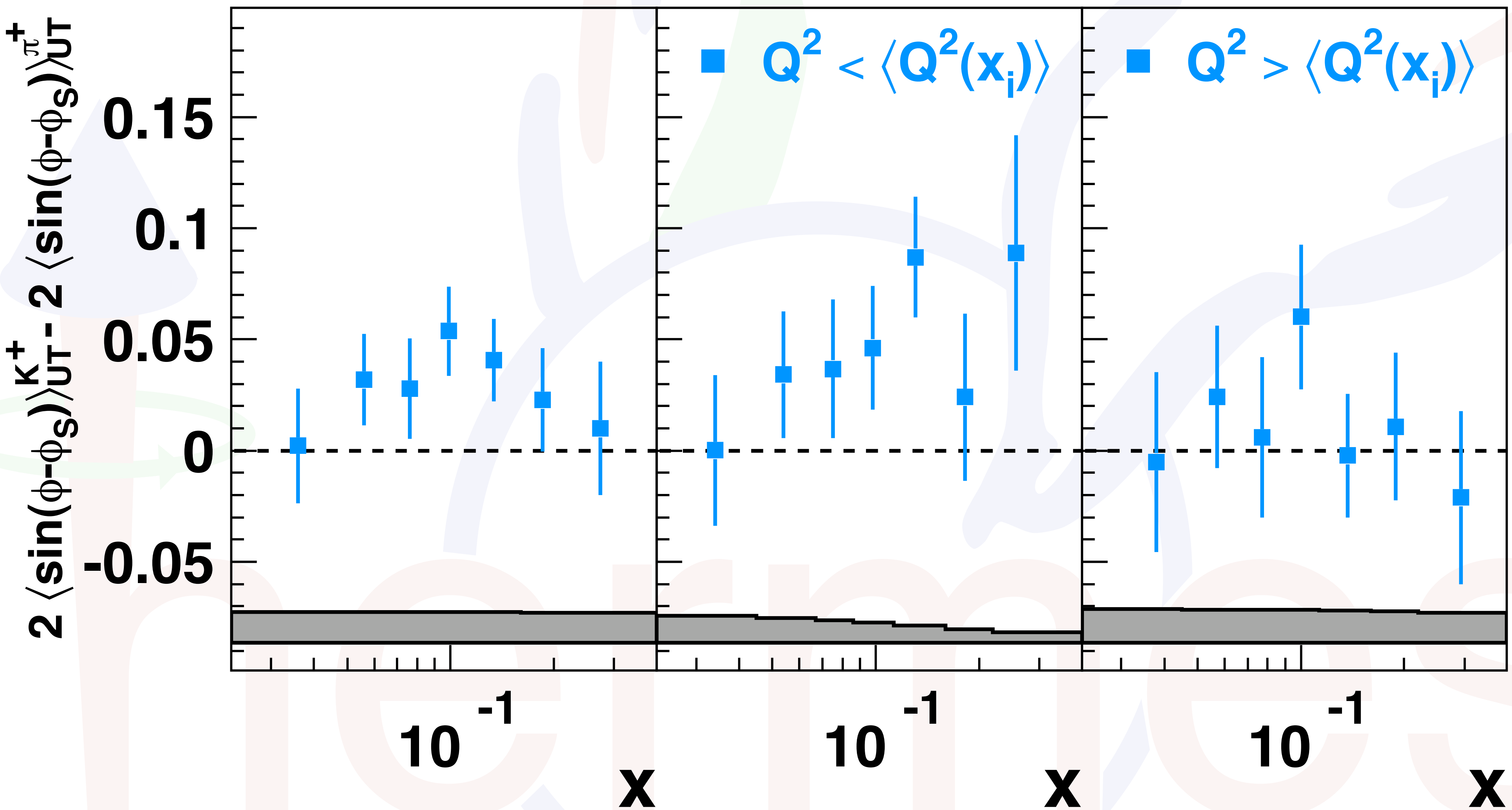
# $Q^2$ dependence of amplitudes

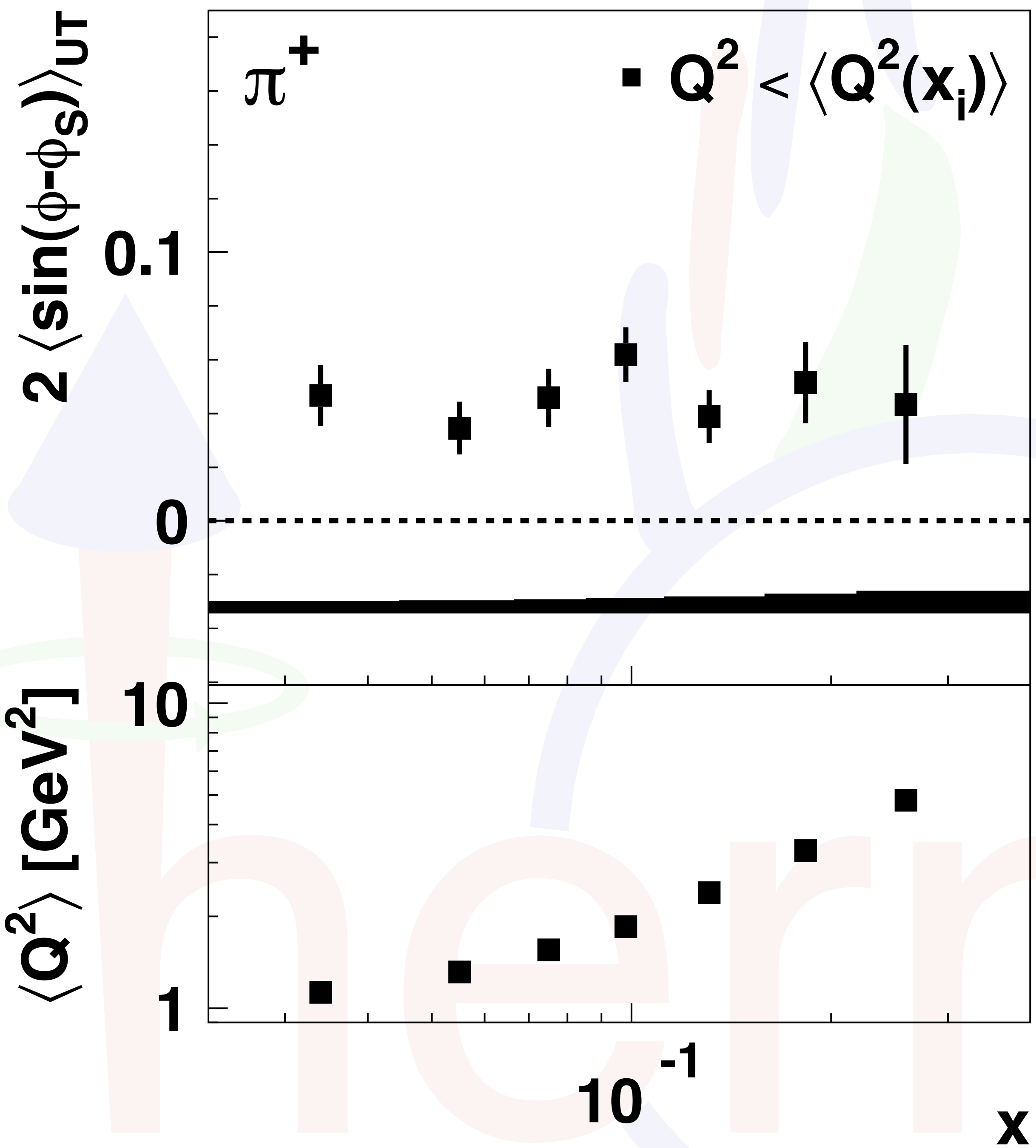
- separate each x-bin into two $Q^2$ bins:




- only in low-$Q^2$ region significant (>90% c.l.) deviation

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# $Q^2$ dependence of amplitudes



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
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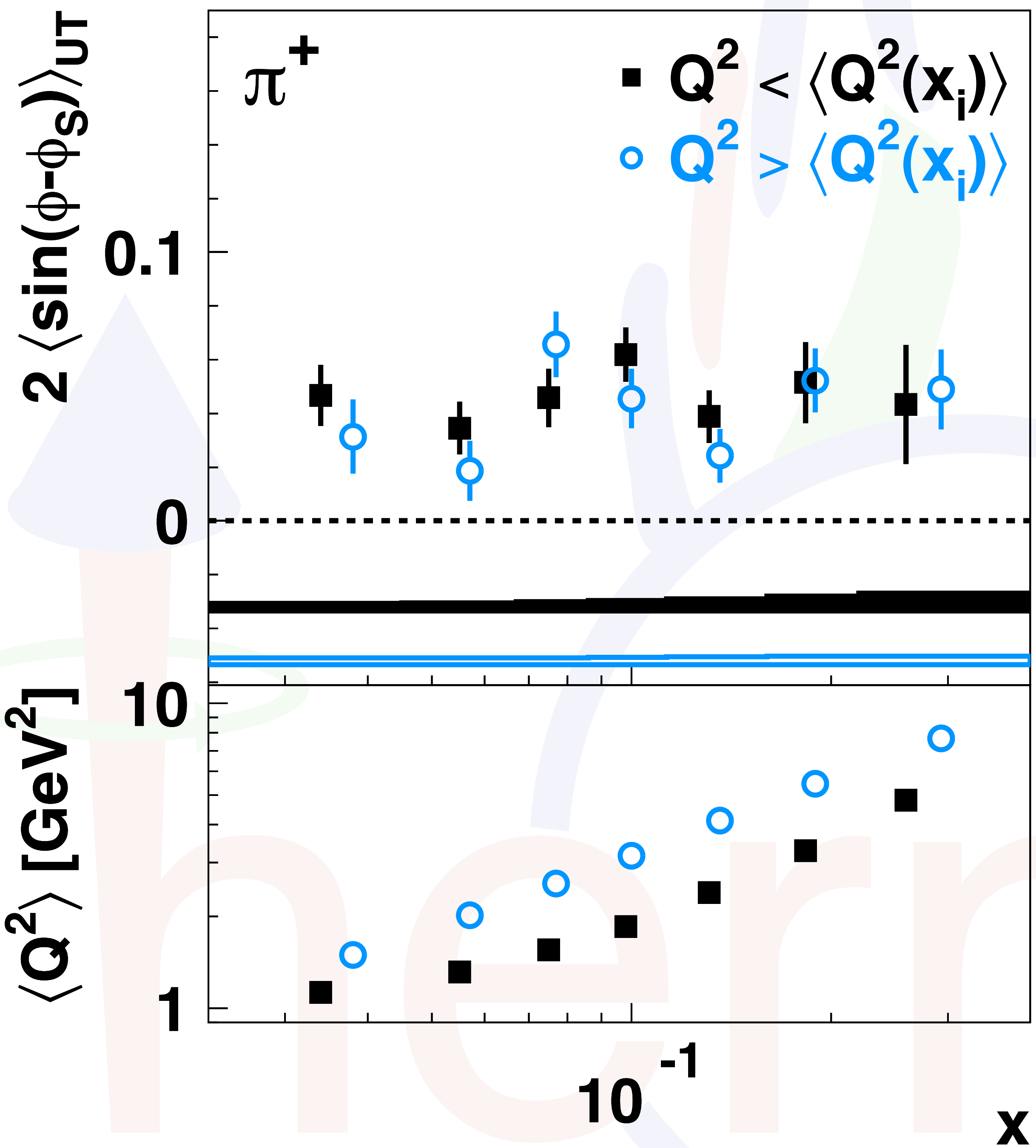
# $Q^2$ dependence of amplitudes



| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
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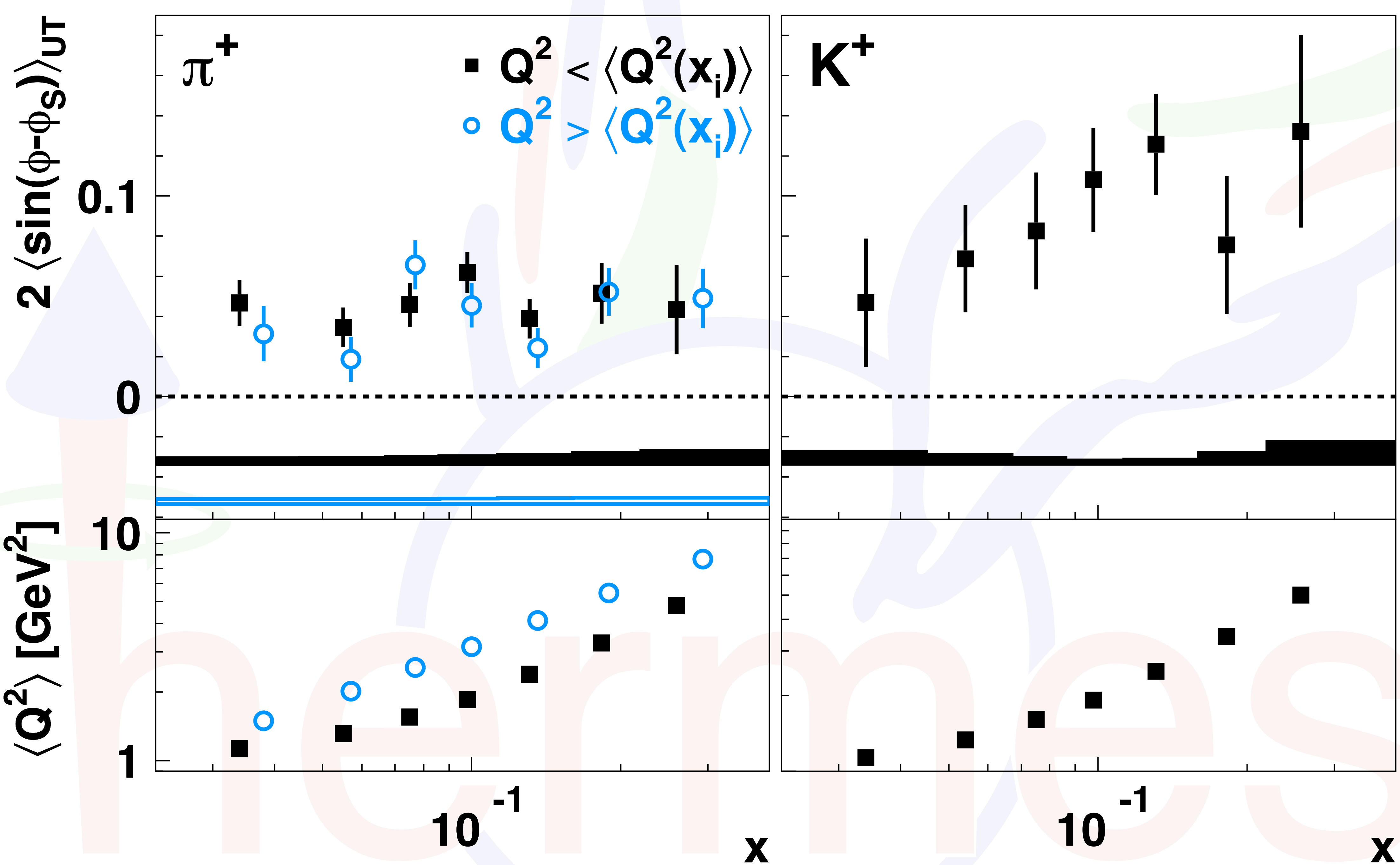

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
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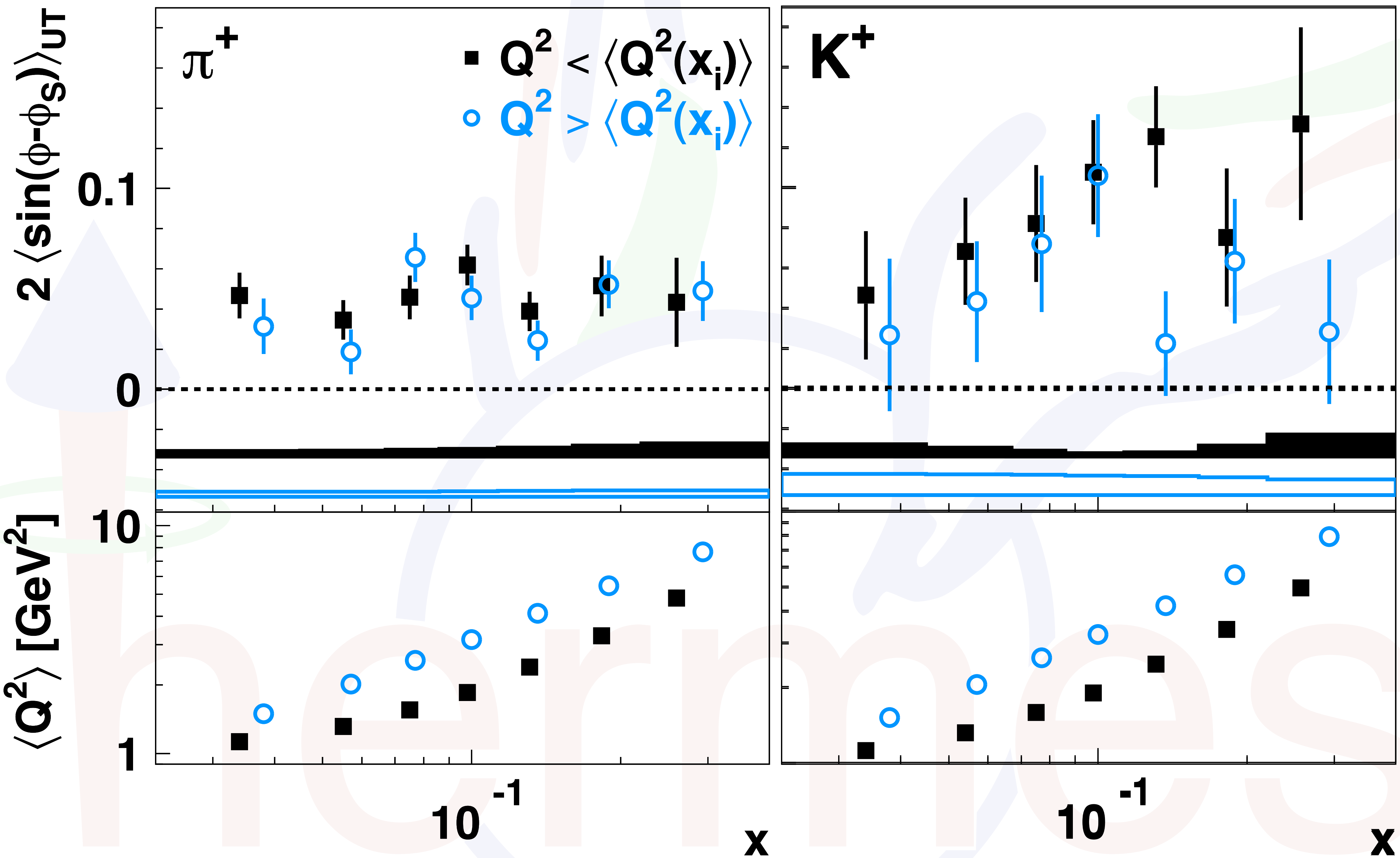
# $Q^2$ dependence of amplitudes




☛ hint of $Q^2$ dependence of kaon amplitude

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Pretzelosity

- chiral-odd ➥ needs Collins FF (or similar)
- leads to $\sin(3\phi-\phi_s)$ modulation in $A_{UT}$
- data consistent with zero
- suppressed by two powers of $P_{h\perp}$ (compared to, e.g., Sivers)

|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |   | $h_1^\perp$ |
| L |   | $g_{1L}$ | $h_{1L}^\perp$ |
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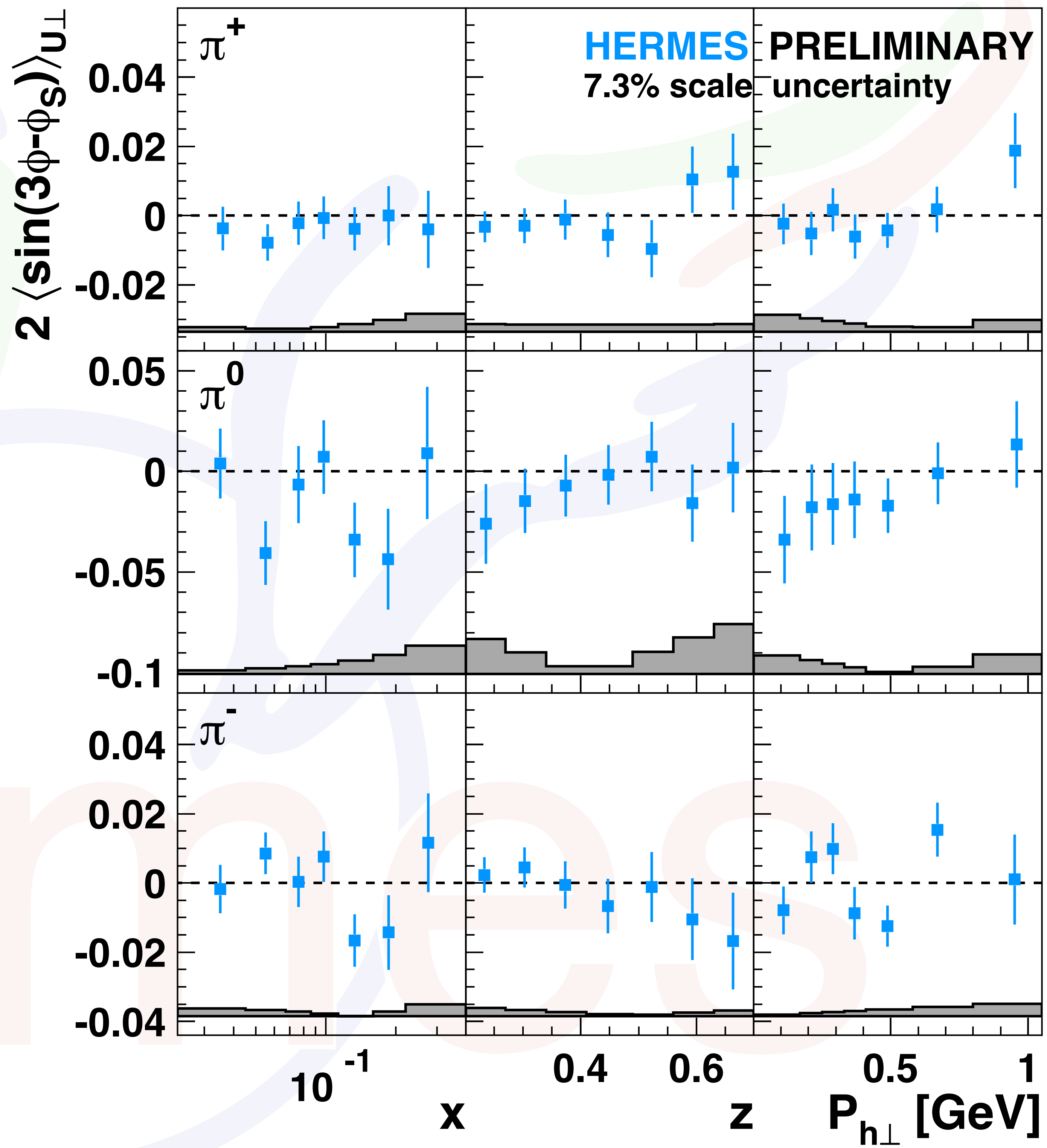
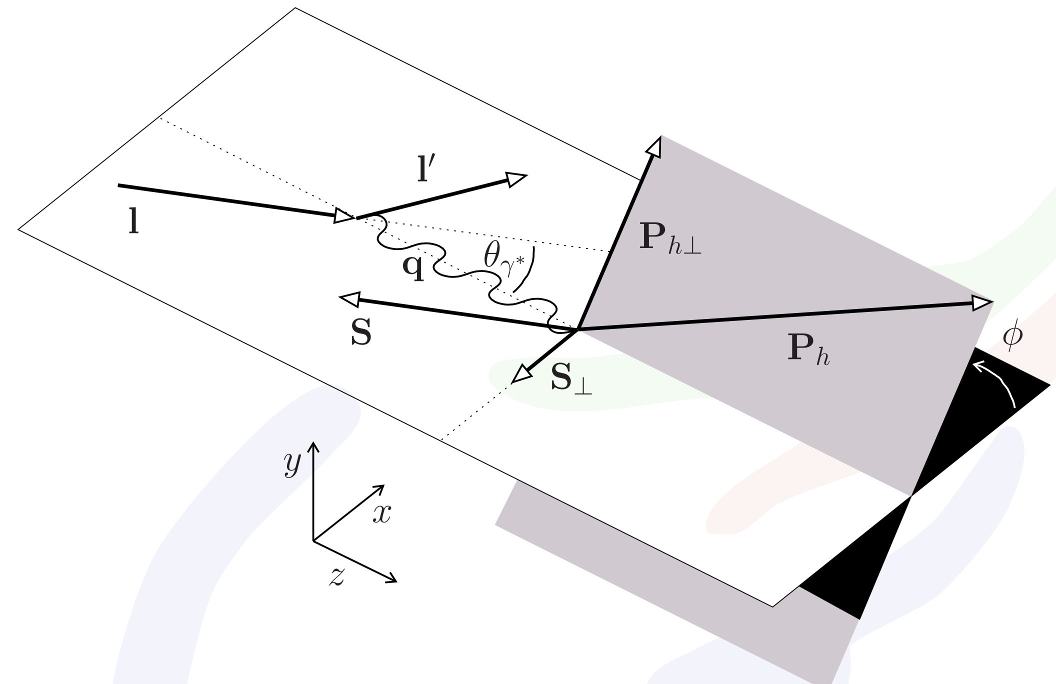
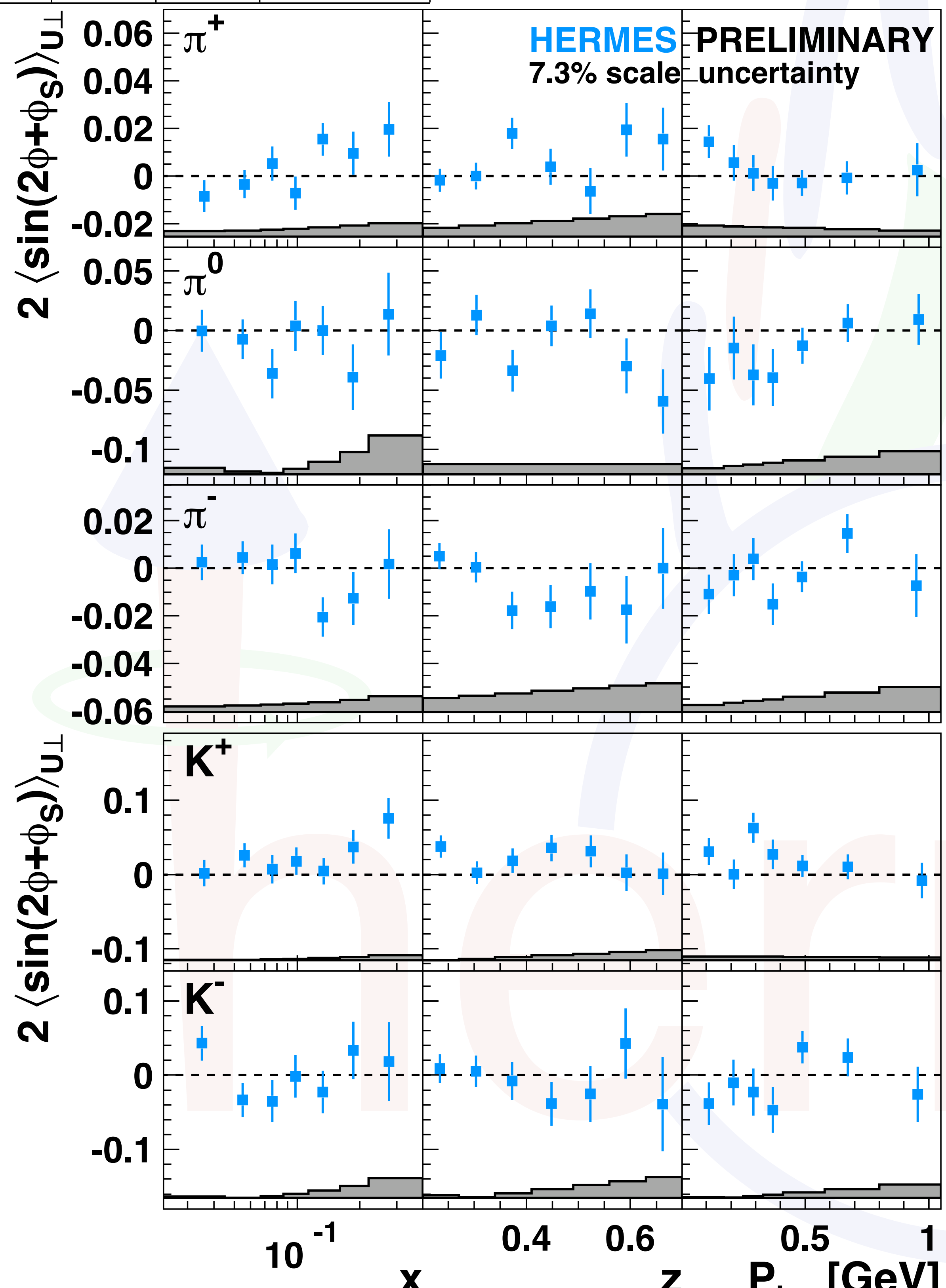


|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |   | $h_1^\perp$ |
| L |   | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Subleading twist I - sin(2ϕ+ϕ$_S$)

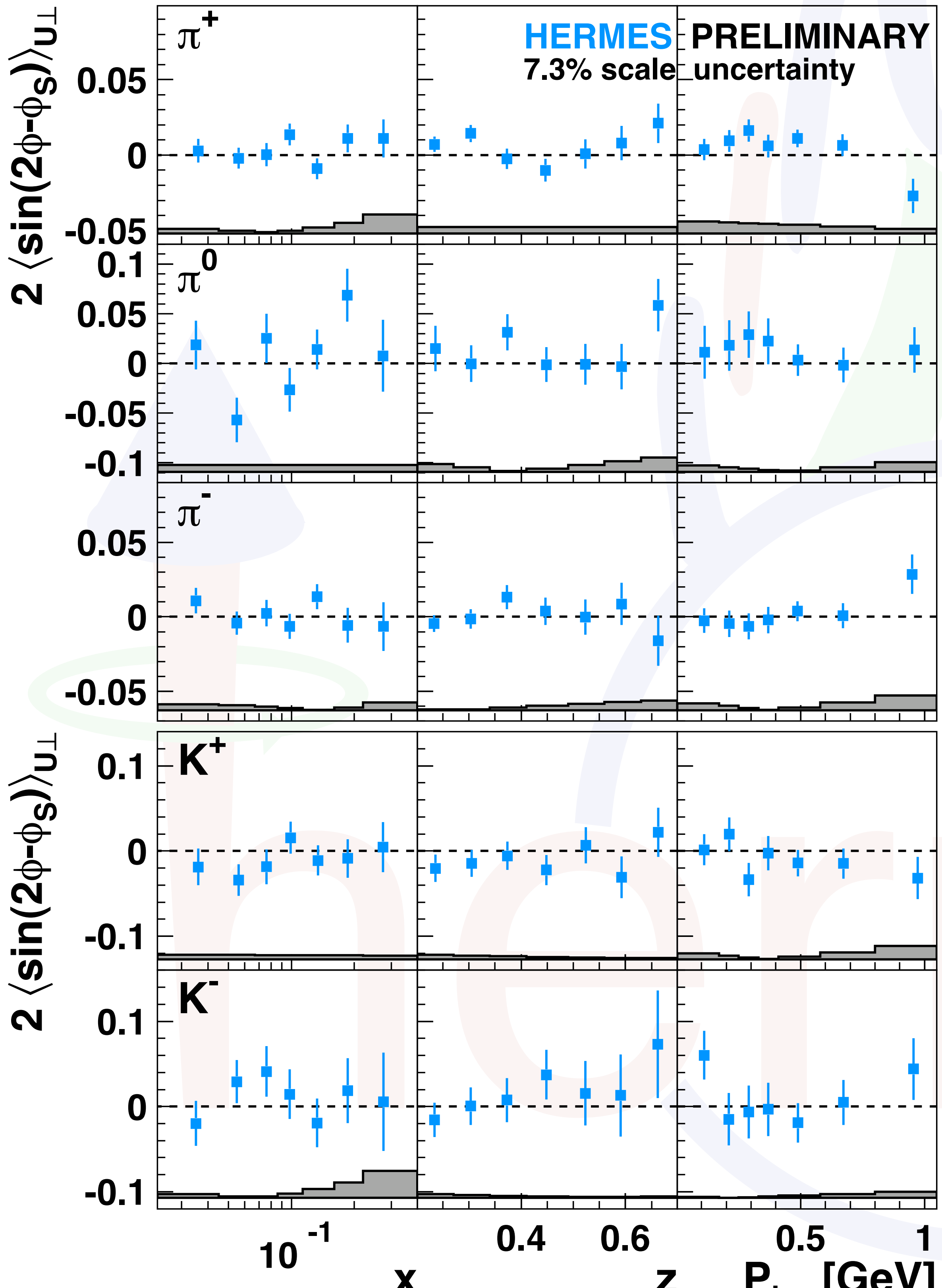



- arises solely from longitudinal component of target-spin ( ≲15% )
- no significant non-zero signal observed (except maybe K+)
- suppressed by one power of $P_{h\perp}$ (compared to, e.g., Sivers)
- related to worm-gear $h_{1L}^\perp$

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

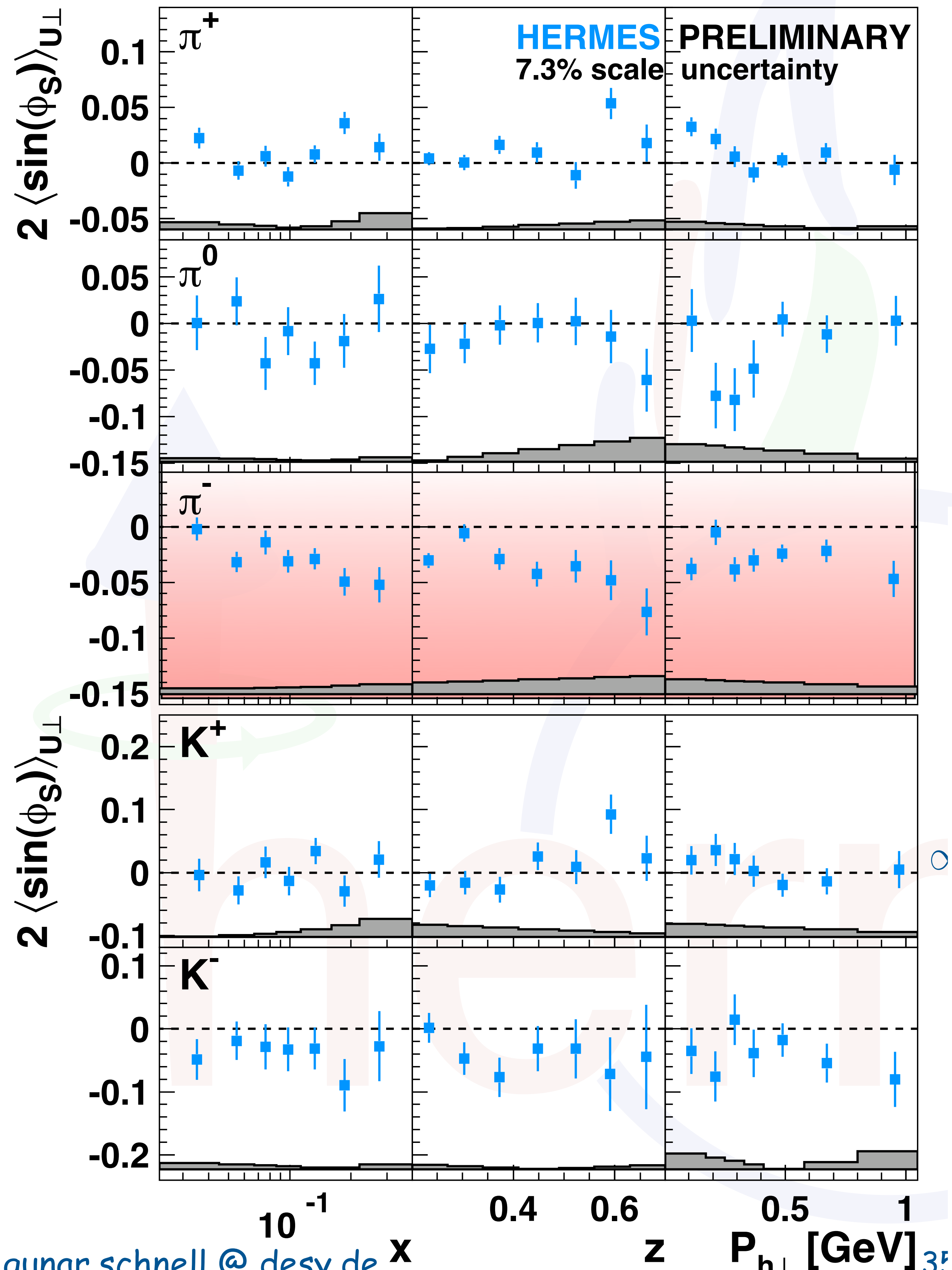
# Subleading twist II - $\sin(2\phi-\phi_S)$




- no significant non-zero signal observed
- suppressed by one power of $P_{h\perp}$ (compared to, e.g., Sivers)
- various terms related to pretzelosity, worm-gear, Sivers etc.:

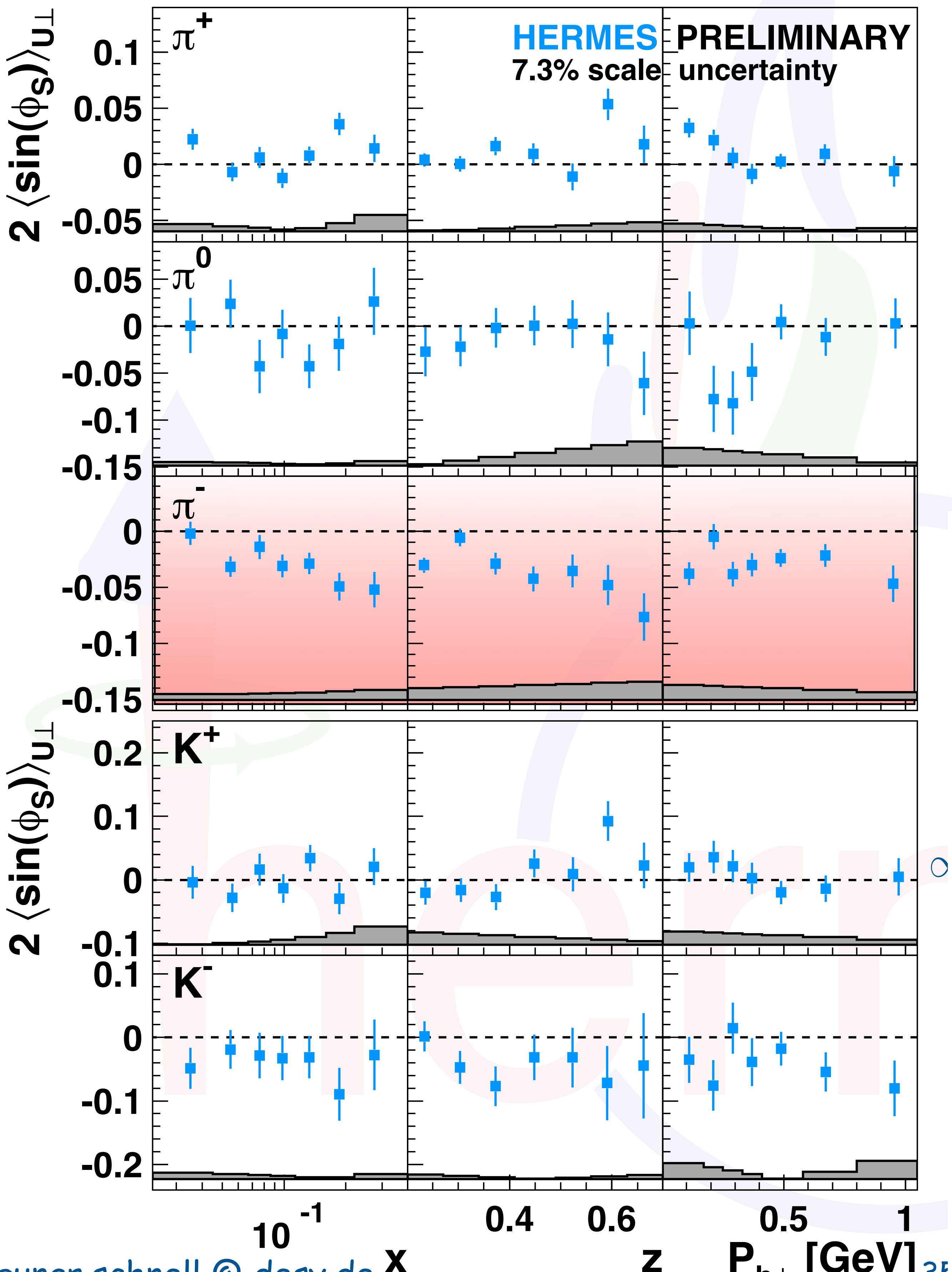
$$\propto \mathcal{W}_1(\mathbf{p_T},\mathbf{k_T},\mathbf{P_{h\perp}})\left(x f_T^\perp D_1 - \frac{M_h}{M} h_{1T}^\perp \frac{\tilde{H}}{z}\right) - \mathcal{W}_2(\mathbf{p_T},\mathbf{k_T},\mathbf{P_{h\perp}})\left[\left(x h_T H_1^\perp + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^\perp}{z}\right) + \left(x h_T^\perp H_1^\perp - \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{D}^\perp}{z}\right)\right]$$

# Subleading twist III - sin($\phi_s$)




- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons

# Subleading twist III - sin($\phi_s$)

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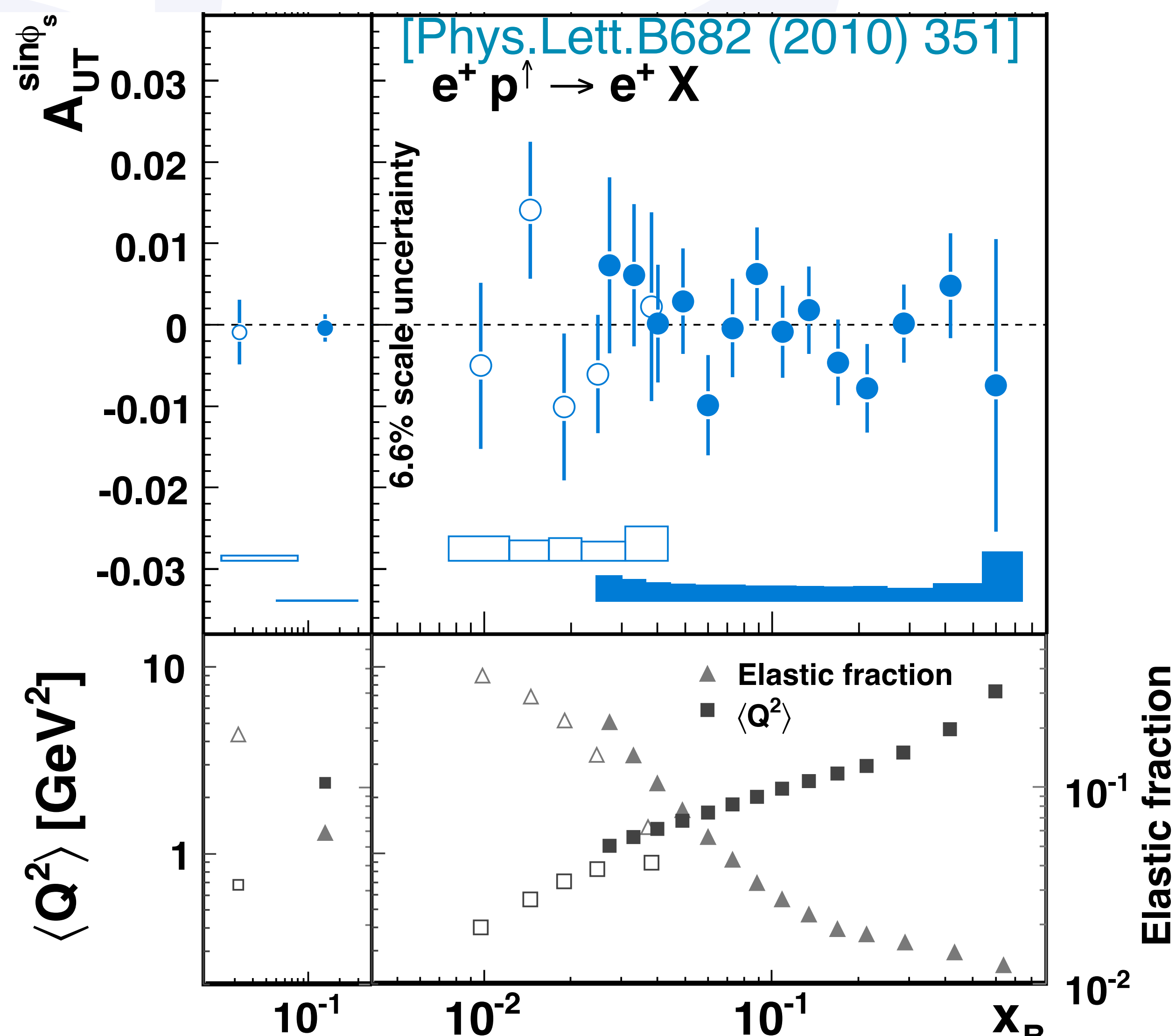
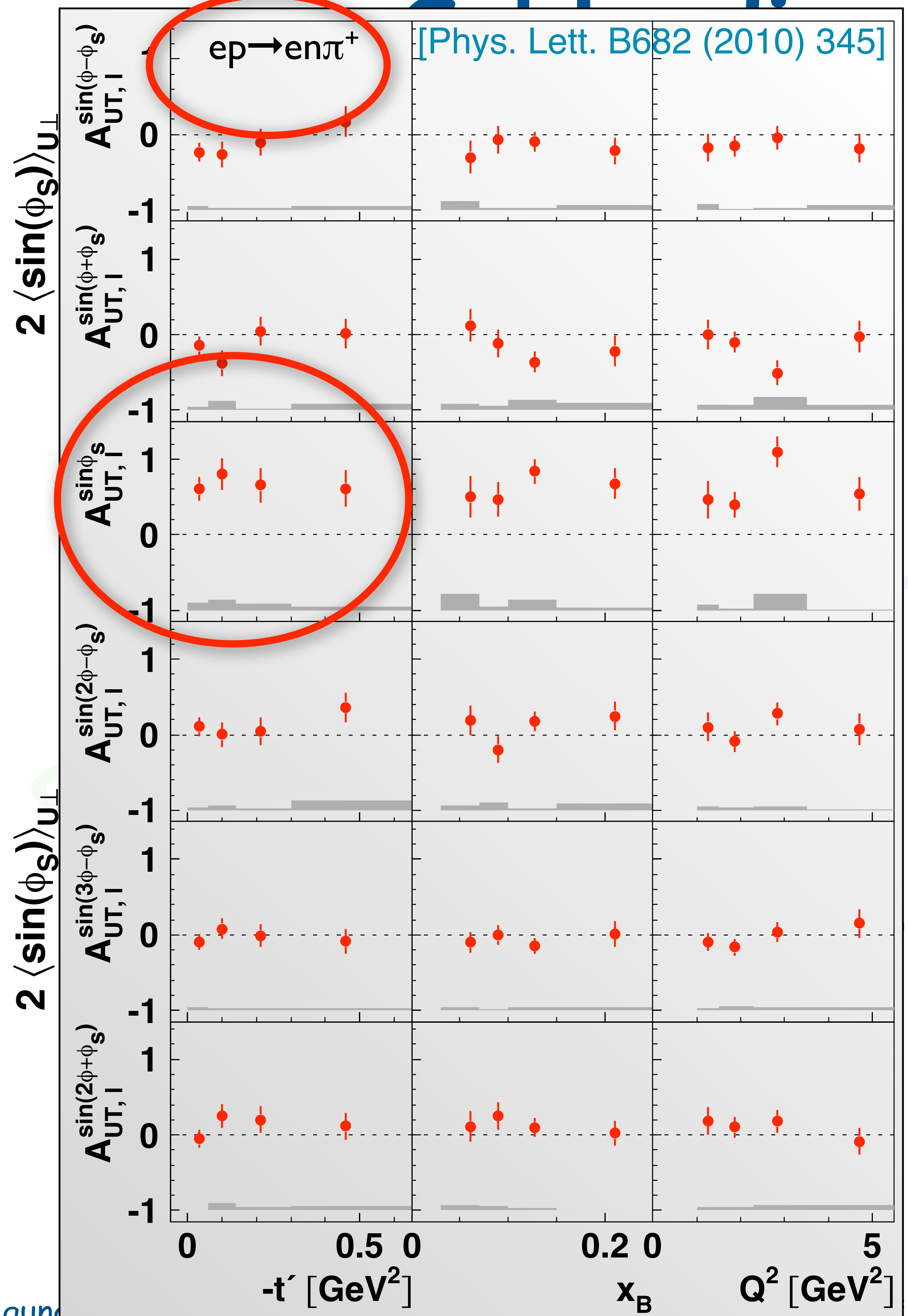
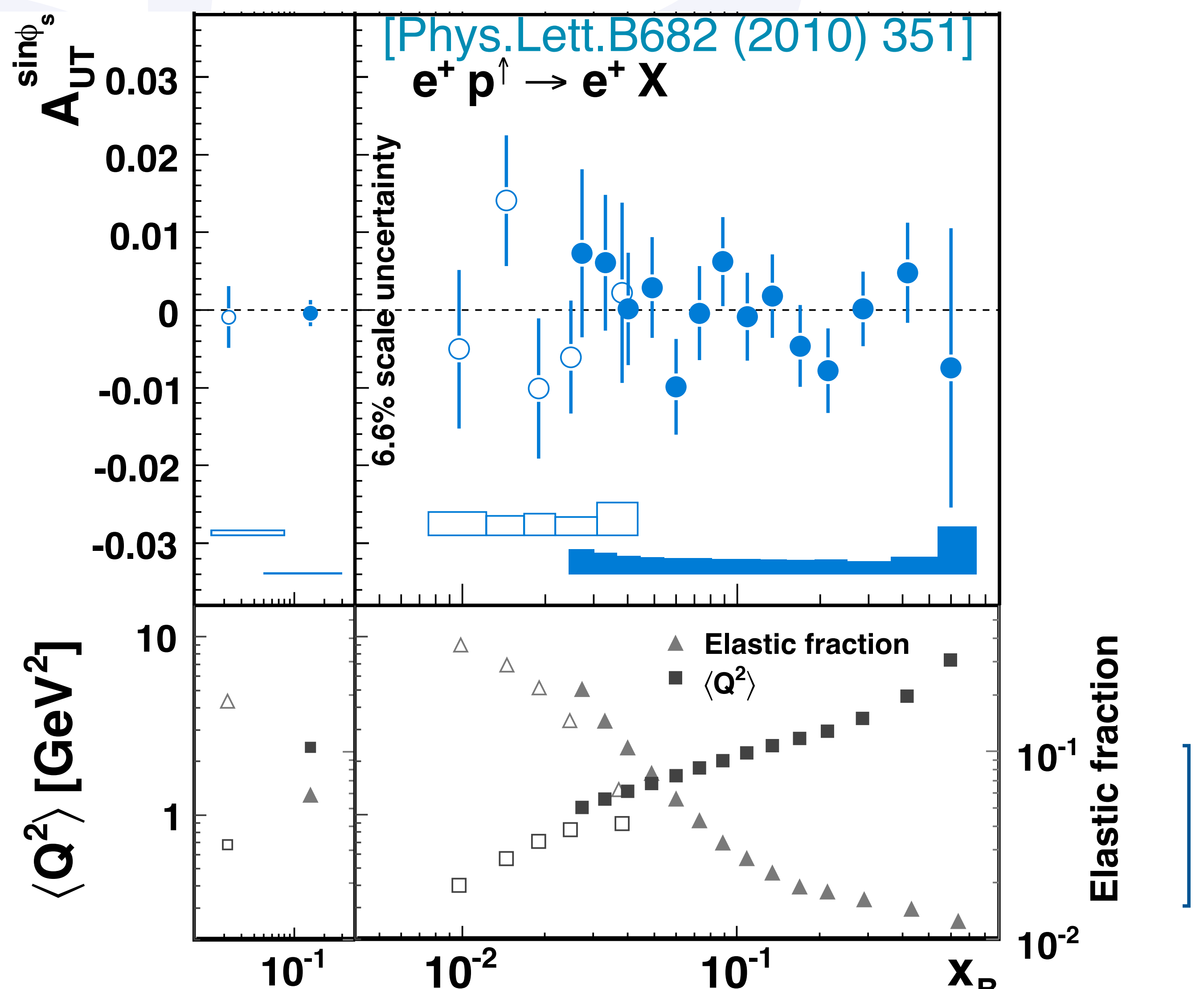


# twist III - $\sin(\phi_s)$

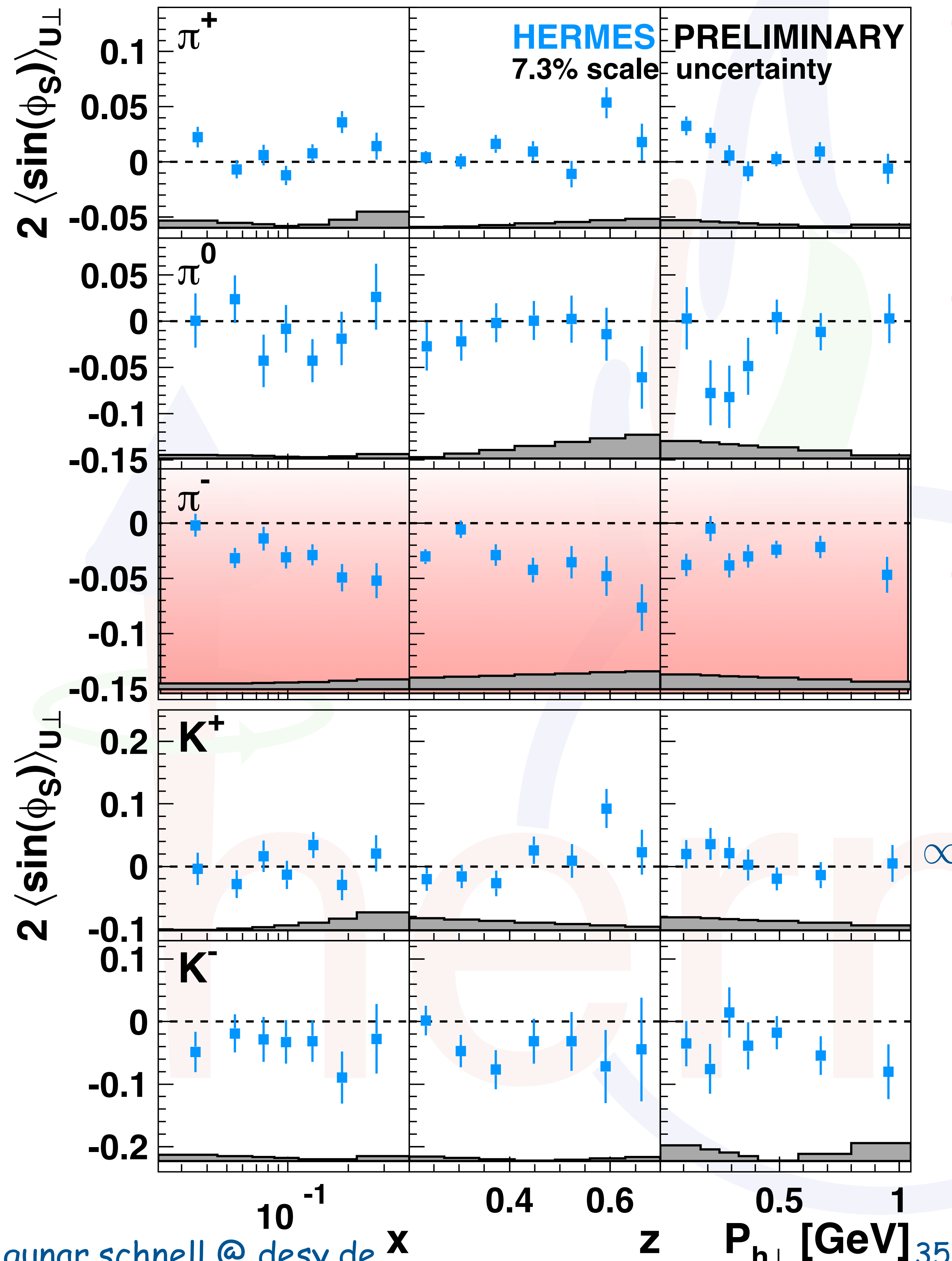
- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons




gun

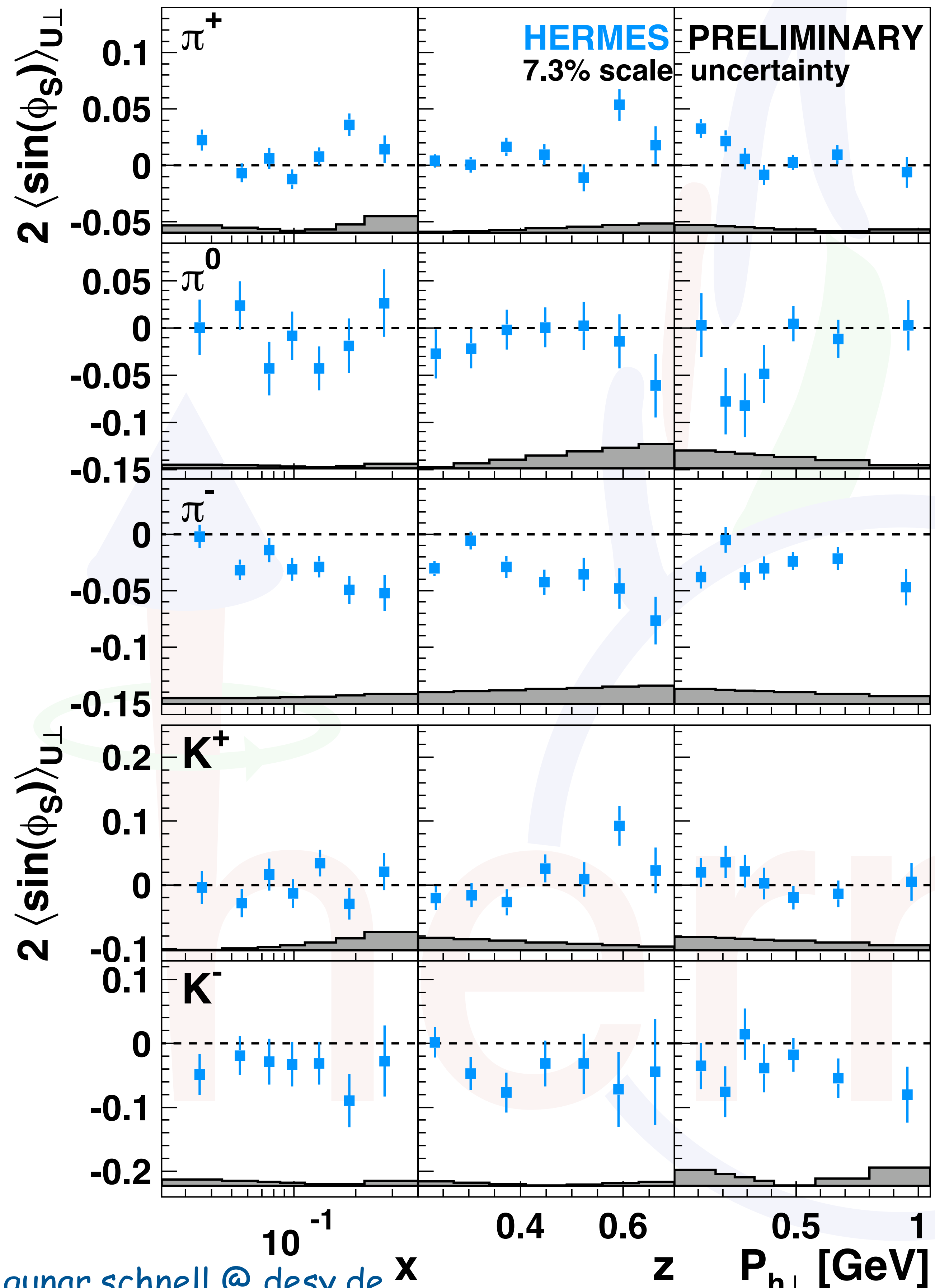
# Subleading twist III - $\sin(\phi_s)$

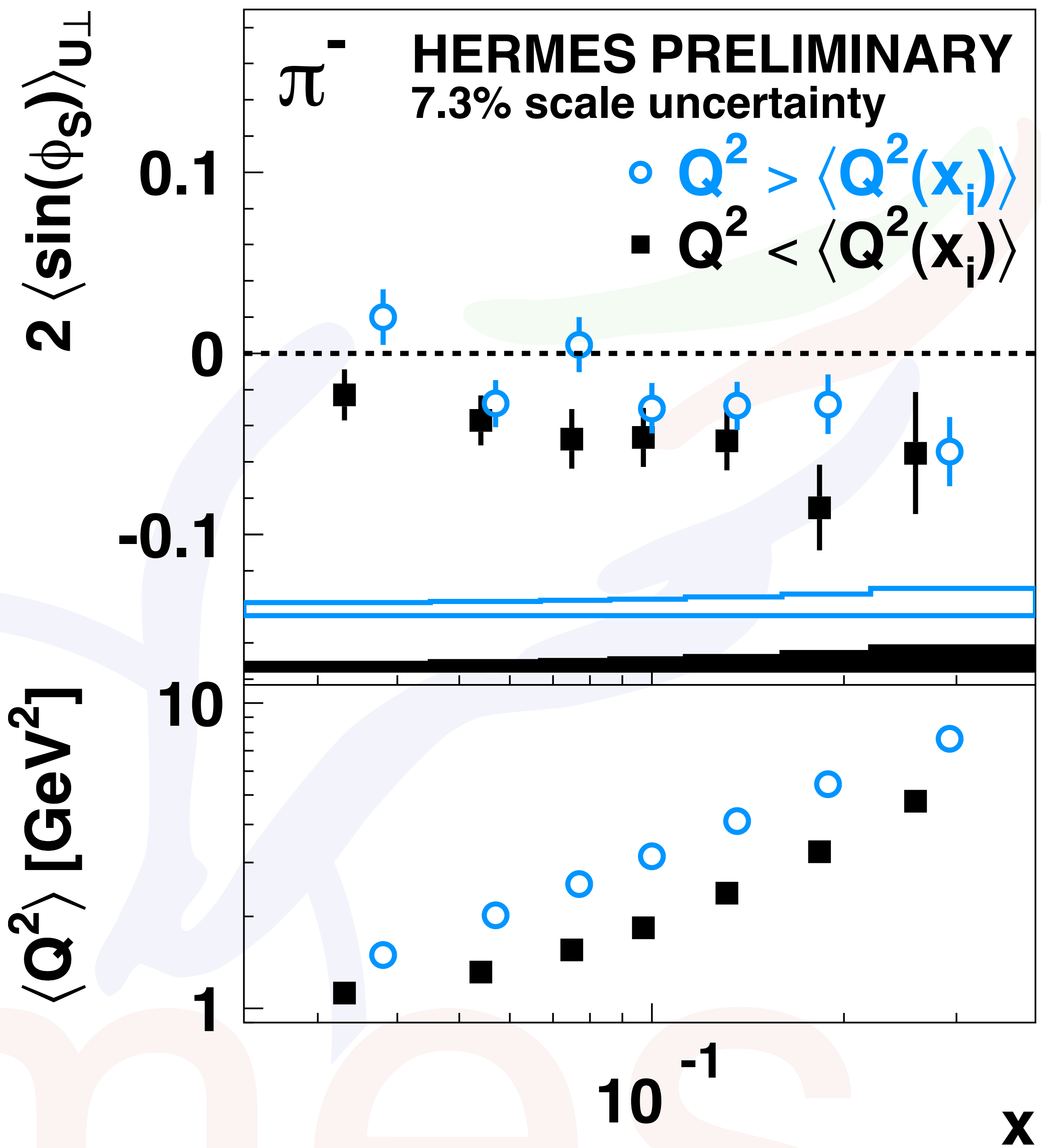



- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

$$\propto \left(x f_T^\perp D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z}\right) - \mathcal{W}(p_T, k_T, P_{h\perp}) \left[\left(x h_T H_1^\perp + \frac{M_h}{M} g_{1T} \frac{\tilde{G}^\perp}{z}\right) - \left(x h_T^\perp H_1^\perp - \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{D}^\perp}{z}\right)\right]$$

# Subleading twist III - sin($\phi_s$)

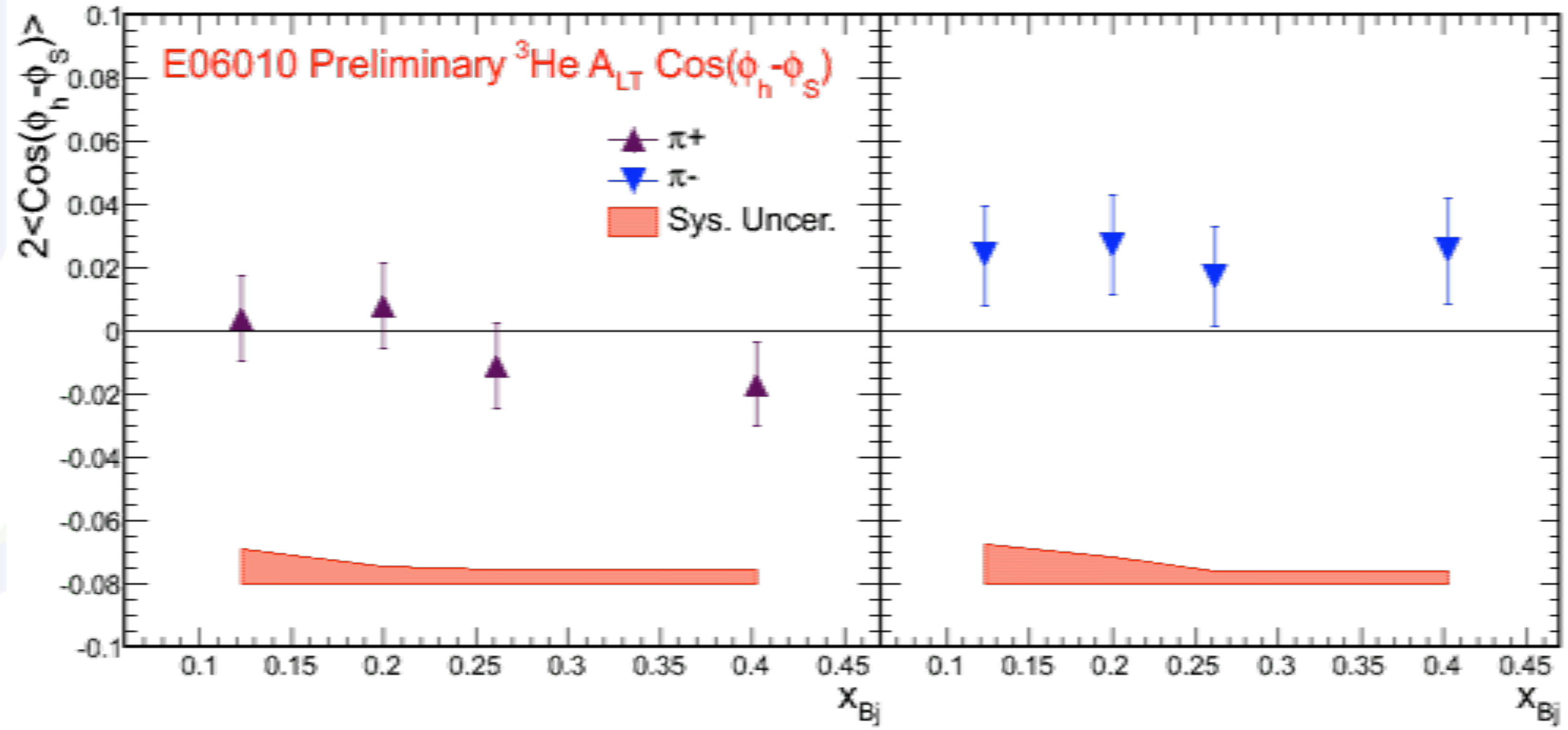



- $Q^2$ dependence seen in signal for negative pions

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
| T | $f_{1T}^\perp$ | $g_{1T}$ | $h_1$, $h_{1T}^\perp$ |

# Worm-Gear $g_{1T}$



# Worm-Gear $g_{1T}$

| | U | L | T |
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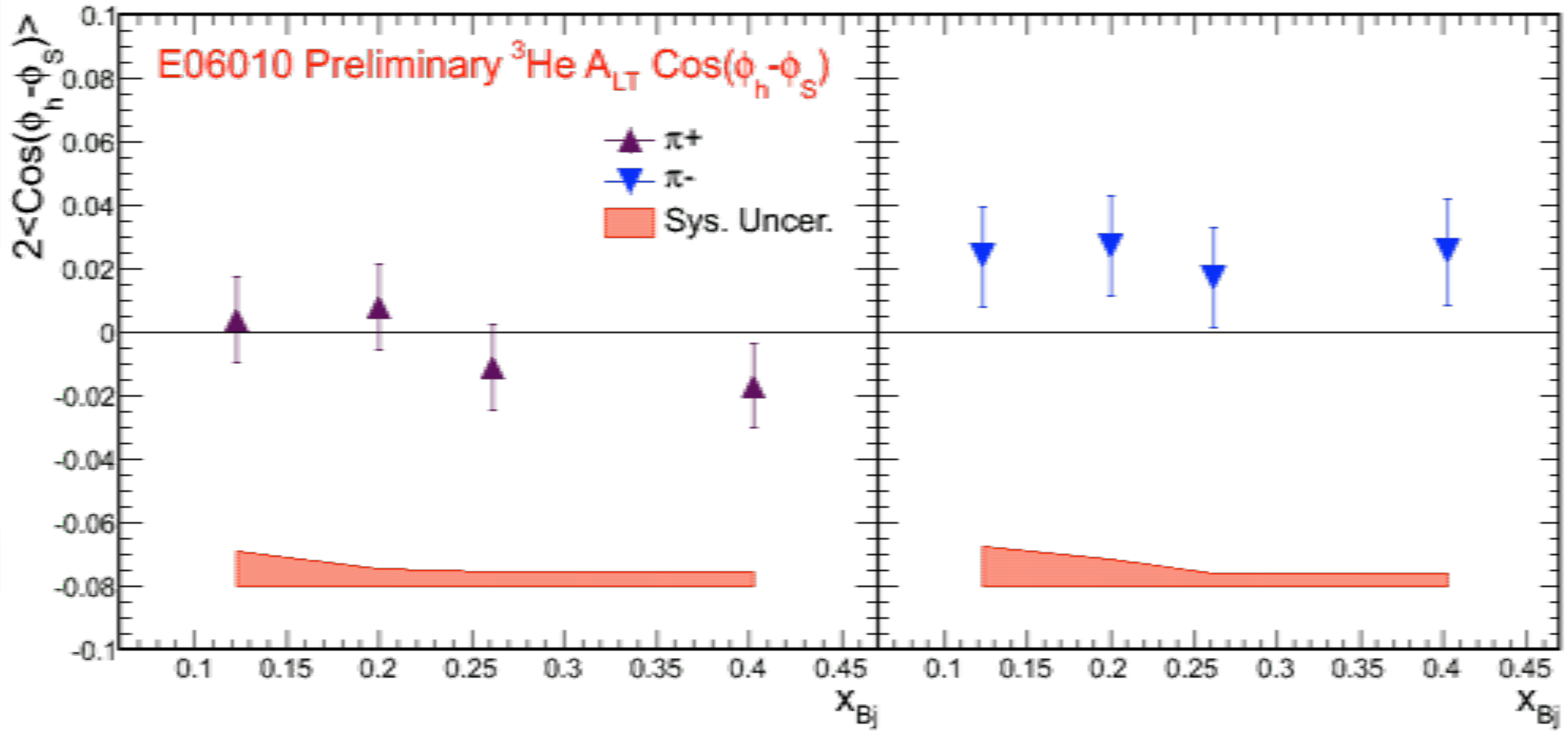


- chiral even

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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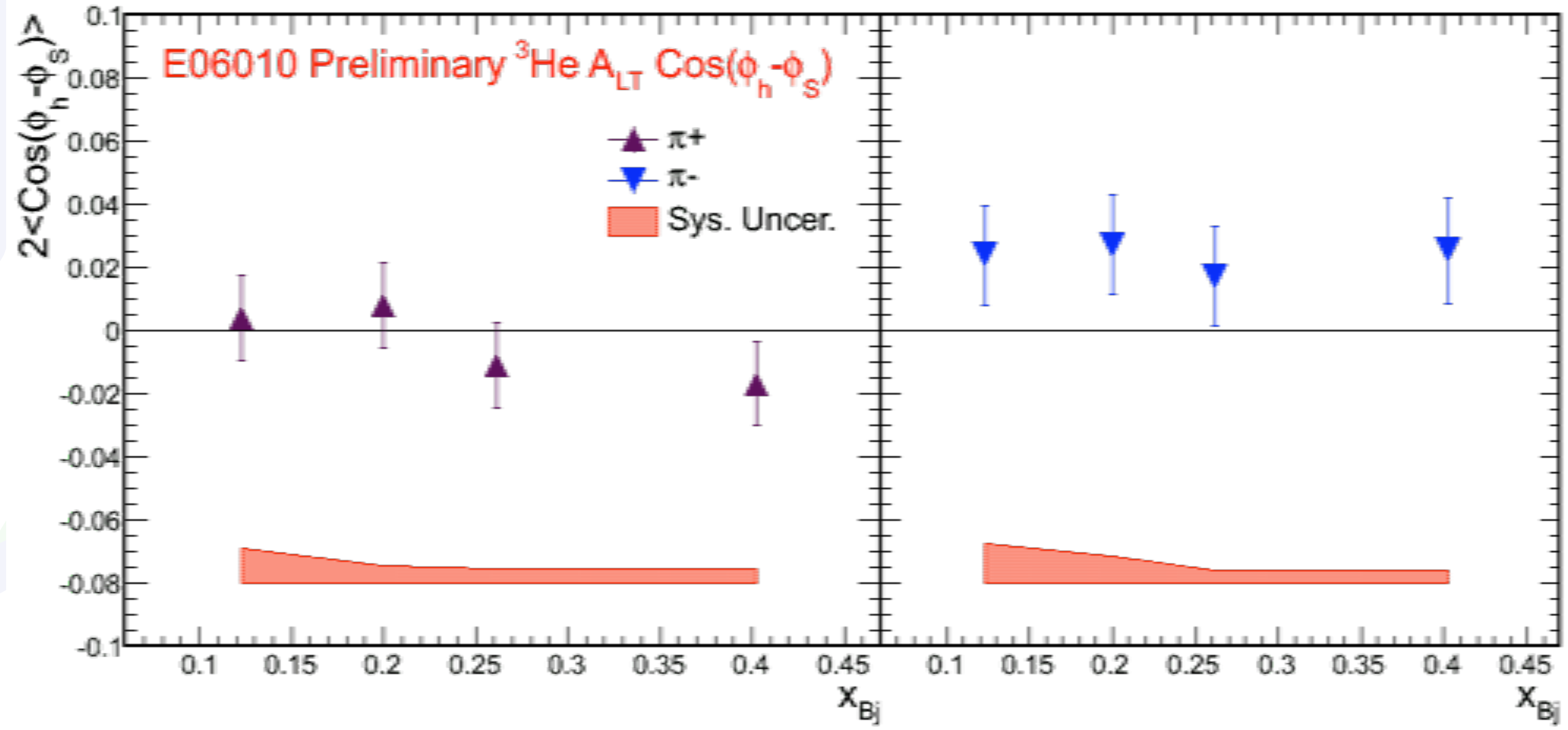


- chiral even
- first direct evidence for worm-gear $g_{1T}$ from JLab

# Worm-Gear $g_{1T}$

| | U | L | T |
|---|---|---|---|
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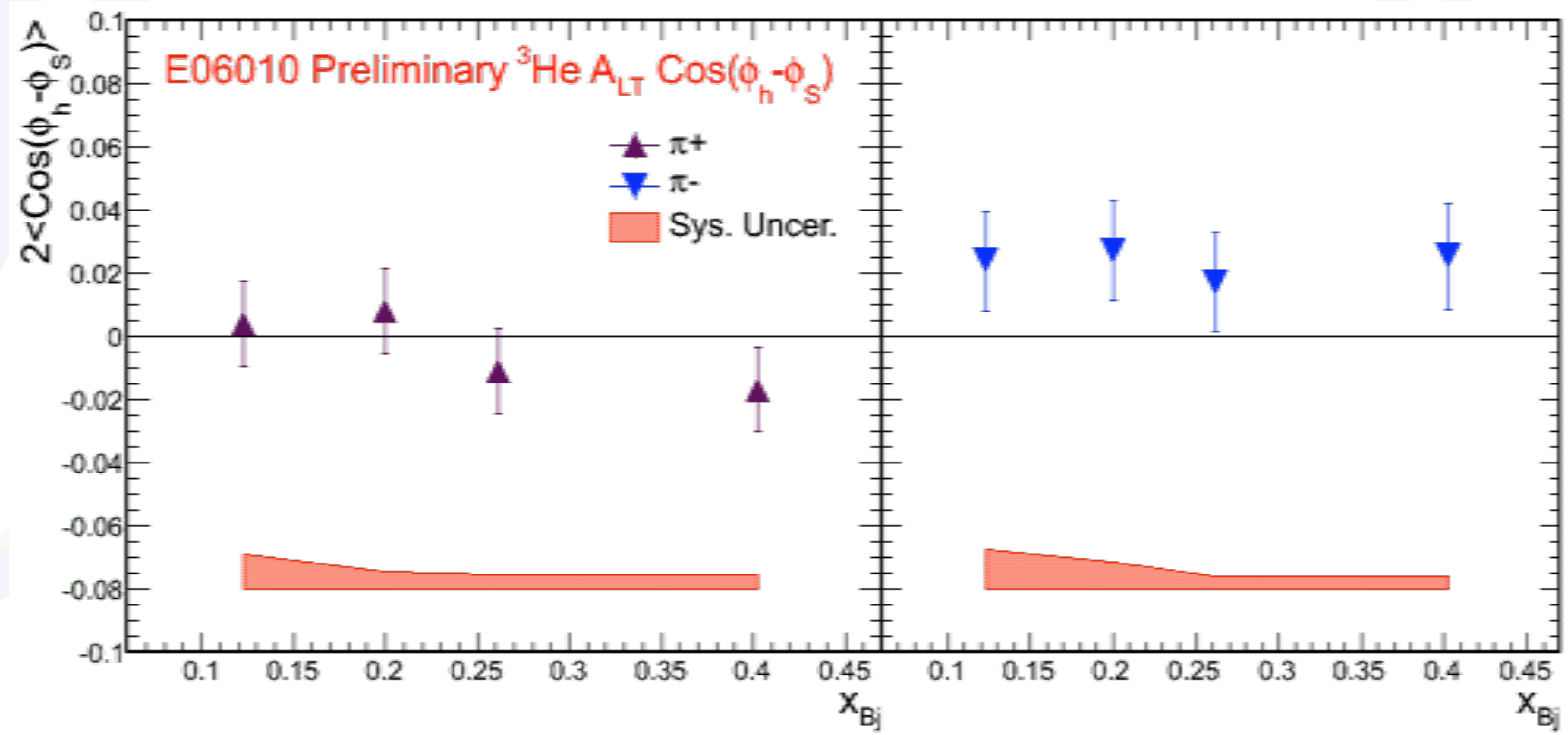
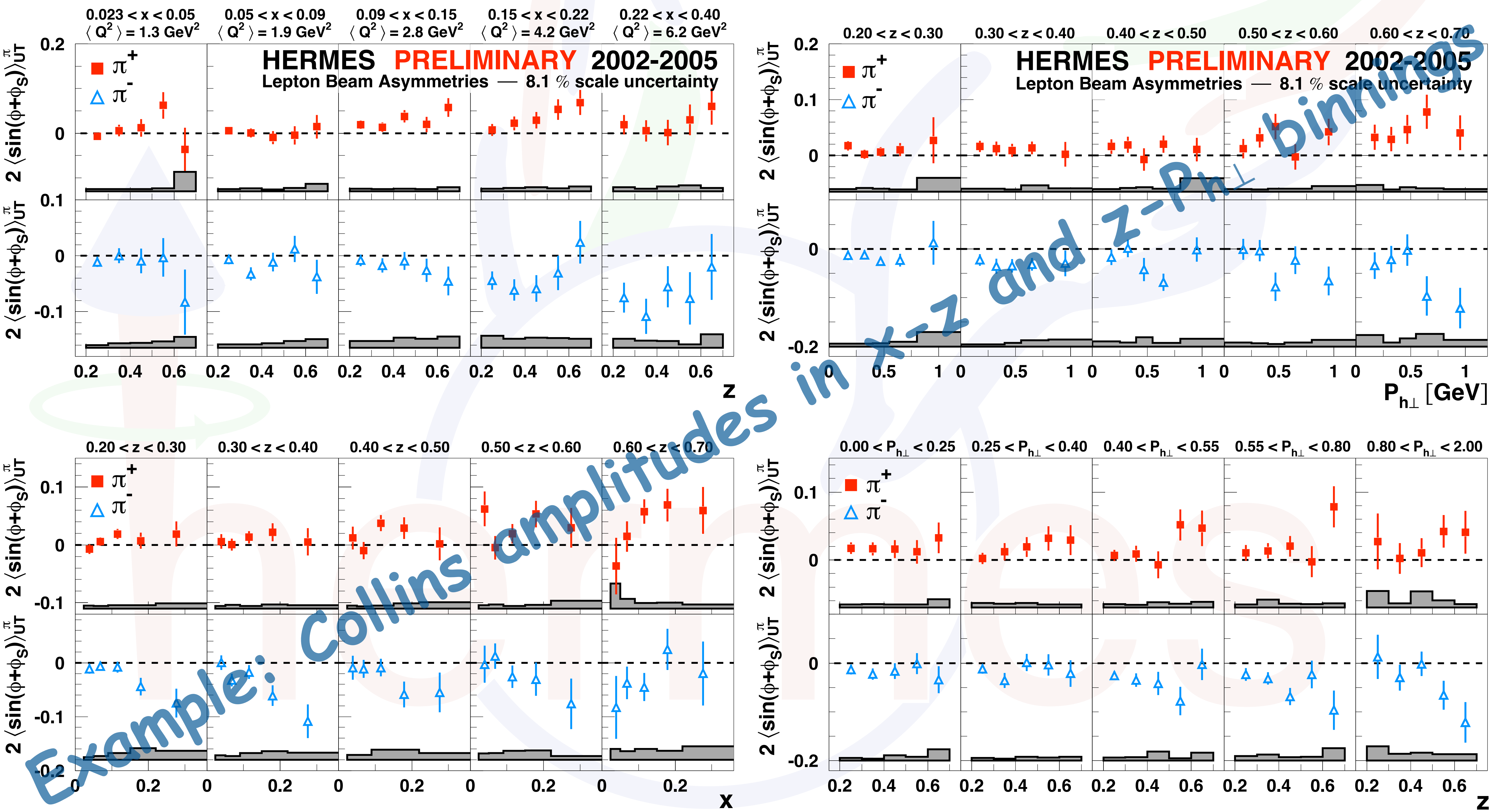



- chiral even
- first direct evidence for worm-gear $g_{1T}$ from JLab
- HERMES results on $A_{LT}$ coming out soon

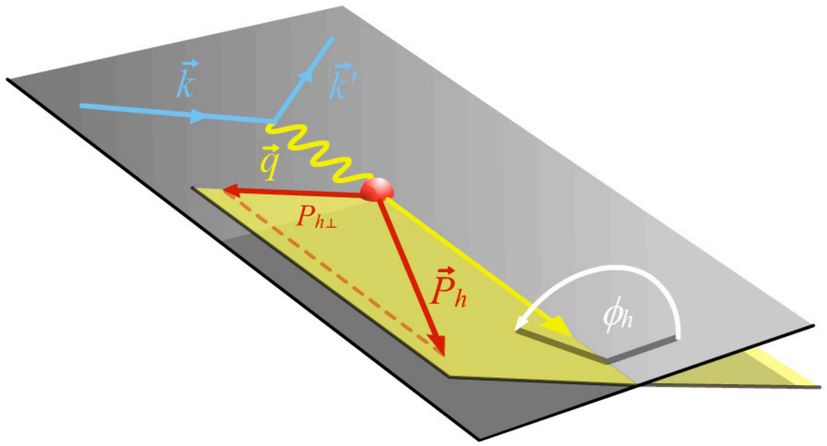
# Multi-dimensional analyses

kinematic dependences often don't factorize

bin in as many independent variables as possible:



# Modulations in spin-independent SIDIS cross section




$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi_h\,\mathrm{d}P_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right)\{A(y)\,F_{\mathrm{UU,T}} + B(y)F_{\mathrm{UU,L}}$$

$$+C(y)\cos\phi_h F_{\mathrm{UU}}^{\cos\phi_h} + B(y)\cos 2\phi_h F_{\mathrm{UU}}^{\cos 2\phi_h}\}$$

BOER-MULDERS EFFECT

leading twist

$$F_{UU}^{\cos 2\phi_h} \propto C\left[-\frac{2(\hat{P}_{h\perp}\cdot\vec{k}_T)(\hat{P}_{h\perp}\cdot\vec{p}_T)-\vec{k}_T\cdot\vec{p}_T}{MM_h}h_1^{\perp}H_1^{\perp}\right]$$

CAHN EFFECT

next to leading twist

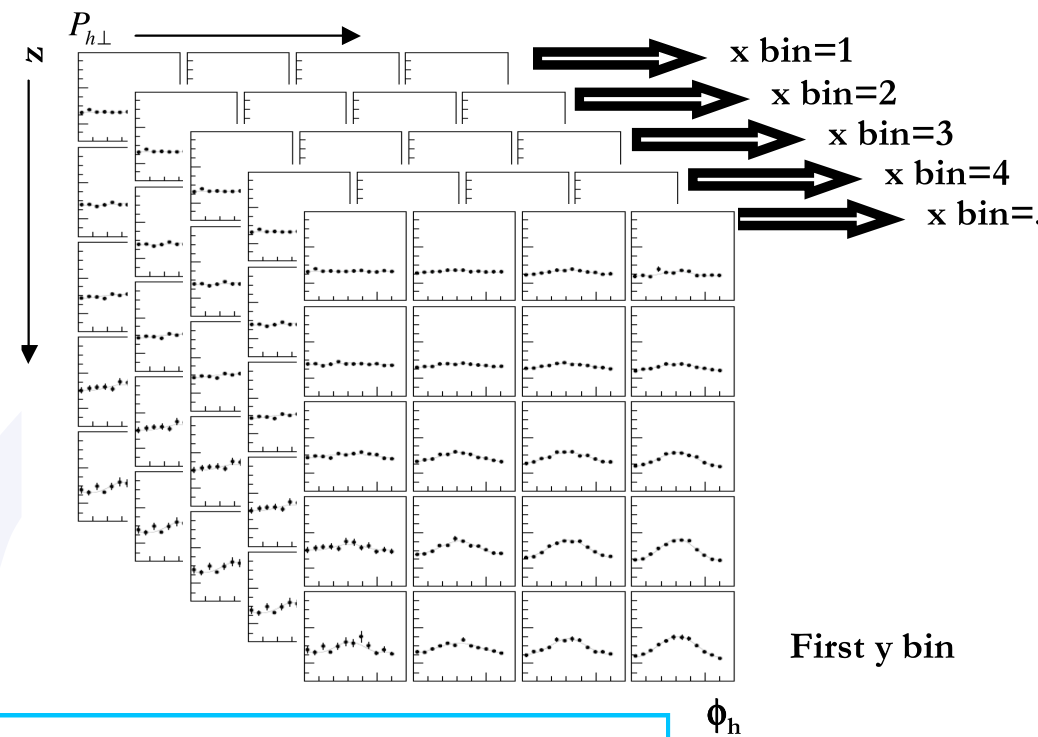
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q}C\left[-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}x\,h_1^{\perp}H_1^{\perp}-\frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}x\,f_1D_1+\ldots\right]$$

Interaction dependent terms neglected

(Implicit sum over quark flavours)

# Extraction of cosine modulations

- **Fully differential** analysis in $(x, y, z, P_{h\perp}, \phi)$




probability that an event generated with a certain kinematics is measured with a different kinematics

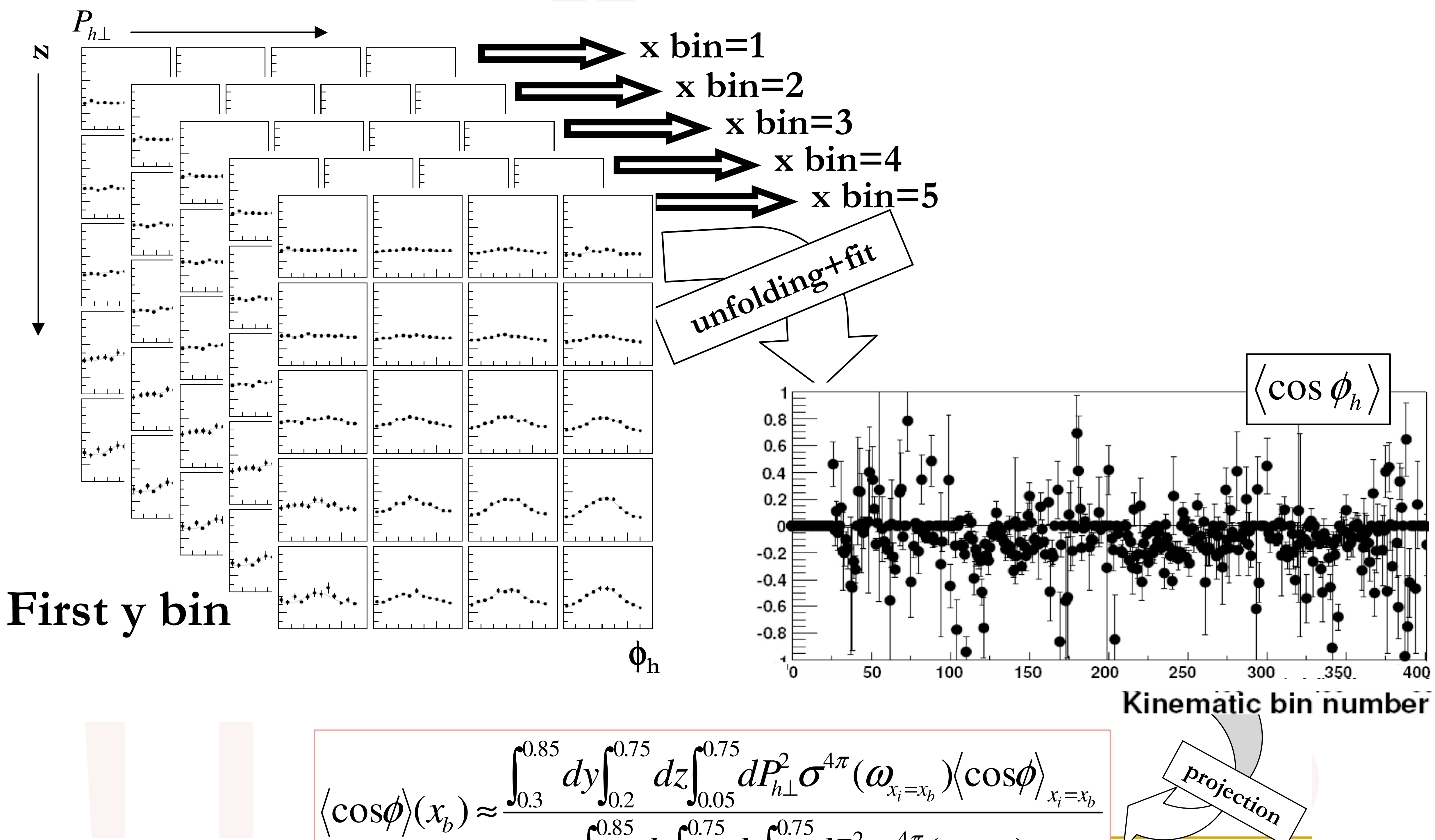
$$n_{EXP} = S \; n_{BORN} + n_{Bg}$$

$$n_{BORN} = S^{-1}\left[n_{EXP} - n_{Bg}\right]$$

includes the events smeared into the acceptance

- **Multi-dimensional unfolding**: correction for finite acceptance, QED radiation, kinematic smearing, detector resolution

# Extraction of cosine modulations




$$\langle \cos\phi \rangle (x_b) \approx \frac{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{4\pi}(\omega_{x_i=x_b}) \langle \cos\phi \rangle_{x_i=x_b}}{\int_{0.3}^{0.85} dy \int_{0.2}^{0.75} dz \int_{0.05}^{0.75} dP_{h\perp}^2 \sigma^{4\pi}(\omega_{x_i=x_b})}$$

| | U | L | T |
|---|---|---|---|
| U | $f_1$ | | $h_1^\perp$ |
| L | | $g_{1L}$ | $h_{1L}^\perp$ |
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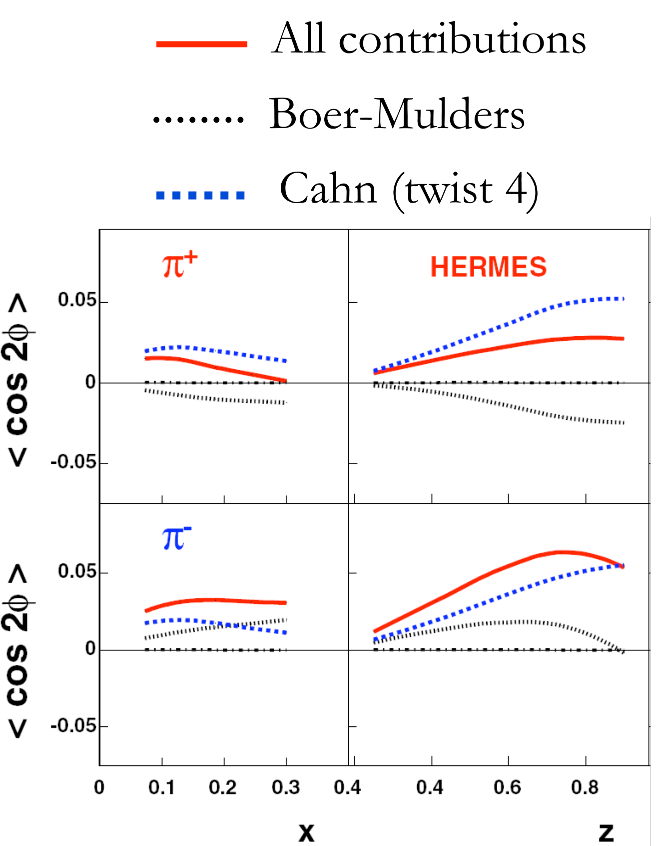
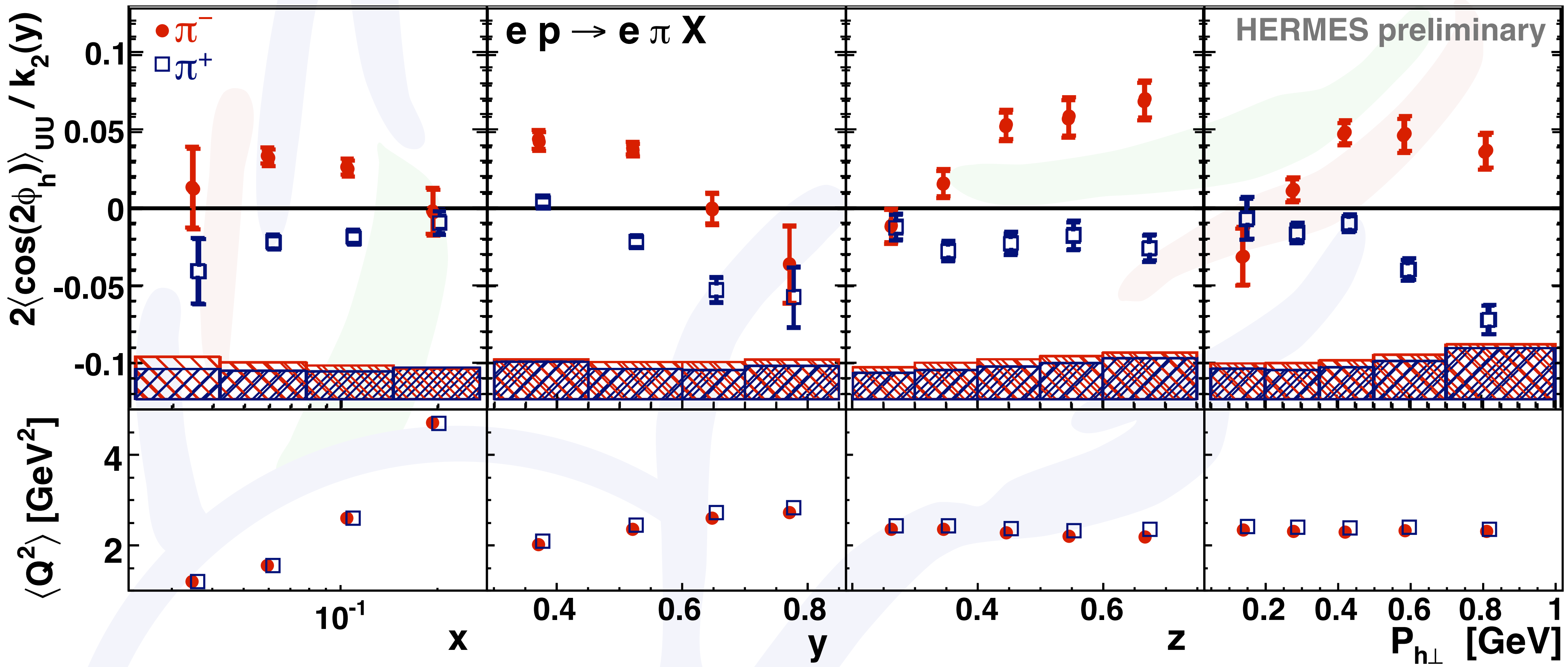
# Signs of Boer-Mulders?!




[V. Barone et al., Phys. Rev.D78 (2008) 045022]




- opposite sign for charged pions (as expected for BM effect?!), with larger magnitude for $\pi^-$

| | U | L | T |
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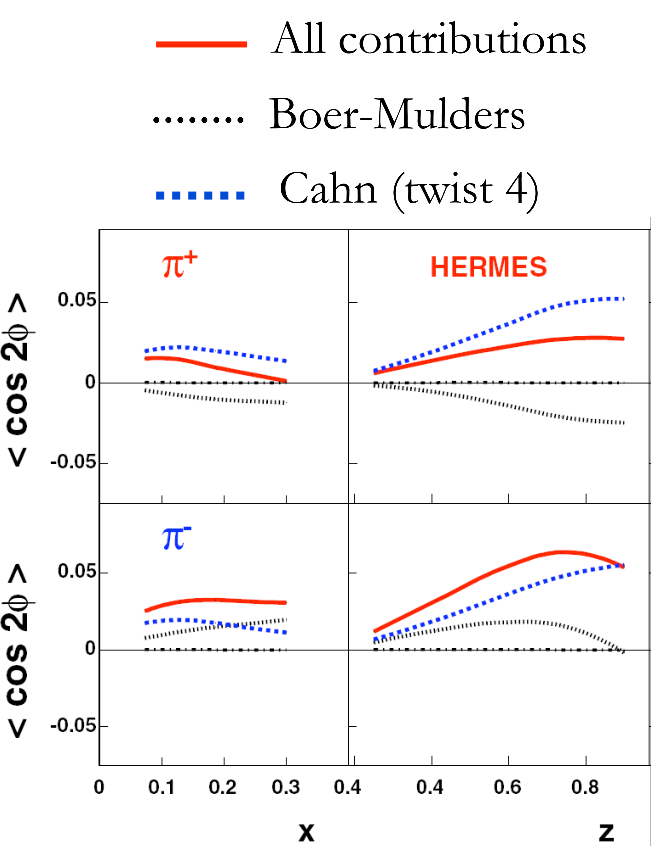


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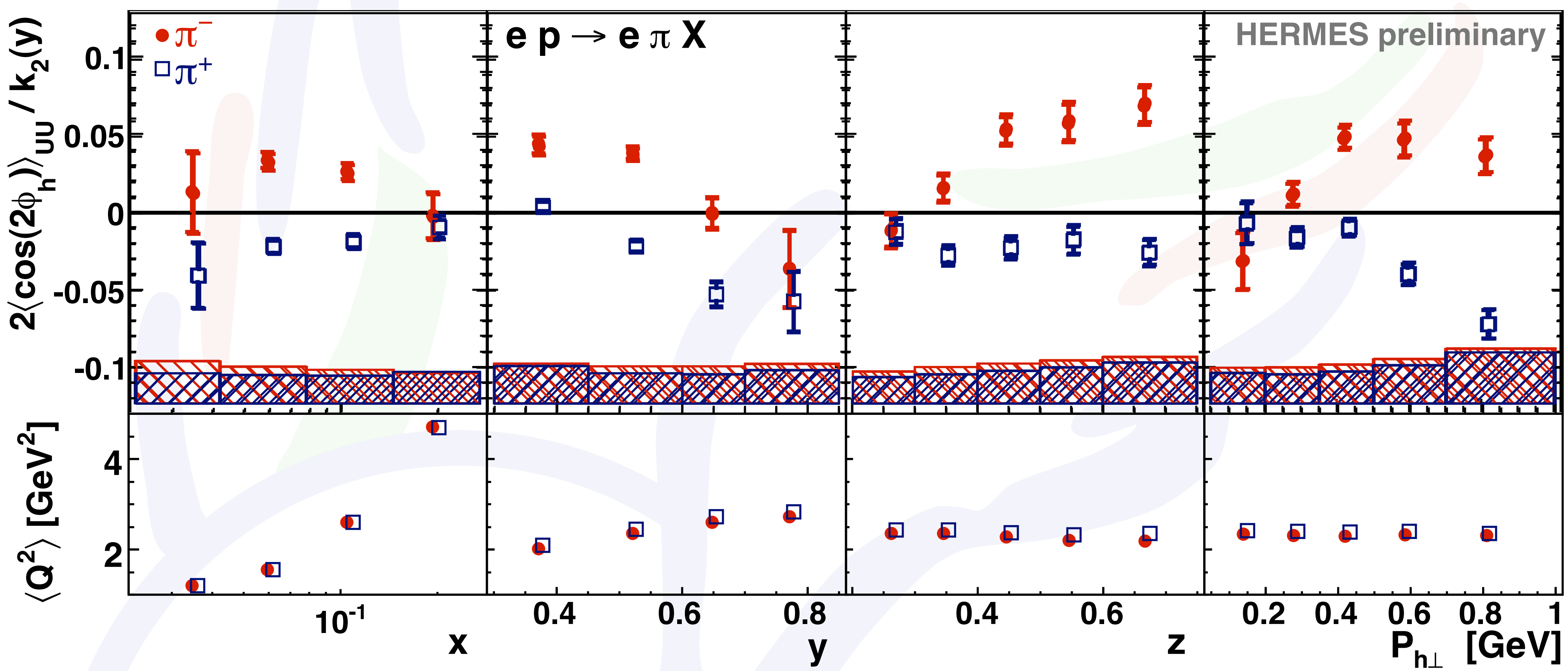



- opposite sign for charged pions (as expected for BM effect?!), with larger magnitude for $\pi^-$
- prediction including Cahn effect does not describe data

# Cahn effect?

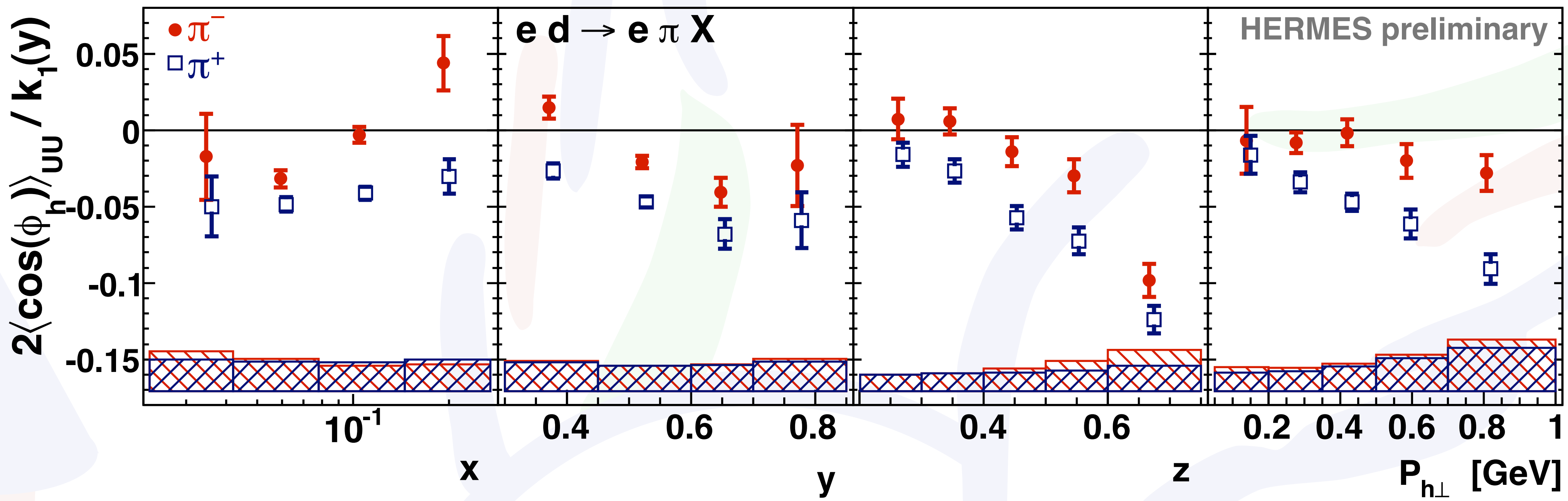
BOER-MULDERS EFFECT

CAHN EFFECT

Interaction dependent terms neglected

next to leading twist

$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[\underbrace{-\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h}\, x\, h_1^\perp H_1^\perp}_{\text{BOER-MULDERS EFFECT}} \underbrace{- \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M}\, x\, f_1 D_1}_{\text{CAHN EFFECT}} + \ldots\right]$$




- no dependence on hadron charge expected

# Cahn effect?

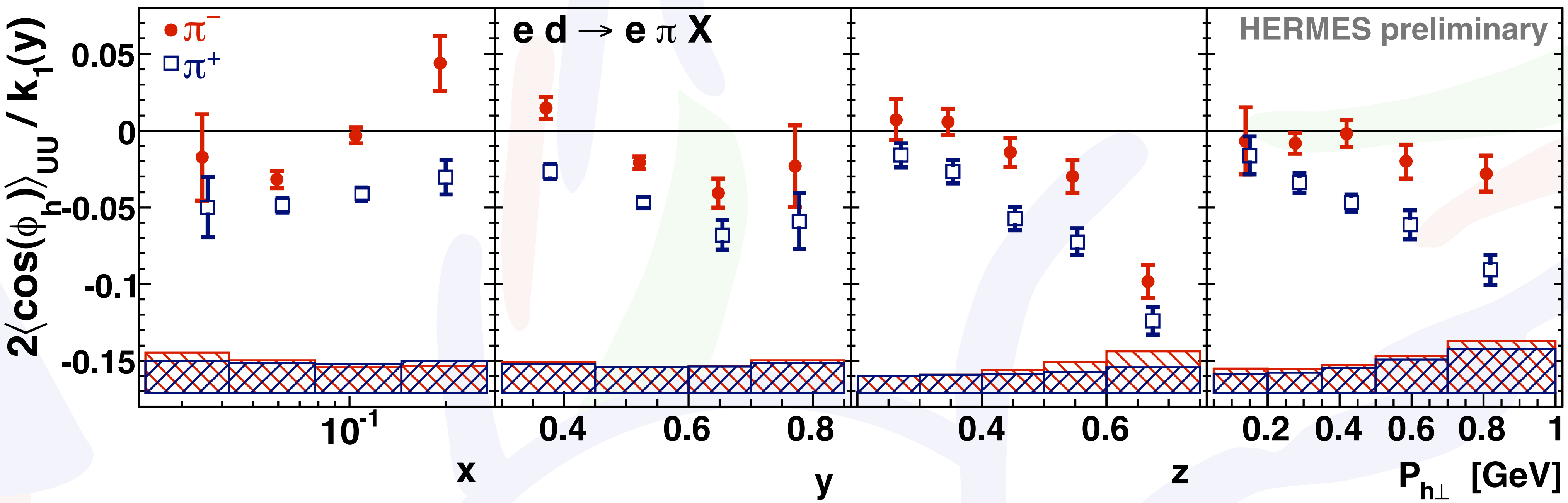
BOER-MULDERS EFFECT

CAHN EFFECT

next to leading twist

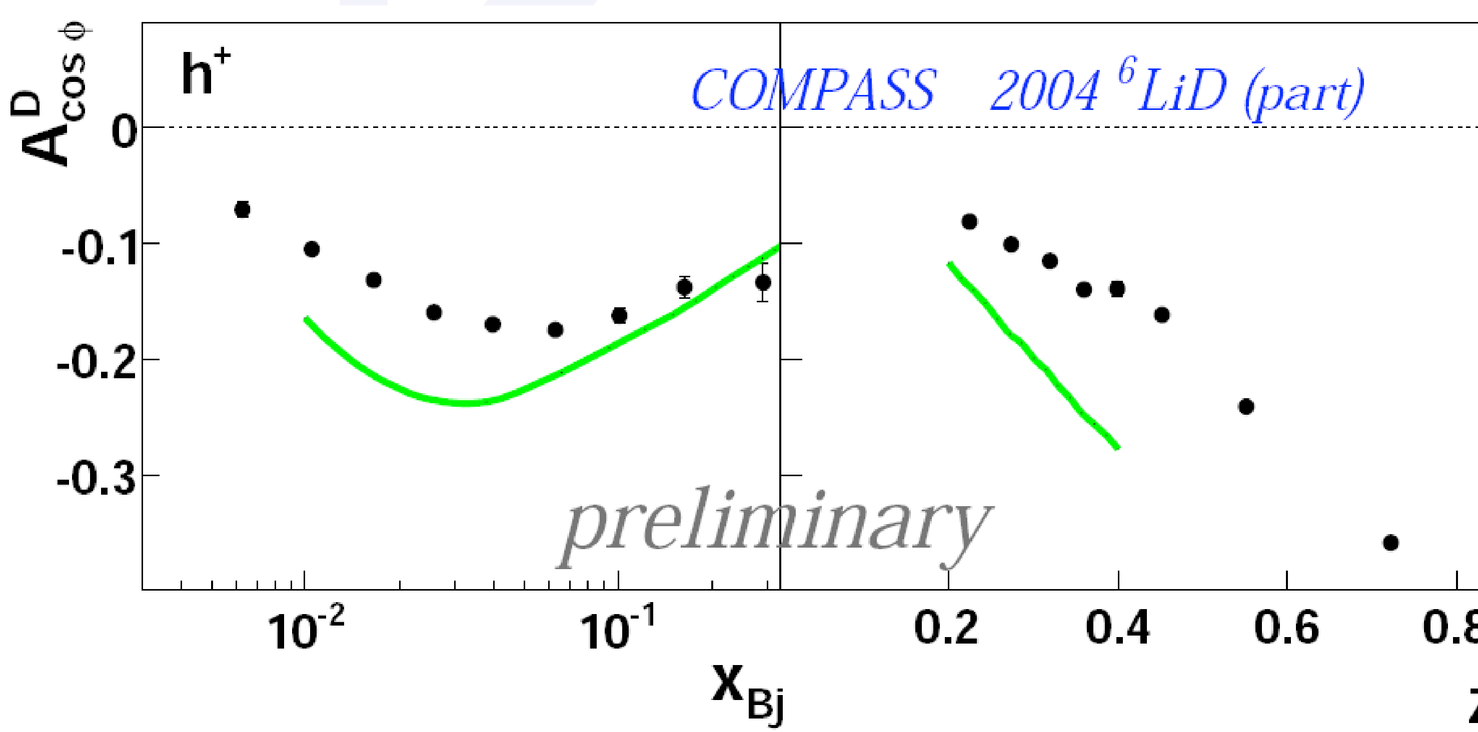
$$F_{UU}^{\cos\phi_h} \propto \frac{2M}{Q} C\left[ -\frac{\hat{P}_{h\perp}\cdot\vec{p}_T}{M_h} x\, h_1^{\perp} H_1^{\perp} - \frac{\hat{P}_{h\perp}\cdot\vec{k}_T}{M} x\, f_1 D_1 + \ldots \right]$$

Interaction dependent terms neglected

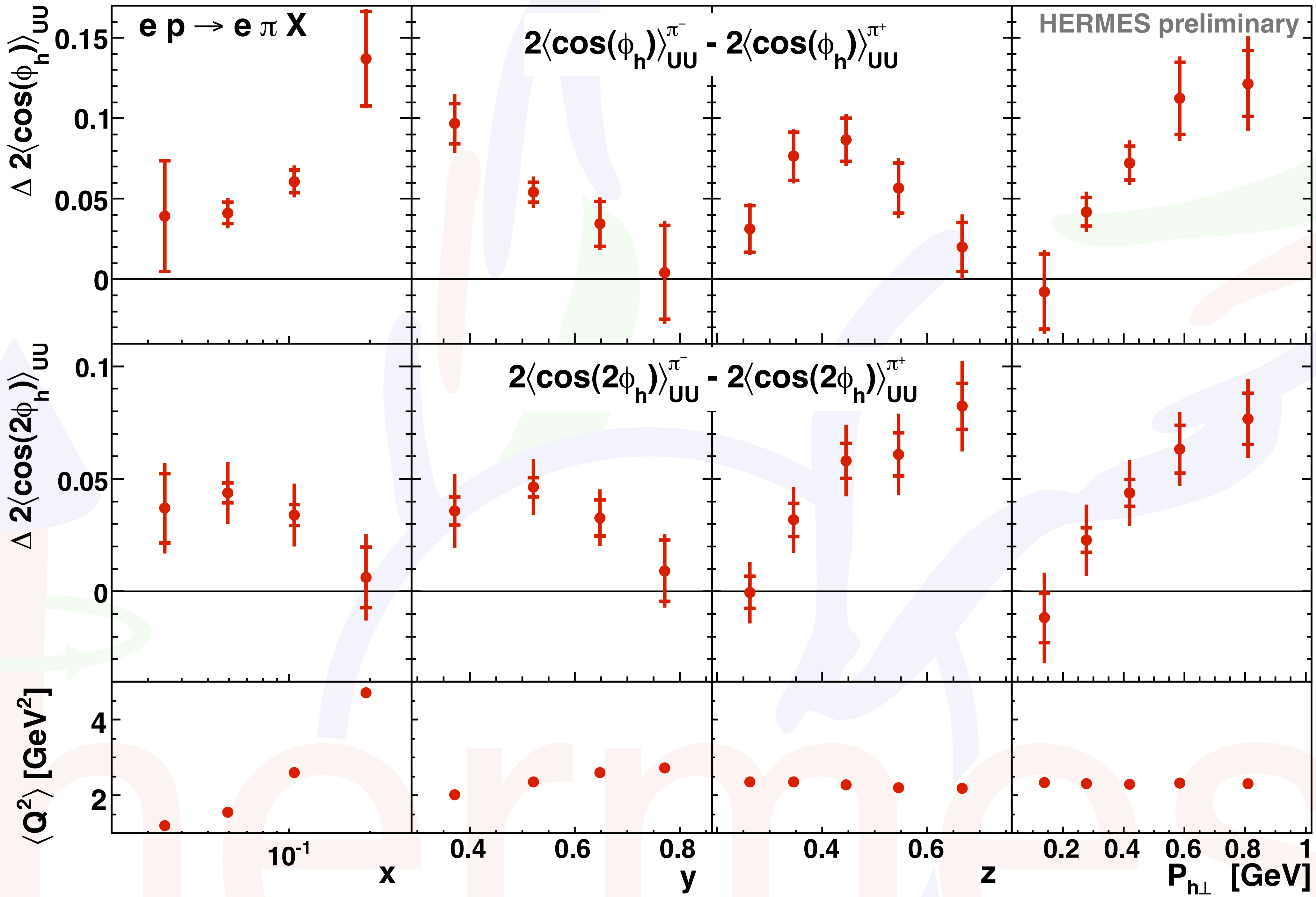



- no dependence on hadron charge expected
- prediction off from data

➡ sign of Boer-Mulders in $\cos\phi$ modulation or "real" twist-3?

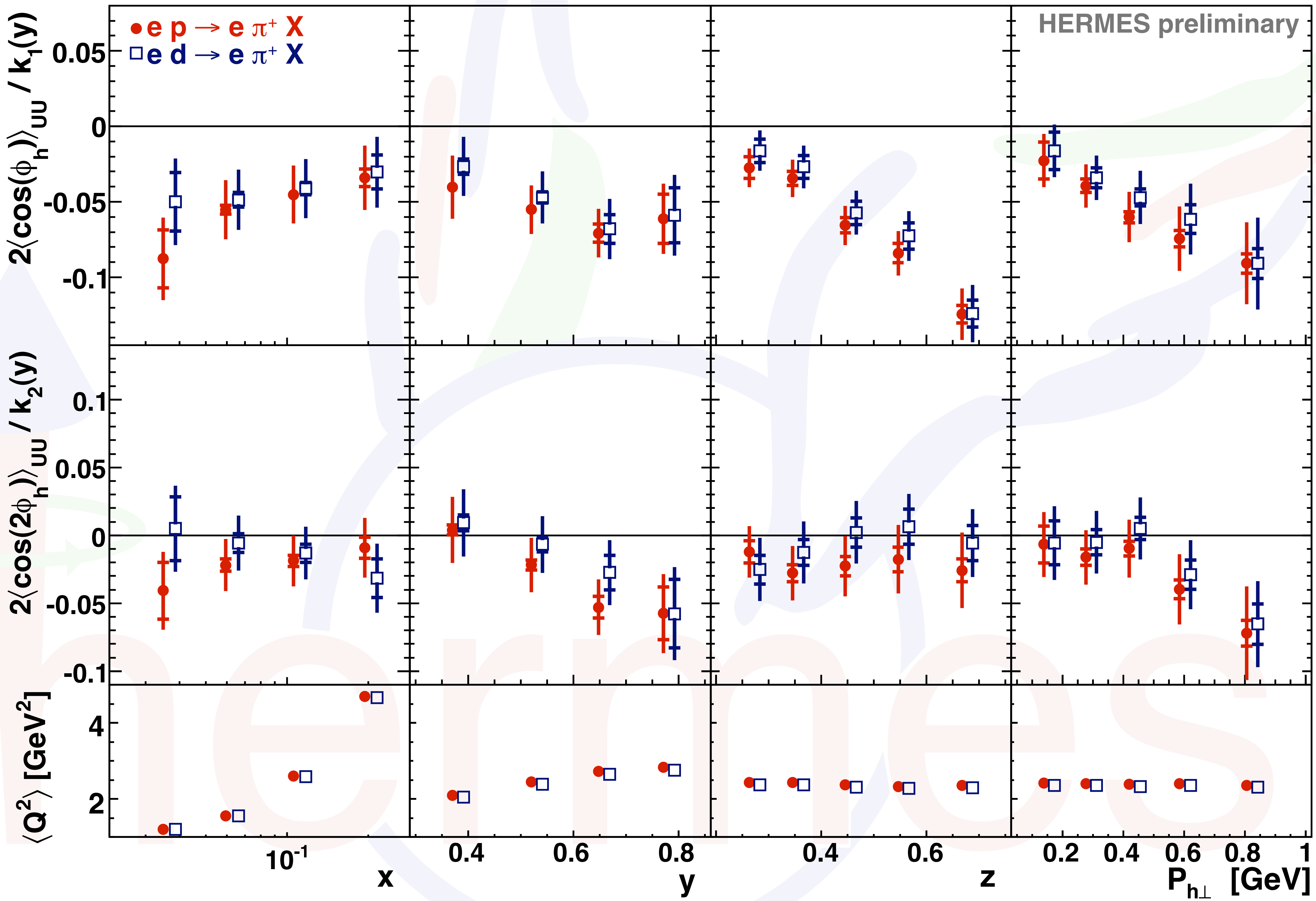


# Difference of pion amplitudes




- charge-symmetric contributions (e.g., Cahn) cancel

# Target (in)dependence of cosine modulations



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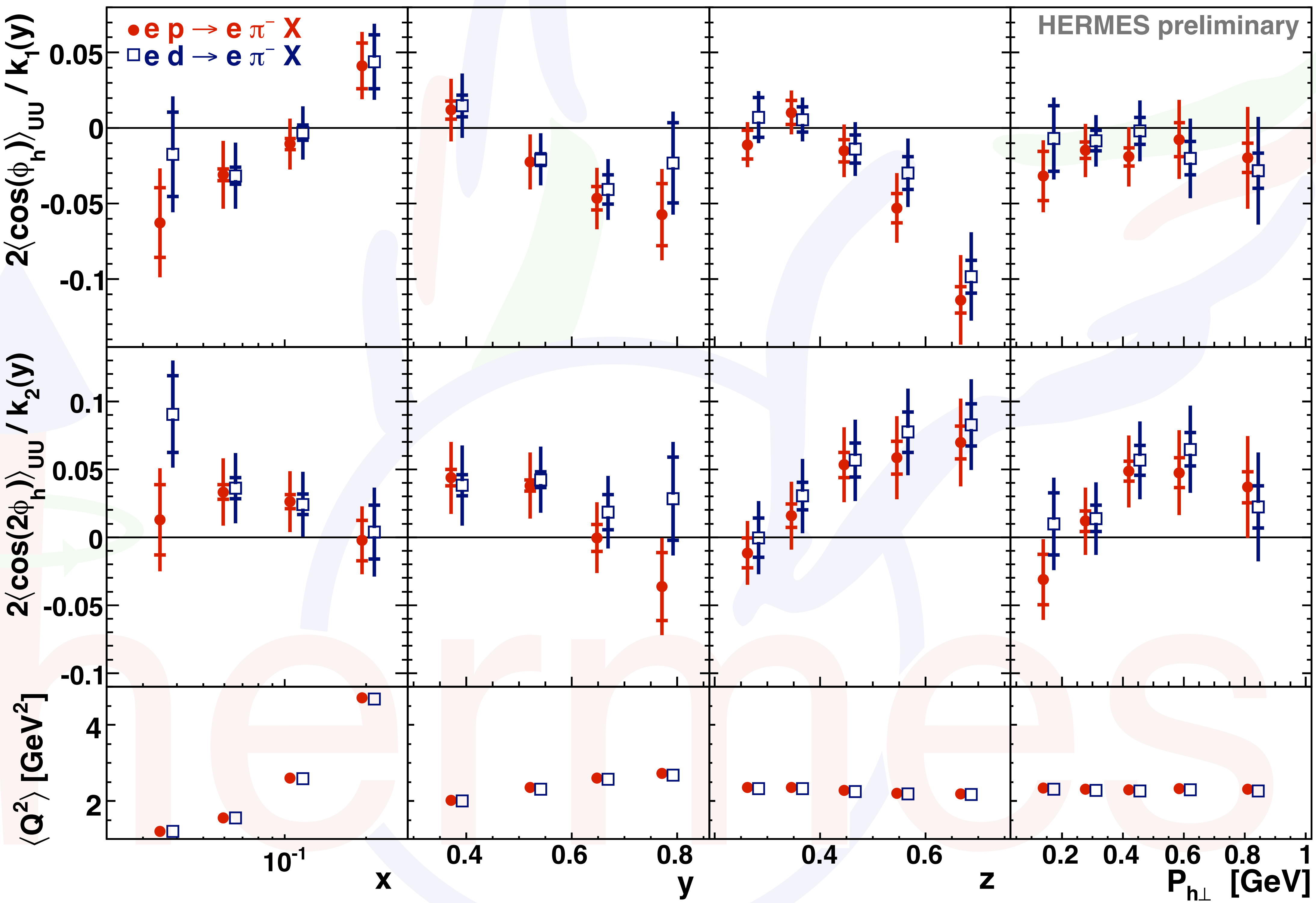

| | U | L | T |
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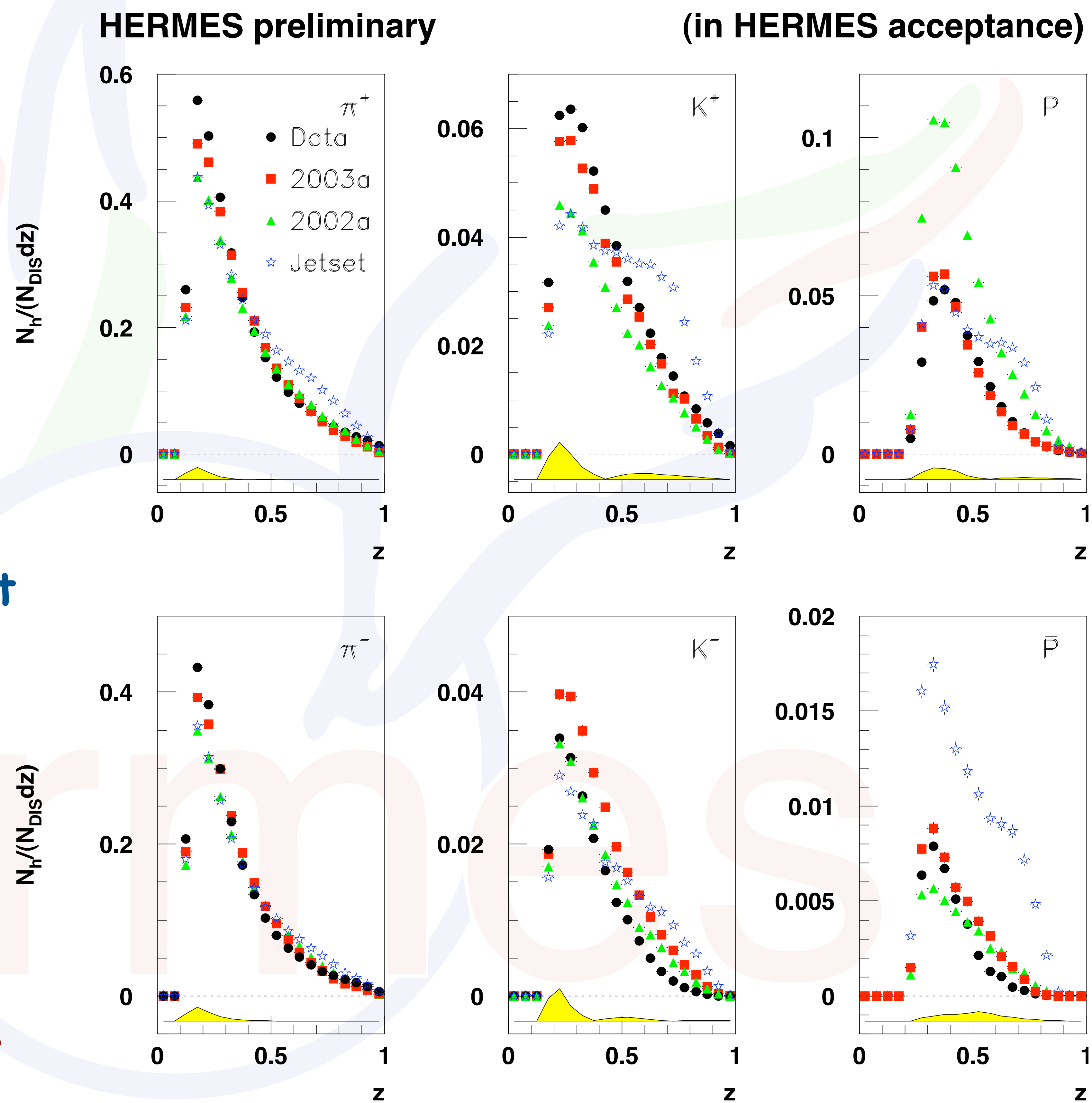
# Momentum density & FFs

- plenty of data on proton and deuteron targets available
- standard Jetset does not describe HERMES data
- even after tuning difficult to describe $K^+$ and $K^-$ simultaneously
- need multiplicities and fragmentation functions not only binned in z but also in $P_{h\perp}$ ➠ coming soon



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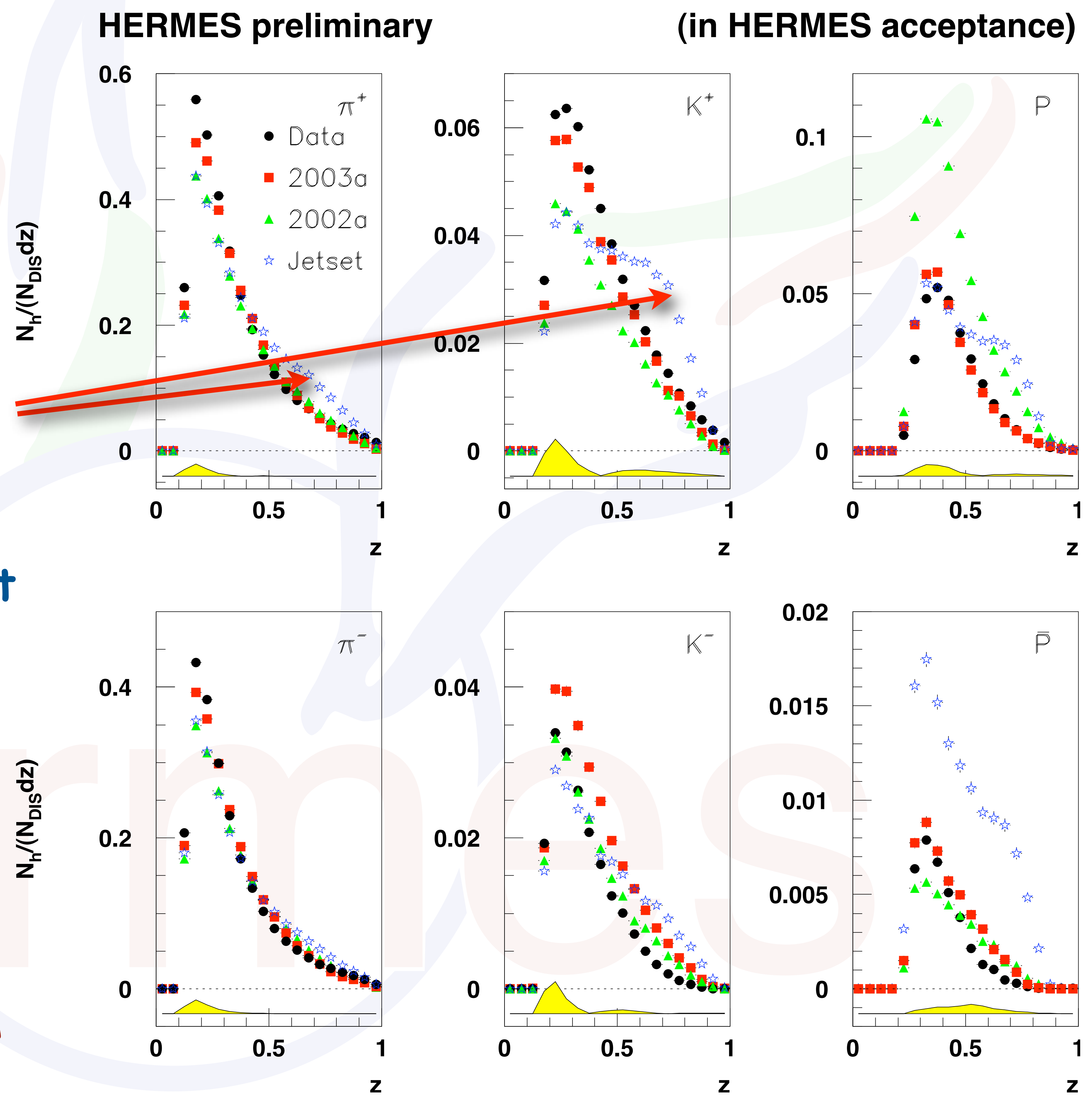

|   | U | L | T |
|---|---|---|---|
| U | $f_1$ |   | $h_1^\perp$ |
| L |   | $g_{1L}$ | $h_{1L}^\perp$ |
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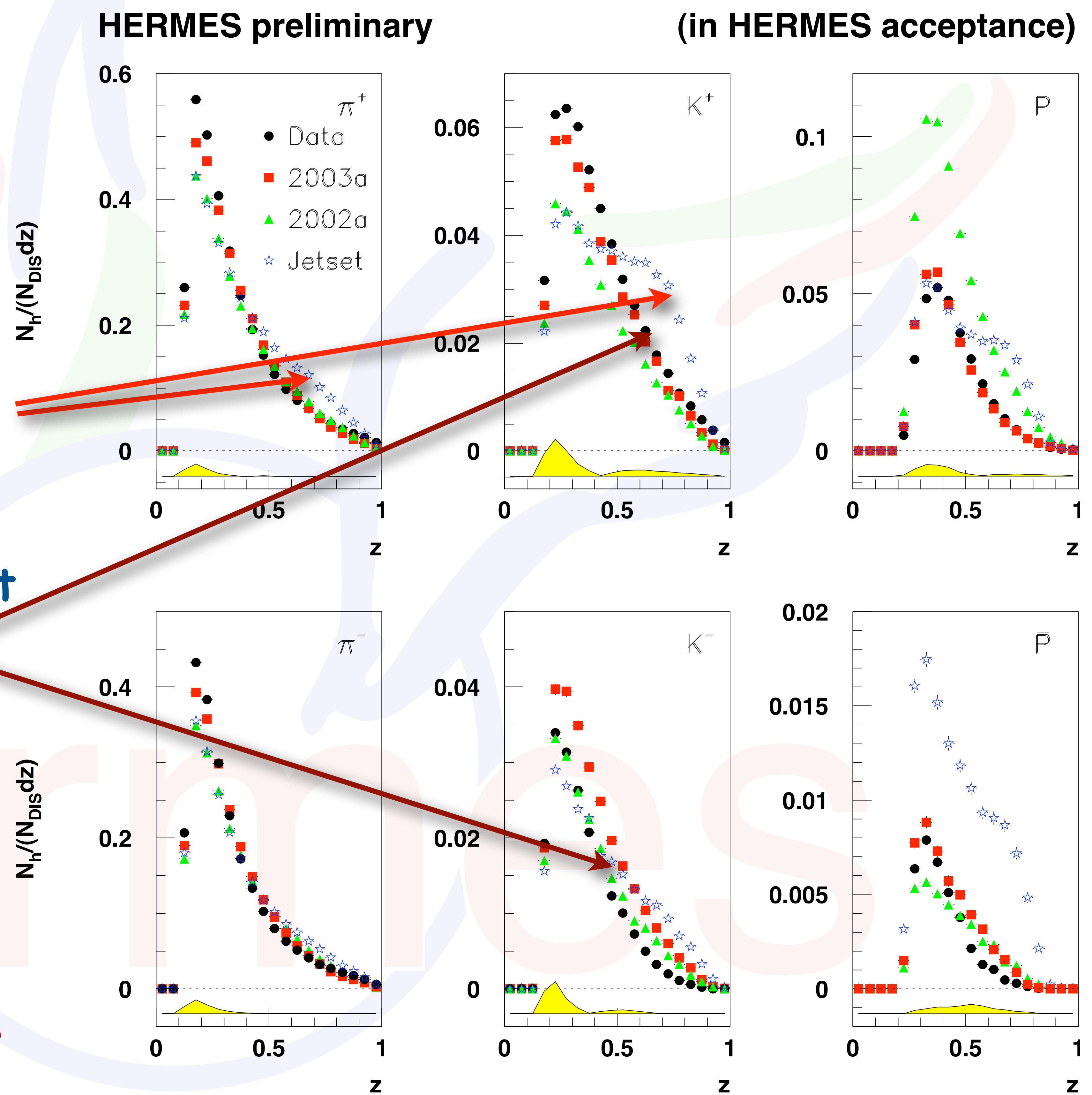

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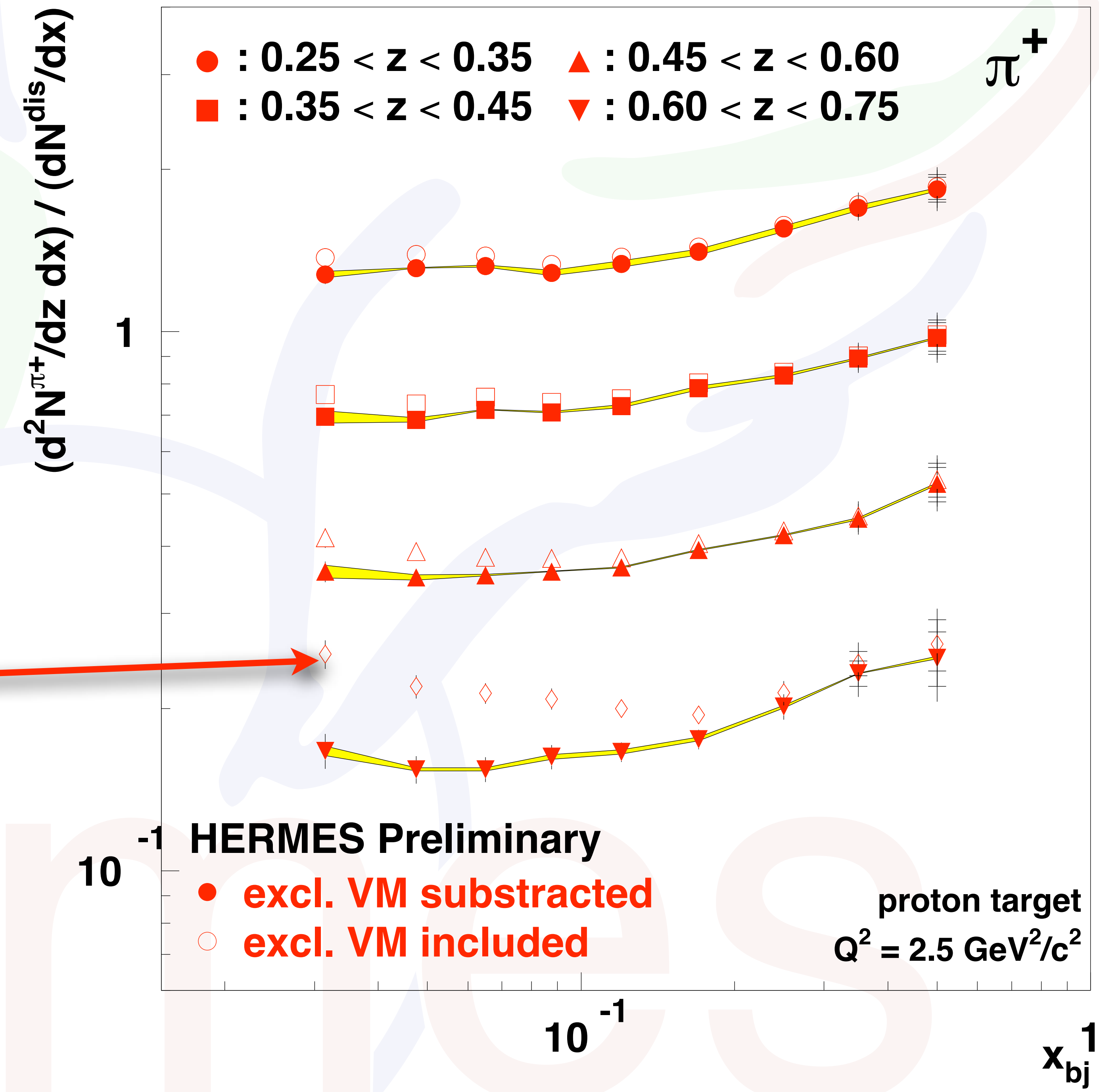
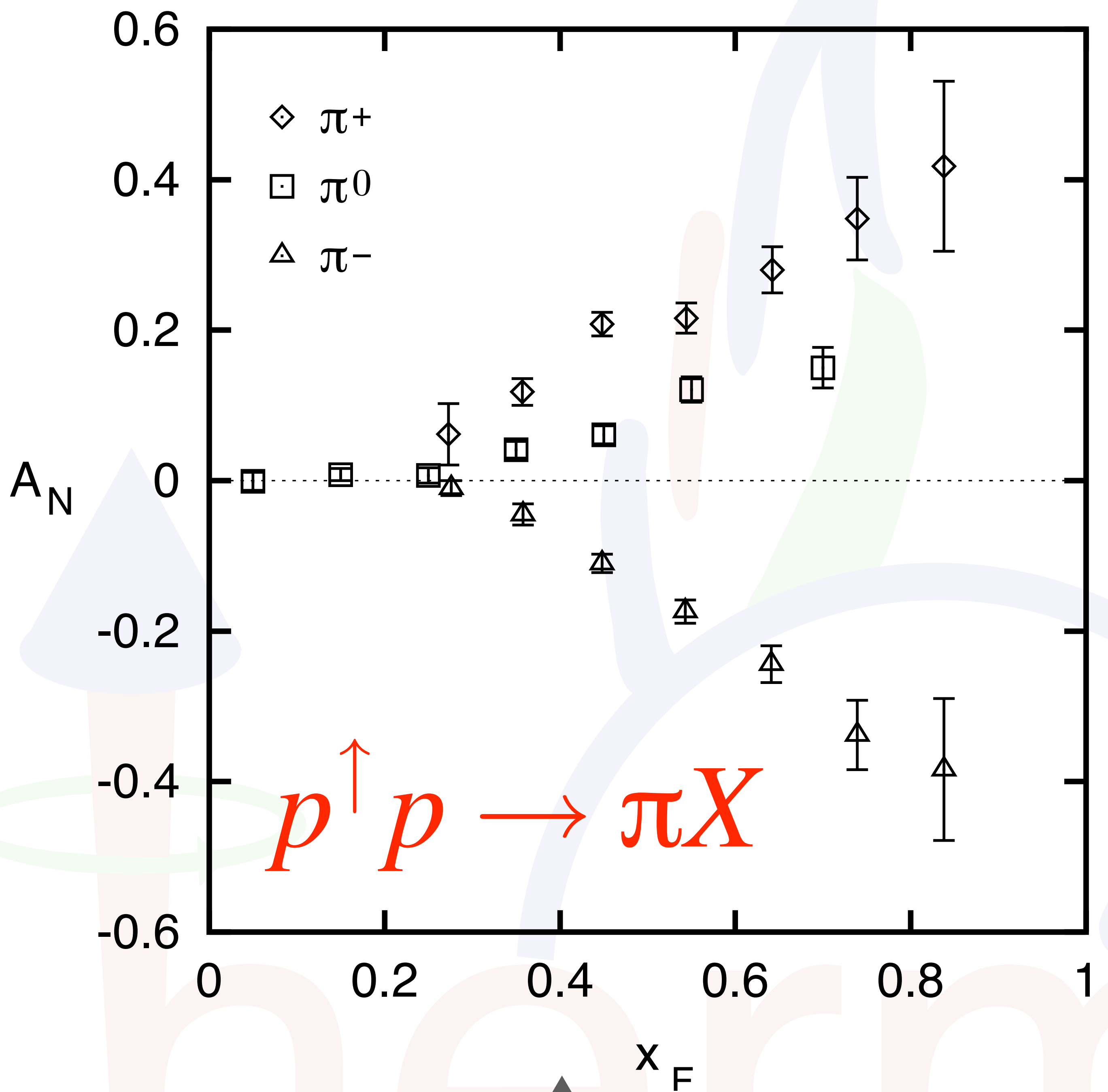
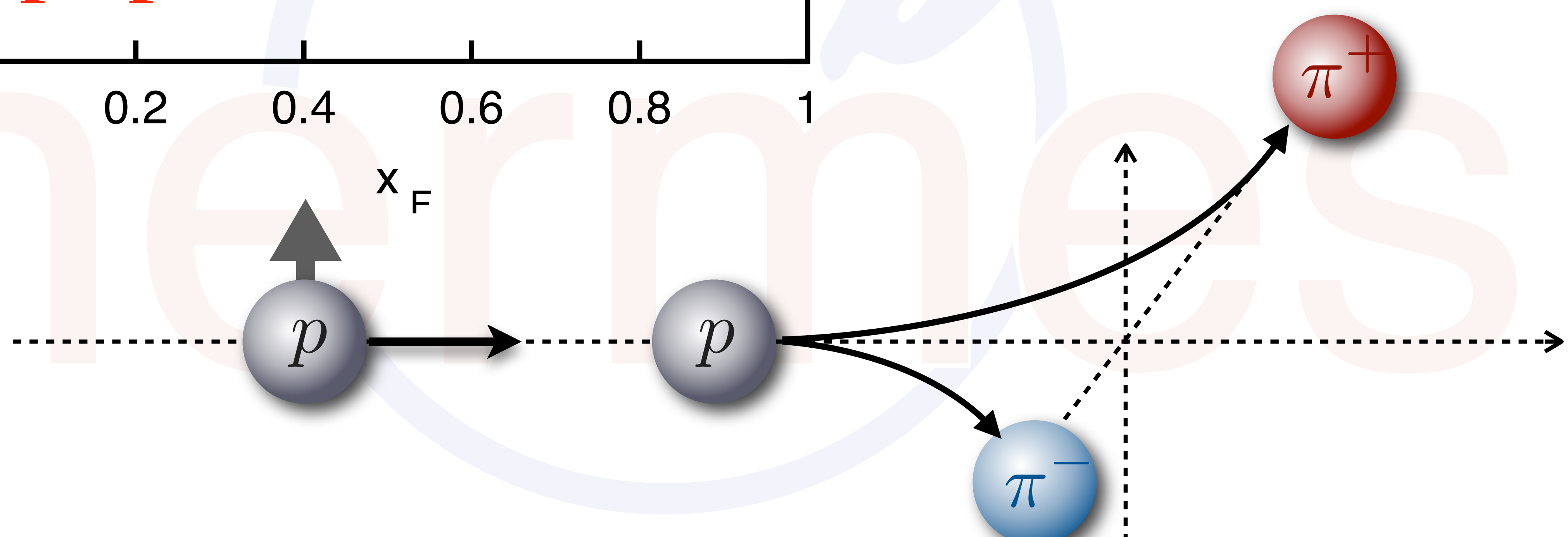
# Momentum density & FFs

- (for the afternoon discussion:) effect of exclusive VM production on multiplicities



# Back to the beginning of Sivers effect



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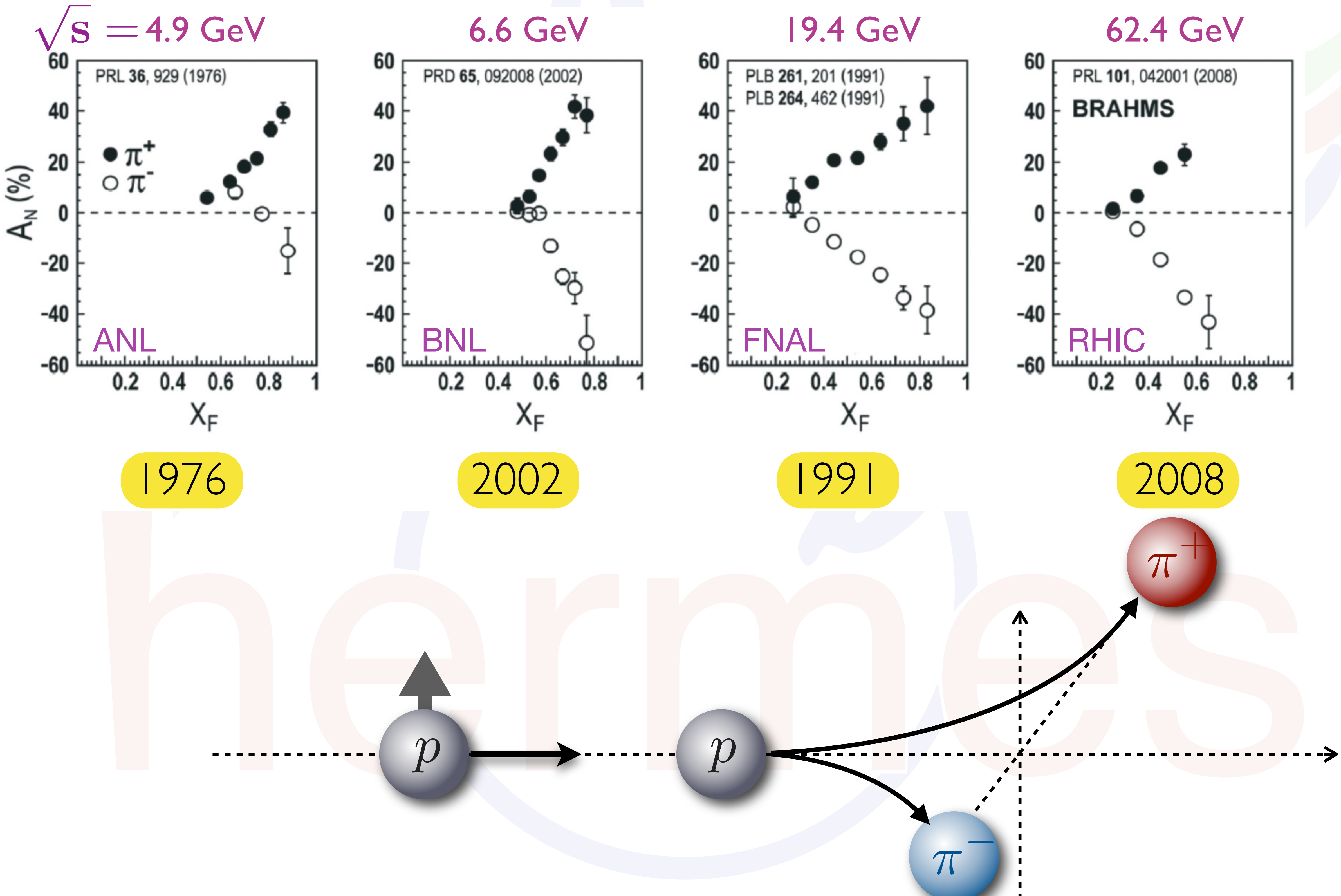
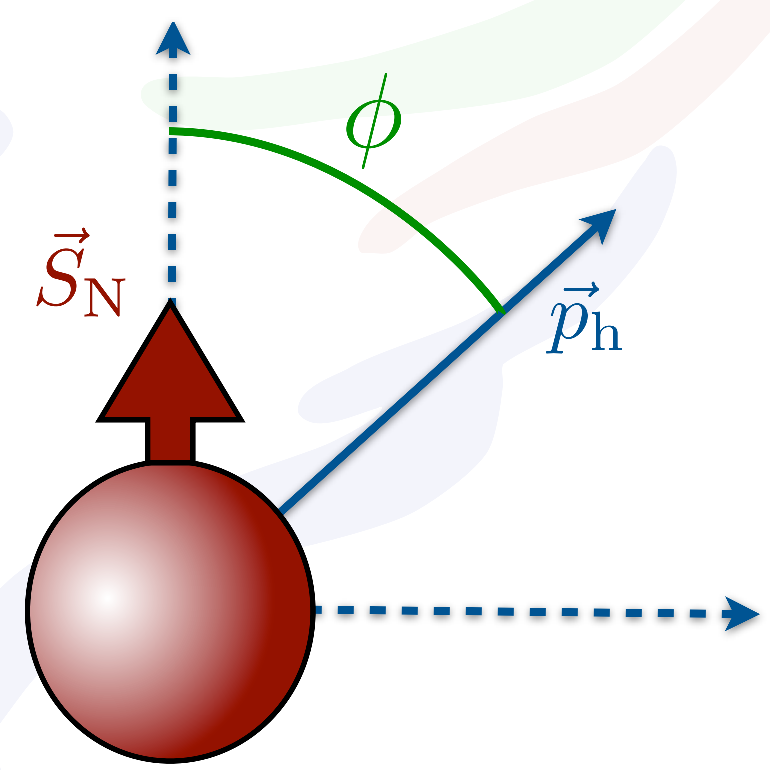


# Inclusive hadron electro-production

$$ep^{\uparrow} \rightarrow hX$$

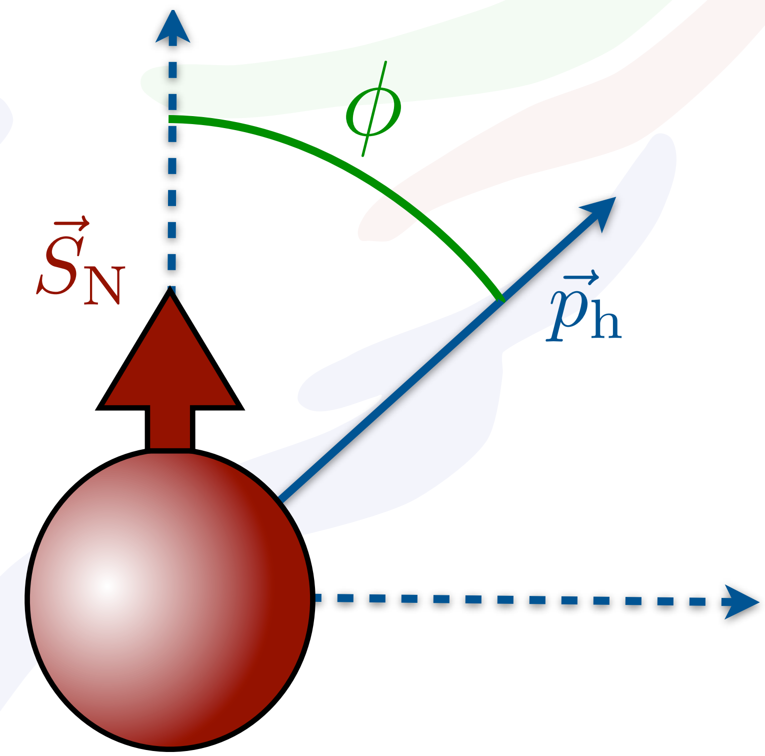



lepton beam going into the page

# Inclusive hadron electro-production

- scattered lepton undetected
  ➥ lepton kinematics unknown

$$ep^\uparrow \rightarrow hX$$




lepton beam going into the page

# Inclusive hadron electro-production

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- dominated by quasi-real photo-production (low $Q^2$)
  ➥ hadronic component of photon relevant?

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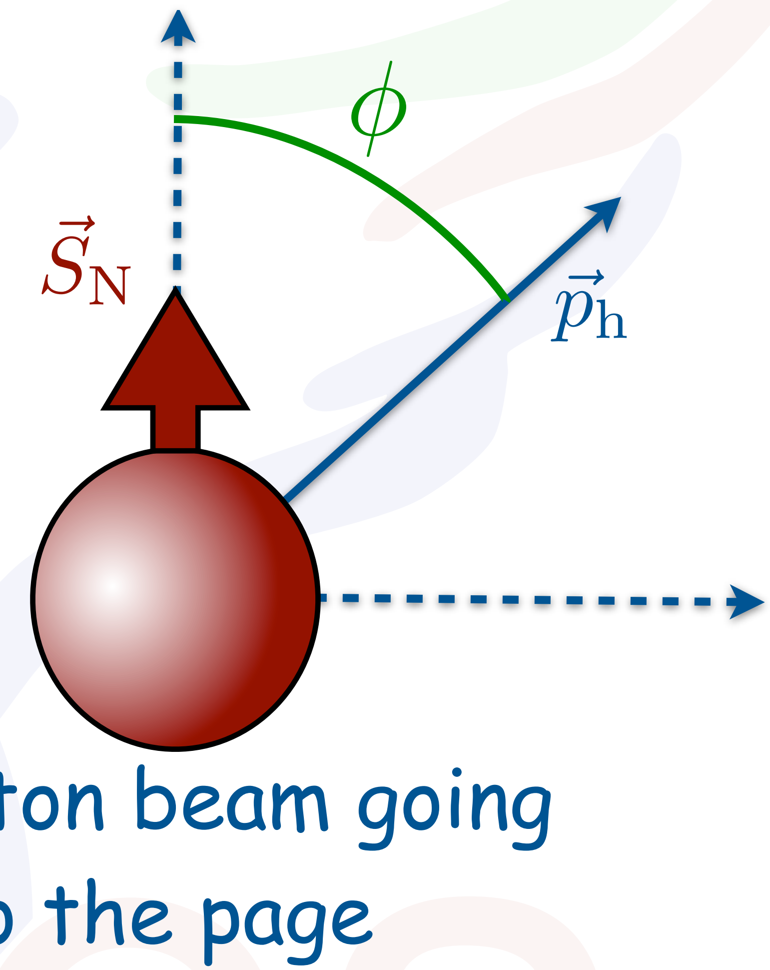

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- cross section proportional to $S_N$ ($k \times p_h$) ~ $\sin\phi$

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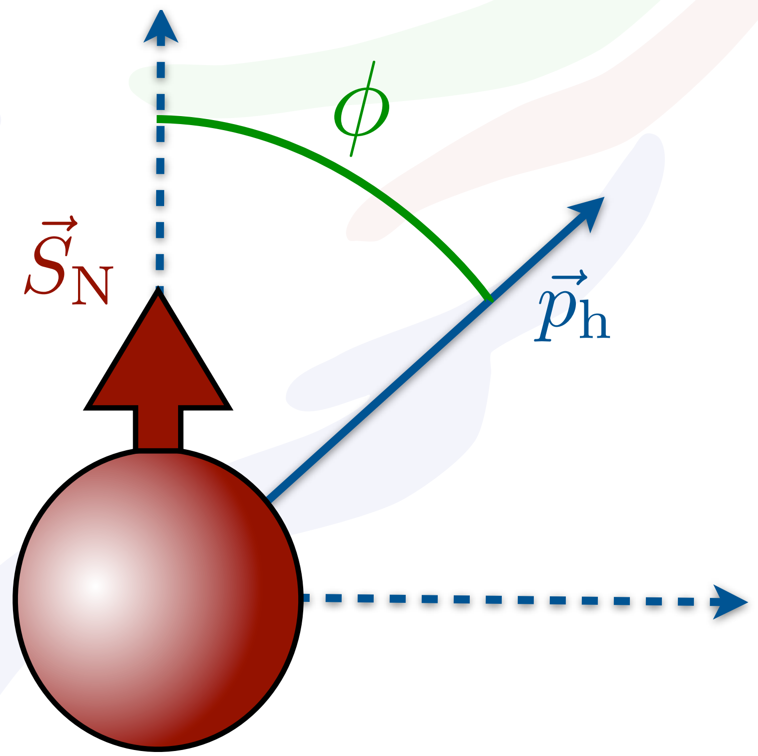


lepton beam going into the page

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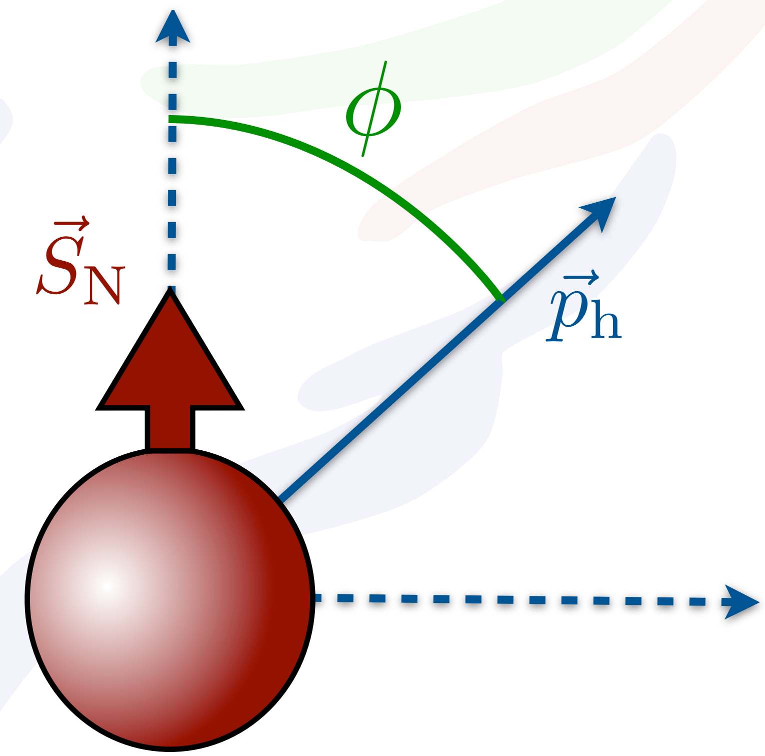
- cross section proportional to $S_N$ ($k \times p_h$) ~ sin $\phi$

$$A_{UT}(p_T, x_F, \phi) =$$

$$A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$

this is what we measure!

$$ep^{\uparrow} \rightarrow hX$$




lepton beam going into the page

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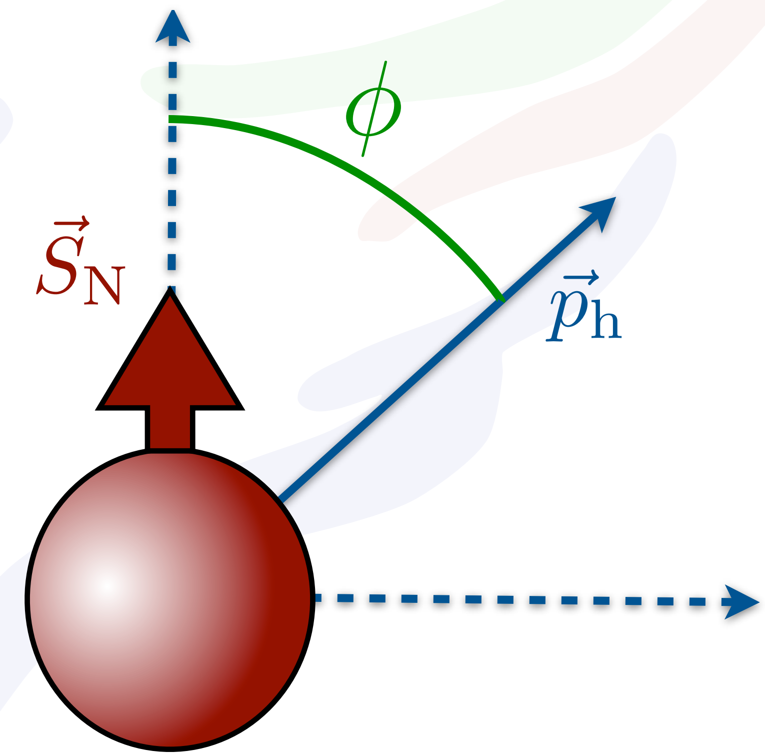
  ➥ hadronic component of photon relevant?
- cross section proportional to $S_N$ (k x $p_h$) ~ $\sin\phi$

$$ep^{\uparrow} \rightarrow hX$$



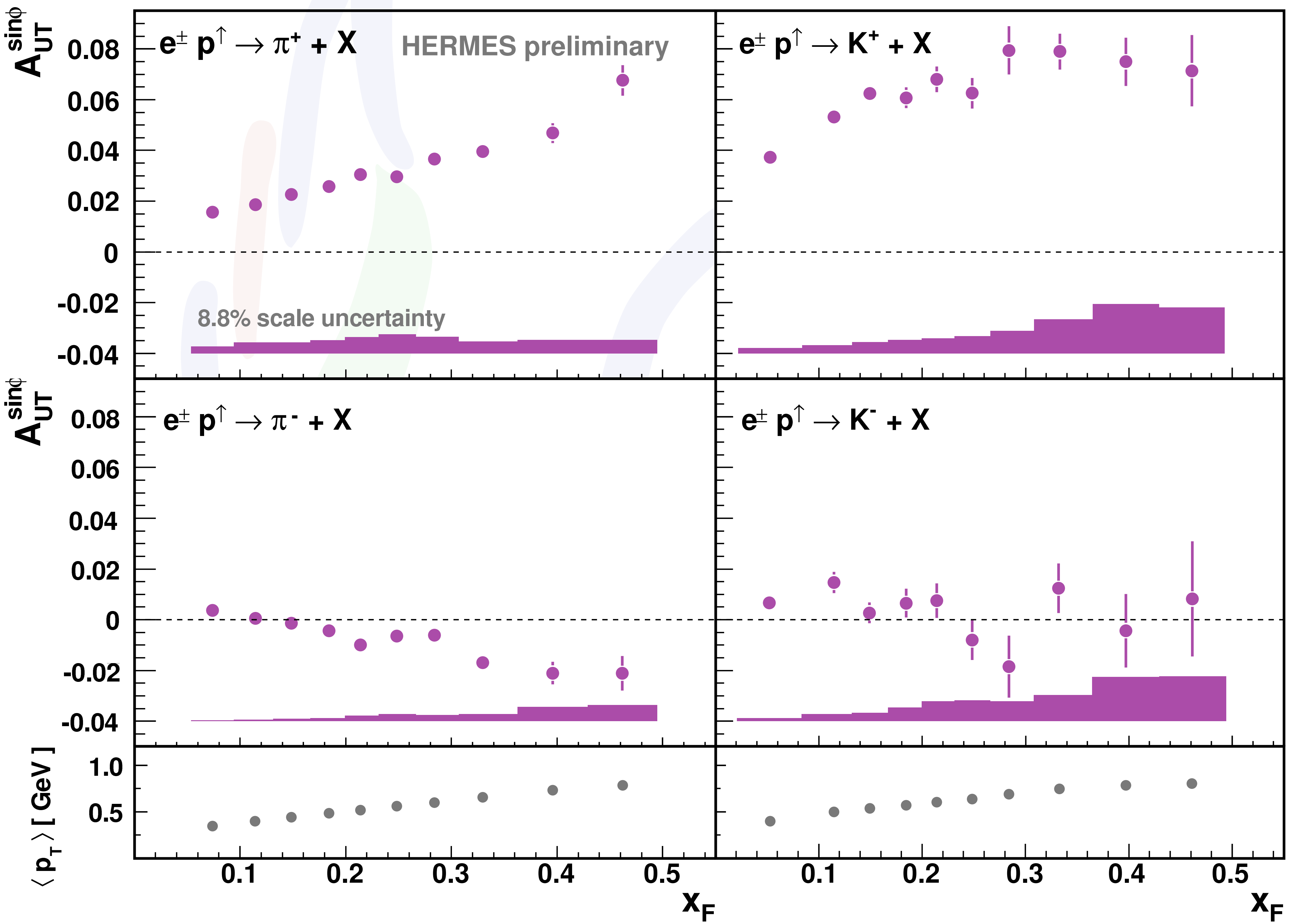

lepton beam going into the page

$$A_{UT}(p_T, x_F, \phi) = A_{UT}^{\sin\phi}(p_T, x_F) \sin\phi$$

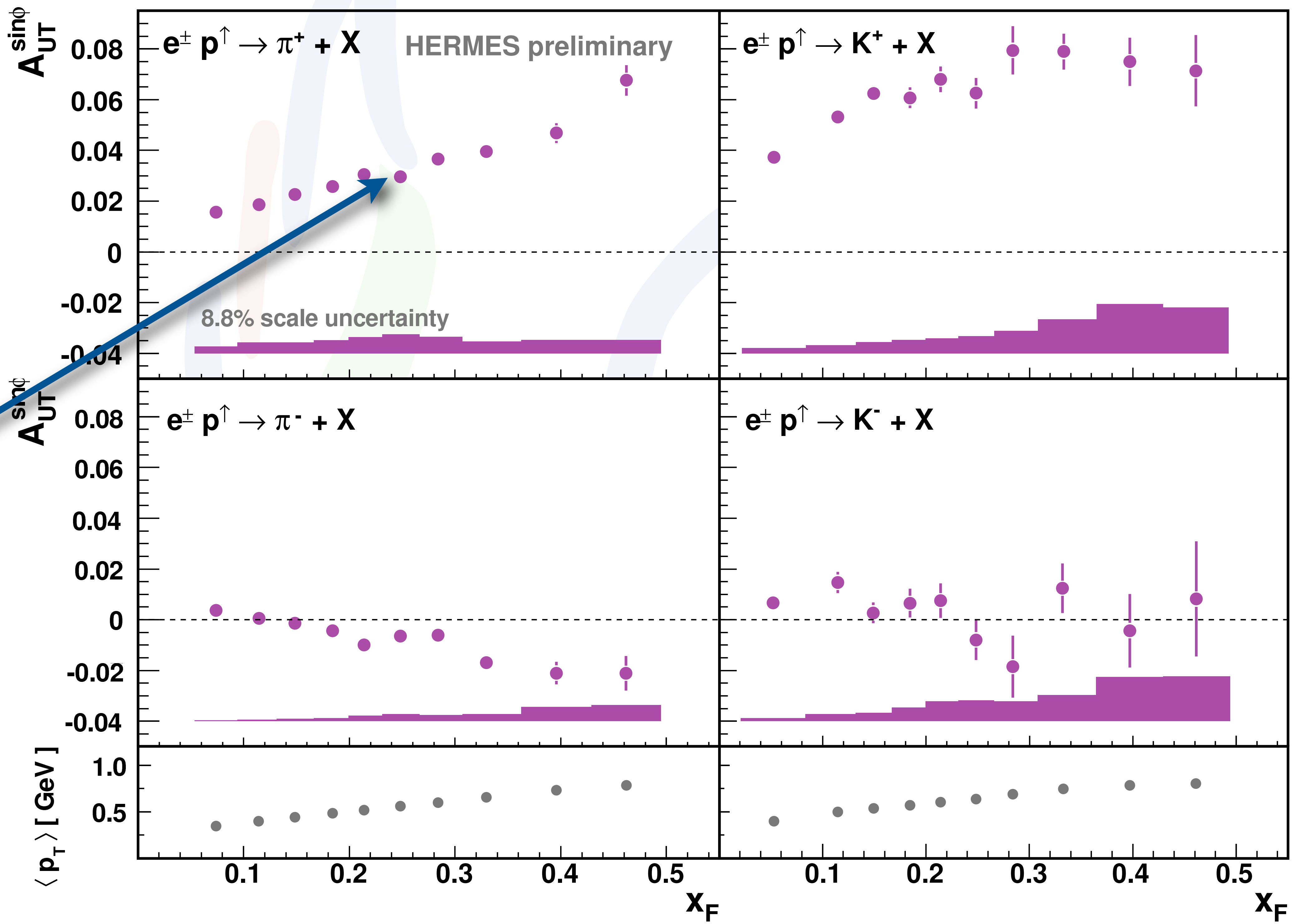
this is what we measure!

$$A_{\mathrm{N}} \equiv \frac{\int_{\pi}^{2\pi} \mathrm{d}\phi\ \sigma_{\mathrm{UT}} \sin\phi - \int_{0}^{\pi} \mathrm{d}\phi\ \sigma_{\mathrm{UT}} \sin\phi}{\int_{0}^{2\pi} \mathrm{d}\phi\ \sigma_{\mathrm{UU}}} = -\frac{2}{\pi} A_{\mathrm{UT}}^{\sin\phi}$$

# $x_F$ dependence of $A_{UT}$ $\sin\phi$ amplitude

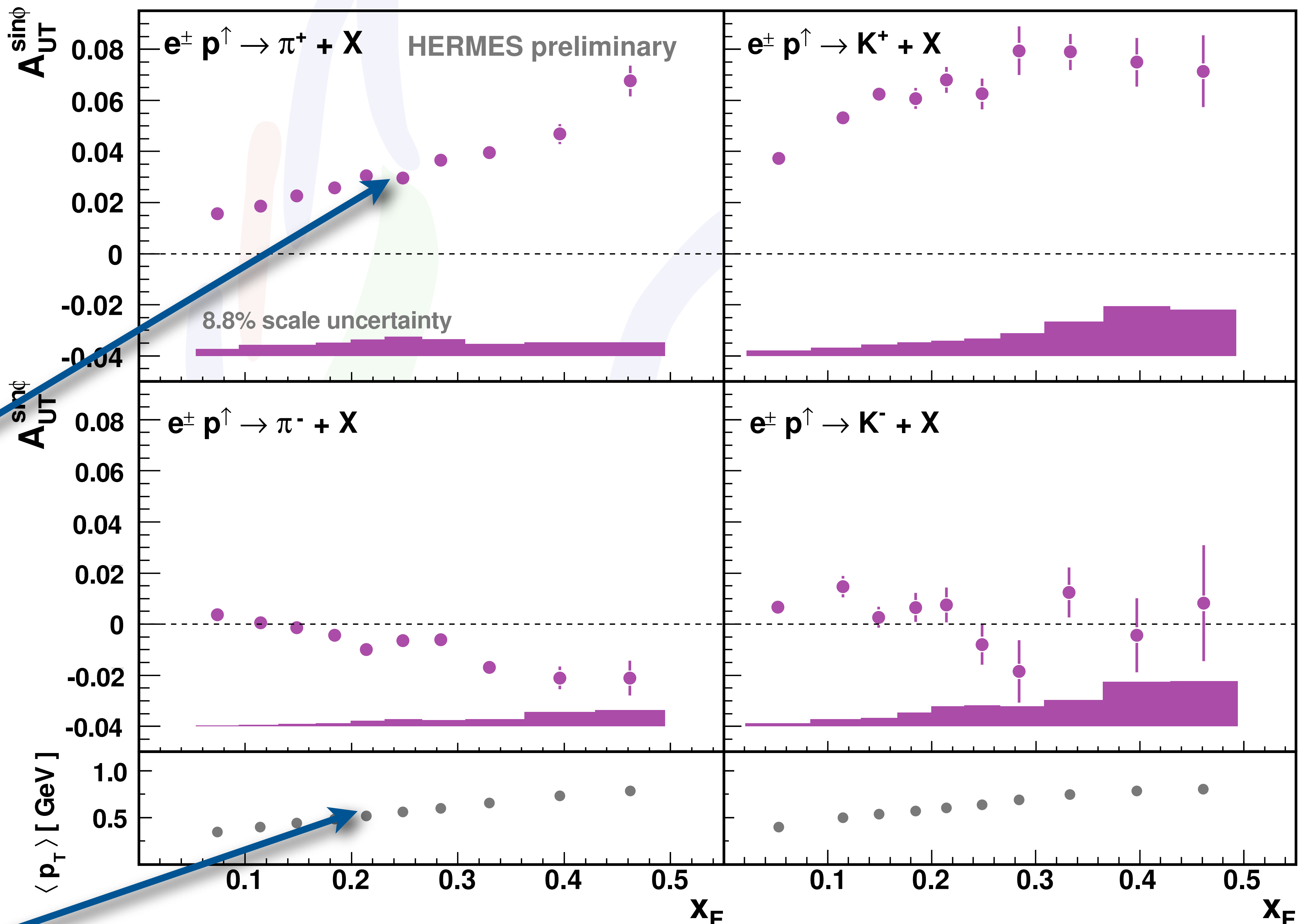


# $x_F$ dependence of $A_{UT}$ $\sin\phi$ amplitude




- opposite in sign to pp
- increasing amplitudes

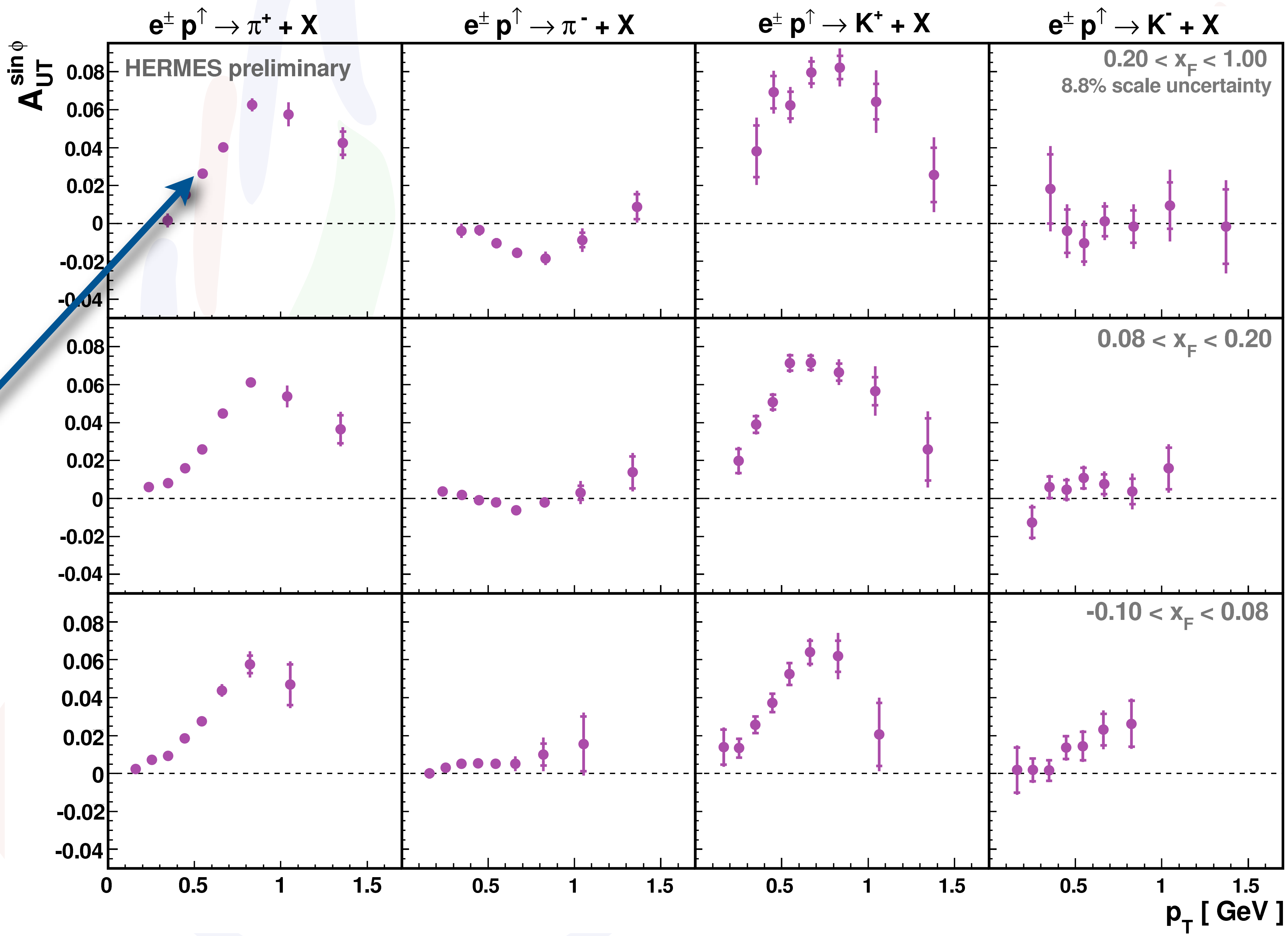
# $x_F$ dependence of $A_{UT}$ $\sin\phi$ amplitude




- opposite in sign to pp
- increasing amplitudes

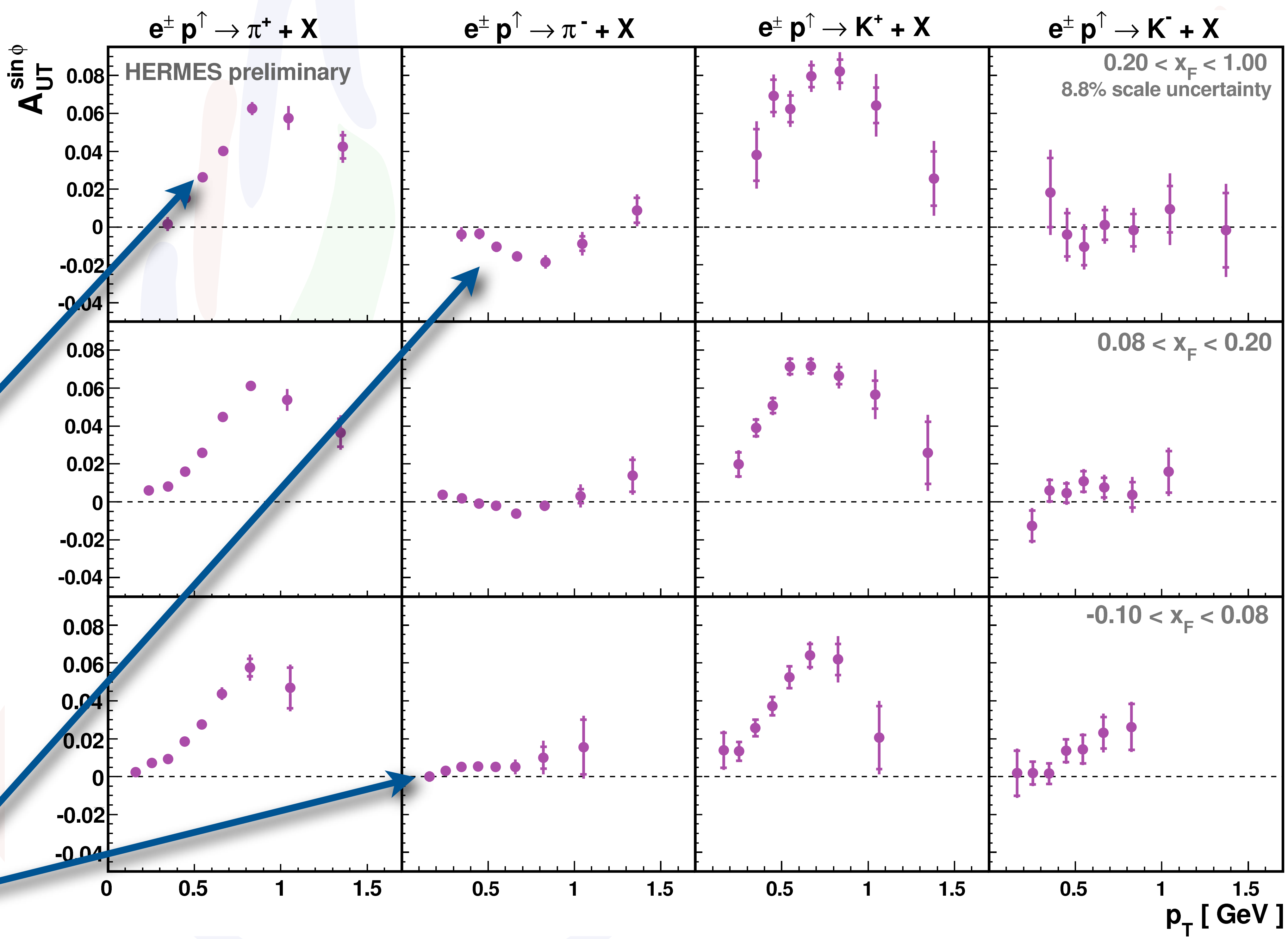
increasing $p_T$

# $p_T$ dependence of $A_{UT}$ $\sin\phi$ amplitude




increasing amplitudes with turnover

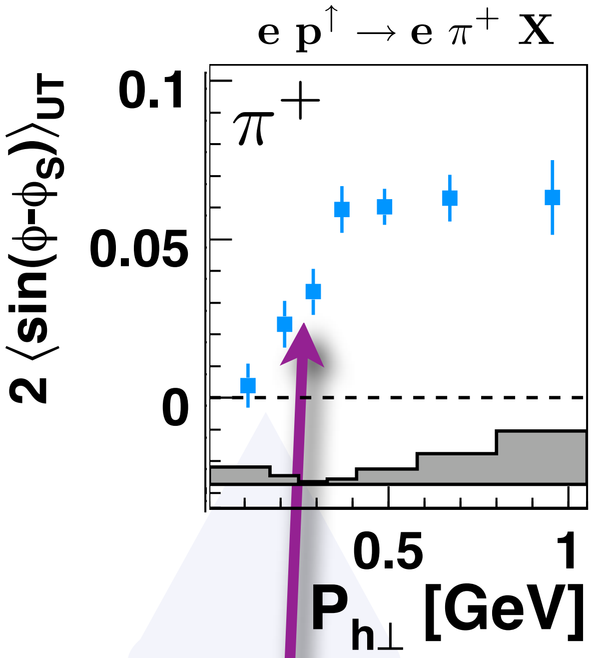
# $p_T$ dependence of $A_{UT}$ $\sin\phi$ amplitude



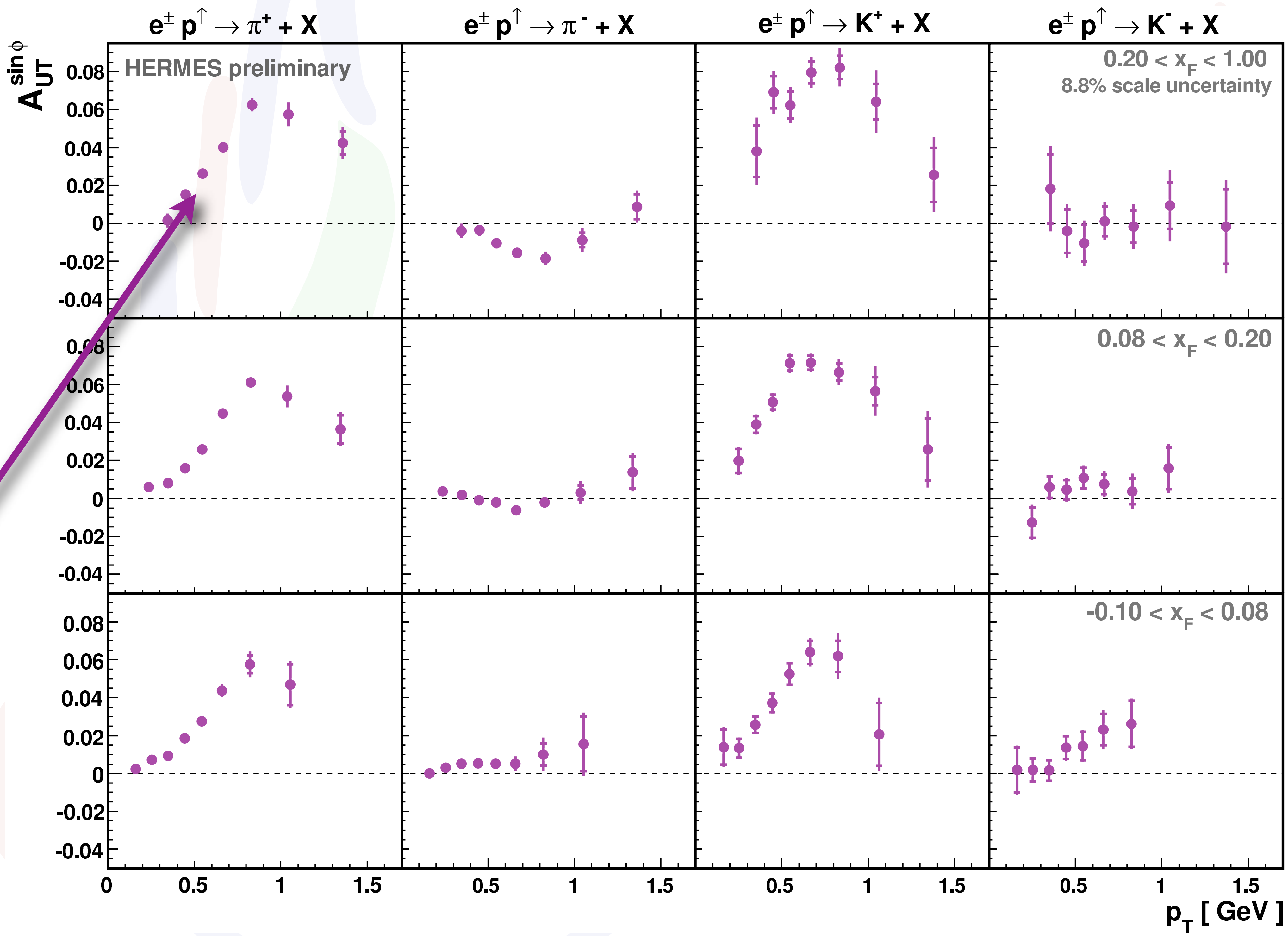

increasing amplitudes with turnover

sign change

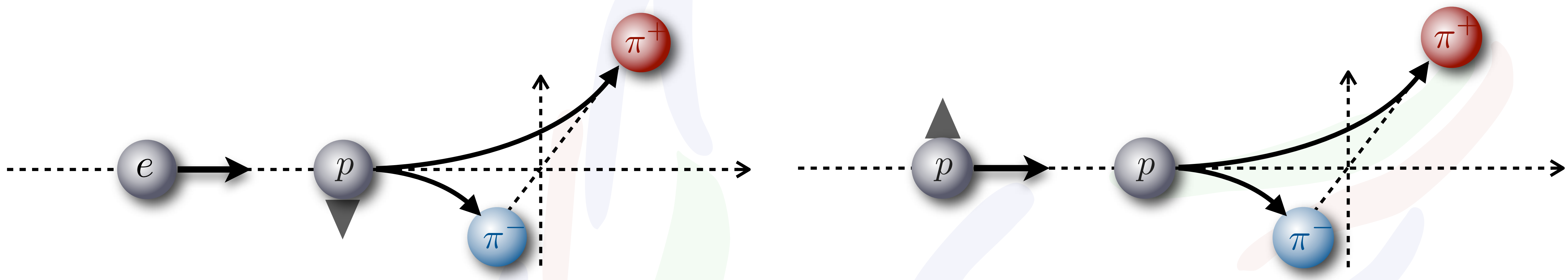
# $p_T$ dependence of $A_{UT}$ $\sin\phi$ amplitude




behavior and size similar to SIDIS Sivers



# Inclusive hadrons in pp & ep




- factorization intricate
- sign in ep opposite to pp and to prediction (see talk by Jian)
- so far results for charged pions and kaons only
  - plan to have $K_S$, $\pi^0$ and $\eta$
  - data with beam polarization allows extraction (and model prediction) of $A_{LT}$

# What else to expect on (semi-)inclusive hadron production

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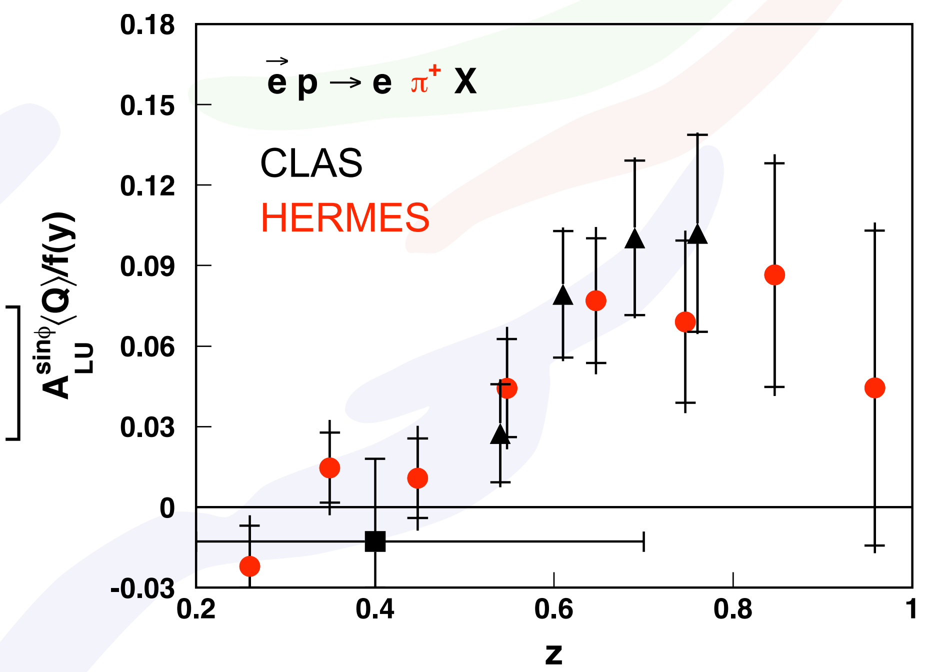
$$\frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp}+\frac{M_h}{M}\,f_1\frac{\tilde{G}^{\perp}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1+\frac{M_h}{M}\,h_1^{\perp}\frac{\tilde{E}}{z}\right)\right]$$



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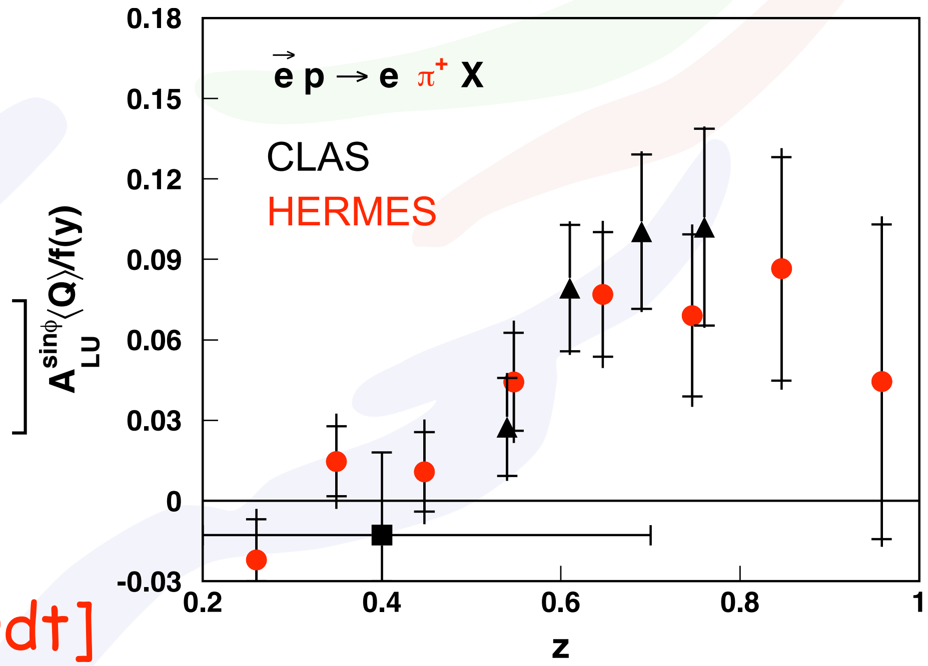
transverse force on transversely pol. quarks [M. Burkardt]



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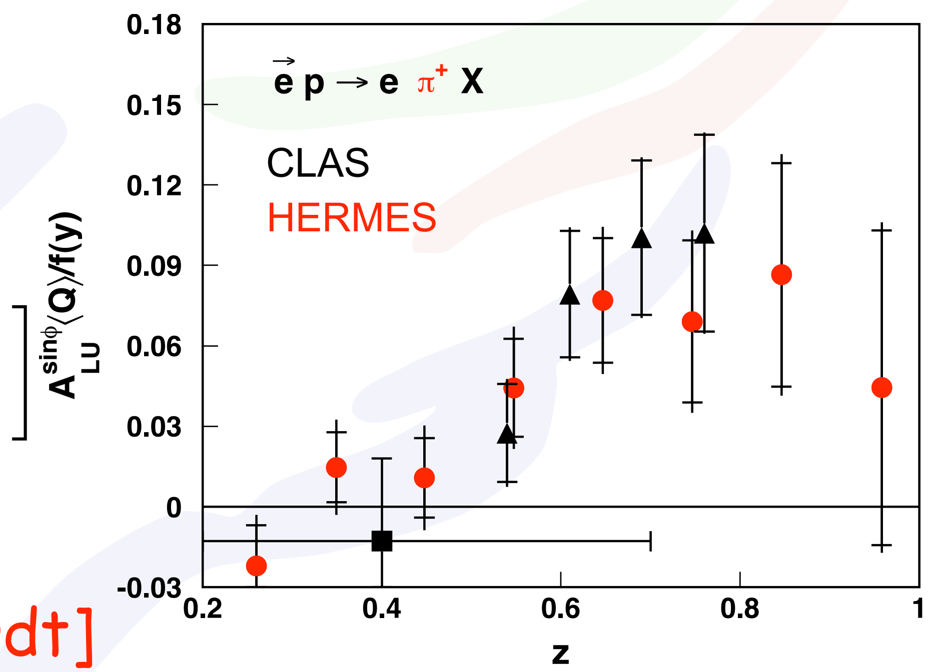


- large data set on p and d on tape

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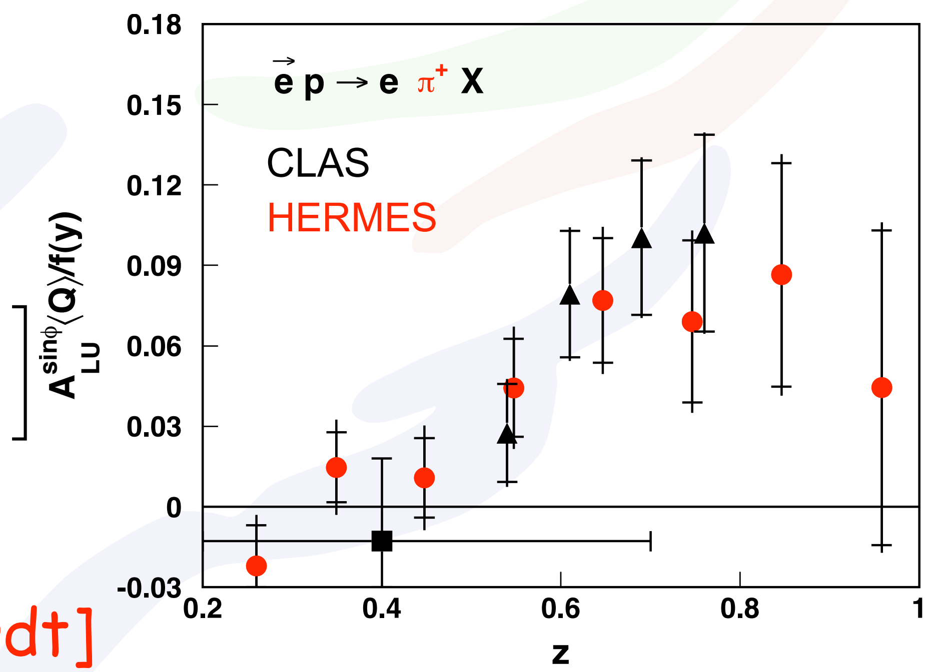


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- RICH allows extraction of amplitudes for kaons as well

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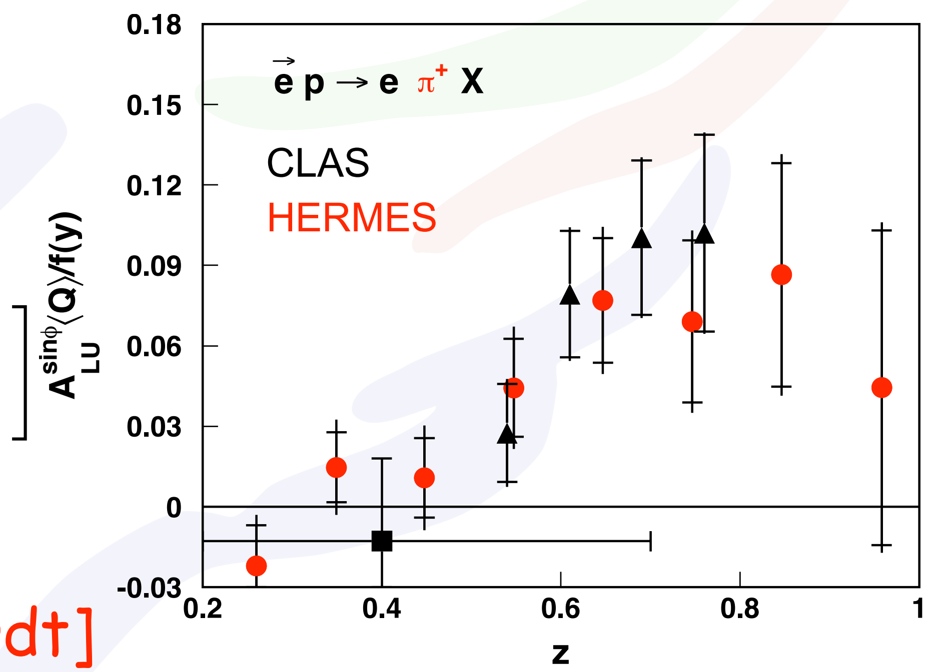
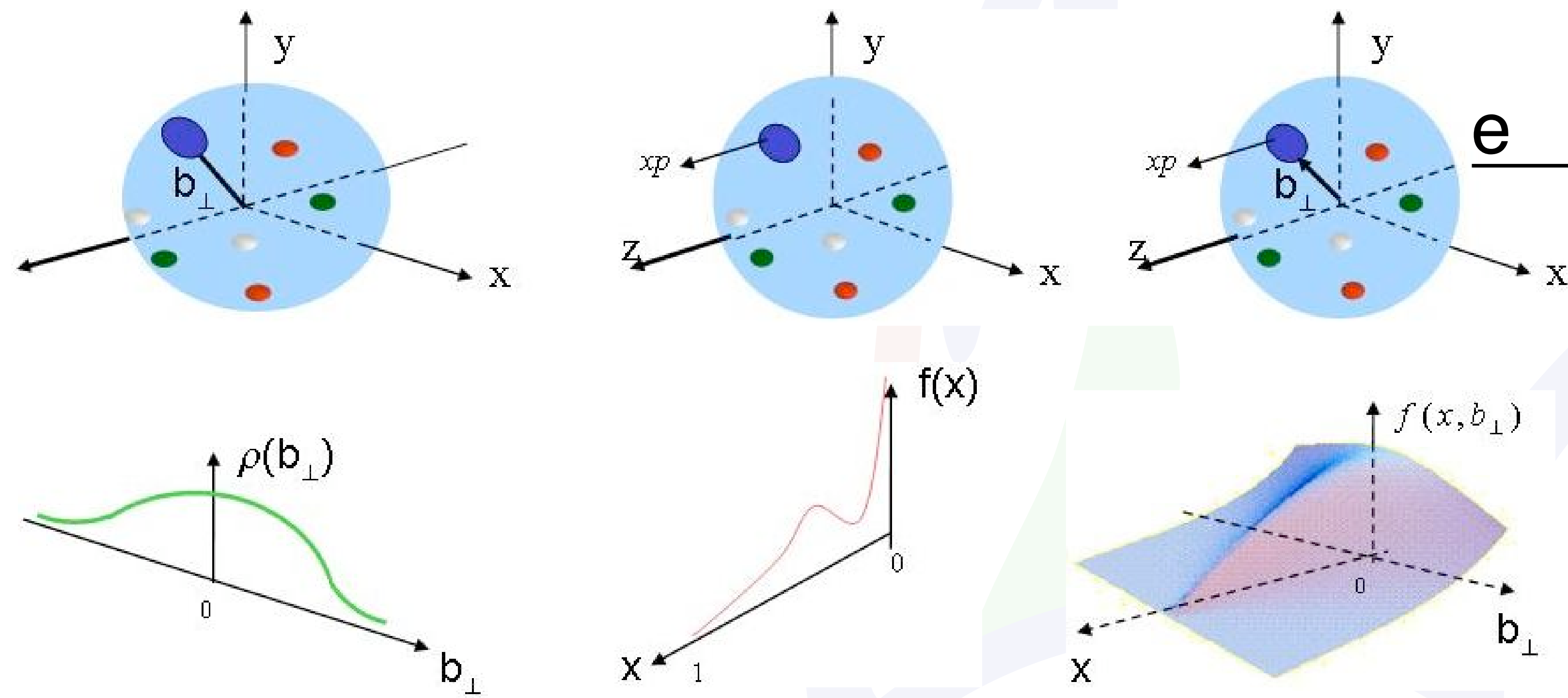


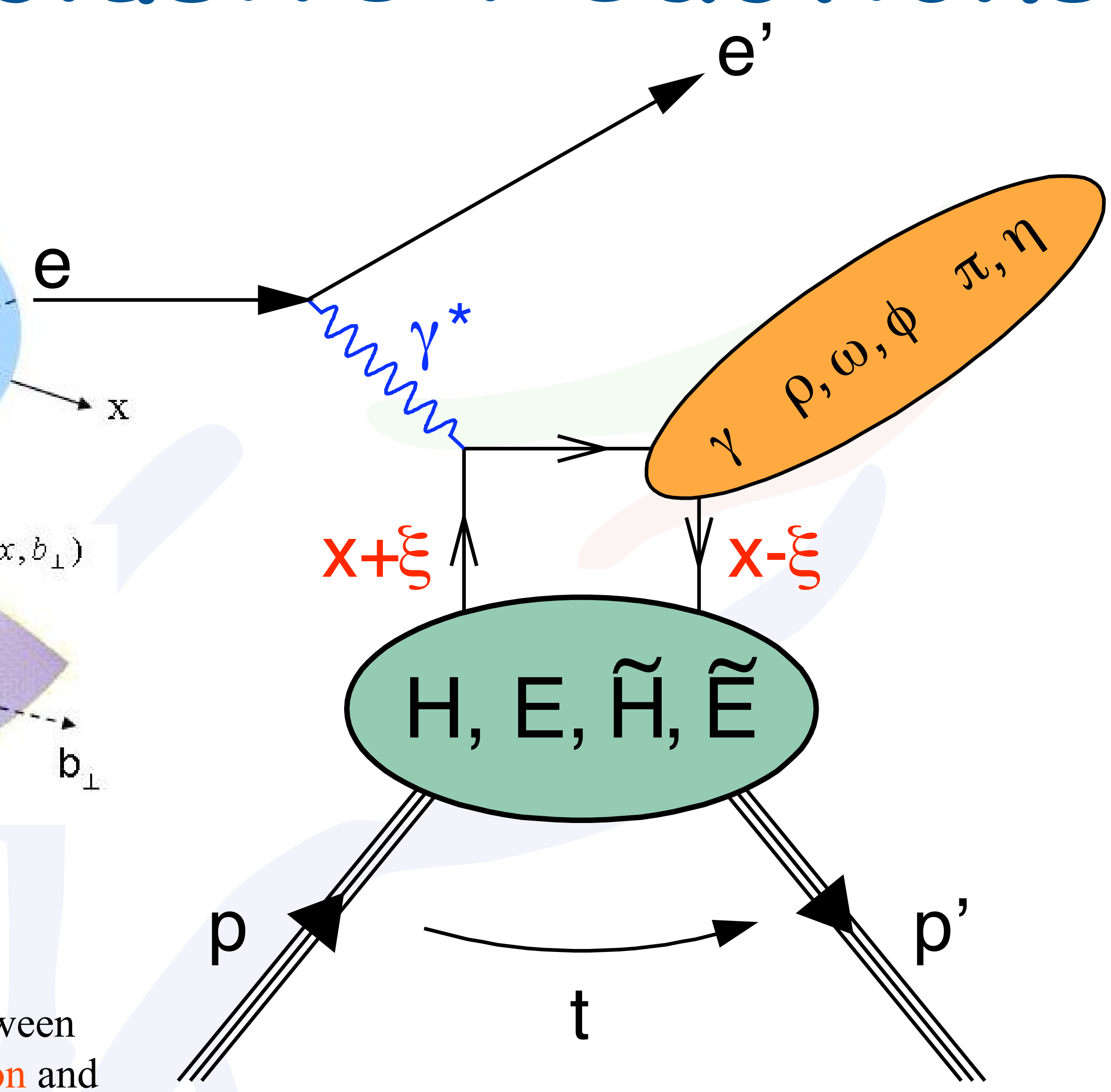

- large data set on p and d on tape
- RICH allows extraction of amplitudes for kaons as well
- work on $P_{h\perp}$-weighted (Sivers/Collins) asymmetries ongoing

# Exclusive reactions

# Probing GPDs in Exclusive Reactions




| 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 |




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

(+ 4 more chiral-odd functions)

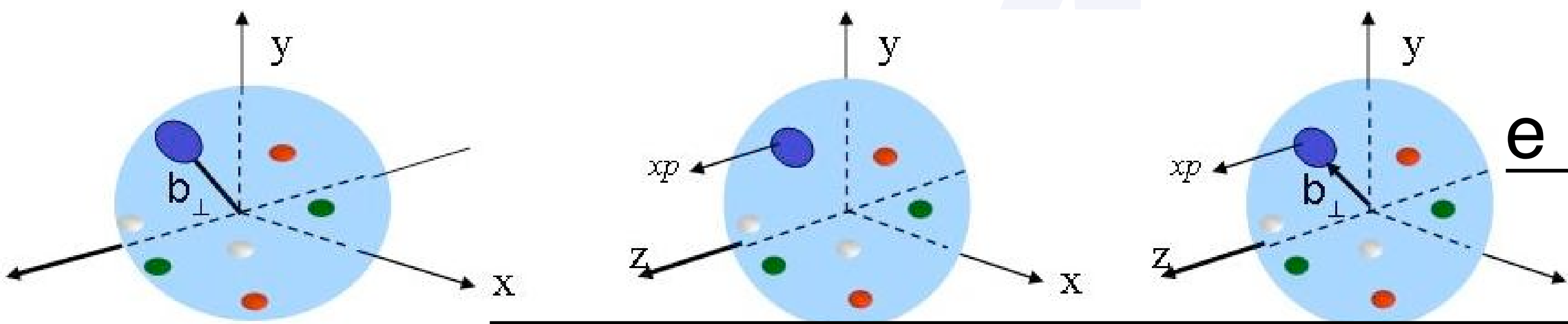
$$\int dx H^q(x,\xi,t) = F_1^q(t)$$

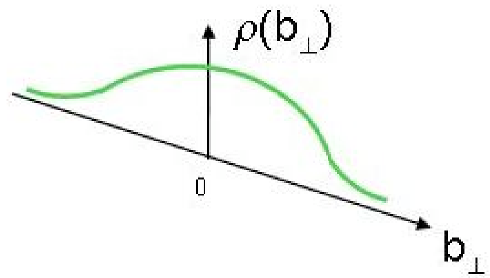
$$\int dx E^q(x,\xi,t) = F_2^q(t)$$

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

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

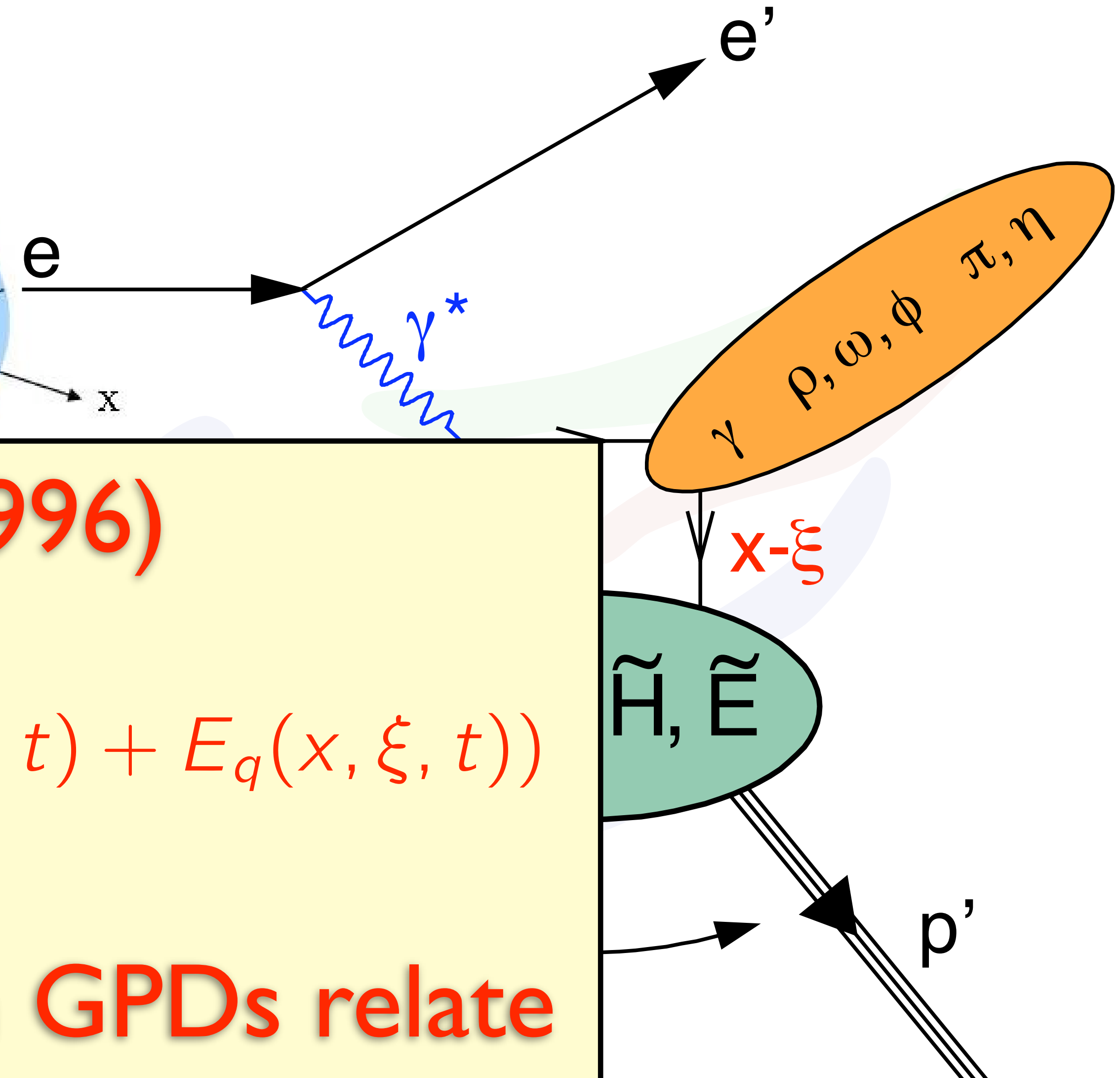
# Probing GPDs in Exclusive Reactions




Form factors

Transverse distribution of quarks in space coordinates




## Ji relation (1996)

$$J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx\, x\, \left(H_q(x, \xi, t) + E_q(x, \xi, t)\right)$$

➜Moments of certain GPDs relate directly to the total angular

| | arized | polarized |
|---|---|---|
| no nucleon hel. flip | $H$ | $\widetilde{H}$ |
| nucleon hel. flip | $E$ | $\widetilde{E}$ |

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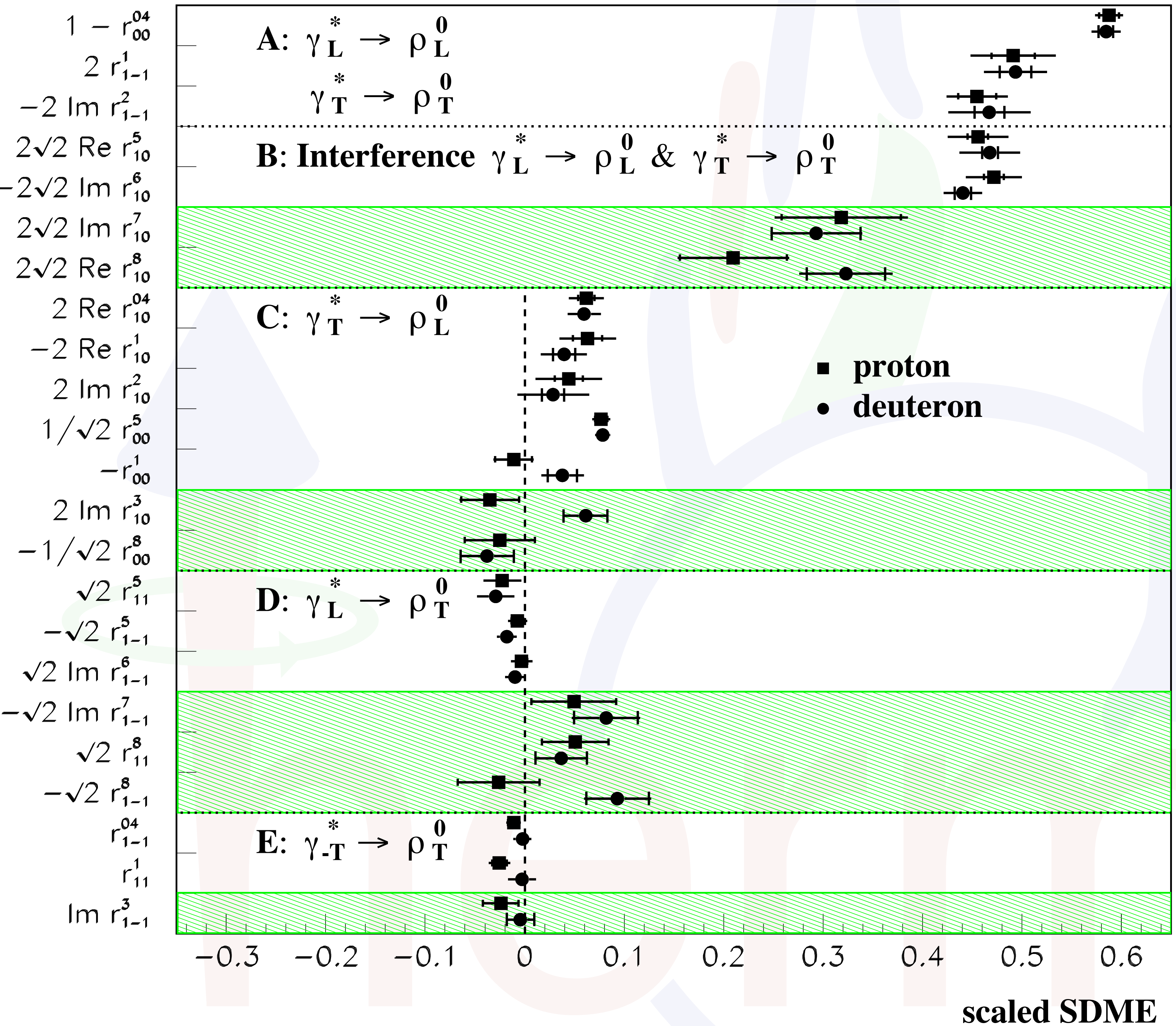
(+ 4 more chiral-odd functions)

# $\rho^0$ SDMEs from HERMES

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




**target-polarization independent SDMEs**

# $\rho^0$ SDMEs from HERMES

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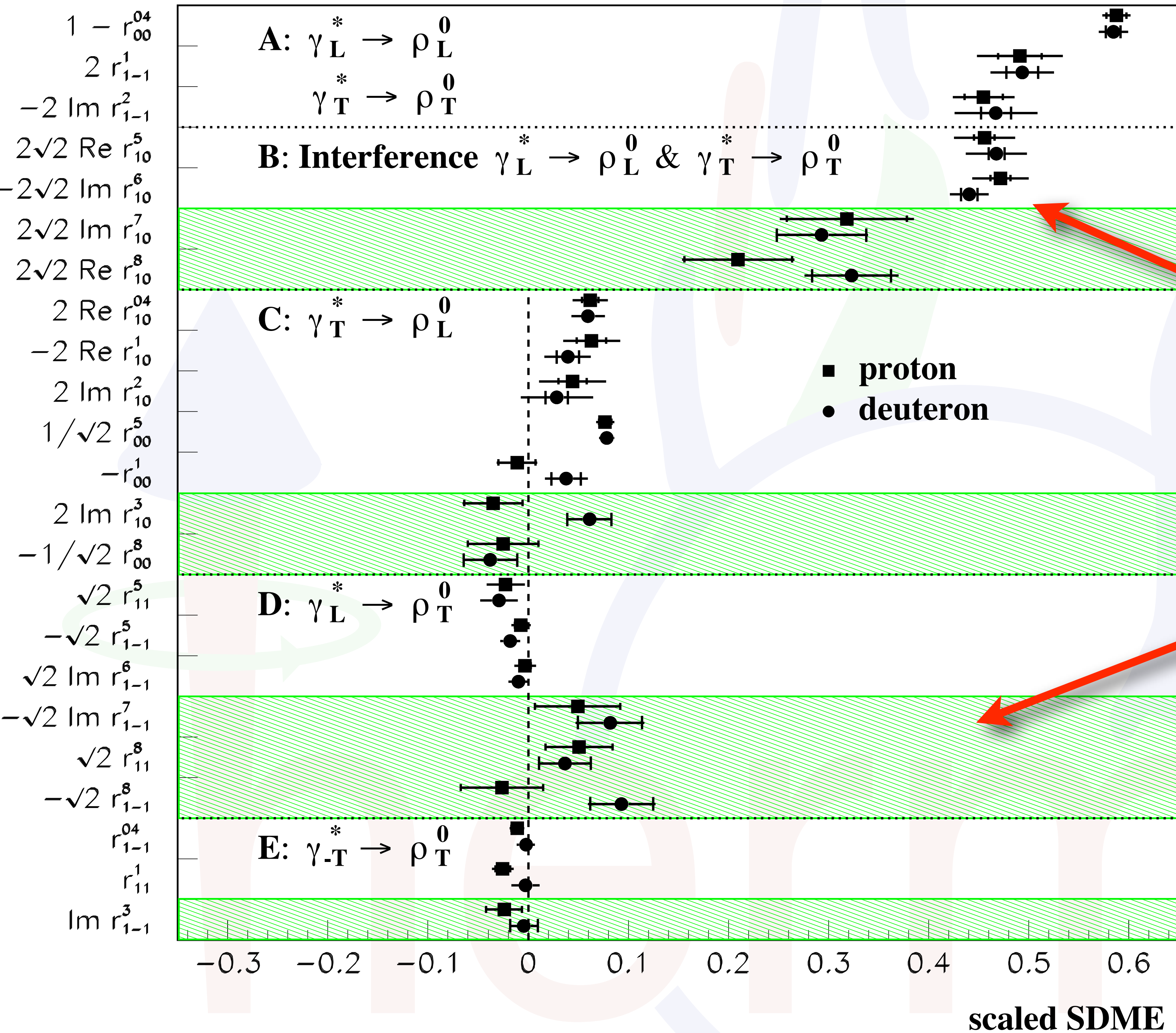


**helicity non-flip much larger than helicity-flip and double helicity-flip**

**target-polarization independent SDMEs**

# $\rho^0$ SDMEs from HERMES

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

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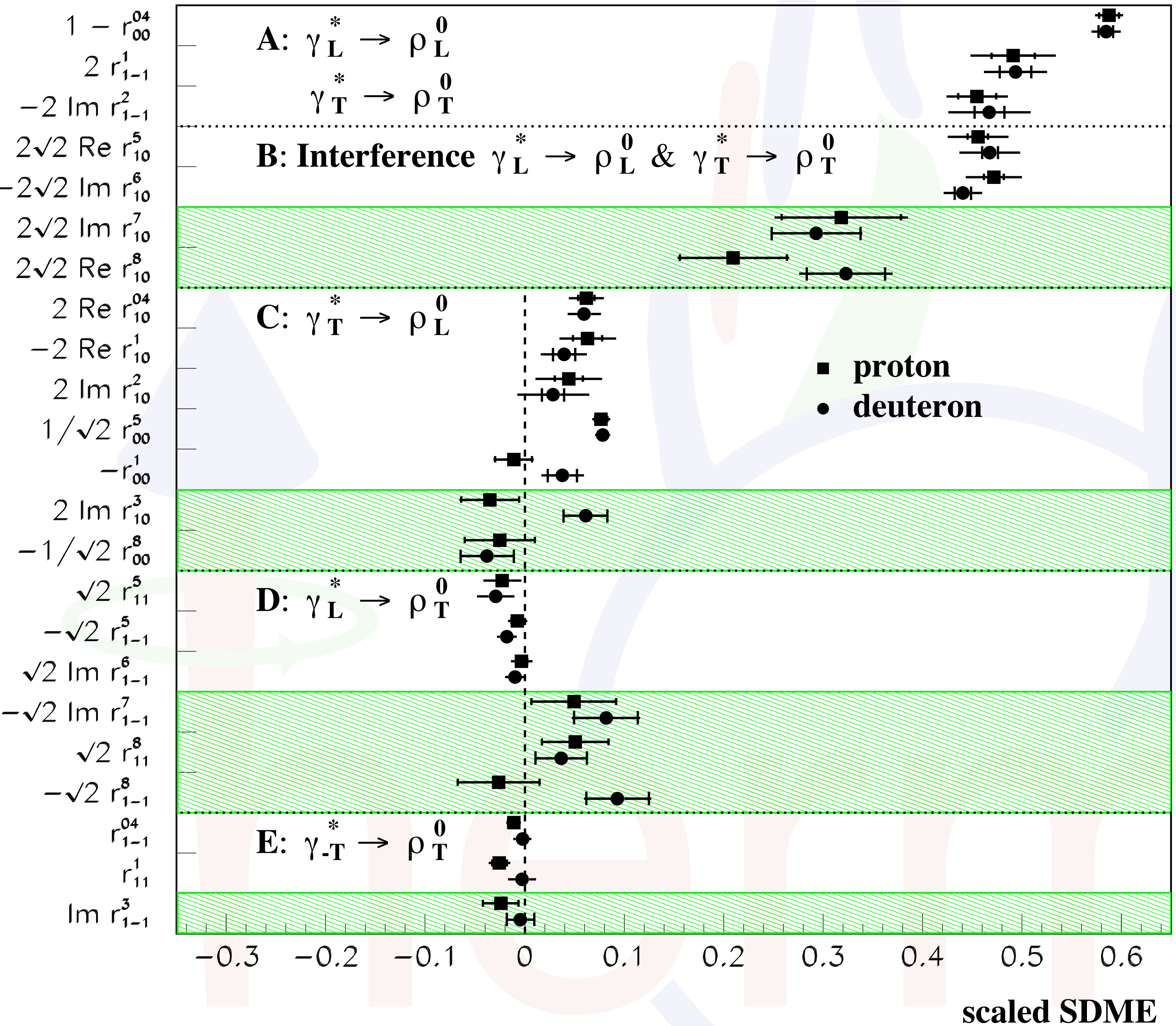


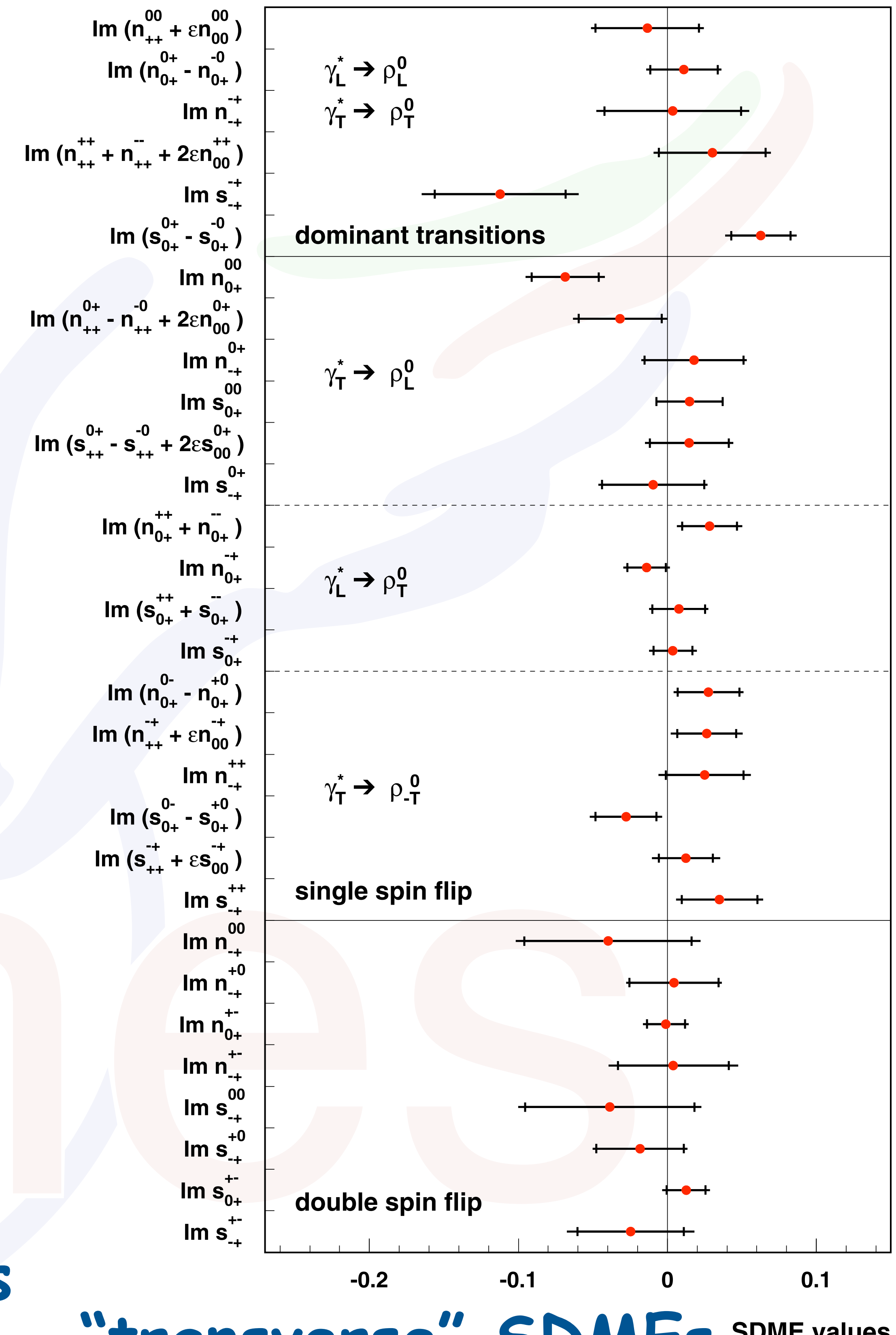


target-polarization independent SDMEs

"transverse" SDMEs

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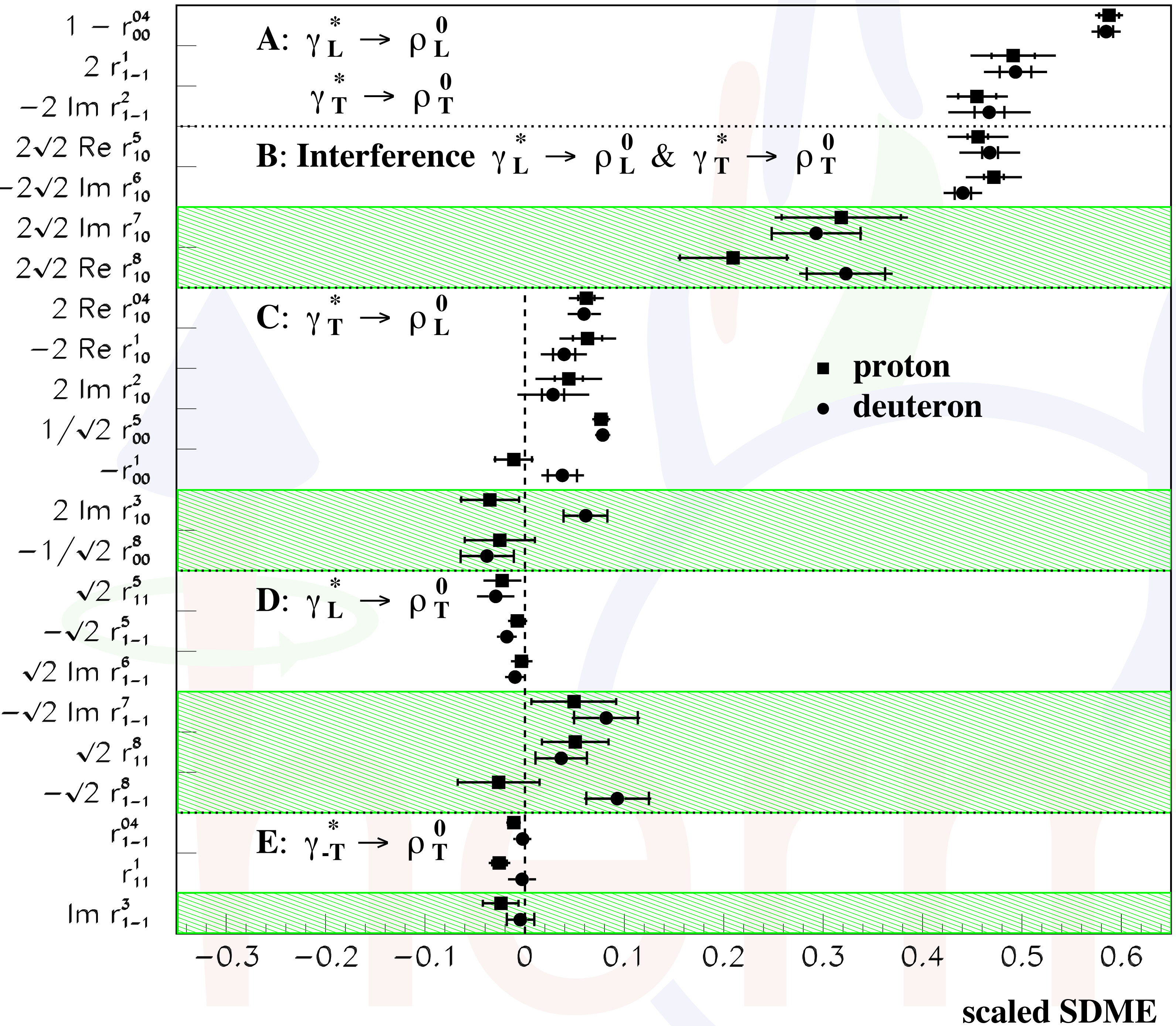


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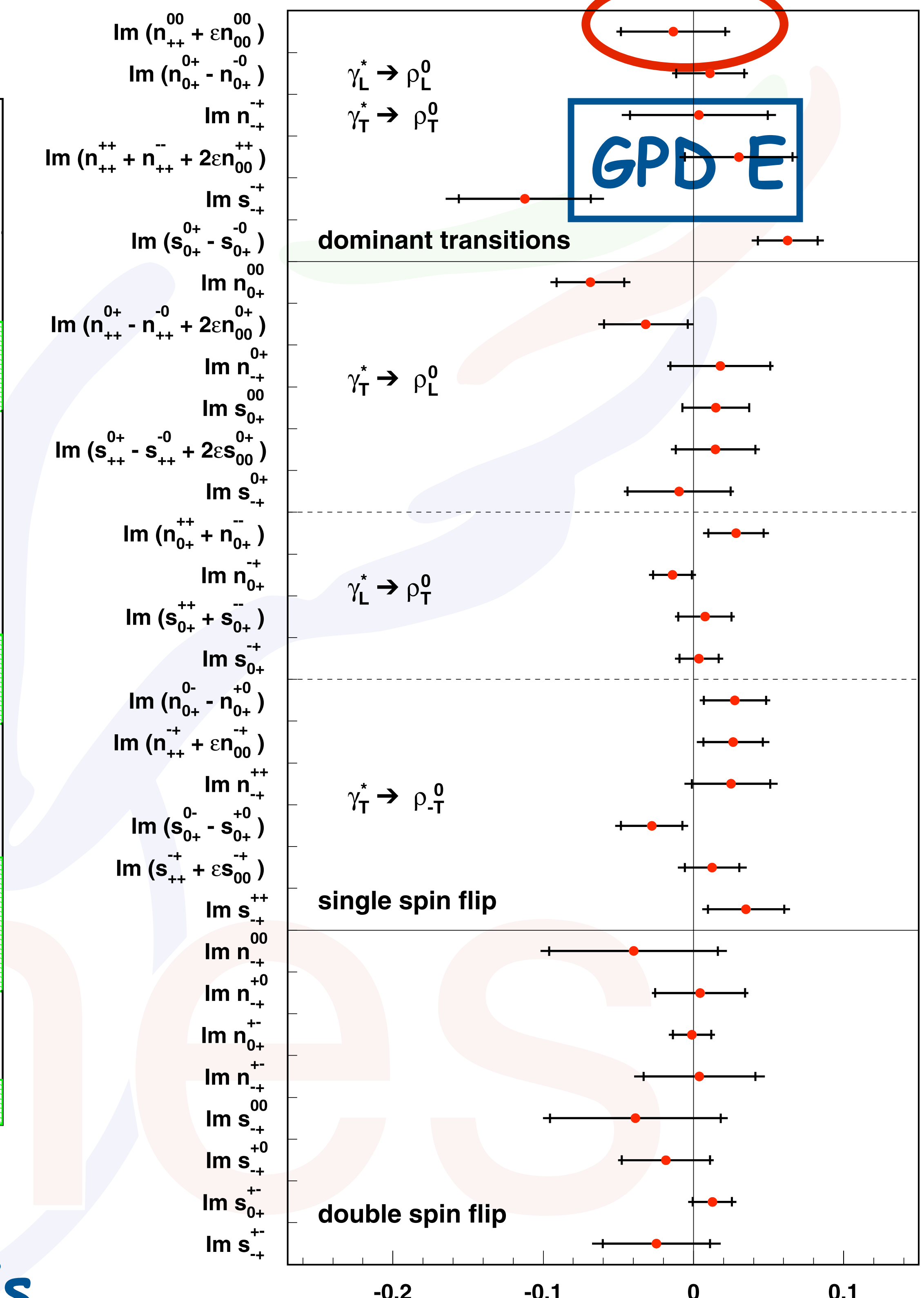


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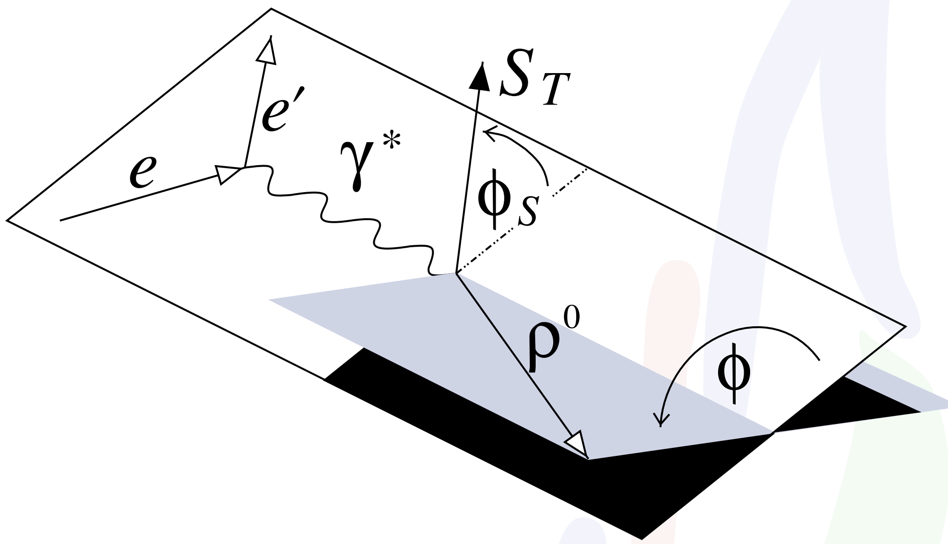


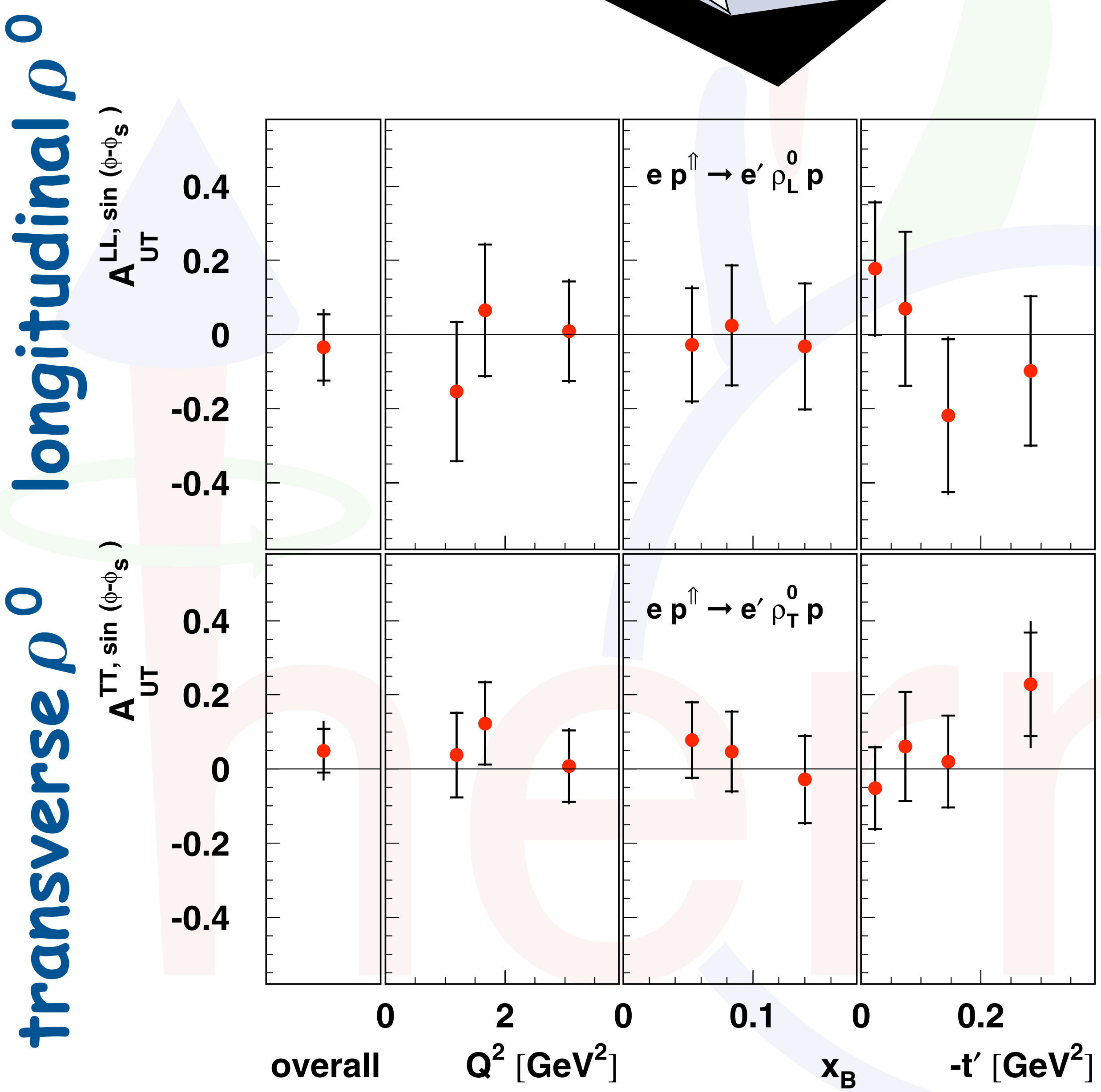


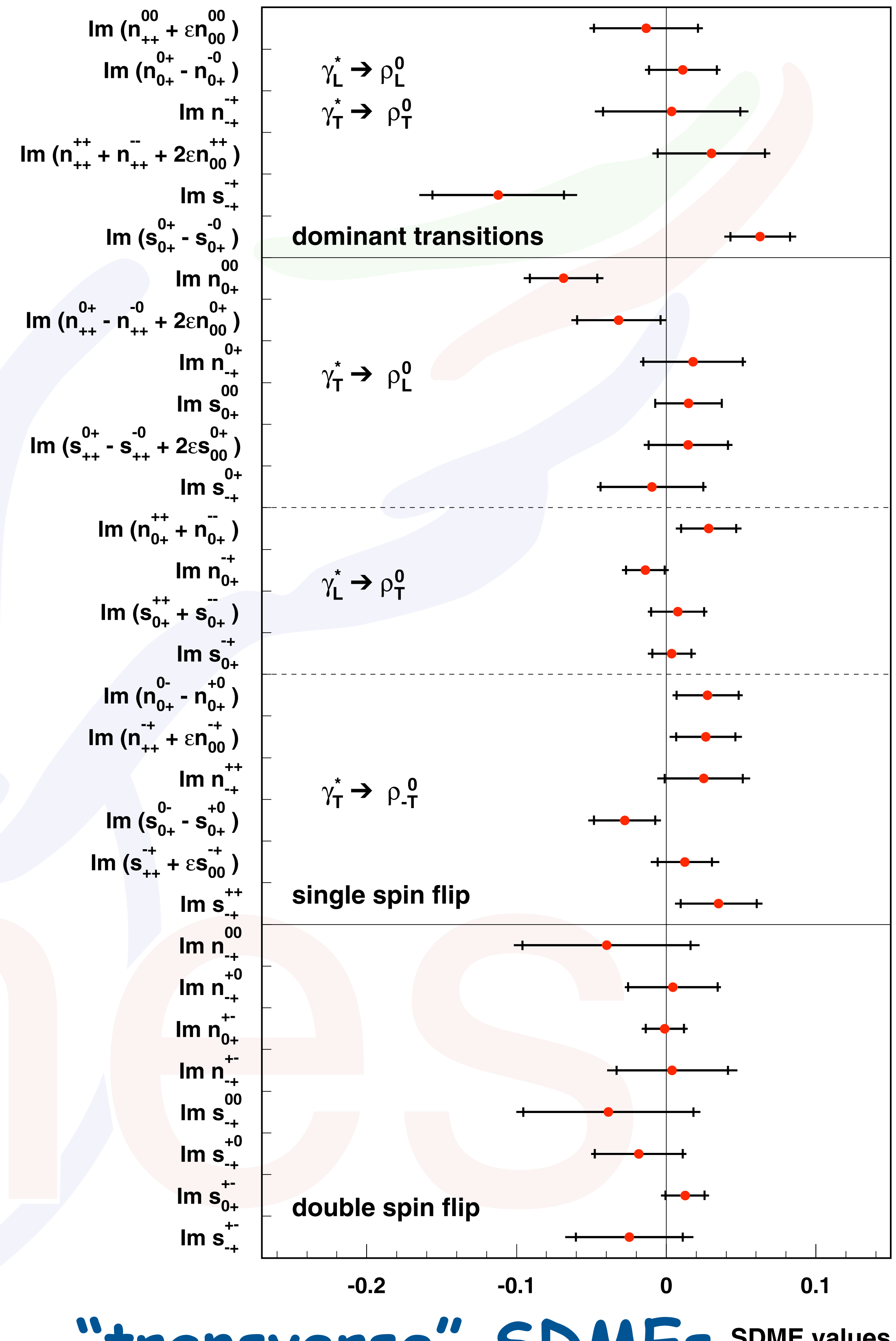


"transverse" SDMEs

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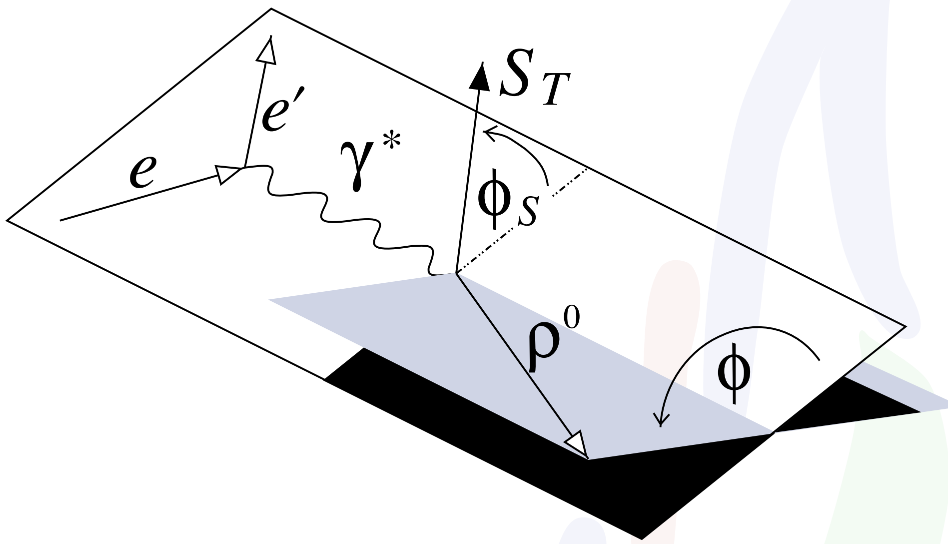
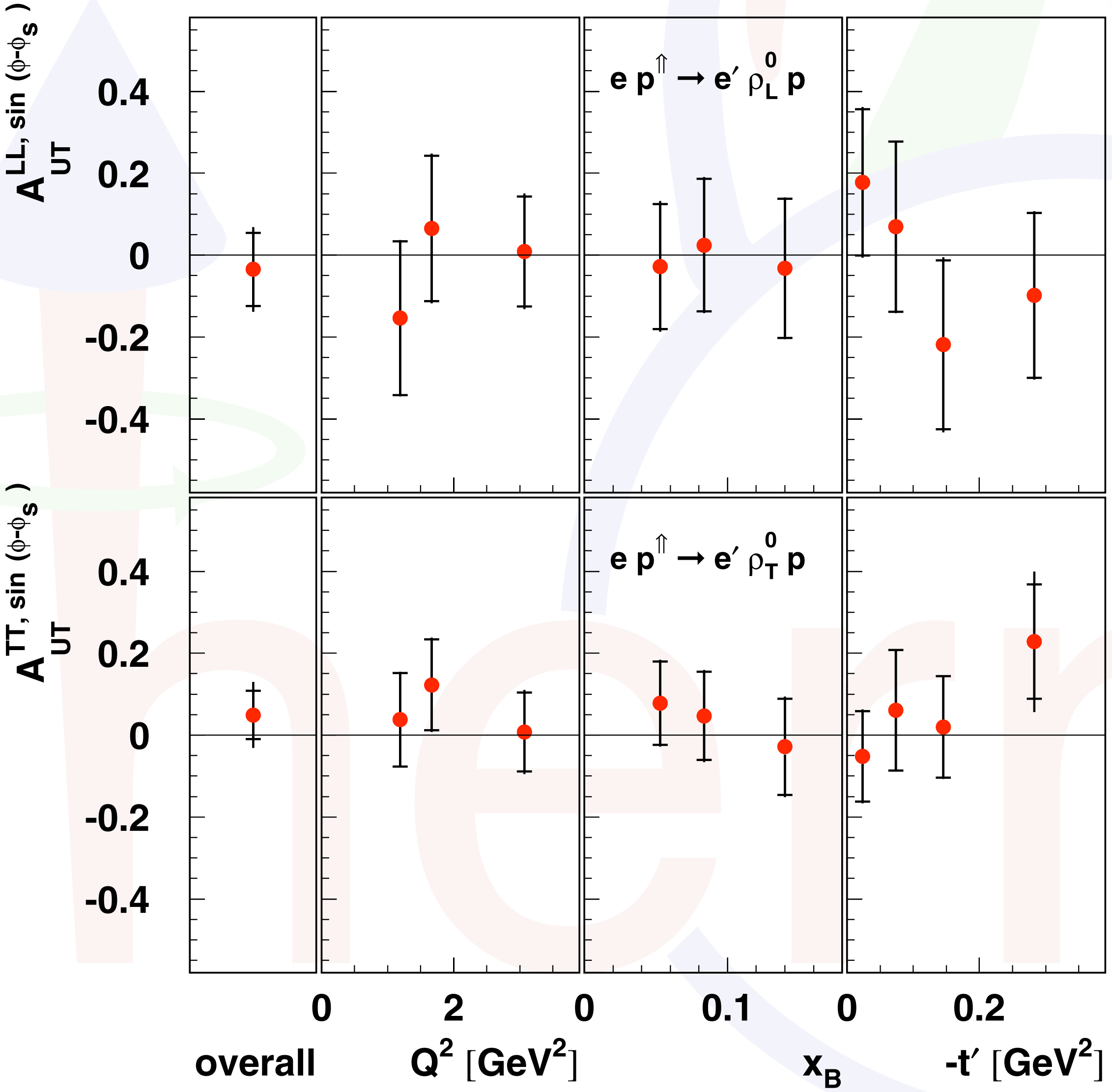
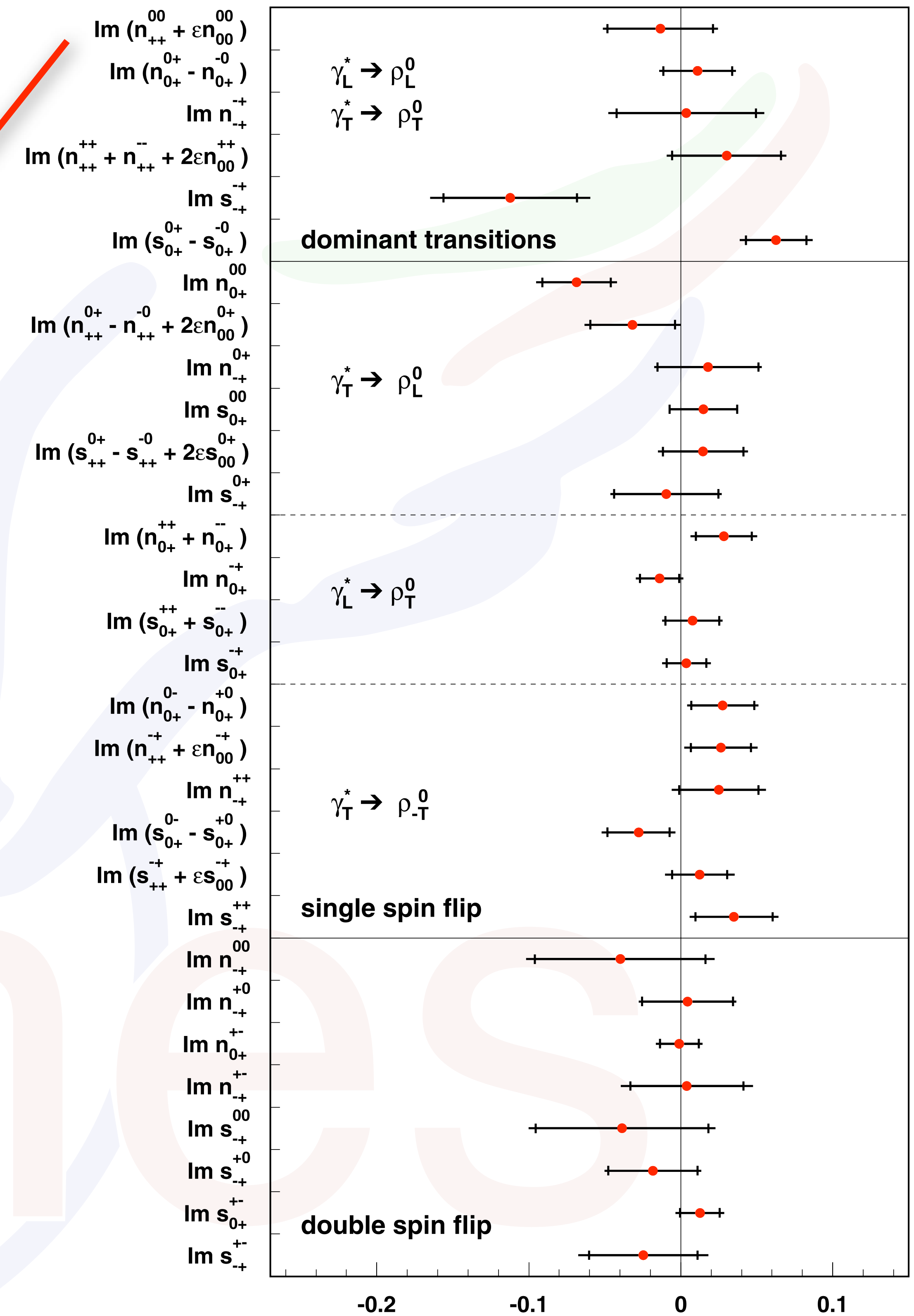



longitudinal $\rho^0$

transverse $\rho^0$




"transverse" SDMEs

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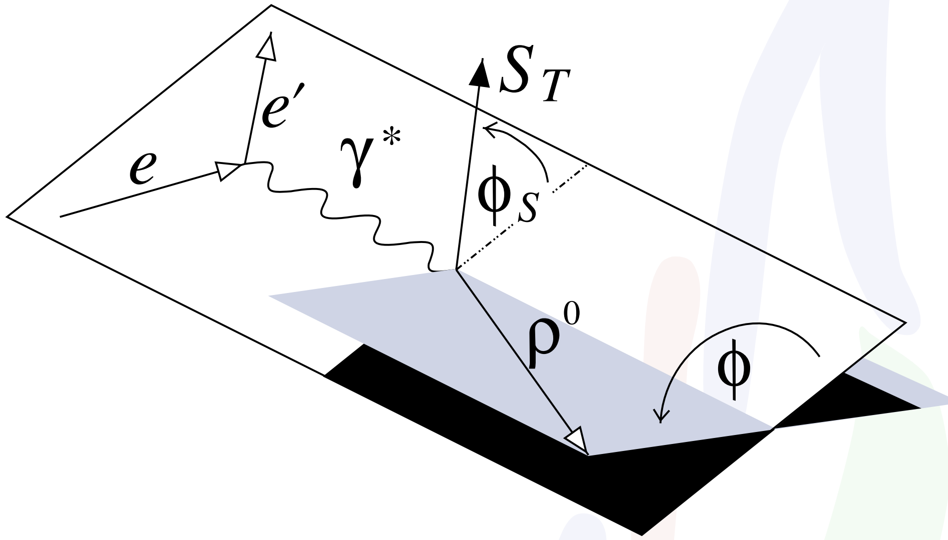


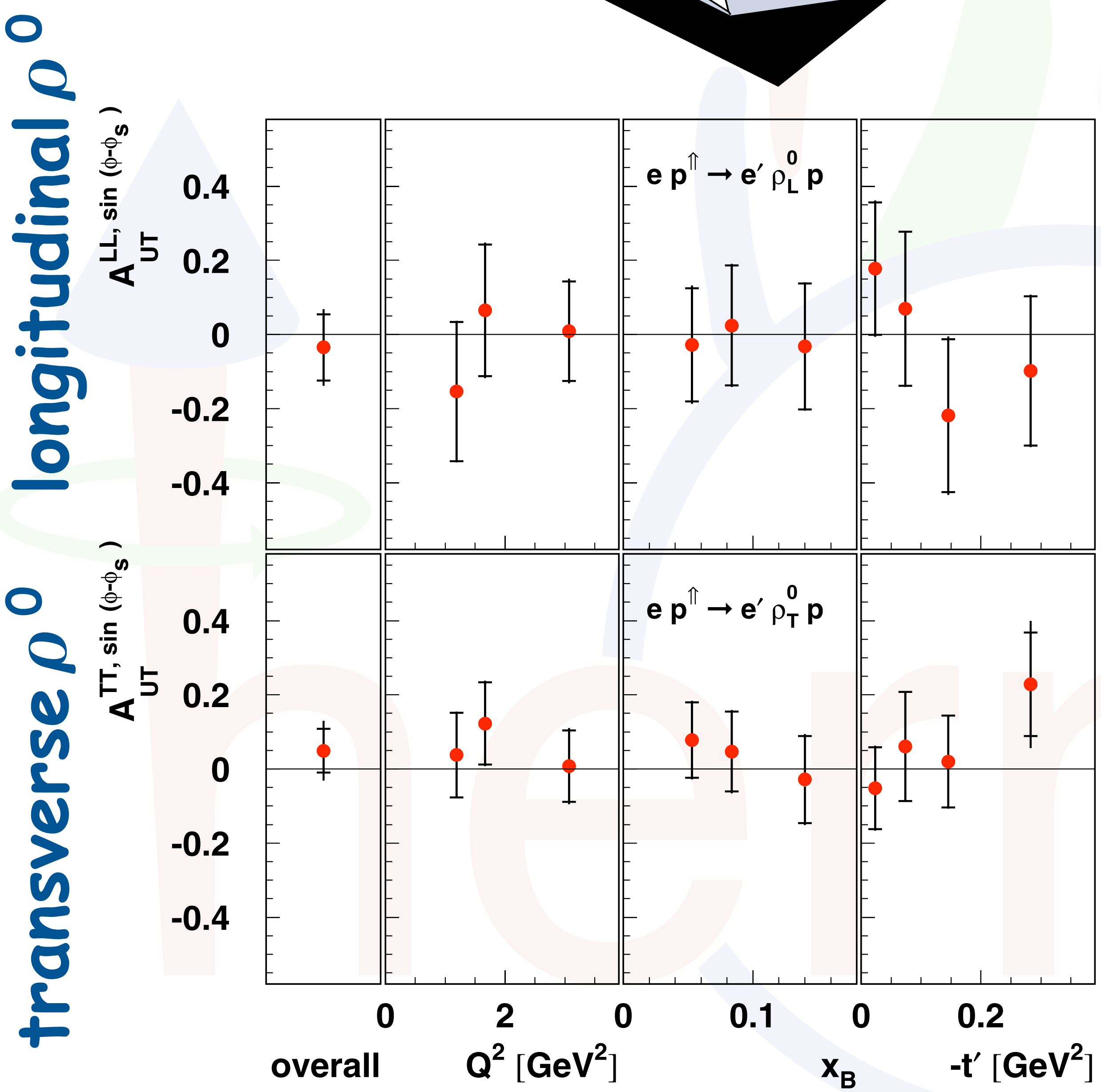


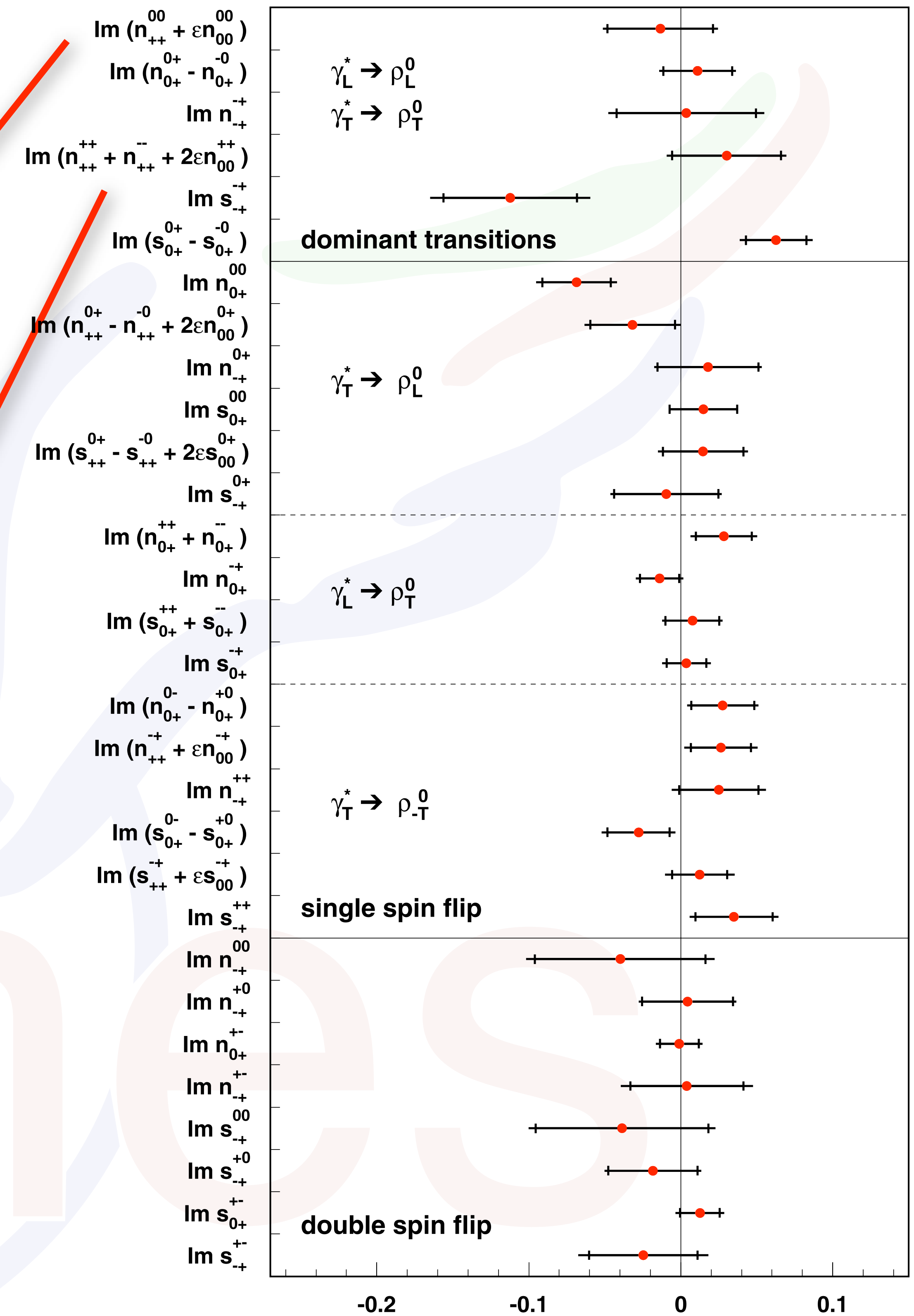


"transverse" SDMEs

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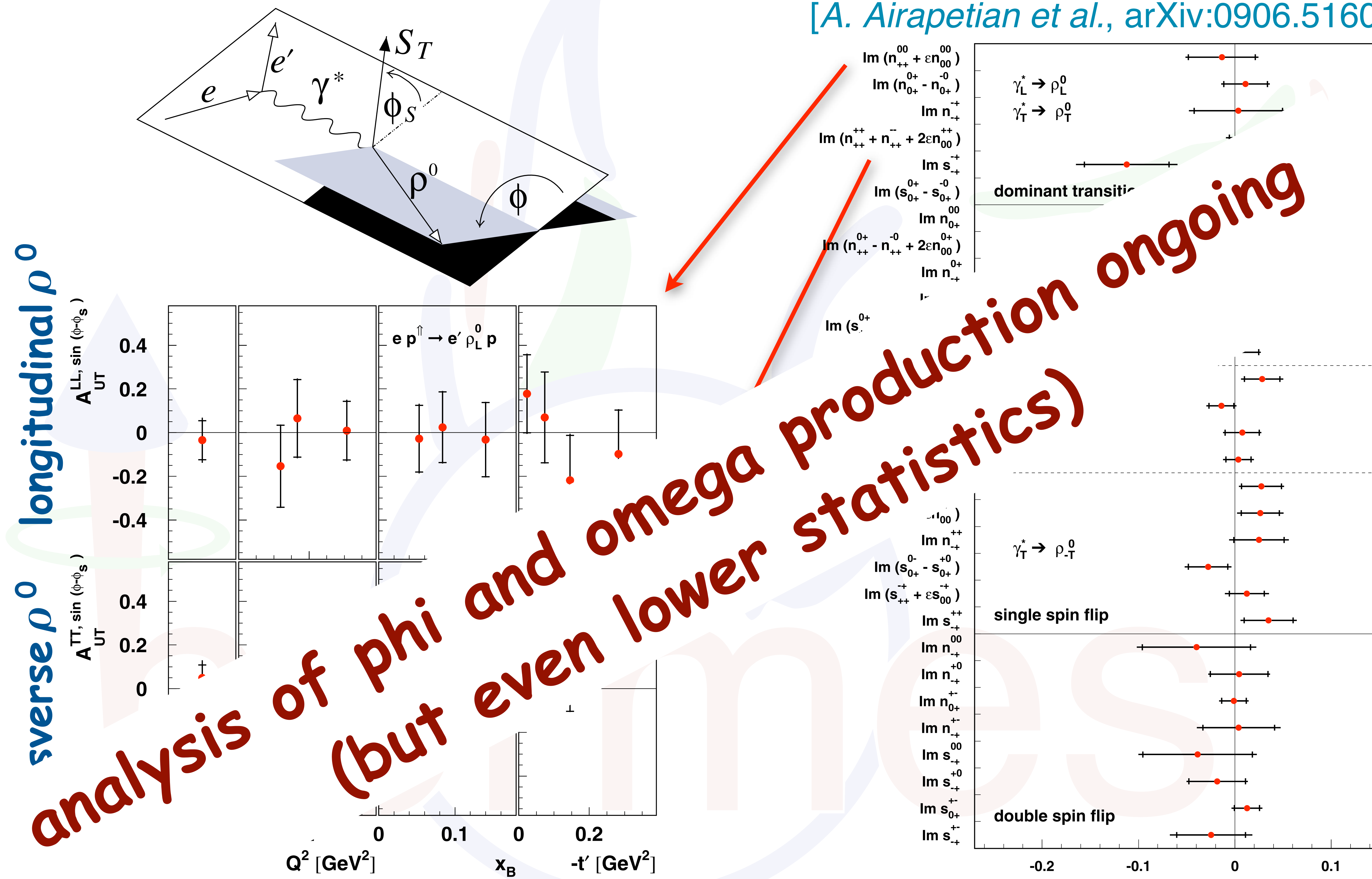
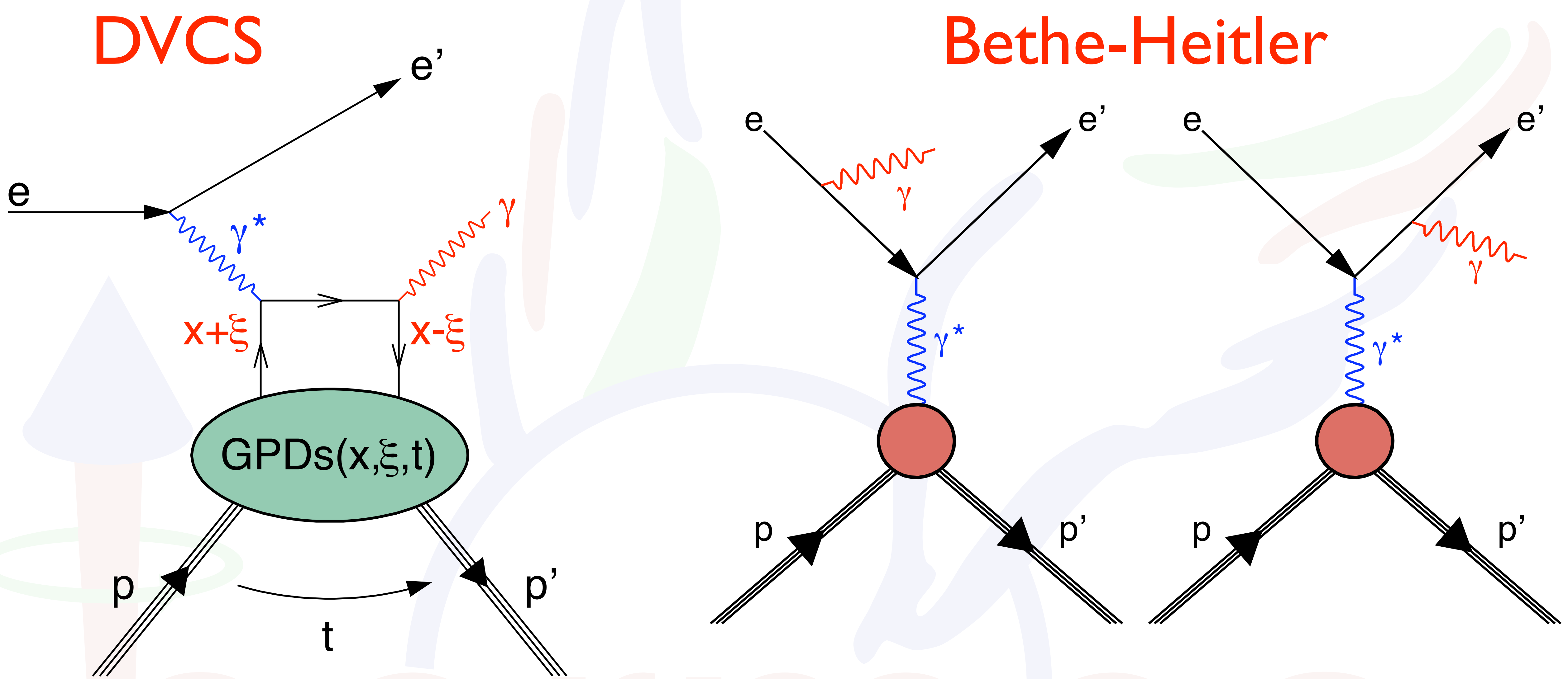



"transverse" SDMEs

# DVCS/Bethe-Heitler interference



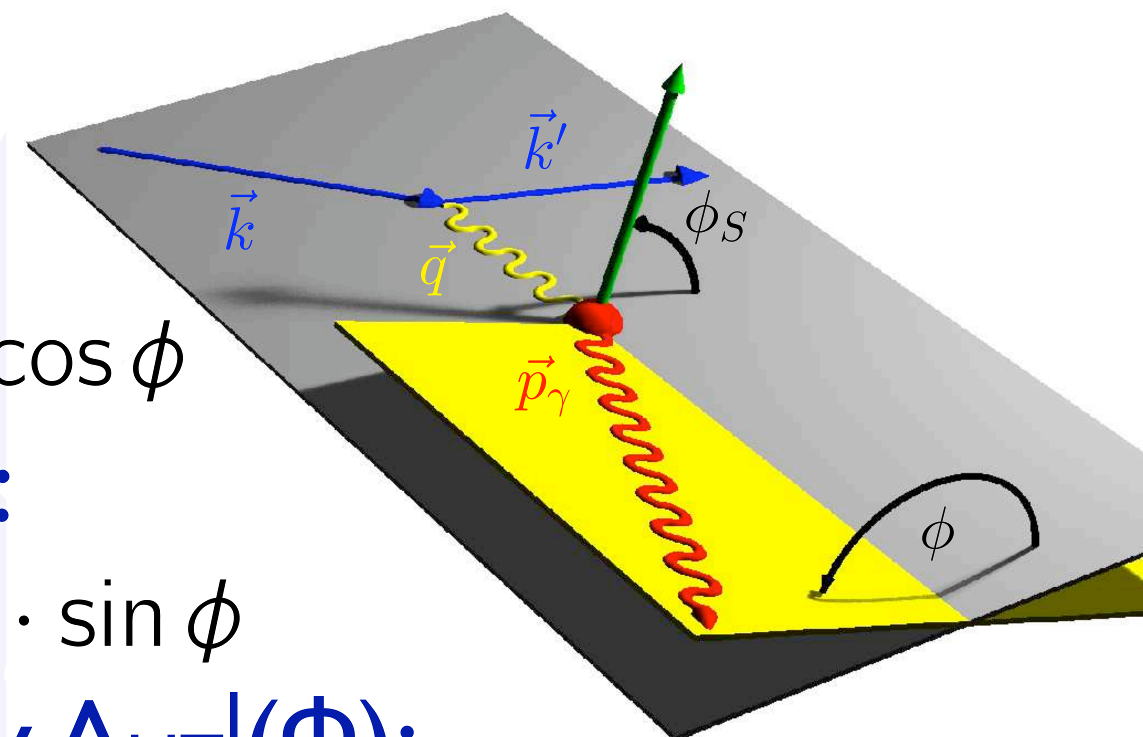

$$\frac{d^4\sigma}{dQ^2\,dx_B\,dt\,d\phi} = \frac{y^2}{32(2\pi))^4\sqrt{1+\frac{4M^2x_B^2}{Q^2}}}\left(|\mathcal{T}_{\mathrm{DVCS}}|^2 + |\mathcal{T}_{\mathrm{BH}}|^2 + \mathcal{I}\right)$$

# Azimuthal asymmetries in DVCS

## Cross section:

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

## 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 $A_{UT}^I(\Phi)$:**

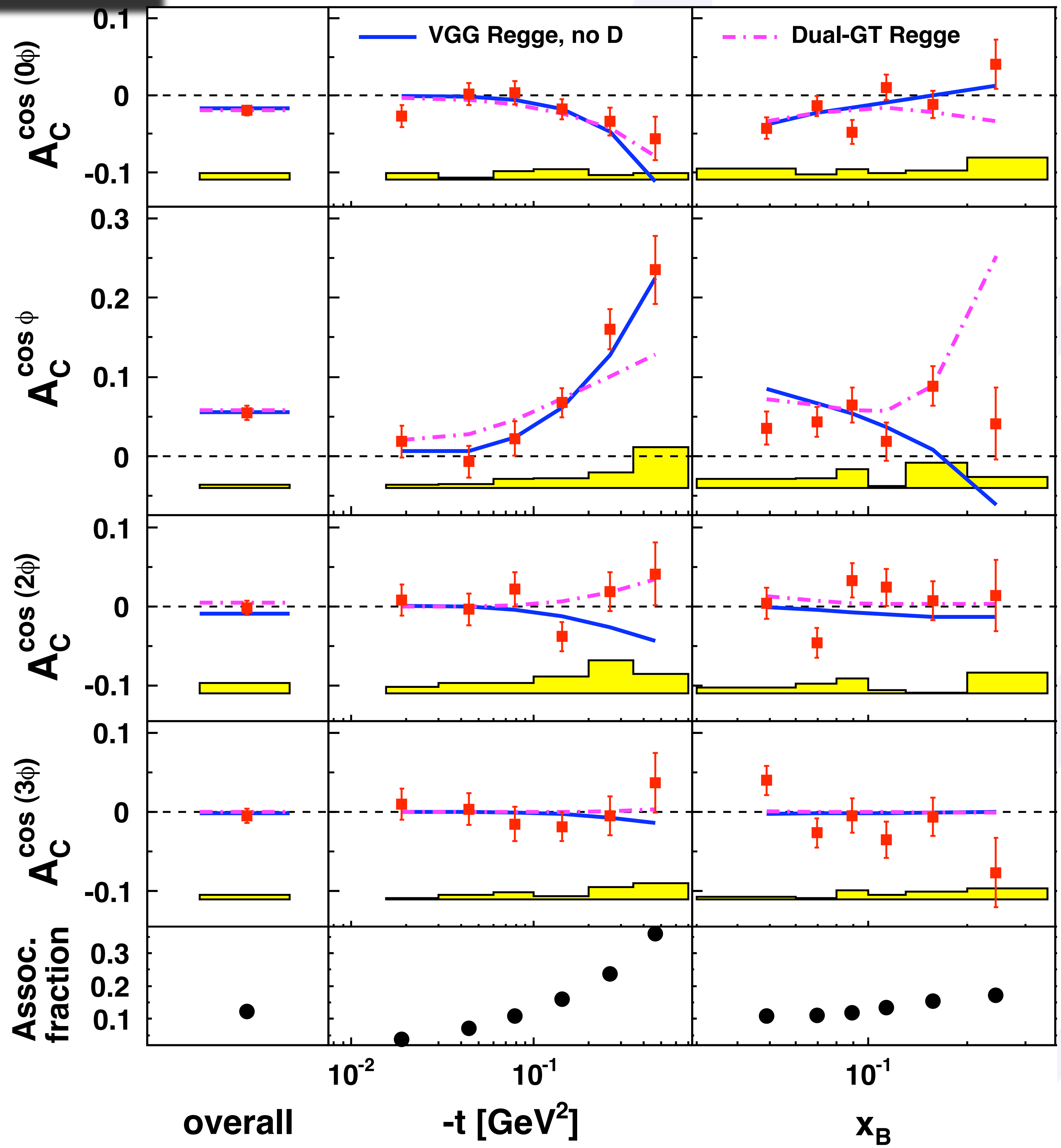
$$d\sigma(\phi,\phi_S)-d\sigma(\phi,\phi_S+\pi)\propto \mathrm{Im}[F_2\mathcal{H}-F_1\mathcal{E}]\cdot\sin(\phi-\phi_S)\cos\phi$$
$$+\ \mathrm{Im}[F_2\widetilde{\mathcal{H}}-F_1\xi\widetilde{\mathcal{E}}]\cdot\cos(\phi-\phi_S)\sin\phi$$

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

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

All data 1996-2005

# Beam-charge asymmetry




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

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

[higher twist]

[gluon leading twist]

Resonant fraction:

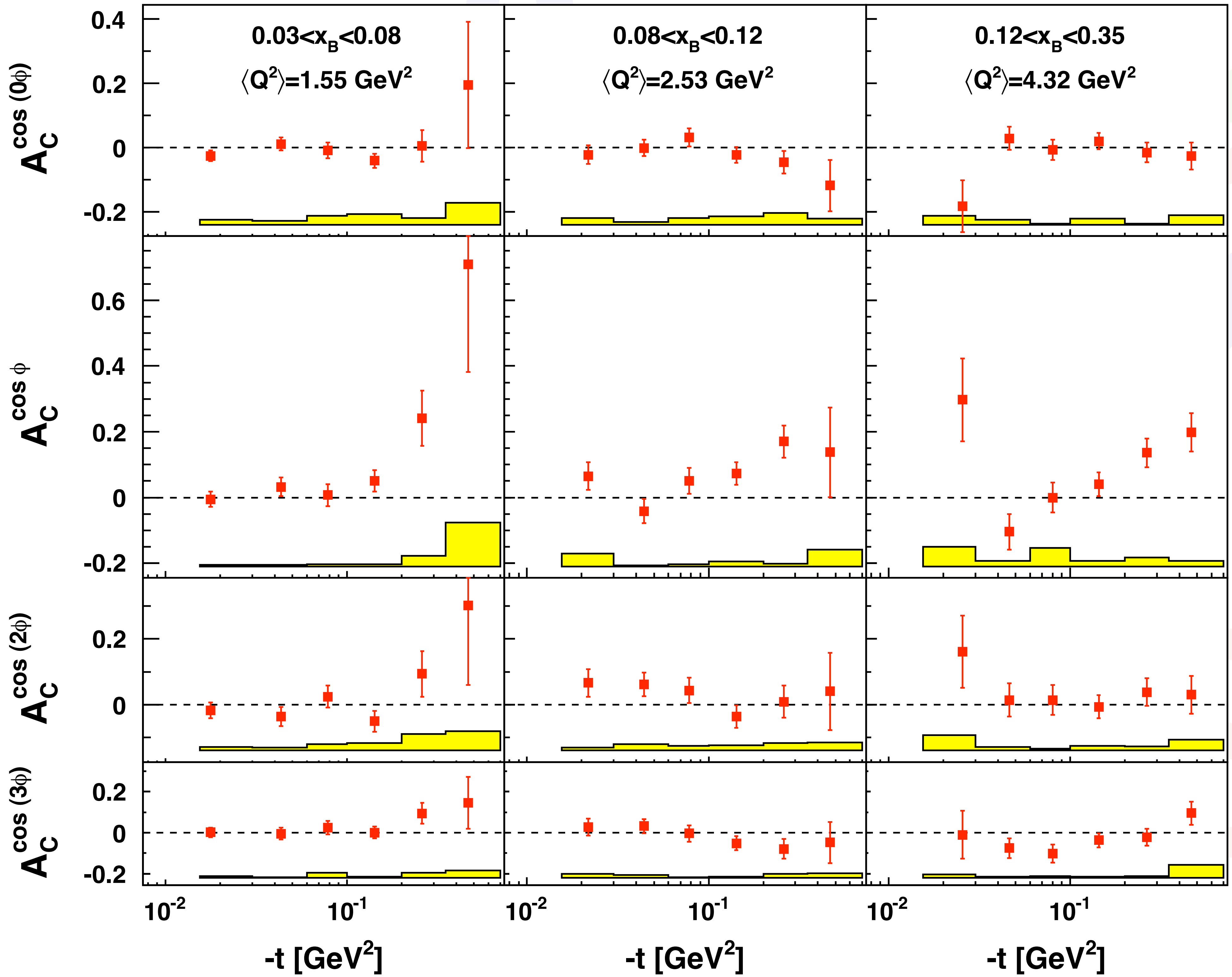
$ep \to e\Delta^+\gamma$

model prediction “VGG”: Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

All data
1996-2005

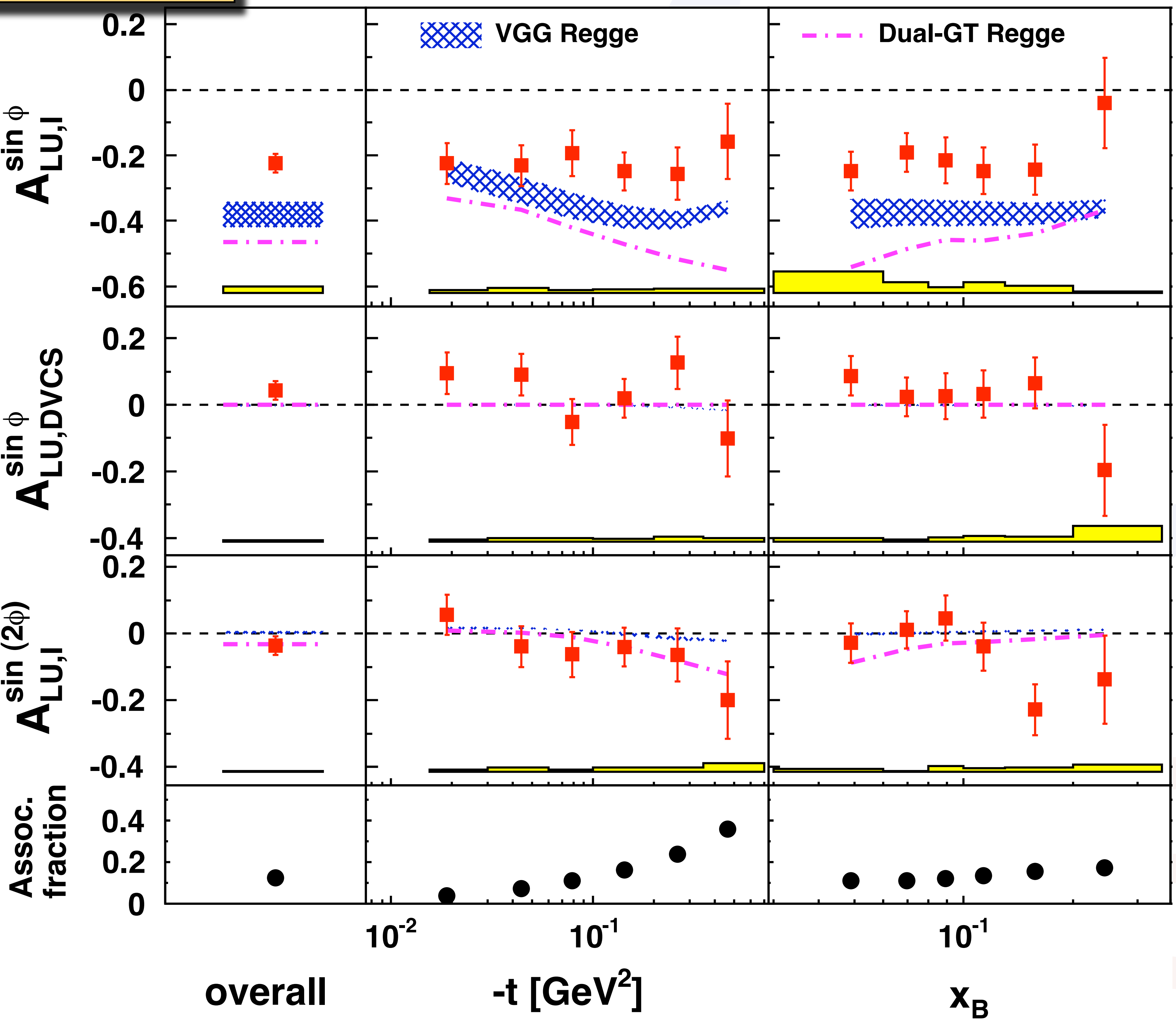
# Beam-charge asymmetry

## 2-D analysis



All data
1996-2005

# Beam-spin asymmetry




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

[higher twist]

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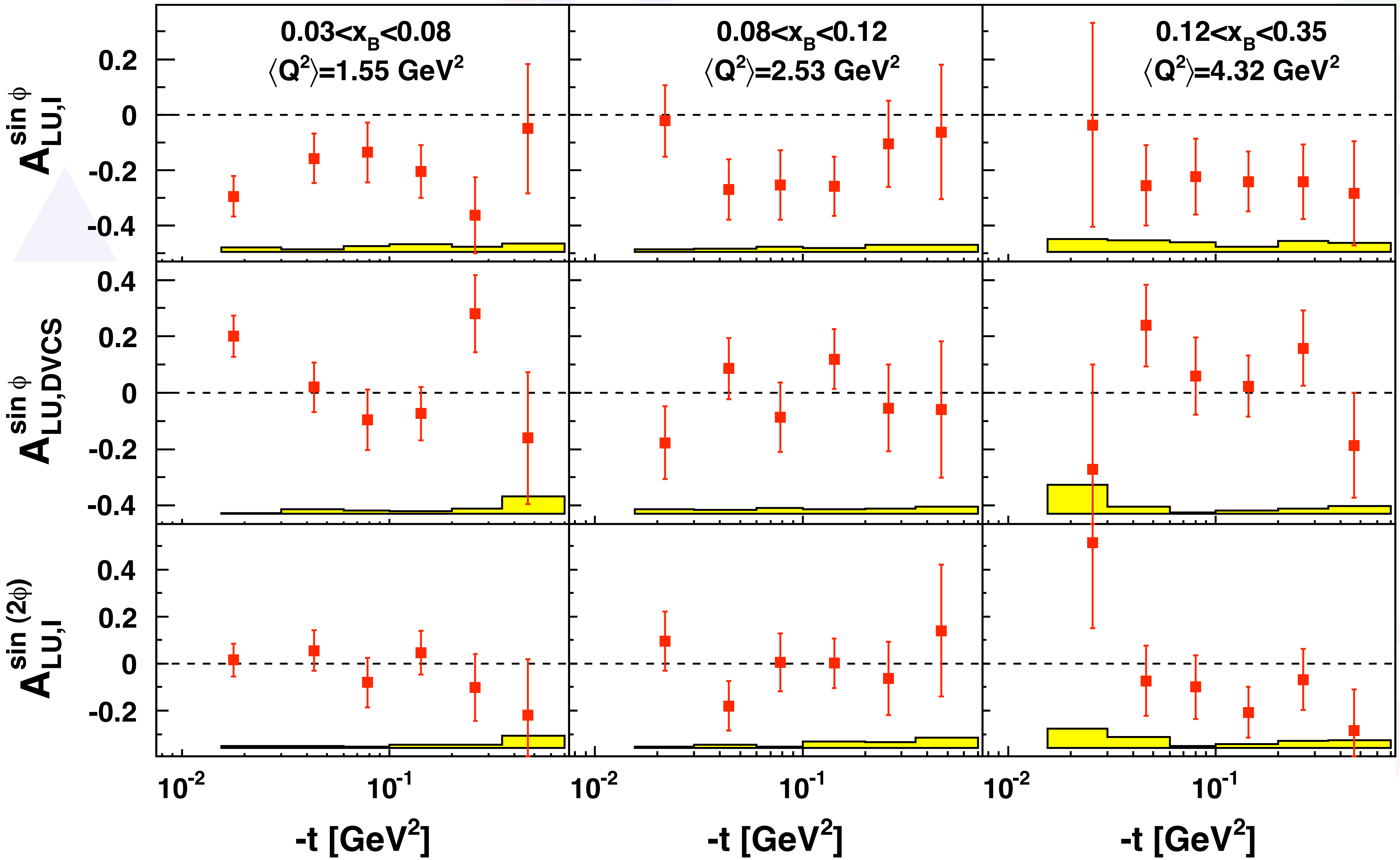
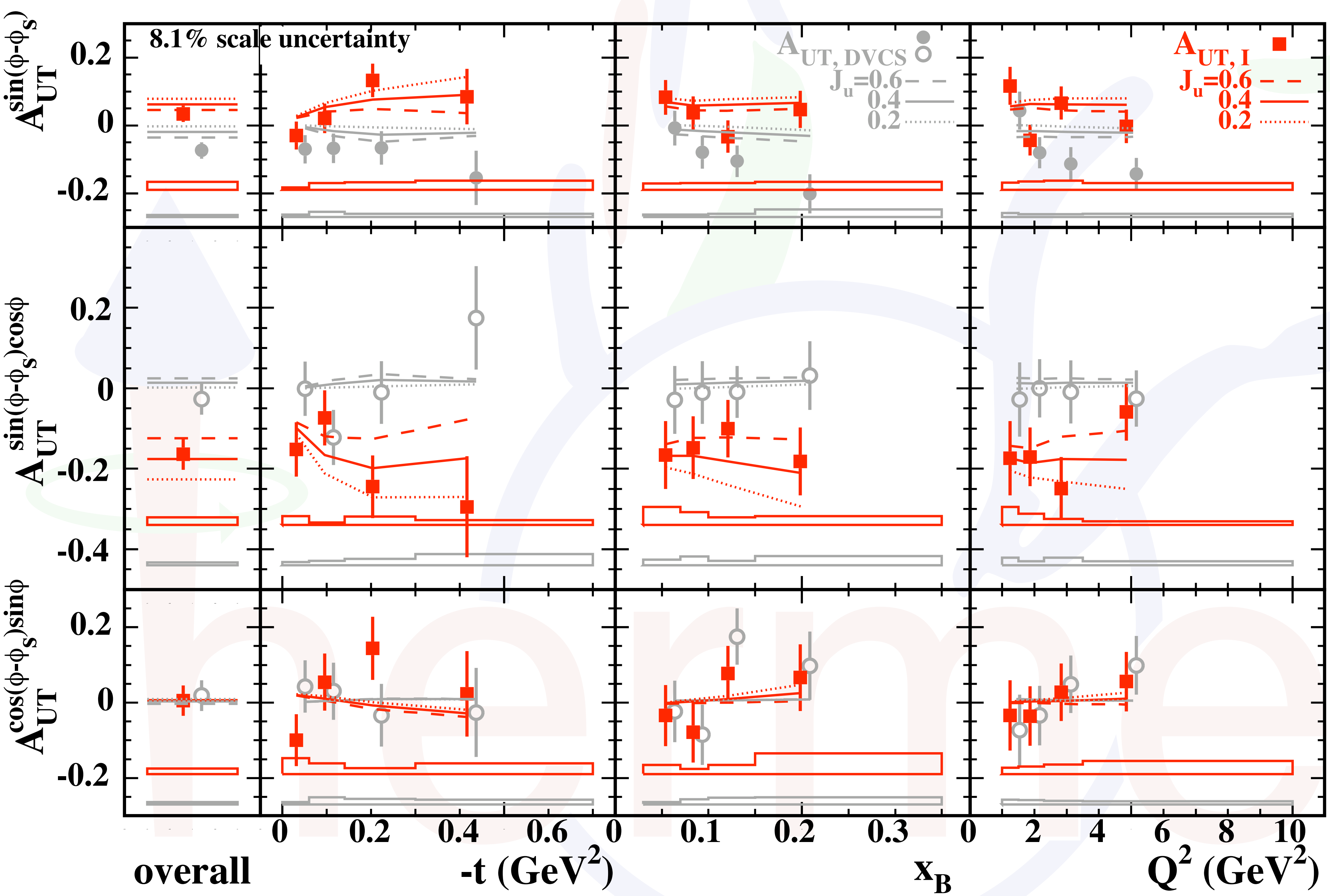
# Beam-spin asymmetry

## 2-D analysis



# Transverse target-spin asymmetry

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




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

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

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

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

# Transverse target-spin asymmetry

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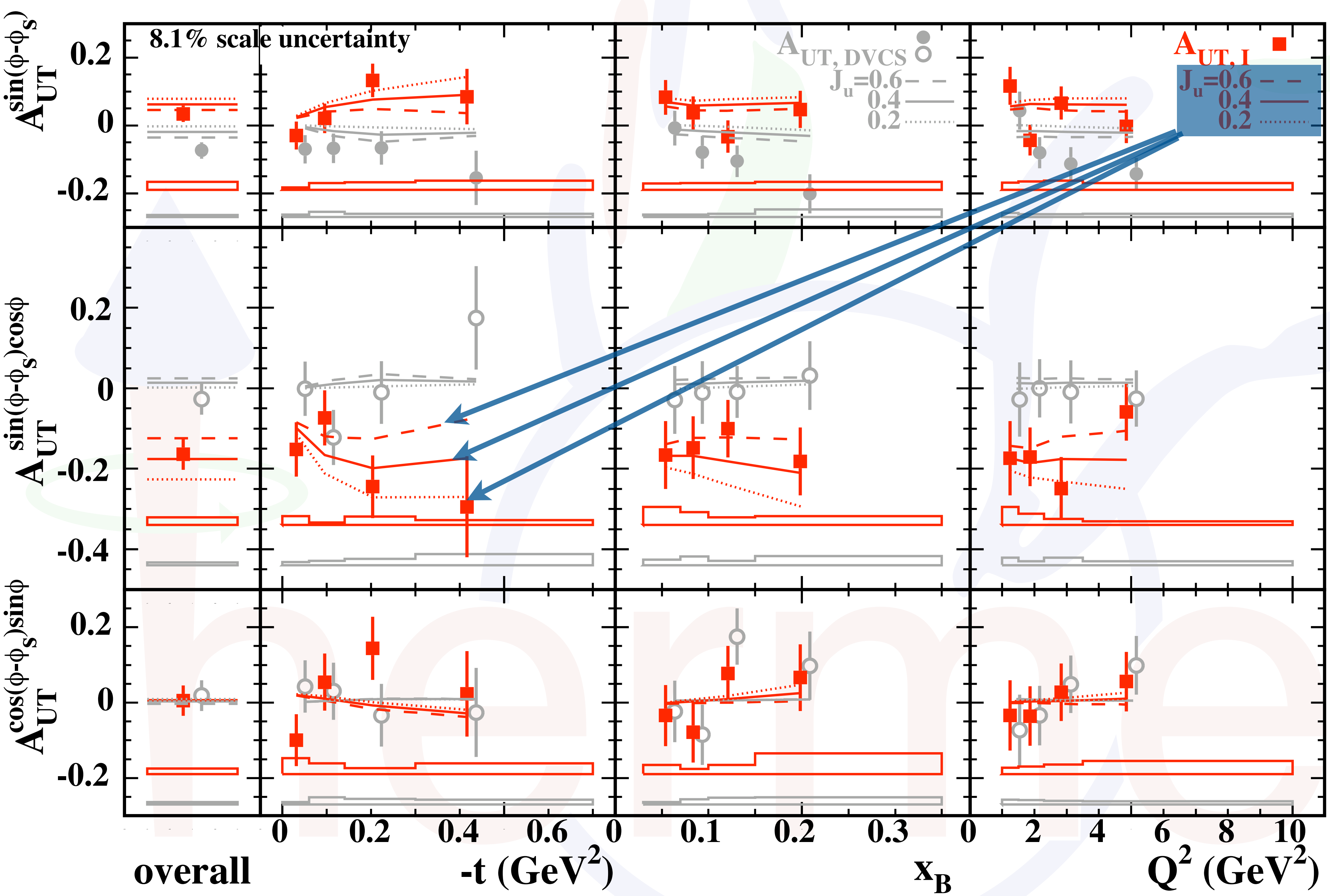


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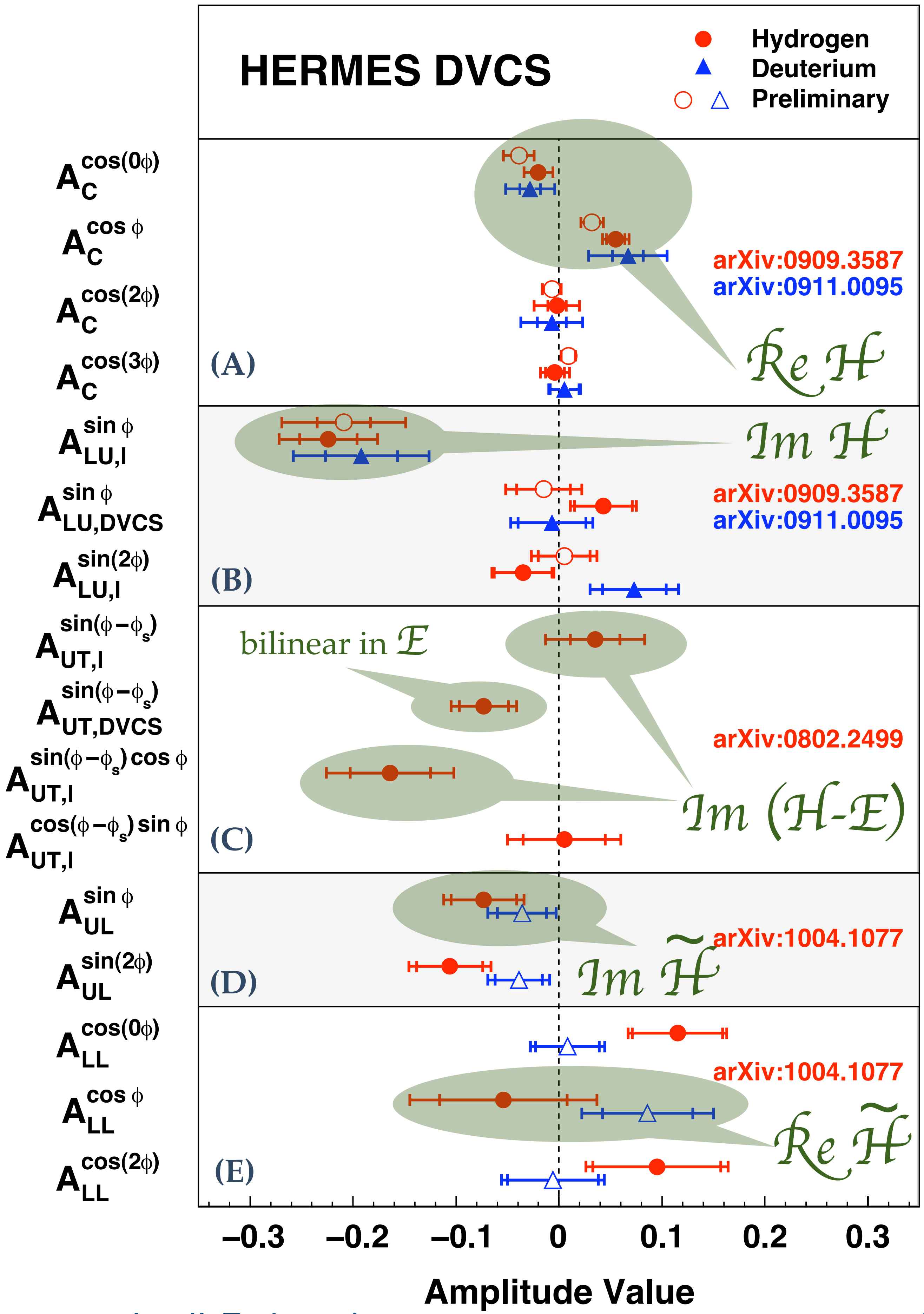
# DVCS Overview




(A) Beam-charge asymmetry:

GPD H

(B) Beam-helicity asymmetry:

GPD H

(C) Transverse target spin asymmetry:

GPD E from proton target

(D) Longitudinal target spin asymmetry:

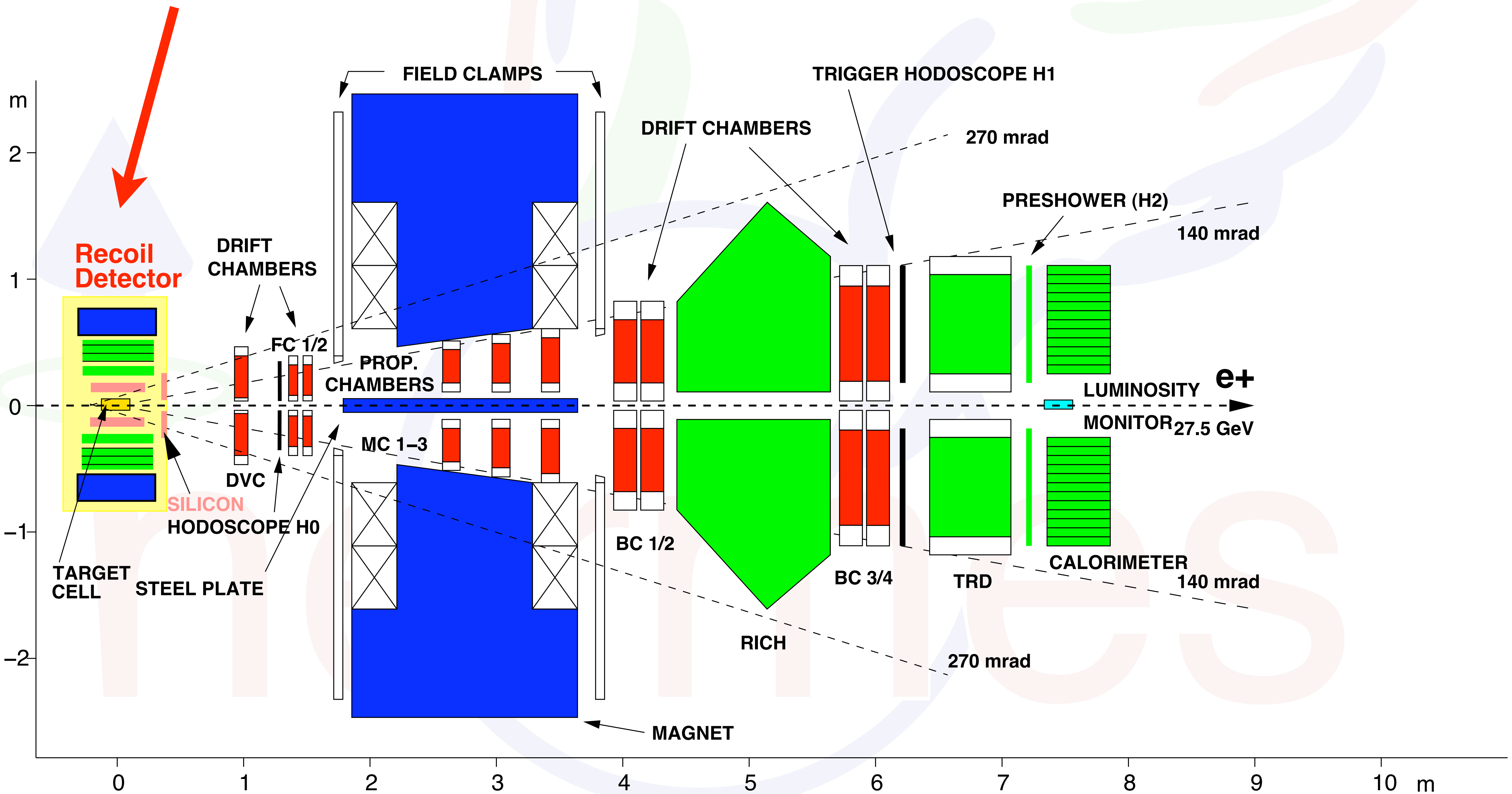
GPD $\tilde{H}$

(E) Double-spin asymmetry:

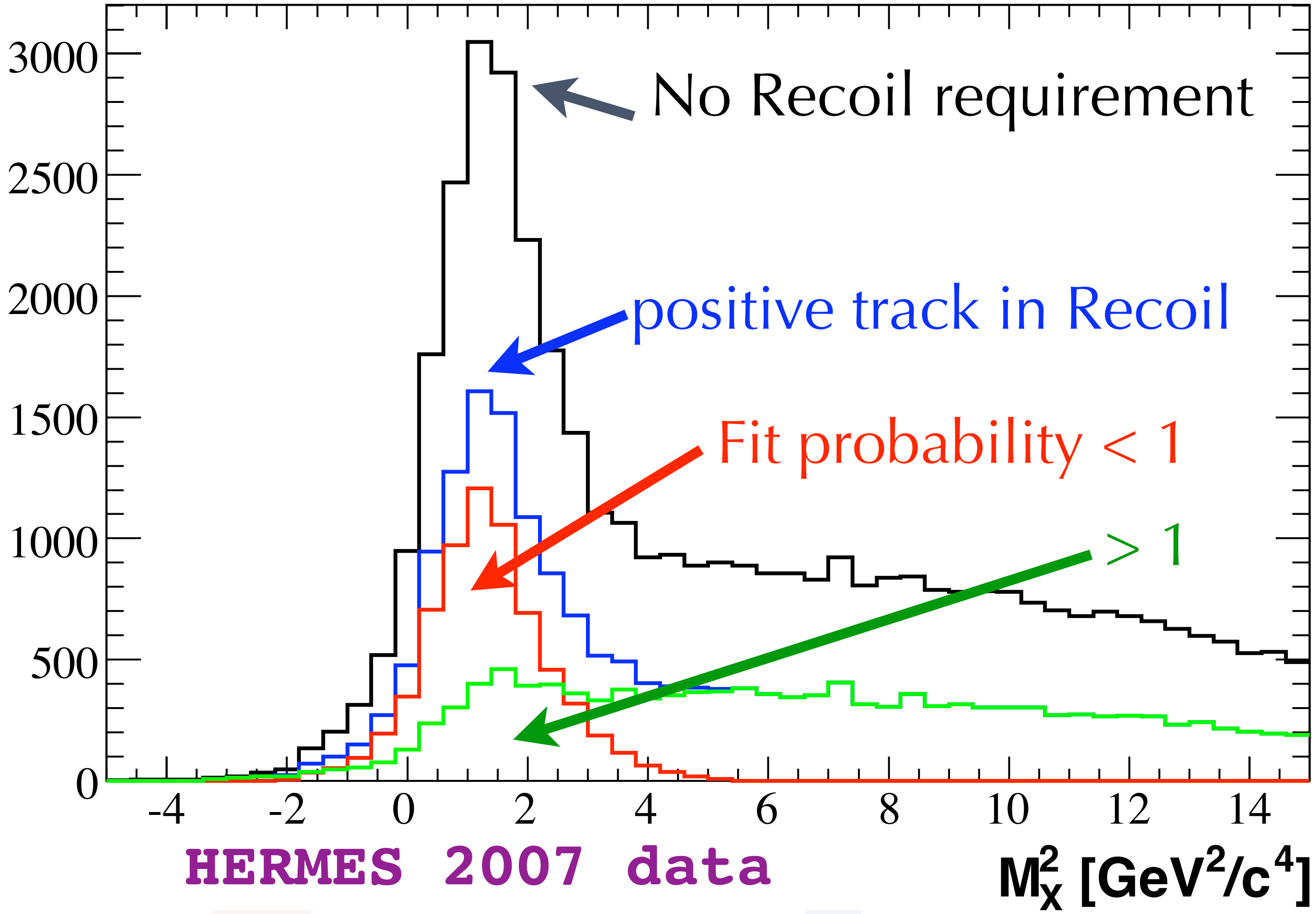
GPD $\tilde{H}$

# HERMES detector (2006/07)

detection of recoiling proton



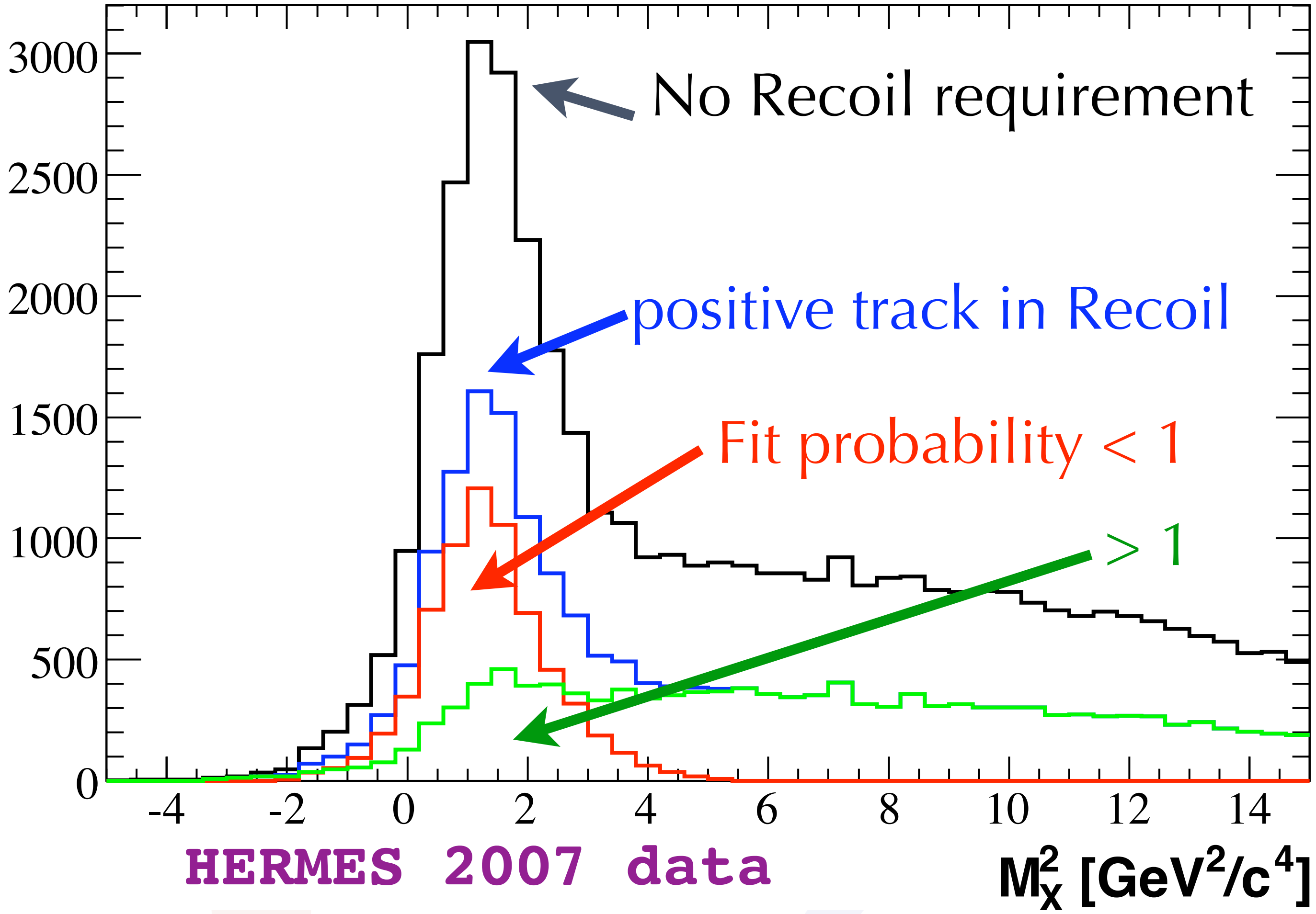
## kinematic fitting




# … still to come …

- purpose: tag exclusive events
- reduce semi-inclusive DIS and resonance background

## kinematic fitting

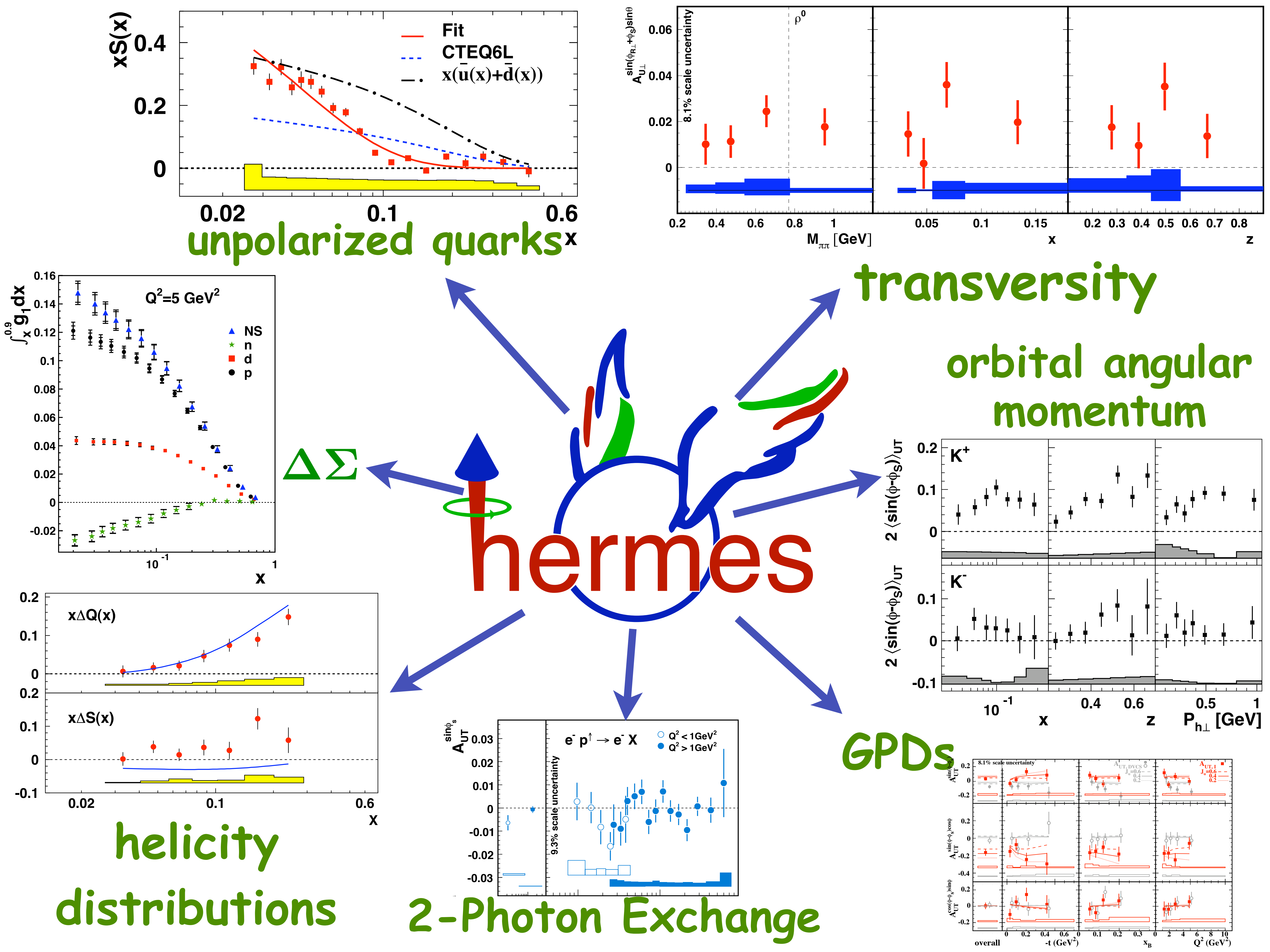



# ... still to come ...

- purpose: tag exclusive events
- reduce semi-inclusive DIS and resonance background

- $A_{LT}$ pre-recoil era
- $A_{LU}$ with RD
- $A_C$ with RD
- Associated DVCS $A_{LU}$ / $A_C$

hermes



unpolarized quarks
transversity
orbital angular momentum
$\Delta\Sigma$
hermes
helicity distributions
2-Photon Exchange
GPDs
Fit
CTEQ6L
$x(\bar{u}(x)+\bar{d}(x))$
$xS(x)$
$Q^2$=5 GeV$^2$
NS
n
d
p
$x\Delta Q(x)$
$x\Delta S(x)$
8.1% scale uncertainty
9.3% scale uncertainty
$M_{\pi\pi}$ [GeV]
$K^+$
$K^-$
$2\langle\sin(\phi-\phi_S)\rangle_{UT}$
$e^- p^\uparrow \rightarrow e^- X$
$Q^2$ < 1GeV$^2$
$Q^2$ > 1GeV$^2$