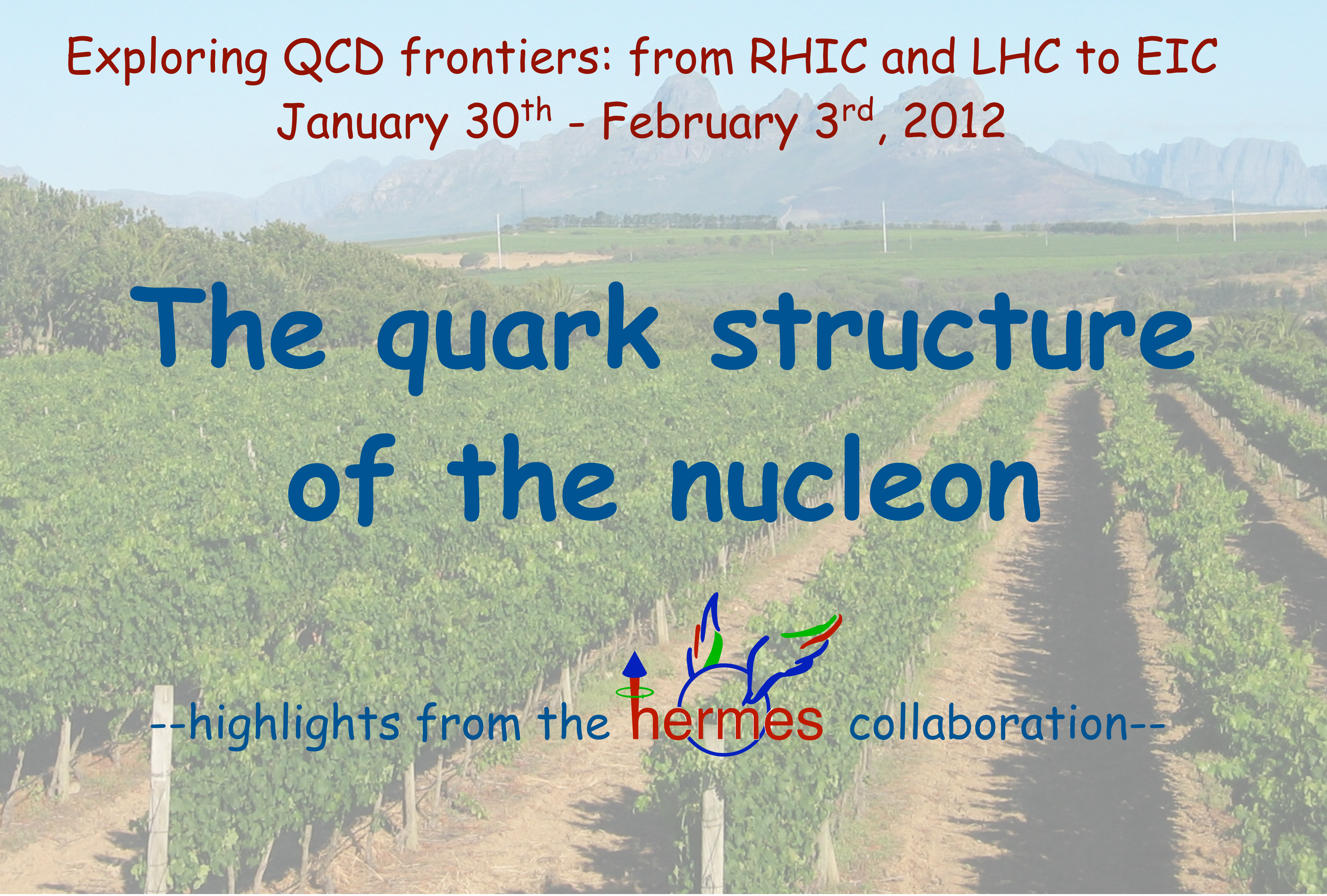

Exploring QCD frontiers: from RHIC and LHC to EIC
January 30th - February 3rd, 2012

The quark structure of the nucleon

--highlights from the hermes collaboration--

ikerbasque
Basque Foundation for Science

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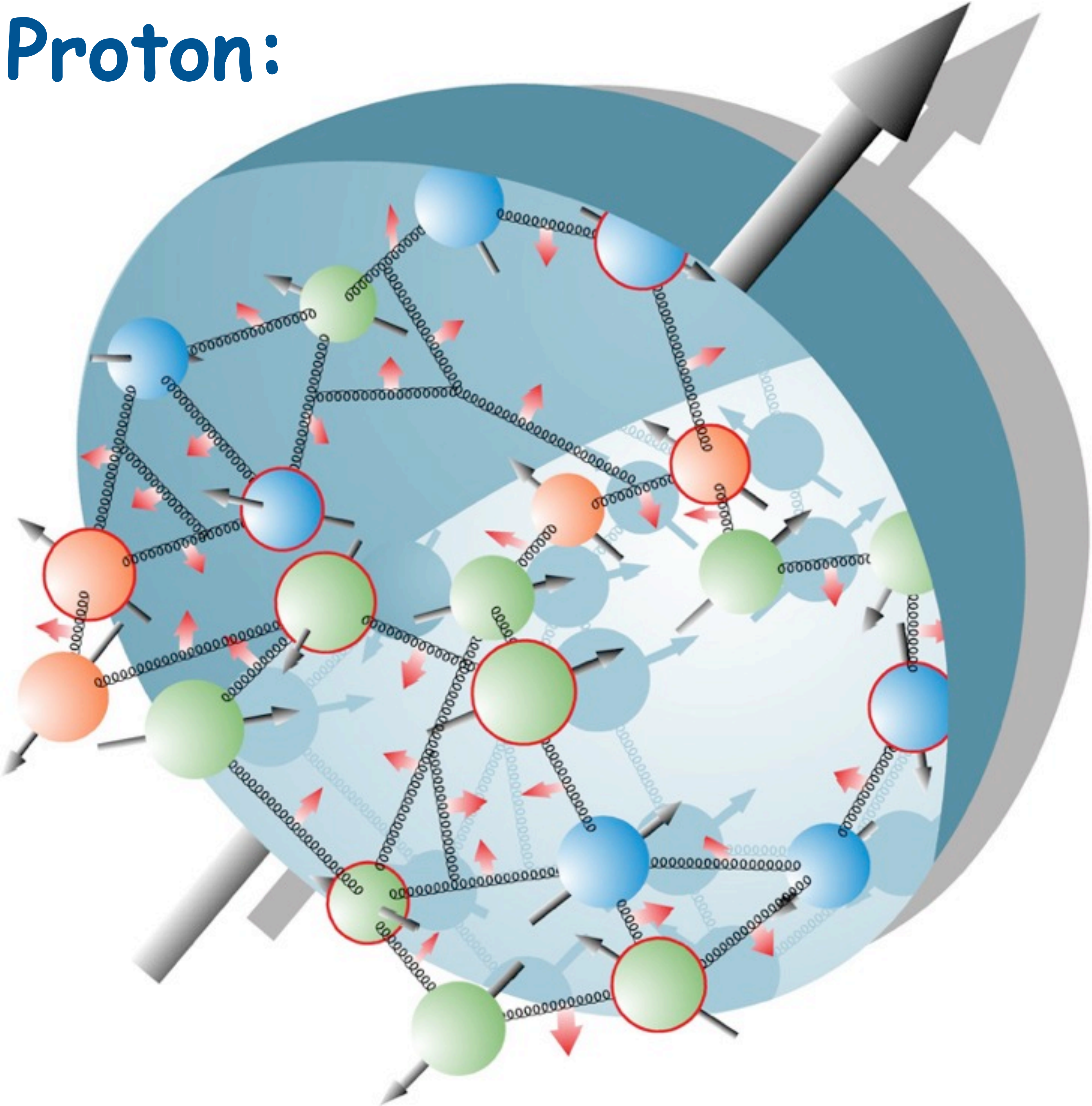
eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

The Proton:



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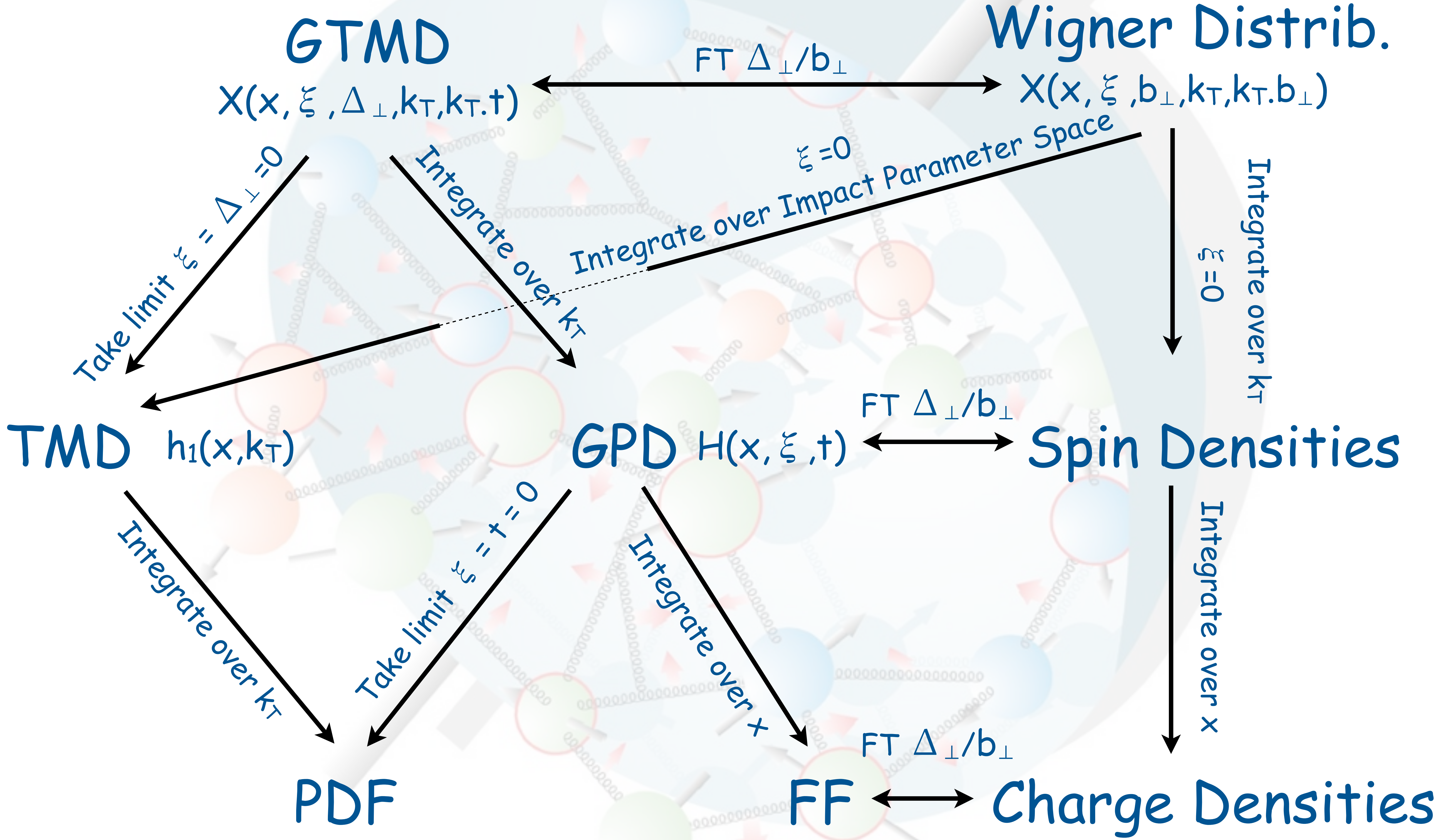
… it's representation:



GTMD $X(x, \xi, \Delta_\perp, k_T, k_T.t)$

FT $\Delta_\perp / b_\perp$

Wigner Distrib. $X(x, \xi, b_\perp, k_T, k_T.b_\perp)$

Take limit $\xi = \Delta_\perp = 0$

Integrate over k_T

$\xi = 0$

Integrate over Impact Parameter Space

$\xi = 0$

Integrate over k_T

TMD $h_1(x, k_T)$

GPD $H(x, \xi, t)$

FT $\Delta_\perp / b_\perp$

Spin Densities

Integrate over k_T

Take limit $\xi = t = 0$

Integrate over x

Integrate over x

PDF

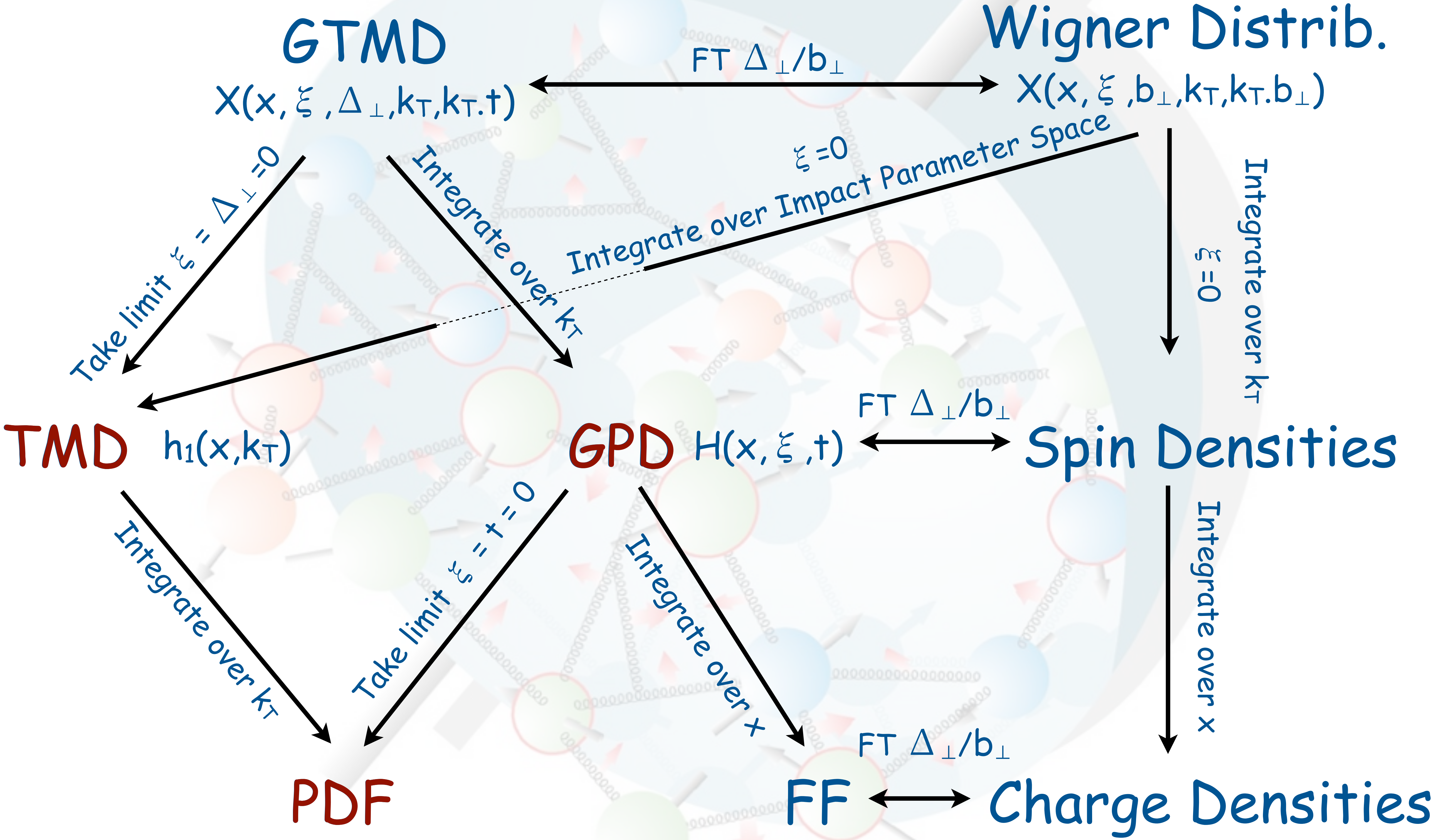
FF

FT $\Delta_\perp / b_\perp$

Charge Densities

[Courtesy of M. Murray, Glasgow]

… it's representation:



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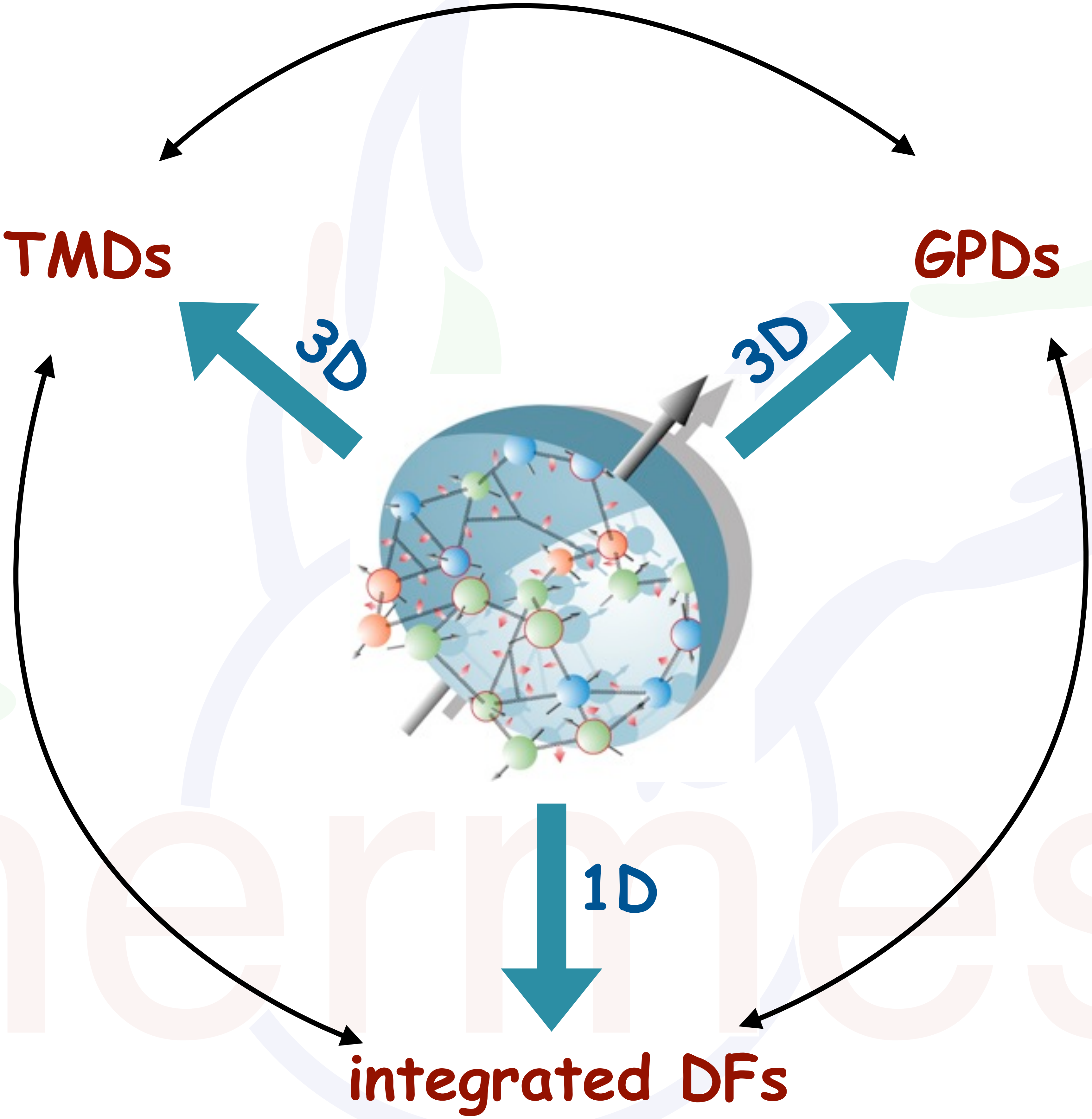
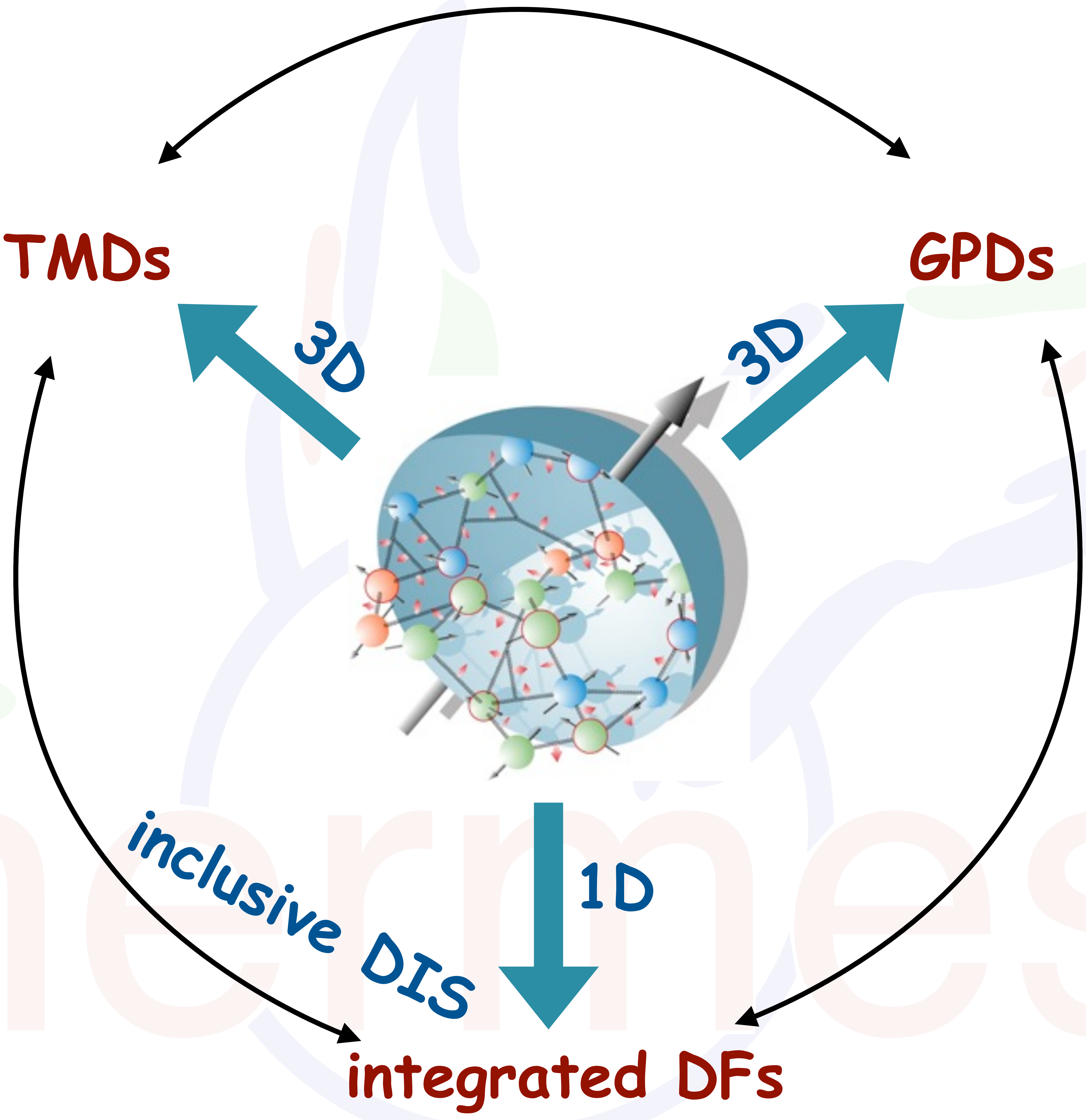
Charge Densities

[Courtesy of M. Murray, Glasgow]


TMDs
GPDs
3D
3D
1D
integrated DFs



TMDs

GPDs

3D

3D

1D

inclusive DIS

integrated DFs

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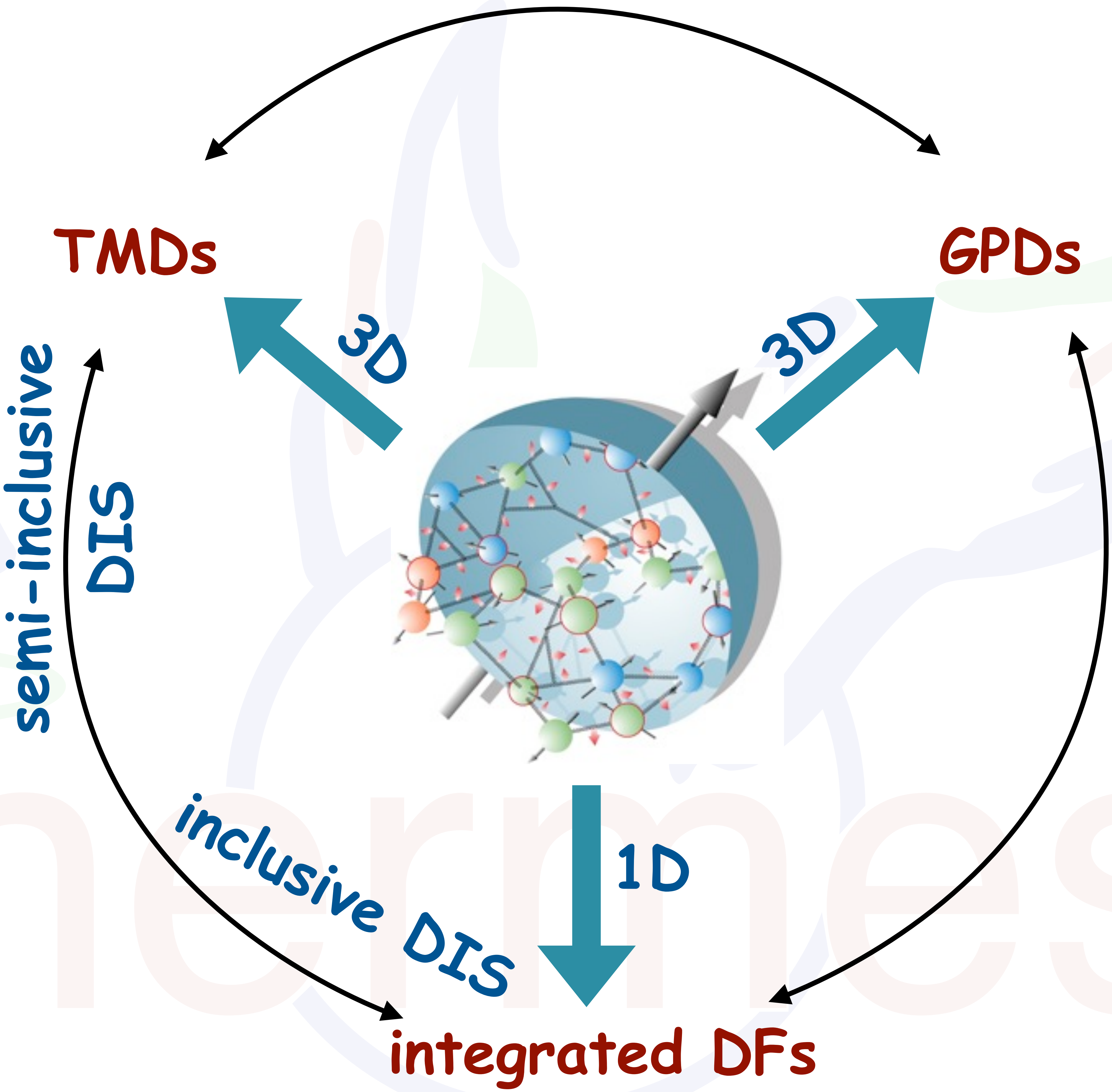


TMDs

GPDs

3D

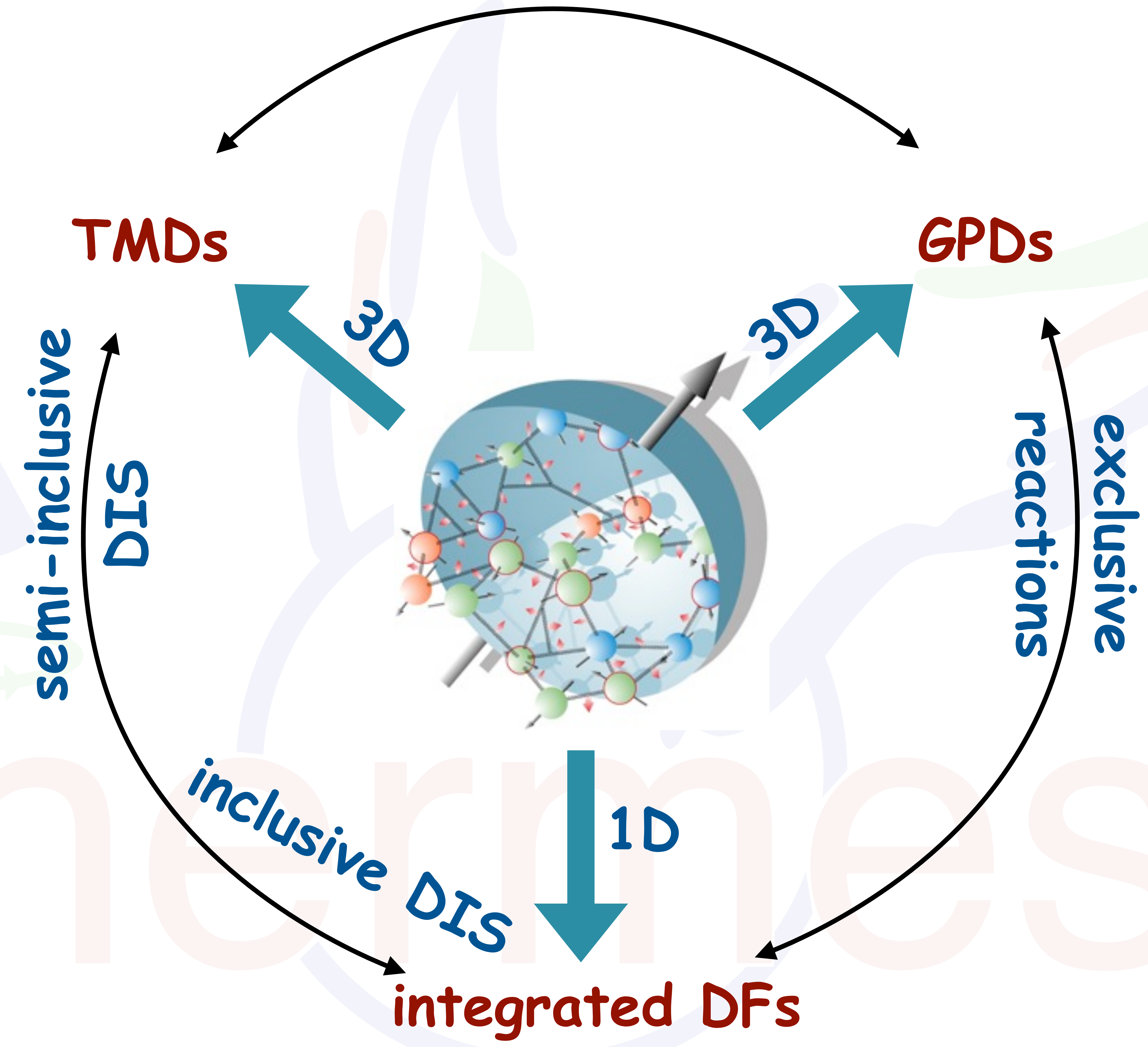
3D

1D

semi-inclusive DIS

inclusive DIS

integrated DFs



TMDs

GPDs

3D

3D

1D

semi-inclusive DIS

exclusive reactions

inclusive DIS

integrated DFs

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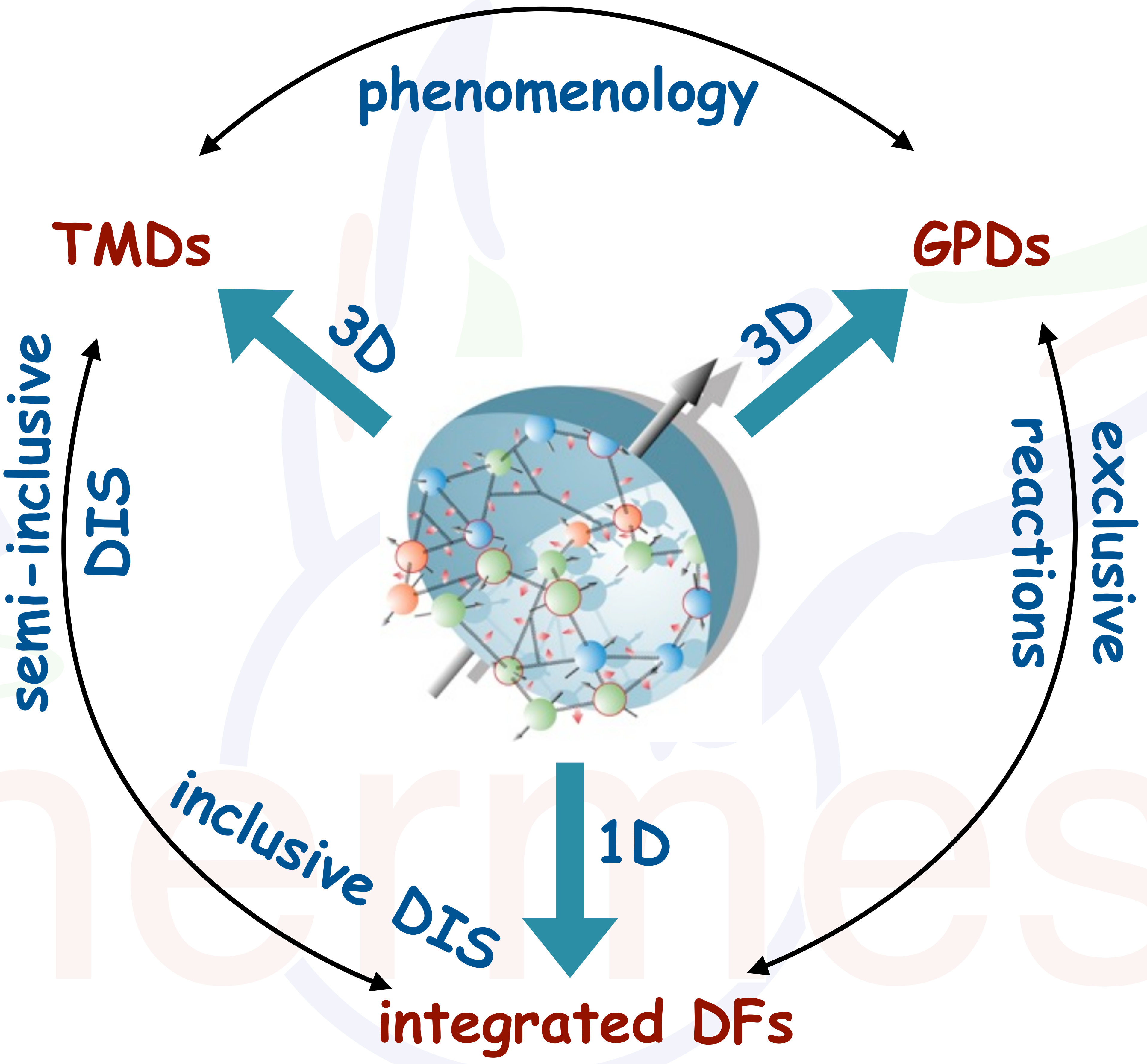
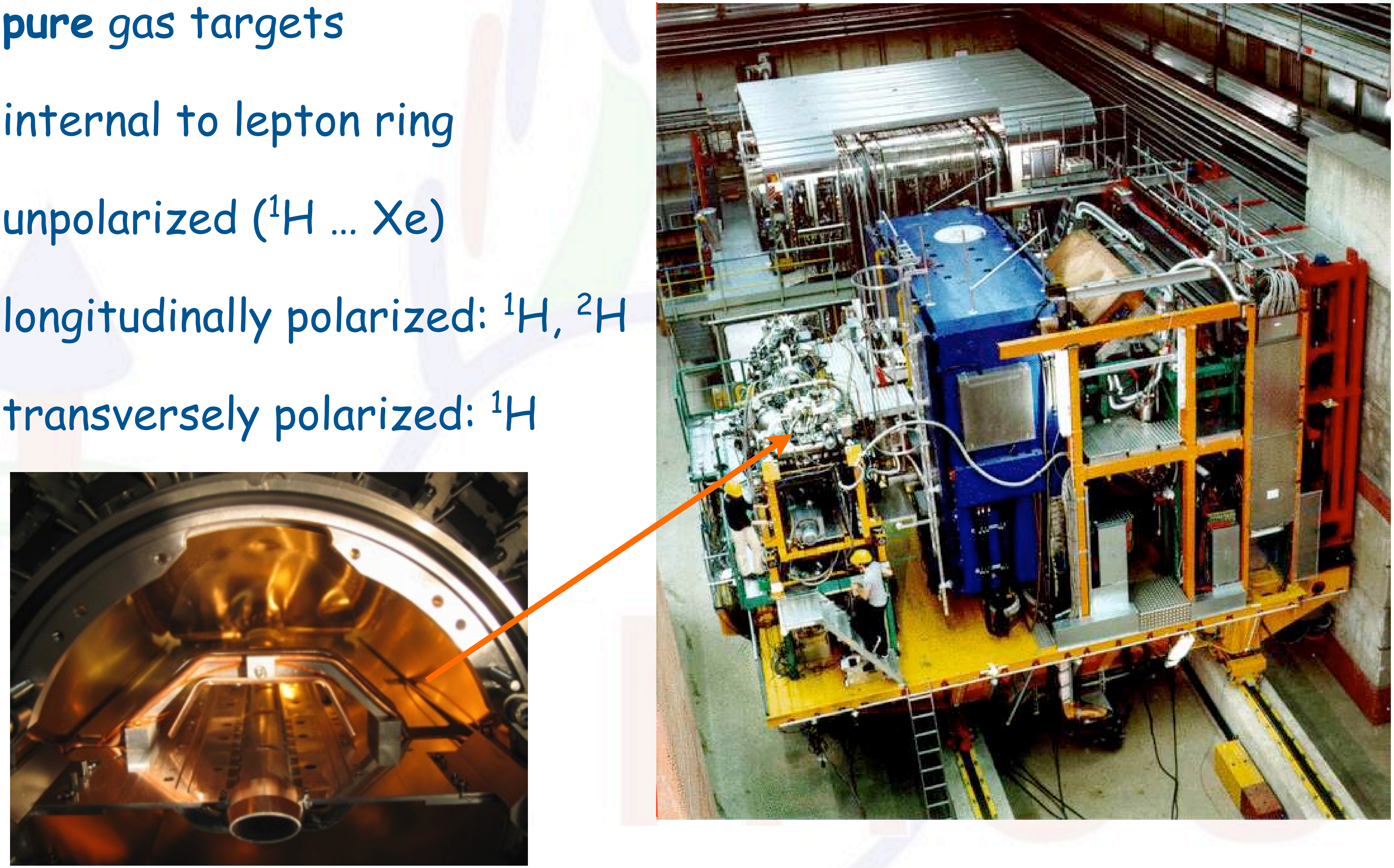
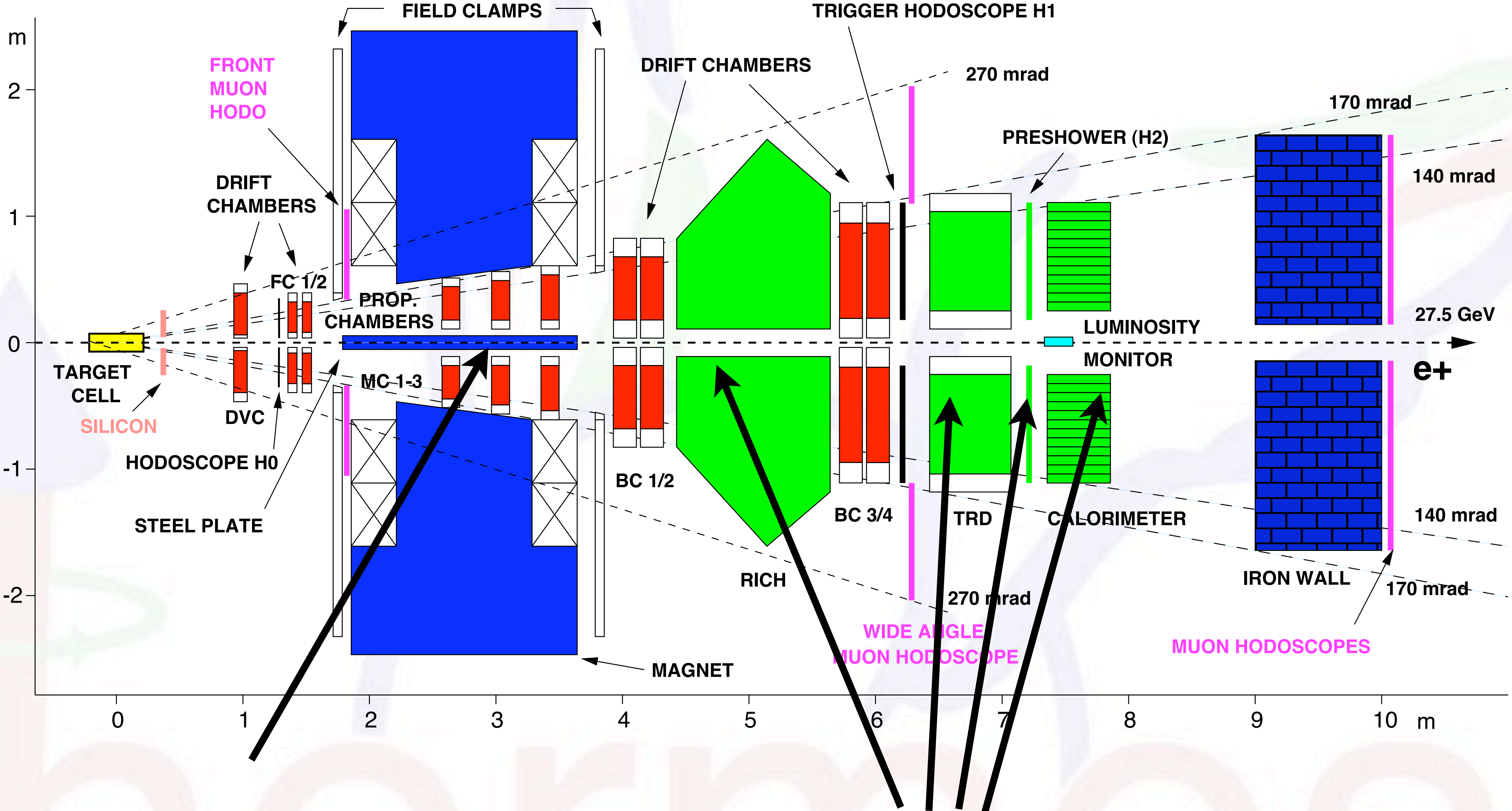

phenomenology
TMDs
GPDs
3D
3D
semi-inclusive DIS
exclusive reactions
1D
inclusive DIS
integrated DFs

The HERMES Detector (°1995, †2007)

- **pure** gas targets
- internal to lepton ring
- unpolarized (^{1}H … Xe)
- longitudinally polarized: ^{1}H, ^{2}H
- transversely polarized: ^{1}H



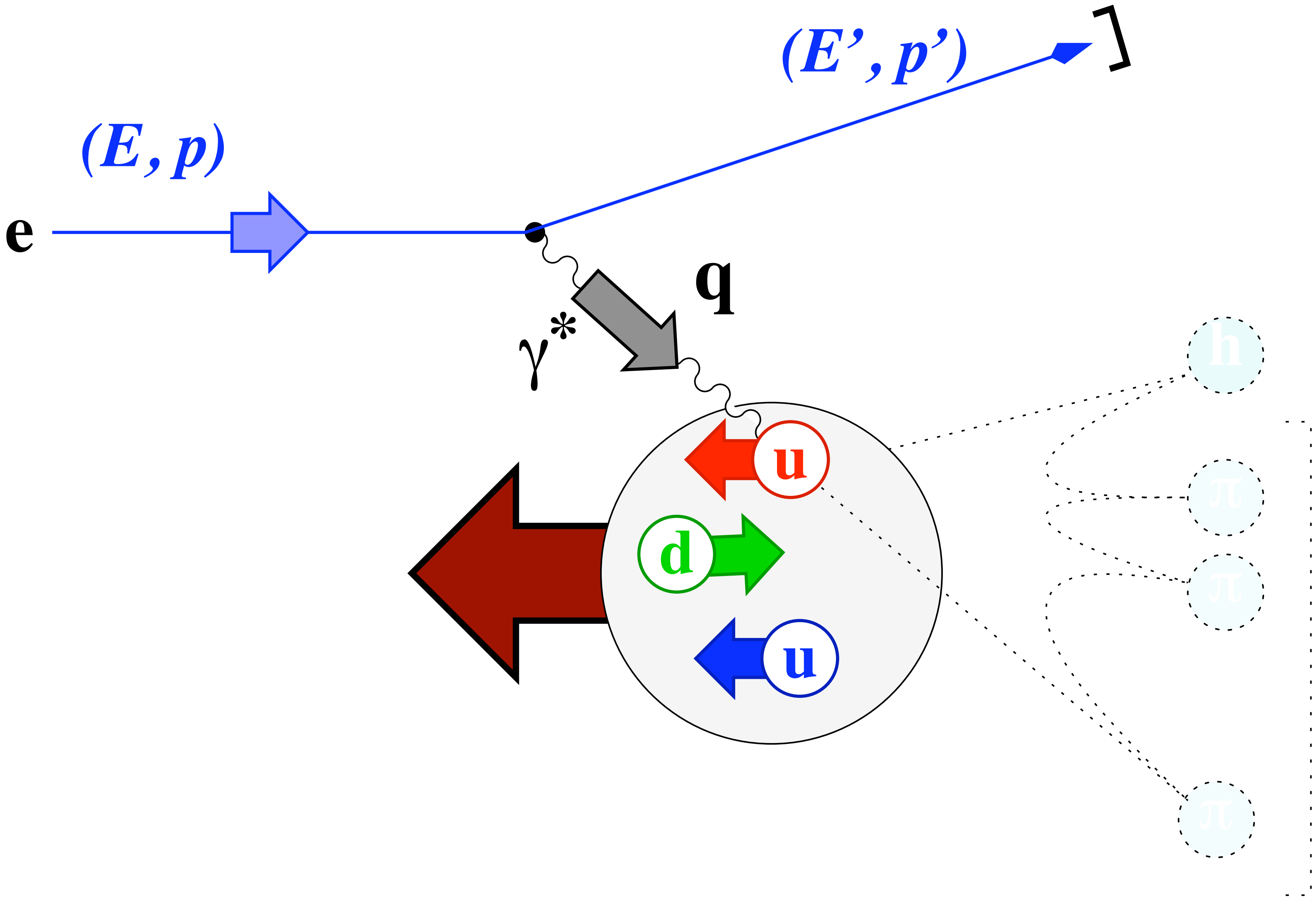
HERMES schematically



two (mirror-symmetric) halves -> no homogenous azimuthal coverage

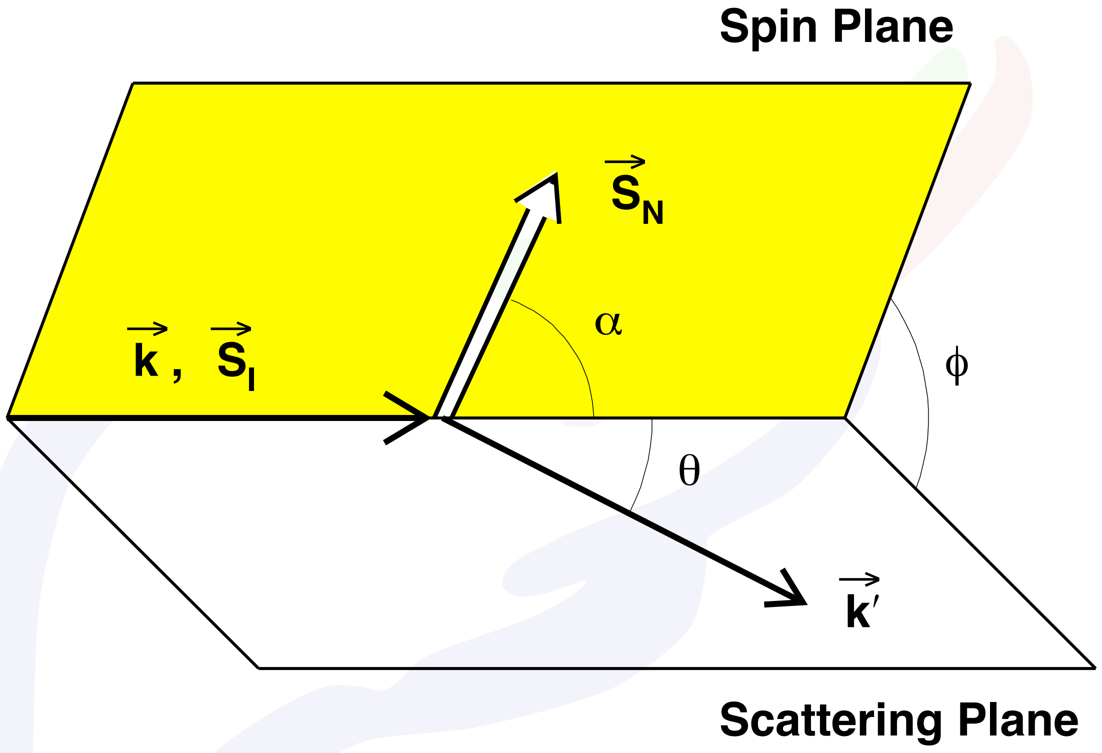
Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

Inclusive DIS



Inclusive DIS

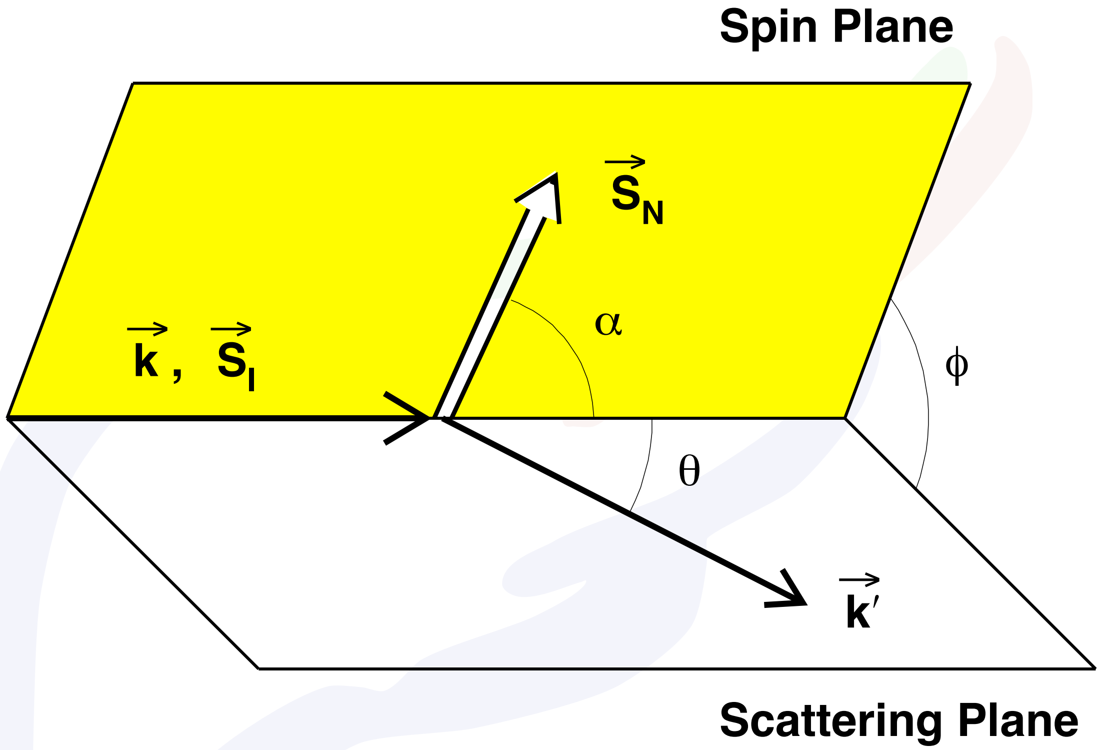
$$\frac{d^2\sigma(s,S)}{dx\ dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$



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



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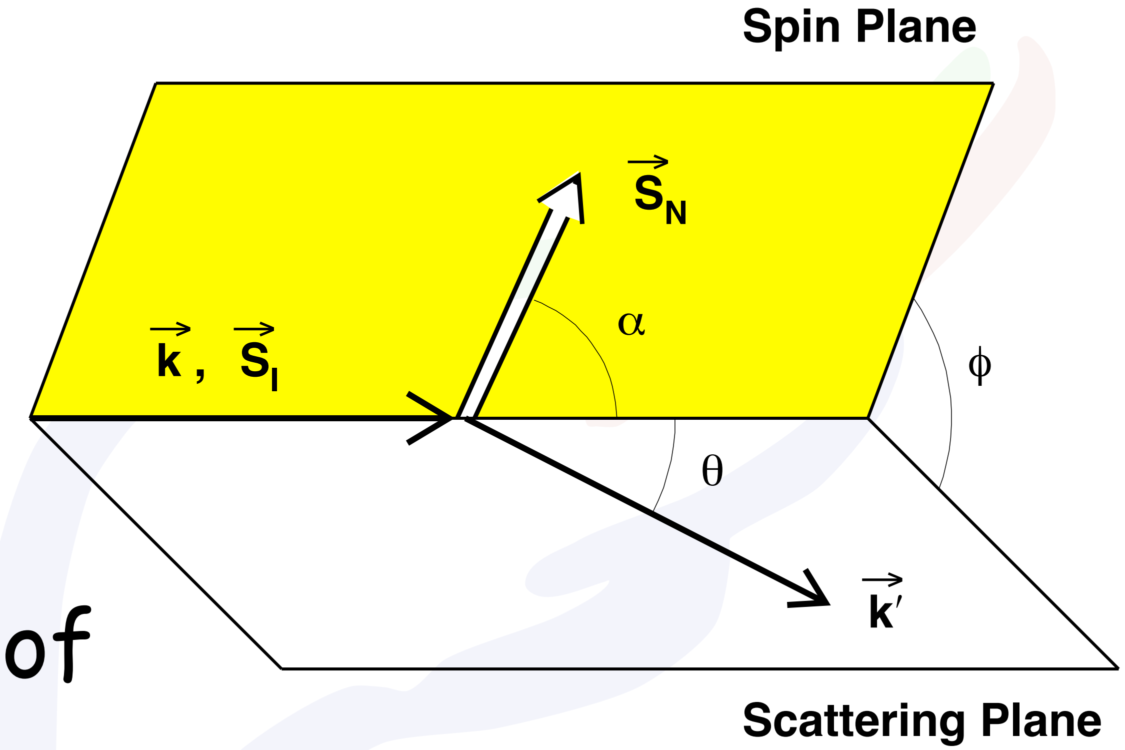
$$\frac{d^2\sigma(s,S)}{dx\ dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$

Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions

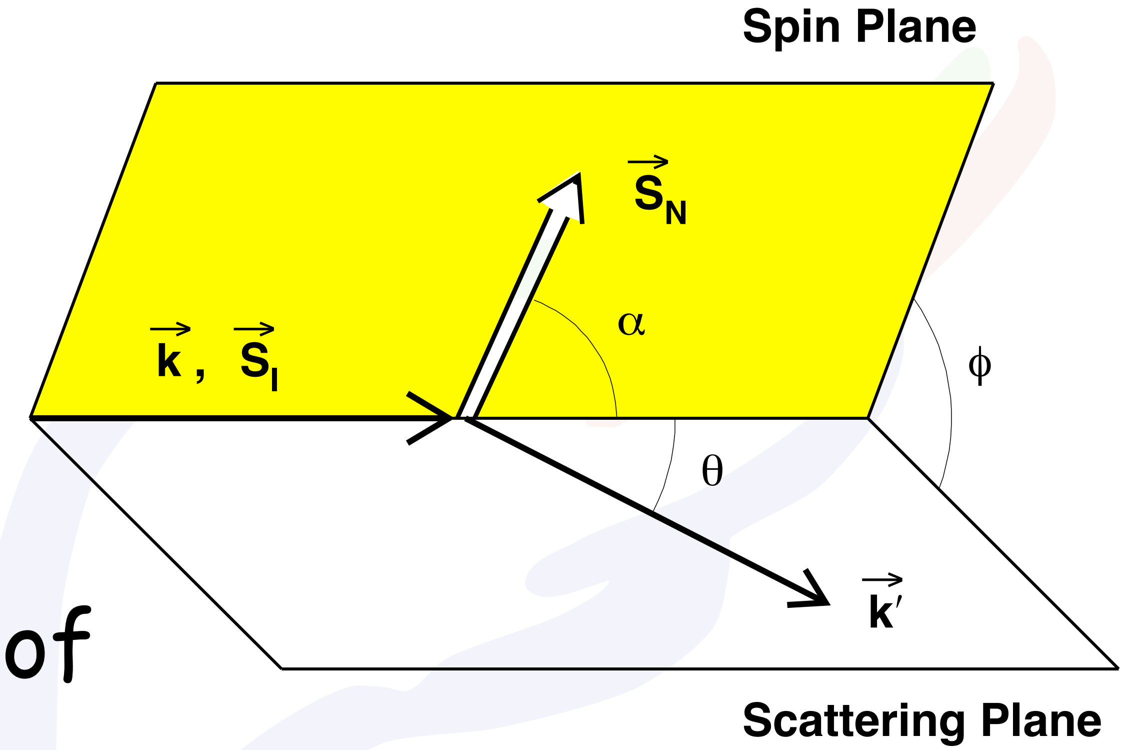


Inclusive DIS

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

Lepton Tensor

Hadron Tensor parametrized in terms of Structure Functions



$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}\boxed{F_1(x,Q^2)} + \frac{1-y-\gamma^2y^2/4}{2xy}\boxed{F_2(x,Q^2)}$$

$$-P_l P_T \cos\alpha\left[\left(1-\frac{y}{2}-\frac{\gamma^2y^2}{4}\right)\boxed{g_1(x,Q^2)} - \frac{\gamma^2 y}{2}\boxed{g_2(x,Q^2)}\right]$$

$$+P_l P_T \sin\alpha\cos\phi\,\gamma\sqrt{1-y-\frac{\gamma^2y^2}{4}}\left(\frac{y}{2}\boxed{g_1(x,Q^2)}+\boxed{g_2(x,Q^2)}\right)$$

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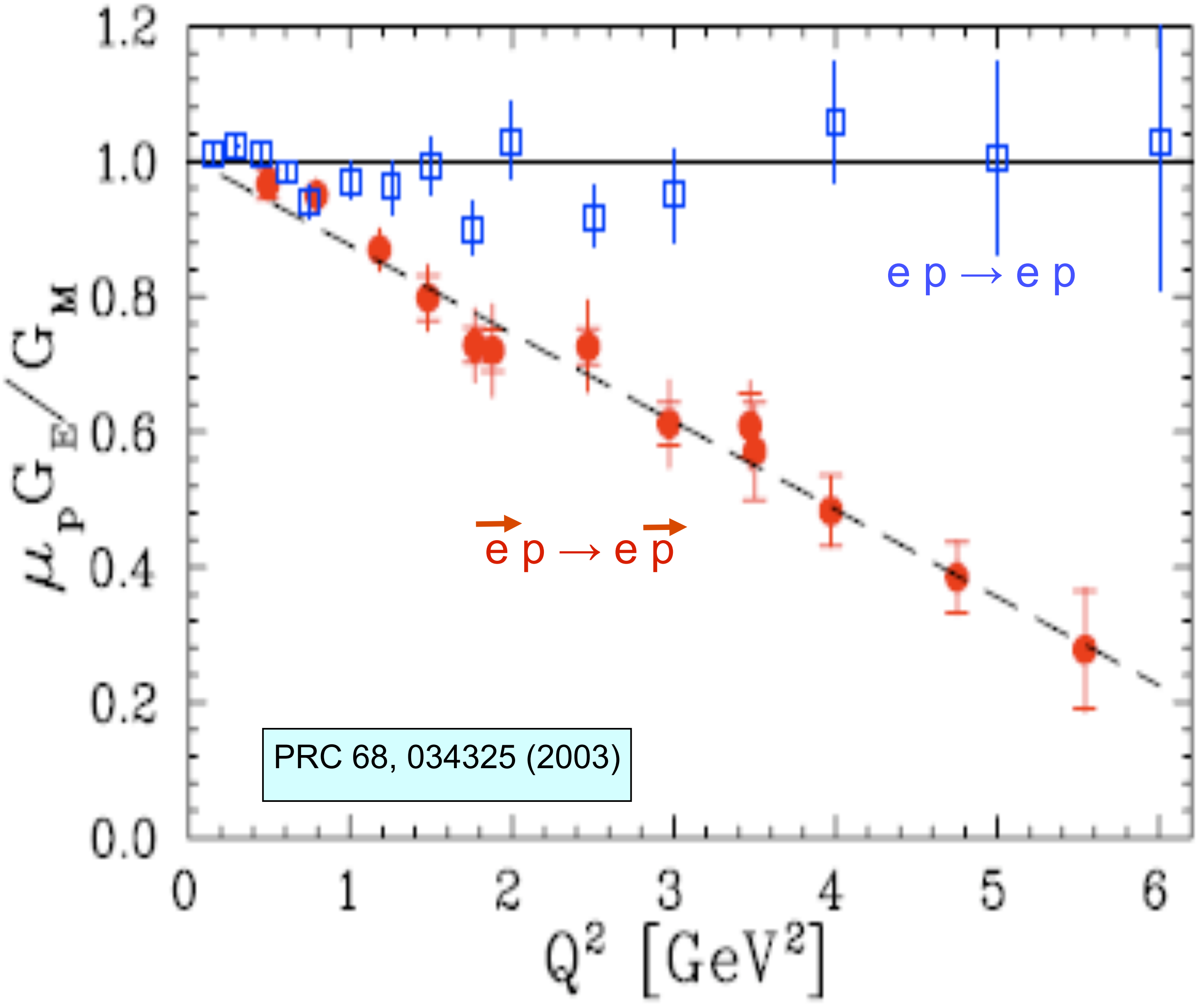
Check the details!

Check the details!

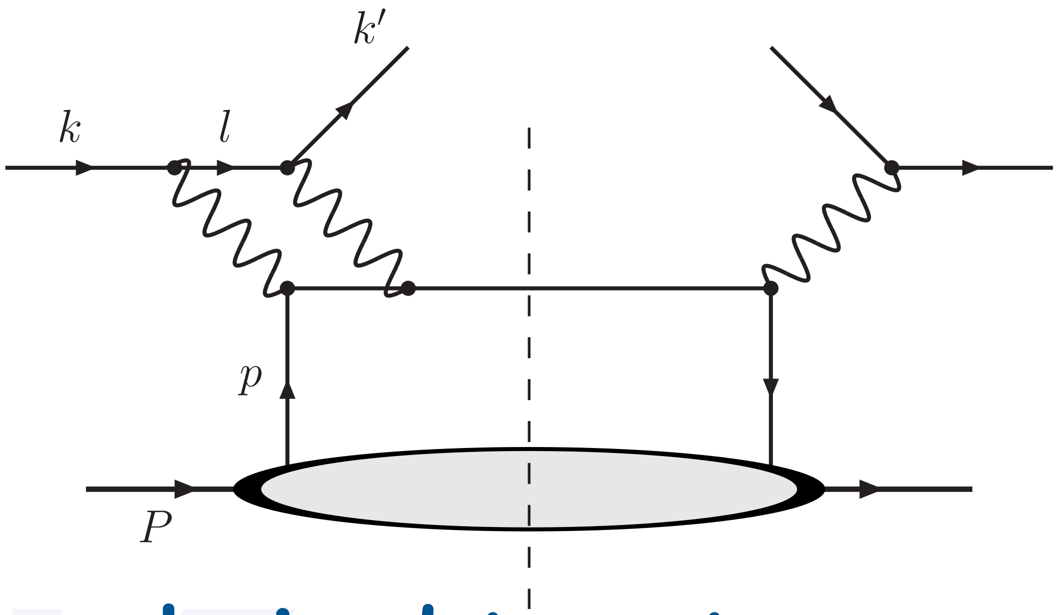


x_F

☛ **two-photon exchange important?!**

Two-photon exchange

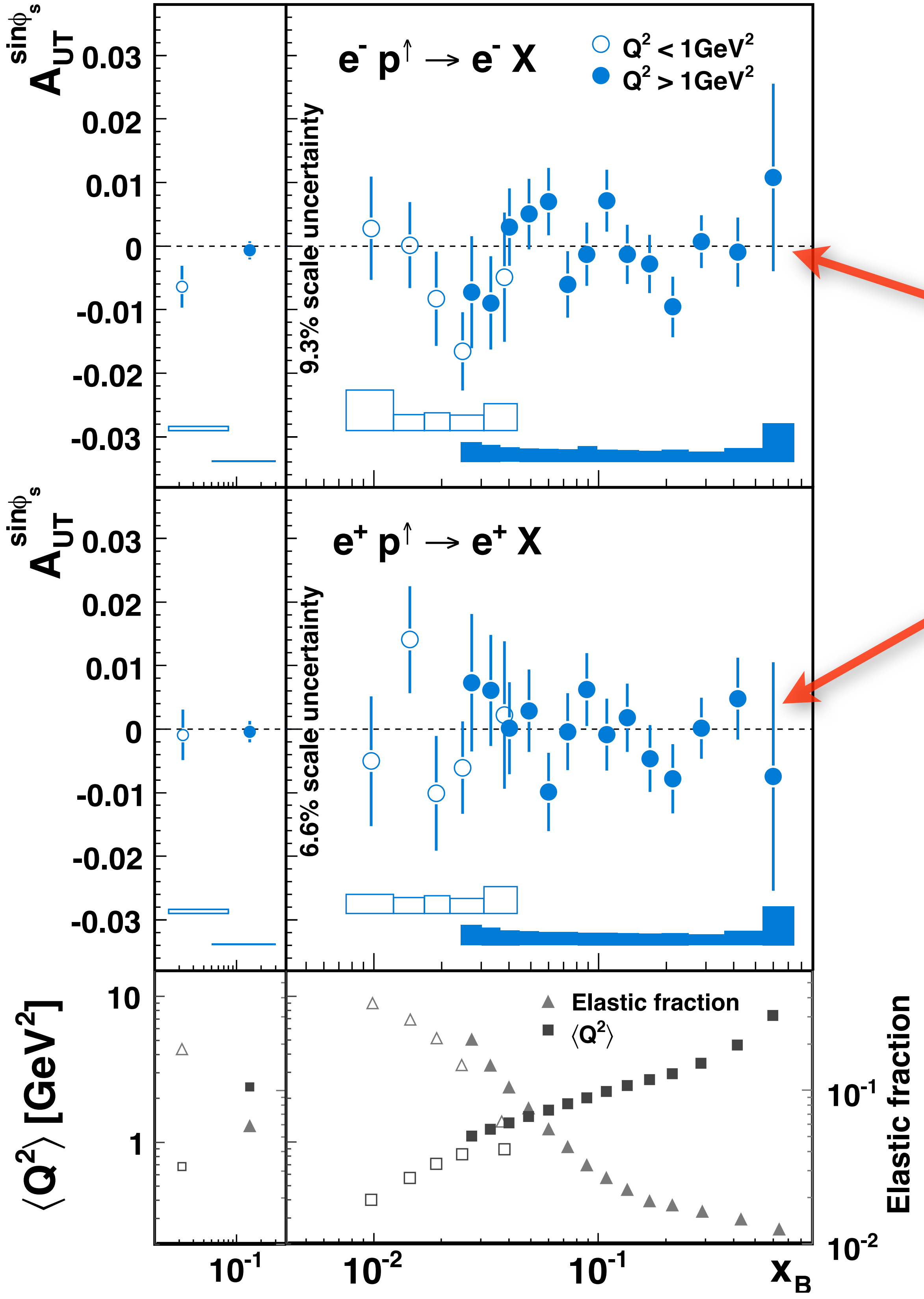
- Candidate to explain discrepancy in form-factor measurements
- Interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets



- cross section proportional to S(kxk') - either measure left-right asymmetries or sine modulation
- sensitive to beam charge due to odd number of e.m. couplings to beam

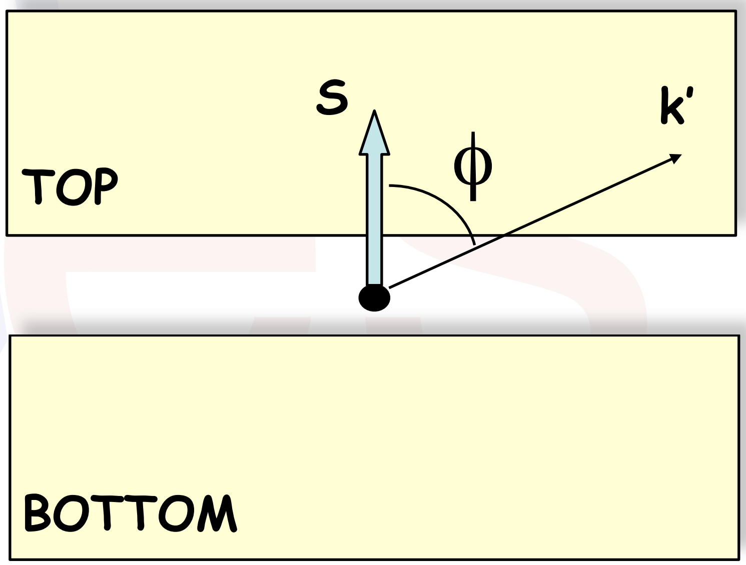
No sign of two-photon exchange

A. Airapetian et al. [HERMES], PLB 682 (2010) 350

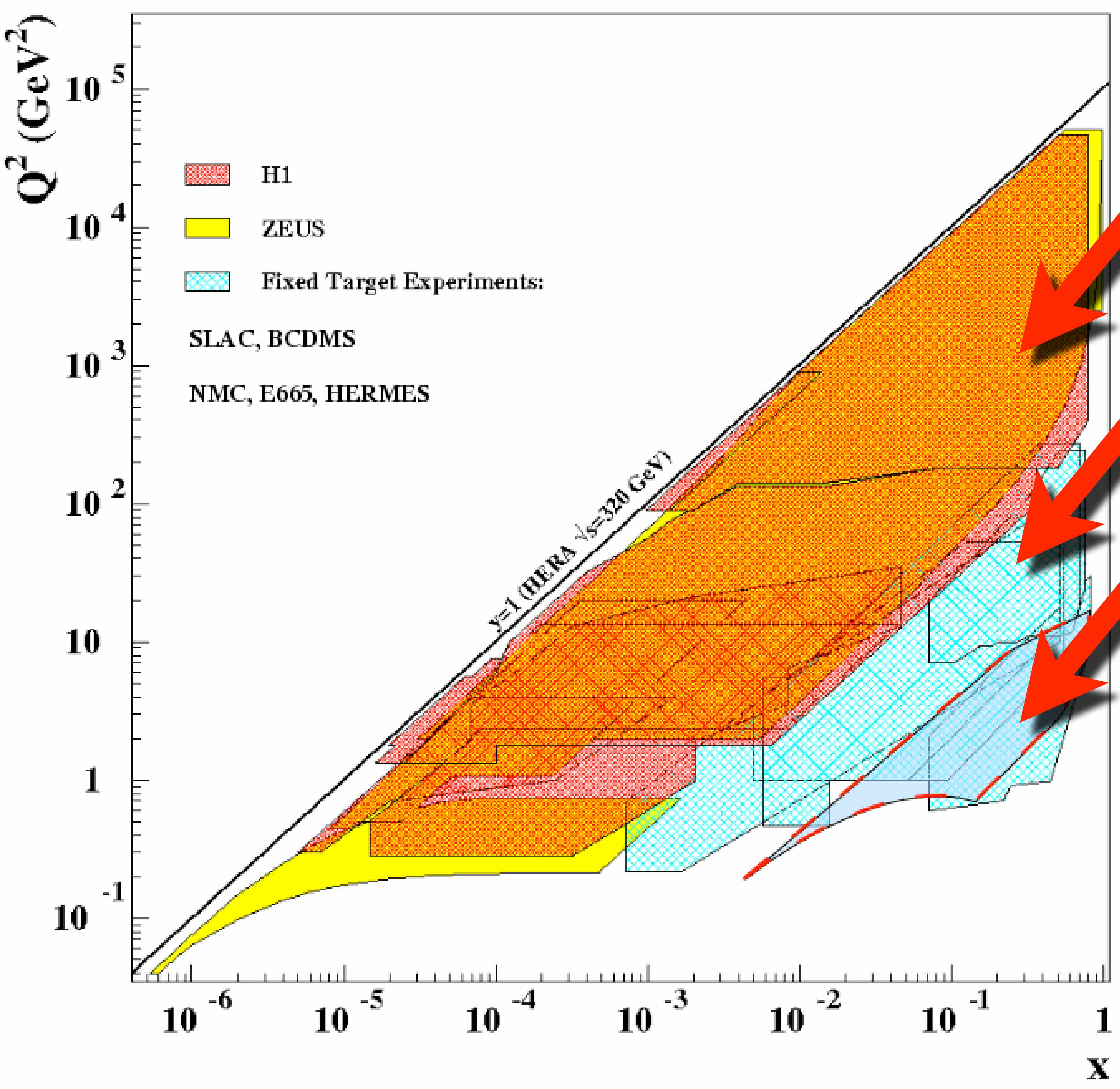


consistent with zero

Front view of HERMES detector



Why measure F_2 at HERMES?



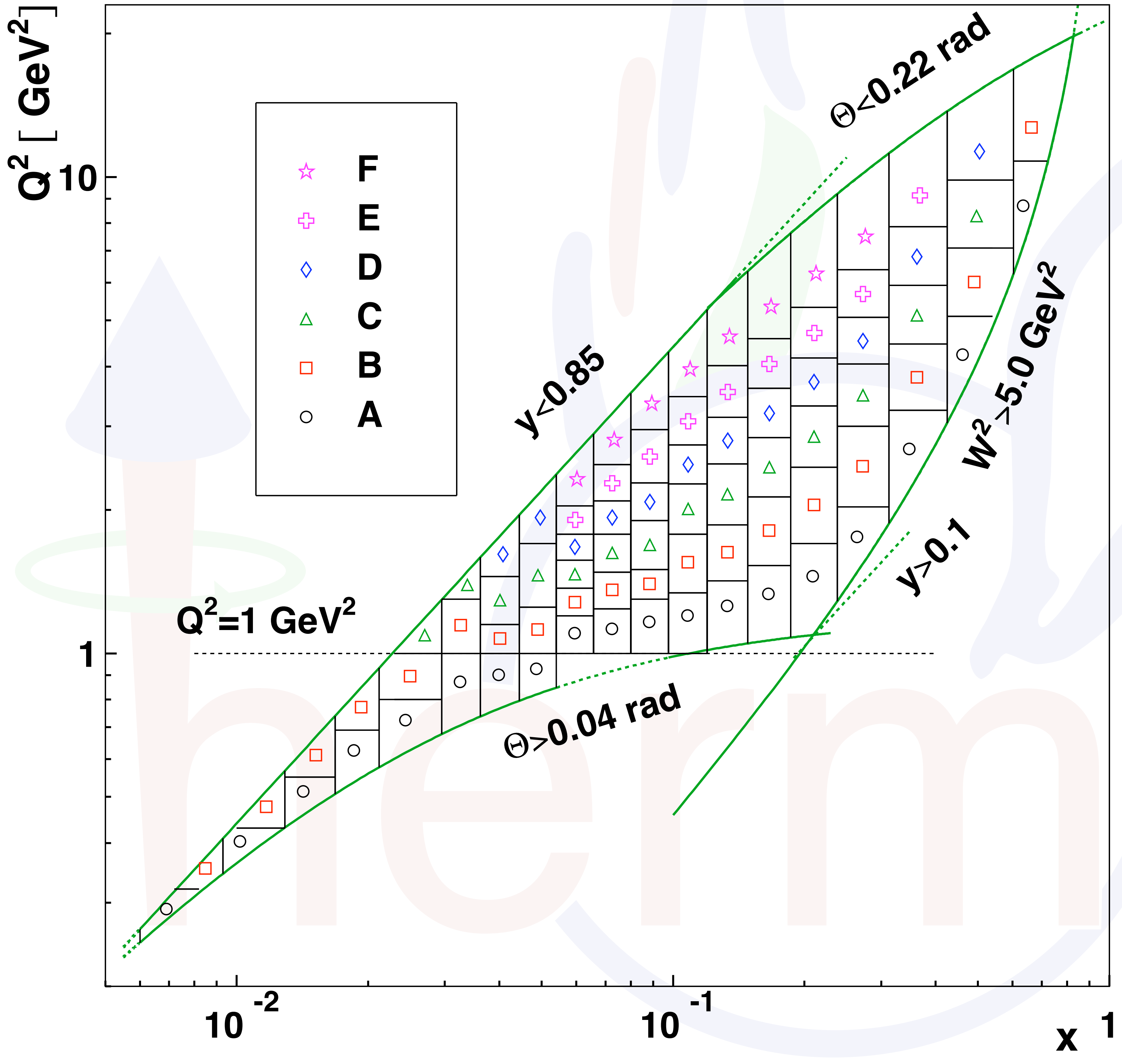
Collider experiments

Fixed target experiments

HERMES

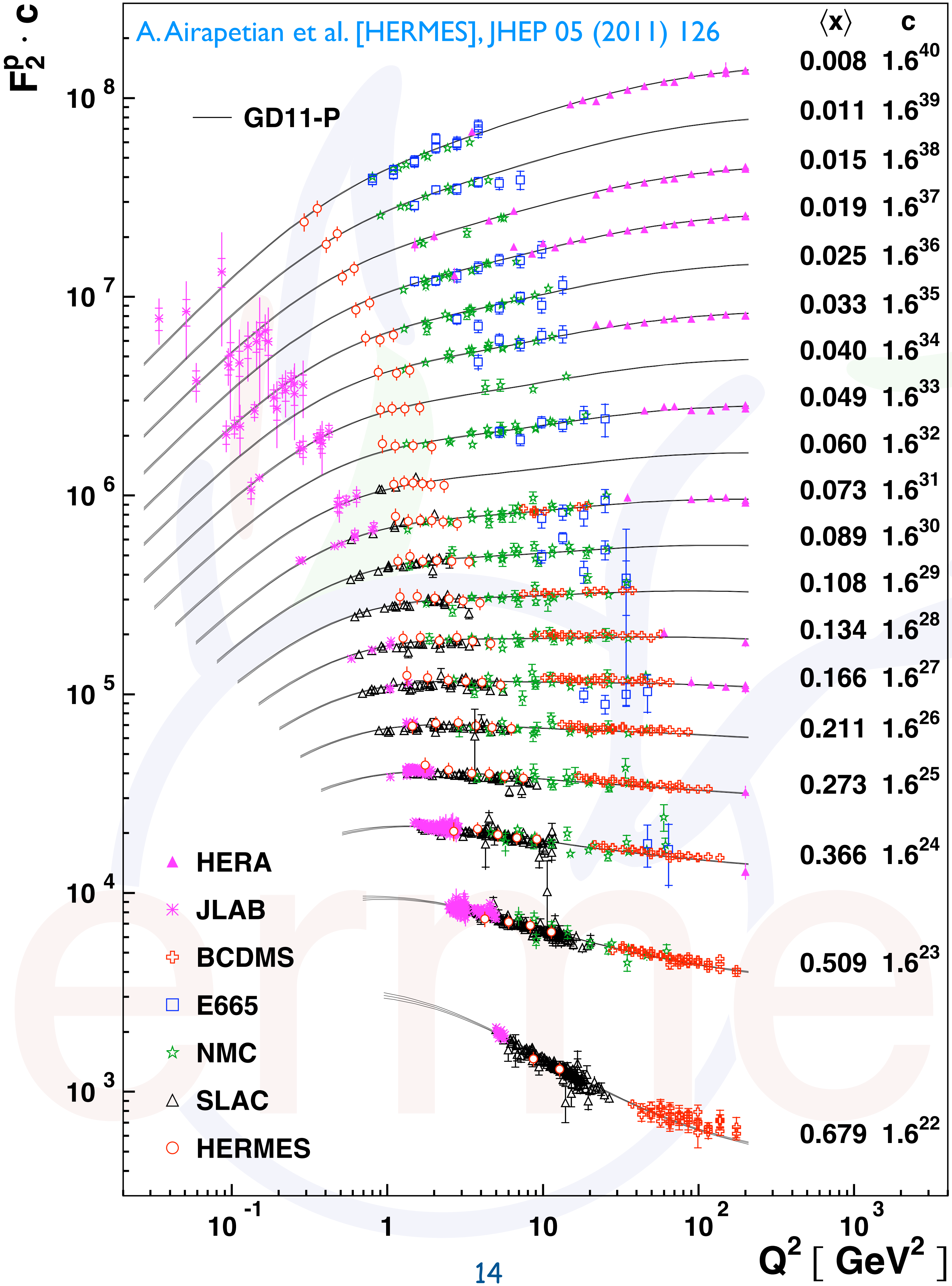
- complementary kinematic coverage compared to colliders
- direct info at HERMES kinematics
- higher statistics compared to other fixed target experiments:
  - HERMES: 58 million DIS (P+D)
  - NMC: 9 million DIS (P+D)

HERMES kinematic plane



binning used for F_2 and g_1

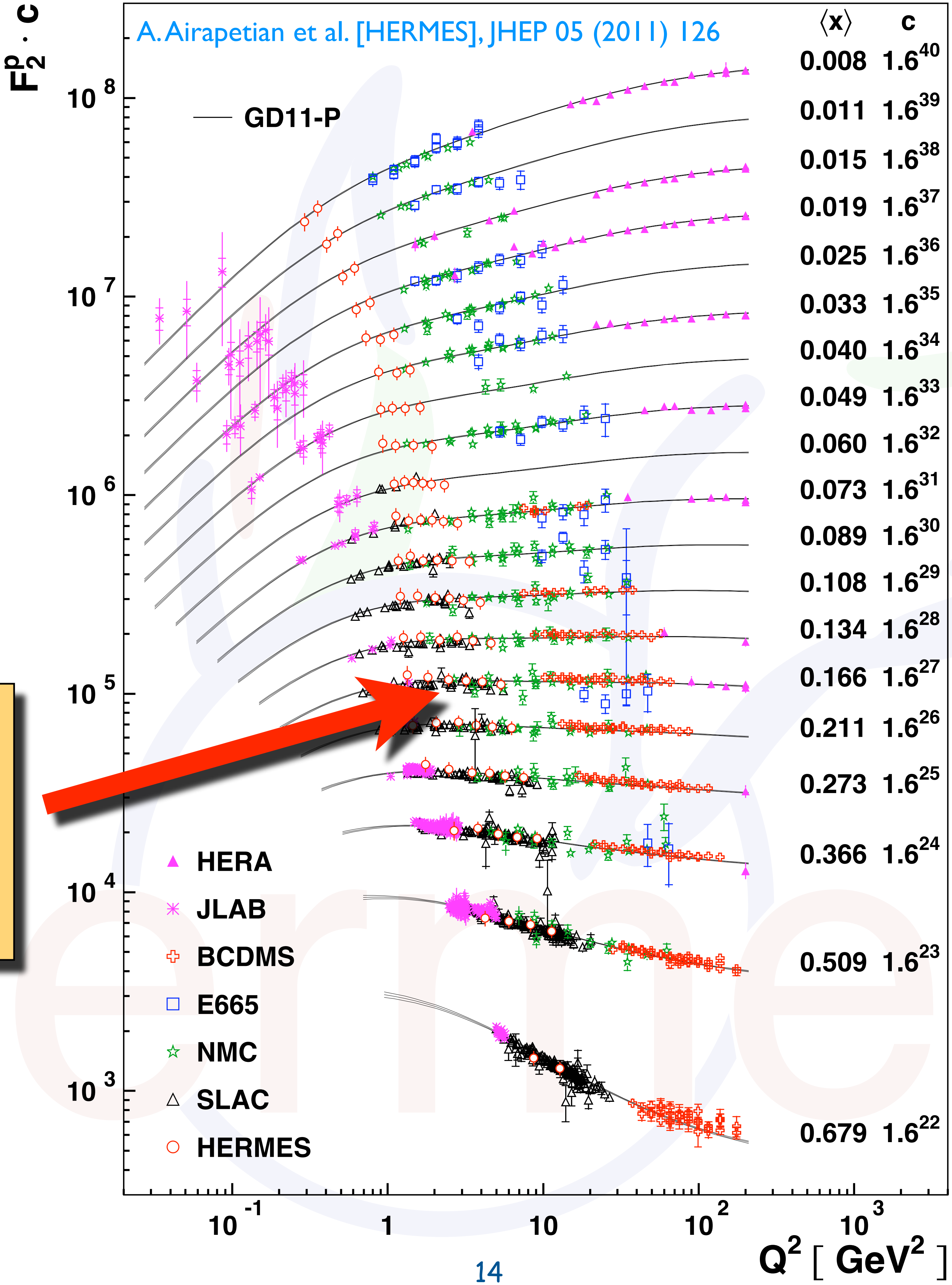
F_2 proton



GD11 - global fit

From global fit GD11:
HERMES relative normalization is
~2% for Proton and Deuteron
~0.5% for the Ratio

F_2 proton



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HERMES relative normalization is
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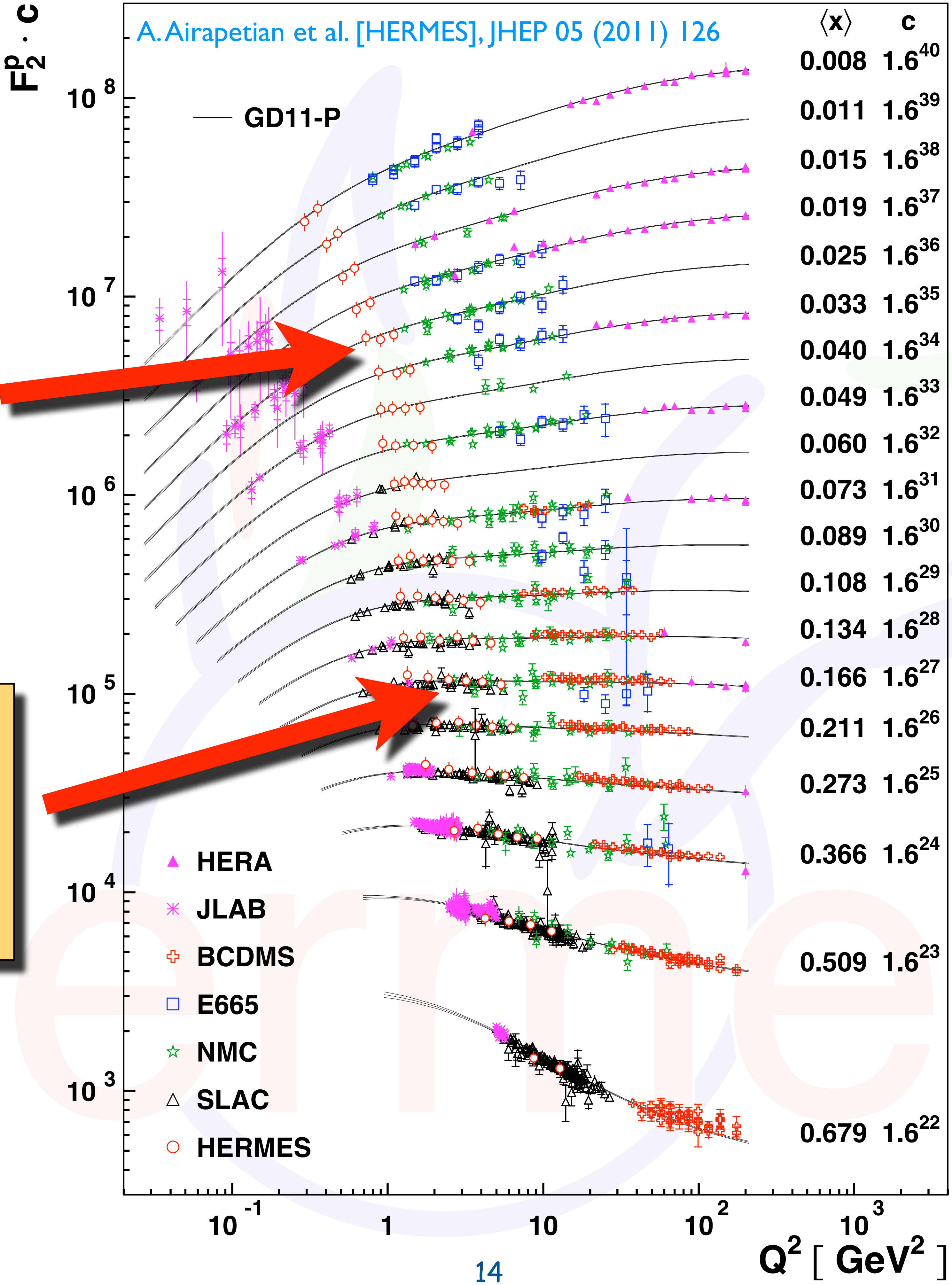
~0.5% for the Ratio

Agreement with world data in the overlap region

F_2 proton

New region covered by HERMES

Agreement with world data in the overlap region



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F_2 deuteron

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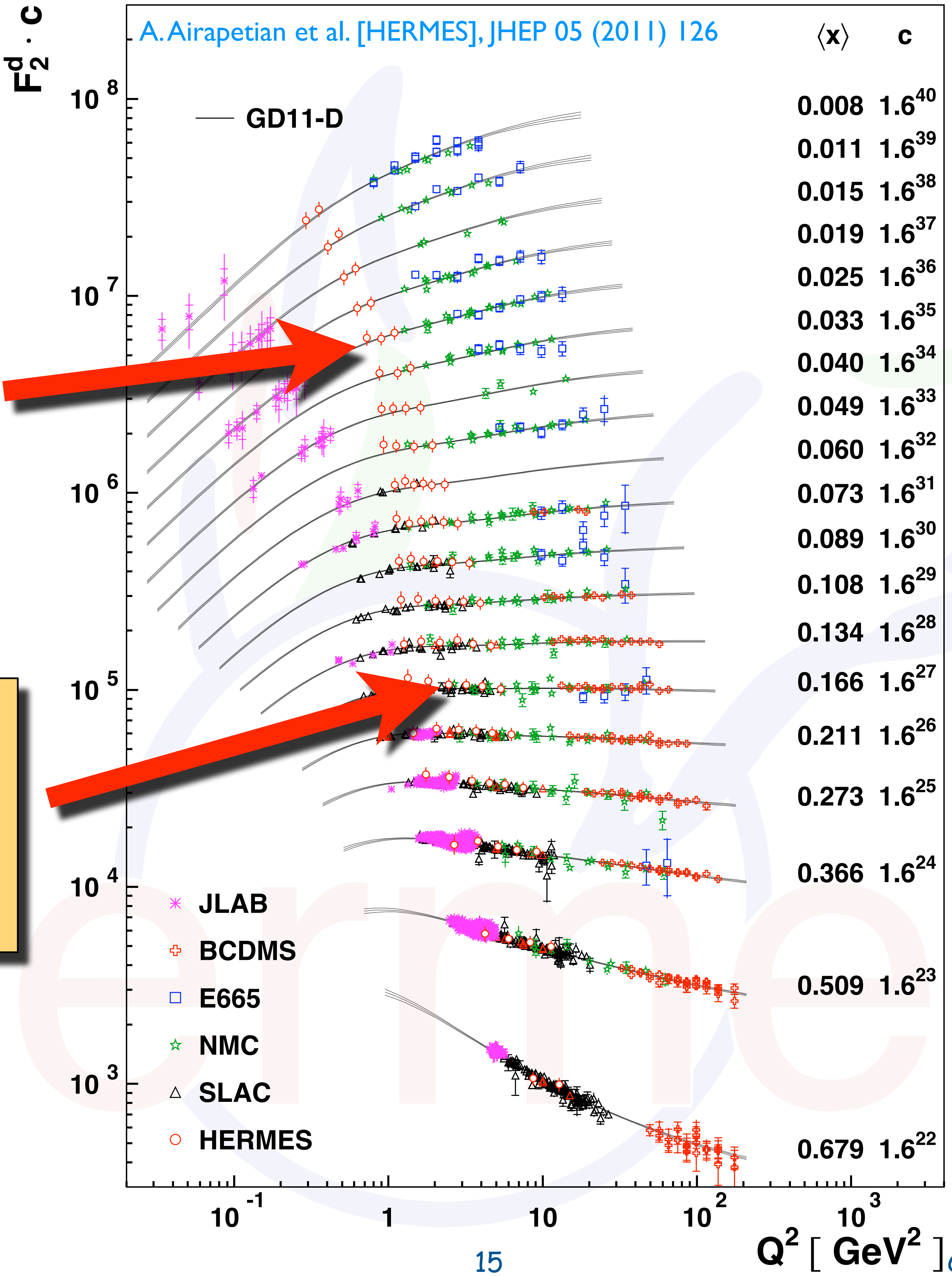
Agreement with world data in the overlap region



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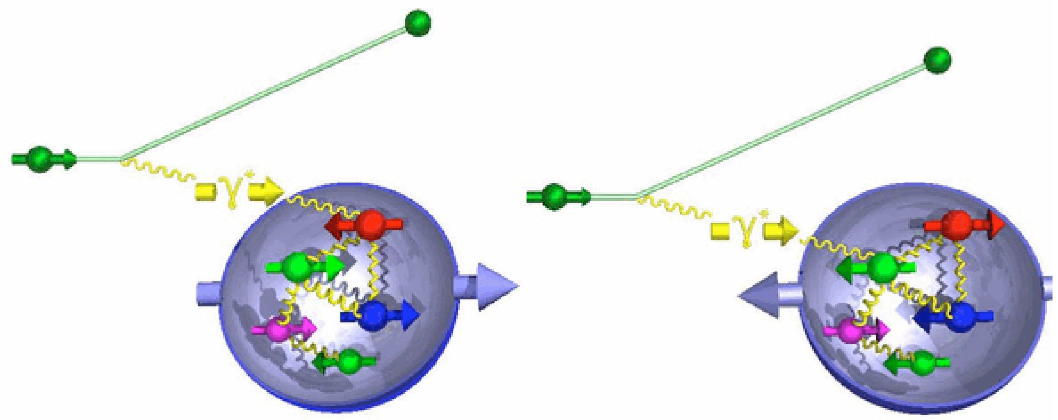
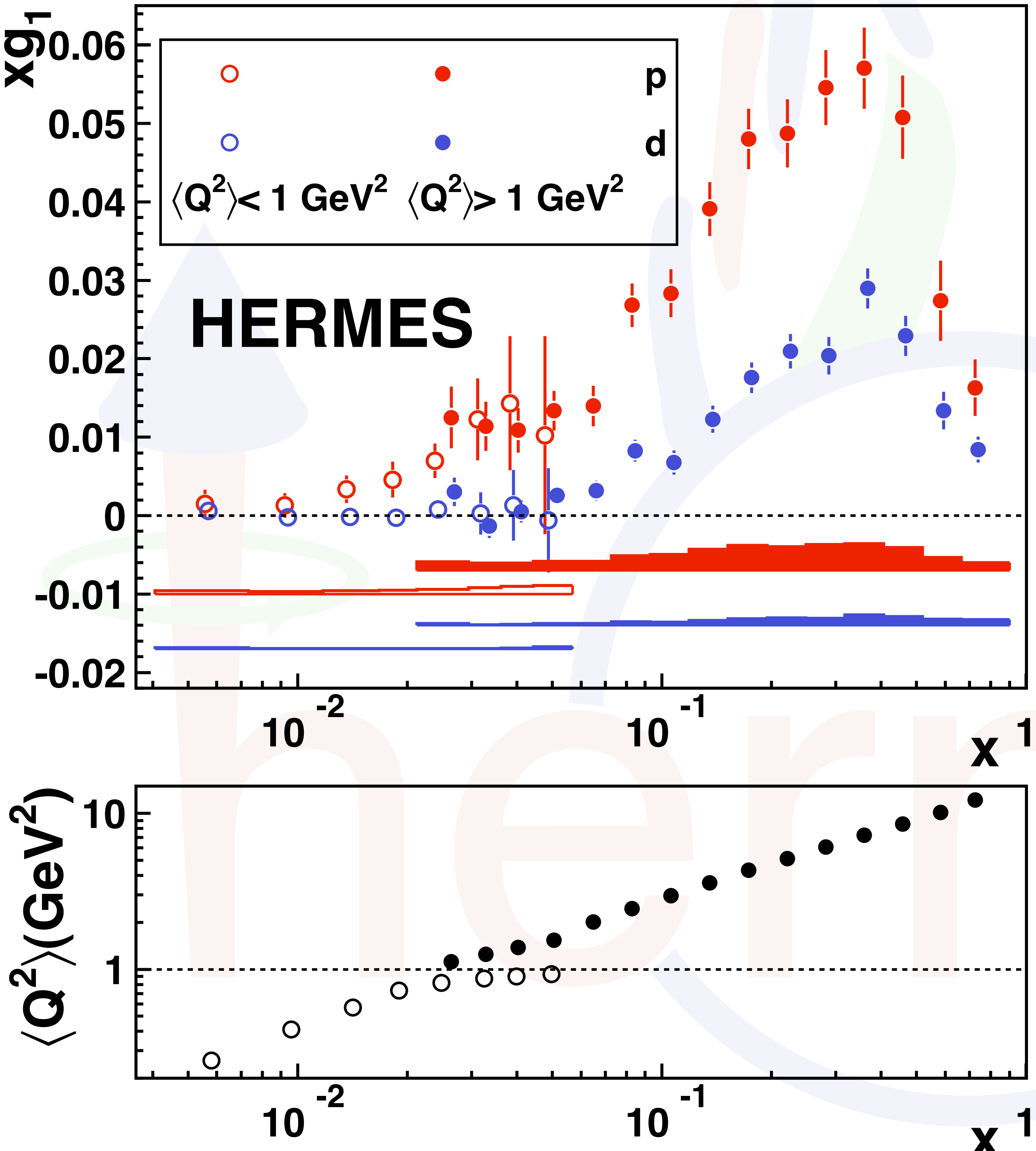
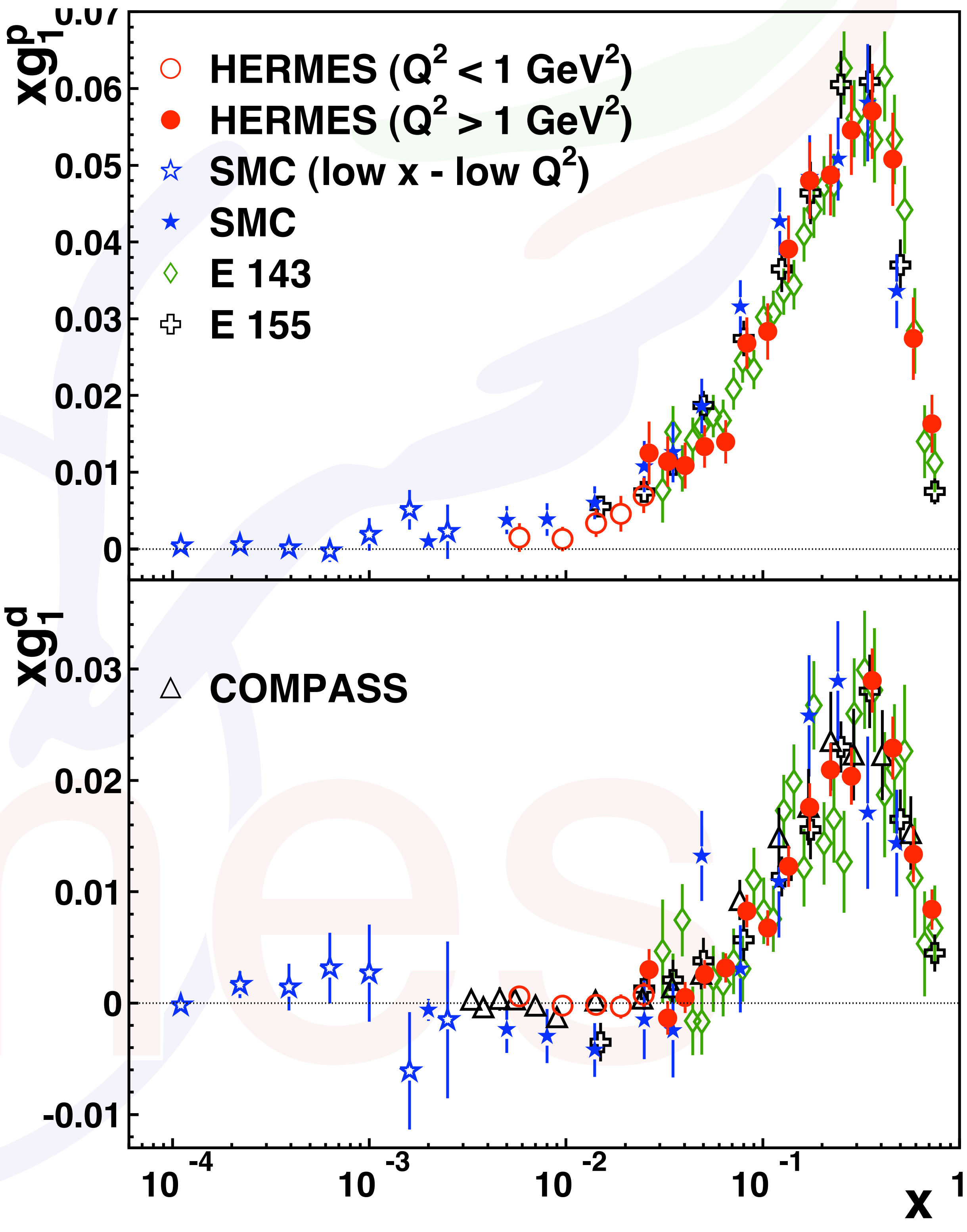
Polarized SF g_1





A. Airapetian et al. [HERMES], PRD 75 (2007)



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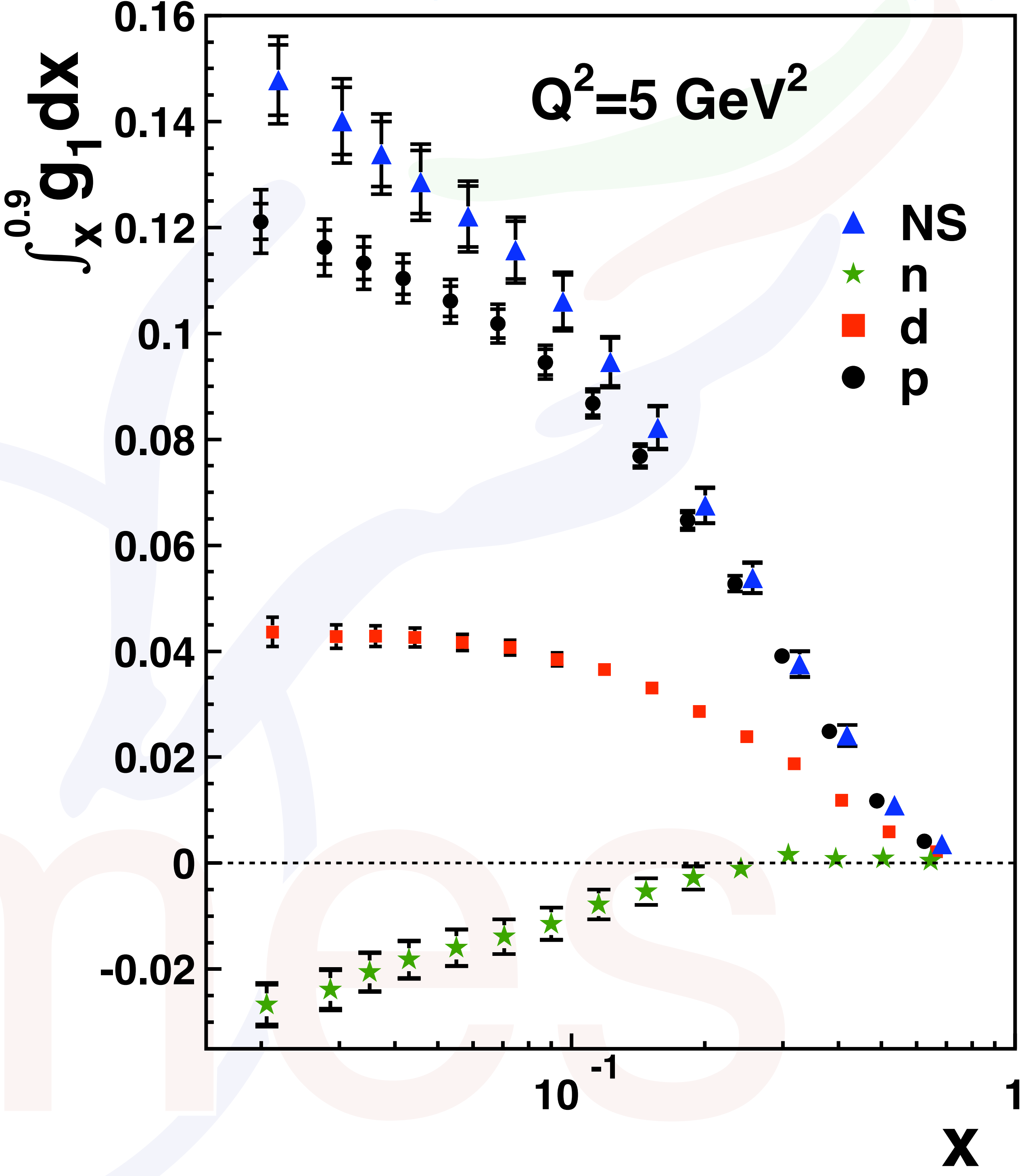
Integral of $g_1(x)$

A. Airapetian et al. [HERMES], PRD 75 (2007)



Integral of $g_1(x)$

Saturation

➠ close to full integral?

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

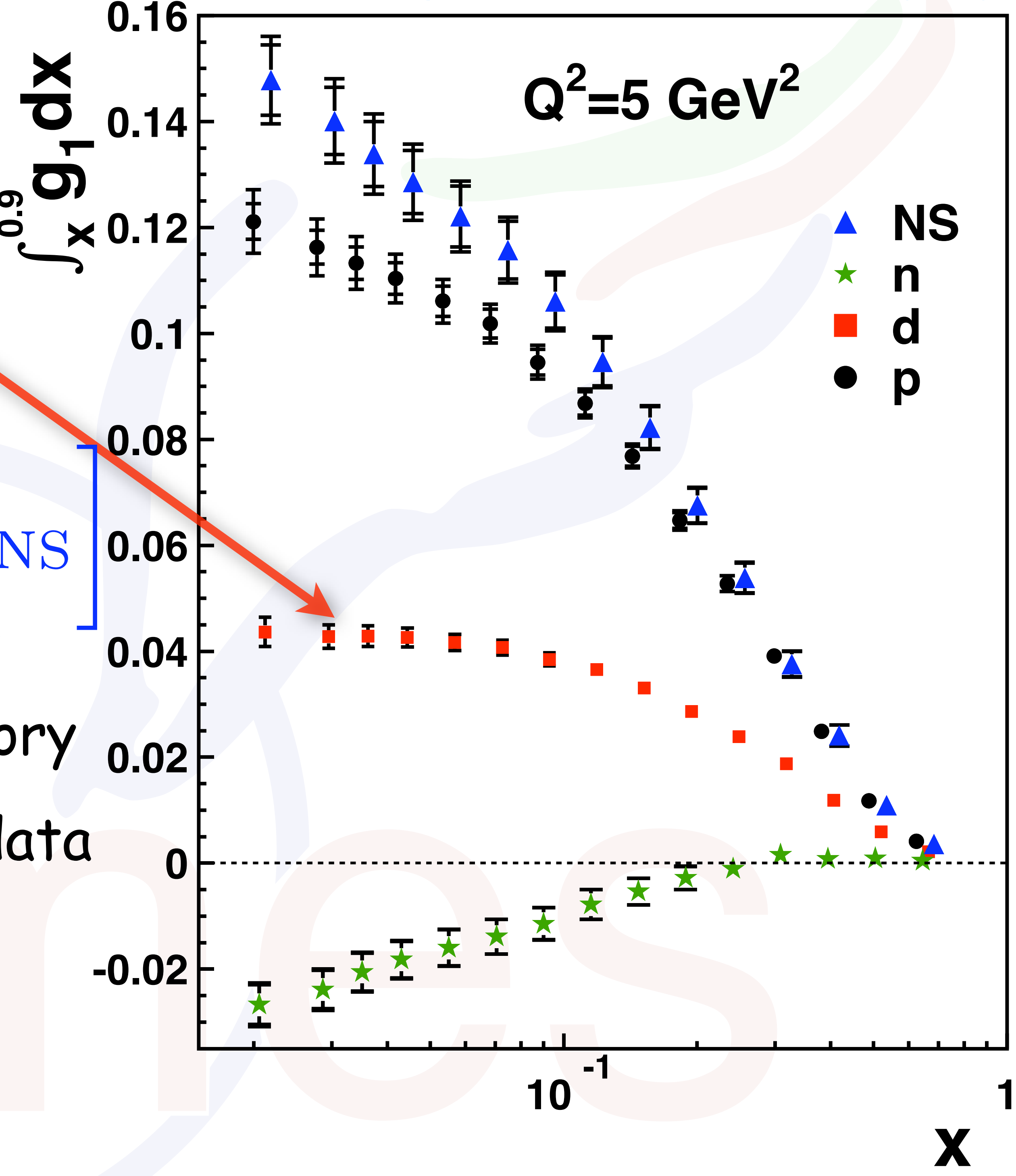
↑ theory

↑ 0.05±0.05

↑ hyperon-decay data

↑ theory

A. Airapetian et al. [HERMES], PRD 75 (2007)



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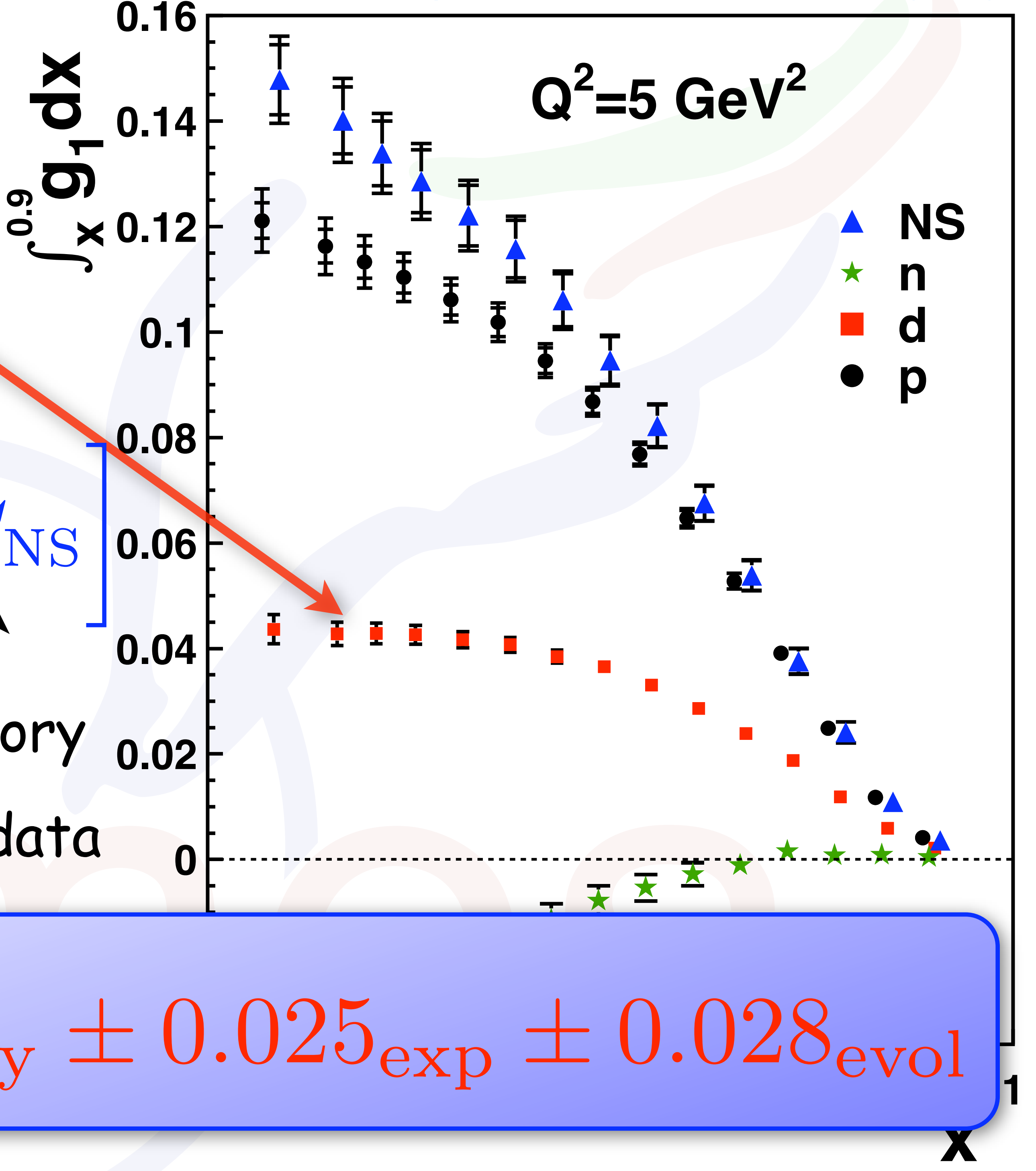

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$$\Delta\Sigma \overset{\overline{\mathrm{MS}}}{=} 0.330 \pm 0.011_{\mathrm{theory}} \pm 0.025_{\mathrm{exp}} \pm 0.028_{\mathrm{evol}}$$

Integral of $g_1(x)$

Saturation

➟ close to full integral?

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

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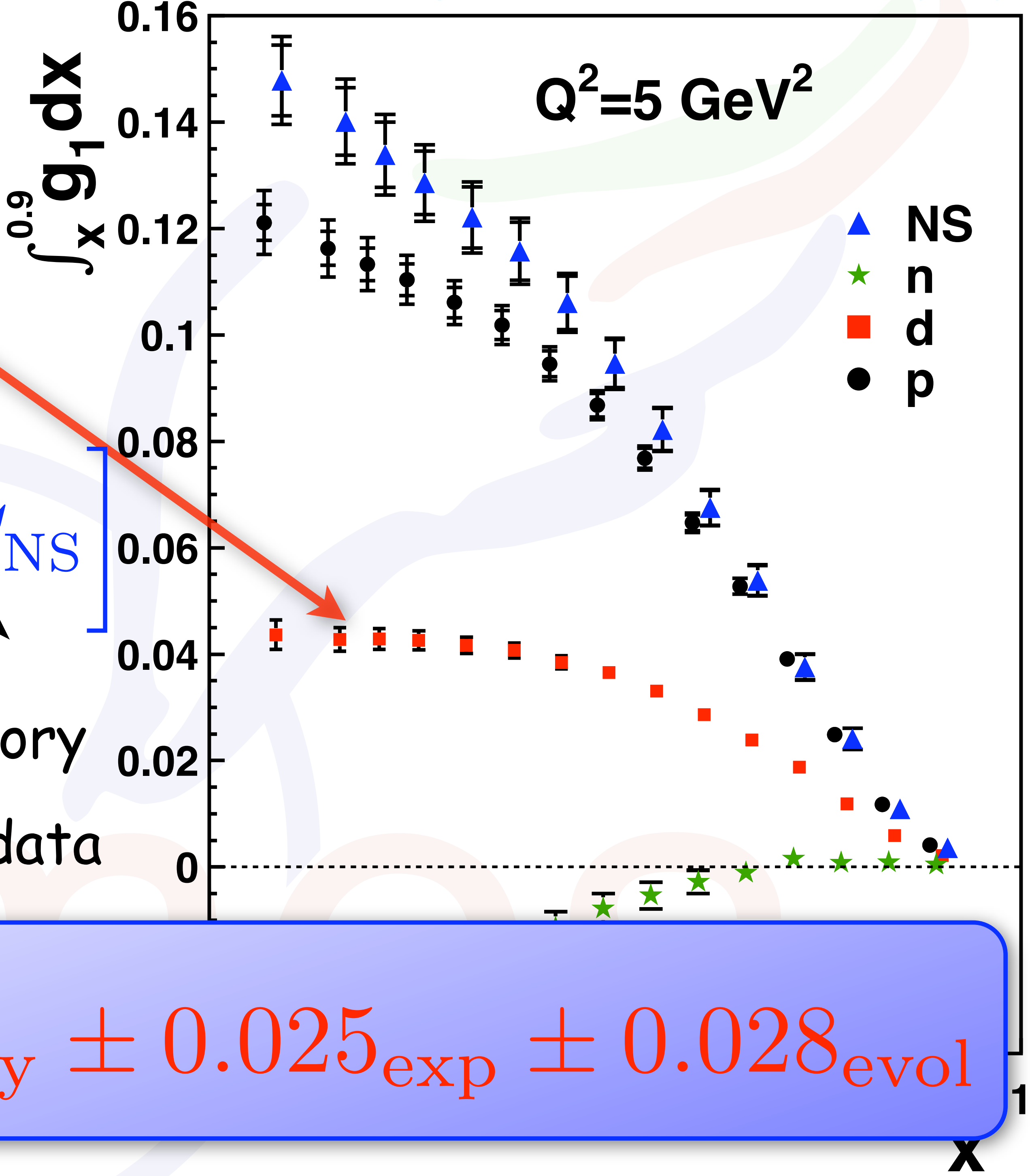
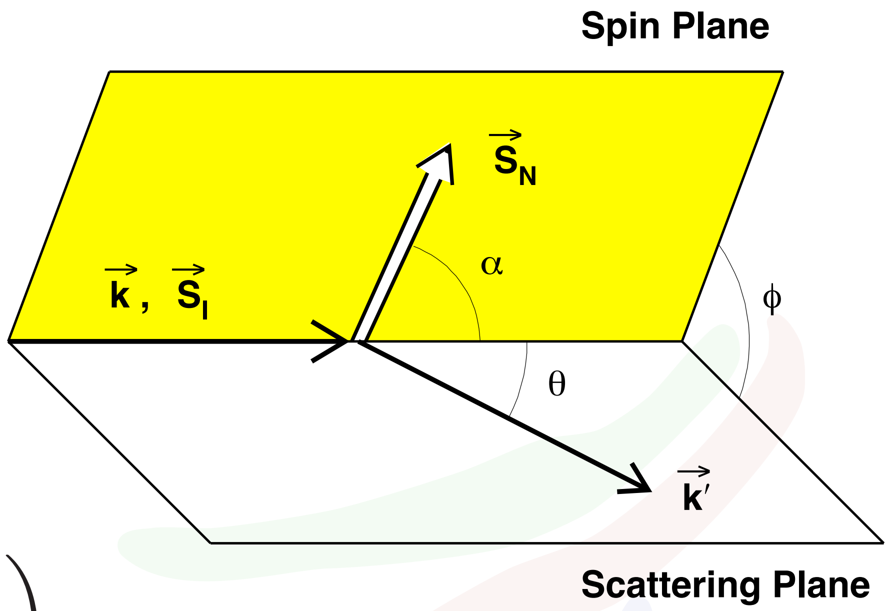


$$\Delta\Sigma \overset{\overline{\mathrm{MS}}}{=} 0.330 \pm 0.011_{\mathrm{theory}} \pm 0.025_{\mathrm{exp}} \pm 0.028_{\mathrm{evol}}$$

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

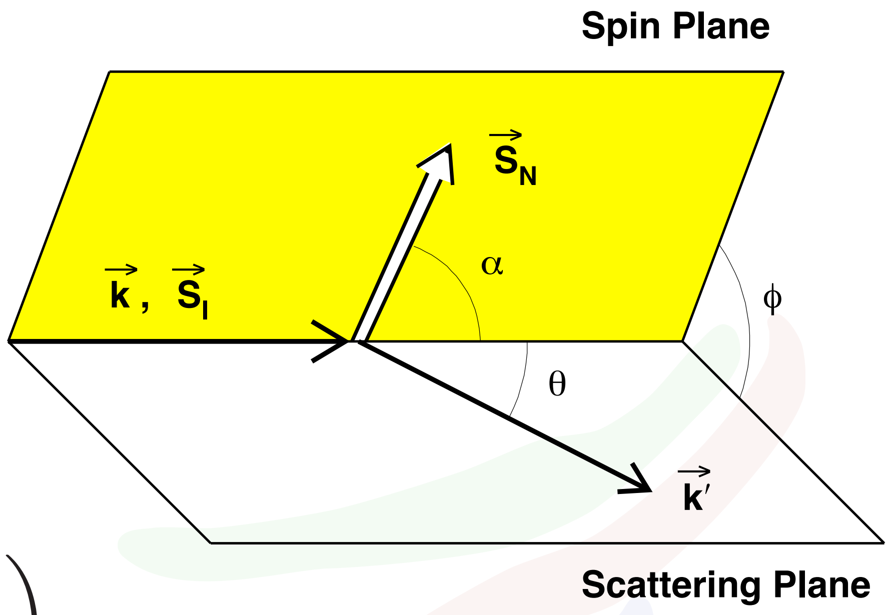
Extraction of g_2



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

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

Extraction of g_2



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

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

fit to double-spin asymmetry

$$\big\downarrow$$

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

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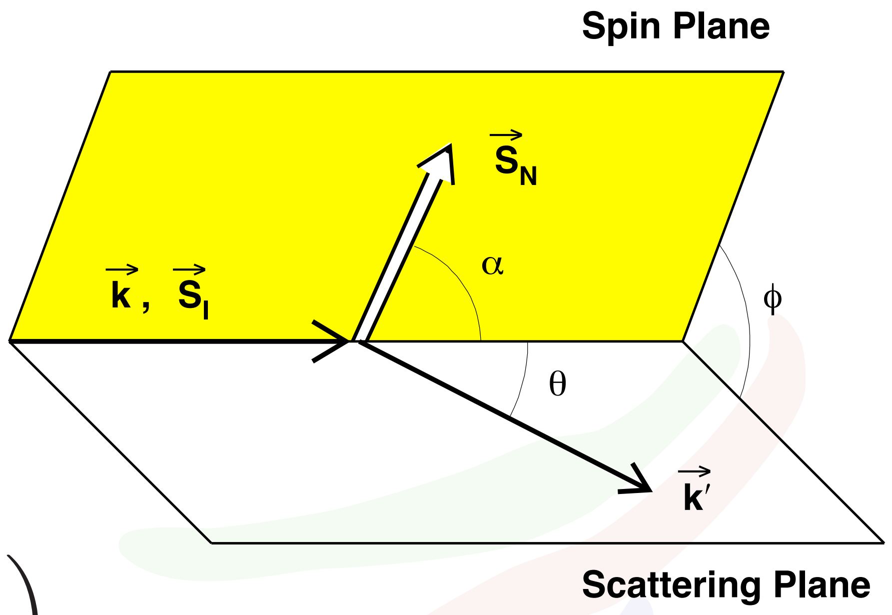
Extraction of g_2



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

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

fit to double-spin asymmetry

parameterizations

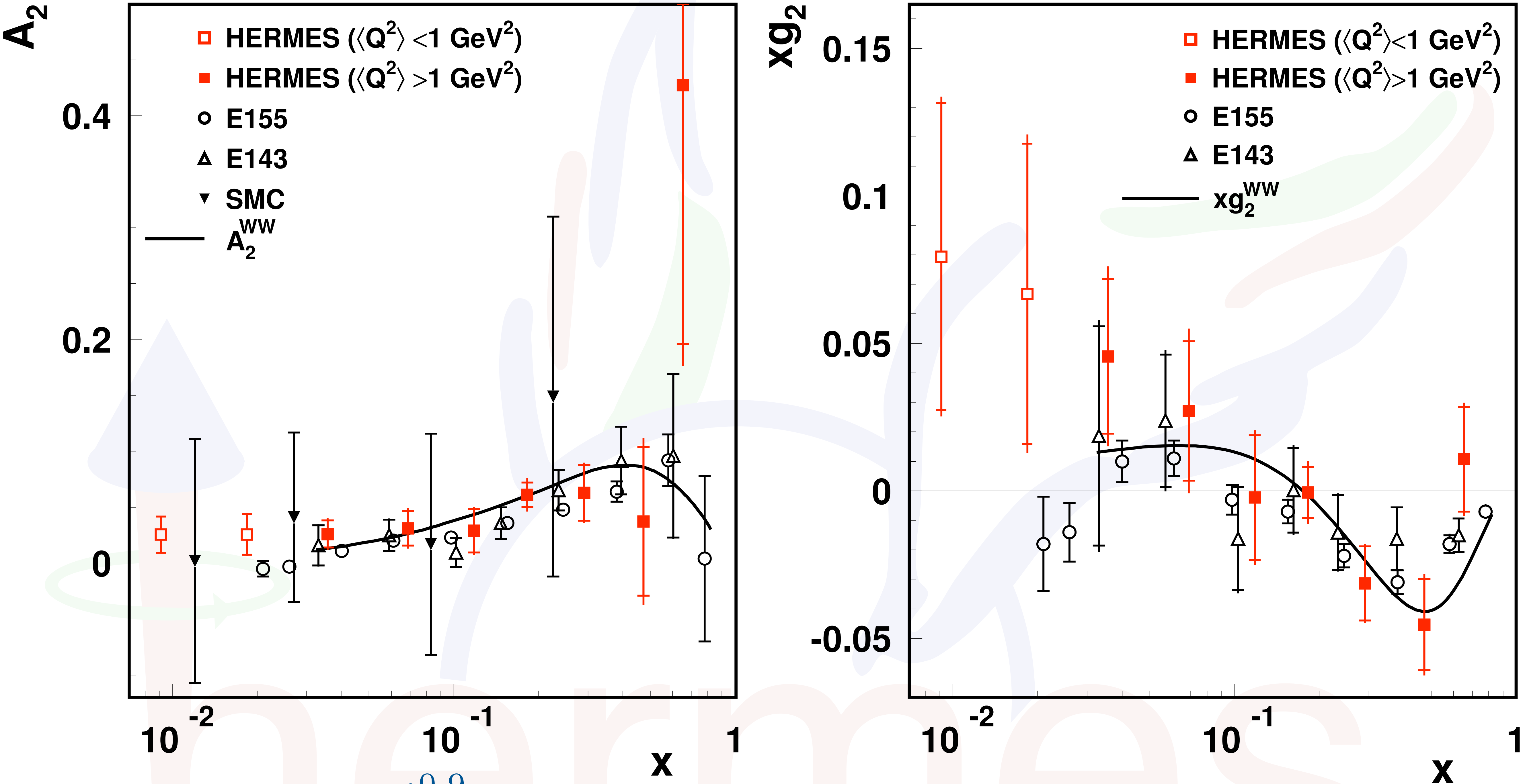
$$A_2 = \frac{1}{d(1+\gamma\xi)}A_T + \frac{\xi(1+\gamma^2)}{1+\gamma\xi}\frac{g_1}{F_1}$$

→

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

Results on A_2 and xg_2

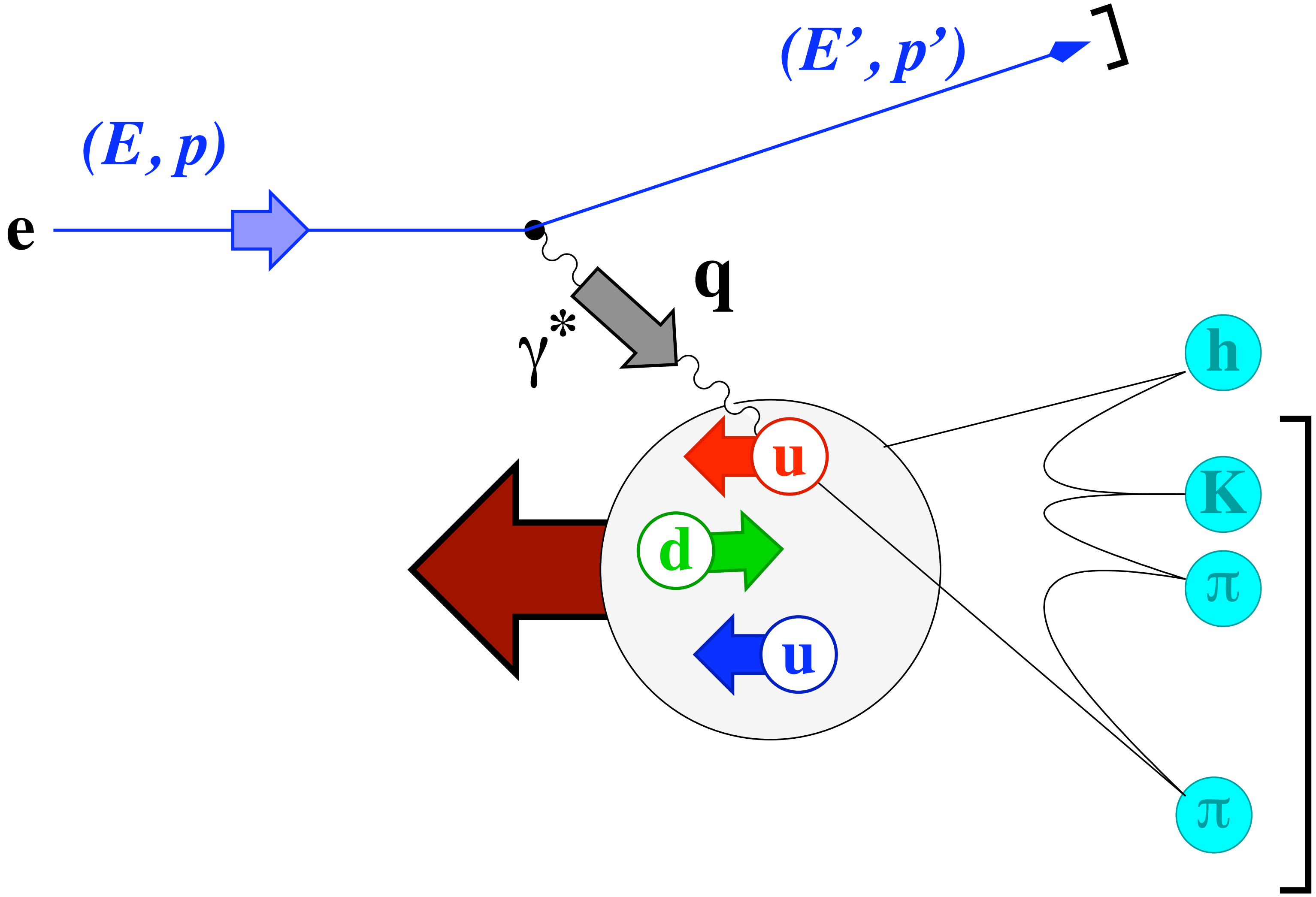
A. Airapetian et al. [HERMES], arXiv:1112.5584



$$\int_{0.023}^{0.9} g_2(x,Q^2)\,dx = \mathbf{0.006 \pm 0.024_{\rm stat} \pm 0.017_{\rm syst}}$$

$$\mathbf{d_2(Q^2)} \equiv 3\int_0^1 x^2\,\bar{g}_2(x,Q^2)\,dx = \mathbf{0.0148 \pm 0.0096_{\rm stat} \pm 0.0048_{\rm syst}}$$

Semi-Inclusive DIS



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

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

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

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

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

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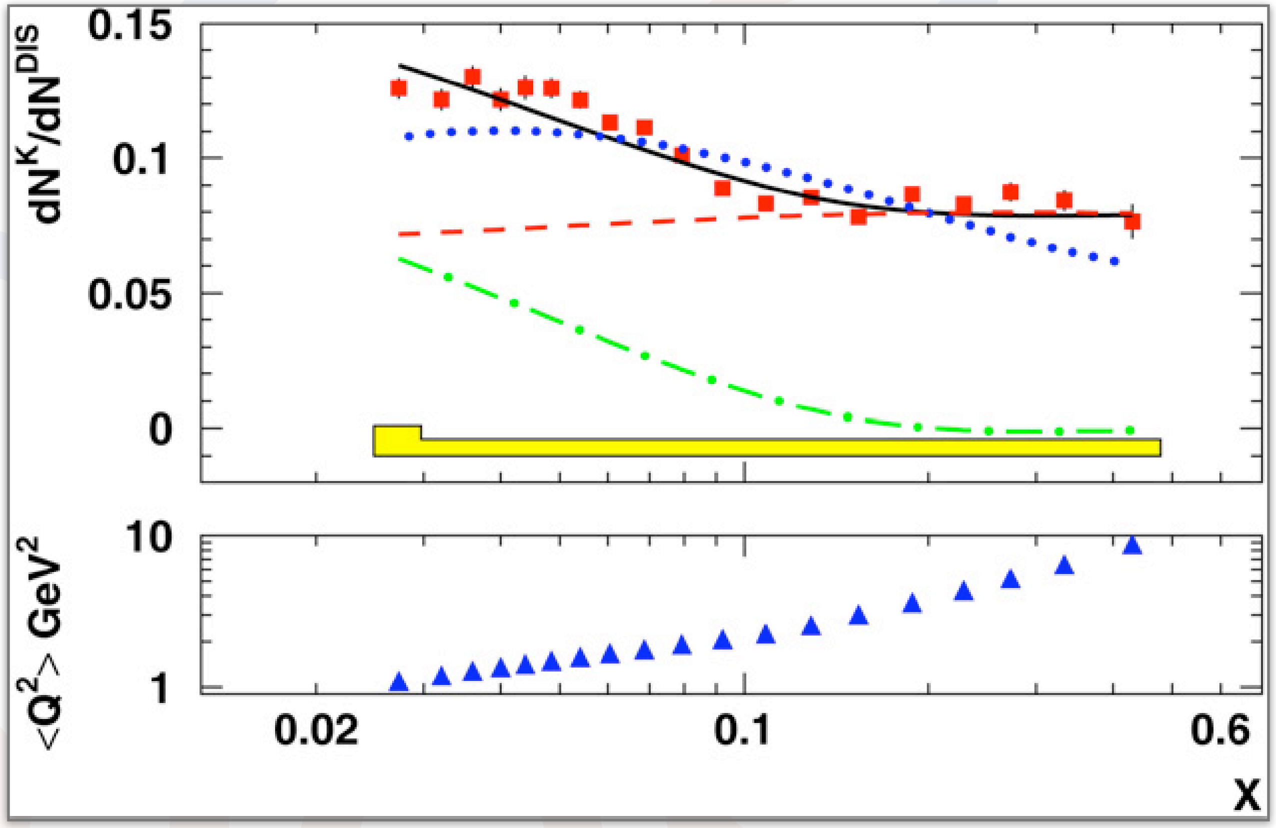
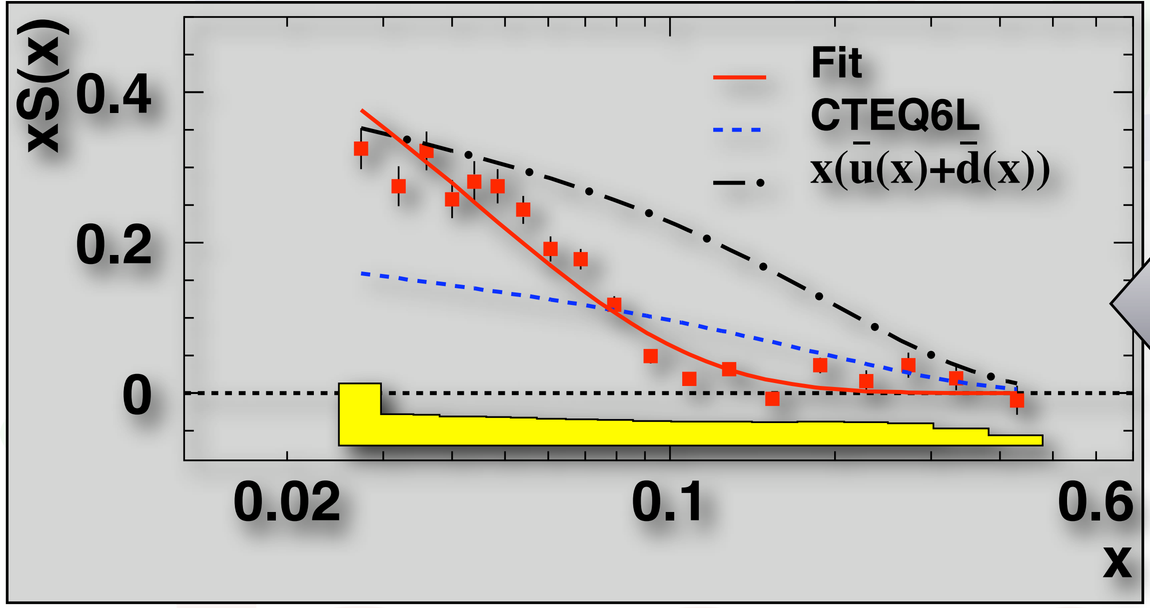
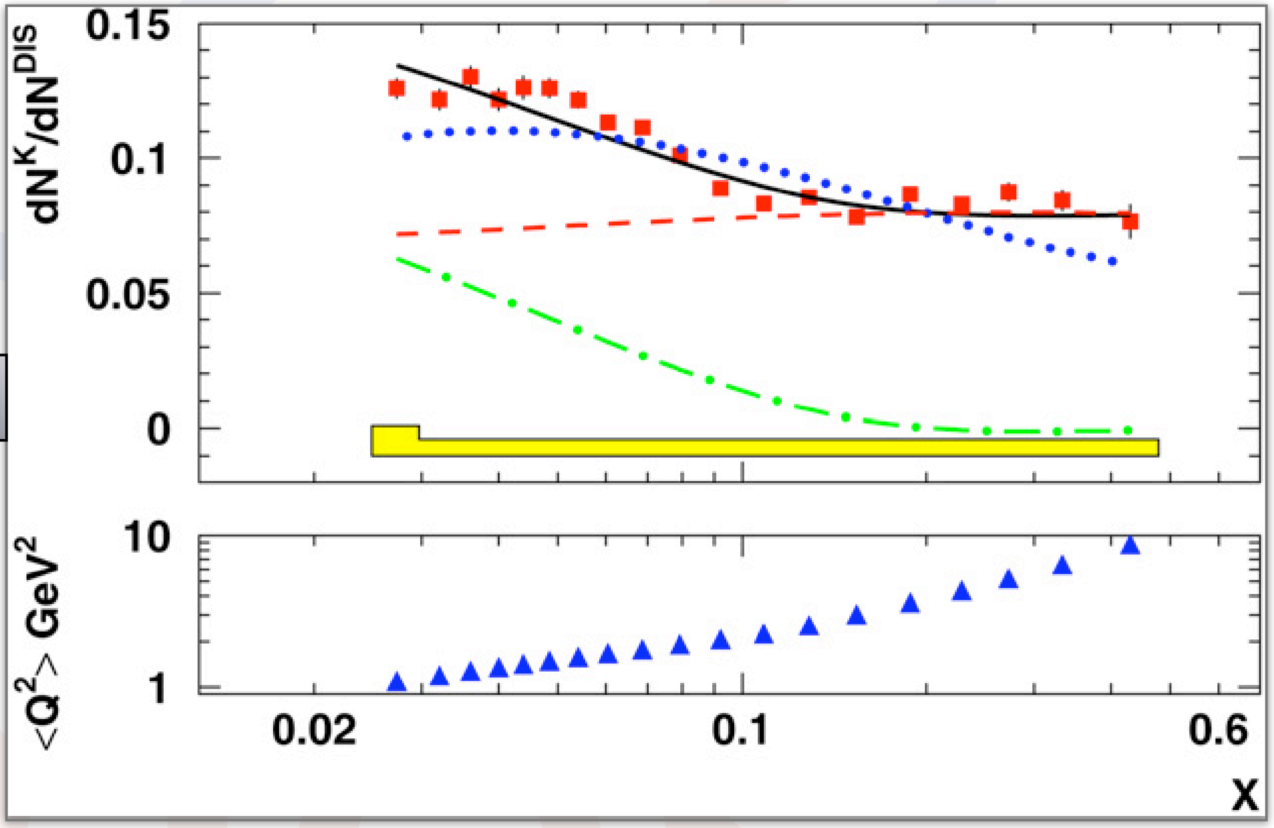


Strange-quark distributions

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

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





Strange-quark distributions

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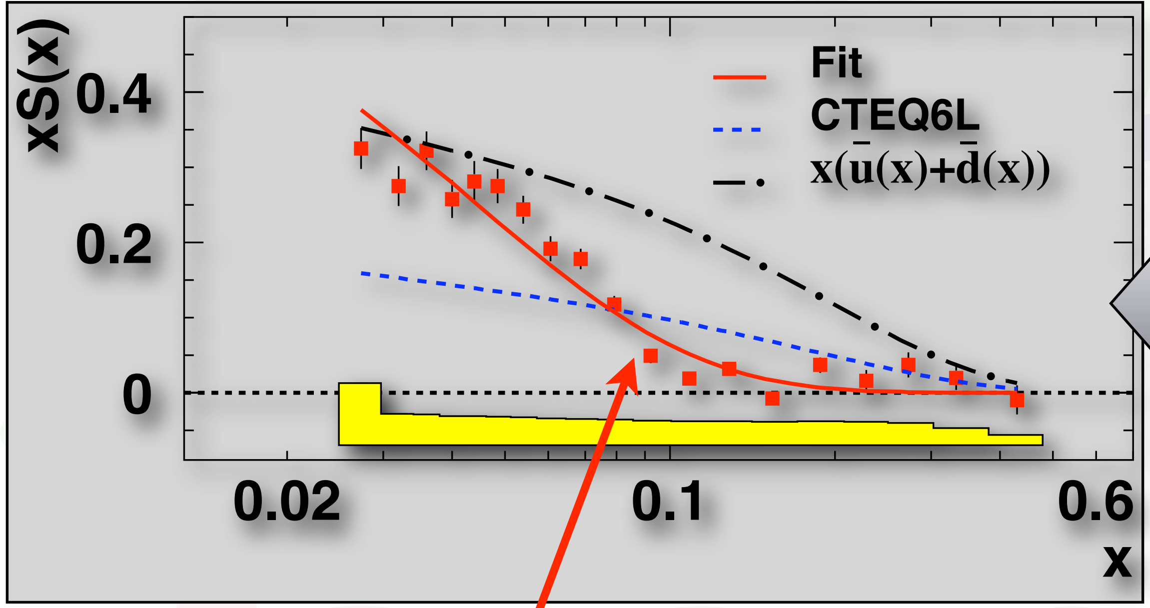
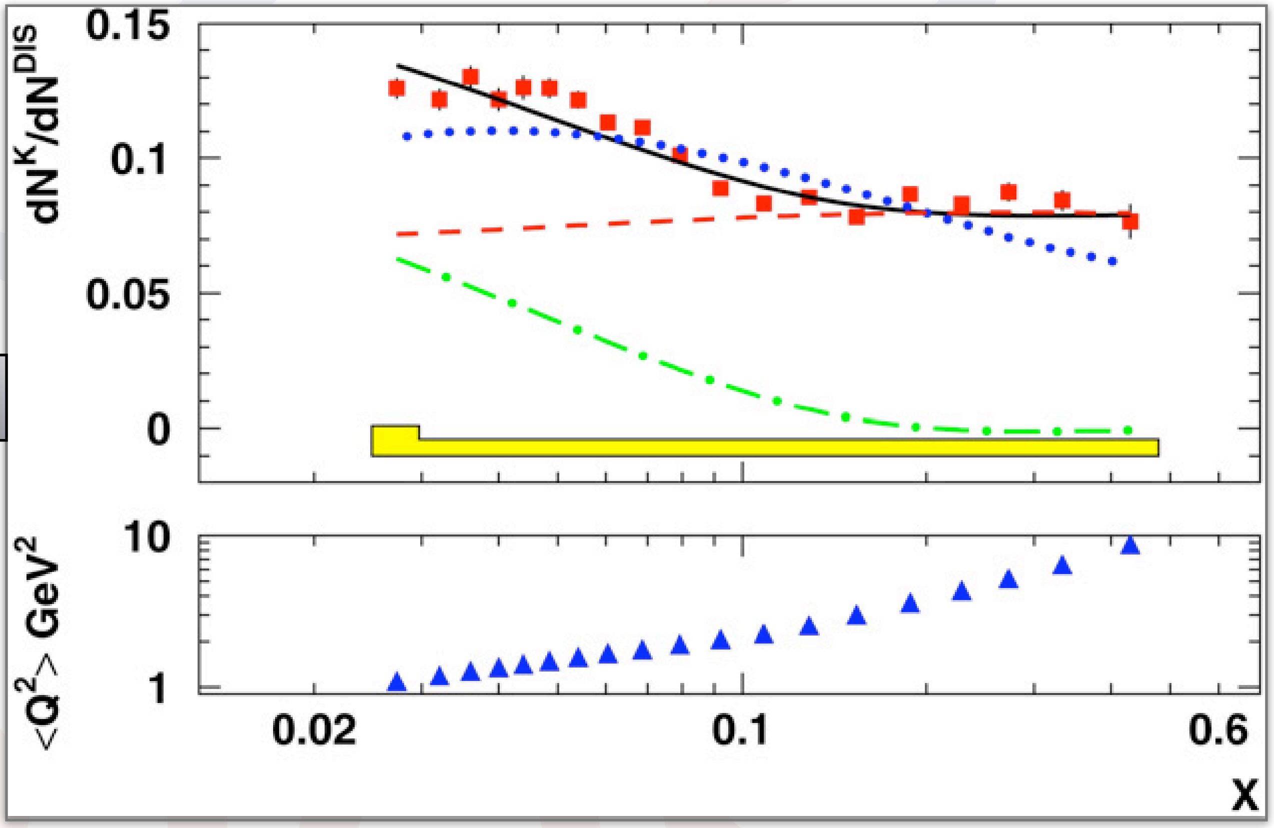
A. Airapetian et al., PLB 666 (2008) 446





Strange-quark distribution

softer than (maybe) expected

Strange-quark distributions

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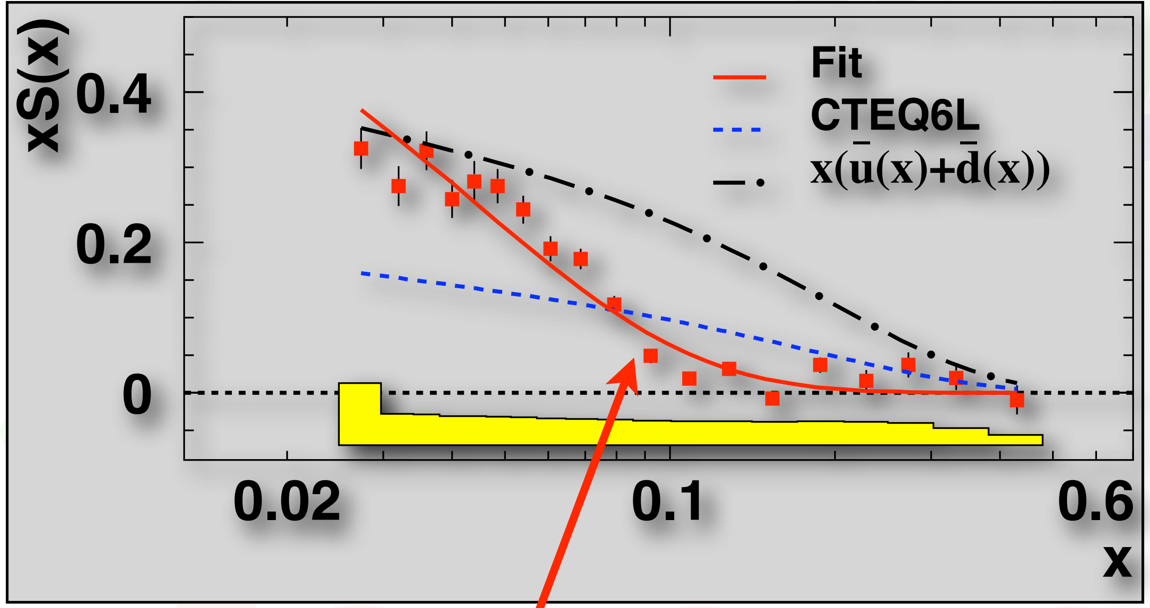
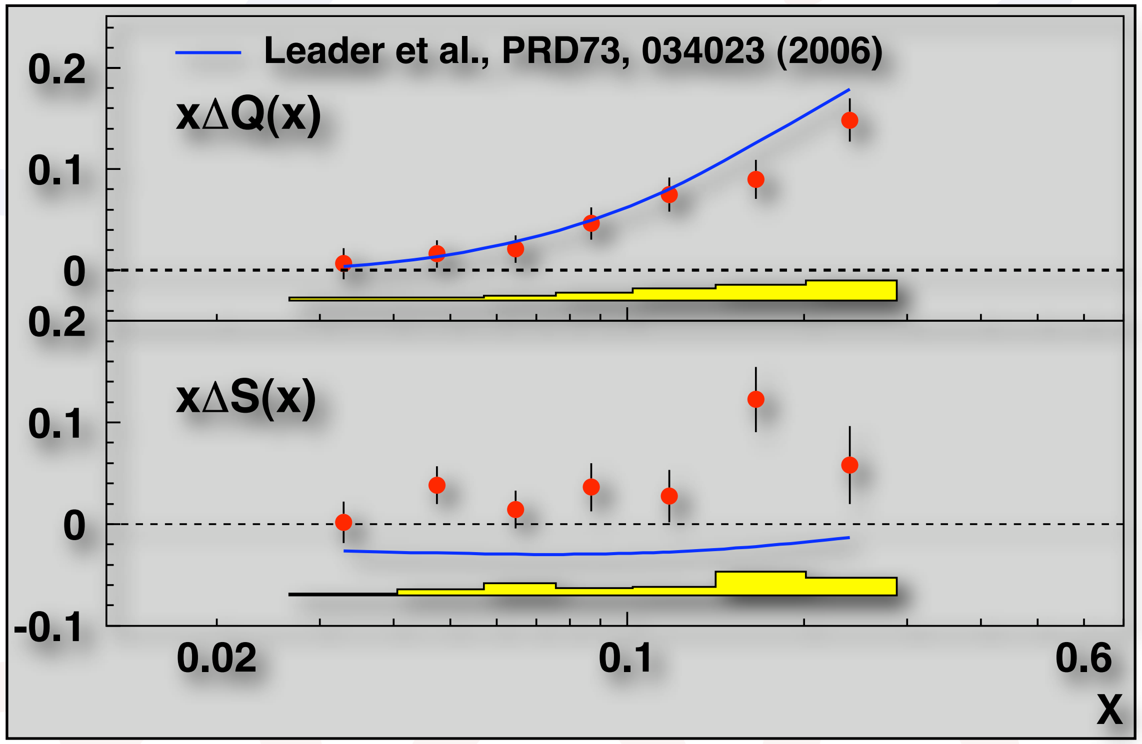
A. Airapetian et al., PLB 666 (2008) 446





Strange-quark distribution

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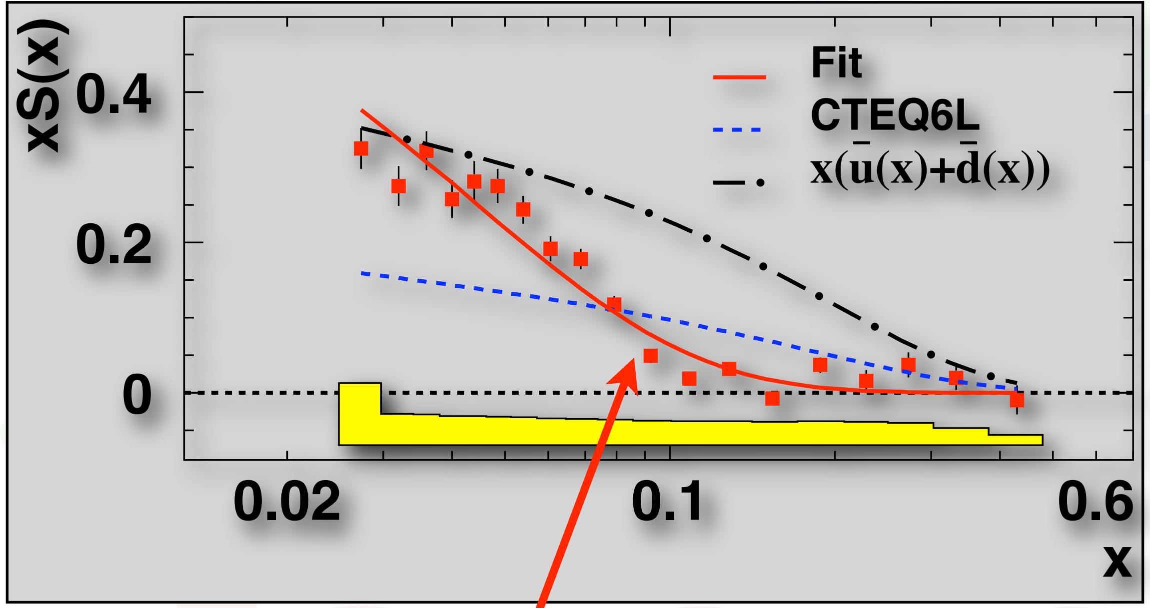
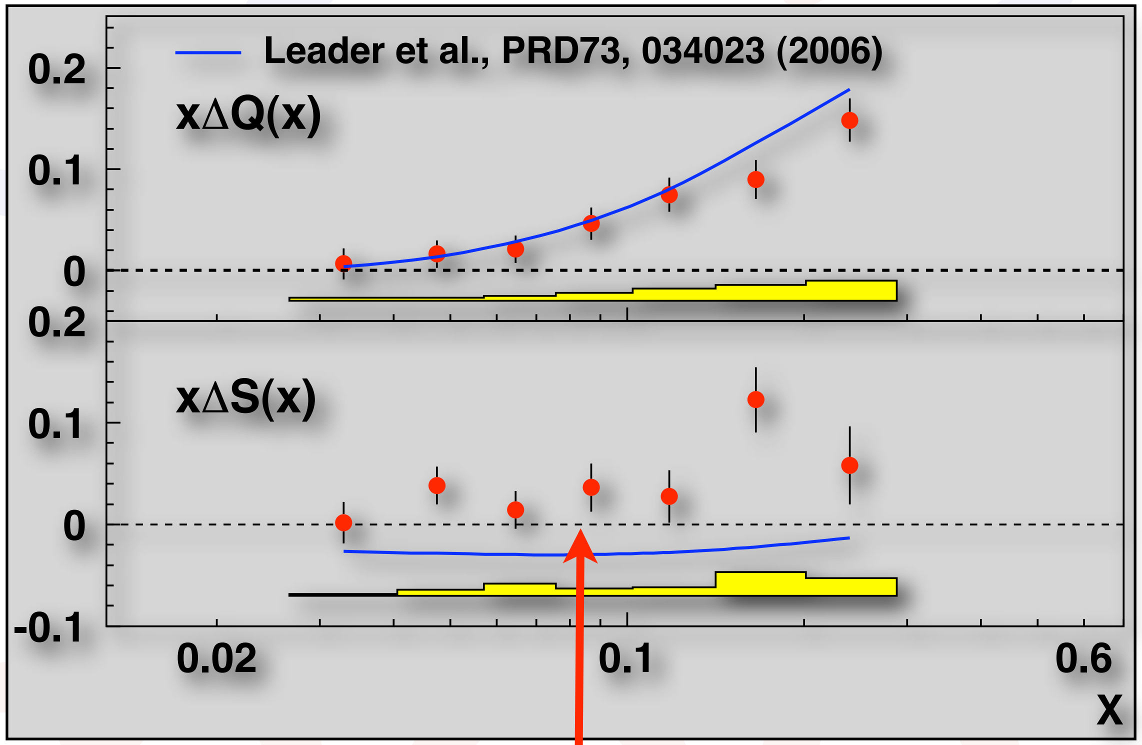
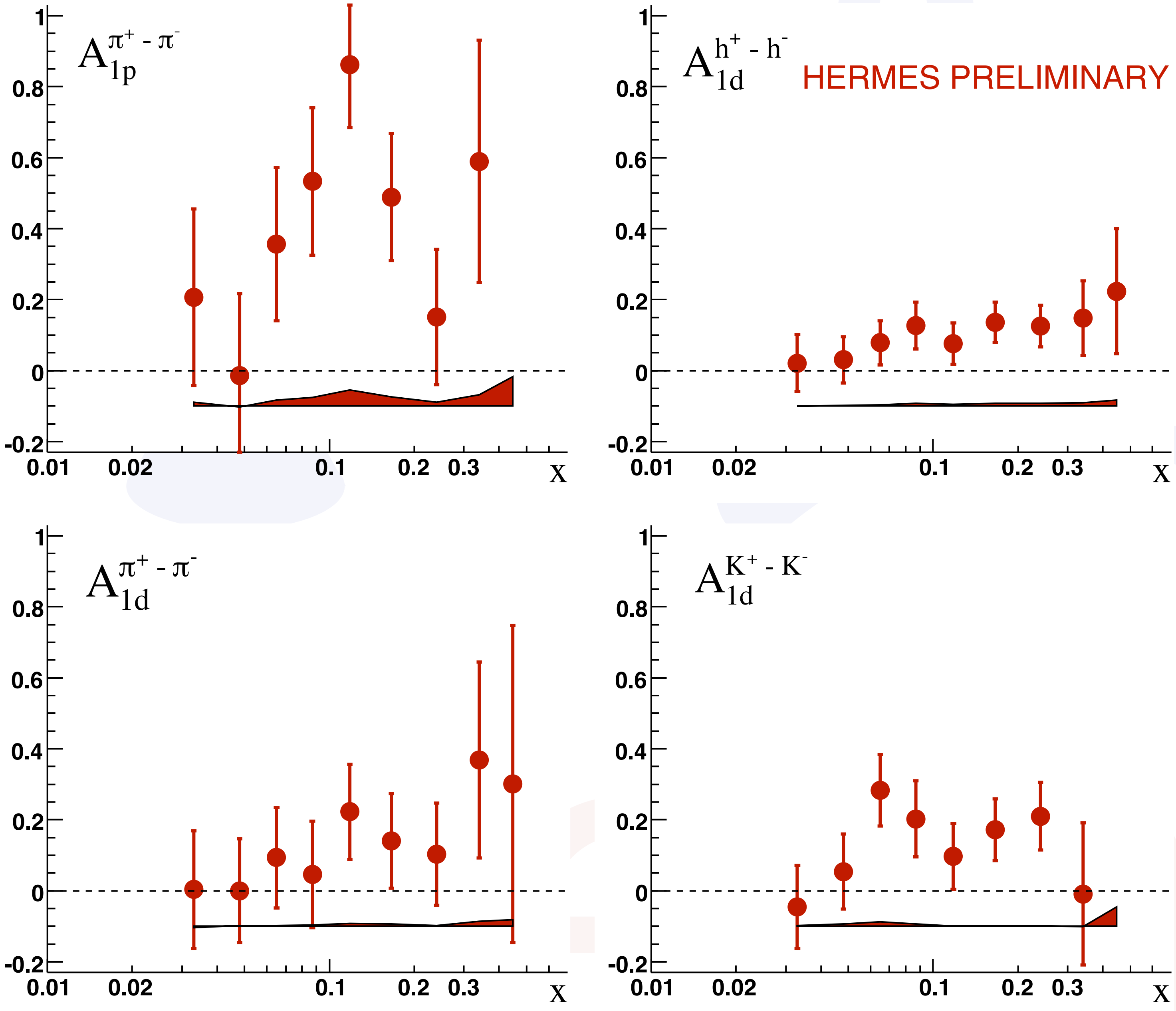




Strange-quark distribution softer than (maybe) expected

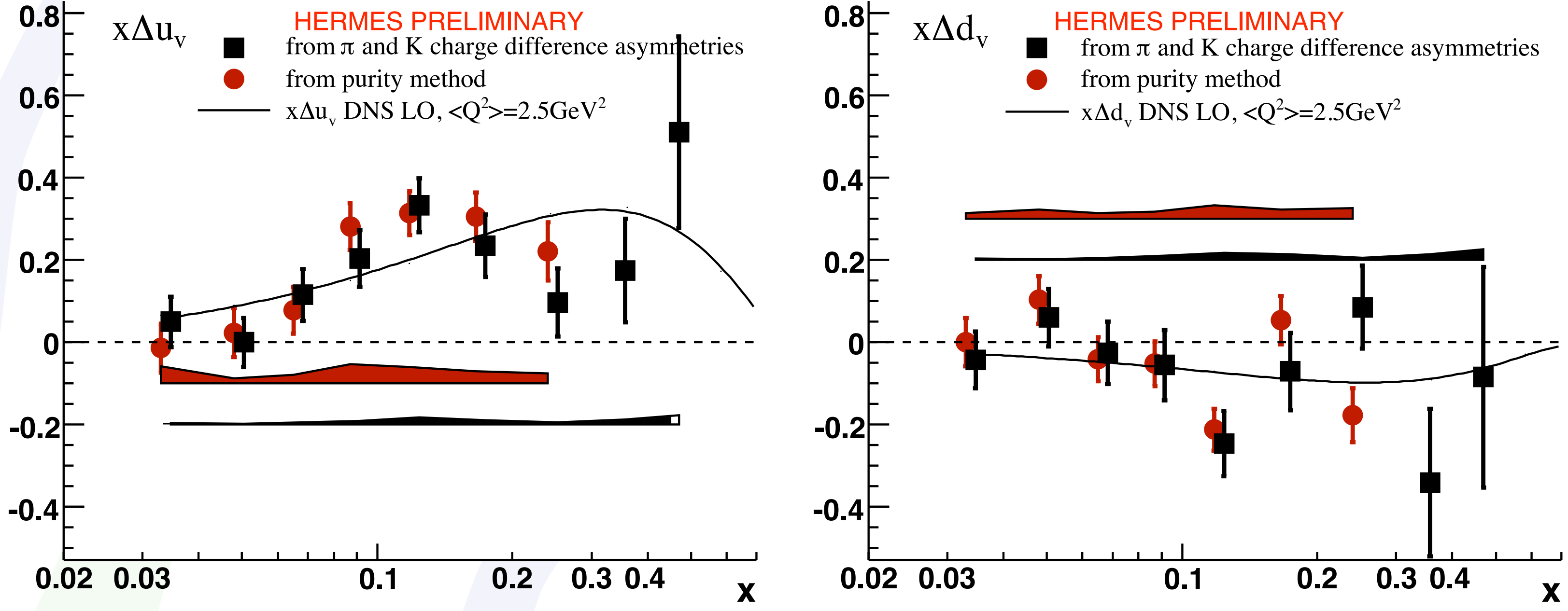
Strange-quark helicity distribution consistent with zero or slightly positive in contrast to inclusive DIS analyses

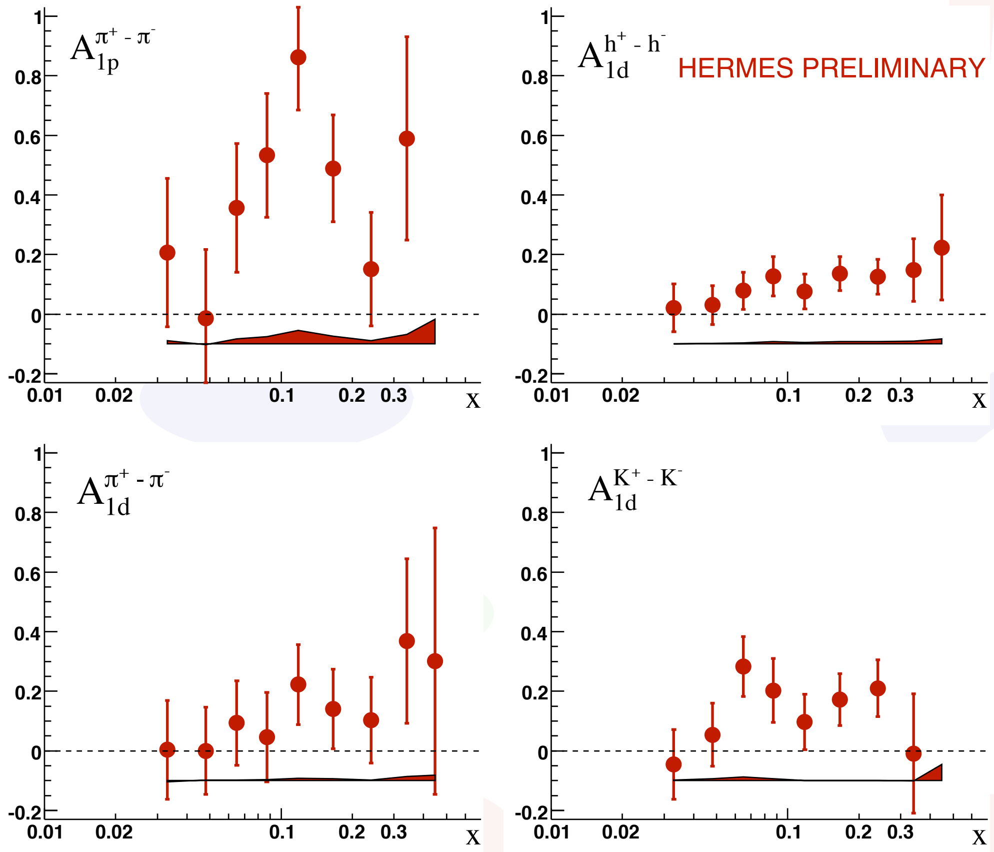
Helicity density - valence quarks



- charge-difference double-spin asymmetries

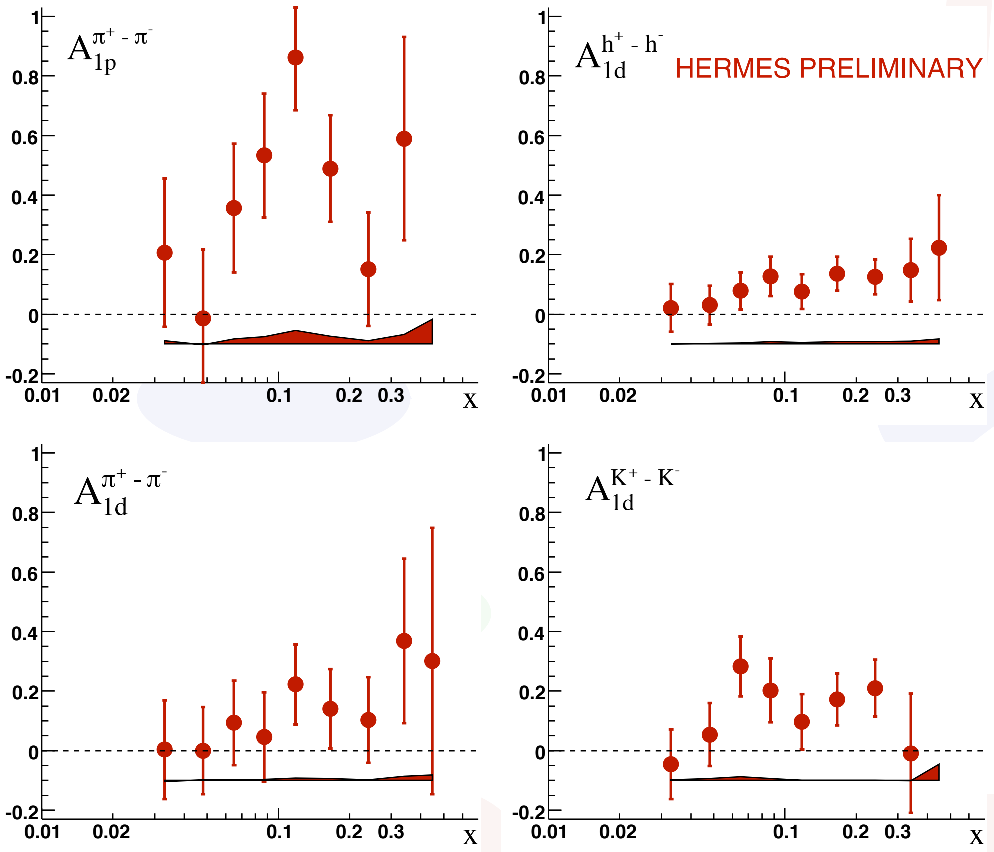
Helicity density - valence quarks

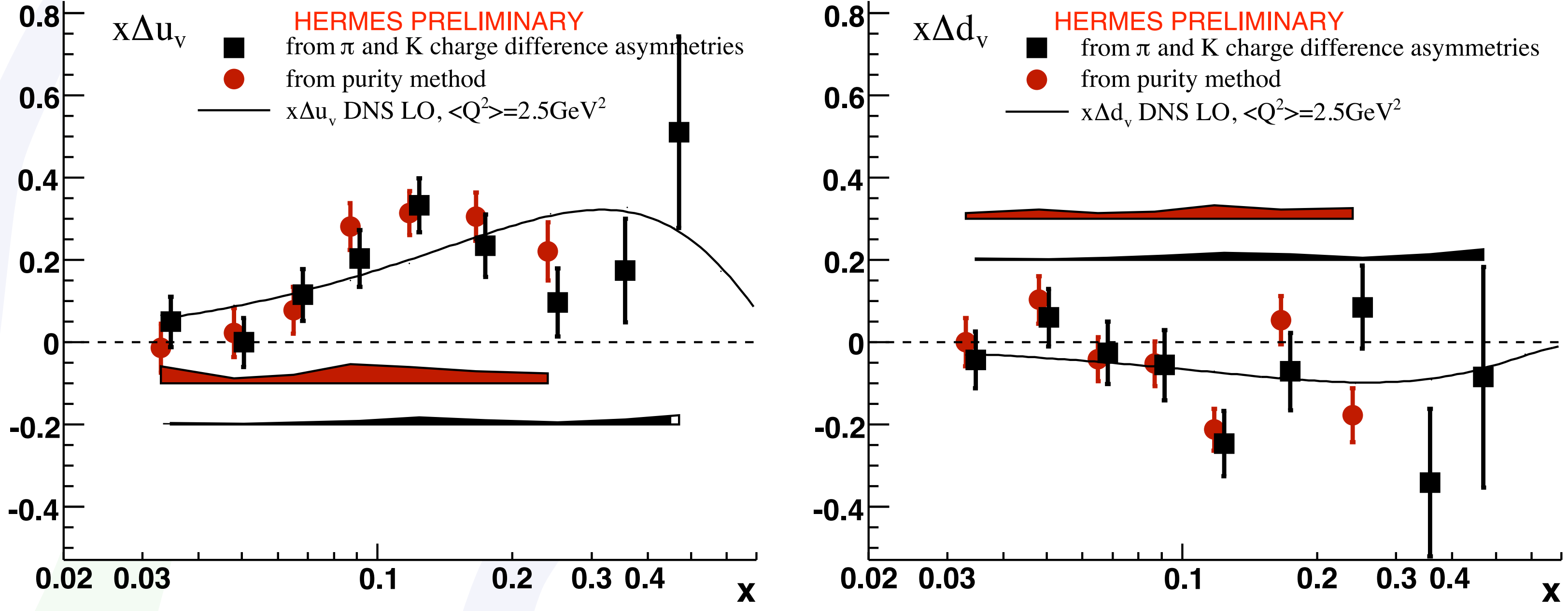


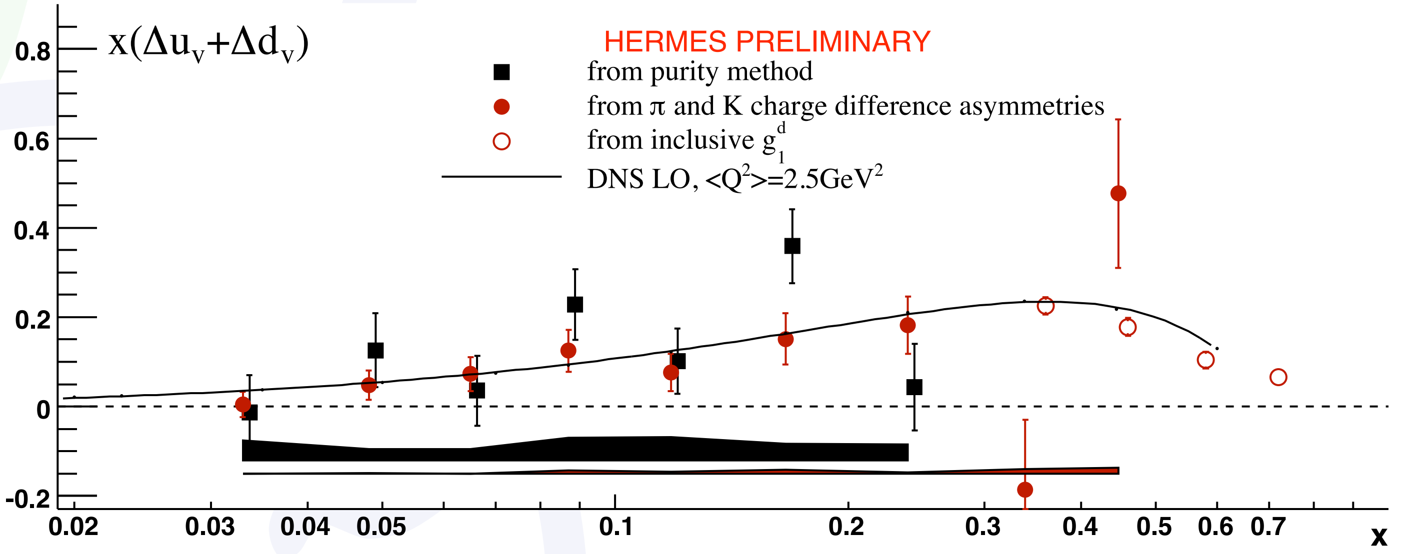


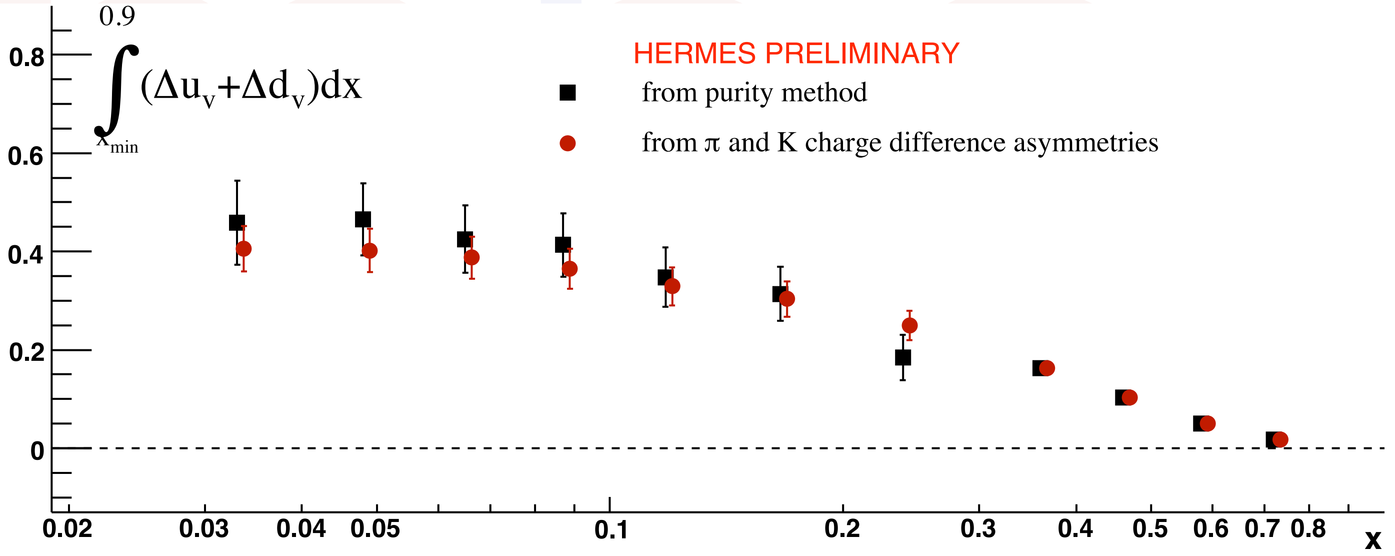
- charge-difference double-spin asymmetries
- use charge-conjugation symmetry to extract, at LO, valence distributions

Helicity density - valence quarks









going beyond collinear

Spin-Momentum Structure of the Nucleon

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

$$\frac{1}{2}\mathrm{Tr}\Big[(\gamma^+ - s^j i\sigma^{+j}\gamma_5)\,\Phi\Big] = \frac{1}{2}\Big[f_1 + S^i\epsilon^{ij}k^j\,\frac{1}{m}\,f_{1T}^\perp + s^i\epsilon^{ij}k^j\,\frac{1}{m}\,h_1^\perp + s^iS^ih_1 + s^i(2k^ik^j - \boldsymbol{k}^2\delta^{ij})S^j\,\frac{1}{2m^2}\,h_{1T}^\perp + \Lambda\,s^ik^i\,\frac{1}{m}\,h_{1L}^\perp\Big]$$

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

- **each TMD describes a particular spin-momentum correlation**
- **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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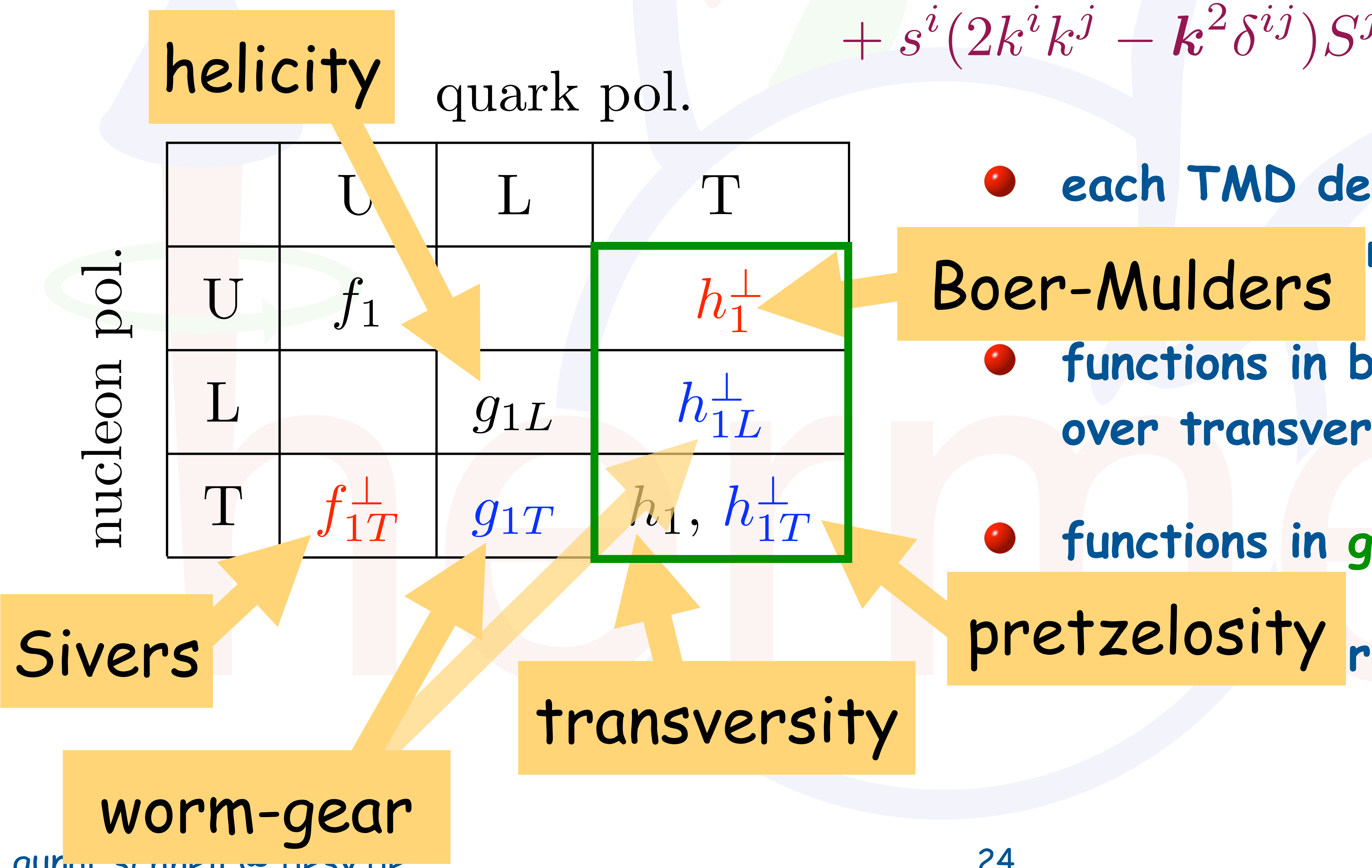

quark pol.

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, $h_{1T}^\perp$

- each TMD describes a particular spin- rrelation
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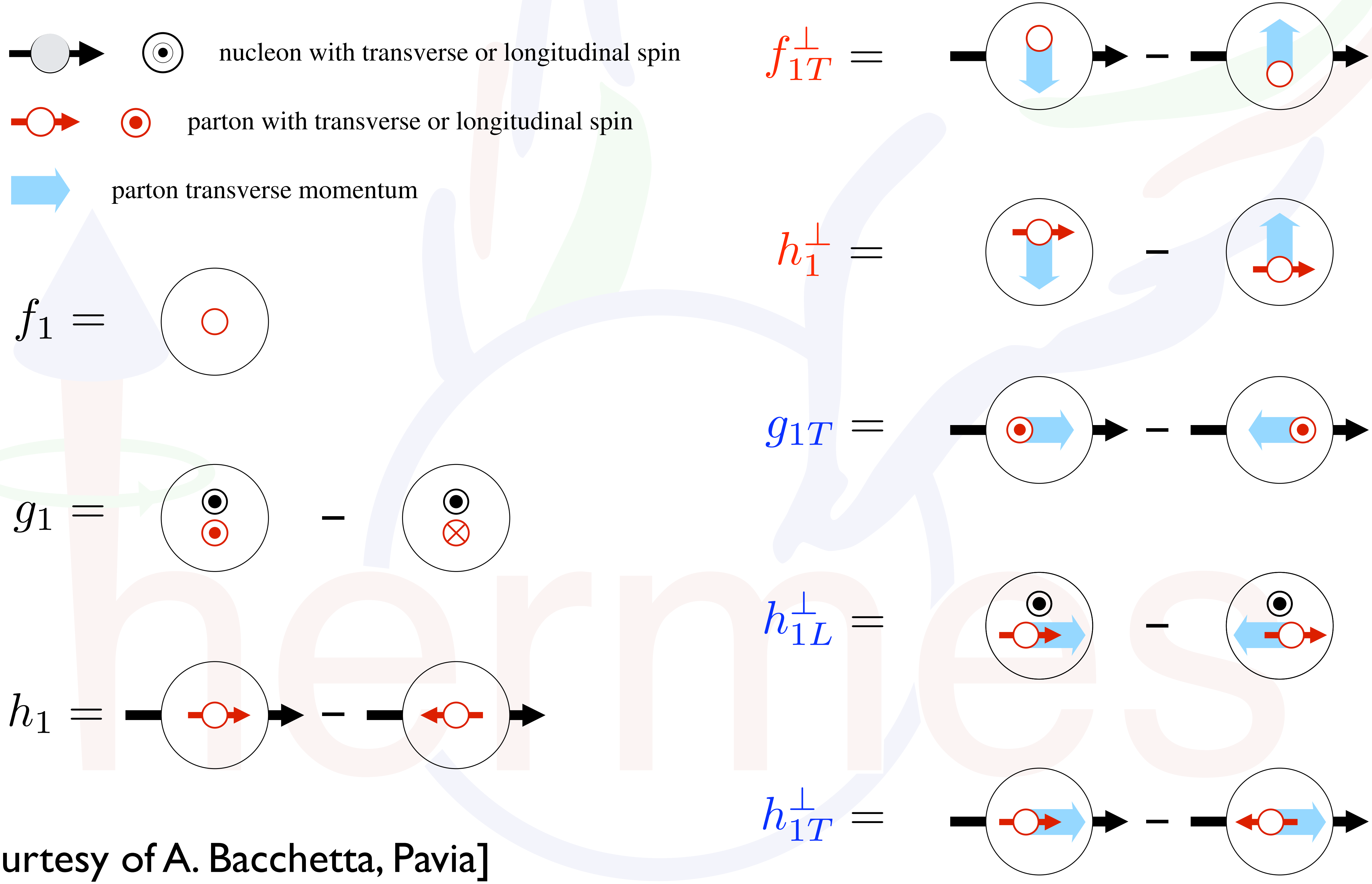
TMDs - Probabilistic interpretation

Proton goes out of the screen/ photon goes into the screen



nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

$f_1 =$

$g_1 =$ –

$h_1 =$ –

$f_{1T}^{\perp} =$ –

$h_1^{\perp} =$ –

$g_{1T} =$ –

$h_{1L}^{\perp} =$ –

$h_{1T}^{\perp} =$ –

[courtesy of A. Bacchetta, Pavia]

Cross section without polarization

$$F_{XY,Z} = F_{\underset{\substack{\Uparrow \\ \text{beam} \\ \text{polarization}}}{X}\overset{\substack{\text{target} \\ \text{polarization} \\ \Downarrow}}{Y},\underset{\substack{\Uparrow \\ \text{virtual-photon} \\ \text{polarization}}}{Z}}(x, y, z, P_{h\perp})$$

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1 + \frac{\gamma^2}{2x}\right) \left\{\boxed{F_{UU,T} + \epsilon F_{UU,L}}\right\}$$

$$\gamma = \frac{2Mx}{Q}$$

$$\varepsilon = \frac{1 - y - \frac{1}{4}\gamma^2 y^2}{1 - y + \frac{1}{2}y^2 + \frac{1}{4}\gamma^2 y^2}$$

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093

Cross section without polarization

$$F_{XY,Z} = F_{\underset{\substack{\text{beam}\\\text{polarization}}}{\overset{\Uparrow}{X}}\,\overset{\substack{\text{target}\\\text{polarization}\\\Downarrow}}{Y},\,\underset{\substack{\text{virtual-photon}\\\text{polarization}}}{\overset{\Uparrow}{Z}}}(x, y, z, P_{h\perp})$$

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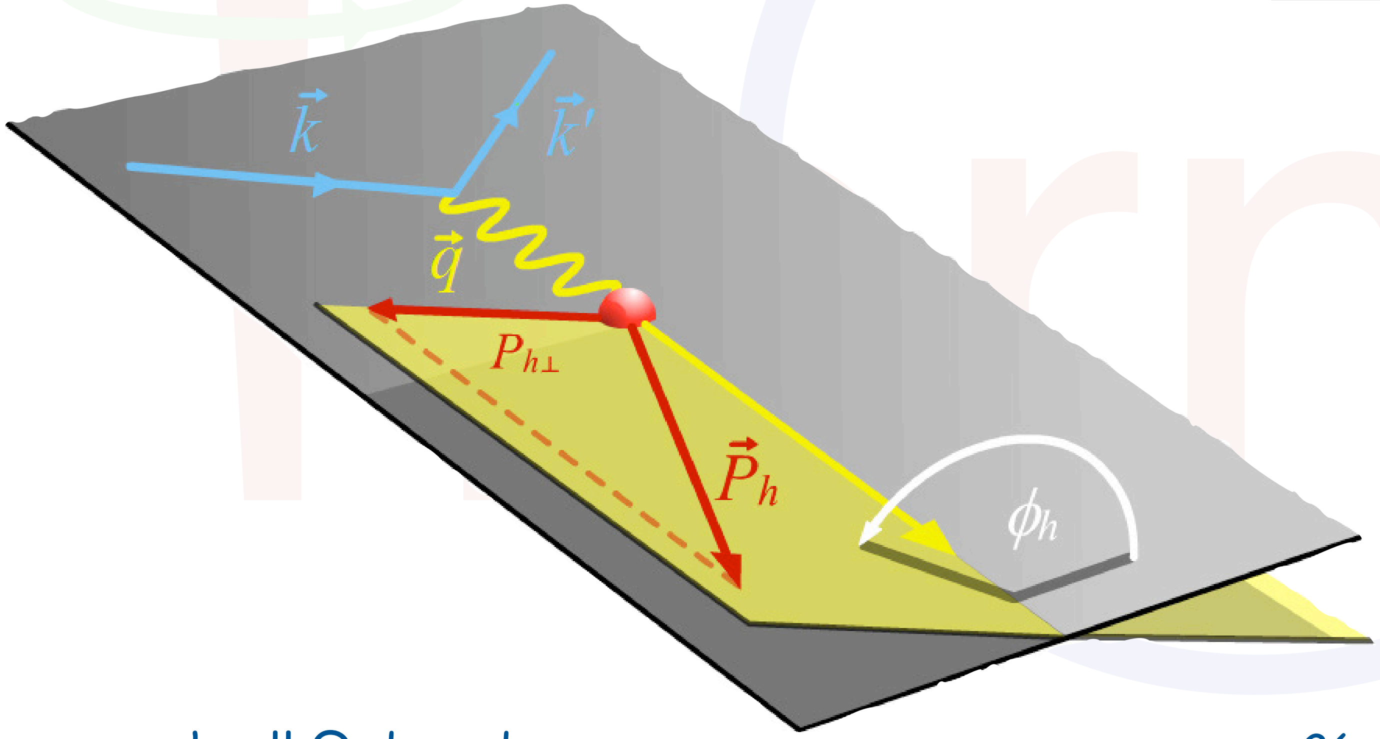
$$\left. + \sqrt{2\epsilon(1-\epsilon)}\,\boxed{F_{UU}^{\cos\phi_h}}\cos\phi_h + \epsilon\,\boxed{F_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\right\}$$



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[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093

... possible measurements

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\left\{F_{UU,T}+\epsilon F_{UU,L}\right.$$

$$\left. + \sqrt{2\epsilon(1-\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\right\}$$

... possible measurements

hadron multiplicity:
normalize to inclusive DIS cross section

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\left\{F_{UU,T}+\epsilon F_{UU,L}\right.$$

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… possible measurements

hadron multiplicity:
normalize to inclusive DIS cross section

$$\frac{d^2\sigma^{\text{incl.DIS}}}{dx\,dy} \propto F_T + \epsilon F_L$$

$$\frac{d^4\mathcal{M}^h(x,y,z,P_{h\perp}^2)}{dx\,dy\,dz\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\frac{F_{UU,T}+\epsilon F_{UU,L}}{F_T+\epsilon F_L}$$

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T}+\epsilon F_{UU,L}$$

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$$\approx \frac{\sum_q e_q^2\, f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}{\sum_q e_q^2\, f_1^q(x)}$$

$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\epsilon F_{UU,L}$$

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$$+\sqrt{2\epsilon(1-\epsilon)}\,F_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\Big\}$$

moments:
normalize to azimuth-independent cross-section

… possible measurements

hadron multiplicity:
normalize to inclusive DIS cross section

$$\frac{d^2\sigma^{\text{incl.DIS}}}{dx\,dy} \propto F_T + \epsilon F_L$$

$$\frac{d^4\mathcal{M}^h(x,y,z,P_{h\perp}^2)}{dx\,dy\,dz\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\frac{F_{UU,T}+\epsilon \cancel{F_{UU,L}}}{F_T+\epsilon \cancel{F_L}}$$

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$$\frac{d^5\sigma}{dx\,dy\,dz\,d\phi_h\,dP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\{F_{UU,T}+\epsilon F_{UU,L}$$

$$+\sqrt{2\epsilon(1-\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\}$$

$$2\langle\cos 2\phi\rangle_{UU} \equiv 2\frac{\int d\phi_h \cos 2\phi\, d\sigma}{\int d\phi_h d\sigma} = \frac{\epsilon F_{UU}^{\cos 2\phi}}{F_{UU,T}+\epsilon F_{UU,L}}$$

moments:
normalize to azimuth-independent cross-section

… possible measurements

hadron multiplicity:
normalize to inclusive DIS cross section

$$\frac{d^2\sigma^{\text{incl.DIS}}}{dxdy} \propto F_T + \epsilon F_L$$

$$\frac{d^4\mathcal{M}^h(x,y,z,P_{h\perp}^2)}{dxdydzdP_{h\perp}^2} \propto \left(1+\frac{\gamma^2}{2x}\right)\frac{F_{UU,T}+\epsilon \cancel{F_{UU,L}}}{F_T+\epsilon \cancel{F_L}}$$

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$$+\sqrt{2\epsilon(1-\epsilon)}F_{UU}^{\cos\phi_h}\cos\phi_h + \epsilon F_{UU}^{\cos 2\phi_h}\cos 2\phi_h\}$$

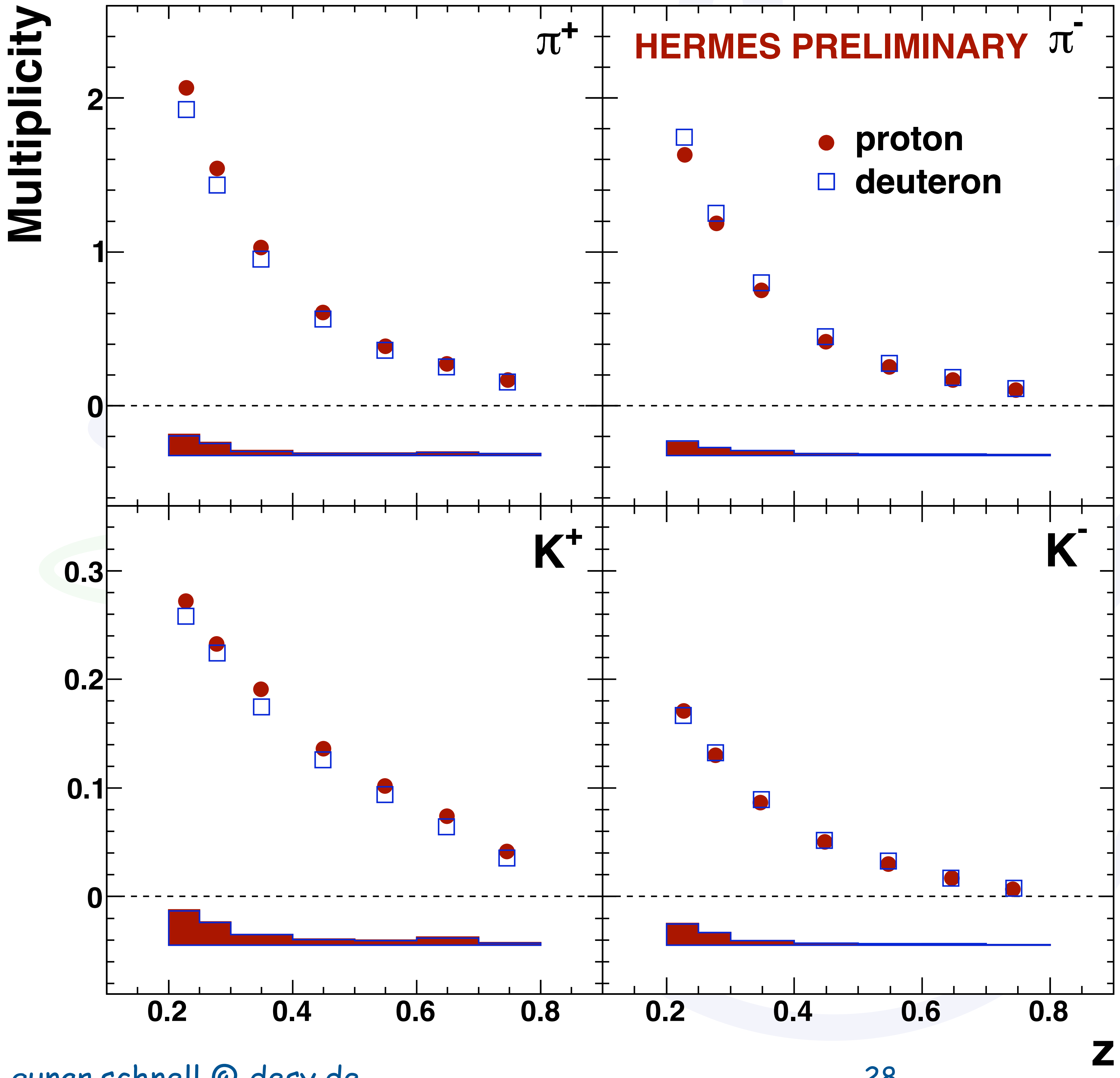
$$2\langle\cos 2\phi\rangle_{UU} \equiv 2\frac{\int d\phi_h \cos 2\phi\, d\sigma}{\int d\phi_h d\sigma} = \frac{\epsilon F_{UU}^{\cos 2\phi}}{F_{UU,T}+\epsilon \cancel{F_{UU,L}}}$$

$$\approx \epsilon\frac{\sum_q e_q^2\; h_1^{\perp,q}(x,p_T^2)\otimes_{\text{BM}} H_1^{\perp,q\to h}(z,K_T^2)}{\sum_q e_q^2\; f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}$$

moments:
normalize to azimuth-independent cross-section

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

Charged-meson multiplicities



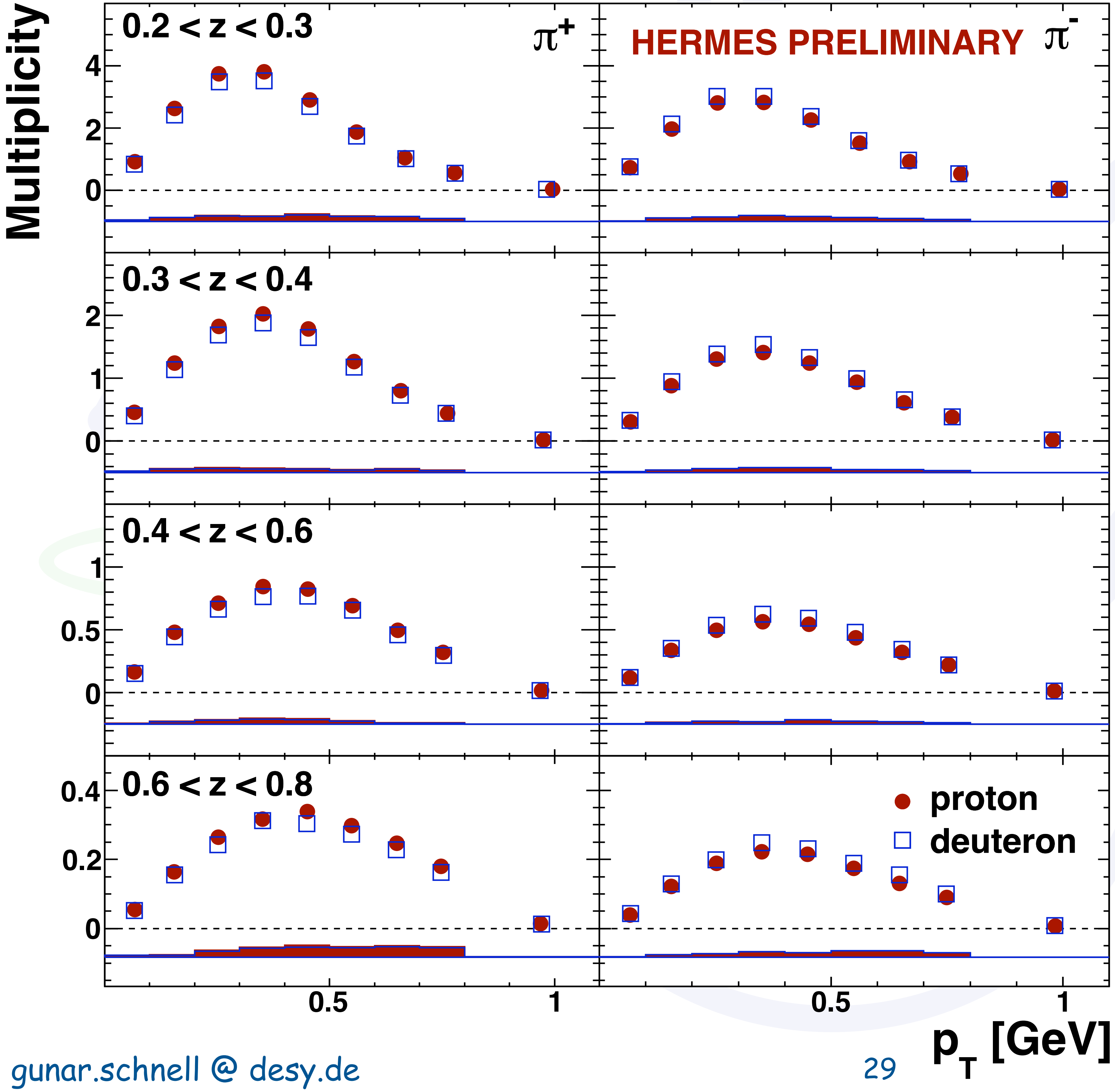
slight differences between proton and deuteron targets

most exhaustive data set on (p_T-integrated) electro-production of charged mesons on nucleons

valuable input for future FF fits, especially quark/anti-quark separation

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

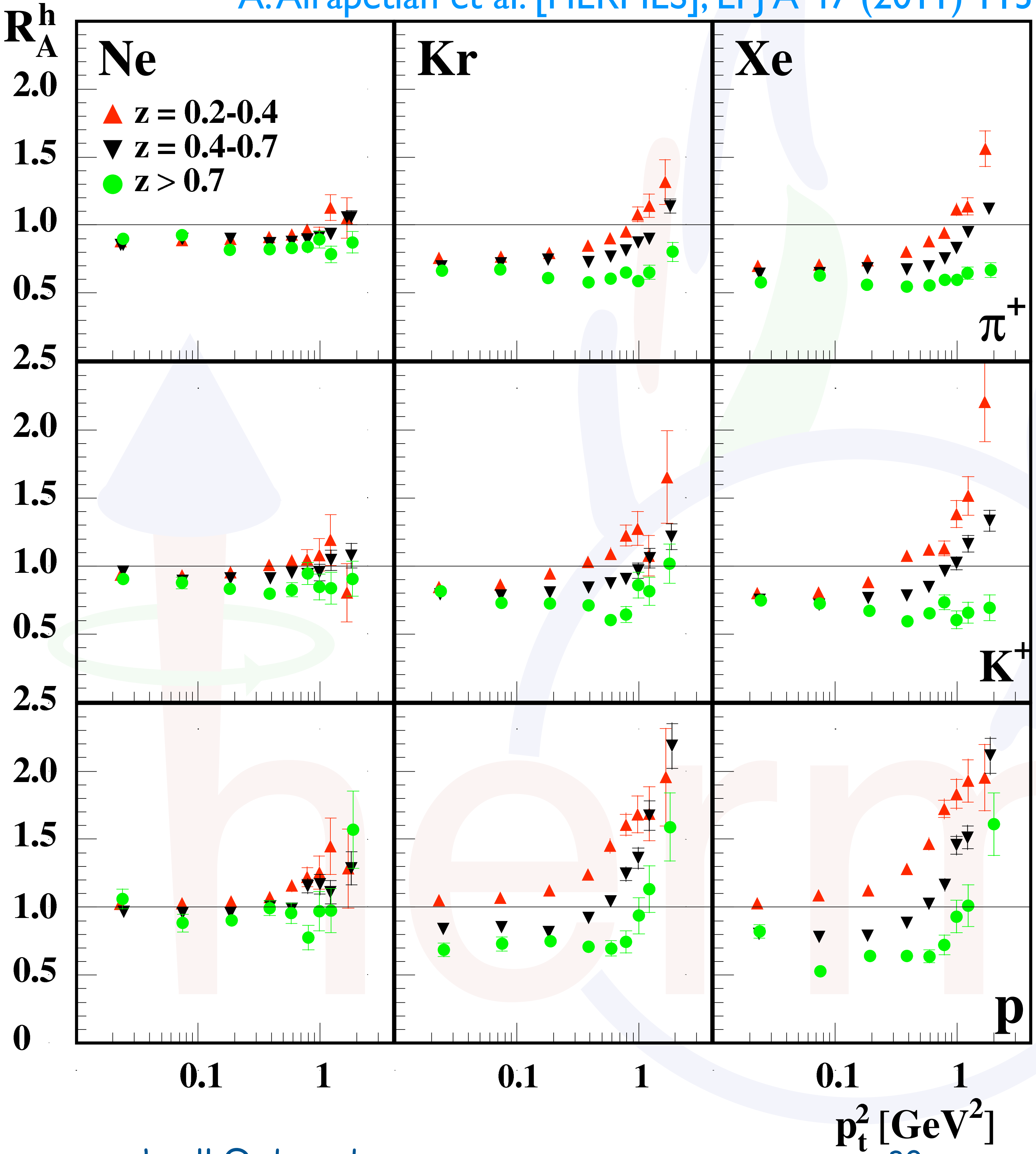
2-D z-p_T dependence



only data on multi-D dependences in electro-production of mesons on pure p and d!

Nuclear targets: study hadronization

A. Airapetian et al. [HERMES], EPJ A 47 (2011) 113



$$R_A^h \equiv \frac{\mathcal{M}_A^h}{\mathcal{M}_d^h}$$

strong p_T dependence of nuclear attenuation

Nuclear targets: study hadronization

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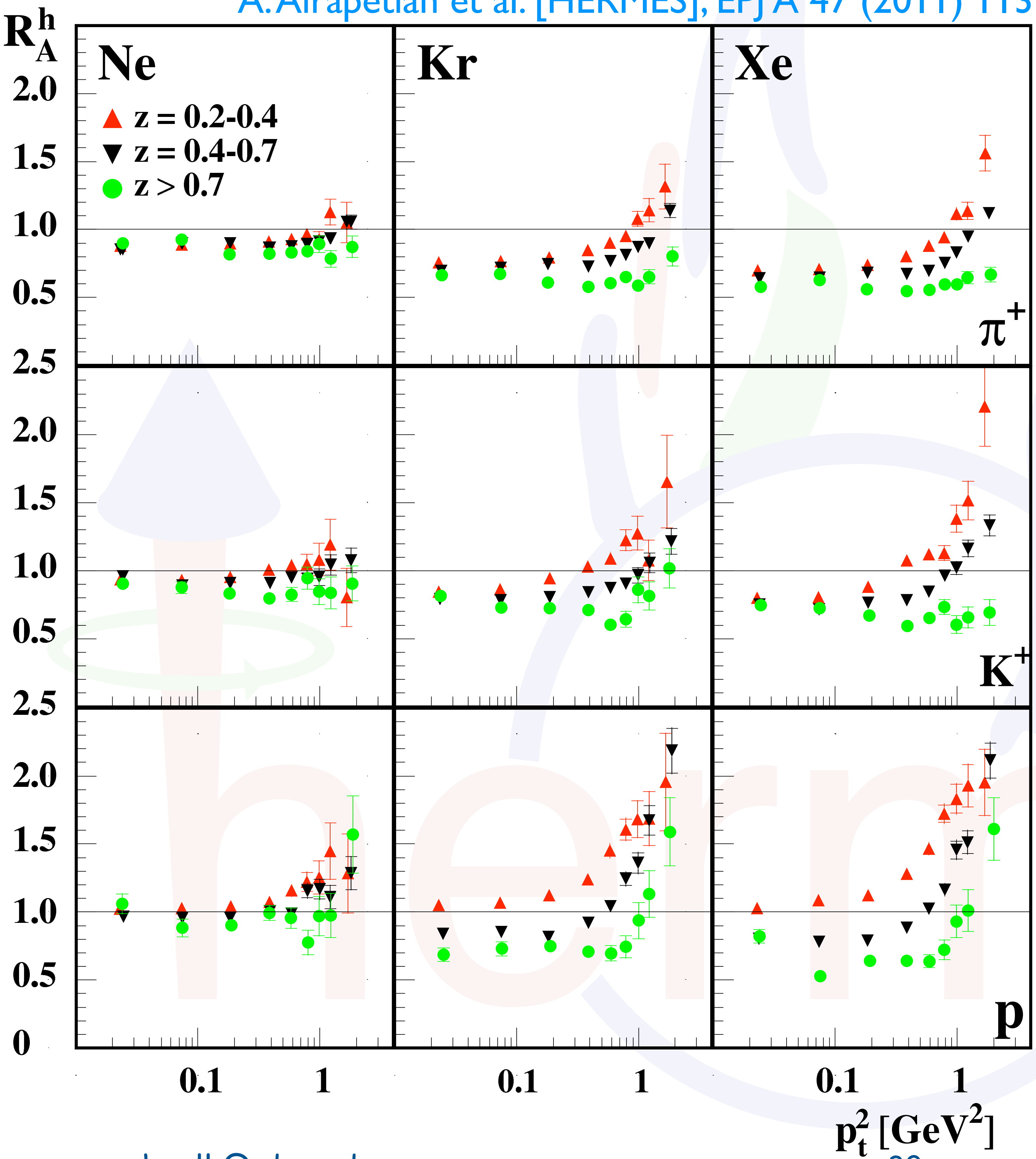


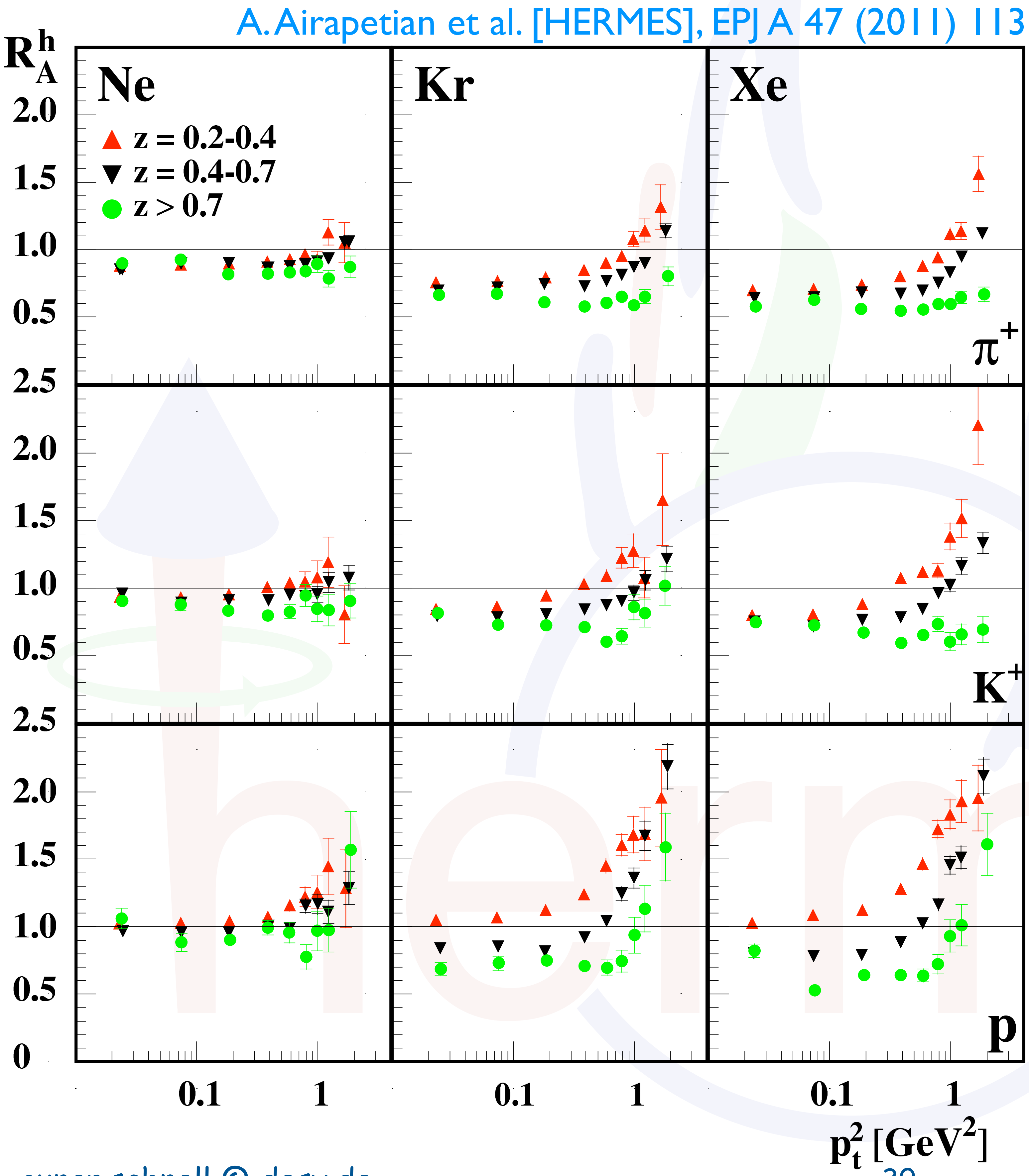
$$R_A^h \equiv \frac{\mathcal{M}_A^h}{\mathcal{M}_d^h}$$

strong p_T dependence of nuclear attenuation

needs to be considered when interpreting TMD effects off nuclear targets (at not-too-high energies)

gunar.schnell @ desy.de

Nuclear targets: study hadronization



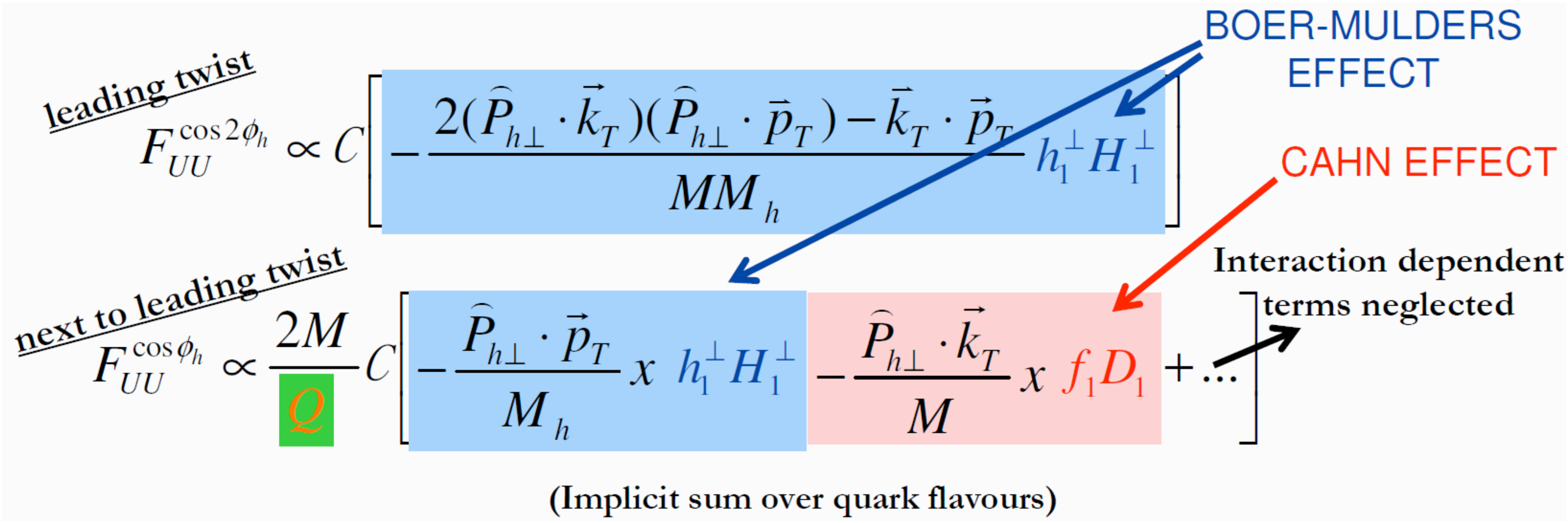
$$R_A^h \equiv \frac{\mathcal{M}_A^h}{\mathcal{M}_d^h}$$

strong p_T dependence of nuclear attenuation

needs to be considered when interpreting TMD effects off nuclear targets (at not-too-high energies)

(other 2D dependences available)

Azimuthal modulations



leading twist

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

next to leading twist

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

BOER-MULDERS EFFECT

CAHN EFFECT

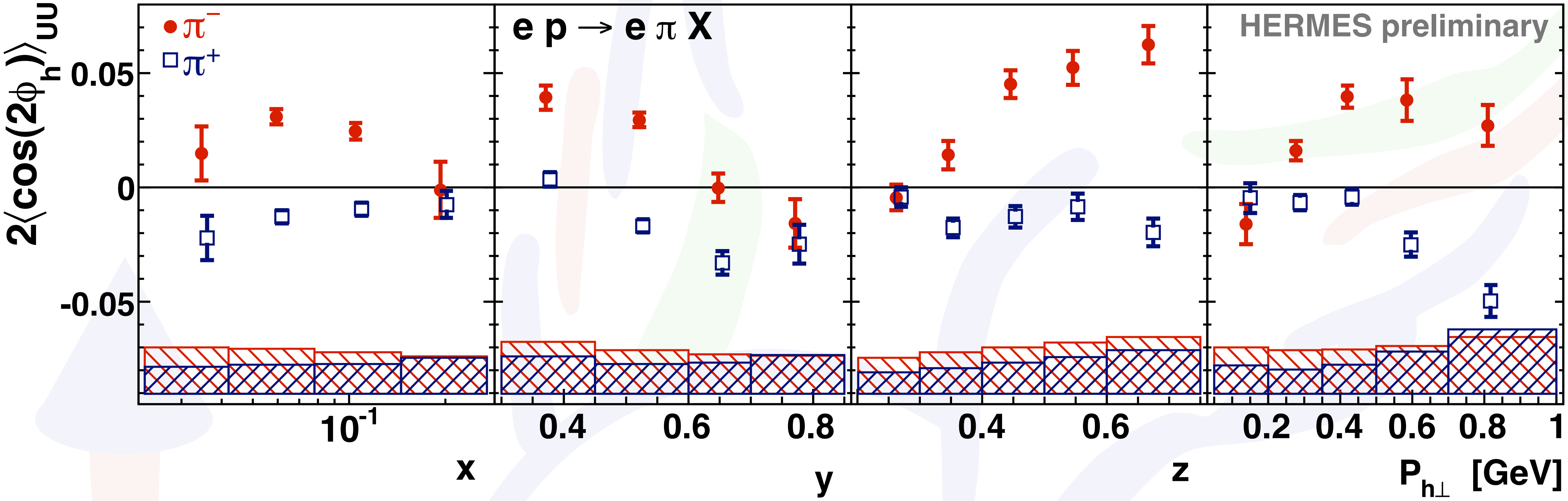
Interaction dependent terms neglected

(Implicit sum over quark flavours)

[courtesy of F. Giordano]

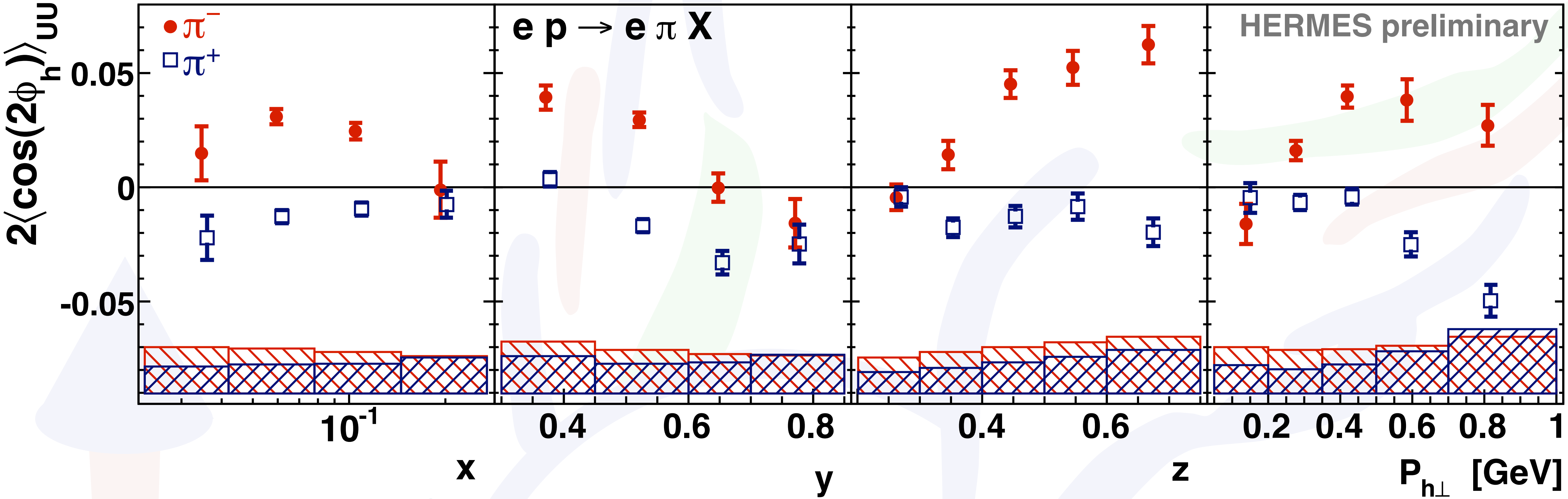
“Boer-Mulders modulation“

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



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

“Boer-Mulders modulation“



- **Cahn effect** (@twist-4) -kinematics modification due to transverse momenta- often **assumed flavor blind**

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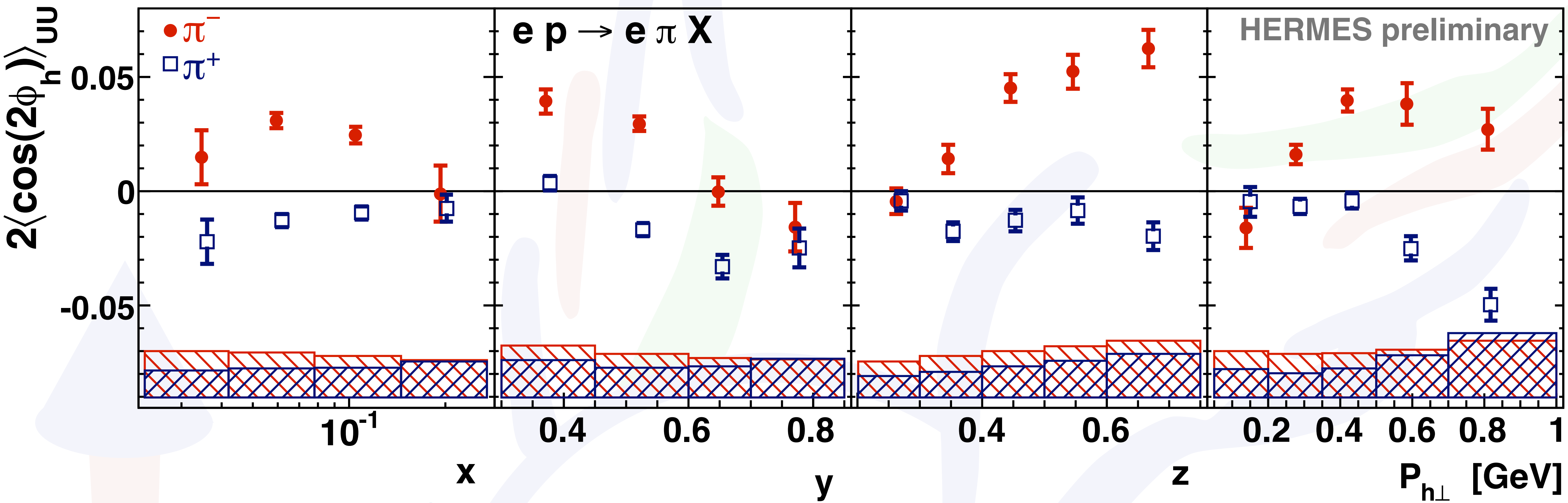

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- large flavor dependence points at **significant** (leading-twist) **Boer-Mulders effect**

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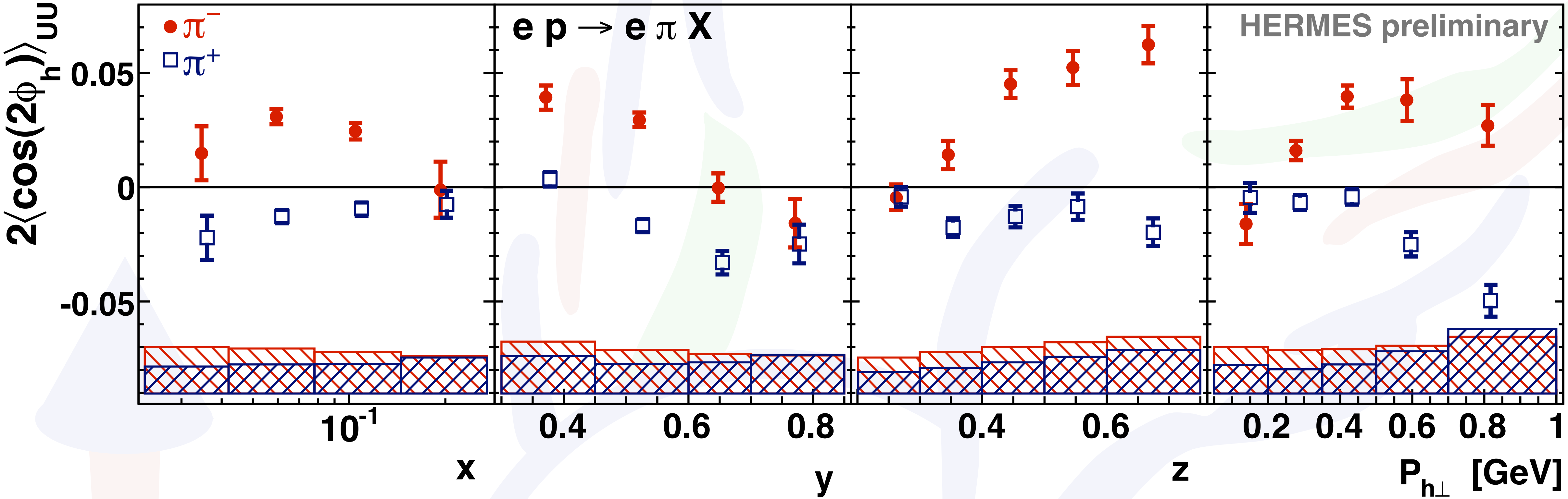

- **Cahn effect** (@twist-4) -kinematics modification due to transverse momenta- often **assumed flavor blind**
- large flavor dependence points at **significant** (leading-twist) **Boer-Mulders effect**
- opposite sign for opposite pion charge can be expected from same-sign BM functions for up and down quarks (if considering opposite sign for up and down Collins functions -> Collins effect)

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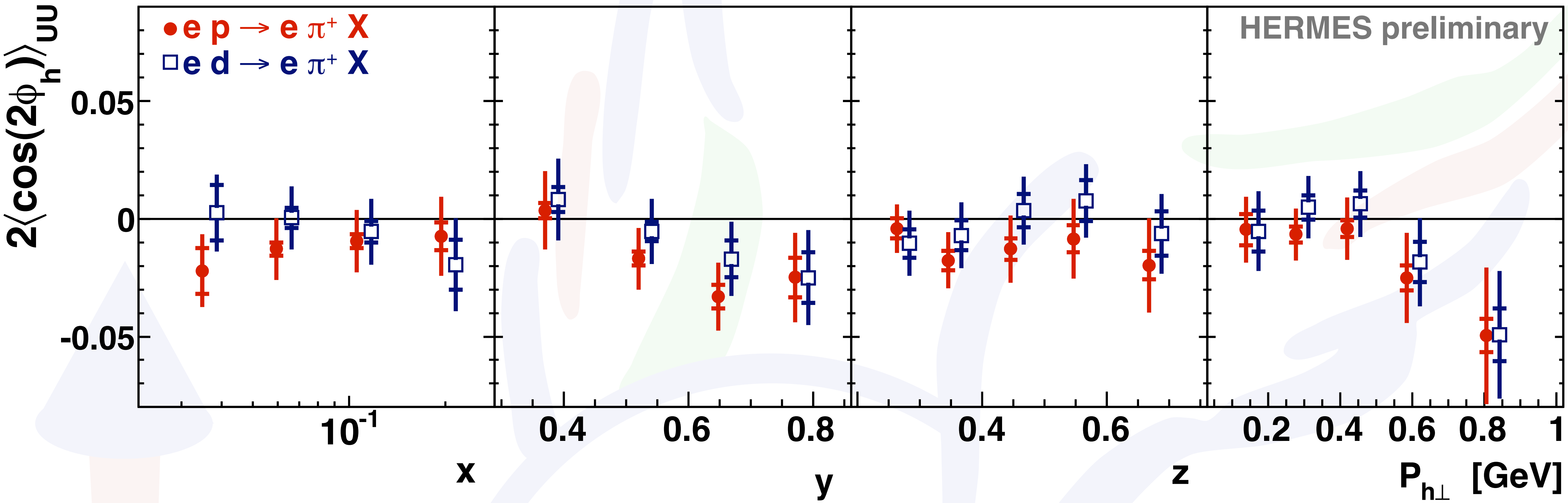

- hardly any dependence on target!
- consistent with **same-sign up/down BM of similar size**

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	U	L	T
U	f_1		$h_1^\perp$
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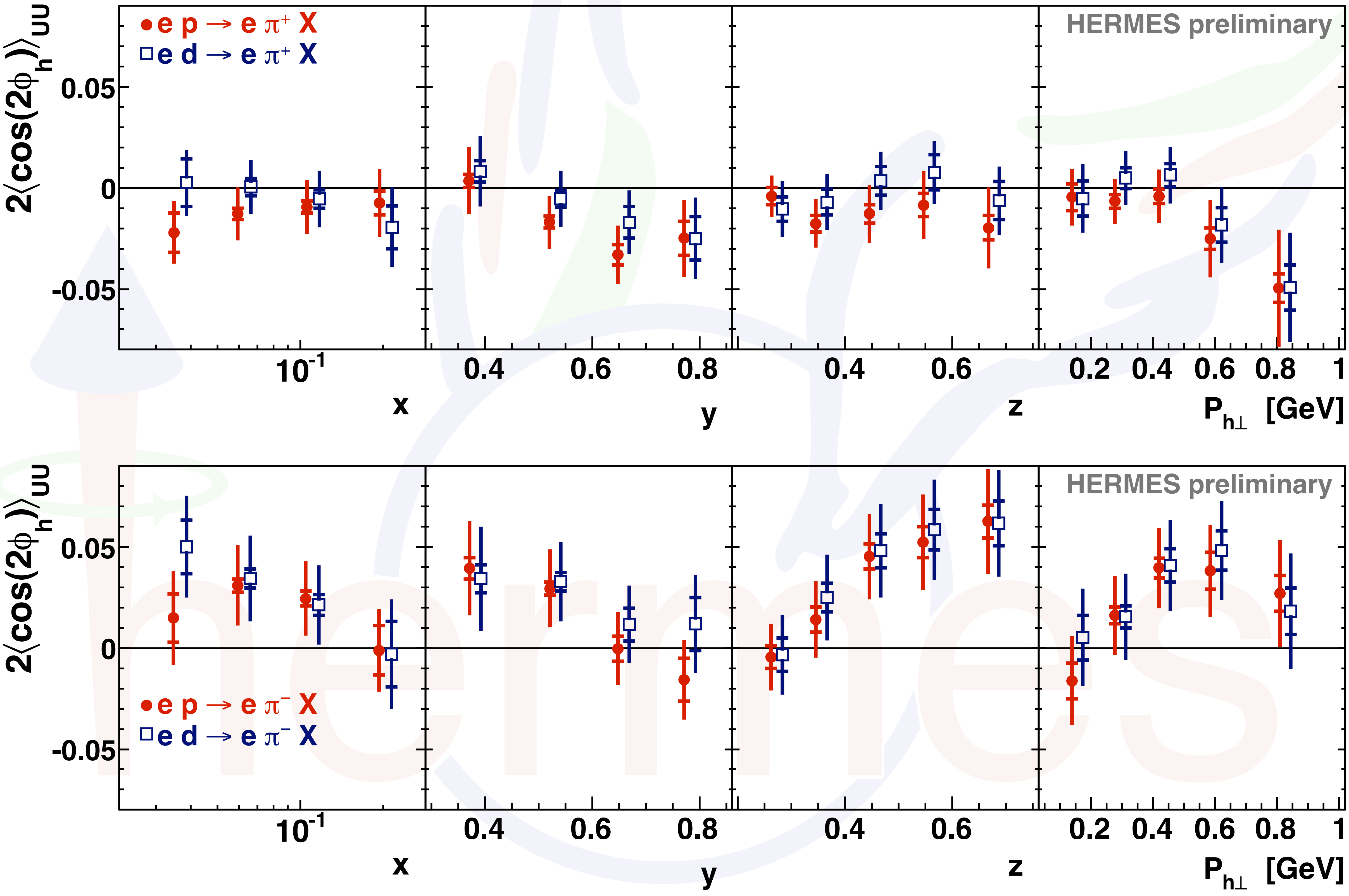

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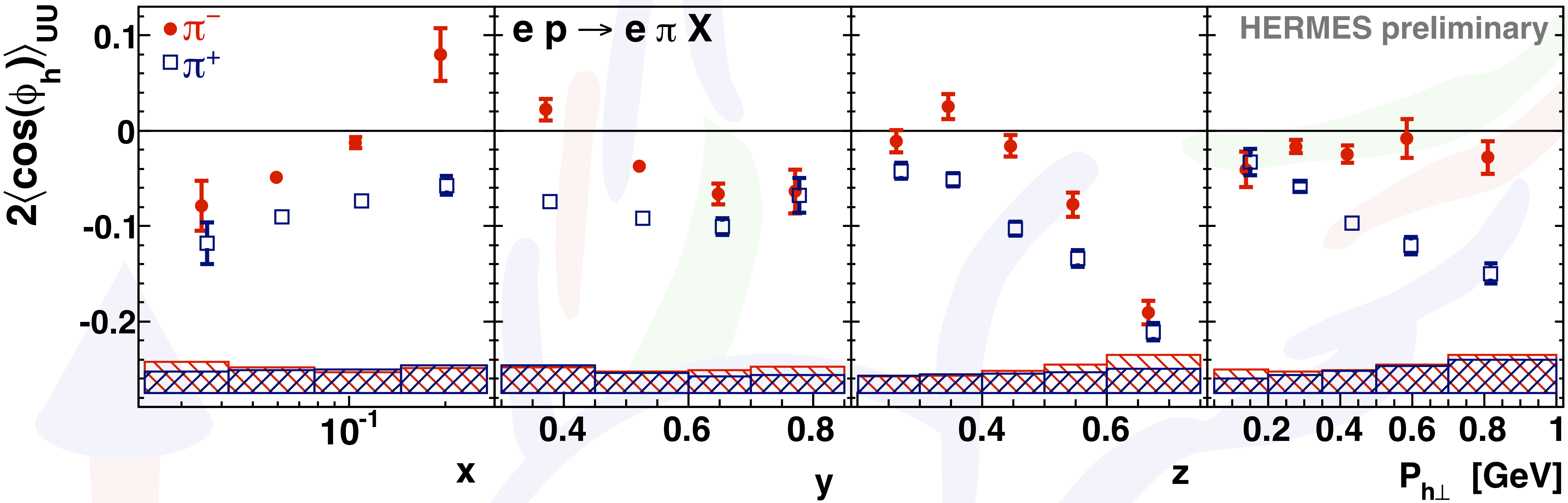
“Cahn modulation“



- no dependence on hadron charge expected for Cahn effect

➡ flavor dependence of transverse momentum

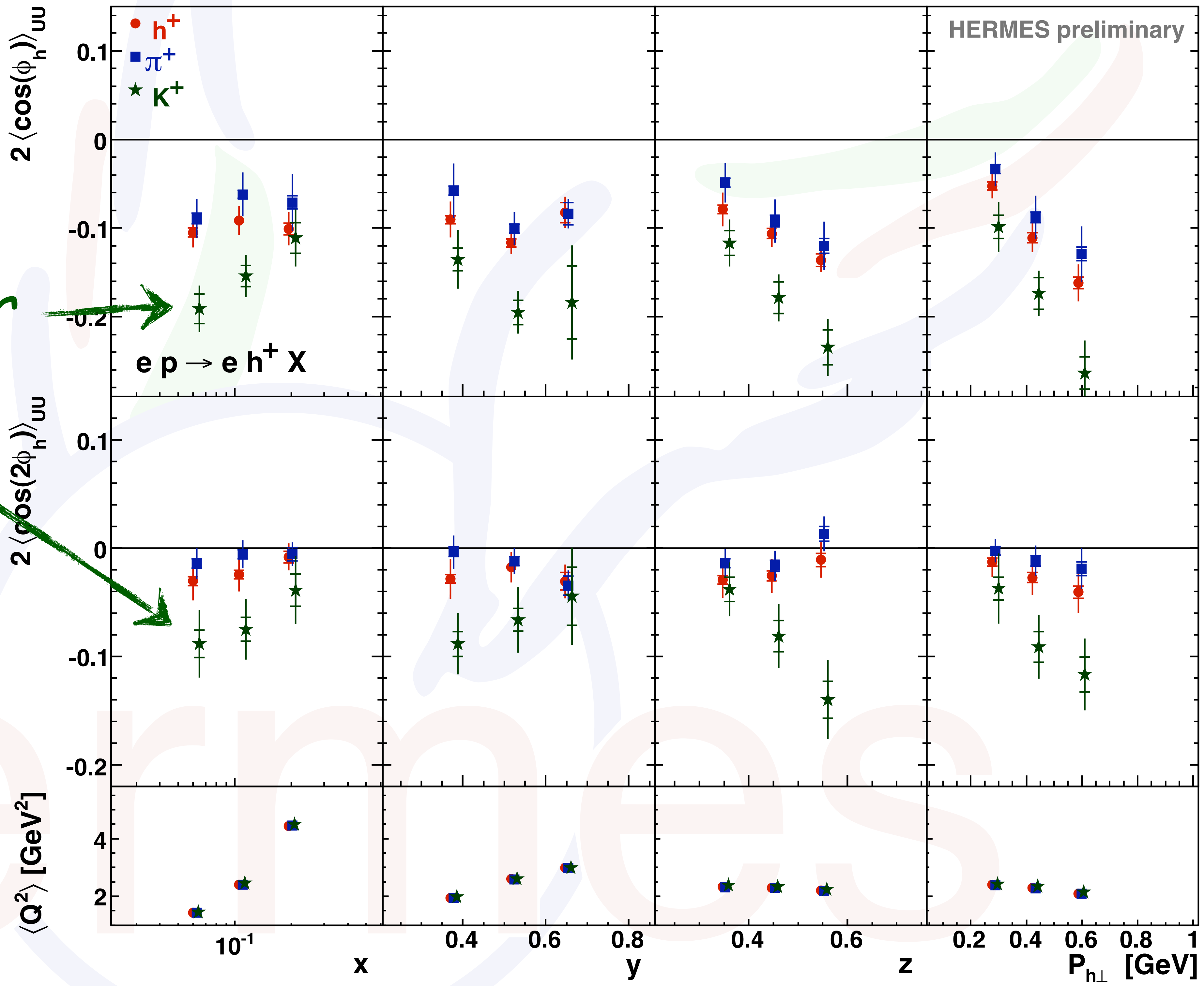
➡ sign of Boer-Mulders in cosϕ modulation
(indeed, overall pattern resembles B-M modulations)

➡ additional “genuine“ twist-3?

	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 results

intriguing behavior
for kaons



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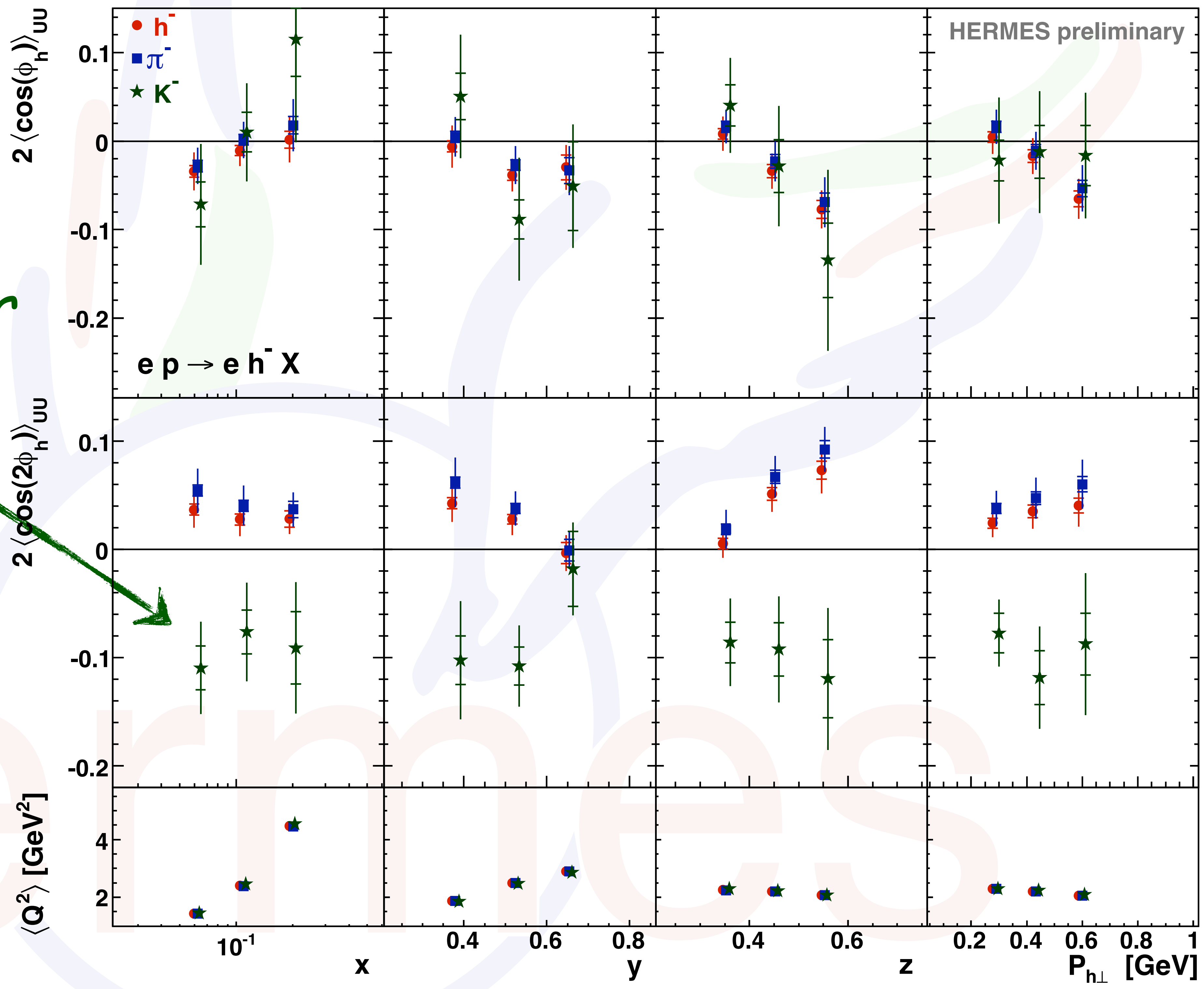

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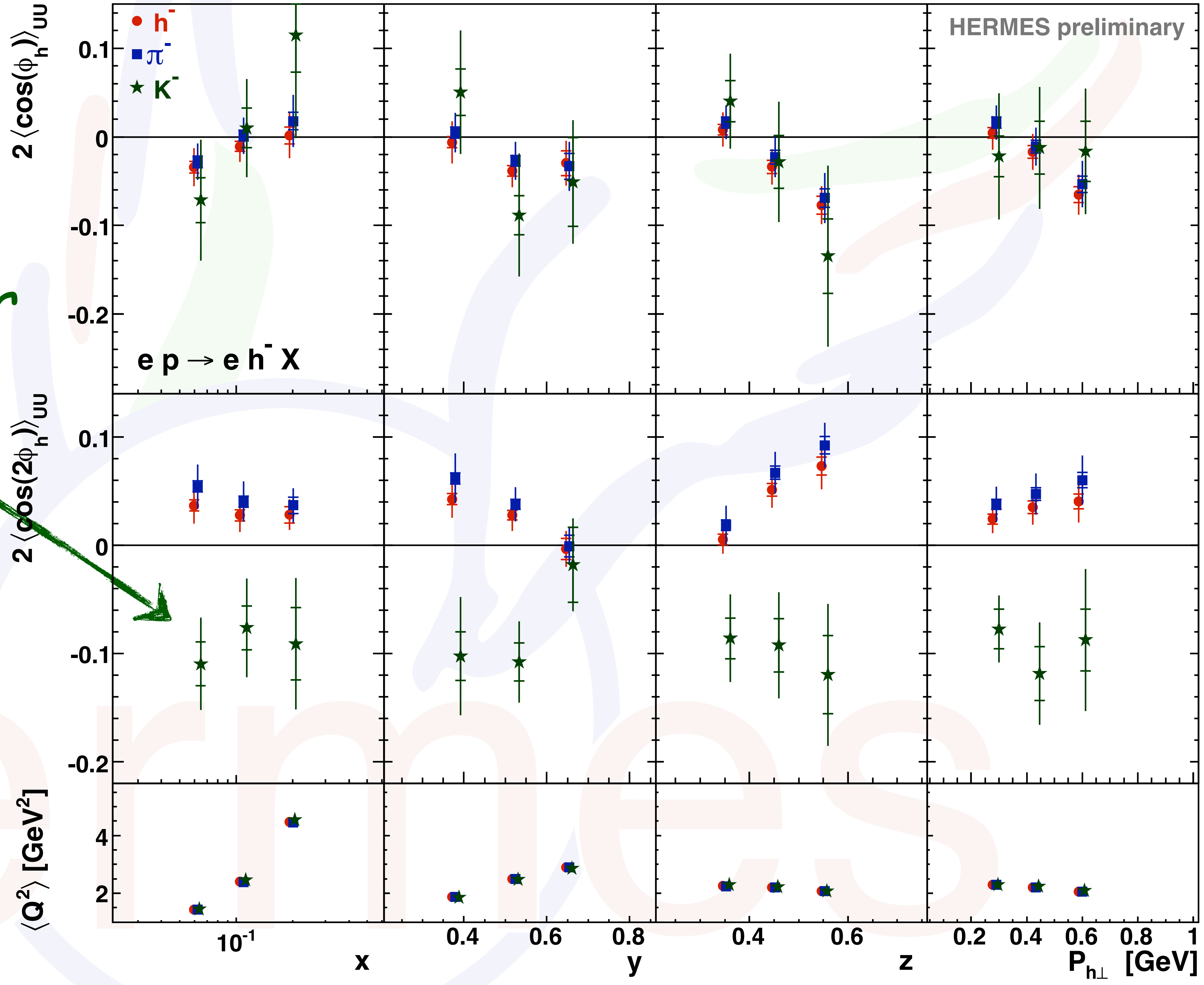

intriguing behavior for kaons

different pattern for kaon Collins function? (cf. BRAHMS A_N and SIDIS Collins)

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... add more transverse spin ...

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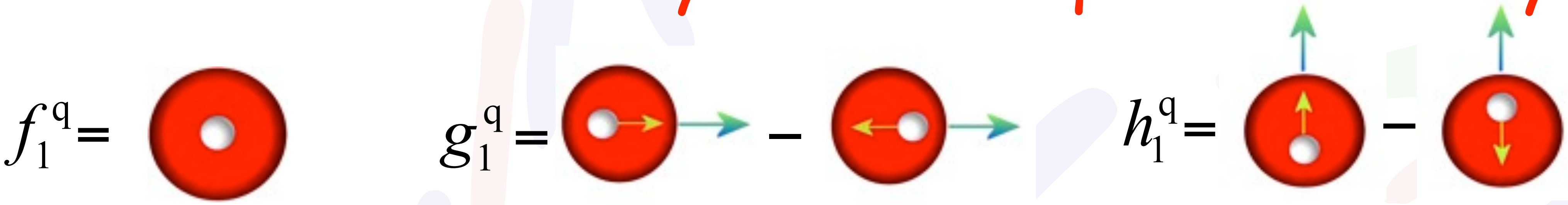
Transversity distribution

chiral-odd transversity involves quark helicity flip



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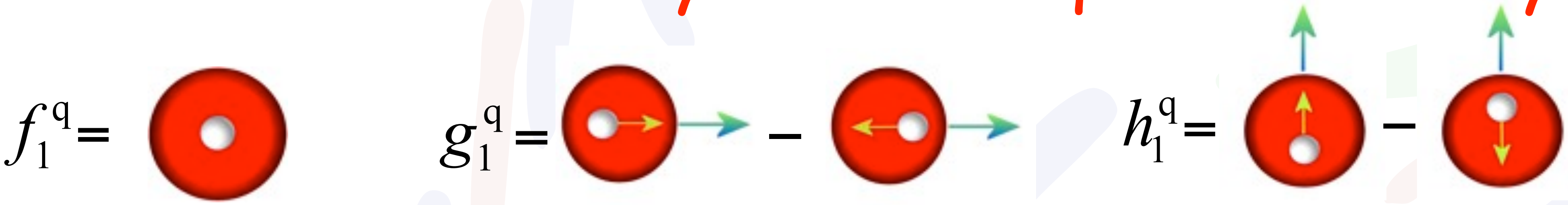

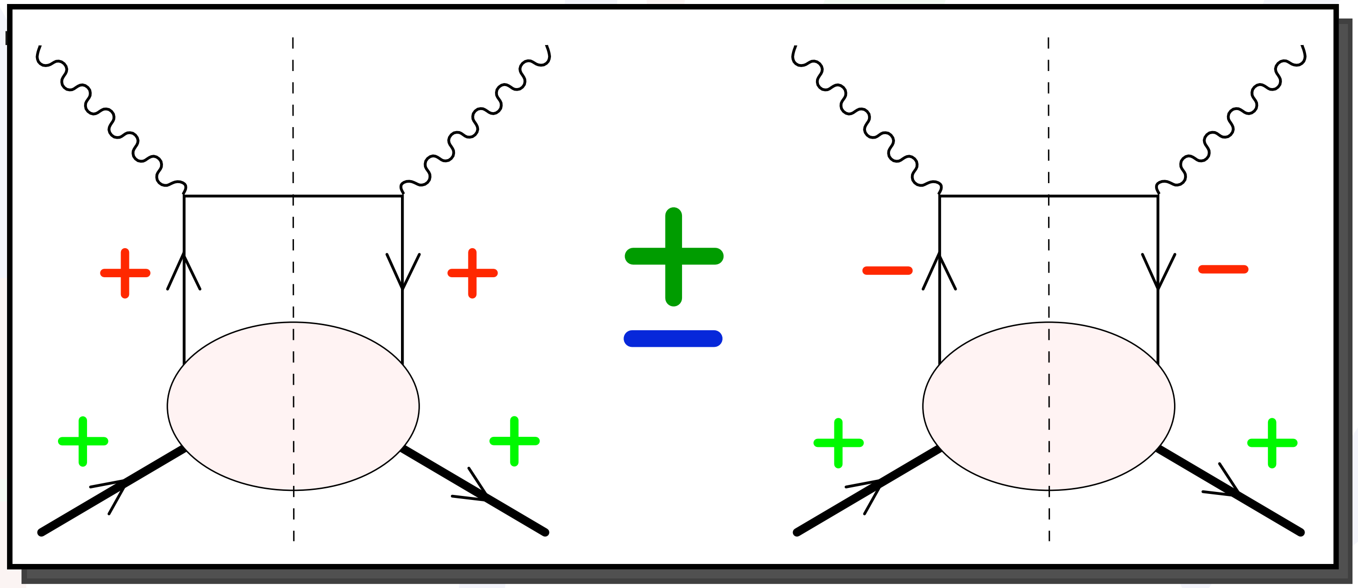

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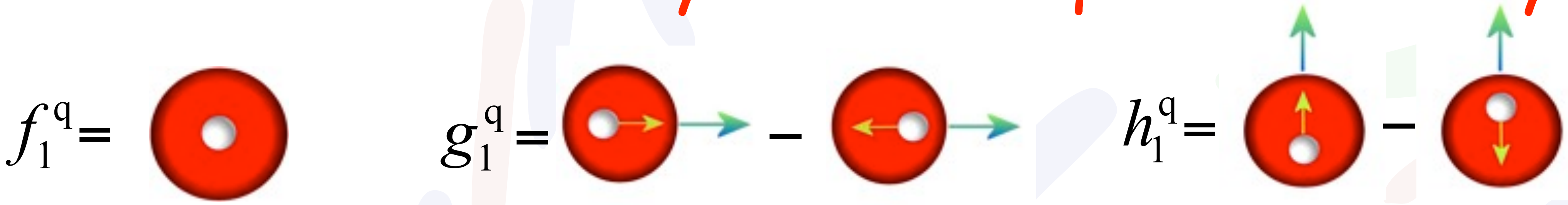

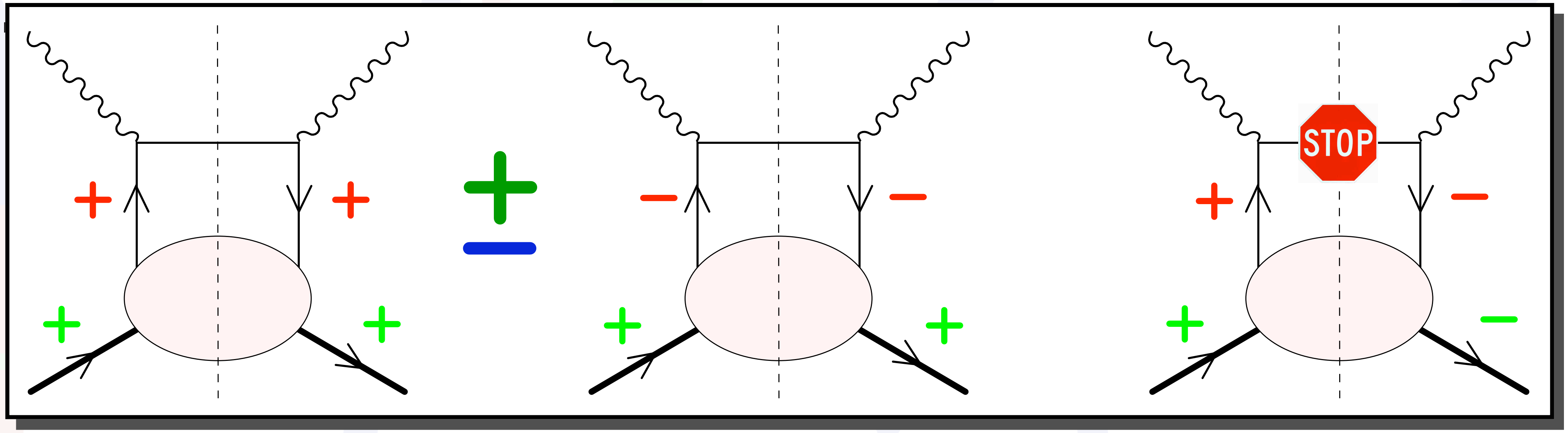

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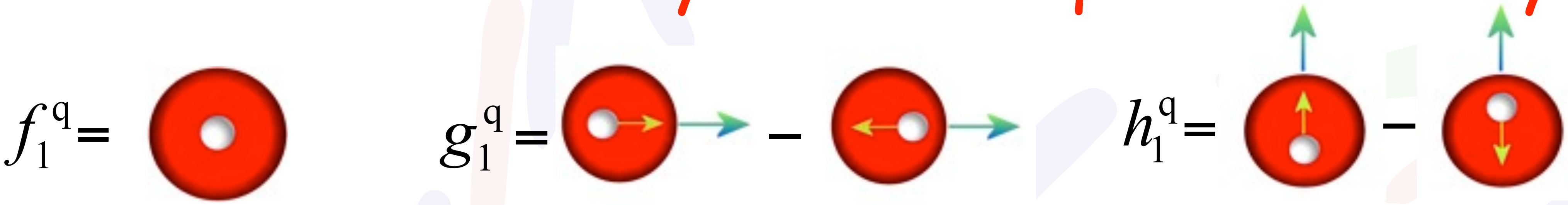

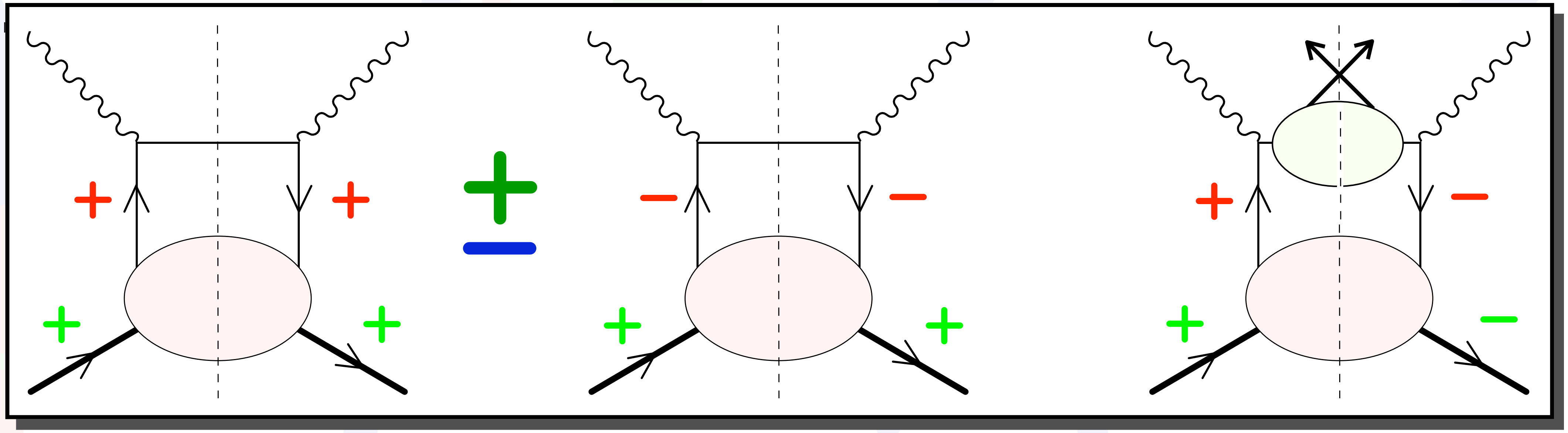

need to couple to chiral-odd fragmentation function:

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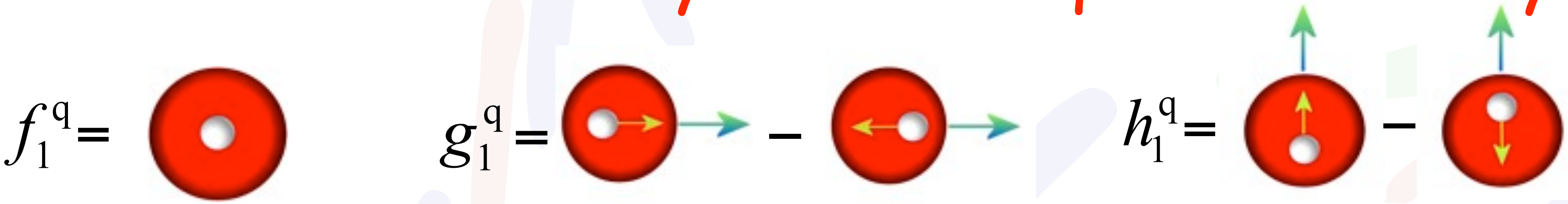

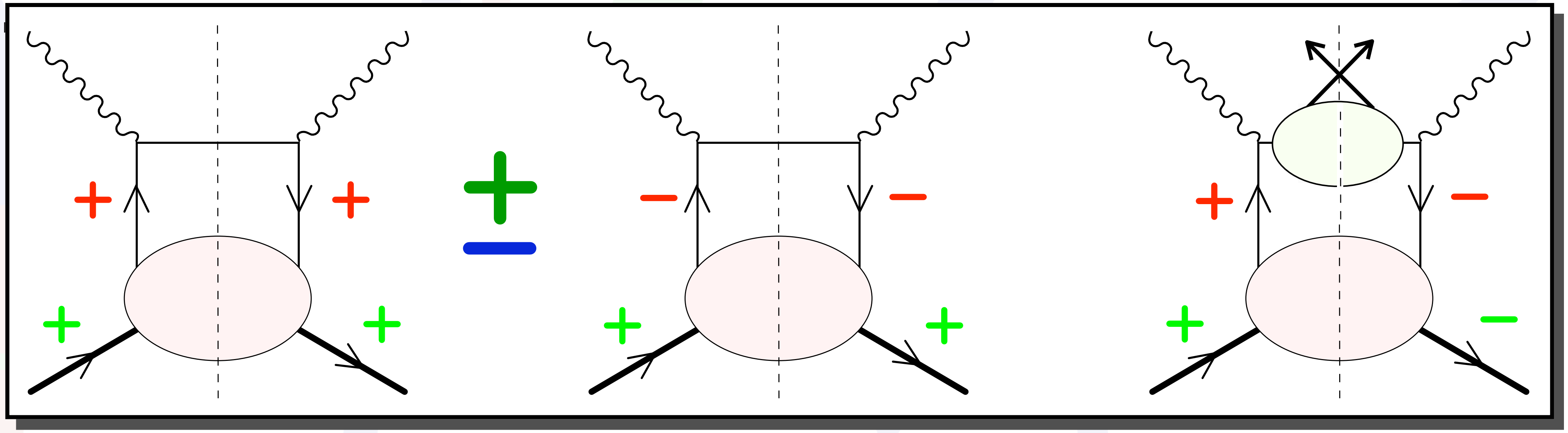

need to couple to chiral-odd fragmentation function:

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

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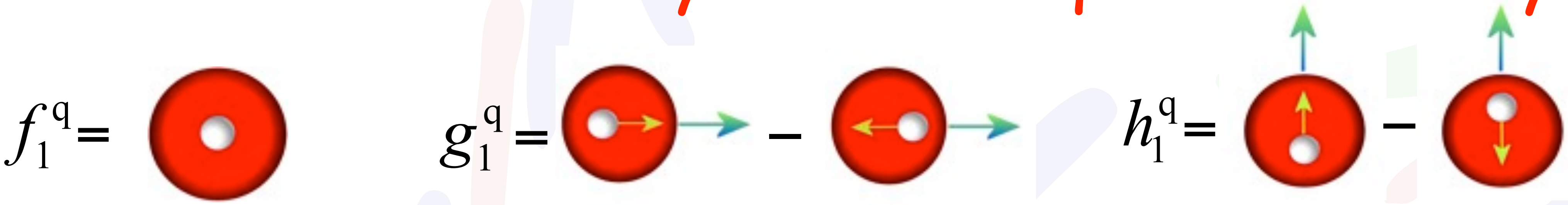

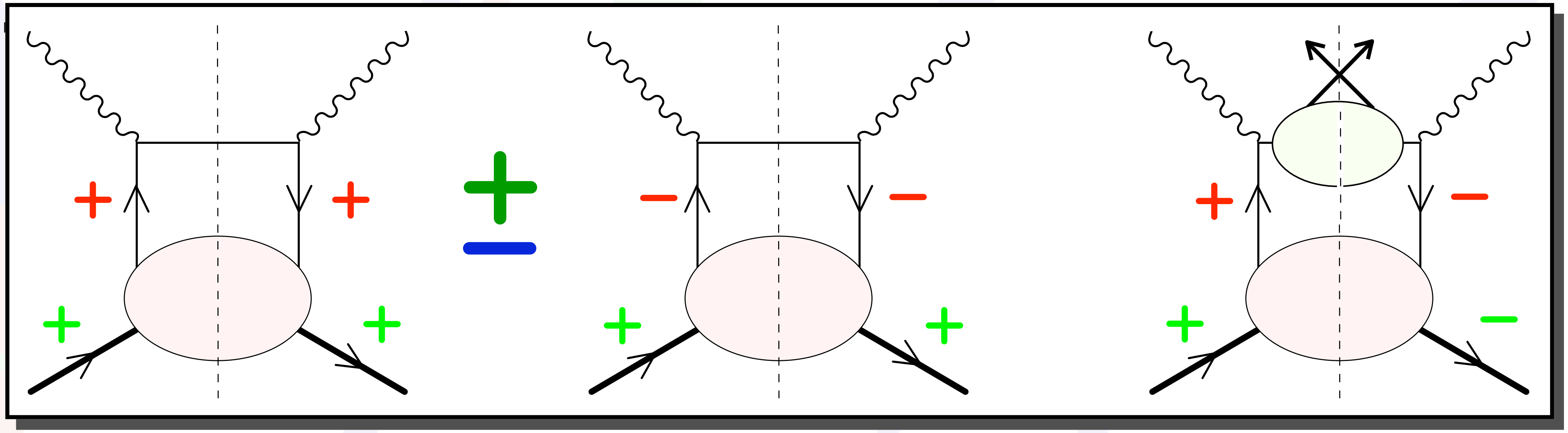

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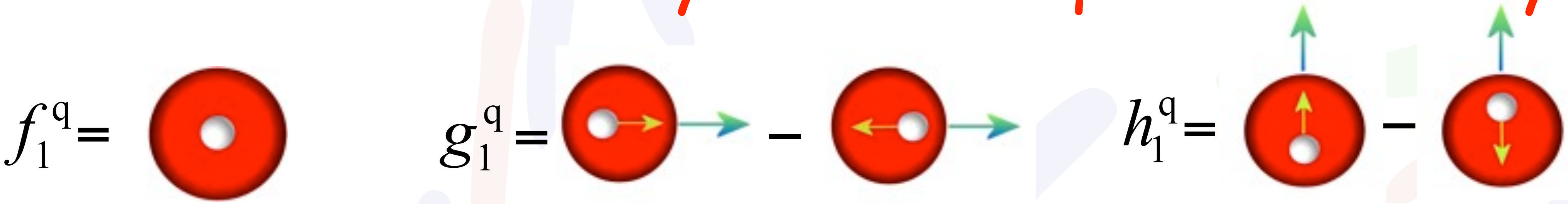

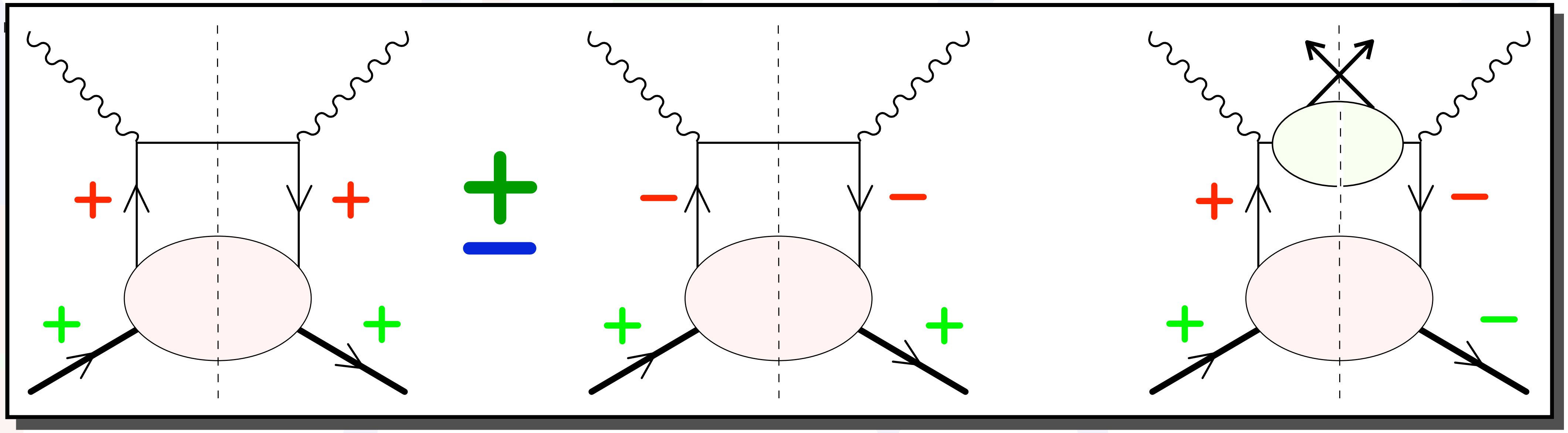

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- ☑ **Collins fragmentation**

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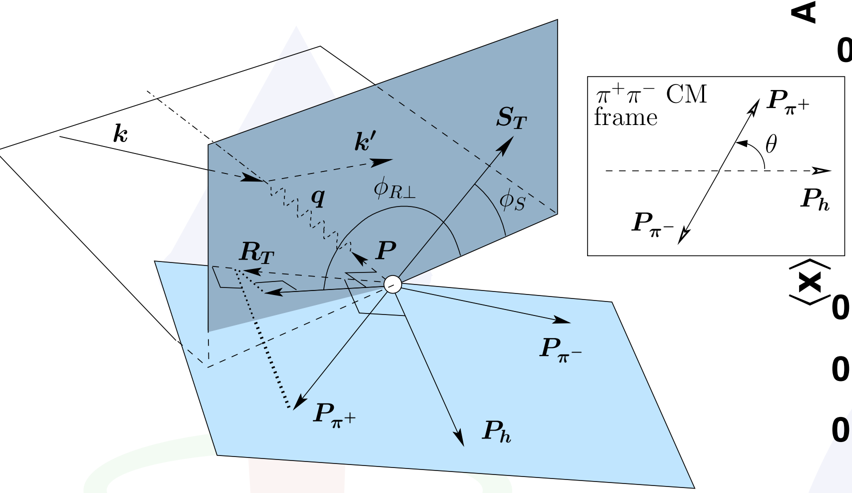
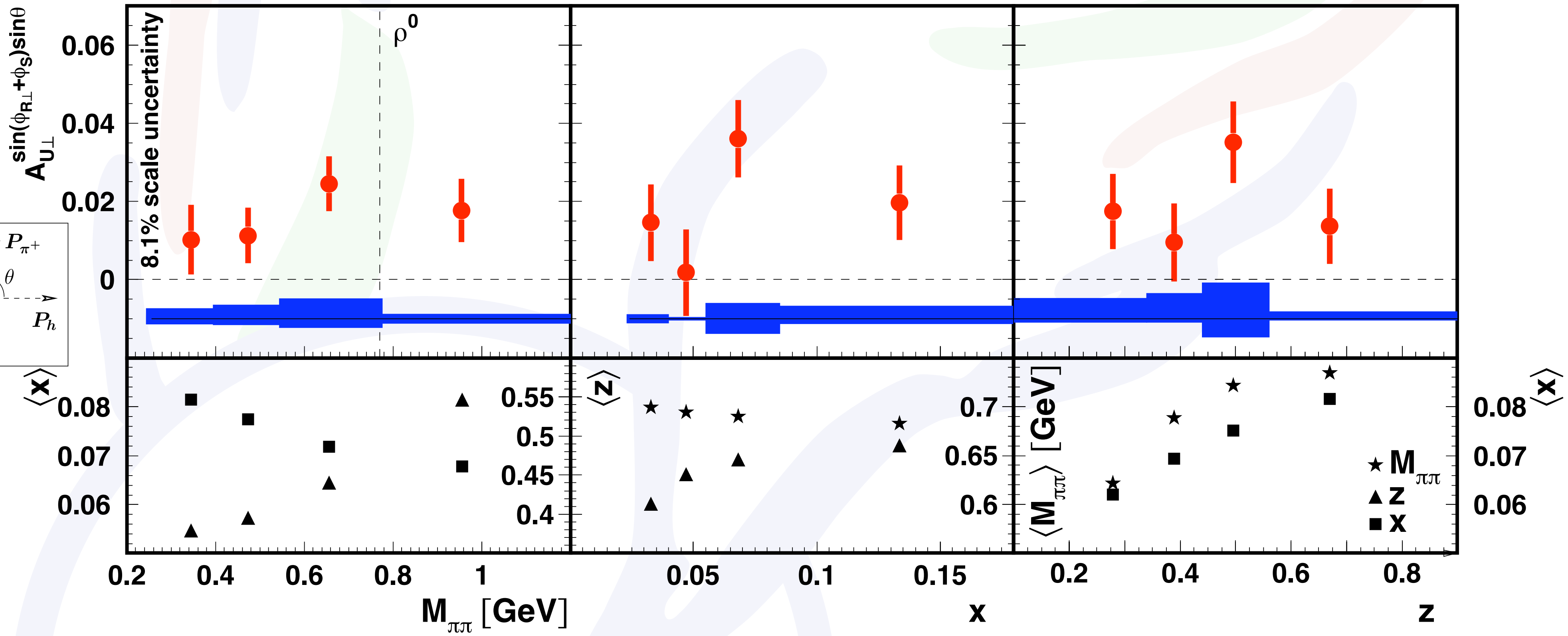
Transversity distribution (2-hadron fragmentation)



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



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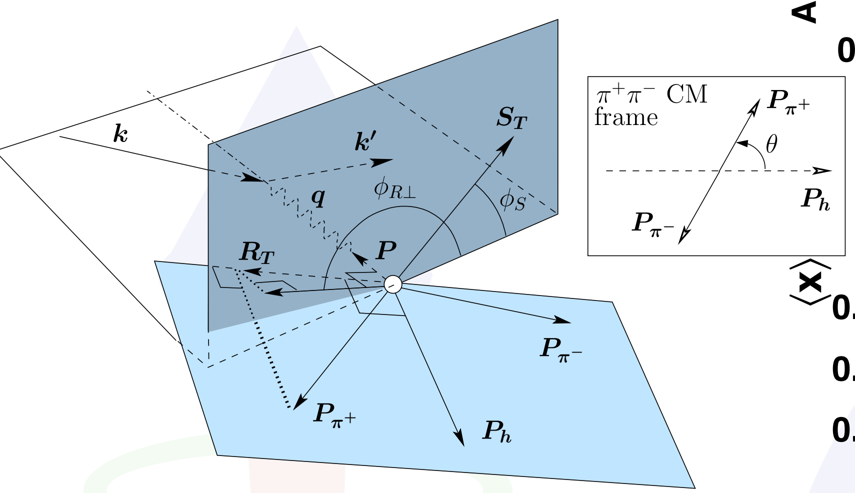

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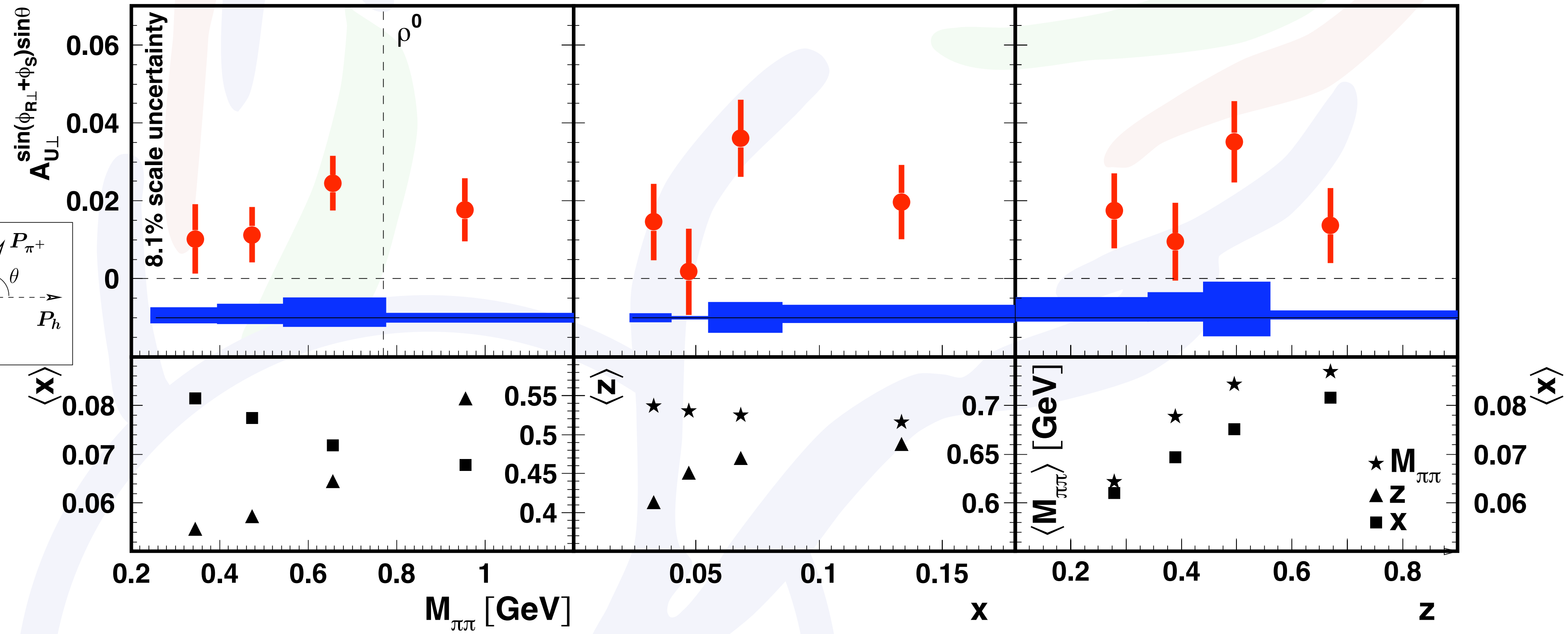

☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS

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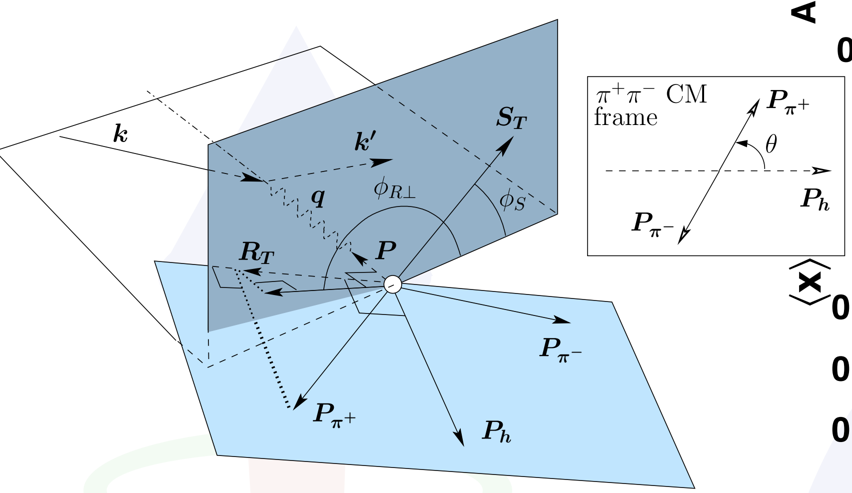

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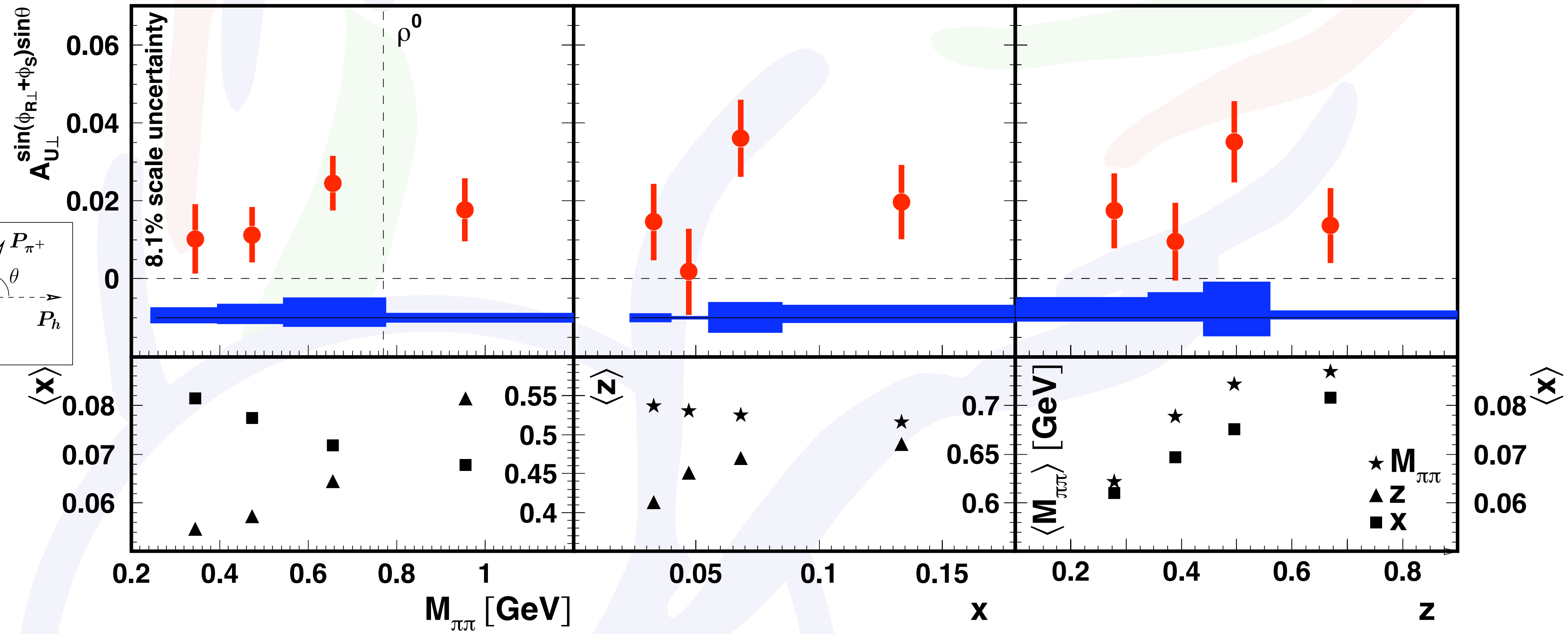

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☑ invariant-mass dependence rules out Jaffe prediction of sign change at ρ mass

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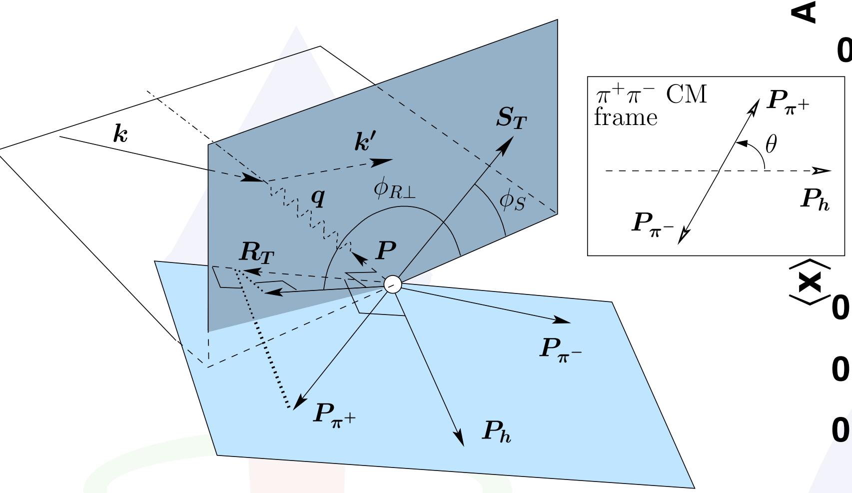

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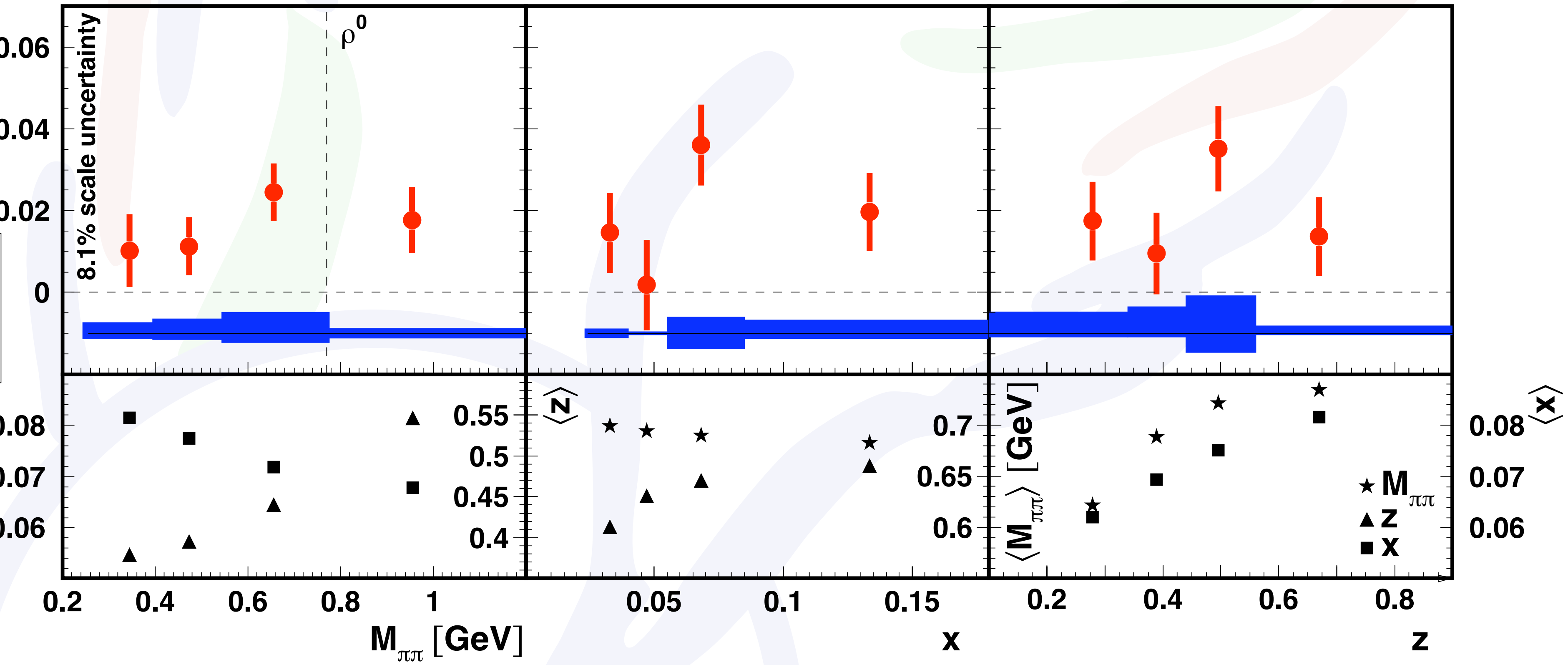
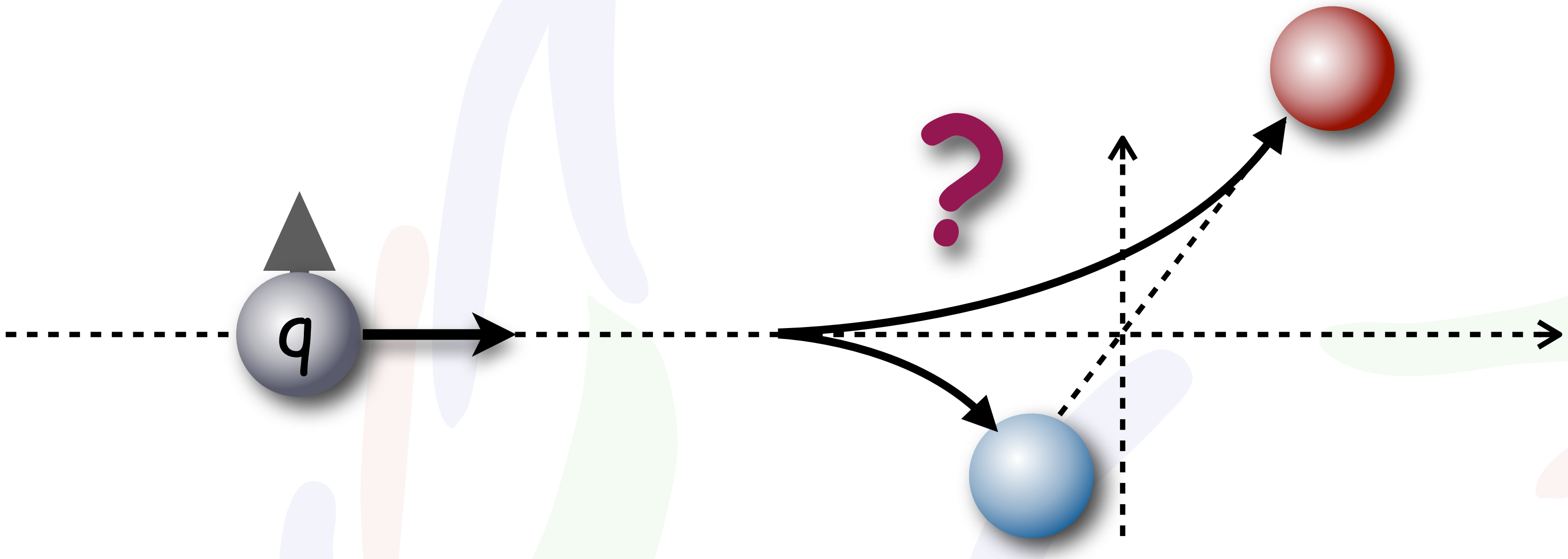


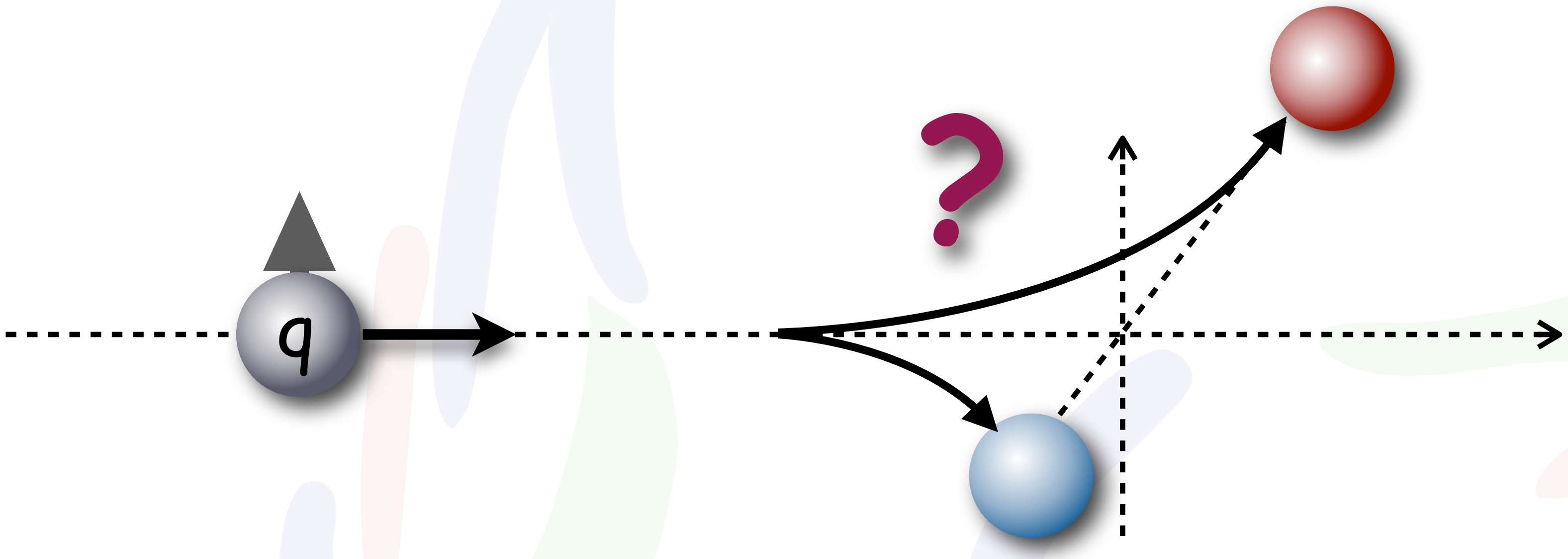
- ☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS
- ☑ invariant-mass dependence rules out Jaffe prediction of sign change at ρ mass
- ☐ more asymmetry amplitudes coming out soon

Collins fragmentation

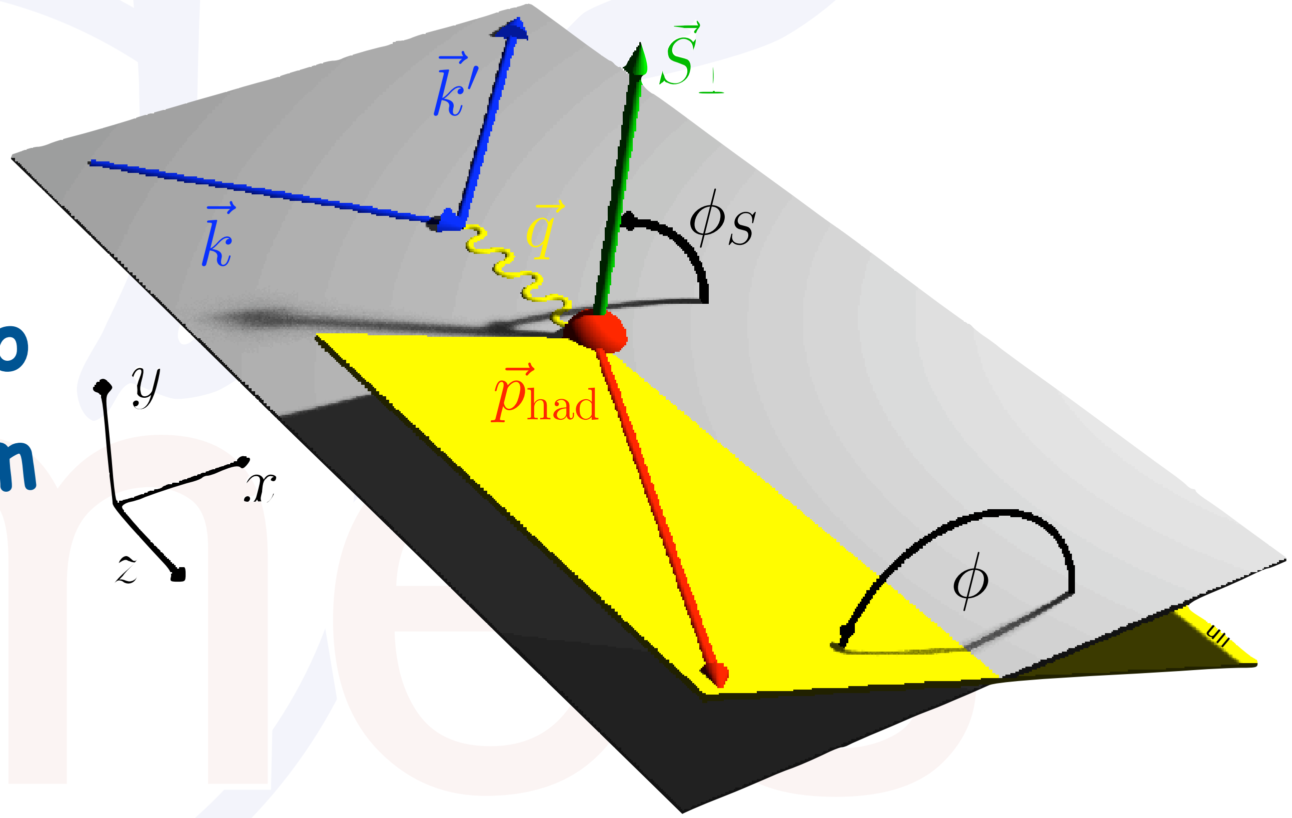


- spin-dependence in fragmentation
- left-right asymmetry in hadron direction transverse to both quark spin and momentum

Collins fragmentation



- spin-dependence in fragmentation
- left-right asymmetry in hadron direction transverse to both quark spin and momentum
- leads to particular azimuthal distribution of hadrons produced in DIS



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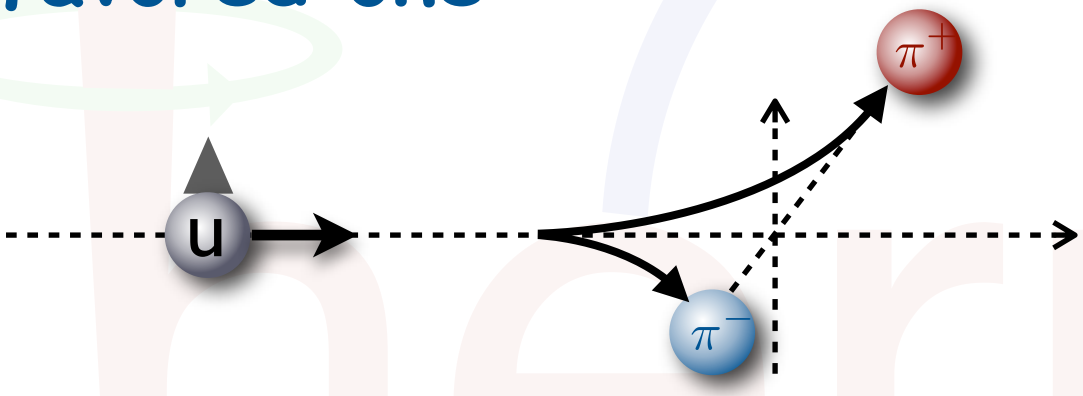
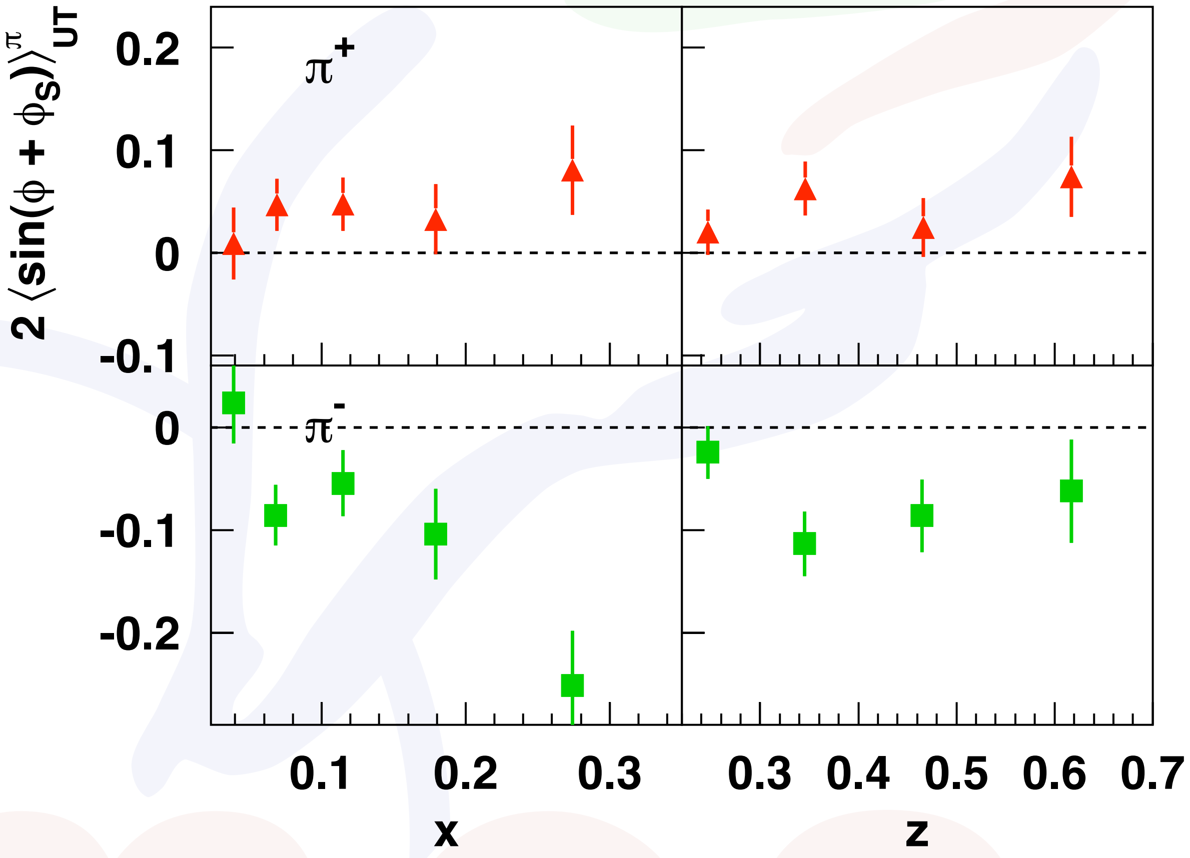
Transversity distribution (Collins fragmentation)

- 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

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	U	L	T
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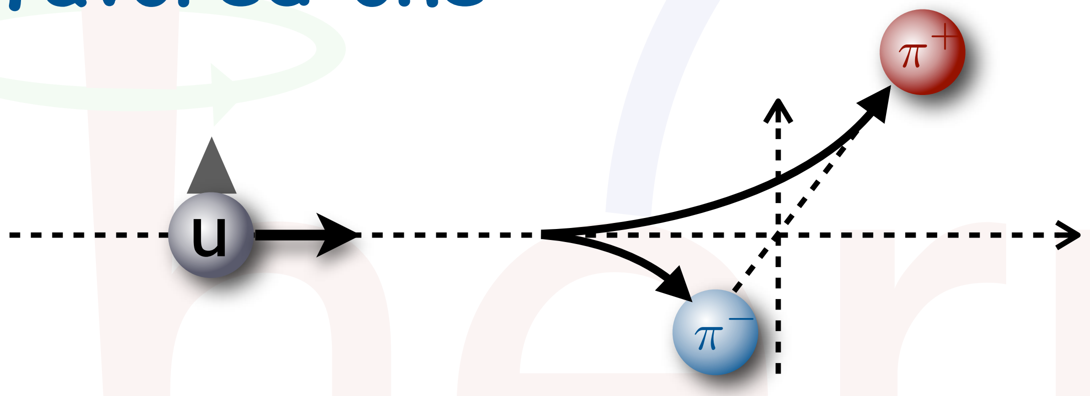

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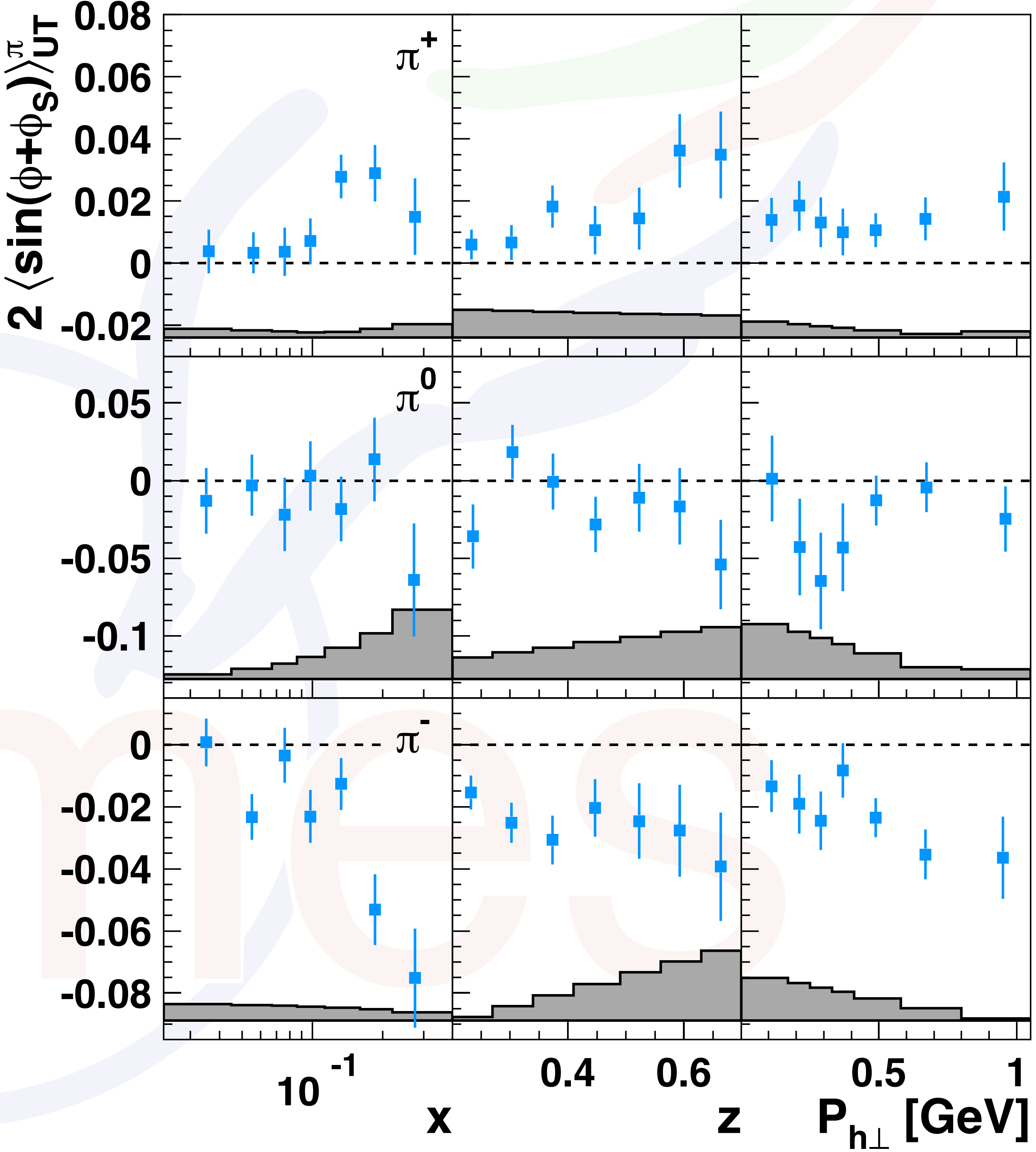
[A.Airapetian et al., PLB 693 (2010) 11]



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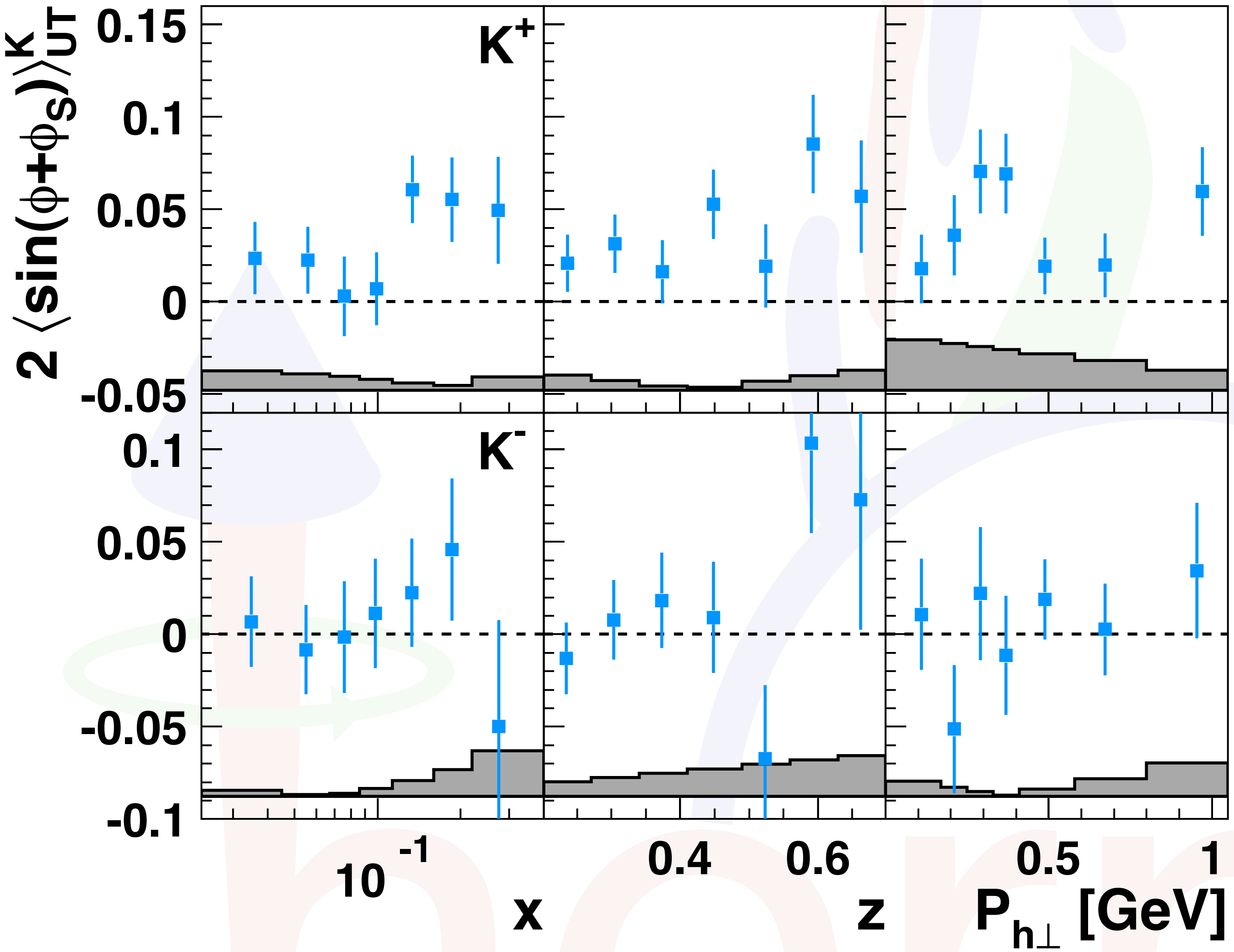

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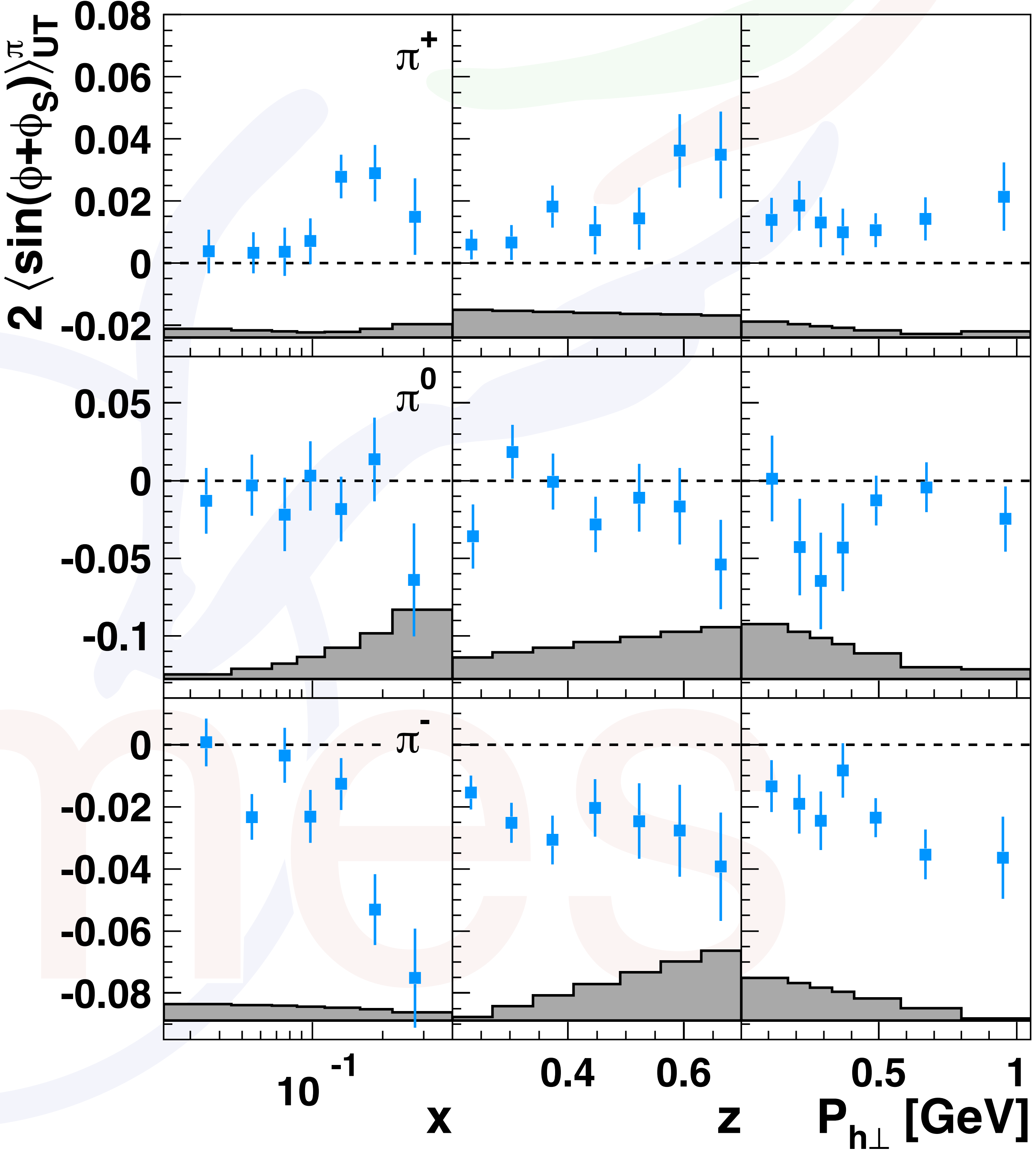

- significantly non-zero amplitudes also for K^+

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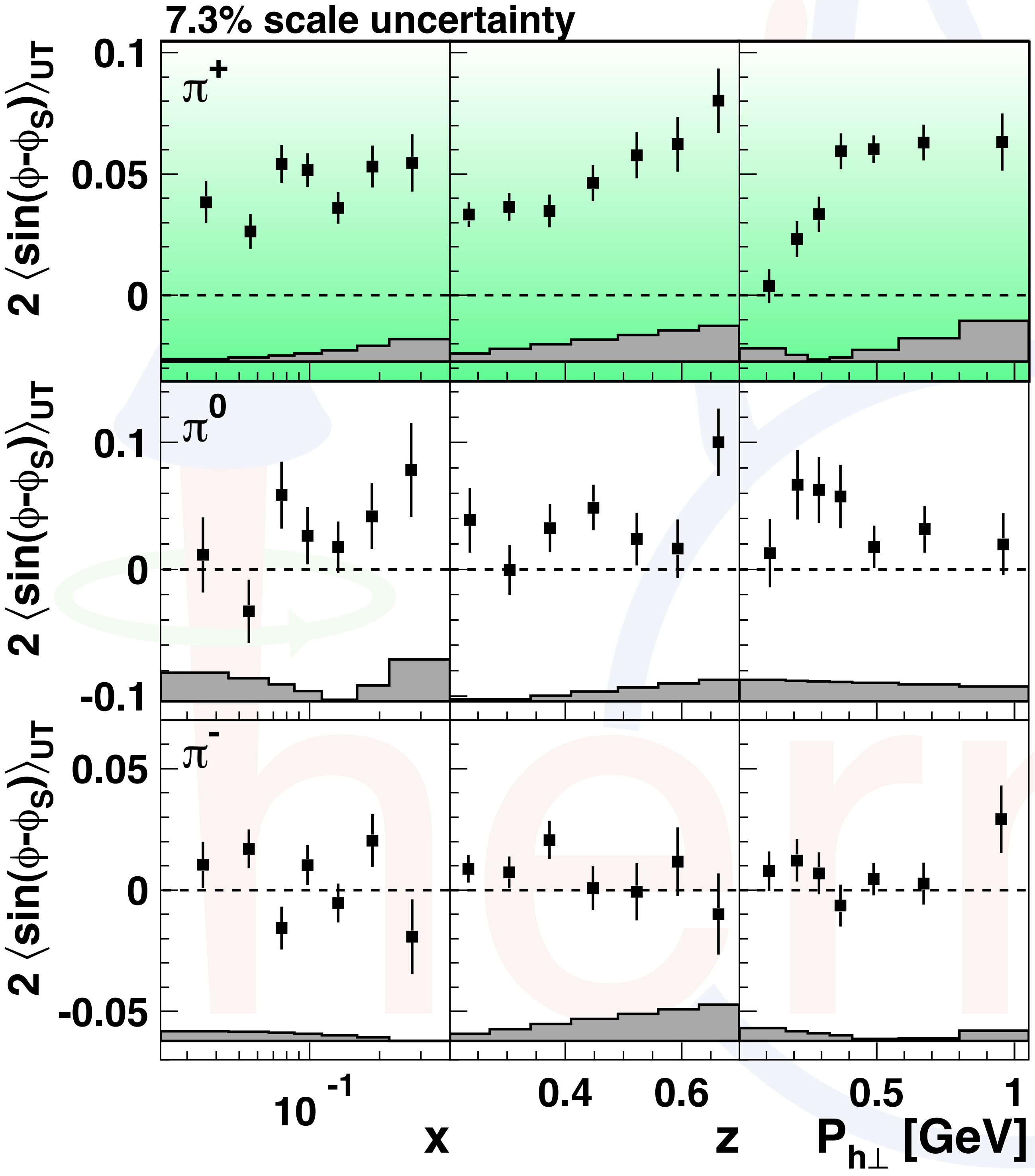
Sivers amplitudes for pions

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



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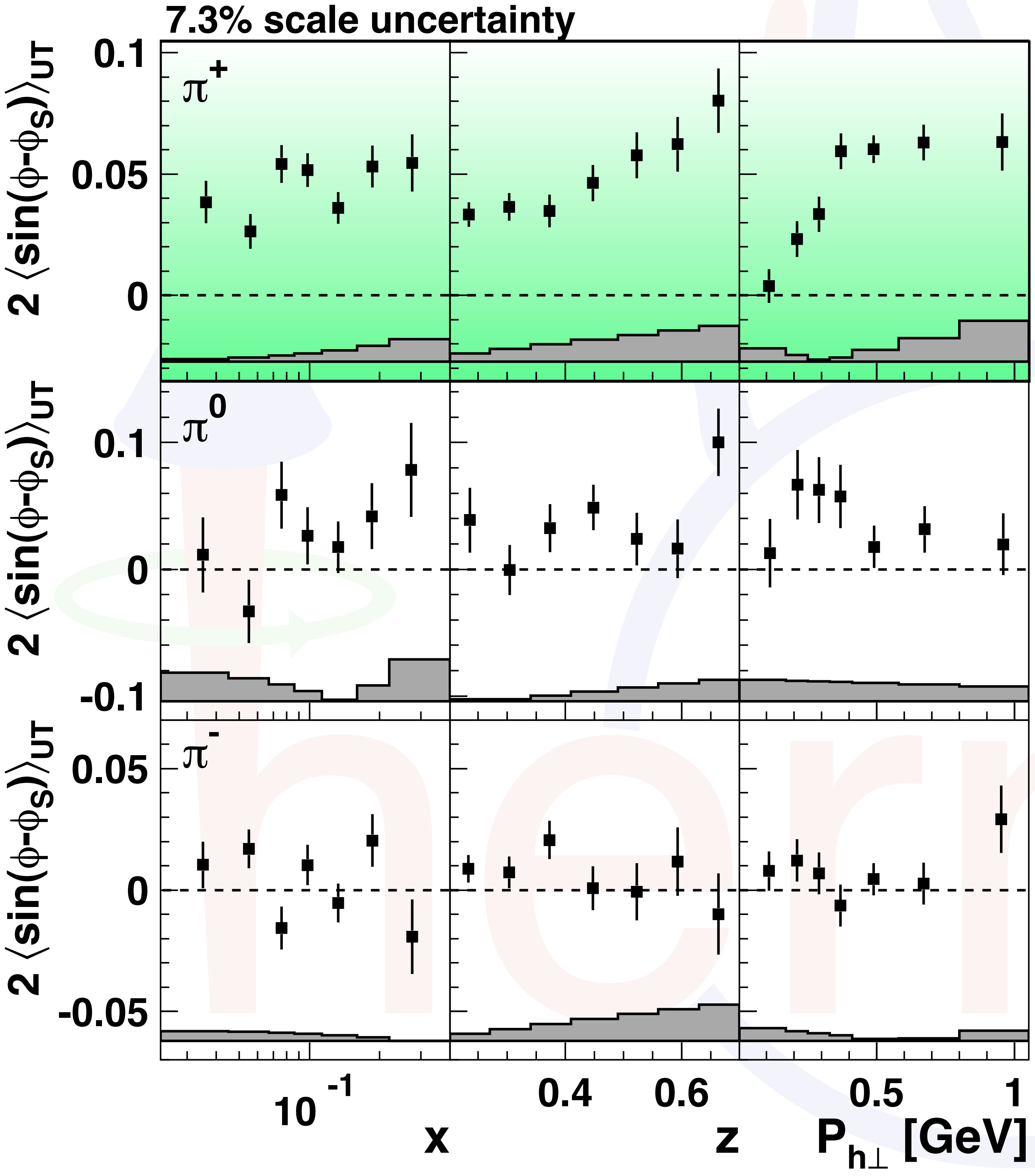

π^+ dominated by u-quark scattering:

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

☛ u-quark Sivers DF < 0

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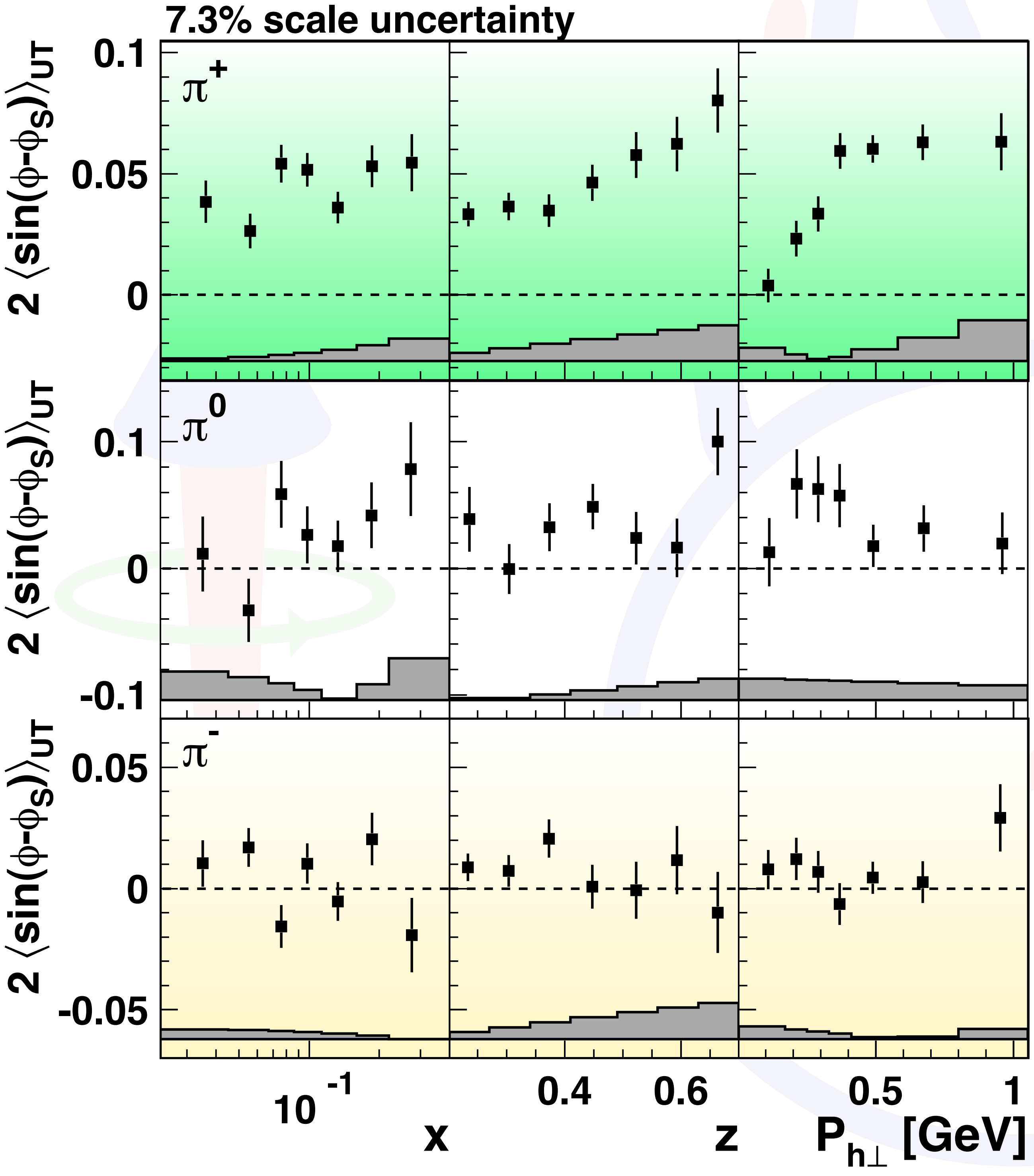

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$$\simeq -\frac{f_{1T}^{\perp,u}(x,p_T^2)\otimes\mathcal{W}\, D_1^{u\to\pi^+}(z,k_T^2)}{f_1^u(x,p_T^2)\otimes D_1^{u\to\pi^+}(z,k_T^2)}$$

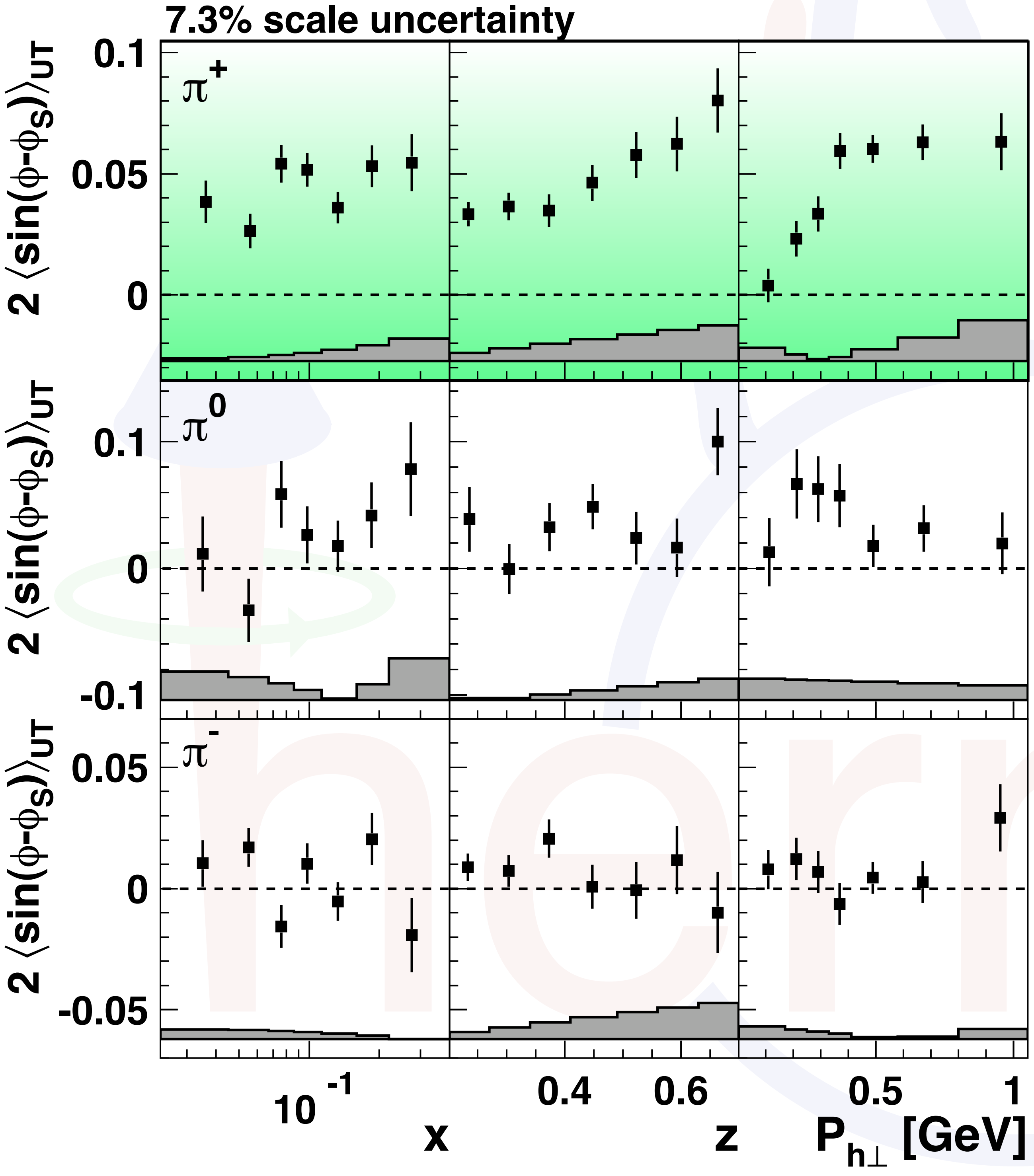
☛ u-quark Sivers DF < 0

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

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

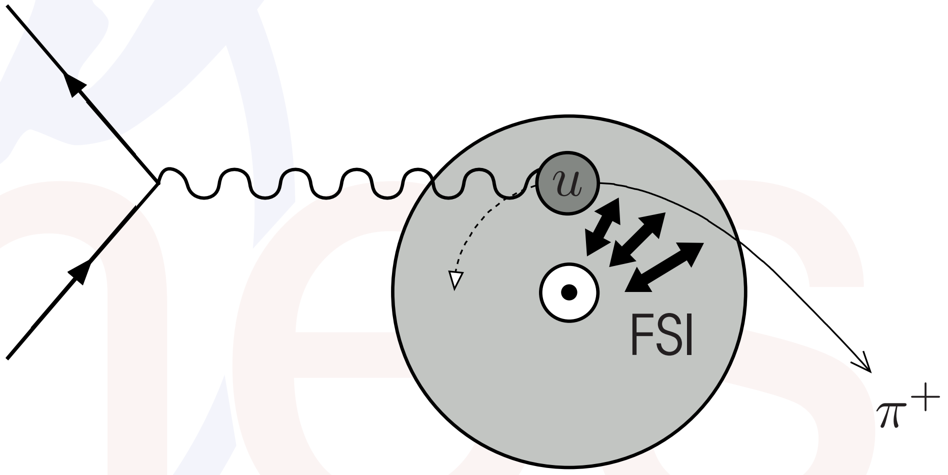
Sivers amplitudes for pions

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



π^+ dominated by u-quark scattering:

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



[*M. Burkardt*, Phys. Rev. D66 (2002) 114005]

gunar.schnell @ desy.de

	U	L	T
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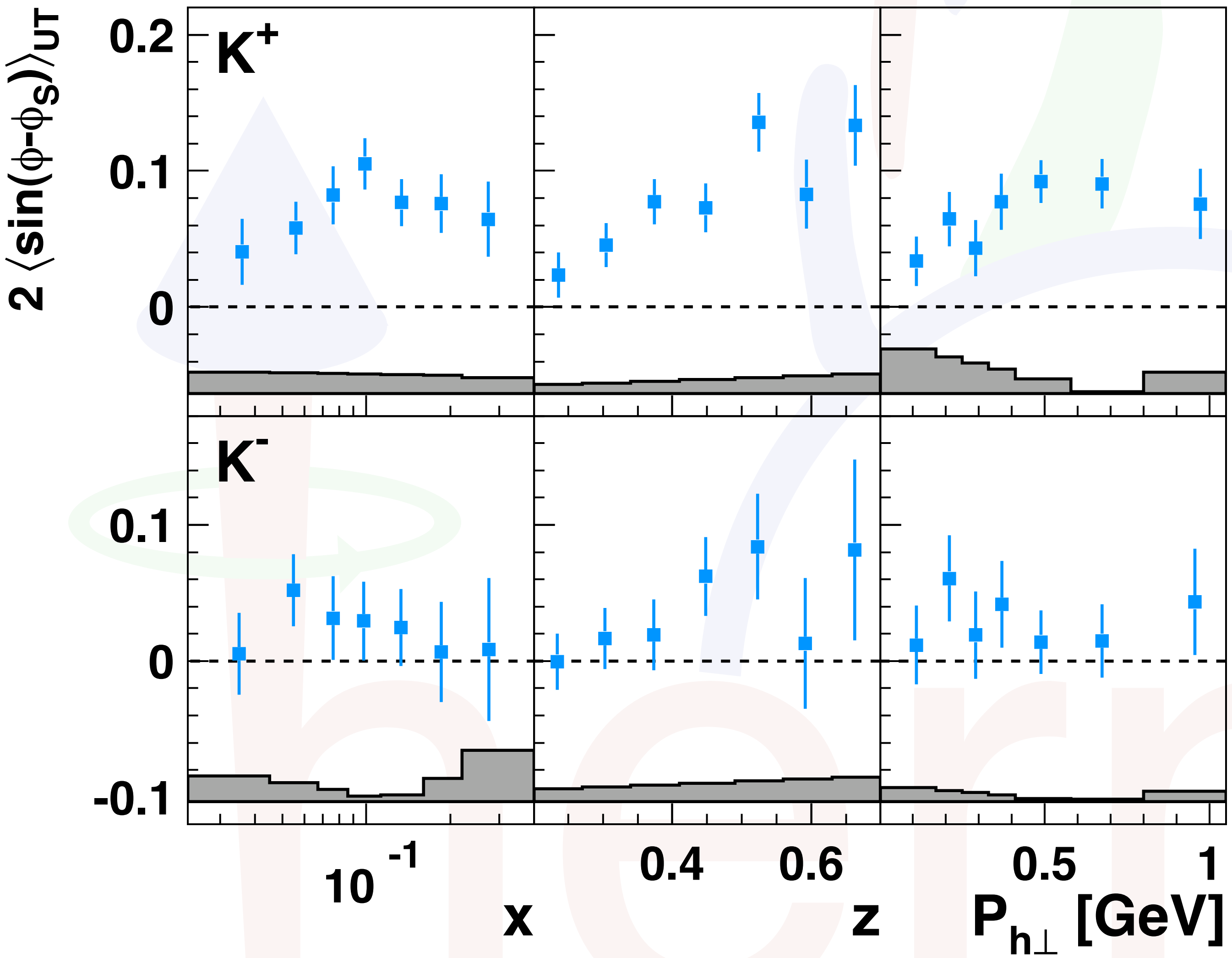
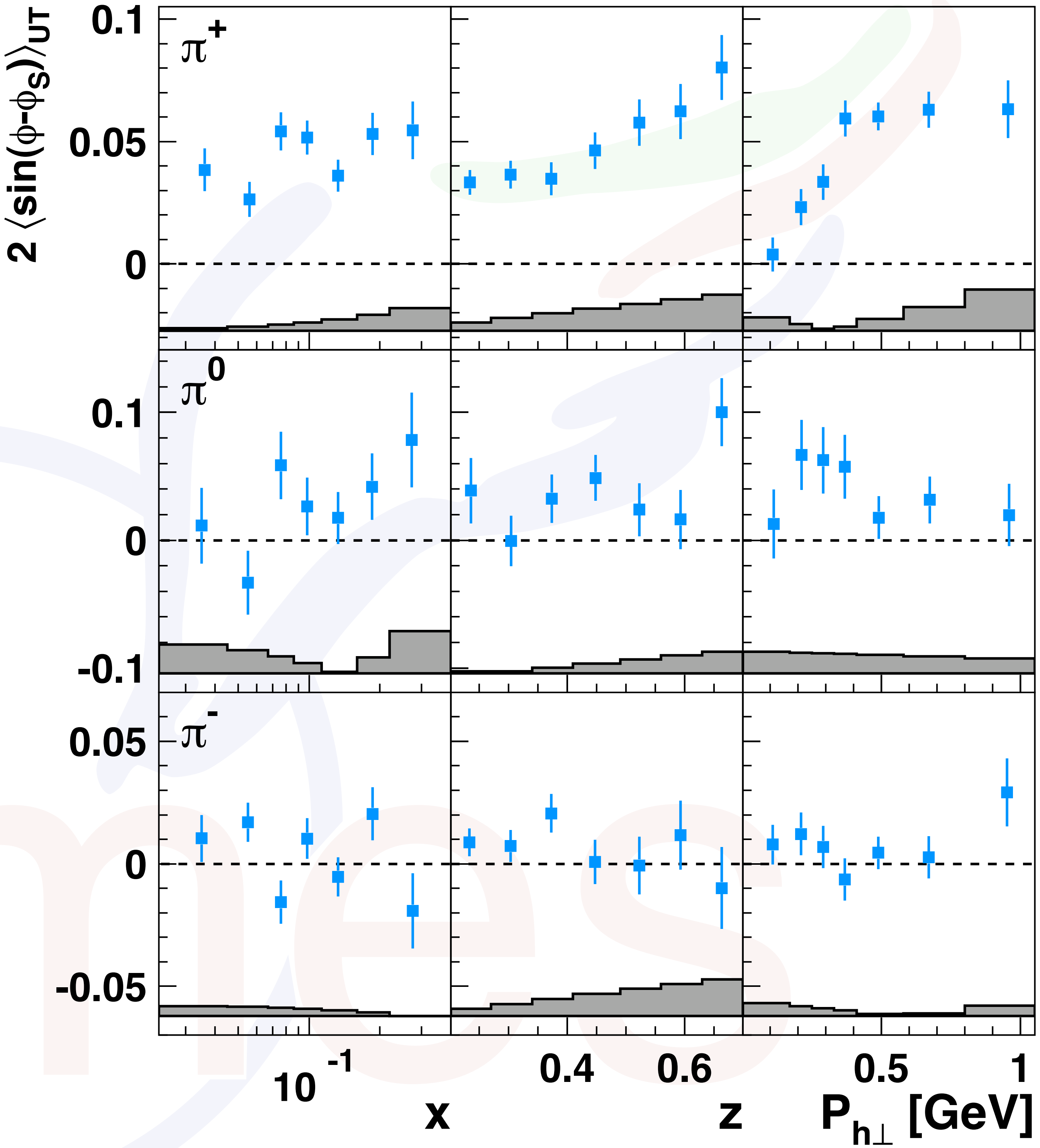
The kaon Sivers amplitudes





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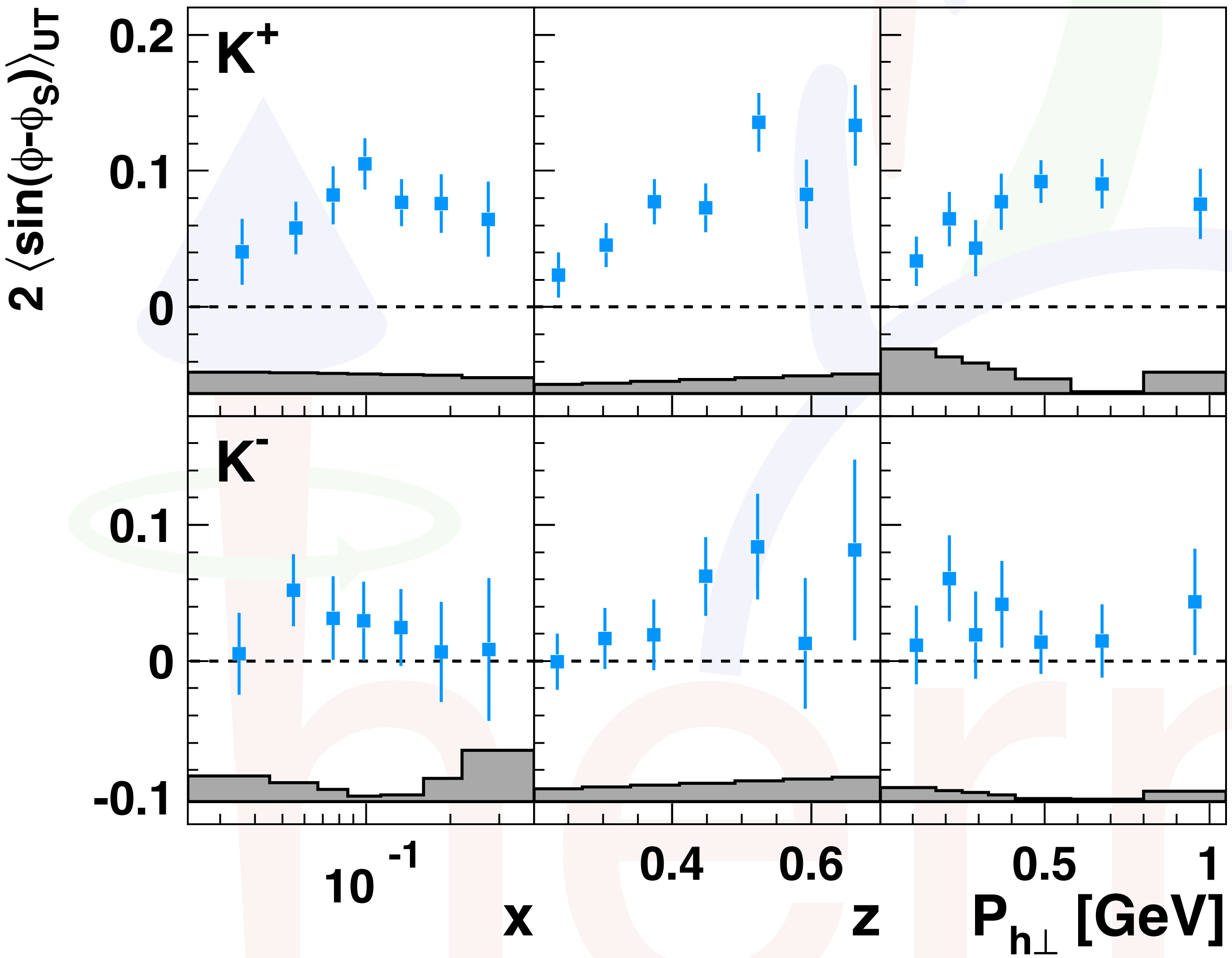

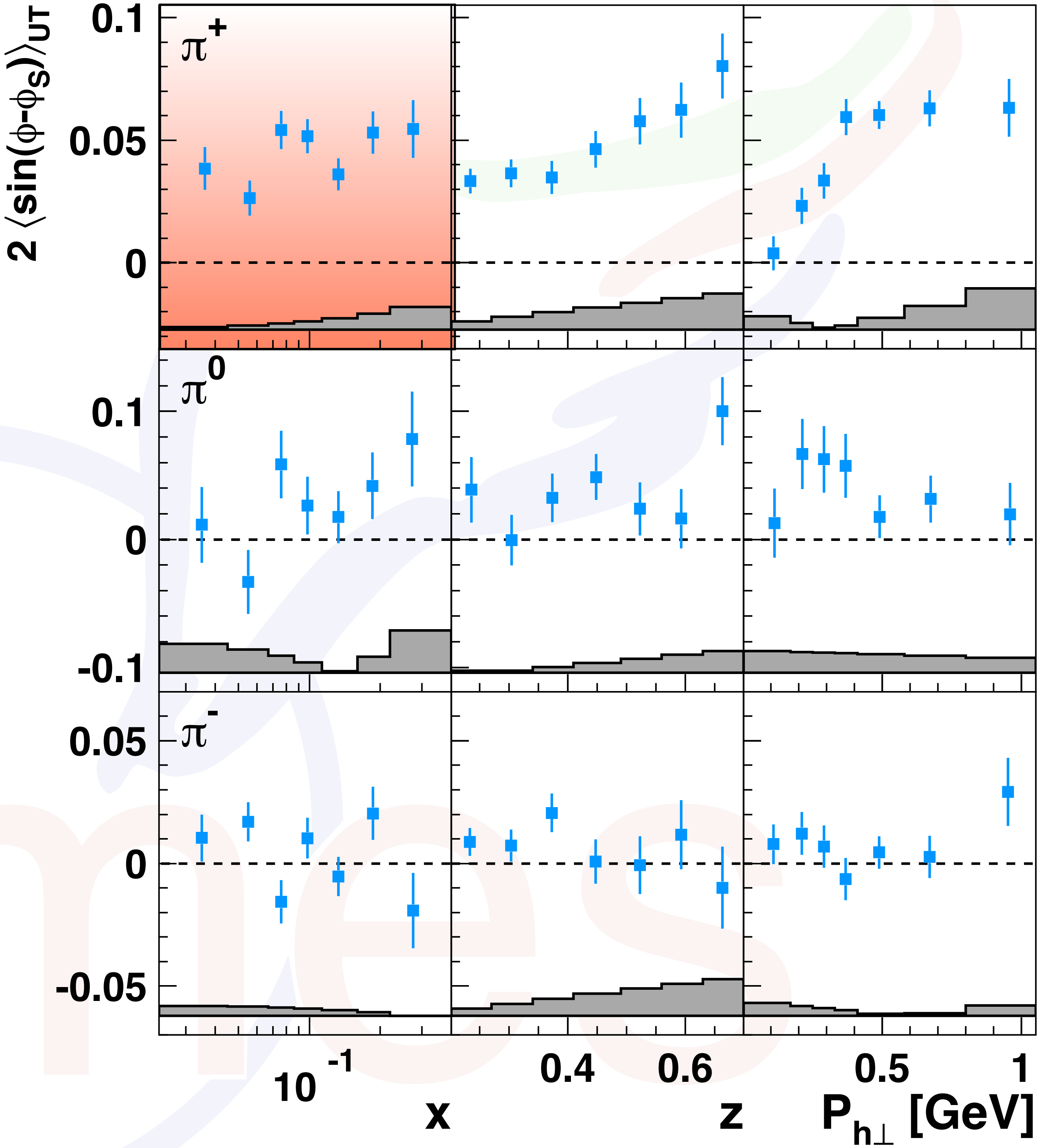

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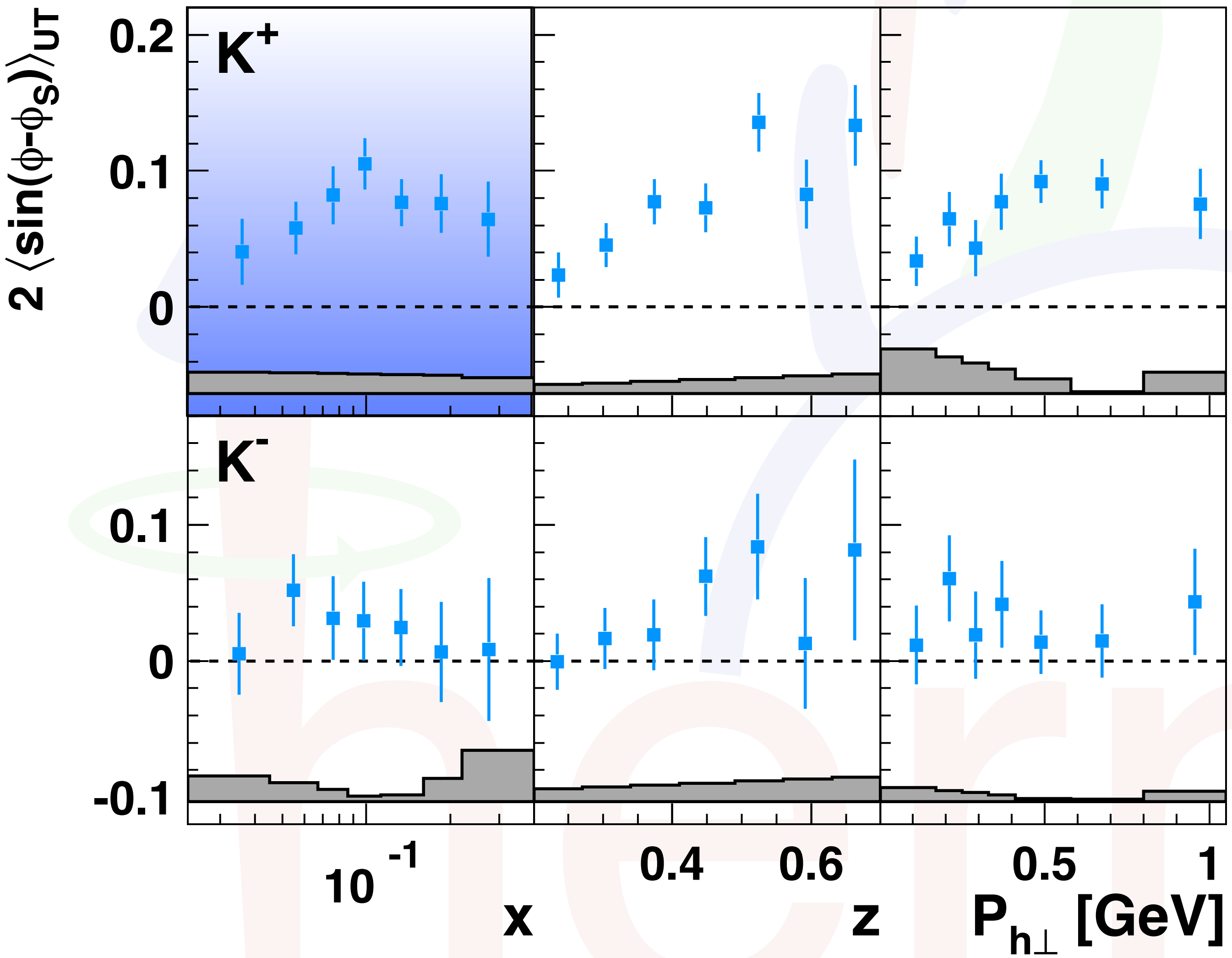

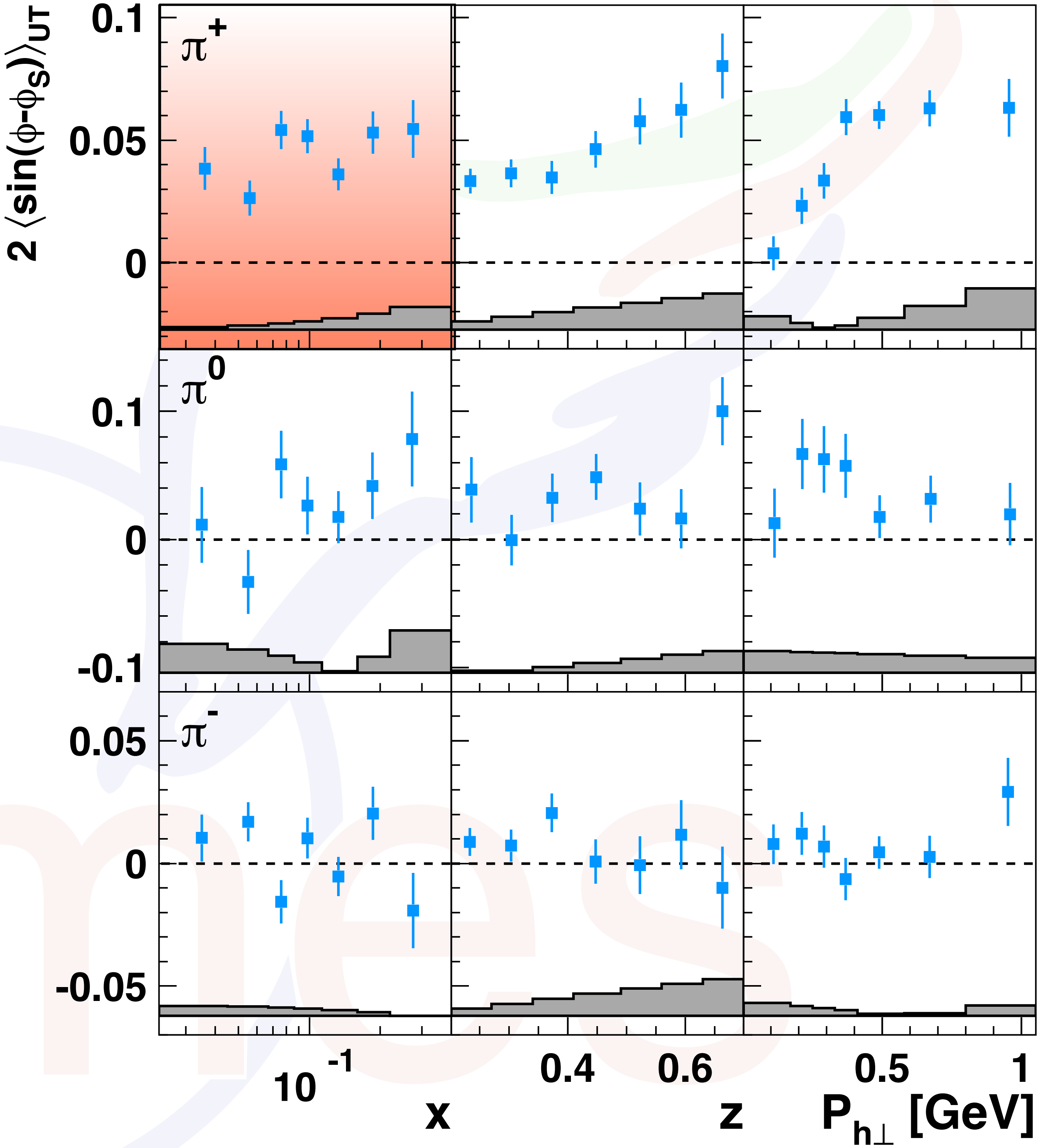

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Pretzelosity

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

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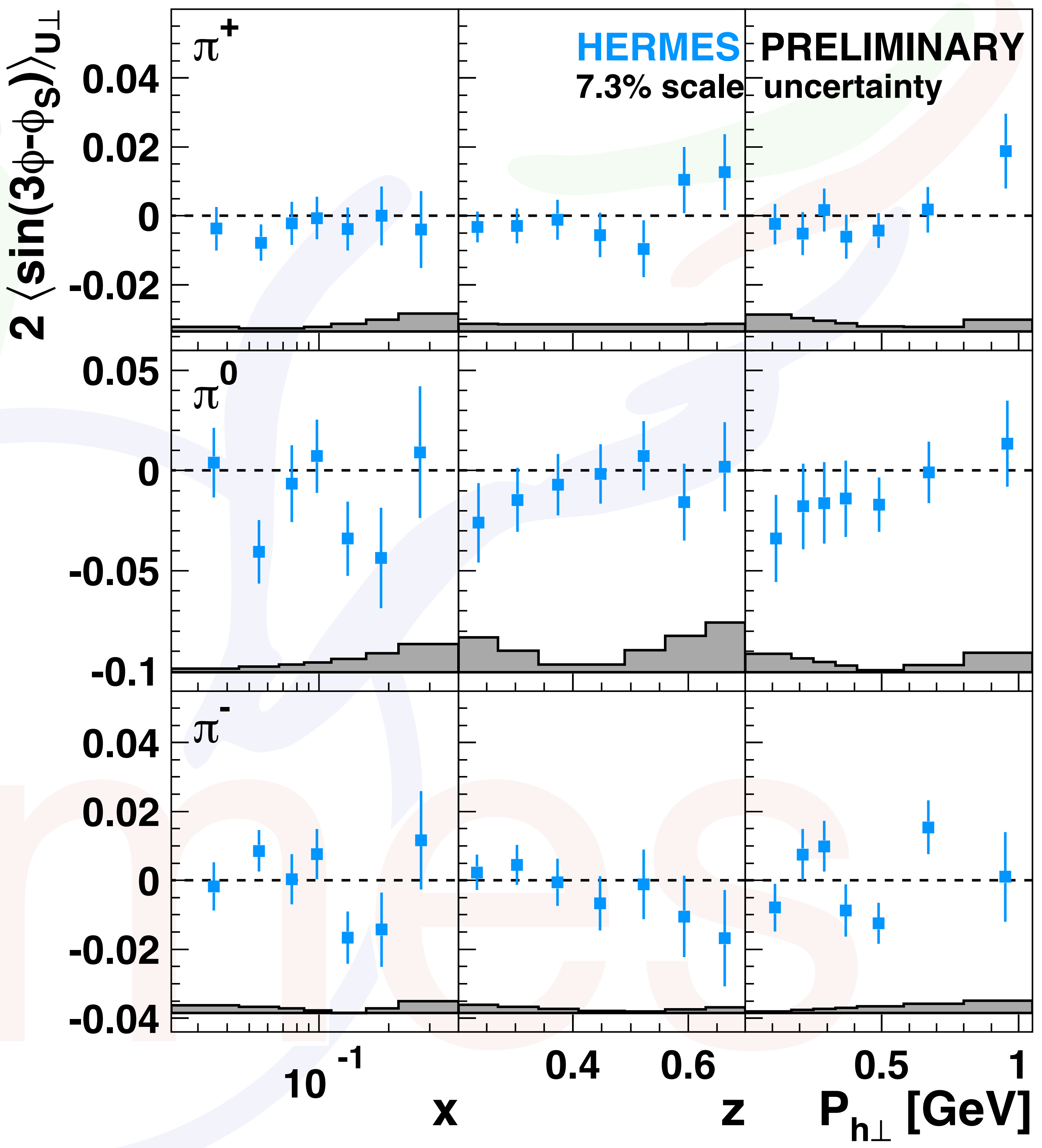
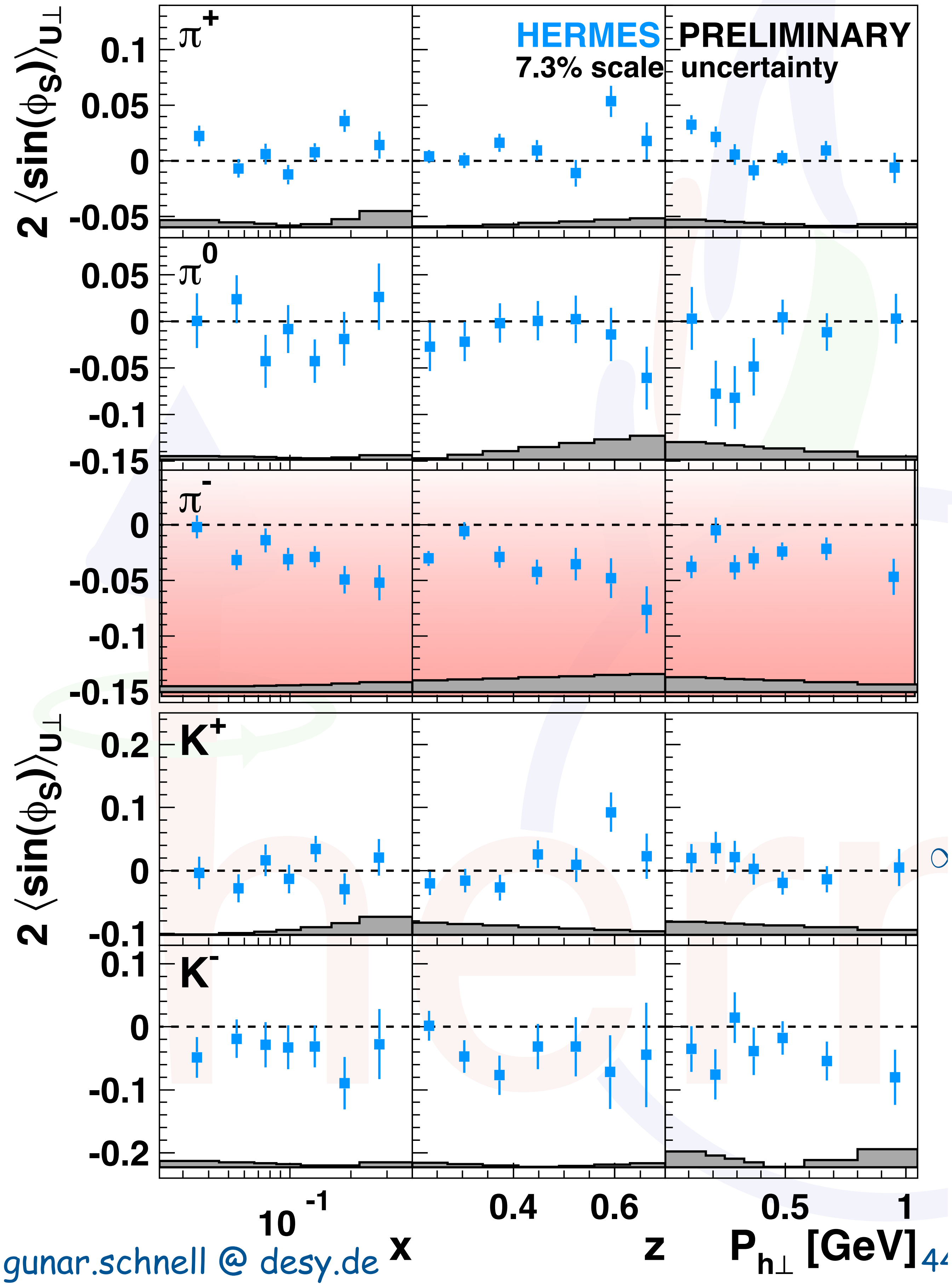
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

Pretzelosity

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



Subleading twist - $\sin(\phi_s)$



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

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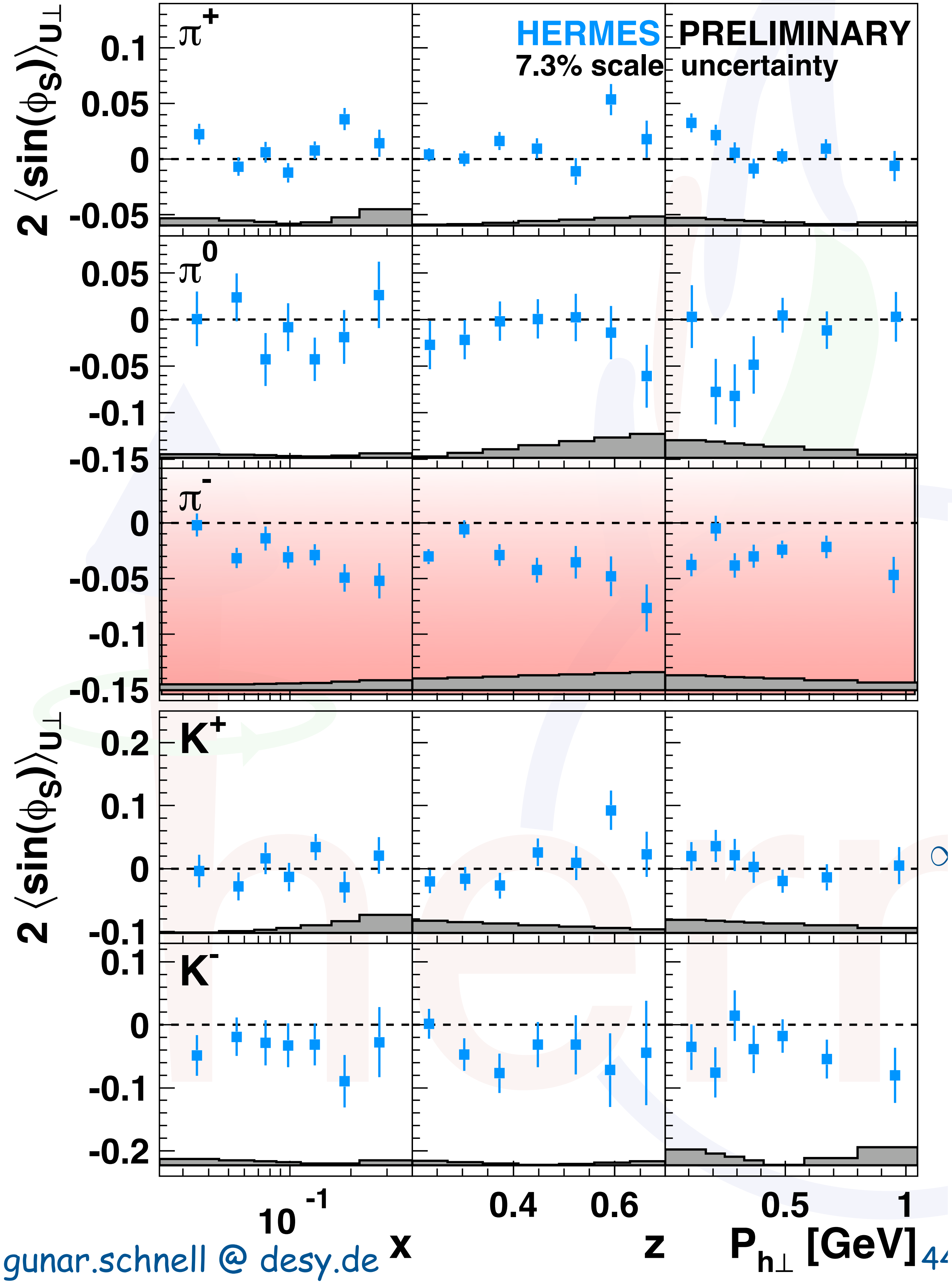
Subleading twist - $\sin(\phi_S)$



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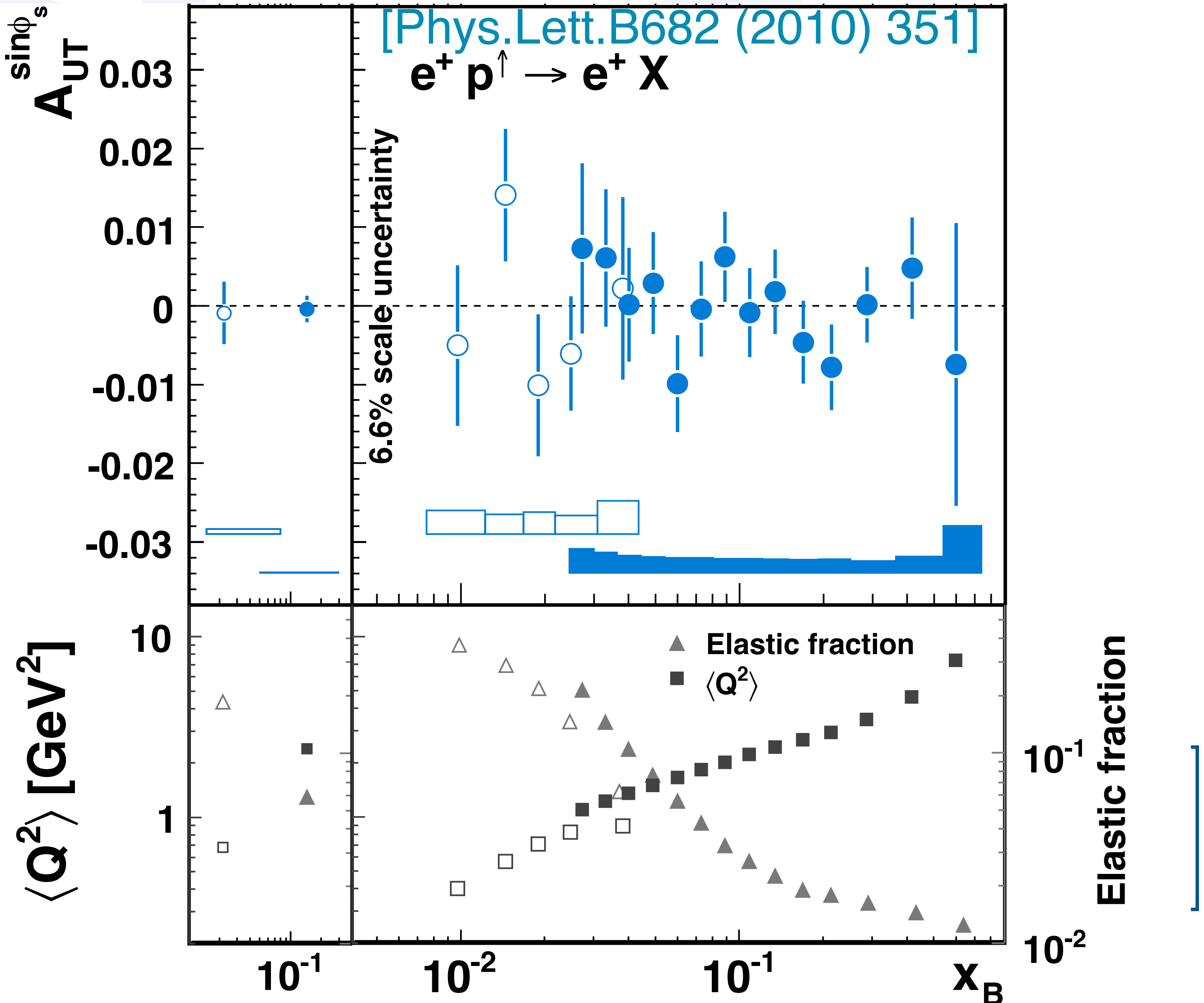

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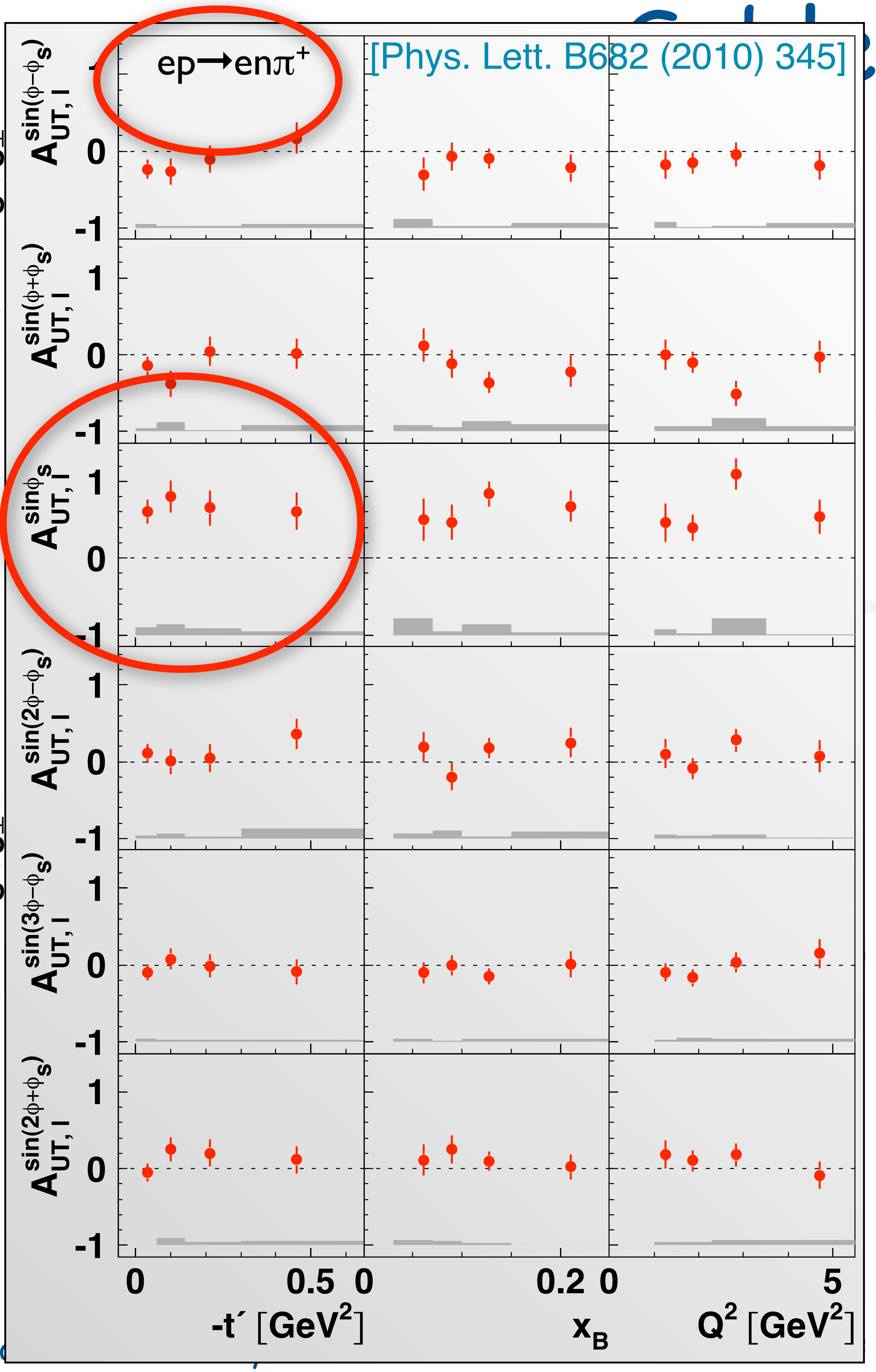
ading twist - sin(ϕ_s)



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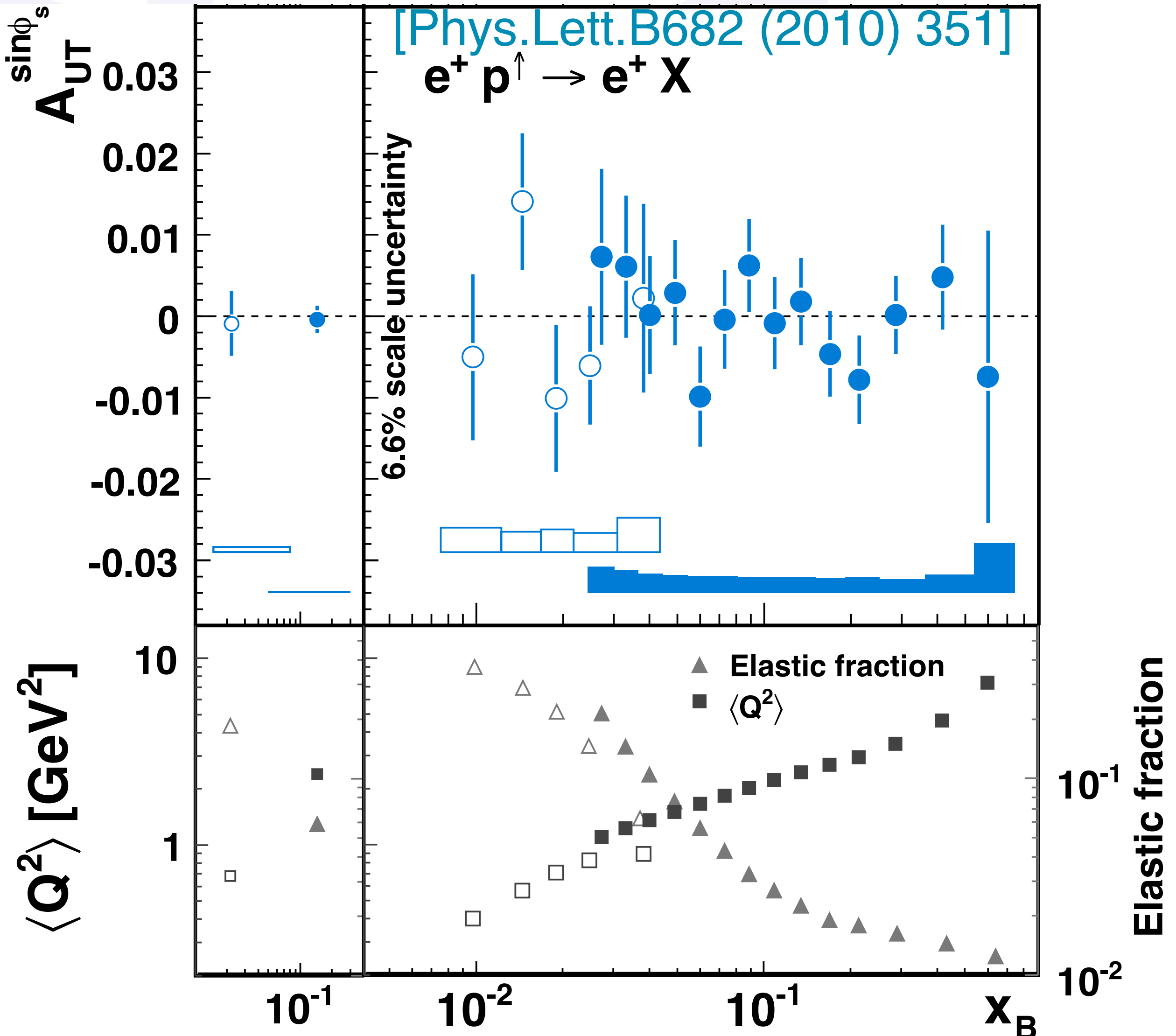
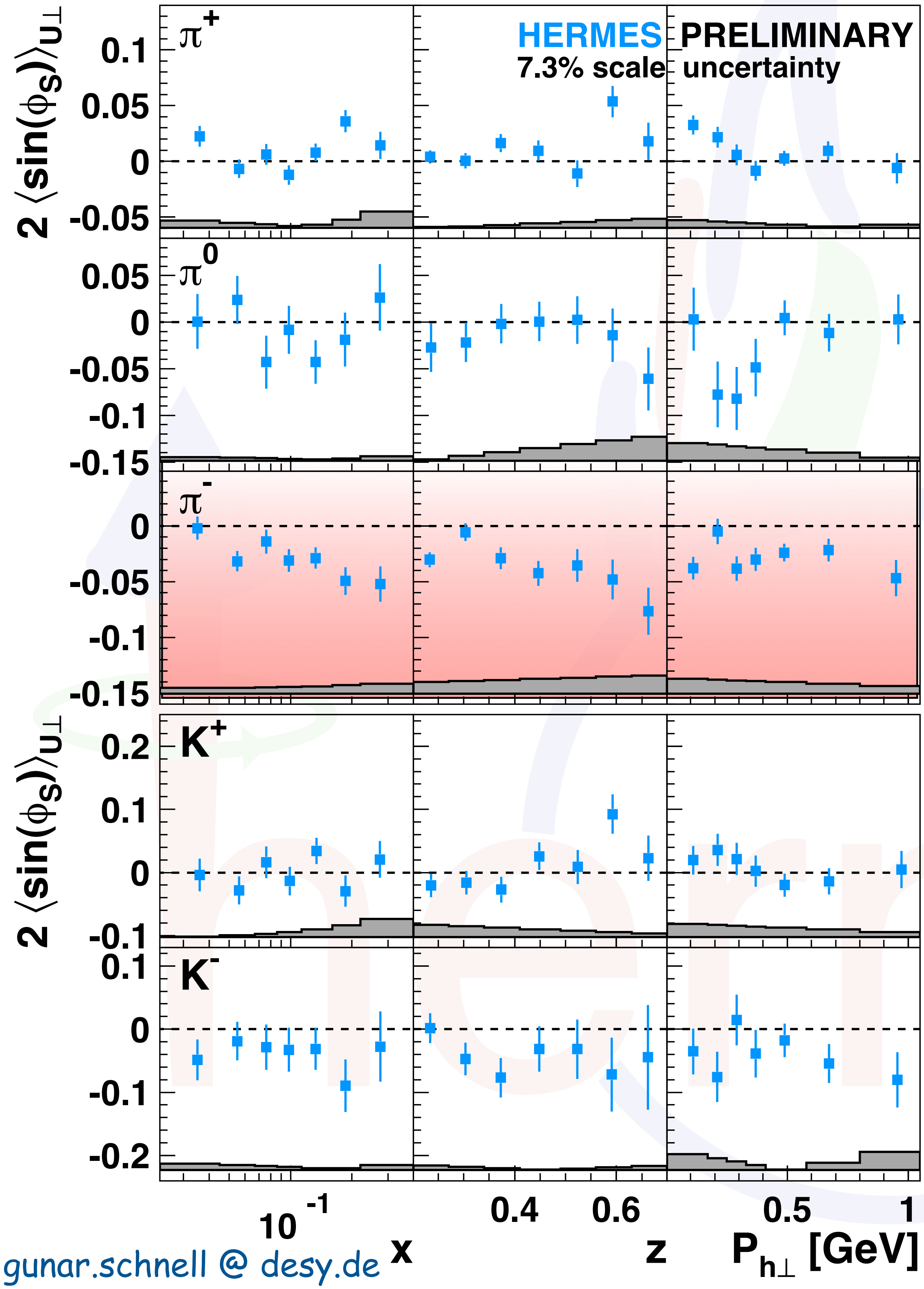


Subleading twist - sin(ϕ_s)



- 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.:

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

	U	L	T
U	f_1		$h_1^\perp$
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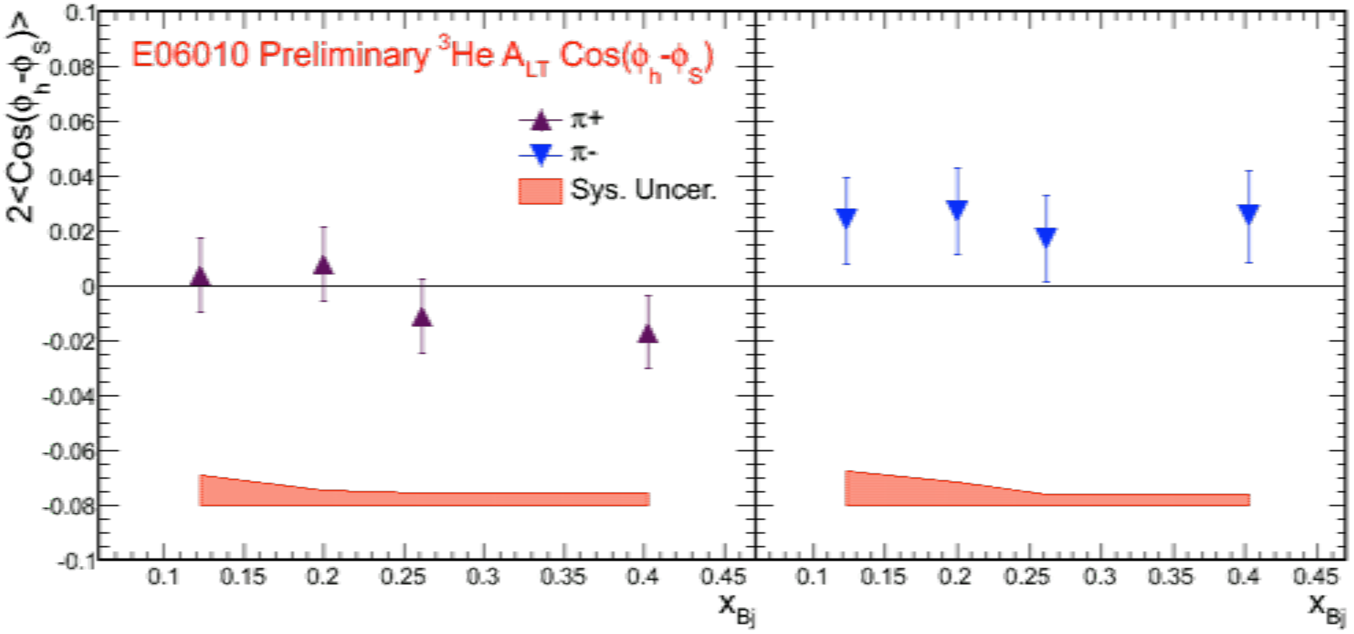
Worm-Gear g_{1T}



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

Worm-Gear g_{1T}

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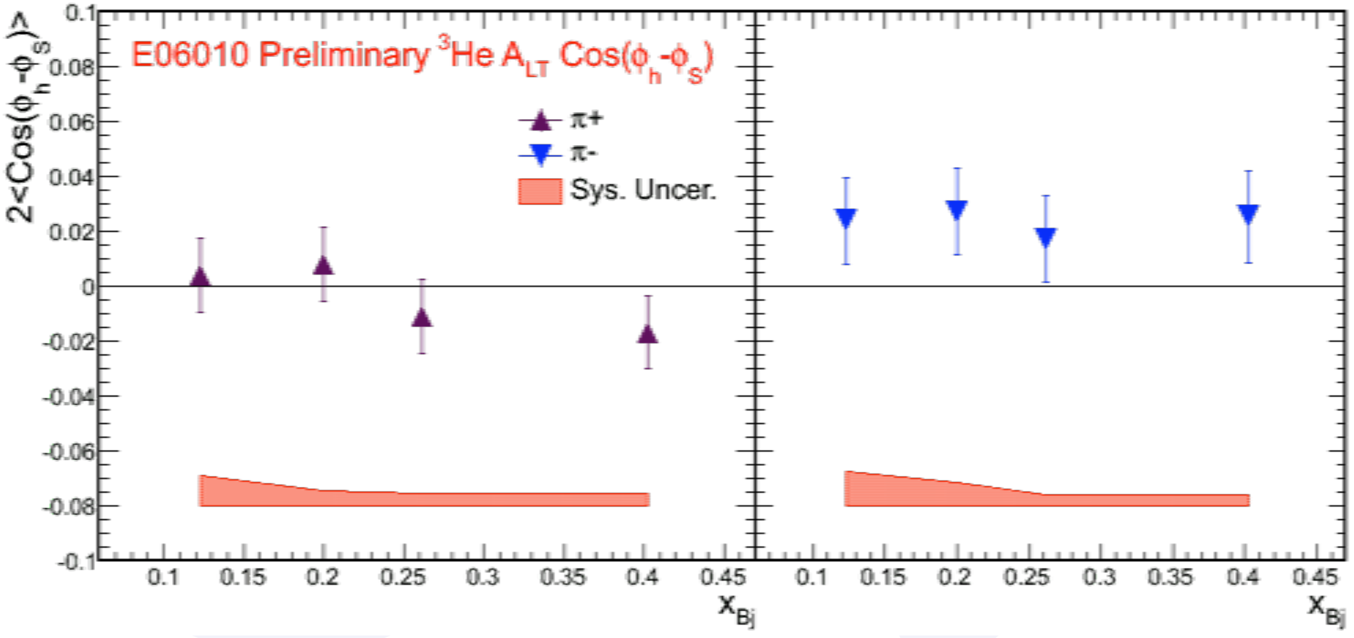
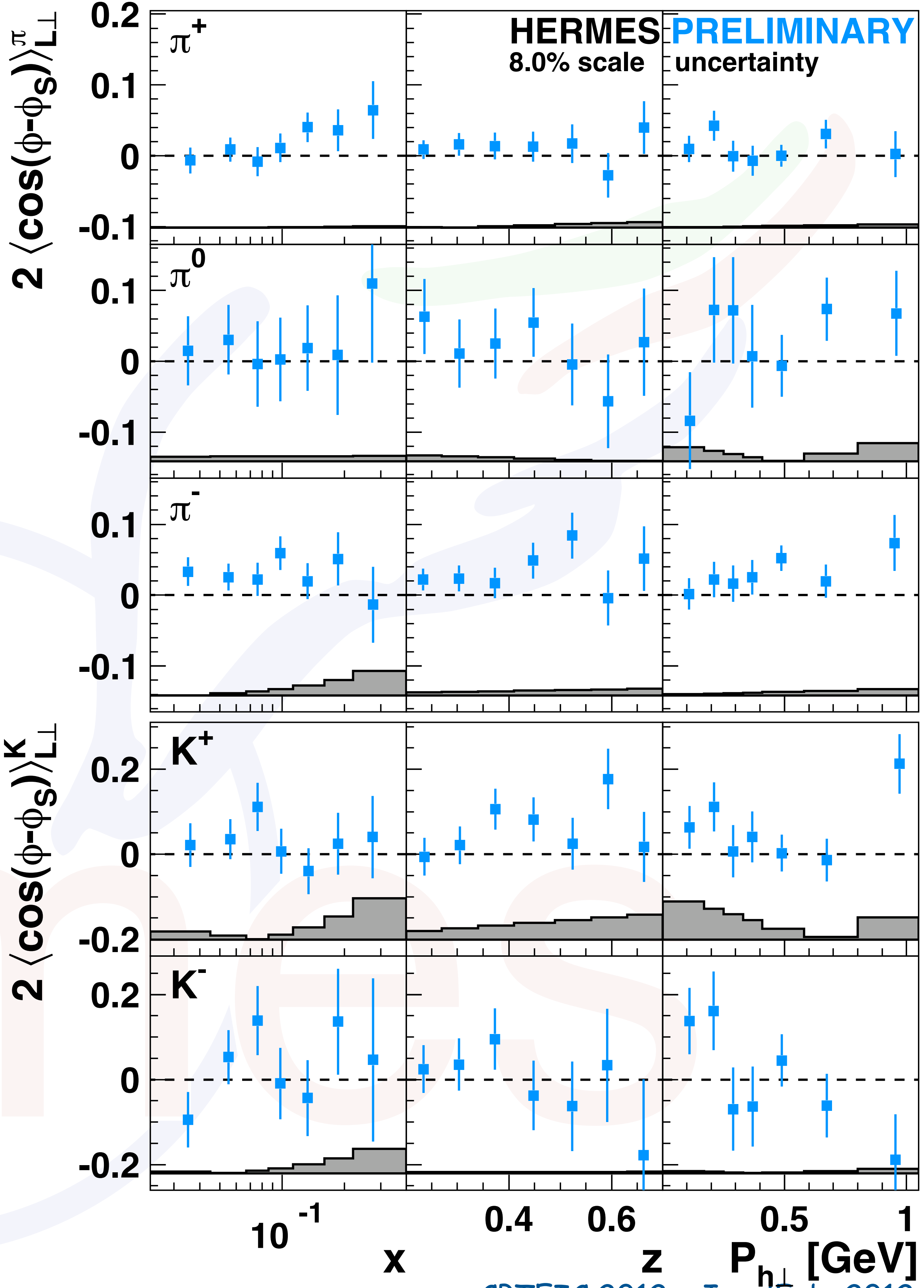
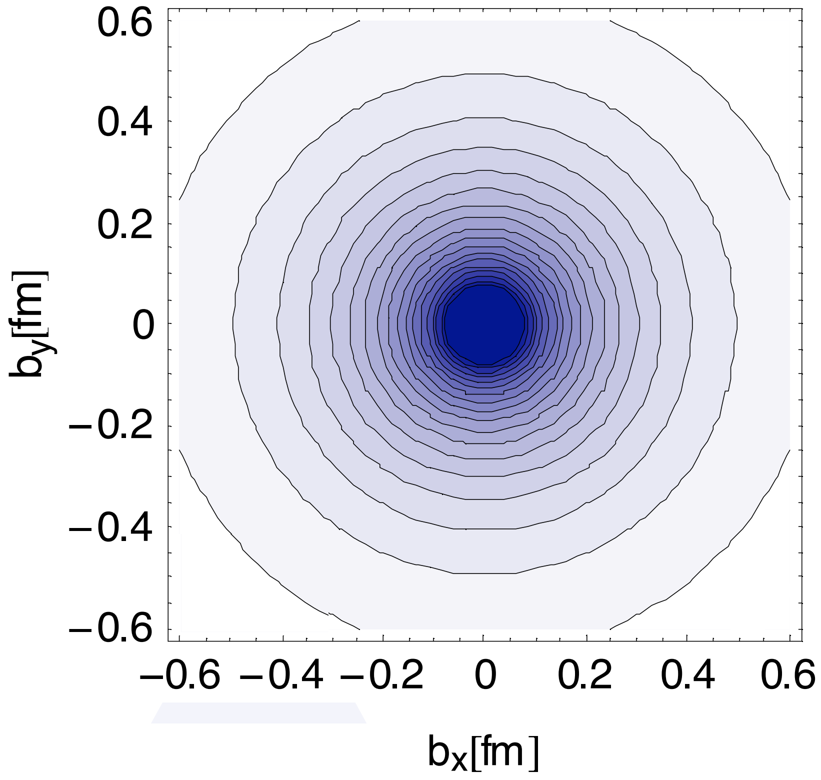


- chiral even
- first direct evidence for worm-gear g_{1T} from JLab
- also HERMES results on A_{LT} for negative pions non-zero



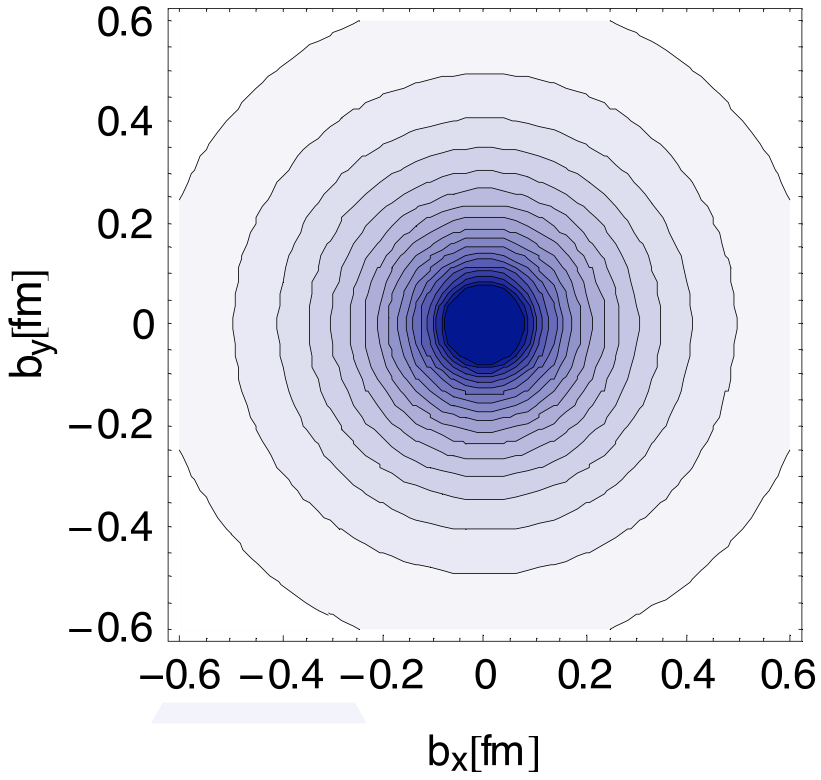
Exclusive reactions

Another 3D picture of the nucleon



Form factors:
transverse distribution
of partons

Another 3D picture of the nucleon



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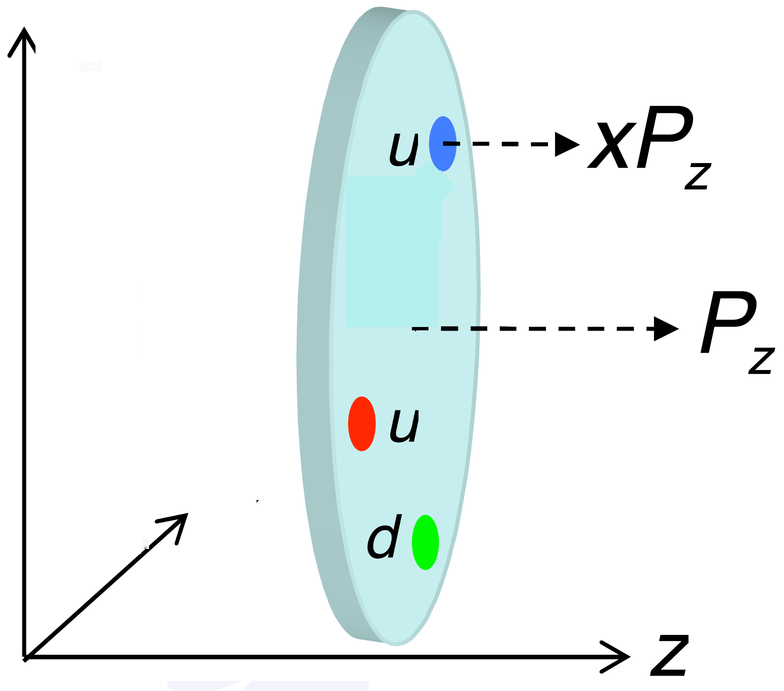

Parton distributions:
longitudinal momentum
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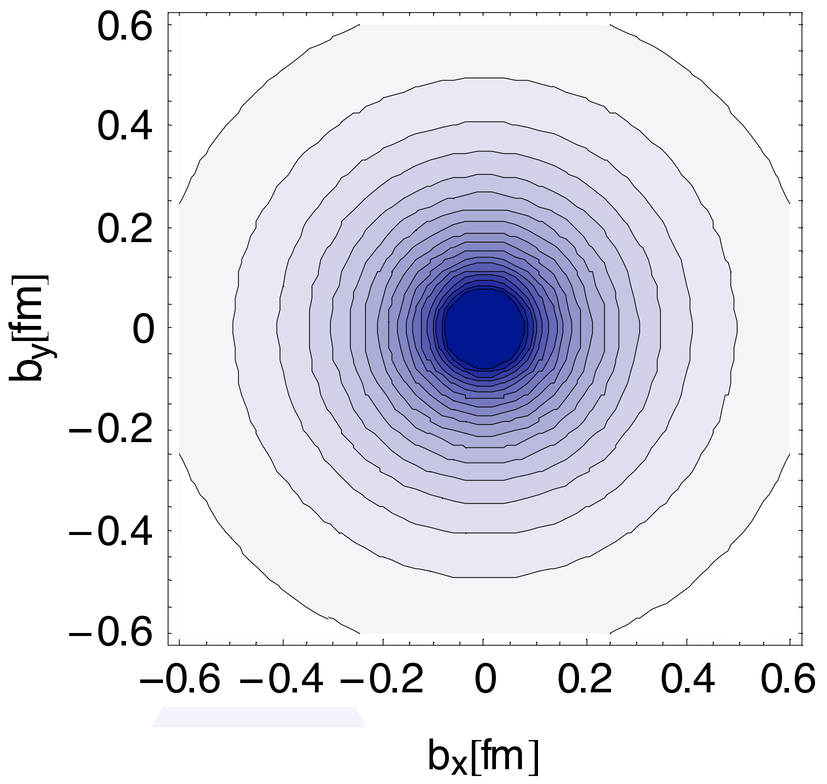
Another 3D picture of the nucleon



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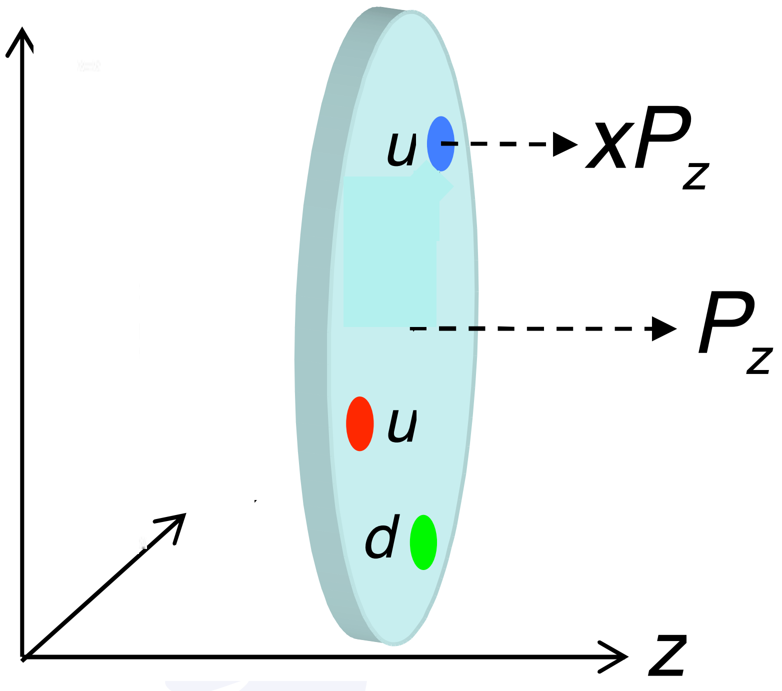

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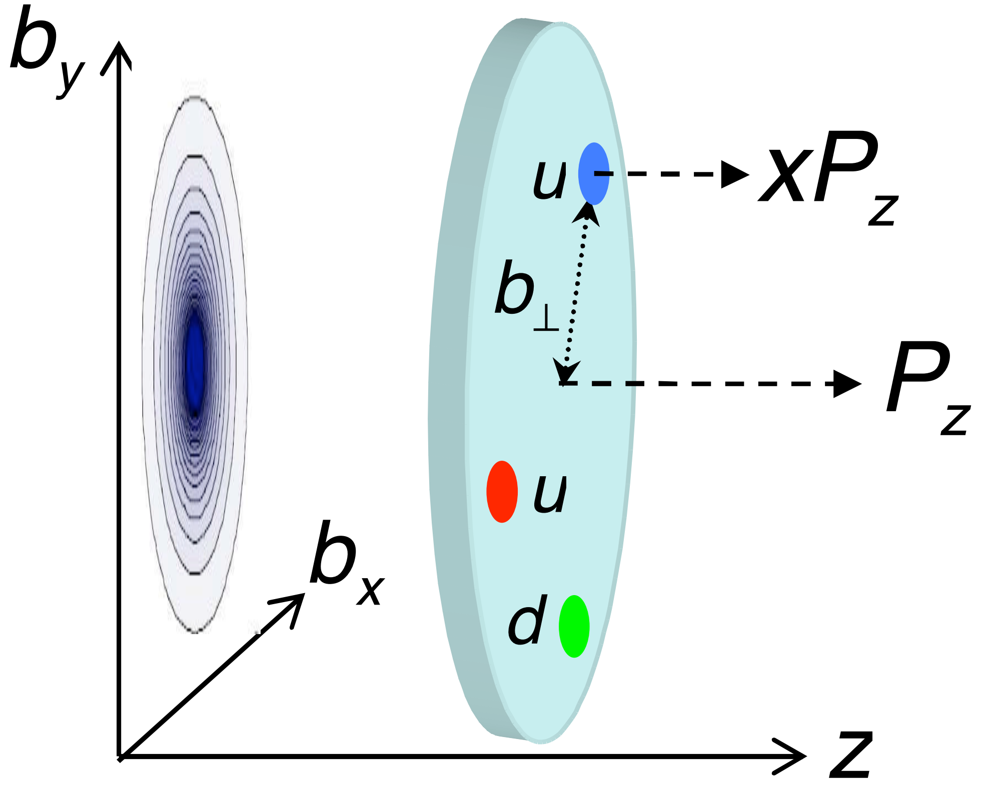
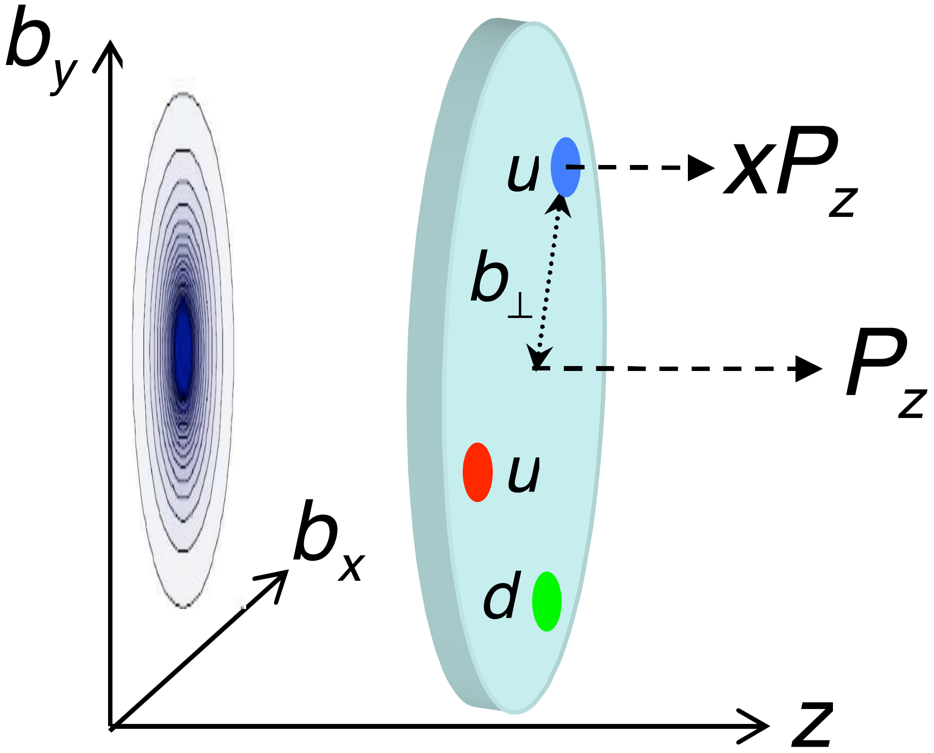
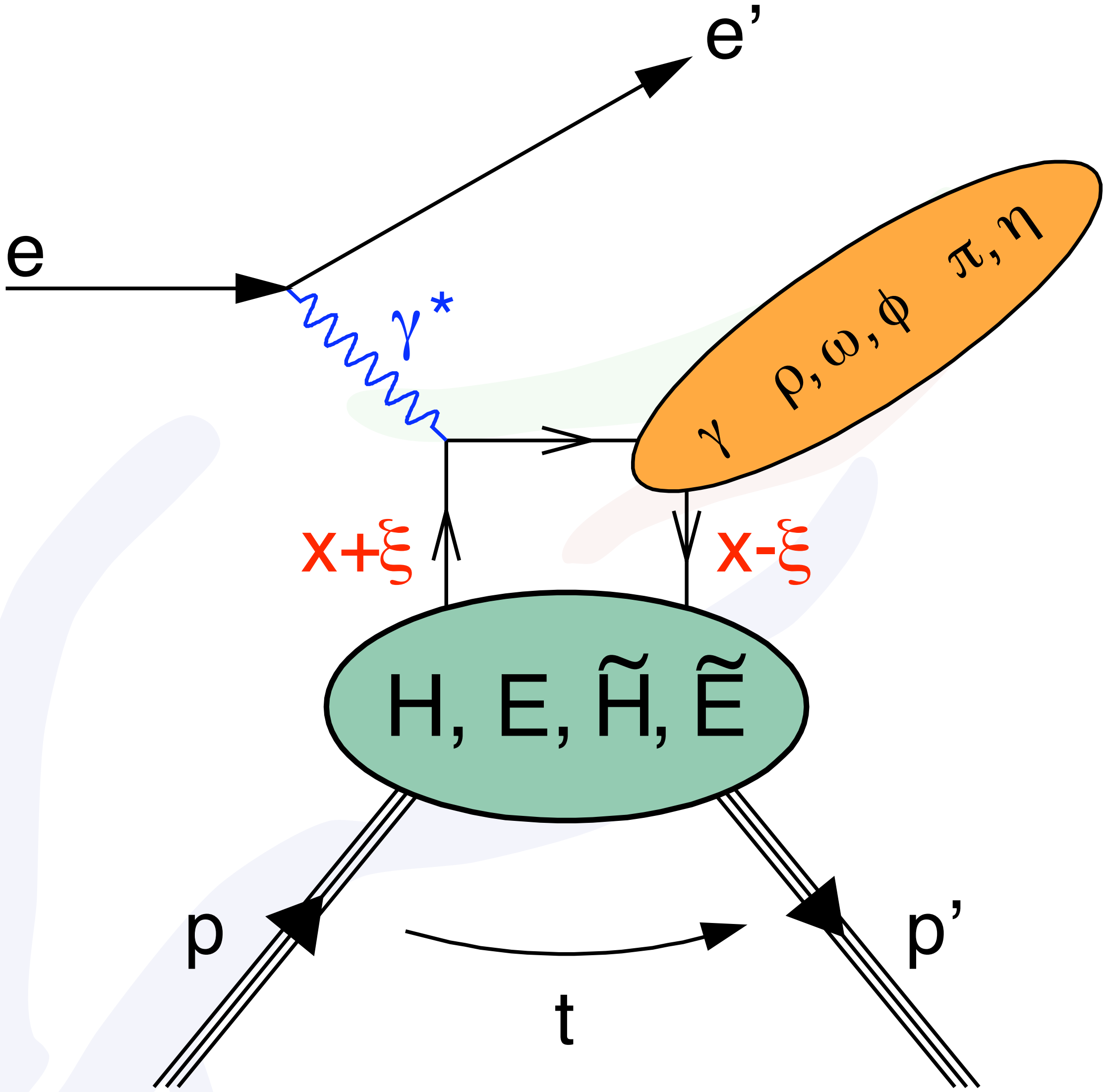


Nucleon Tomography
correlated info on transverse position and longitudinal momentum

Probing GPDs in Exclusive Reactions

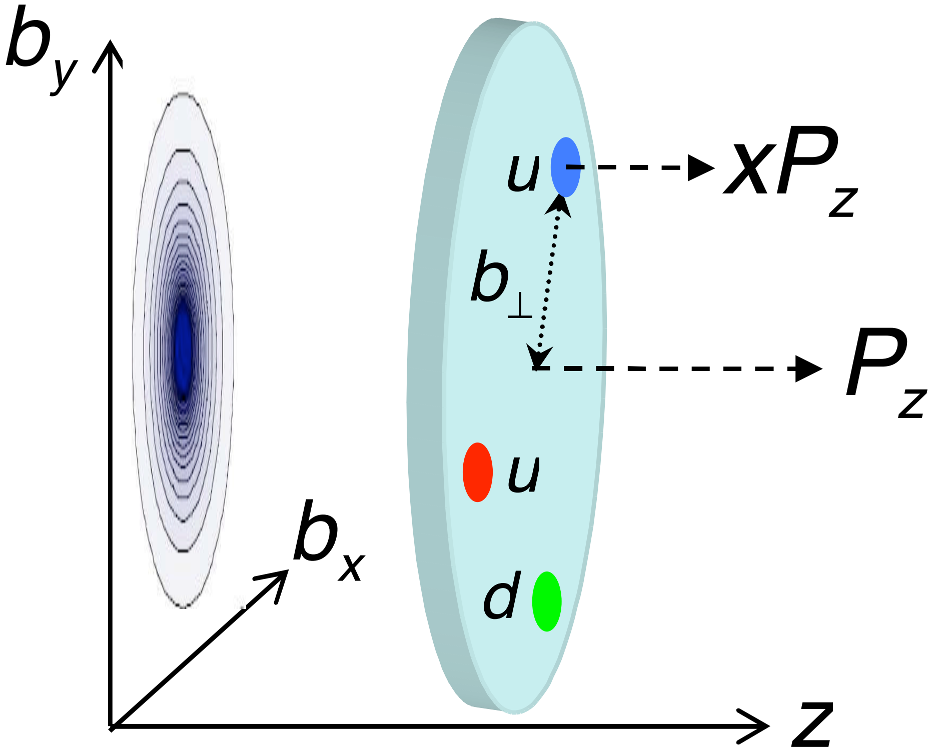


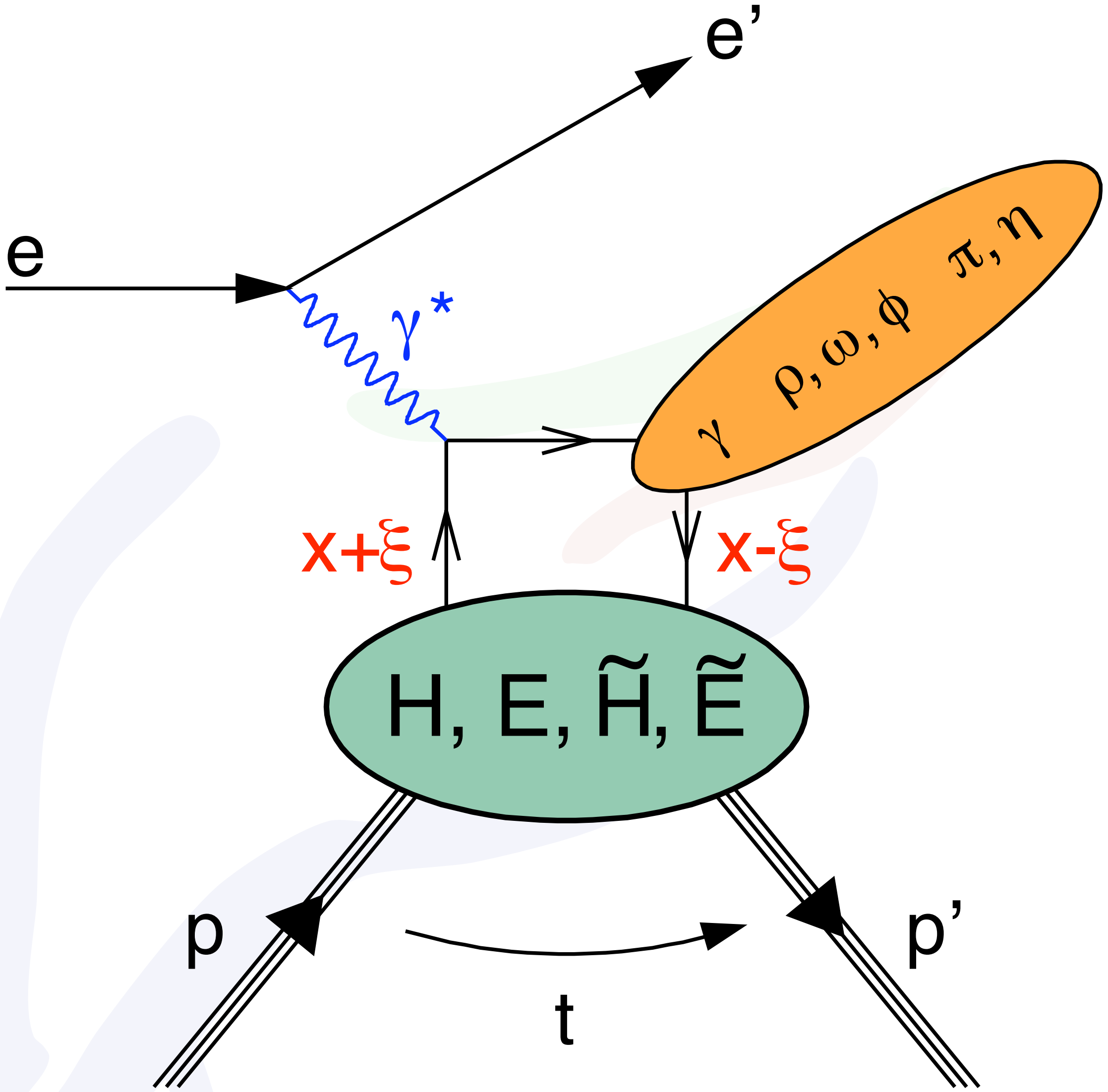


x: average longitudinal momentum fraction of active quark (usually not observed & $x \neq x_B$)

ξ: half the longitudinal momentum change $\approx x_B/(2-x_B)$

Probing GPDs in Exclusive Reactions

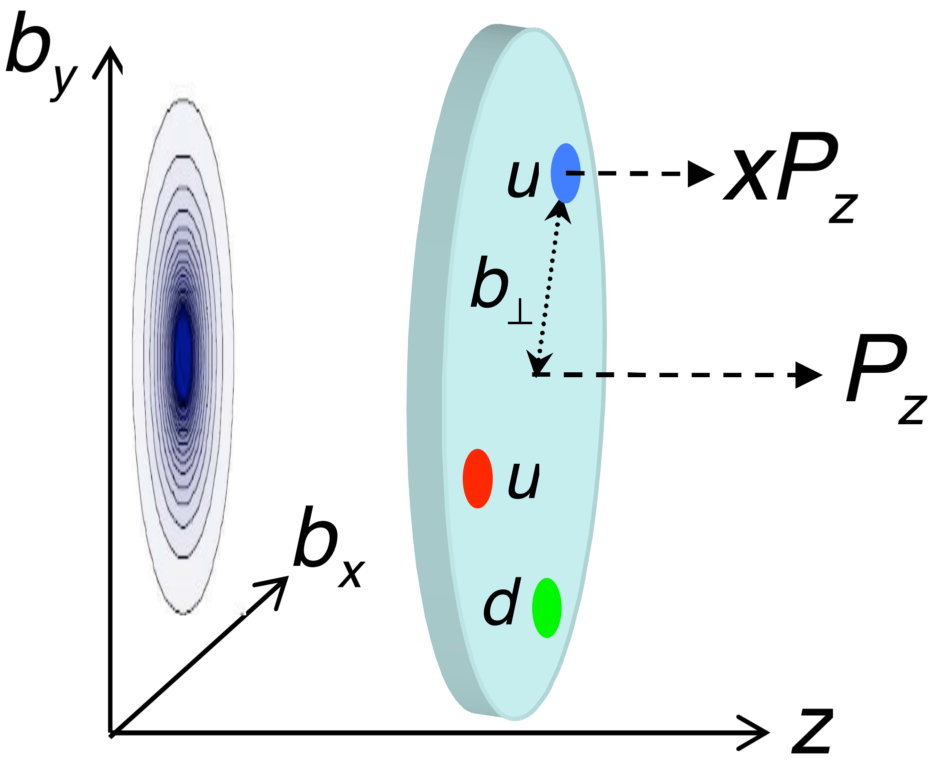


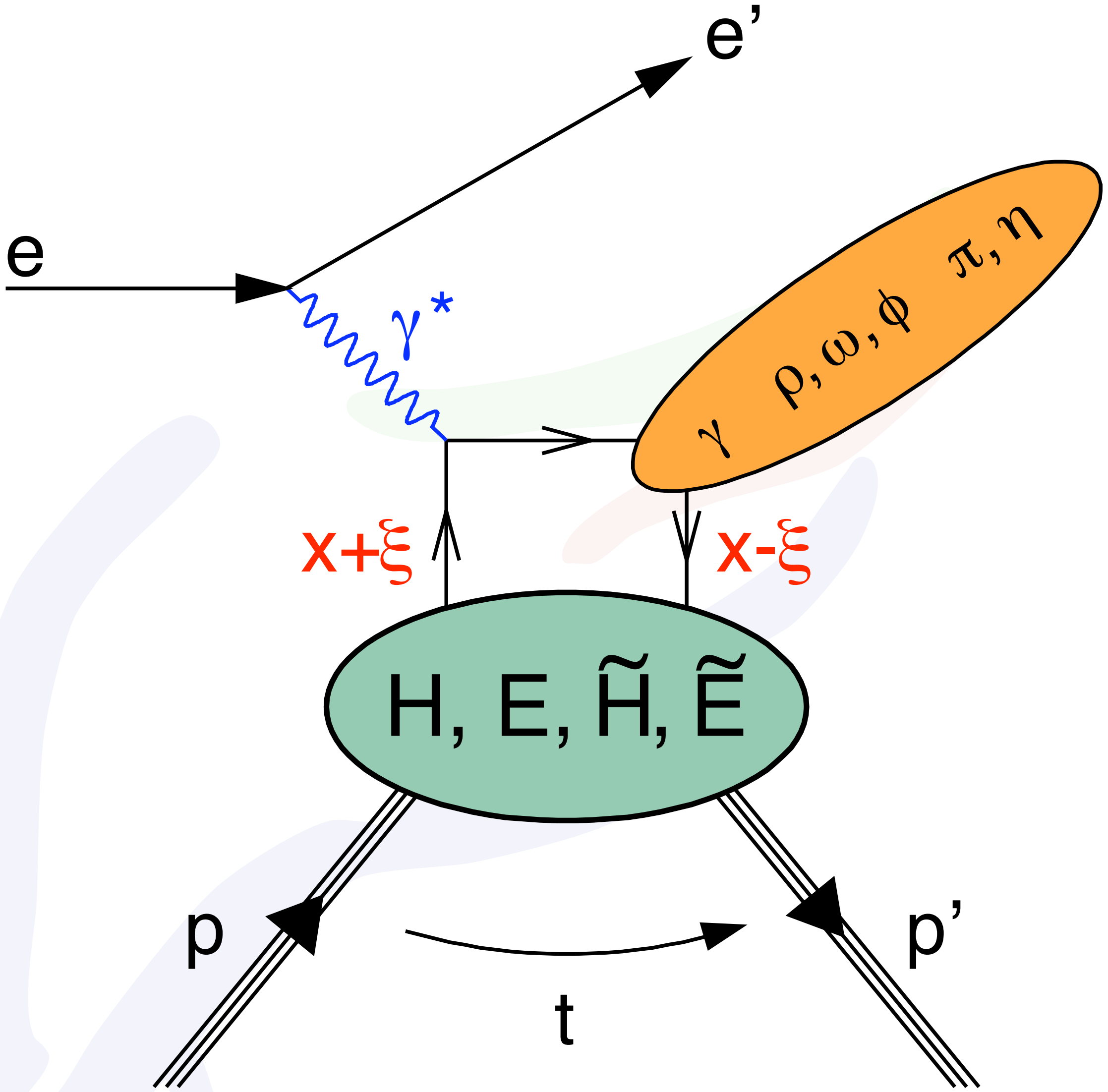


	no quark helicity flip	quark helicity flip
no nucleon helicity flip	H	$\widetilde{H}$
nucleon helicity flip	E	$\widetilde{E}$

(+ 4 more chiral-odd functions)

Probing GPDs in Exclusive Reactions





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

$$\int \mathrm{d}x E^q(x,\xi,t) = F_2^q(t)$$

	no quark helicity flip	quark helicity flip
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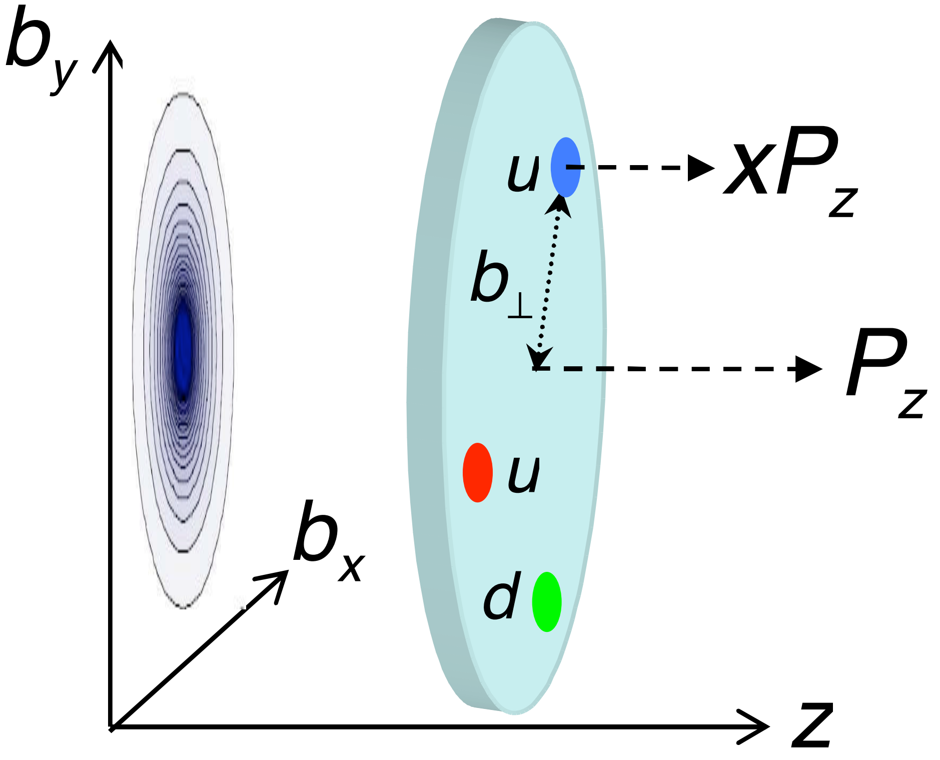
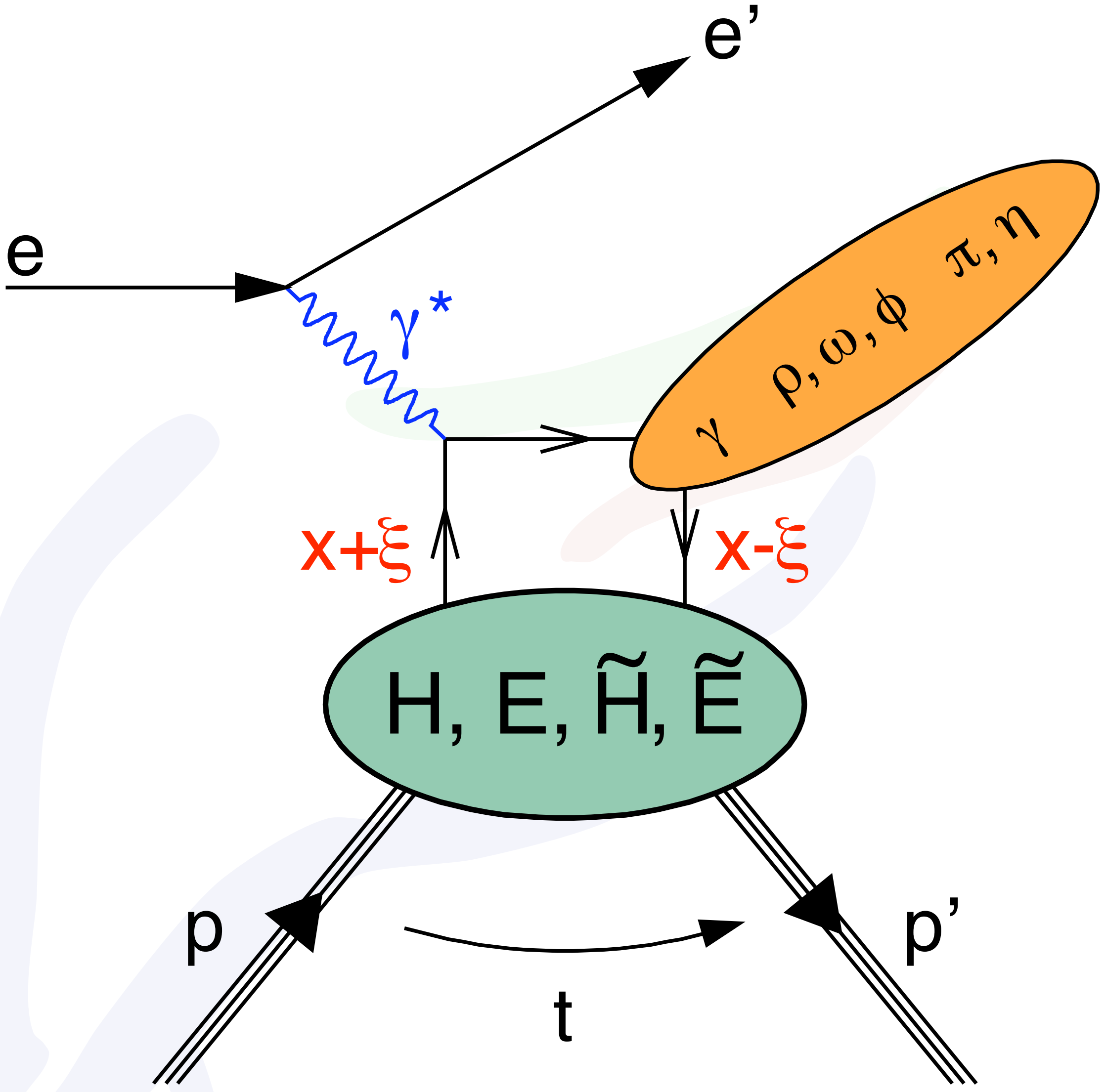
(+ 4 more chiral-odd functions)

Probing GPDs in Exclusive Reactions





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

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

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

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

	no quark helicity flip	quark helicity flip
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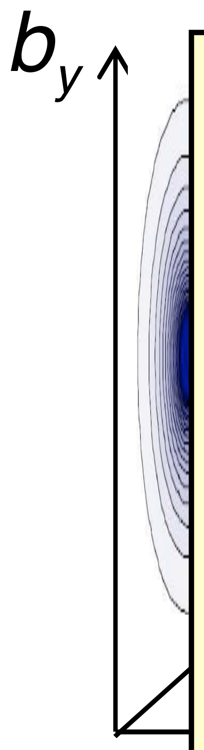

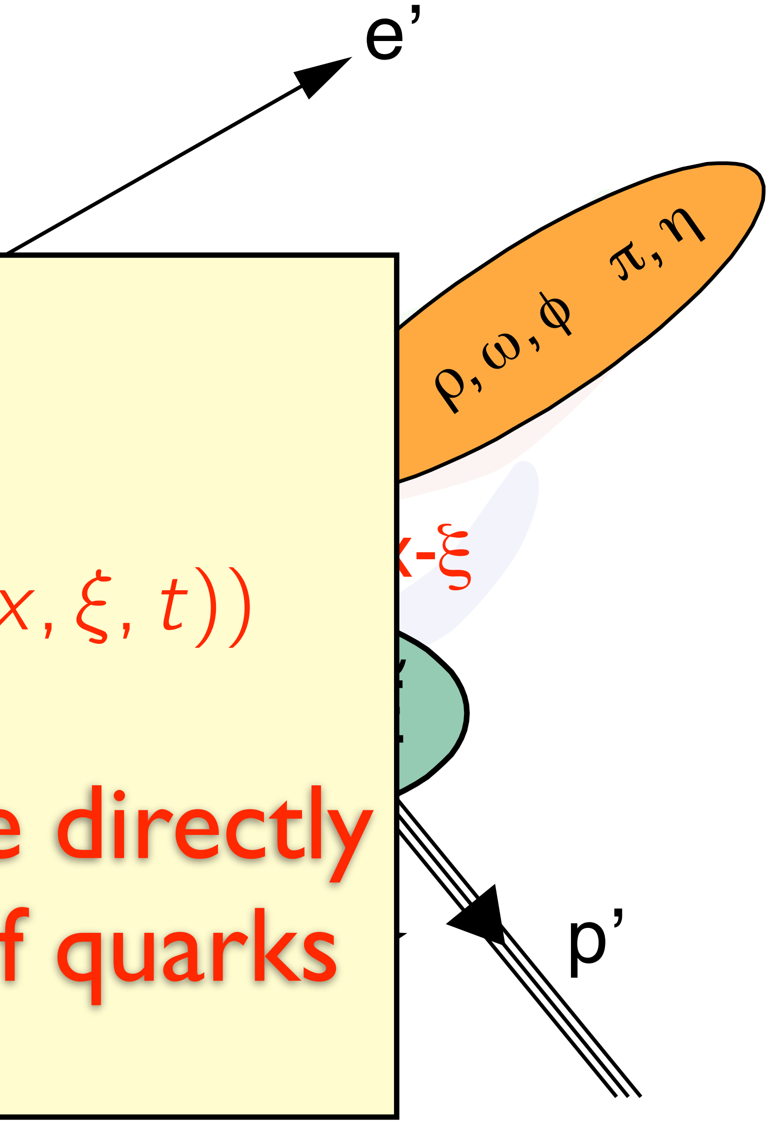

Ji relation (1996)

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

➔Moments of certain GPDs relate directly to the total angular momentum of quarks

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

$$\int \mathrm{d}x E^q(x,\xi,t) = F_2^q(t)$$

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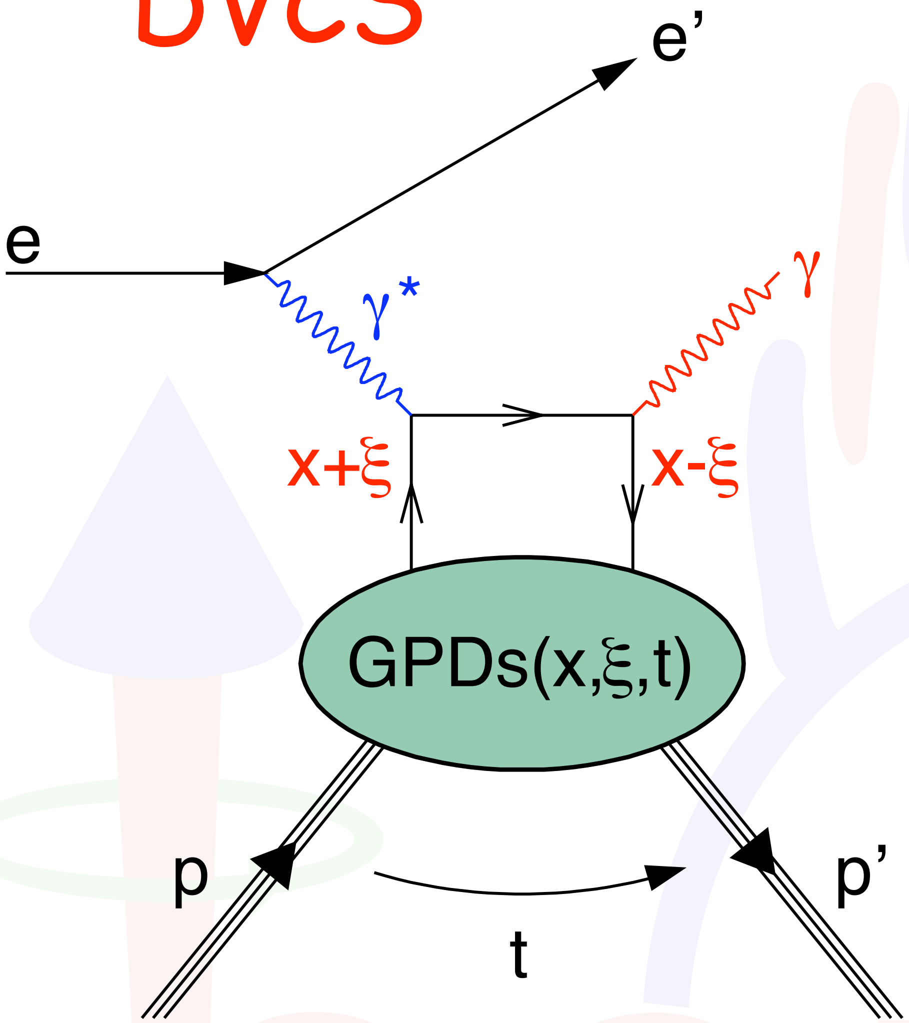
gunar.schnell @ desy.de

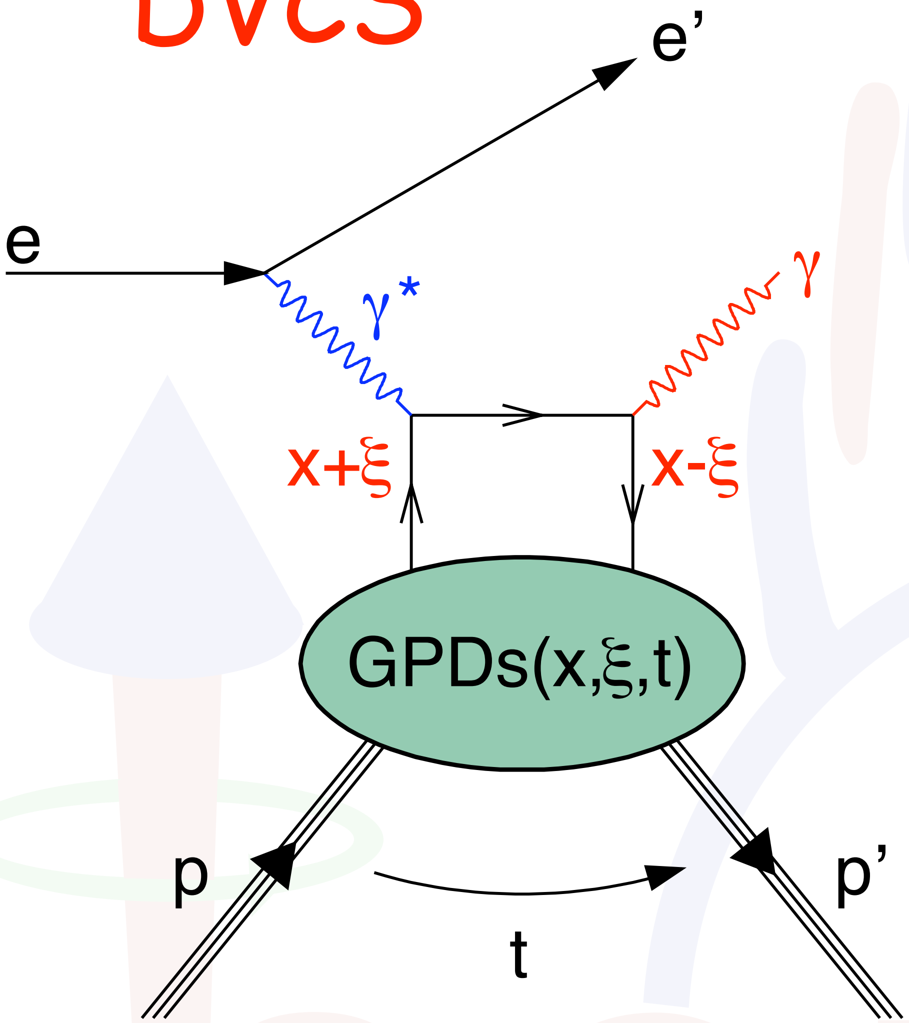
Real-photon production

DVCS

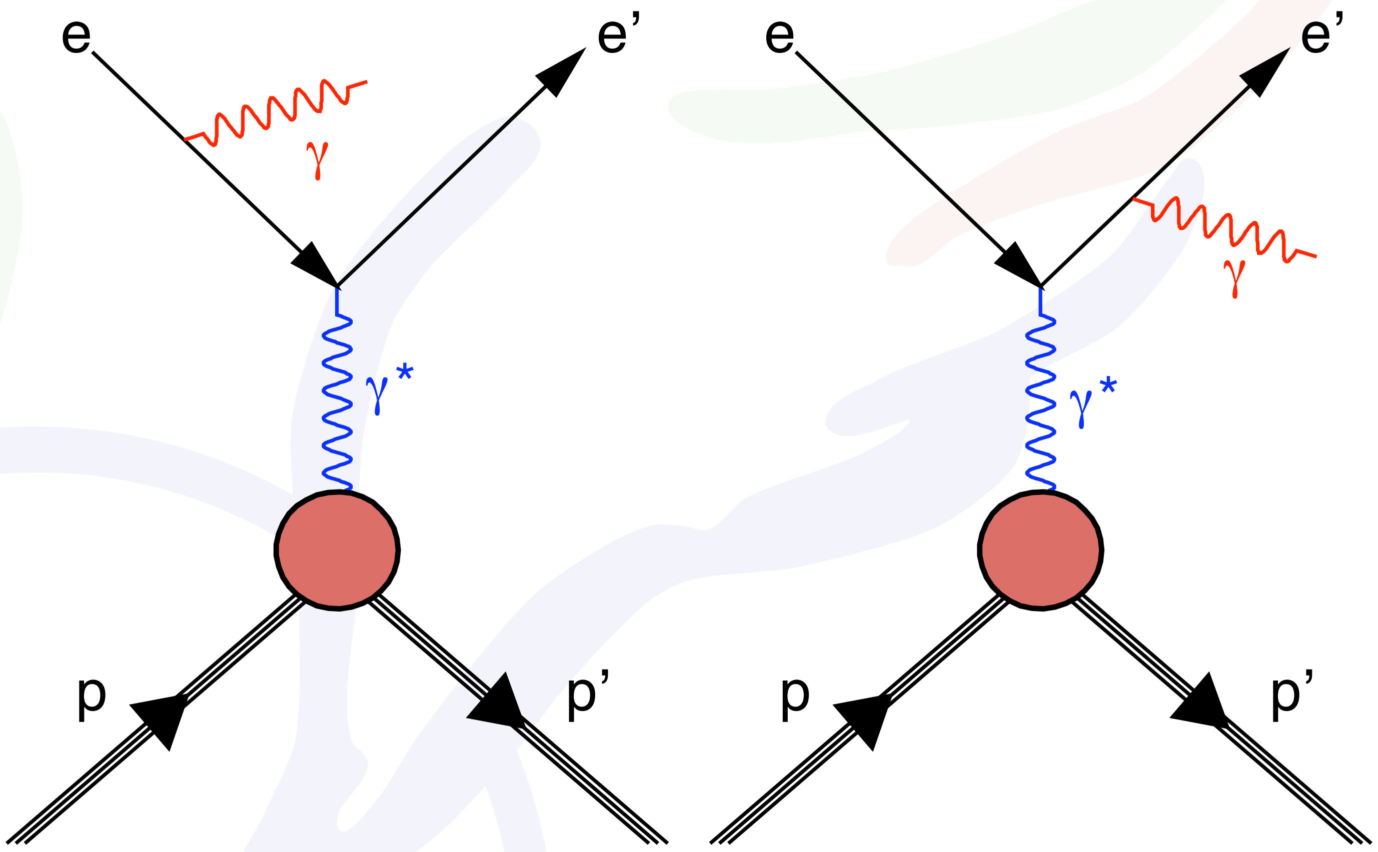


Real-photon production

DVCS



Bethe-Heitler



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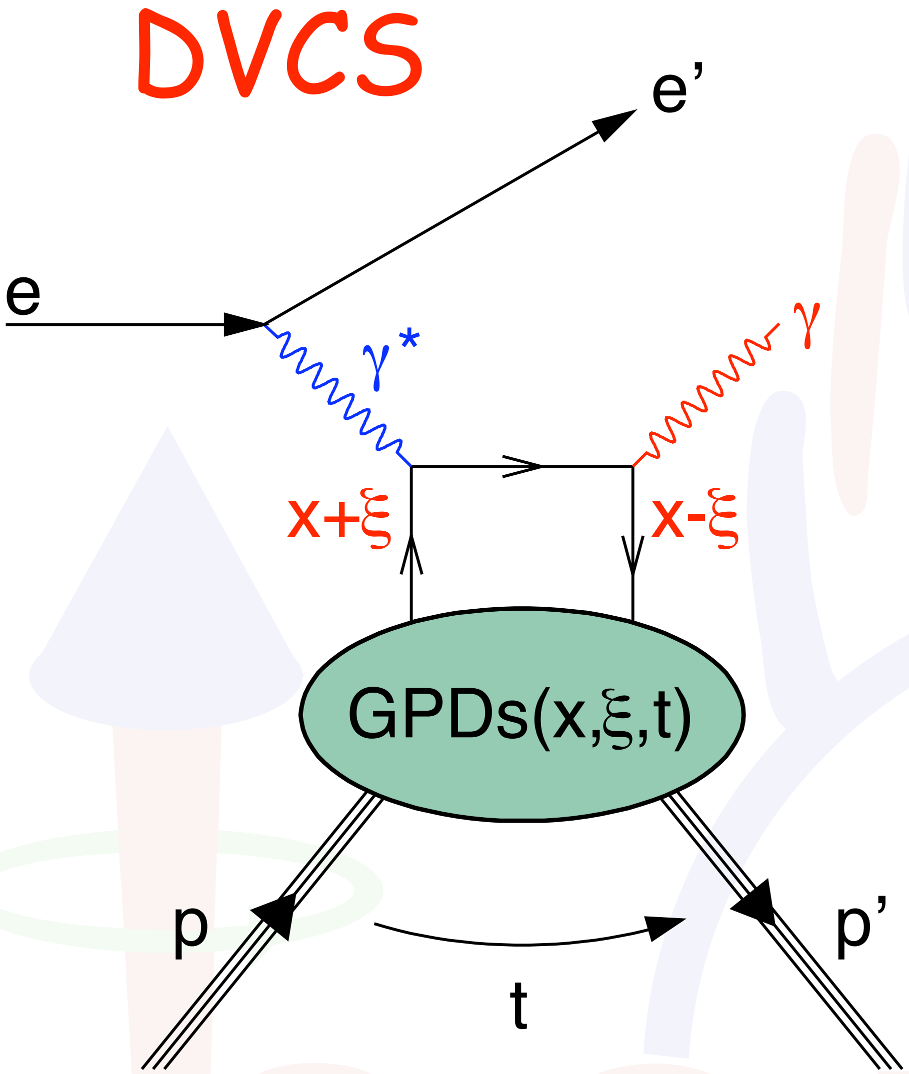
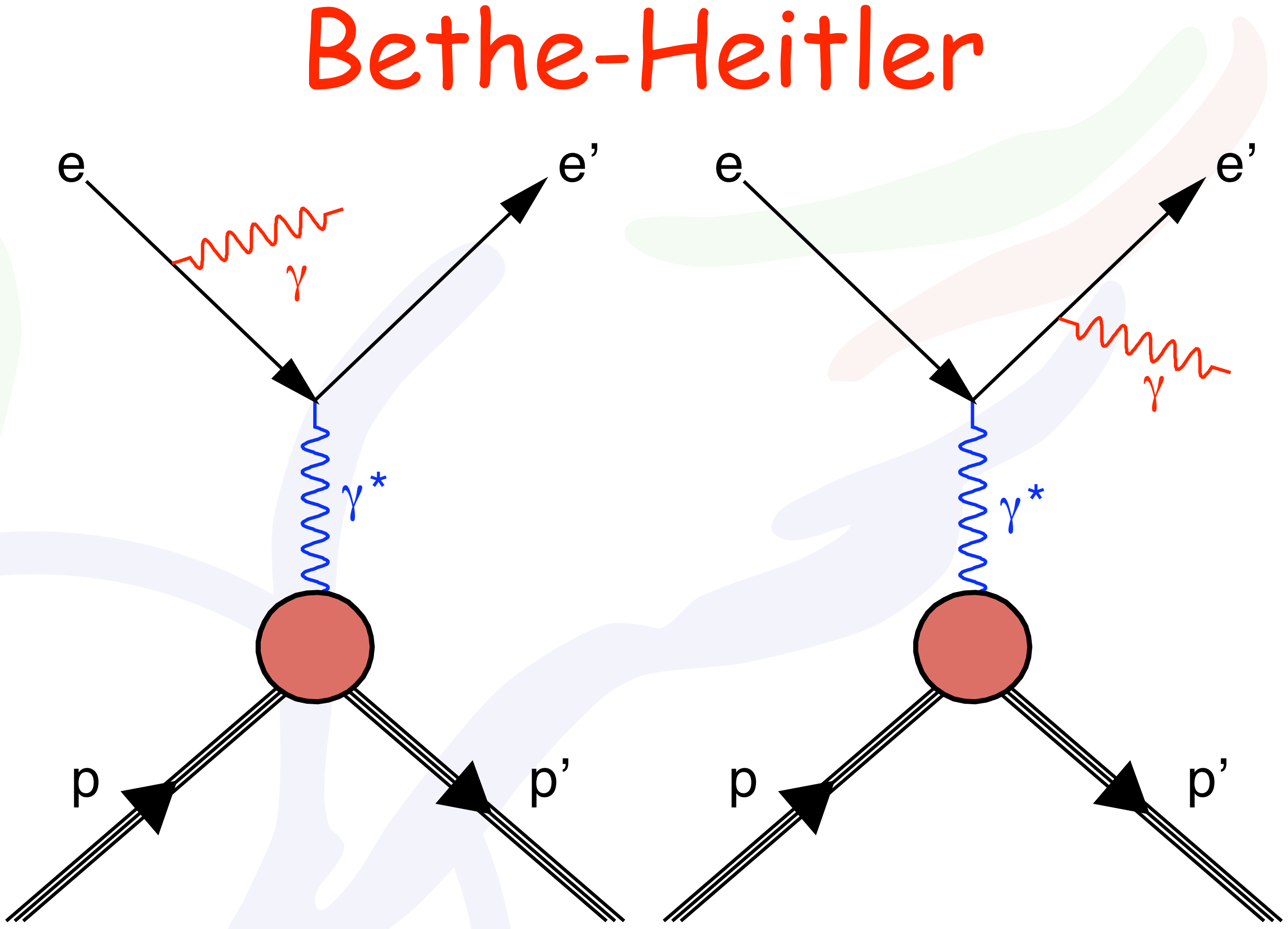
Real-photon production

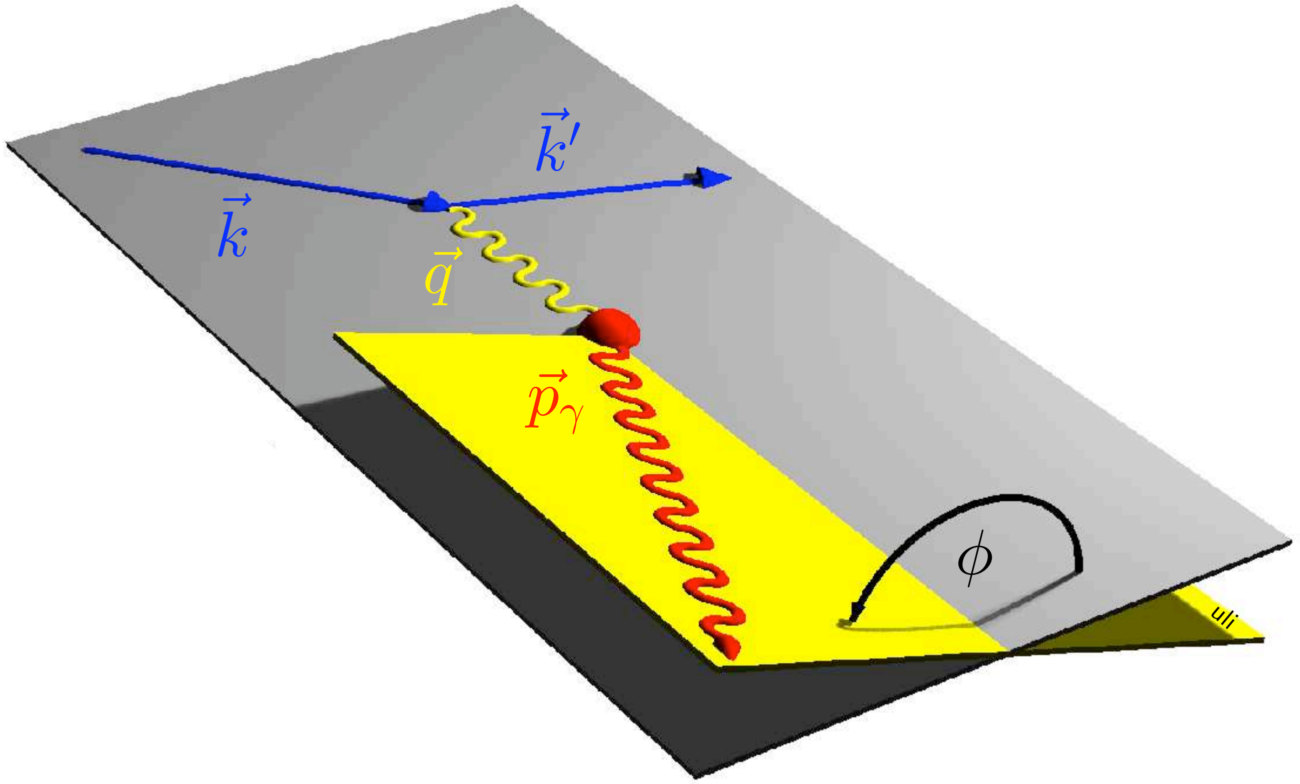




$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} = \frac{y^2}{32(2\pi))^4\sqrt{1+\frac{4M^2x_B^2}{Q^2}}}\left(|\mathcal{T}_{\text{DVCS}}|^2 + |\mathcal{T}_{\text{BH}}|^2 + \mathcal{I}\right)$$

Azimuthal dependences in DVCS/BH

- beam polarization P_B
- beam charge C_B
- here: unpolarized target



Fourier expansion for ϕ:

$$|\mathcal{T}_{\mathrm{BH}}|^2 = \frac{K_{\mathrm{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\mathrm{BH}} \cos(n\phi)$$

calculable in QED (using FF measurements)

Azimuthal dependences in DVCS/BH

- beam polarization P_B
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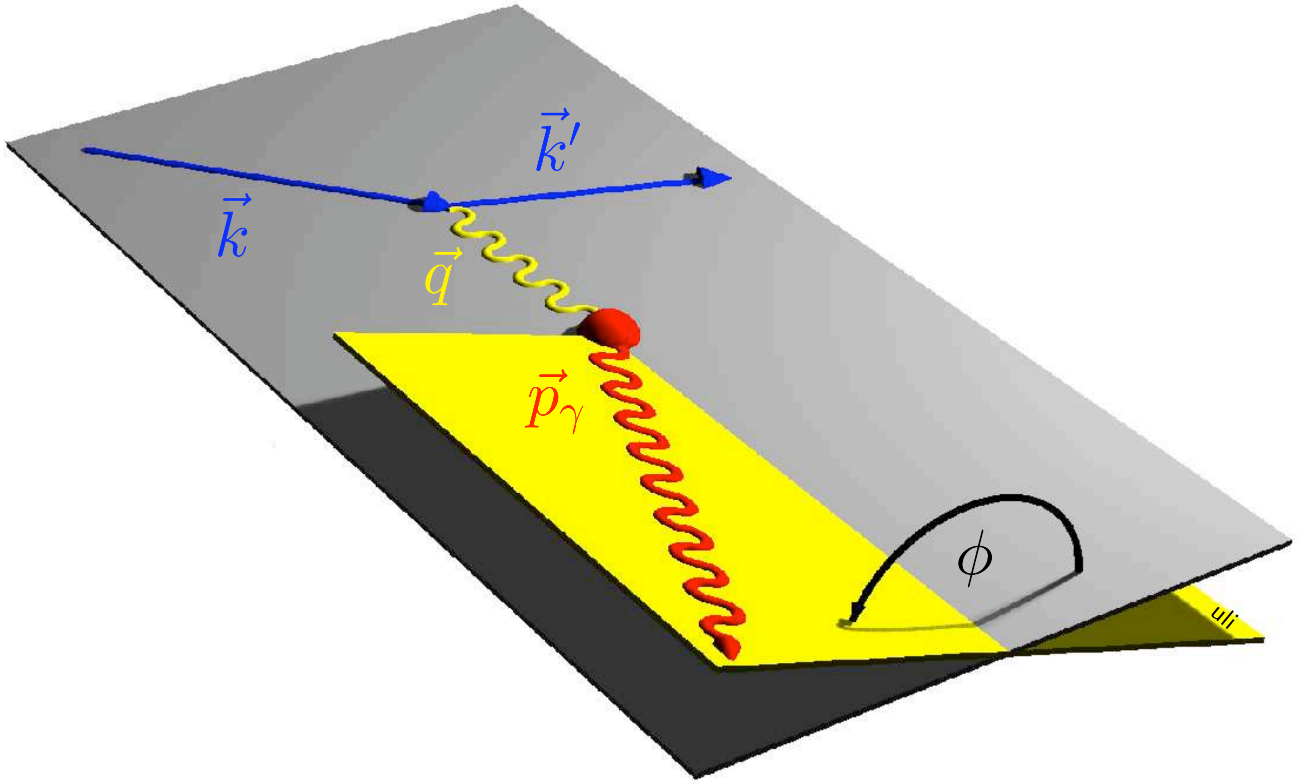

Fourier expansion for ϕ:

$$|\mathcal{T}_{\rm BH}|^2 = \frac{K_{\rm BH}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\rm BH} \cos(n\phi)$$

$$|\mathcal{T}_{\rm DVCS}|^2 = K_{\rm DVCS} \left[\sum_{n=0}^{2} c_n^{\rm DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\rm DVCS} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH

- beam polarization P_B
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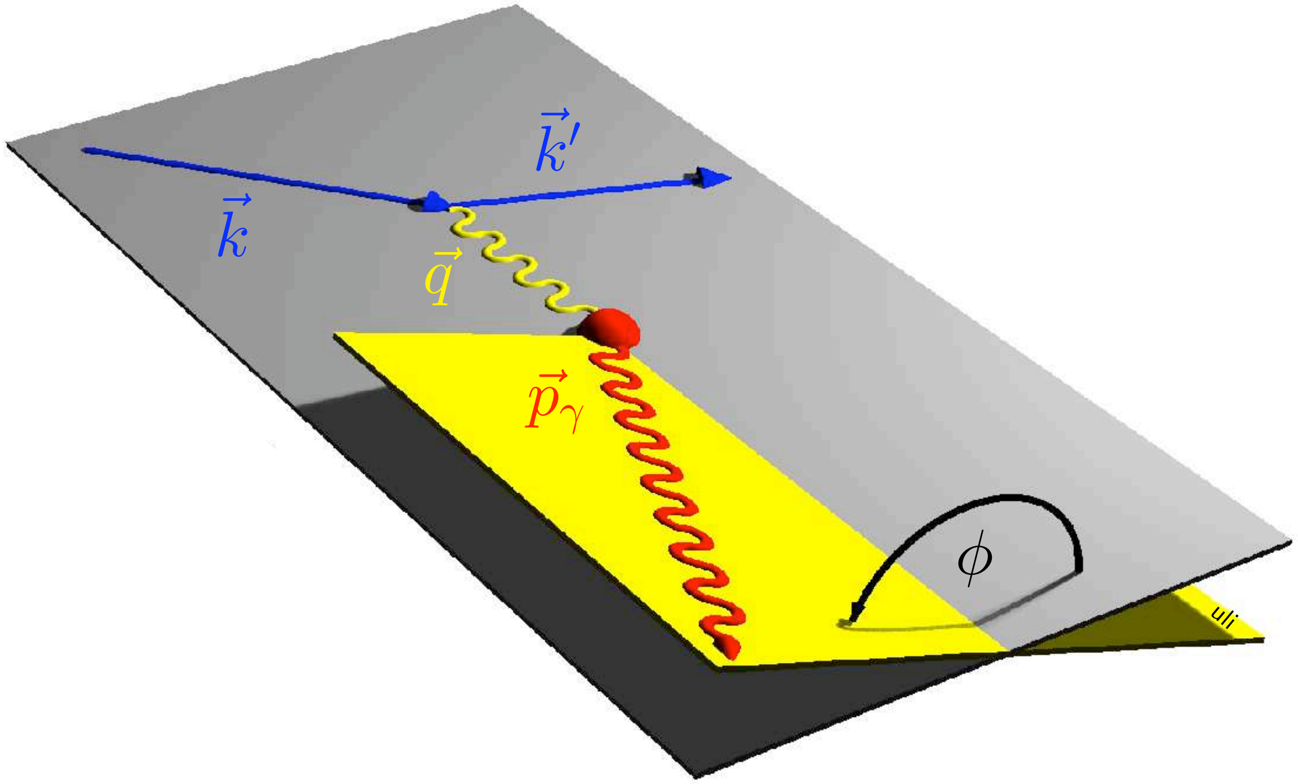

Fourier expansion for ϕ:

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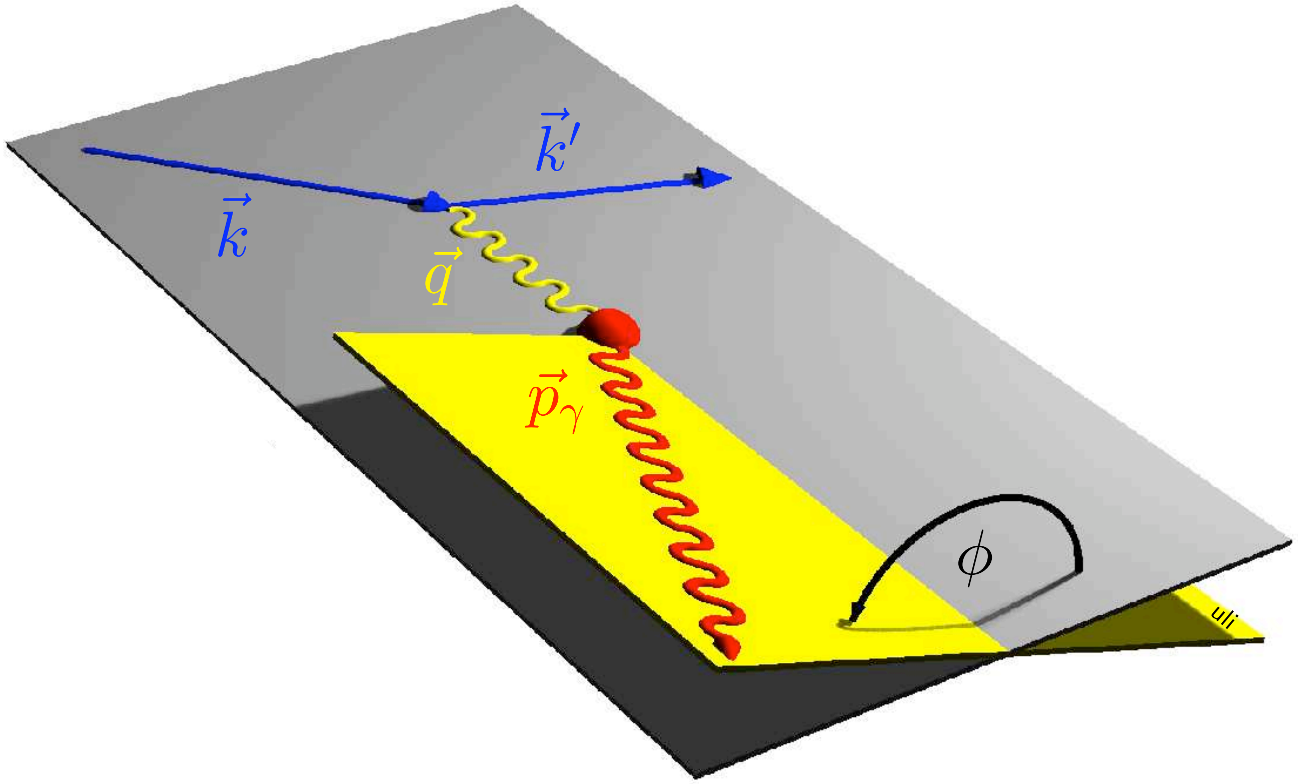
$$|\mathcal{T}_{\rm DVCS}|^2 = K_{\rm DVCS} \left[\sum_{n=0}^{2} c_n^{\rm DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\rm DVCS} \sin(n\phi) \right]$$

$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH

- beam polarization P_B
- beam charge C_B
- here: unpolarized target



Fourier expansion for ϕ:

$$|\mathcal{T}_{\text{BH}}|^2 = \frac{K_{\text{BH}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \sum_{n=0}^{2} c_n^{\text{BH}} \cos(n\phi)$$

$$|\mathcal{T}_{\text{DVCS}}|^2 = K_{\text{DVCS}} \left[\sum_{n=0}^{2} c_n^{\text{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\text{DVCS}} \sin(n\phi) \right]$$

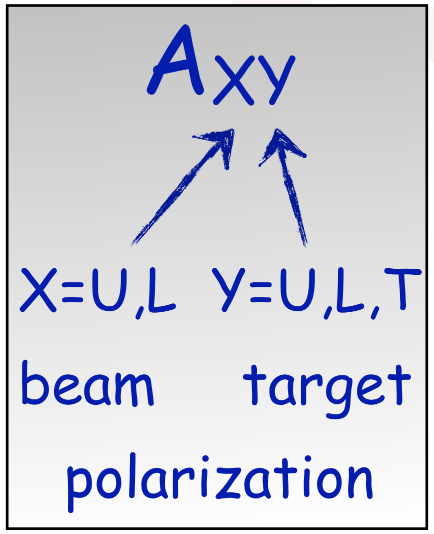
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

bilinear ("DVCS") or linear in GPDs

Azimuthal asymmetries in DVCS/BH

Cross section:

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

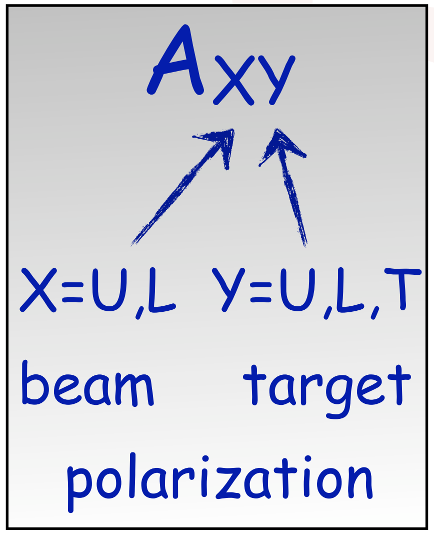


Azimuthal asymmetries in DVCS/BH

Cross section:

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

$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}}\, P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi)$$



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$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi)\right]$$

A_{XY}

X=U,L Y=U,L,T

beam target

polarization

Azimuthal asymmetries in DVCS/BH

Cross section:

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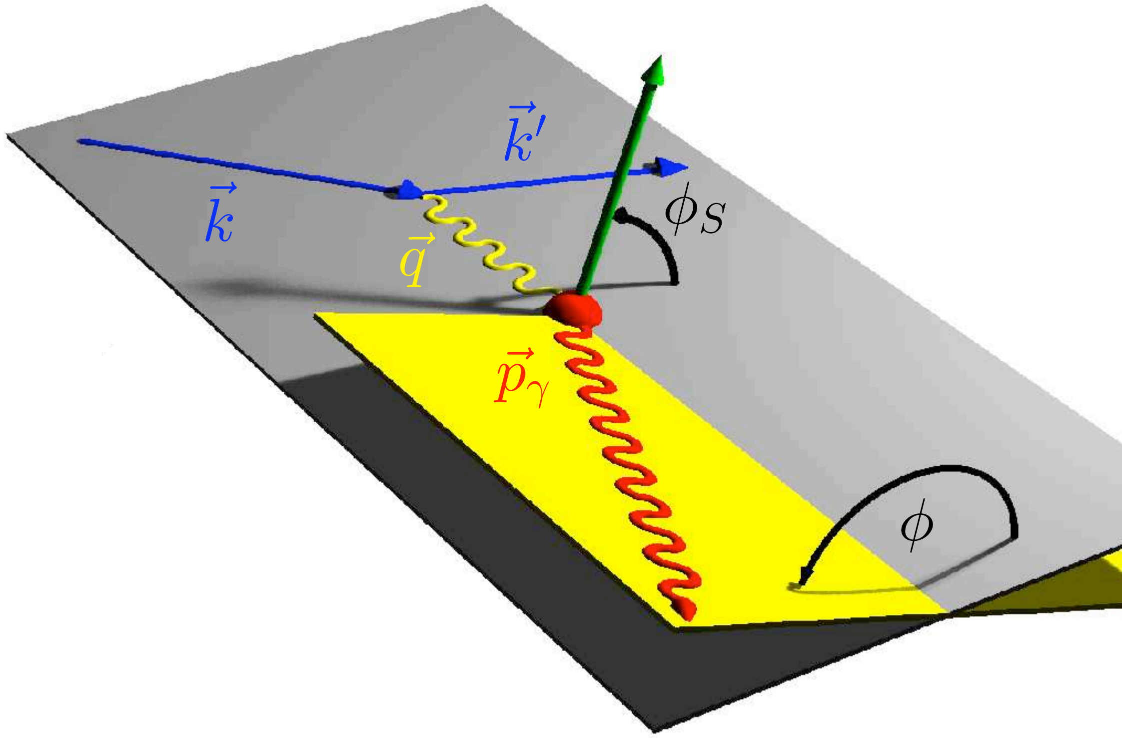

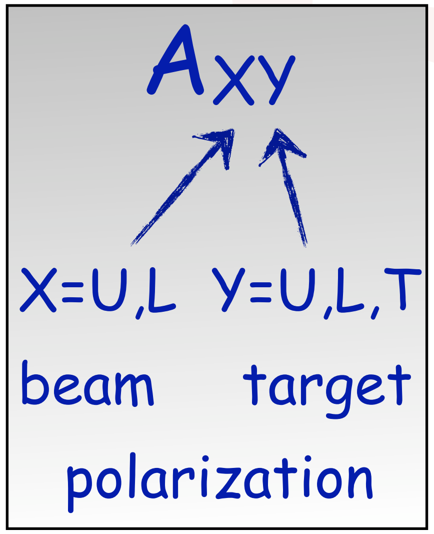

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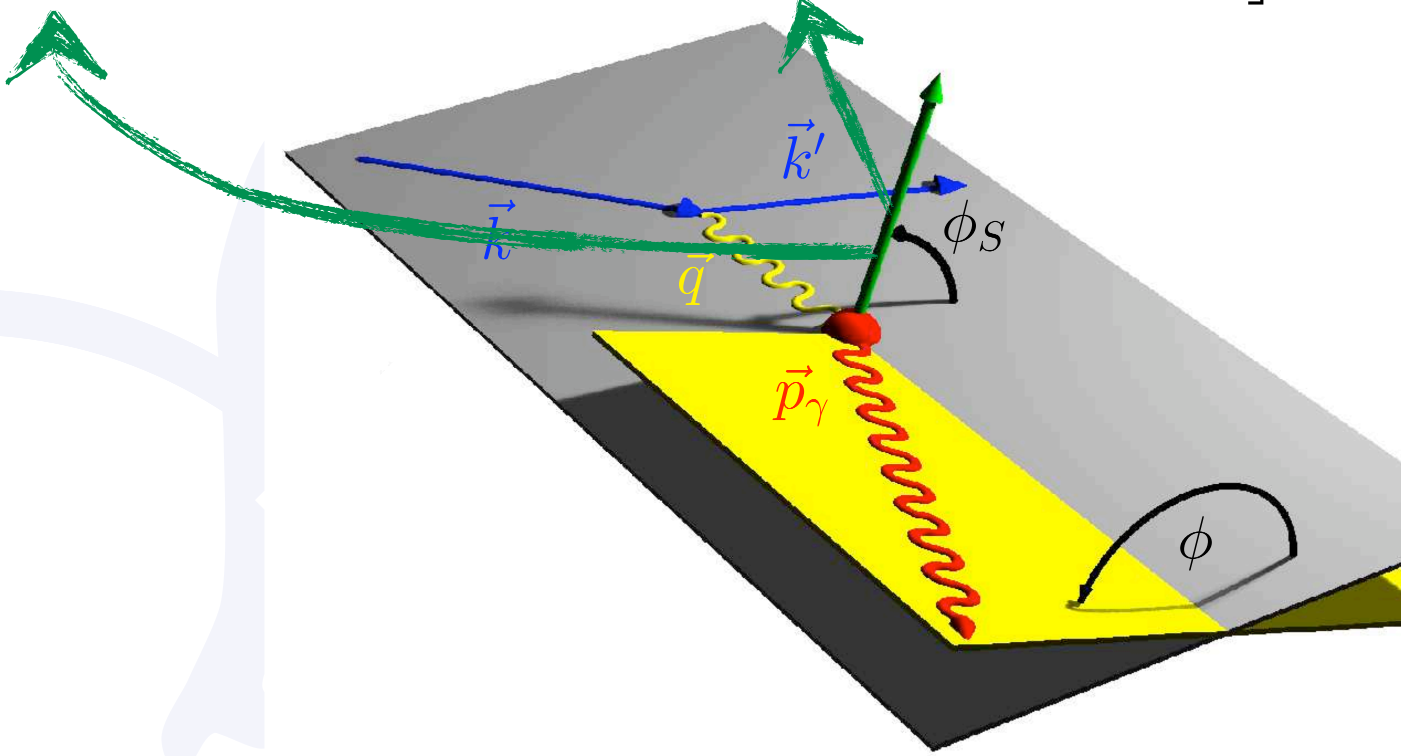

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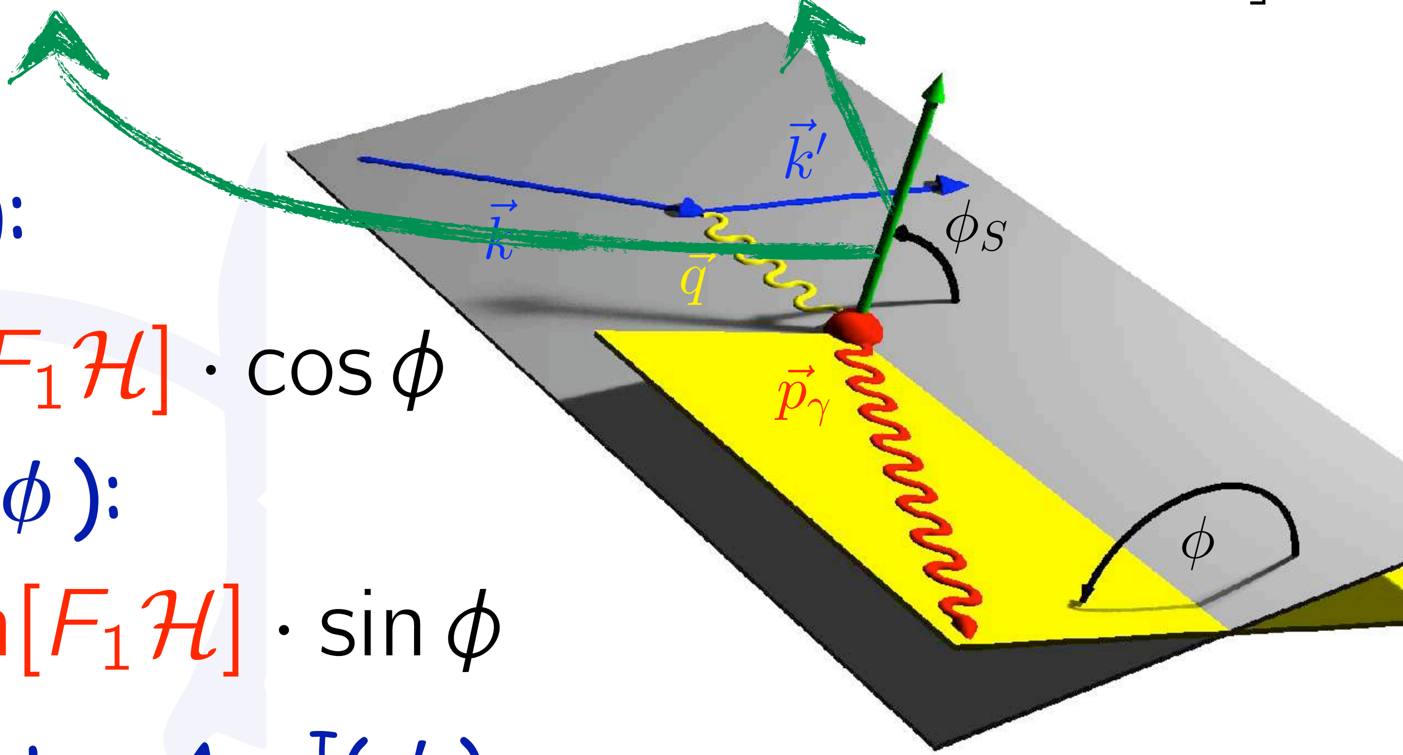
$$+ P_T \mathcal{A}_{\mathrm{UT}}^{\mathrm{DVCS}}(\phi, \phi_S) + C_B P_T \mathcal{A}_{\mathrm{UT}}^{\mathcal{I}}(\phi, \phi_S)\Big]$$

Azimuthal asymmetries, e.g.,



- **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 $A_{LU}^I(\phi)$:**

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

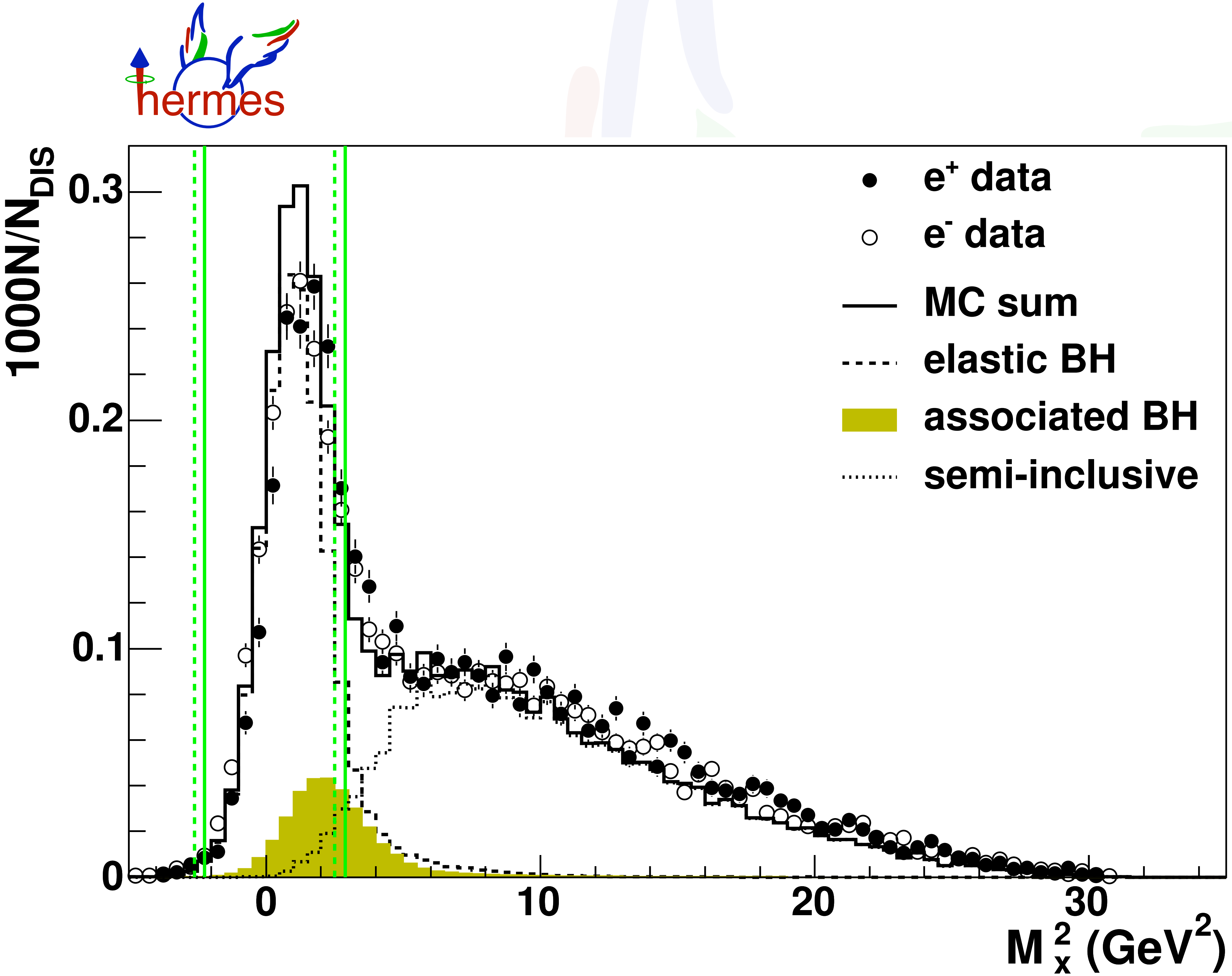
- **Transverse target-spin asymmetry $A_{UT}^I(\phi)$:**

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

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

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

Exclusivity: missing-mass technique



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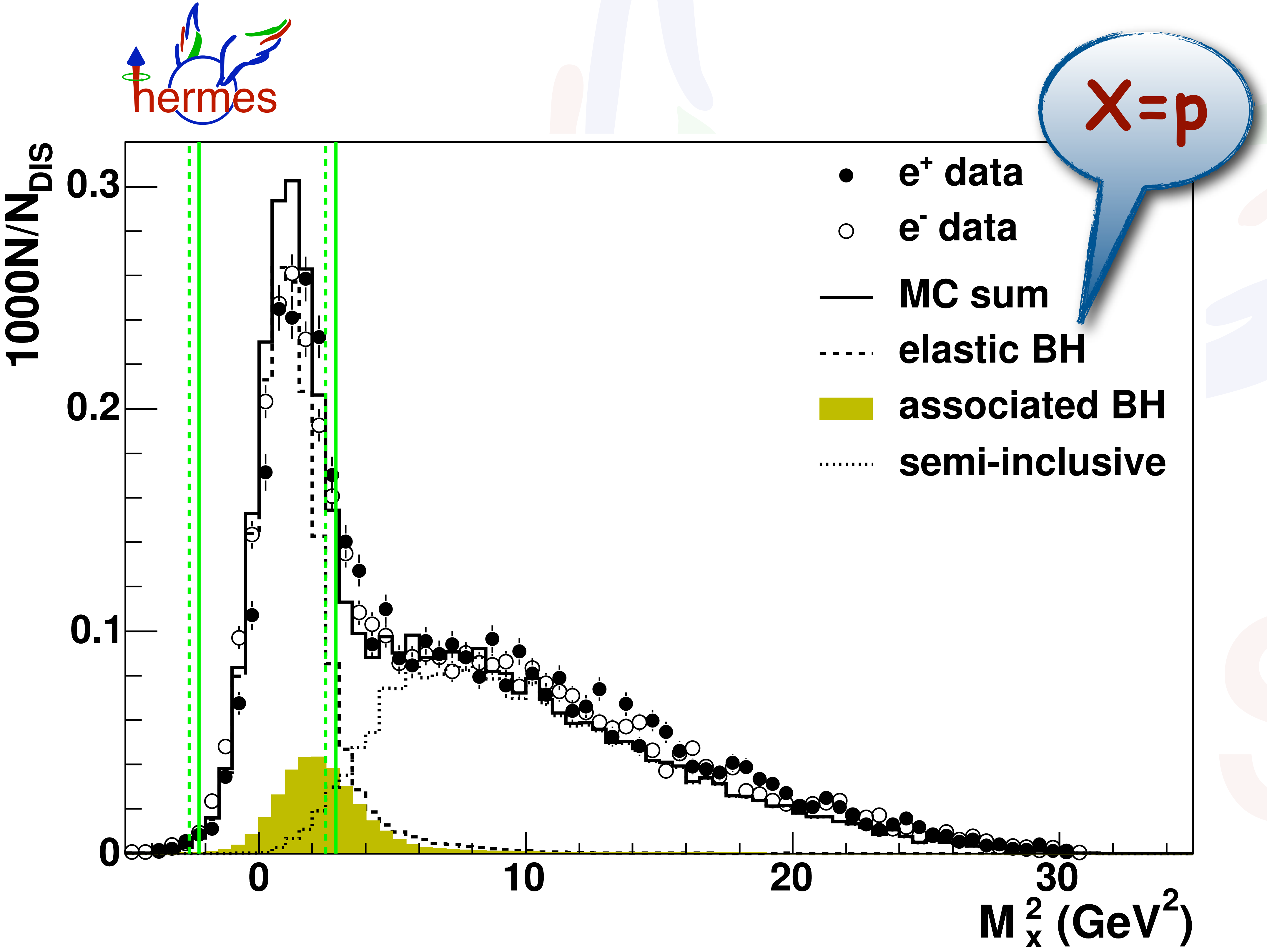

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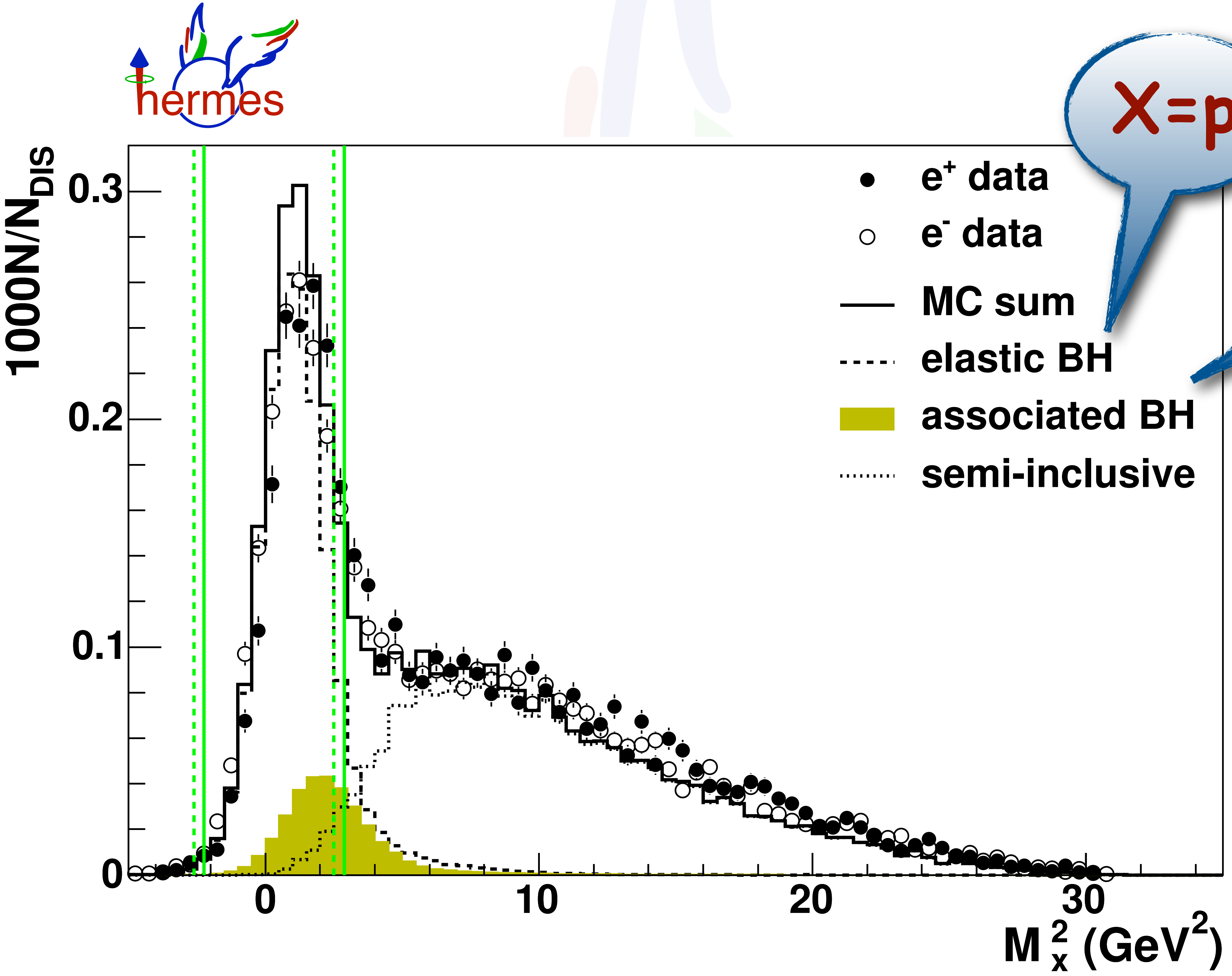
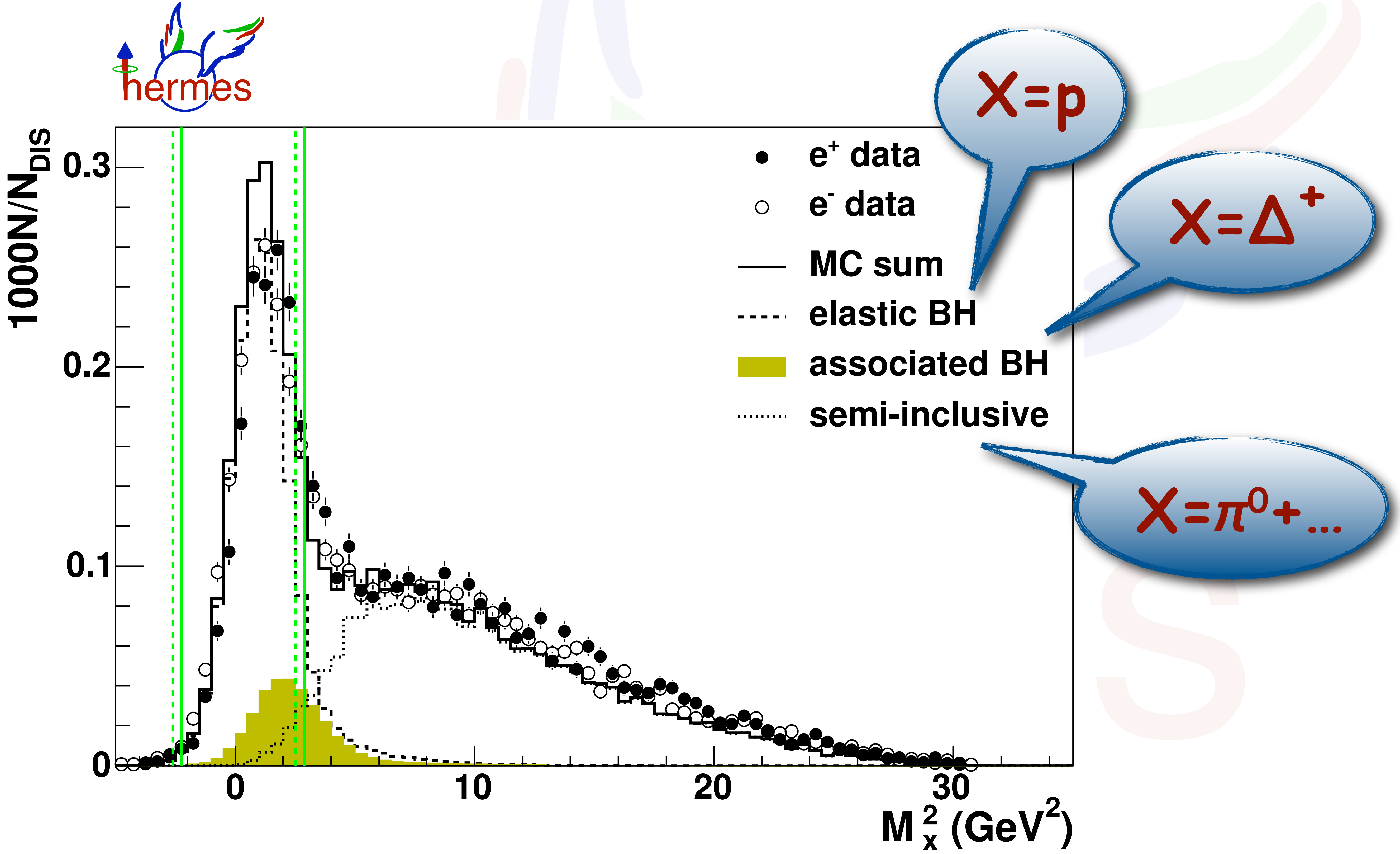


X=p

X=Δ^+

Exclusivity: missing-mass technique

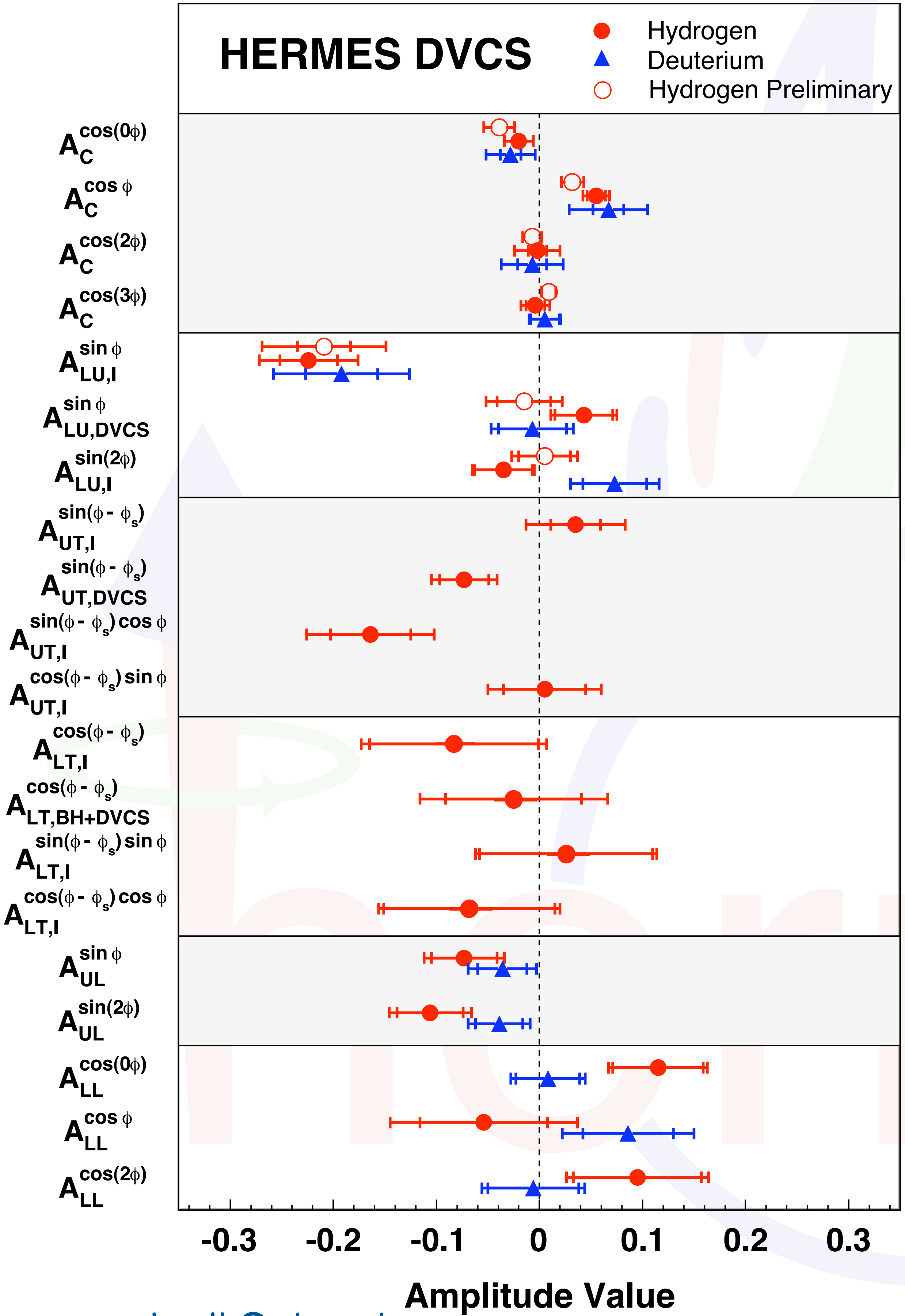


X=p

$X=\Delta^+$

$X=\pi^0+\ldots$

A wealth of azimuthal amplitudes



Beam-charge asymmetry:

GPD H

Beam-helicity asymmetry:

GPD H

Transverse target spin asymmetries:

GPD E from proton target

Longitudinal target spin asymmetry:

GPD $\tilde{H}$

Double-spin asymmetry:

GPD $\tilde{H}$

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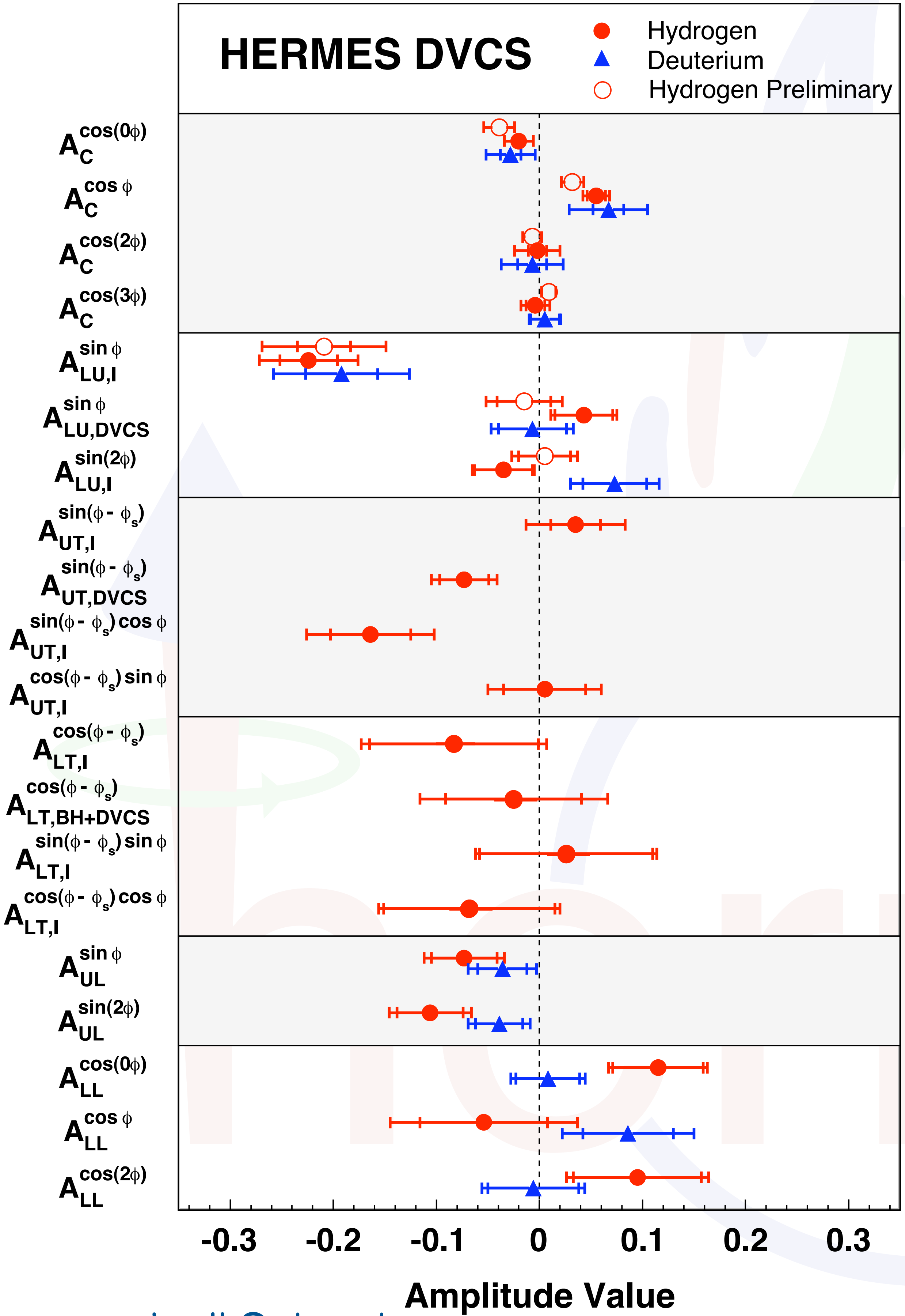
A wealth of azimuthal amplitudes



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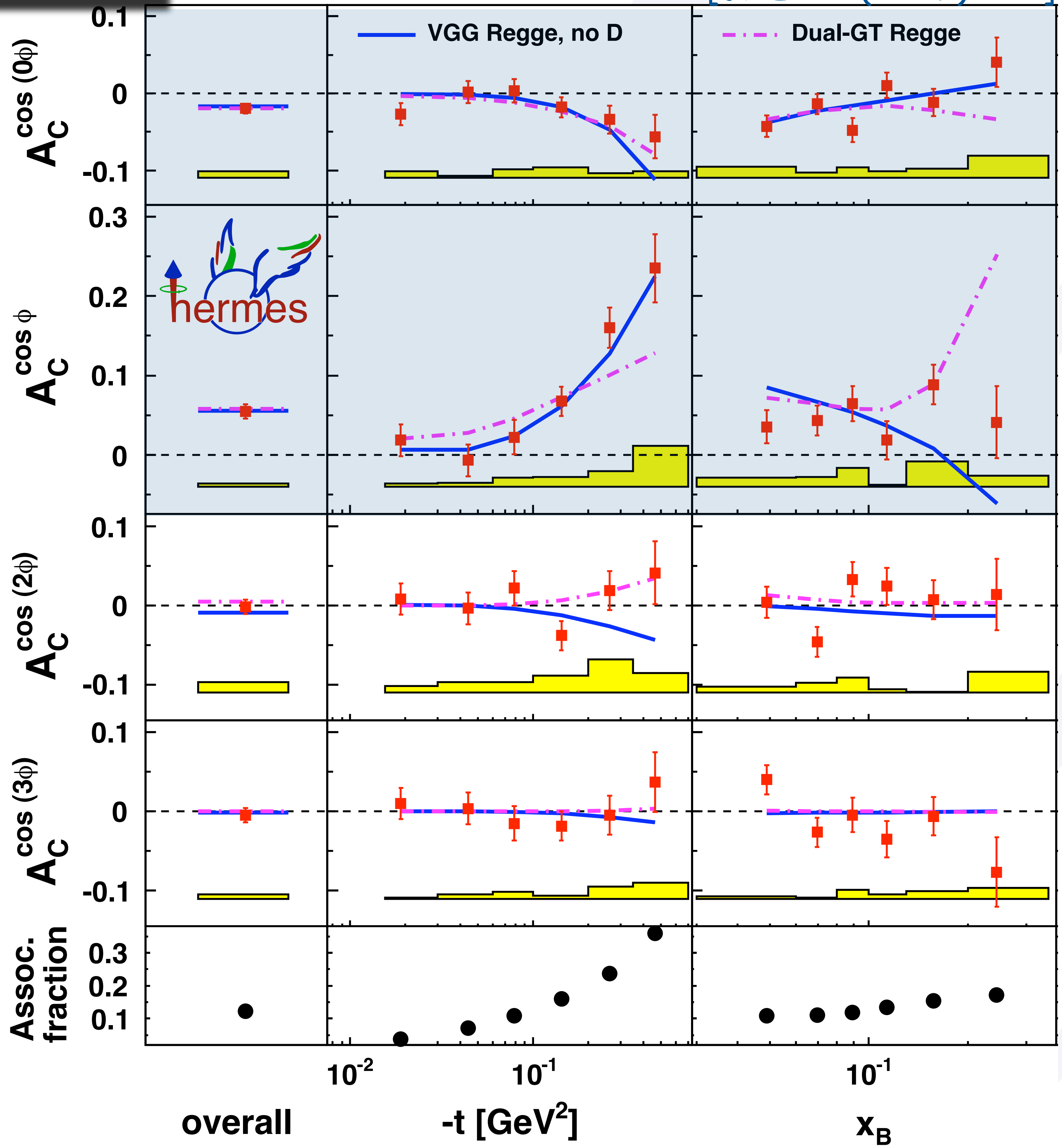
data:
1996-2005

Beam-charge asymmetry

[JHEP 11 (2009) 083]



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

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

[higher twist]

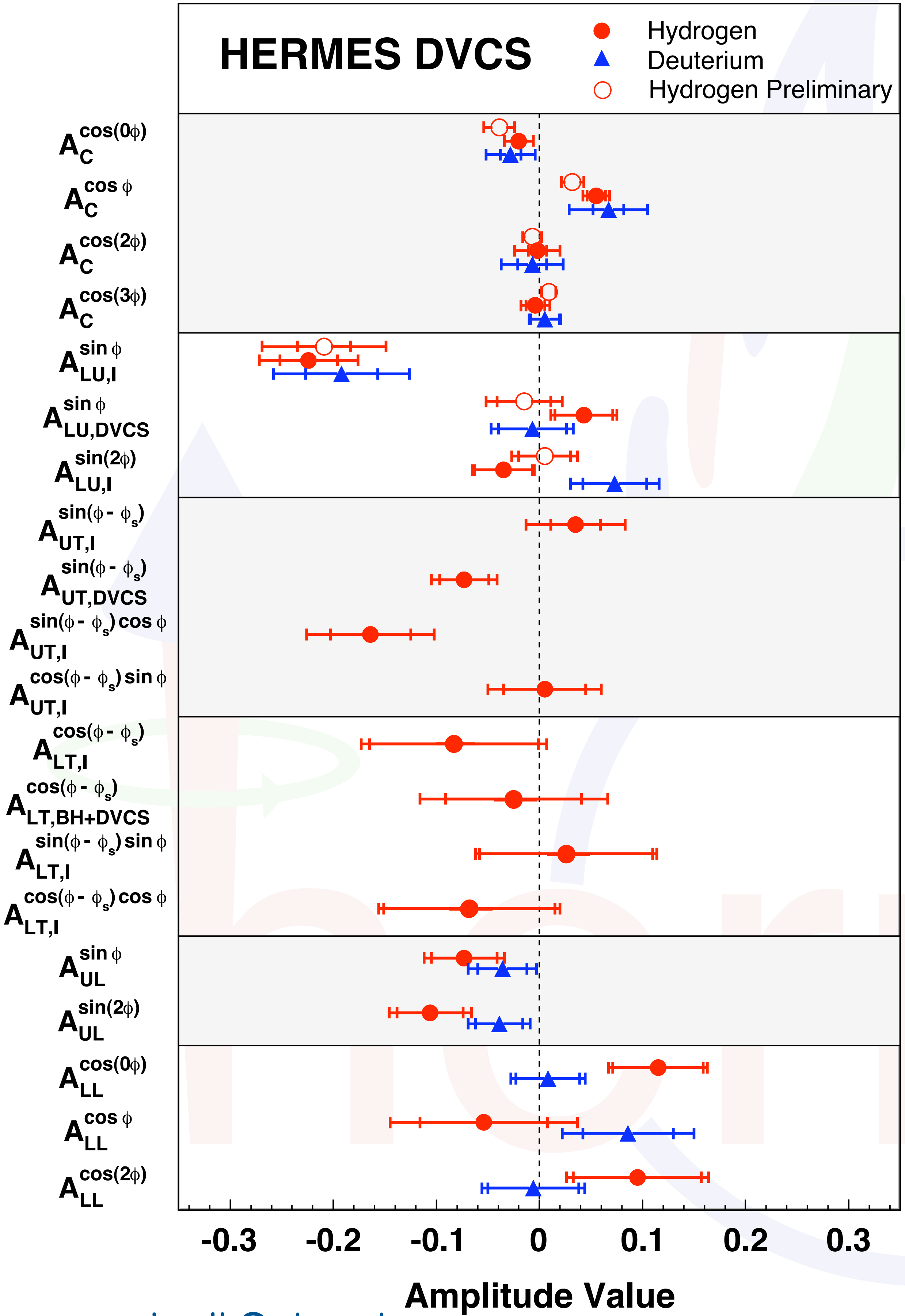
[gluon leading twist]

Resonant fraction:

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

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

A wealth of azimuthal amplitudes



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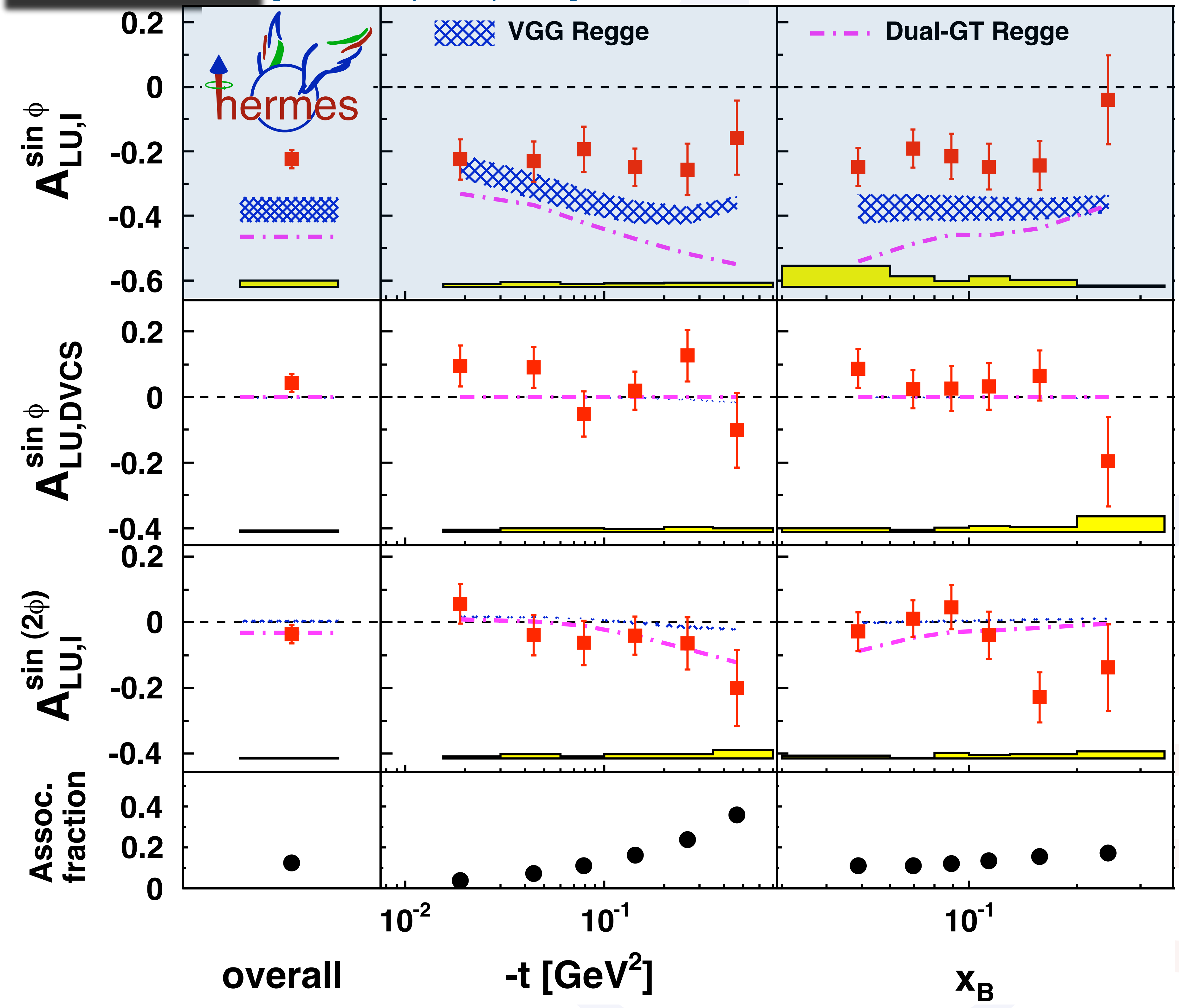

$\propto \mathrm{Im}[F_1\mathcal{H}]$

[higher twist]

Resonant fraction:

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

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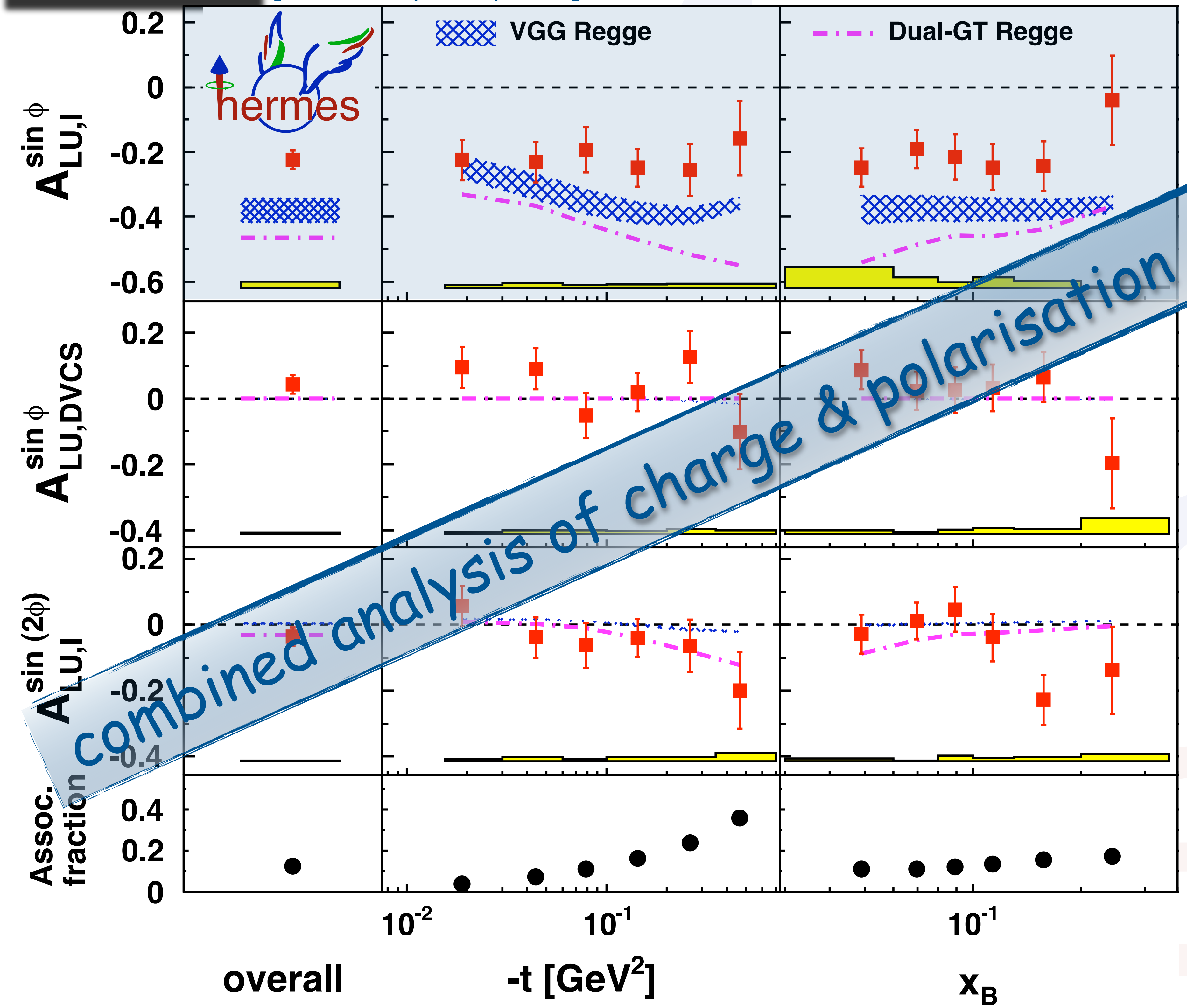
Beam-spin asymmetry

[JHEP 11 (2009) 083]



combined analysis of charge & polarisation observables

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

[higher twist]

Resonant fraction:

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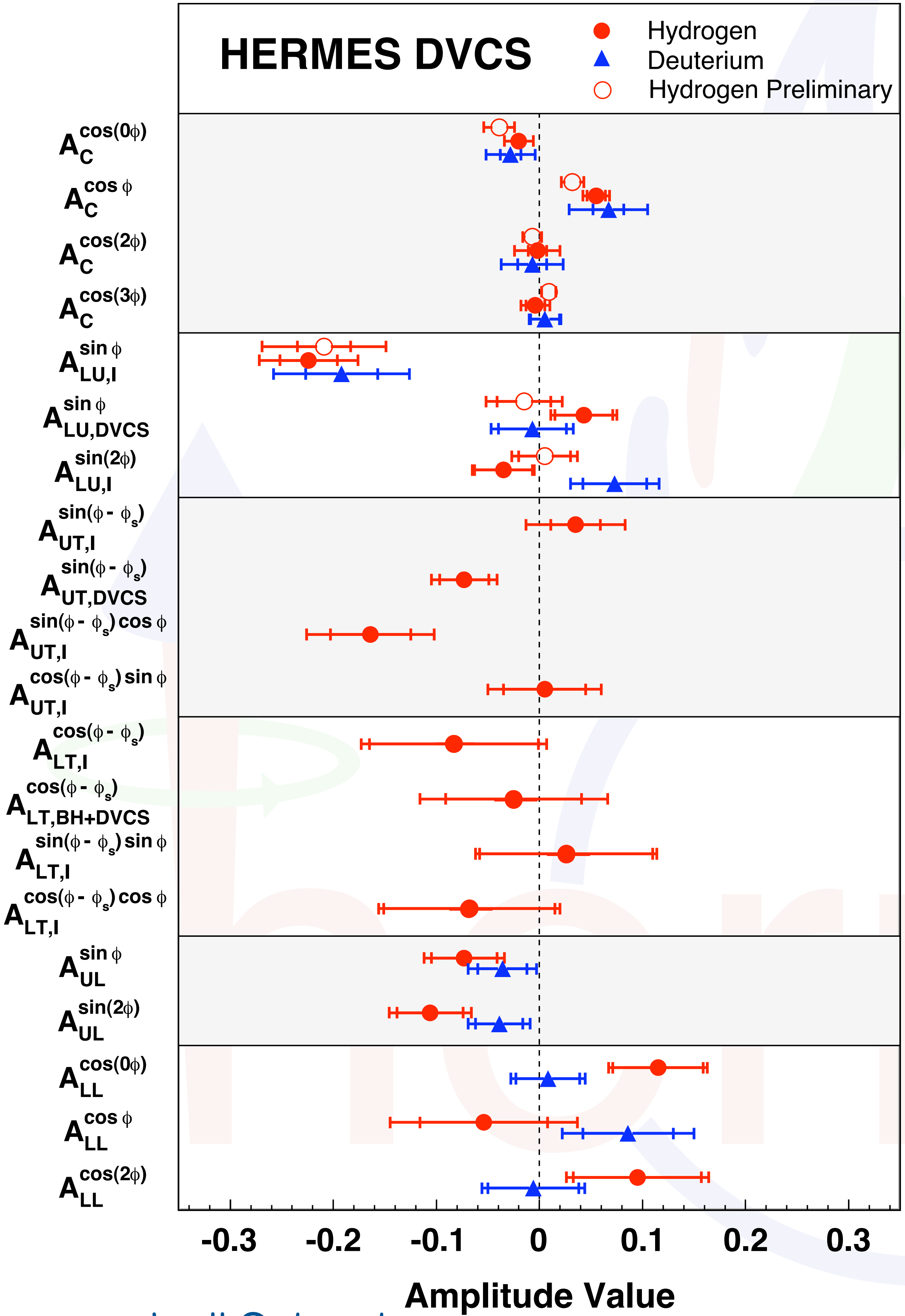
A wealth of azimuthal amplitudes



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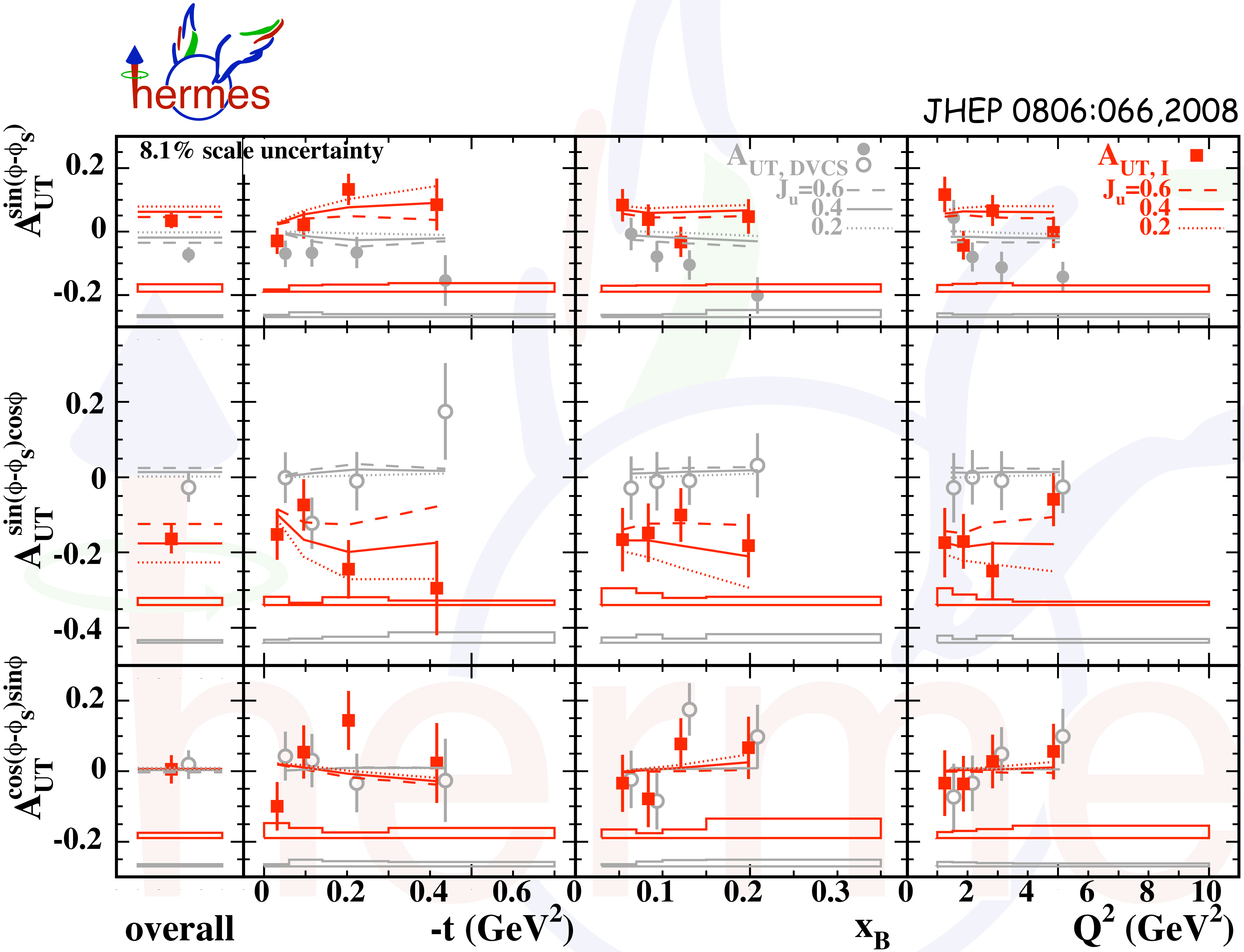
Transverse target-spin asymmetry



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

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

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

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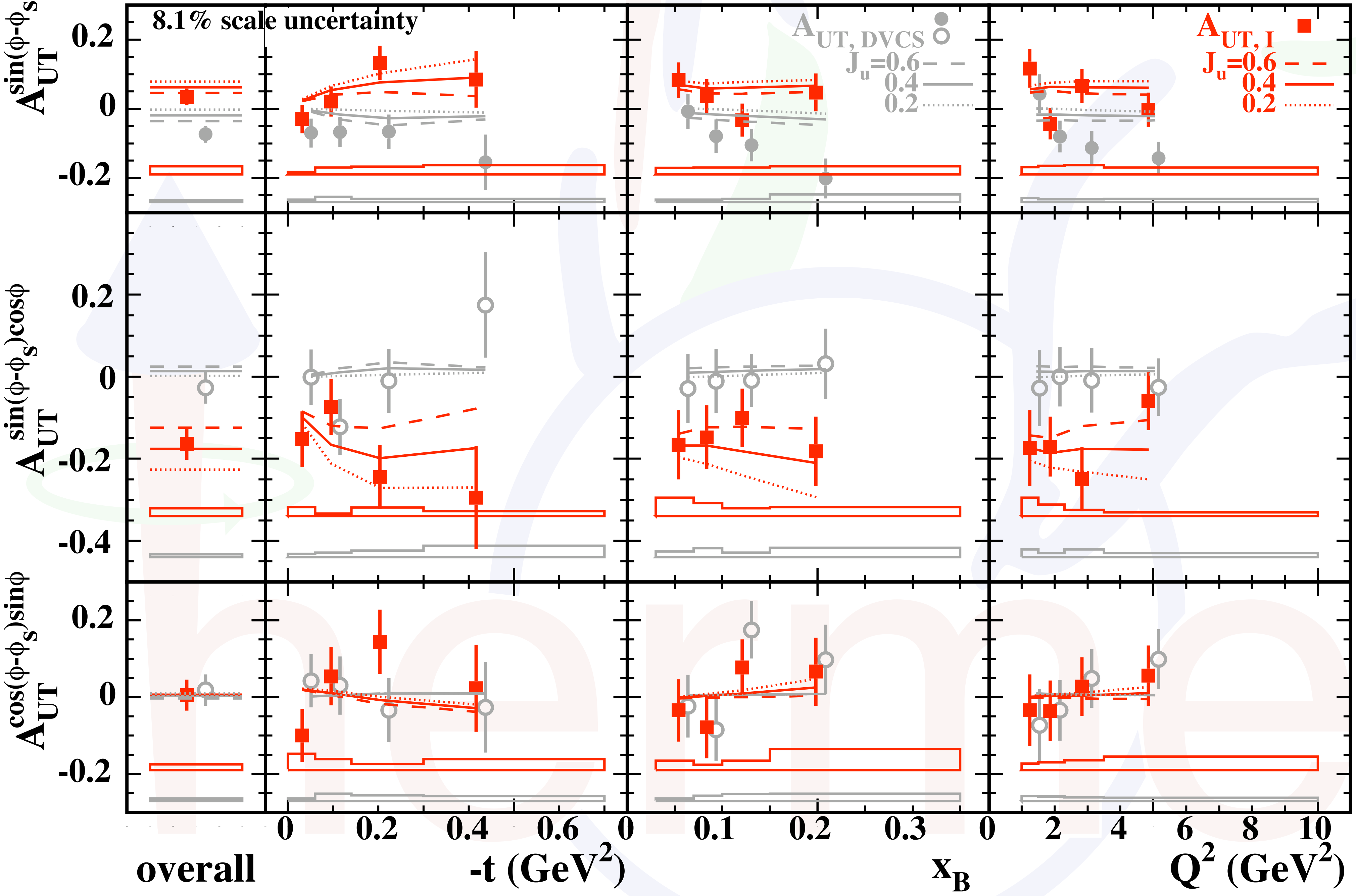
Transverse target-spin asymmetry

JHEP 0806:066,2008



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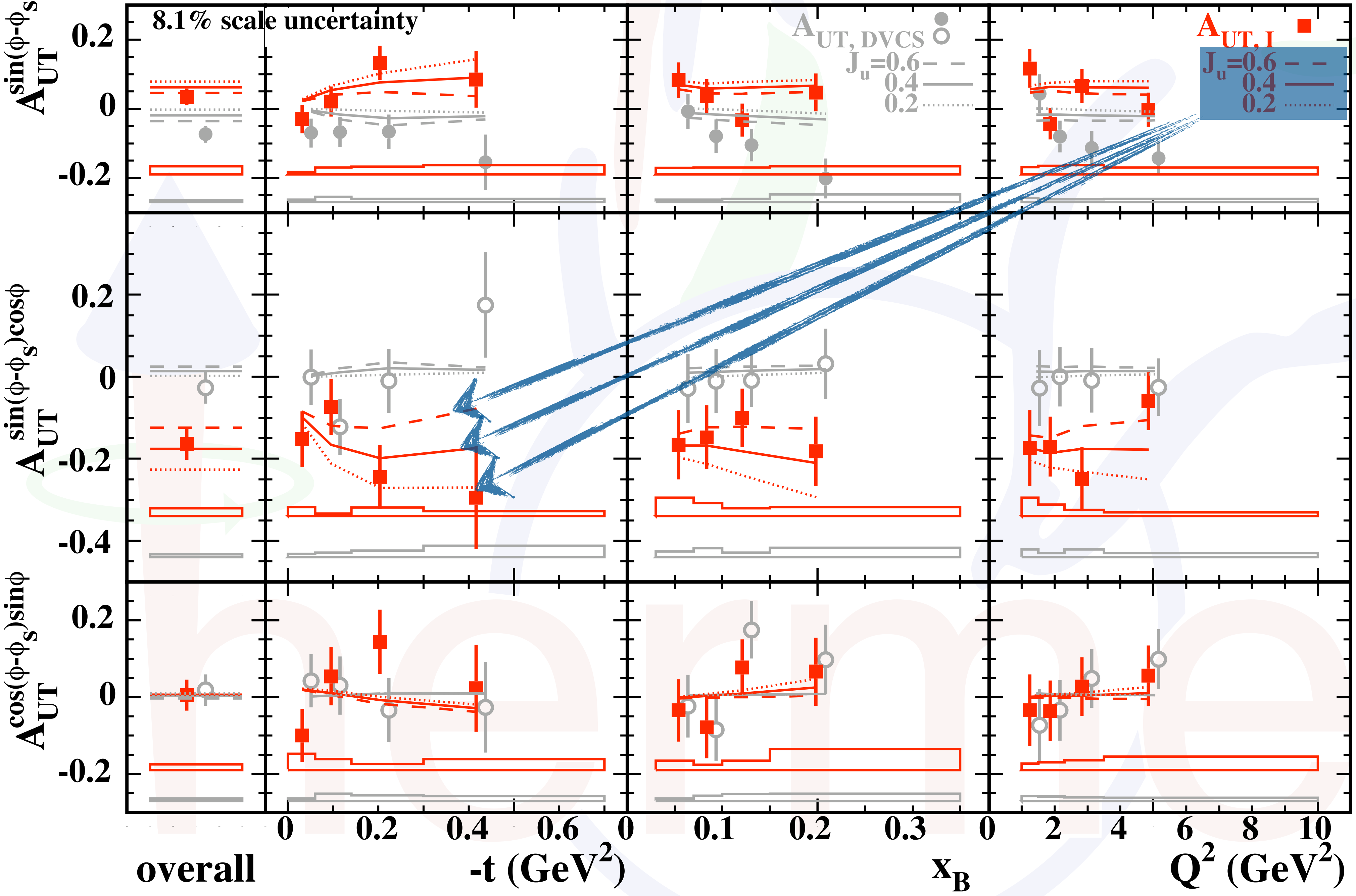
model "VGG": Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

Transverse target-spin asymmetry

JHEP 0806:066,2008



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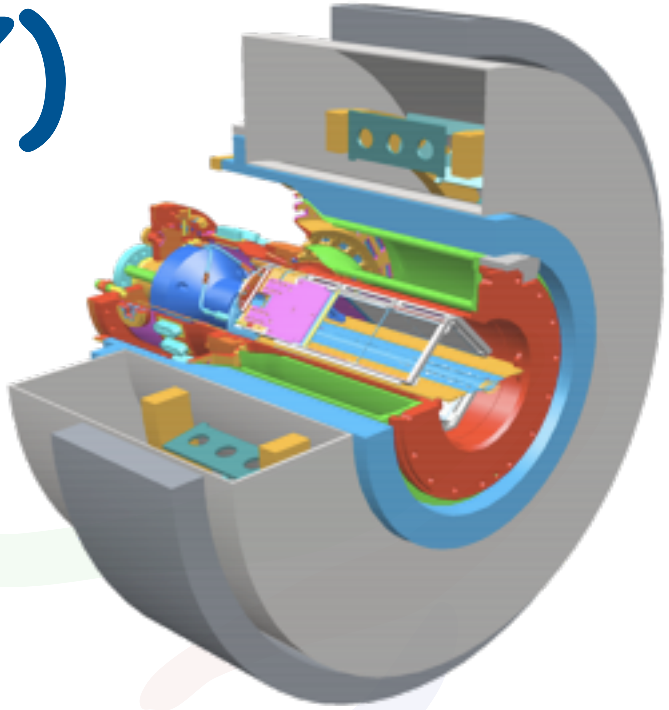
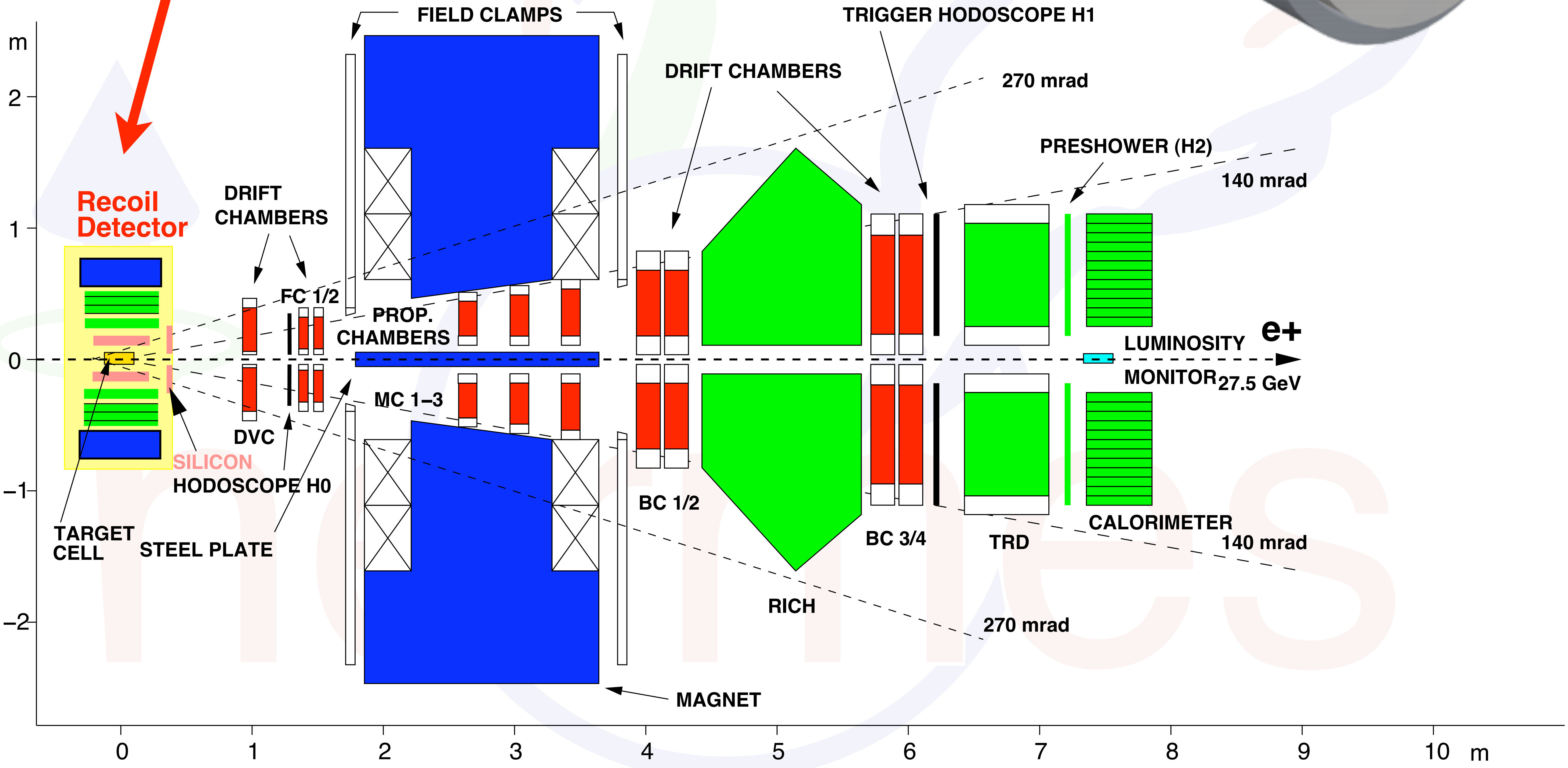
model "VGG": Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

HERMES detector (2006/07)

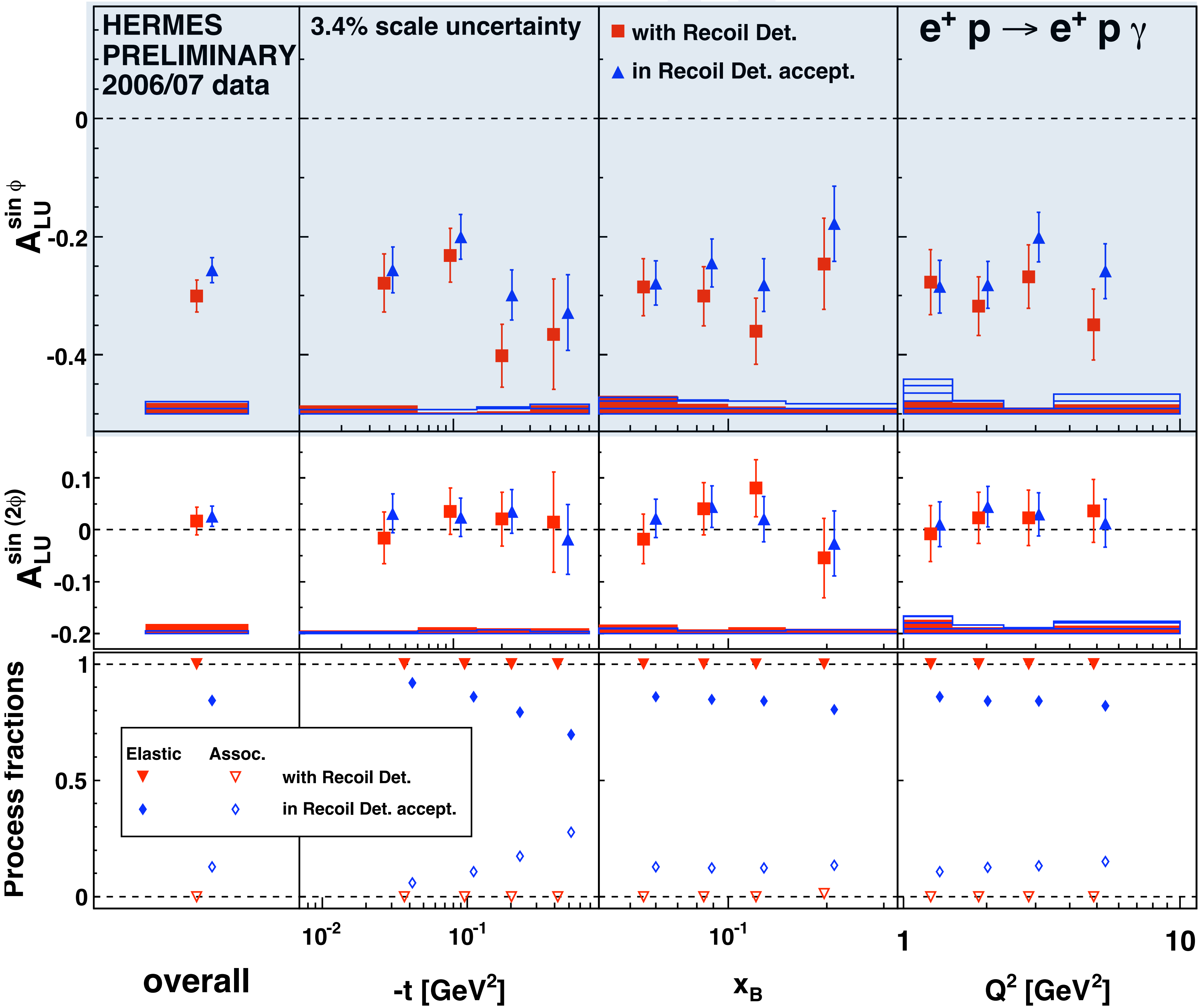


detection of recoiling proton



DVCS with recoil detector

first DVCS data with recoil-proton detection



basically pure DVCS/BH sample

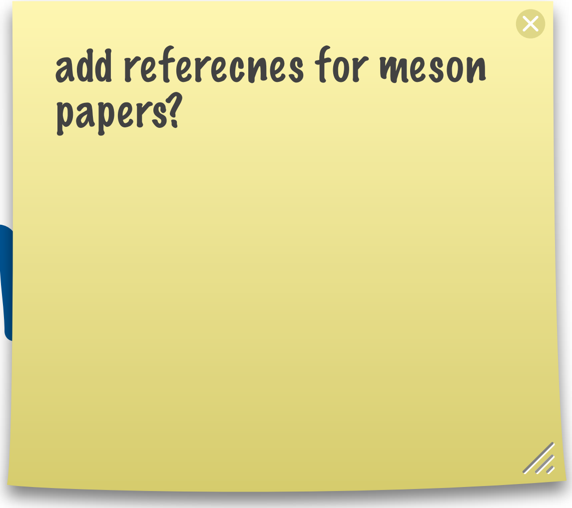
indication of larger amplitudes for pure sample

extraction of amplitudes for associated production underway

Exclusive n production

add referecnes for meson papers?

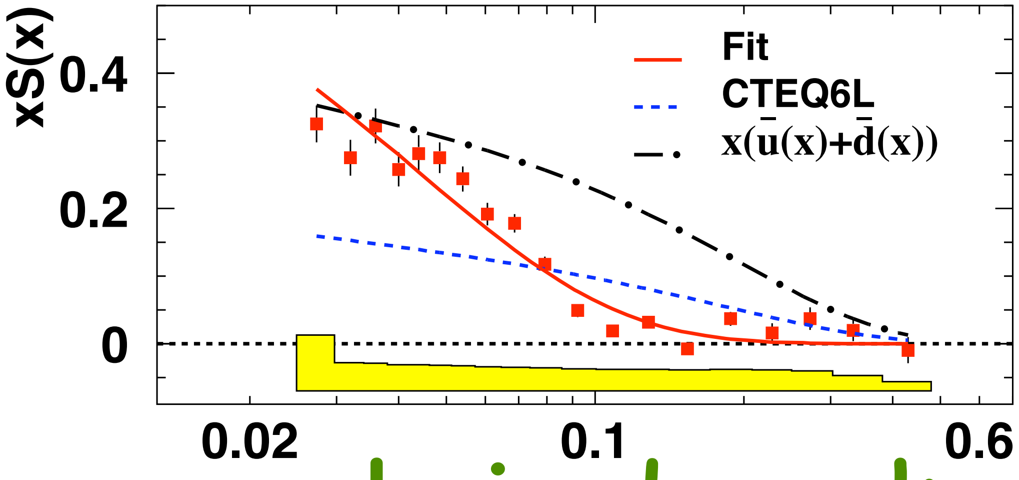
Exclusive n production



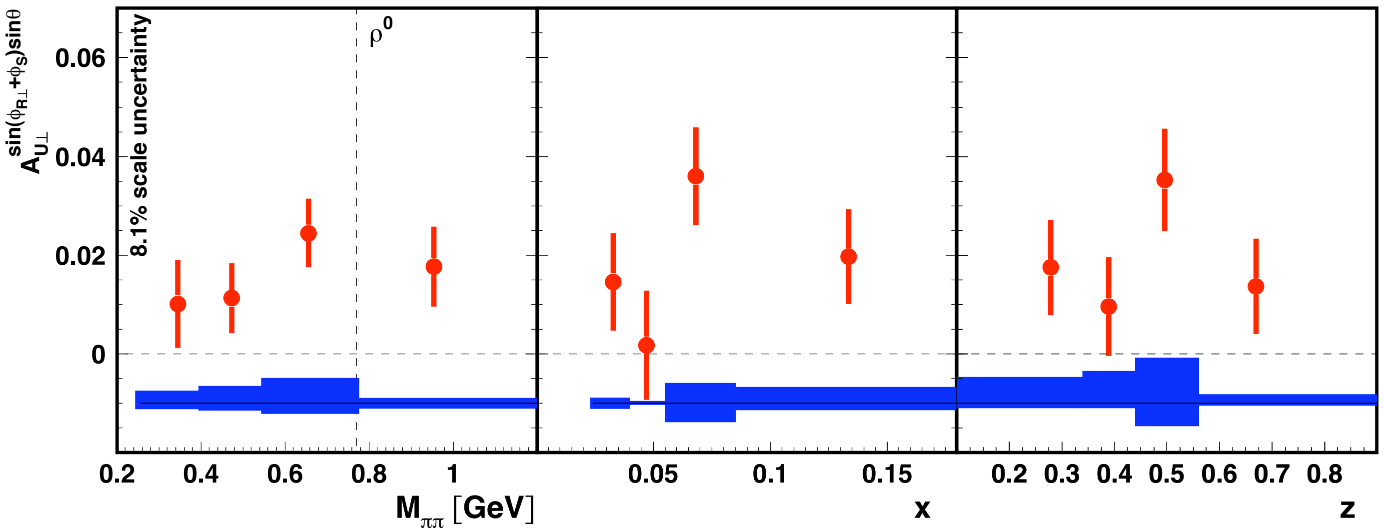
add referecnes for meson papers?

… next time!

hermes

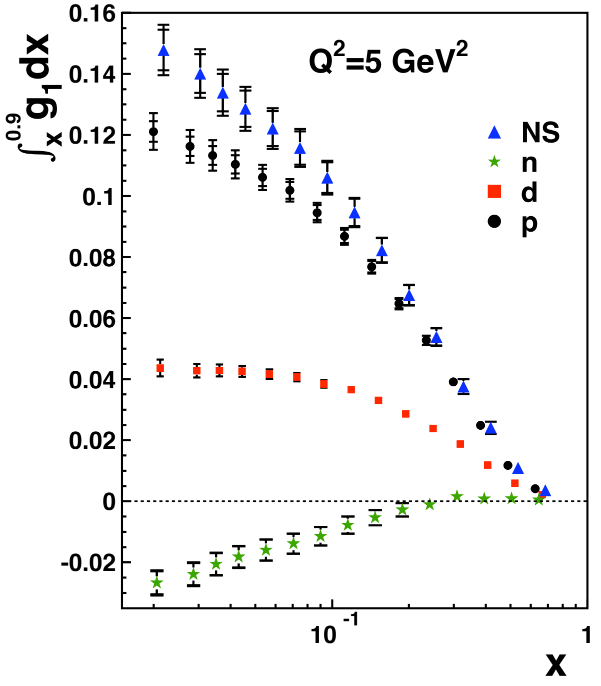


unpolarized quarks



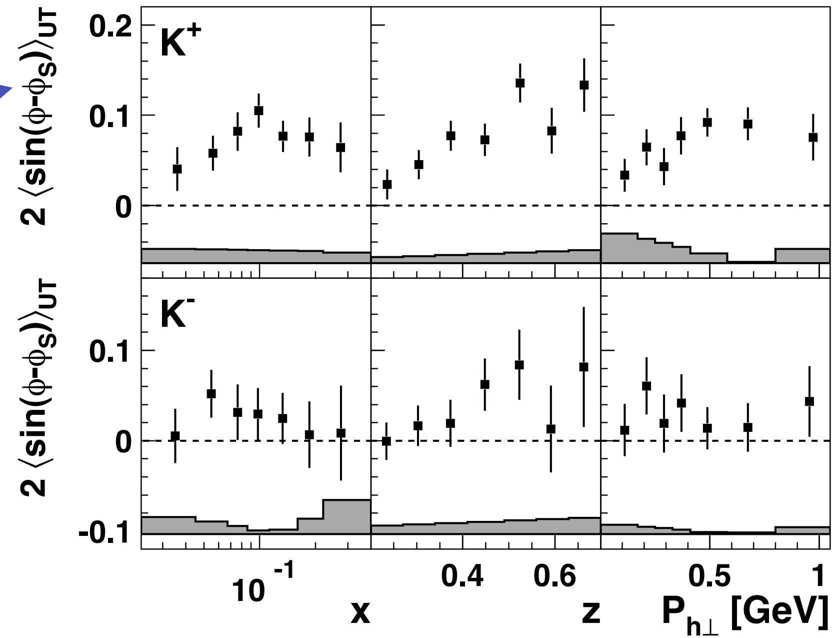
transversity

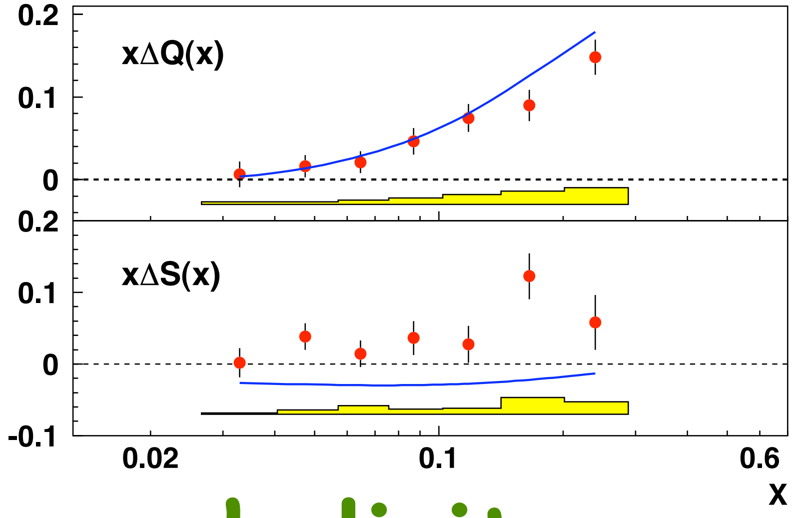
orbital angular momentum



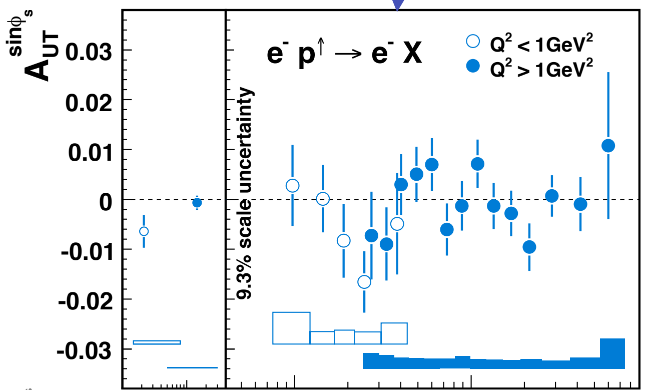
$\Delta\Sigma$

hermes



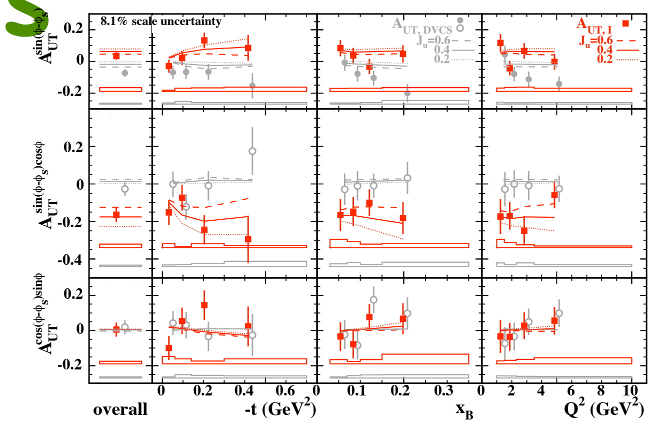


helicity distributions



2-Photon Exchange

GPDs



QCD-N'12 Bilbao - Oct. 22nd-26th, 2012

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http://tp.lc.ehu.es/QCD-N2012/qcdn2012.html

You are all invited to try out Spanish wine and Basque cousine