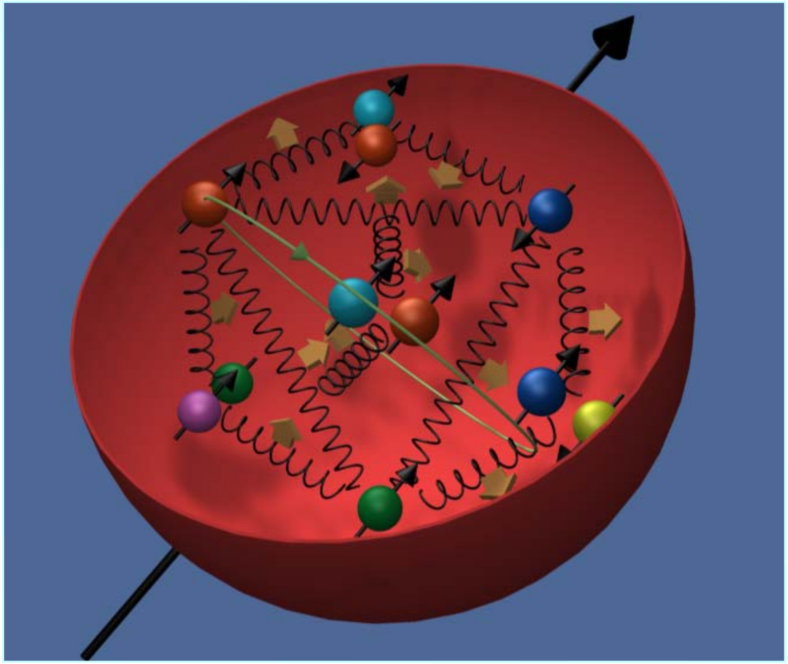
Selected Recent hermes Results on Parton Distribution and Fragmentation Functions

Klaus Rith

University of Erlangen-Nürnberg & DESY



Main HERMES research topics:

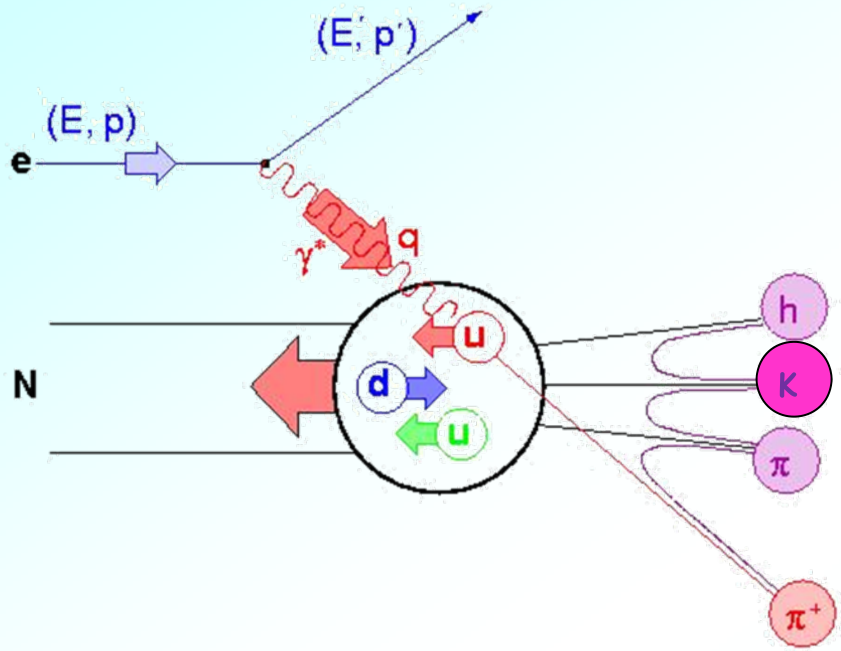
- Origin of nucleon spin
- Details of nucleon structure

HERMES Experiment

27.5 GeV e^+/e^- beam of HERA

transversely/longitudinally polarized as well as unpolarized internal gas targets
(H, D, He, N, …, Xe)

(Semi-)Inclusive Deep-Inelastic Scattering



$$Q^2 \overset{lab}{=} 4EE' \sin^2(\theta/2)$$

$$\nu \overset{lab}{=} E - E'$$

$$W^2 \overset{lab}{=} M^2 + 2M\nu - Q^2$$

$$x \overset{lab}{=} Q^2/2M\nu$$

$$y \overset{lab}{=} \nu/E$$

$$z \overset{lab}{=} E_h/\nu$$

Factorisation ⇒ $\sigma^{eN\to ehX} = \sum_q DF^{N\to q} \otimes \sigma^{eq\to eq} \otimes FF^{q\to h}$

DF(x,Q^2): Parton Distribution Function – $q(x,Q^2)$, $\Delta q(x,Q^2)$, $\delta q(x,Q^2)$...

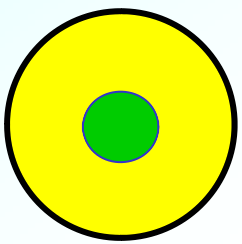
FF(z,Q^2): Fragmentation Function – $D_1(z,Q^2)$, $H_1^{\perp}(z,Q^2)$, ...

Leading-twist Parton Distributions

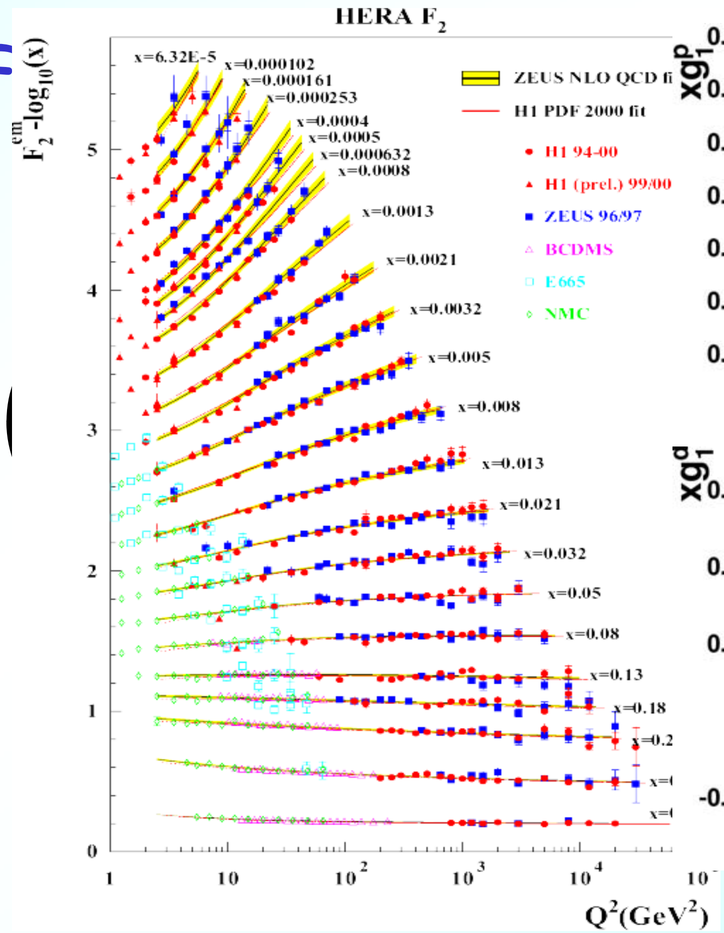
Complete description of nucleon by quark momentum and spin distributions at leading-twist: 3 k_T-integrated distribution functions

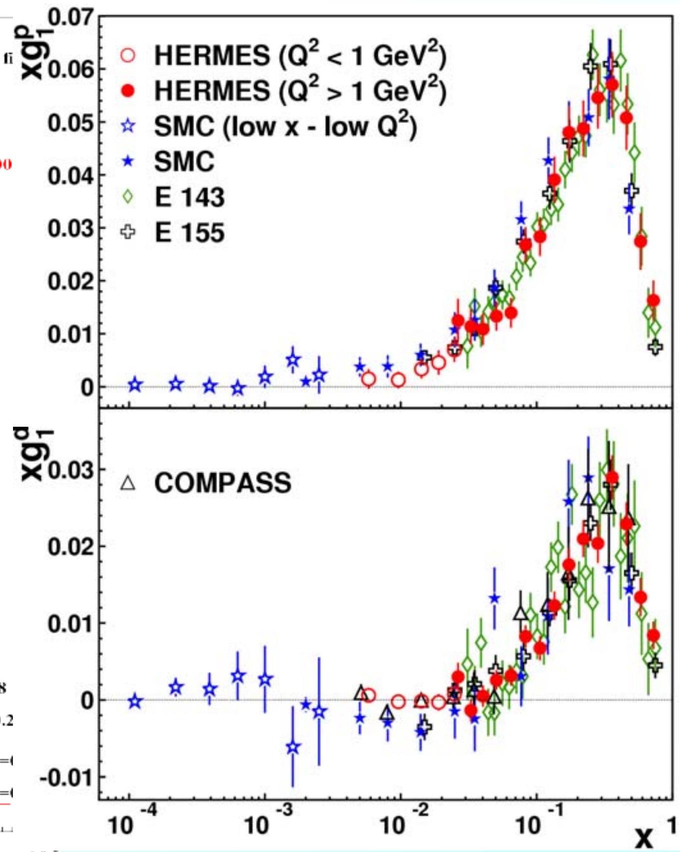
Unpolarised DF

$$q(x) \equiv f_1^q(x)$$



well known





Transverse Momentum Dependent DFs

Quark distribution functions

Mulders and Tangerman,
Nucl. Phys. B 461 (1996) 197

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

Boer-Mulders DF

(chiral-odd)

Transversity DF

(chiral-odd)

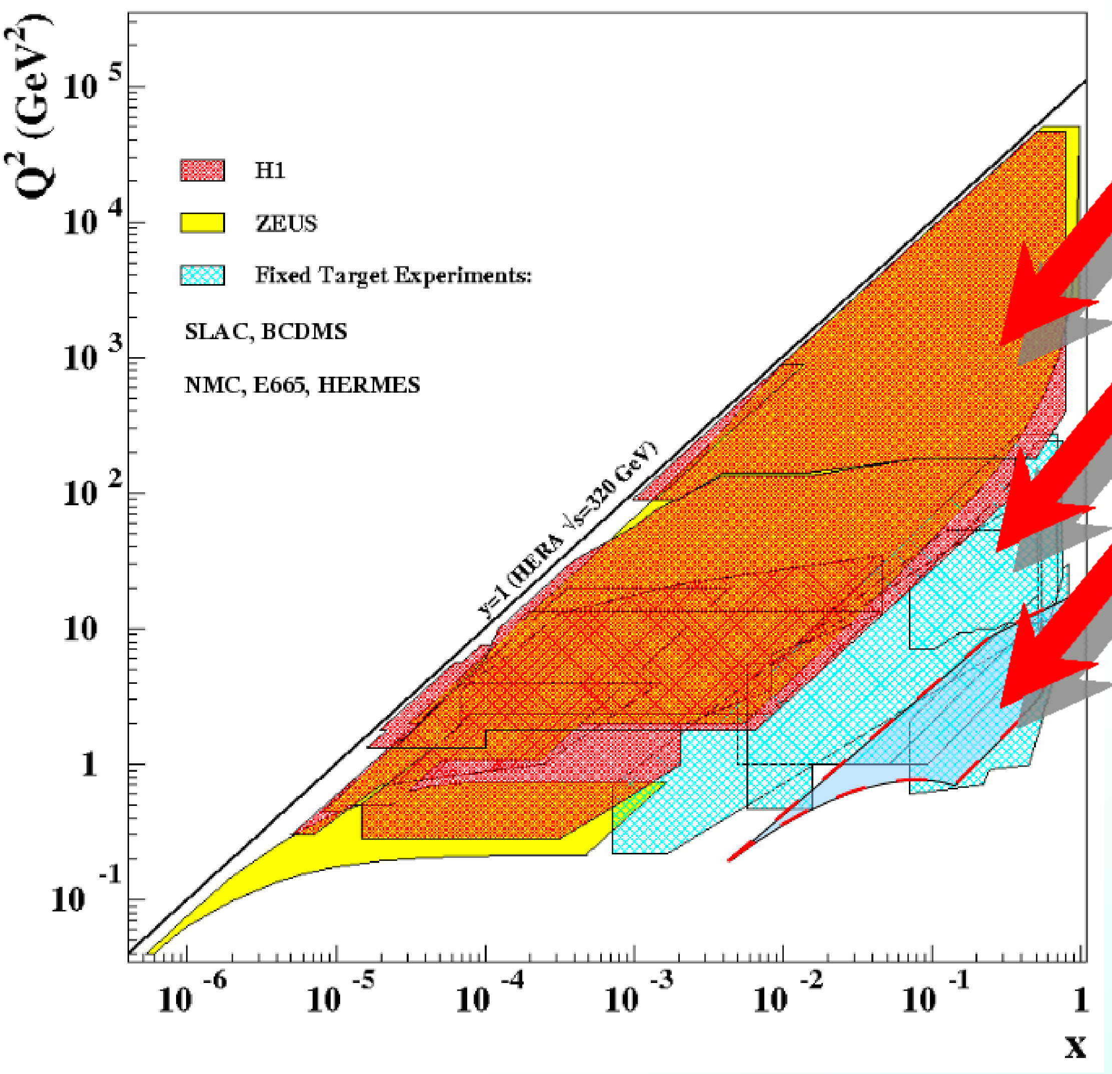
Sivers DF (T-odd)

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 (chiral-odd)

Unpolarised Structure Function F_2

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



Collider experiments

Fixed target experiments

HERMES

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

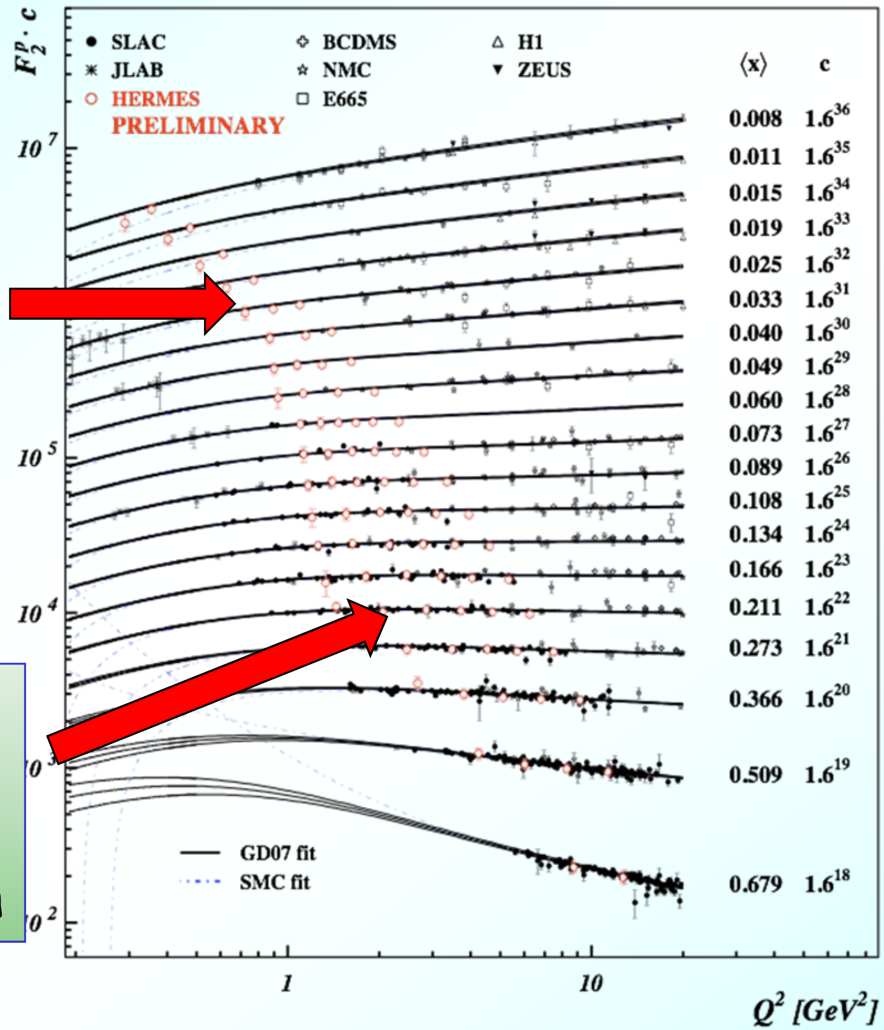
Unpolarised Structure Function F_2

$$d^2\sigma/dQ^2dx = f\{F_2(x,Q^2),\ F_1(x,Q^2)\}$$

$$F_2(x,Q^2) = \sum_q e_q^2\ x\ q(x,Q^2)$$

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 $h_{1T}^\perp$

proton



New region covered by HERMES

Agreement with world data in the overlap region

Comparison with parameterisation by GD07 and SMC

GD07: hep-ph0708.3196
SMC: Phys. Rev. D, Vol. 58, 112001

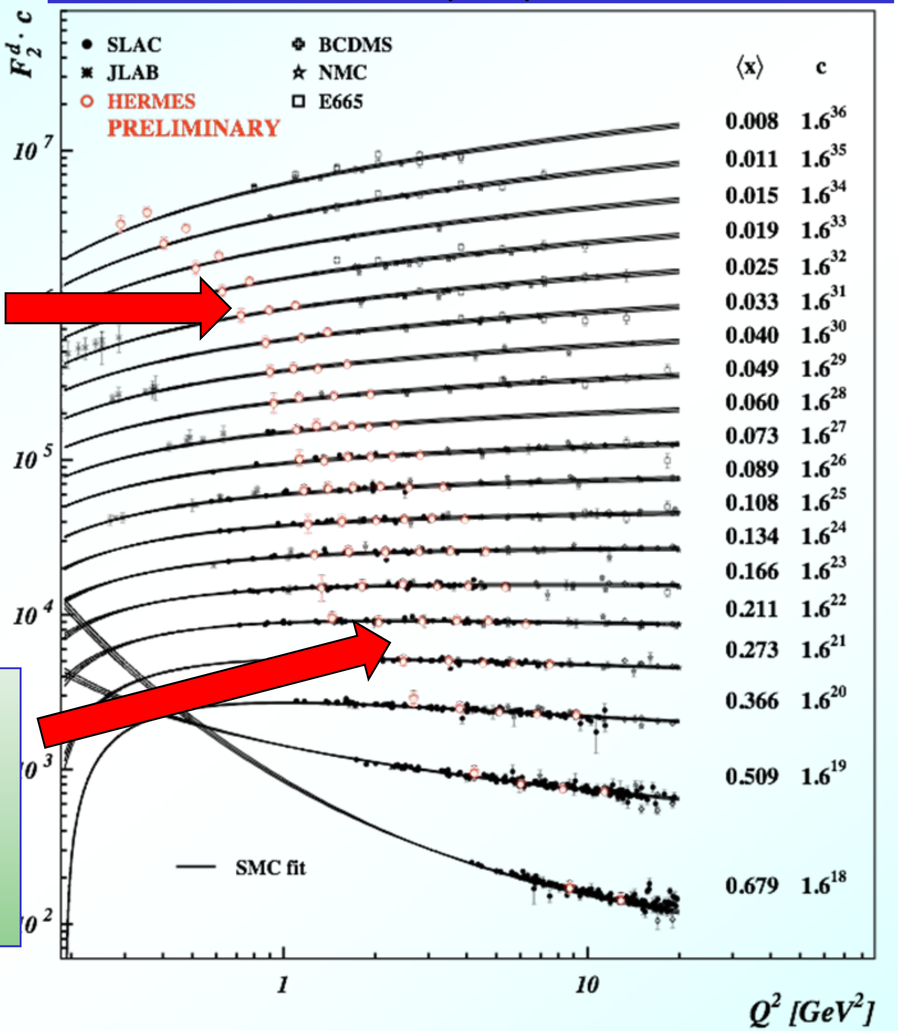
Unpolarised Structure Function F_2

$$d^2\sigma/dQ^2dx = f\,\{F_2(x,Q^2),\, F_1(x,Q^2)\}$$

$$F_2(x,Q^2) = \sum_q e_q^2\, x\, q(x,Q^2)$$

N/q	U	L	T
U	f_1		h_1
L		g_1	h_{1L}
T	f_{1T}	g_{1T}	h_1 h_{1T}

deuteron



New region covered by HERMES

Agreement with world data in the overlap region

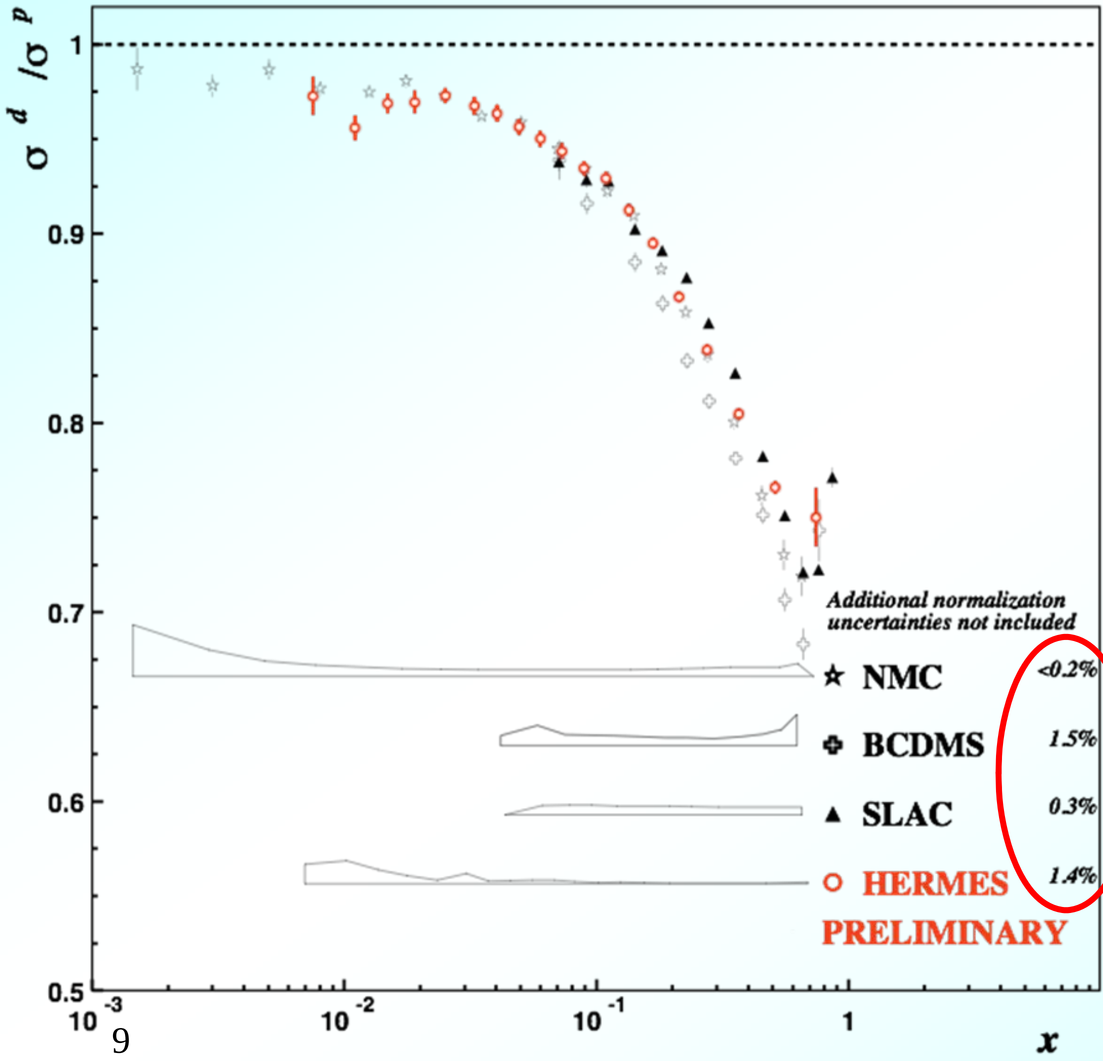
Comparison with parameterisation by SMC

SMC: Phys. Rev. D, Vol. 58, 112001

Unpolarised Structure Function F_2

$$\sigma^d/\sigma^p \cong (1 + F_2^n/F_2^p)/2$$

N/q	U	L	T
U	f_1		h_1
L		g_1	h_{1L}
T	f_{1T}	g_{1T}	h_1 h_{1T}



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

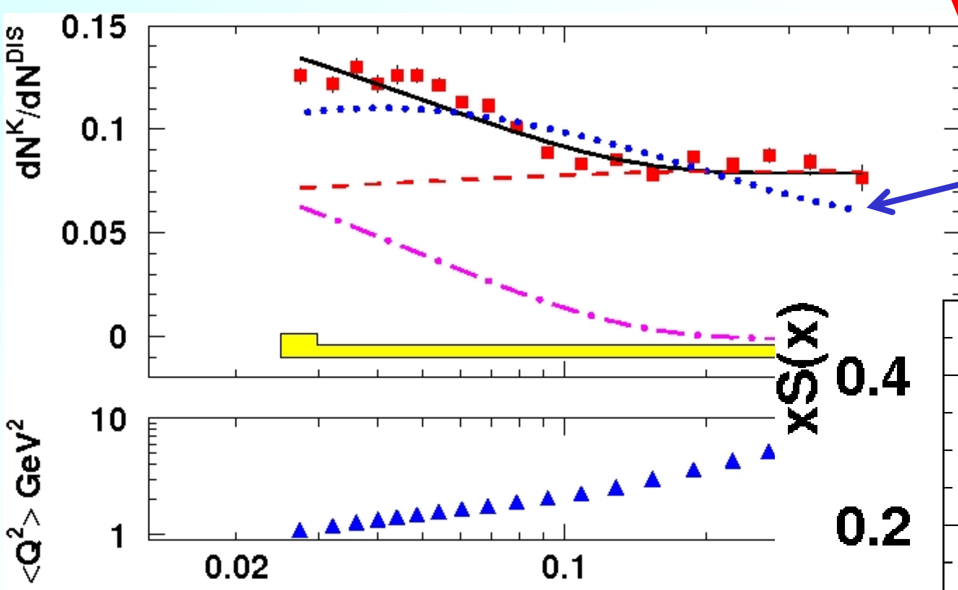
Normalization uncertainties

S(x) from Kaon Multiplicities

$$\frac{dN^{K\pm}}{dN^{DIS}} = \frac{Q(x)\int D_Q^K(z)dz + S(x)\int D_S^K(z)dz}{5\,Q(x) + 2\,S(x)} \xrightarrow{x>0.3} \frac{\int D_Q^K(z)dz}{5}$$

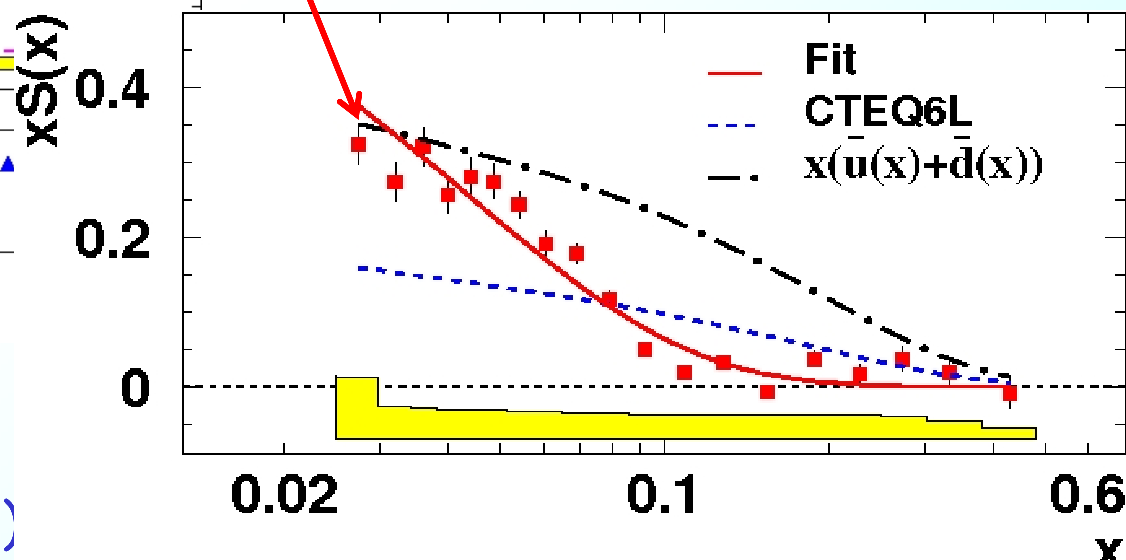
$Q(x) = u(x)+\bar{u}(x)+d(x)+\bar{d}(x)$; $S(x) = s(x) + \bar{s}(x)$

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 $h_{1T}^\perp$



- S(x) from CTEQ6L with $\int D_Q^K(z)dz$ & $\int D_S^K(z)dz$ as free parameters (dotted) does not fit the data

P.L. B666 (2008) 466



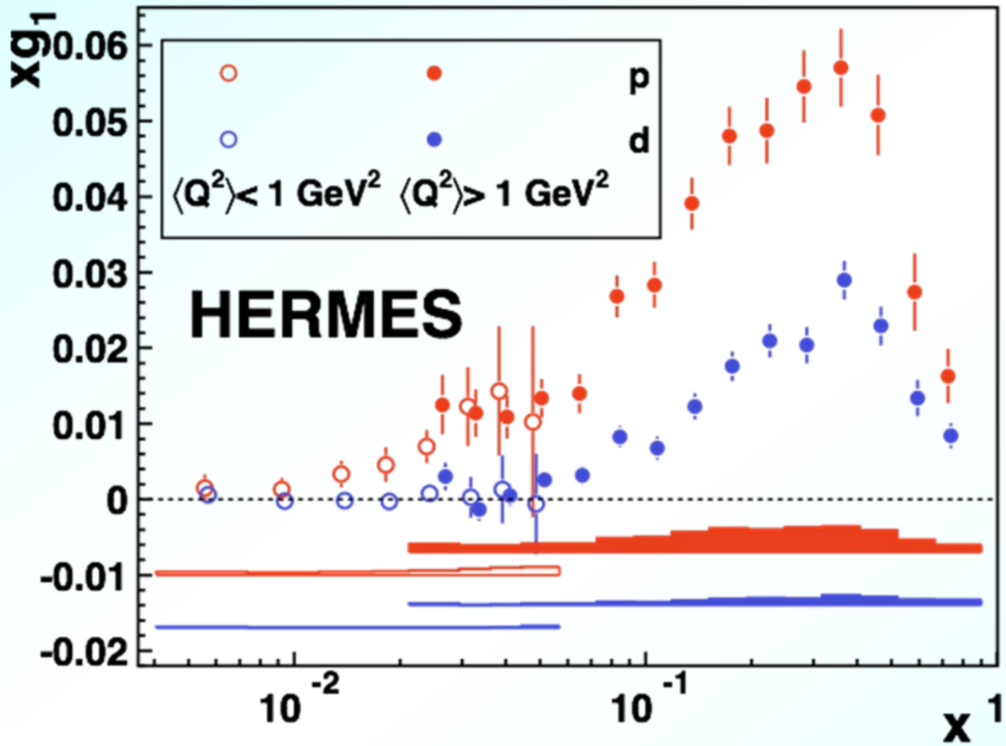
- S(x) much softer than assumed by current PDFs (mainly based on $\overset{(-)}{\nu}N\to\mu^+\mu^-X$)

Take $\int D_S^K(z)dz = 1.27 \pm 0.13$ from de Florian et al.

Polarised Structure Function $g_1(x)$

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

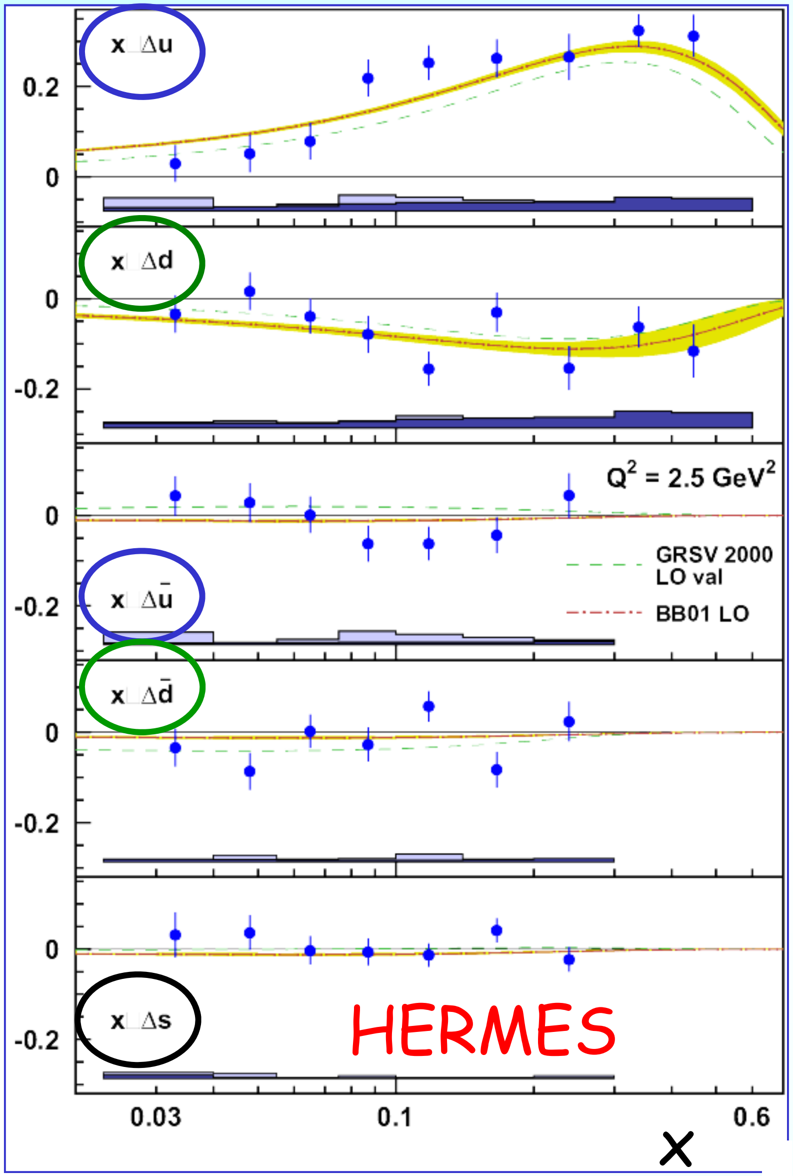
P. R. D 75 (2007) 012007



$$\Delta\Sigma^{\overline{MS}} = 0{,}330 \pm 0{,}025_{(exp)} \pm 0{,}011_{(theory)} \pm 0{,}028_{(evol.)}$$

Quark Helicity Distributions $\Delta q(x)$

PRD 71 (2005) 012003

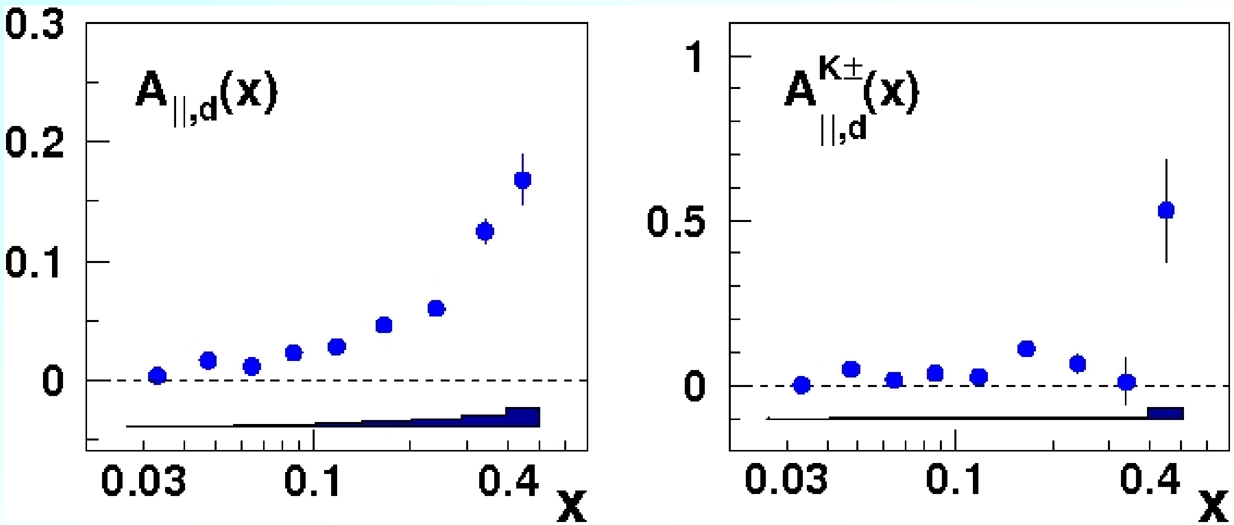


N/q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

$$A_{LL}(x,z) \cong \frac{\sum_q e_q^2 \Delta q(x)\, D_q^h(z)}{\sum_q e_q^2\, q(x)\, D_q^h(z)}$$

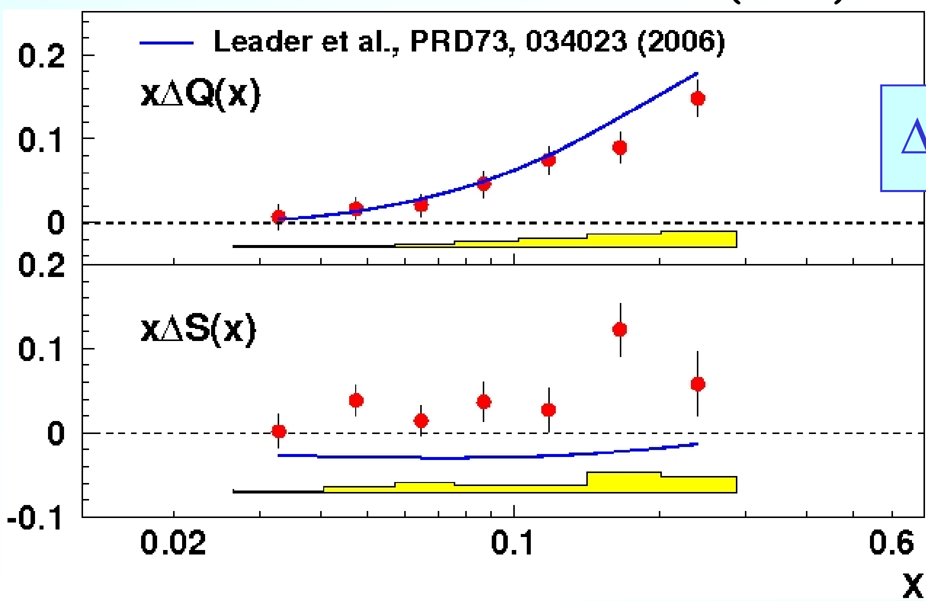
- u quarks: large positive polarisation
- d quarks: negative polarisation
- Sea quarks ($\bar{u}$, $\bar{d}$, s): polarisation compatible with 0.

$\Delta S(x)$ from Kaon Asymmetries



N/q	U	L	T
U	f_1		h_1
L		g_1	h_{1L}
T	f_{1T}	g_{1T}	h_1 h_{1T}

P.L. B666 (2008) 466



$\Delta S = 0.037 \pm 0.019(\text{stat.}) \pm 0.027(\text{syst.})$

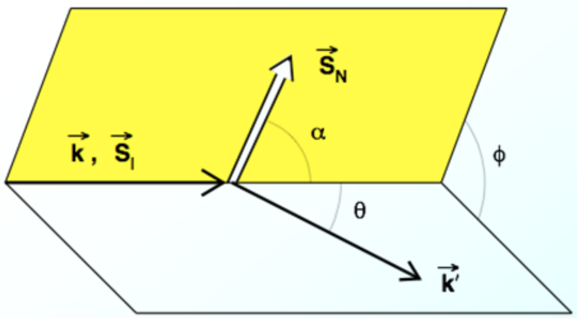
compared to

$\Delta S = -0.085 \pm 0.013(\text{stat.}) \pm 0.012(\text{syst.})$
from inclusive data and SU(3)

Large negative contribution from low x?

A_2 and g_2

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 $h_{1T}^\perp$



$$\frac{\sigma^{\rightarrow\Downarrow} - \sigma^{\rightarrow\Uparrow}}{\sigma^{\rightarrow\Downarrow} + \sigma^{\rightarrow\Uparrow}} = \frac{-\Delta\sigma_T^{\rightarrow\Downarrow} + \Delta\sigma_T^{\rightarrow\Uparrow}}{2\overline{\sigma} - \Delta\sigma_T^{\rightarrow\Downarrow} - \Delta\sigma_T^{\rightarrow\Uparrow}} = \frac{\Delta\sigma_T}{\overline{\sigma}} =$$

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

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

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

QPM:

$g_2(x,Q^2) = 0$

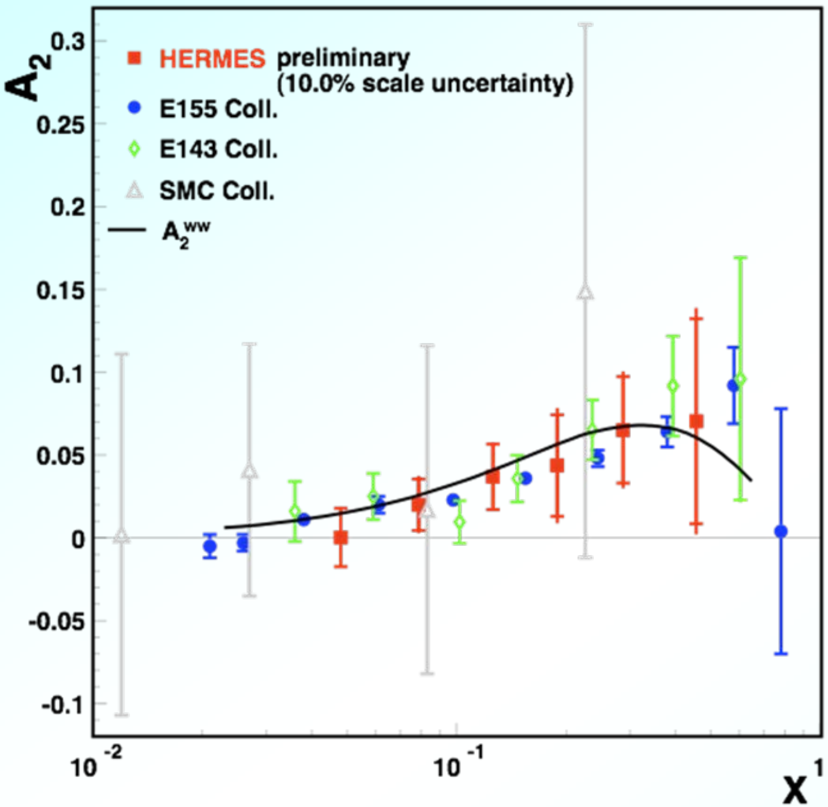
OPE:

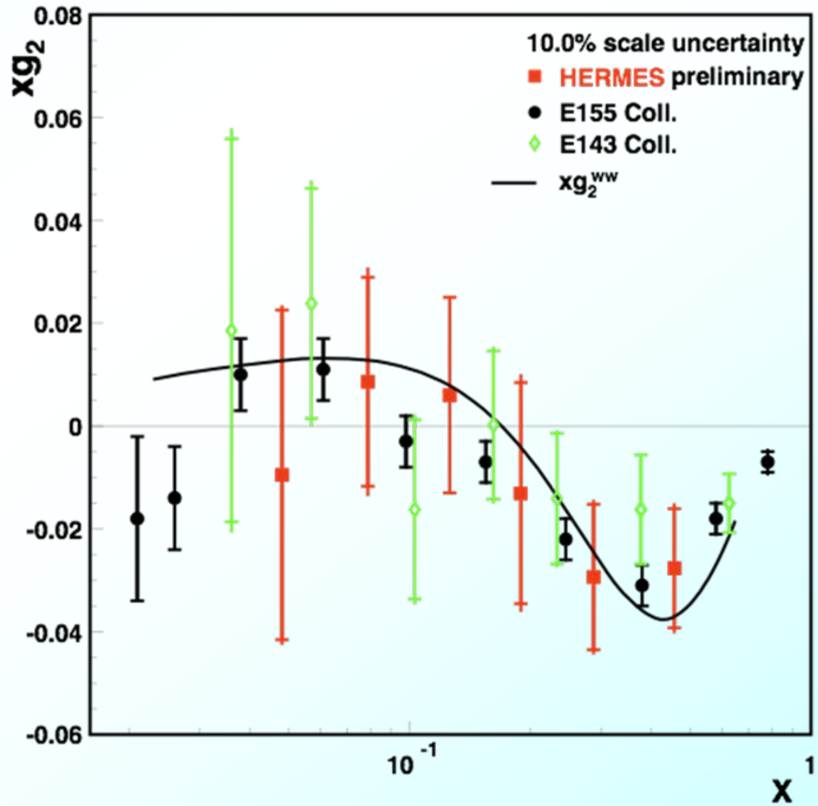
$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \tilde{g}_2(x,Q^2)$

$g_2^{WW}(..) = -g_1(..) + \int_x^1 g_1(z,Q^2)dz/z$

Results for A_2 and g_2

N/q	U	L	T
U	f_1		h_1
L		g_1	h_{1L}
T	f_{1T}	g_{1T}	h_1 h_{1T}





- consistent with (sparse) world data
- low beam polarization during HERA II ➡ small f.o.m.

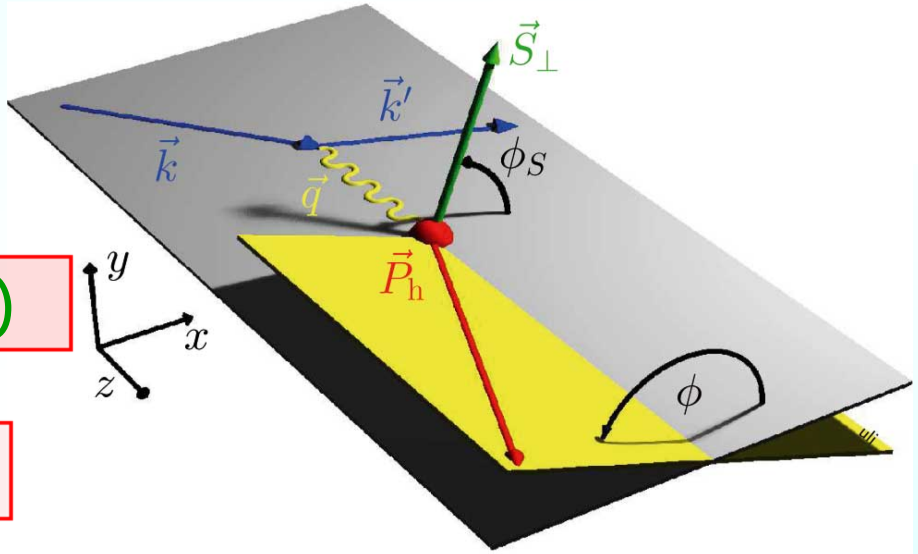
Transverse Azimuthal Angular Asymmetries

Amplitude has 2 components:

Transversity DF

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

Collins FF



U: unpol. e±-beam
T: transv. pol. Target

Unpolarised FF

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

Sivers DF

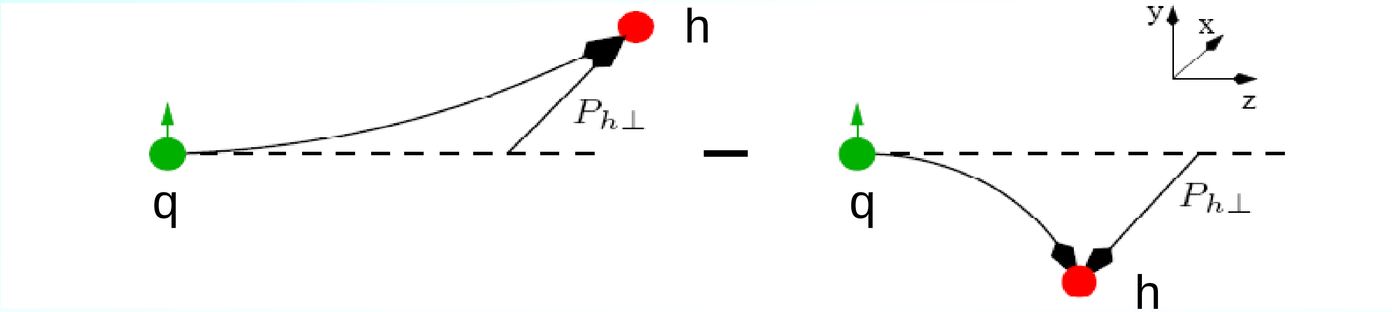
(Requires non-vanishing orbital angular momenta L_q of quarks)

Azimuthal angular asymmetries

C O L L I N S

Transverse quark spin + spin-dependent fragmentation

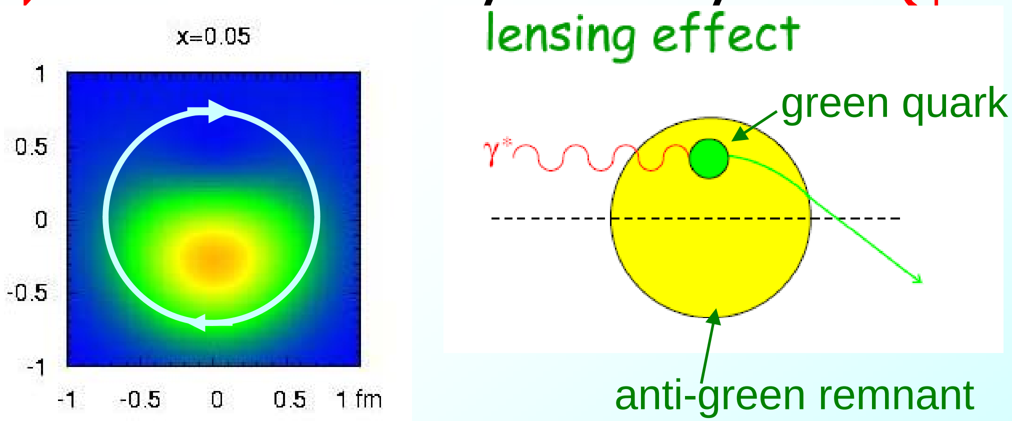
➡ Azimuthal asymmetry ~ $\sin(\phi + \phi_S)^h$



S I V E R S

Left-right distribution asymmetry (due to orbital angular momentum) + final state interaction

➡ Azimuthal asymmetry ~ $\sin(\phi - \phi_S)^h$



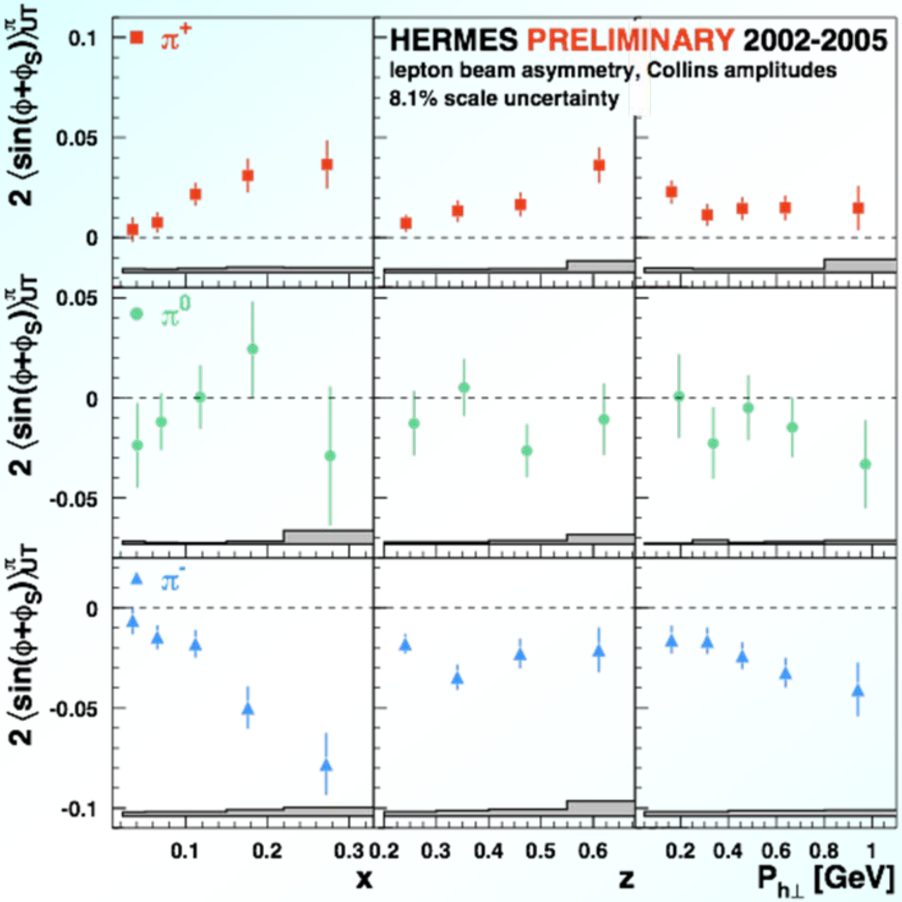
Collins Amplitudes

Transversity DF

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

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 $h_{1T}^\perp$



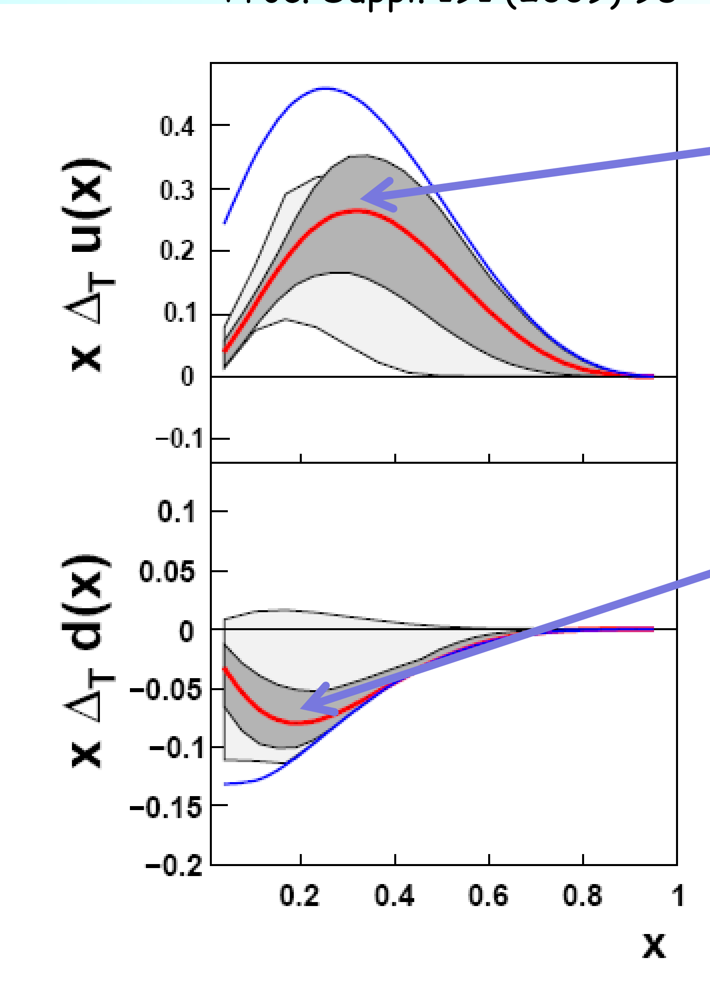
- **First** measurement of non-zero Collins effect
- Both Collins fragmentation function and transversity distribution function are sizeable
- Surprisingly large π^- asymmetry
- Possible source: large contribution (with opposite sign) from unfavored fragmentation, i.e. $u \rightarrow \pi^-$

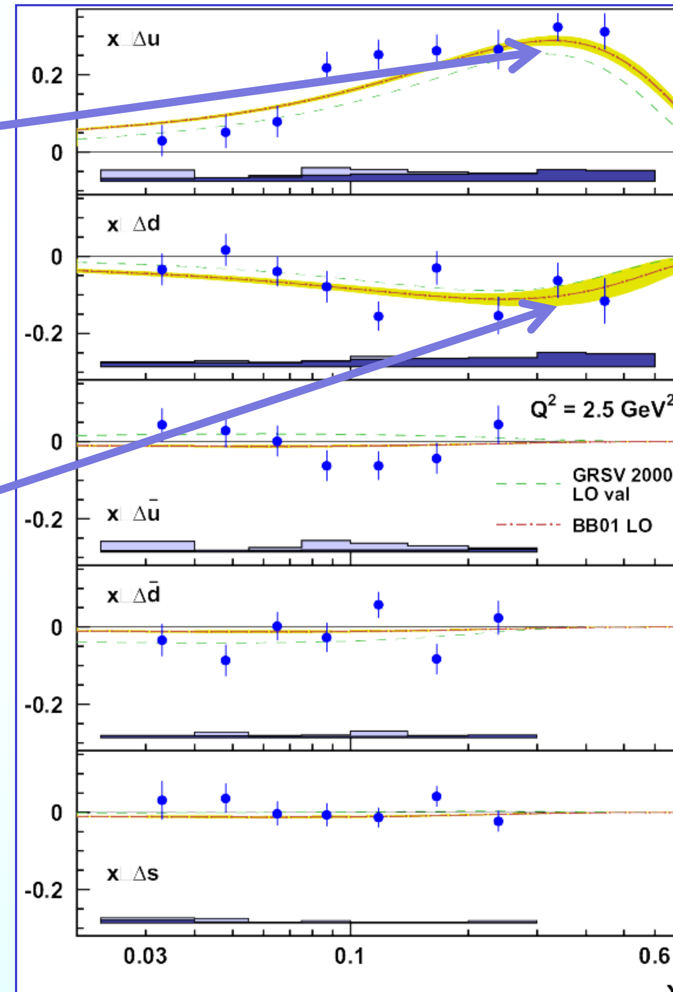
$H_1^{\perp}{}_{,disf} \approx - H_1^{\perp}{}_{,fav}$

First Glimpse at Transversity

M. Anselmino et al., Nucl. Phys. Proc. Suppl. 191 (2009) 98

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





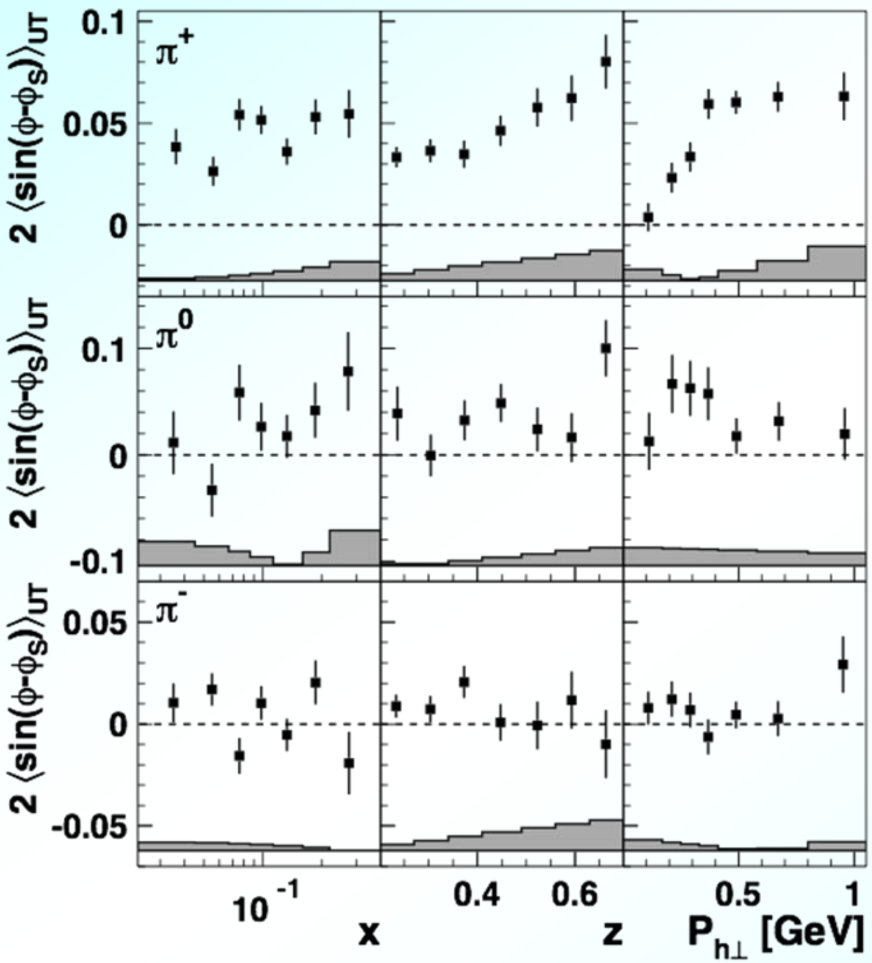
Sivers Amplitudes for Pions

Sivers DF

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

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 $h_{1T}^\perp$

arXiv:0906.3918



- First observation of non-zero Sivers distribution function in DIS

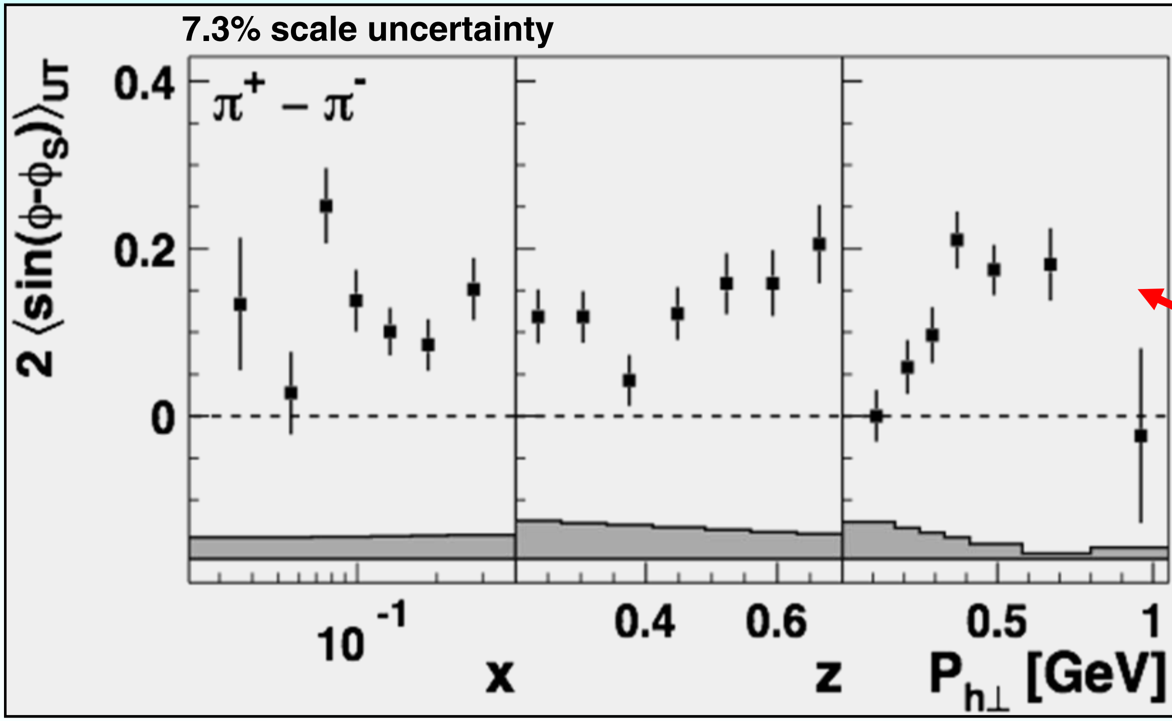
➡ Experimental evidence for orbital angular momentum L_q of quarks

But: Quantitative contribution of L_q to nucleon spin still unclear

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 $h_{1T}^\perp$

arXiv:0906.3918



access to
Sivers valence
distribution

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

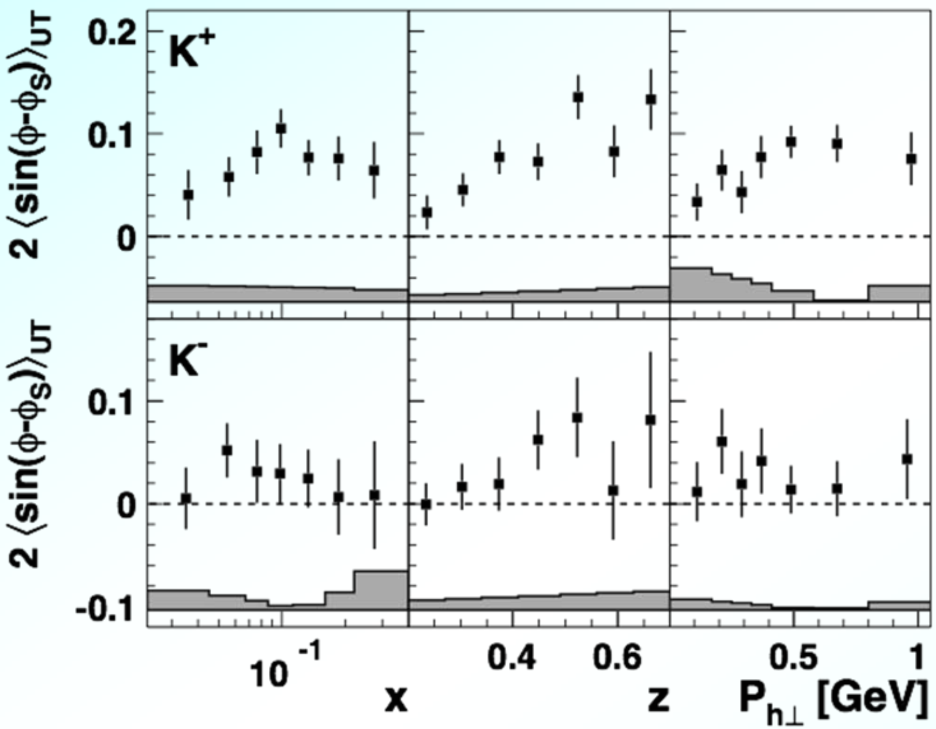
Sivers Amplitudes for Kaons

Sivers DF

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

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 $h_{1T}^\perp$

arXiv:0906.3918



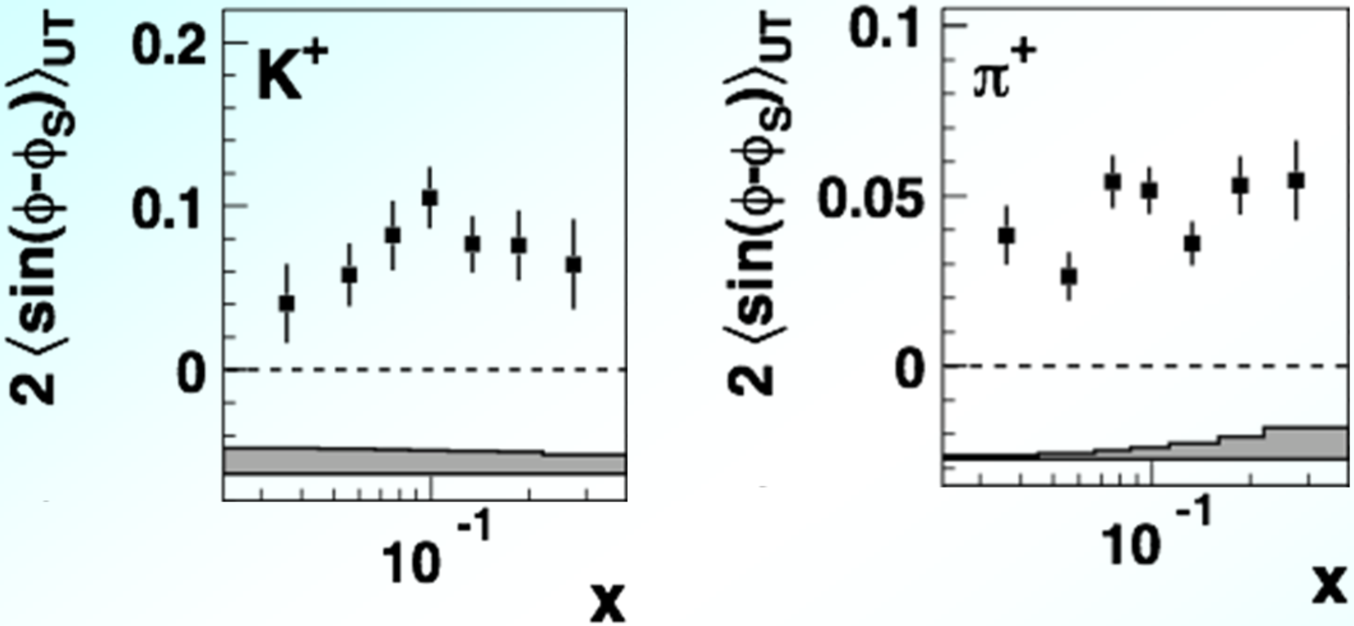
→ Large and positive

→ Slightly positive

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

arXiv:0906.3918

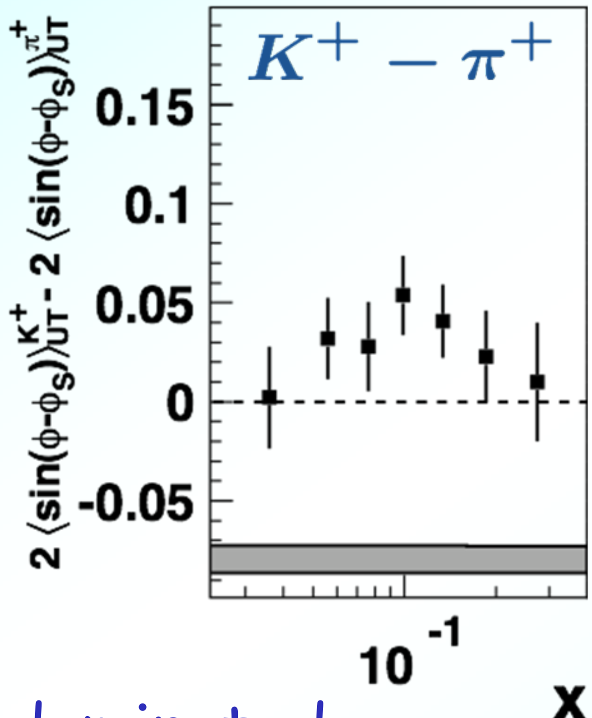


π^+/K^+ production dominated by scattering off u-quarks: $\simeq - \dfrac{f_{1T}^{\perp,u}(x,p_T^2) \otimes D_1^{u\to\pi^+/K^+}(z,K_T^2)}{f_1^u(x)\; D_1^{u\to\pi^+/K^+}(z)}$

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 $h_{1T}^\perp$

arXiv:0906.3918

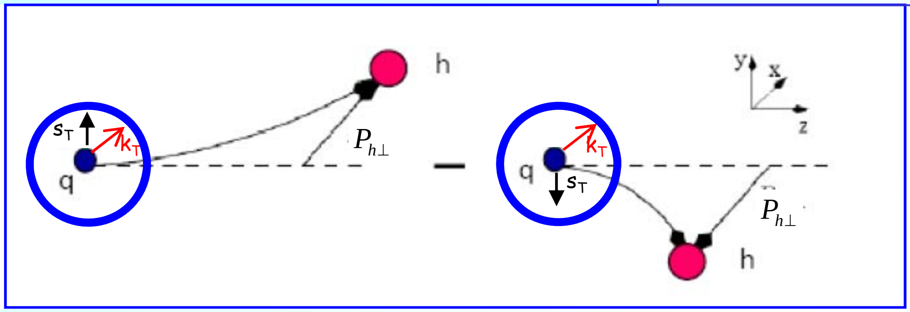


π^+/K^+ production dominated by scattering off u-quarks: $\simeq - \dfrac{f_{1T}^{\perp,u}(x,p_T^2) \otimes D_1^{u\to\pi^+/K^+}(z,K_T^2)}{f_1^u(x)\ D_1^{u\to\pi^+/K^+}(z)}$

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

Azimuthal Asymmetries in Unpolarised SIDIS

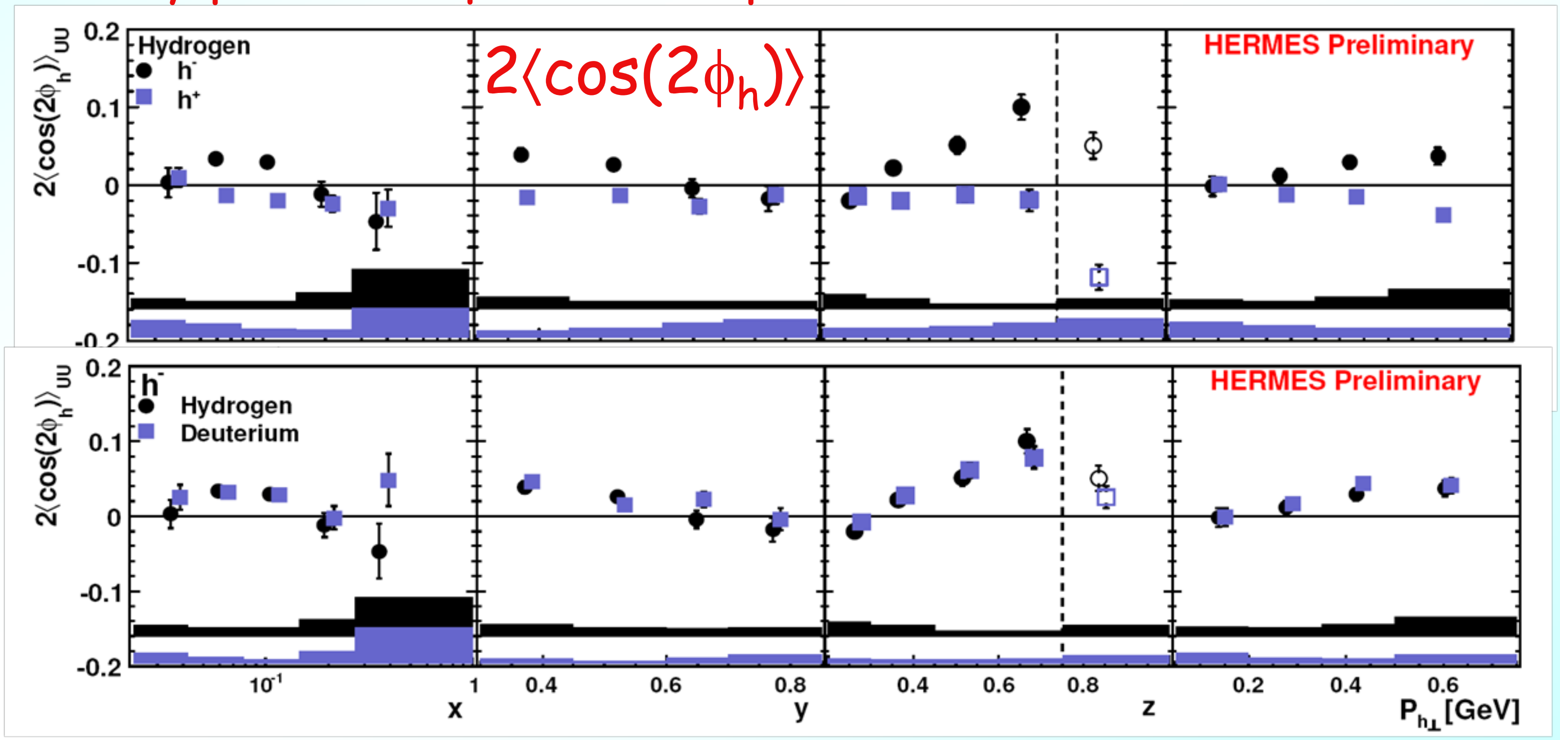
Boer-Mulders DF



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

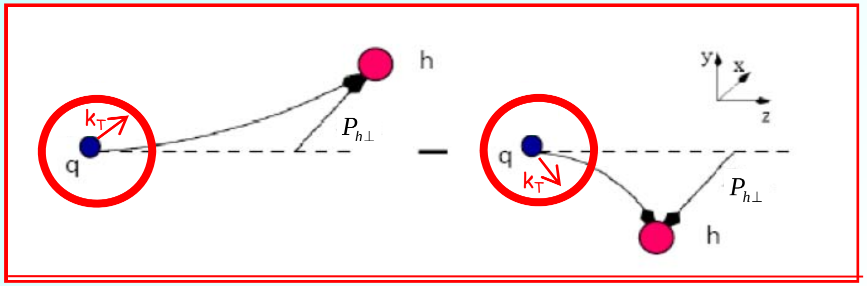
$$F_{UU}^{\cos 2\phi} = C\left[-\frac{2(\hat{h}\cdot\vec{k}_T)(\hat{h}\cdot\vec{p}_T) - \vec{k}_T\cdot\vec{p}_T}{MM_h} h_1^{\perp} H_1^{\perp} \right]$$

transversely polarised quarks in unpolarised nucleon



Azimuthal Asymmetries in Unpolarised SIDIS

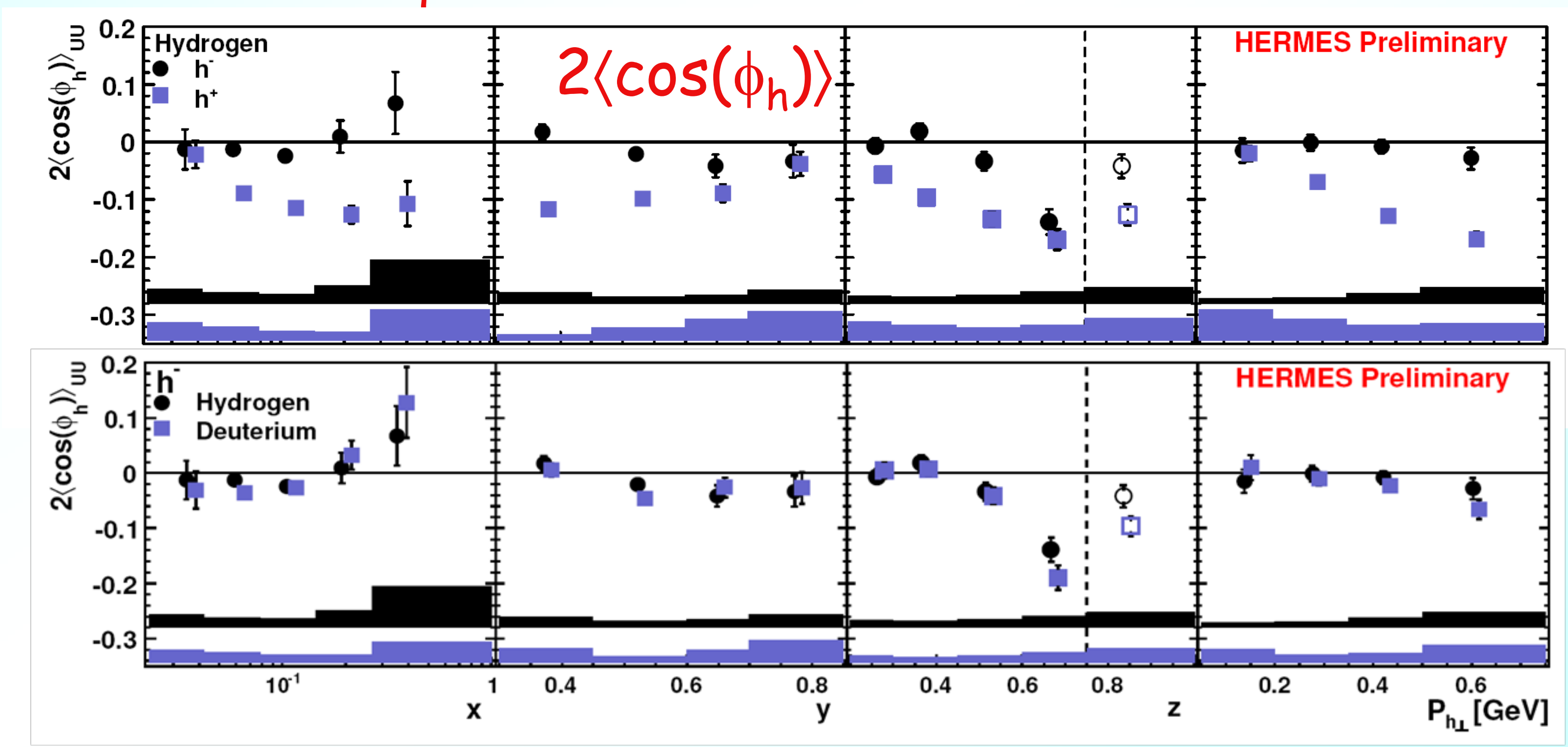
Cahn effect



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

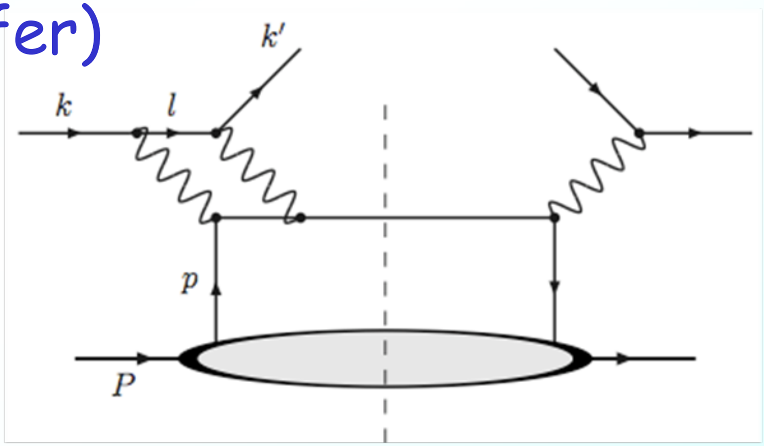
$$F_{UU}^{\cos\phi} = \frac{2M}{Q} C\left[-\frac{\hat{h}\cdot\vec{p}_T}{M_h} x h_1^{\perp} H_1^{\perp} - \frac{\hat{h}\cdot\vec{k}_T}{M} x f_1 D_1 \right]$$

Intrinsic transverse quark momentum



Search for two-photon exchange effect

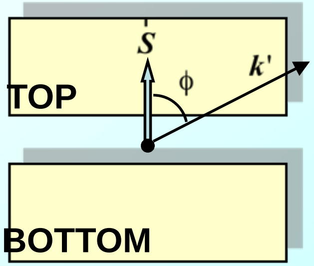
- 2-γ exchange best candidate to explain discrepancy in measurements of nucleon form factor $G_E(Q^2)$ (Rosenbluth $\leftrightarrow$ polarisation transfer)



- Interference between 1-γ and 2-γ exchange amplitudes

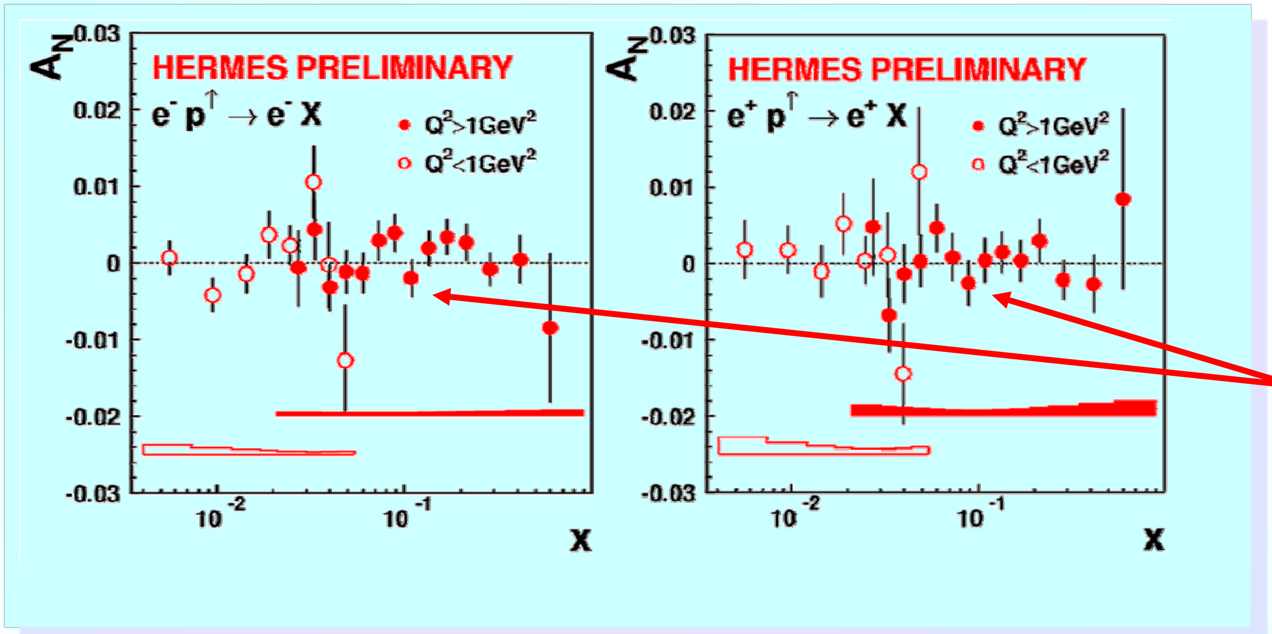
  ➡ transverse target SSA in inclusive DIS

- SSA ~ beam charge
- SSA ~ $\vec{S}(\vec{k}\times\vec{k}')$ - either measure left-right asymmetries or sin(ϕ) modulation



Transverse Azimuthal Asymmetry in DIS

1-photon exchange approximation: TAA forbidden



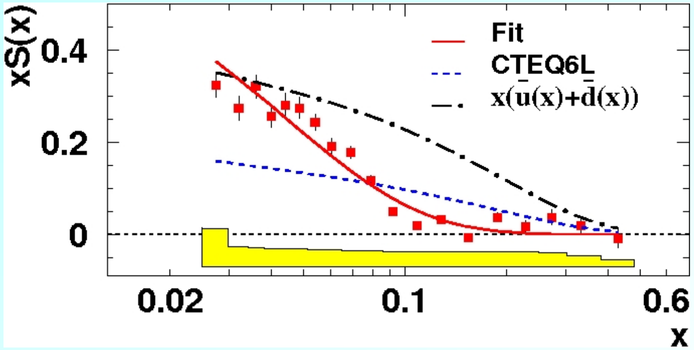
(Spin-flip every 90 s)

$A_N \neq 0$: Signature of 2-photon exchange

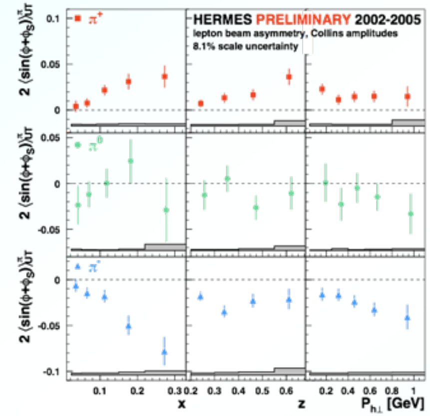
$A_N = O(10^{-3})$

Compatible with zero !

Submission to arXiv: this weekend

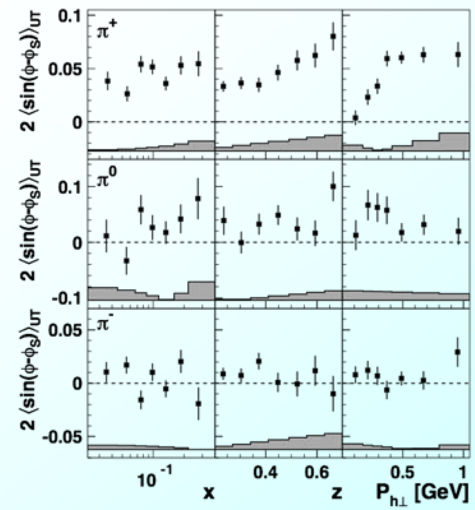


unpolarised quark DFs

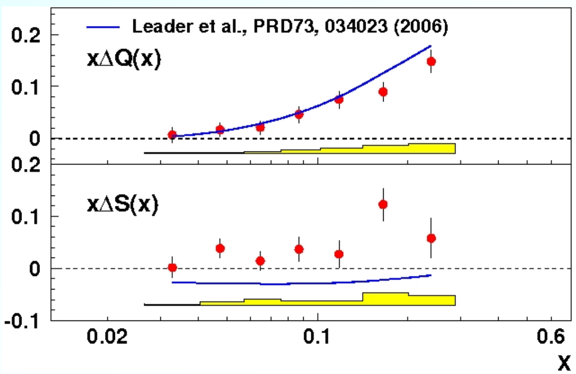


transversity DFs

Sivers DFs

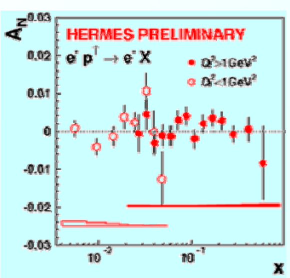


L_z^q



Quark helicity DFs

2-γ exchange



Boer-Mulders DF, Cahn