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--

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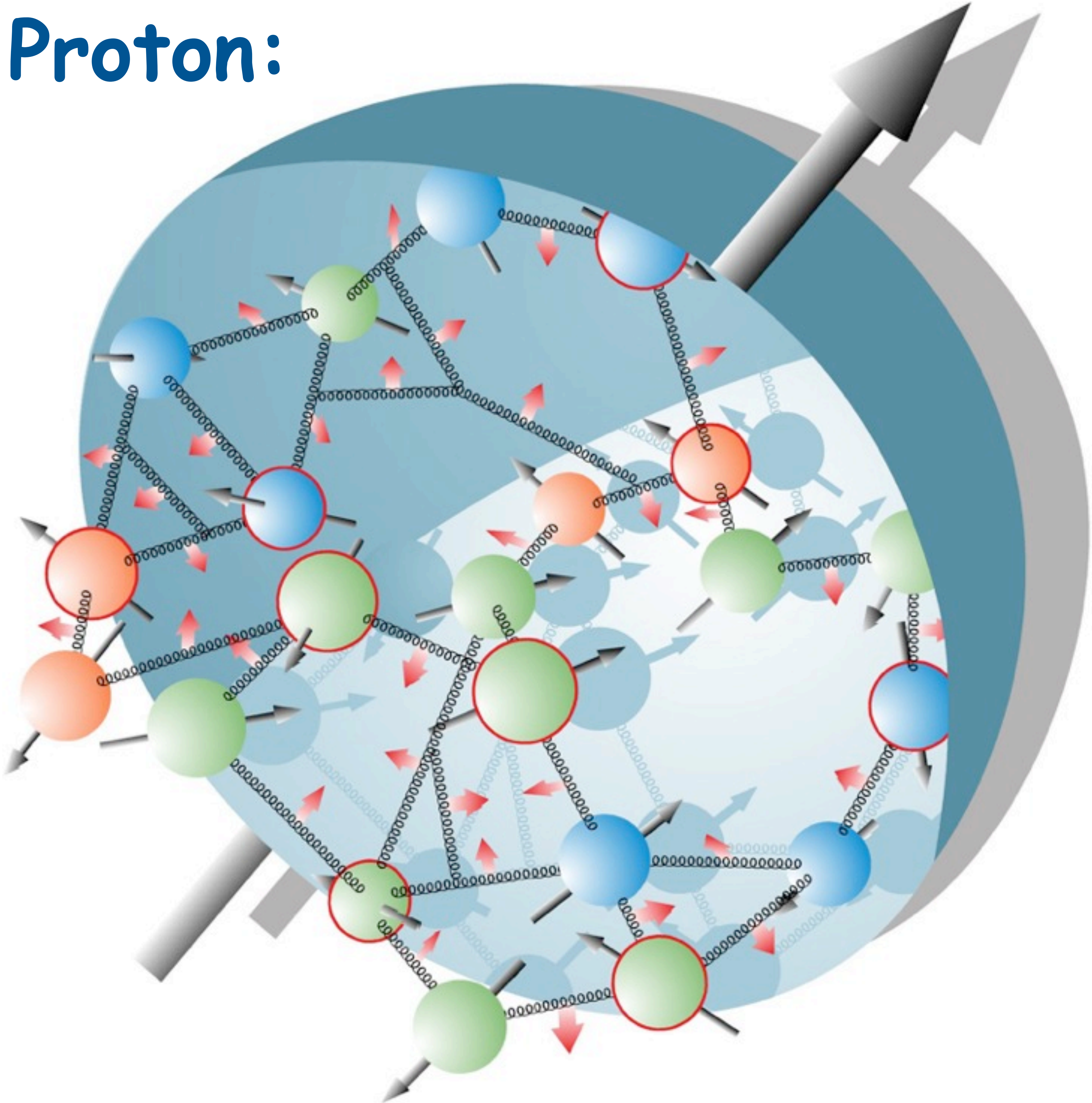
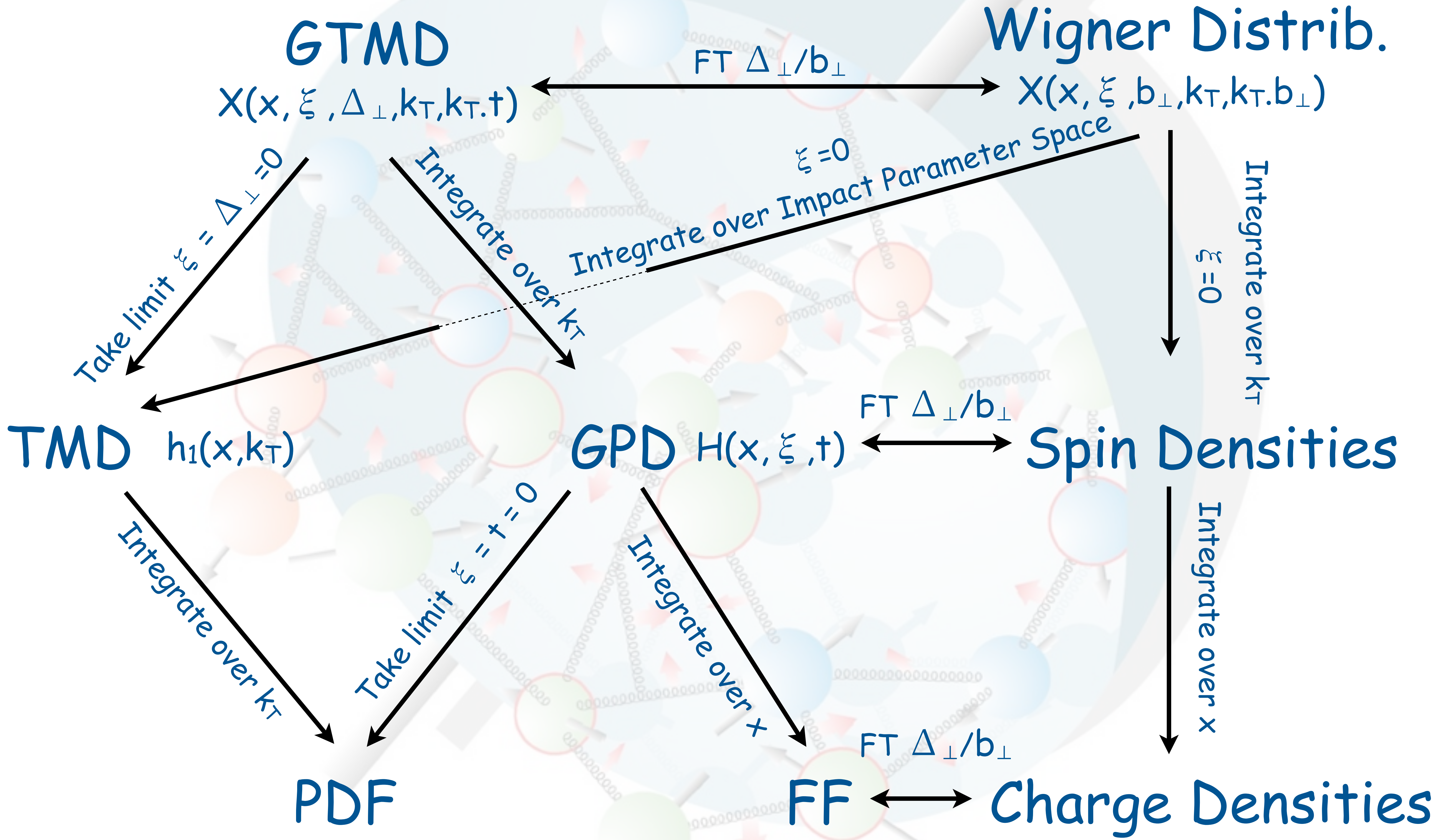
The Proton:



… it's representation:



[Courtesy of M. Murray, Glasgow]

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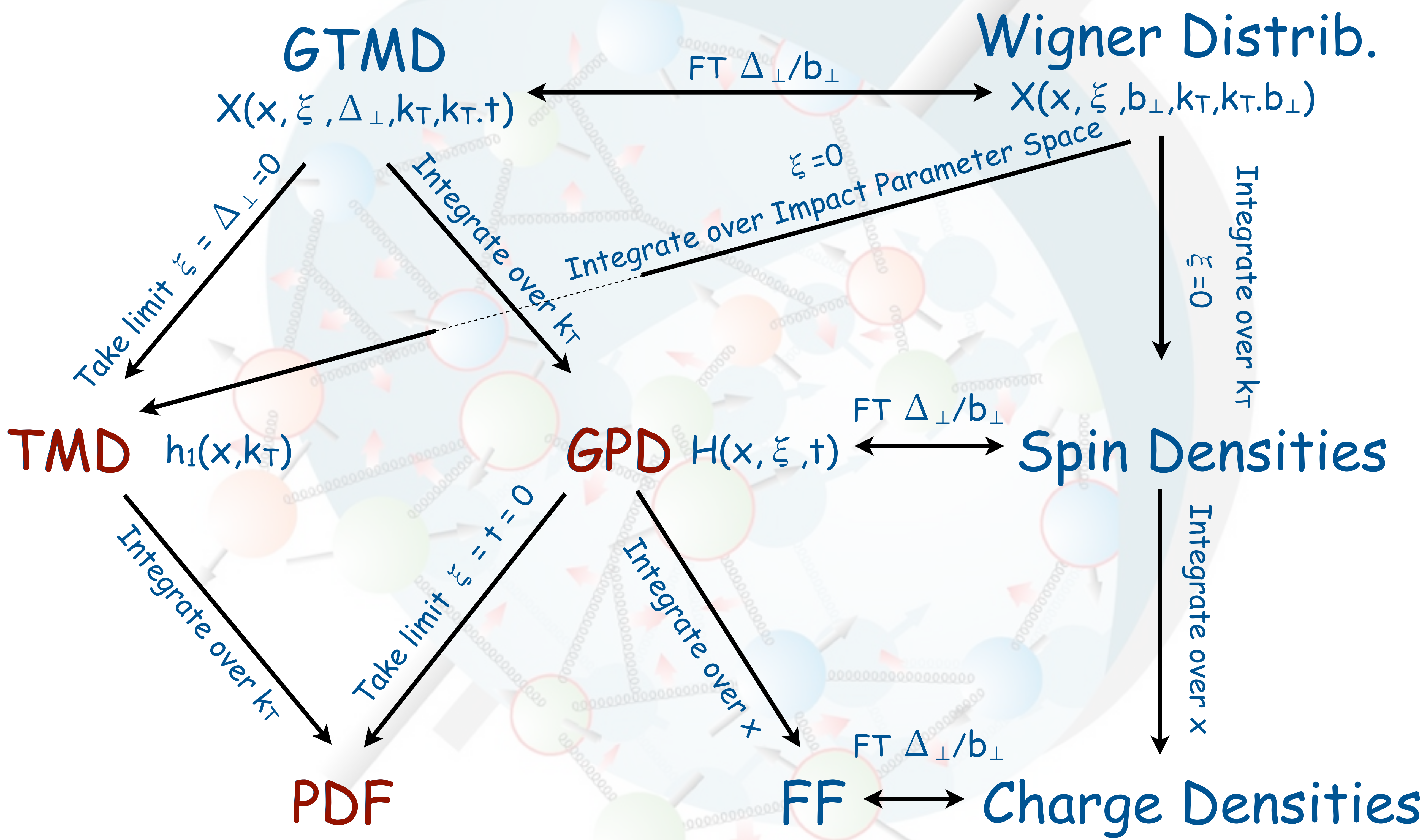
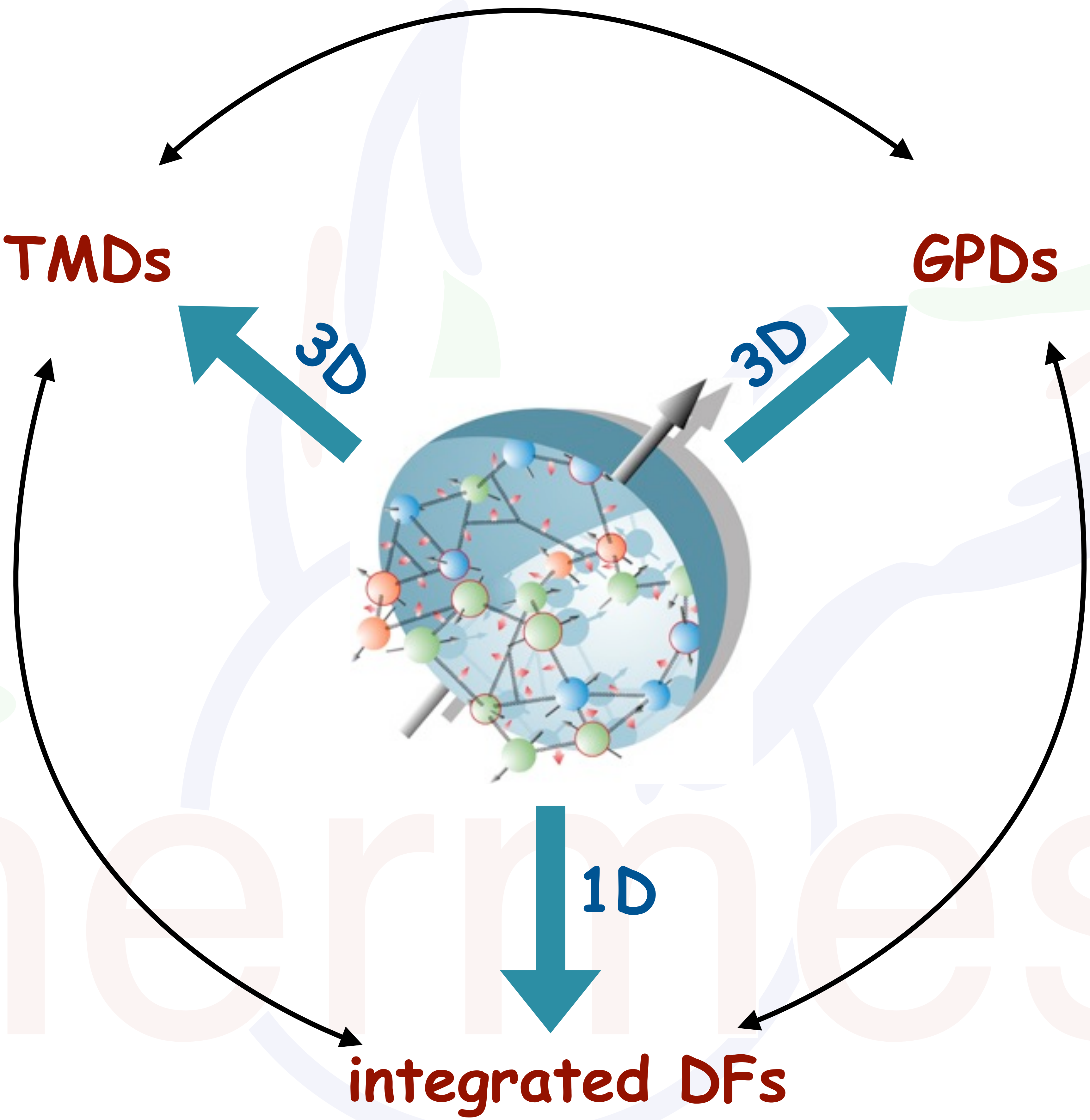
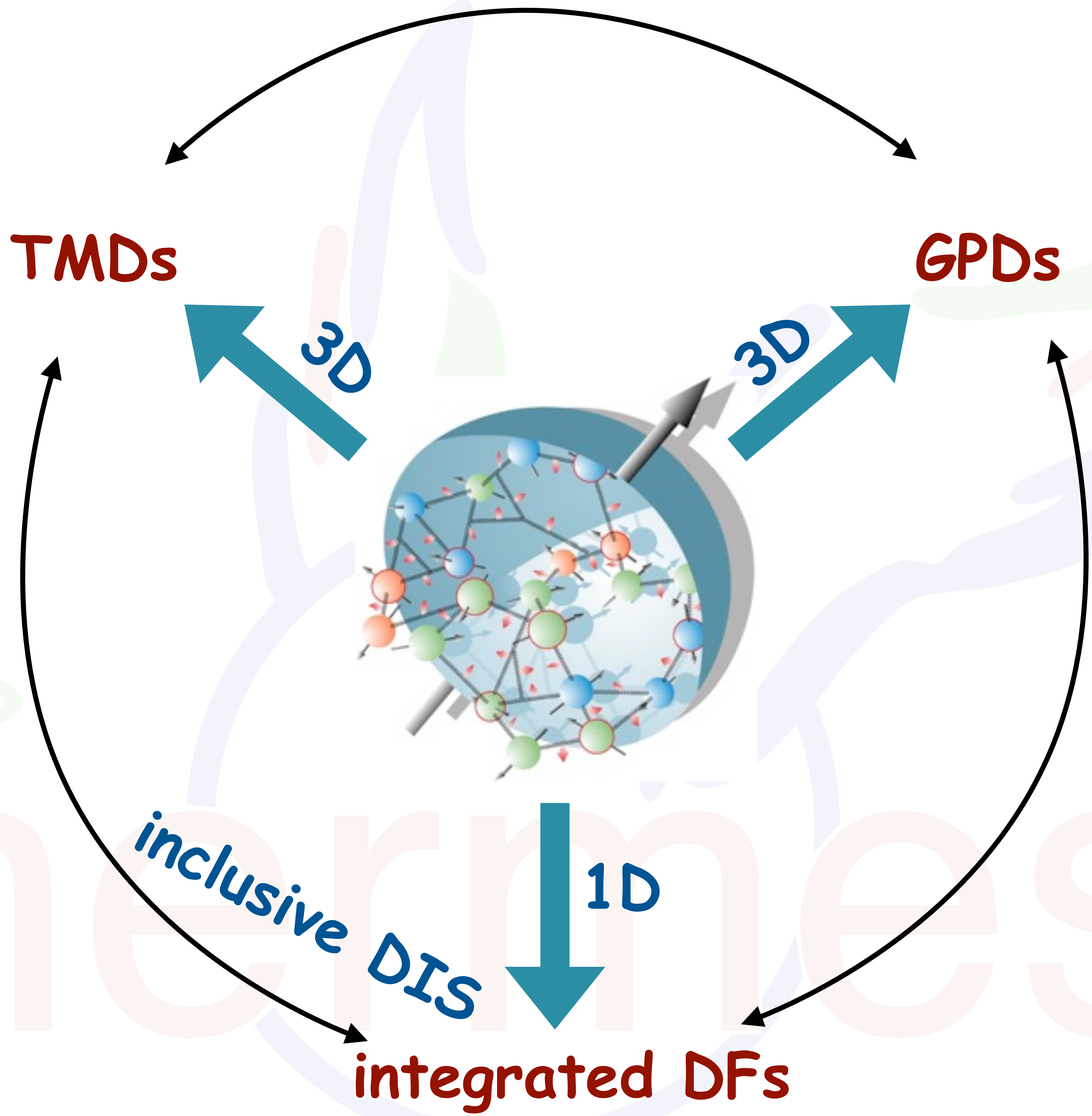
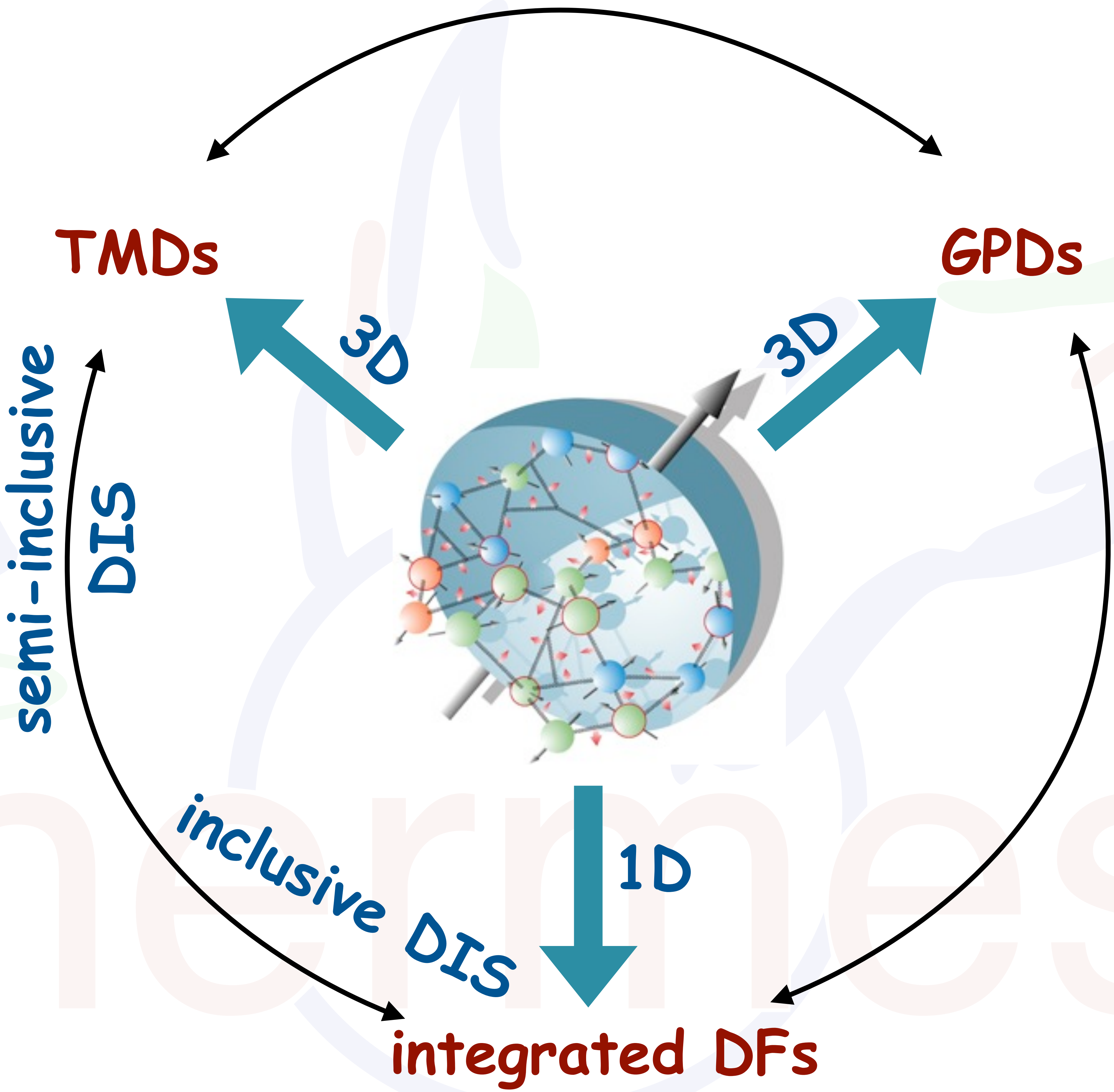
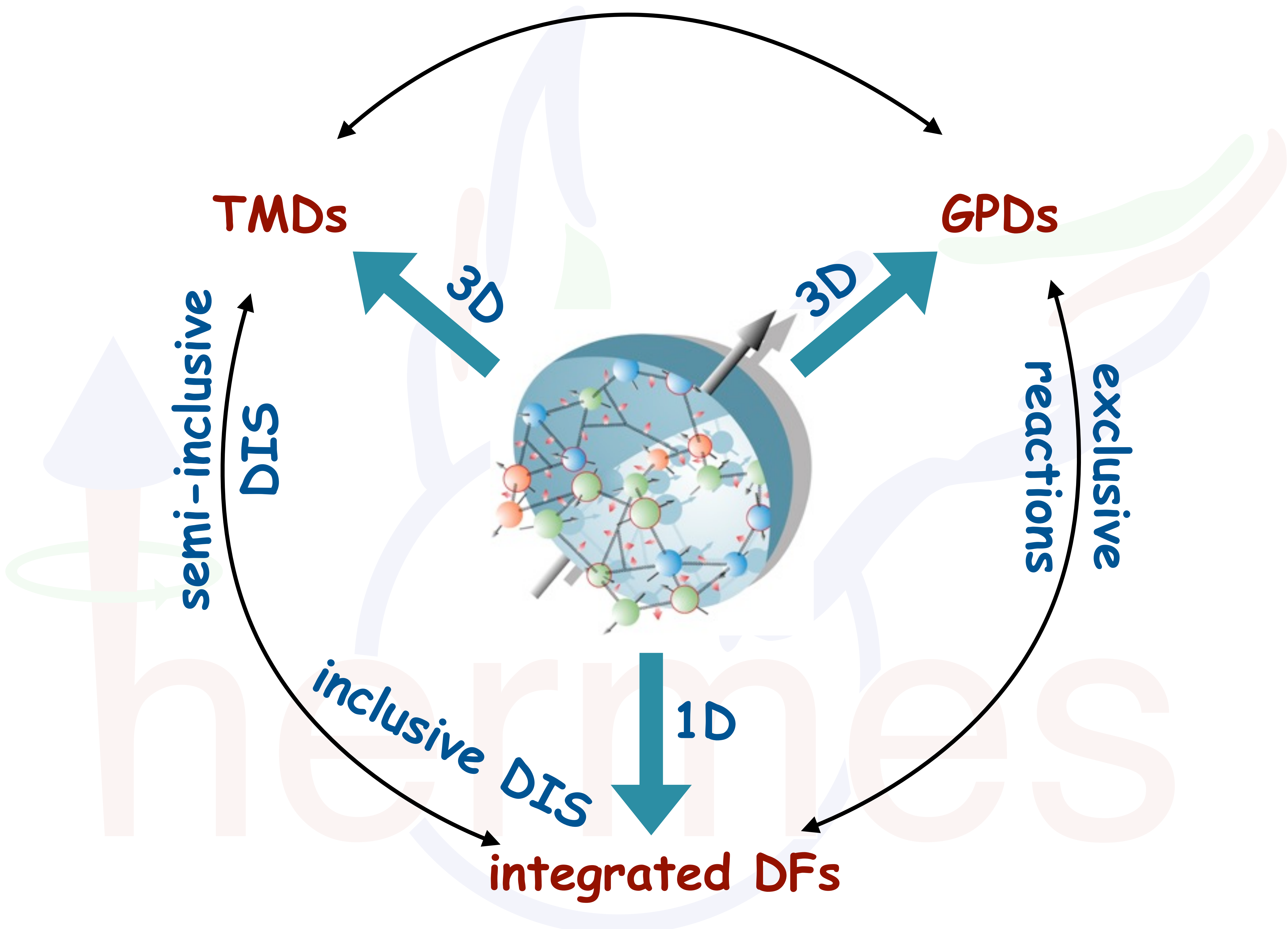


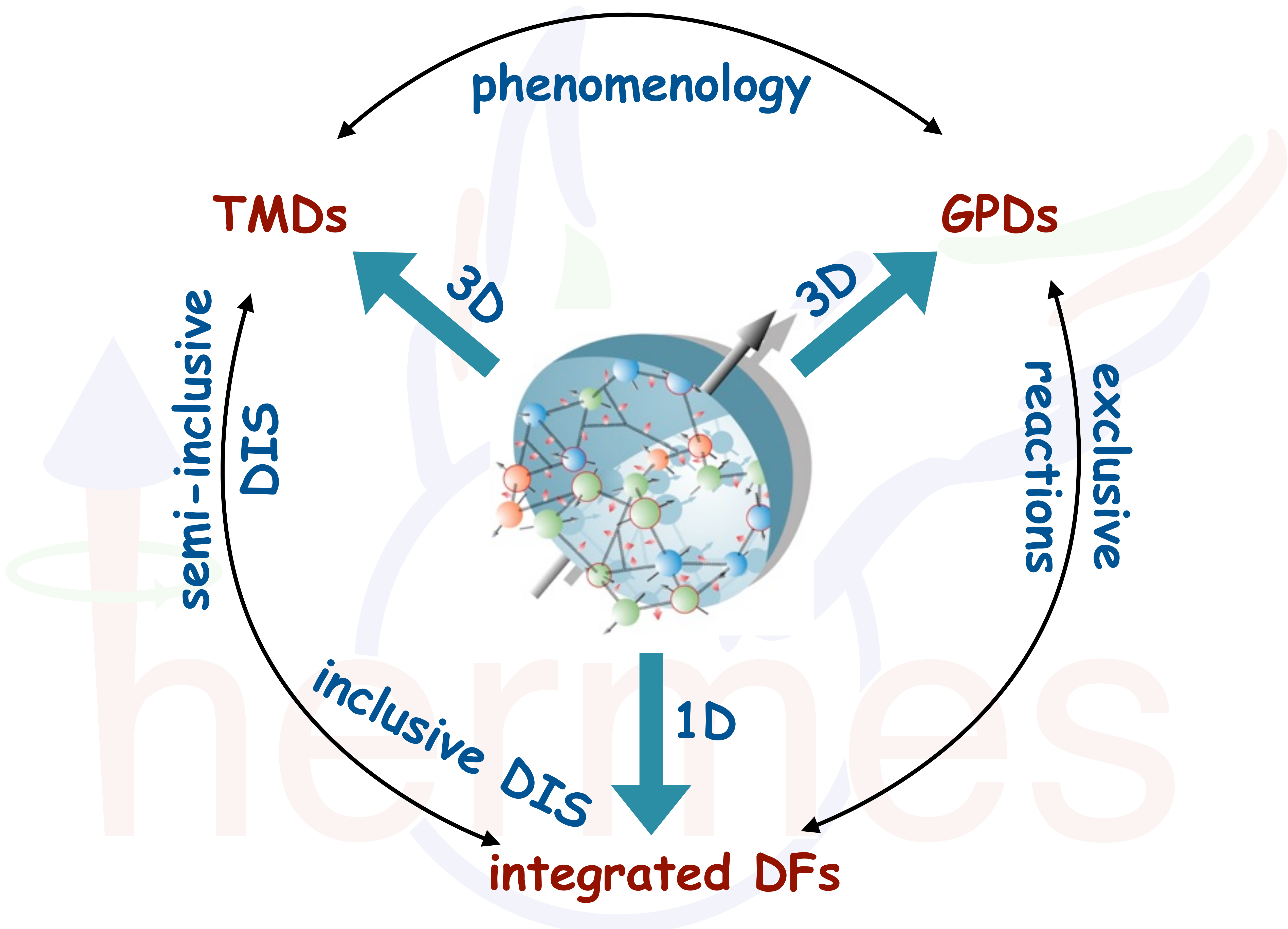
[Courtesy of M. Murray, Glasgow]


TMDs
GPDs
3D
3D
1D
integrated DFs


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


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


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

The HERMES Exp. (°1995, †2007)

Targets: Unpolarized H, D, nuclei

Longitudinally polarized H, D (P ~ 85 %)

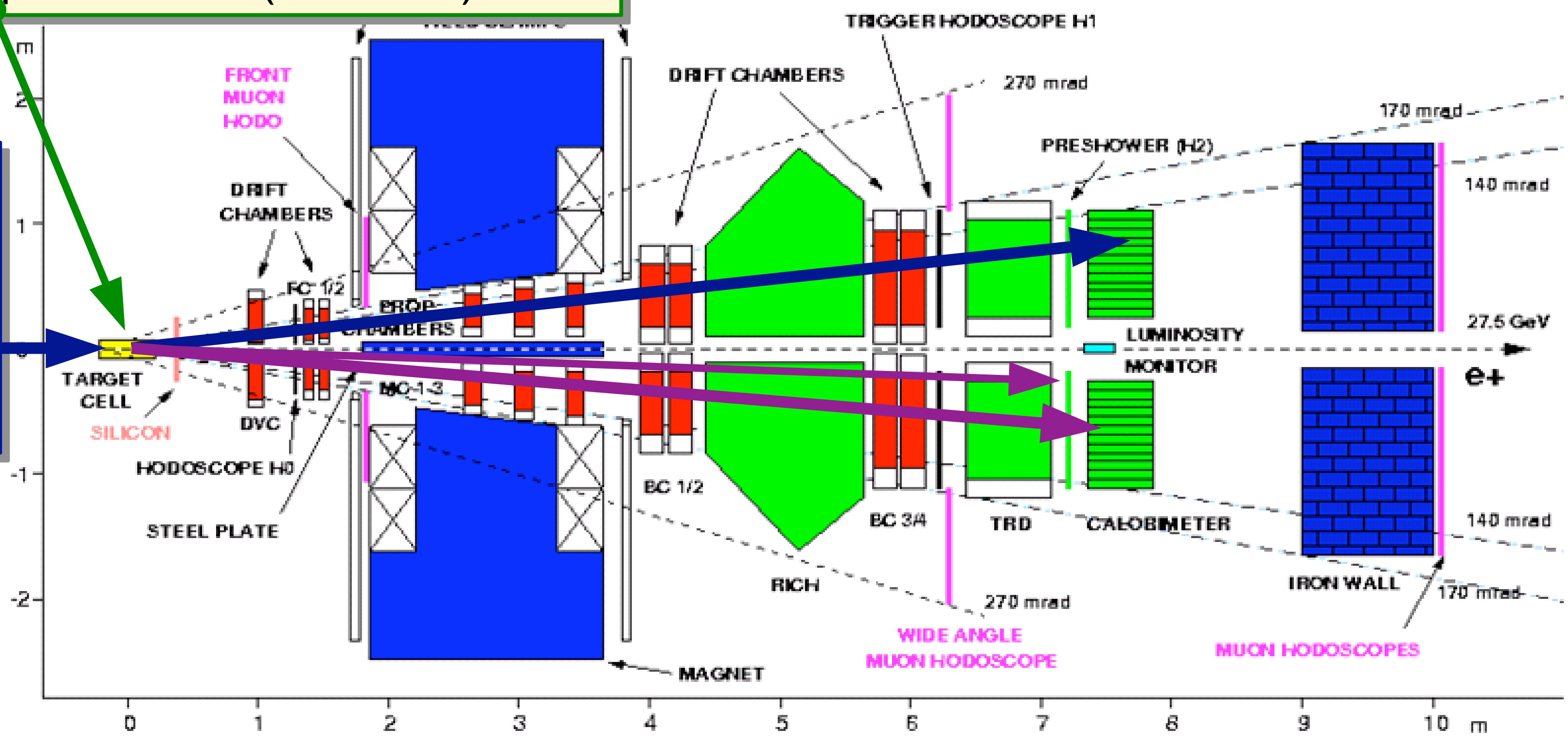
Transversely polarized H (P ~ 75%)

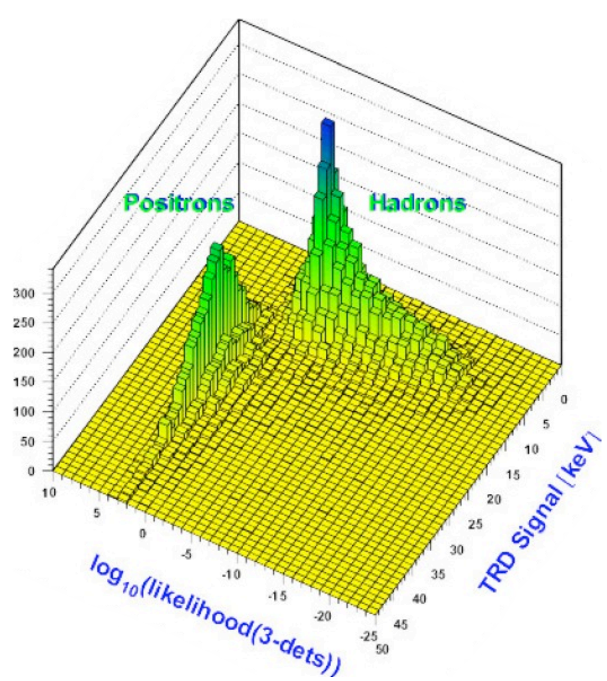
$$e + N \rightarrow e' + h + X$$

HERA: 27.6 GeV

polarized

electron/positron





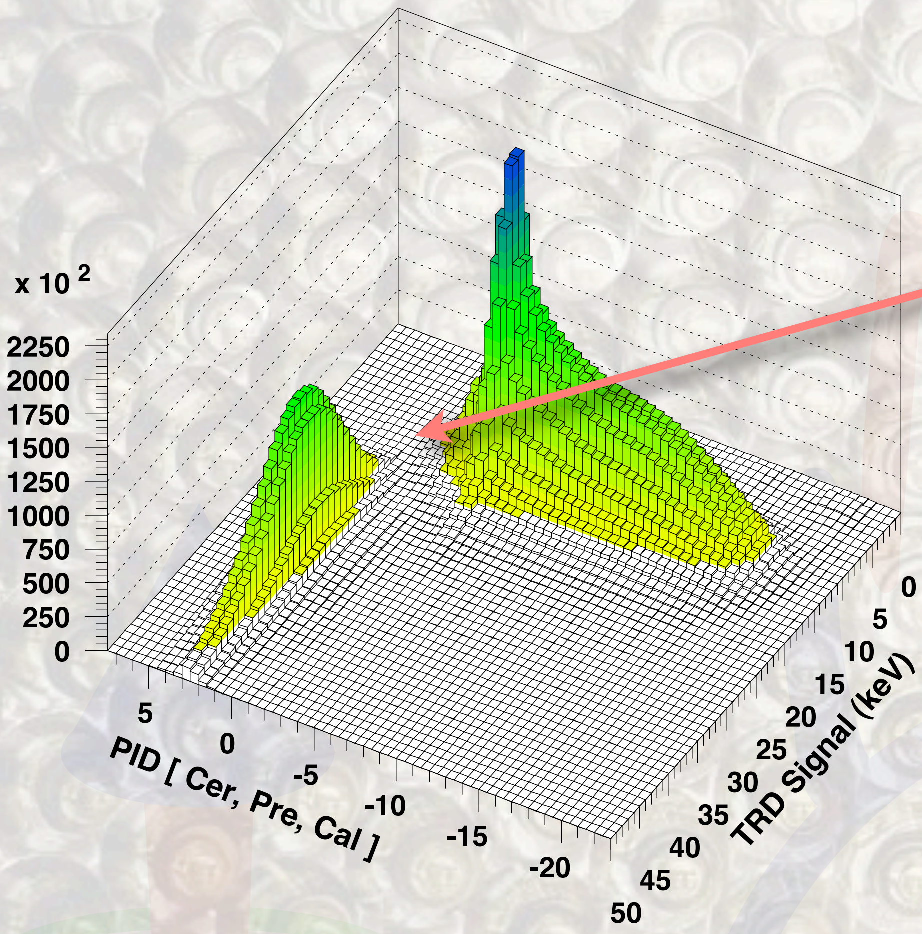
Reconstruction: Δp/p < 2%, Δθ<0.6 mrad

Lepton selection efficiency: > 99%

with hadron contamination < 1%

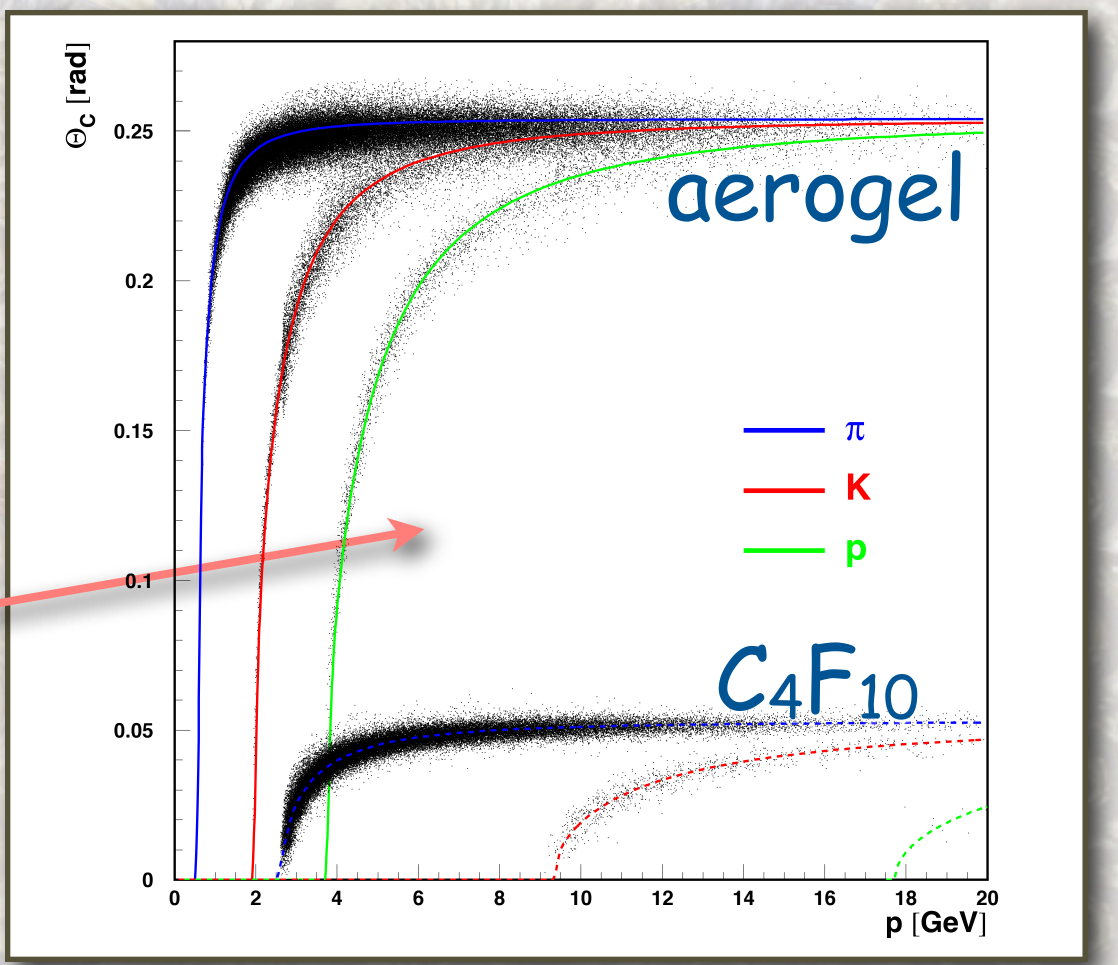
Hadron ID with RICH: π, K, p in 2 < p < 15 GeV/c

Particle Identification



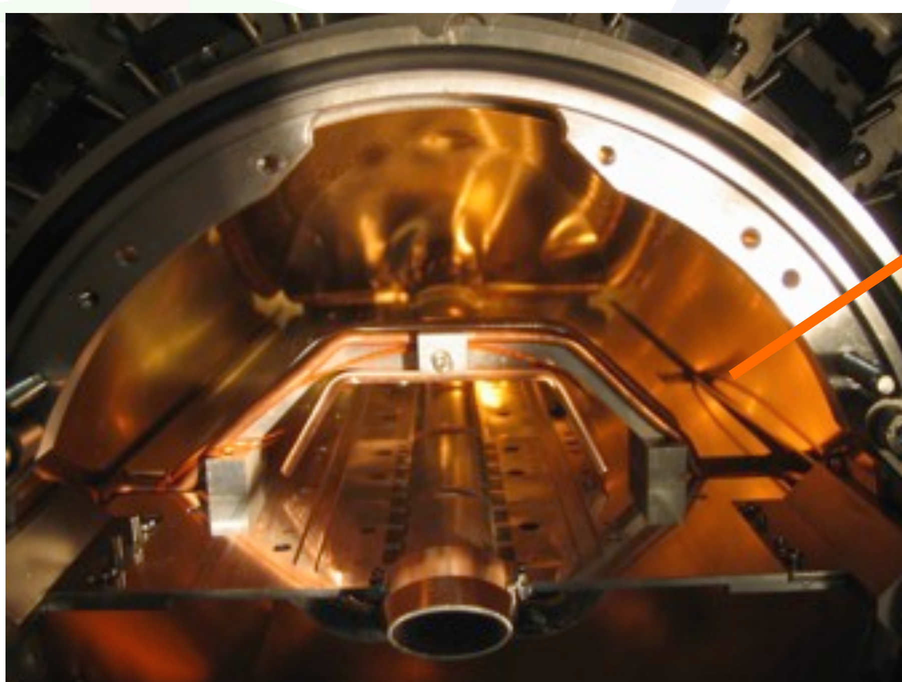
excellent lepton/hadron separation

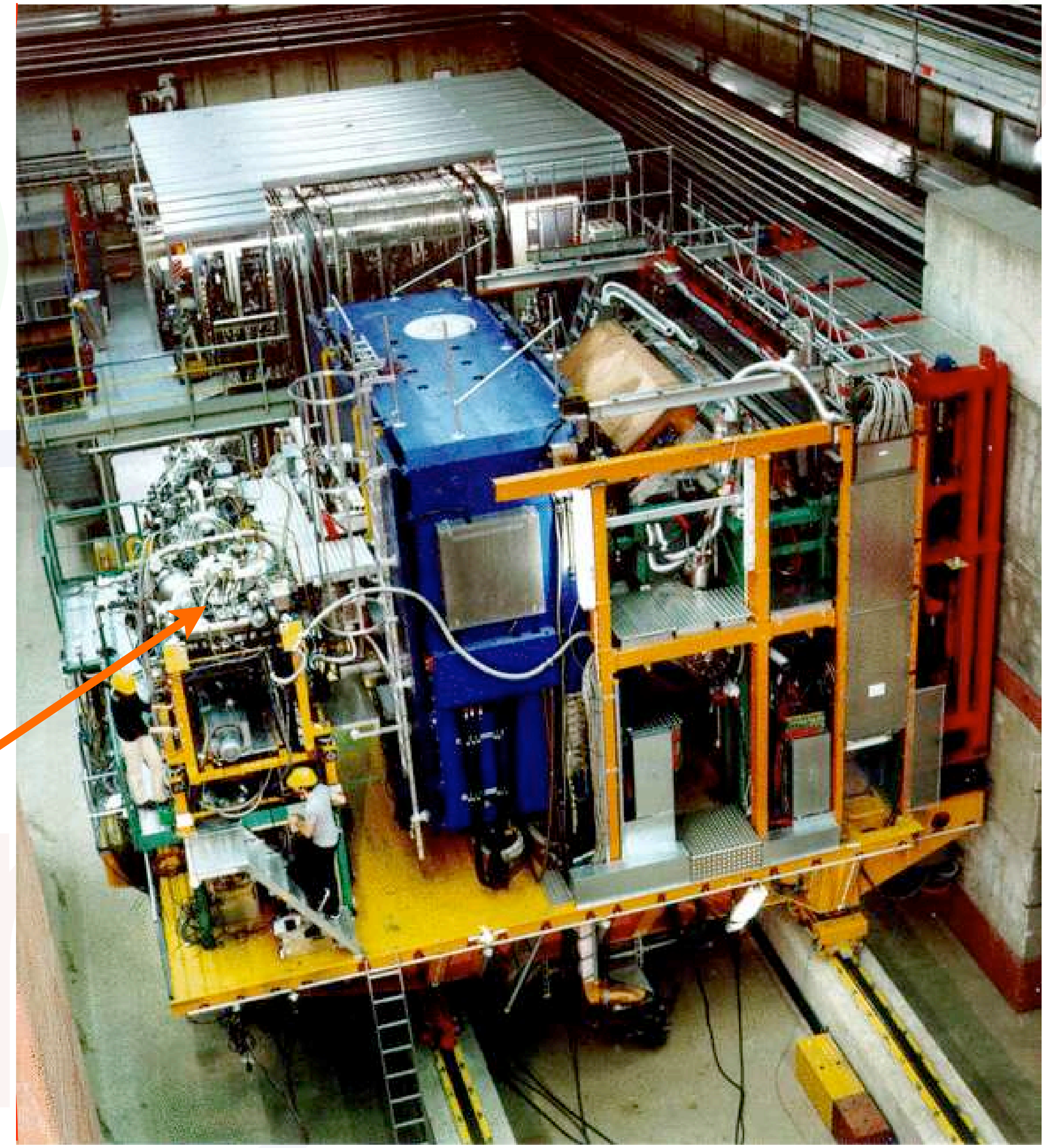
Dual-Radiator RICH hadron ID for momenta 2-15 GeV



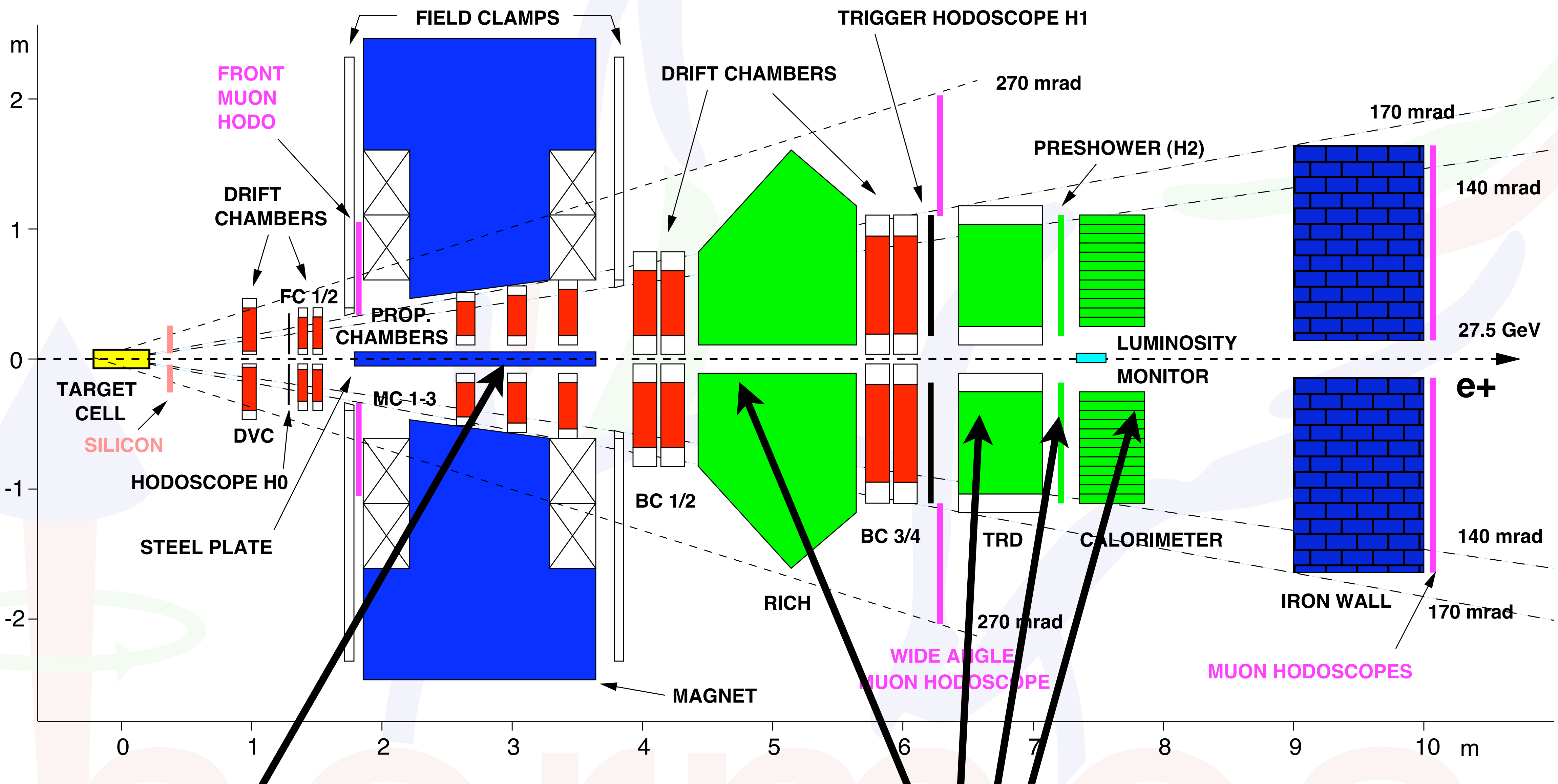
The HERMES Detector (°1995,

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





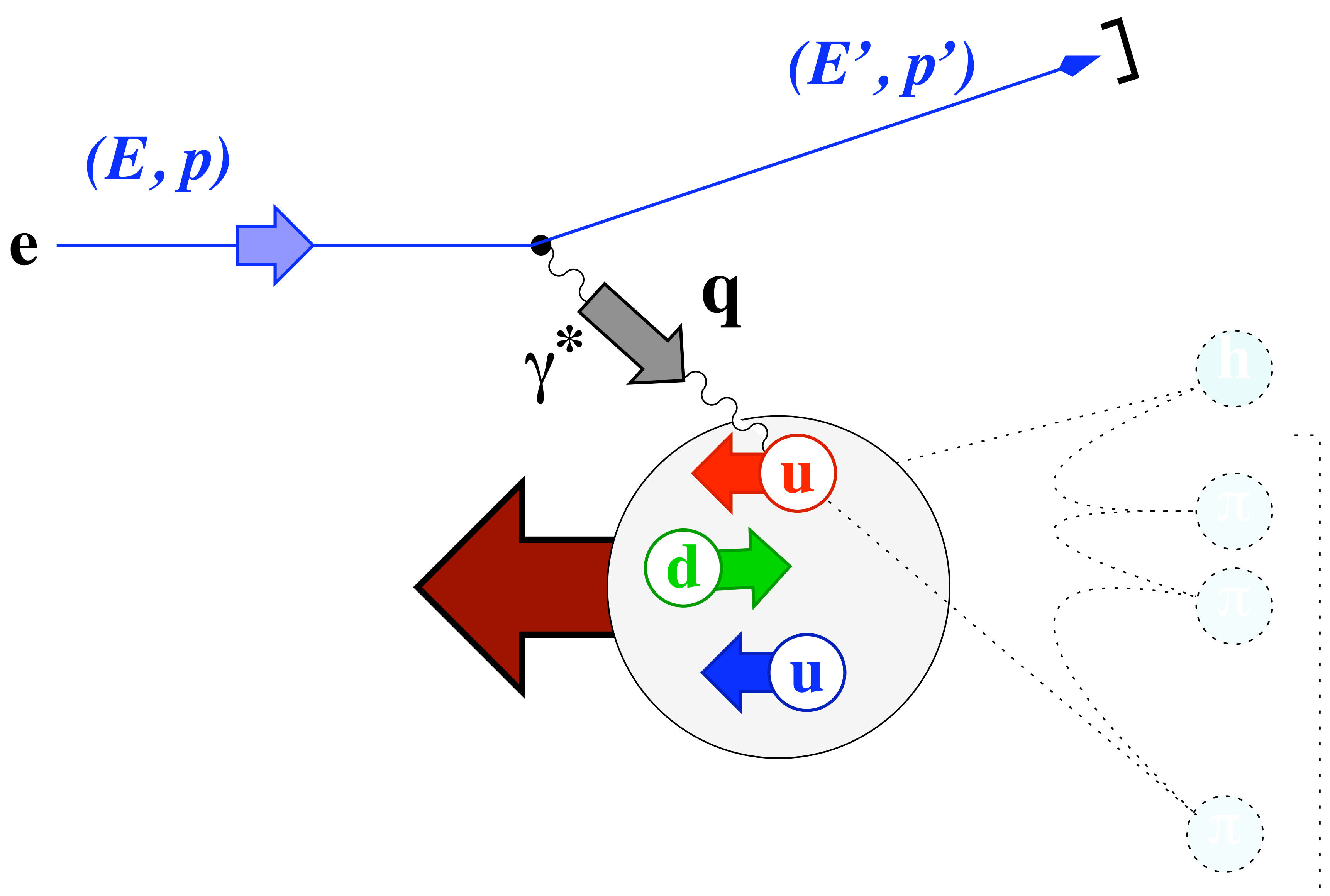
HERMES schematically



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

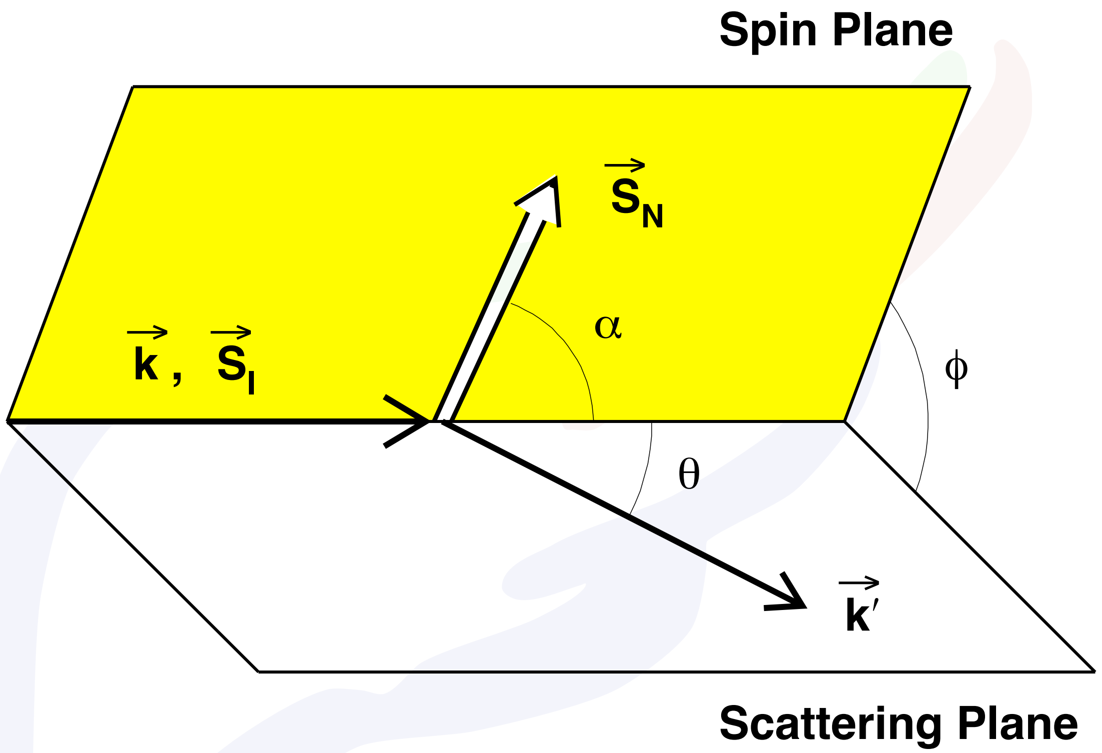
Particle ID detectors allow for
- lepton/hadron separation
- RICH: pion/kaon/proton discrimination 2GeV<p<15GeV

Inclusive DIS



Inclusive DIS

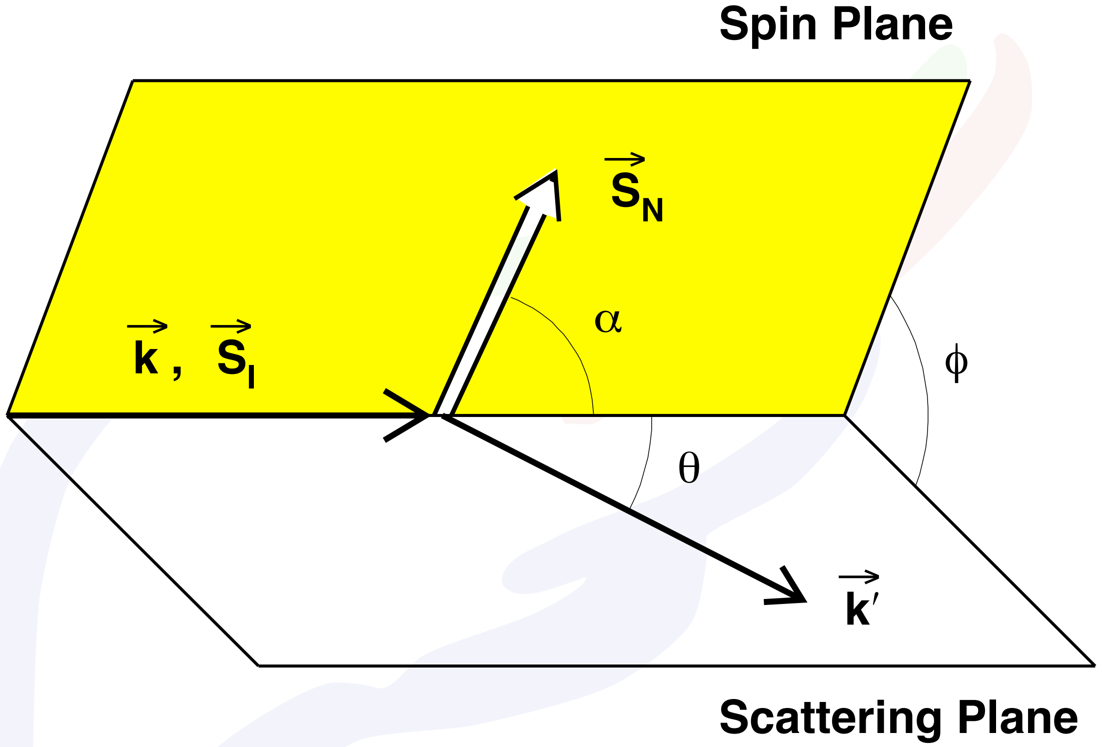
$$\frac{\mathrm{d}^2\sigma(s,S)}{\mathrm{d}x\ \mathrm{d}Q^2} = \frac{2\pi\alpha^2 y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$



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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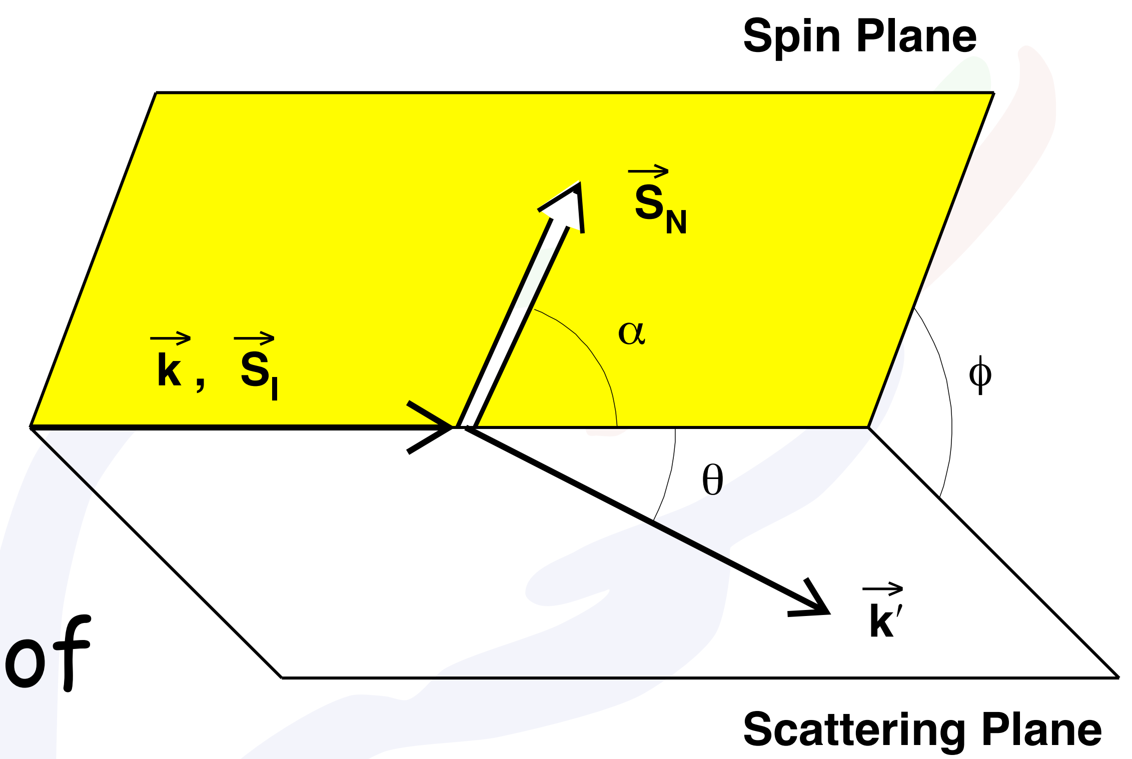
Lepton Tensor

Hadron Tensor
parametrized in terms of
Structure Functions



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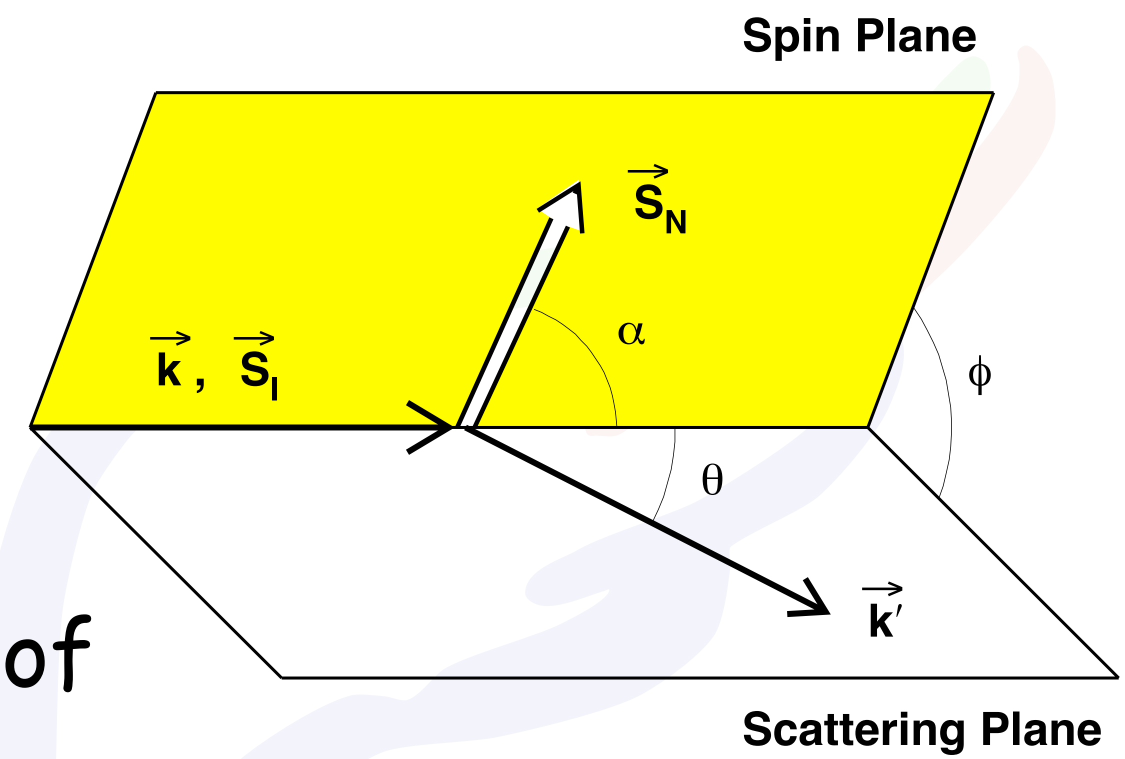


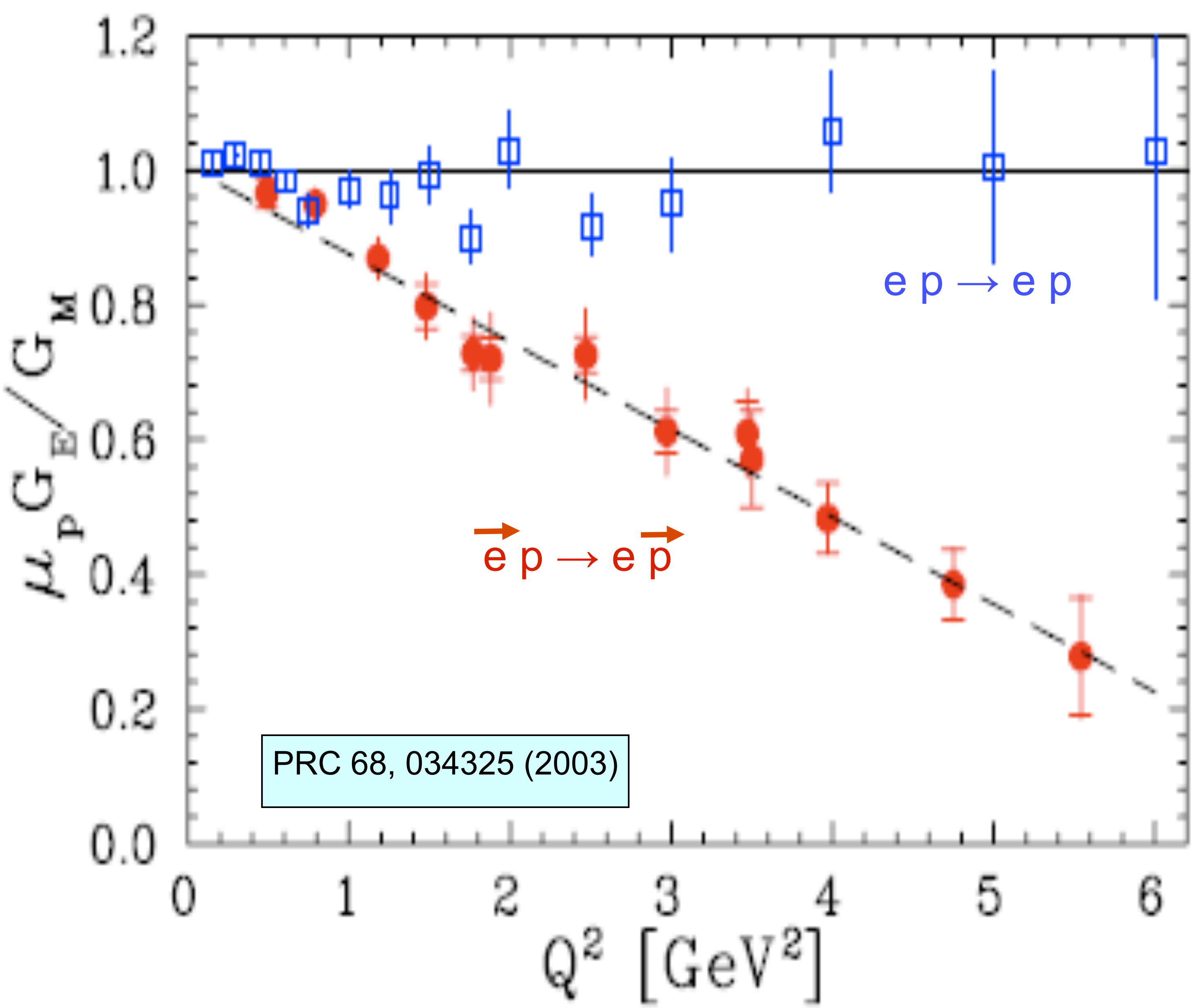
$$\frac{d^3\sigma}{dx\,dy\,d\phi} \propto \frac{y}{2}\boxed{F_1(x,Q^2)} + \frac{1-y-\gamma^2y^2/4}{2xy}\boxed{F_2(x,Q^2)}$$

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

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

Check the details!

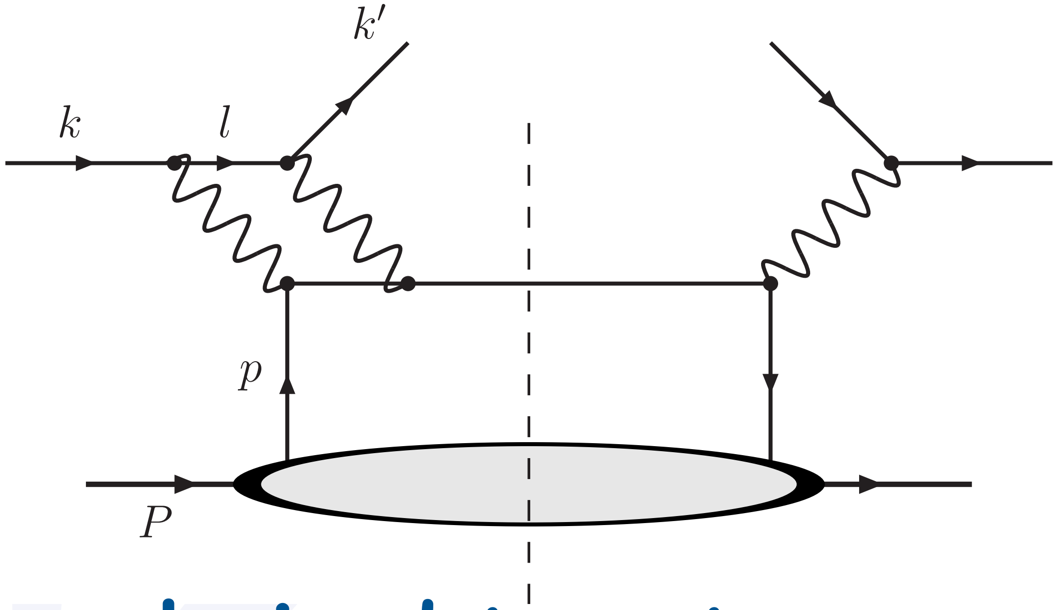
Check the details!



☛ **two-photon exchange important?!**

Two-photon exchange

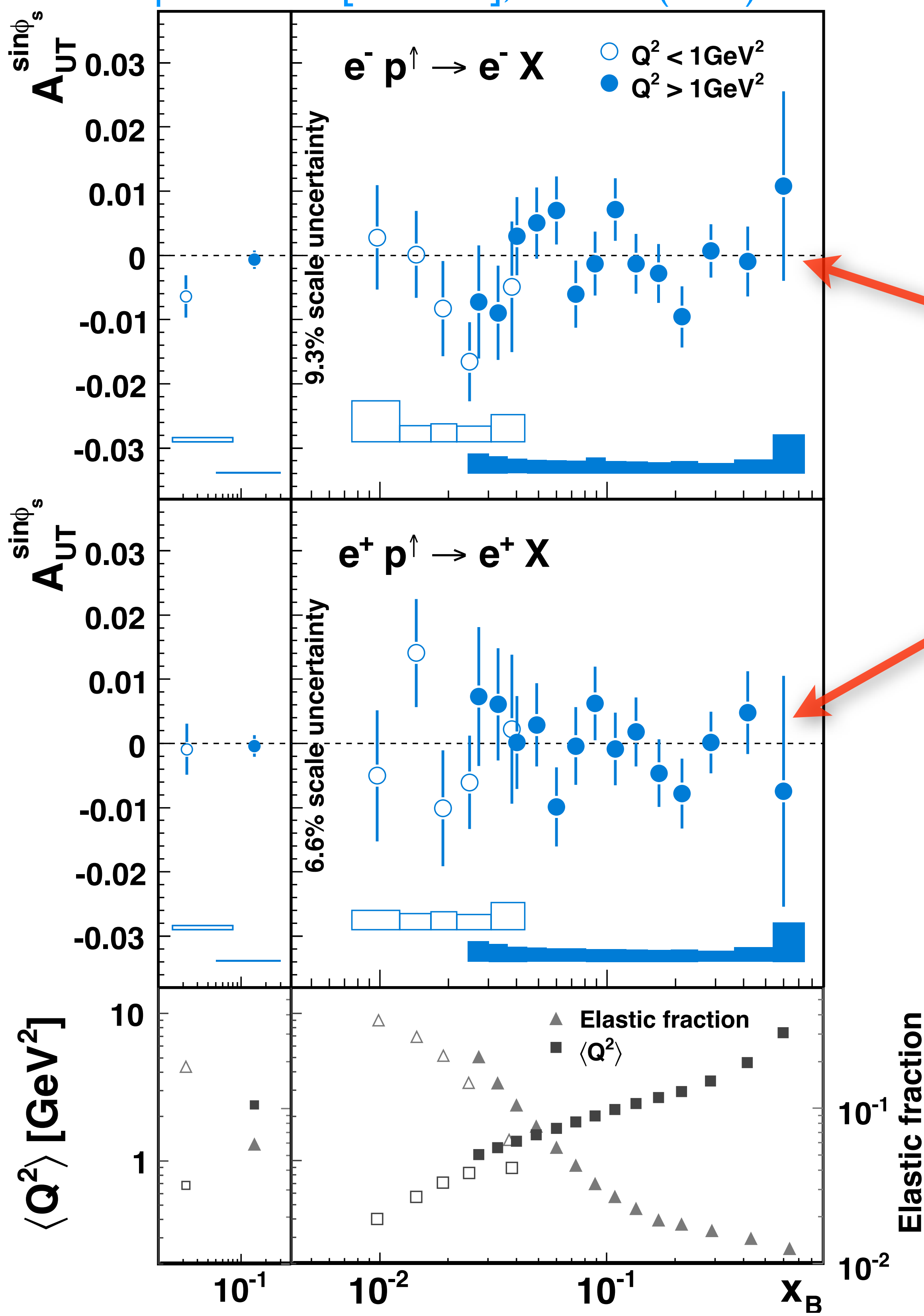
- Candidate to explain discrepancy in form-factor measurements
- Interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets



- 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

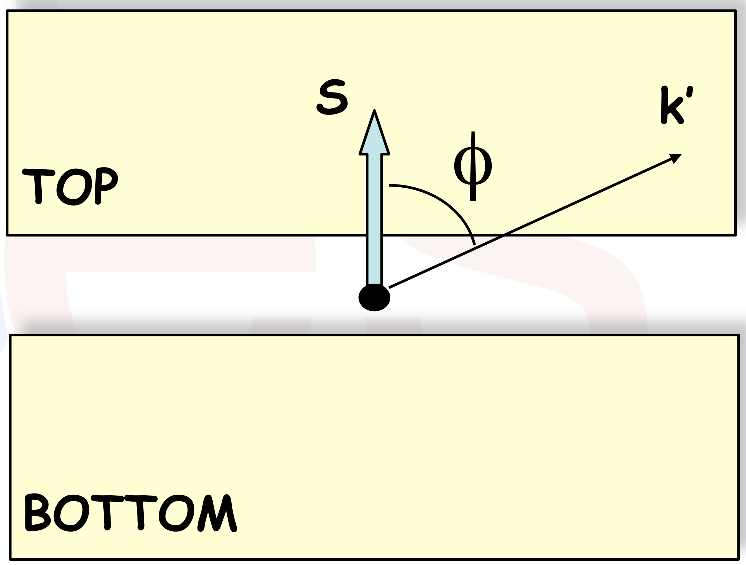
No sign of two-photon exchange

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

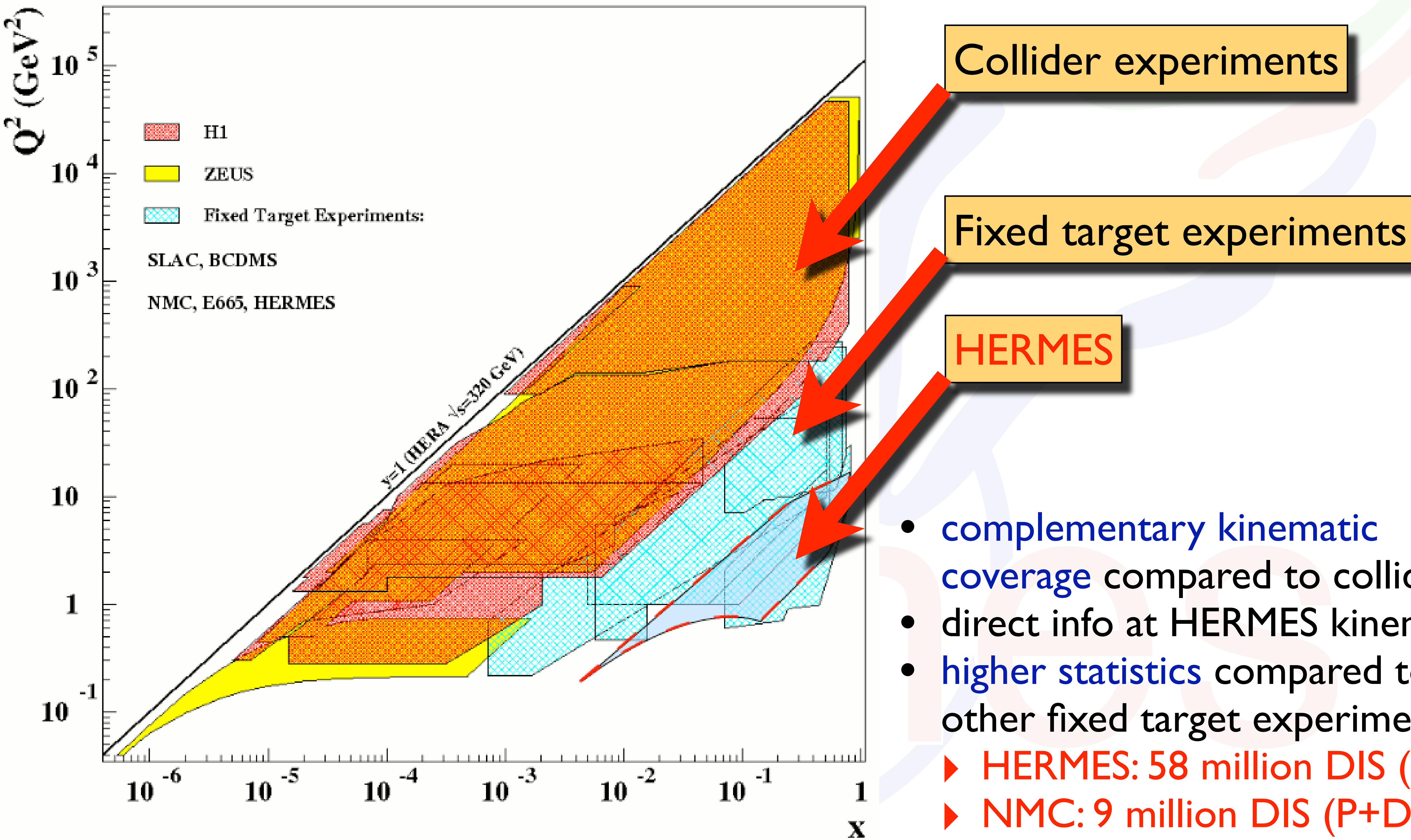


consistent with zero

Front view of HERMES detector

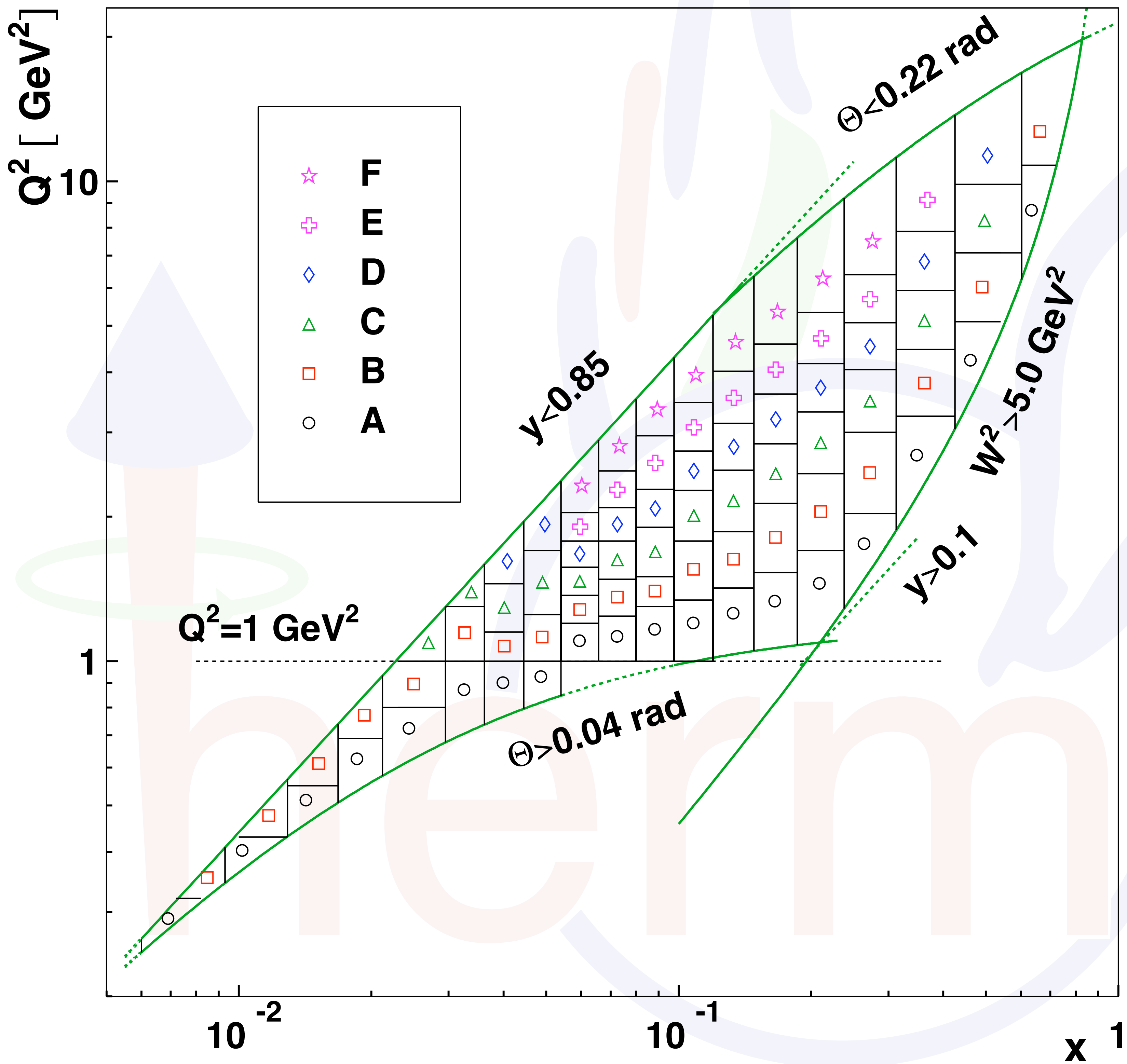


Why measure F_2 at HERMES?



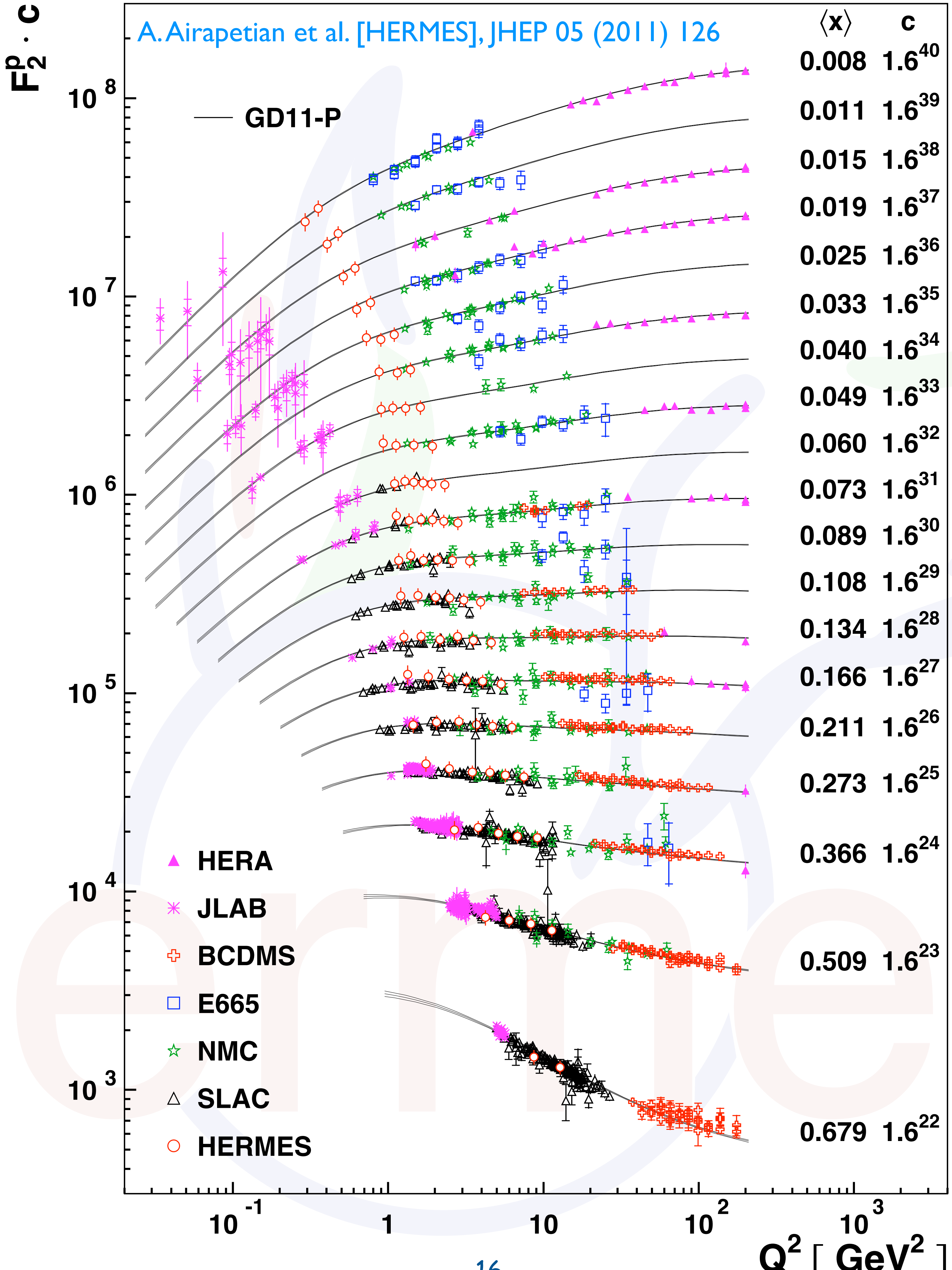
- complementary kinematic coverage compared to colliders
- direct info at HERMES kinematics
- higher statistics compared to other fixed target experiments:
  - HERMES: 58 million DIS (P+D)
  - NMC: 9 million DIS (P+D)

HERMES kinematic plane



binning used for F_2 and g_1

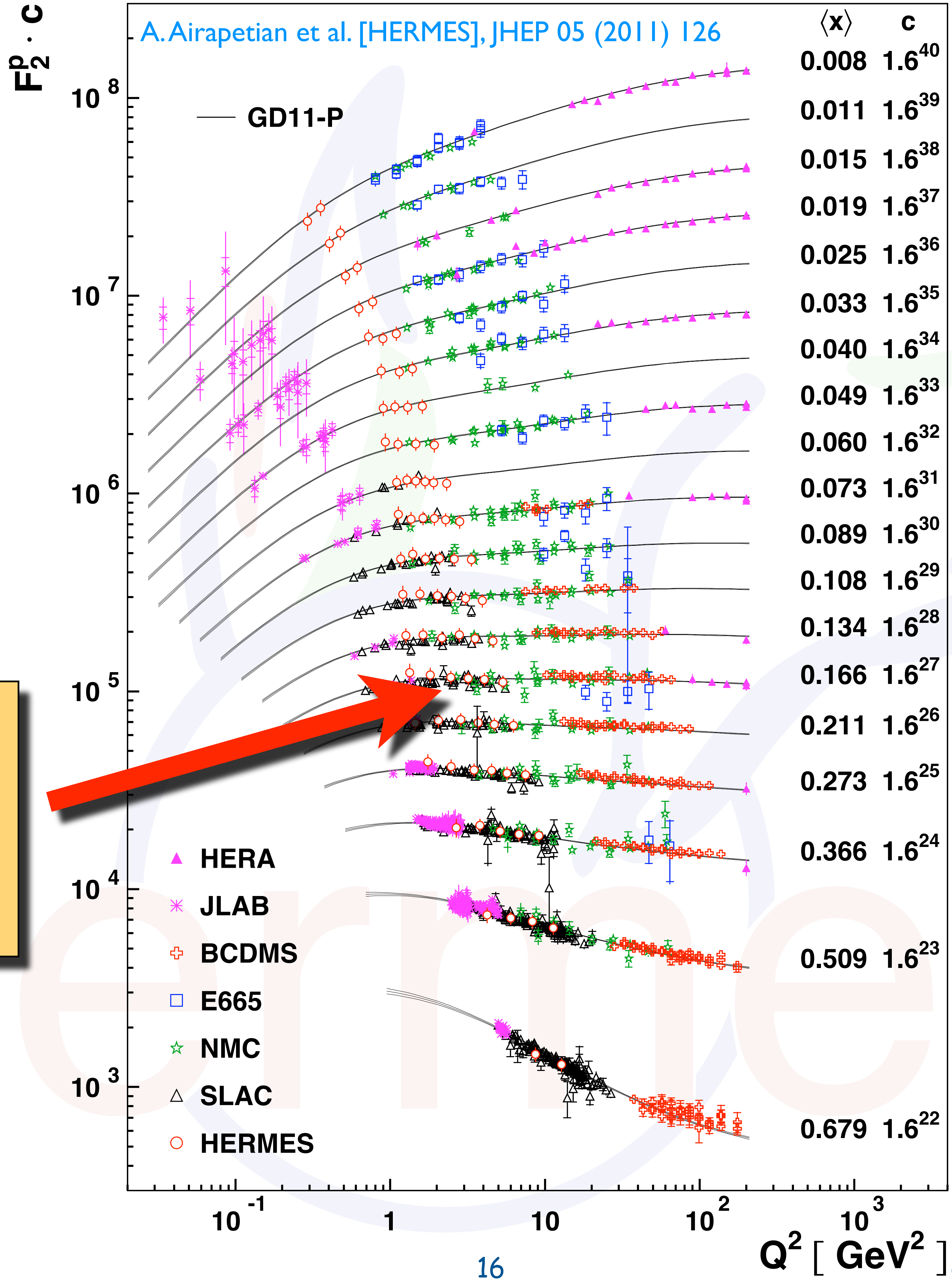
F_2 proton



GD11 - global fit

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

F_2 proton



Agreement with world data in the overlap region

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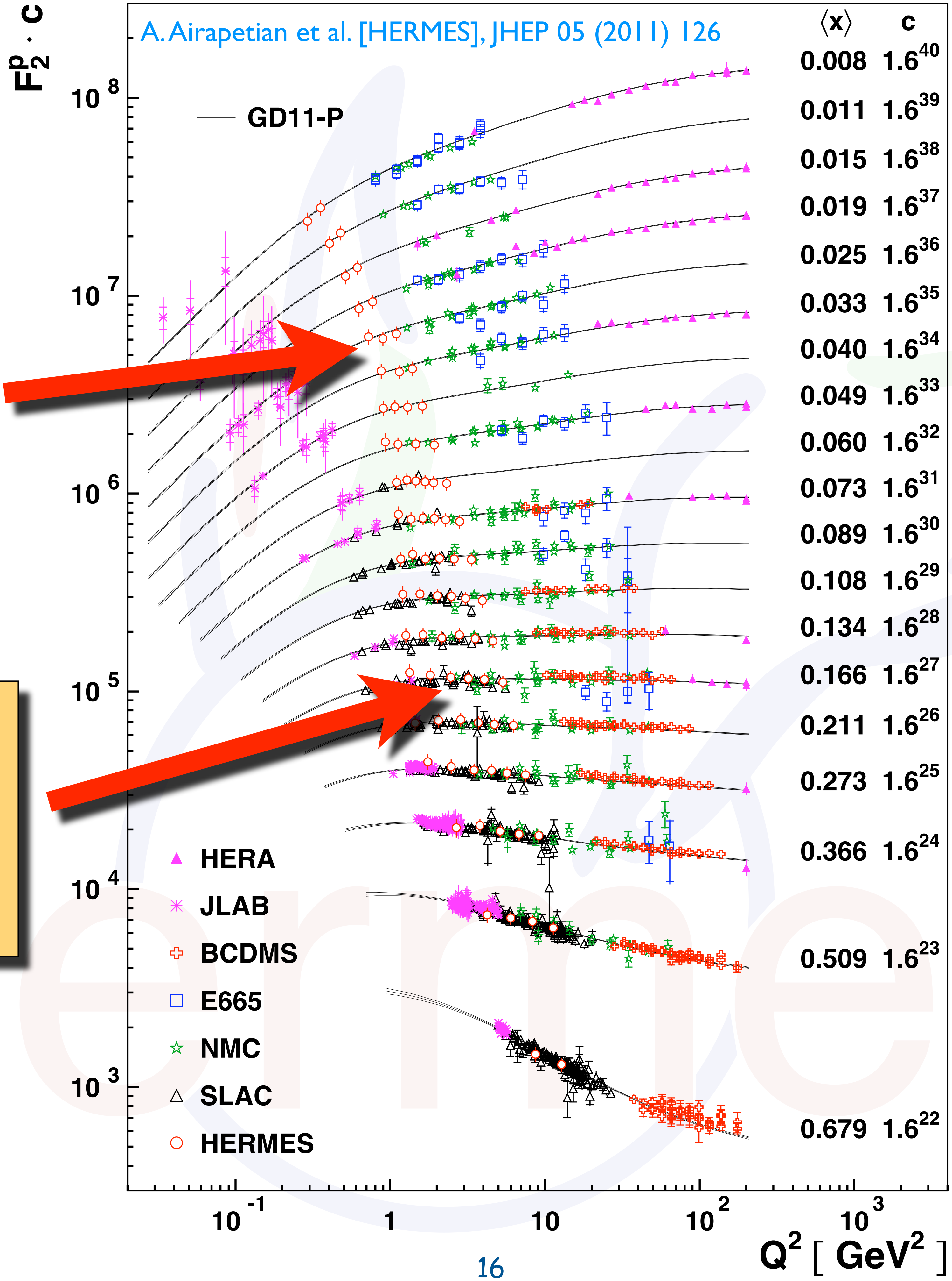
New region covered by HERMES



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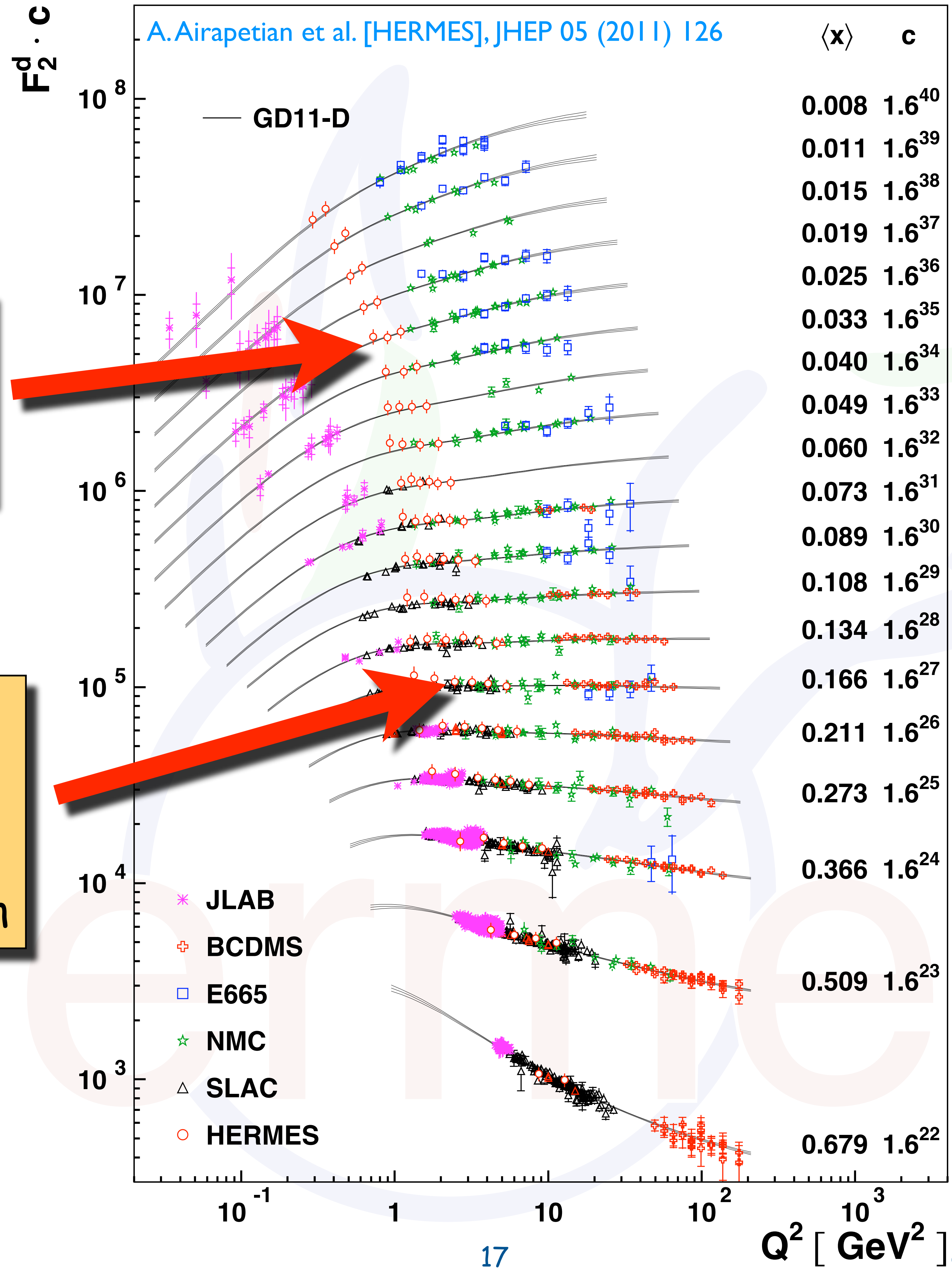

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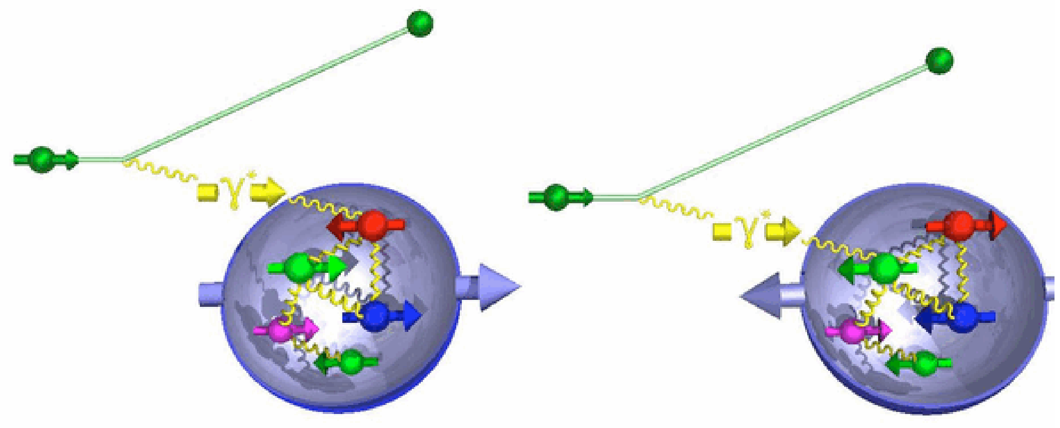
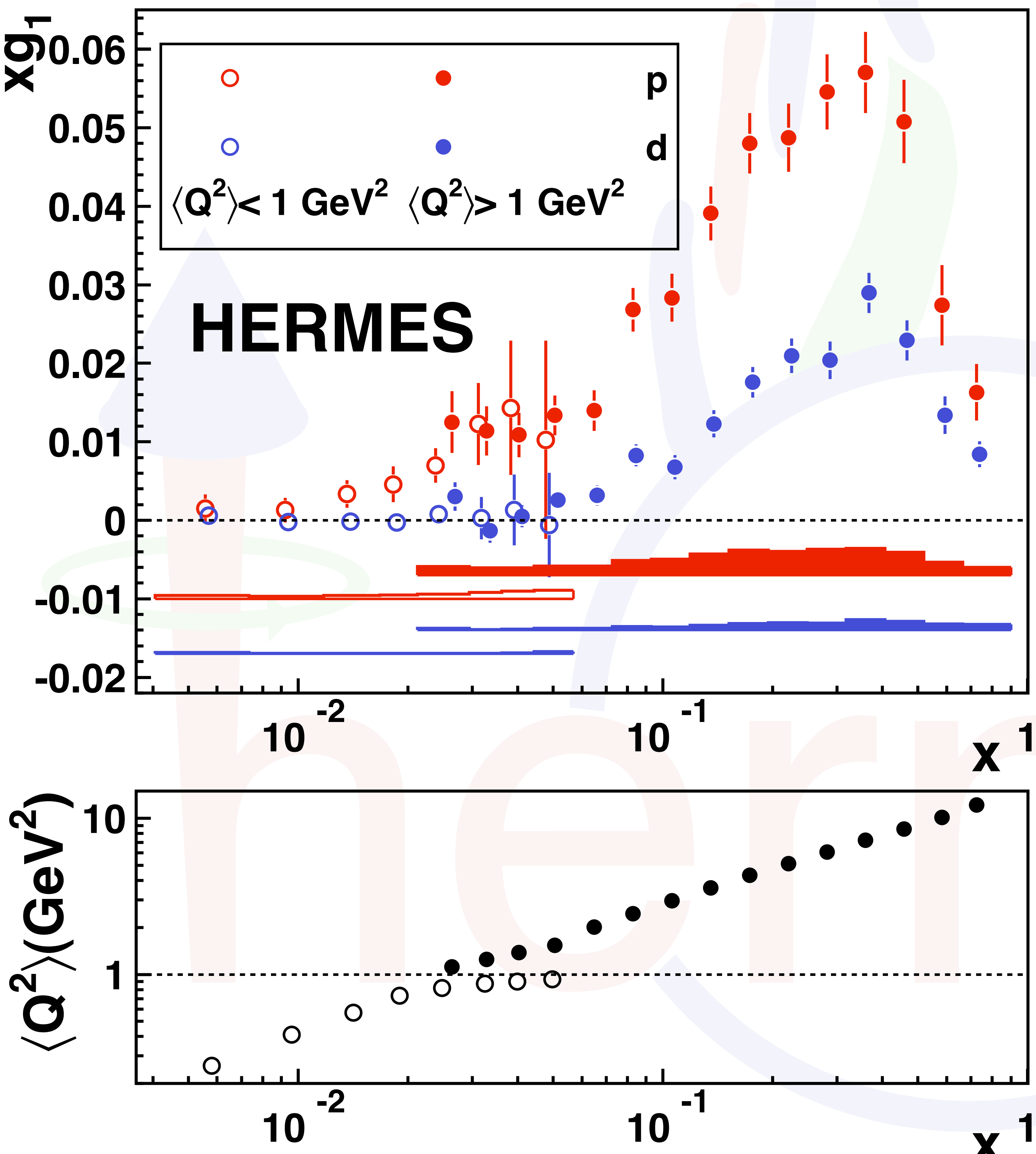
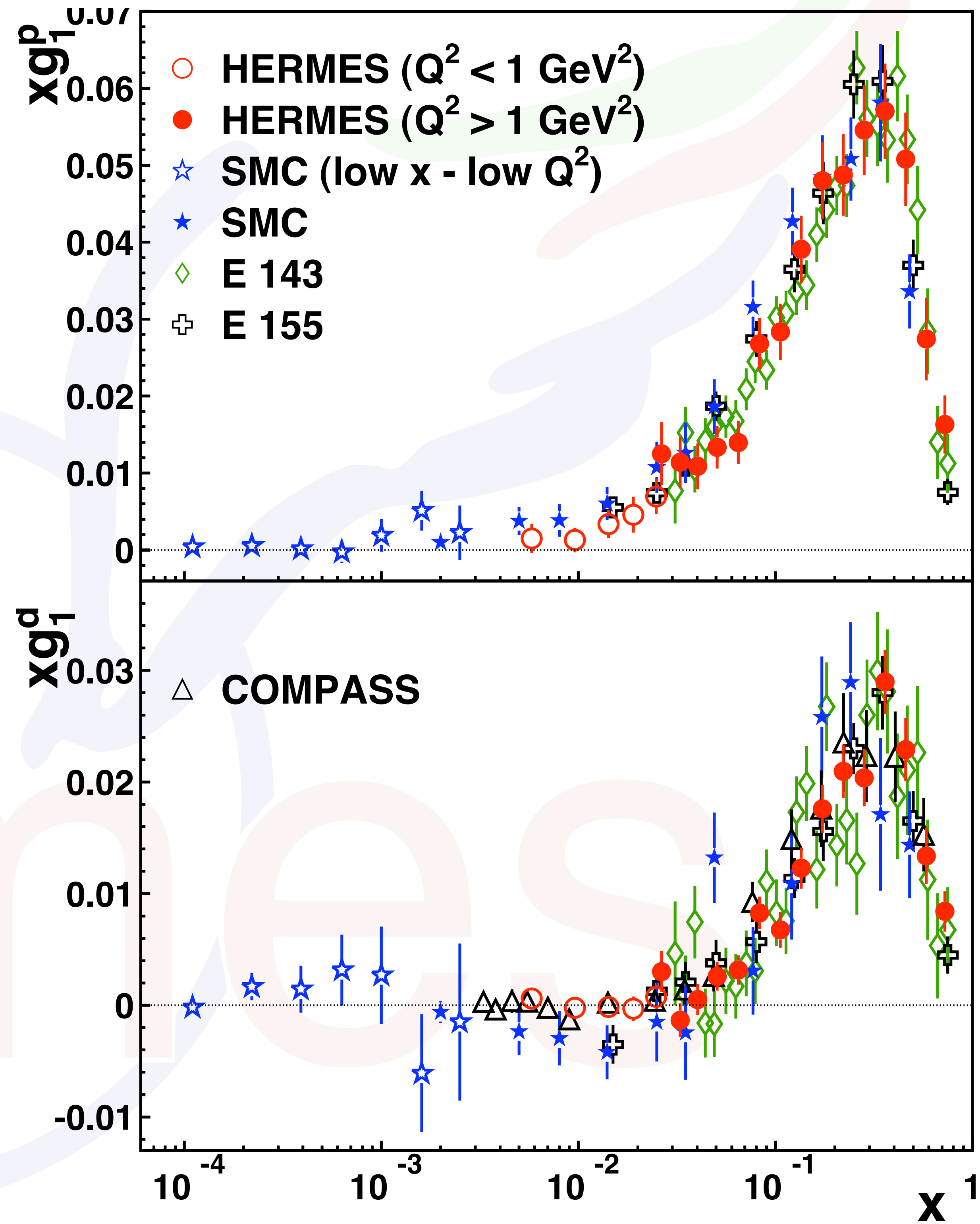
Polarized SF g_1



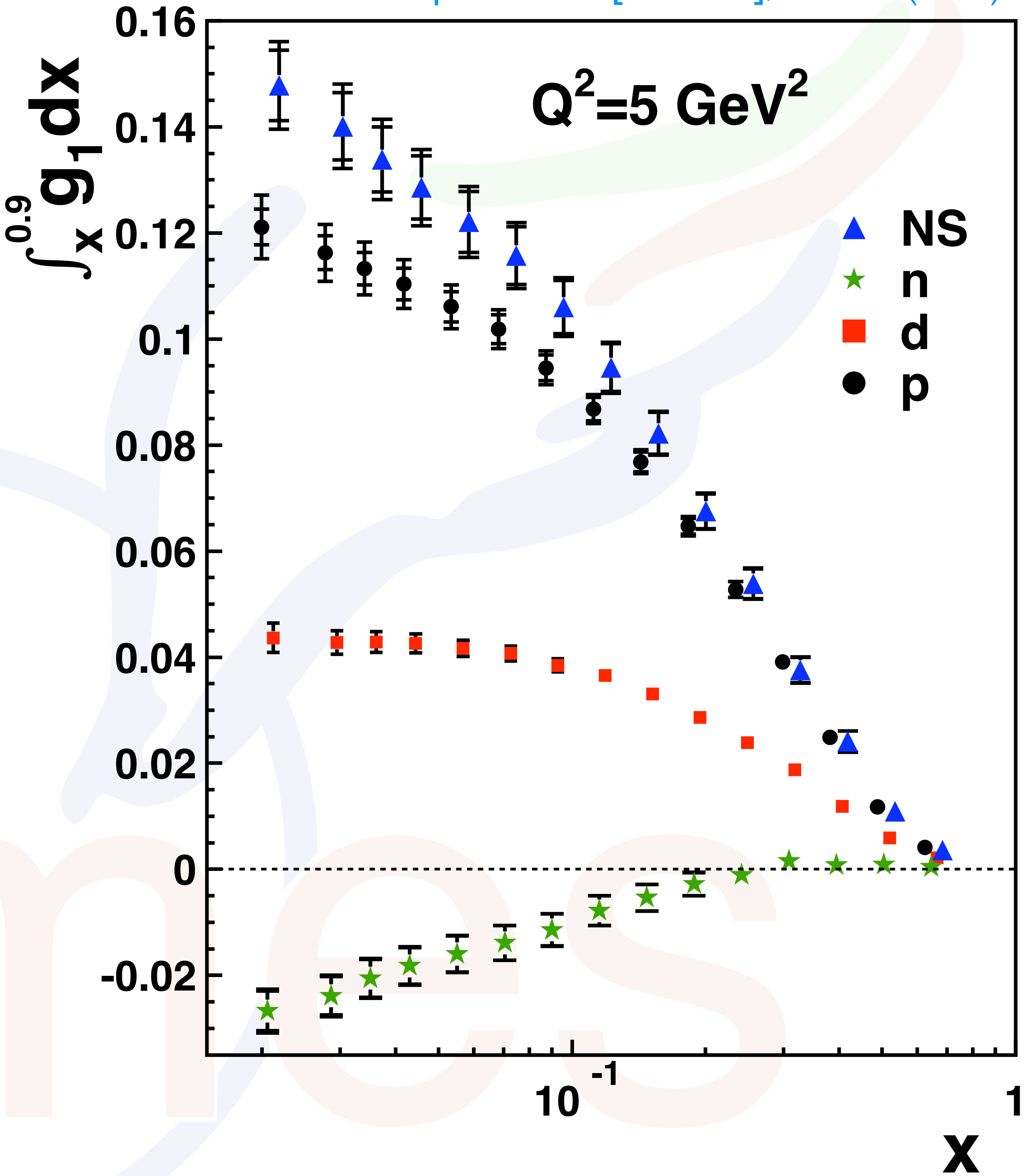


A. Airapetian et al. [HERMES], PRD 75 (2007)



Integral of $g_1(x)$

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



Integral of $g_1(x)$

Saturation

➟ **close to full integral?**

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

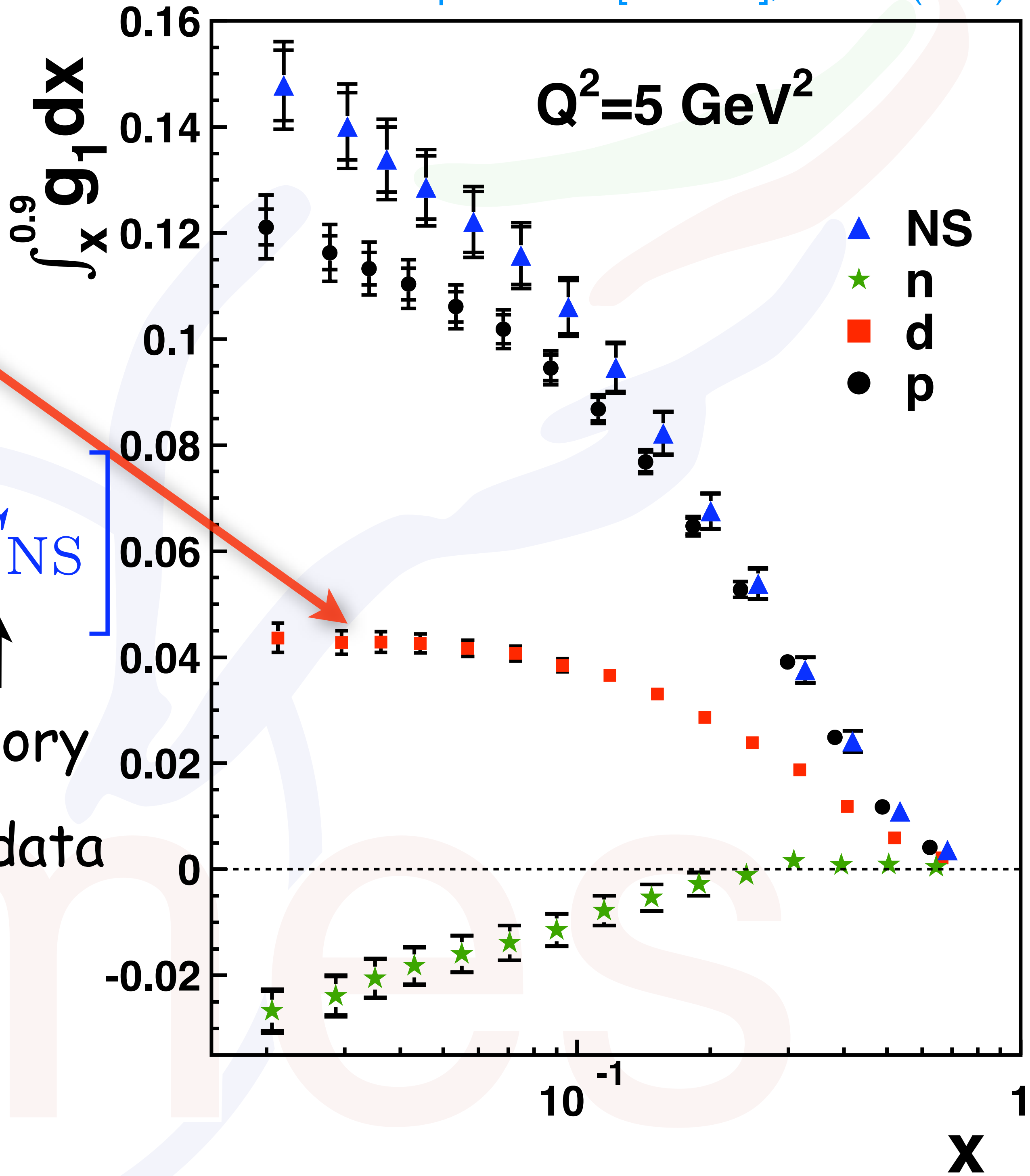
theory

0.05±0.05

hyperon-decay data

theory

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



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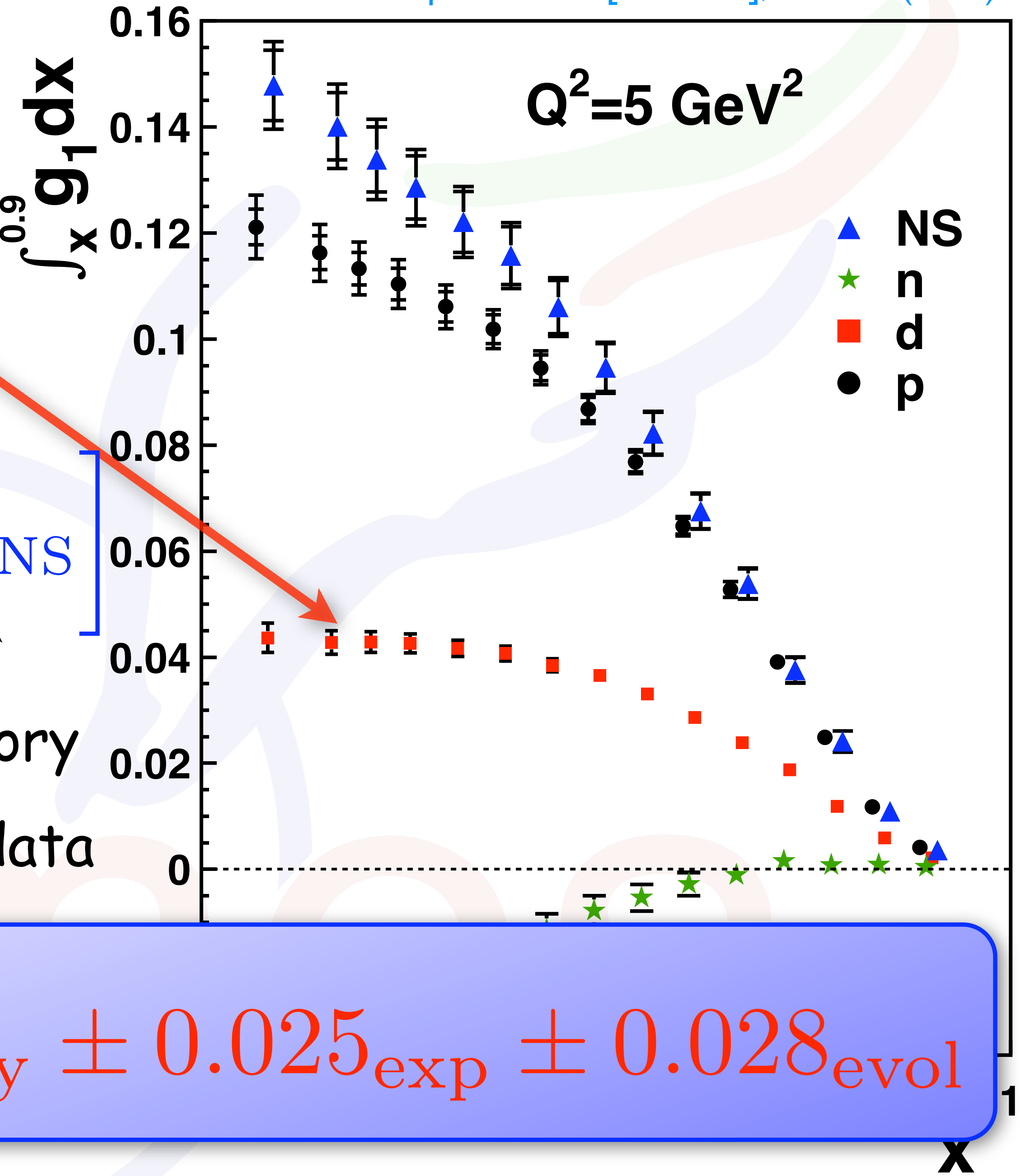

$$\Delta\Sigma \overset{\overline{\mathrm{MS}}}{=} 0.330 \pm 0.011_{\mathrm{theory}} \pm 0.025_{\mathrm{exp}} \pm 0.028_{\mathrm{evol}}$$

Integral of $g_1(x)$

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theory — 0.05±0.05 — hyperon-decay data — theory

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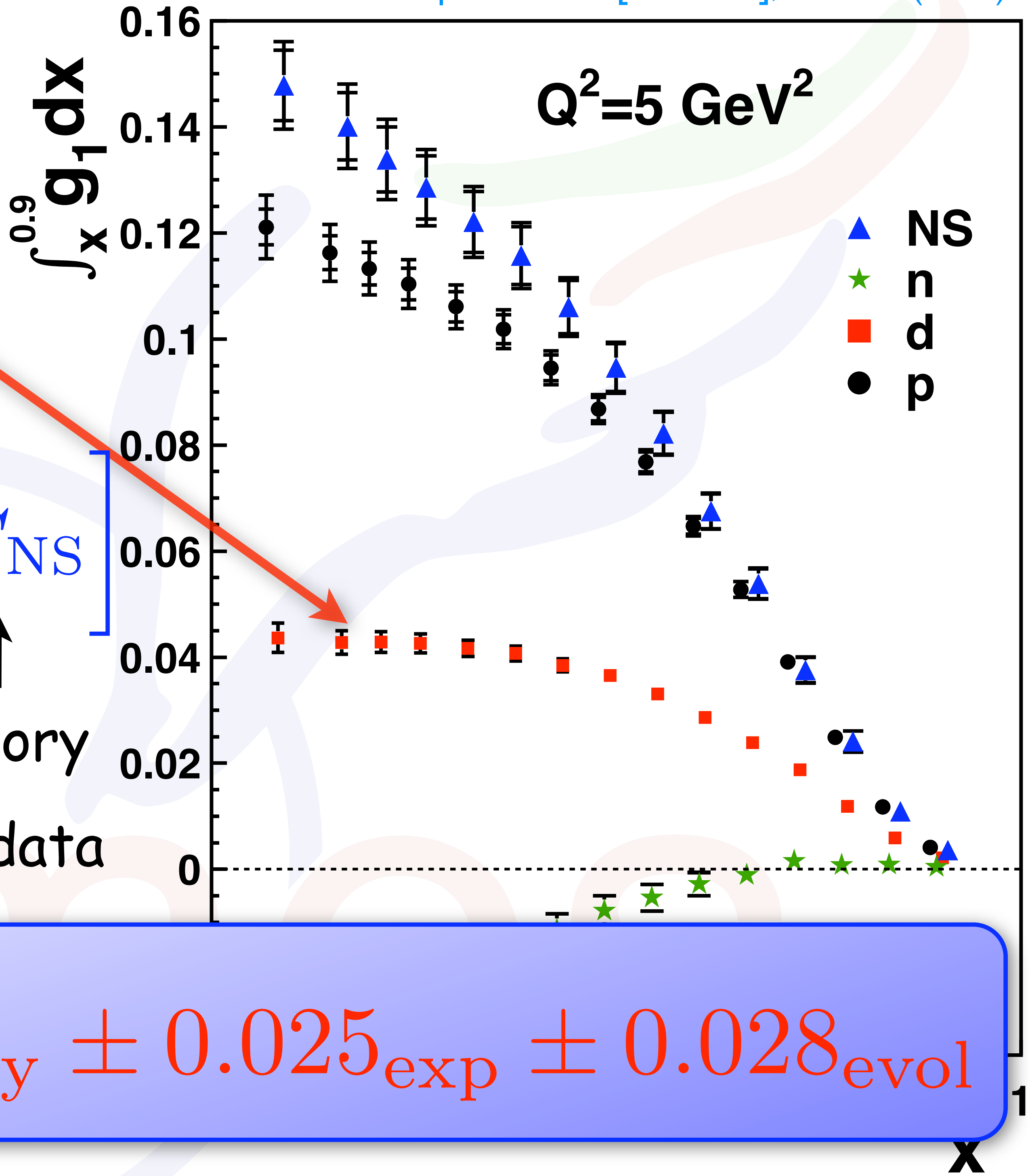
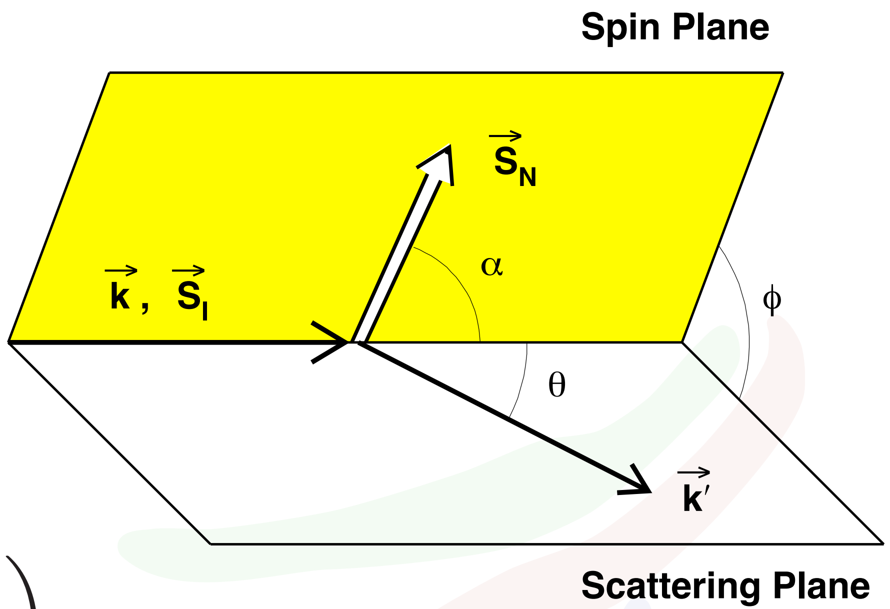


$$\Delta\Sigma \stackrel{\overline{\mathrm{MS}}}{=} 0.330 \pm 0.011_{\mathrm{theory}} \pm 0.025_{\mathrm{exp}} \pm 0.028_{\mathrm{evol}}$$

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

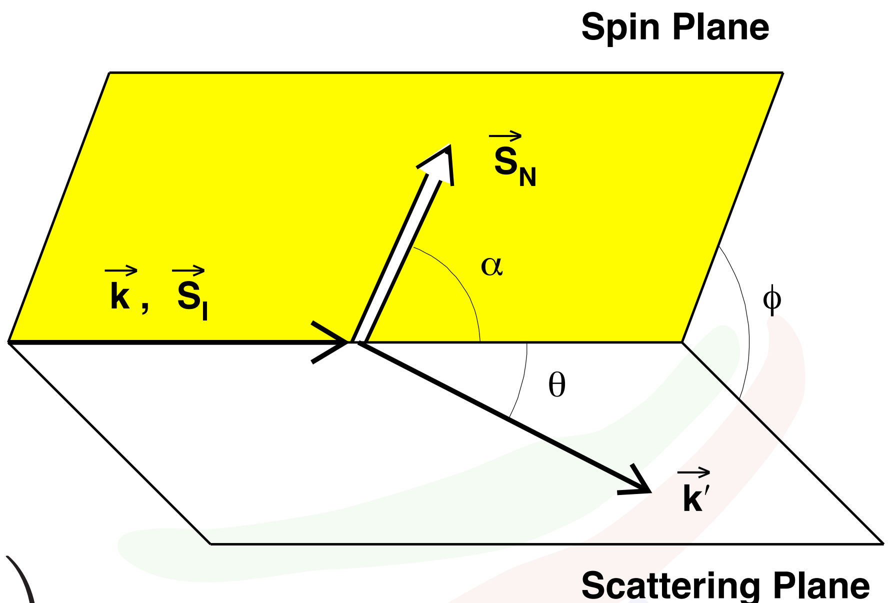
Extraction of g_2



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

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

Extraction of g_2



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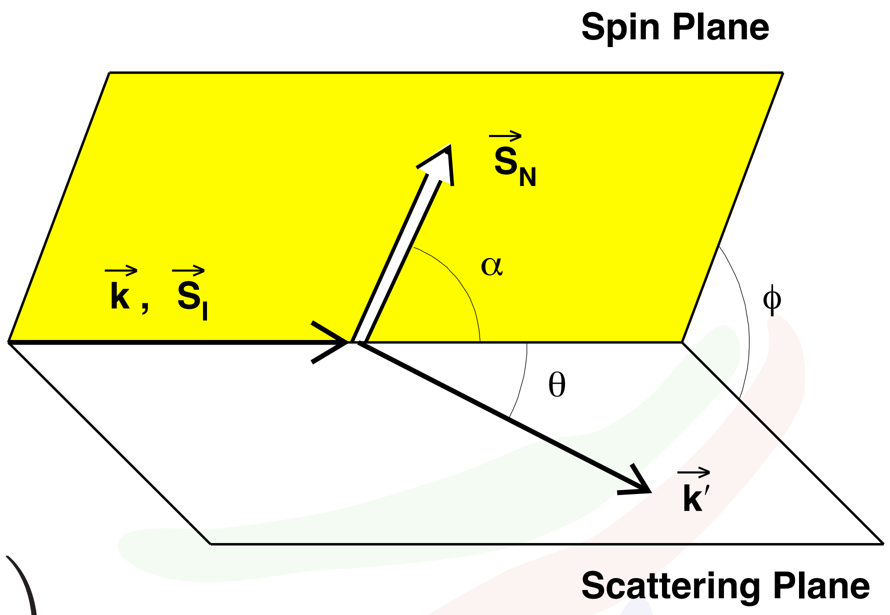
fit to double-spin asymmetry

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

Extraction of g_2



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fit to double-spin asymmetry

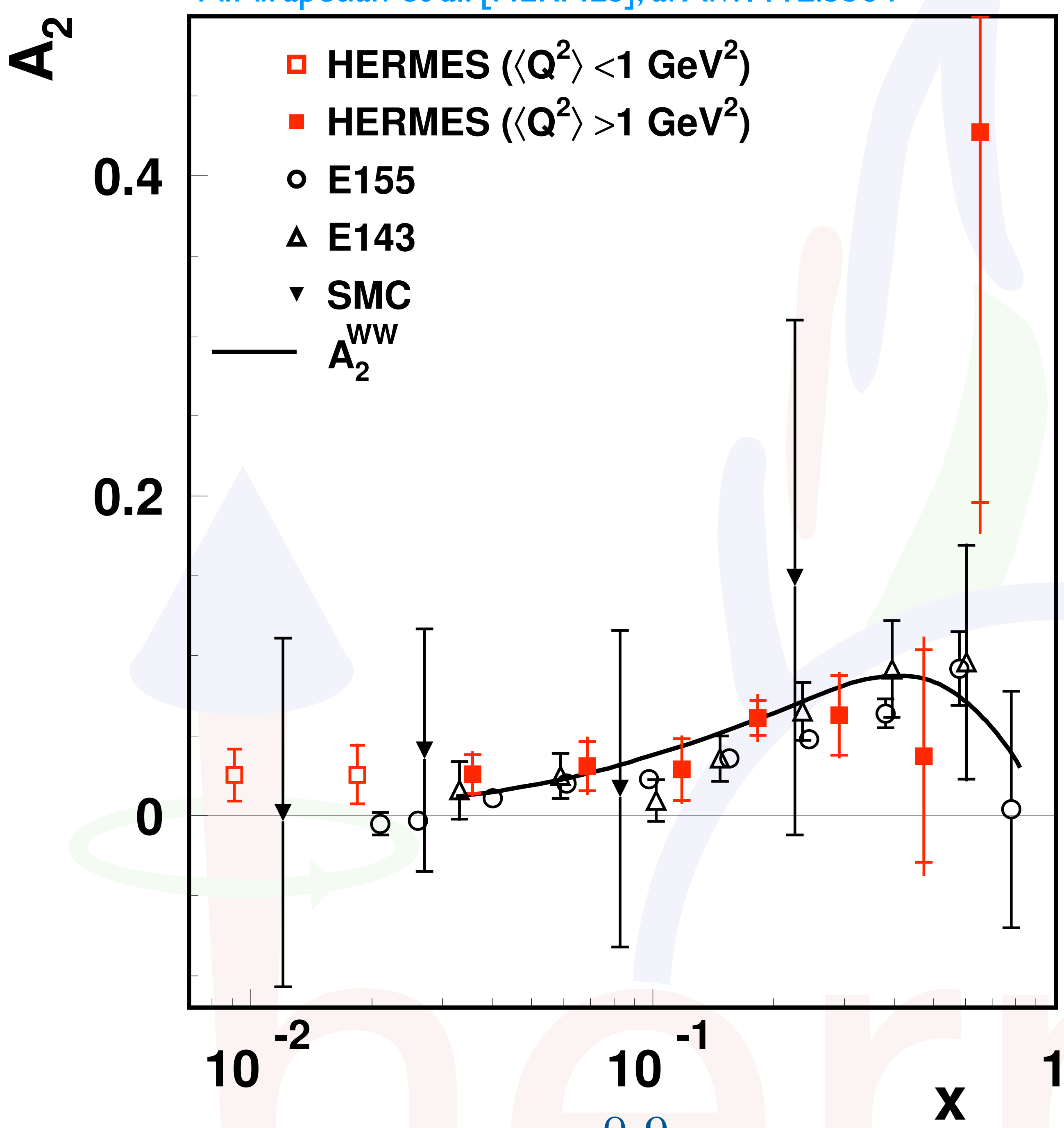
parameterizations

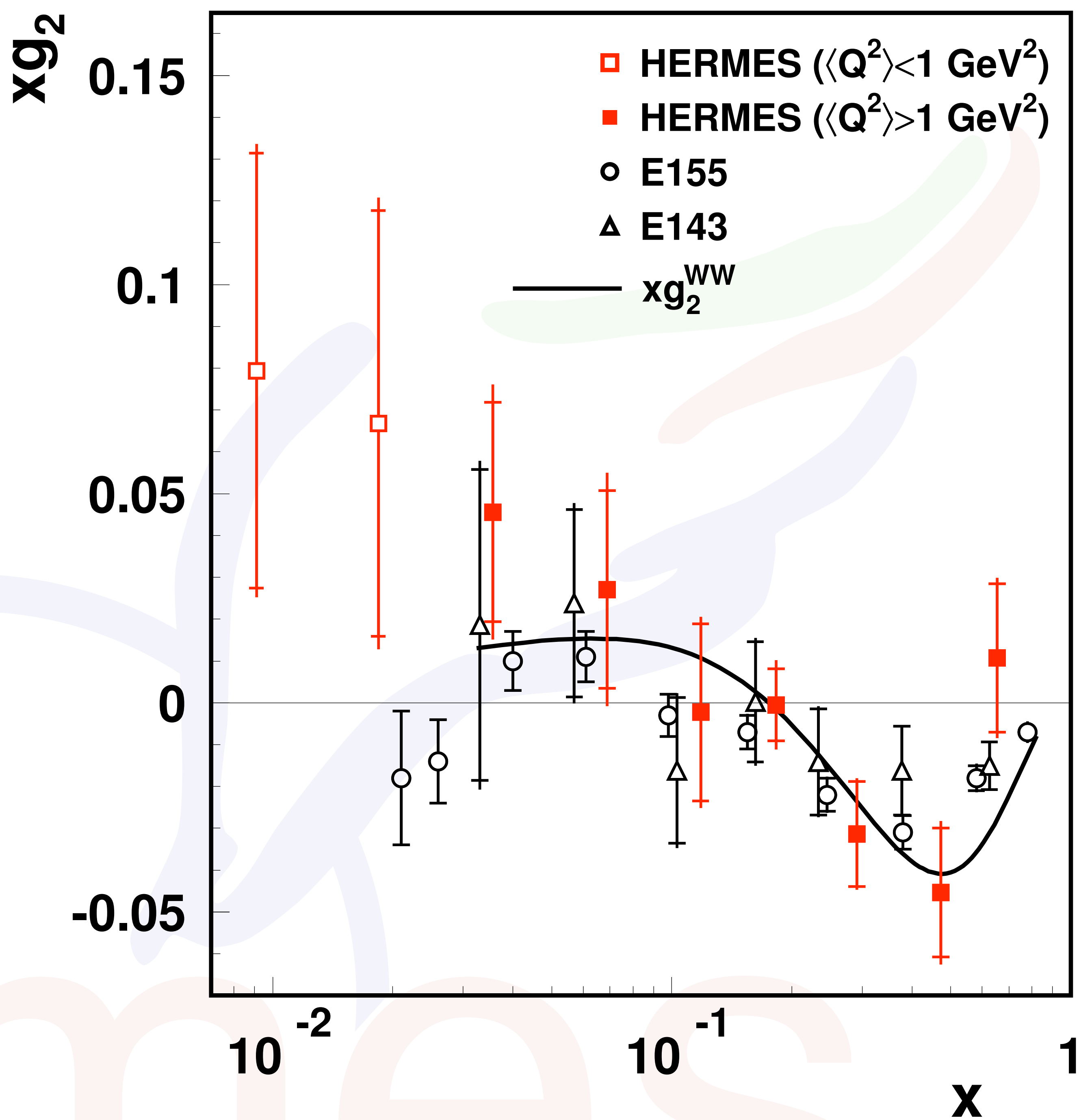
$$A_2 = \frac{1}{d(1+\gamma\xi)}\,A_T + \frac{\xi(1+\gamma^2)}{1+\gamma\xi}\,\frac{g_1}{F_1}$$

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

Results on A_2 and xg_2

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

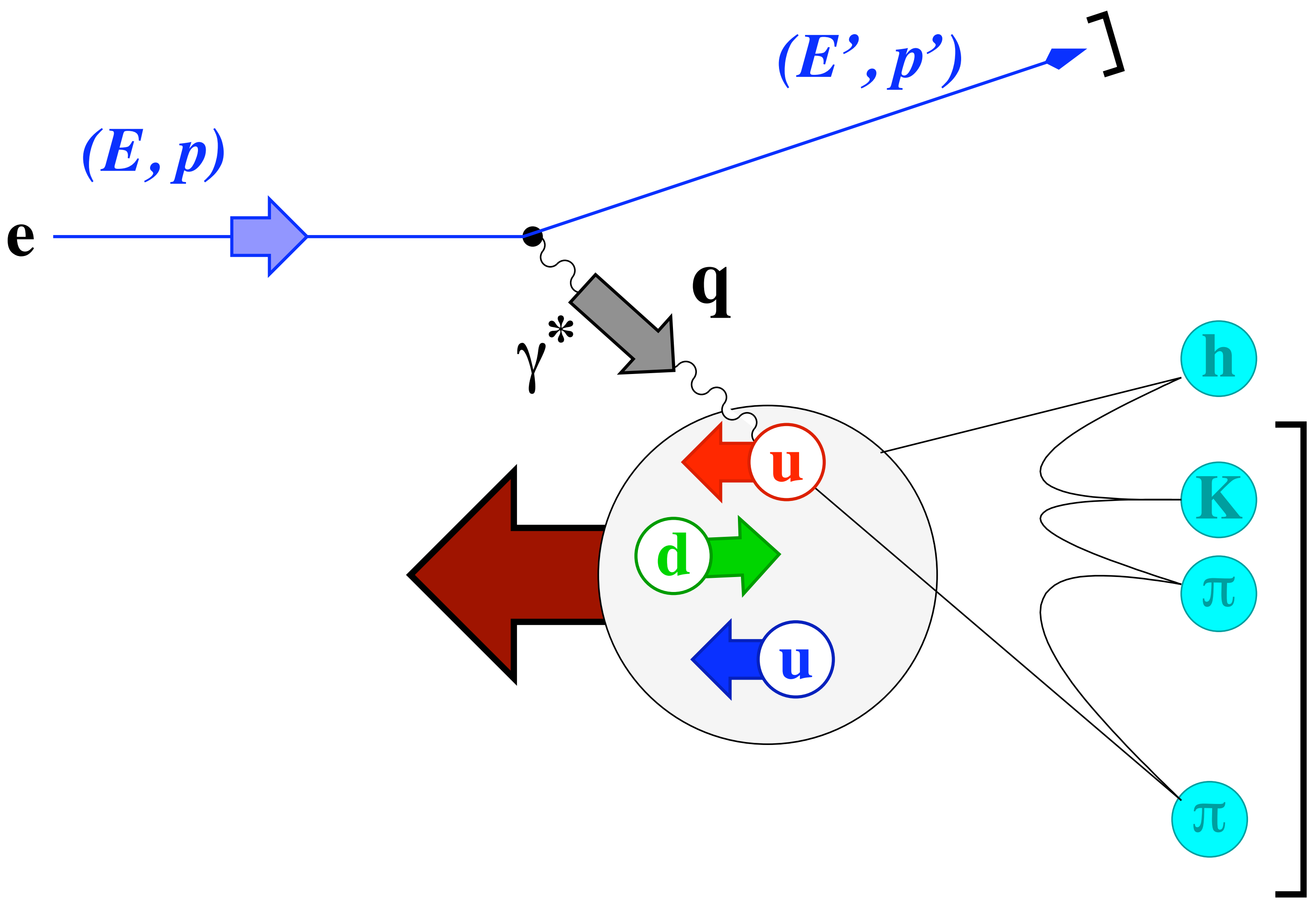




$$\int_{0.023}^{0.9} g_2(x,Q^2)\,dx = \mathbf{0.006} \pm \mathbf{0.024}_{\rm stat} \pm \mathbf{0.017}_{\rm syst}$$

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

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., $A_{\parallel,d}(x,Q^2)$ and $A_{\parallel,d}^{K^{+}+K^{-}}(x,z,Q^2)$, as well as K⁺+K⁻ multiplicities on deuteron

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

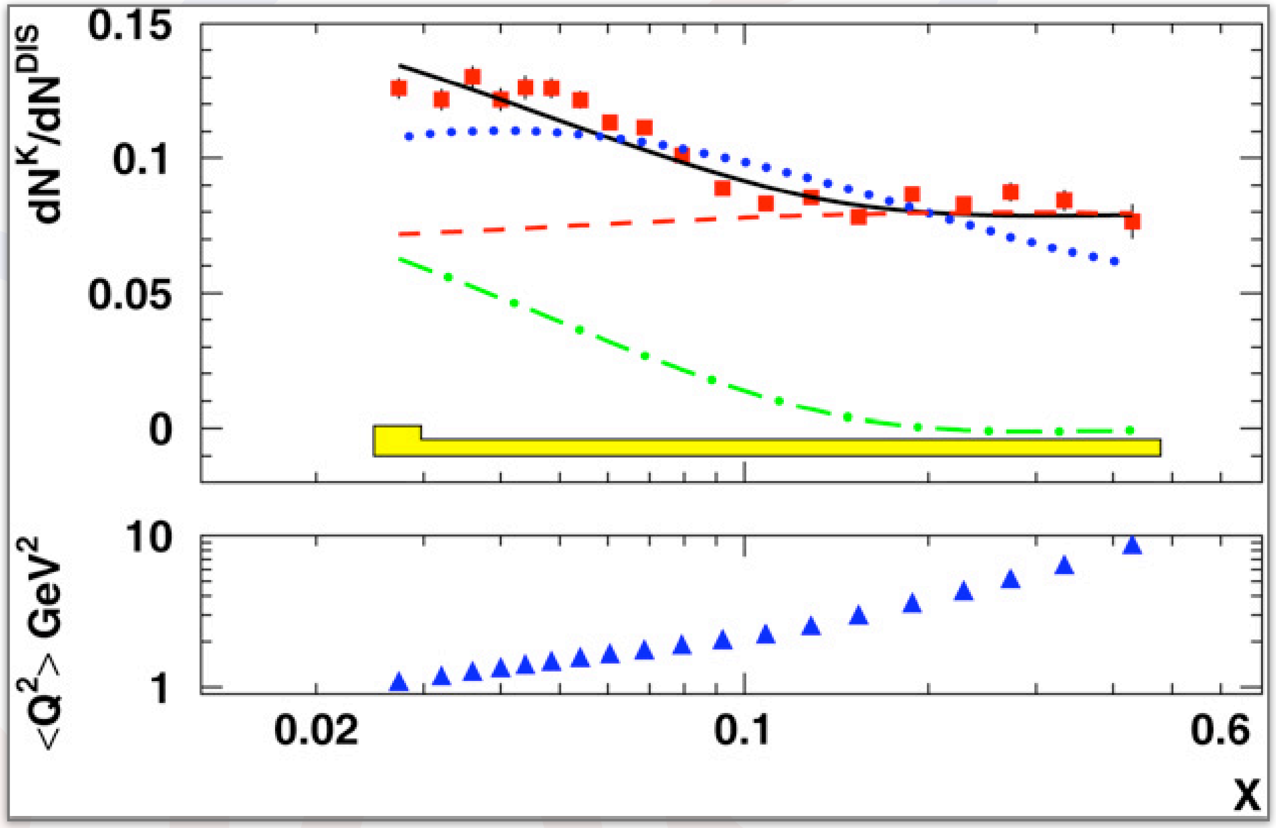
$$A_{\parallel,d}(x)\frac{\mathrm{d}^2N^{\mathrm{DIS}}(x)}{\mathrm{d}x\,\mathrm{d}Q^2} = \mathcal{K}_{LL}(x,Q^2)\left[5\Delta Q(x) + 2\boxed{\Delta S(x)}\right]$$

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

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

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



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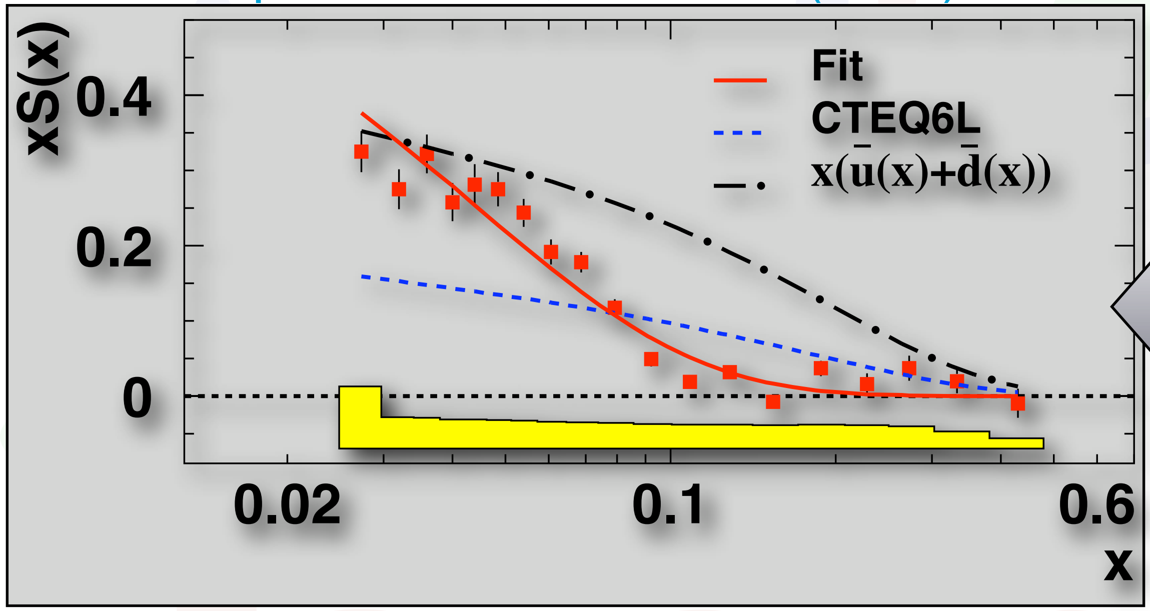
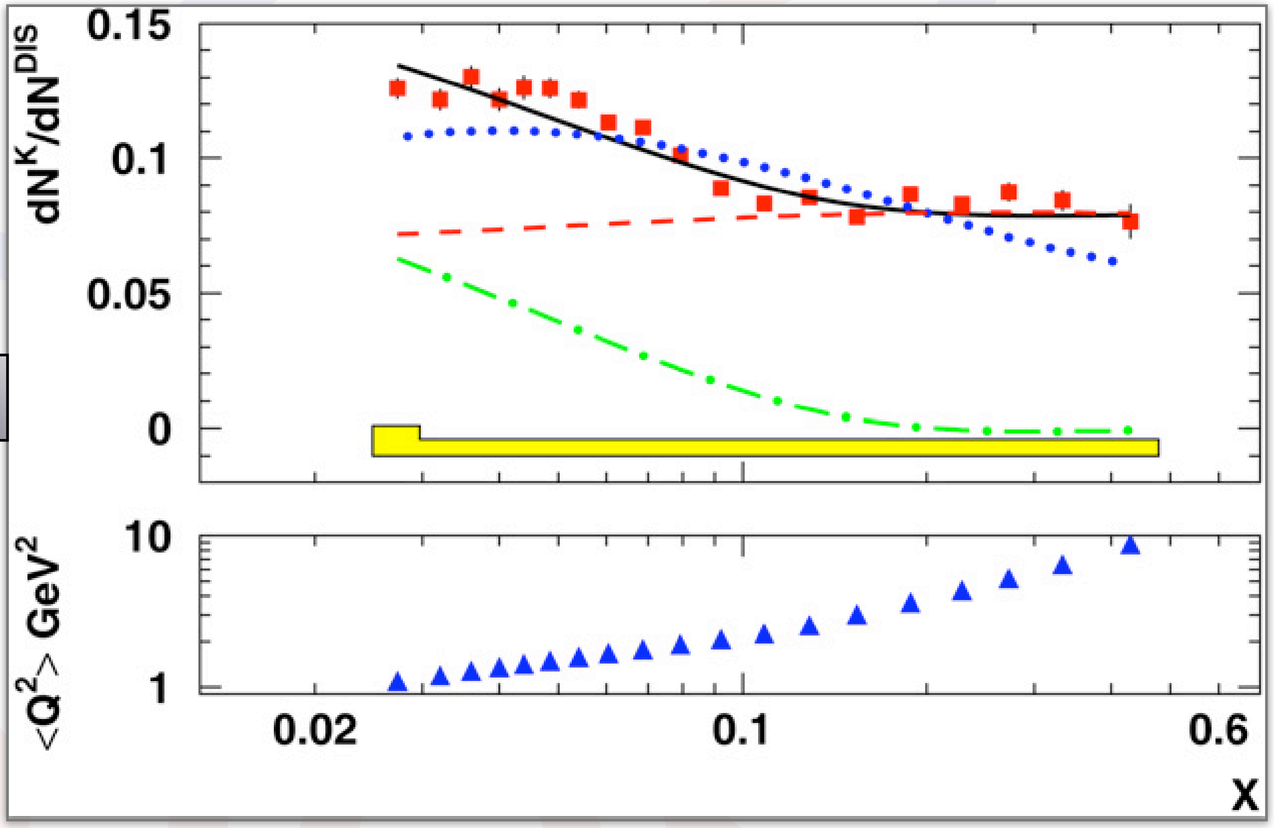
A. Airapetian et al., PLB 666 (2008) 446





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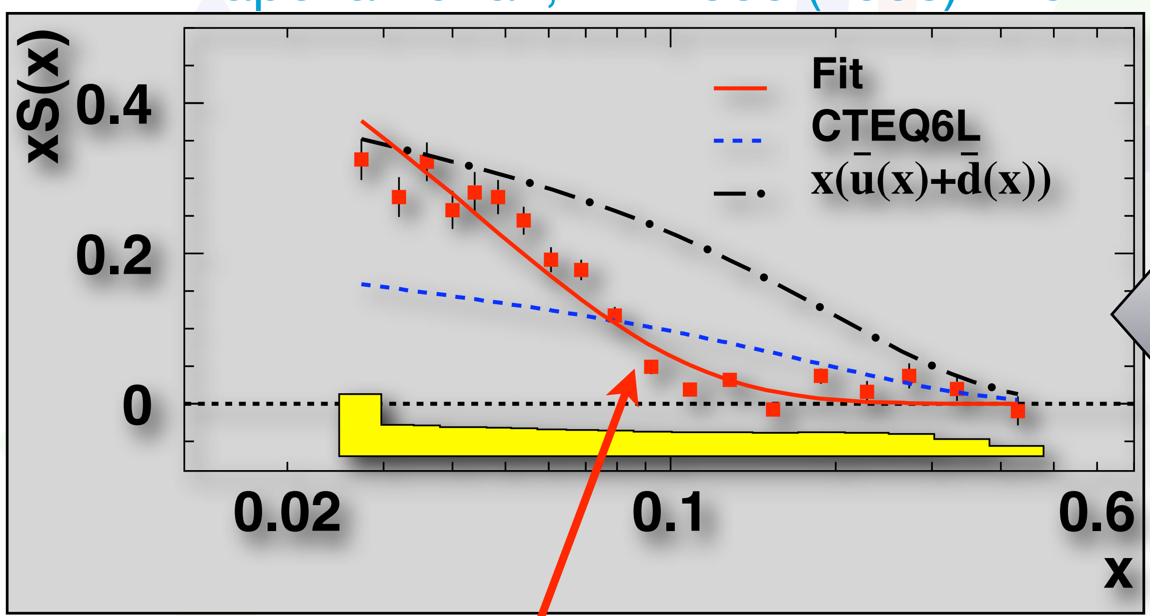

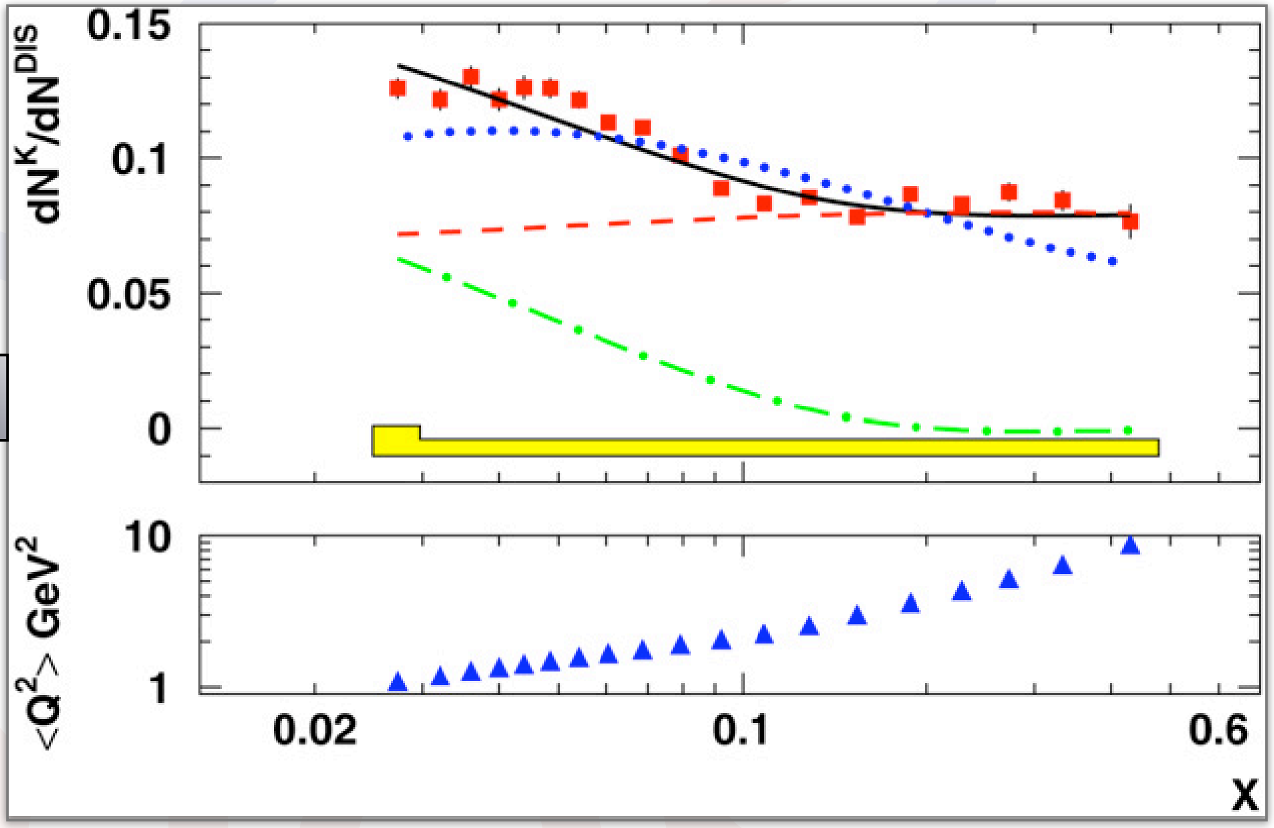

Strange-quark distribution softer than (maybe) expected

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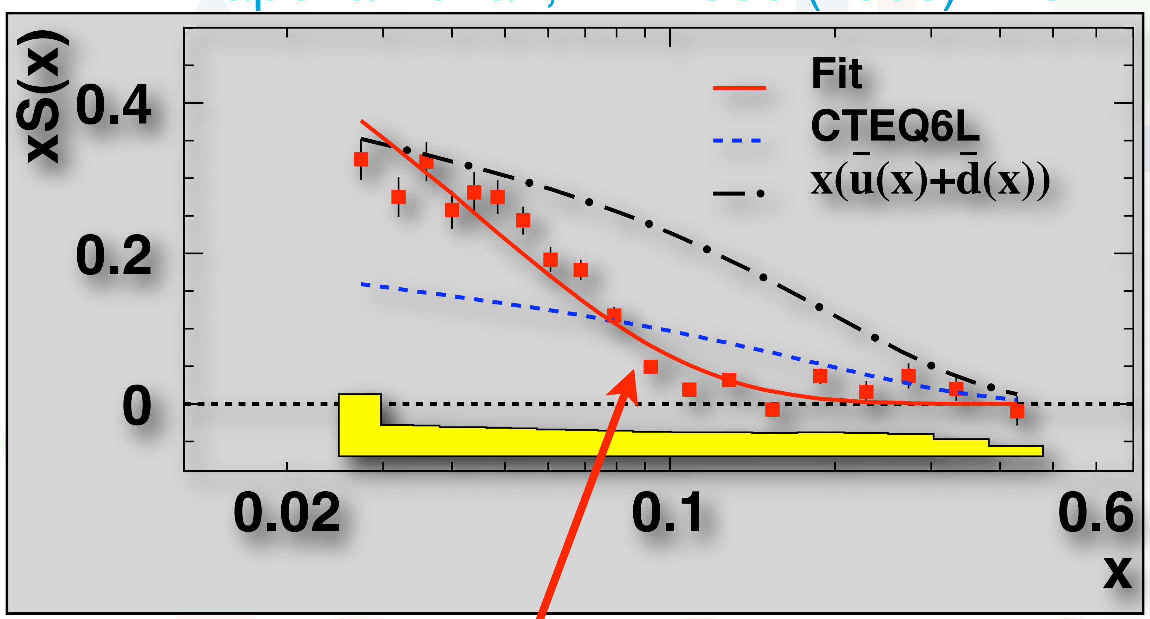

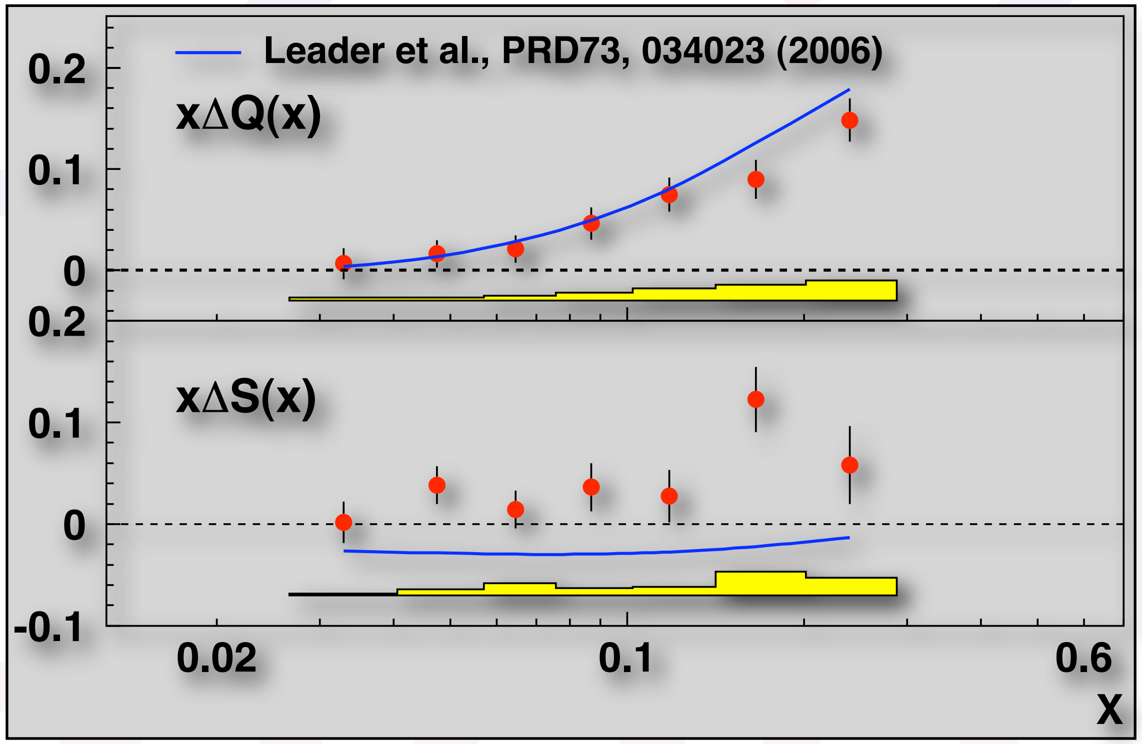

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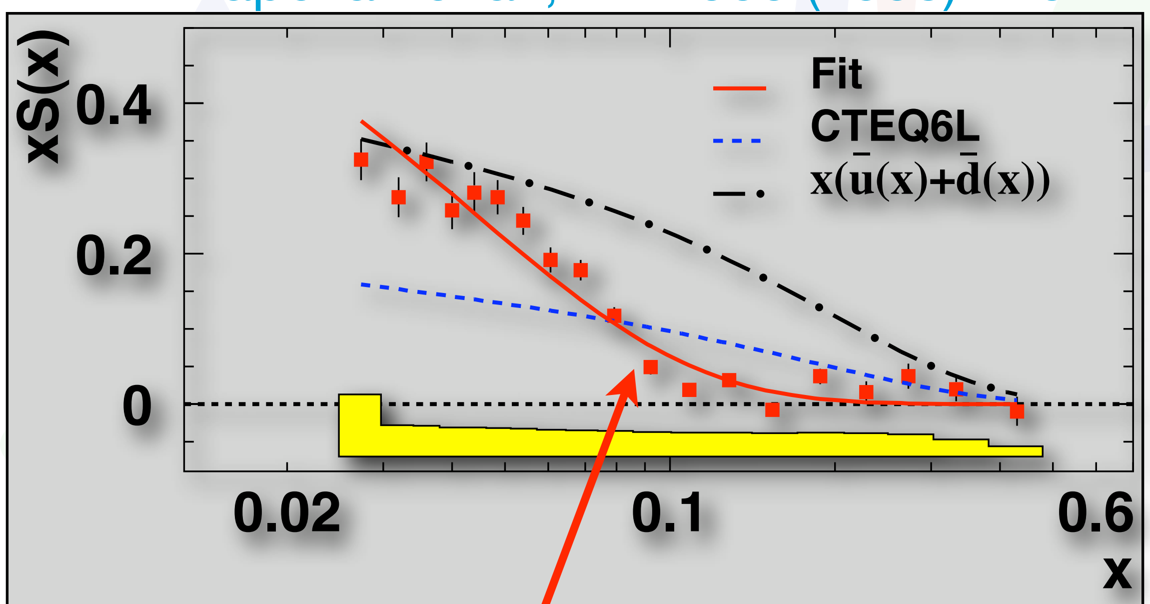
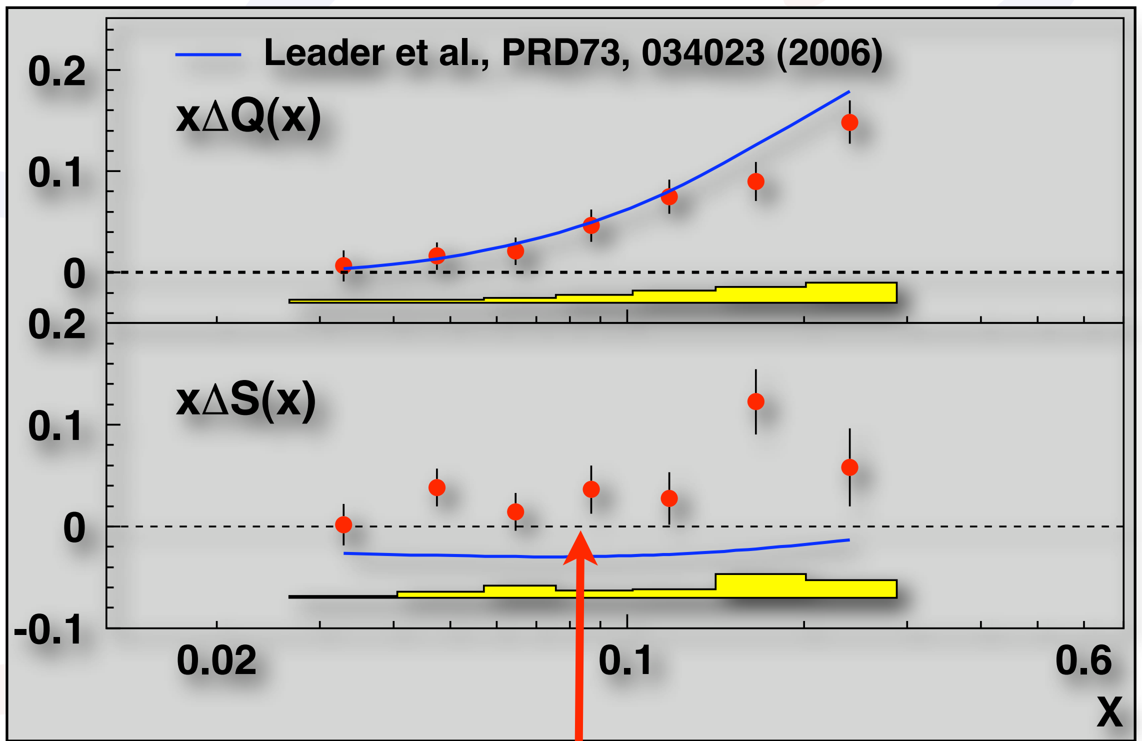
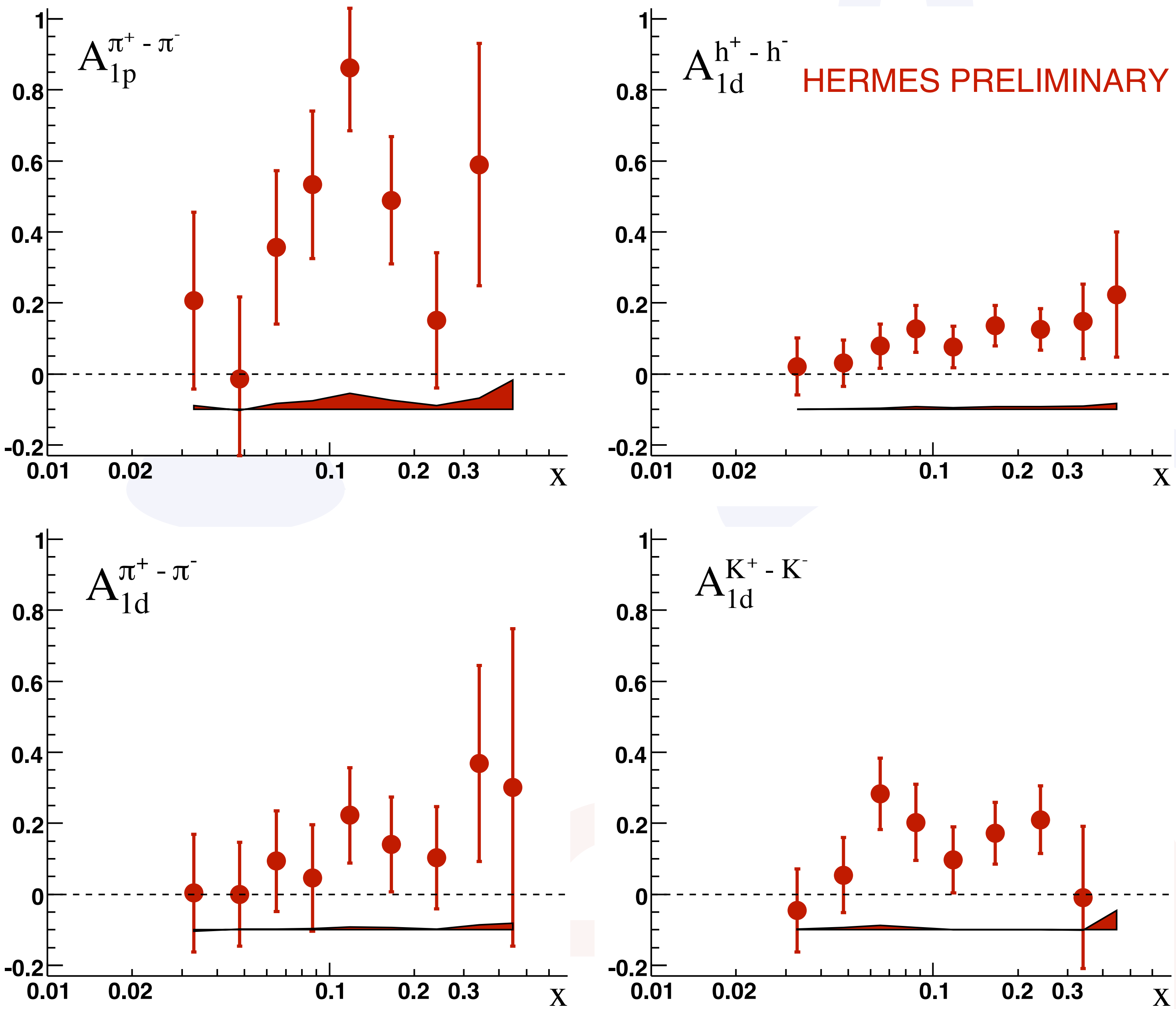




Strange-quark distribution softer than (maybe) expected

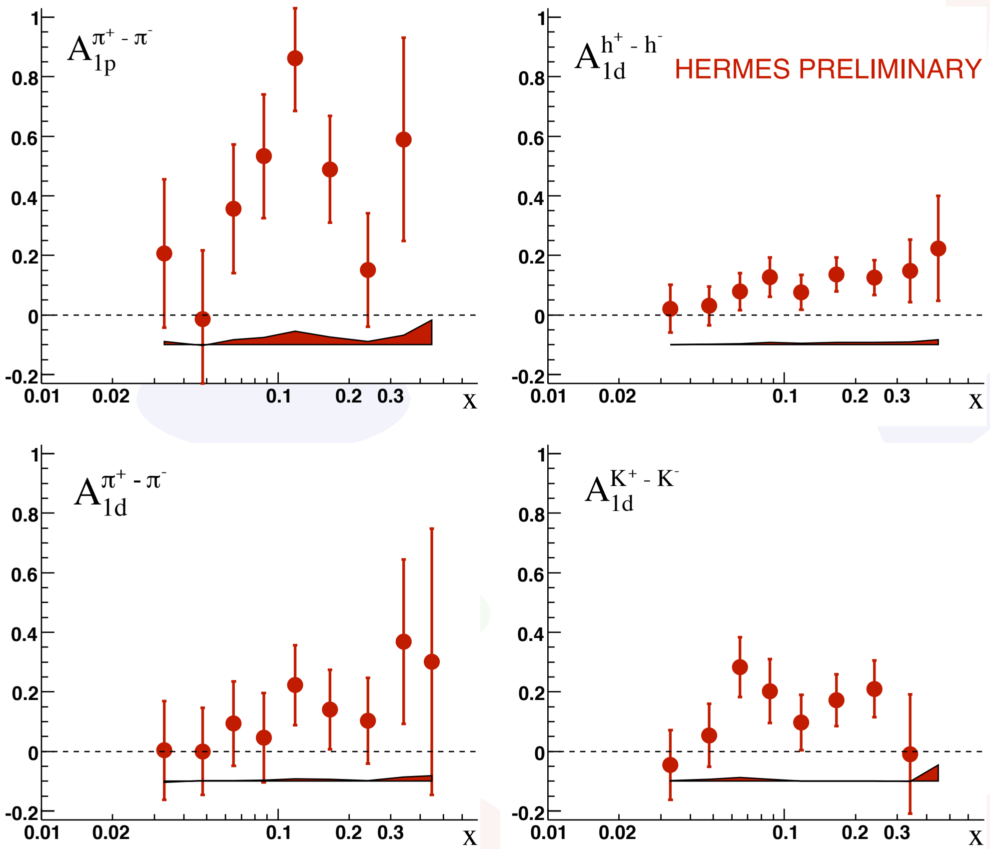
Strange-quark helicity distribution consistent with zero or slightly positive in contrast to inclusive DIS analyses

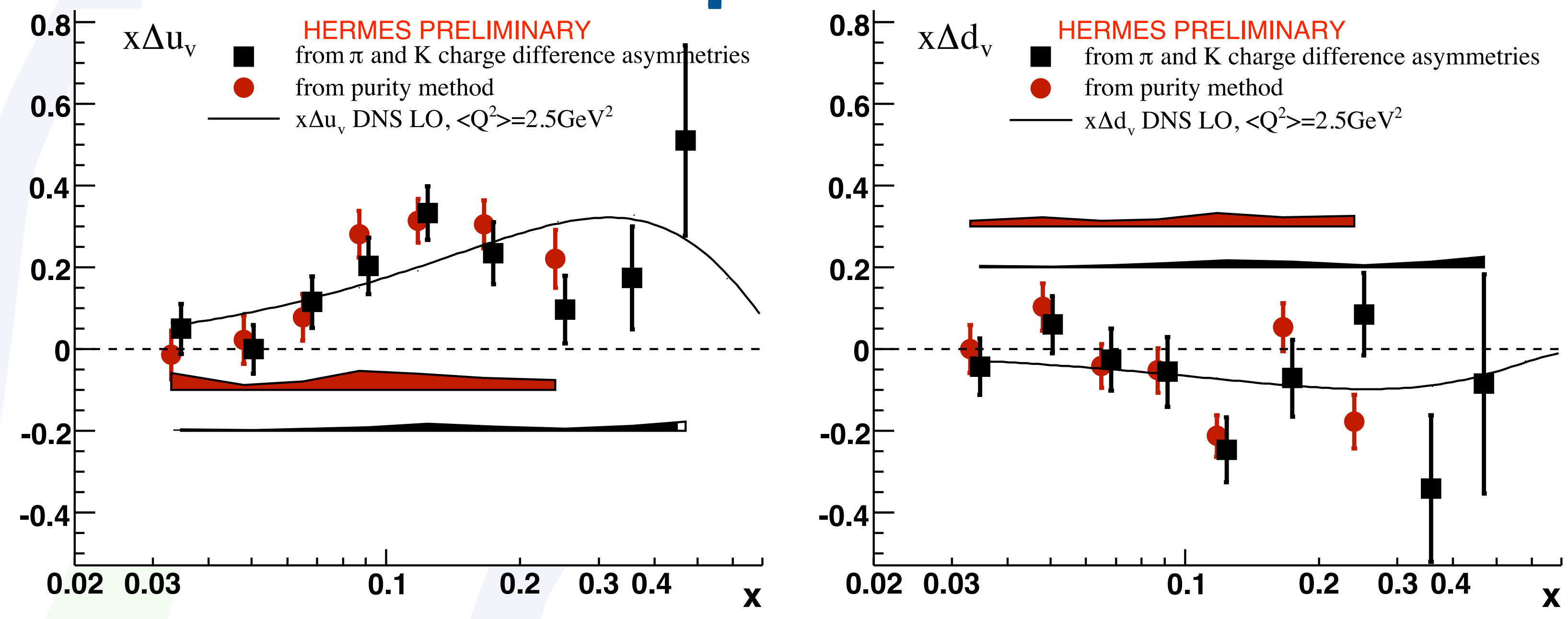
Helicity density - valence quarks



- charge-difference double-spin asymmetries

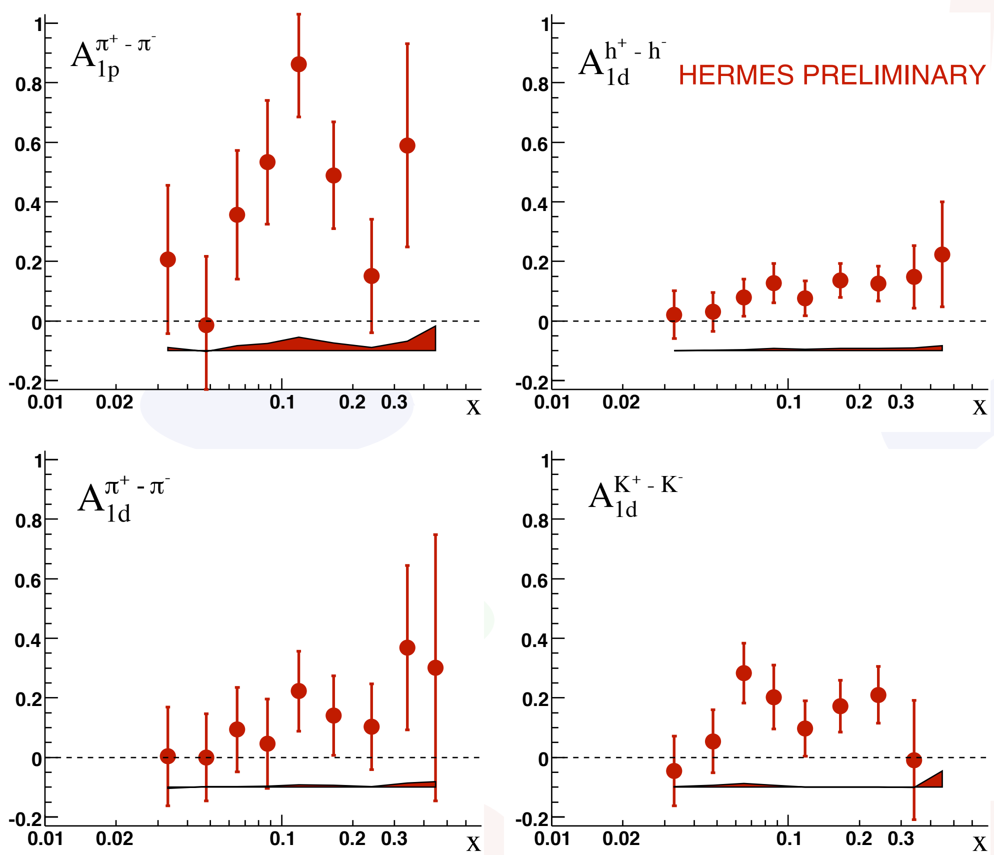
Helicity density - valence quarks

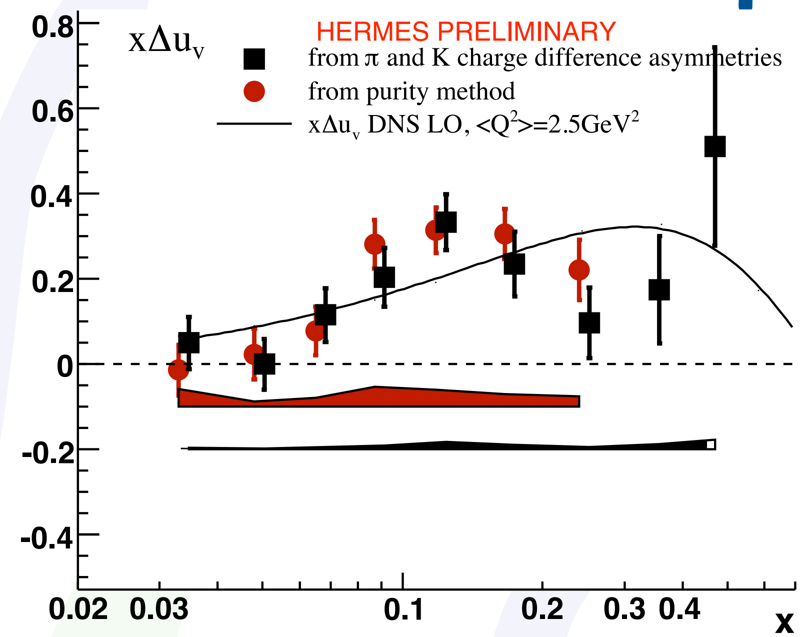


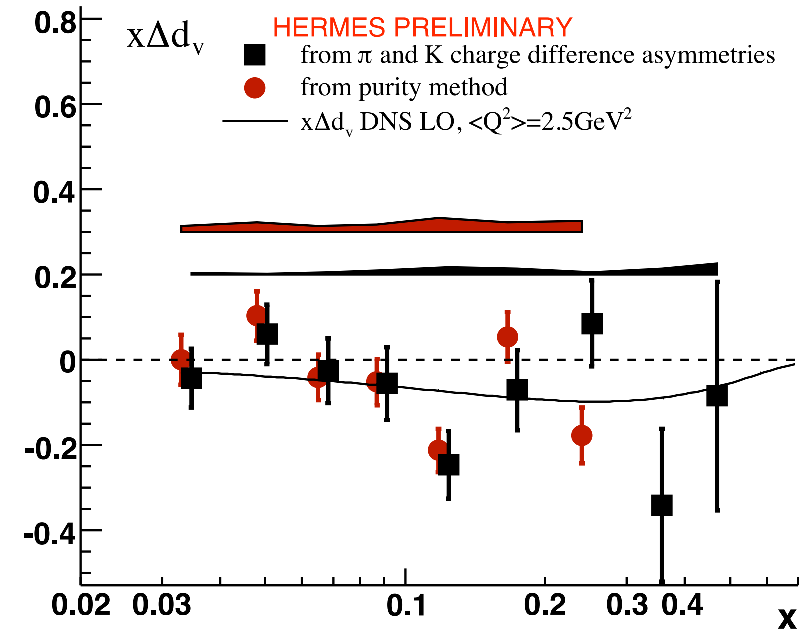


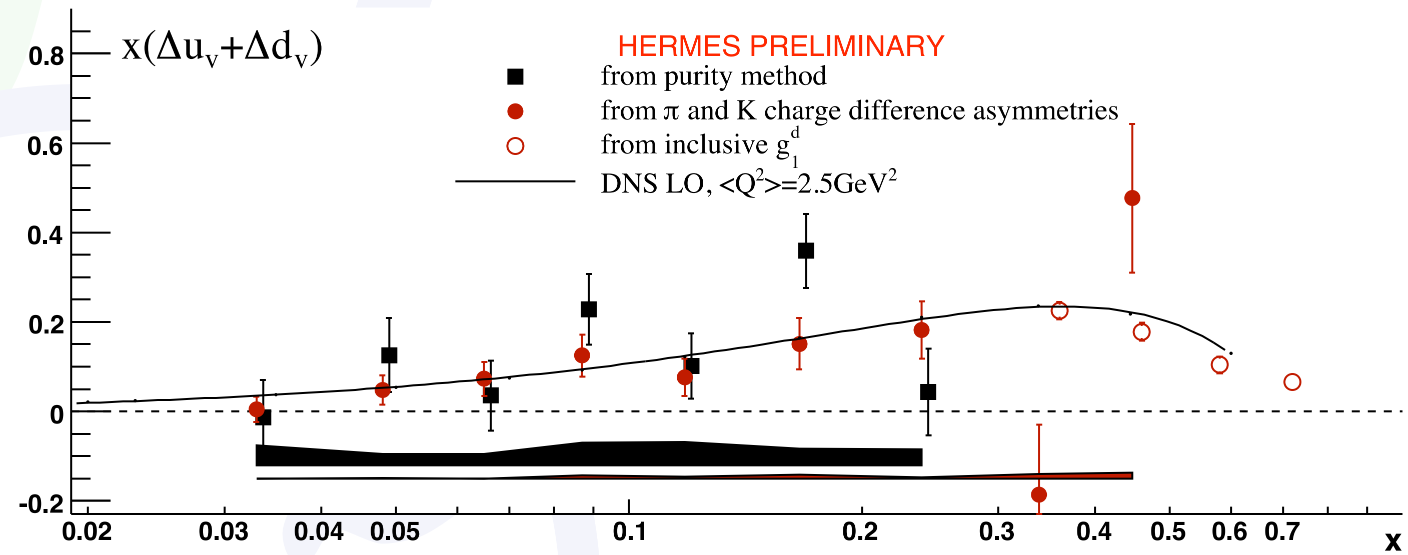
- charge-difference double-spin asymmetries
- use charge-conjugation symmetry to extract, at LO, valence distributions

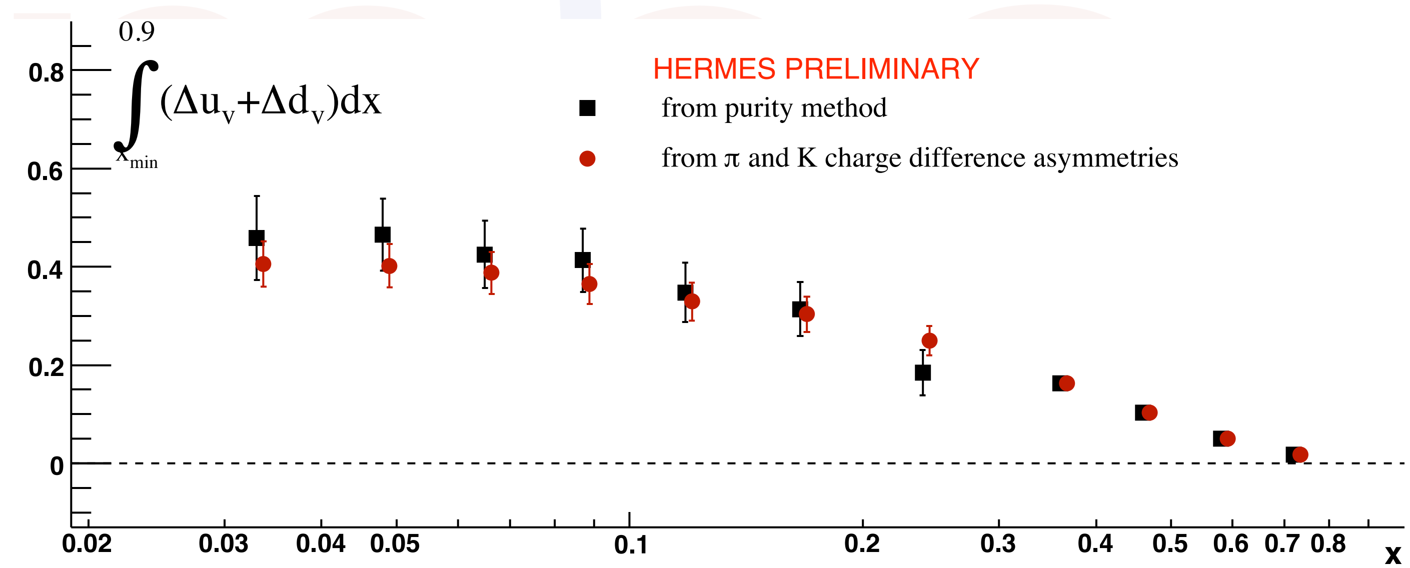
Helicity density - valence quarks











going beyond collinear

Spin-Momentum Structure of the Nucleon

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

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

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

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-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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helicity

quark pol.

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Boer-Mulders

Sivers

worm-gear

transversity

pretzelosity

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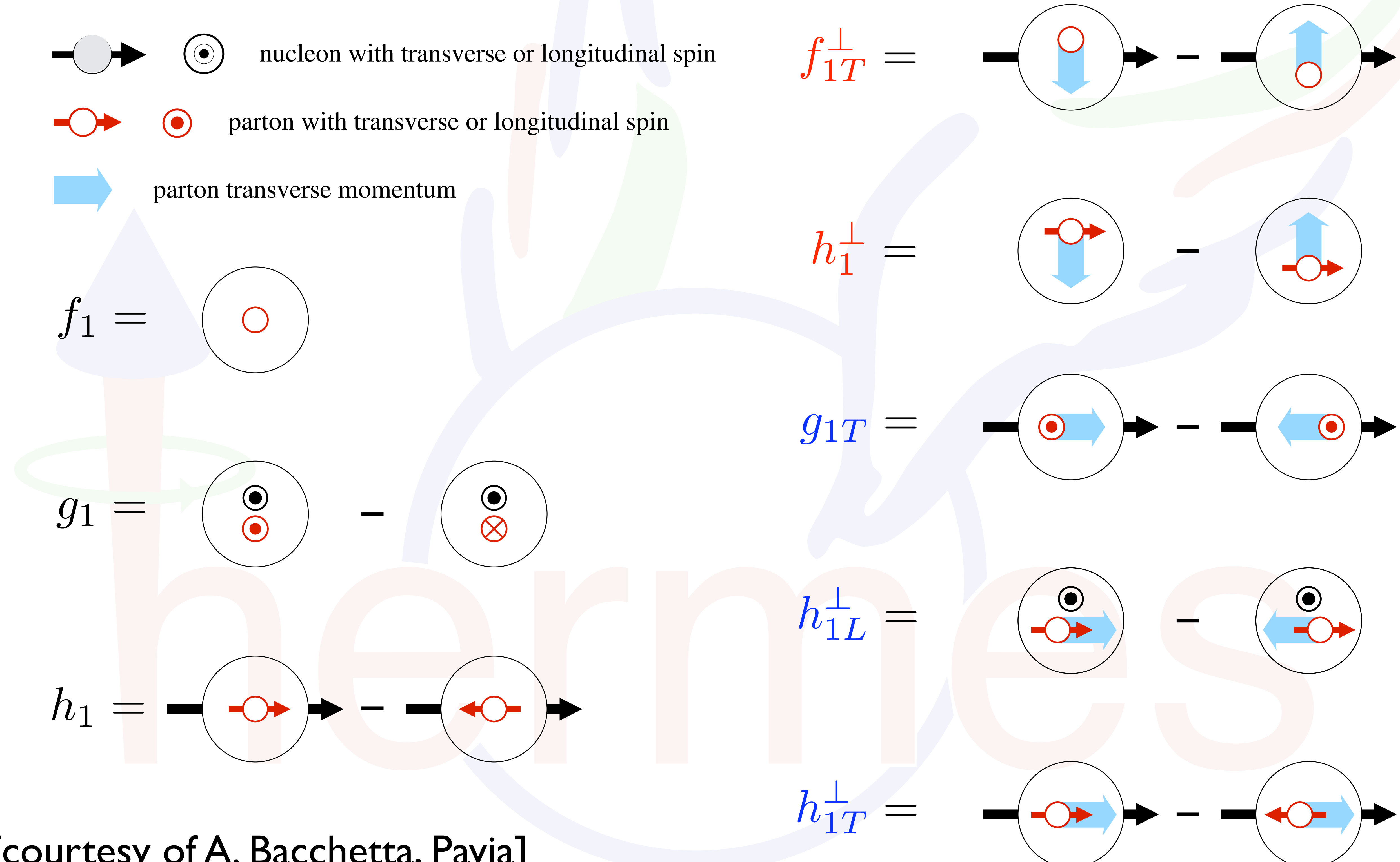
TMDs - Probabilistic interpretation

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



[courtesy of A. Bacchetta, Pavia]

Cross section without polarization

$$F_{XY,Z} = F_{XY,Z}(x, y, z, P_{h\perp})$$

target polarization (Z); beam polarization (X); virtual-photon polarization (Y)

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

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

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

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

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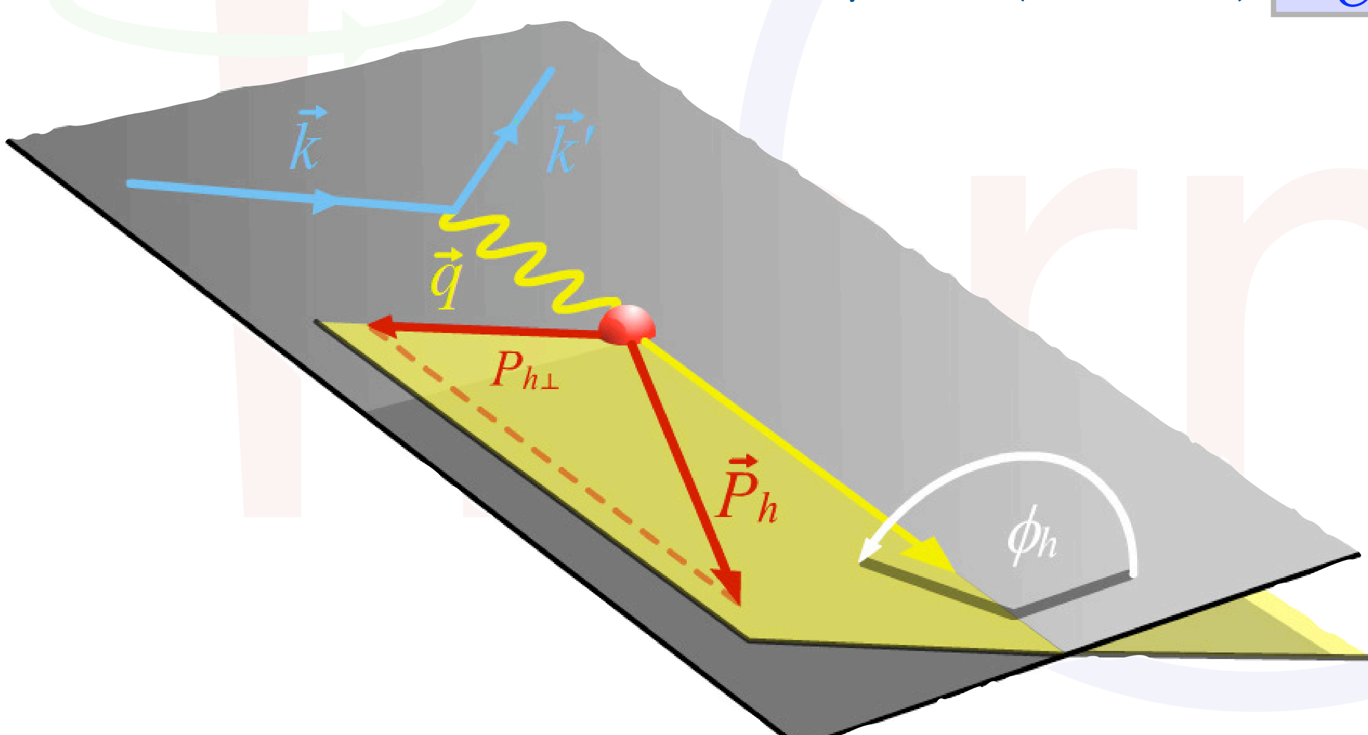
$$\left. + \sqrt{2\epsilon(1-\epsilon)}\boxed{F_{UU}^{\cos\phi_h}}\cos\phi_h + \epsilon\boxed{F_{UU}^{\cos 2\phi_h}}\cos 2\phi_h\right\}$$



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... possible measurements

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

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hadron multiplicity:
normalize to inclusive DIS cross section

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... possible measurements

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

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

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

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moments:
normalize to azimuth-independent cross-section

... possible measurements

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normalize to inclusive DIS cross section

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

moments:
normalize to azimuth-independent cross-section

... possible measurements

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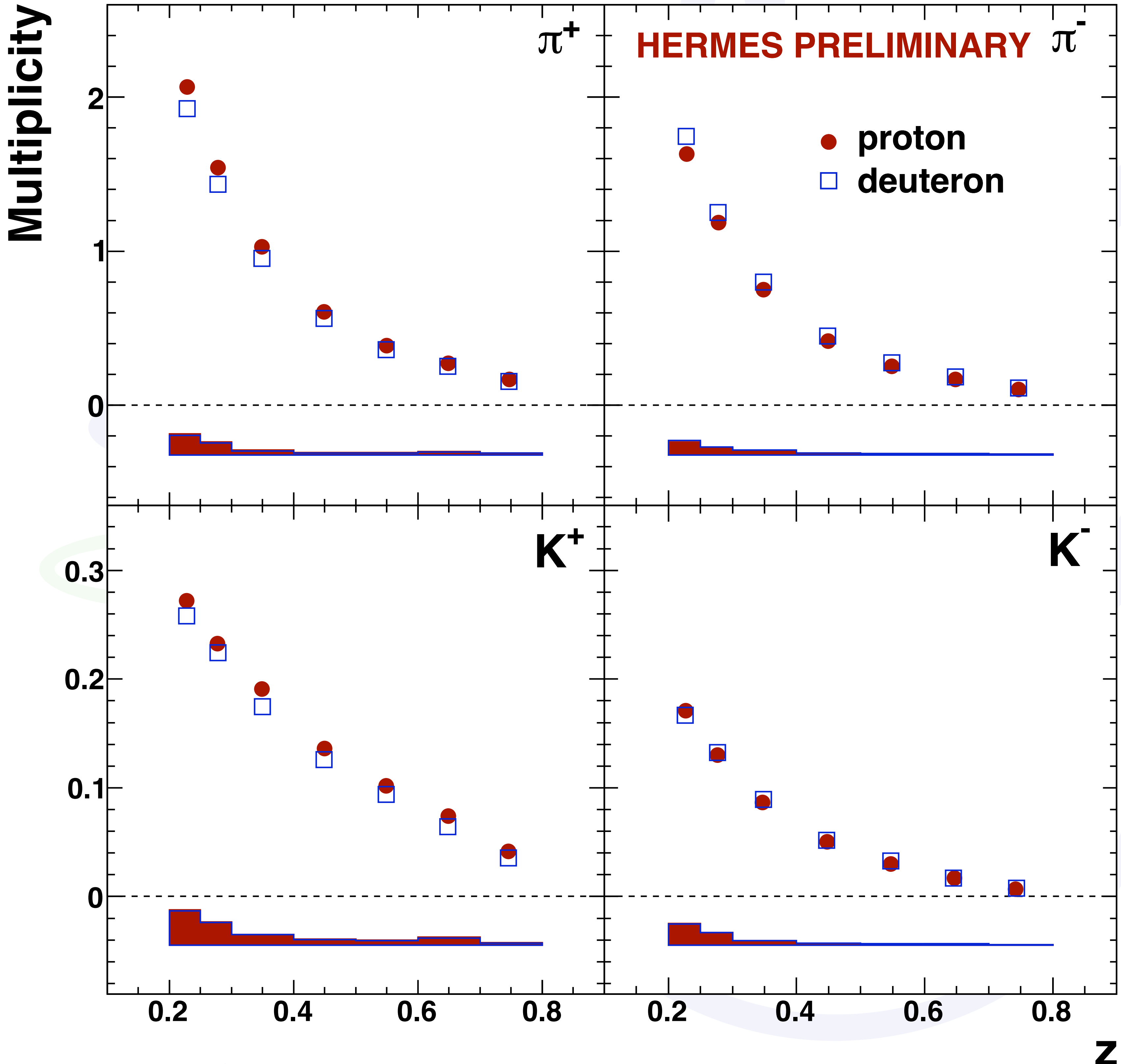
$$\approx \epsilon\frac{\sum_q e_q^2\, h_1^{\perp,q}(x,p_T^2)\otimes_{\text{BM}} H_1^{\perp,q\to h}(z,K_T^2)}{\sum_q e_q^2\, f_1^q(x,p_T^2)\otimes D_1^{q\to h}(z,K_T^2)}$$

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



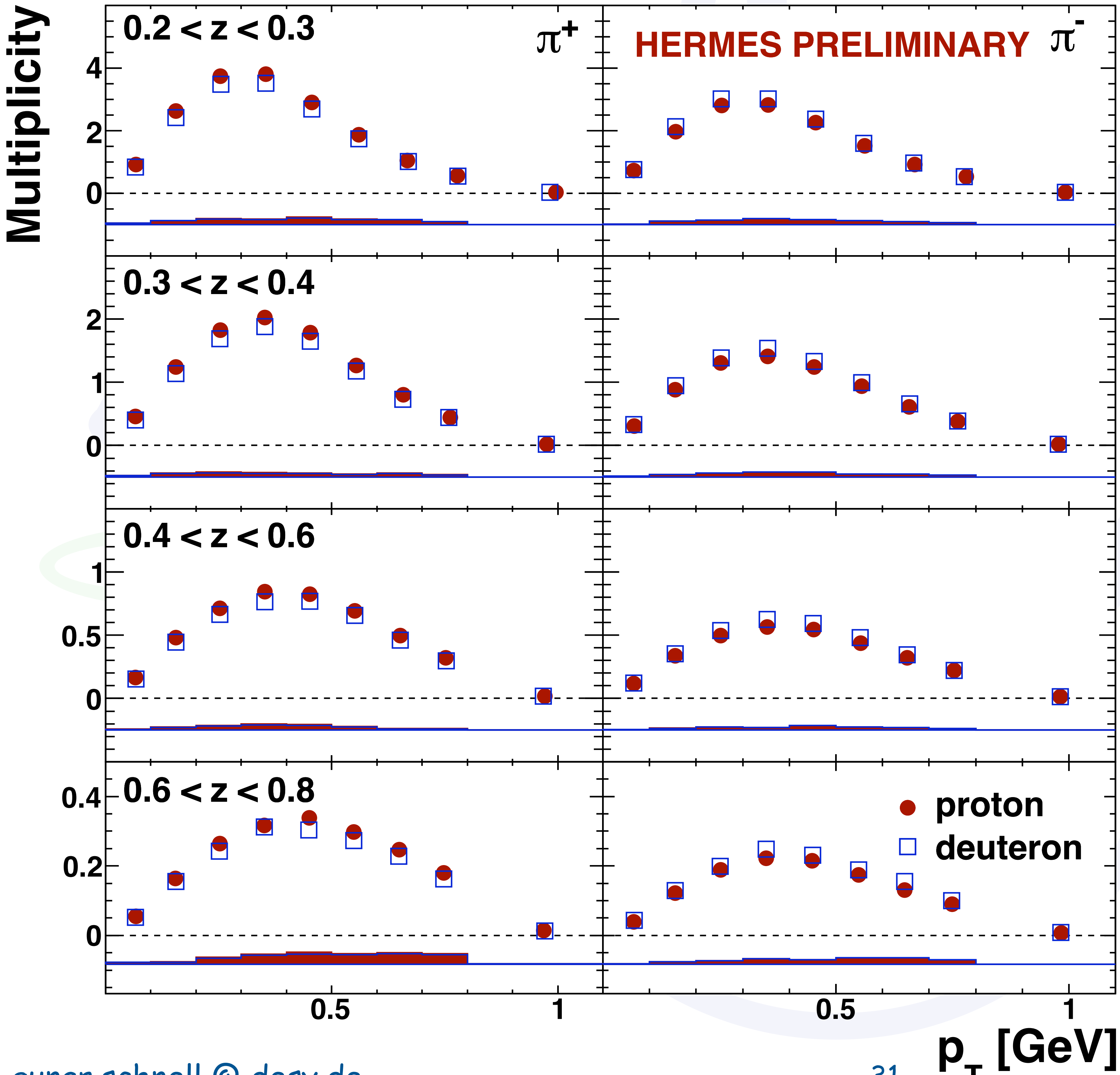
slight differences between proton and deuteron targets

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, $h_{1T}^\perp$

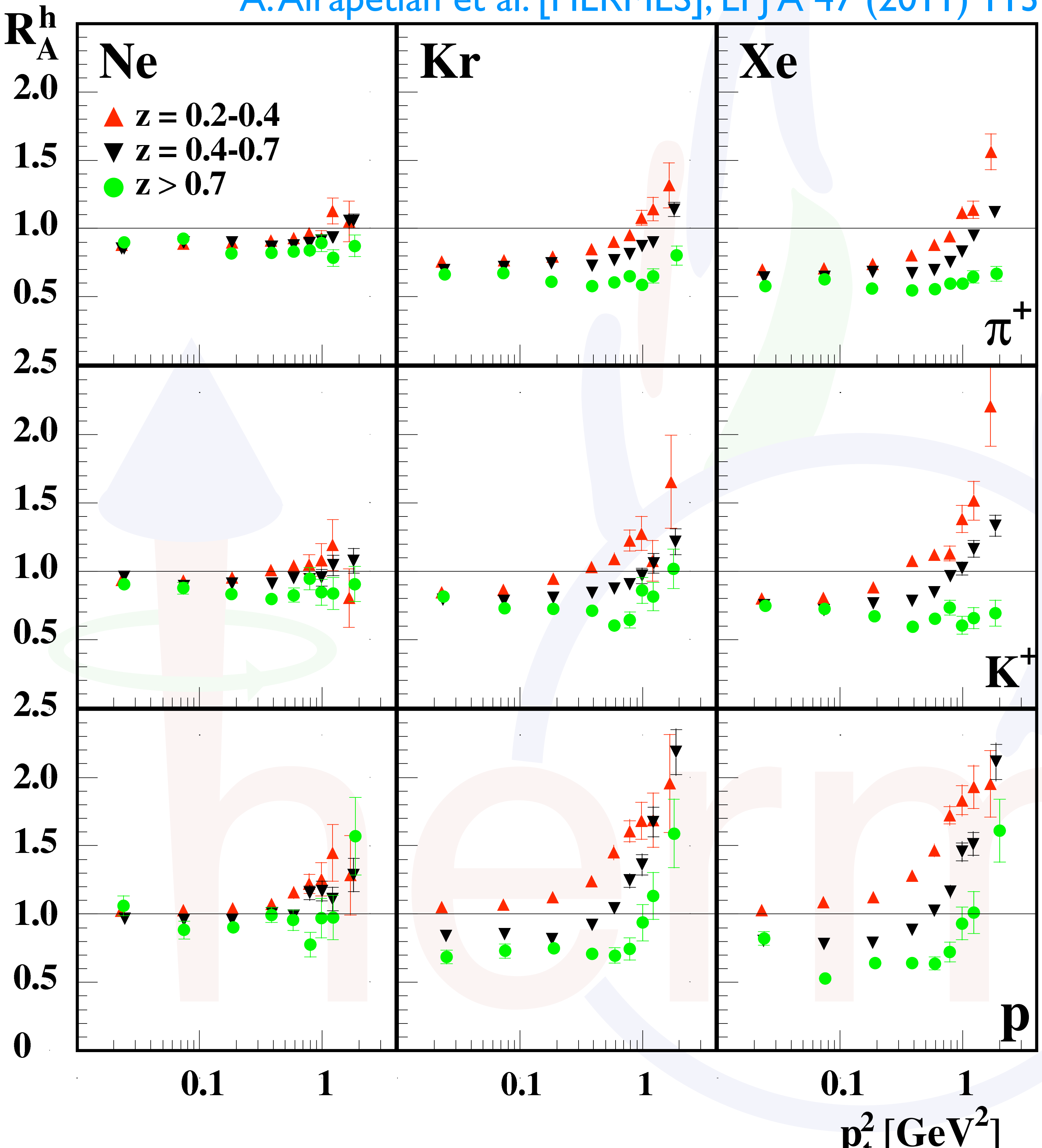
2-D z-p_T dependence



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

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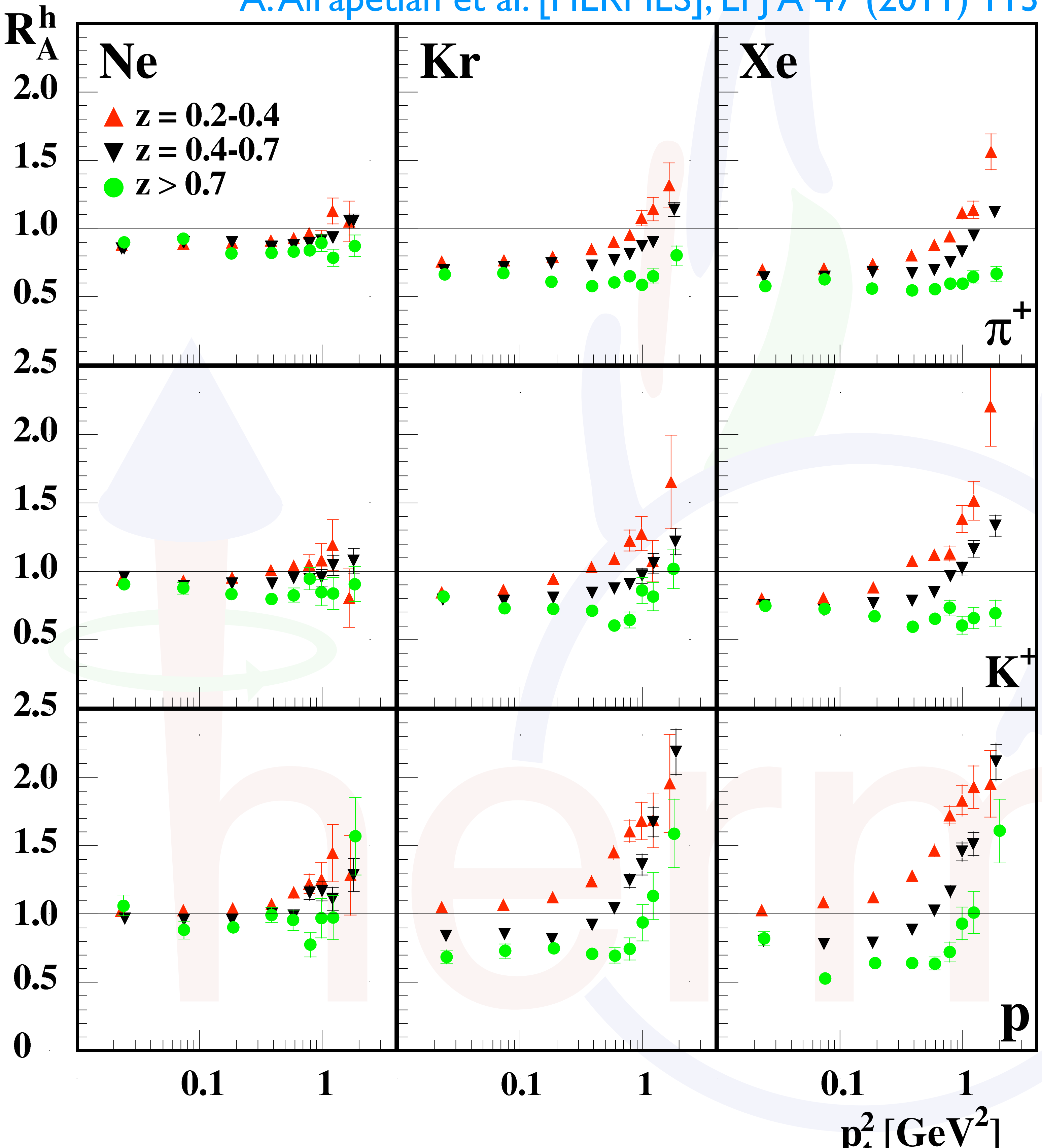

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needs to be considered when interpreting TMD effects off nuclear targets (at not-too-high energies)

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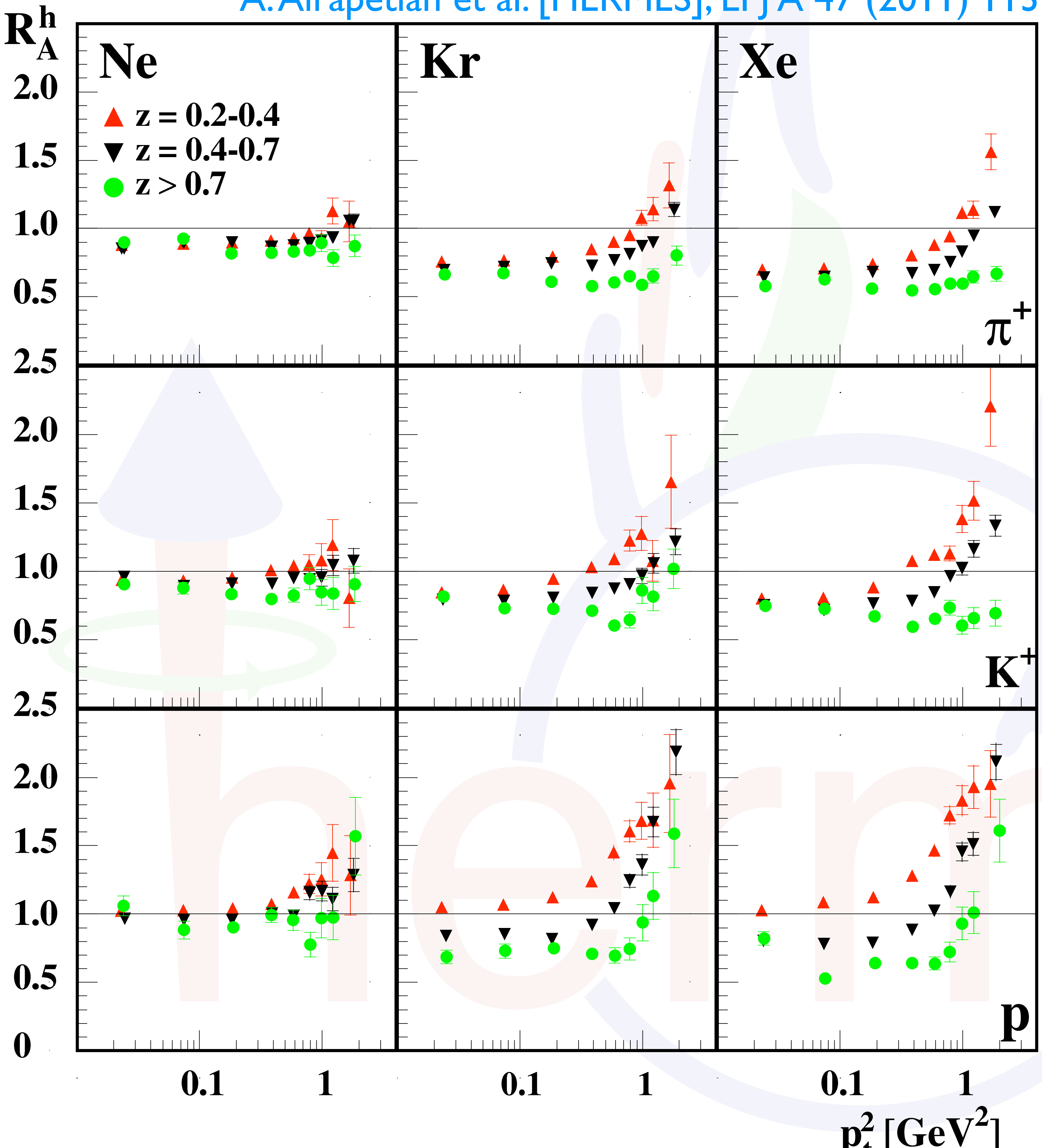


$$R_A^h \equiv \frac{\mathcal{M}_A^h}{\mathcal{M}_d^h}$$

strong p_T dependence of nuclear attenuation

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

(other 2D dependences available)

Azimuthal modulations

leading twist

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

BOER-MULDERS EFFECT

CAHN EFFECT

next to leading twist

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

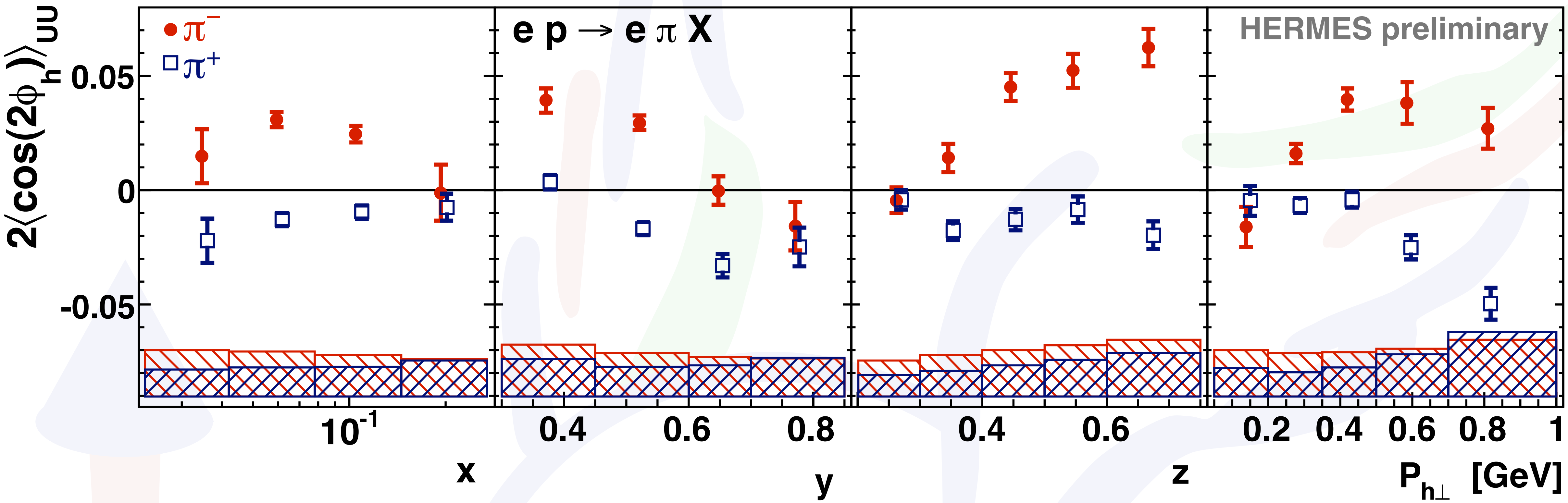
Interaction dependent terms neglected

(Implicit sum over quark flavours)

[courtesy of F. Giordano]

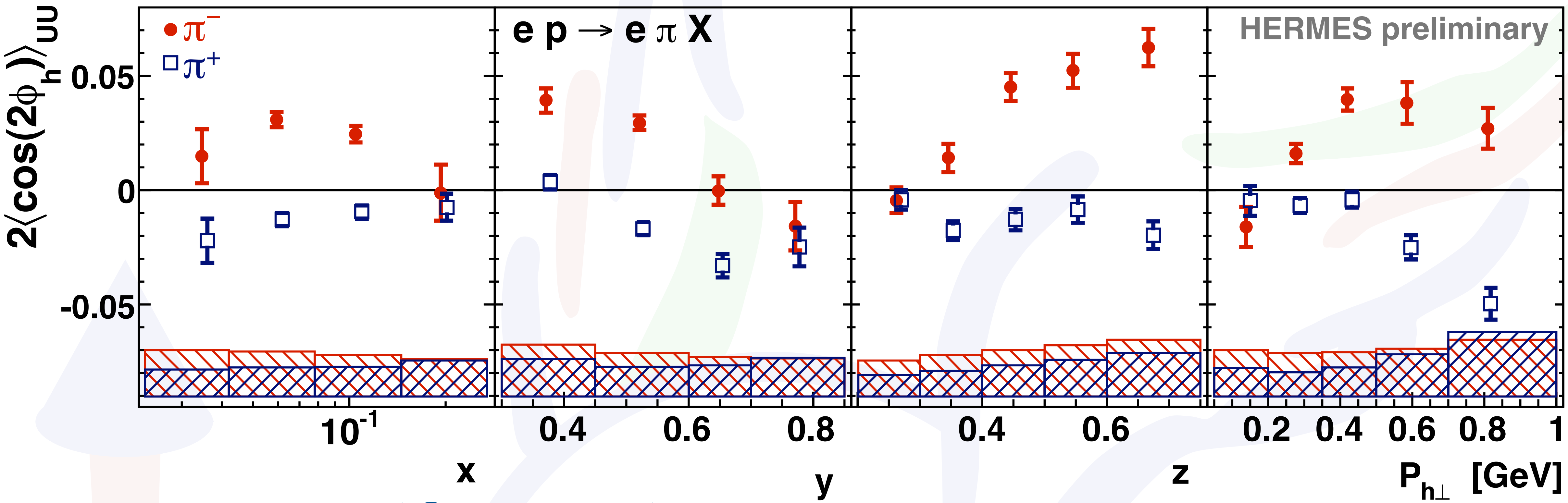
	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

"Boer-Mulders modulation"



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

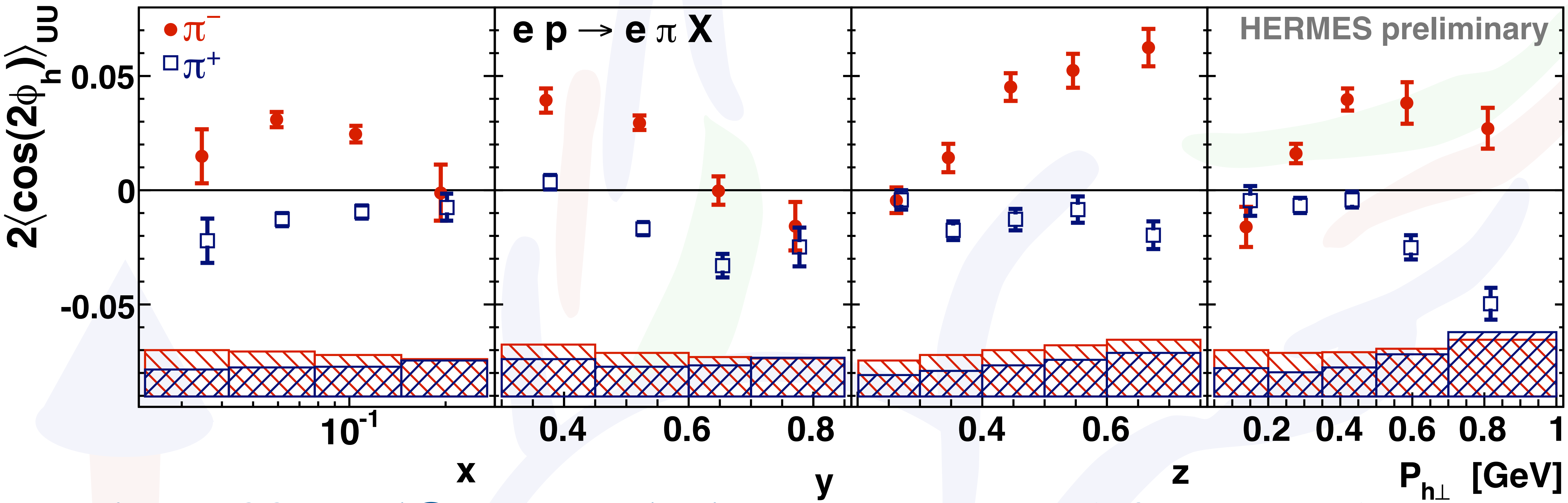
"Boer-Mulders modulation"



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

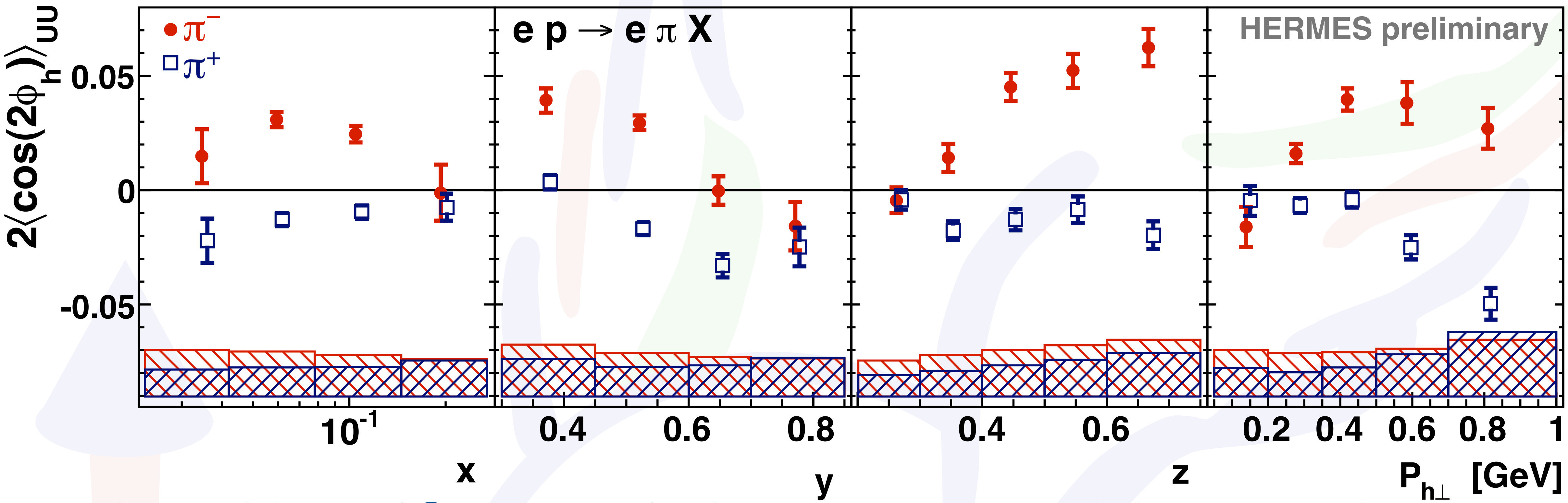
"Boer-Mulders modulation"



- **Cahn effect** (@twist-4) -kinematics modification due to transverse momenta- often **assumed flavor blind**
- large flavor dependence points at **significant** (leading-twist) **Boer-Mulders effect**

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

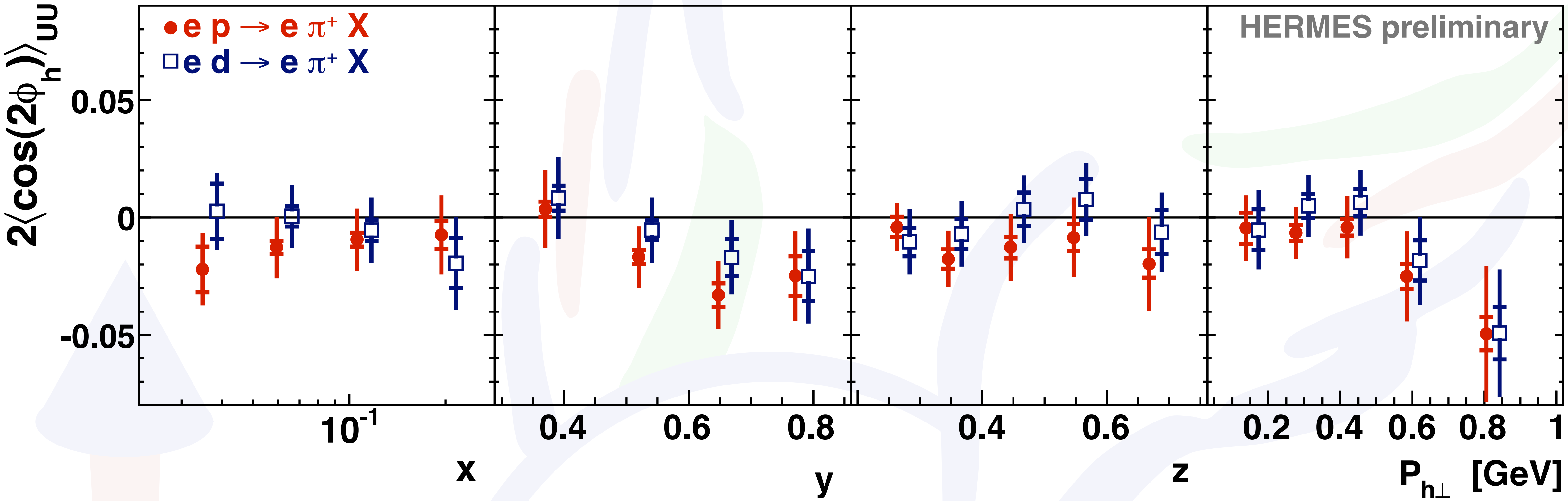
"Boer-Mulders modulation"



- **Cahn effect** (@twist-4) -kinematics modification due to transverse momenta- often **assumed flavor blind**
- 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}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

"Boer-Mulders modulation"



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

	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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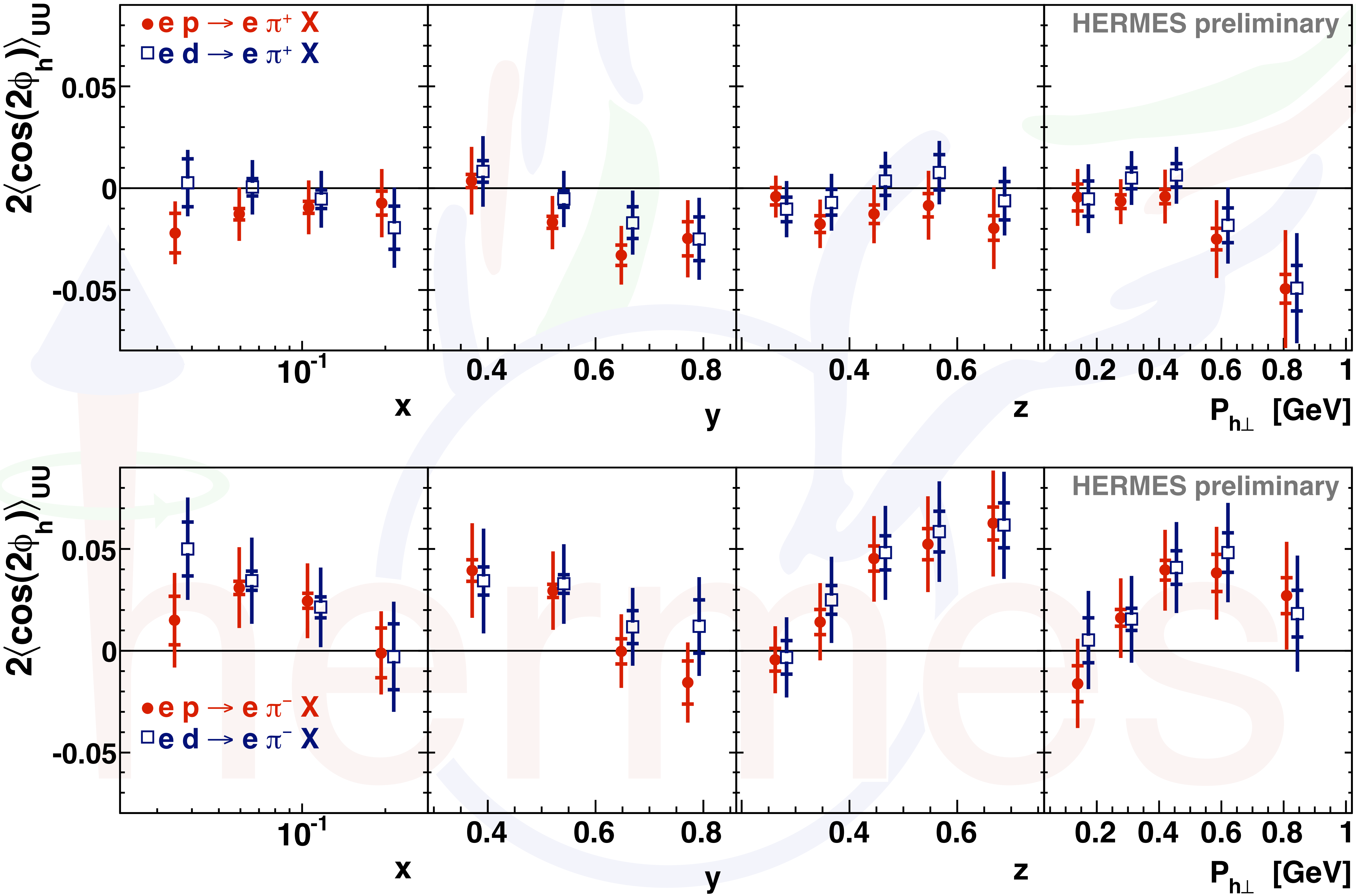
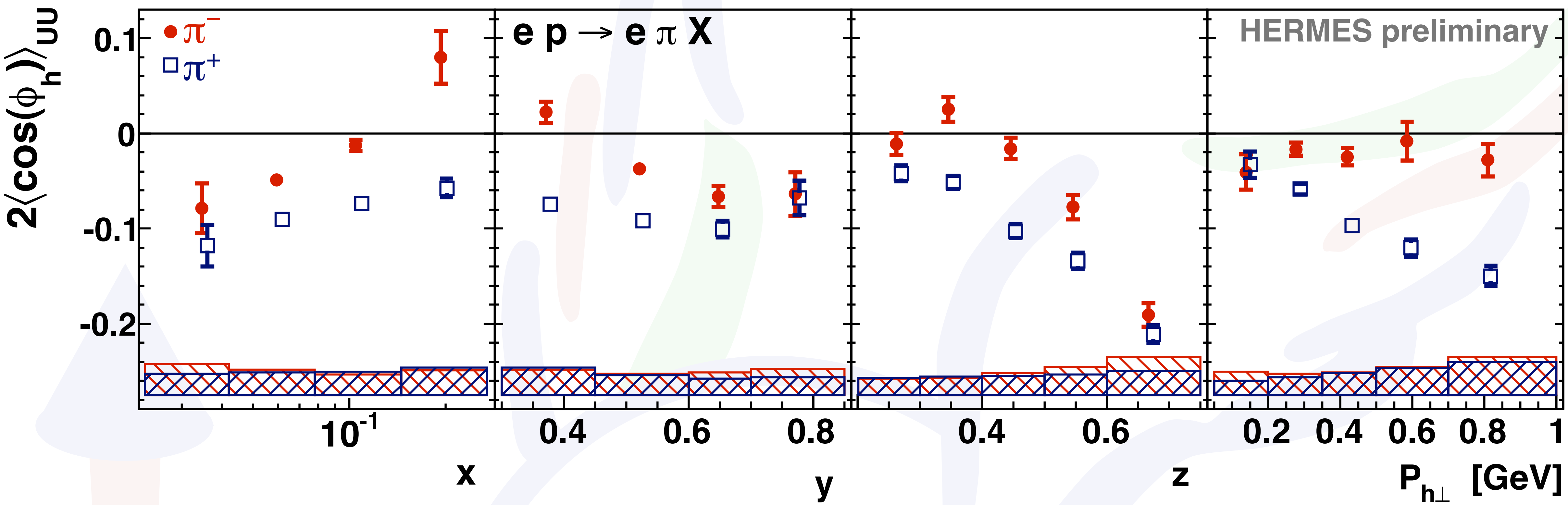


"Cahn modulation"

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



- no dependence on hadron charge expected for Cahn effect

➡ flavor dependence of transverse momentum

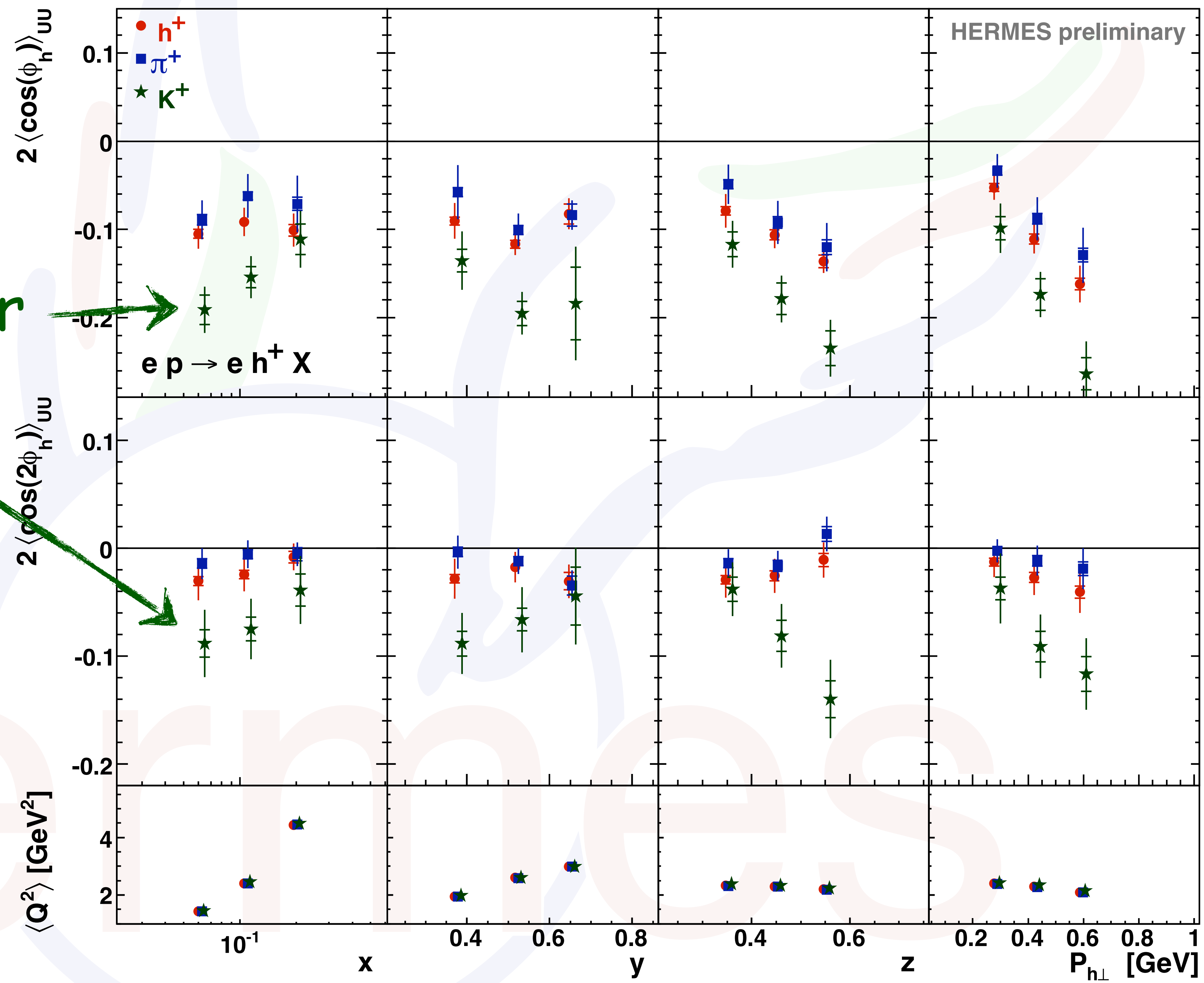
➡ sign of Boer-Mulders in cosϕ modulation
(indeed, overall pattern resembles B-M modulations)

➡ 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



	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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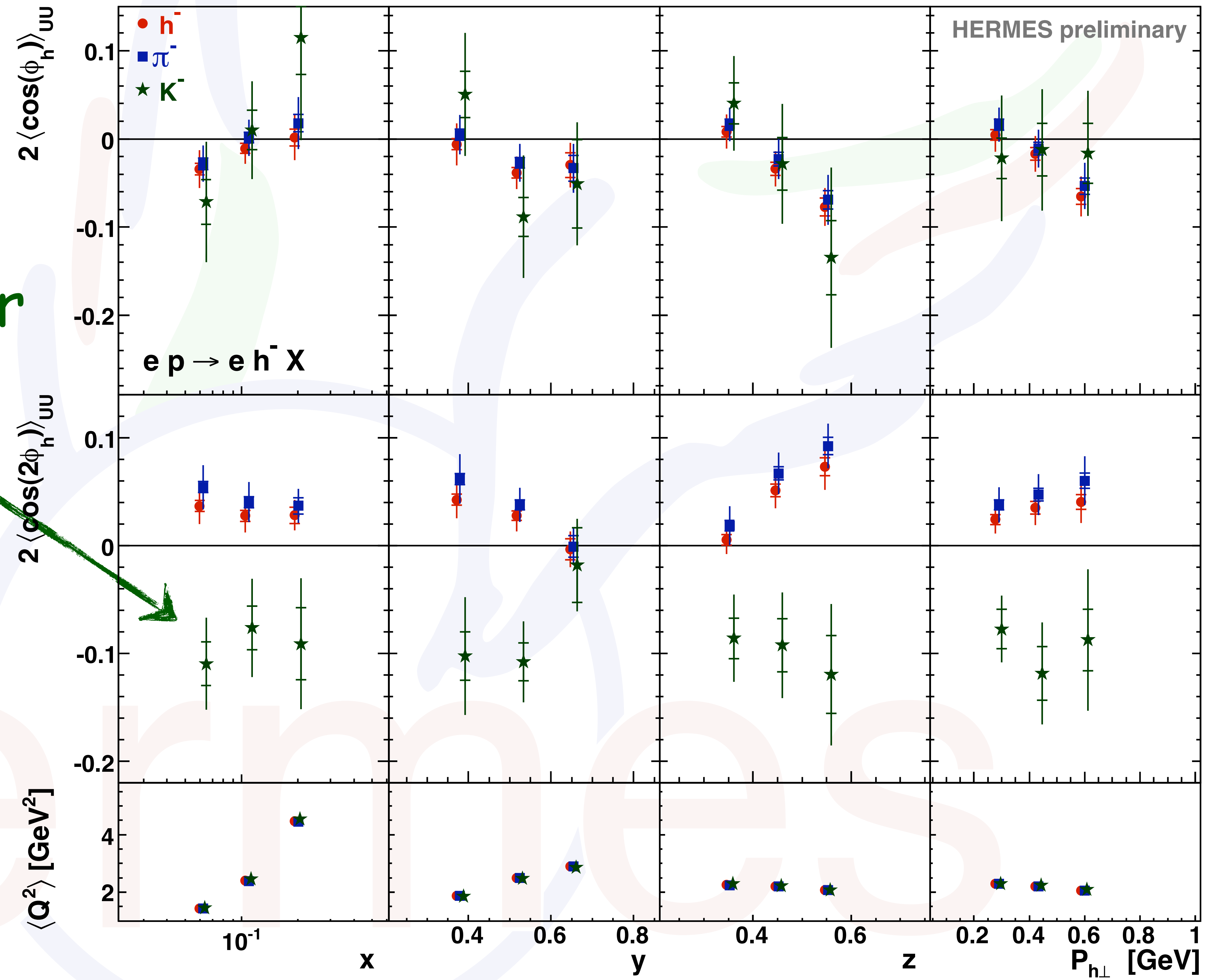
intriguing behavior for kaons

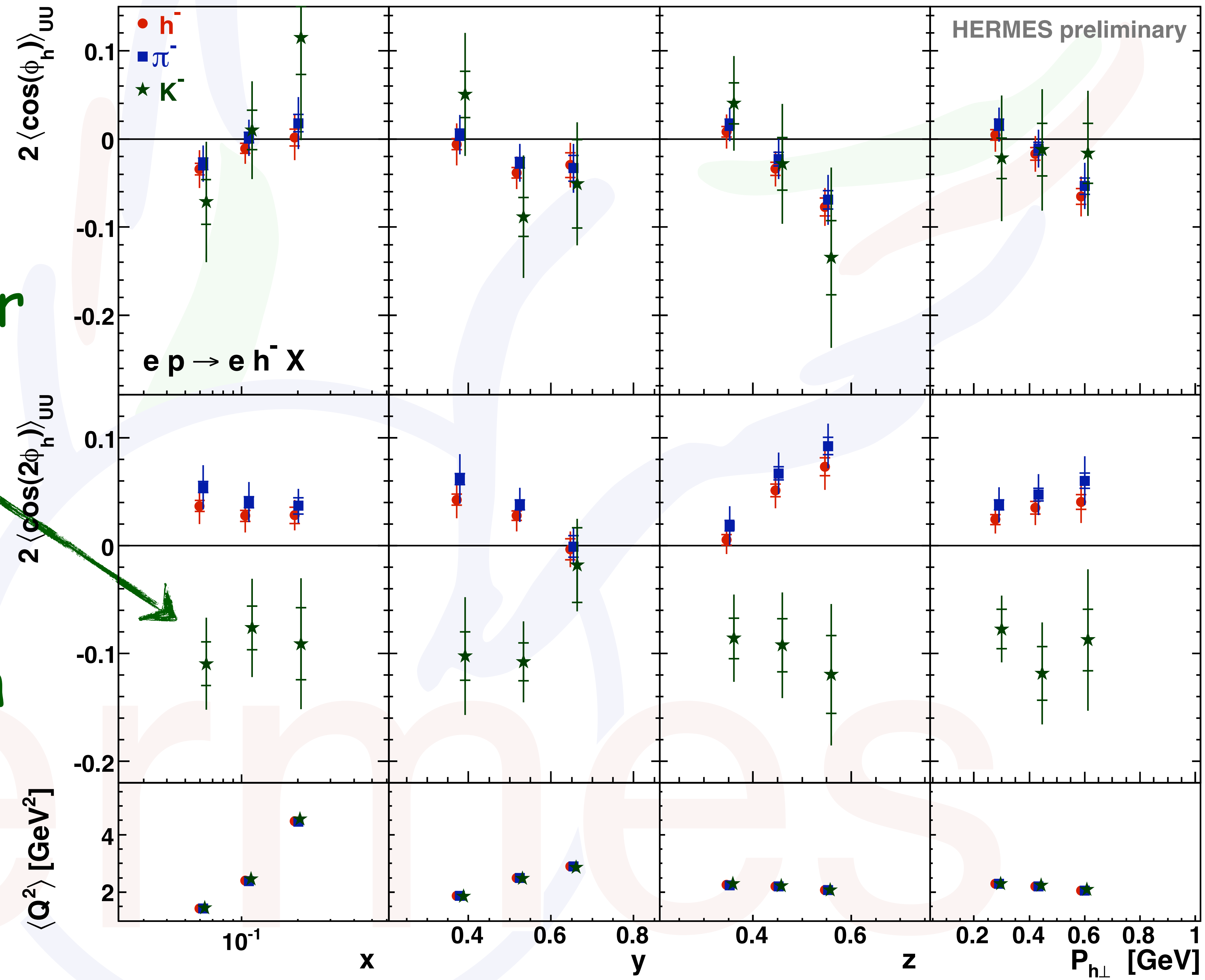


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1,\ h_{1T}^\perp$

strange results

intriguing behavior for kaons

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



... add more transverse spin ...

	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

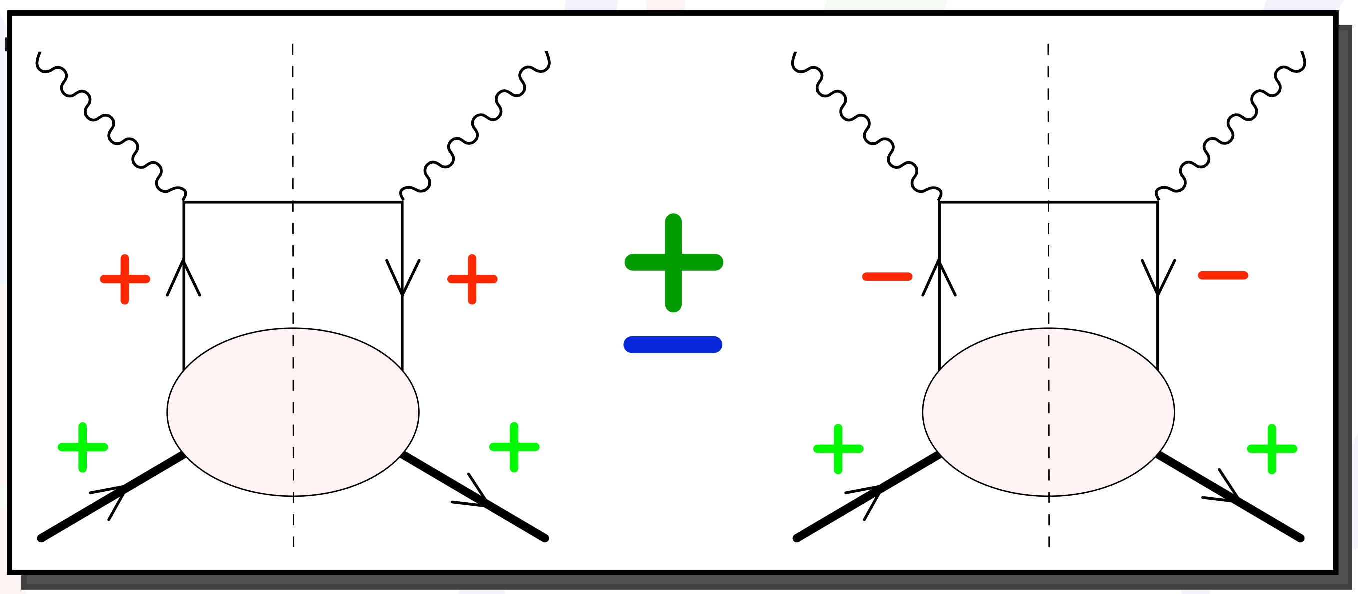
chiral-odd transversity involves quark helicity flip

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

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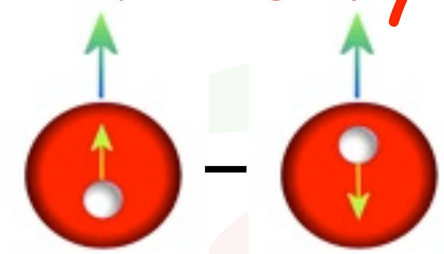
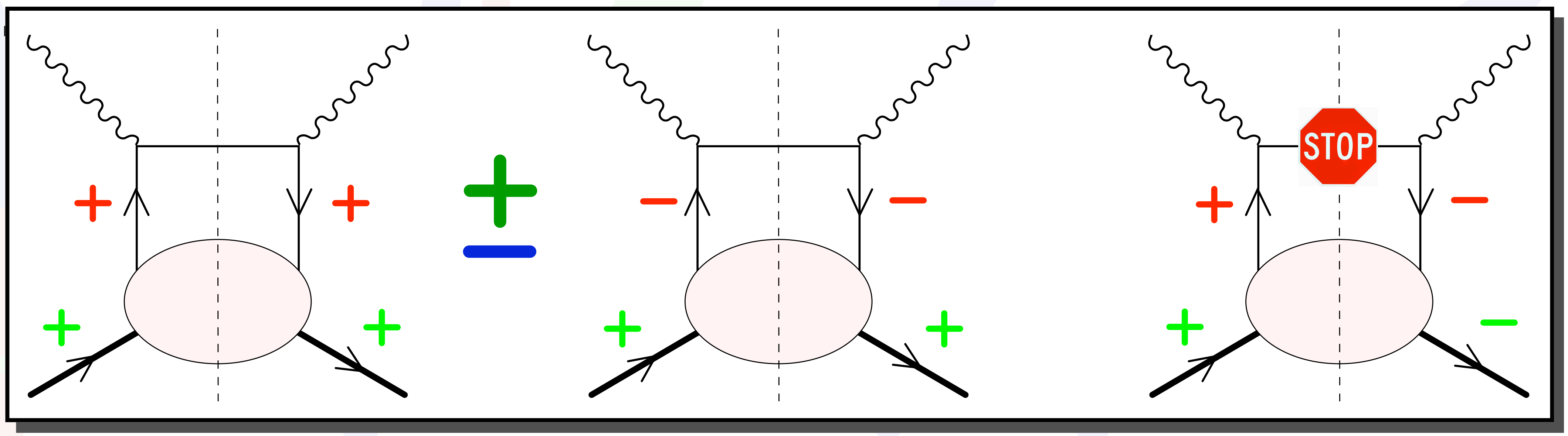
$f_1^q =$  $g_1^q =$  $h_1^q =$ 



	U	L	T
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Transversity distribution

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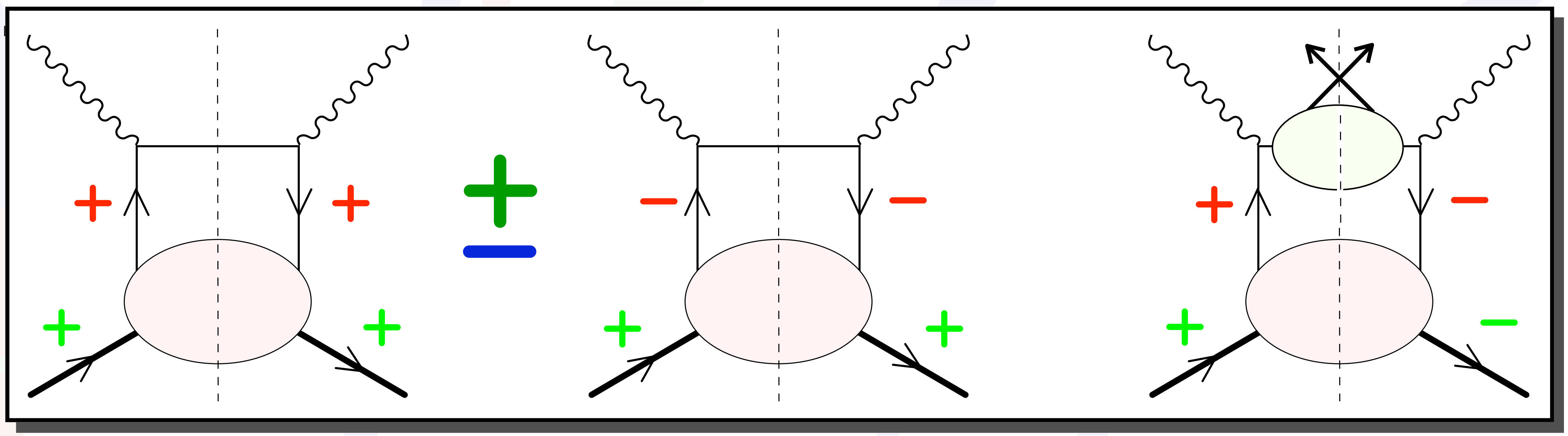
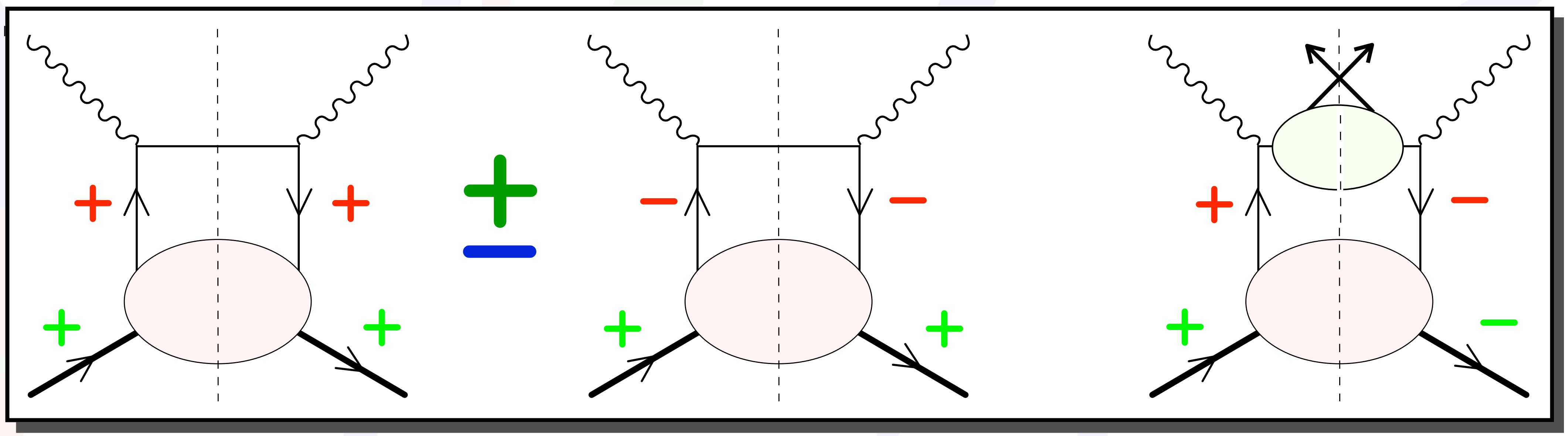


need to couple to chiral-odd fragmentation function:

	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



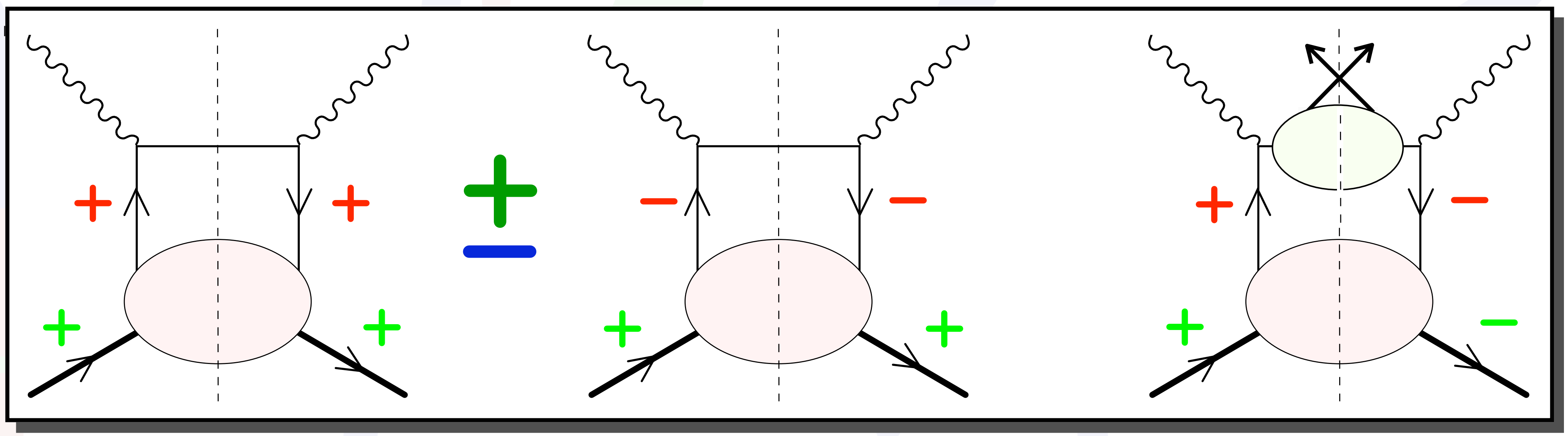
need to couple to chiral-odd fragmentation function:

- **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



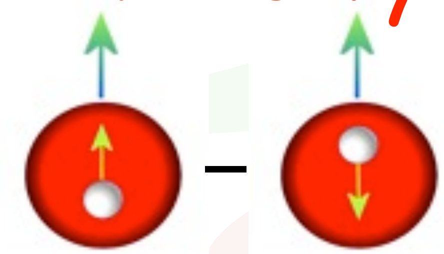
need to couple to chiral-odd fragmentation function:

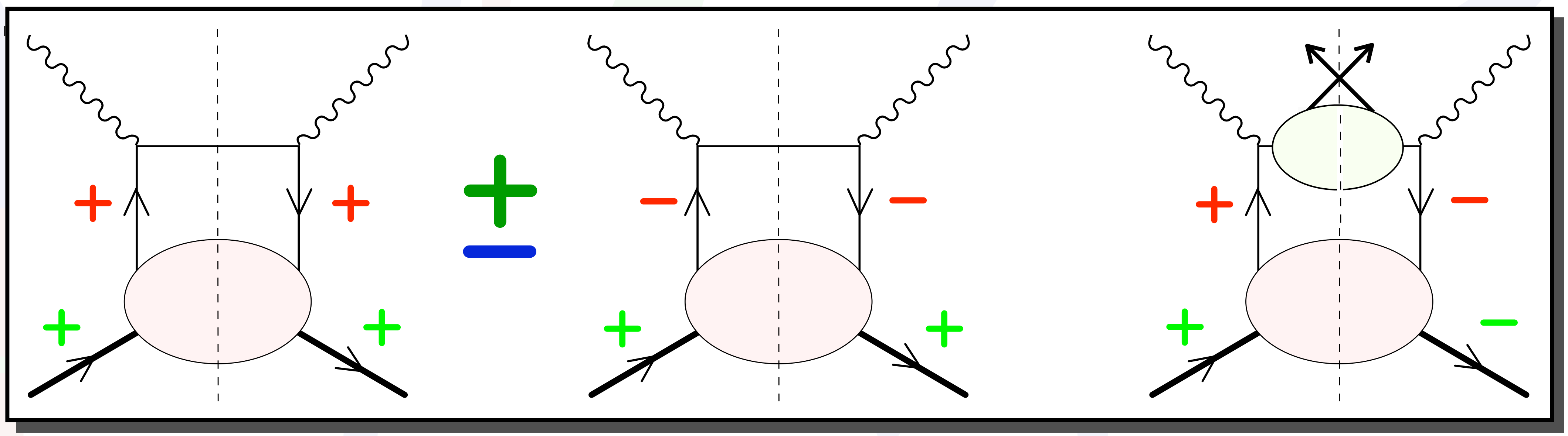
- ☐ **transverse spin transfer** (polarized final-state hadron)
- ☑ **2-hadron fragmentation**

	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

$f_1^q =$  $g_1^q =$  $h_1^q =$ 



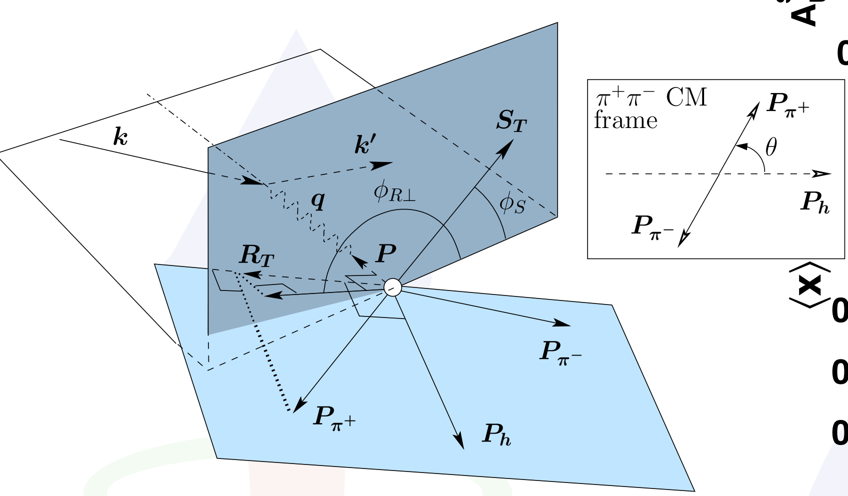
need to couple to chiral-odd fragmentation function:

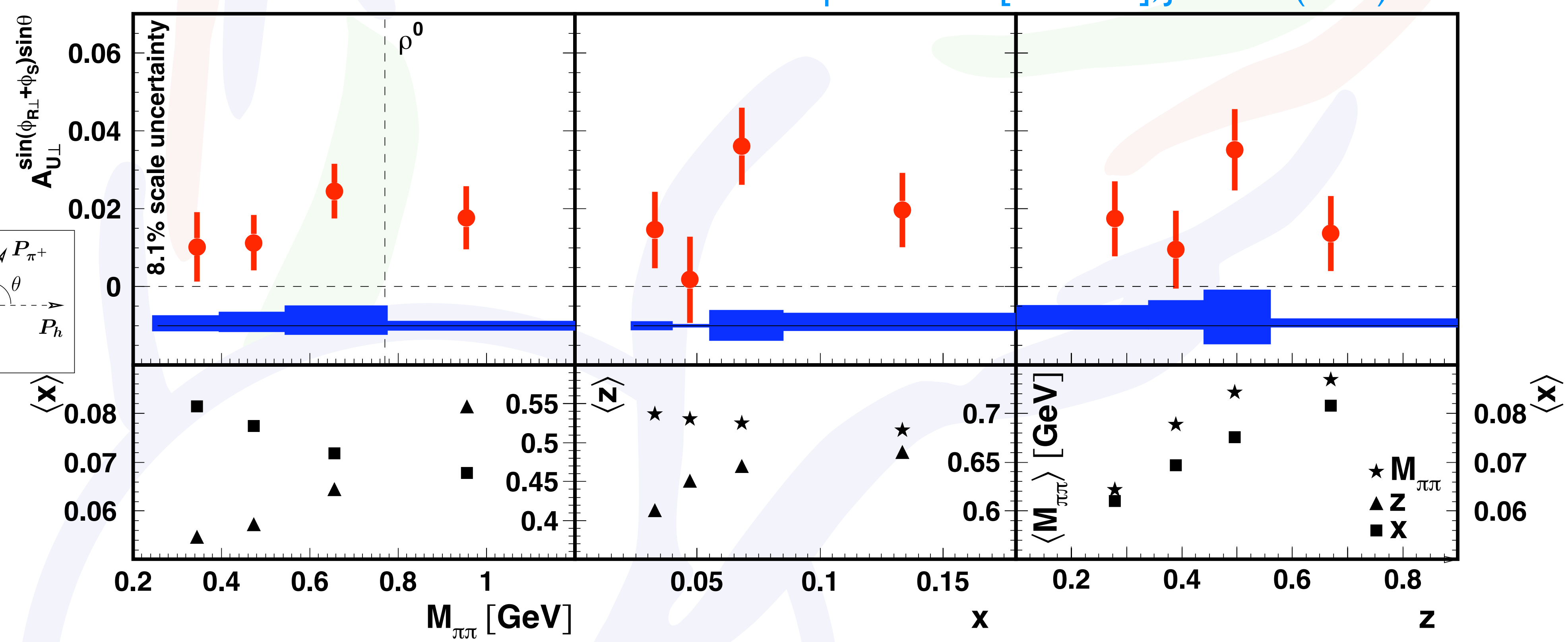
- ☐ **transverse spin transfer** (polarized final-state hadron)
- ☑ **2-hadron fragmentation**
- ☑ **Collins fragmentation**

	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 (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, $h_{1T}^\perp$

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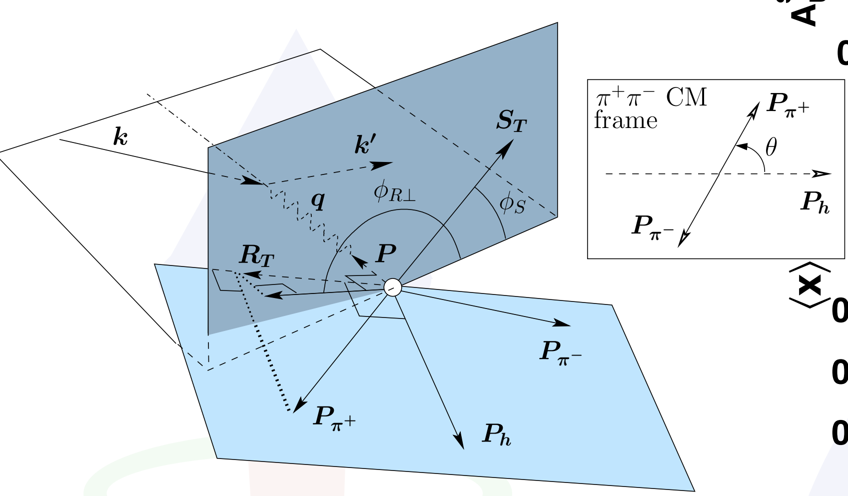

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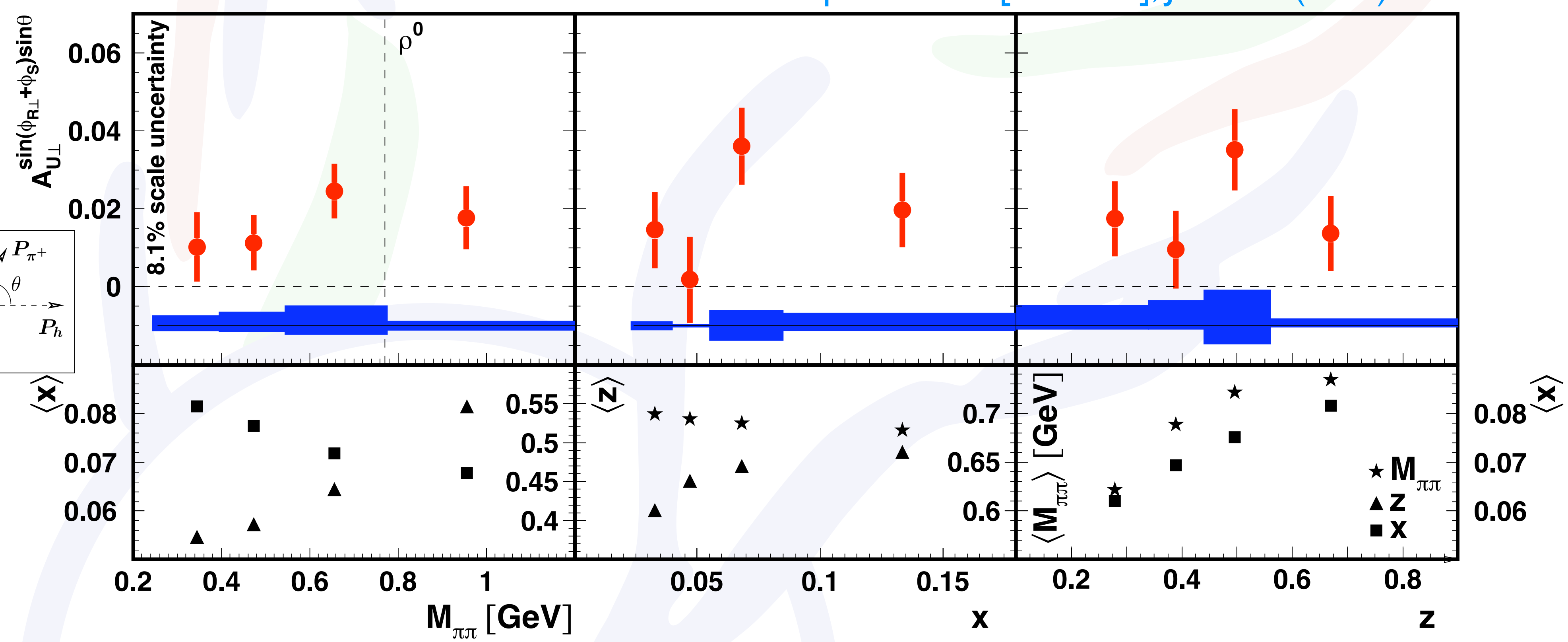
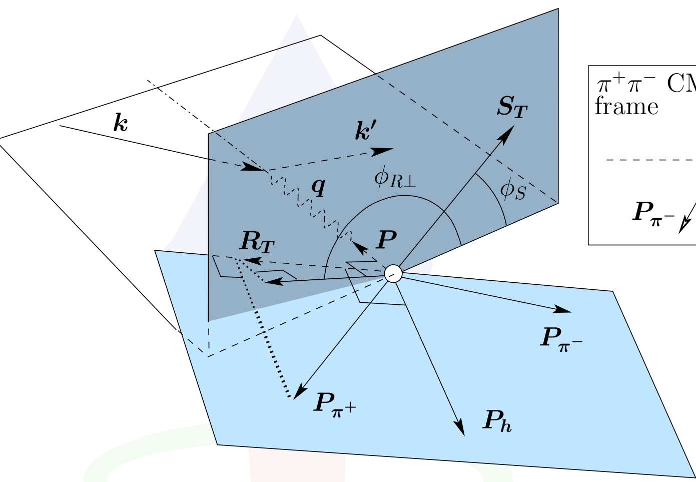


☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS

	U	L	T
U	f_1		$h_1^{\perp}$
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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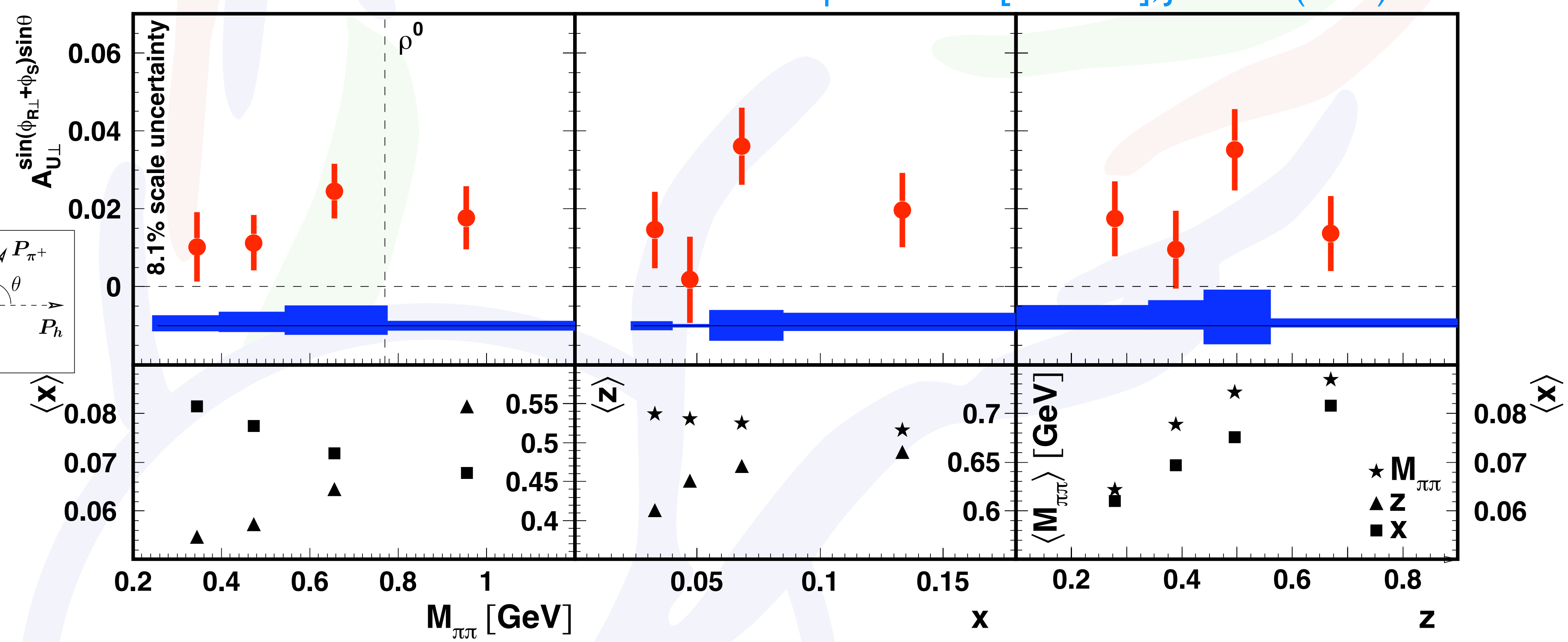
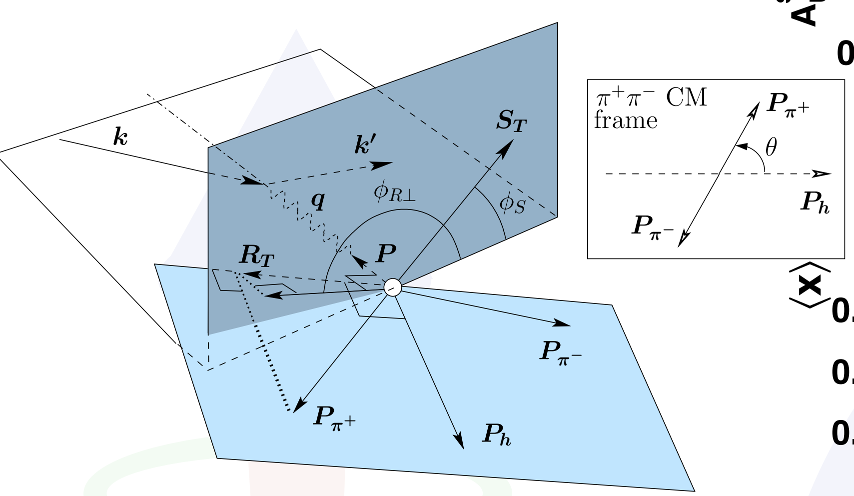


☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS

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

	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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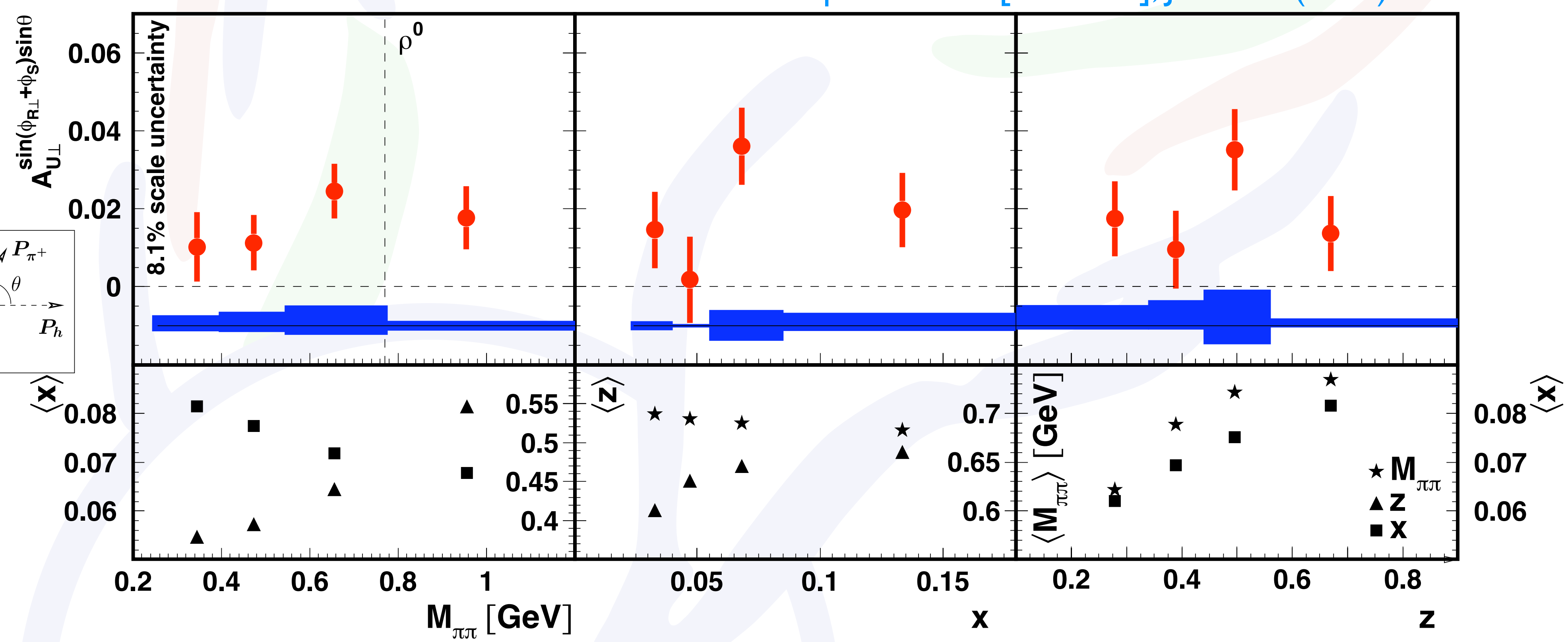
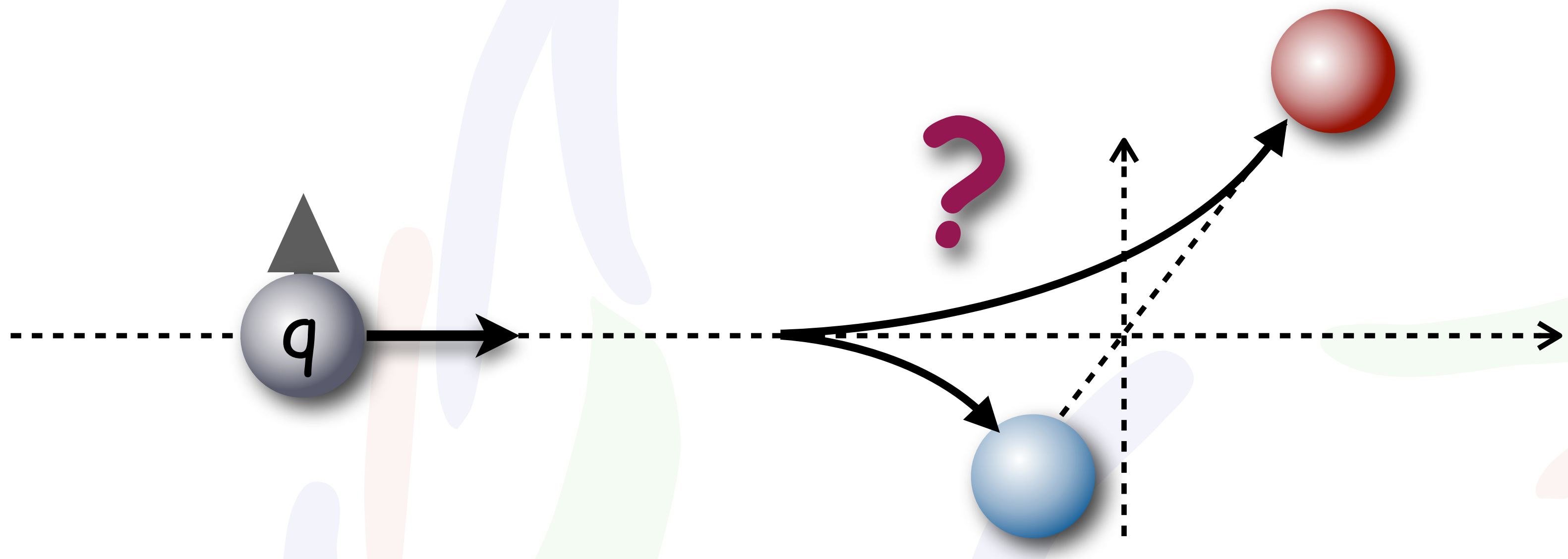


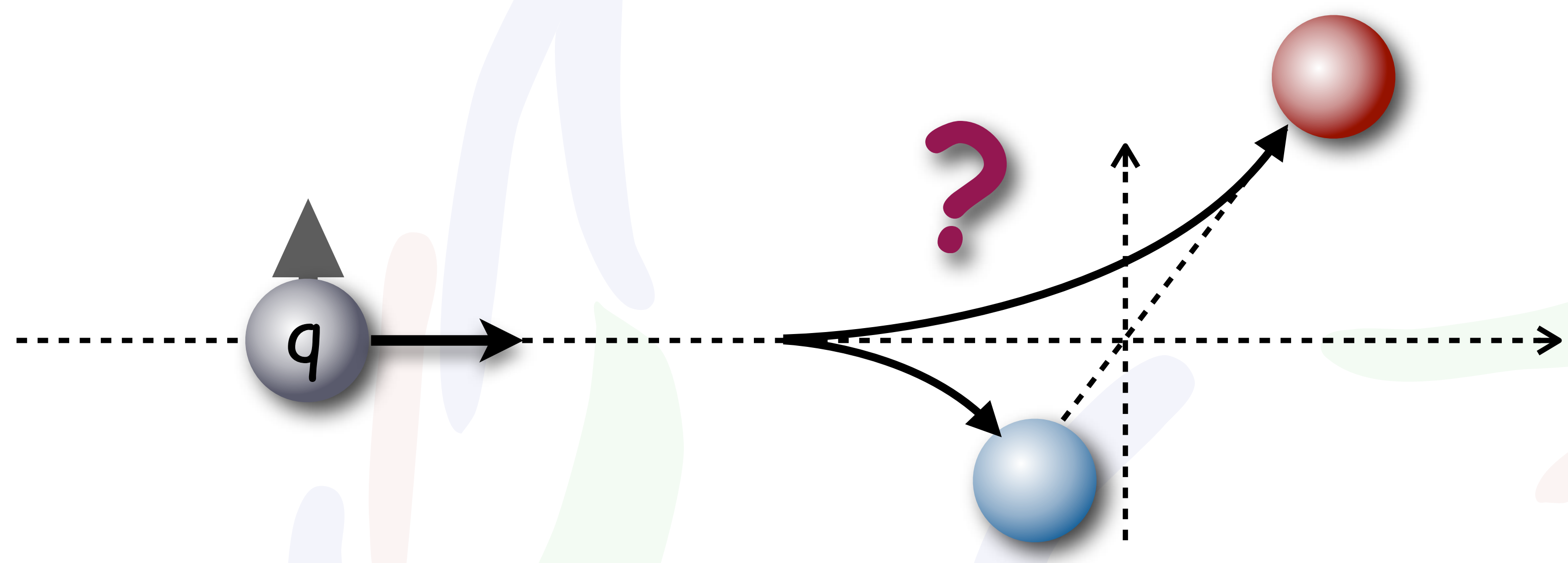
- ☑ first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS
- ☑ invariant-mass dependence rules out Jaffe prediction of sign change at ρ mass
- ☐ more asymmetry amplitudes coming out soon

Collins fragmentation

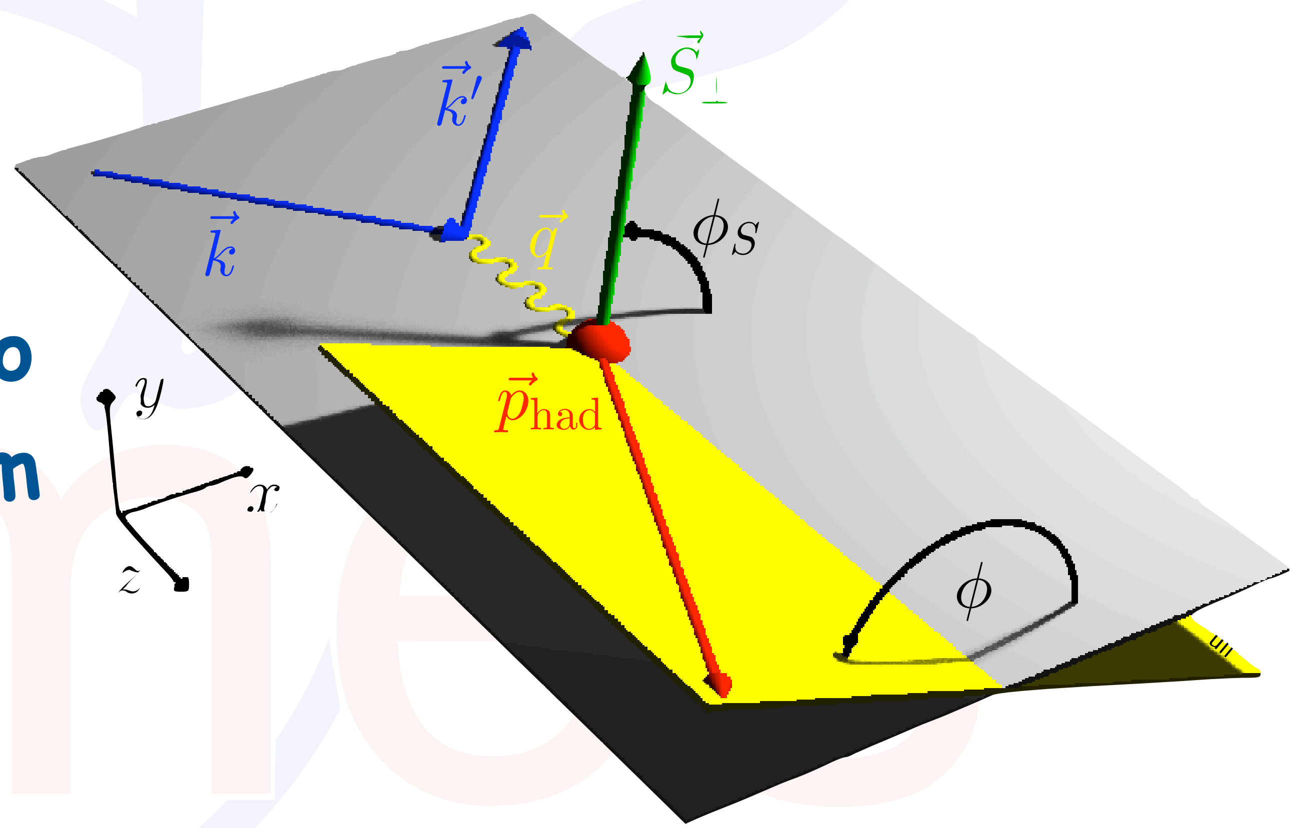


- spin-dependence in fragmentation
- left-right asymmetry in hadron direction transverse to both quark spin and momentum

Collins fragmentation



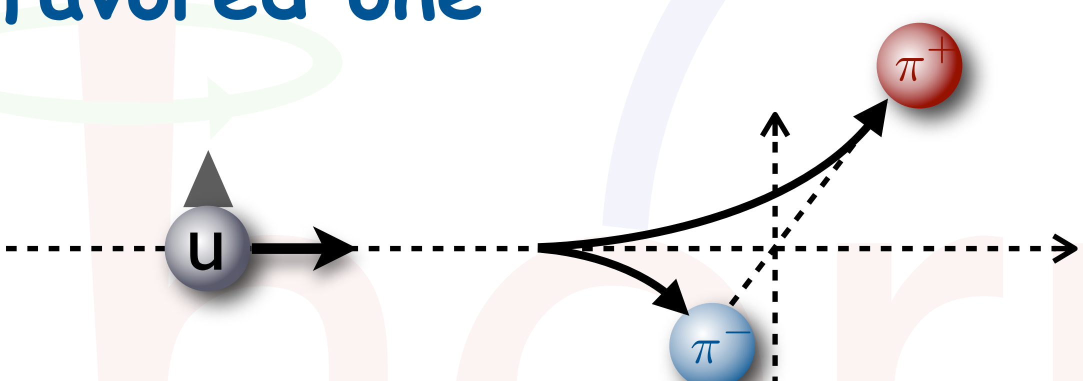
- spin-dependence in fragmentation
- left-right asymmetry in hadron direction transverse to both quark spin and momentum
- leads to particular azimuthal distribution of hadrons produced in DIS



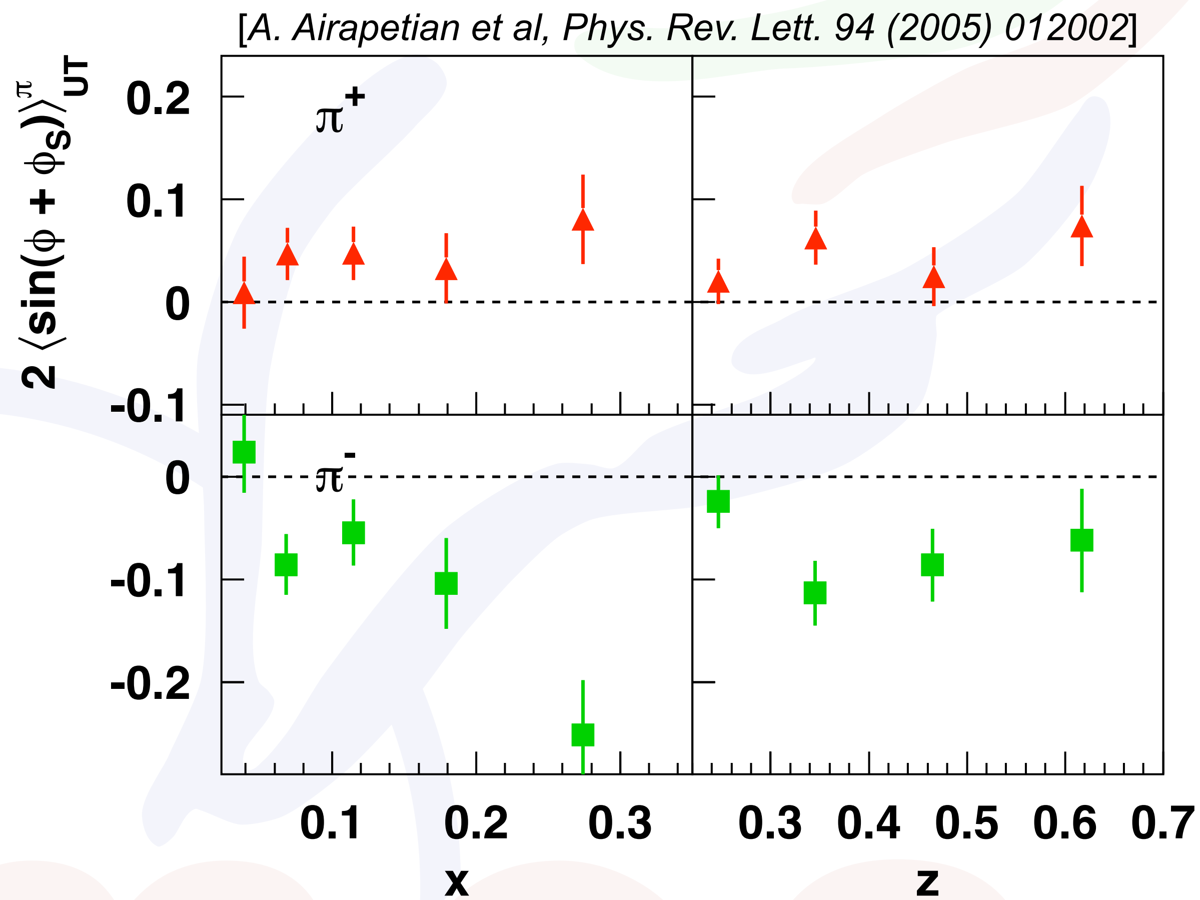
	U	L	T
U	f_1		$h_1^{\perp}$
L		g_{1L}	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1, $h_{1T}^{\perp}$

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



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

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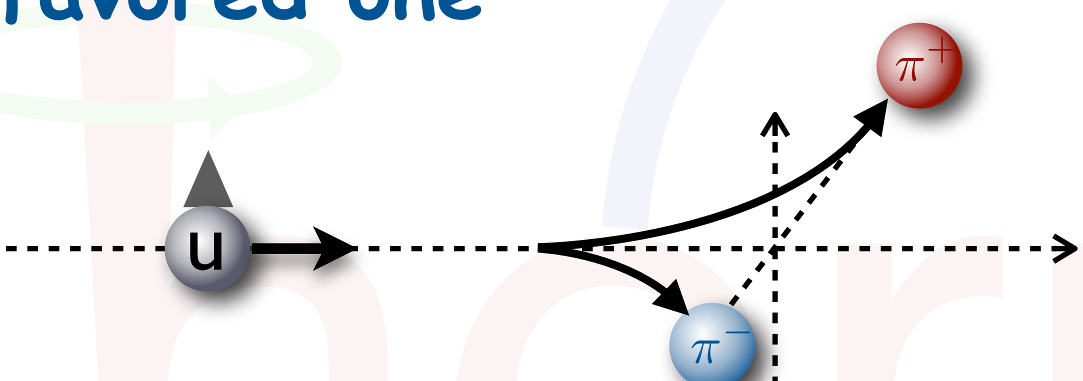
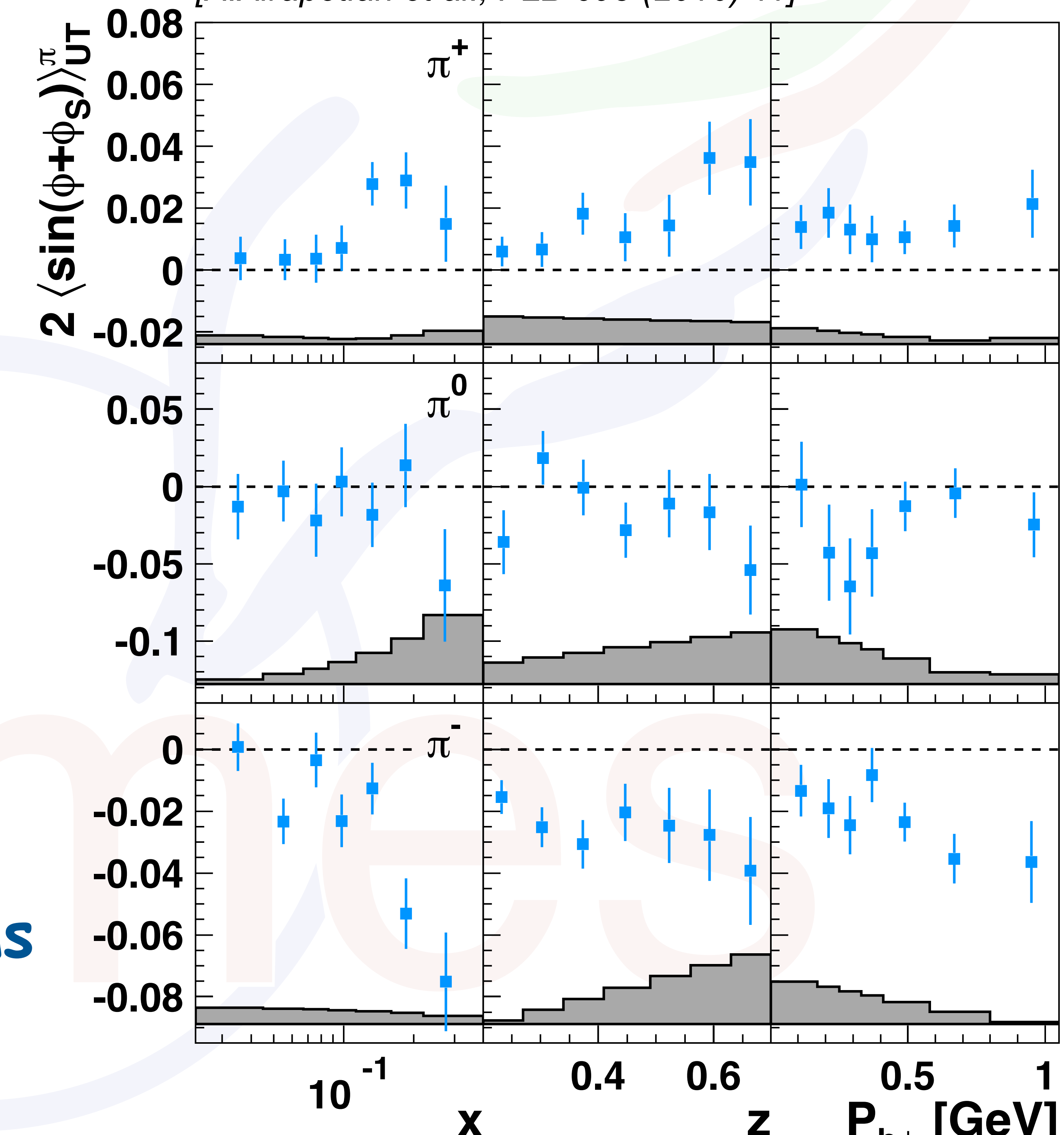


- leads to various cancellations in SSA observables

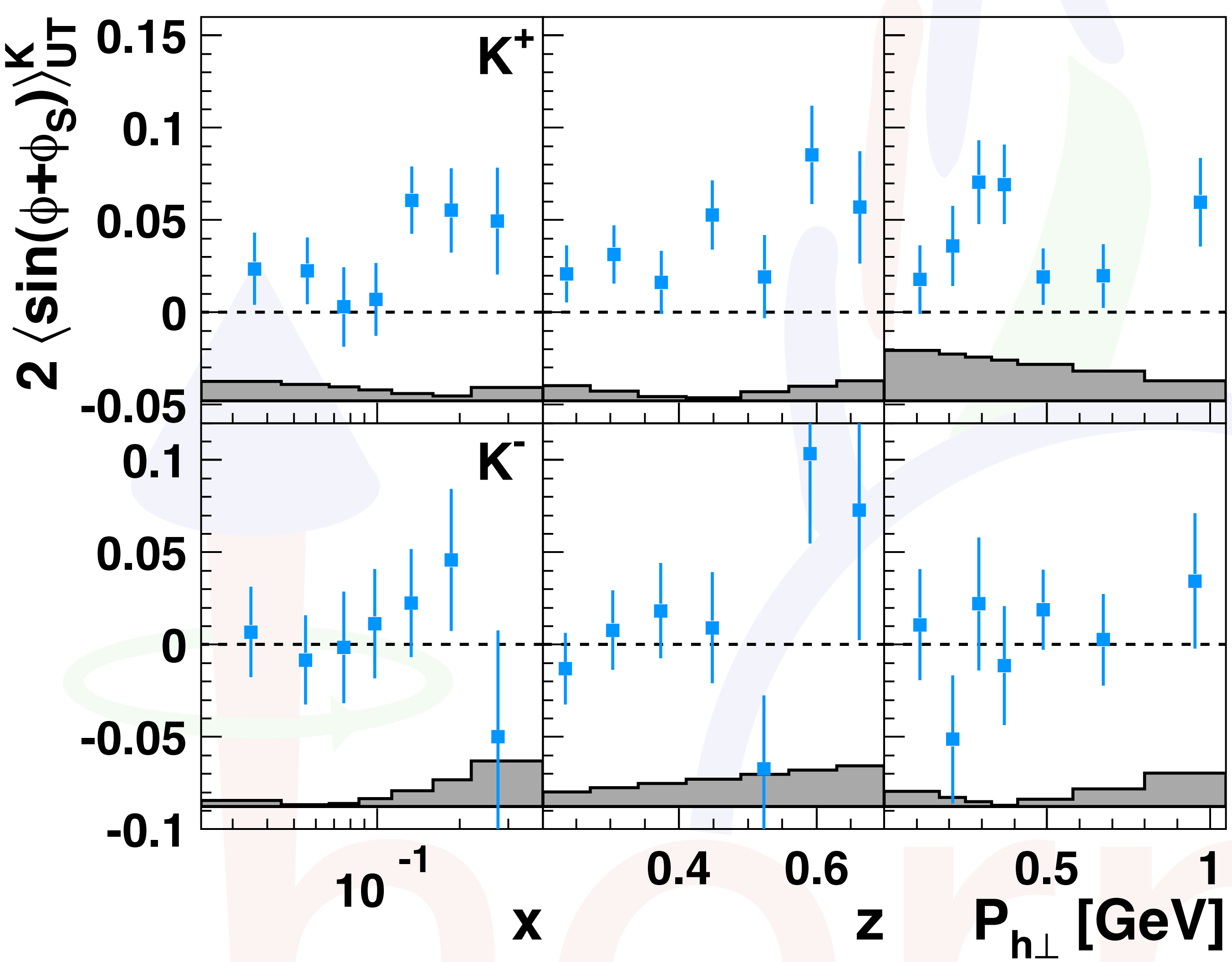
[A.Airapetian et al., PLB 693 (2010) 11]

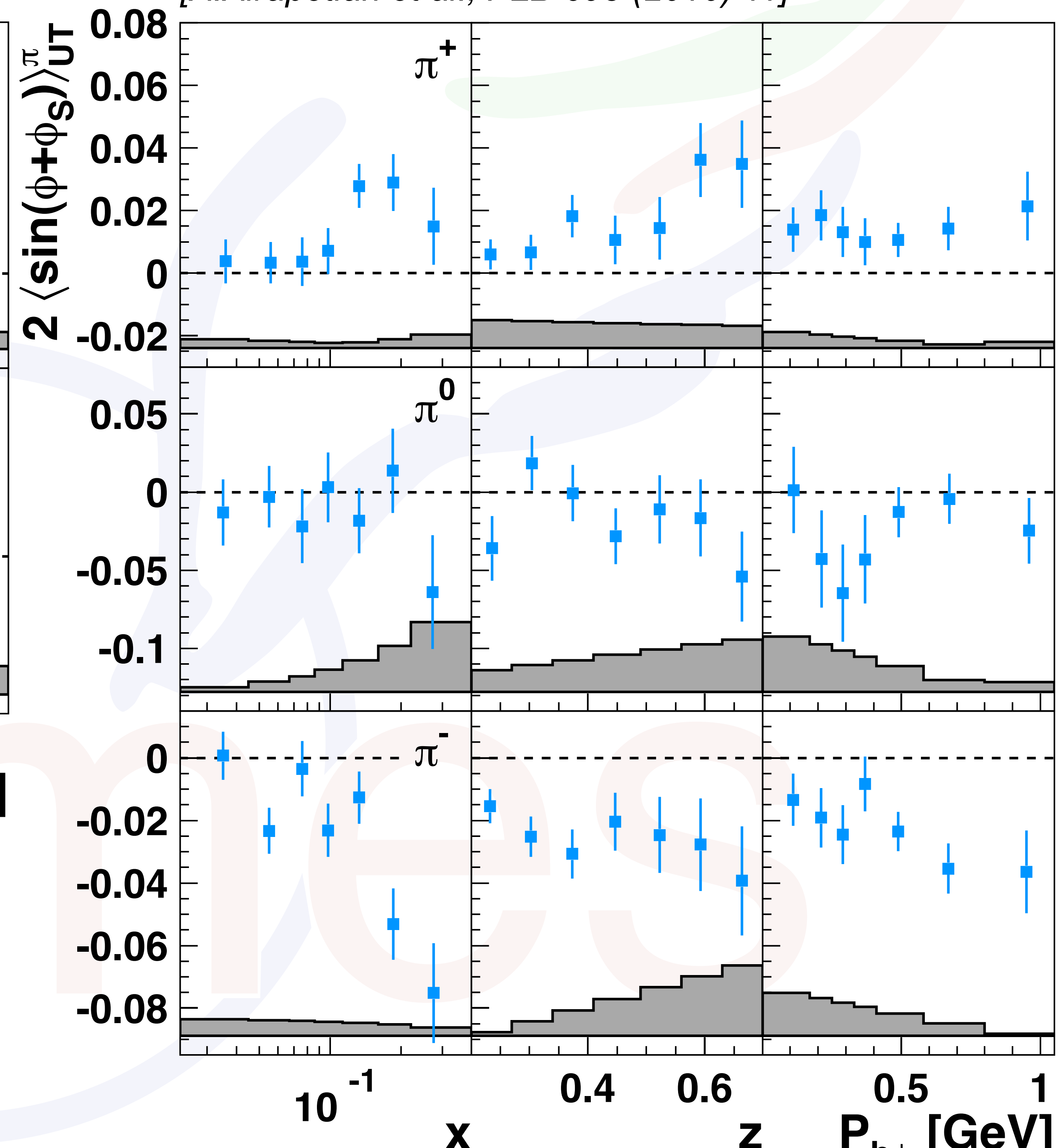


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$

Transversity distribution (Collins fragmentation)

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



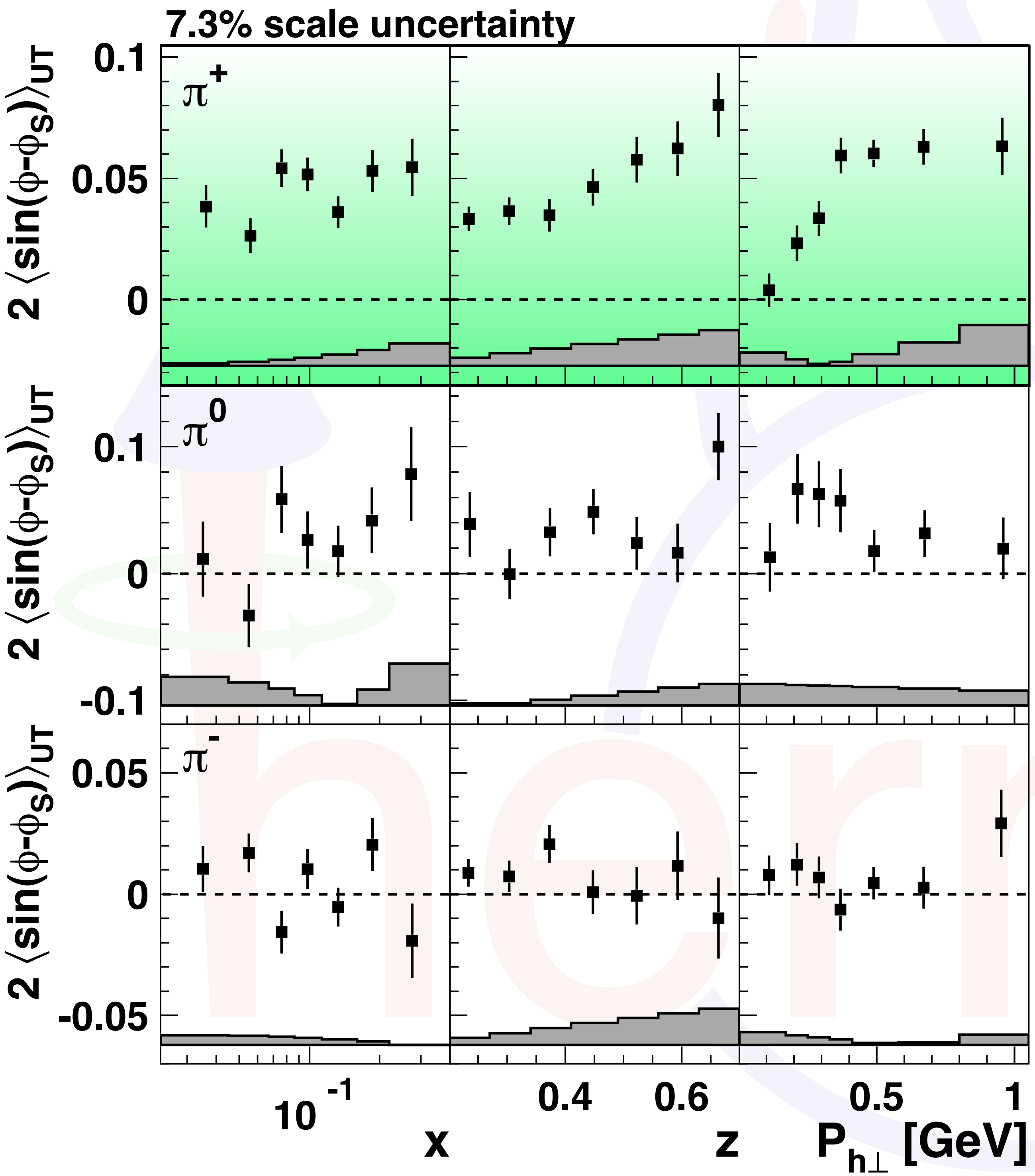


- significantly non-zero amplitudes also for K^+

	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		$h_1^\perp$
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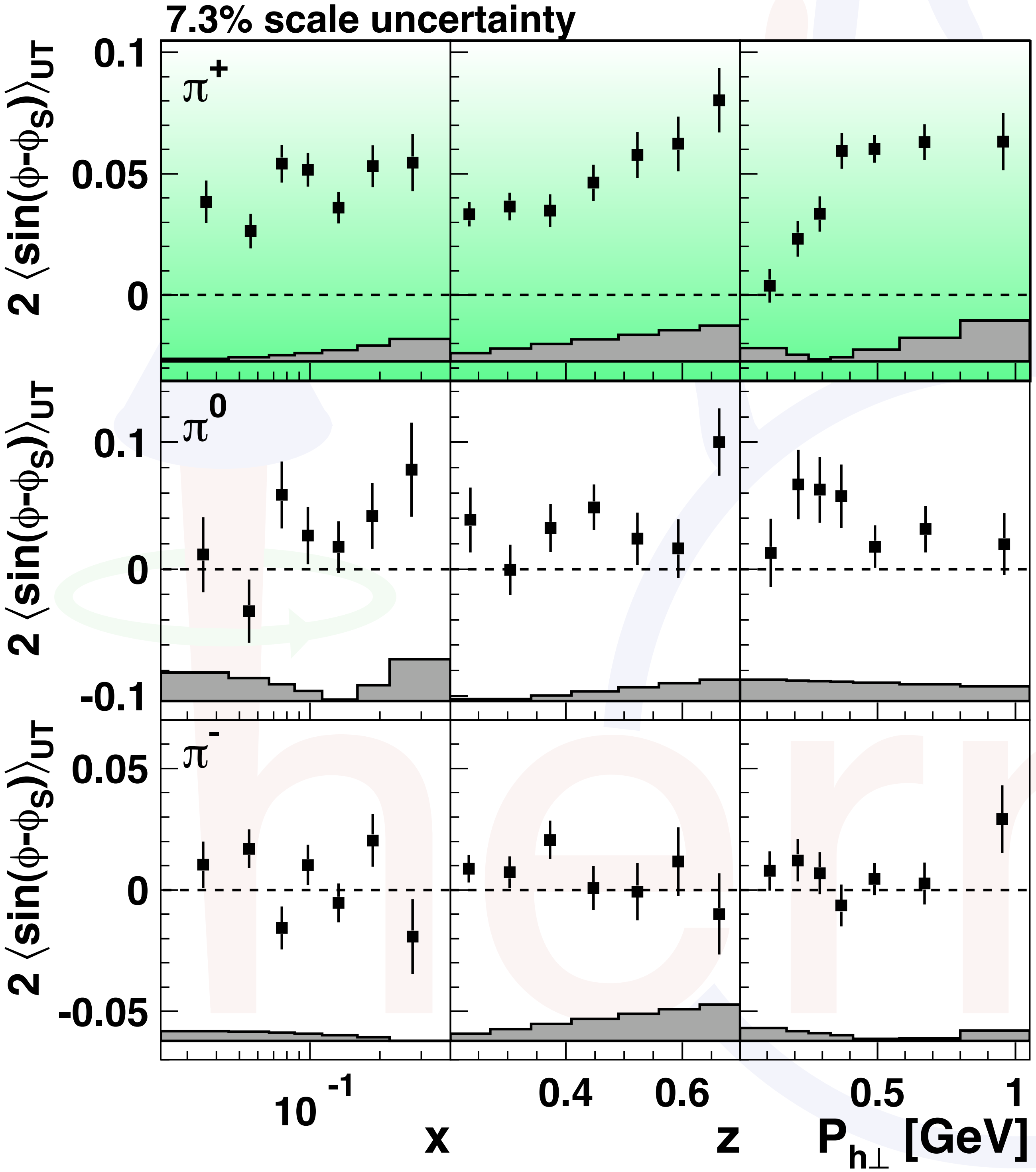

π^+ dominated by u-quark scattering:

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

☛ **u-quark Sivers DF < 0**

	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

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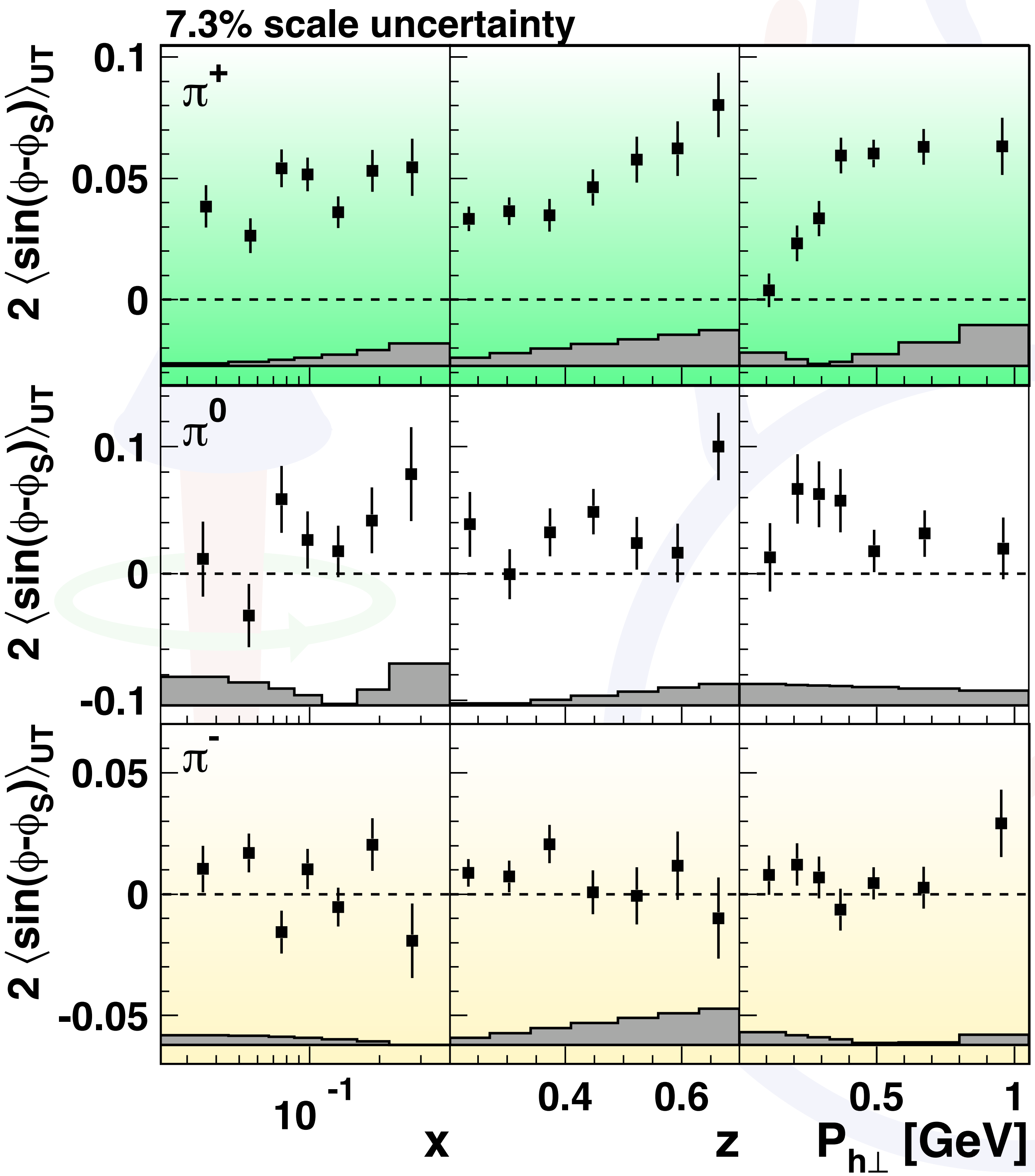

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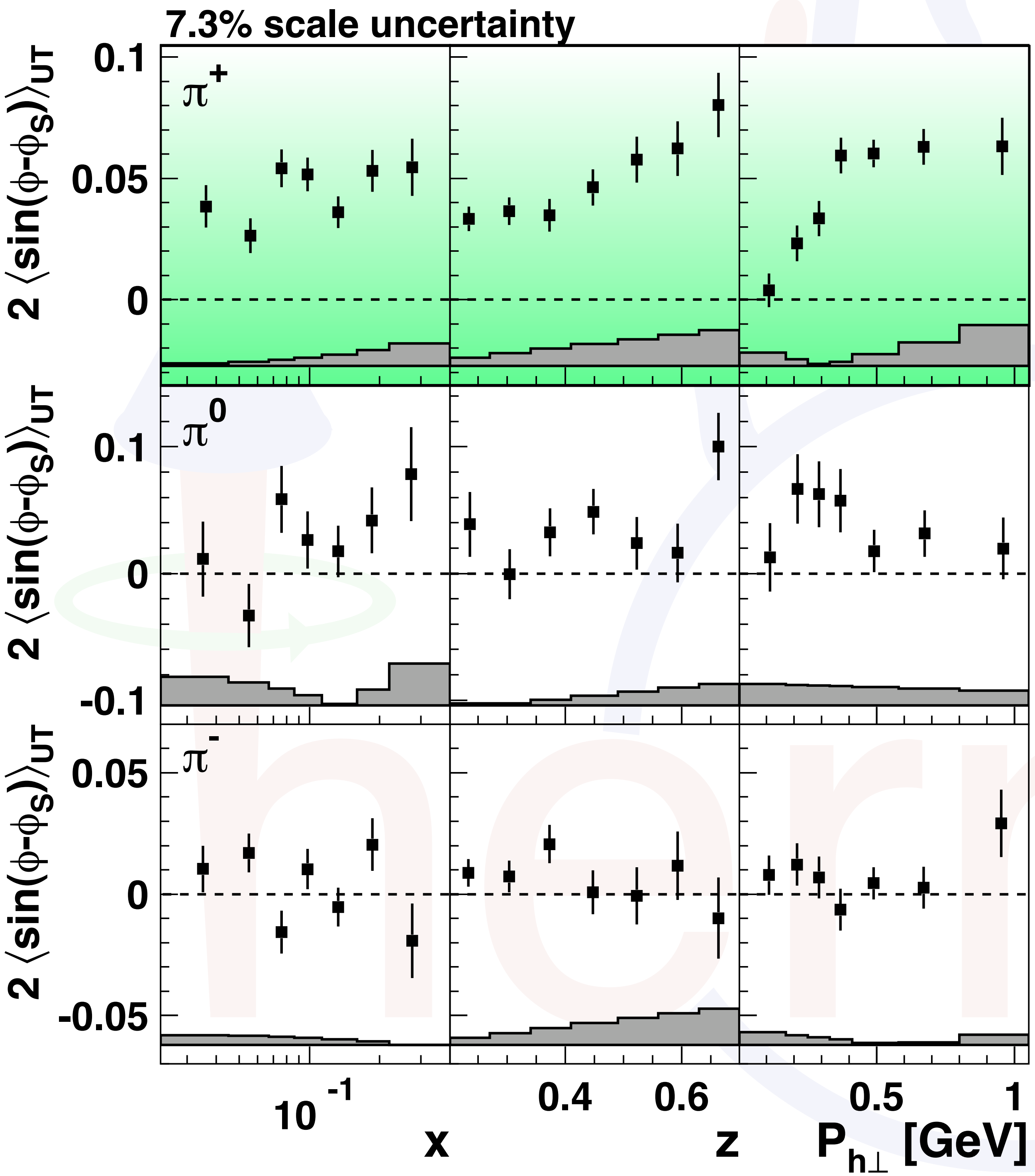
☛ u-quark Sivers DF < 0

☛ 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

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



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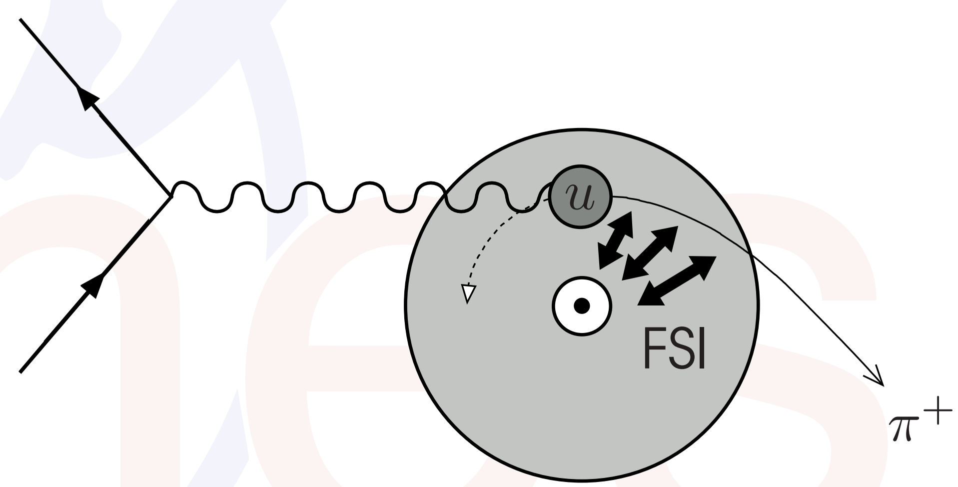

[*M. Burkardt*, Phys. Rev. D66 (2002) 114005]

	U	L	T
U	f_1		$h_1^\perp$
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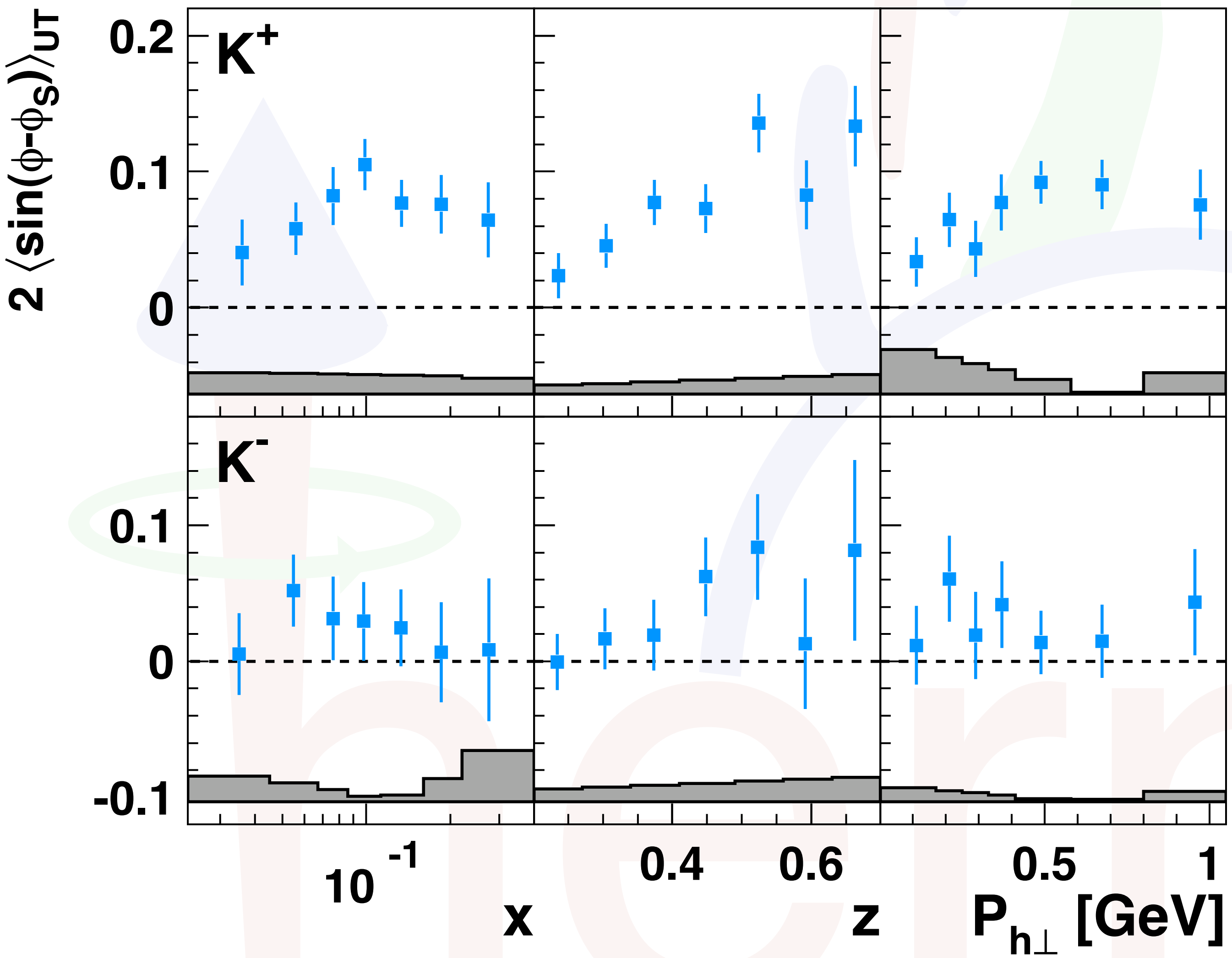
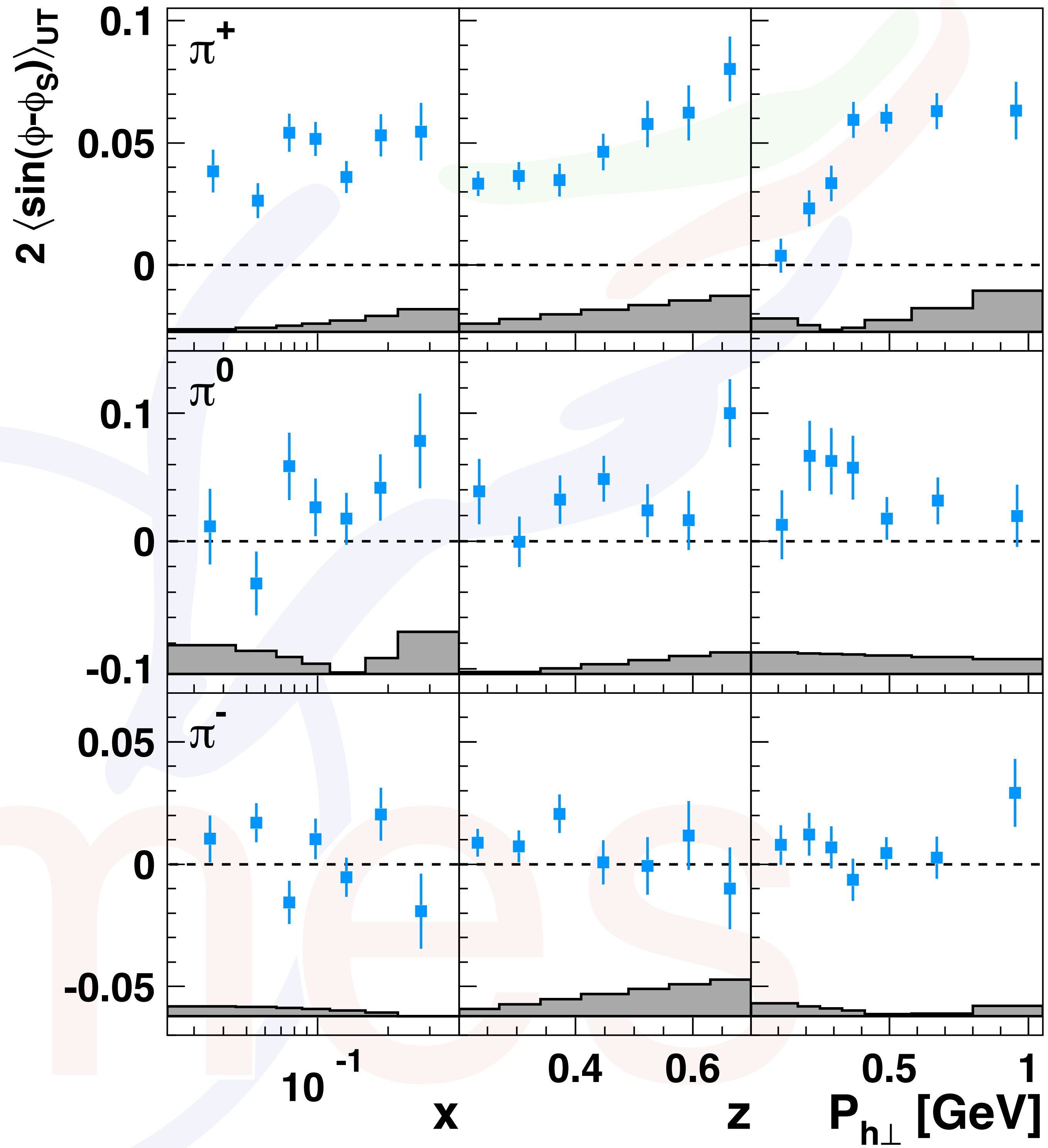
The kaon Sivers amplitudes





The kaon Sivers amplitudes

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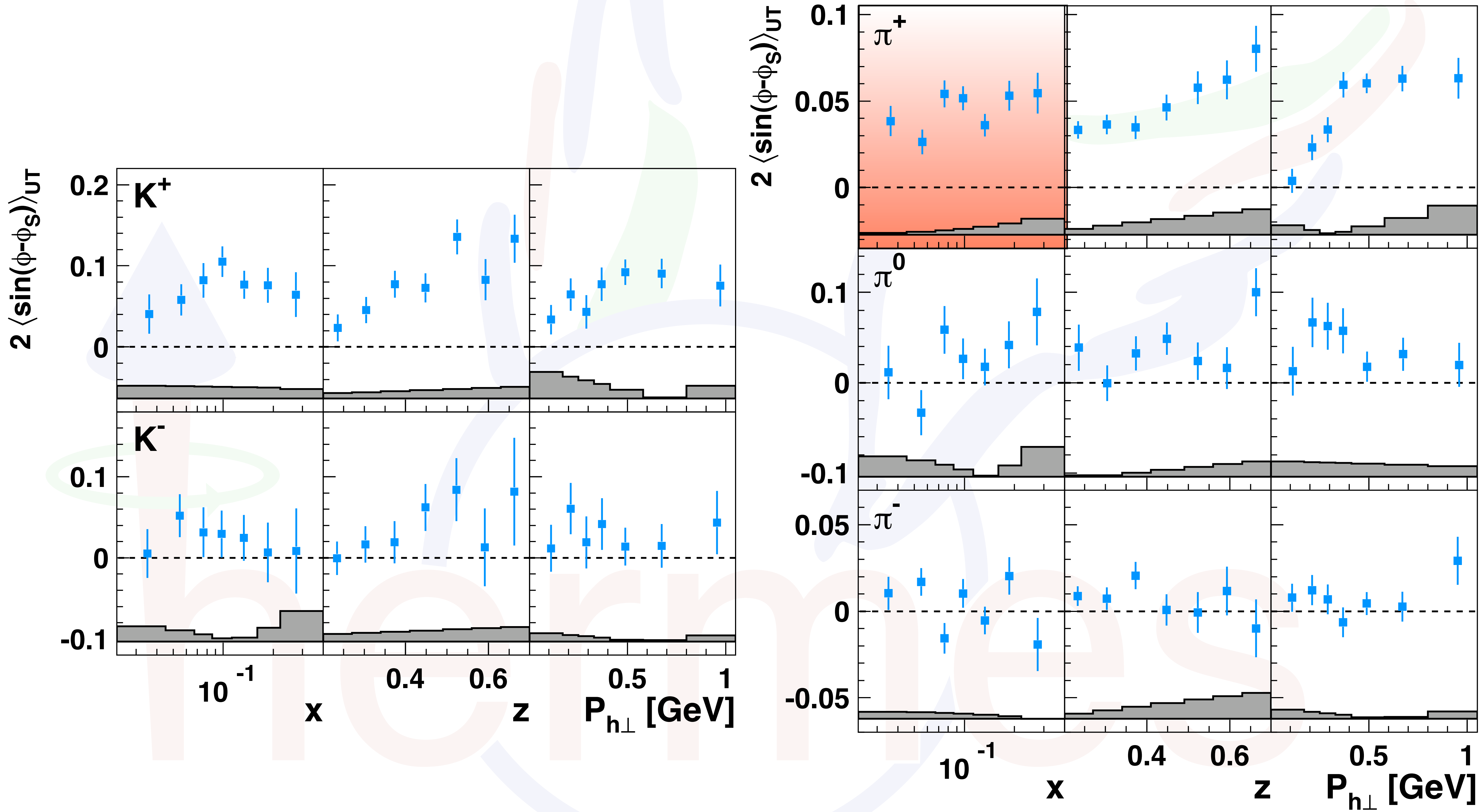
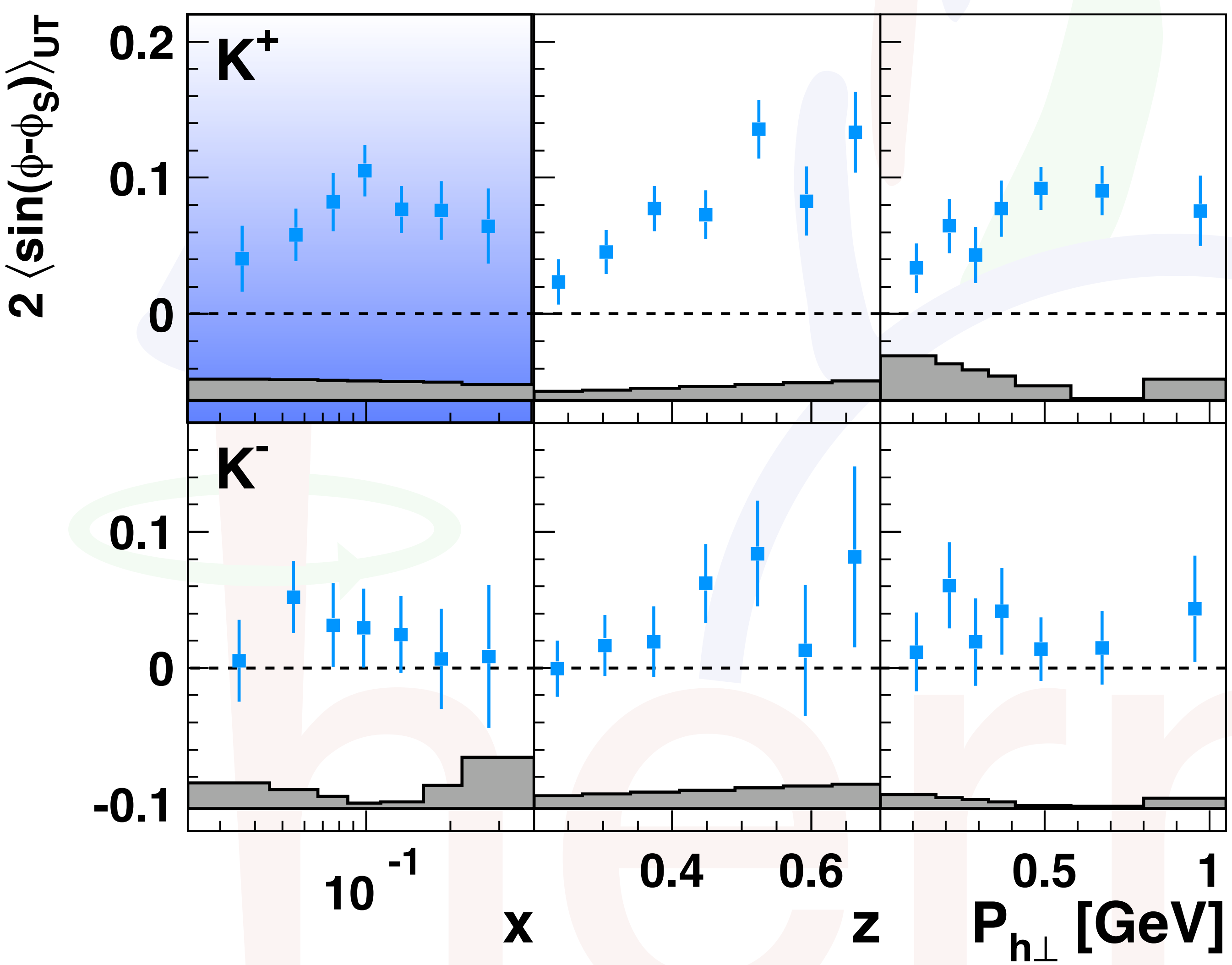
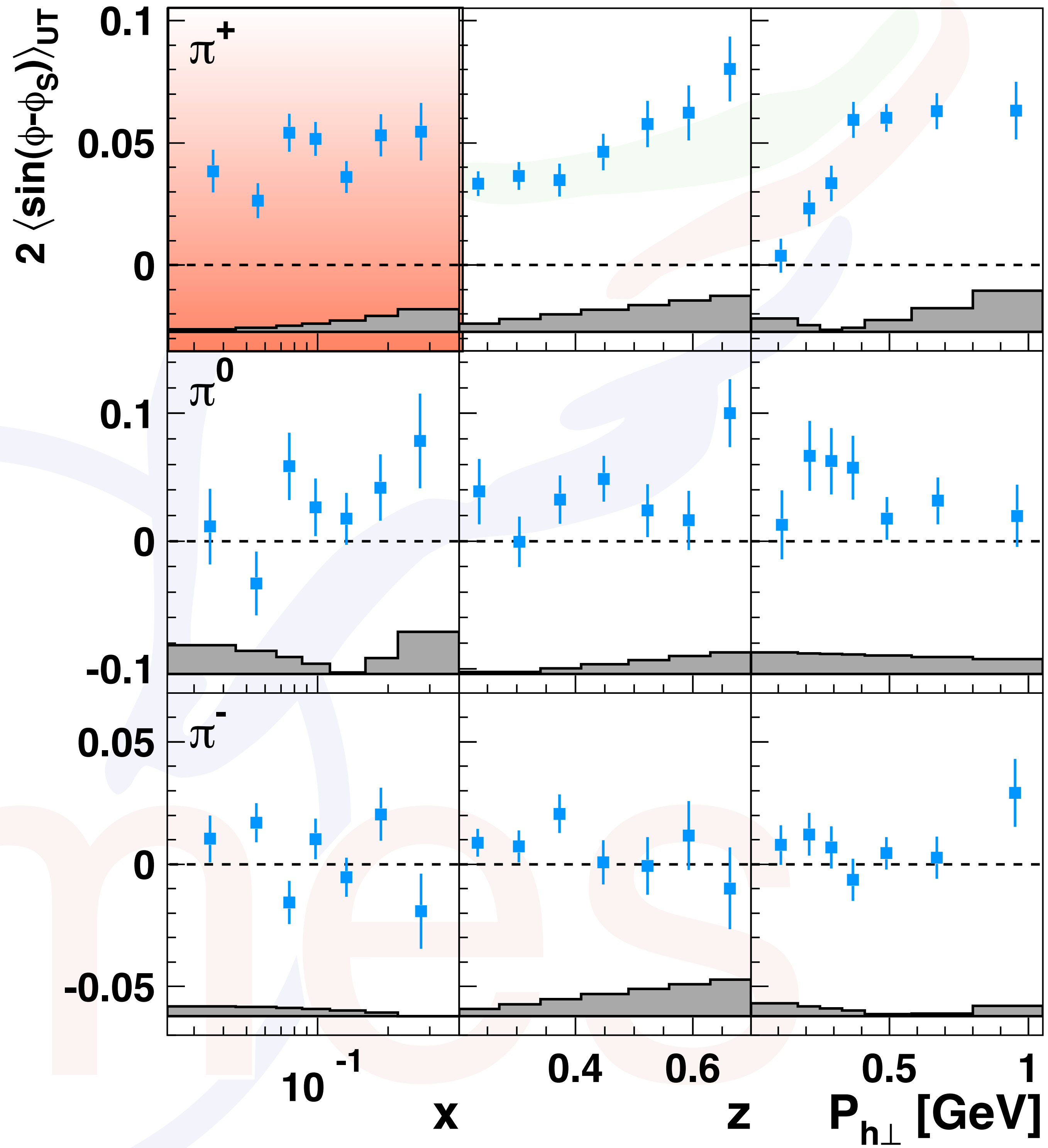


	U	L	T
U	f_1		$h_1^\perp$
L		g_{1L}	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1, $h_{1T}^\perp$

The kaon Sivers amplitudes





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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 $\sin(3\phi-\phi_s)$ modulation in A_{UT}
- suppressed by two powers of $P_{h\perp}$ (compared to, e.g., Sivers)

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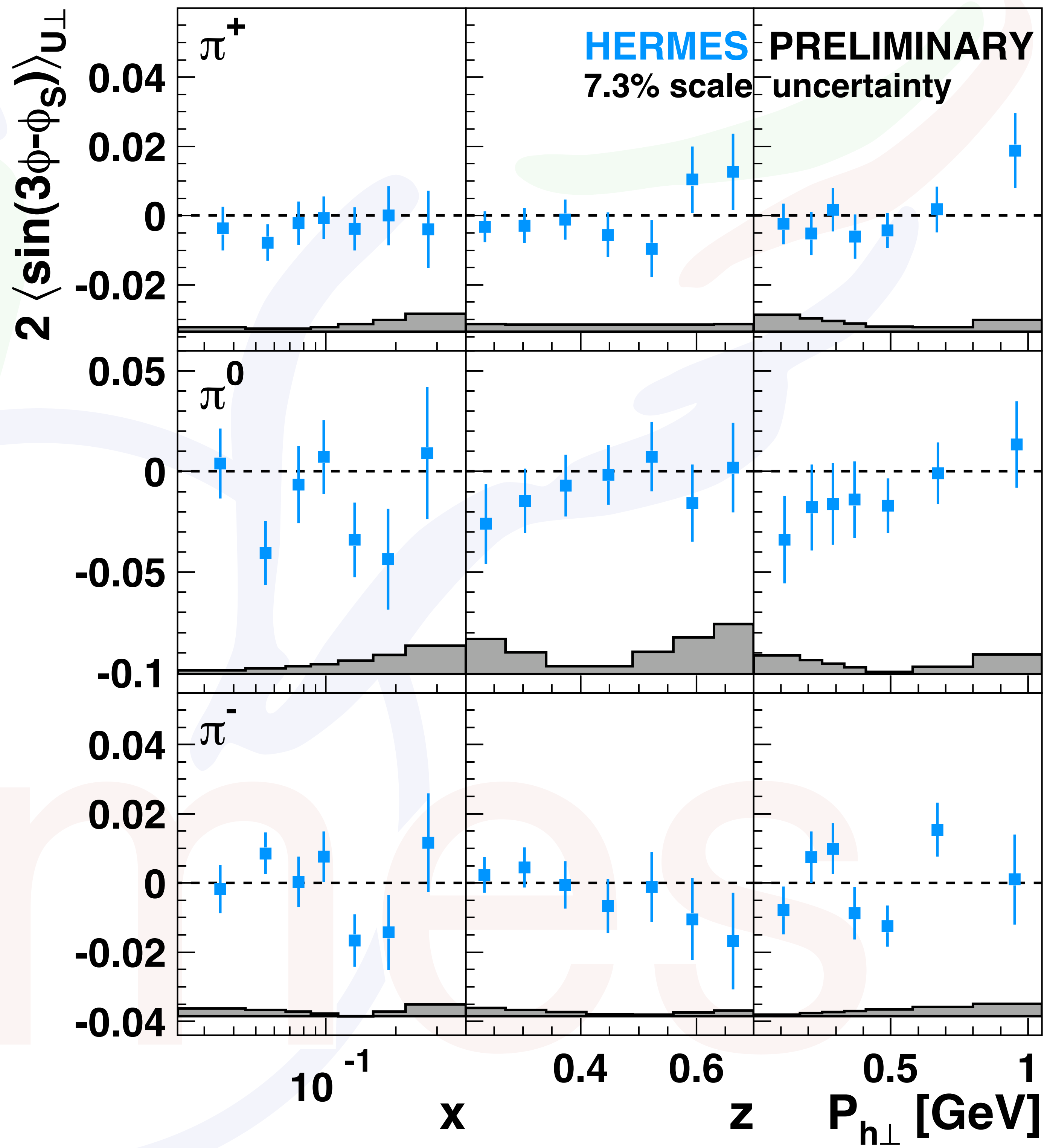
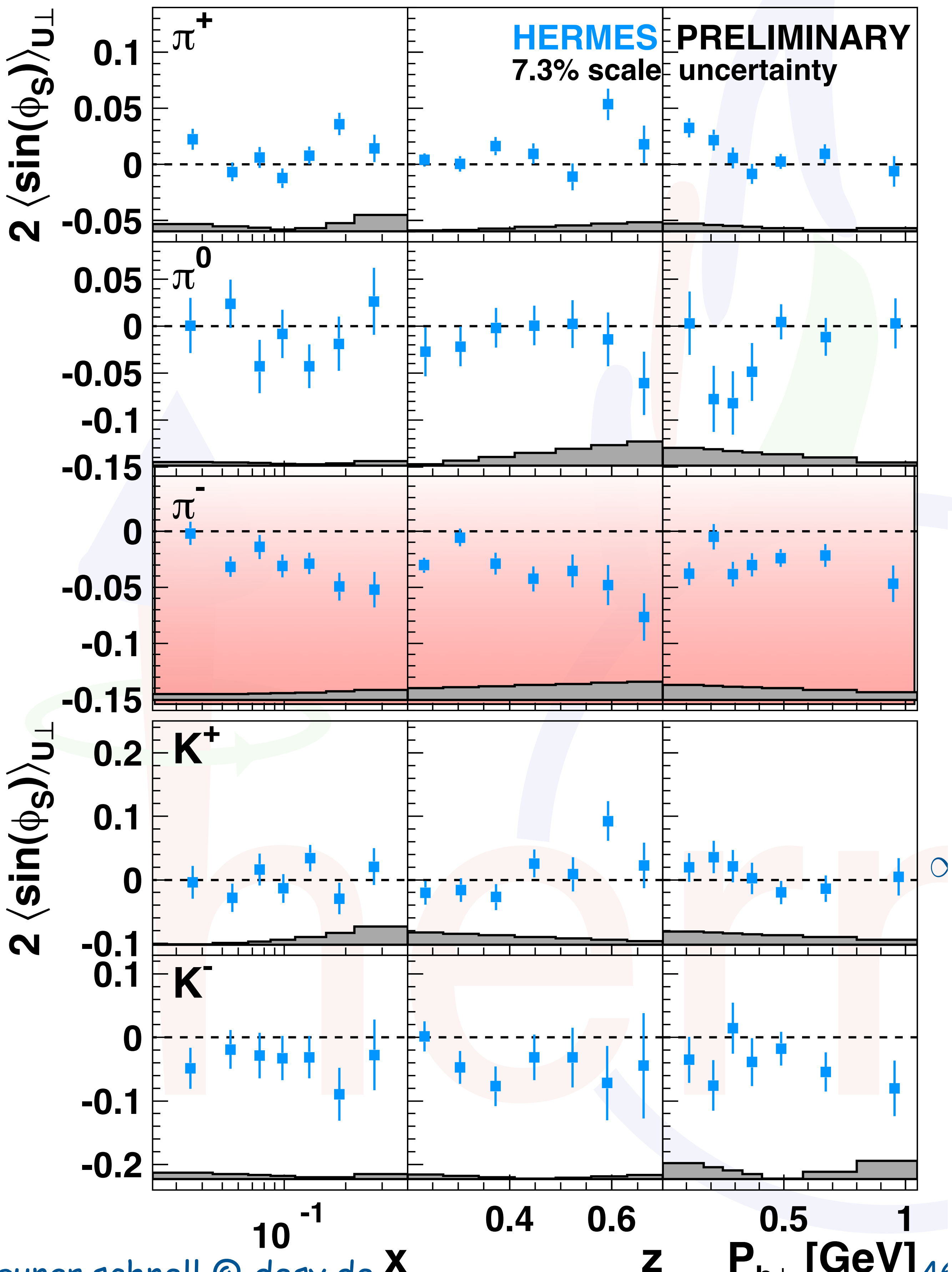
- suppressed by two powers of $P_{h\perp}$ (compared to, e.g., Sivers)
- data consistent with zero

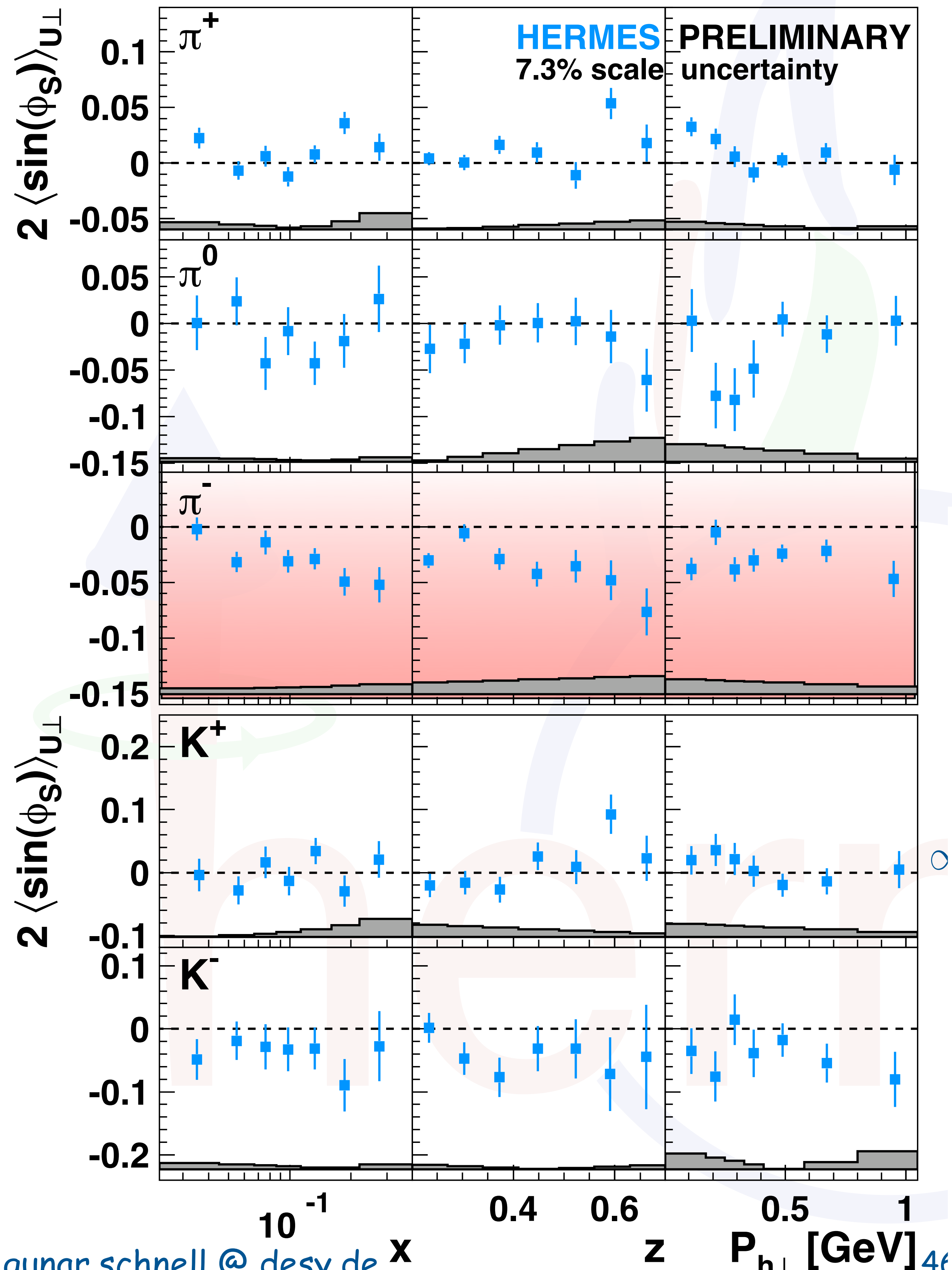


Subleading twist - sin(ϕ_S)



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

Subleading twist - $\sin(\phi_s)$



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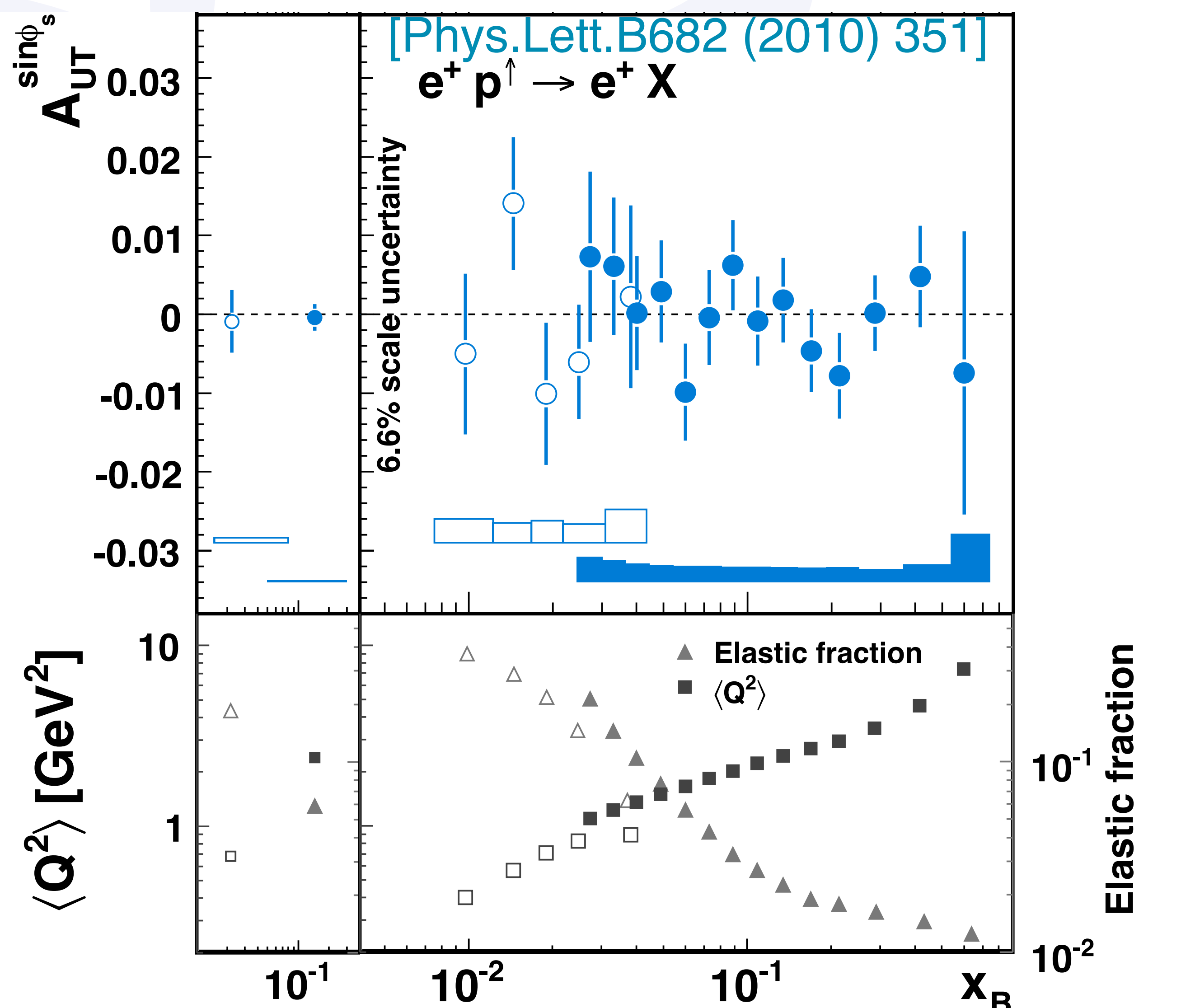
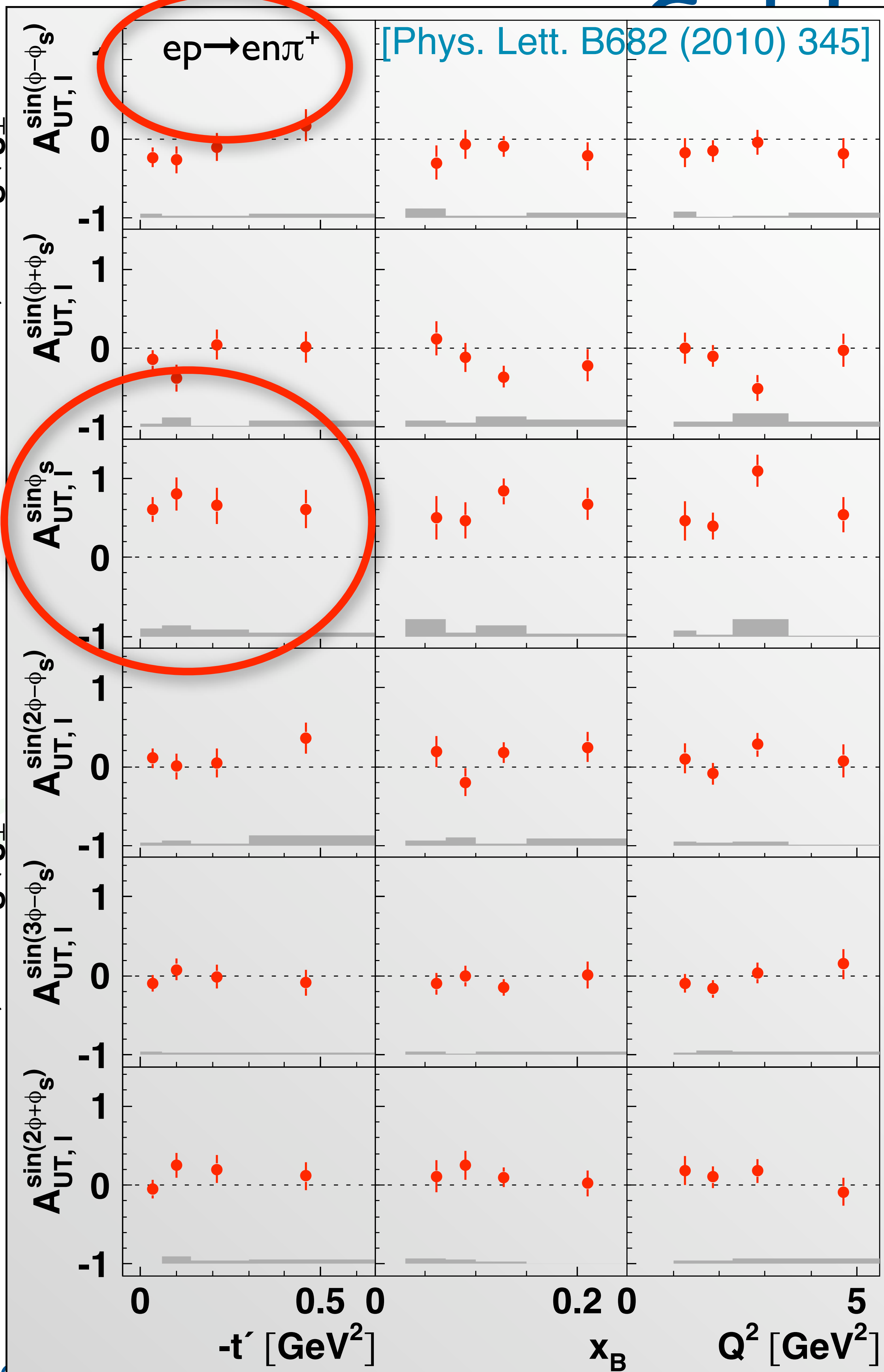


Subleading twist - $\sin(\phi_s)$



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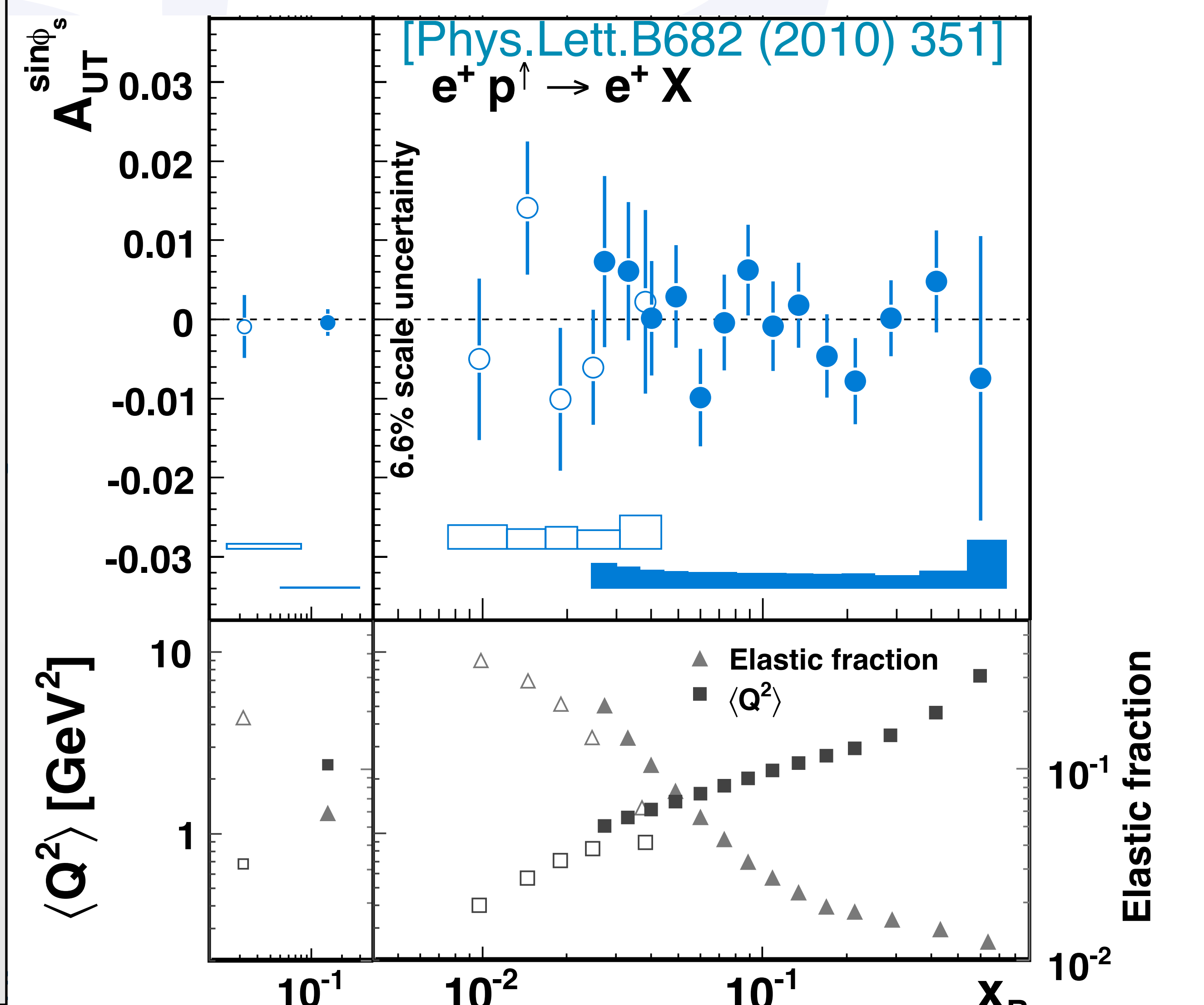
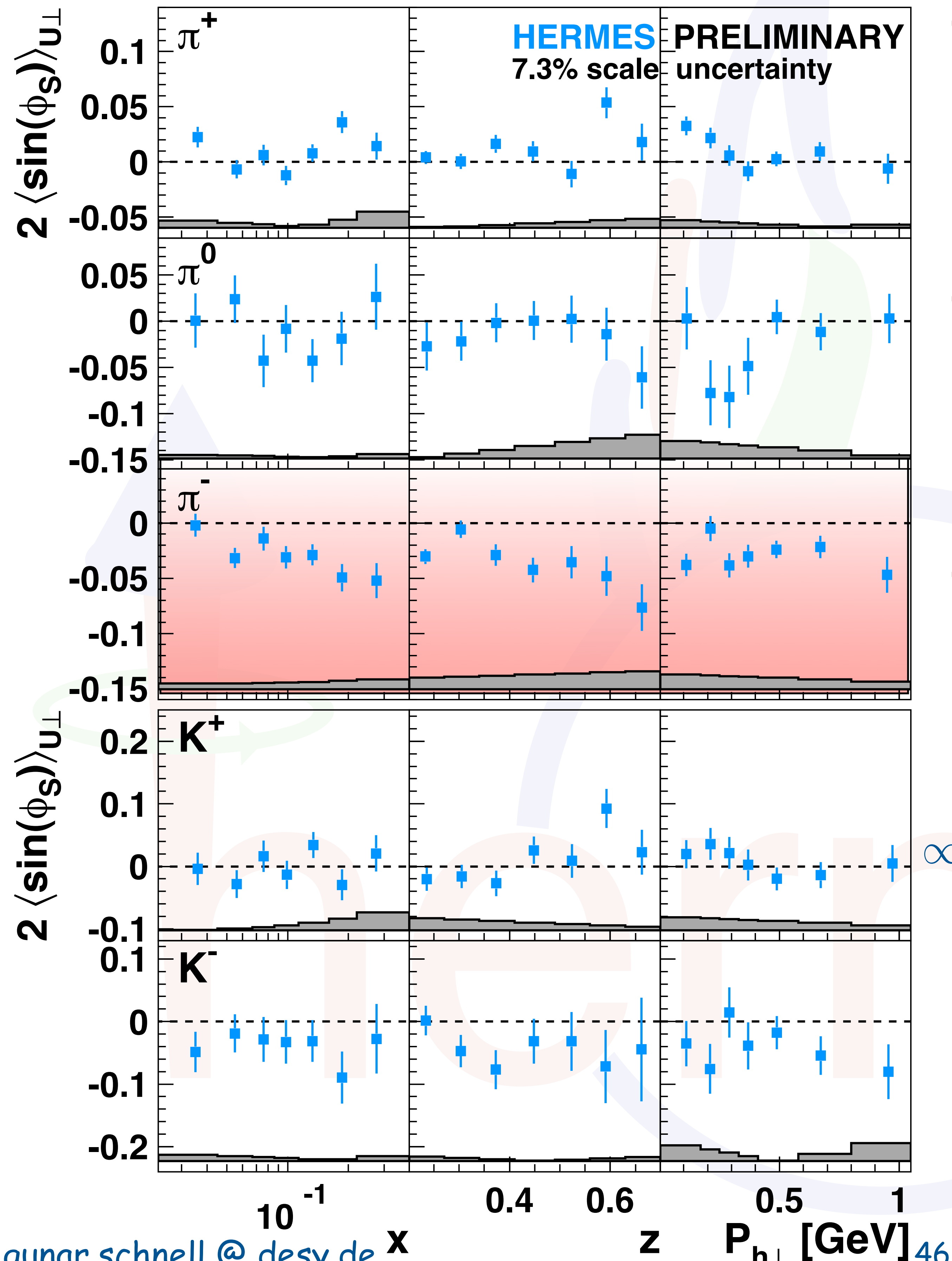


Subleading twist - $\sin(\phi_S)$

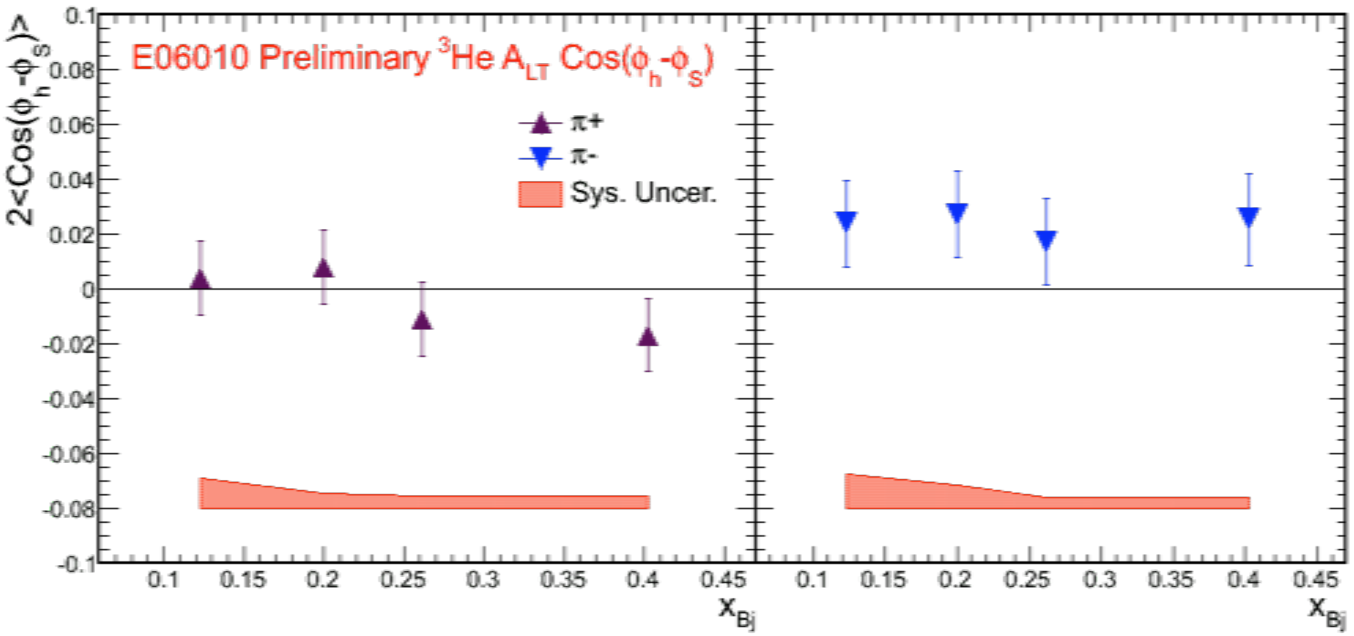


- significant non-zero signal observed for negatively charged mesons
- must vanish after integration over $P_{h\perp}$ and z, and summation over all hadrons
- various terms related to transversity, worm-gear, Sivers etc.:

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

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

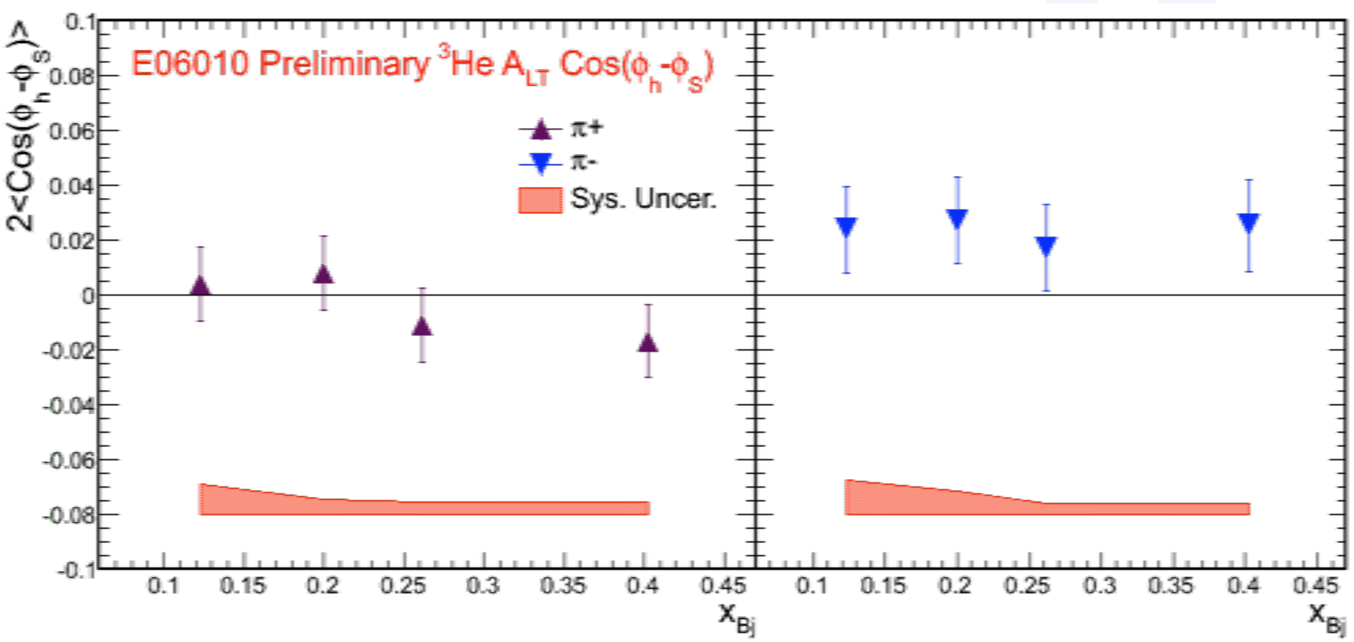
Worm-Gear g_{1T}

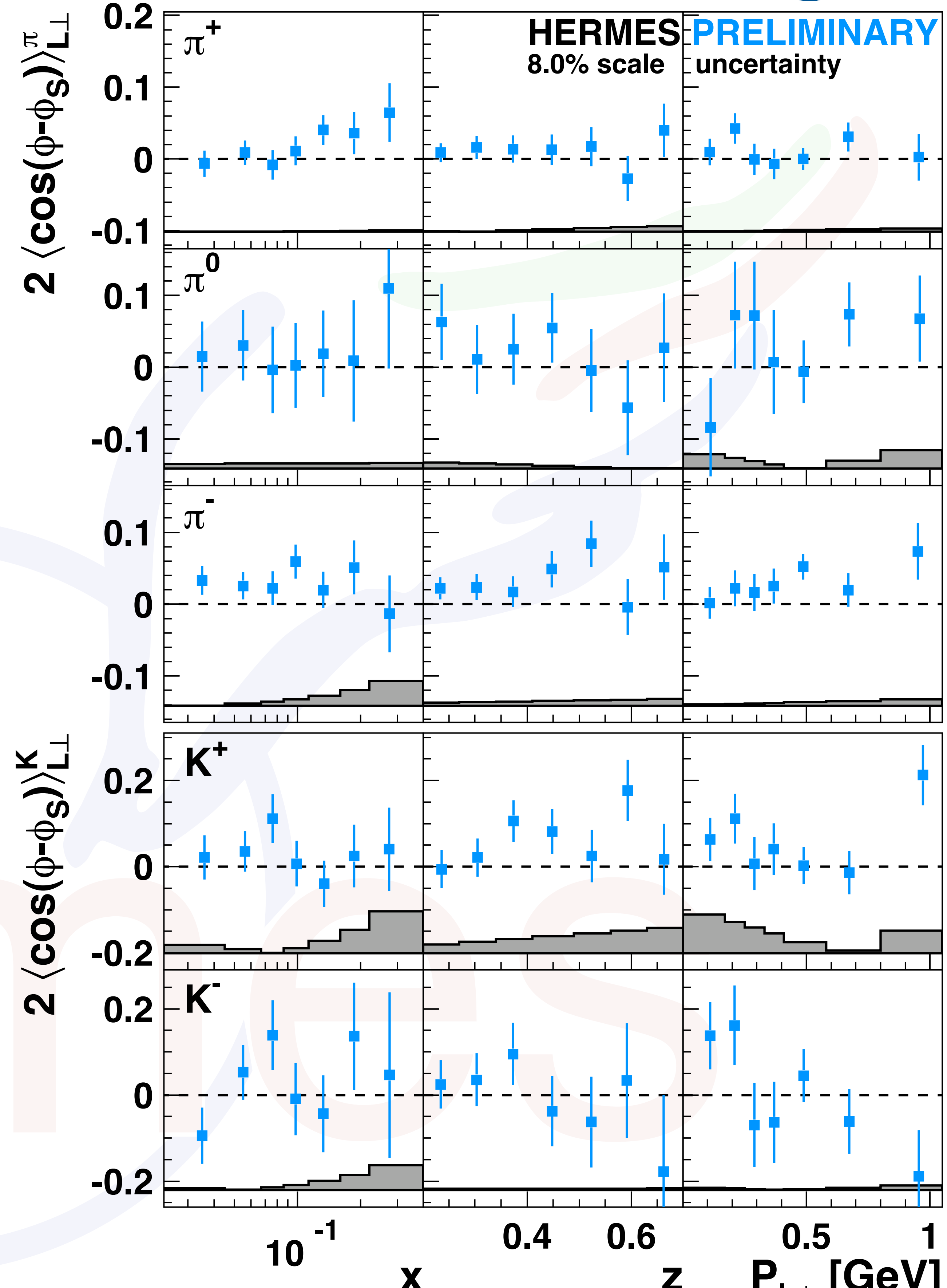


- chiral even
- first direct evidence for worm-gear g_{1T} from JLab

Worm-Gear g_{1T}

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

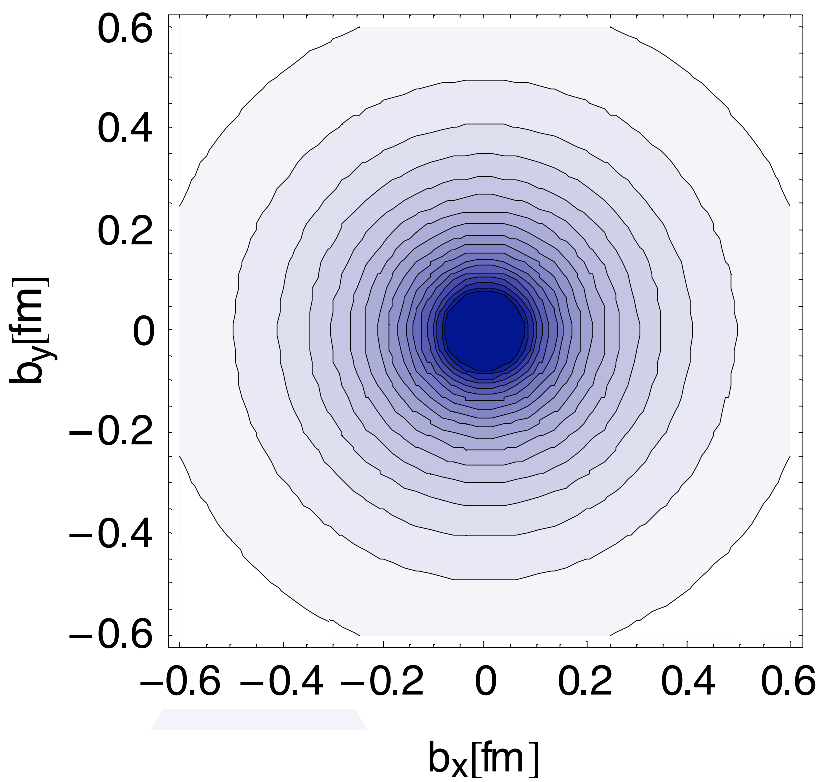




- chiral even
- first direct evidence for worm-gear g_{1T} from JLab
- also HERMES results on A_{LT} for negative pions non-zero

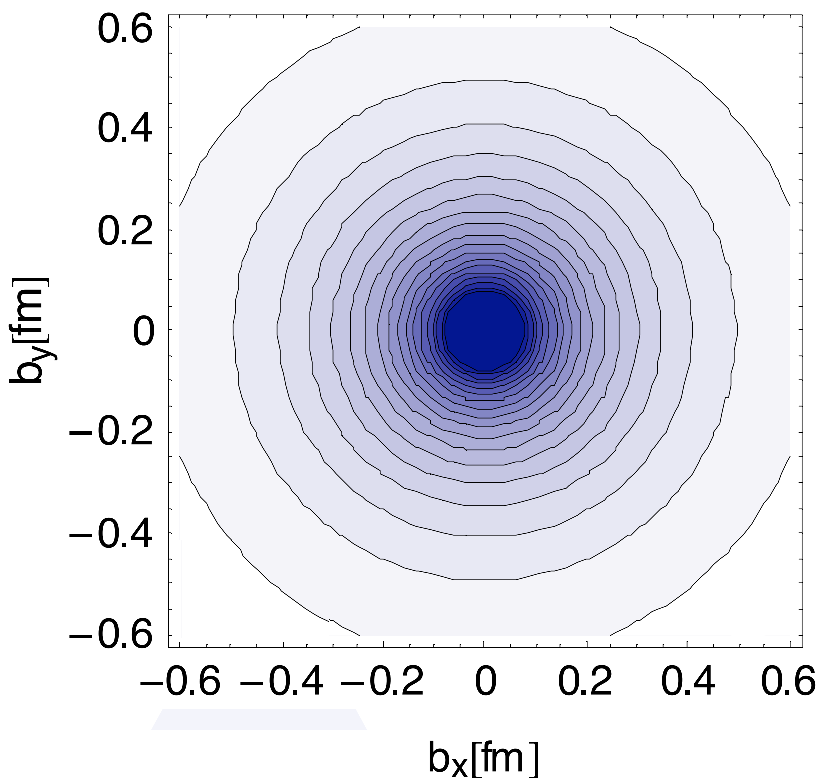
Exclusive reactions

Another 3D picture of the nucleon



Form factors:
transverse distribution of partons

Another 3D picture of the nucleon



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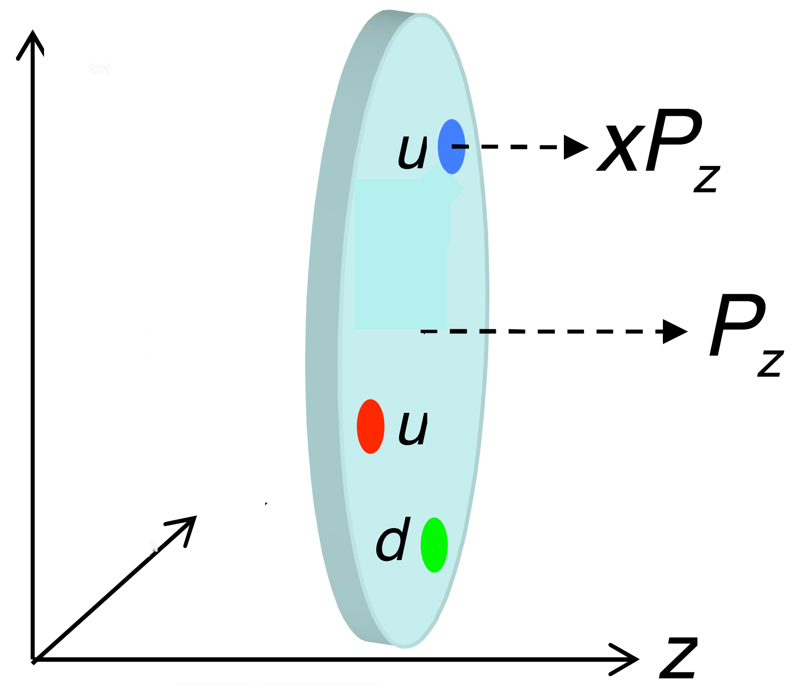
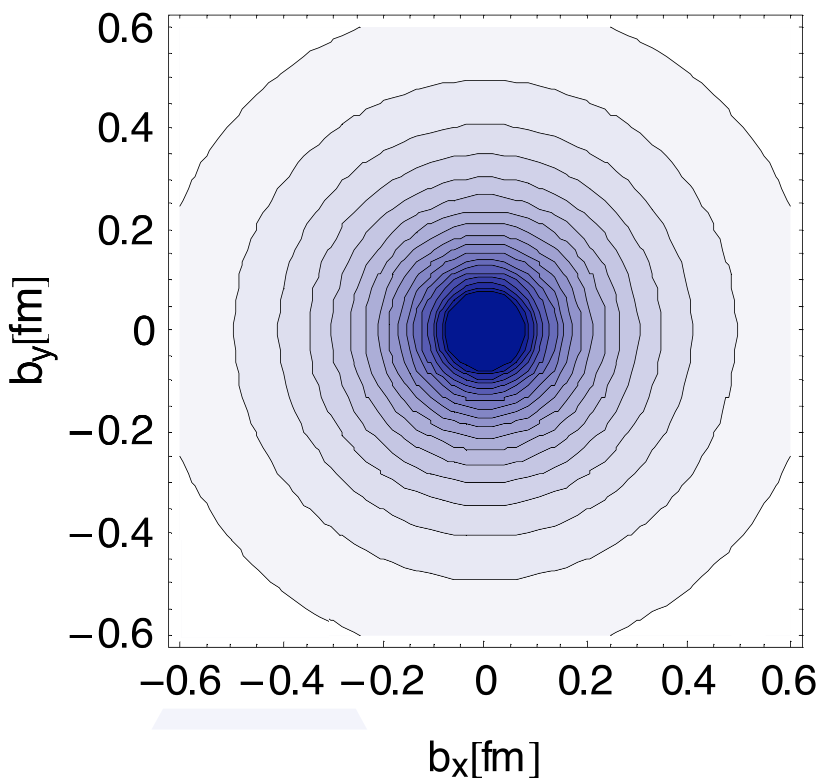
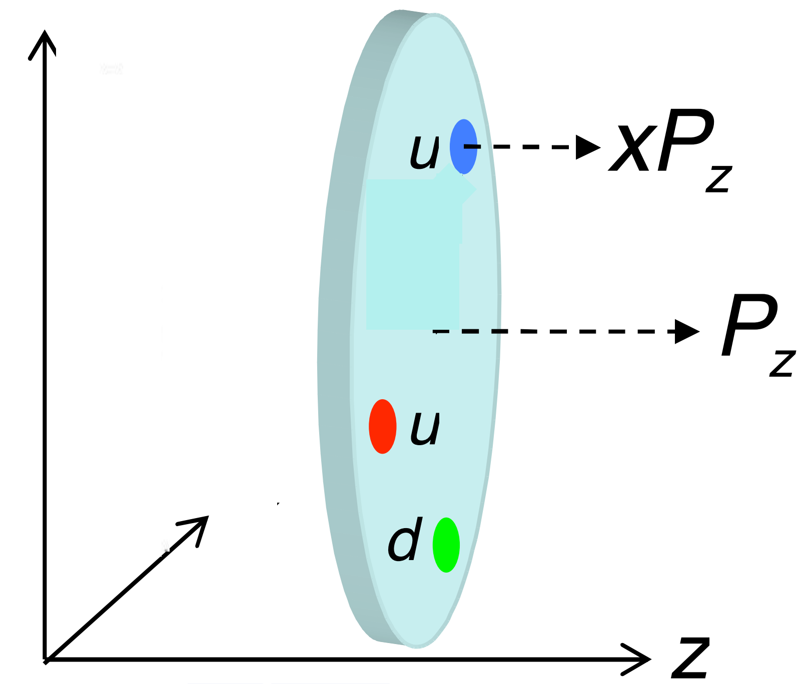


Parton distributions:
longitudinal momentum of partons

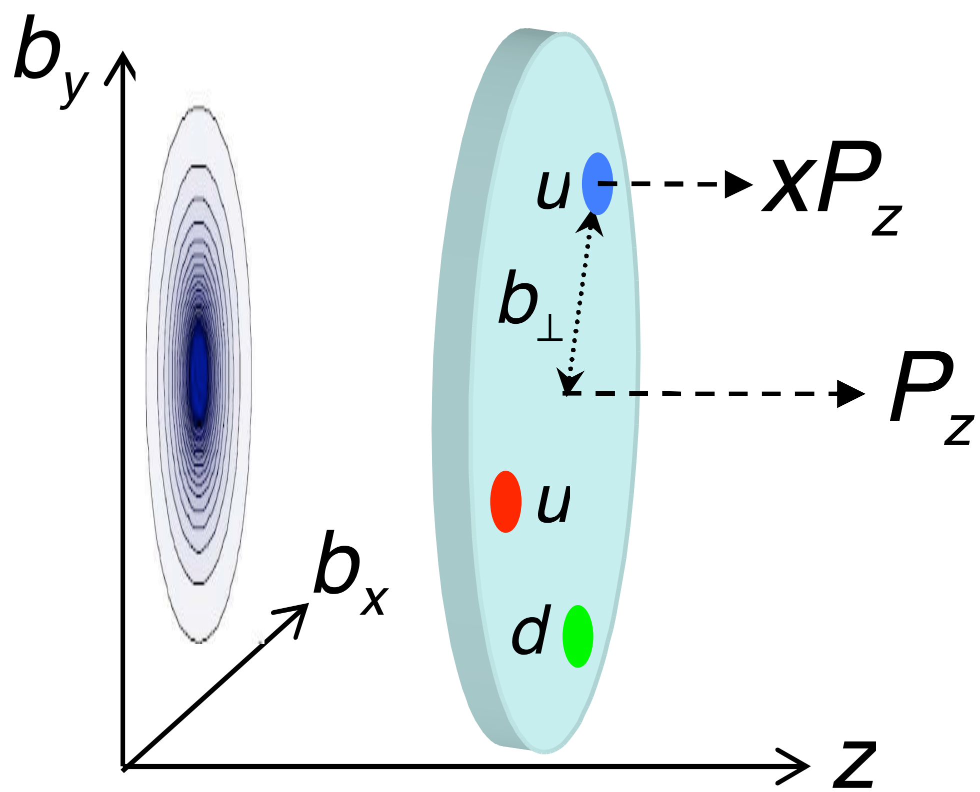
Another 3D picture of the nucleon





Form factors:
transverse distribution of partons

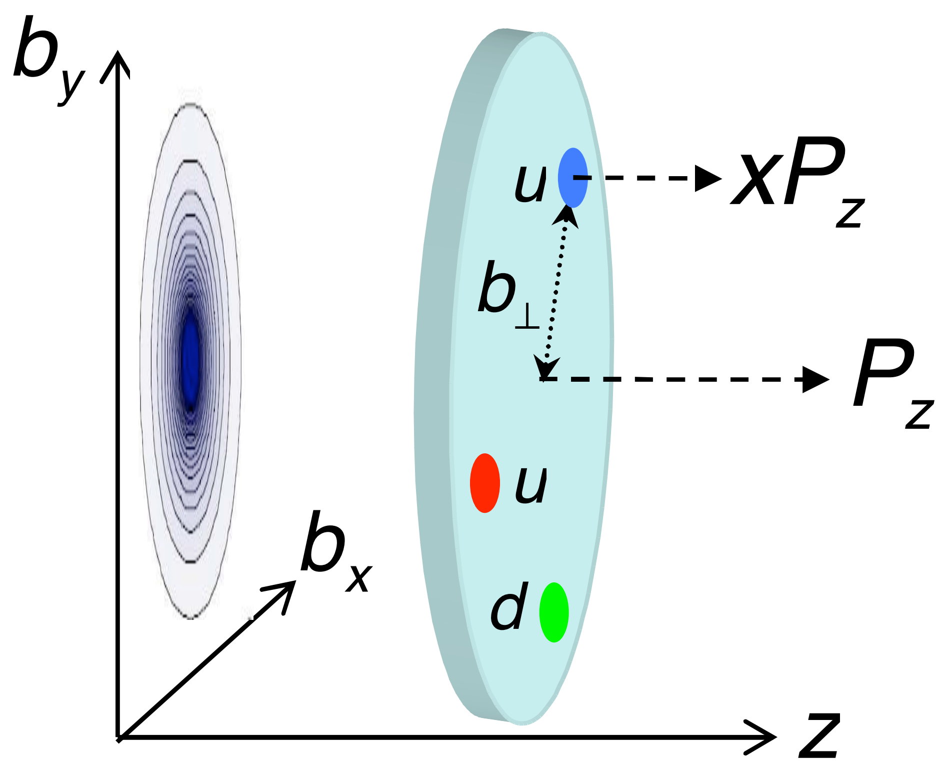
Parton distributions:
longitudinal momentum of partons

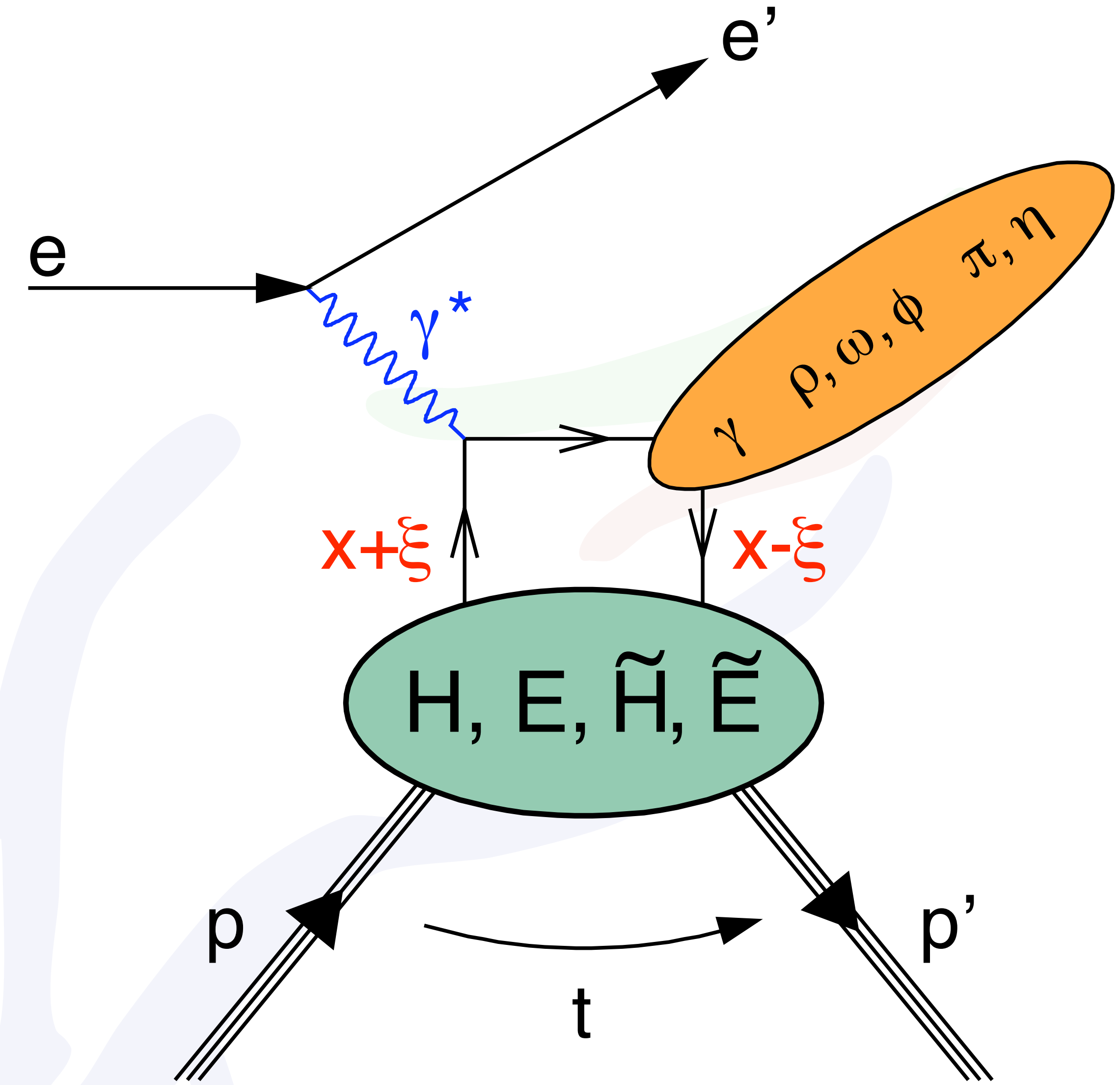


Nucleon Tomography

correlated info on transverse position and longitudinal momentum

Probing GPDs in Exclusive Reactions

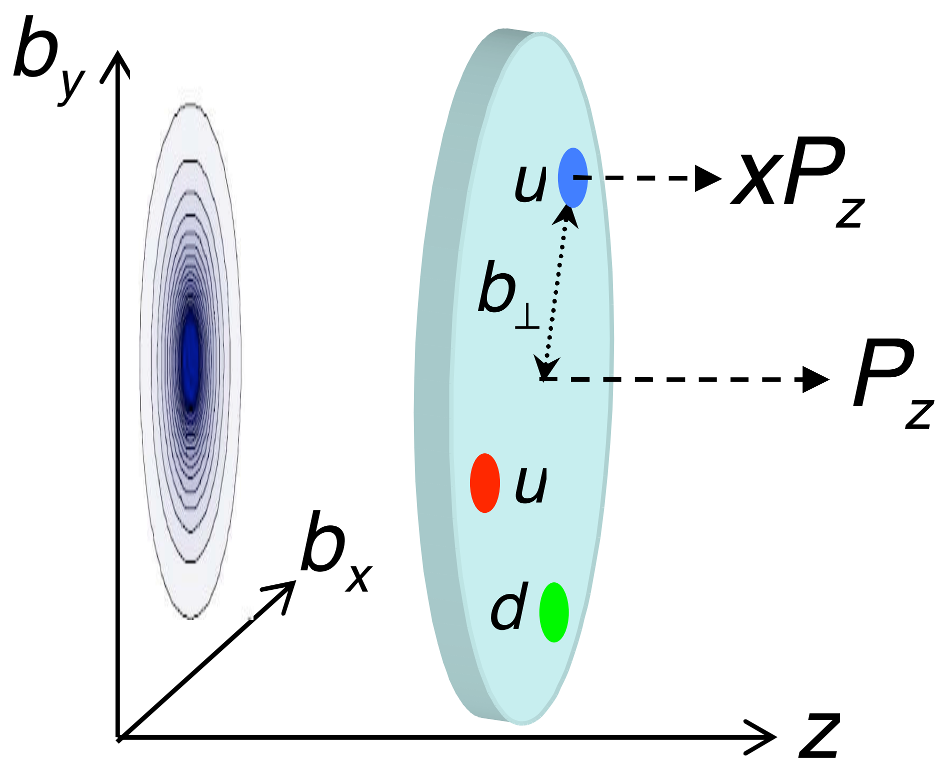


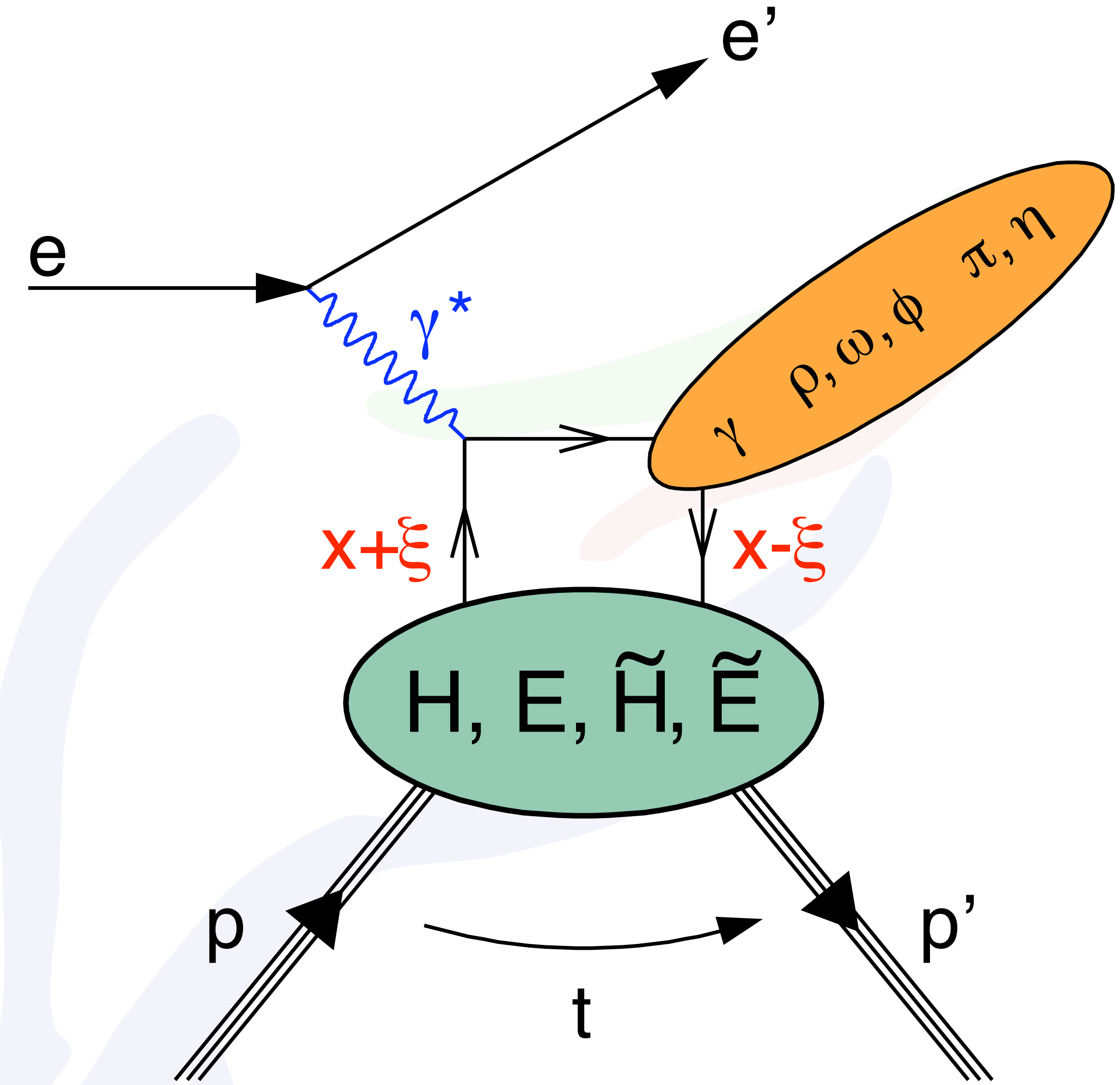


x: average longitudinal momentum fraction of active quark (usually not observed & $x \neq x_B$)

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

Probing GPDs in Exclusive Reactions

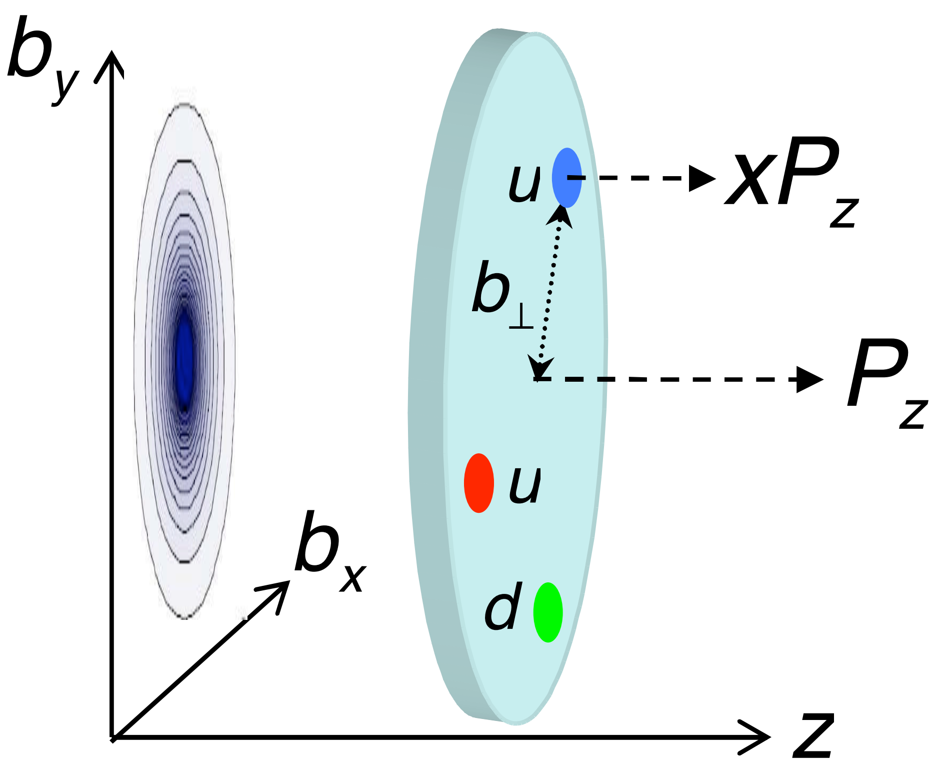


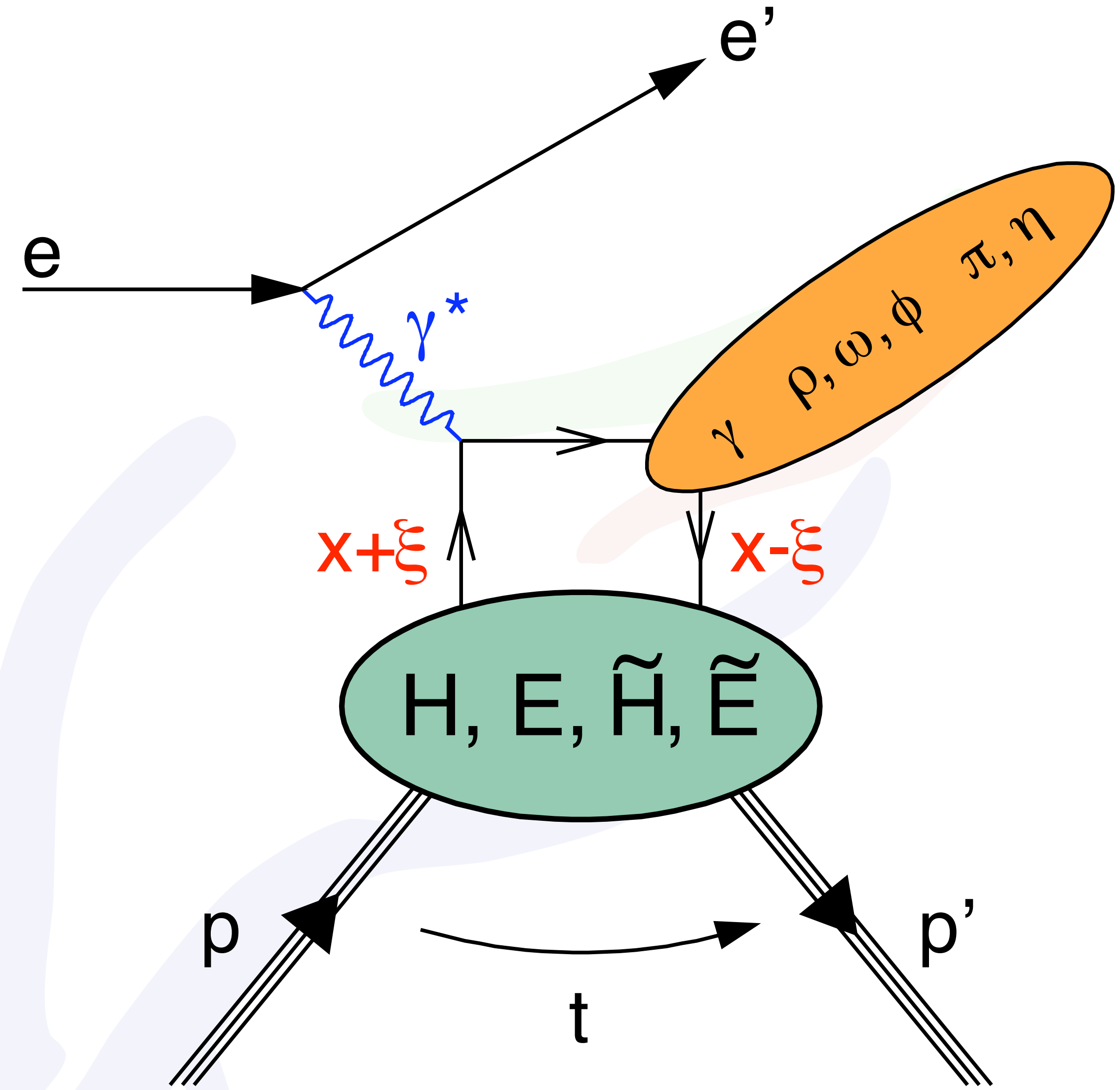


	no quark helicity flip	quark helicity flip
no nucleon helicity flip	H	$\widetilde{H}$
nucleon helicity flip	E	$\widetilde{E}$

(+ 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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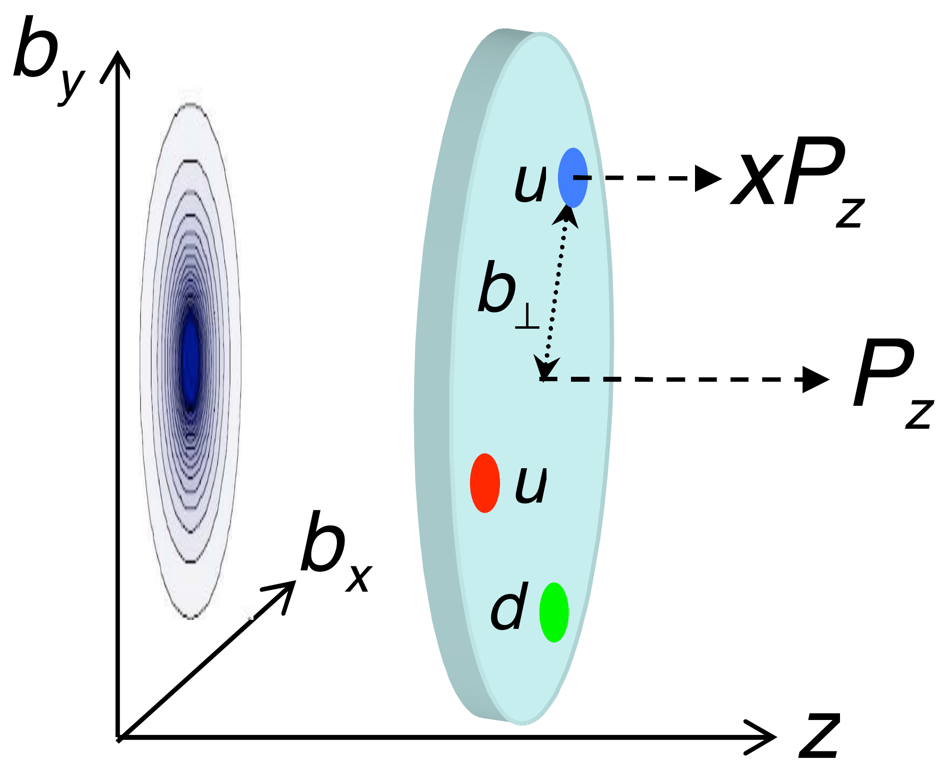
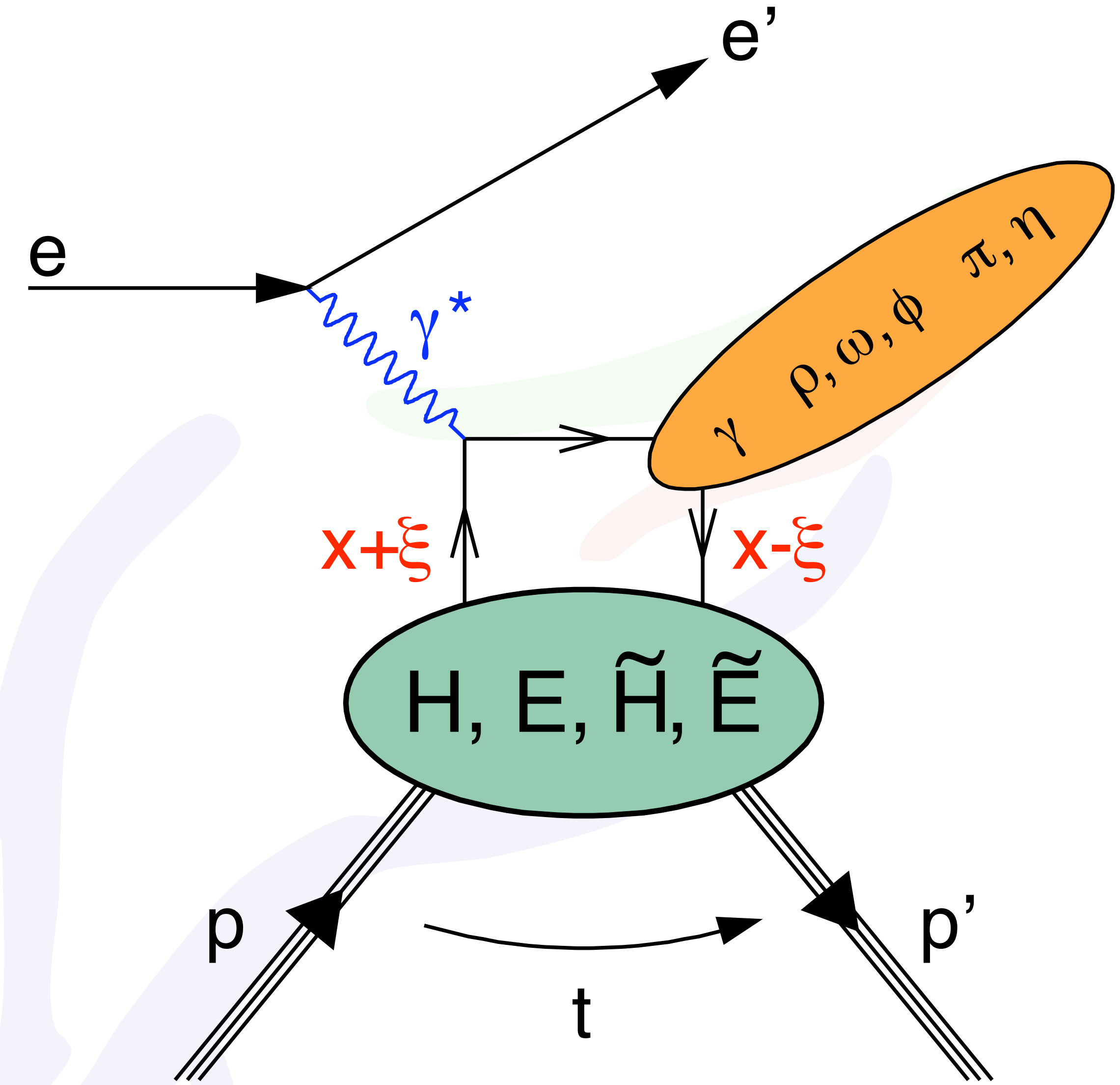
(+ 4 more chiral-odd functions)

Probing GPDs in Exclusive Reactions





$$\int \mathrm{d}x H^q(x,\xi,t) = F_1^q(t)$$
$$\int \mathrm{d}x E^q(x,\xi,t) = F_2^q(t)$$

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

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

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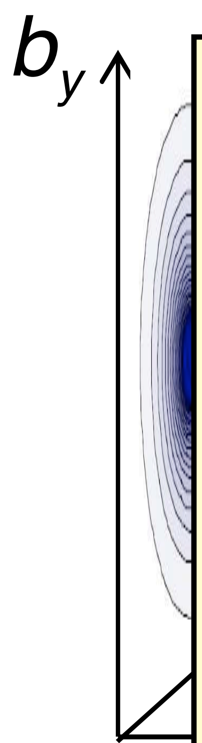
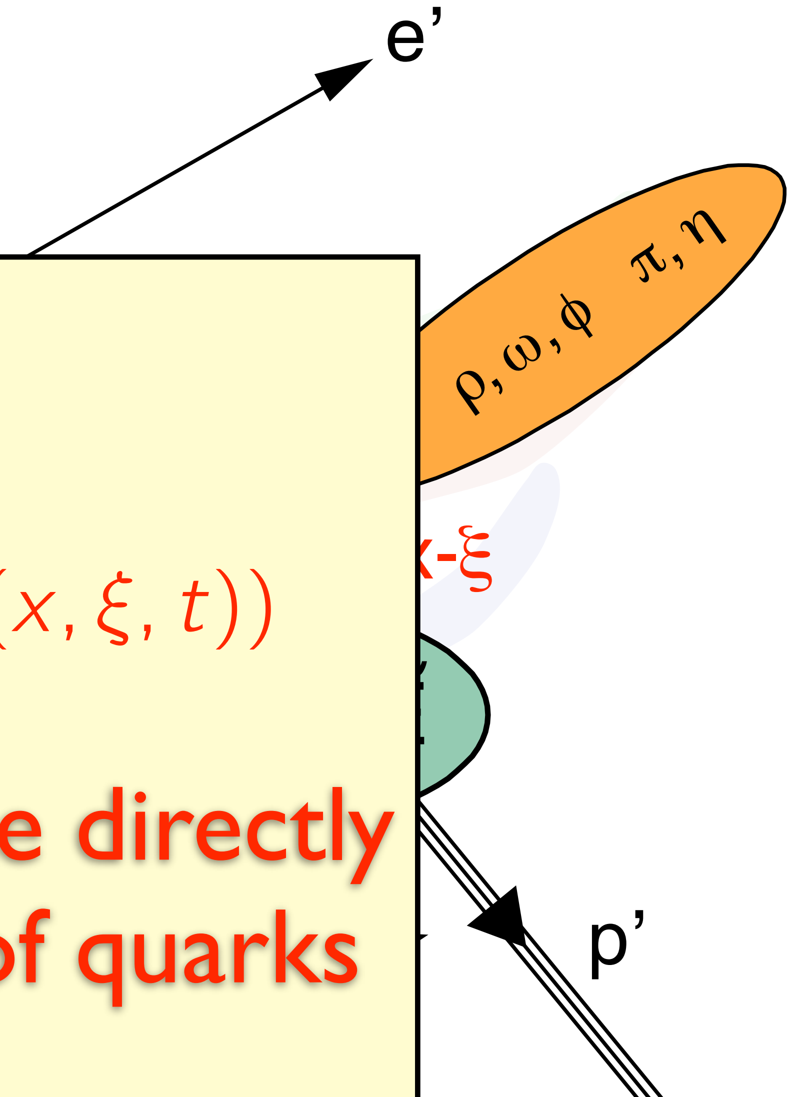
Probing GPDs in Exclusive Reactions





Ji relation (1997)

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

➔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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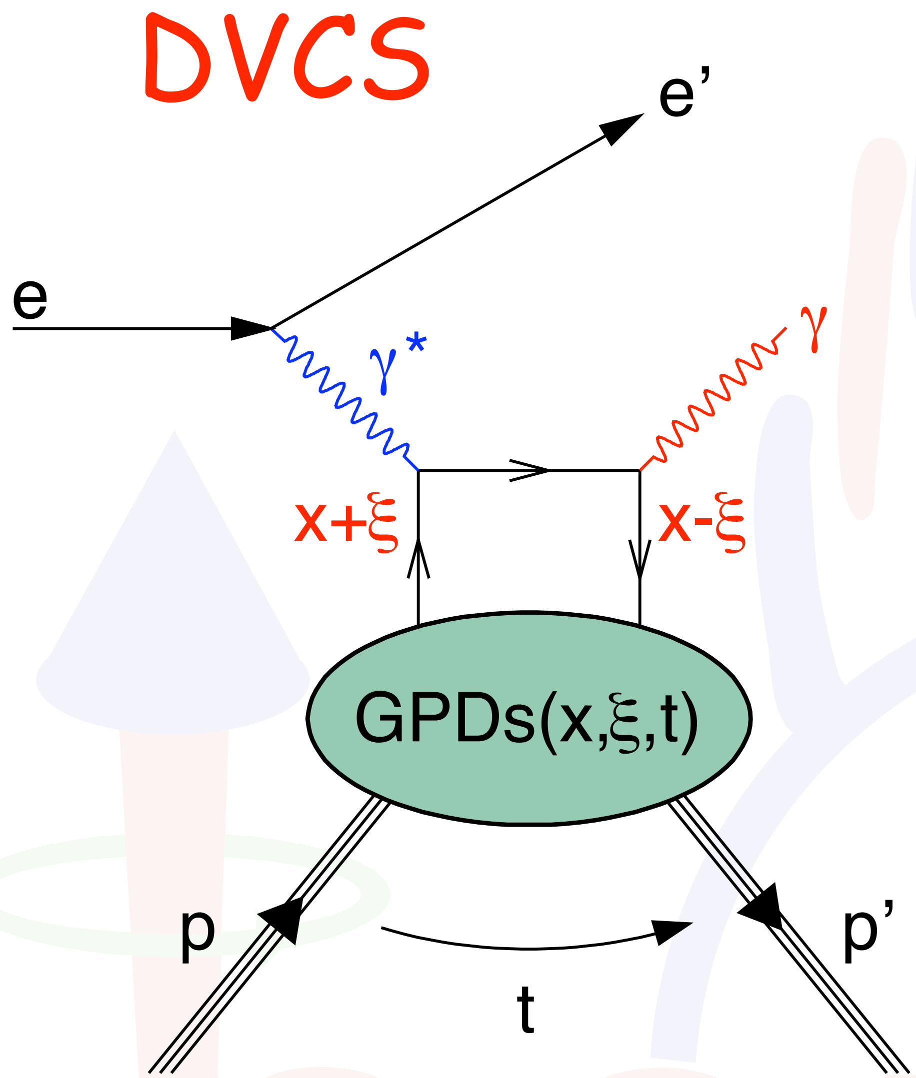
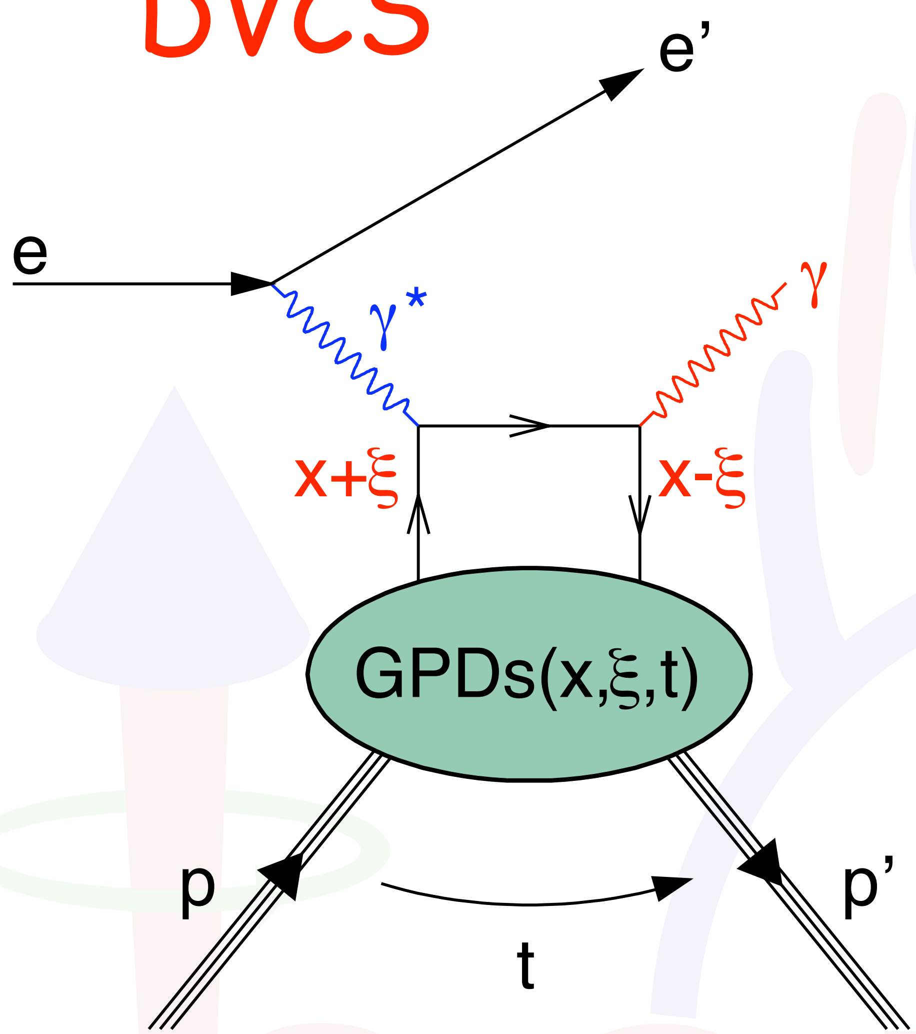
(+ 4 more chiral-odd functions)

Real-photon production

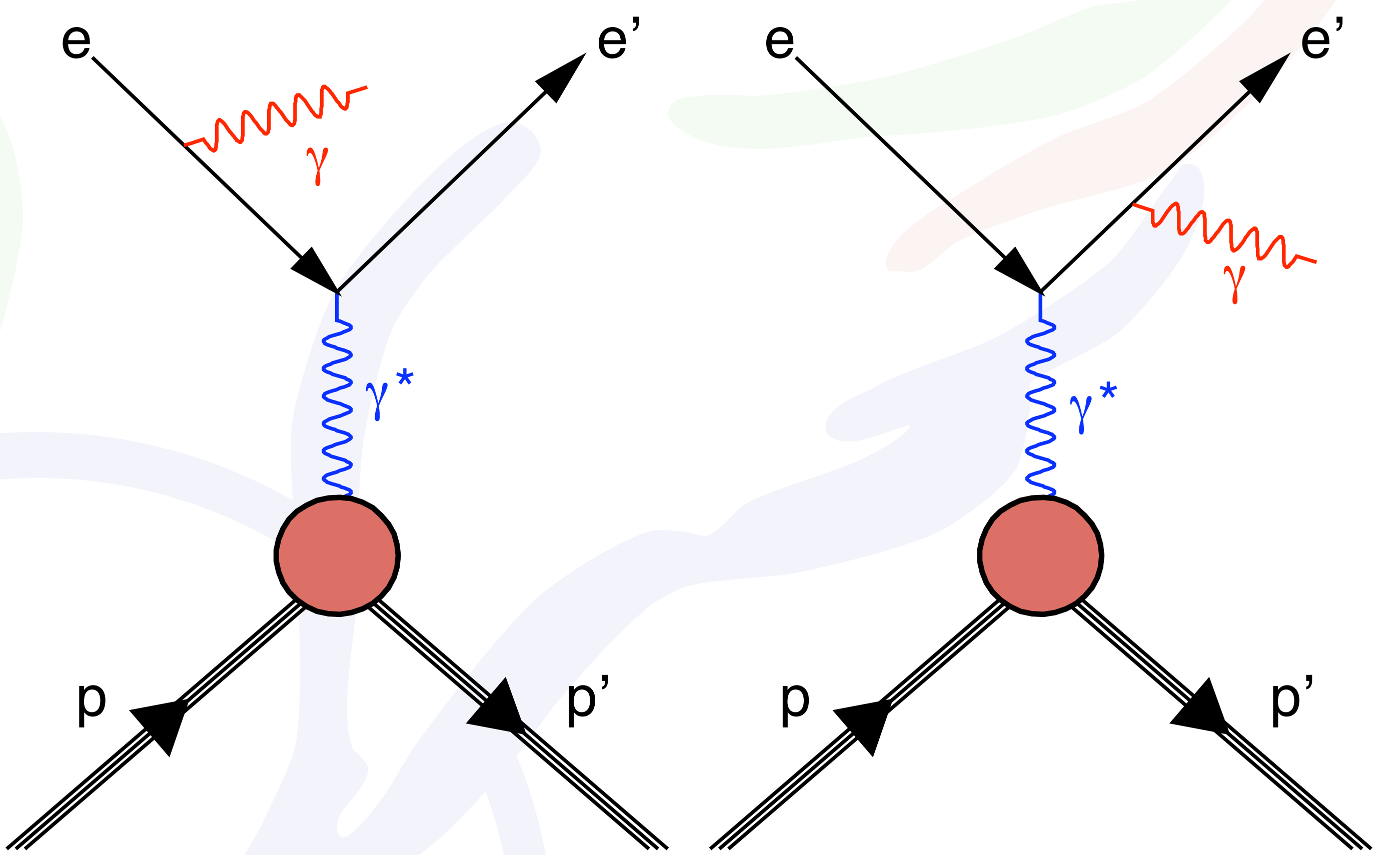


Real-photon production

DVCS



Bethe-Heitler



Real-photon production

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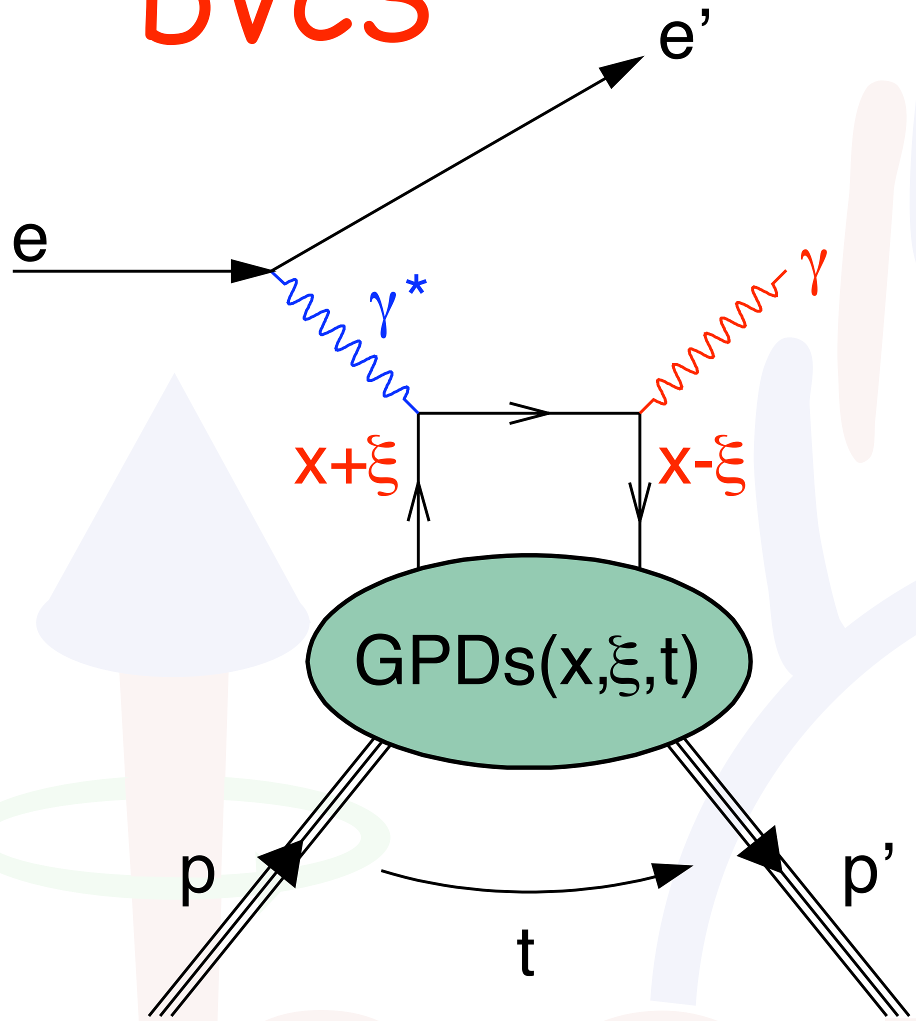
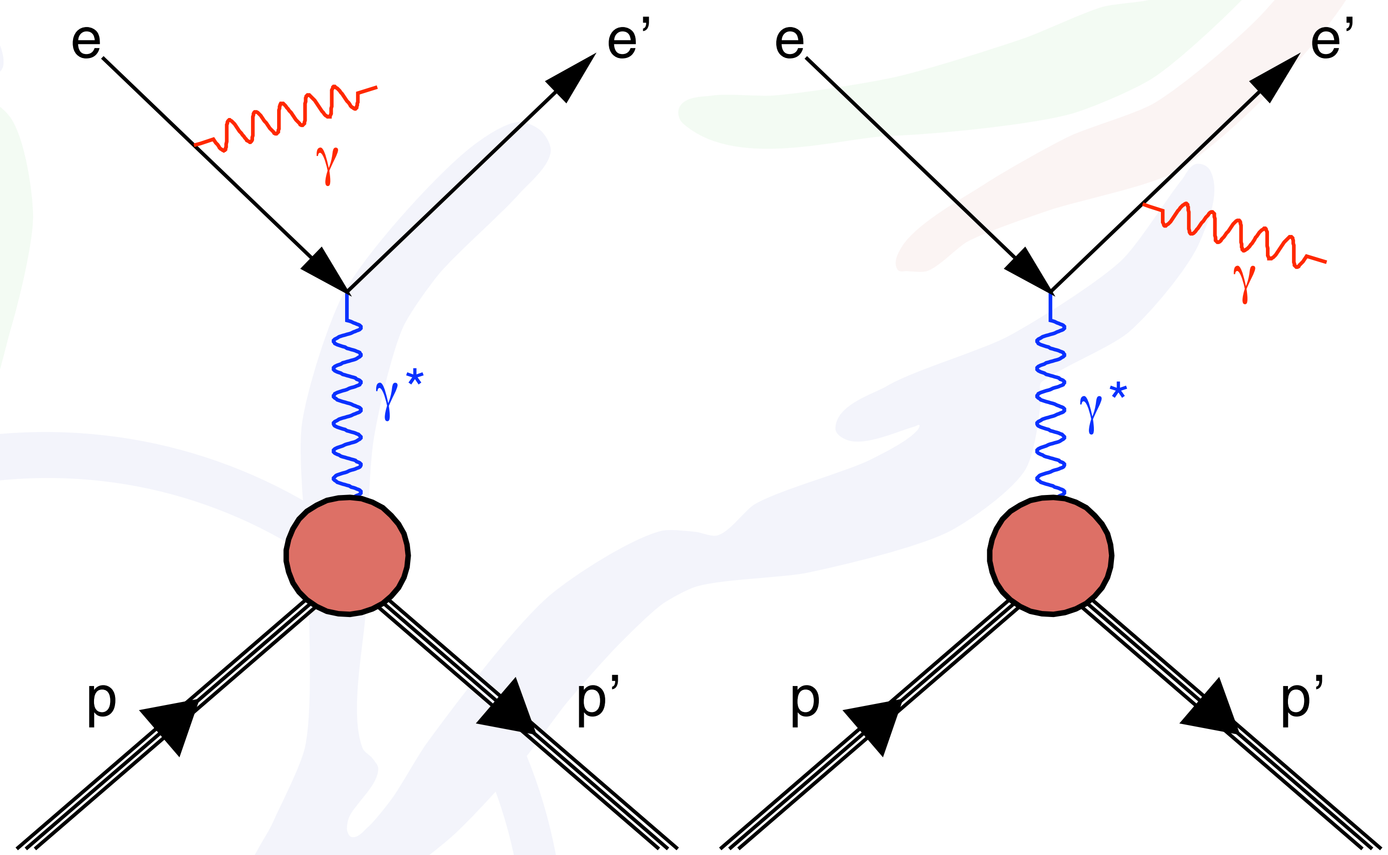


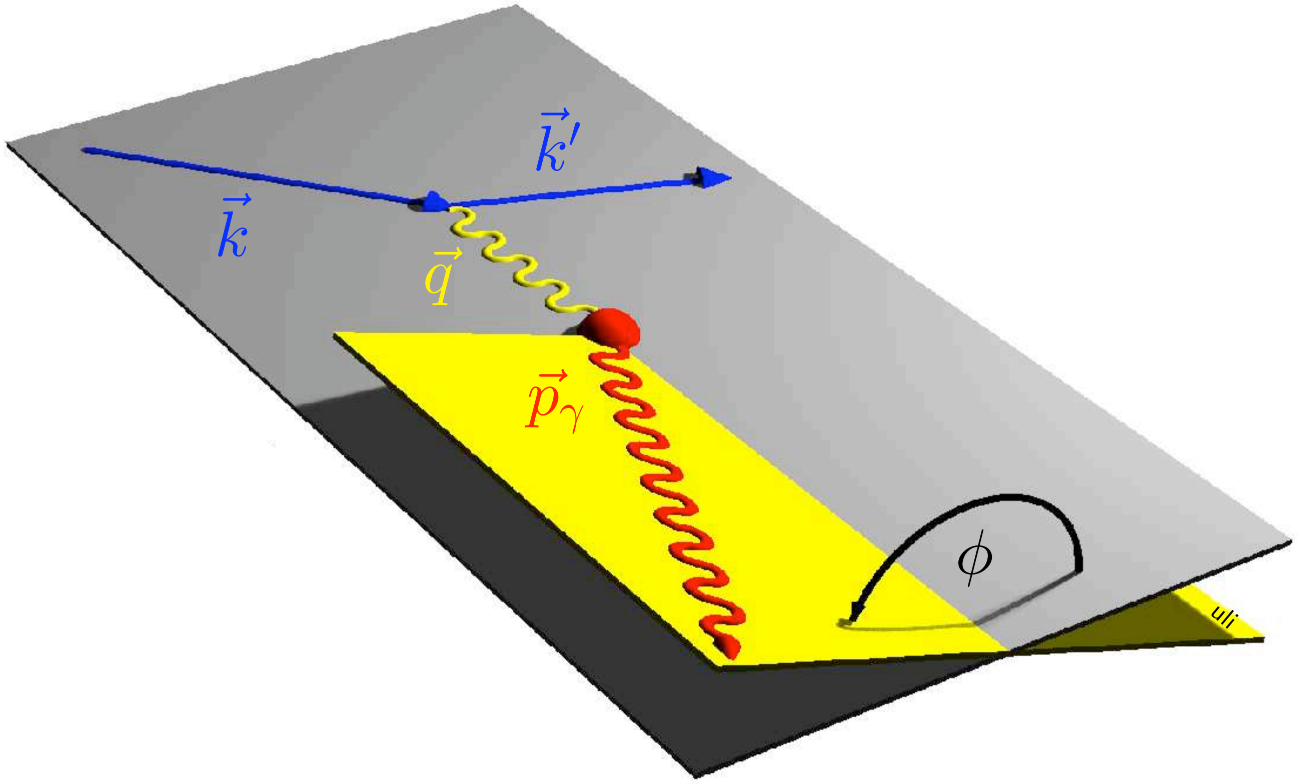
Bethe-Heitler



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

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

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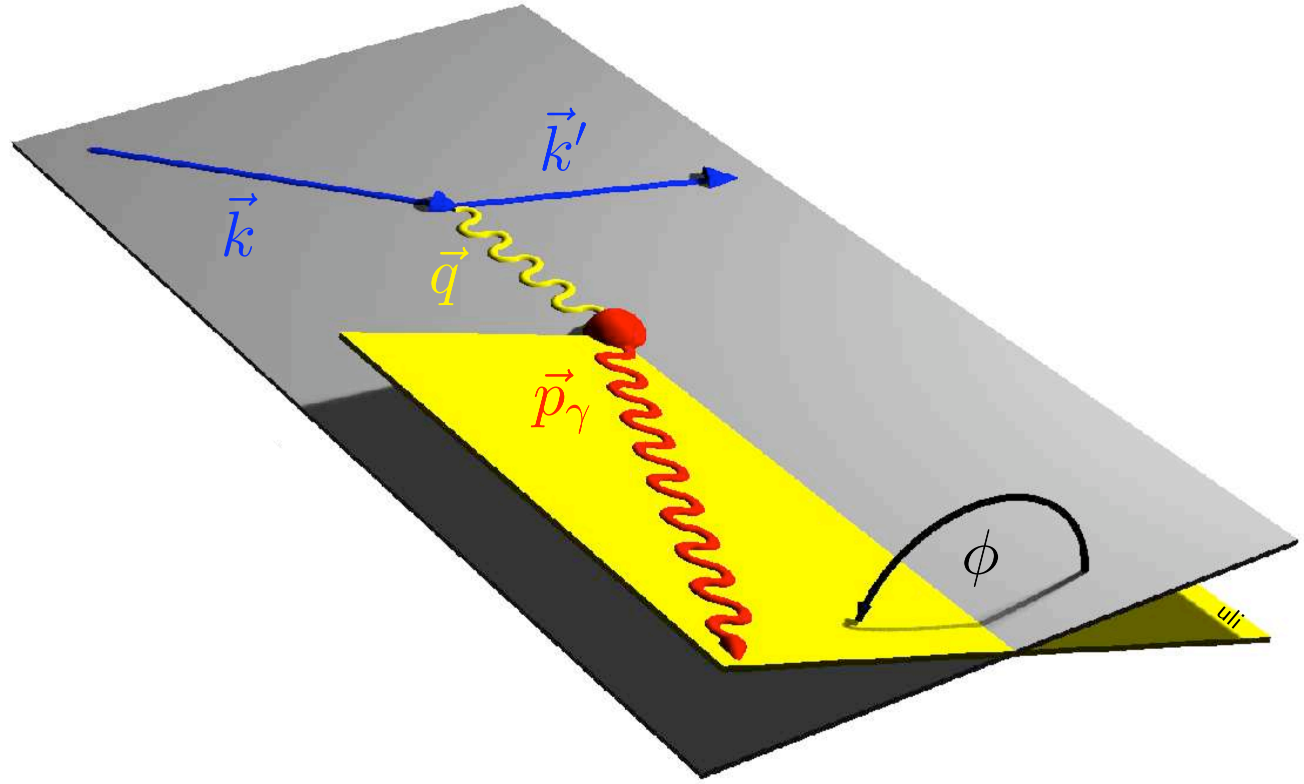

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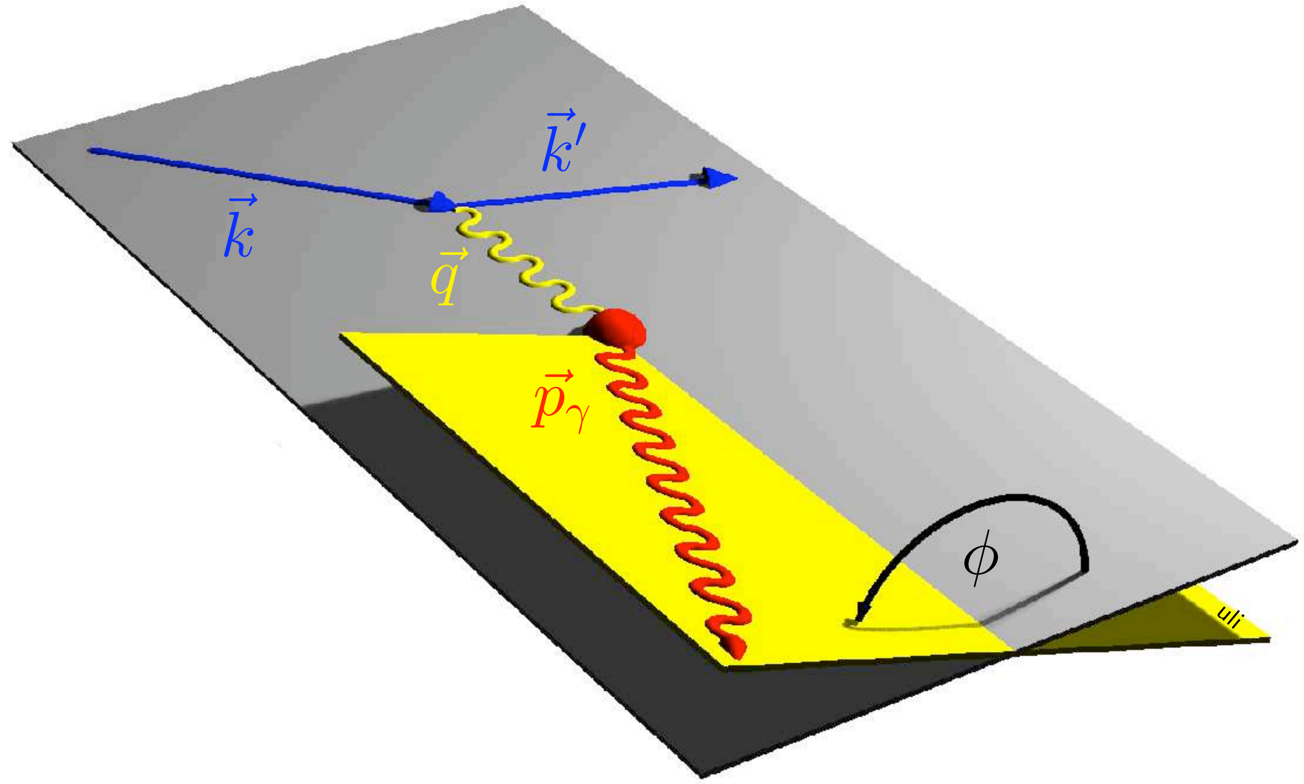
$$|\mathcal{T}_{\mathrm{DVCS}}|^2 = K_{\mathrm{DVCS}} \left[\sum_{n=0}^{2} c_n^{\mathrm{DVCS}} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{\mathrm{DVCS}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH



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Fourier expansion for ϕ:

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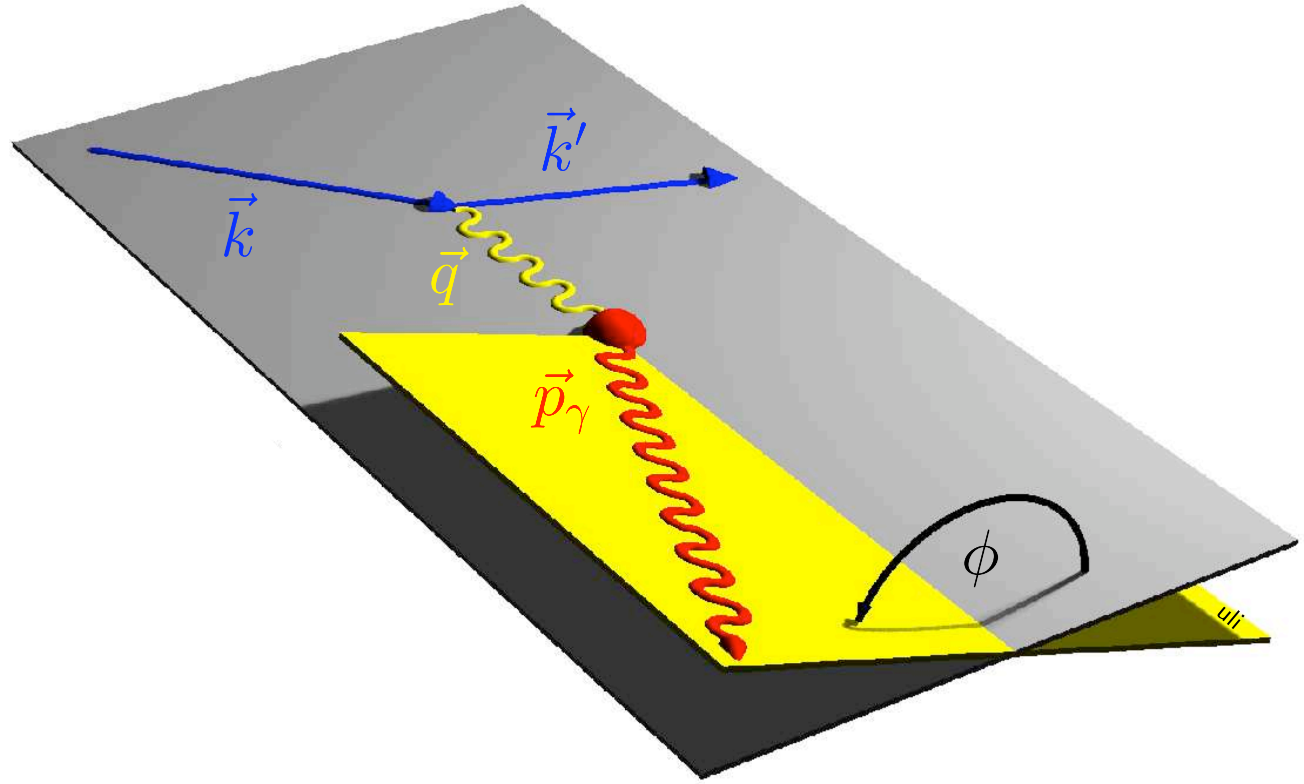
$$\mathcal{I} = \frac{C_B K_{\mathcal{I}}}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left[\sum_{n=0}^{3} c_n^{\mathcal{I}} \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^{\mathcal{I}} \sin(n\phi) \right]$$

Azimuthal dependences in DVCS/BH

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



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bilinear ("DVCS") or linear in GPDs

Azimuthal asymmetries in DVCS/BH

Cross section:

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

A_{XY}

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

beam target

polarization

Azimuthal asymmetries in DVCS/BH

Cross section:

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

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

A_{XY}

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

beam target

polarization

Azimuthal asymmetries in DVCS/BH

Cross section:

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

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

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

A_{XY}

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

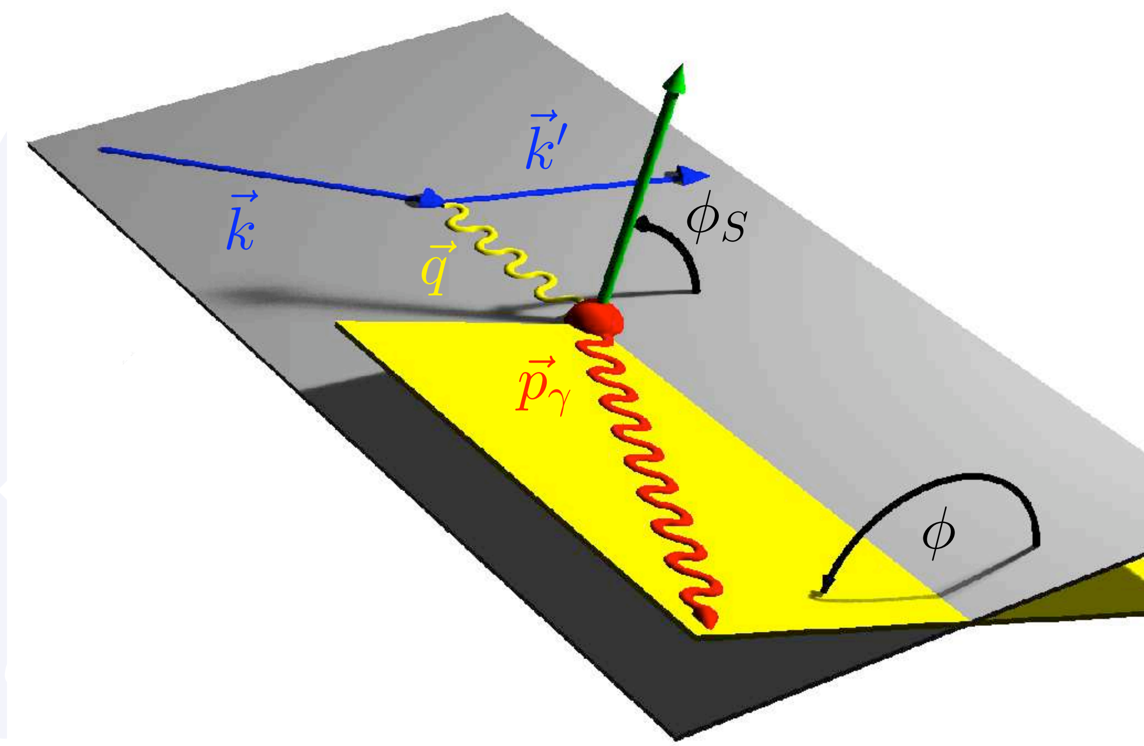
beam target

polarization

Azimuthal asymmetries in DVCS/BH

Cross section:

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



A_{XY}

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

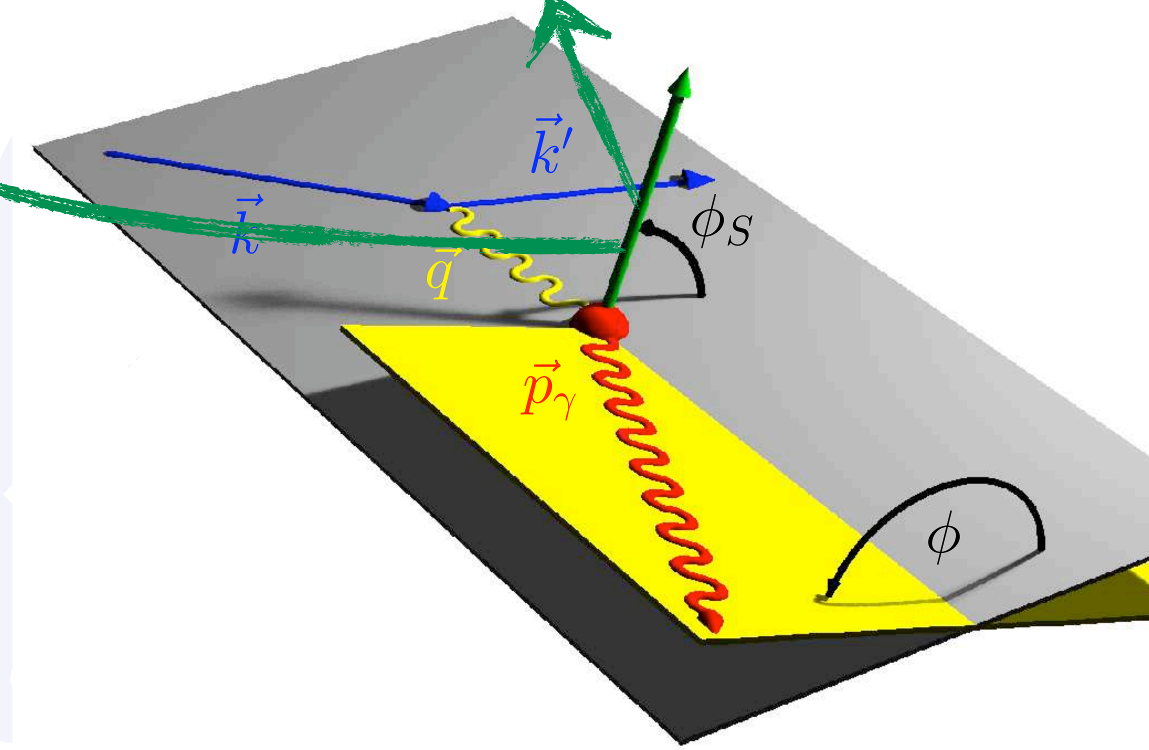
beam target

polarization

Azimuthal asymmetries in DVCS/BH

Cross section:

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



A_{XY}

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

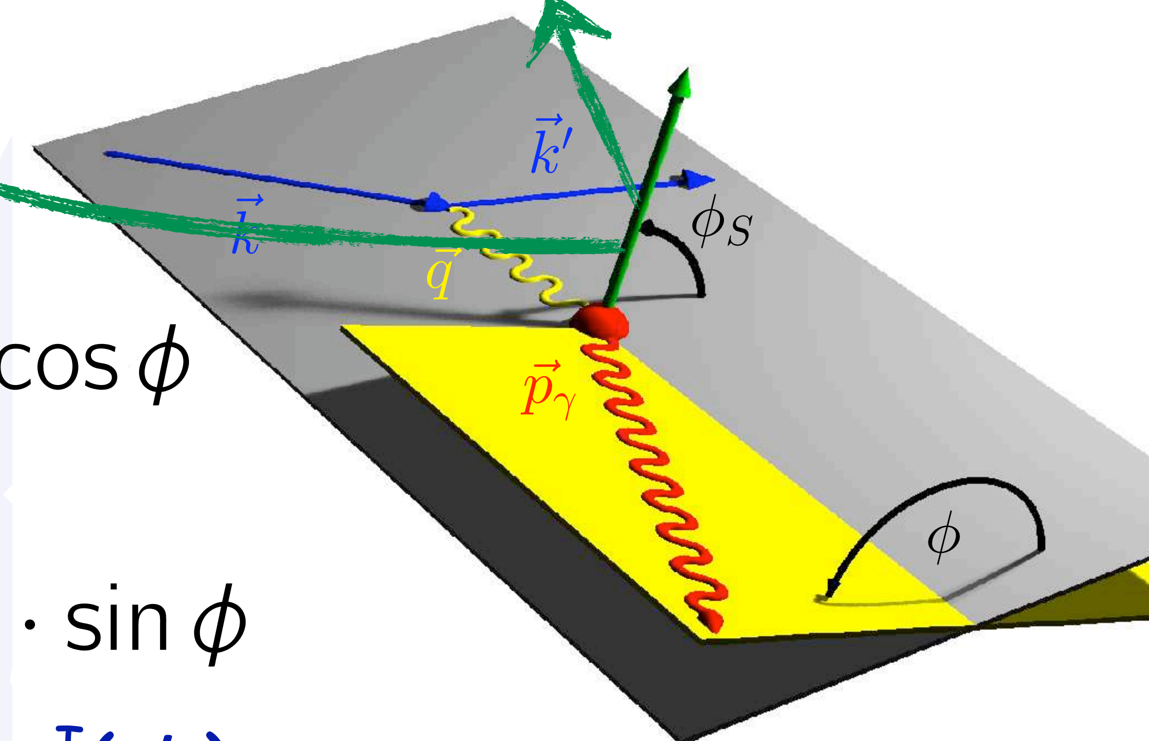
beam target

polarization

Azimuthal asymmetries in DVCS/BH

Cross section:

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



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

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

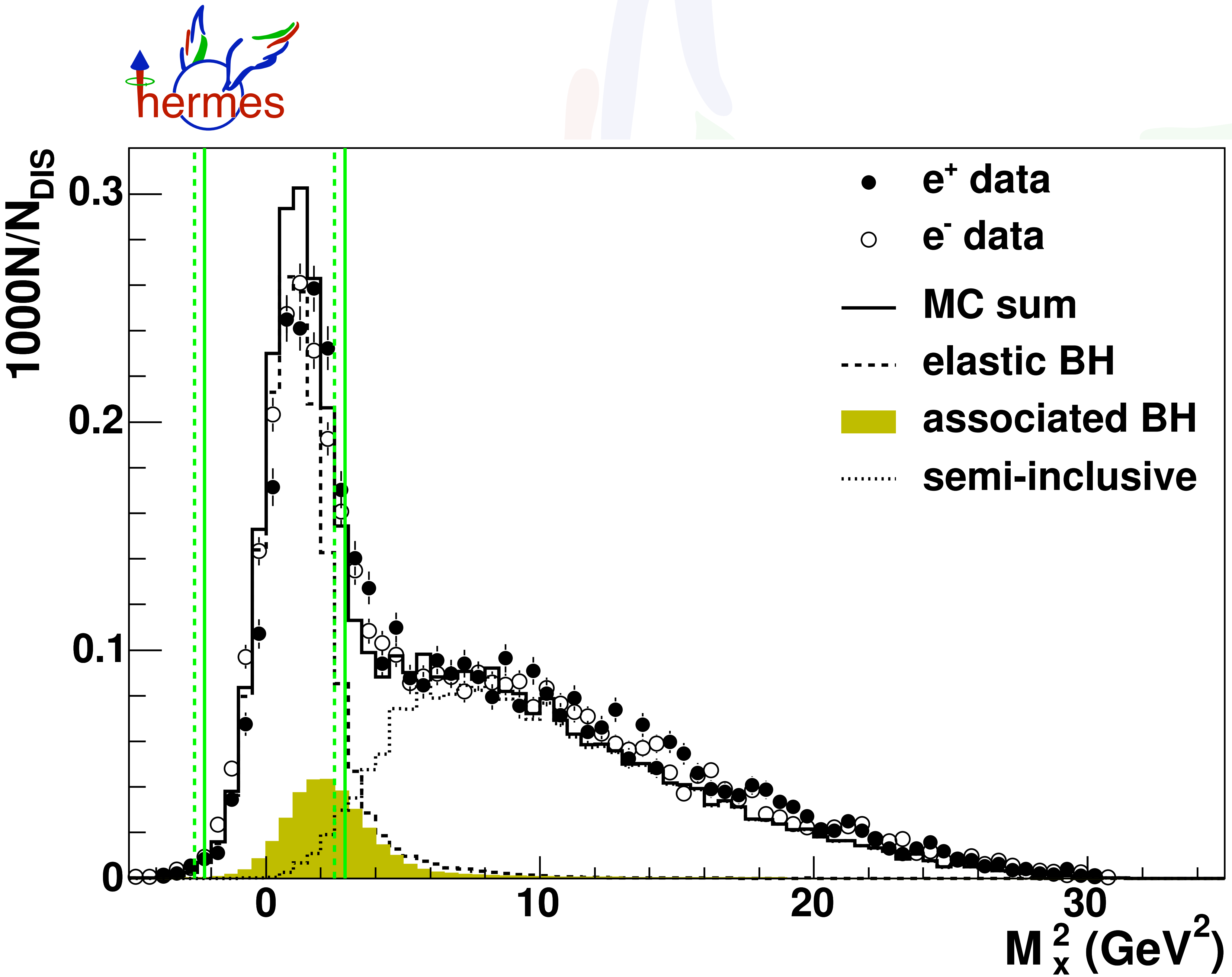
- Transverse target-spin asymmetry $A_{UT}^{I}(\phi)$:

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

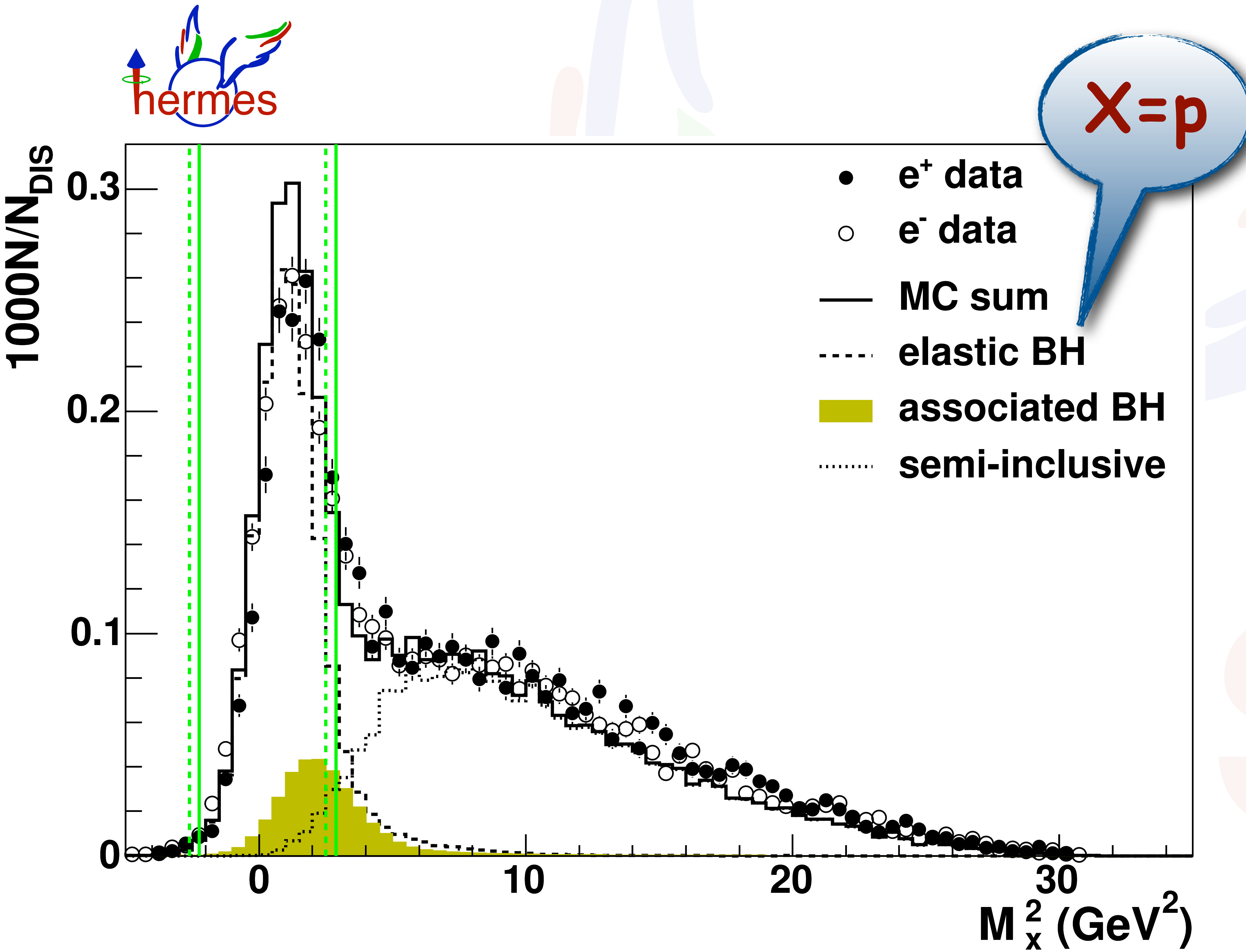
(F_1, F_2 are the Dirac and Pauli form factors)

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

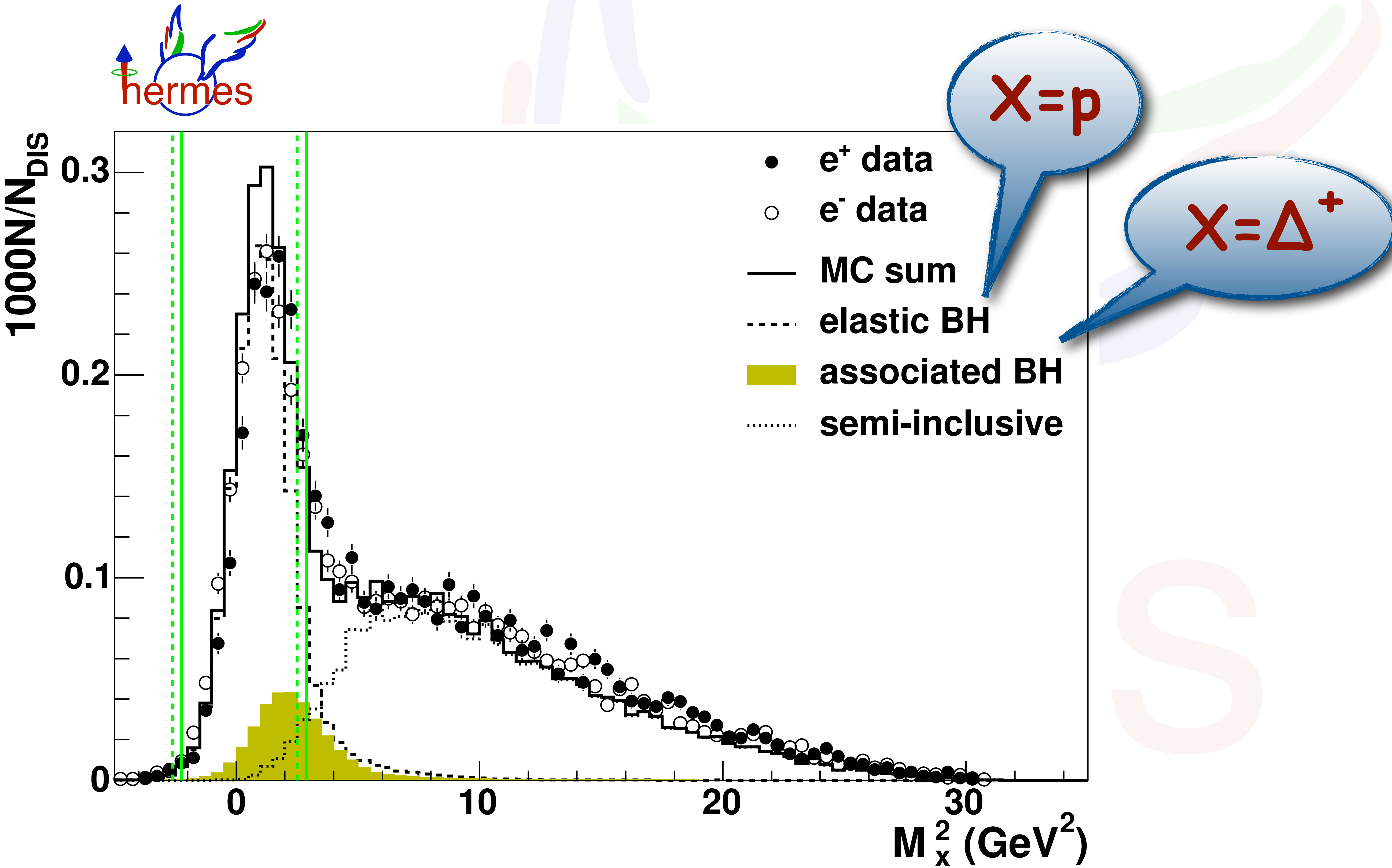
Exclusivity: missing-mass technique



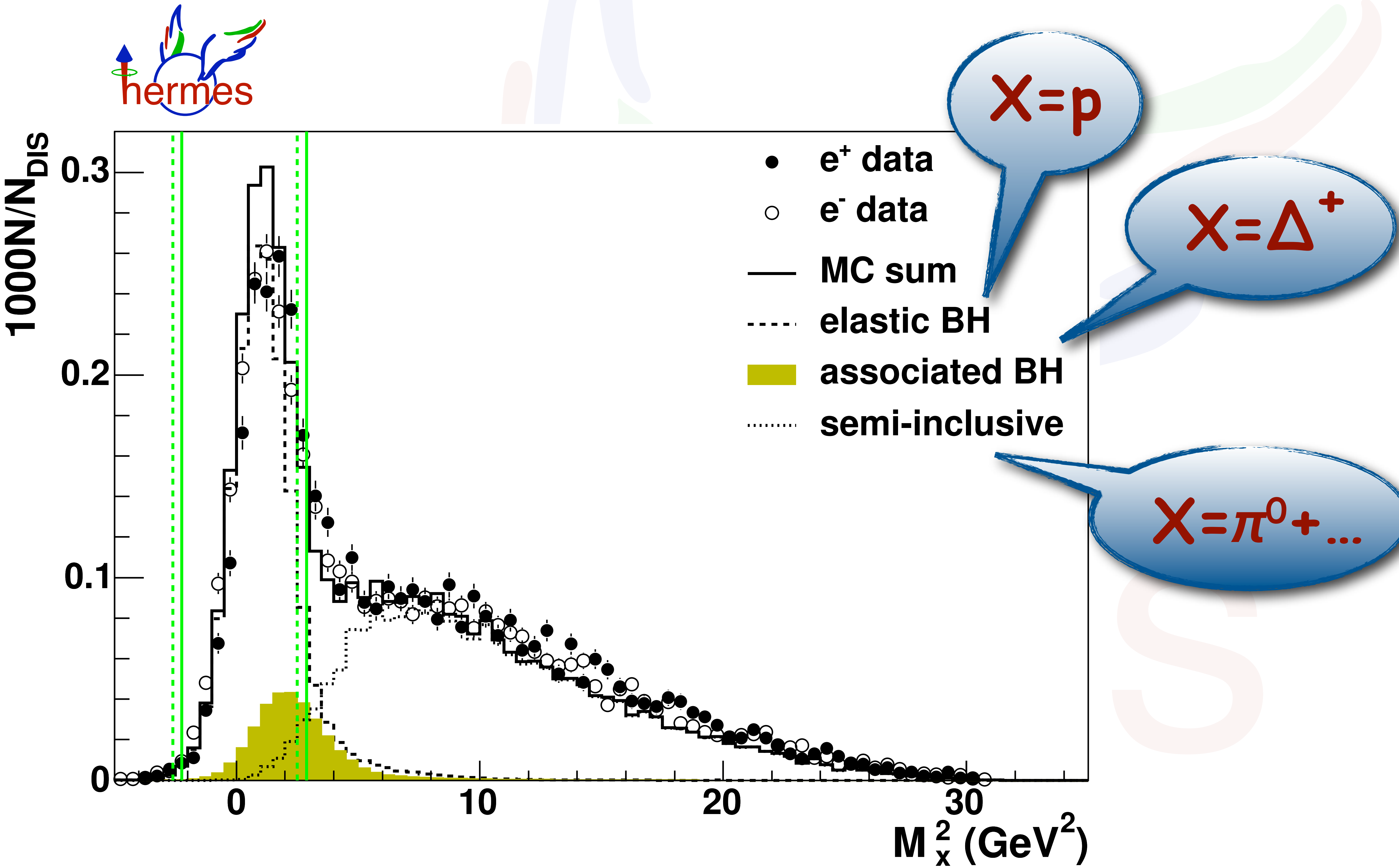
Exclusivity: missing-mass technique



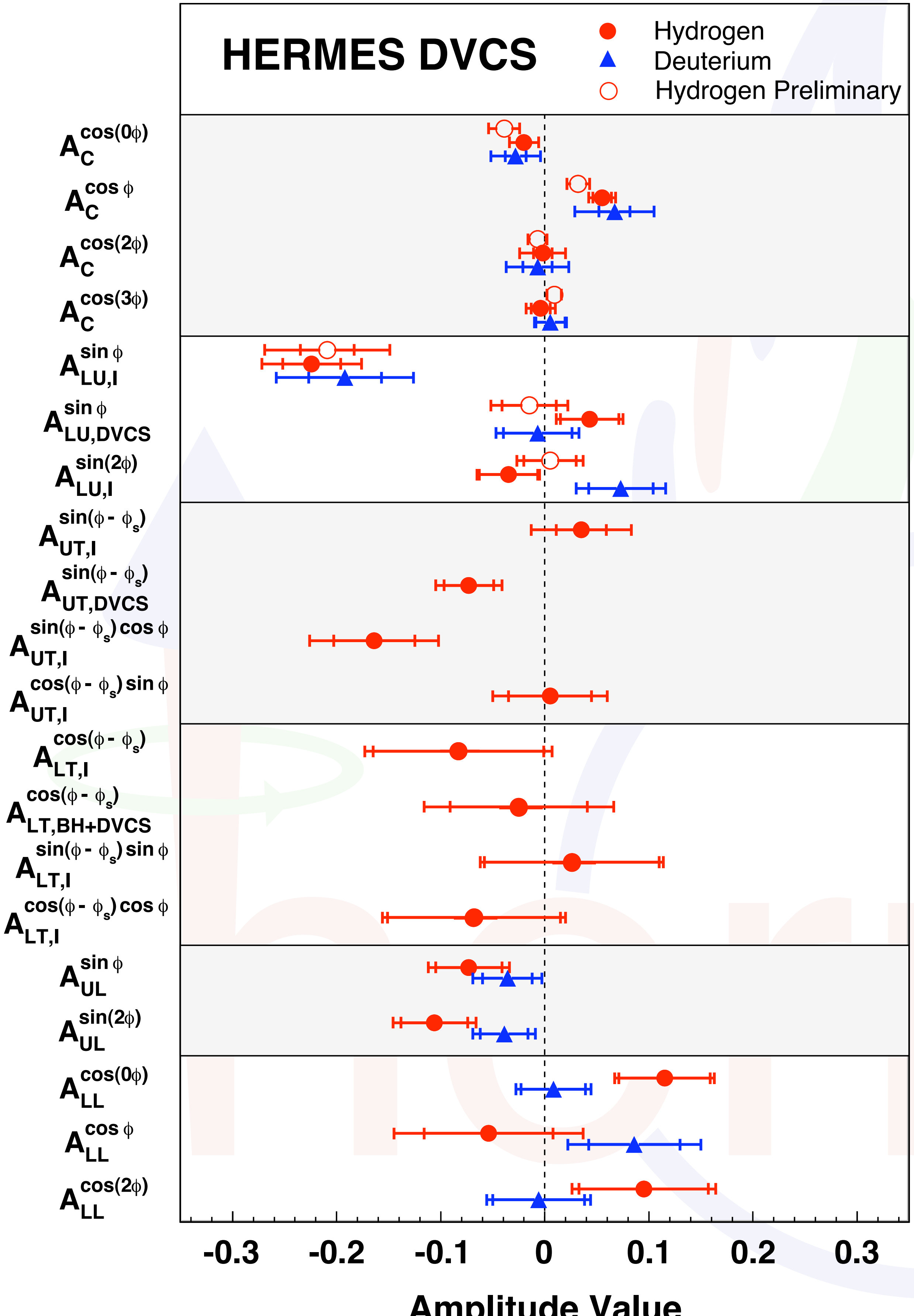
Exclusivity: missing-mass technique



Exclusivity: missing-mass technique



A wealth of azimuthal amplitudes



Beam-charge asymmetry:

GPD H

Beam-helicity asymmetry:

GPD H

Transverse target spin asymmetries:

GPD E from proton target

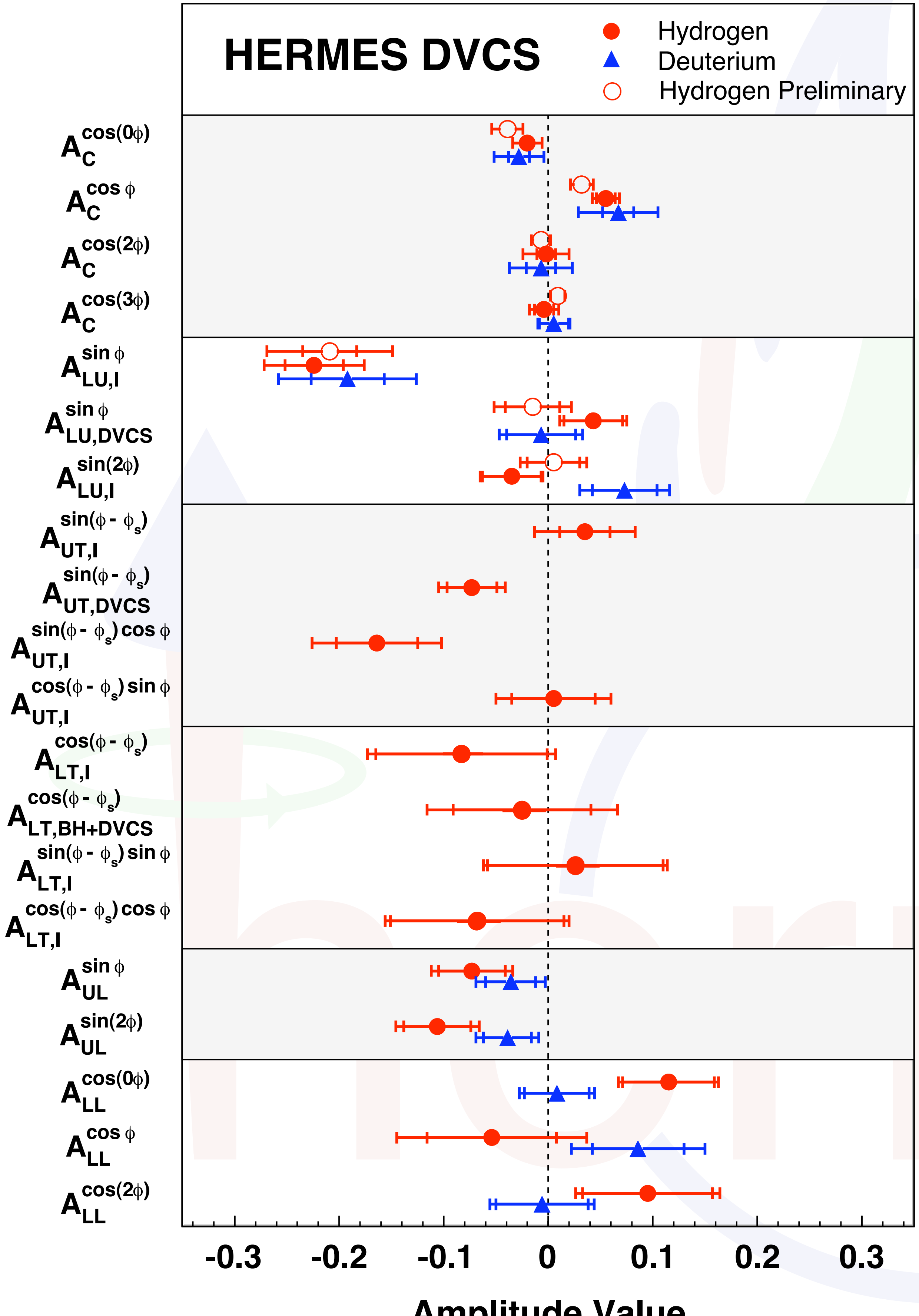
Longitudinal target spin asymmetry:

GPD $\tilde{H}$

Double-spin asymmetry:

GPD $\tilde{H}$

A wealth of azimuthal amplitudes



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GPD $\tilde{H}$

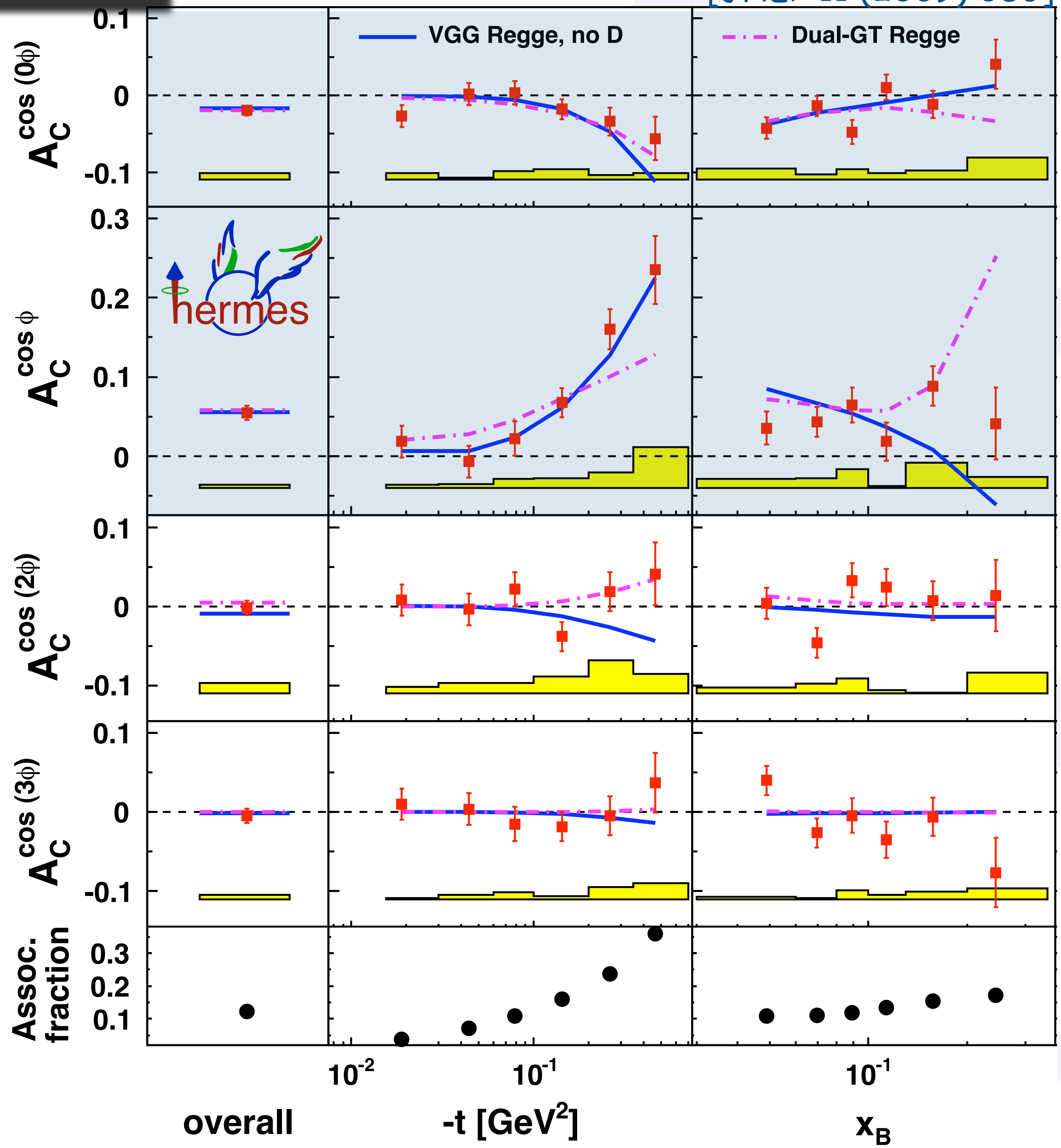
Double-spin asymmetry:

GPD $\tilde{H}$

data:
1996-2005

Beam-charge asymmetry

[JHEP 11 (2009) 083]



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

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

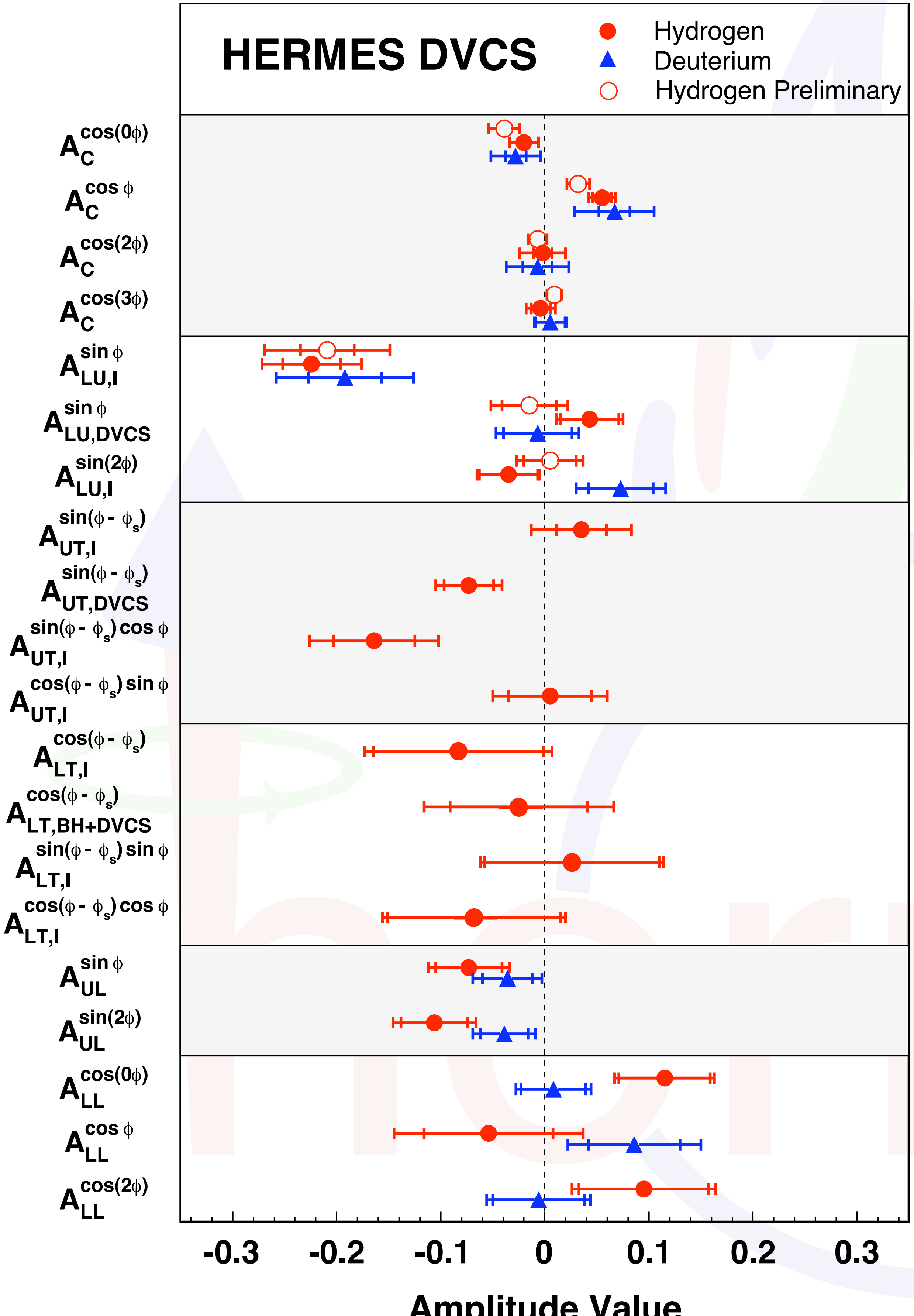
[higher twist]

[gluon leading twist]

Resonant fraction:
$ep \rightarrow e\Delta^+\gamma$

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

A wealth of azimuthal amplitudes



Beam-charge asymmetry:

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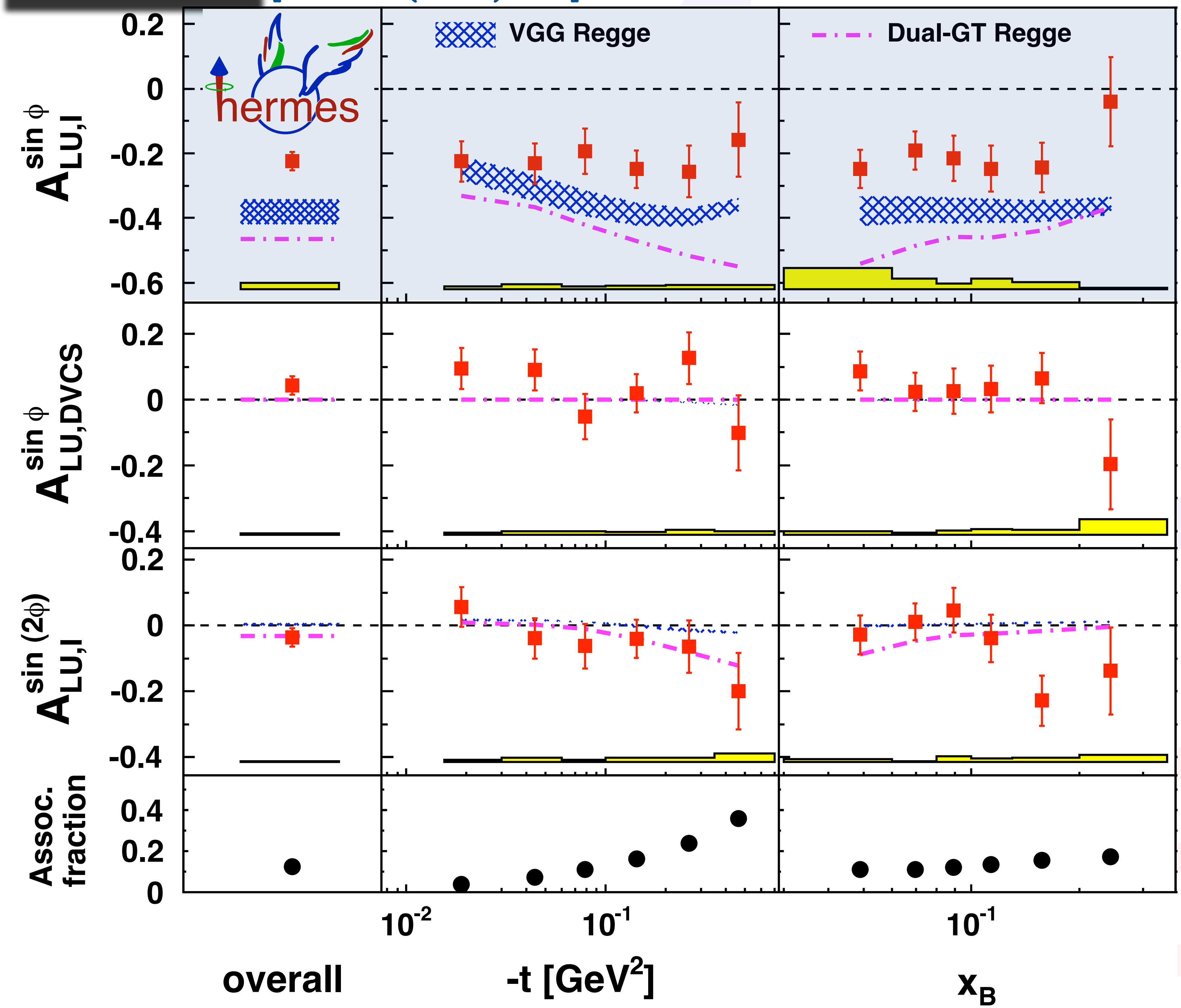
GPD $\tilde{H}$

Beam-spin asymmetry

data:
1996-2005

[JHEP 11 (2009) 083]



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

[higher twist]

Resonant fraction:

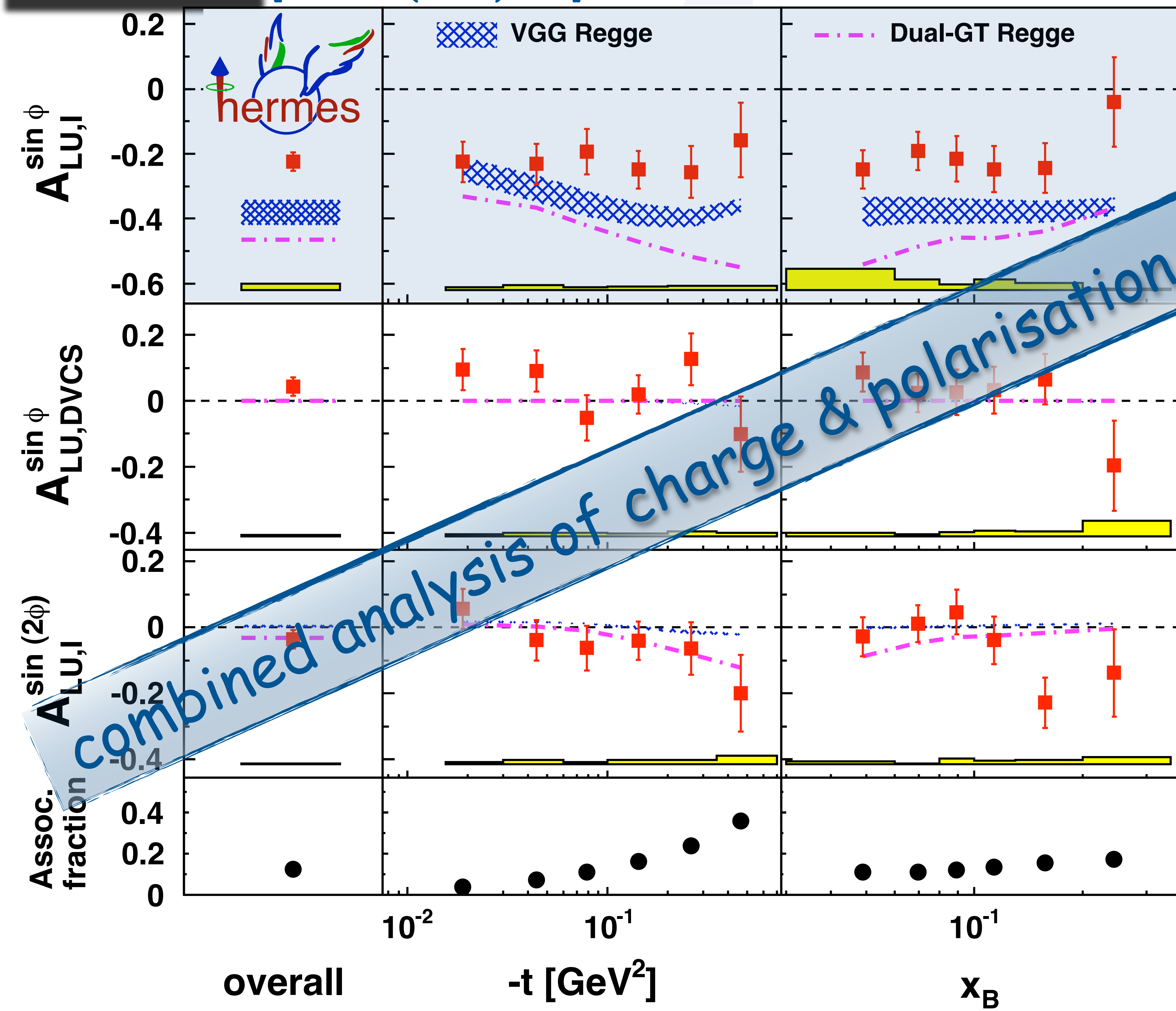
$$ep \to e\Delta^+\gamma$$

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

Beam-spin asymmetry

data:
1996-2005

[JHEP 11 (2009) 083]



combined analysis of charge & polarisation observables

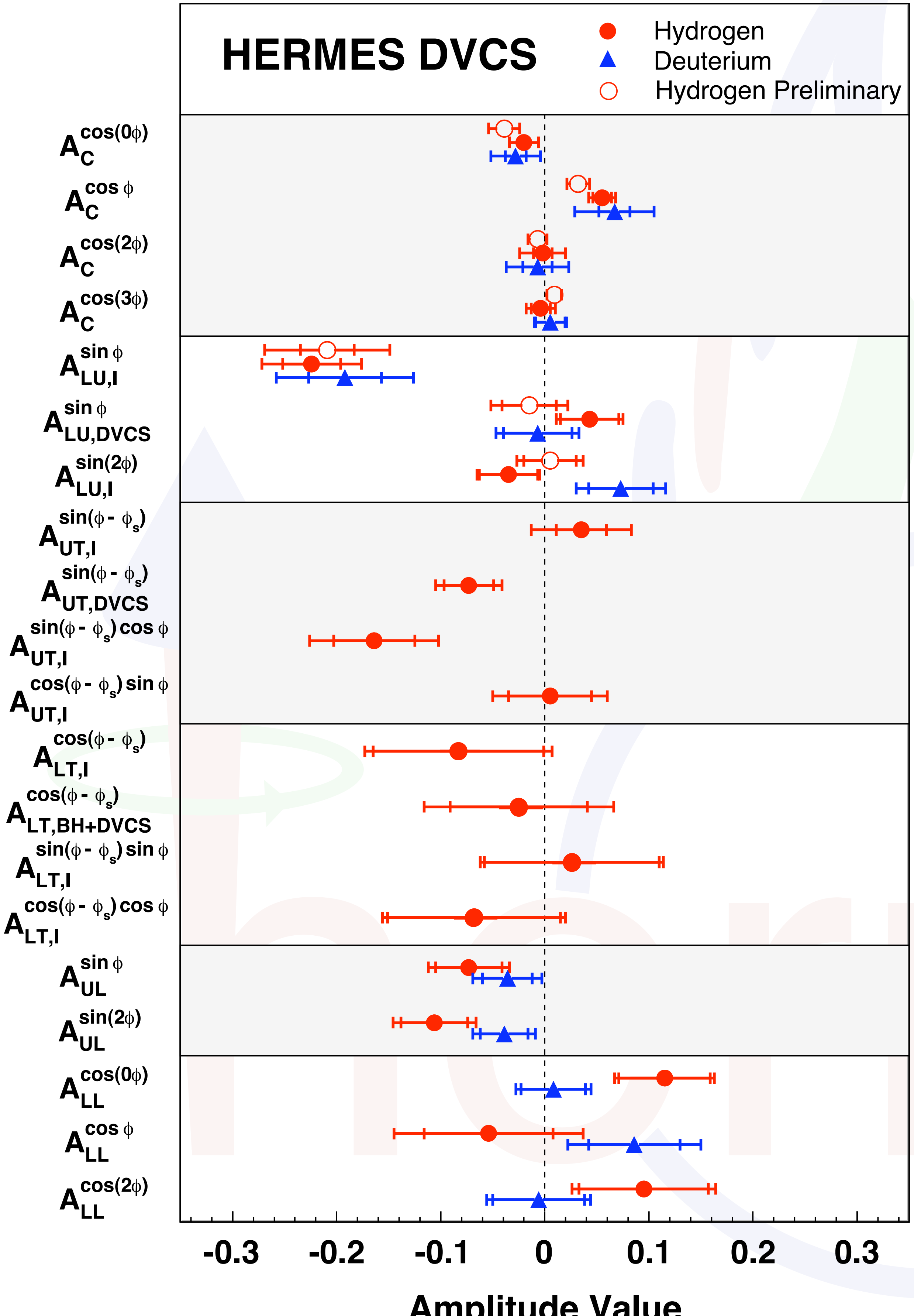
[higher twist]

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



Beam-charge asymmetry:

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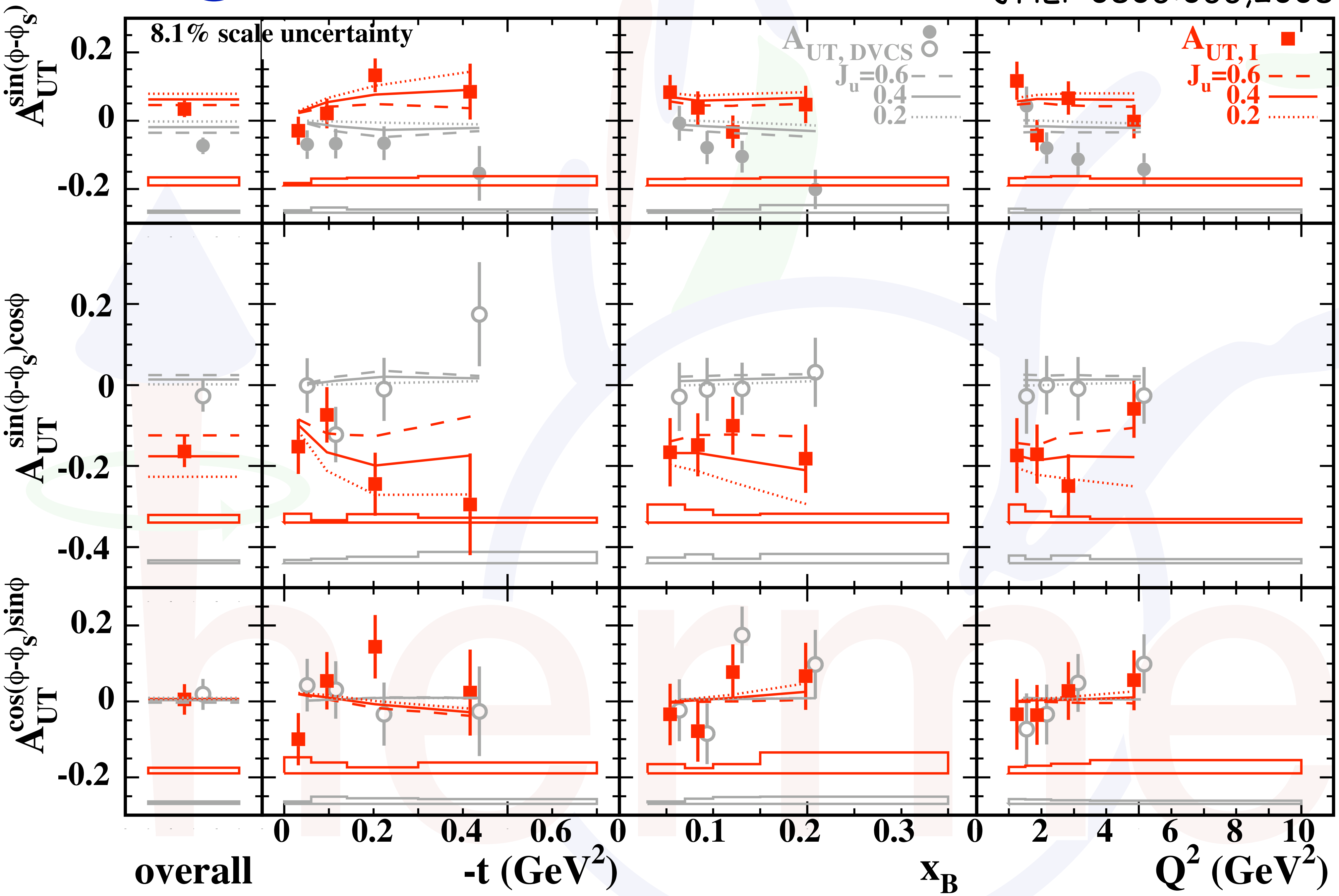
Transverse target-spin asymmetry

JHEP 0806:066,2008



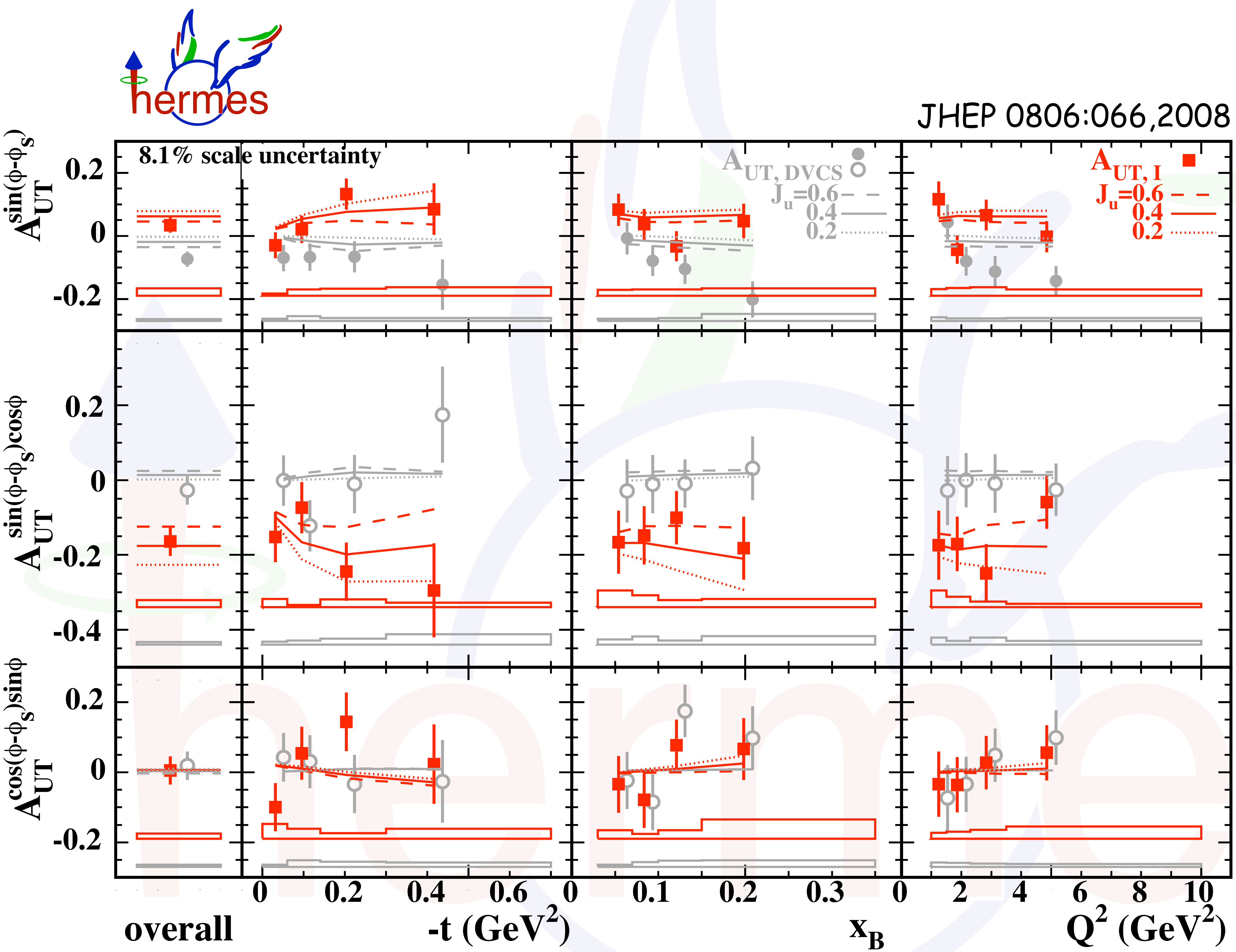
$\propto -A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$

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

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

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

Transverse target-spin asymmetry



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

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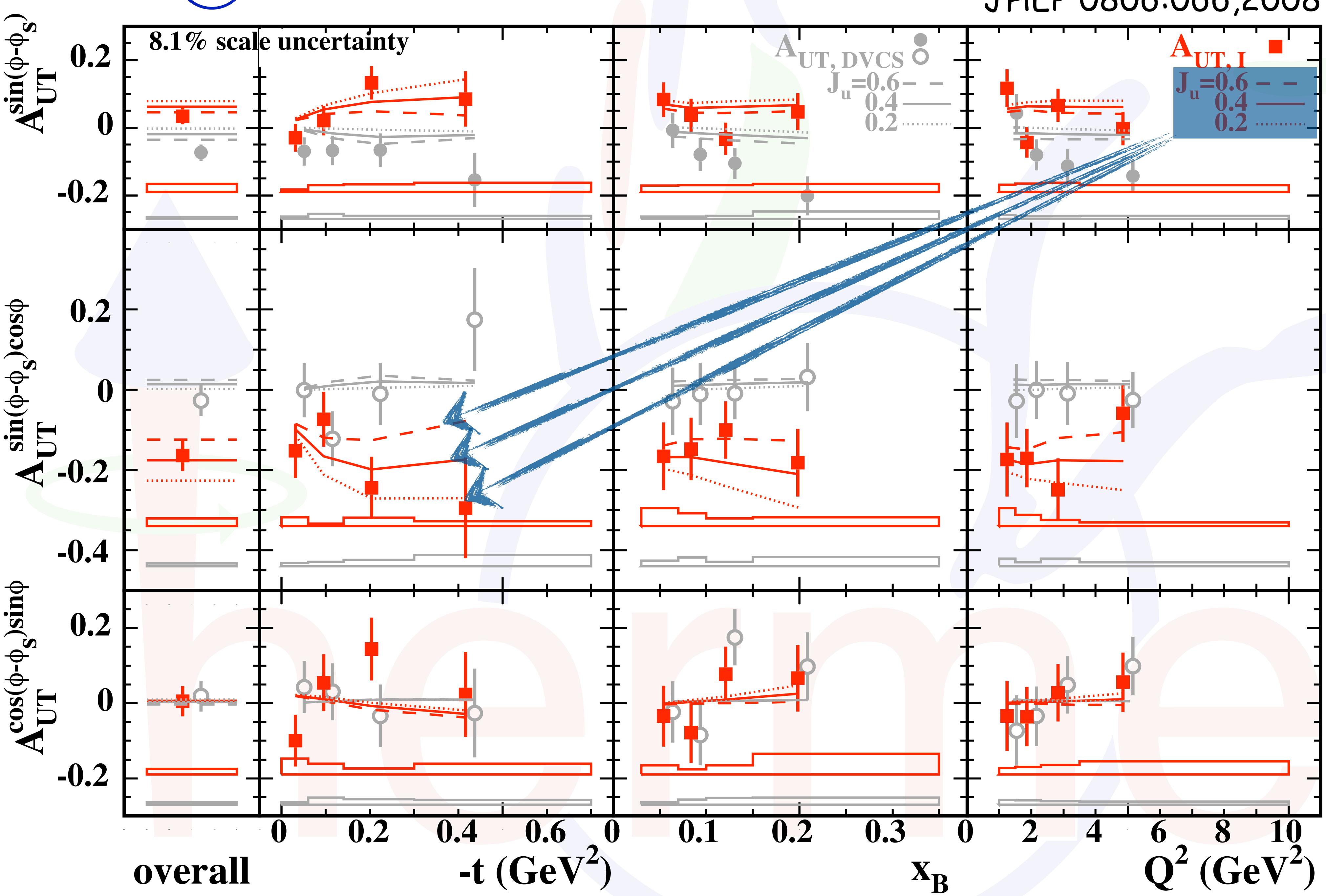
model "VGG": Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

Transverse target-spin asymmetry

JHEP 0806:066,2008



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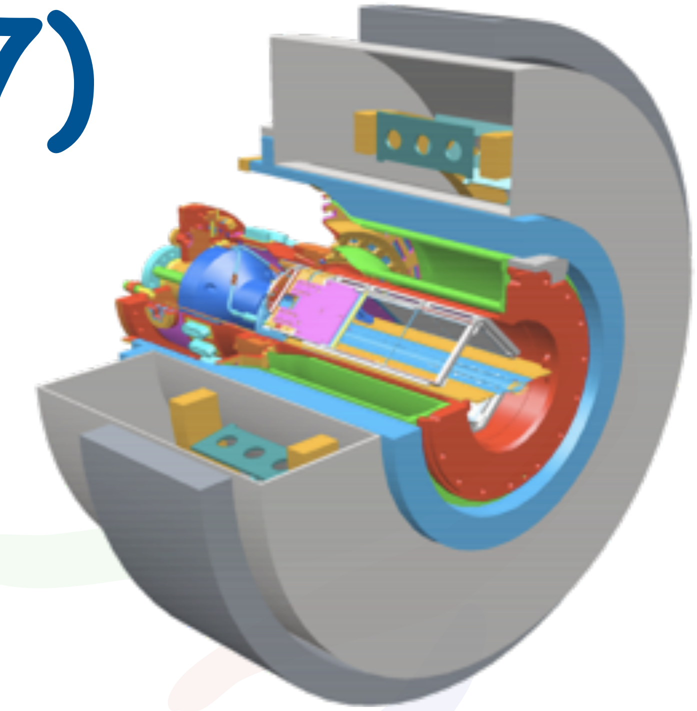
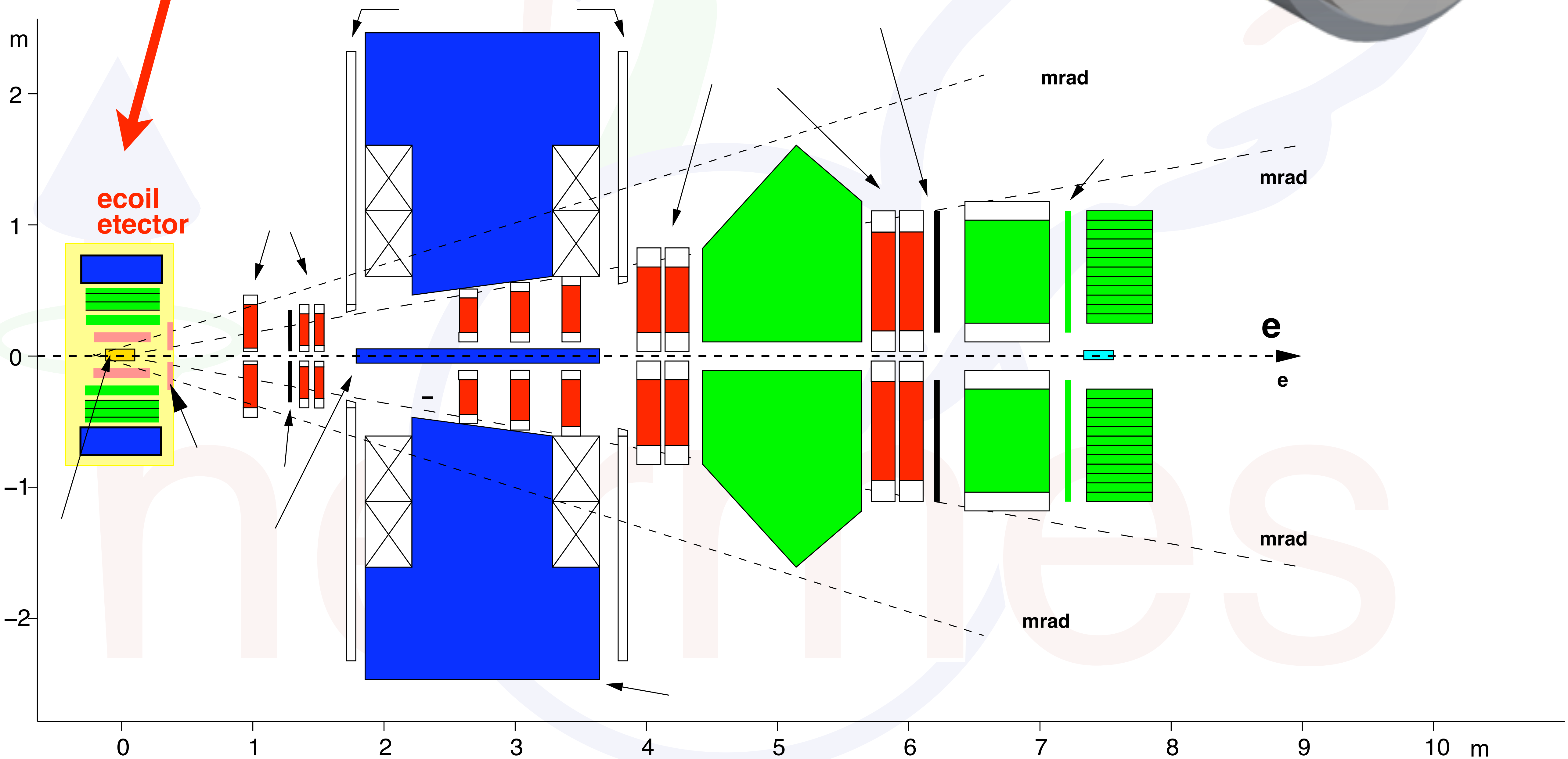
model "VGG": Phys. Rev. D60 (1999) 094017 & Prog. Nucl. Phys. 47 (2001) 401

HERMES detector (2006/07)

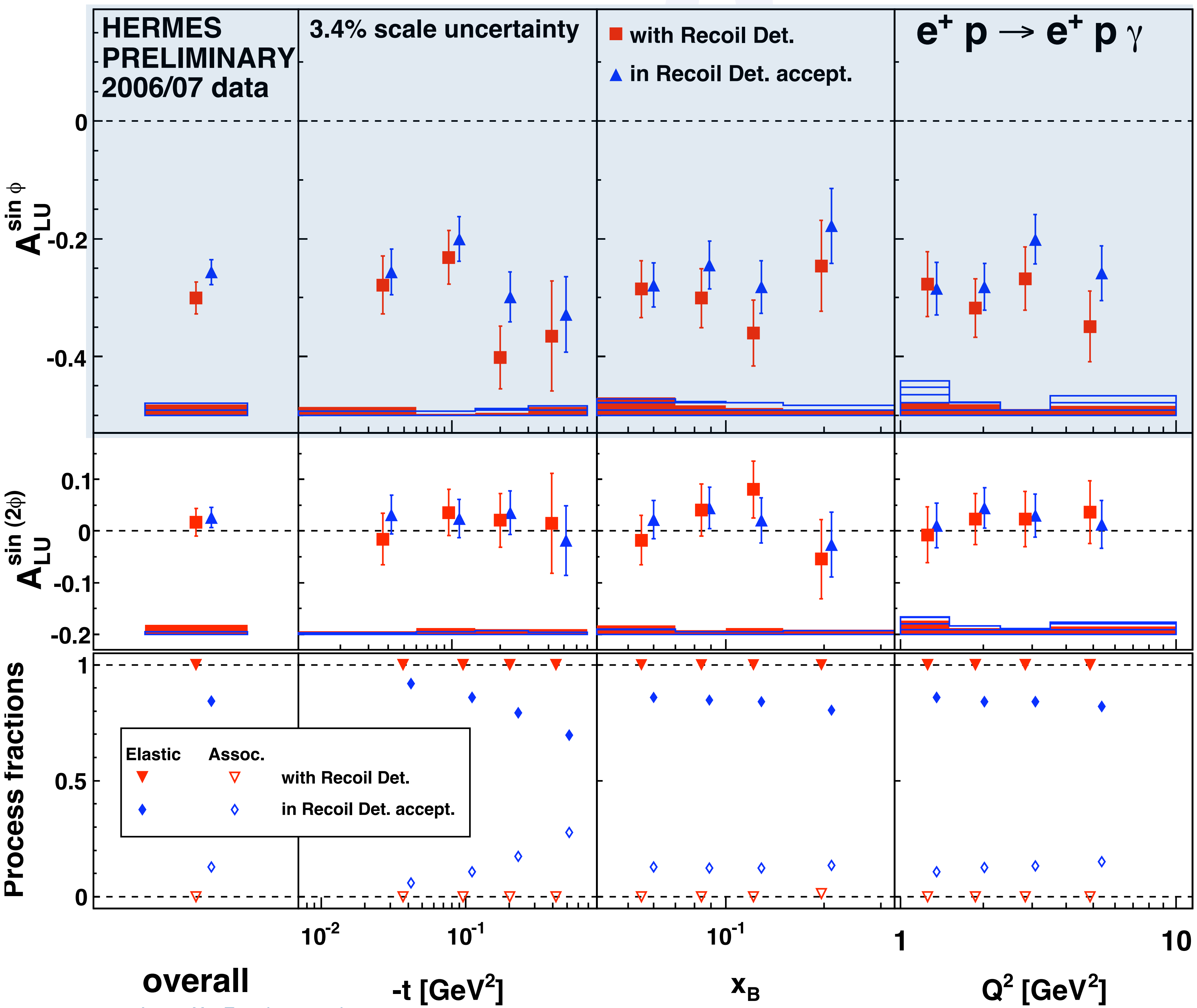


detection of
recoiling proton



DVCS with recoil detector

first DVCS data with recoil-proton detection



basically pure DVCS/BH sample

indication of larger amplitudes for pure sample

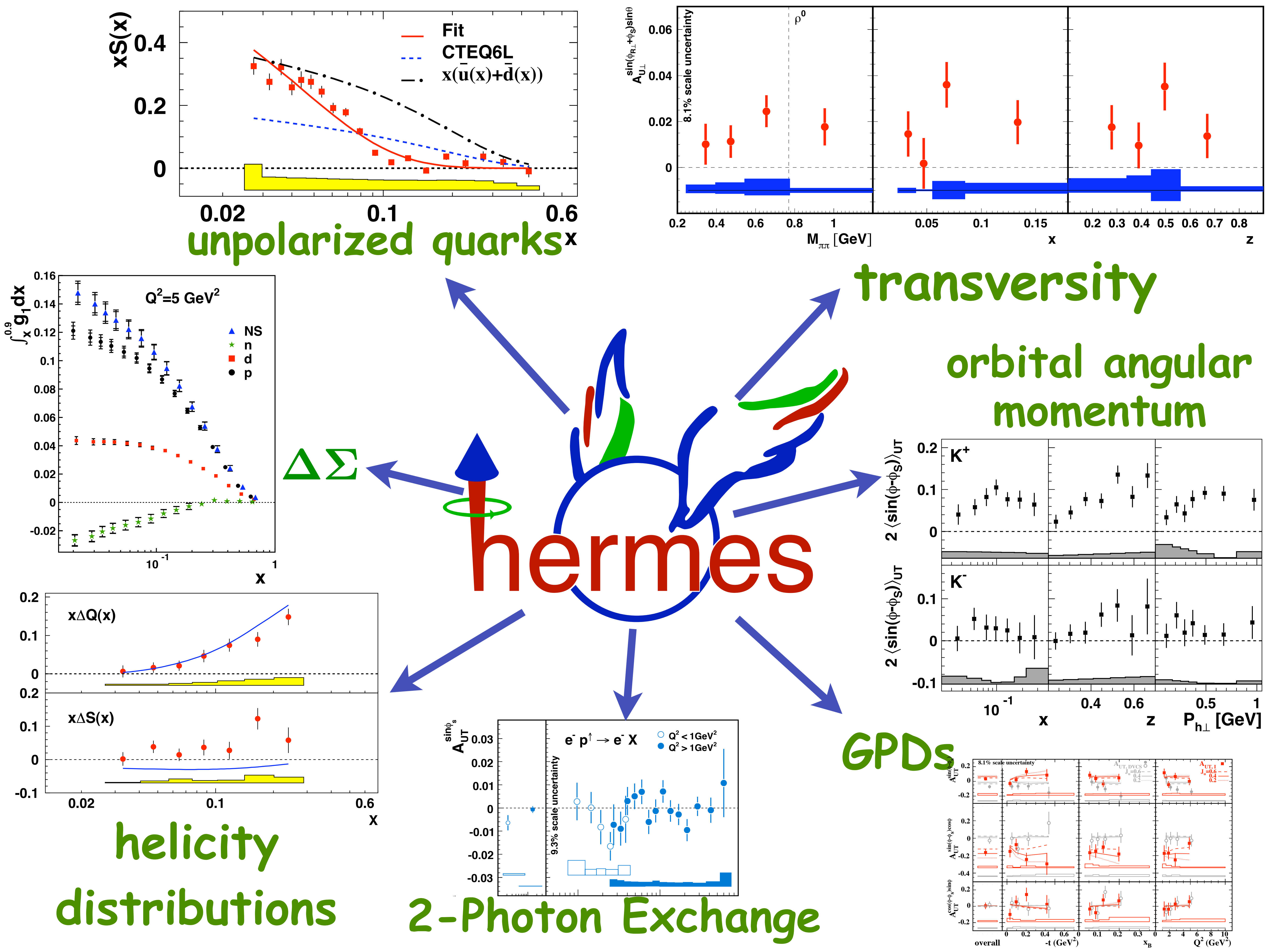
extraction of amplitudes for associated production underway

Exclusive meson production

Exclusive meson production

... next time!

hermes


unpolarized quarks
Fit
CTEQ6L
x(ū(x)+d̄(x))
xS(x)
transversity
8.1% scale uncertainty
M_ππ [GeV]
orbital angular momentum
K+
K-
GPDs
ΔΣ
Q²=5 GeV²
NS
n
d
p
hermes
xΔQ(x)
xΔS(x)
helicity distributions
e⁻ p↑ → e⁻ X
Q² < 1GeV²
Q² > 1GeV²
9.3% scale uncertainty
2-Photon Exchange