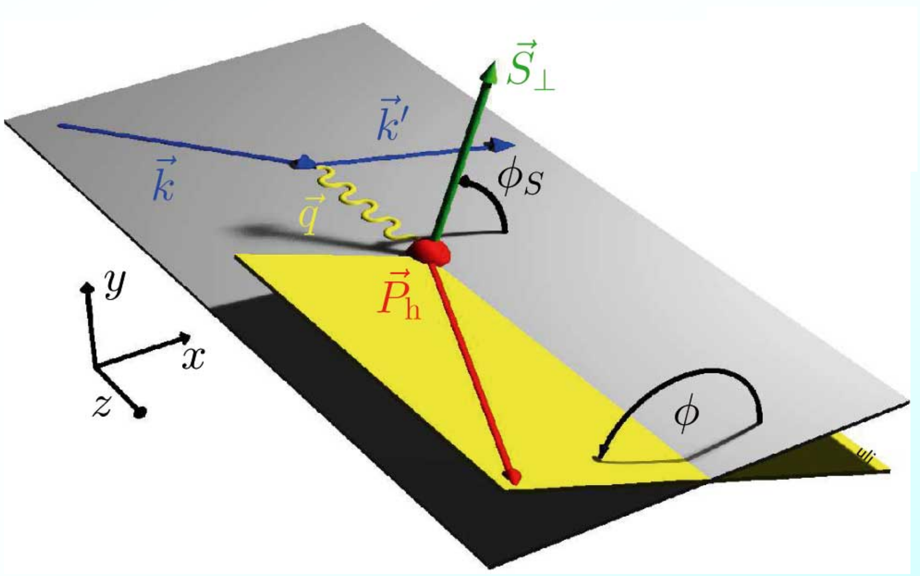
hermes Results on Azimuthal Asymmetries related to TMDs and DVCS

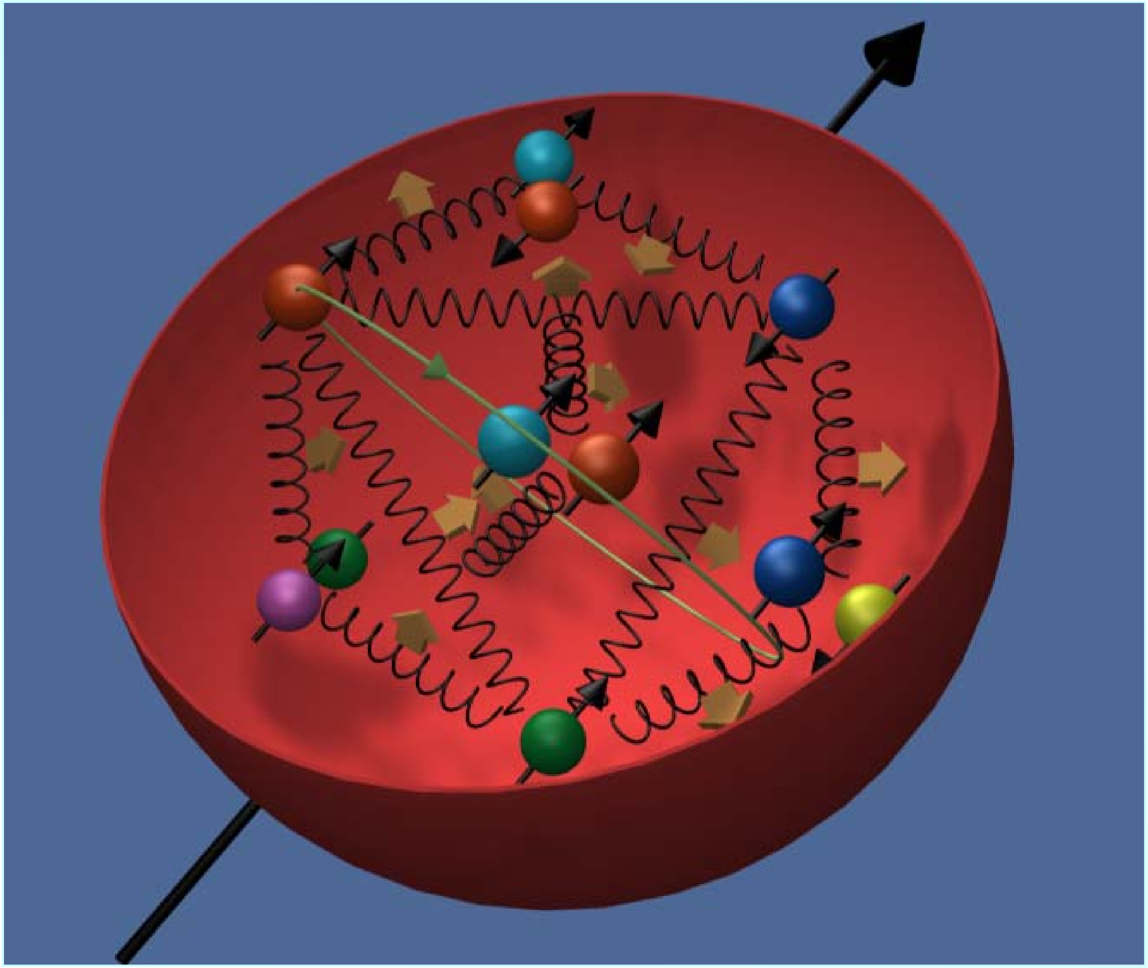
Klaus Rith

University of Erlangen-Nürnberg & DESY

(on behalf of the HERMES collaboration)



The Nucleon – QCD picture



Constituents: quarks and gluons

Properties: longitudinal momentum $x\vec{P}$, intrinsic transverse momentum $\vec{p}_T$, spin $\vec{s}$, orbital angular momentum $\vec{L}$

Transverse Momentum Dependent DFs

LO quark distribution functions

Mulders and Tangerman, Nucl. Phys. B 461 (1996) 197
A. Bacchetta et al., JHEP 0702 (2007)

See talk by A. Prokudin

		quark U	quark L	quark T
nucleon	U	f_1		$h_1^\perp$
nucleon	L		g_1	$h_{1L}^\perp$
nucleon	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1, $h_{1T}^\perp$

Boer-Mulders DF

'worm-gear 1' DF

Transversity DF

Prezelosity DF

Sivers DF

'worm-gear 2' DF

Only f_1 and g_1 measurable in inclusive DIS, all others in SIDIS

$D_1 \equiv D_q^h$ = ‚normal' FF,
$H_1^\perp$ = spin-dependent Collins FF

Transverse Momentum Dependent DFs

LO quark distribution functions

Mulders and Tangerman, Nucl. Phys. B 461 (1996) 197
A. Bacchetta et al., JHEP 0702 (2007)

See talk by A. Prokudin

		quark		
		U	**L**	**T**
nucleon	**U**	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

$h_1^\perp$: Boer-Mulders DF *
$h_{1L}^\perp$: 'worm-gear 1' DF
h_1: Transversity DF
$h_{1T}^\perp$: Prezelosity DF
$f_{1T}^\perp$: Sivers DF*
$g_{1T}^\perp$: 'worm-gear 2' DF

Only f_1 and g_1 measurable in inclusive DIS, all others in SIDIS

$D_1 \equiv D_q^h$ = ‚normal' FF,
$H_1^\perp$ = spin-dependent Collins FF *

* T-odd requires FSI/ISI

Transverse Momentum Dependent DFs

LO quark distribution functions

Mulders and Tangerman, Nucl. Phys. B 461 (1996) 197
A. Bacchetta et al., JHEP 0702 (2007)

See talk by A. Prokudin

nucleon		quark U	quark L	quark T
	U	f_1		$h_1^{\perp}$ – Boer-Mulders DF *#
	L		g_1	$h_{1L}^{\perp}$ – 'worm-gear 1' DF#
	T	$f_{1T}^{\perp}$ – Sivers DF*	g_{1T} – 'worm-gear 2' DF	h_1 – Transversity DF#; $h_{1T}^{\perp}$ – Prezelosity DF#

Only f_1 and g_1 measurable in inclusive DIS, all others in SIDIS

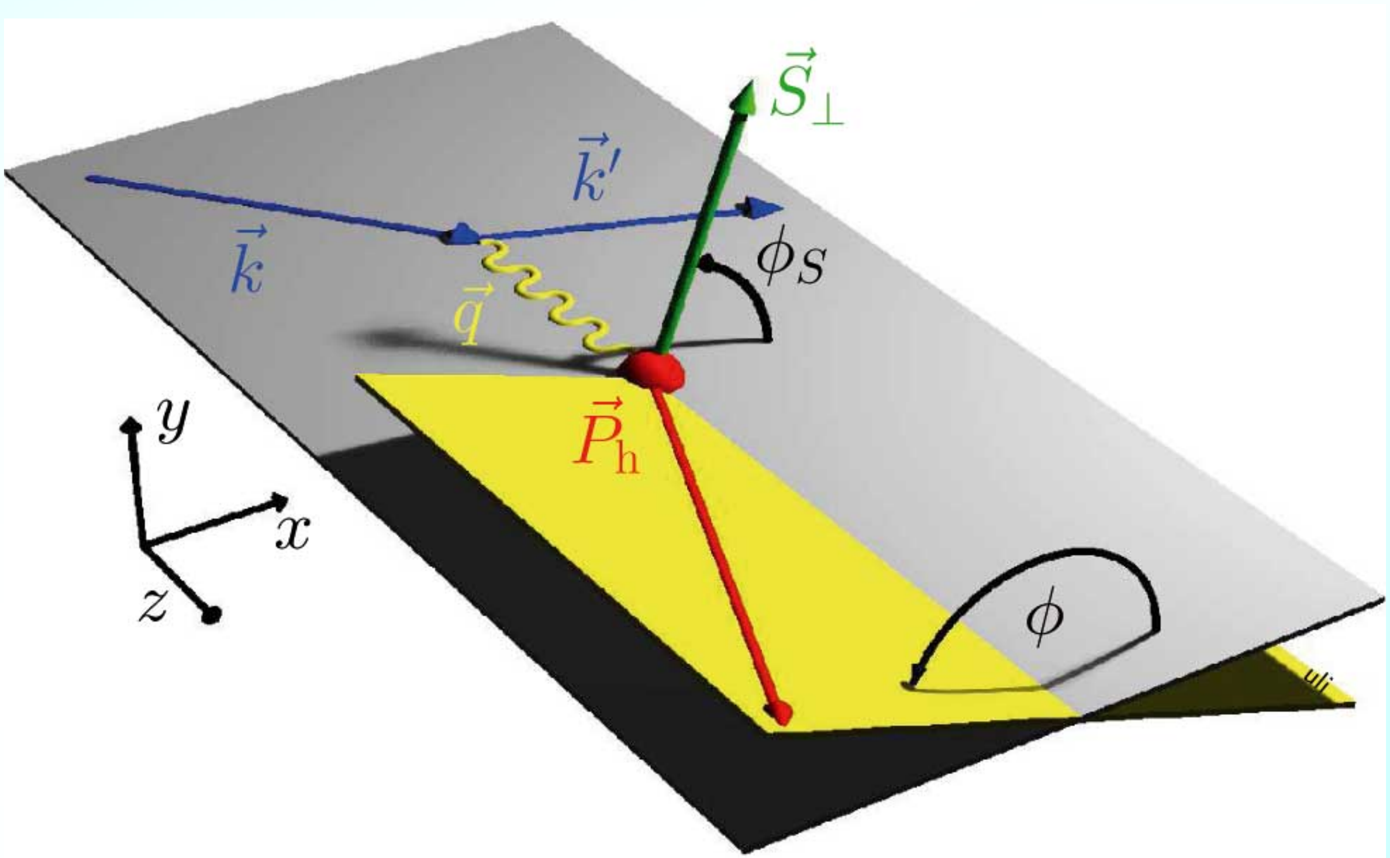
$D_1 \equiv D_q^h$ = ‚normal' FF,
$H_1^{\perp}$ = spin-dependent Collins FF *#

* T-odd requires FSI/ISI
# chiral-odd

Angular distributions in electroproduction

ϕ: angle between lepton scattering plane and hadron production plane

ϕ_S: angle between lepton scattering plane and transverse spin component $S_\perp$ of target nucleon



TMDs from SIDIS

$$d\sigma \equiv \frac{d^6\sigma}{dx\, dy\, dz\, d\phi\, d\phi_s\, dP_T{}^h}$$

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

$$+ S_T \Big\{ \sin(\phi-\phi_S)\; d\sigma_{UT}^{8} + \sin(\phi+\phi_S)\; d\sigma_{UT}^{9} + \sin(3\phi-\phi_S)\; d\sigma_{UT}^{10}$$

$$+ \frac{1}{Q}\sin(2\phi-\phi_S)\; d\sigma_{UT}^{11} + \frac{1}{Q}\sin\phi_S\, d\sigma_{UT}^{12}$$

$$+ \lambda_e \Big[\cos(\phi-\phi_S)\; d\sigma_{LT}^{13} + \frac{1}{Q}\cos\phi_S\, d\sigma_{LT}^{14} + \frac{1}{Q}\cos(2\phi-\phi_S)\, d\sigma_{LT}^{15} \Big]\Big\}$$

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

$d\sigma_{XY}$: X → Beam, Y → Target Polarisation

Detailed studies require: longitudinally polarised beam (λ_e), longitudinally and transversely polarised target (S_L, S_T)

TMDs from SIDIS

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

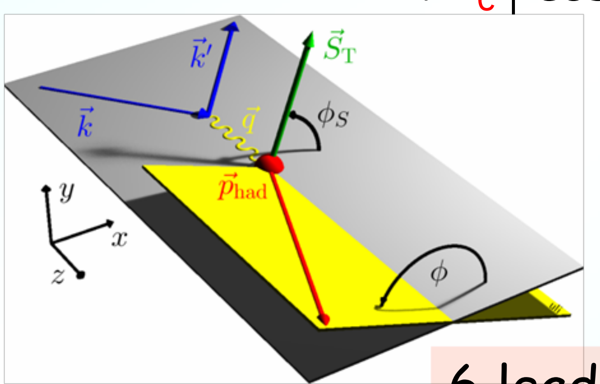
$$+ S_T\Big\{ \sin(\phi-\phi_S)\, d\sigma^8_{UT} + \sin(\phi+\phi_S)\, d\sigma^9_{UT} + \sin(3\phi-\phi_S)\, d\sigma^{10}_{UT}$$

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

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

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

$d\sigma_{XY}$
Beam Target
Polarisation



6 leading twist contributions

8 subleading (~1/Q)

TMDs in SIDIS at LO

LO Function	Moment	Convolution	Name
$d\sigma^{9}_{UT}$	$\sin(\phi + \phi_s)$	$h_1 \otimes H_1^{\perp}$	Transversity
$d\sigma^{8}_{UT}$	$\sin(\phi - \phi_s)$	$f_{1T}^{\perp} \otimes D_1$	Sivers
$d\sigma^{1}_{UU}$	$\cos(2\phi)$	$h_1^{\perp} \otimes H_1^{\perp}$	Boer-Mulders
$d\sigma^{10}_{UT}$	$\sin(3\phi - \phi_s)$	$h_{1T}^{\perp} \otimes H_1^{\perp}$	Prezelosity
$d\sigma^{4}_{UL}$	$\sin(2\phi)$	$h_{1L}^{\perp} \otimes H_1^{\perp}$	Worm-gear 1 Mulders-Kotzinian
$d\sigma^{13}_{LT}$	$\cos(\phi - \phi_s)$	$g_{1T}^{\perp} \otimes D_1$	Worm-gear 2

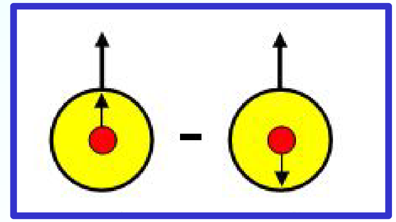
The others are subleading, i.e., suppressed by $1/Q$

Transversity, Collins Amplitudes

Transversity DF

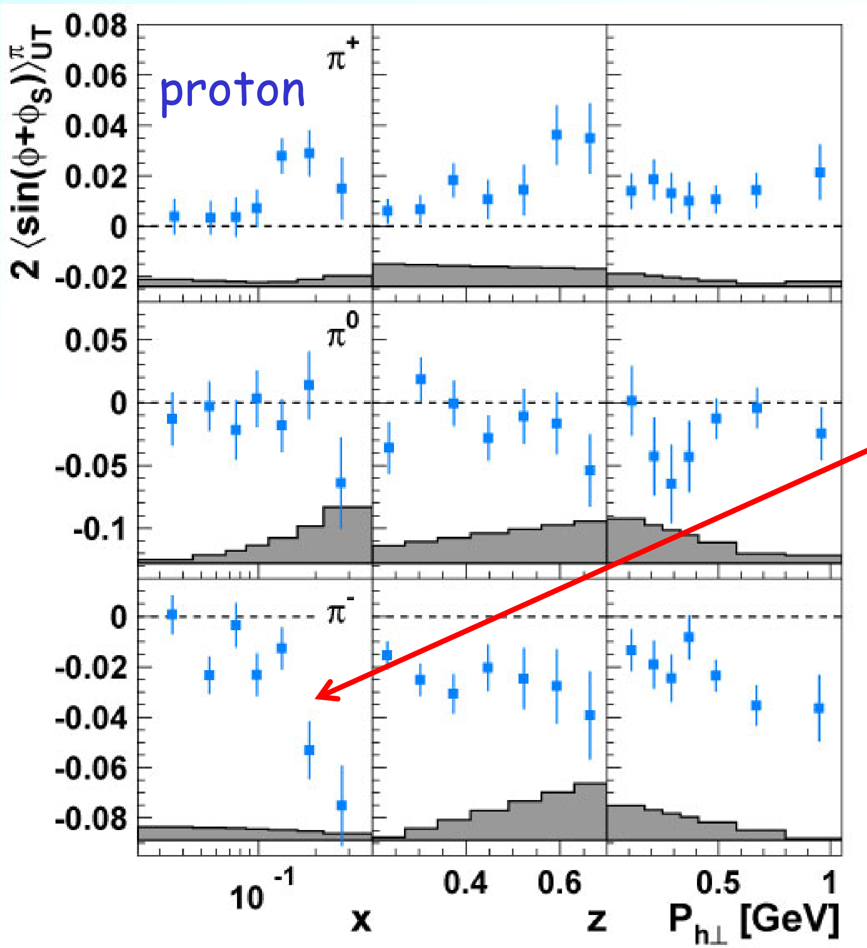
$2\langle \sin(\phi + \phi_S)\rangle^h_{UT} \propto h_1^q(x) \otimes H_1^{\perp q}(z)$

Collins FF



N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

arXiv:1006.4221



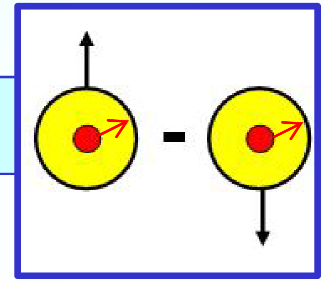
- Both Collins fragmentation function and transversity distribution function are sizeable
- Surprisingly large π^- asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation,

$H_1^{\perp}{}_{,disf} \approx - H_1^{\perp}{}_{,fav}$

Sivers Amplitudes for Pions

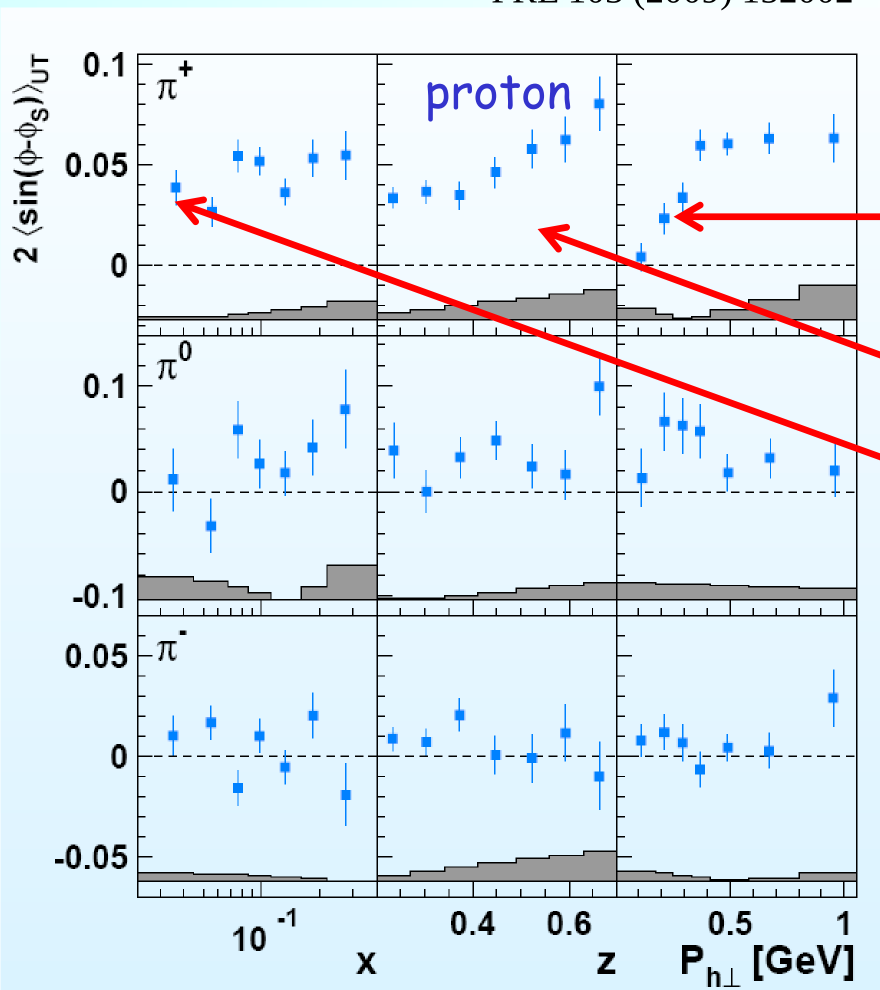
Sivers DF

$$2\langle\sin(\phi - \phi_S)\rangle^h_{UT} \propto f_{1T}^{\perp,q}(x) \otimes D_1^q(z)$$



N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

PRL 103 (2009) 152002



- First observation of non-zero Sivers DF in DIS
- Rise at low $P_{h\perp}$, plateau at high $P_{h\perp}$
- Clear rise with z
- Non-zero at low x

Experimental evidence for orbital angular momentum L_q of quarks

But: Quantitative contribution of L_q to nucleon spin still unclear

TSA in inclusive hadron electroproduction

TSA: Tranverse target single-spin asymmetry

Reminder: Large A_N in $p\uparrow p \rightarrow \pi$ (K) X

Interpretation: Collins?, Sivers? Twist-3? …?

TSA in inclusive hadron electroproduction

TSA: Tranverse target single-spin asymmetry

Reminder: Large A_N in $p\uparrow p \rightarrow \pi\ (K)\ X$

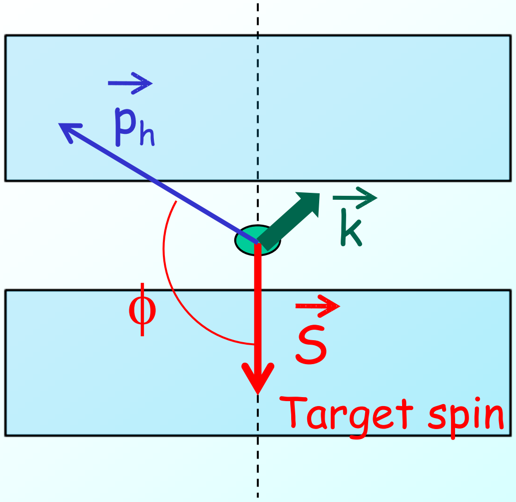
Interpretation: Collins?, Sivers? Twist-3? ...?

Inclusive hadron electroproduction:
$e^{\pm}\ p\uparrow \rightarrow h\ X$

Scattered lepton not detected:
➡ quasi-real photoproduction

π^+	π^-	K^+	K^-
66.4 M	56.8 M	5.5 M	3.0 M

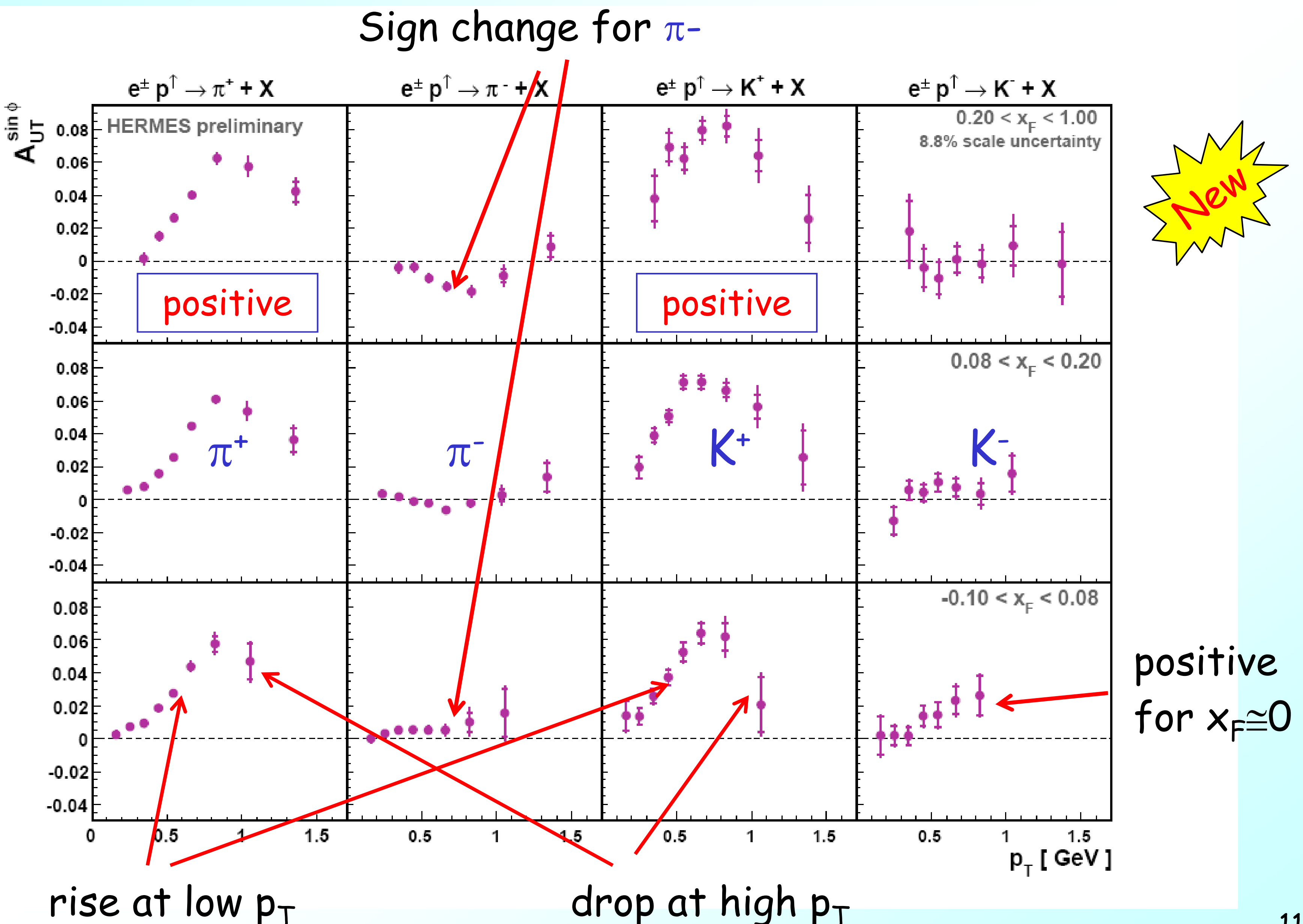
Front view of HERMES



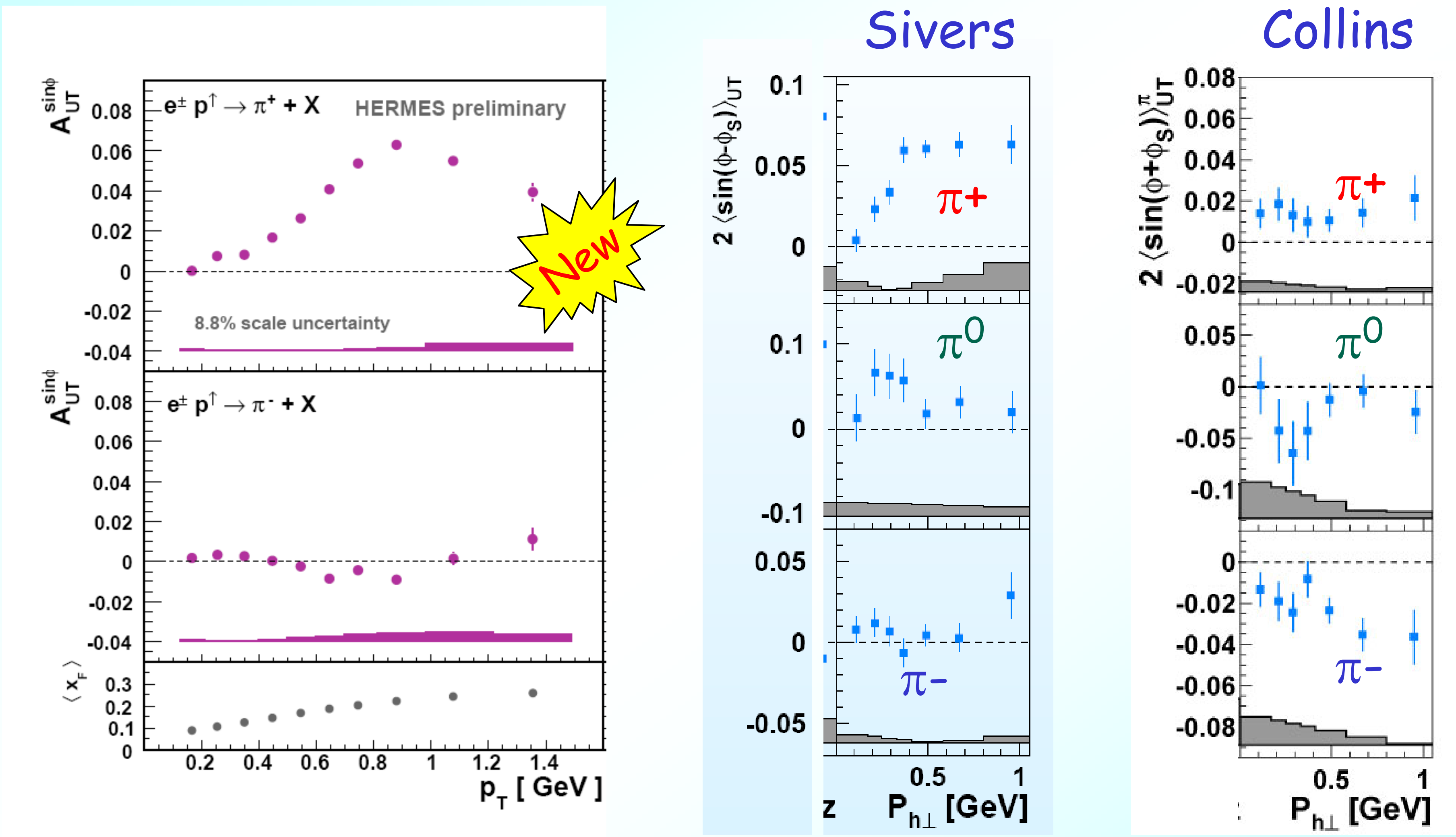
Target-spin reversal every 90 s
➡ acceptance effects cancel

$$A_{UT}(x_B, Q^2, \phi) \cong A_{UT}^{\sin\phi}(x_B, Q^2)\ \sin\phi$$

Inclusive hadron TSA



Inclusive hadron TSA



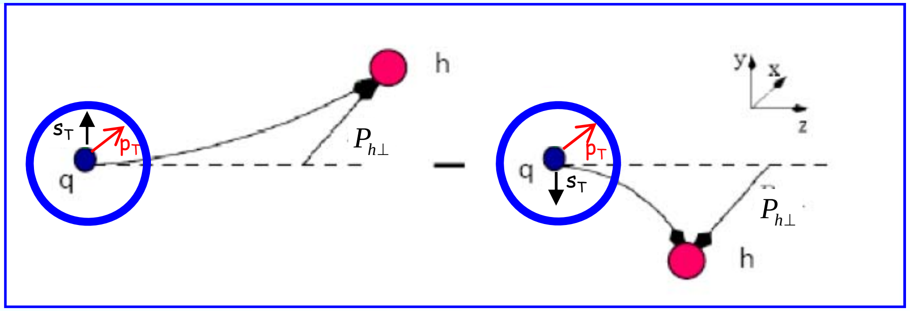
A_N resembles Sivers as predicted in M. Anselmino et al., PRD 81 (2010) 034007

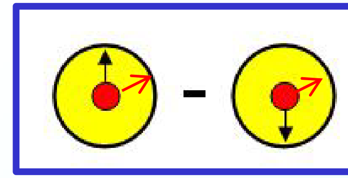
Boer-Mulders DF & Cahn effect

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

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

$\langle \cos 2\phi \rangle_{UU}$





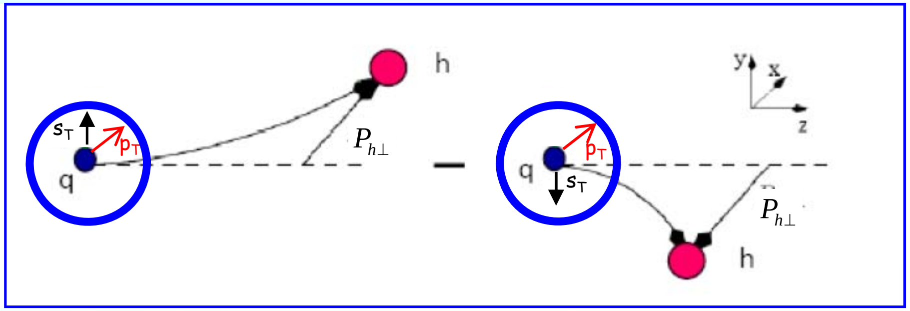
transversely polarised quarks with p_T in unpolarised nucleon

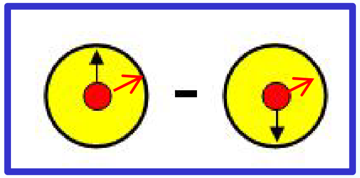
Boer-Mulders DF & Cahn effect

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

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

$\langle\cos 2\phi\rangle_{UU}$





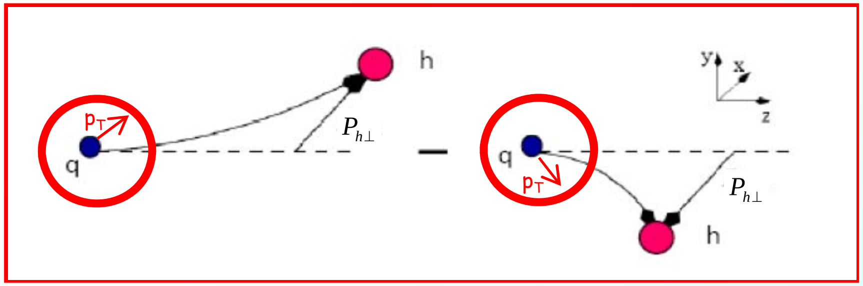
transversely polarised quarks with p_T in unpolarised nucleon

---

$$F_{UU}^{\cos\phi} = \frac{2M}{Q} C\left[-\frac{\hat{h}\cdot\vec{p}_T}{M_h} x h_1^{\perp} H_1^{\perp} - \frac{\hat{h}\cdot\vec{k}_T}{M} x f_1 D_1\right]$$

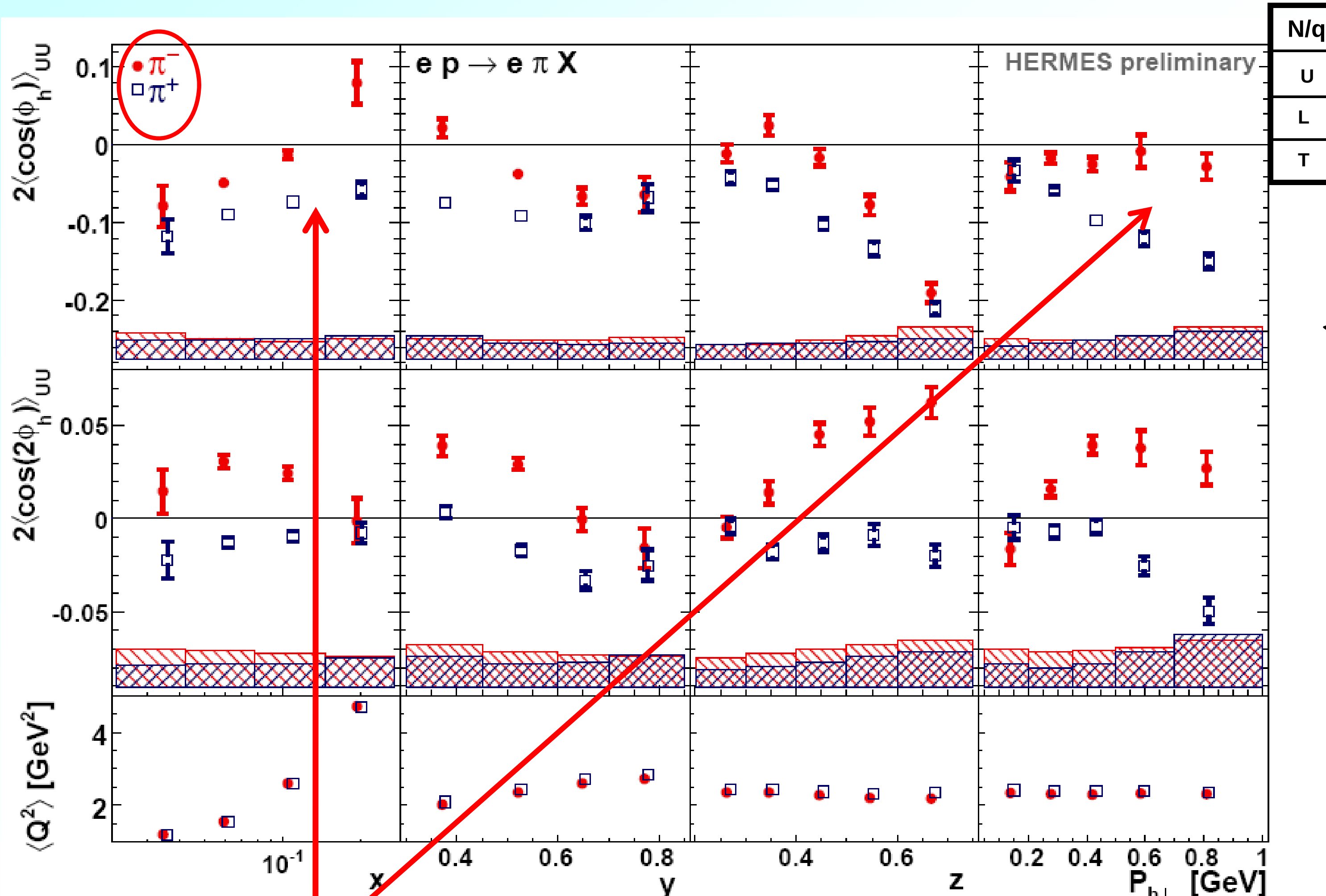
Cahn effect

$\langle\cos\phi\rangle_{UU}$



intrinsic transverse momentum p_T of quarks

$\cos(n\phi)_{UU}$ moments for $\pi^{\pm}$ - H target



N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

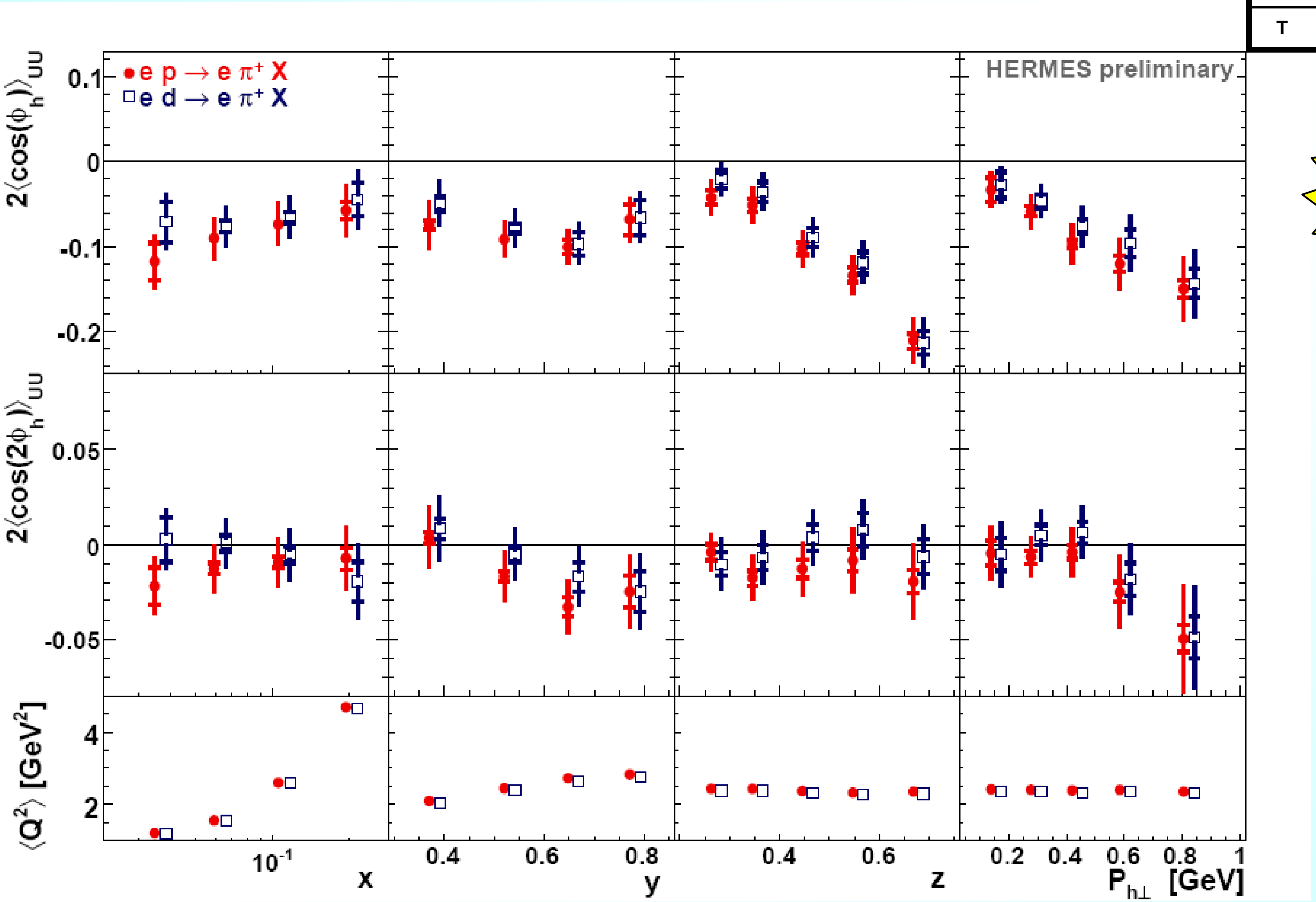
New

Quark flavour dependent p_T ?

Significant Boer-Mulders contribution to <cosϕ> ?

cos(nϕ)$_{UU}$ moments for π^+ - H, D target

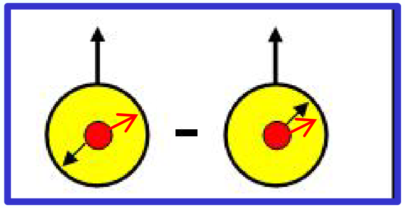
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



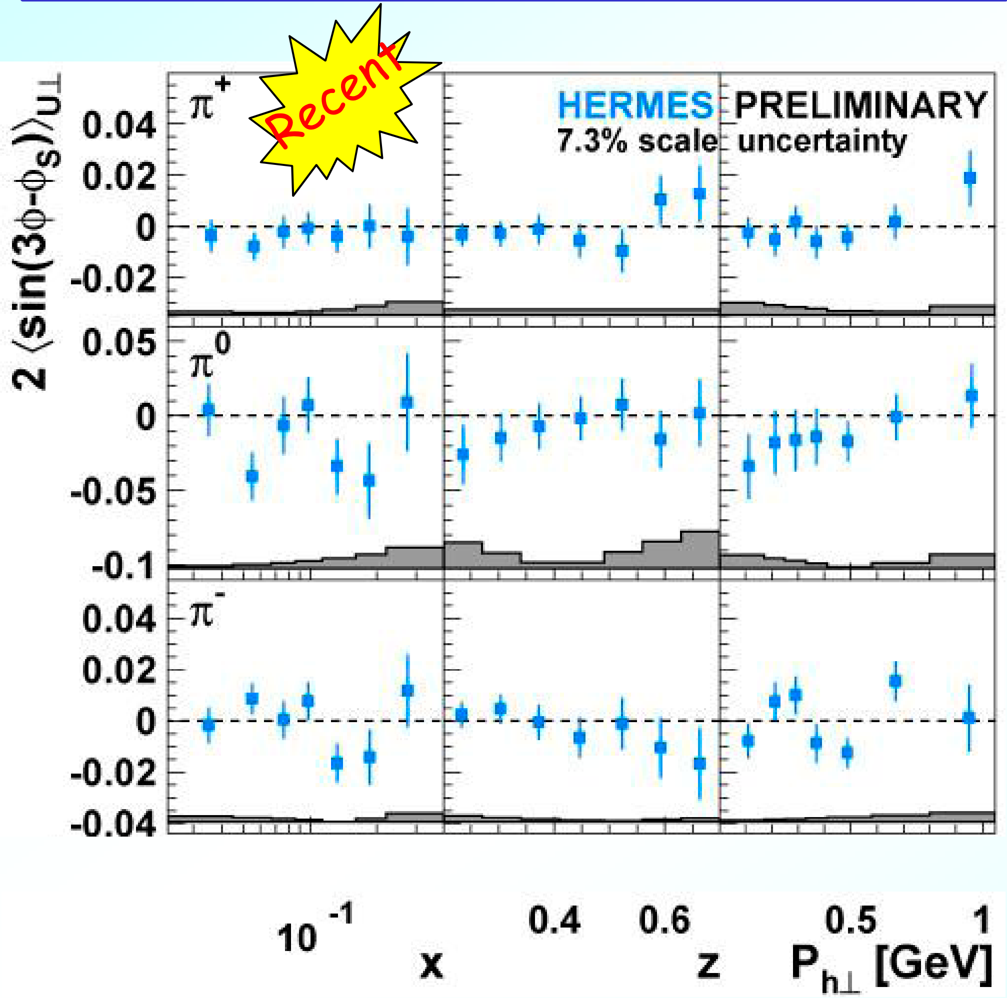
New

Pretzelosity DF $h_{1T}^{\perp}$

$$F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{C}\left[\frac{2\left(\hat{h}\cdot p_T\right)\left(p_T\cdot k_T\right)+p_T^2\left(\hat{h}\cdot k_T\right)-4\left(\hat{h}\cdot p_T\right)^2\left(\hat{h}\cdot k_T\right)}{2M^2M_h}\, h_{1T}^{\perp}H_1^{\perp}\right]$$



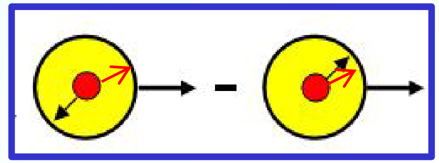
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$



- Suppressed w.r.t. Sivers and Collins amplitudes due to $p_T^{2}*k_T$
- Compatible with zero within uncertainties
- $h_{1T}^{\perp}$ might be non-zero, look at higher $p_{h\perp}$

Worm-gear (Mulders-Kotzinian) DF $h_{1L}^{\perp}$

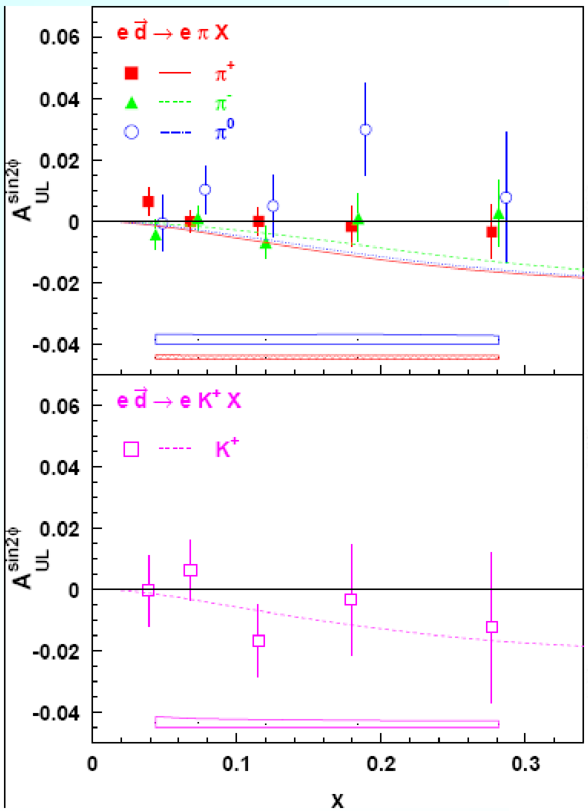
$$A_{UL}^{\sin 2\phi} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$$

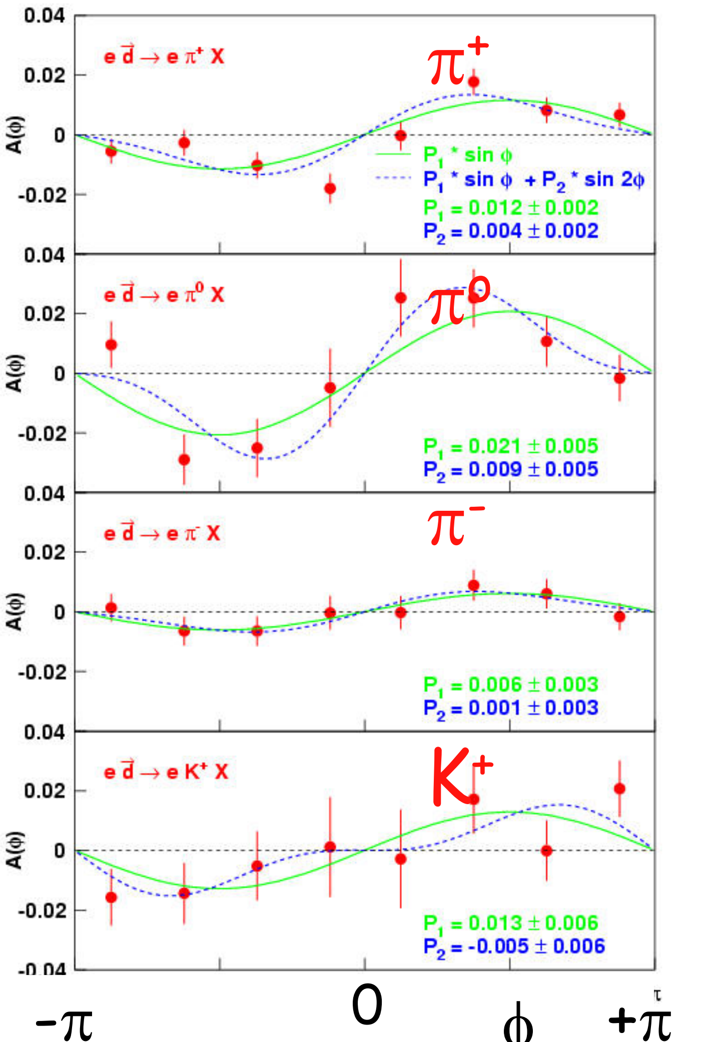


N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

First attempt:

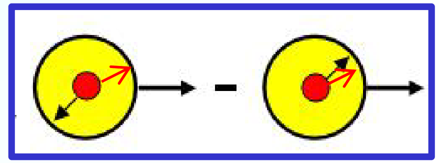
PLB 562 (2003) 182





Worm-gear (Mulders-Kotzinian) DF $h_{1L}^{\perp}$

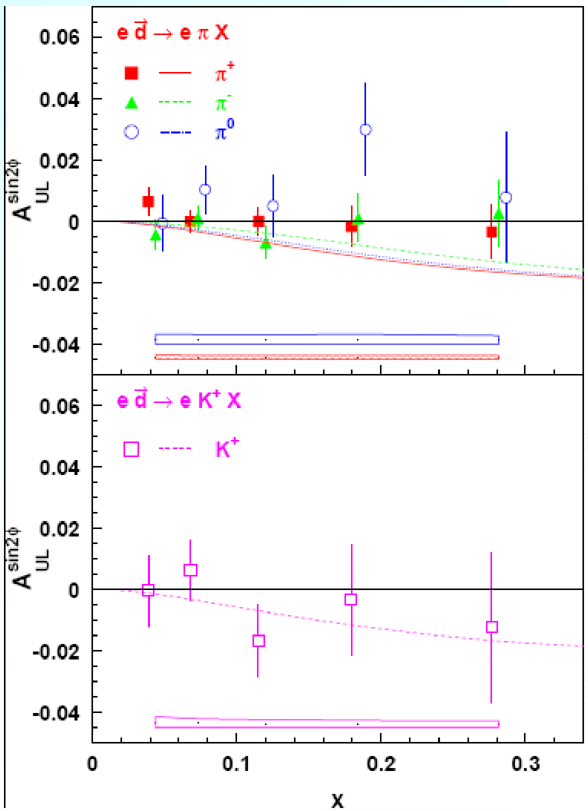
$A_{UL}^{\sin 2\phi} \propto h_{1L}^{\perp} \otimes H_1^{\perp}$

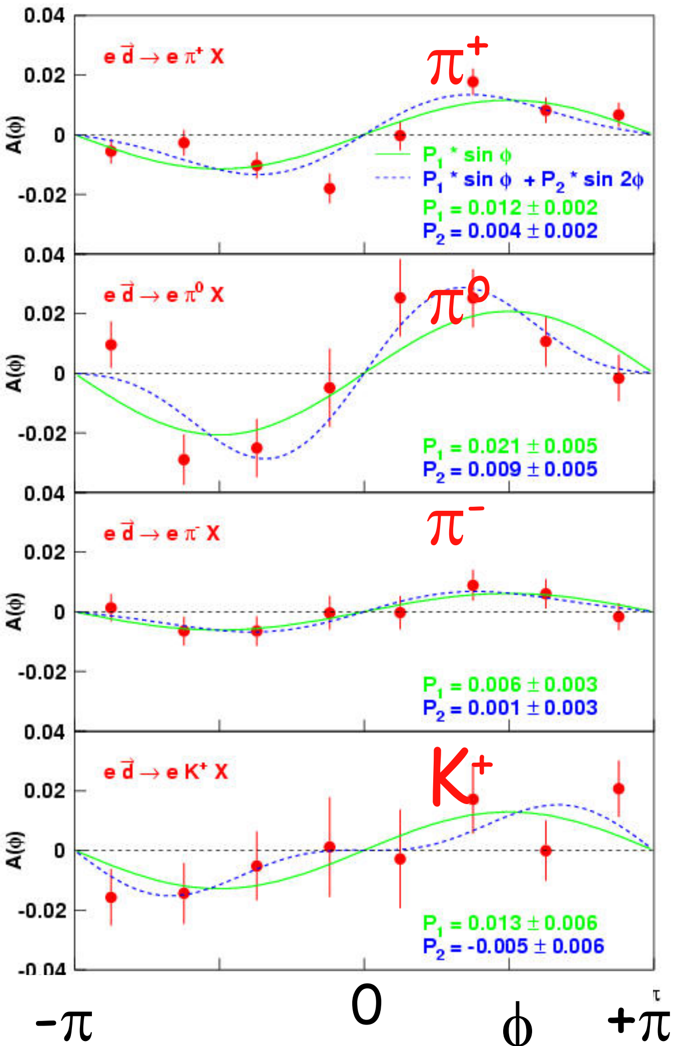


N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

First attempt:

PLB 562 (2003) 182





Recent result from

$A_{U\perp}^{\sin(2\phi + \phi s)}$

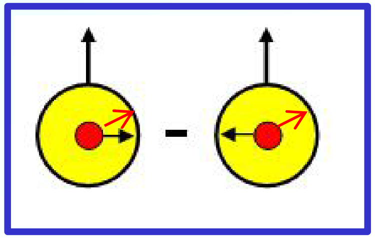
longt. component

$\sim \sin\theta_{\gamma^*} \langle \sin(2\phi)_{UL} \rangle$

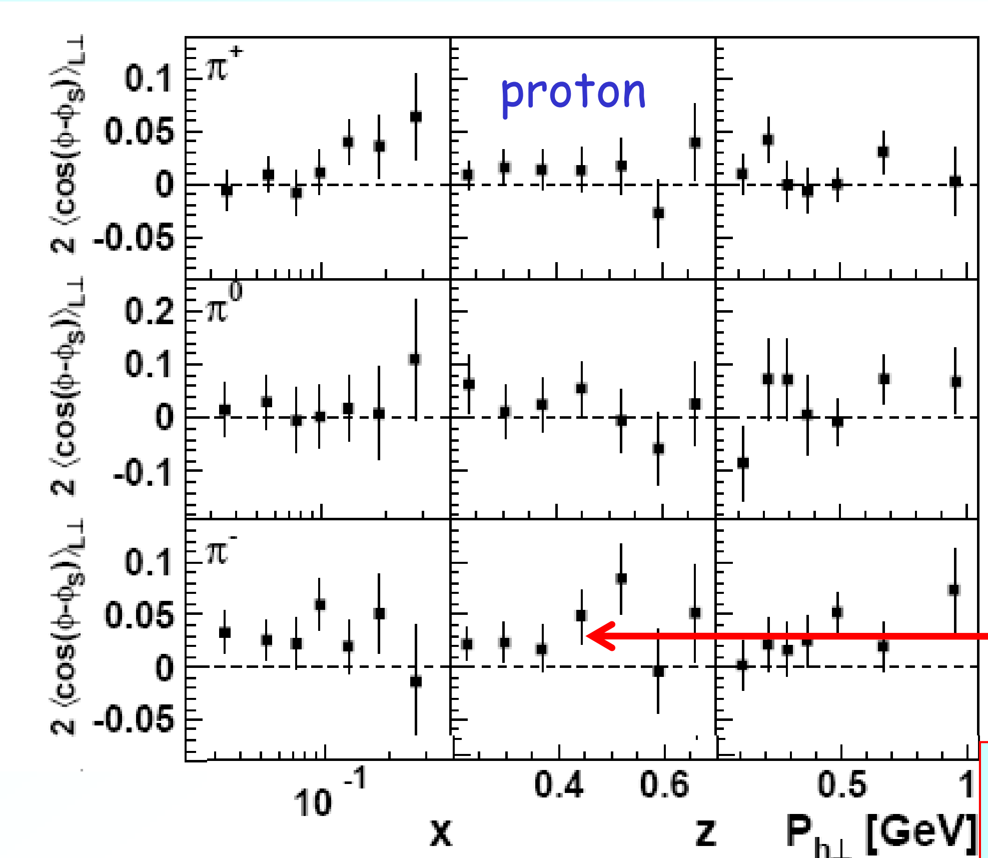
Compatible with zero within uncertainties

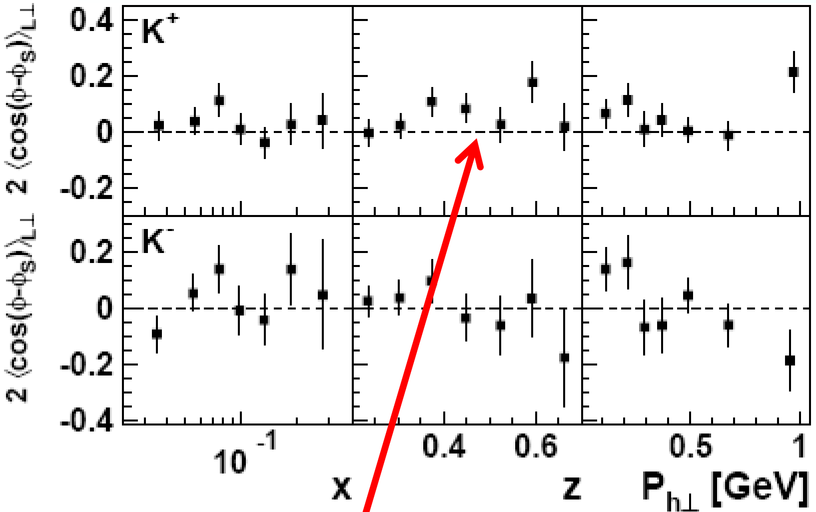
Worm-gear DF $g_{1T}^{\perp}$

$A_{LT}^{\cos(\phi - \phi_S)} \propto g_{1T}^{\perp} \otimes D_1$



N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$





Slightly non-zero by > 2σ

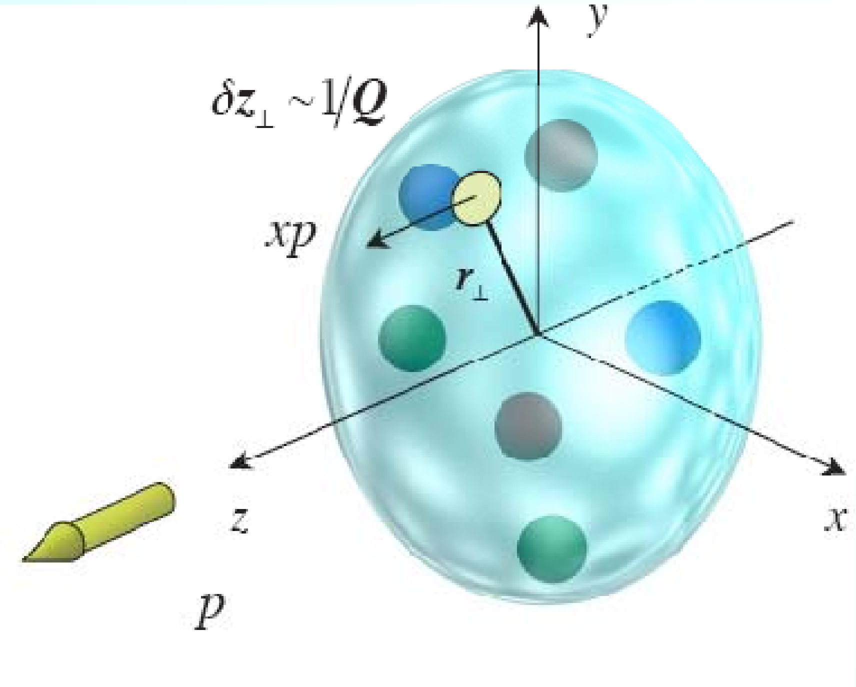
From doctoral thesis M. Diefenthaler
Not yet official HERMES result!!

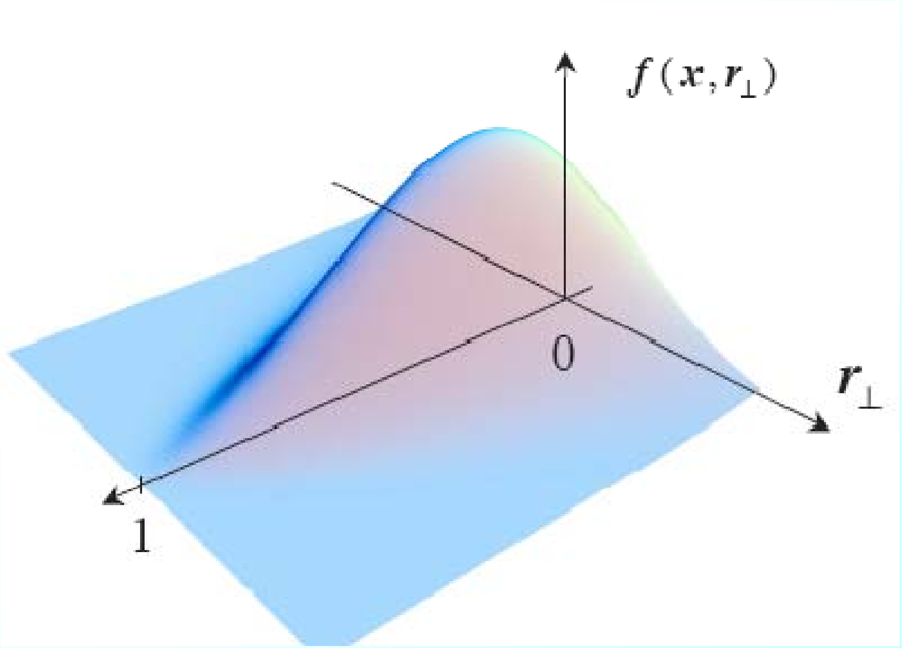
small !

Generalised Parton Distributions (GPDs)

Generalisation of Form Factors (moments of GPDs) and PDFs (forward limit)

Generalised description of nucleon structure in 2+1 dim





Number density of quarks with longitudinal momentum fraction x at radial position $r_\perp$

GPDs and quark total angular momentum

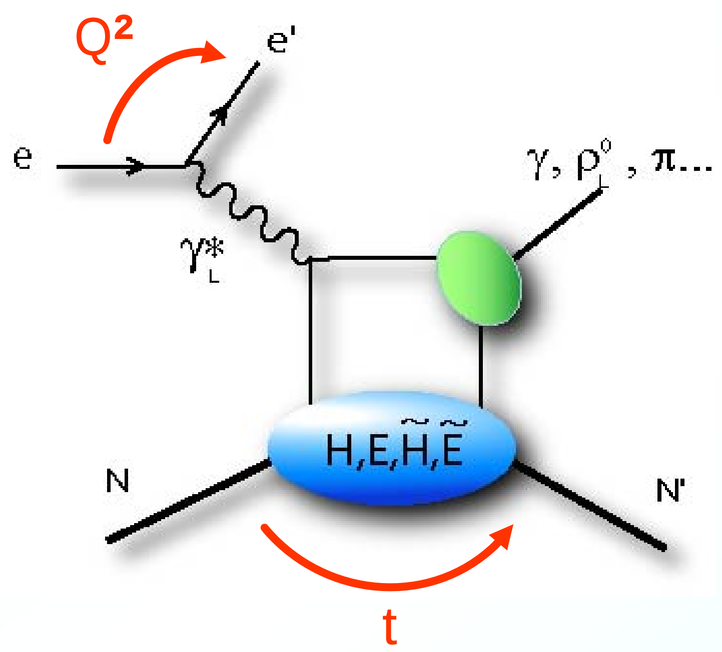
See talk by M. Guidal

Ji relation:

$$J_q = 1/2\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{1} dx\, x\, [H(x,\zeta,t) + E(x,\zeta,t)]$$

$H(x,\zeta,t)$, $E(x,\zeta,t)$: Generalised Parton Distributions

Access: *exclusive processes*



Final state sensitive to different GPDs

Spin-½ target: 4 chiral-even leading-twist quark GPDs

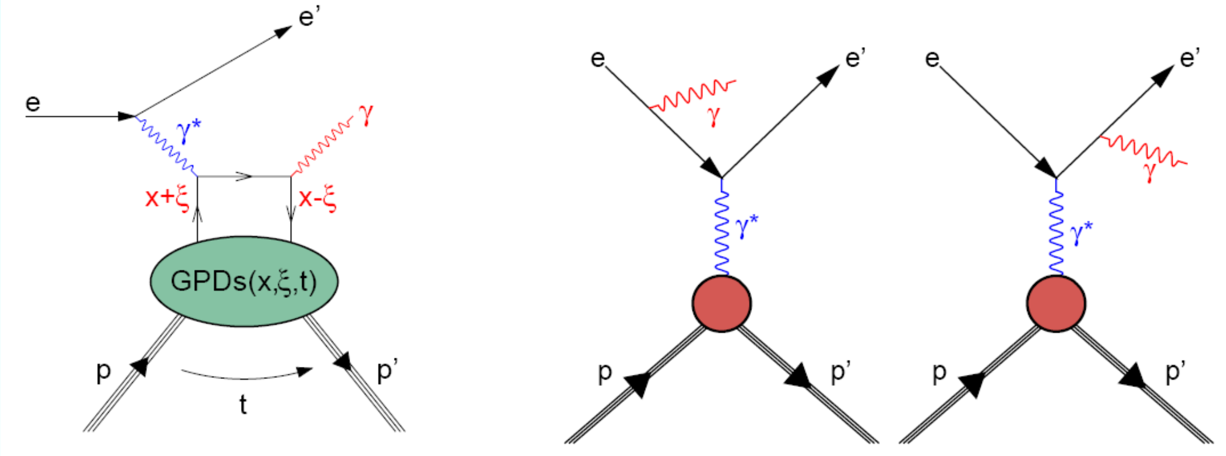
$H, \tilde{H}$ ($E, \tilde{E}$) conserve (flip) nucleon helicity

Vector mesons (ρ, ω, ϕ) H, E

Pseudoscalar mesons(π,η) $\tilde{H}$, $\tilde{E}$

DVCS (γ) H, E, $\tilde{H}$, $\tilde{E}$

Deeply Virtual Compton Scattering & GPDs



- Same initial and final states in DVCS and Bethe-Heitler ⟹ Interference
- $$\sigma_{ep} \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

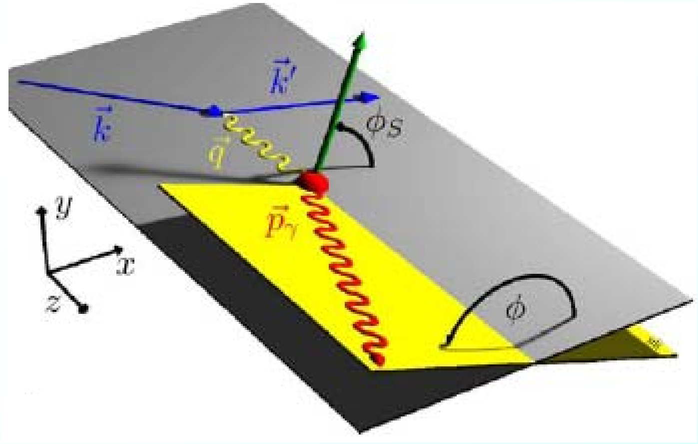
$$\begin{aligned}
d\sigma \sim d\sigma^{BH}_{UU} \quad &+ \quad e_\ell d\sigma^{I}_{UU} \quad + \quad d\sigma^{DVCS}_{UU} \\
&+ \quad e_\ell P_\ell d\sigma^{I}_{LU} \quad + P_\ell d\sigma^{DVCS}_{LU} \\
&+ \quad e_\ell S_L d\sigma^{I}_{UL} \quad + S_L d\sigma^{DVCS}_{UL} \\
&+ \quad e_\ell S_T d\sigma^{I}_{UT} \quad + S_T d\sigma^{DVCS}_{UT} \\
+P_\ell S_L d\sigma^{BH}_{LL} \quad &+ \quad e_\ell P_\ell S_L d\sigma^{I}_{LL} + P_\ell S_L d\sigma^{DVCS}_{LL} \\
+P_\ell S_T d\sigma^{BH}_{LT} \quad &+ \quad e_\ell P_\ell S_T d\sigma^{I}_{LT} + P_\ell S_T d\sigma^{DVCS}_{LT}
\end{aligned}$$

- BH calculable in QED
- $|\mathcal{T}_{DVCS}|$ << $|\mathcal{T}_{BH}|$ @ HERMES
- Access to GPD combinations through azimuthal asymmetries

DVCS @ HERMES

Complete measurement of amplitudes in $eN \rightarrow e'N\gamma$ possible at HERMES:

- Both beam charges
- Longitudinal beam polarisation (both helicities)
- Unpolarised H, D and nuclear targets
- Longitudinally polarised H and D targets
- Transversely polarised H target
- Recoil Detector

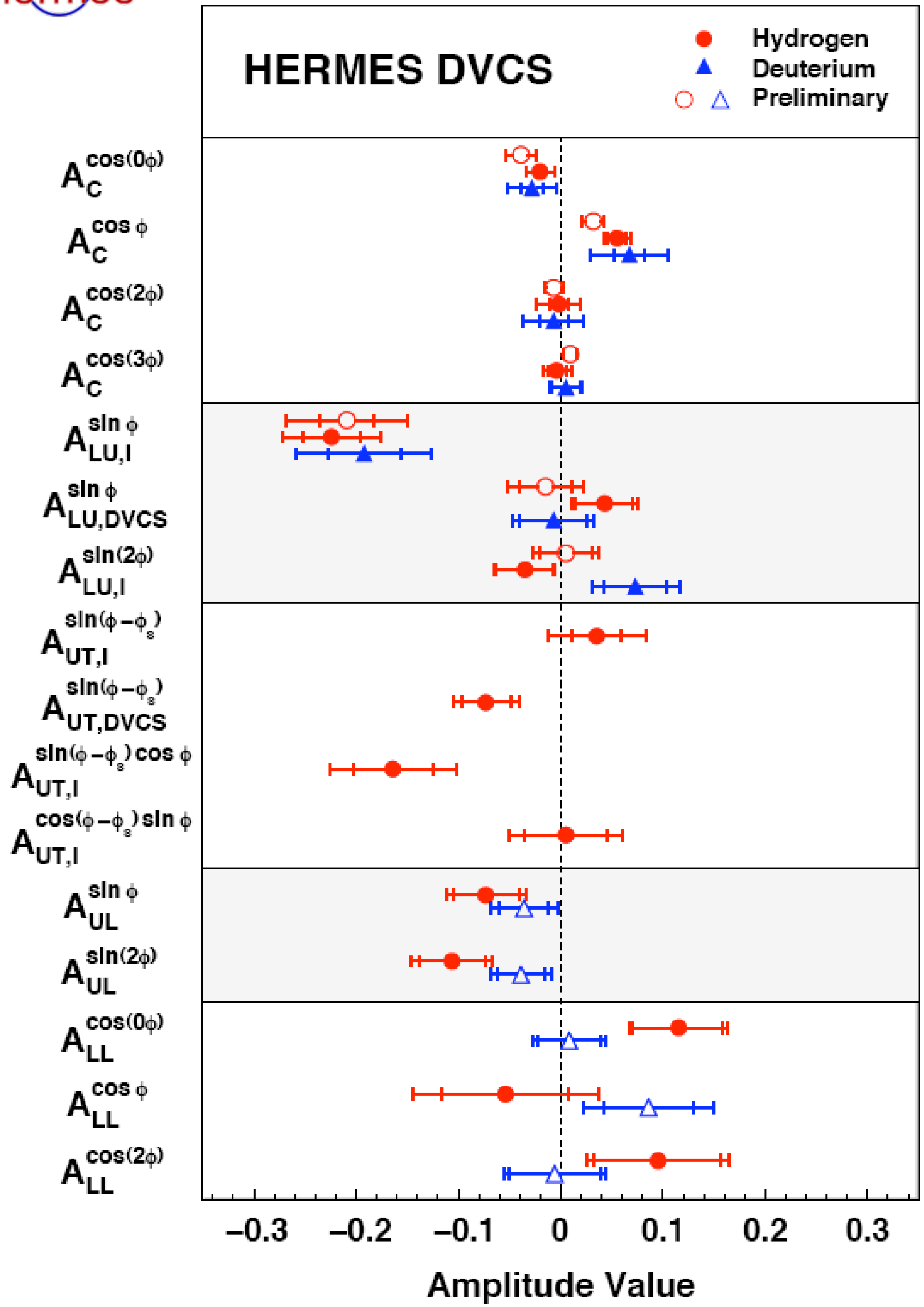


A_{XY}

beam target

polarisation

DVCS asymmetries measured @ HERMES



- Beam charge asymmetry
  GPD H

H: JHEP 11 (2009) 083

D: Nucl. Phys. B 829 (2010) 1

- Beam helicity asymmetry
  GPD H

- Transverse target spin asymmetry
  GPD E

H: JHEP 06 (2008) 066

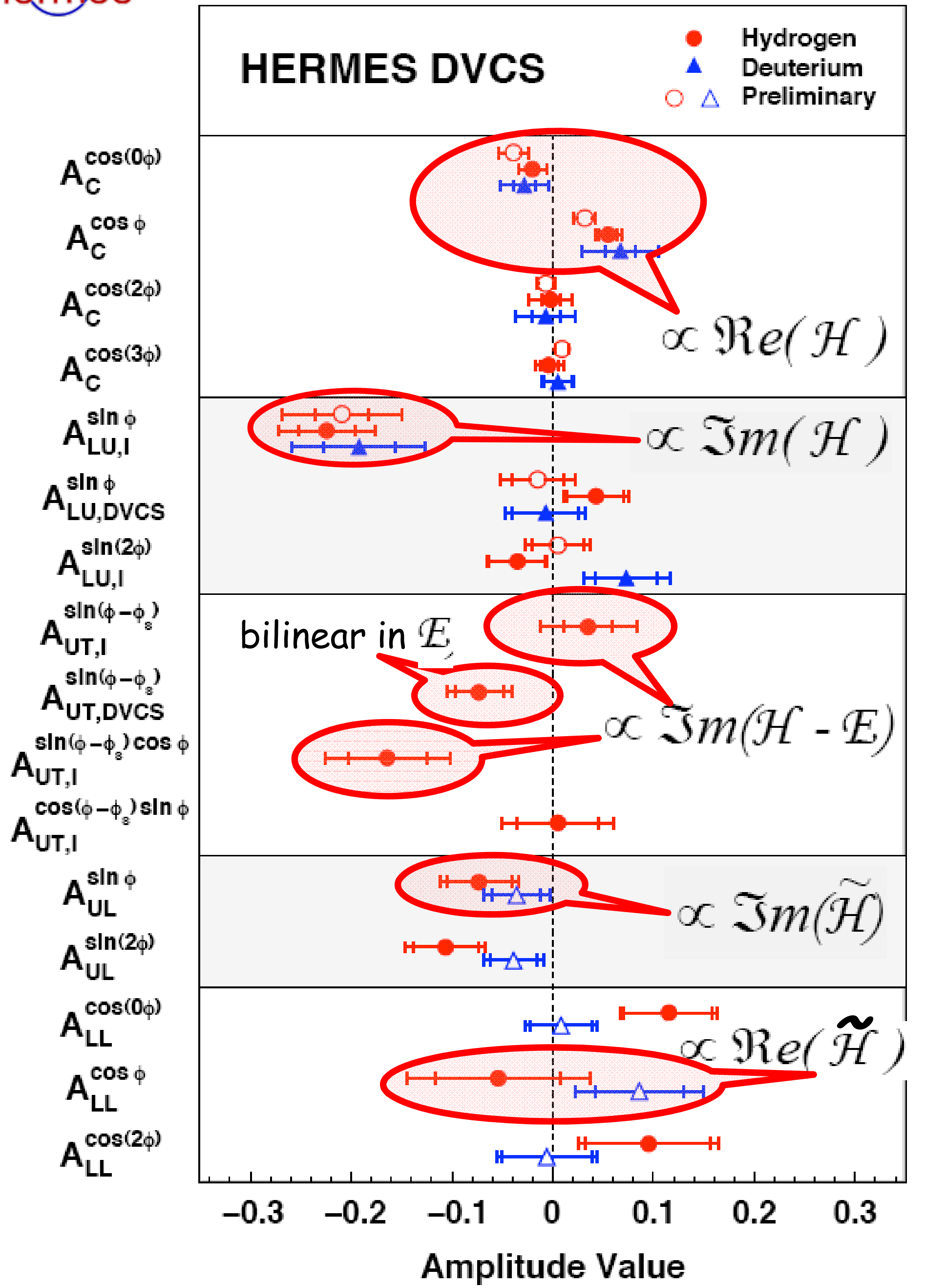
- Longitudinal target spin asymmetry
  GPD $\tilde{H}$

H: JHEP 06 (2010) 019

D: to be published soon

- Longitudinal double spin asymmetry
  GPD $\tilde{H}$

DVCS asymmetries measured @ HERMES



- Beam charge asymmetry
  GPD H

H: JHEP 11 (2009) 083
D: Nucl. Phys. B 829 (2010) 1

- Beam helicity asymmetry
  GPD H

- Transverse target spin asymmetry
  GPD E

H: JHEP 06 (2008) 066

- Longitudinal target spin asymmetry
  GPD $\tilde{H}$

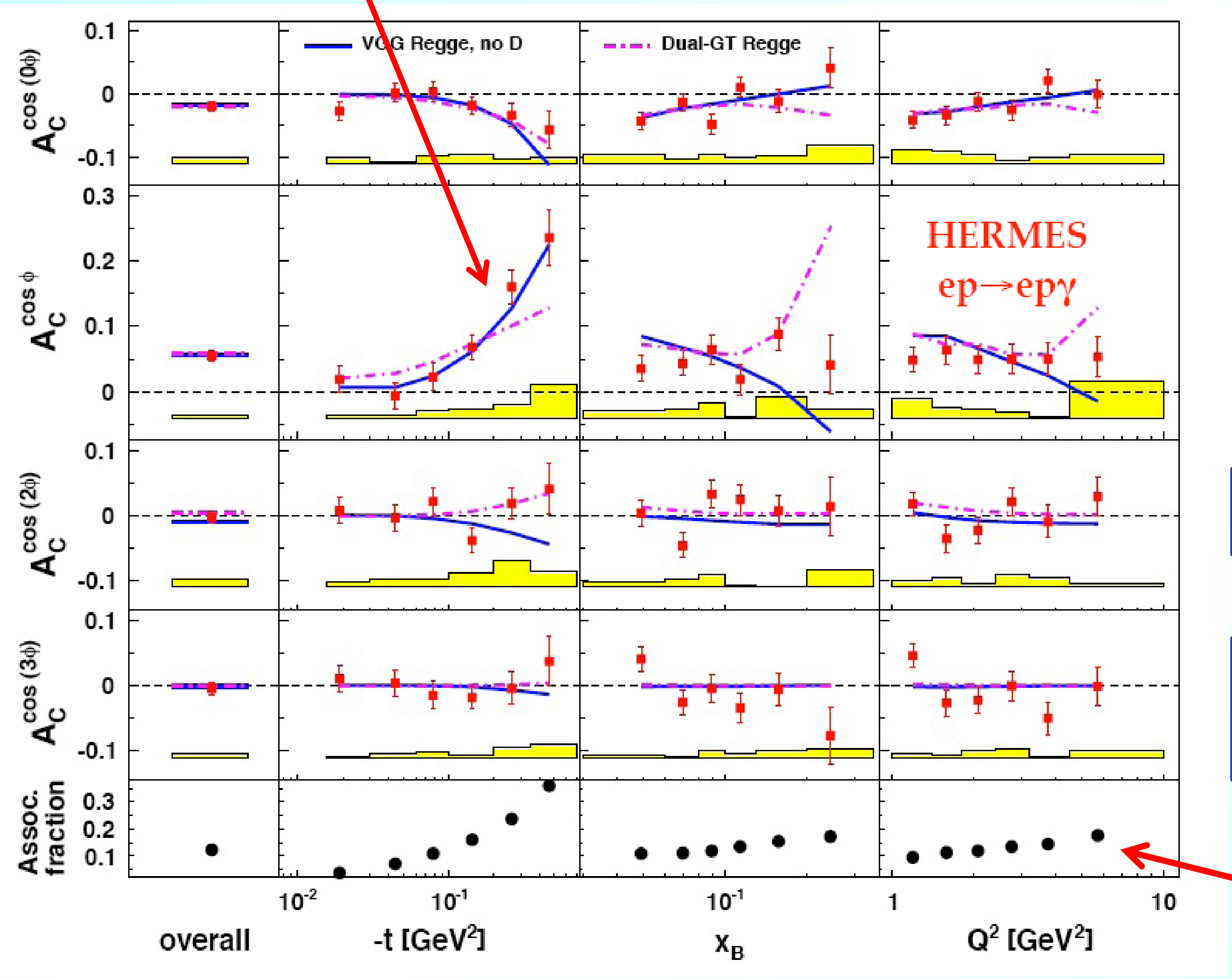
H: JHEP 06 (2010) 019
D: to be published soon

- Longitudinal double spin asymmetry
  GPD $\tilde{H}$

Proton: beam charge asymmetry

Strong t dependence

JHEP 11 (2009) 083



$\propto -\frac{t}{Q} A_C^{\cos\phi}$

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

≈ 0: twist-3 GPDs

≈ 0: gluon helicity-flip GPDs

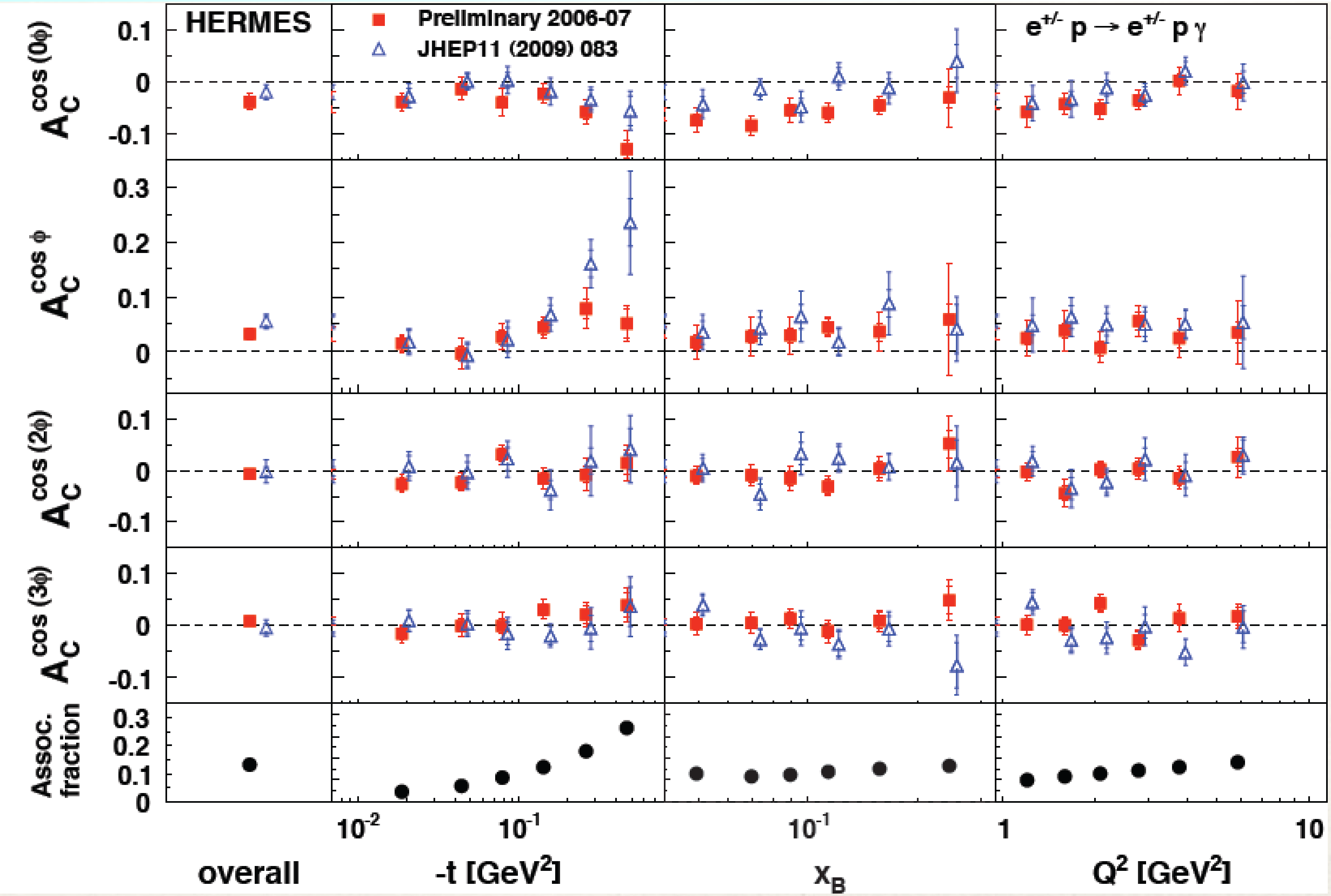
fraction of
ep → e'Δ+ γ

VGG: Phys. Rev D 60 (1999) 4017, Prog. Nucl. Part. Phys. 42 (2001) 401

Dual: Phys. Rev D 79 (2009) 017501

Proton: beam charge asymmetry – new data

Large 2006/07 data set (1700 pb^{-1})

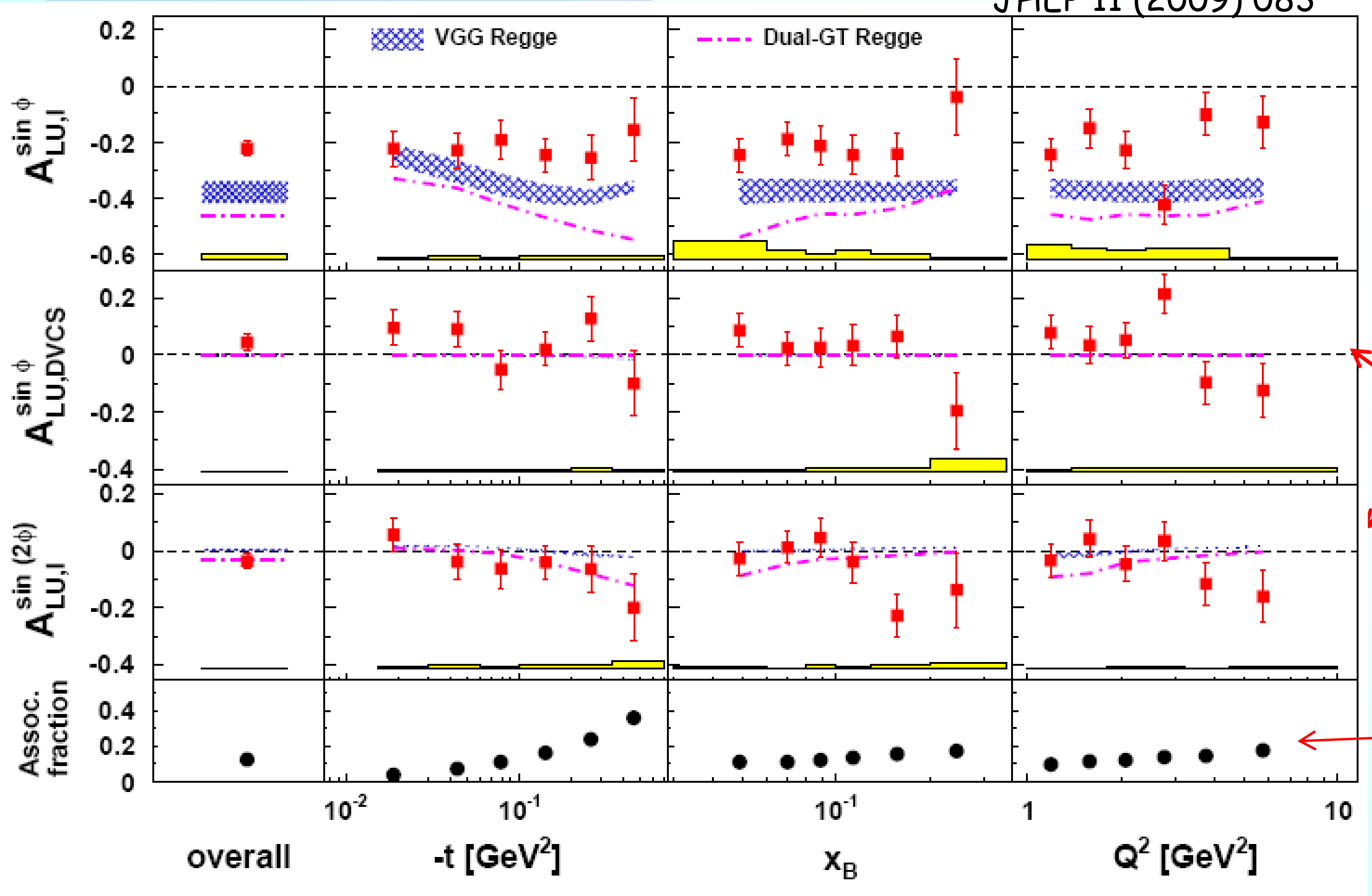


Proton: beam helicity asymmetry

$$\mathcal{A}_{LU}^{I}(\phi) = \sum_{n=1}^{2} A_{LU,\mathrm{I}}^{\sin(n\phi)} \sin(n\phi)$$

$$A_{LU,\mathrm{DVCS}}^{\sin\phi} \propto s_1^{\mathrm{DVCS}} \sin\phi$$

JHEP 11 (2009) 083



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

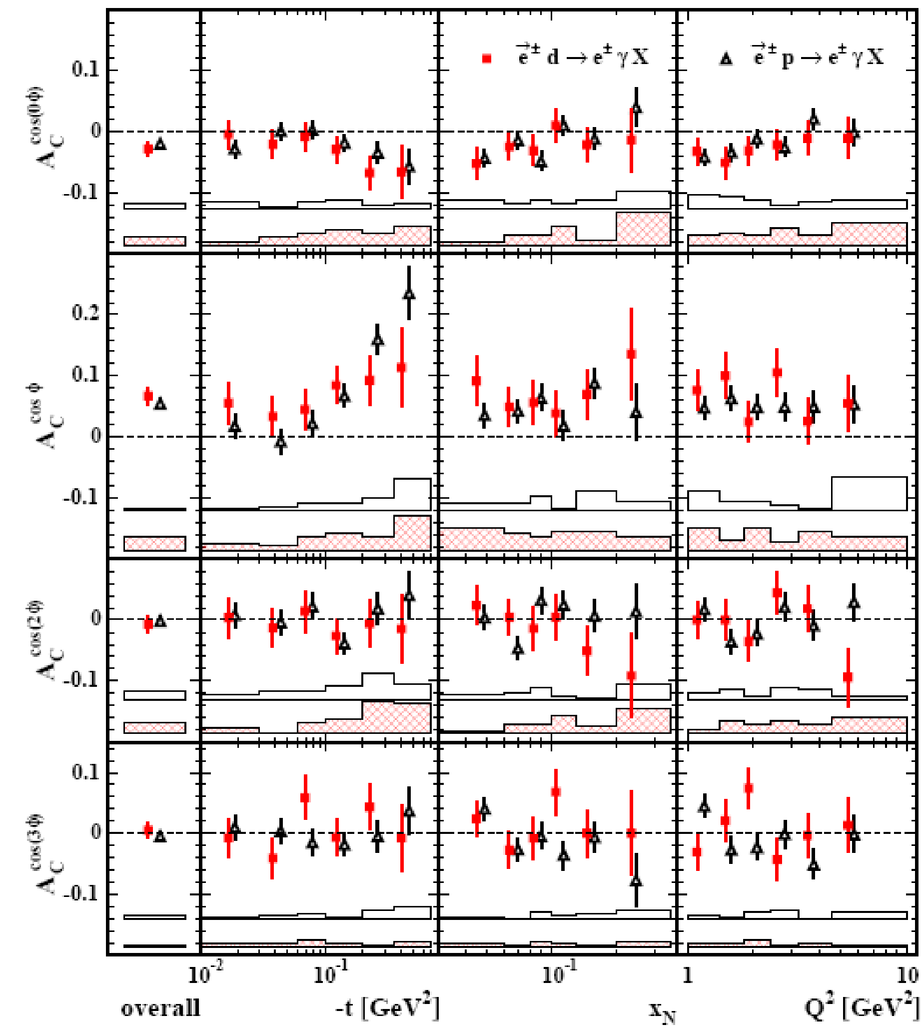
twist-3

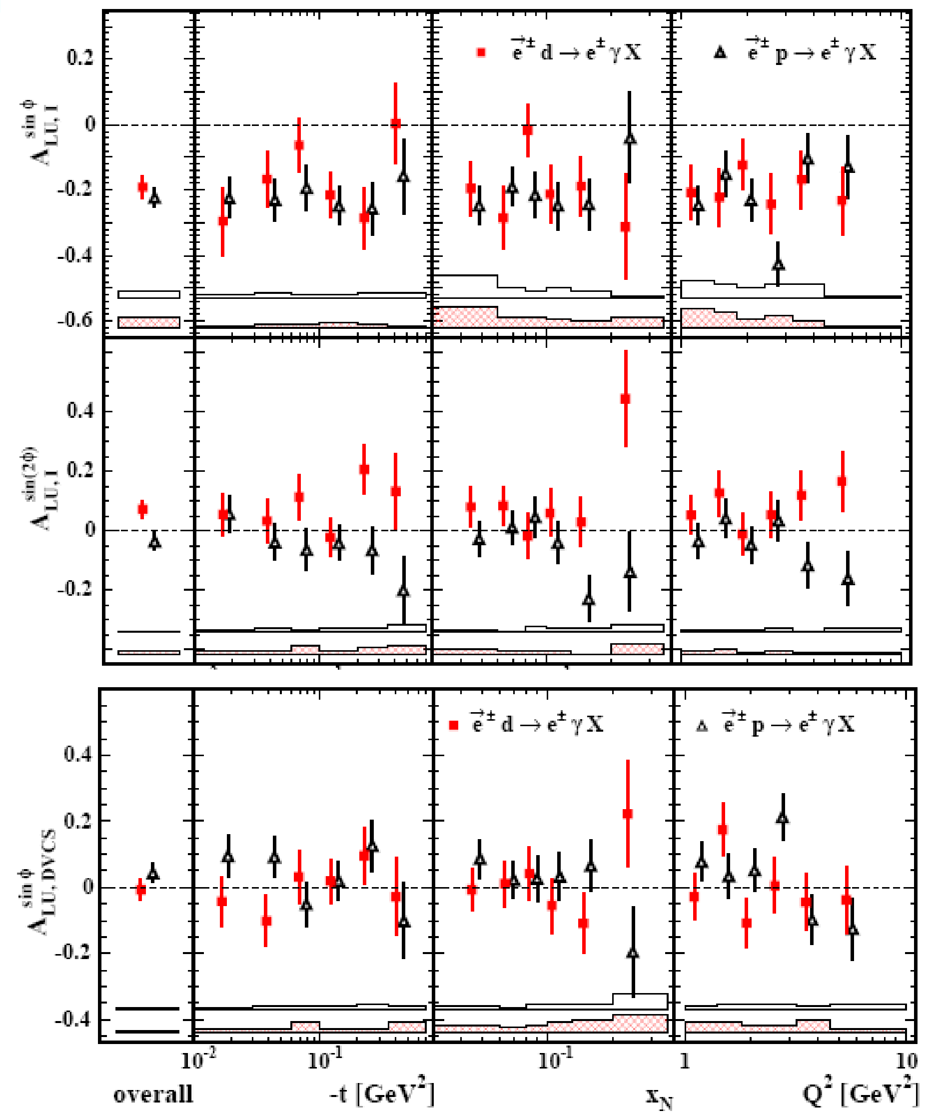
fraction of $ep \to e'\Delta + \gamma$

Model that fits A_C overshoots $A_{LU,I}^{\sin\phi}$ by factor of 2

$A_{C,LU}$: Proton vs deuteron

Nucl. Phys. B 829 (2010) 1



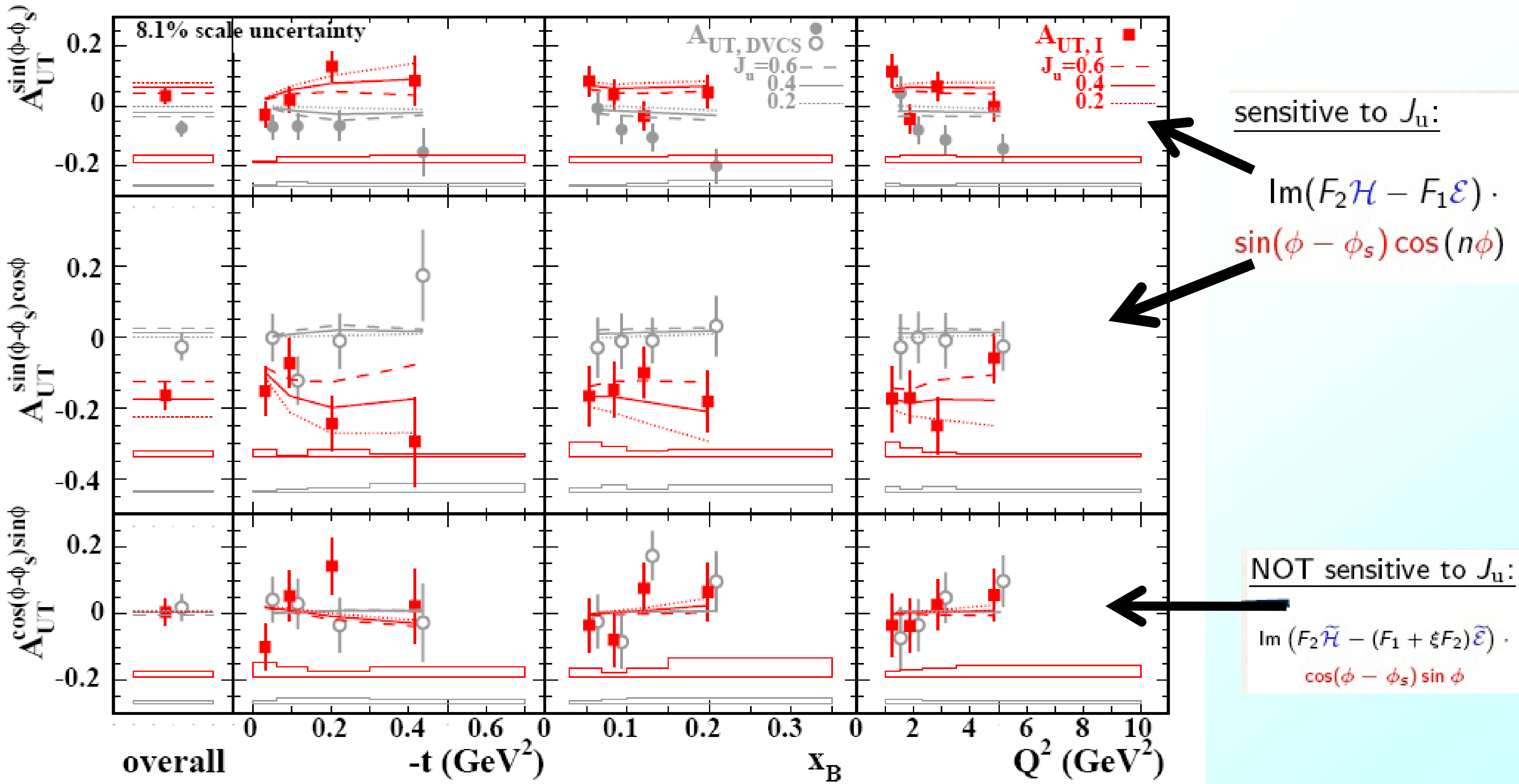


Proton and deuteron data are compatible for all leading amplitudes

Proton: transverse target pol. asymmetry

Sensitive to GPD E

JHEP 06 (2008) 066

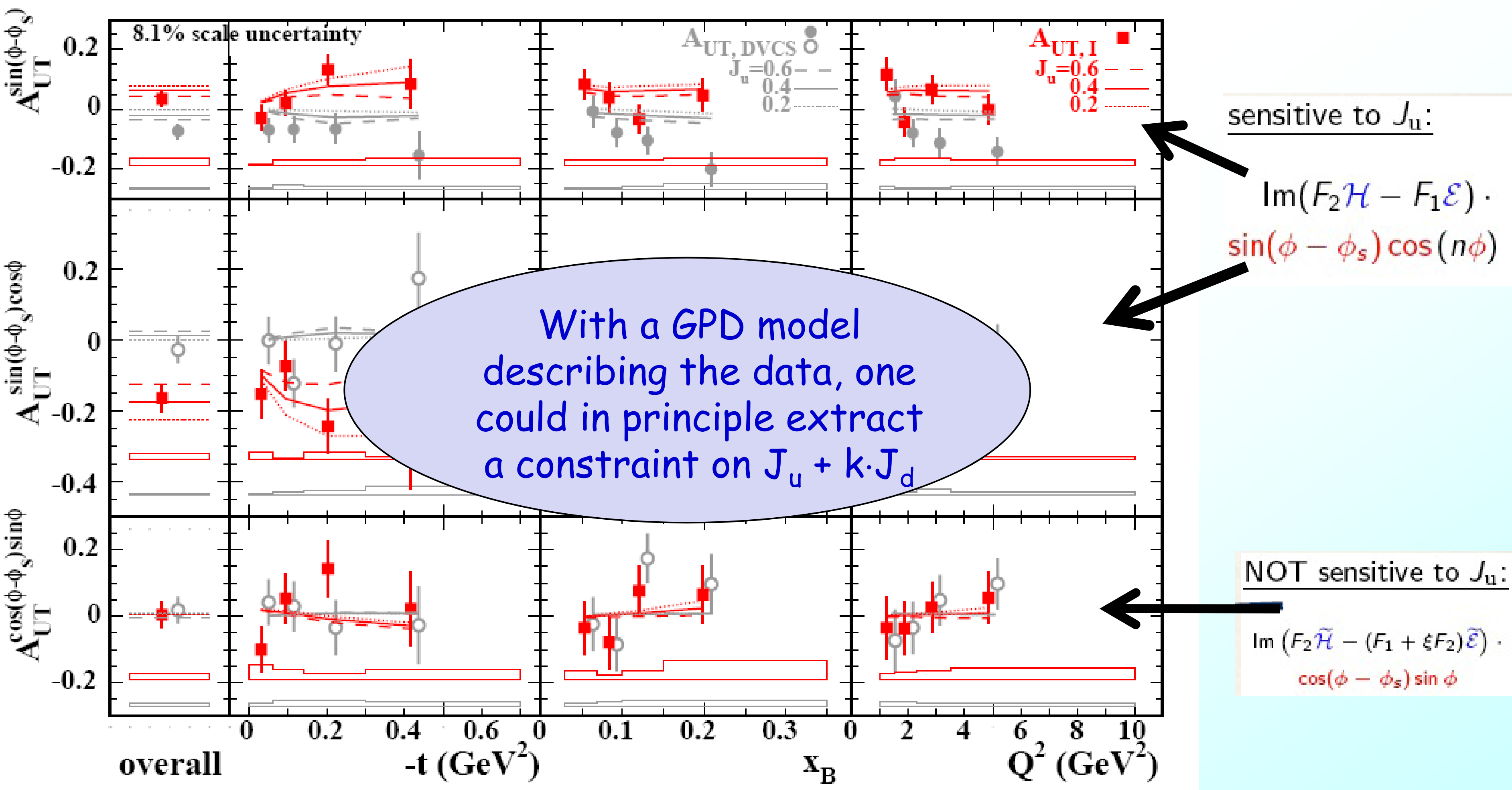


Model: VGG with variation of J_u, while J_d=0

Proton: transverse target pol. asymmetry

Sensitive to GPD E

JHEP 06 (2008) 066



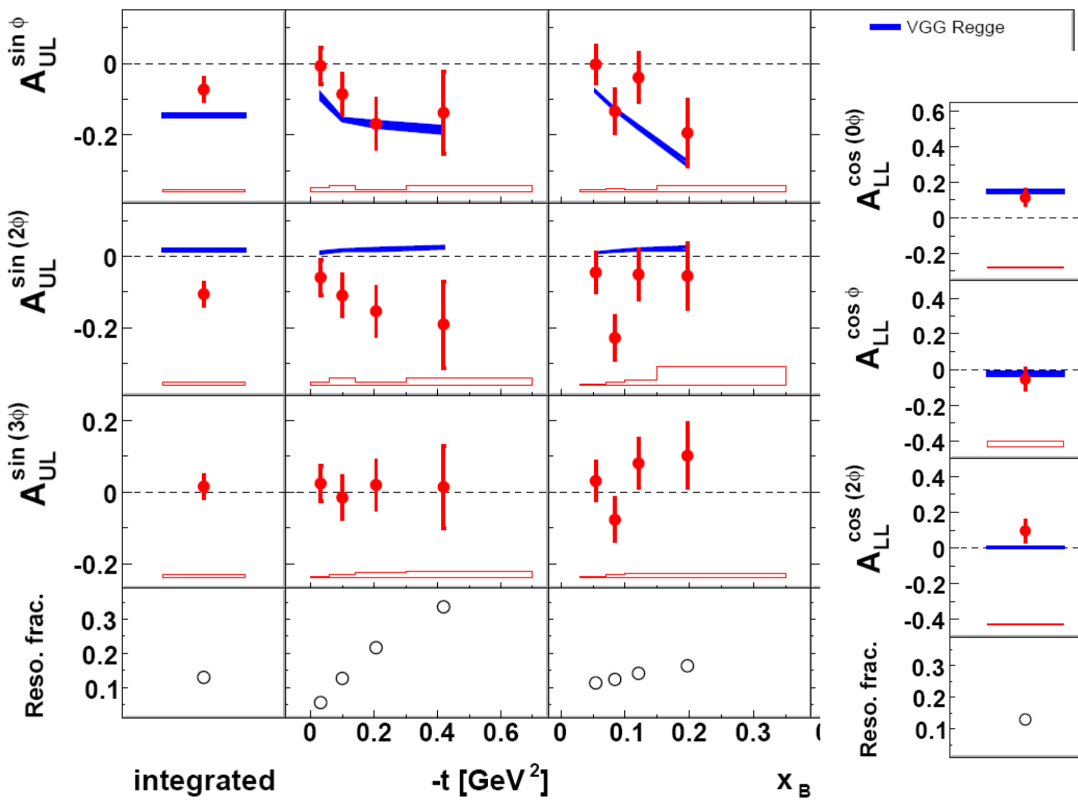
Model: VGG with variation of J_u, while J_d=0

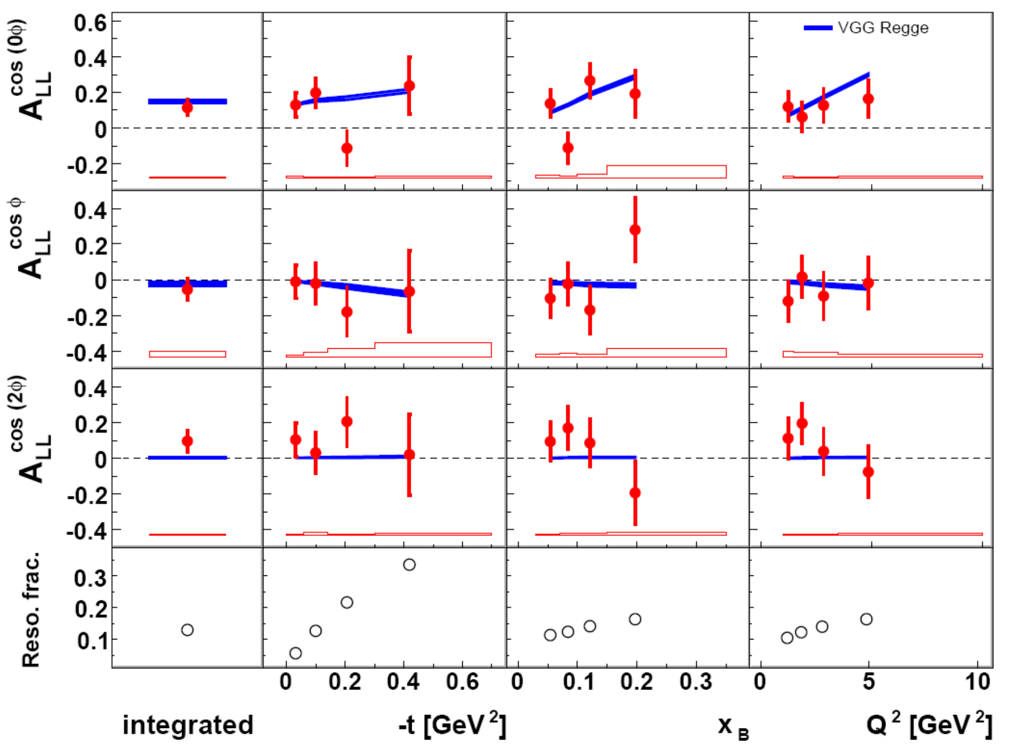
Proton: longitudinal target pol. asymmetry

Long. target-spin asymmetry

Double-spin asymmetry

JHEP 06 (2010) 019





$\propto \Im m(\tilde{\mathcal{H}})$

$\propto \Re e(\tilde{\mathcal{H}})$

hermes

Pol. and unpol. DIS + SIDIS

Azimuthal asymmetries in SIDIS

Azimuthal asymmetries in excl. processes

PDFs

TMDs

GPDs

Longitudinal spin/momentum structure

Transverse spin/momentum structure

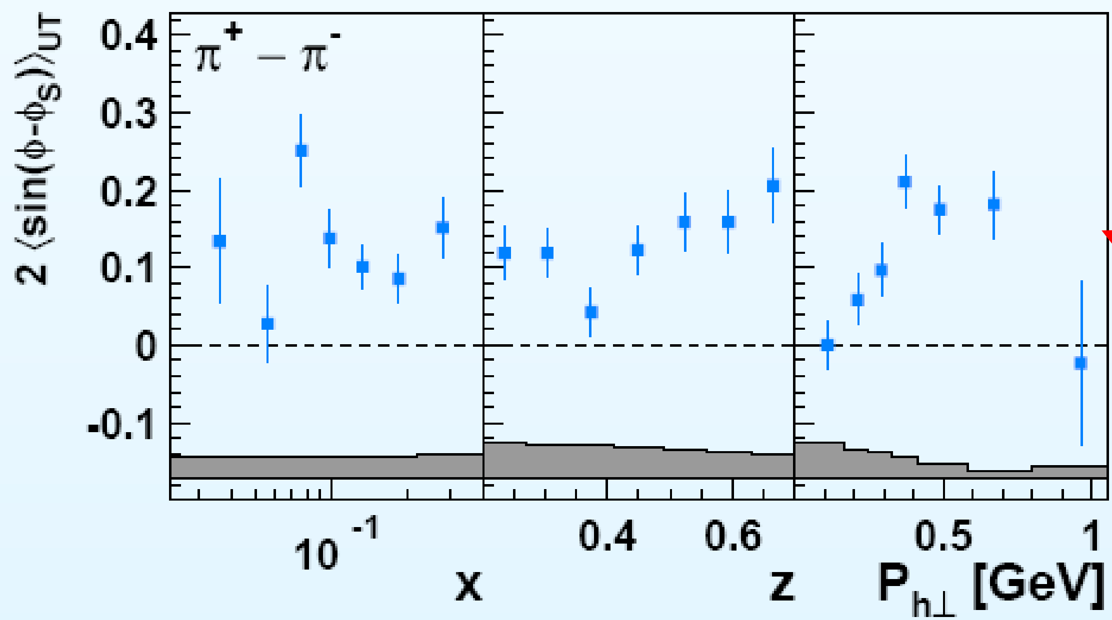
Long. momentum – transv. coordinate structure

Backups

Transverse SSA for $\pi^+ - \pi^-$

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

PRL 103 (2009) 152002



access to
Sivers valence
distribution

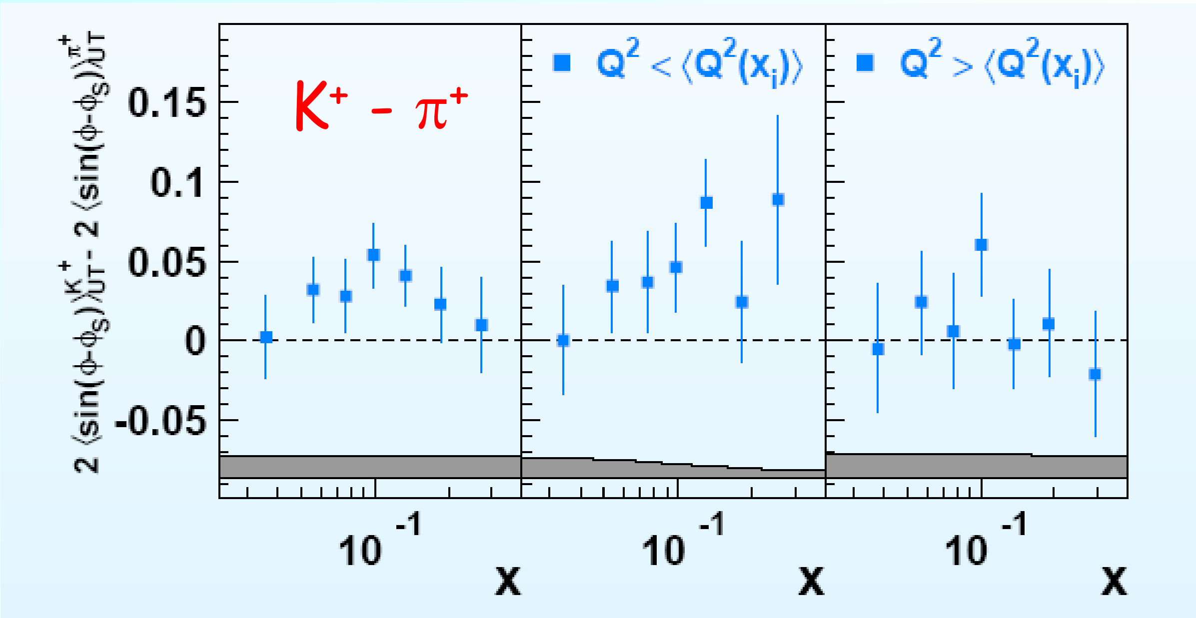
$$2\langle \sin(\phi-\phi_S)\rangle_{UT}^{\pi^+-\pi^-} = -2\,\frac{4\, f_{1T}^{\perp,u_v} - f_{1T}^{\perp,d_v}}{4\, f_1^{\perp,u_v} - f_1^{\perp,d_v}}$$

The „Kaon Challenge"

N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

Sivers

PRL 103 (2009) 152002



Similarly for Collins: $K^+ > \pi^+$

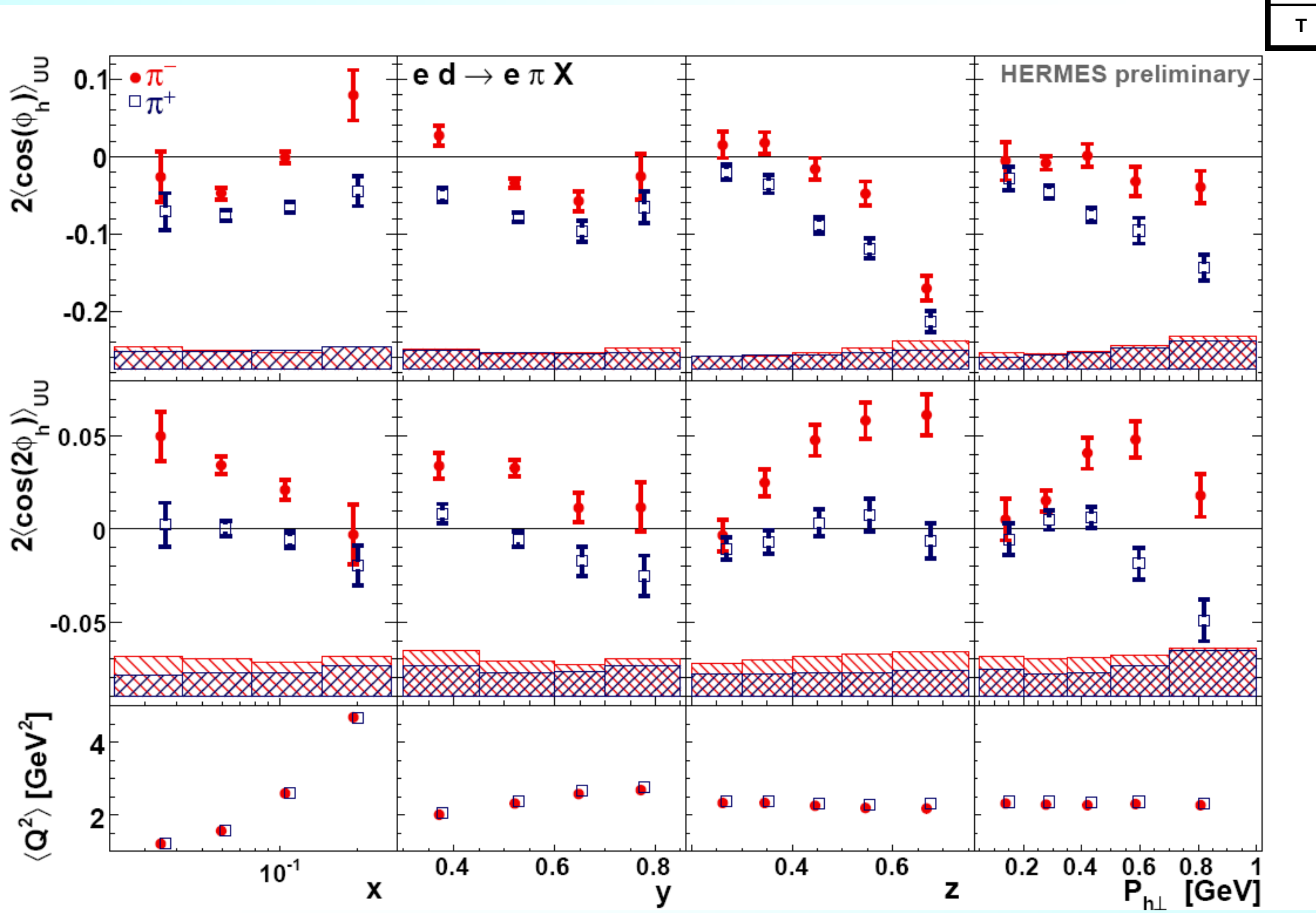
π^+/K^+ production dominated by scattering off u-quarks: $\simeq -\dfrac{f_{1T}^{\perp,u}(x,p_T^2)\otimes D_1^{u\to\pi^+/K^+}(z,K_T^2)}{f_1^u(x)\;D_1^{u\to\pi^+/K^+}(z)}$

- $K^+ = |u\bar{s}\rangle$, $\pi^+ = |u\bar{d}\rangle$ → non-trivial role of sea quarks ?
- K_T dependence of FF ?
- Different kinematic dependences ?

$\cos(n\phi)_{UU}$ moments for $\pi^\pm$ - D target

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

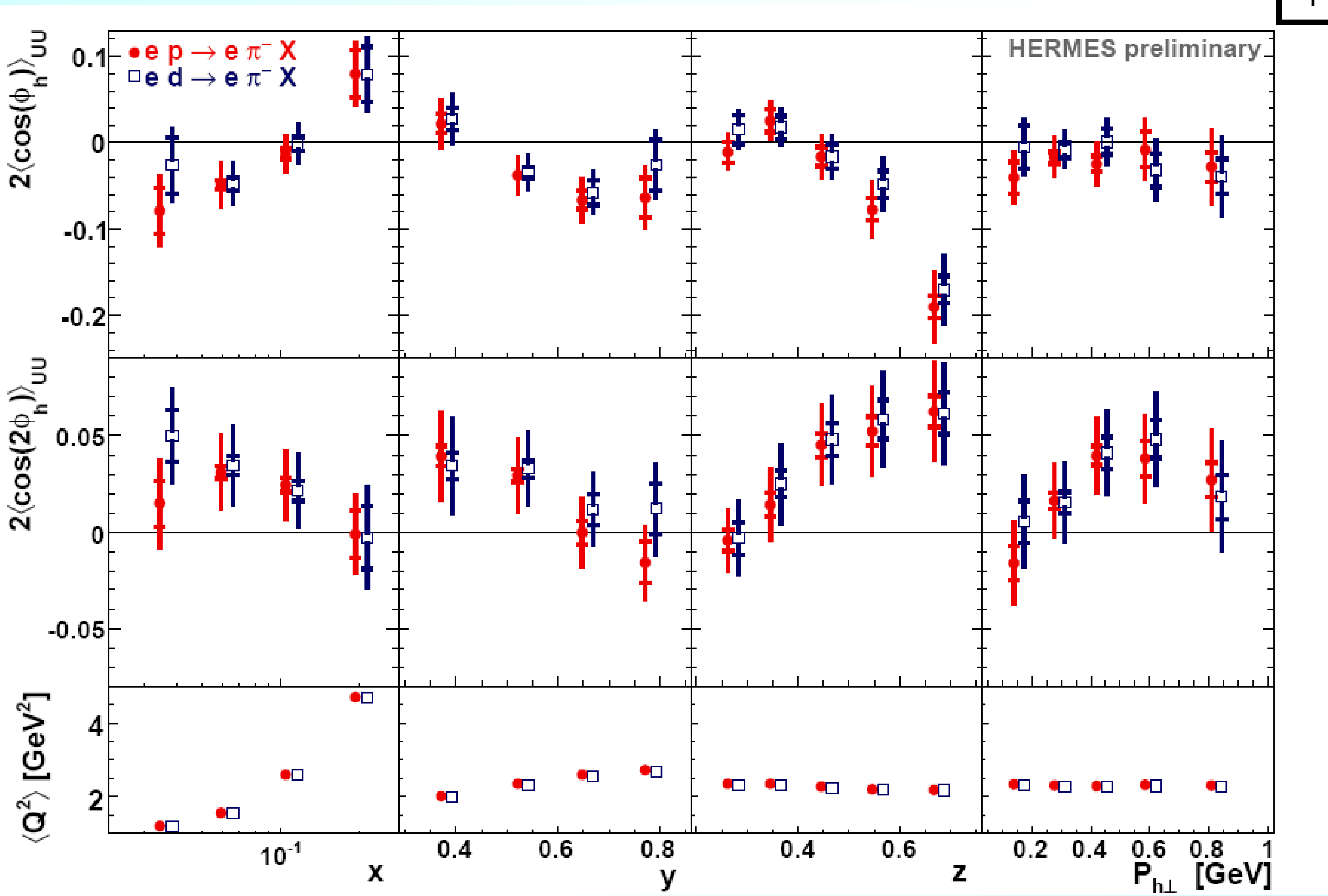
New



cos(nϕ)$_{UU}$ moments for π^- - H, D target

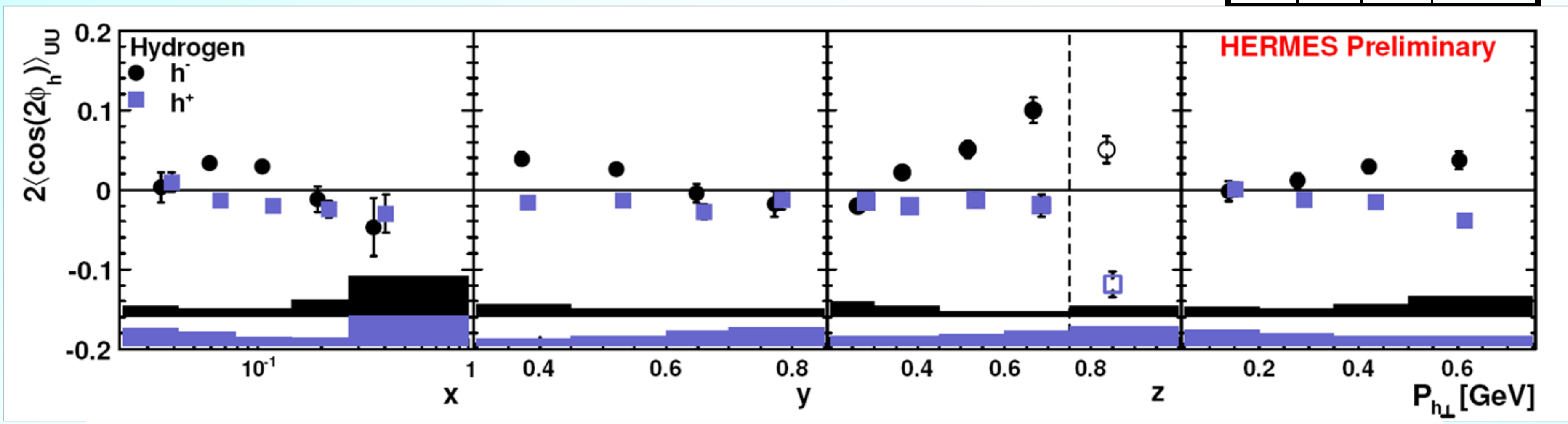
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

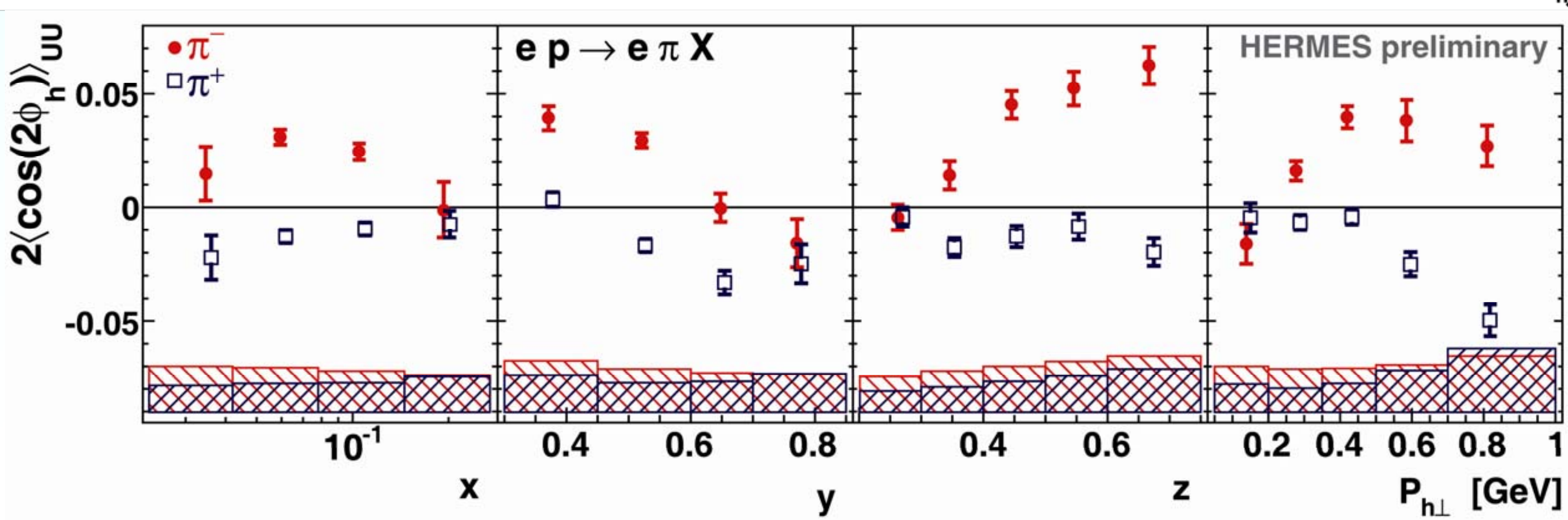
New



Boer-Mulders DF

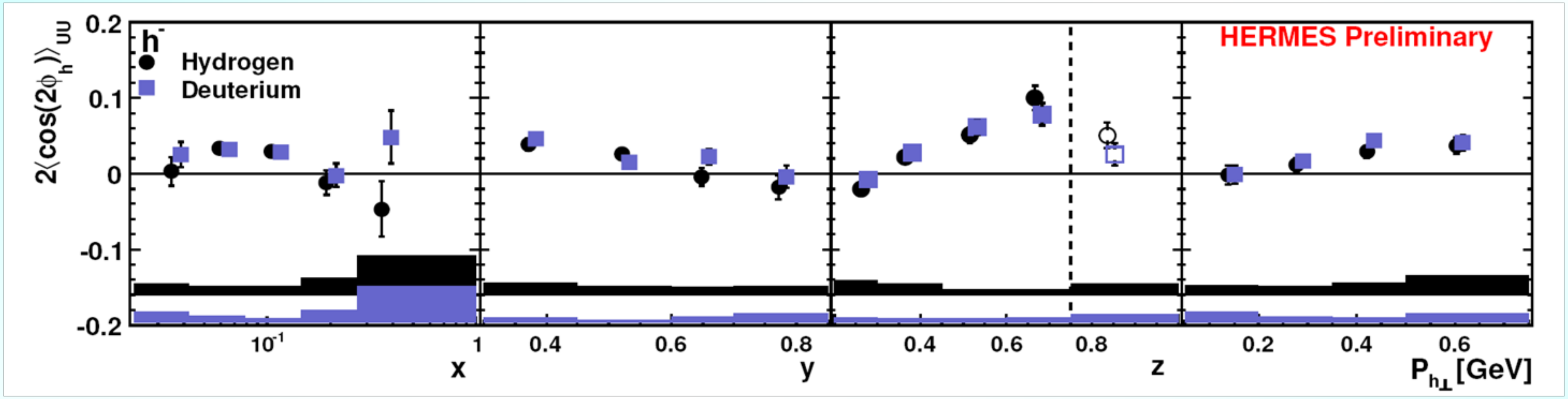
N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

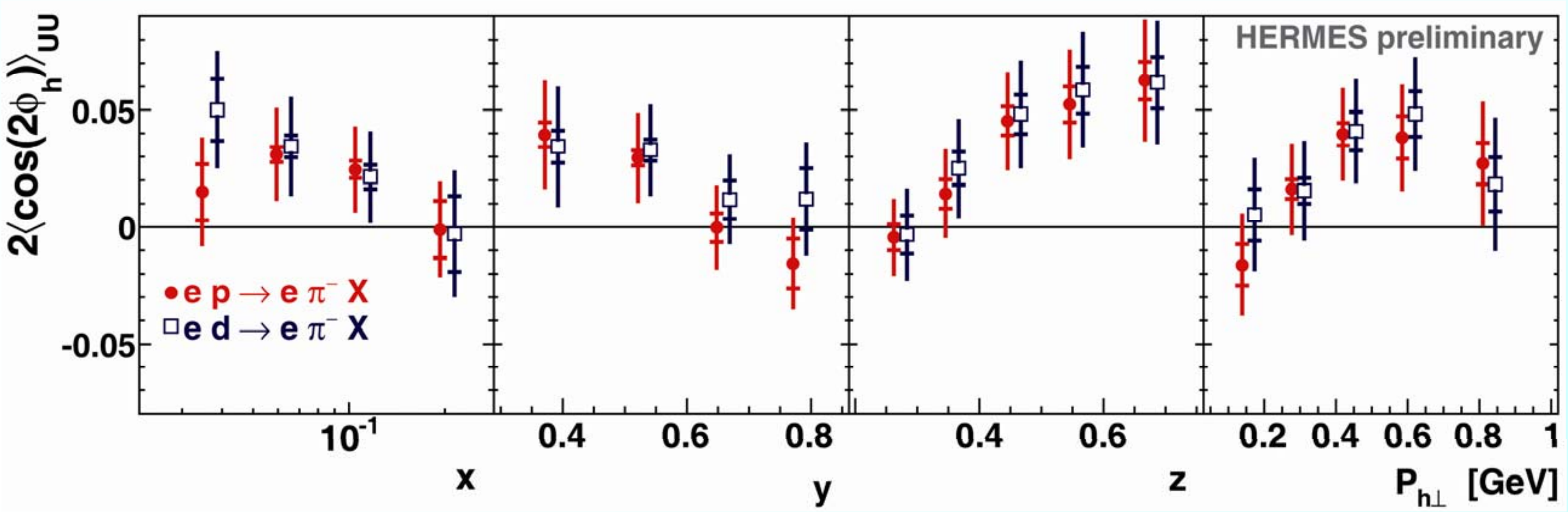




Boer-Mulders DF

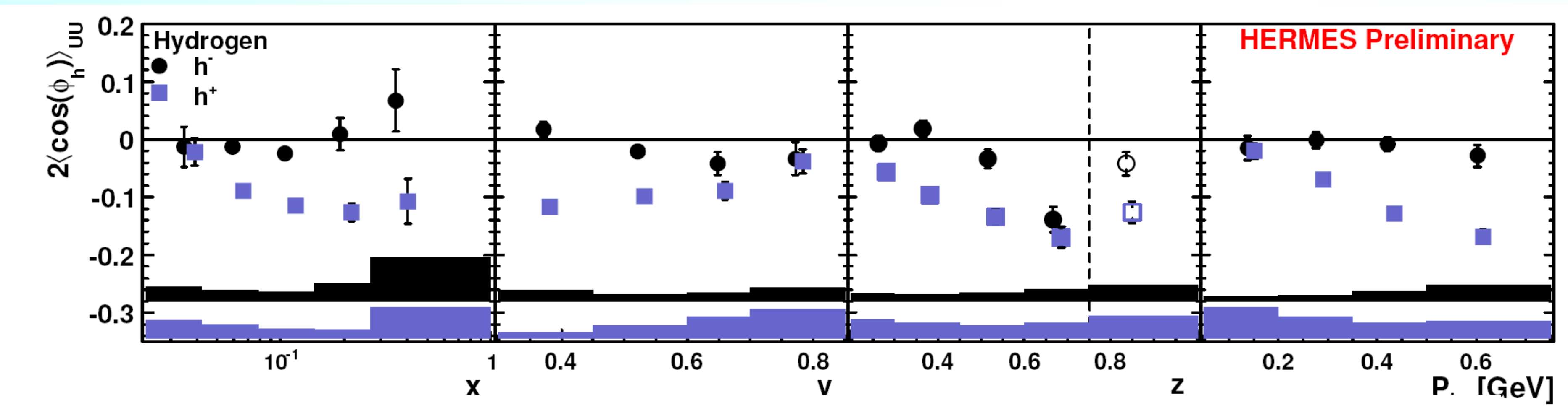
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

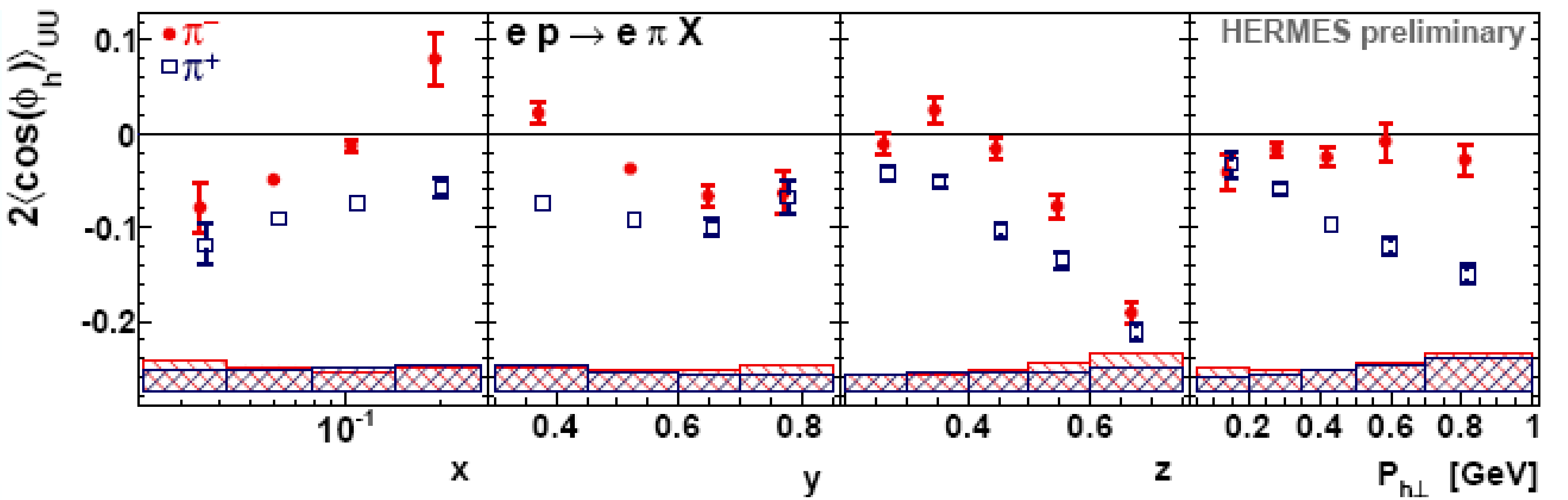




$\langle\cos\phi\rangle_{UT}$

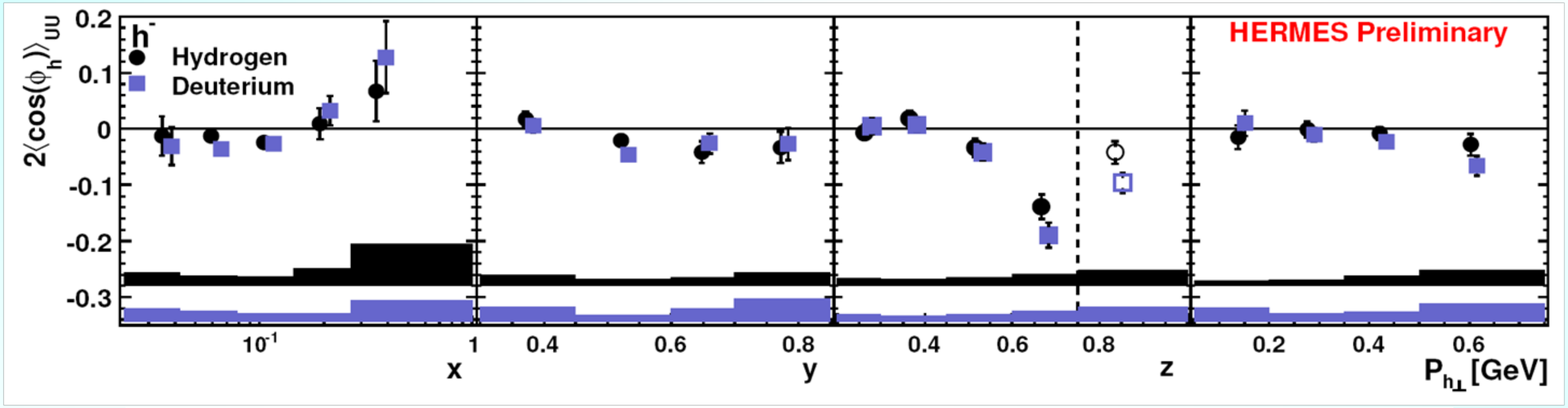
N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

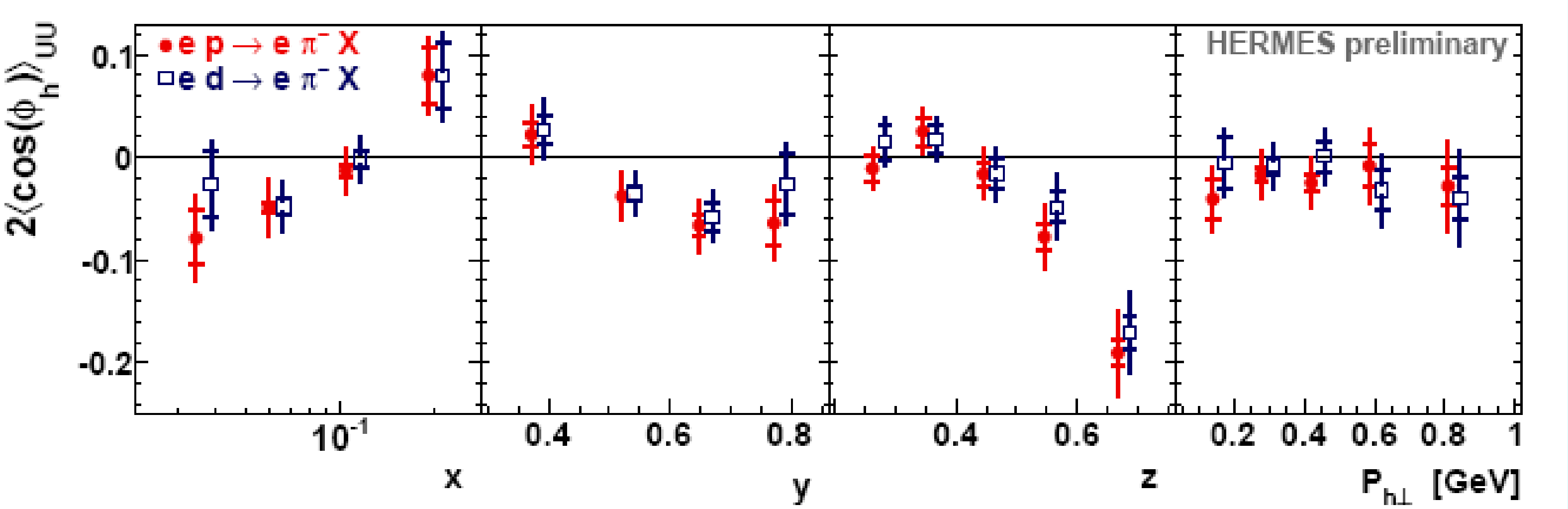




$\langle\cos\phi\rangle_{UT}$

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

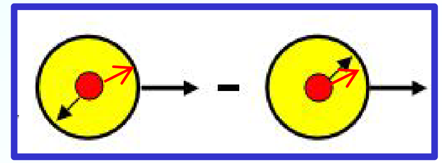




Worm-gear (Mulders-Kotzinian) DF $h_{1L}^{\perp}$

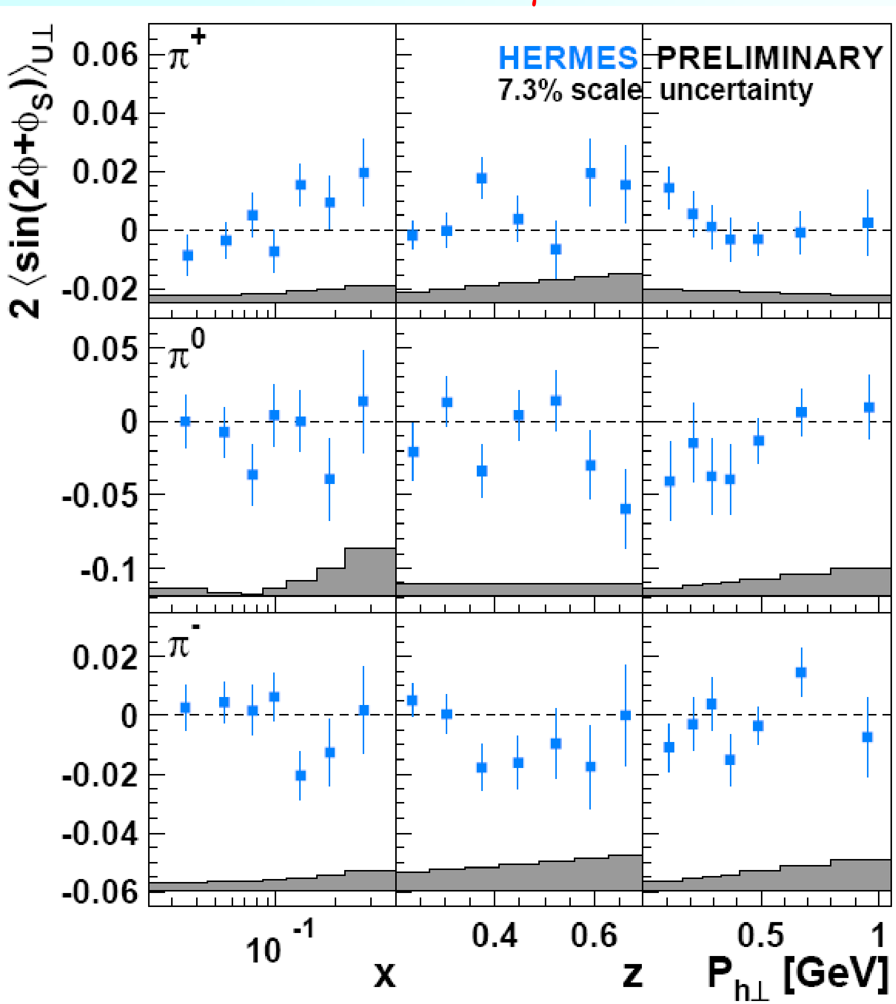
$\langle \sin(2\phi+\phi_s) \rangle_{U\perp}$

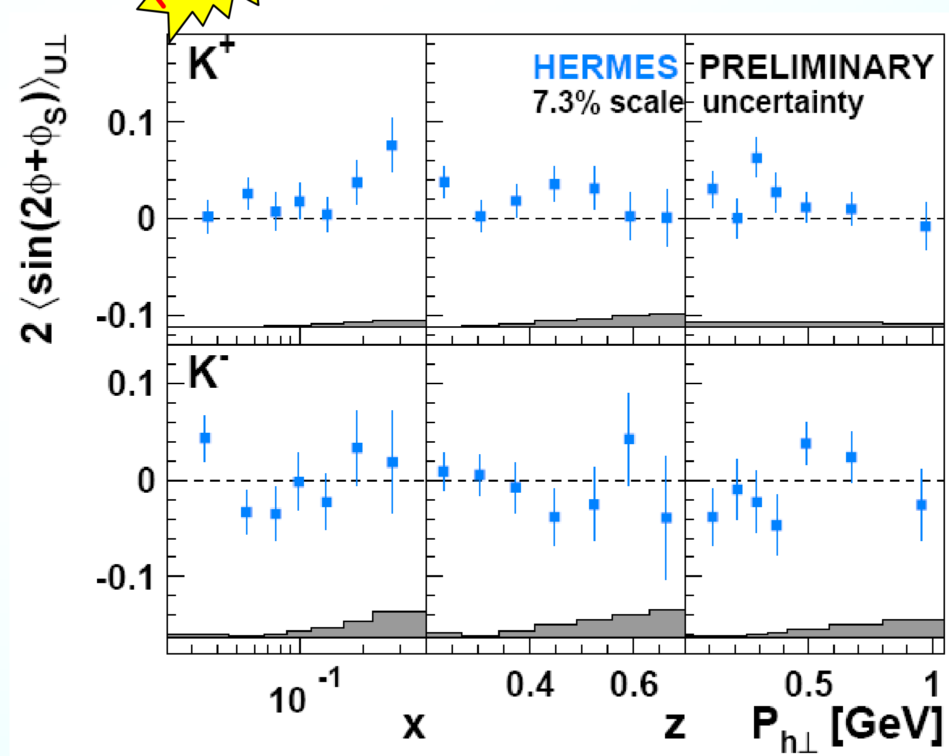
Longt. comp.: $\sin\theta_{\gamma^*} \langle \sin(2\phi)_{UL} \rangle$



N/q	U	L	T
U	f_1		$h_1^{\perp}$
L		g_1	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	g_{1T}	h_1 $h_{1T}^{\perp}$

Recent



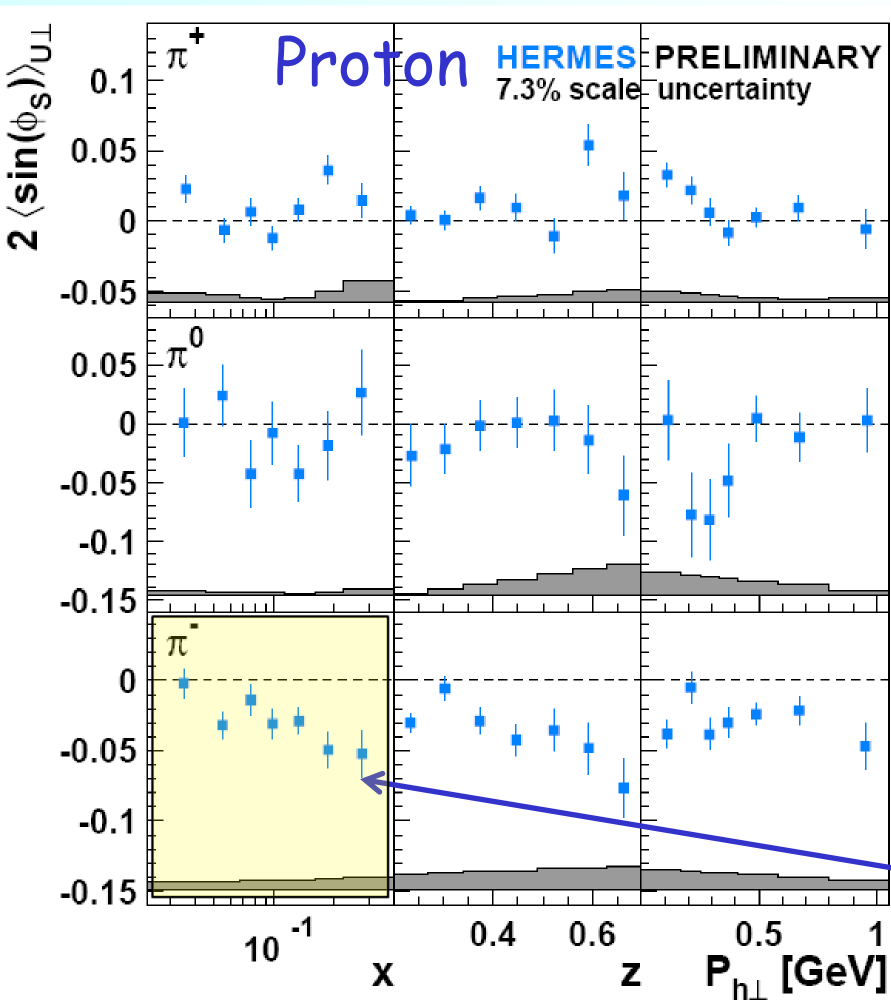


Compatible with zero within uncertainties

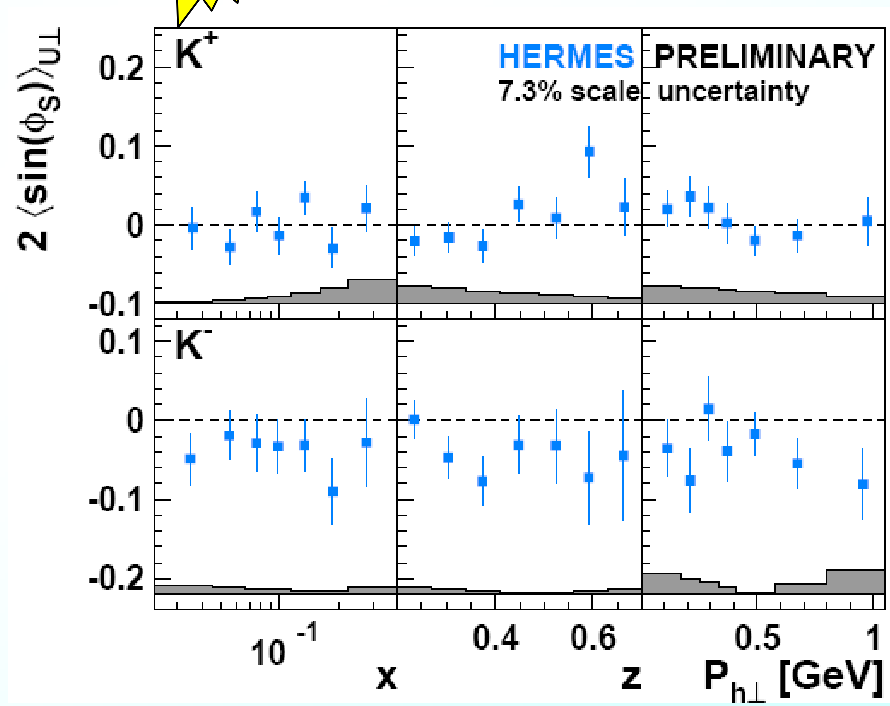
Subleading term $\sin(\phi_s)_{UT}$

$$\langle \sin(\phi_s) \rangle_{UT} \propto h_1 \otimes H_1^\perp + f_{1T}^\perp \otimes D_1$$

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



Recent

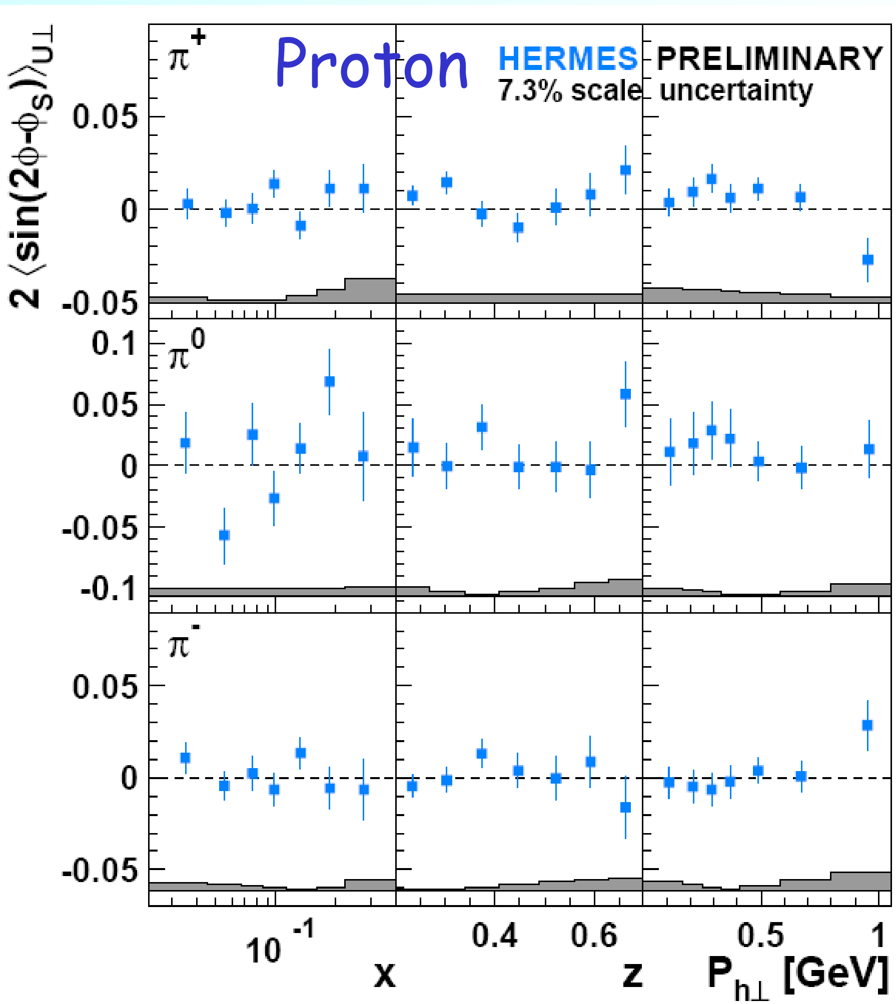


Similar to Collins

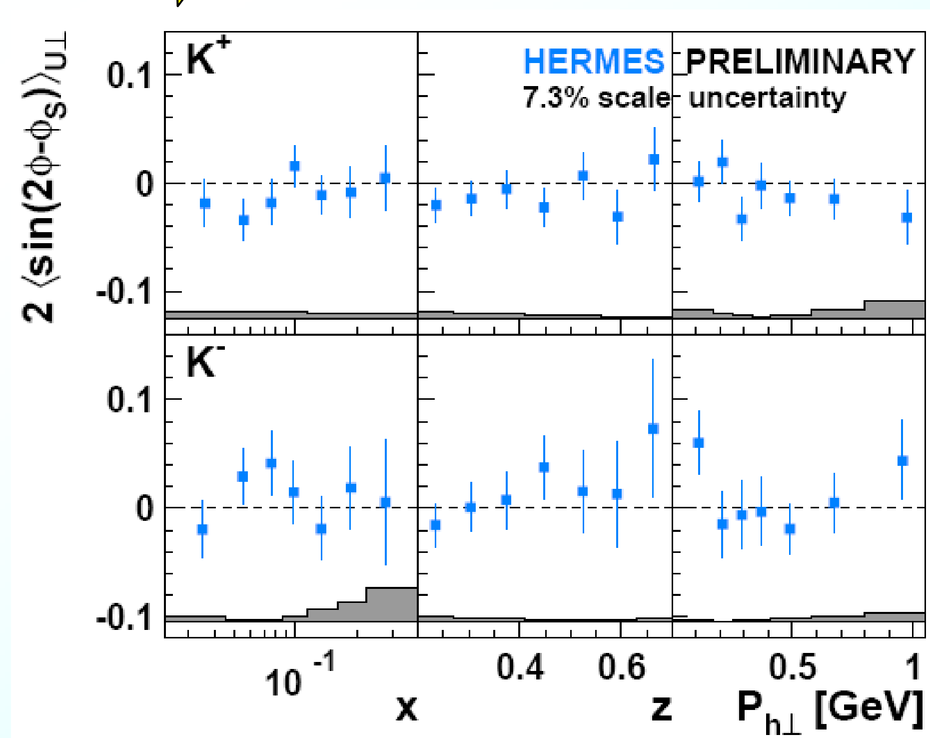
Subleading term $\sin(2\phi-\phi_s)_{UT}$

N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

$$\langle\sin(2\phi-\phi_s)\rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp + f_{1T}^\perp \otimes D_1$$



Recent



Azimuthal dependences in DVCS

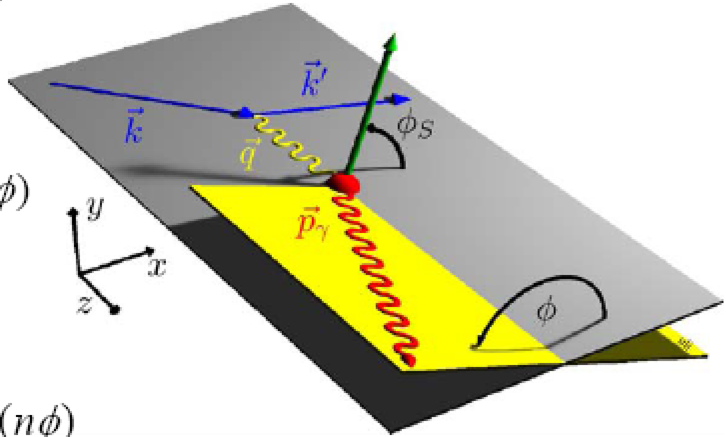
Example: unpolarised proton target

- Cross section

$$\sigma_{LU}(\phi; P_B, C_B) = \sigma_{UU}[1 + P_\ell A_{LU}^{DVCS} + e_\ell P_\ell A_{LU}^{I} + e_\ell A_C]$$

- Beam-charge asymmetry

$$A_C(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) - (\sigma^{-\leftarrow} + \sigma^{-\rightarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\leftarrow} + \sigma^{-\rightarrow})} = -\frac{1}{D(\phi)} \frac{x_B^2}{y} \sum_{n=0}^{3} c_n^I \cos(n\phi)$$



- Charge-difference beam-helicity asymmetry

$$A_{LU}^I(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{-\leftarrow}) - (\sigma^{+\leftarrow} + \sigma^{-\rightarrow})}{(\sigma^{+\rightarrow} + \sigma^{-\leftarrow}) + (\sigma^{+\leftarrow} + \sigma^{-\rightarrow})} = -\frac{1}{D(\phi)} \frac{x_B^2}{Q^2} \sum_{n=1}^{2} s_n^I \sin(n\phi)$$

- Charge-averaged beam-helicity asymmetry

$$A_{LU}^{DVCS}(\phi) = \frac{(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}) - (\sigma^{-\leftarrow} - \sigma^{-\rightarrow})}{(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}) + (\sigma^{-\leftarrow} + \sigma^{-\rightarrow})} = \frac{1}{D(\phi)} \cdot \frac{x_B^2 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)}{Q^2} s_1^{DVCS} \sin(\phi)$$

A_{XY} — X: beam, Y: target

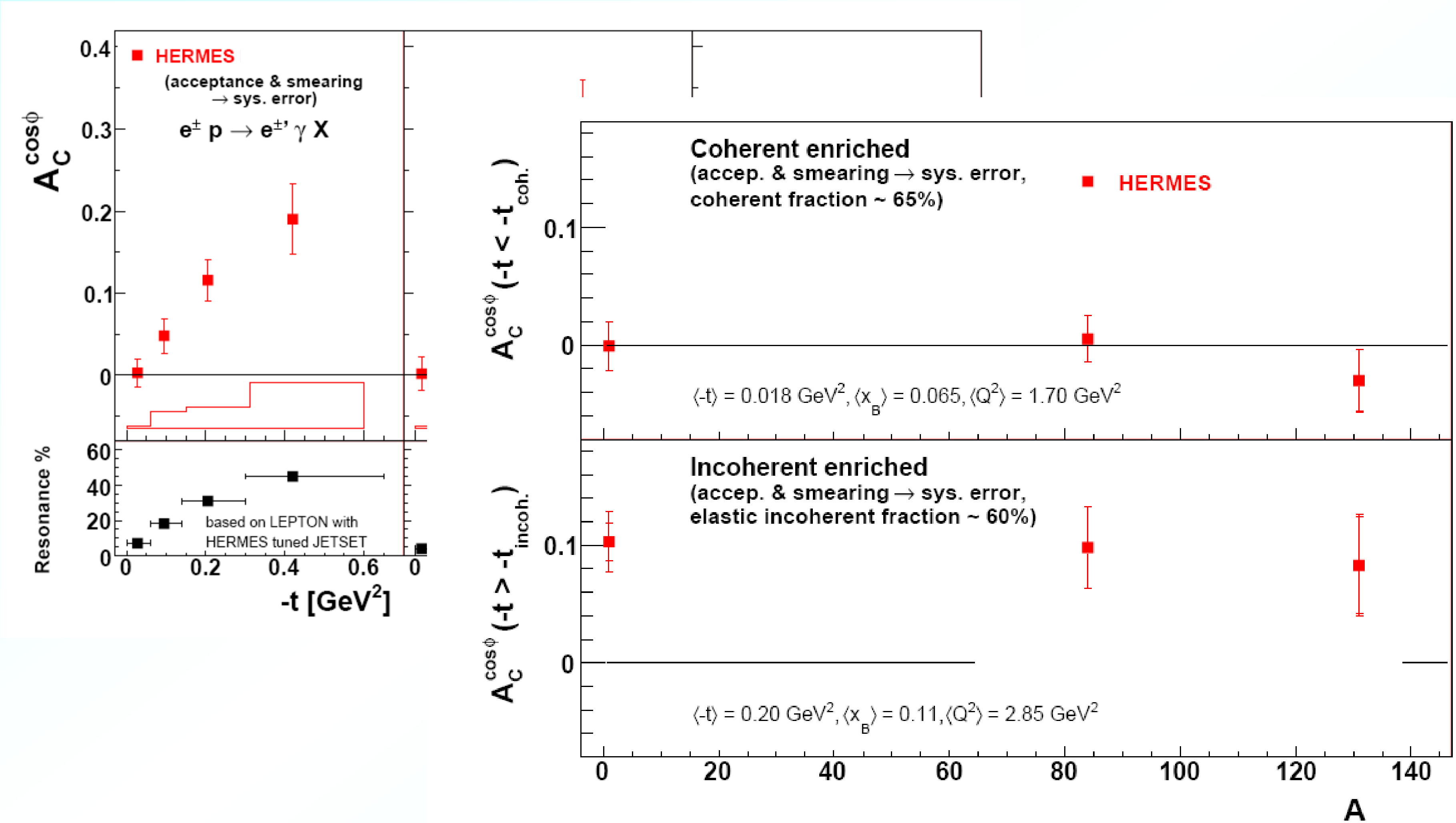
- Measurements of these beam-helicity asymmetries allow to separate contributions from DVCS and interference term

- This separation is impossible in measurements of single-charge beam-helicity asymmetry

$$A_{LU}(\phi) = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$

DVCS - nuclear mass dependence of A_C

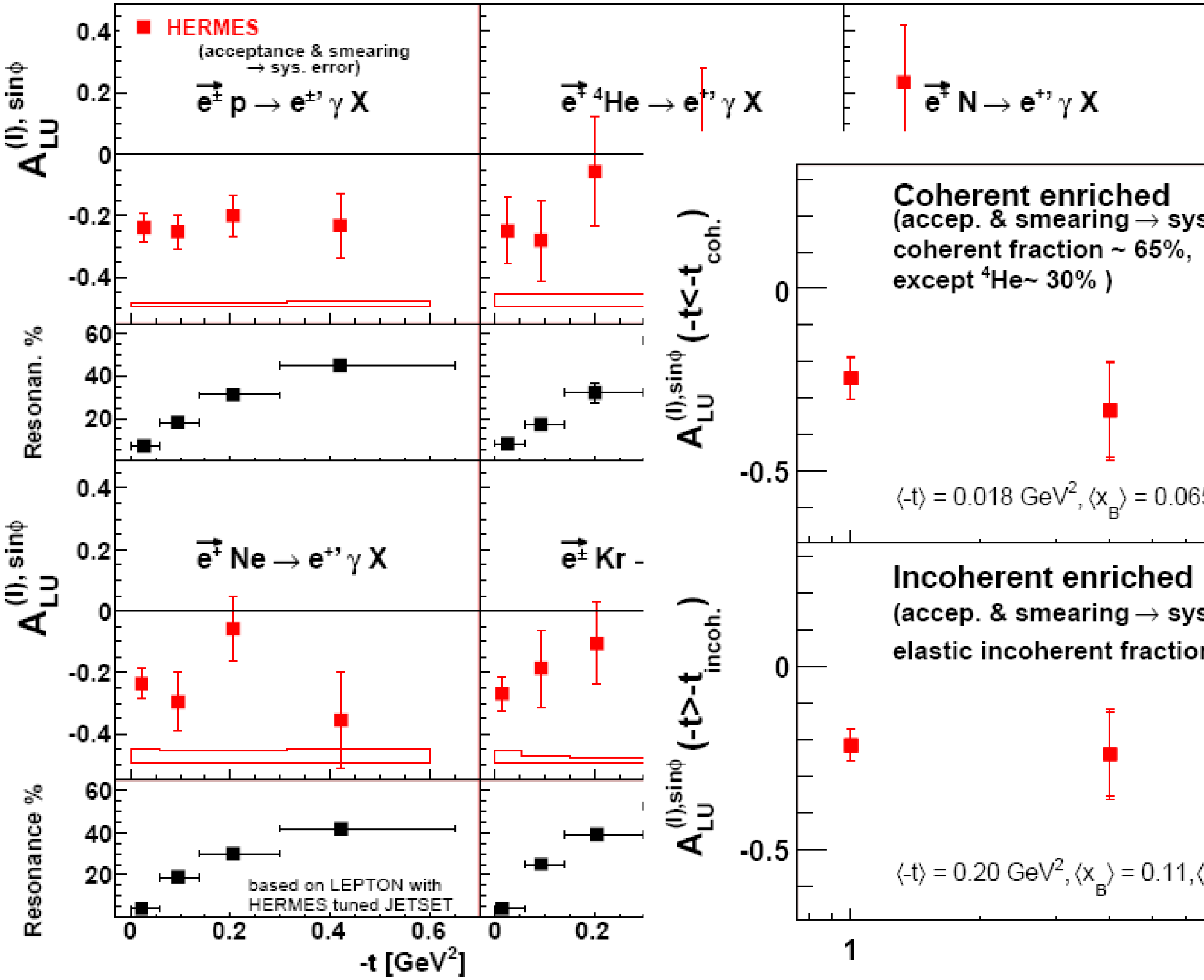
PRC 81 (2010) 035202



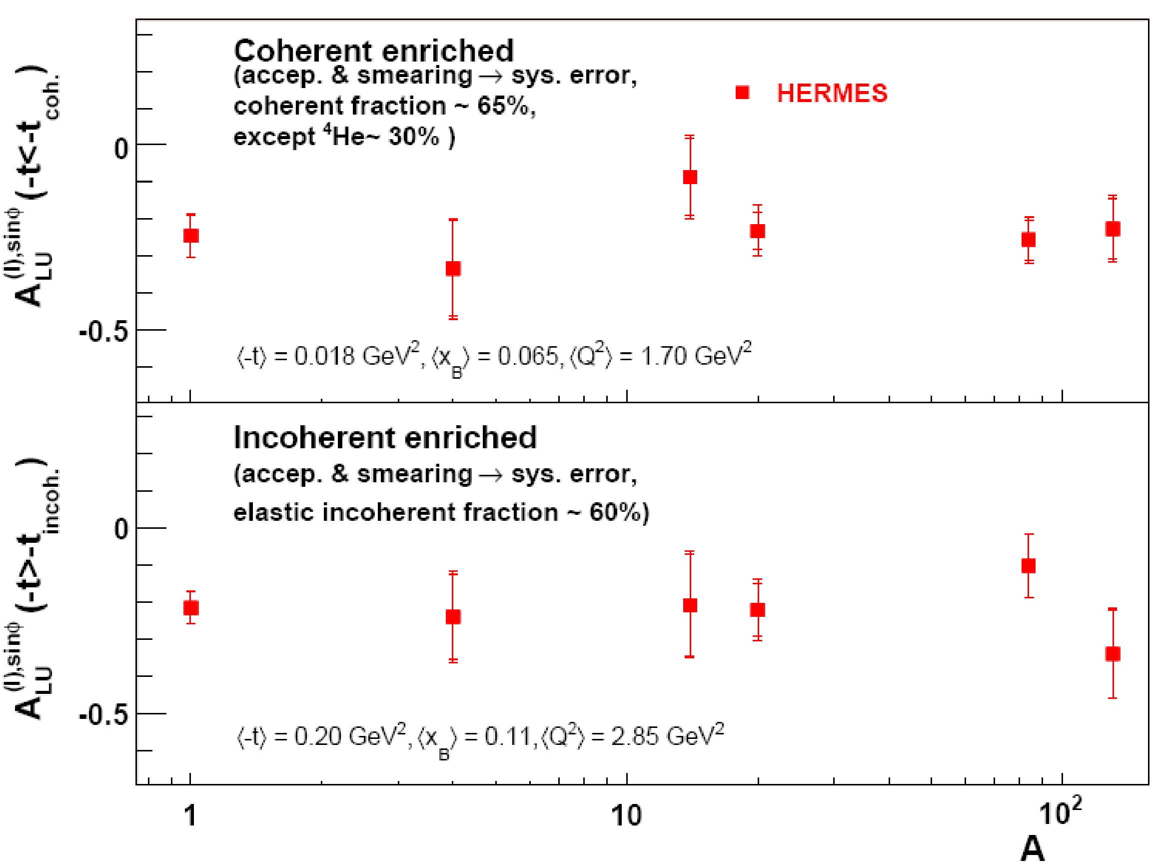
No enhancement of nuclear asymmetries visible!!!

DVCS - nuclear mass dependence

$$H, Kr, Xe:\ A_{LU}^{I}(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{-\leftarrow}) - (\sigma^{+\leftarrow} + \sigma^{-\rightarrow})}{(\sigma^{+\rightarrow} + \sigma^{-\leftarrow}) + (\sigma^{+\leftarrow} + \sigma^{-\rightarrow})} \qquad {}^{4}He, N, Ne:\ A_{LU}^{I}(\phi) = \frac{\sigma^{\rightarrow} - \sigma^{\leftarrow}}{\sigma^{\rightarrow} + \sigma^{\leftarrow}}$$



PRC 81 (2010) 035202



No enhancement of nuclear asymmetries visible!!!