

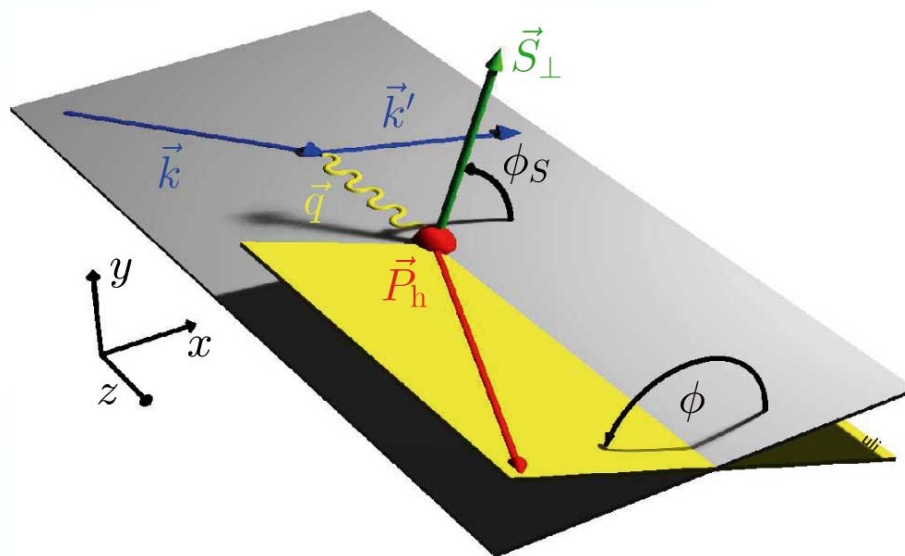


hermes Results on Azimuthal Asymmetries related to TMDs and DVCS

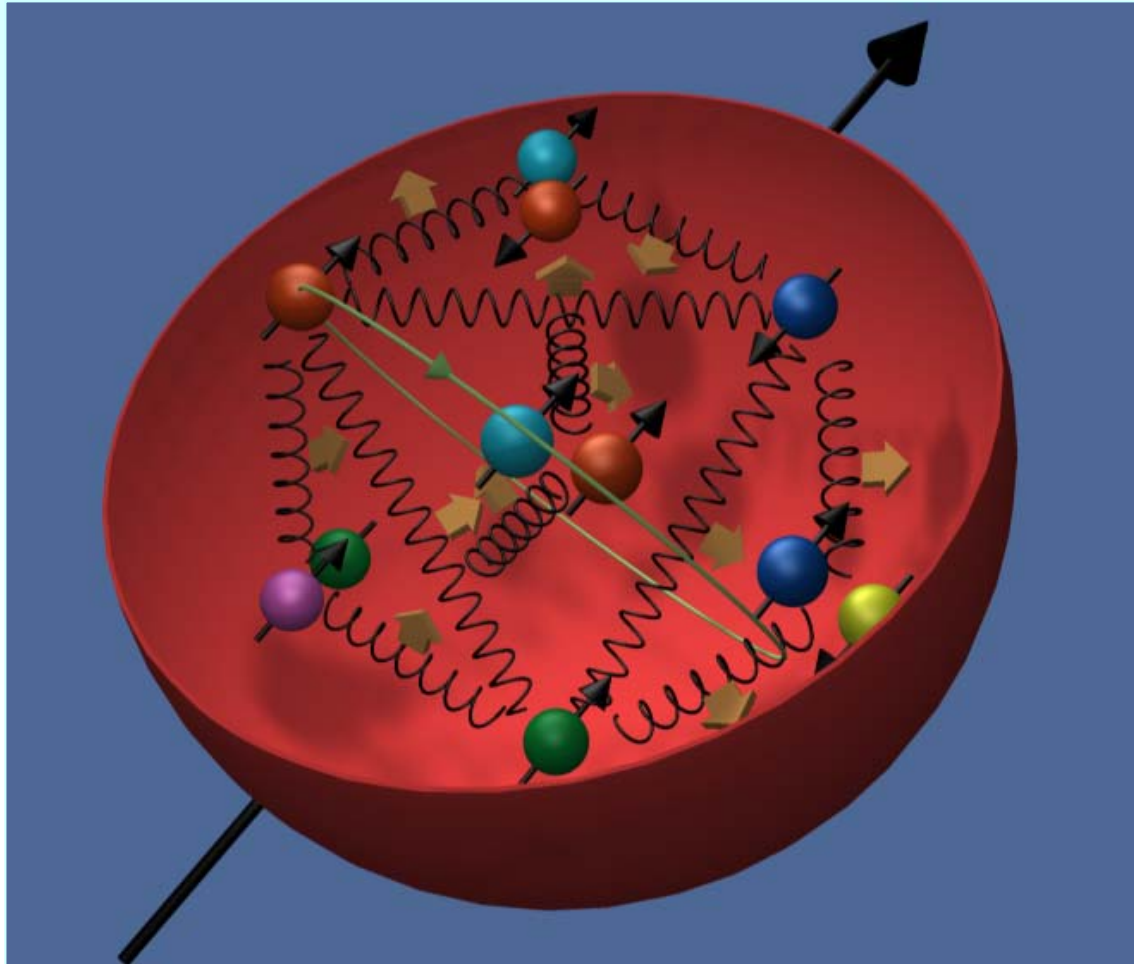
Klaus Rith

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}_2



Transverse Momentum Dependent DFs

LO quark distribution functions

		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 -

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

See talk by A. Prokudin

Boer-Mulders DF

'worm-gear 1' DF

Transversity DF

Prezelocity 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



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	T	f_{1T}^\perp -	g_{1T}^\perp -	h_1 - h_{1T}^\perp -

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



Transverse Momentum Dependent DFs

LO quark distribution functions

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		U	L	T
n	U	f_1		h_1^\perp -
	L		g_1 -	h_{1L}^\perp -
	T	f_{1T}^\perp -	g_{1T}^\perp -	h_1 - h_{1T}^\perp -

Sivers DF*

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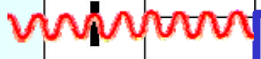
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Boer-Mulders DF *#

'worm-gear 1' DF#

Transversity DF#

Prezelocity DF#



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

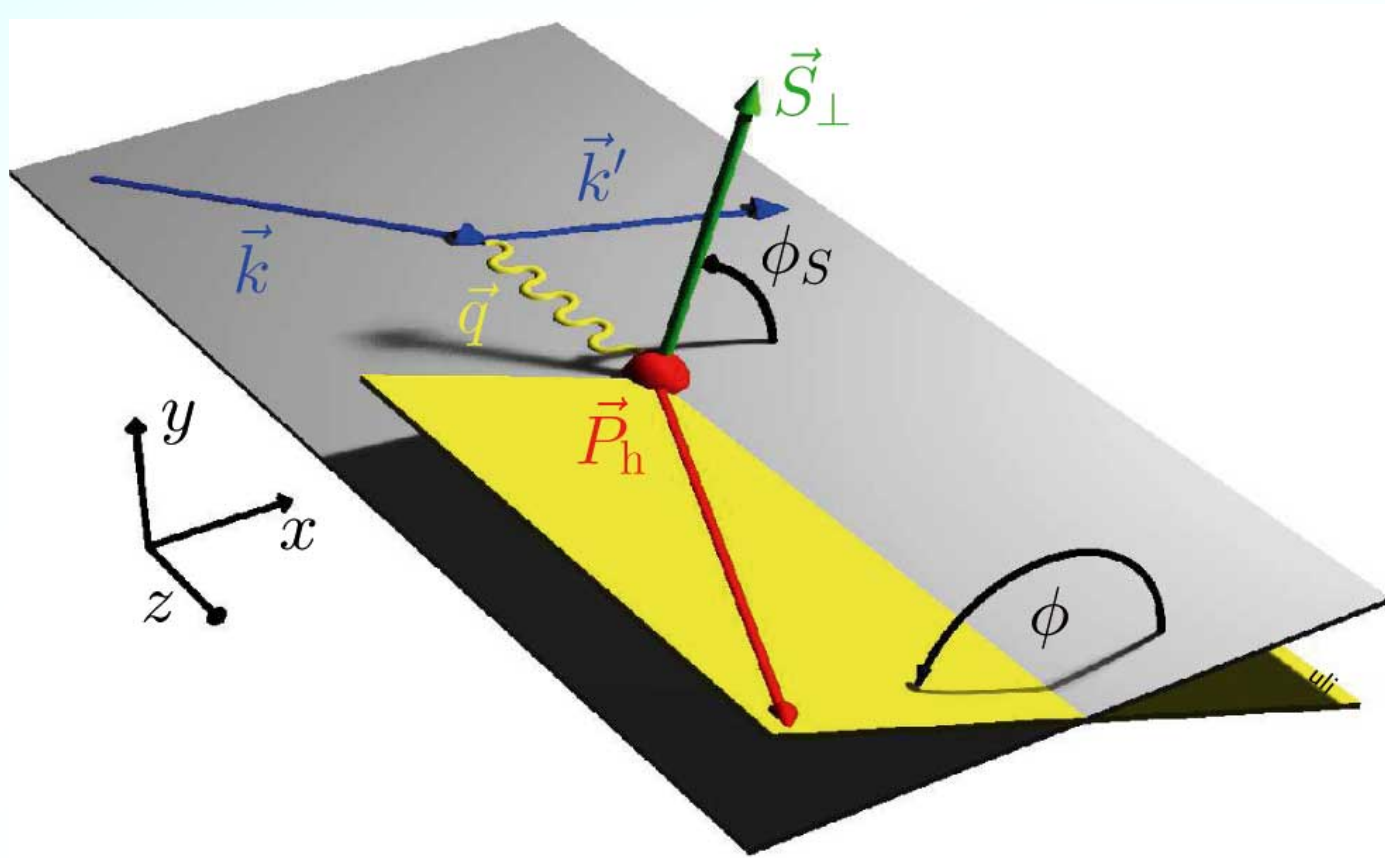
$D_1 \equiv D_q^h =$,normal' FF,
 H_1^\perp = spin-dependent Collins FF *#

* 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



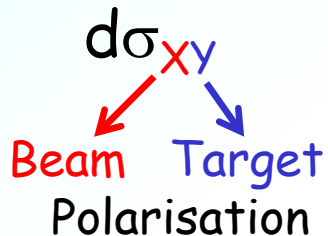
$$d\sigma \equiv \frac{d^6\sigma}{dx dy dz d\phi d\phi_s dP_T^h}$$

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

$$+ \boxed{S_T} \left\{ \sin(\phi - \phi_S) d\sigma_{UT}^8 + \sin(\phi + \phi_S) d\sigma_{UT}^9 + \sin(3\phi - \phi_S) d\sigma_{UT}^{10} \right.$$

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

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

$d\sigma_{xy}$

 Beam Polarisation
 Target Polarisation

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

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

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

$$+ S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^8 + \sin(\phi + \phi_S) \, d\sigma_{UT}^9 + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \right.$$

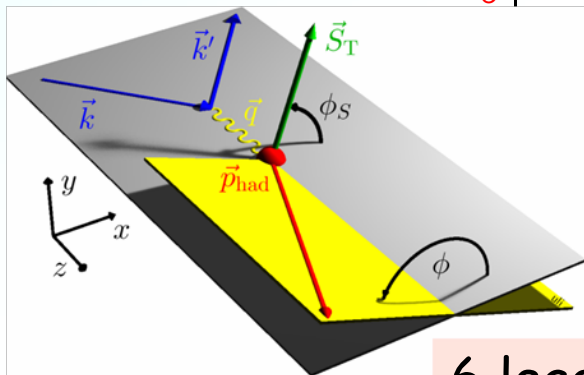
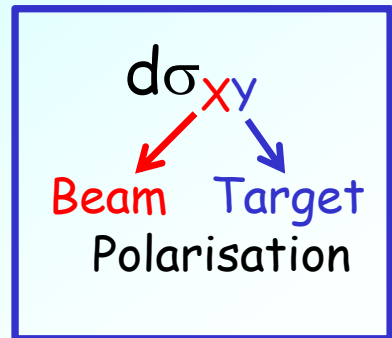
$$+ \frac{1}{Q} \sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \frac{1}{Q} \sin \phi_S \, d\sigma_{UT}^{12}$$

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

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

6 leading twist contributions

8 subleading ($\sim 1/Q$)



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
$d\sigma^{10}_{UT}$	$\sin(3\phi - \phi_s)$	$h_{1T}^\perp \otimes H_1^\perp$	Prezelocity
$d\sigma^4_{UL}$	$\sin(2\phi)$	$h_{1L}^\perp \otimes H_1^\perp$	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 $1/Q$

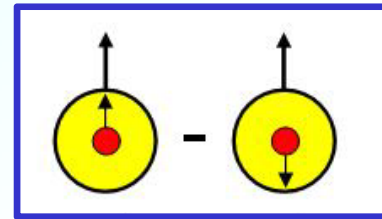


Transversity, Collins Amplitudes

Transversity DF

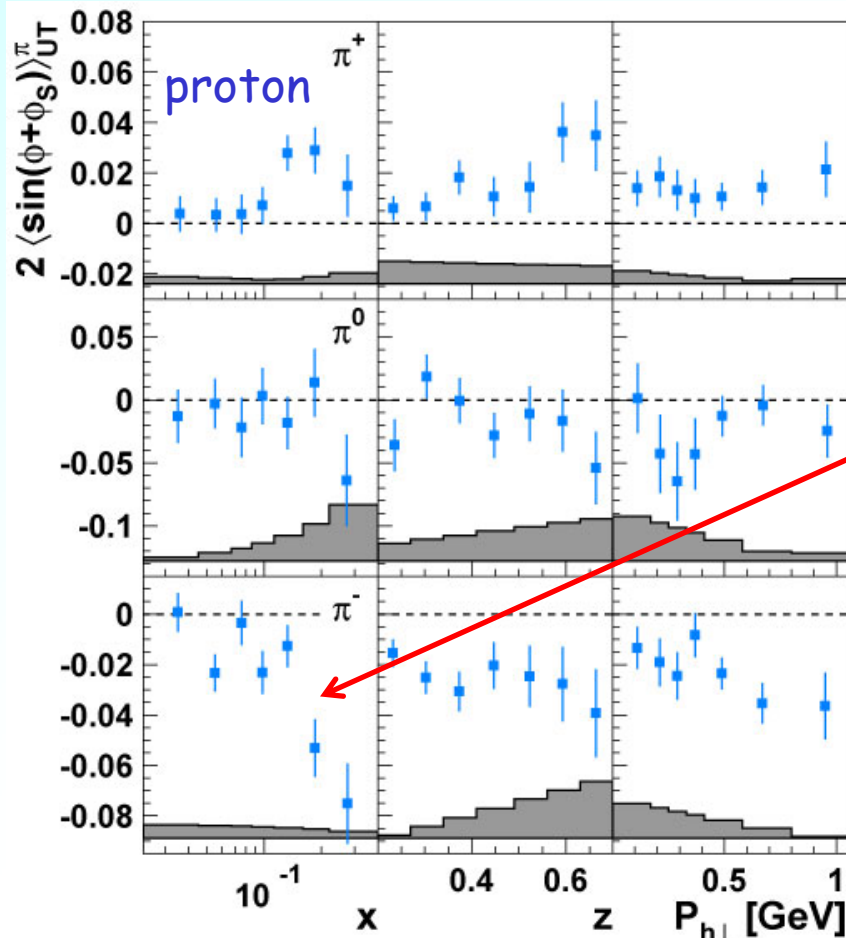
$$2\langle \sin(\phi + \phi_S) \rangle_{UT}^{\pi} \propto h_1^q(x) \otimes H_1^{\perp q}(z)$$

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^{\perp} h_{1T}^{\perp}

arXiv:1006.4221

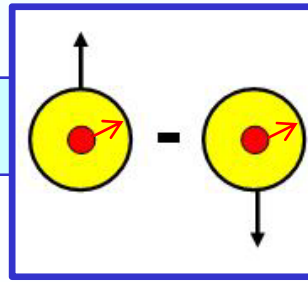


- Both Collins fragmentation function and transversity distribution function are sizeable
- Surprisingly large π^- asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation,

$$H_{1,disf}^{\perp} \approx -H_{1,fav}^{\perp}$$

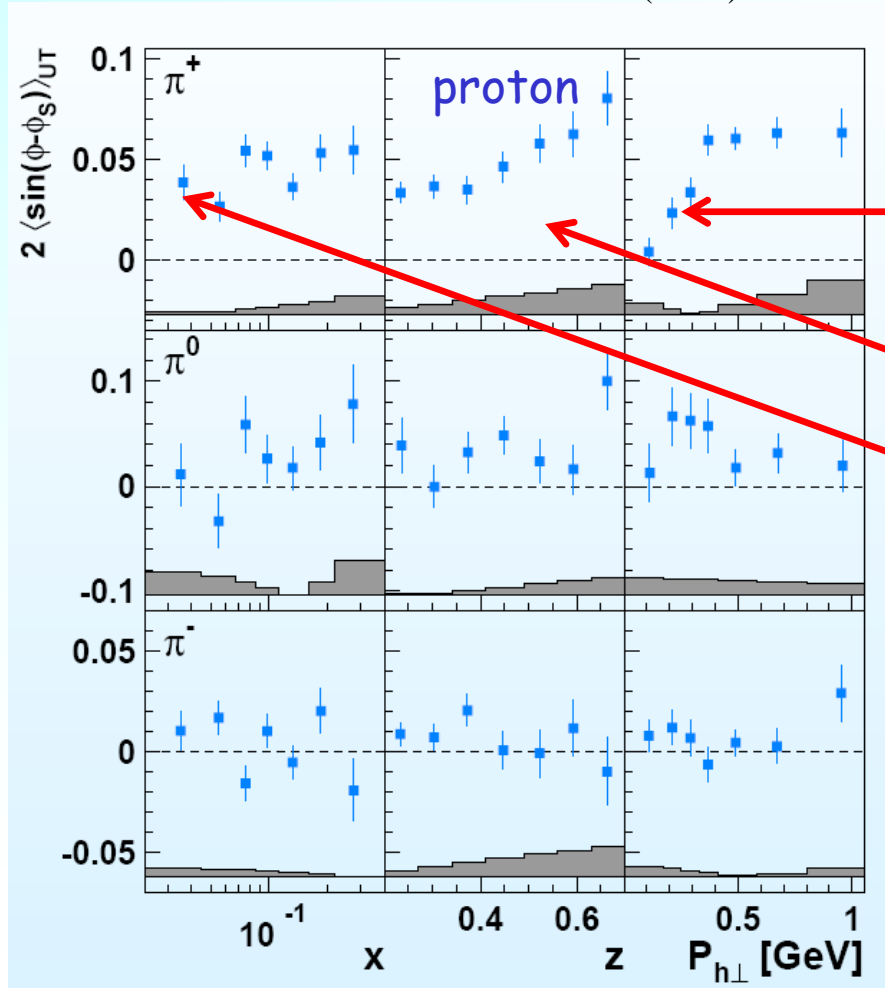
Sivers DF

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



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: Transverse 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

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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**:

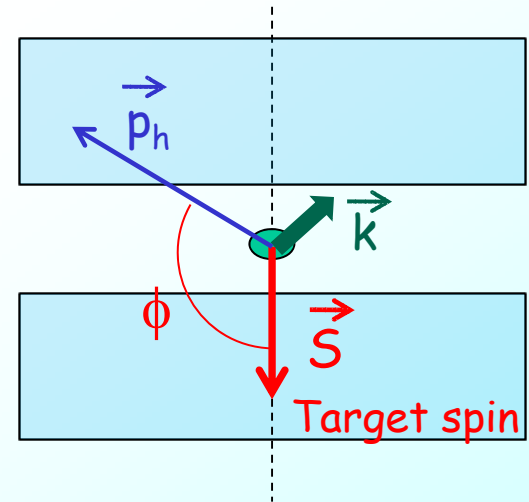
→ quasi-real photoproduction

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

Target-spin reversal every 90 s

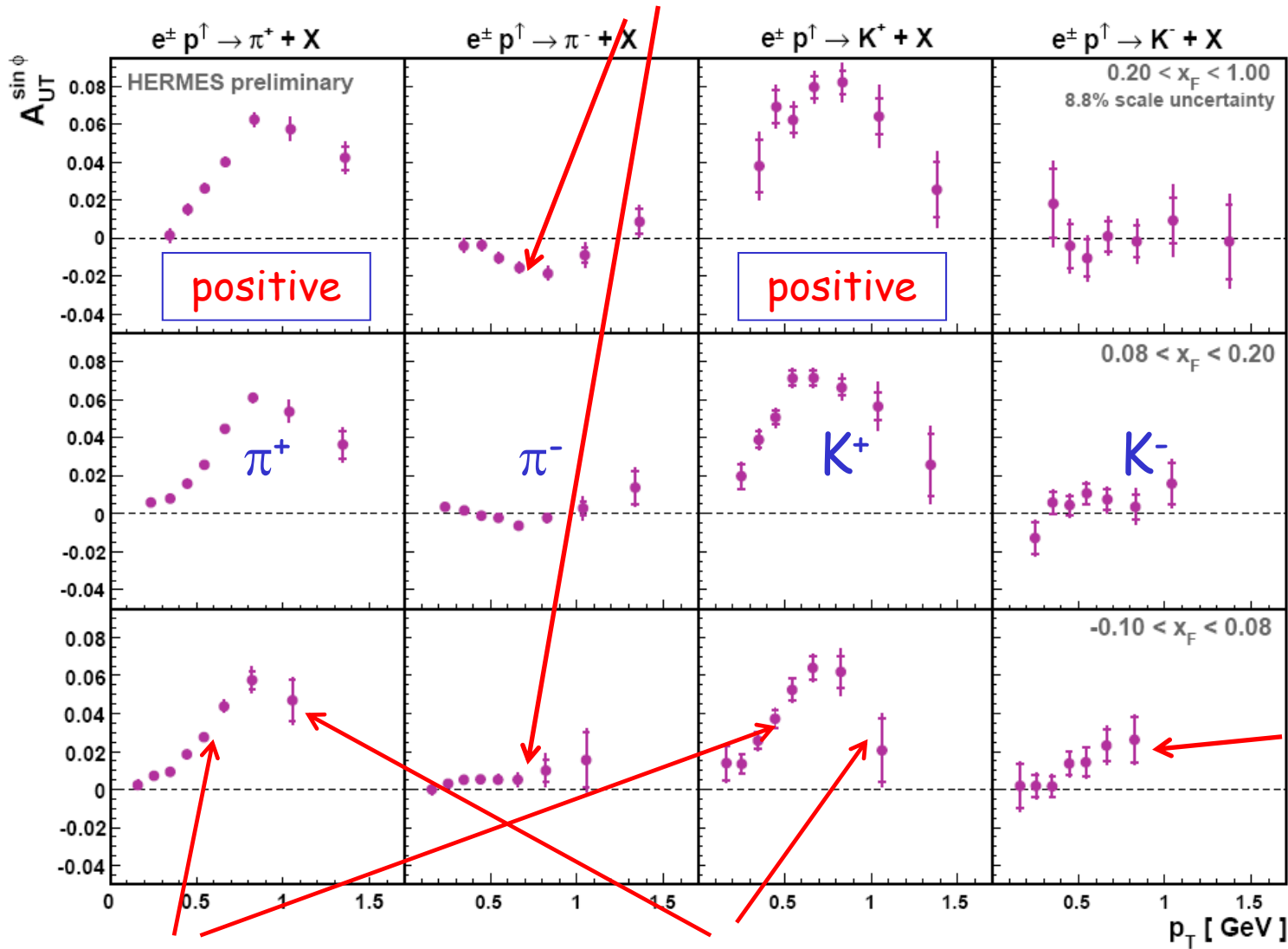
→ acceptance effects cancel

Front view of HERMES



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

Sign change for π^-

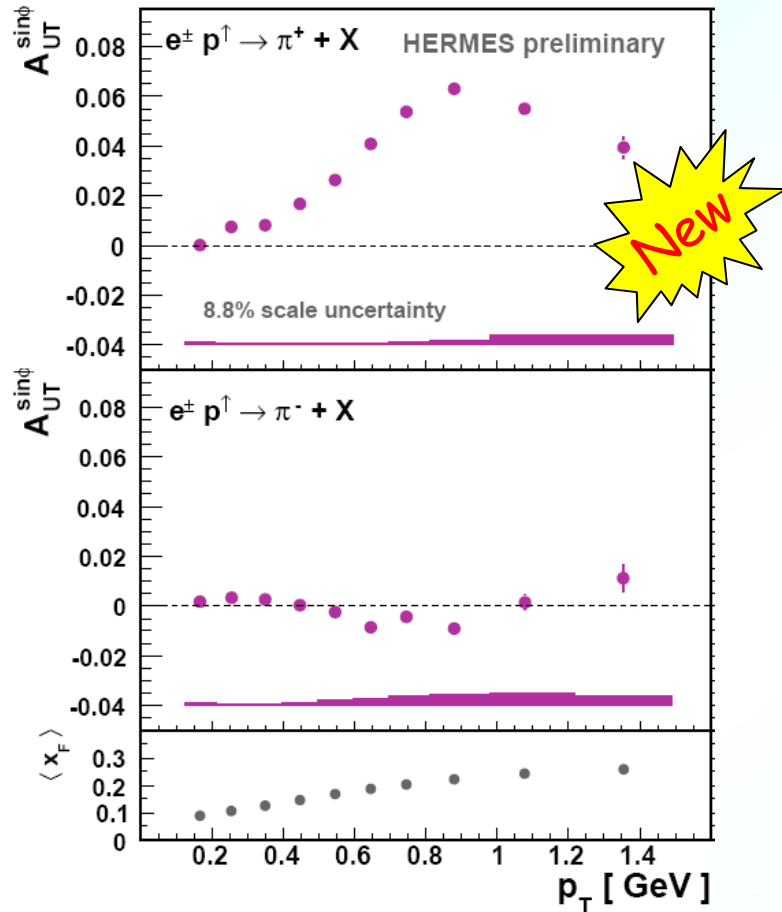


New

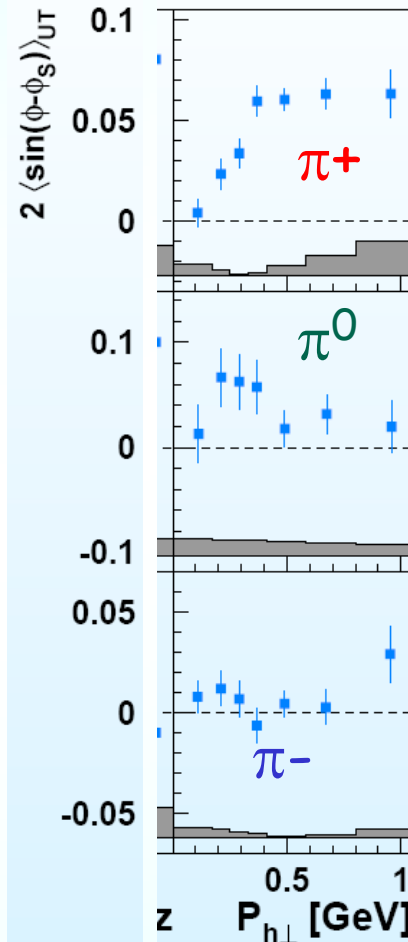
positive
for $x_F \approx 0$

rise at low p_T

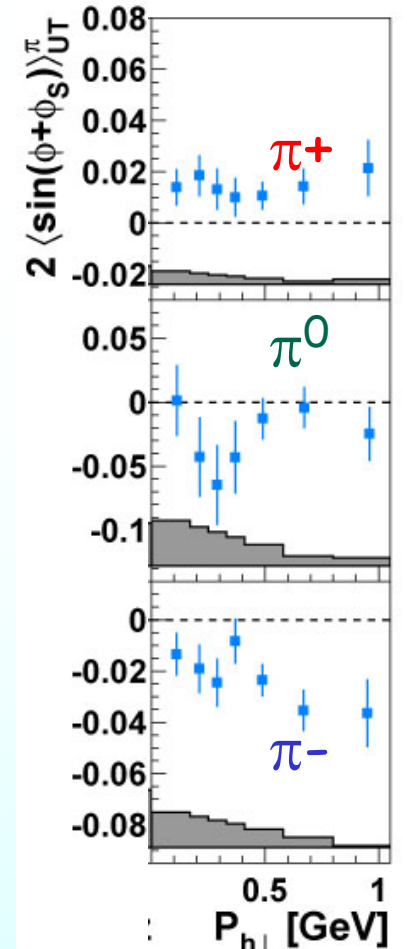
drop at high p_T



Sivers



Collins

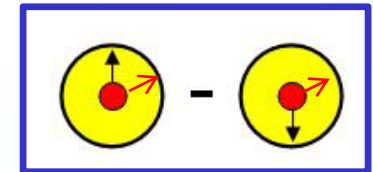
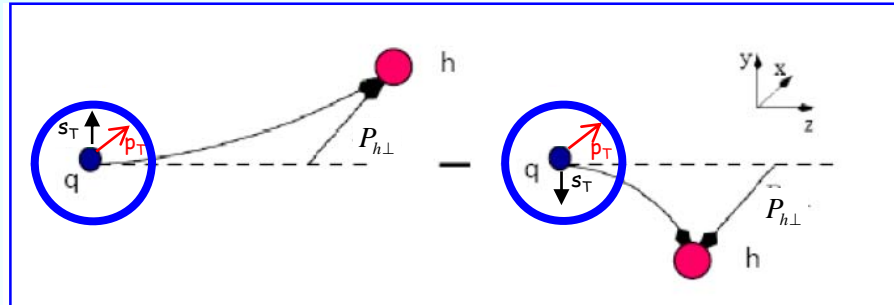


A_N resembles Sivers as predicted in M. Anselmino et al., PRD 81 (2010) 034007

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



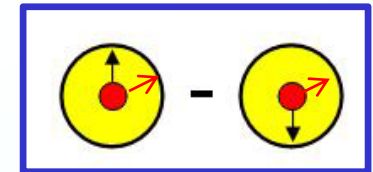
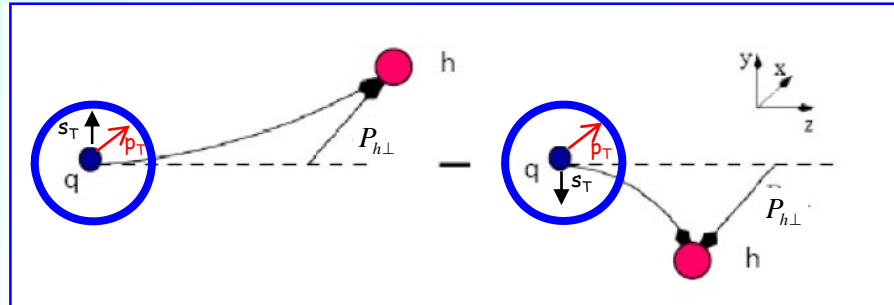
$\langle \cos 2\phi \rangle_{UU}$

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

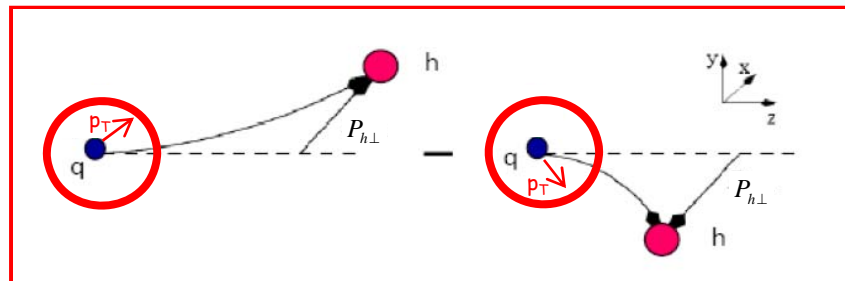


$\langle \cos 2\phi \rangle_{UU}$

transversely polarised quarks with p_T in unpolarised nucleon

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

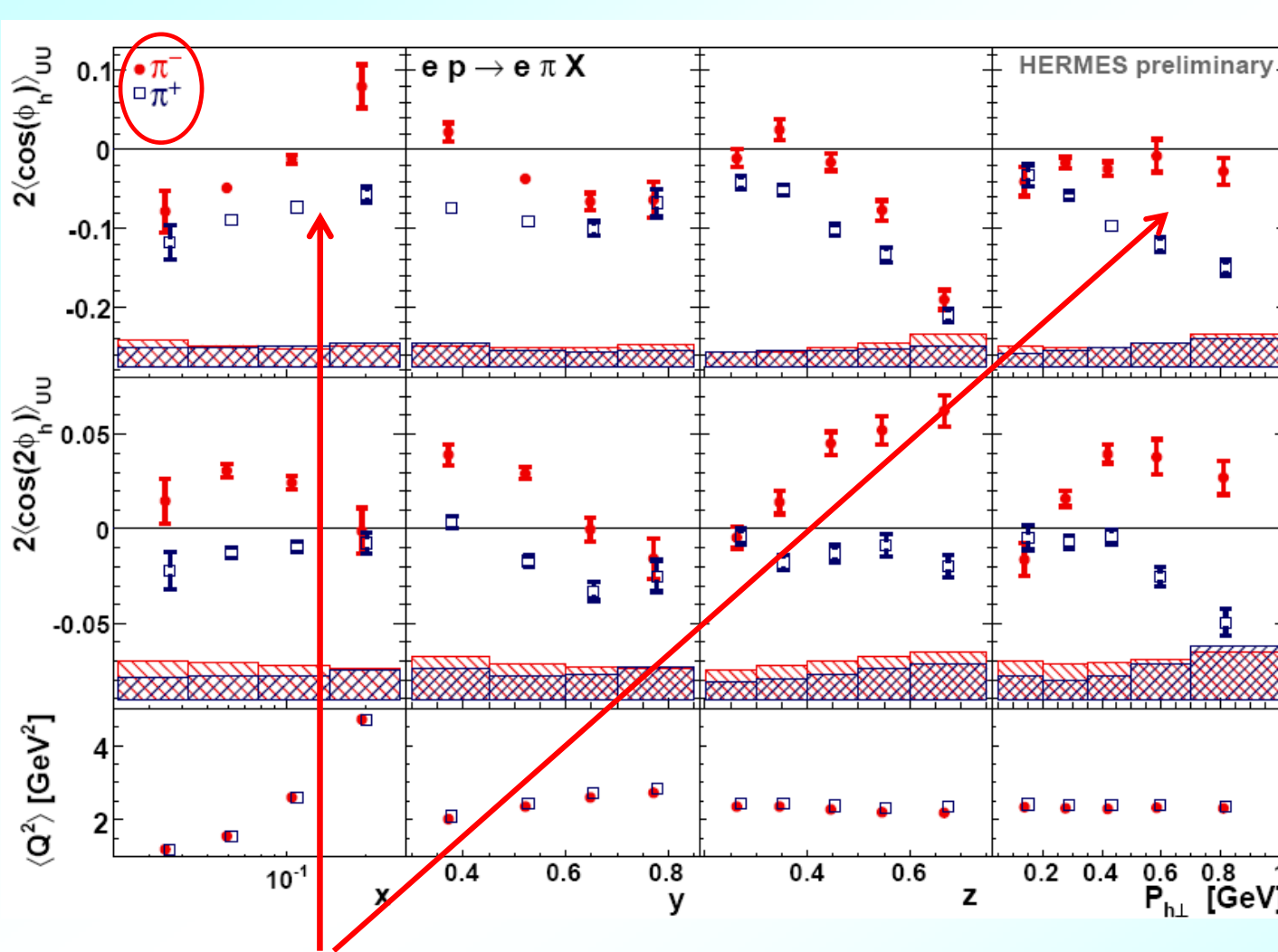
Cahn effect



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

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_{1T}^\perp
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}	h_1 h_{1T}^\perp

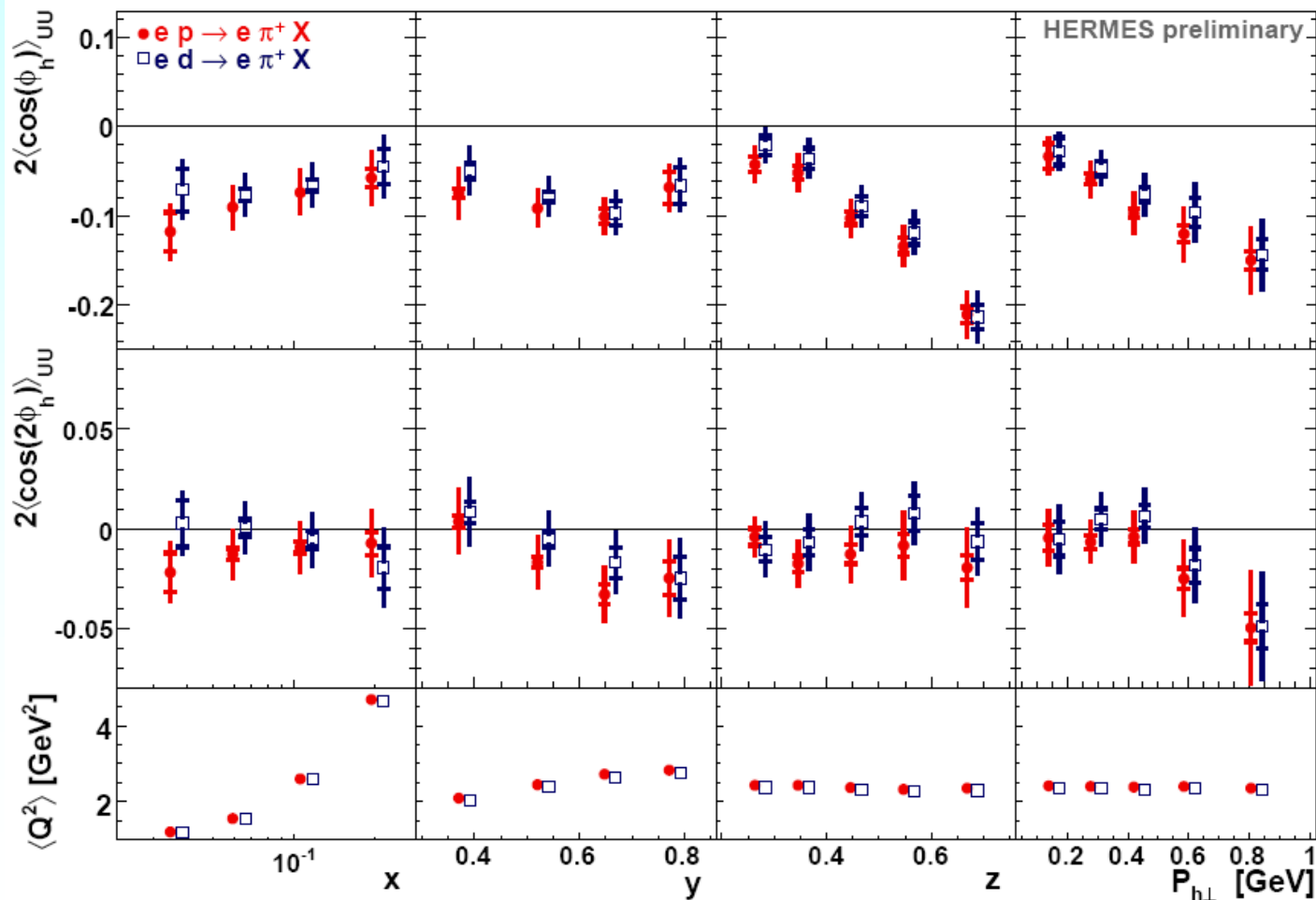


Quark flavour dependent p_T ?

Significant Boer-Mulders contribution to $\langle \cos\phi \rangle$?

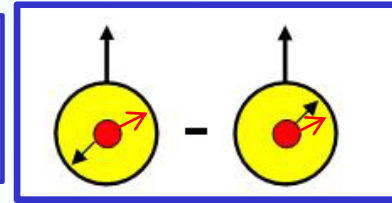
$\cos(n\phi)_{UU}$ moments for π^+ - H, D target

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

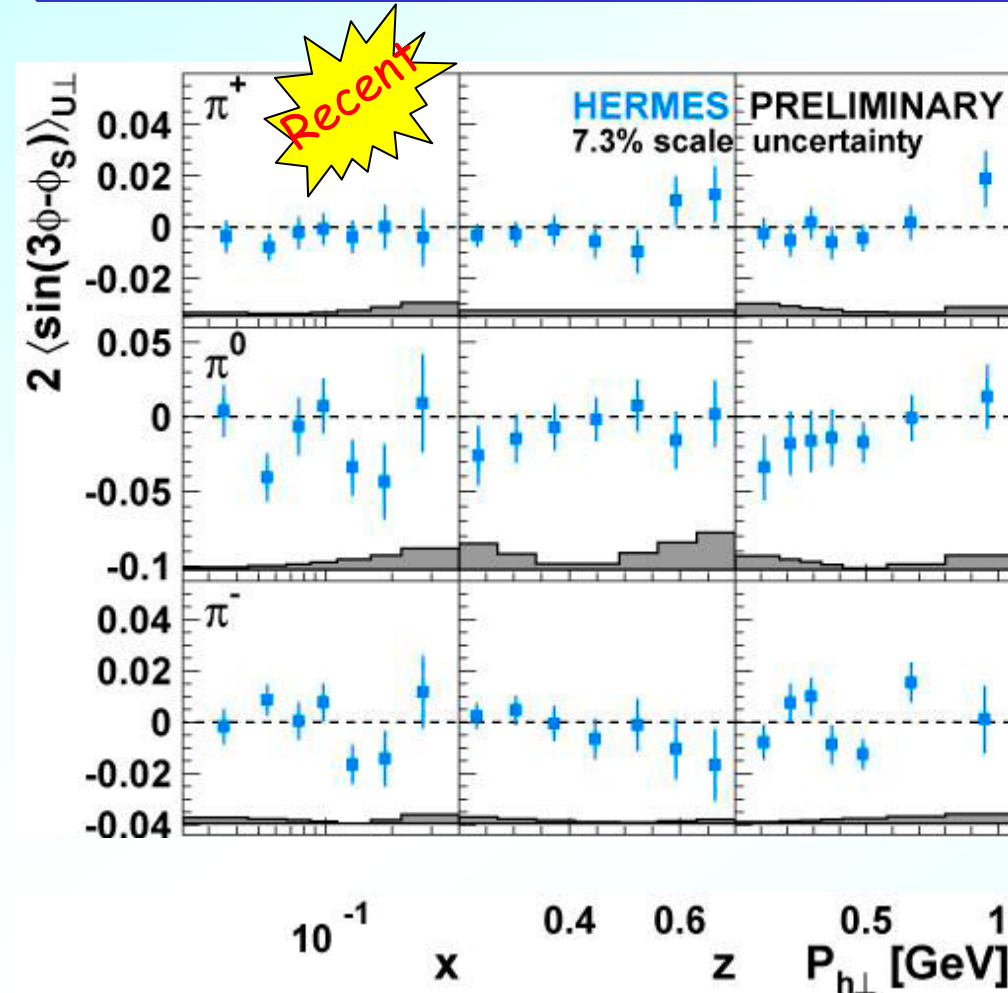


New

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

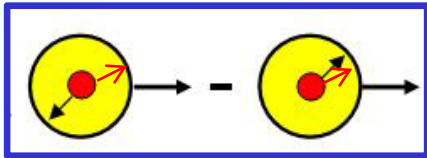


N/q	U	L	T
U	f_1		h_{1^\perp}
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}	h_{1^\perp} h_{1T}^\perp



- 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 $p_{h\perp}$

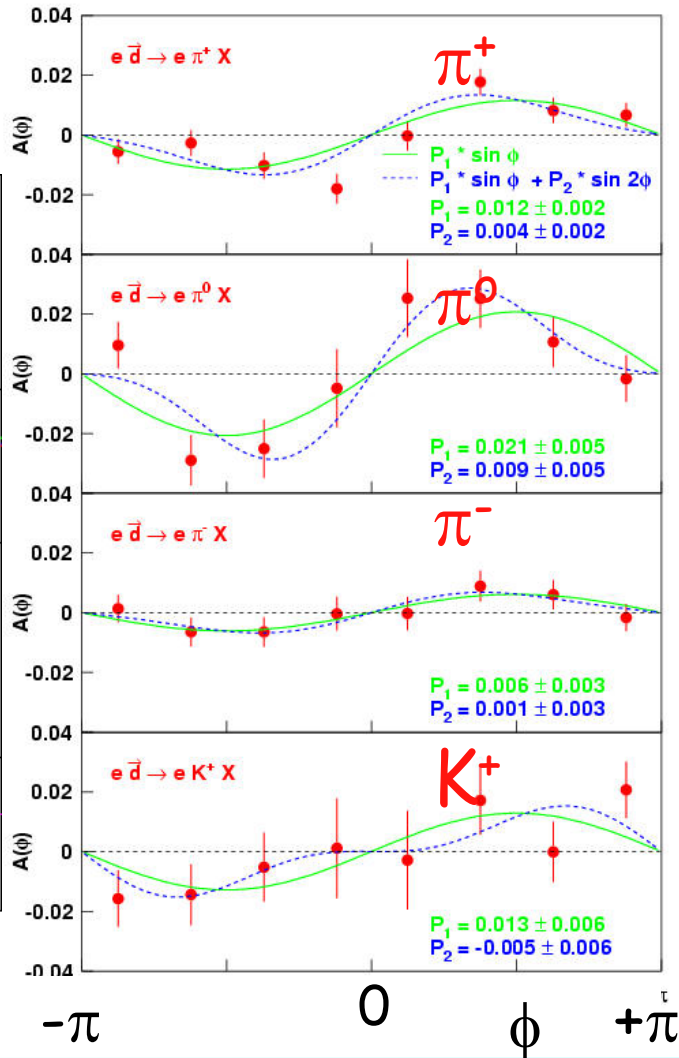
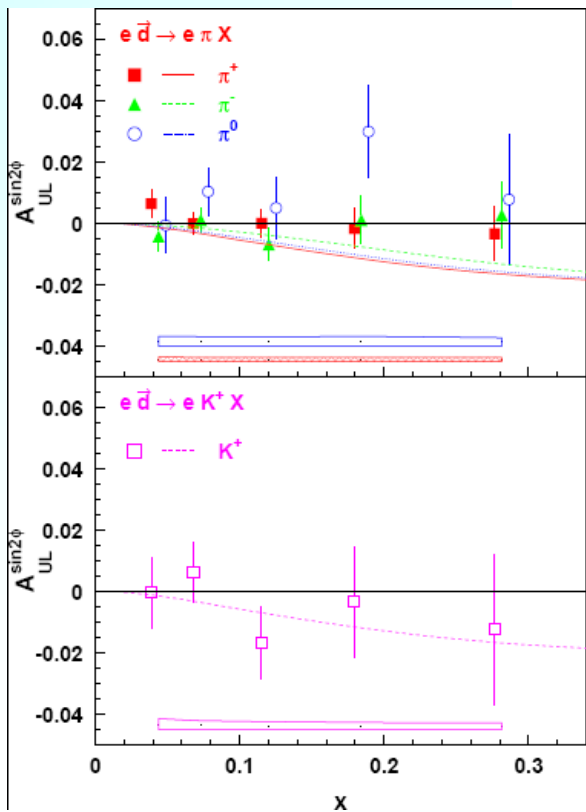
$$A_{UL} \sin 2\phi \propto h_{1L}^\perp \otimes H_1^\perp$$



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

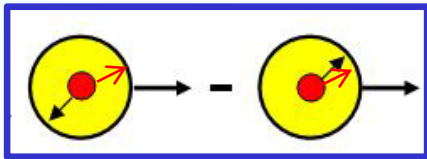
First attempt:

PLB 562 (2003) 182



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

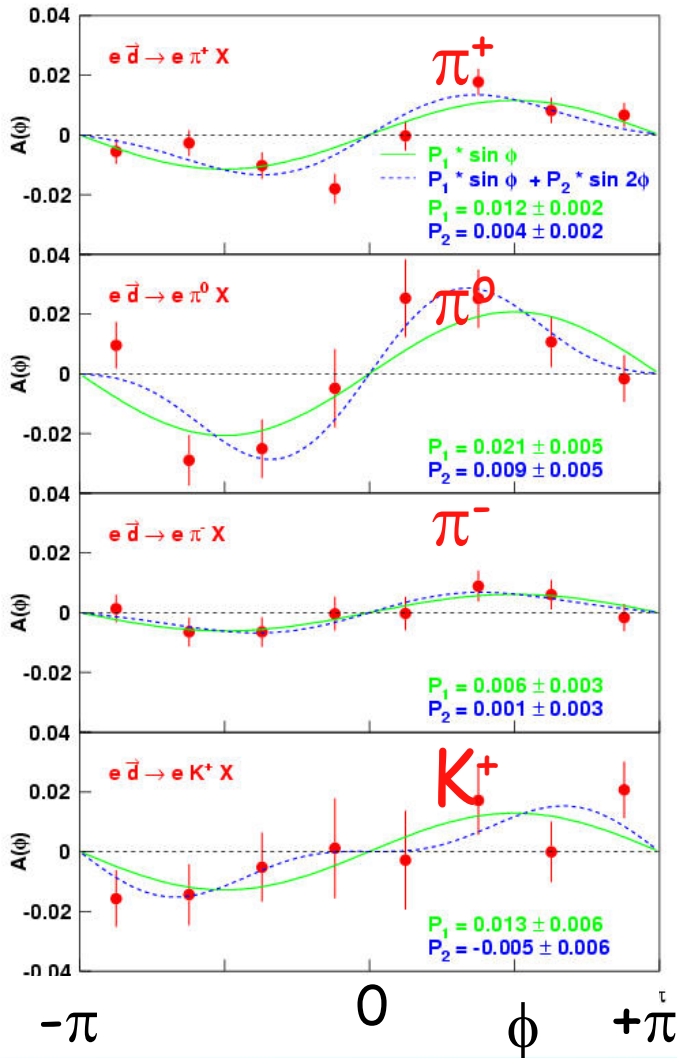
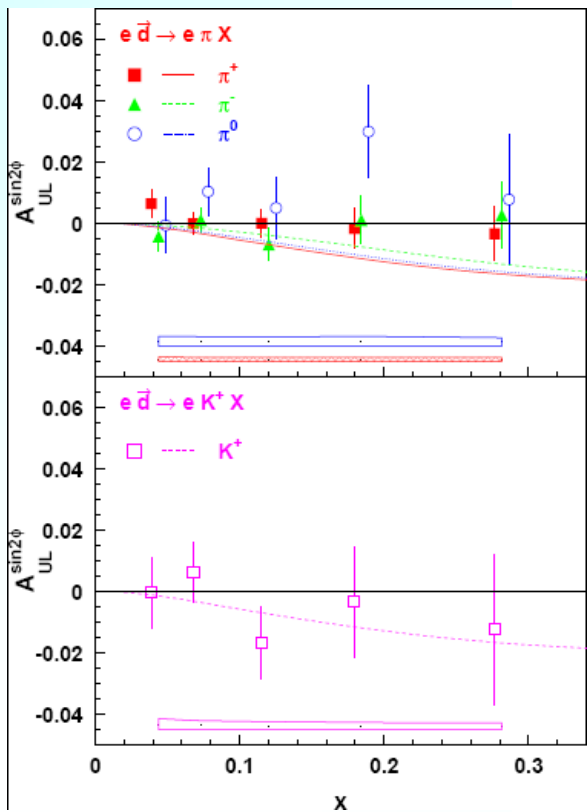
$$A_{UL} \sin 2\phi \propto h_{1L}^\perp \otimes H_1^\perp$$



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

First attempt:

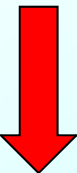
PLB 562 (2003) 182



Recent result from

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

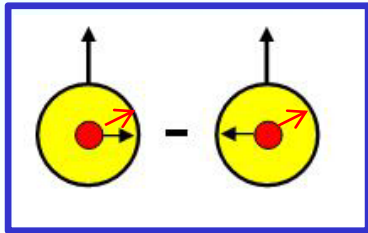
longt. component
 $\sim \sin\theta_{\gamma^*} \langle \sin(2\phi)_{UL} \rangle$



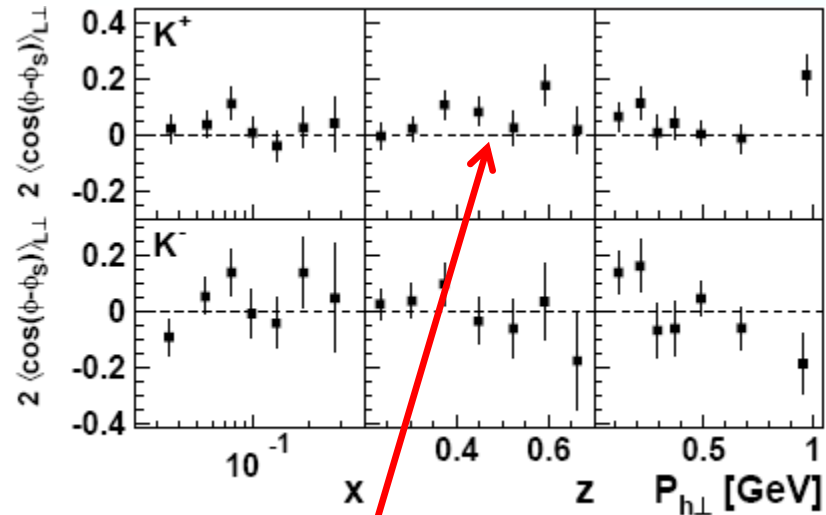
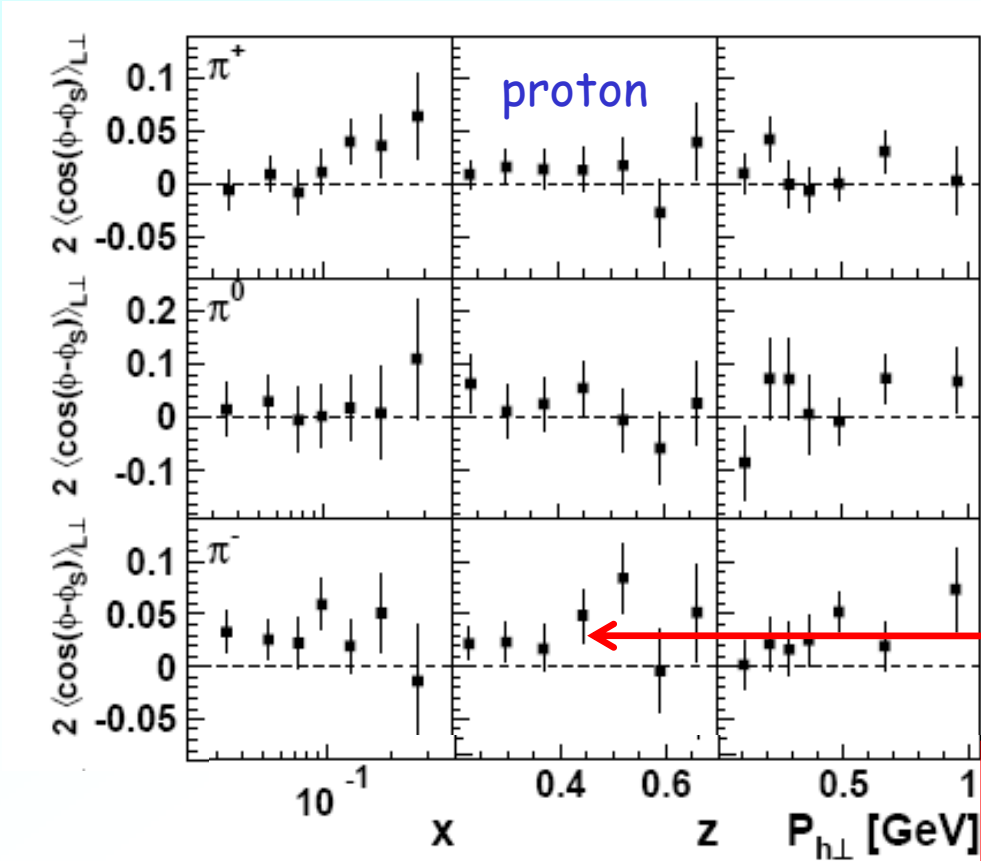
Compatible with zero within uncertainties

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_{1T}^\perp
L		g_1	h_{1L}^\perp
T	f_{1T}^\perp	g_{1T}	h_{1T}^\perp



Slightly non-zero by $> 2\sigma$

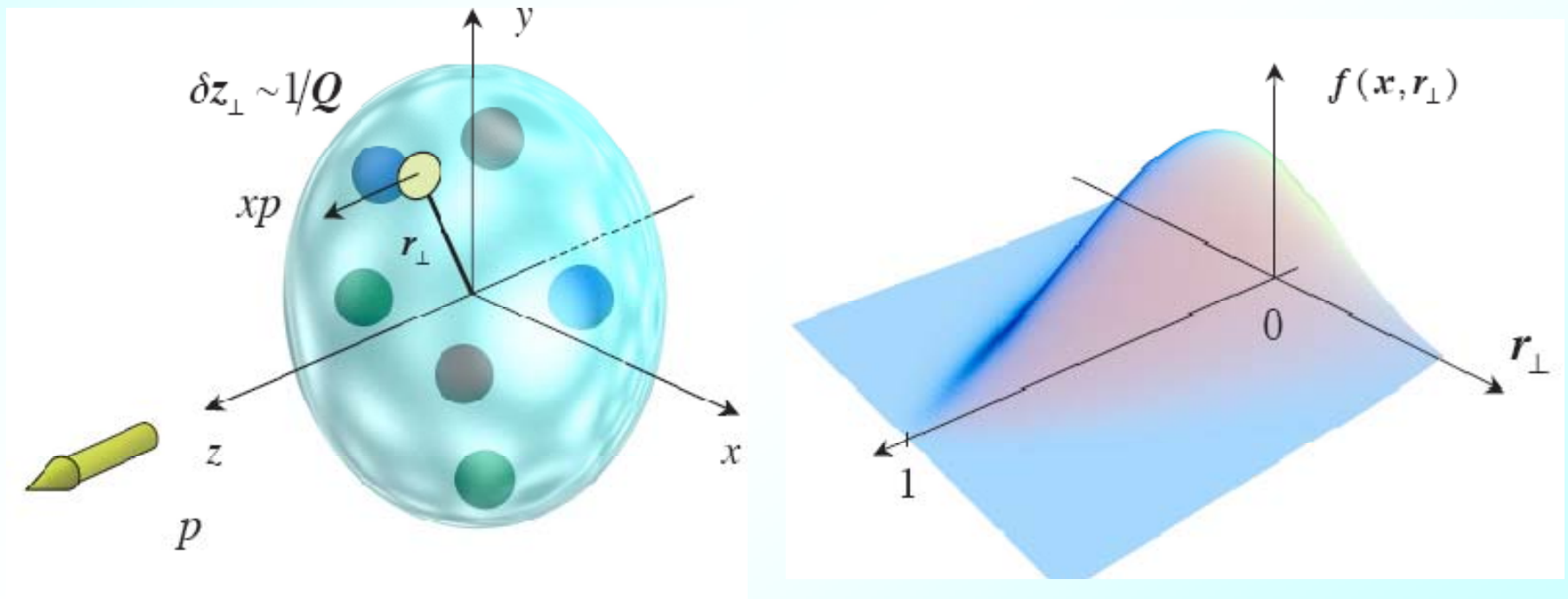
From doctoral thesis M. Diefenthaler
Not yet official HERMES result!!

➔ 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



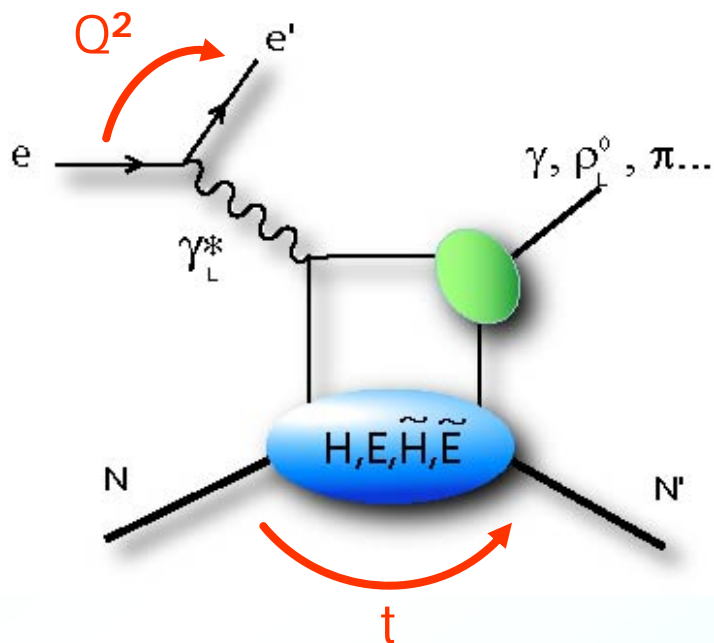
Number density of quarks with longitudinal momentum fraction x at radial position r_{\perp}

Ji relation:

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

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

Access: exclusive processes



Final state sensitive to different GPDs

Spin- $\frac{1}{2}$ target: 4 chiral-even leading-twist quark GPDs

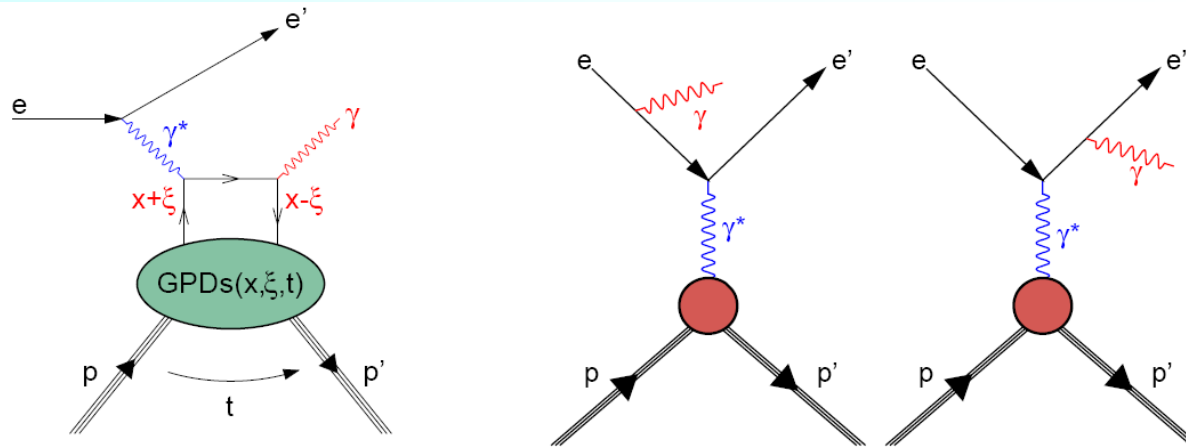
$H, \tilde{H} (E, \tilde{E})$ conserve (flip) nucleon helicity

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 \rightarrow Interference

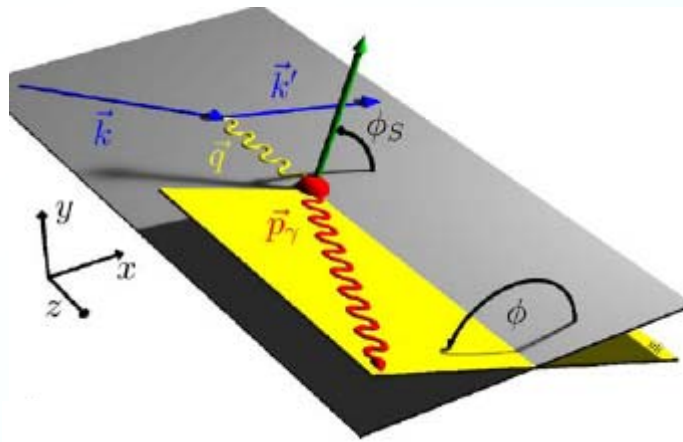
$$\sigma_{ep} \propto |T_{BH}|^2 + |T_{DVCS}|^2 + \underbrace{T_{BH}T_{DVCS}^* + T_{BH}^*T_{DVCS}}_I$$

$$\begin{aligned}
 d\sigma \sim & d\sigma_{UU}^{BH} + e_l d\sigma_{UU}^I + d\sigma_{UU}^{DVCS} \\
 & + e_l P_l d\sigma_{LU}^I + P_l d\sigma_{LU}^{DVCS} \\
 & + e_l S_L d\sigma_{UL}^I + S_L d\sigma_{UL}^{DVCS} \\
 & + e_l S_T d\sigma_{UT}^I + S_T d\sigma_{UT}^{DVCS} \\
 & + P_l S_L d\sigma_{LL}^{BH} + e_l P_l S_L d\sigma_{LL}^I + P_l S_L d\sigma_{LL}^{DVCS} \\
 & + P_l S_T d\sigma_{LT}^{BH} + e_l P_l S_T d\sigma_{LT}^I + P_l S_T d\sigma_{LT}^{DVCS}
 \end{aligned}$$

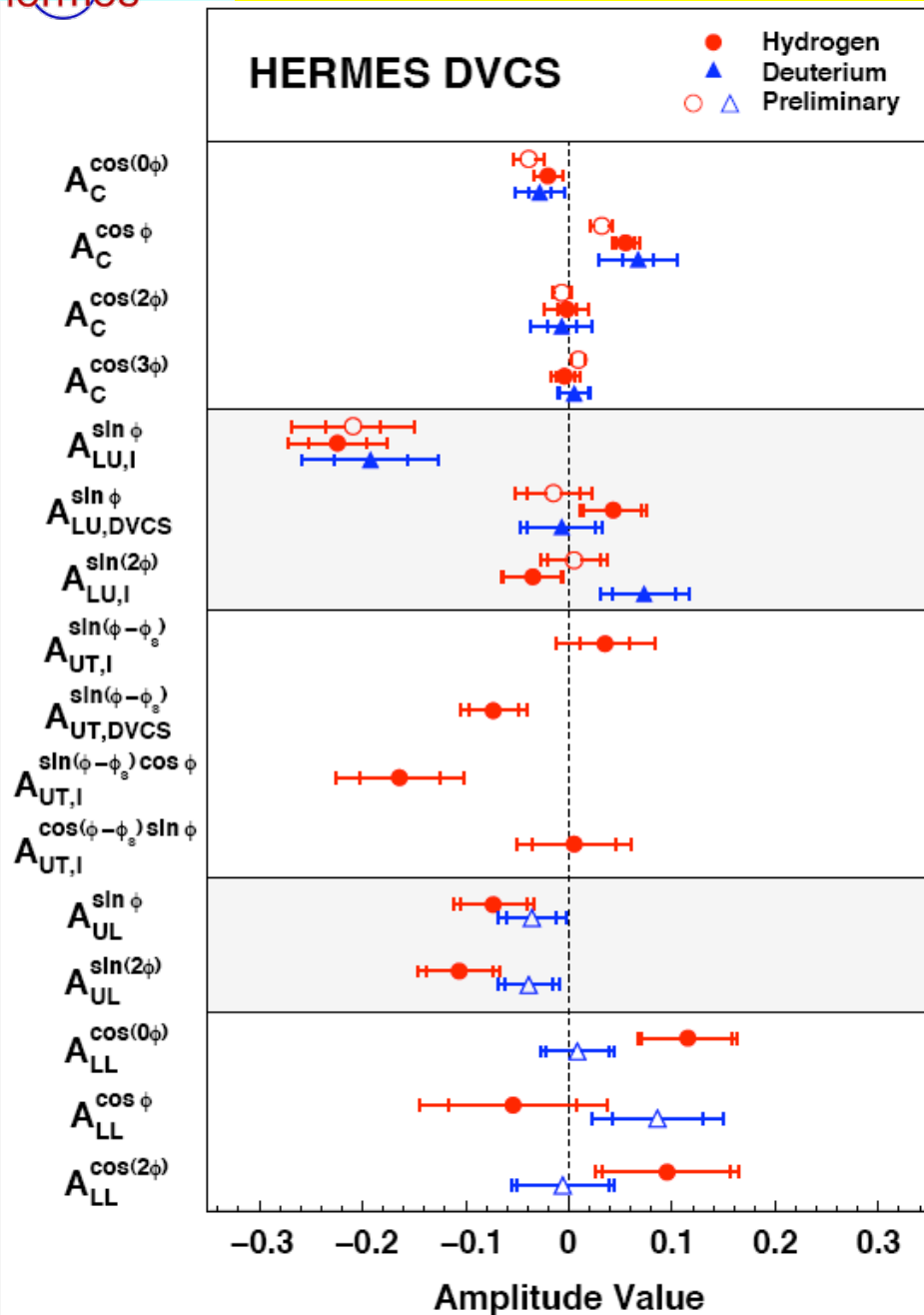
- BH calculable in QED
- $|T_{DVCS}| \ll |T_{BH}|$ @ HERMES
- Access to GPD combinations through azimuthal asymmetries

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

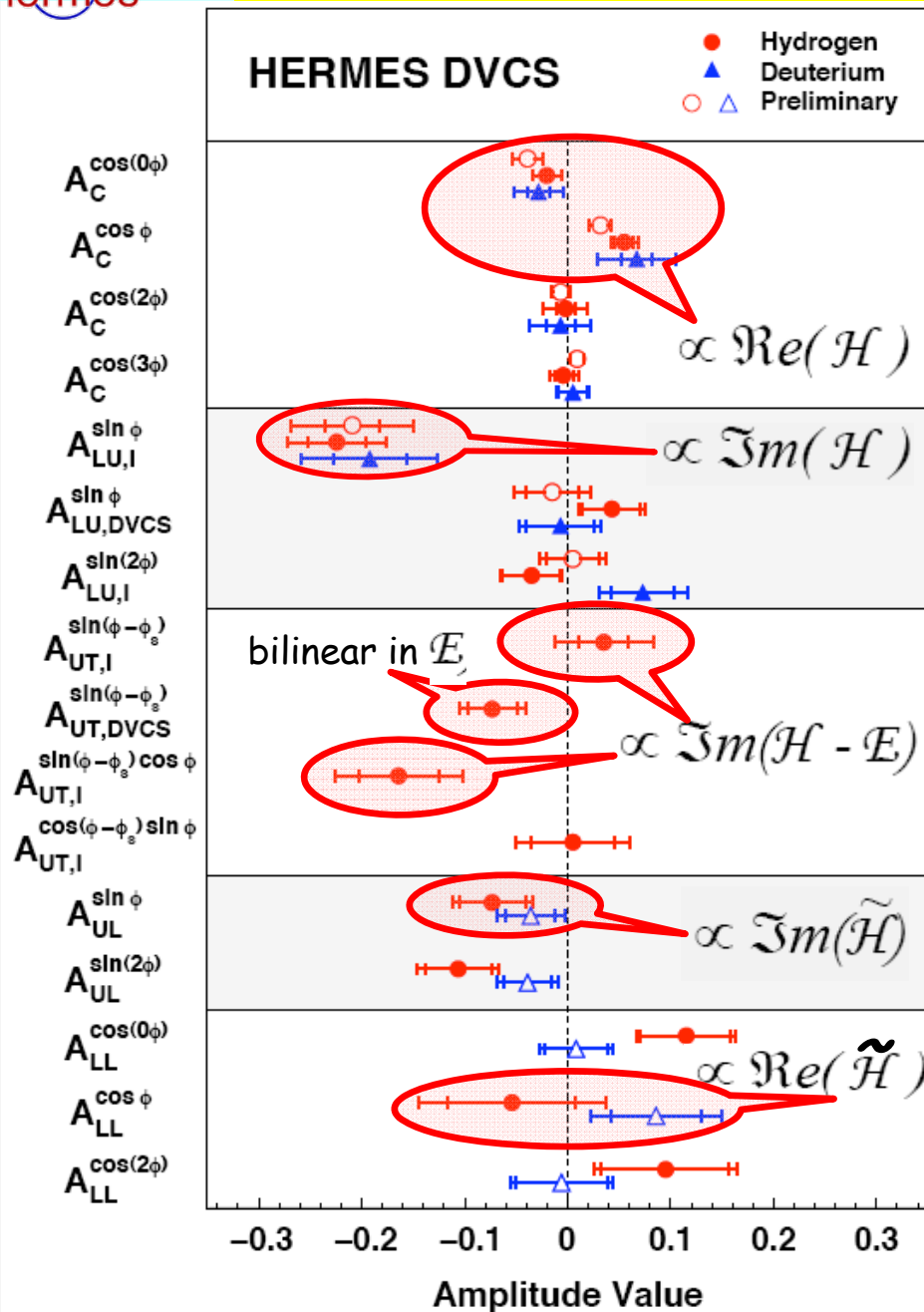
- Both beam charges
- Longitudinal beam polarisation (both helicities)
- Unpolarised H, D and nuclear targets
- Longitudinally polarised H and D targets
- Transversely polarised H target
- Recoil Detector



A_{XY}
 beam target
 polarisation



- 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}



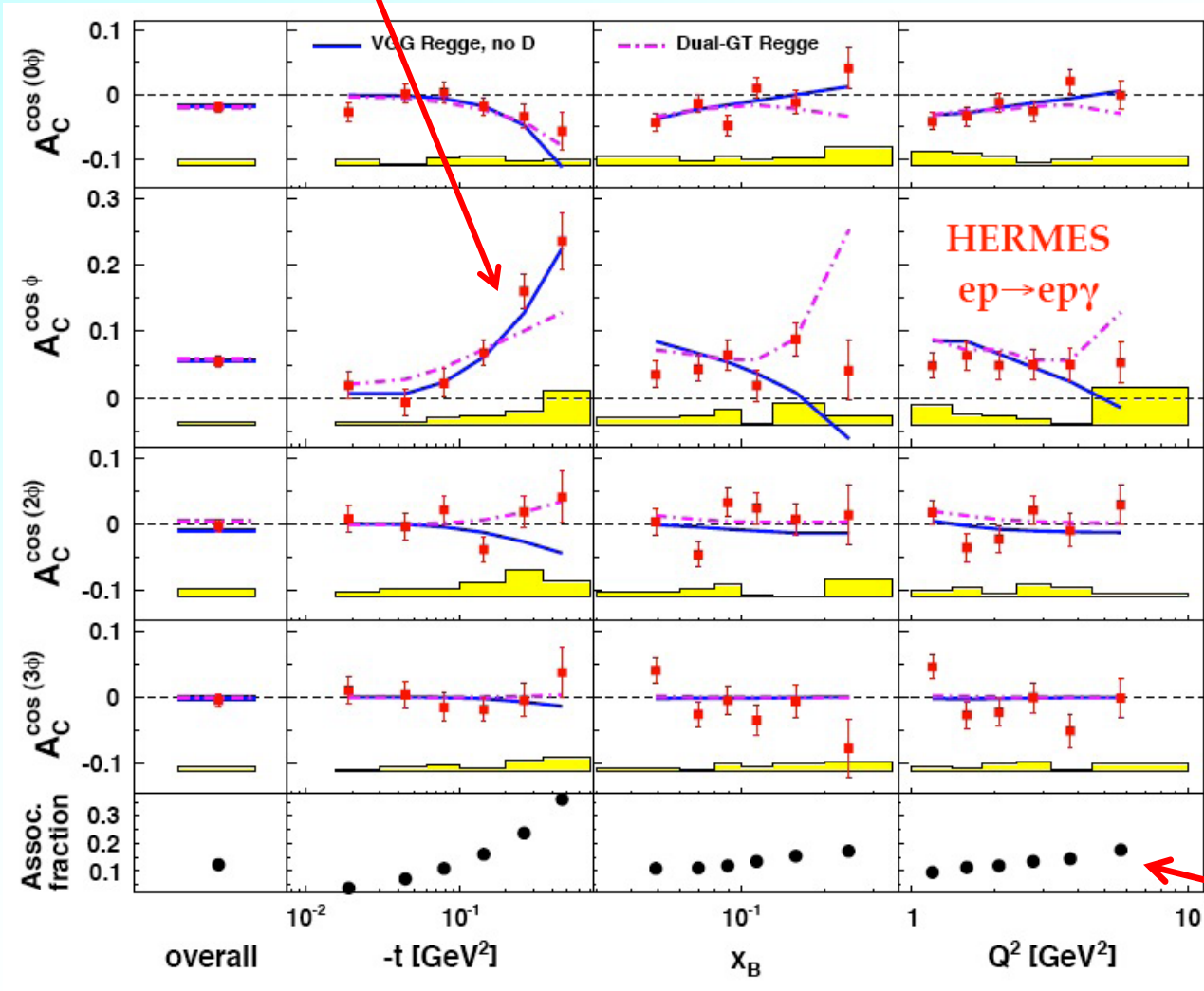
- Beam charge asymmetry
GPD H
H: JHEP 11 (2009) 083
D: Nucl. Phys. B 829 (2010) 1
- Beam helicity asymmetry
GPD H
- Transverse target spin asymmetry
GPD E
H: JHEP 06 (2008) 066
- Longitudinal target spin asymmetry
GPD \tilde{H}
H: JHEP 06 (2010) 019
D: to be published soon
- Longitudinal double spin asymmetry
GPD \tilde{H}



Proton: beam charge asymmetry

Strong t dependence

JHEP 11 (2009) 083



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

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

≈ 0 : twist-3 GPDs

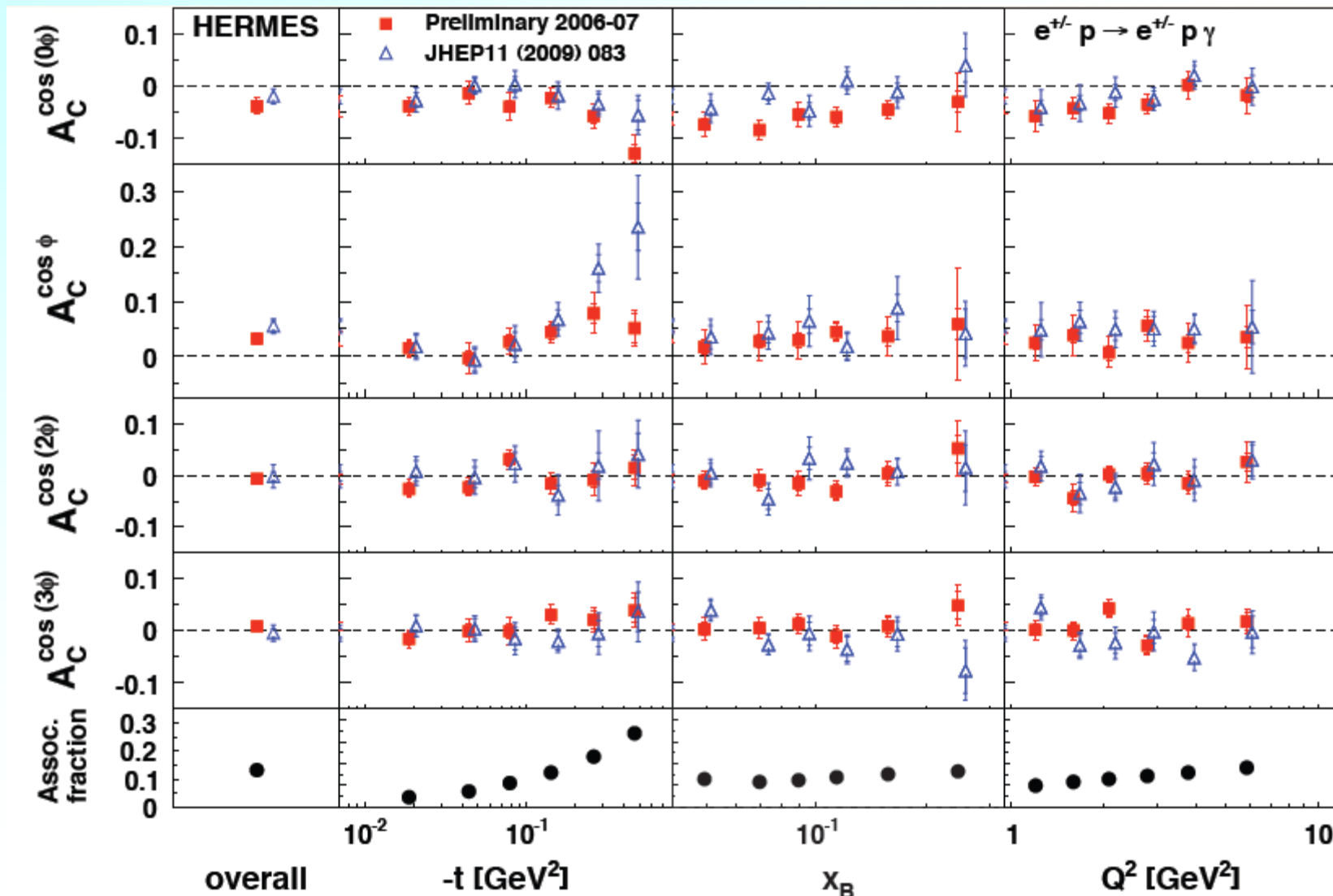
≈ 0 : gluon helicity-flip GPDs

fraction of $ep \rightarrow e'\Delta^+ \gamma$

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

Dual: Phys. Rev D 79 (2009) 017501

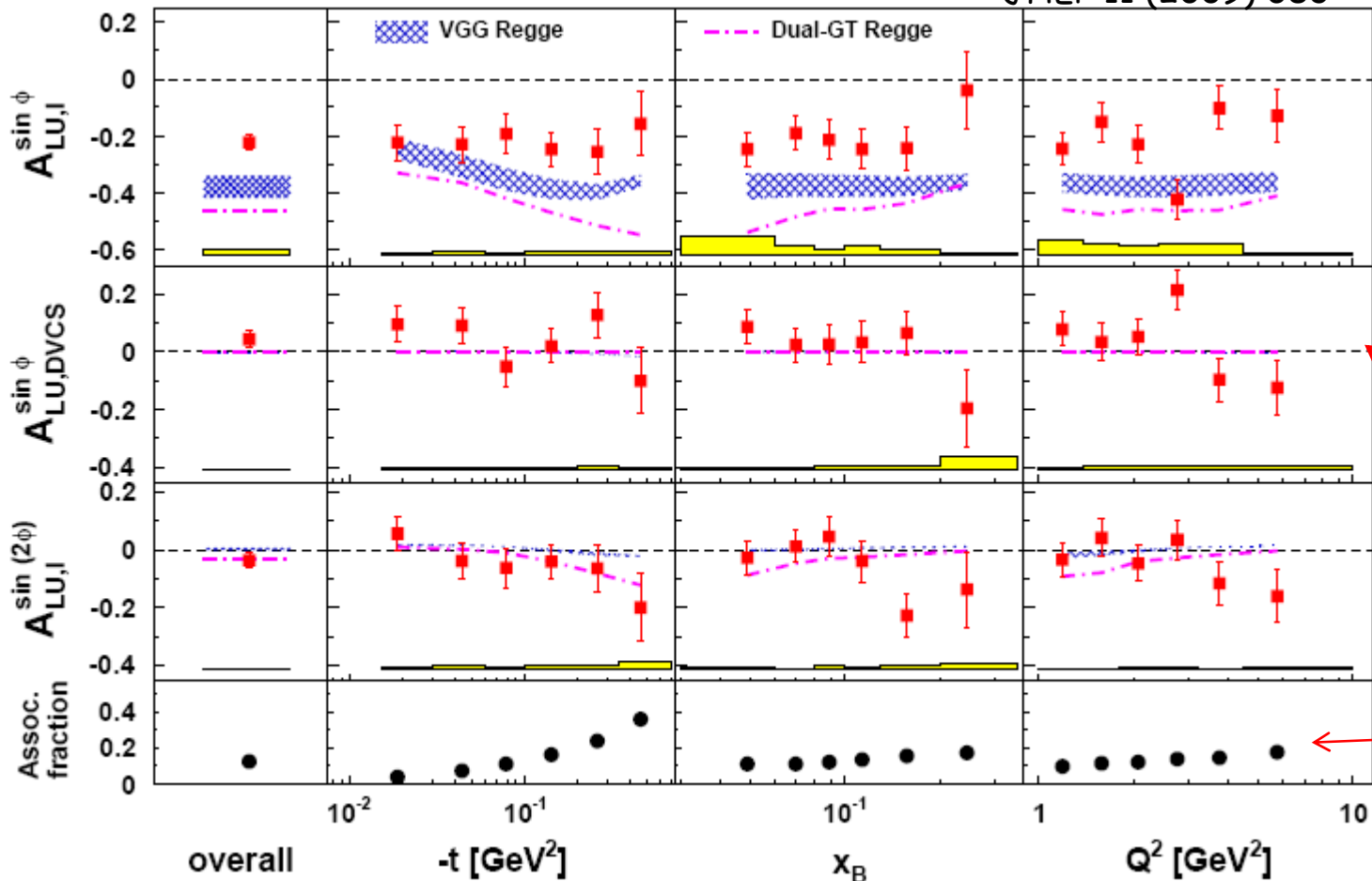
Large 2006/07 data set (1700 pb⁻¹)



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

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

JHEP 11 (2009) 083



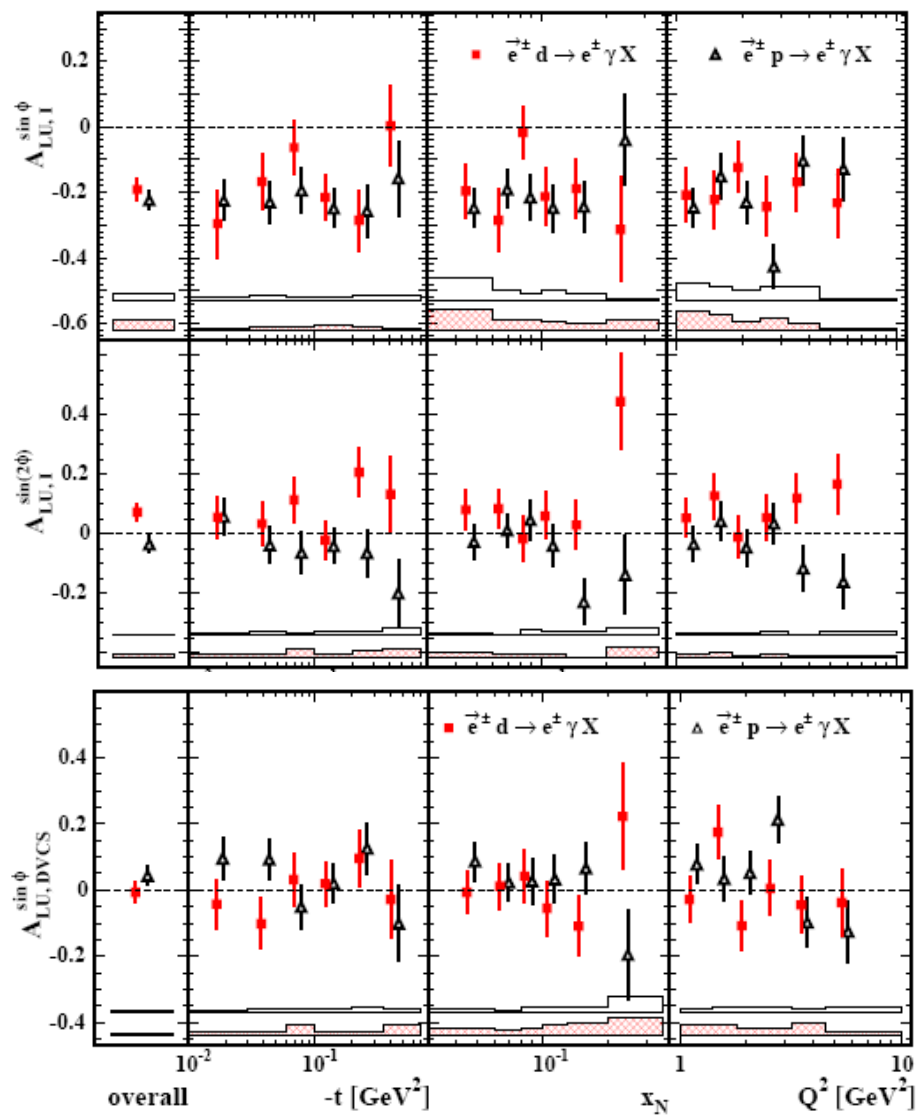
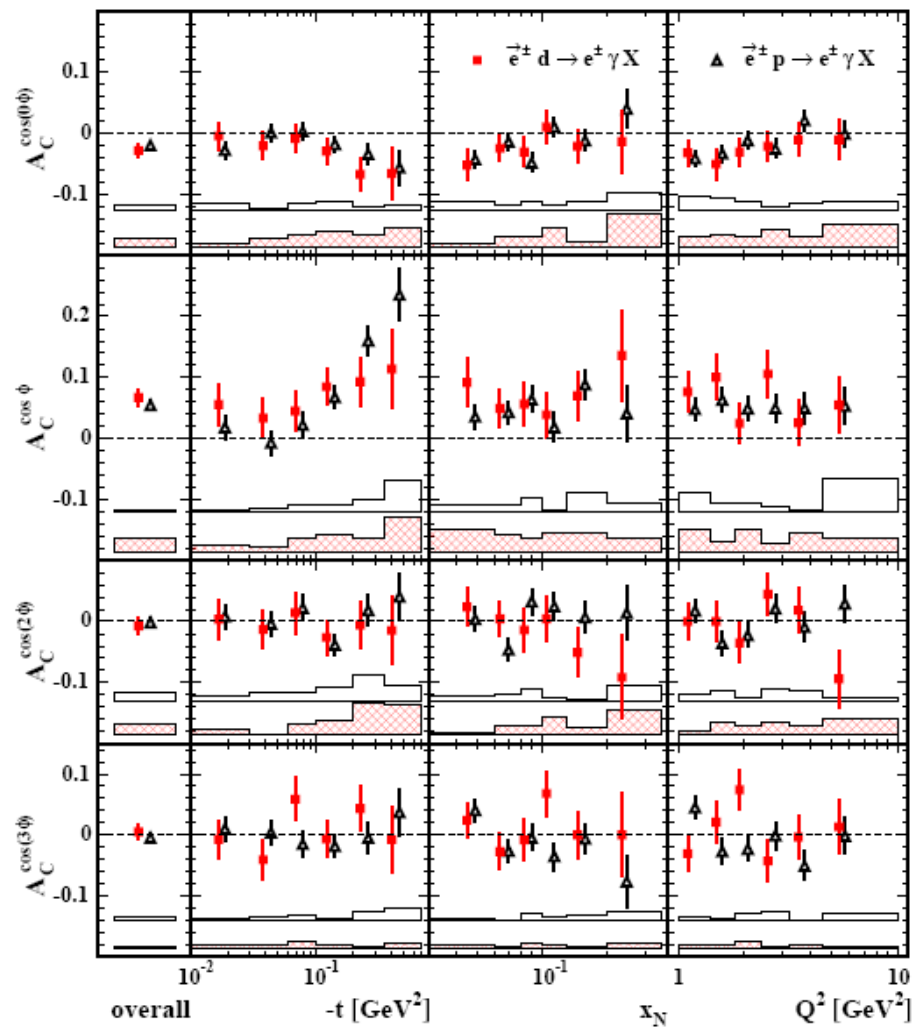
$\propto \Im m[F_1 \mathcal{H}]$

twist-3

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

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

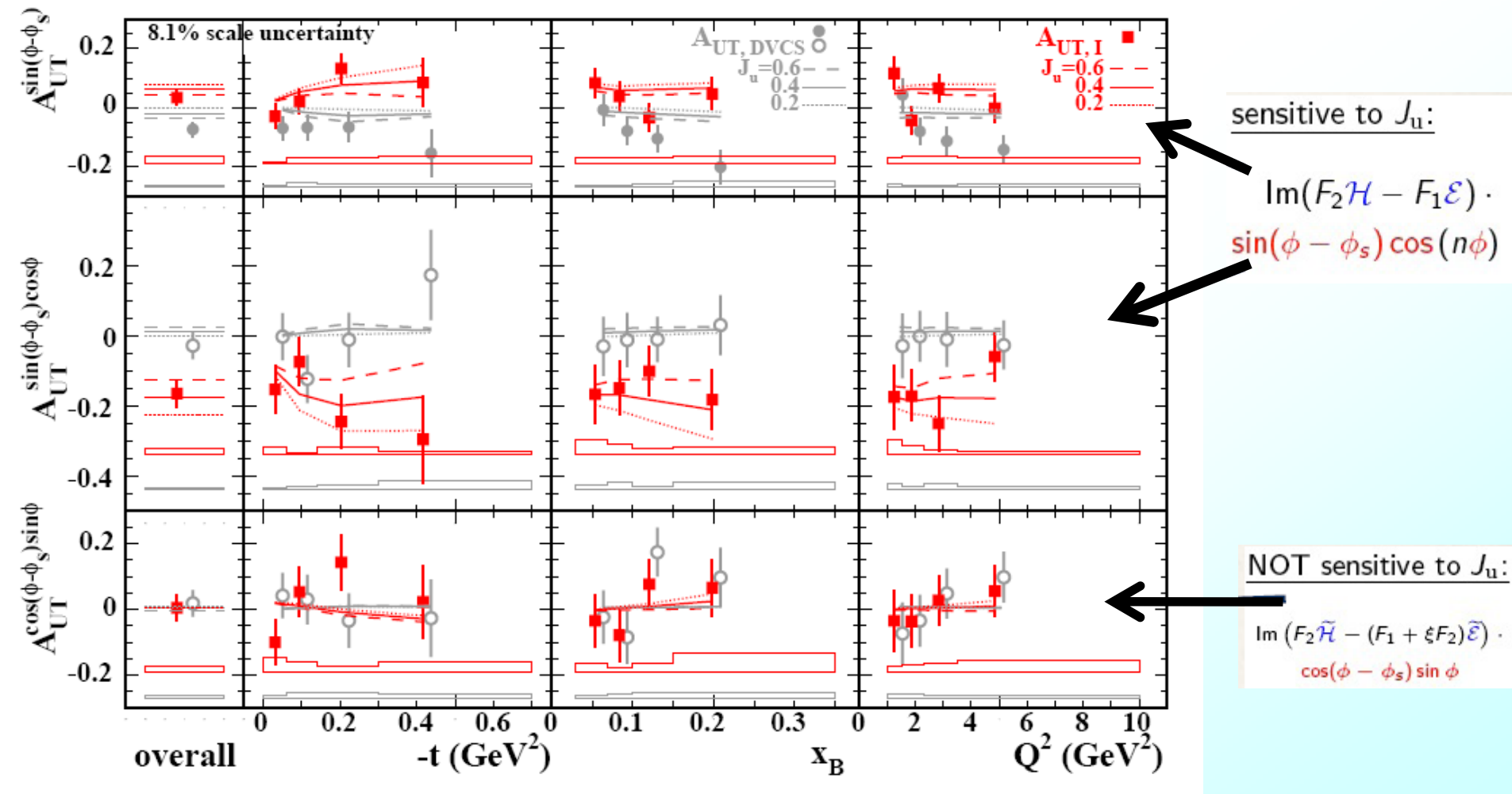
Nucl. Phys. B 829 (2010) 1



Proton and deuteron data are compatible for all leading amplitudes

Sensitive to GPD E

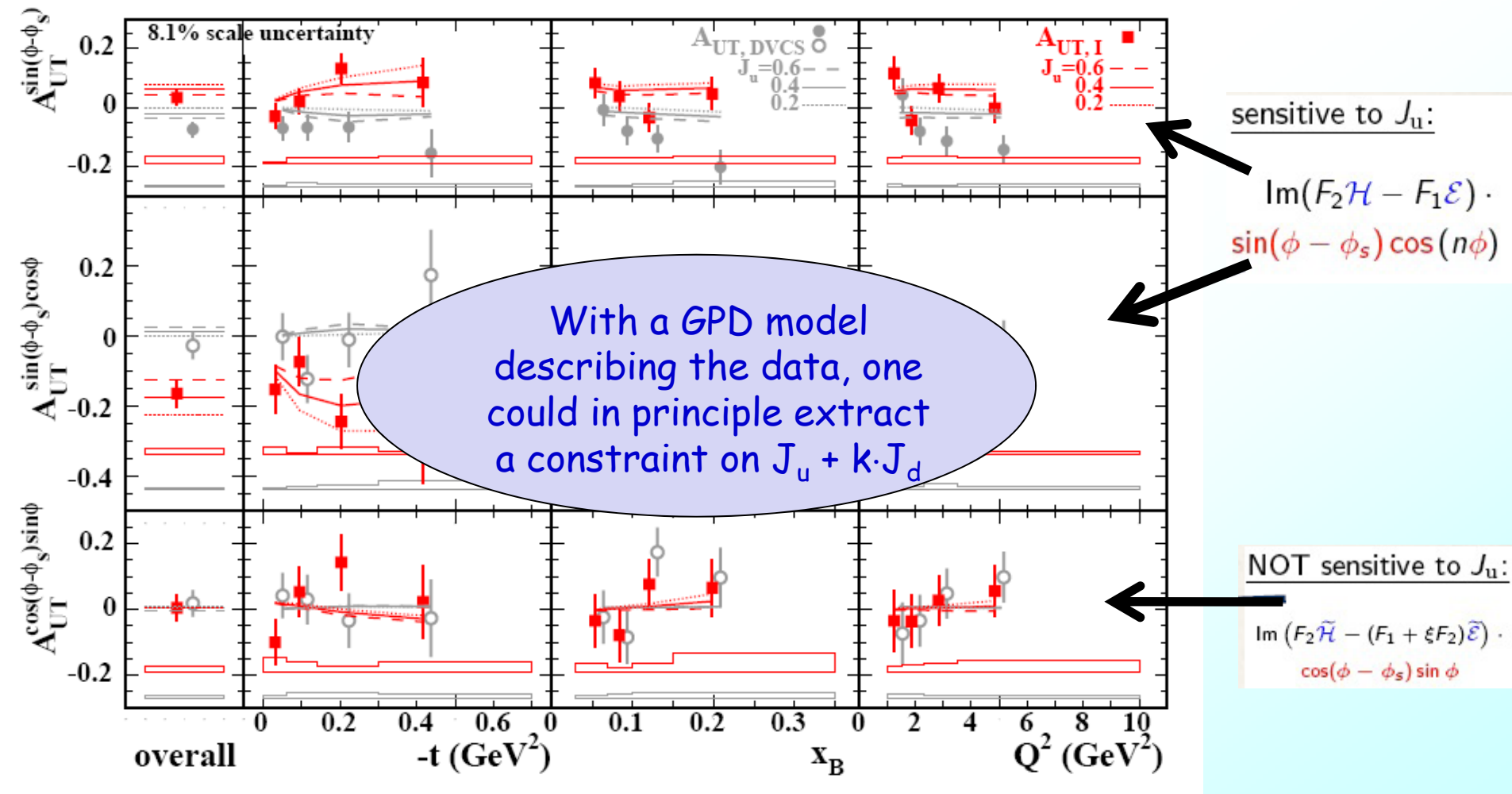
JHEP 06 (2008) 066



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

Sensitive to **GPD E**

JHEP 06 (2008) 066

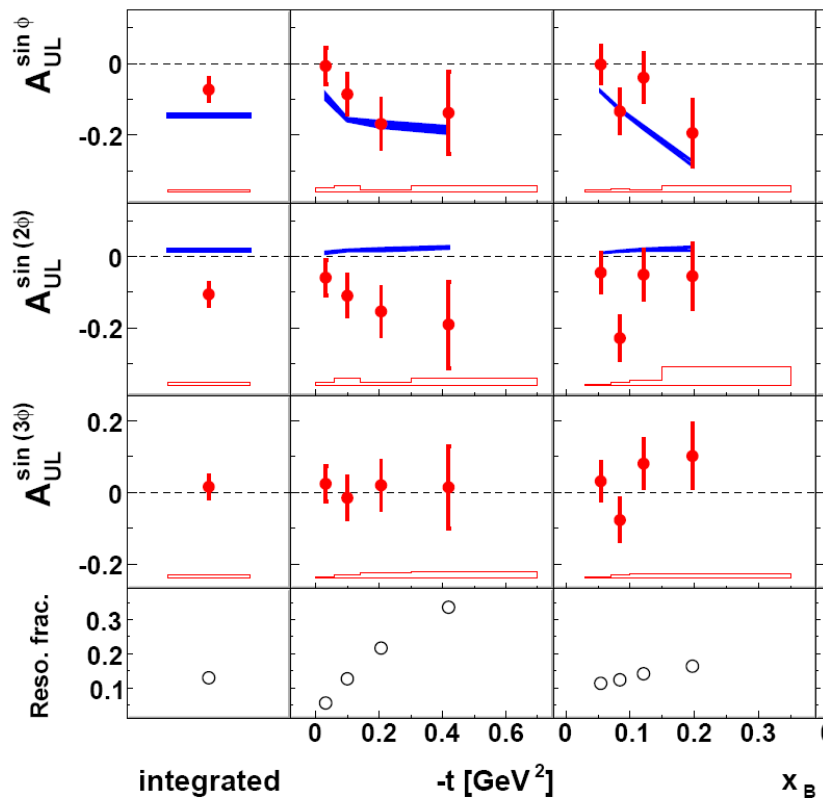


Model: VGG with variation of J_u , while $J_d=0$

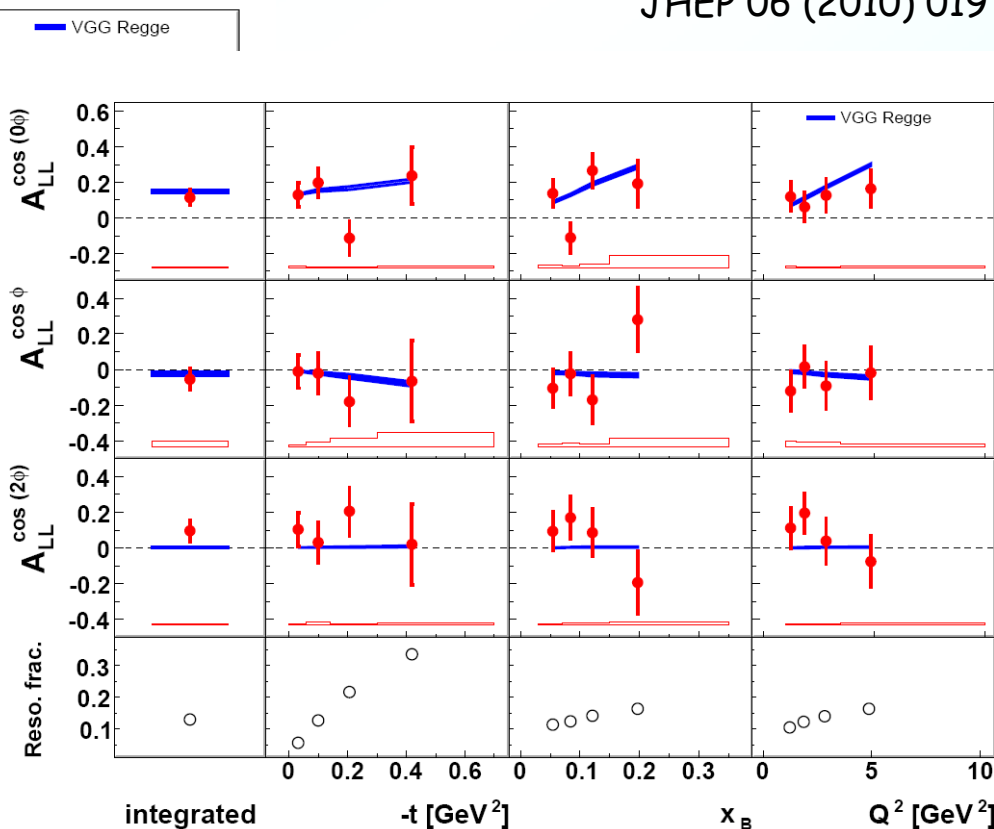
Long. target-spin asymmetry

Double-spin asymmetry

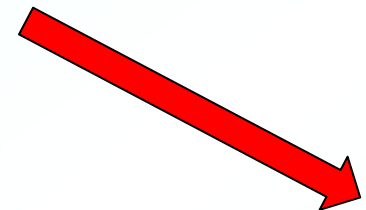
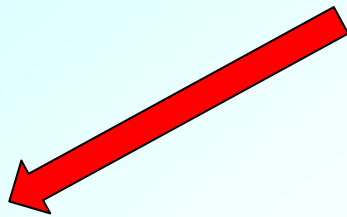
JHEP 06 (2010) 019



$$\propto \text{Im}(\tilde{H})$$



$$\propto \text{Re}(\tilde{H})$$



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