Overview of Experimental Results From HERMES

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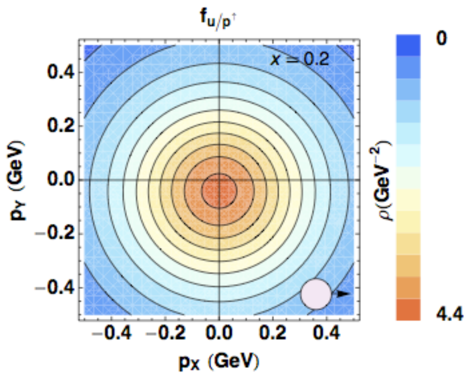
QCD Evolution Workshop
May 14, 2011 JLab

Quantum Phase-space Distributions of Quarks

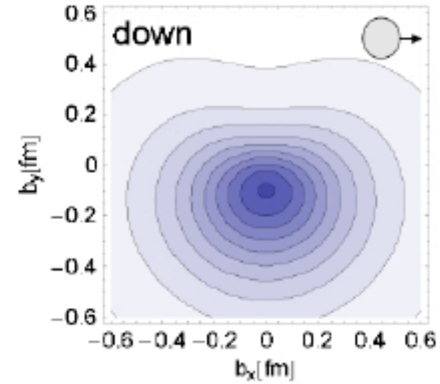
$W_p^q(x,k_T,r)$ "Mother" Wigner distributions

Probability to find a quark q in a nucleon P with a certain polarization in a position r & momentum k



d^3r

d^2k_T (FT)



TMD PDFs: $f_p^u(x,k_T)$,…

Semi-inclusive measurements
Momentum transfer to quark
Direct info about momentum distribution

GPDs: $H_p^u(x,\xi,t)$, …

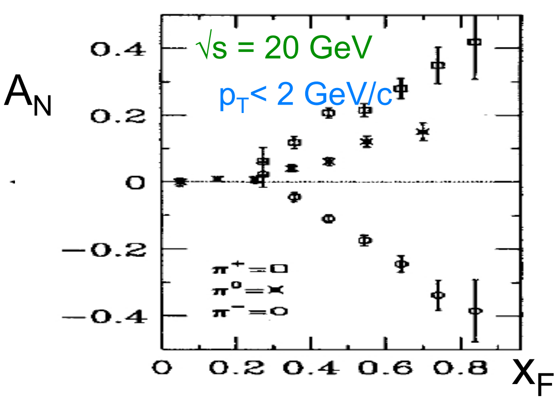
Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

d^2k_T

$\xi=0, t=0$

PDFs $f_p^u(x)$,…

May explain SSA & Lam-Tung



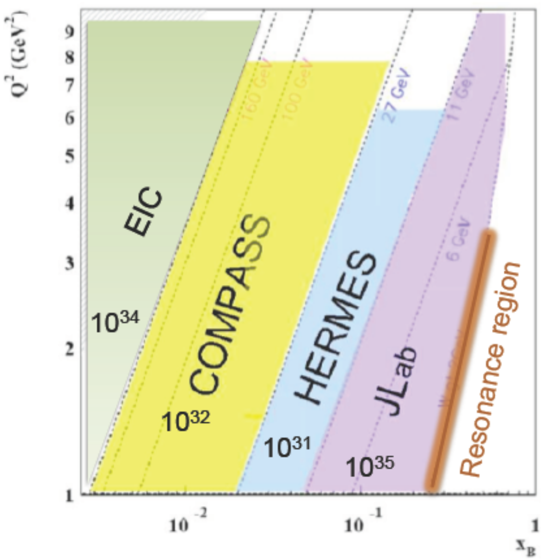
May solve
proton spin puzzle

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

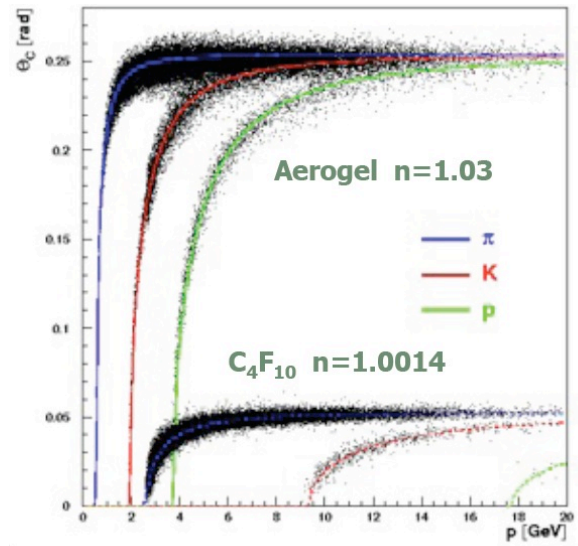
The HERMES Experiment

27.6 GeV e+/e- HERA beam

Valence and sea



Electron and Hadron ID

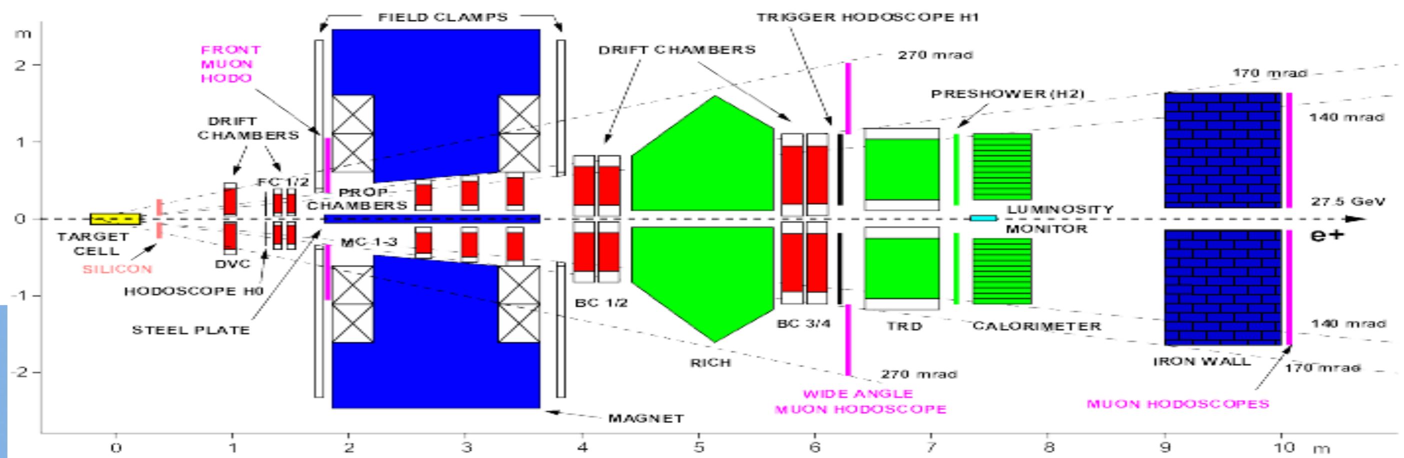


hermes

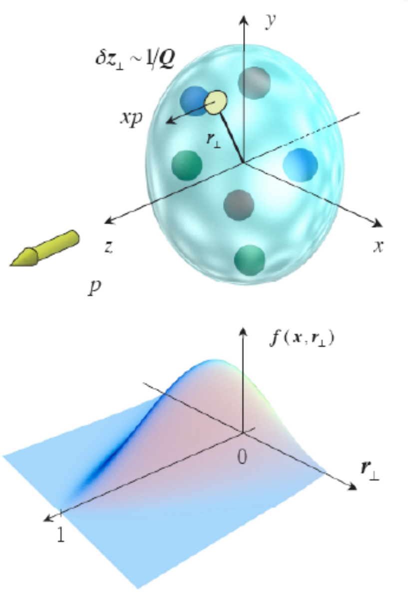
Data taking: 95-07

Internal gaseous target:

96-00 (p/d) Lpol
02-05 (p) Tpol
06-07 (p/d) Unpol



Generalized parton distributions

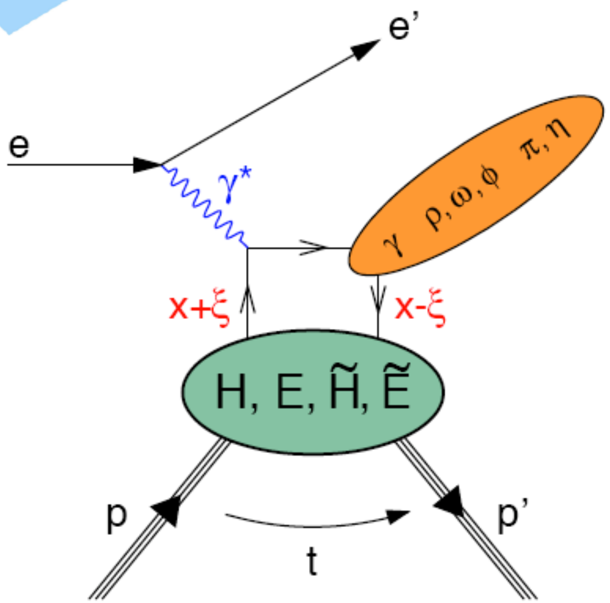


Encompass parton distributions and form factors

longitudinal momentum and transverse spatial position correlated information

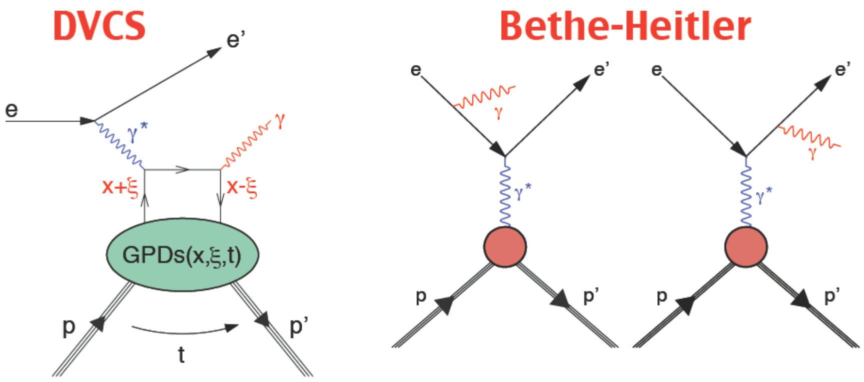
Access OAM $L_q = J_q - \frac{1}{2}\Delta\Sigma$ via Ji sum rule

$$J_q = \lim_{t \to 0} \int_{-1}^{1} dx\, x \left[H_q(x,\xi,t) + E_q(x,\xi,t) \right]$$

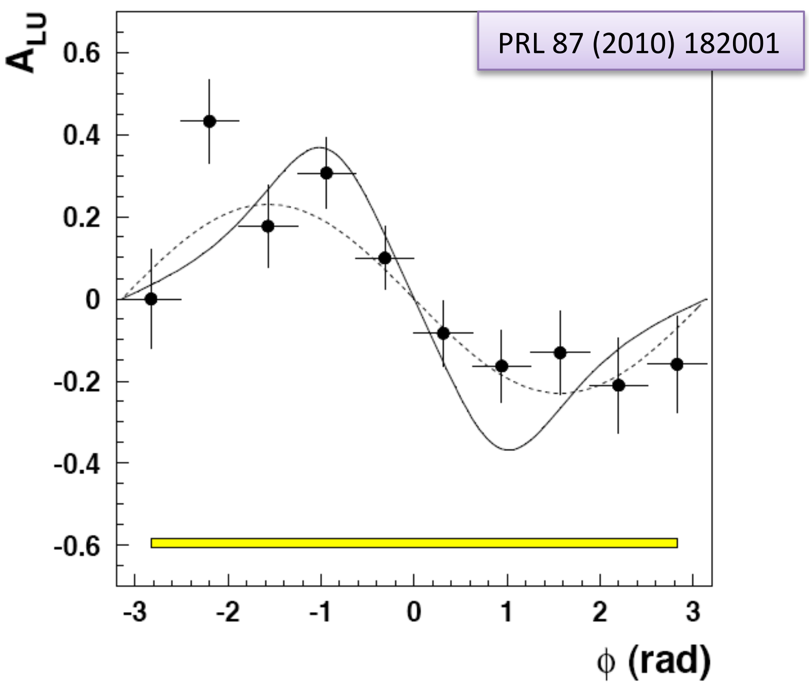


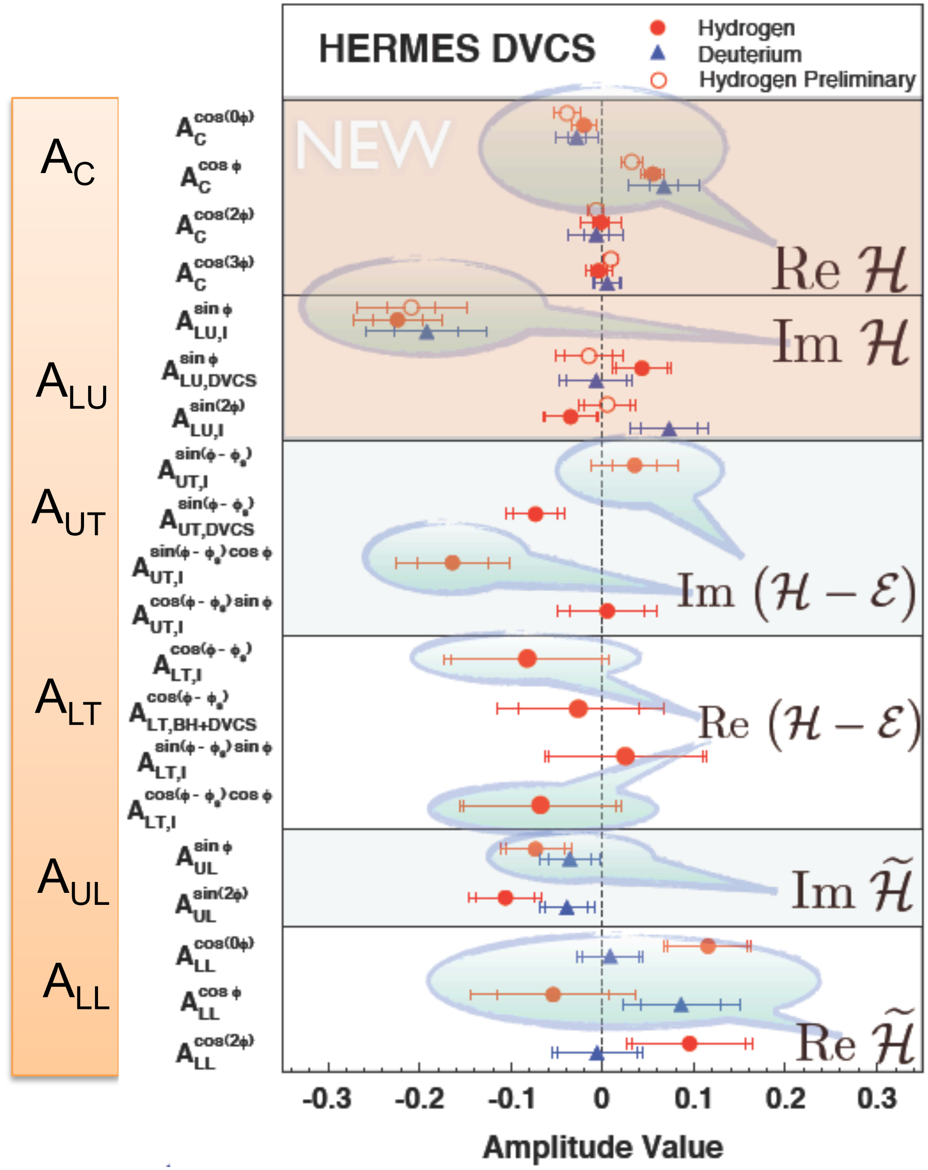
- Sensitivity of different final states to different GPDs
- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$
- $H, \tilde{H}$ conserve nucleon helicity, $E, \tilde{E}$ involve nucleon helicity flip
- DVCS (γ) → $H, E, \tilde{H}, \tilde{E}$
- Vector mesons (ρ, ω, ϕ) → H, E
- Pseudoscalar mesons (π, η) → $\tilde{H}, \tilde{E}$

The DVCS Landscape



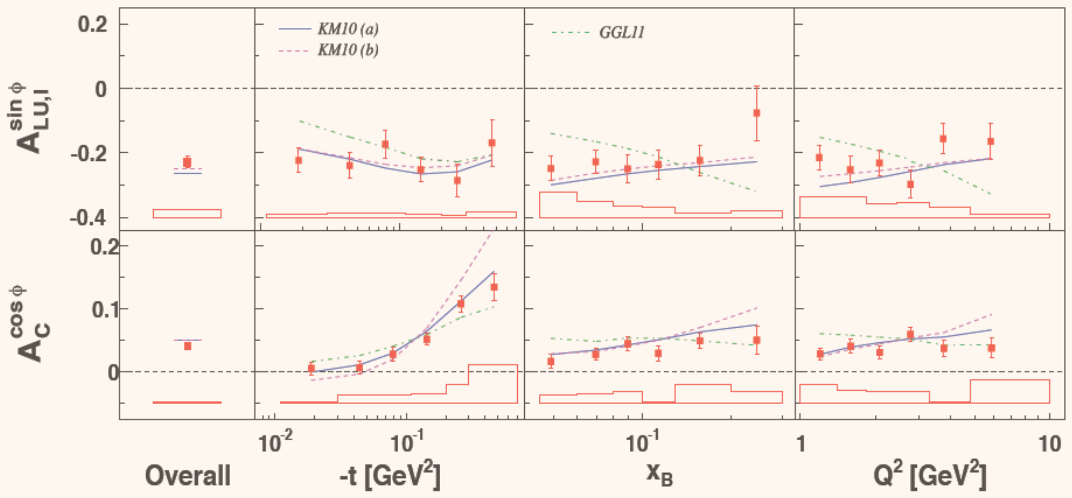
$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} \propto \left(|\mathcal{T}_{DVCS}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{I}\right)$$



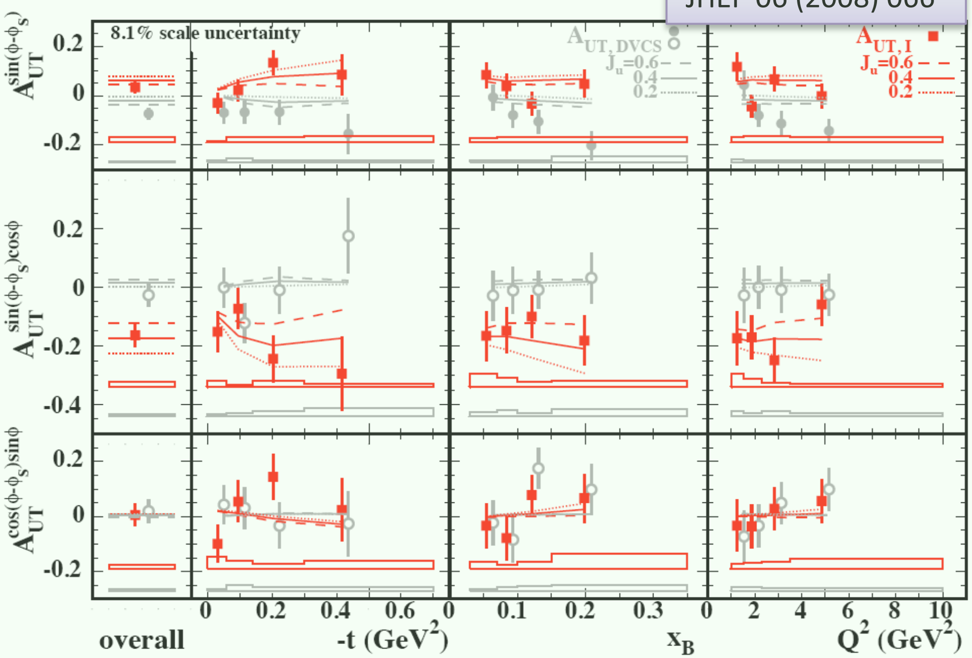


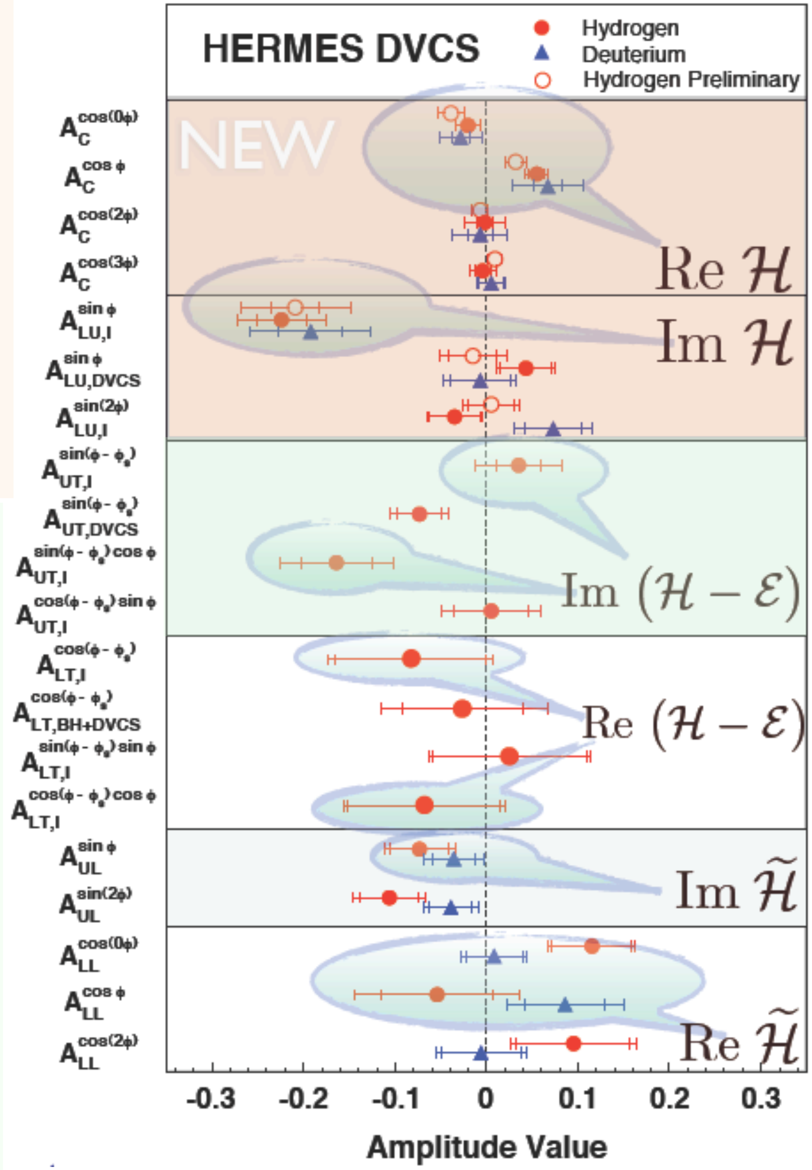
The DVCS Landscape

$\mathcal{H}$

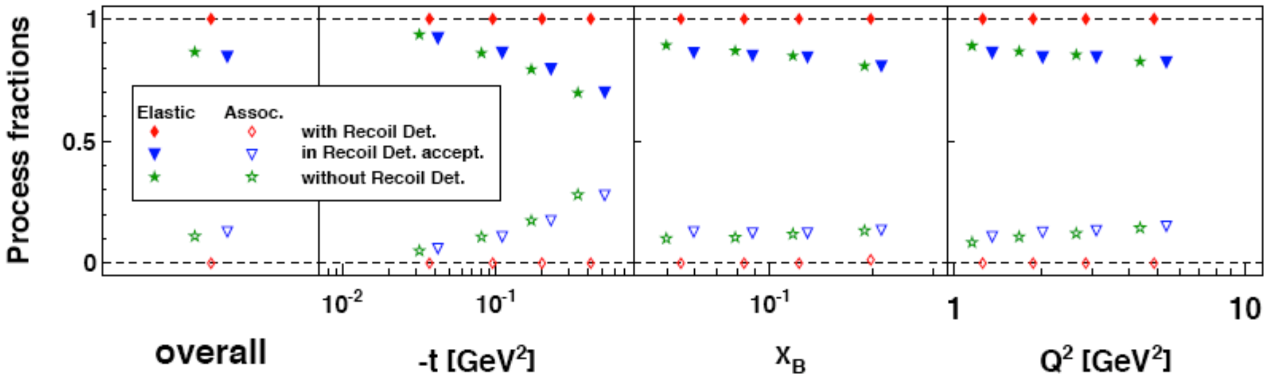


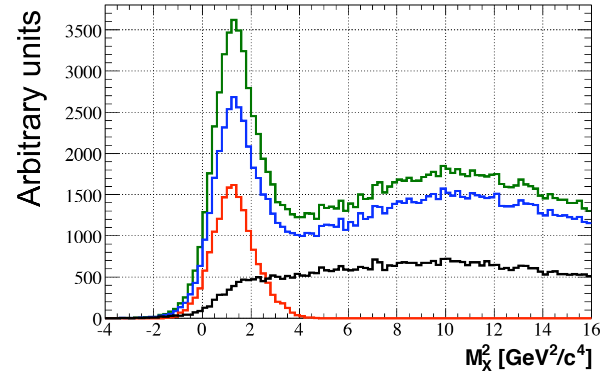
JHEP 06 (2008) 066



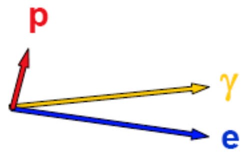


The Pure DVCS Sample

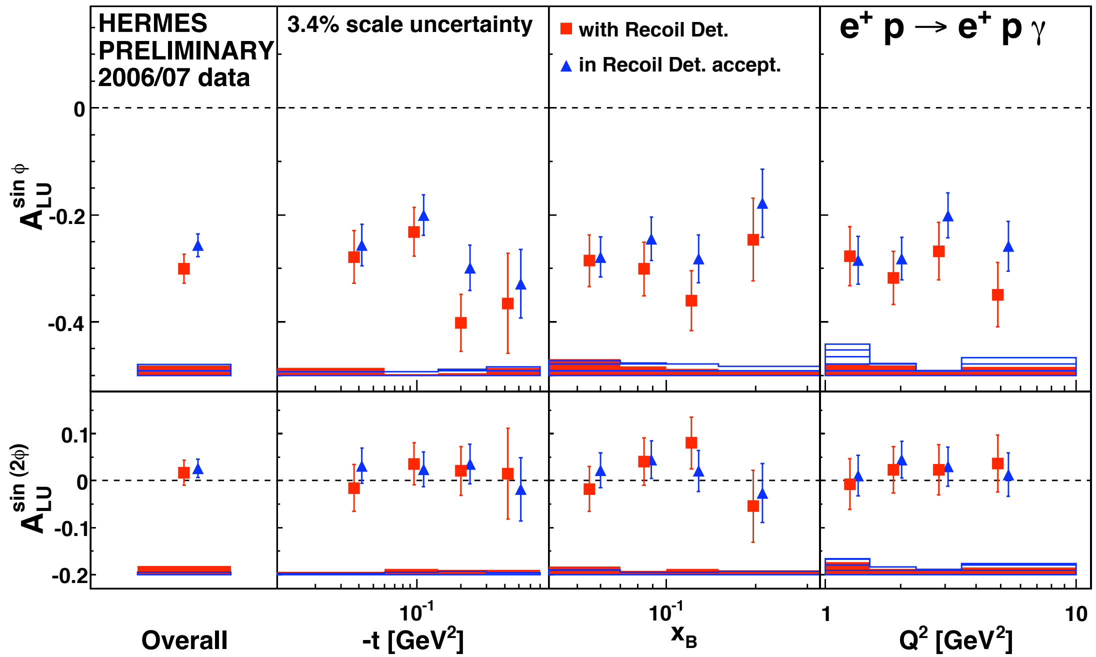




Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation



- No requirement for Recoil
- Charged recoil track in acceptance
- Kinematic fit probability > 1 %
- Kinematic fit probability < 1 %



Leading Twist TMDs

quark polarisation (columns) / **nucleon polarisation** (rows)

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$ *Pretzelosity*

Number density and helicity:

Focusing here in transverse momentum dependence

Transversity:

Survives transverse momentum integration (missing leading-twist collinear piece)

Differs from helicity due to relativistic effects and no mix with gluons in the spin-1/2 nucleon

Off-diagonal elements:

Interference between wave functions with different angular momenta: contains information about parton orbital angular motion and spin-orbit effects

Testing QCD at the amplitude level

T-odd elements:

→ sign change between DY and SIDIS
- universality of TMDs

Strict prediction from TMDs + QCD !

quark polarisation (columns) / **nucleon polarisation** (rows)

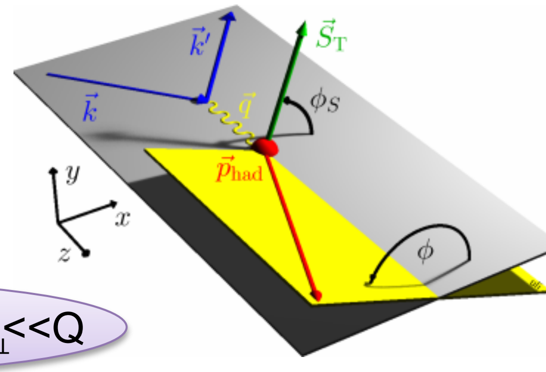
N/q	U	L	T
U	D_1 *Unpolarized*		$H_1^\perp$ *Collins*
L		G_{1L}	$H_{1L}^\perp$
T	$D_{1T}^\perp$	G_{1T}	H_1 $H_{1T}^\perp$

The SIDIS Case

quark polarisation (columns) / **nucleon polarisation** (rows)

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$ *Pretzelosity*

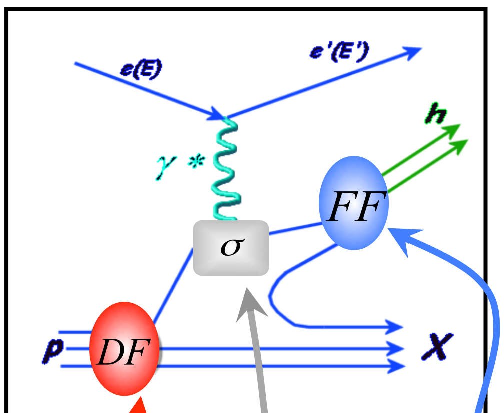
SIDIS cross section (transversely pol. target):



TMD factorization for $P_{h\perp} << Q$

$$f \otimes D = \int_q e_q^2 d^2 p_T d^2 k_T \ldots w(k_T, p_T) f^q(x, k_T^2) D^q(z, p_T^2)$$

Involved phenomenology due to the convolution over transverse momentum



$$\sigma^{ep\to ehX} = \sum_q DF \otimes \sigma^{eq\to eq} \otimes FF$$

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \underset{Twist}{\overset{Leading}{\propto}} S_T \left\{ \sin(\phi - \phi_S) F_{UT,T}^{\sin(\phi-\phi_S)} \right\}$$

$h_1 \otimes H_1^\perp$

$f_{1T}^\perp \otimes D_1$

$h_{1T}^\perp \otimes H_1^\perp$

$$+ S_T \left\{ \varepsilon \sin(\phi + \phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon \sin(3\phi - \phi_S) F_{UT}^{\sin(3\phi-\phi_S)} \right\}$$

$g_{1T}^\perp \otimes D_1$

$$+ S_T \lambda_e \left\{ \sqrt{1-\varepsilon^2} \cos(\phi - \phi_S) F_{LT}^{\cos(\phi-\phi_S)} \right\} + \ldots$$

First TMD Evidences

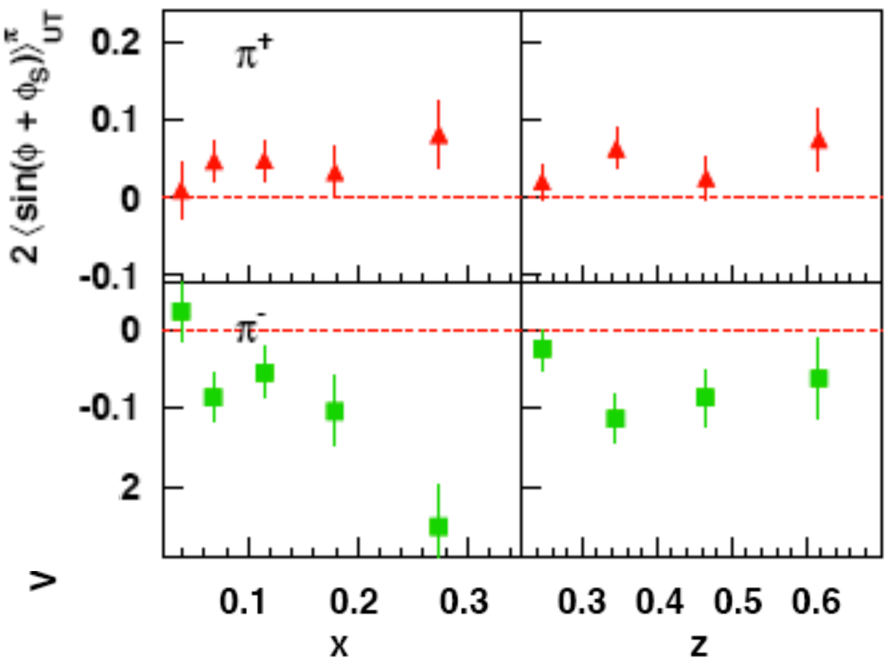
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

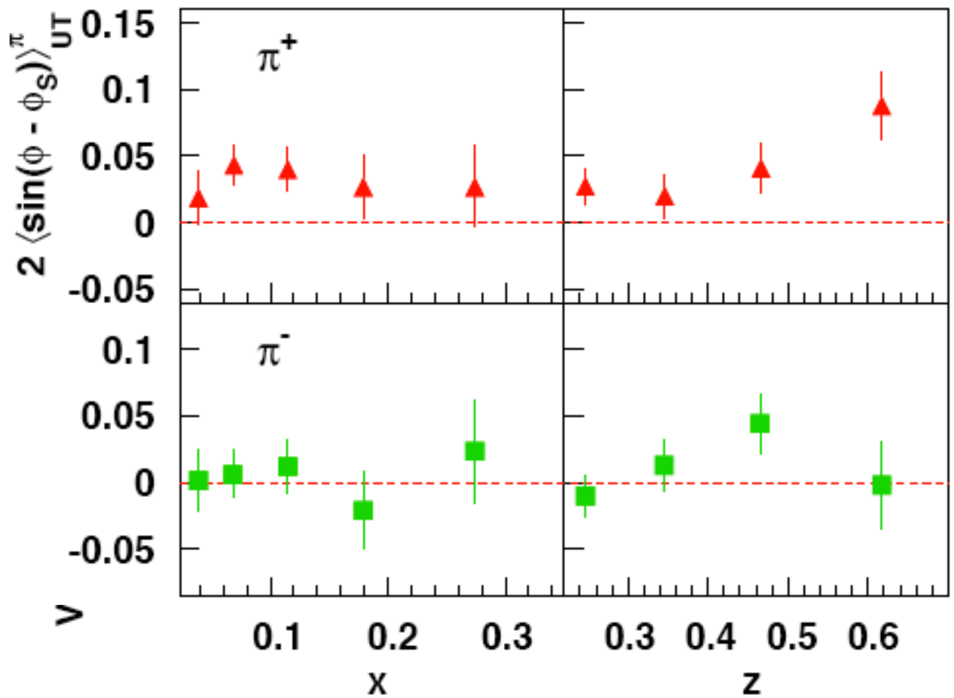
SIDIS:
ep → e'hX

$$\sigma_{UT}^{\sin(\phi-\phi_S)} \propto f_{1T}^{\perp} \otimes D_1$$

2005: First evidence from HERMES measuring SIDIS on proton

A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002





Non-zero transversity !!
Non-zero Collins function !!

Non-zero Sivers function !!

Leading Twist TMDs

Quark polarisation (columns) / **Nucleon polarisation** (rows)

	U	L	T
U	f_1 **Number Density**		$h_1^{\perp}$ **Boer Mulders**
L		g_1 **Helicity**	$h_{1L}^{\perp}$ **Worm-gear**
T	$f_{1T}^{\perp}$ **Sivers**	$g_{1T}^{\perp}$ **Worm-gear**	h_1 **Transversity** $h_{1T}^{\perp}$ **Pretzelosity**

Indication to be not-zero ! Preliminary result (Boer Mulders)

$P_{h\perp}$ dependence Preliminary result (Helicity)

Consistent with zero PLB 562 (2003) 182 PRL 84 (2000) 4047 (Worm-gear $h_{1L}^{\perp}$)

Different from zero ! *PRL 94 (2005) 012002 JHEP 06 (2008) 017 PLB 693 (2010) 11* (Transversity)

Consistent with zero Preliminary result (Pretzelosity)

Different from zero ! *PRL 94 (2005) 012002 PRL 103 (2009) 152002* (Sivers)

Hint of non-zero signal Preliminary result (Worm-gear $g_{1T}^{\perp}$)

HERMES has access to all of them through specific azimuthal modulations (ϕ, ϕ_S) of the cross-section thanks to the polarized beam and target

Number Density

nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^{\perp}$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^{\perp}$ *Worm-gear*
T	$f_{1T}^{\perp}$ *Sivers*	$g_{1T}^{\perp}$ *Worm-gear*	h_1 *Transversity* $h_{1T}^{\perp}$ *Pretzelosity*

(The Baseline)

The Hadron Multiplicities

$f_1 \cdot D_1$

LO interpretation:

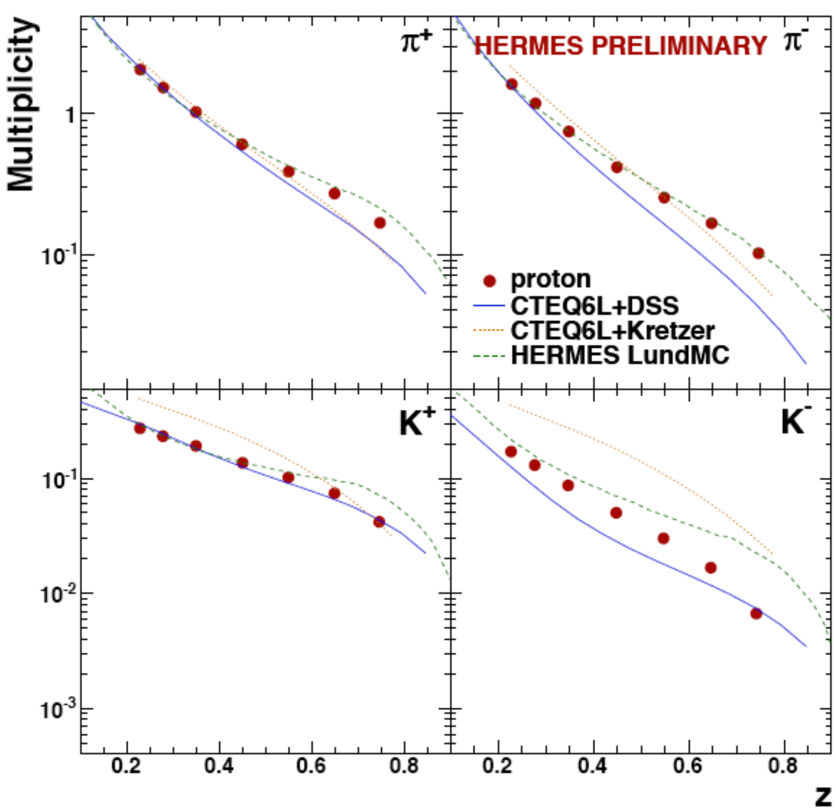
$$M_N^h = \frac{1}{N_N^{DIS}(Q^2)}\frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2)}$$

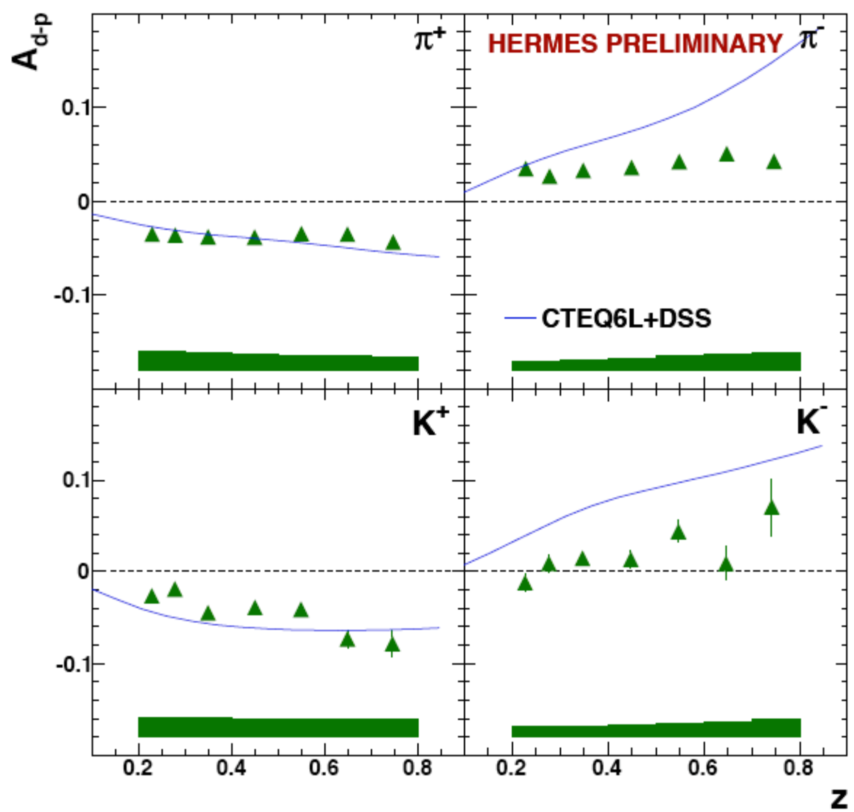
SIDIS data constrain fragmentation at low c.m. energy and bring enhanced flavor sensitivity

Proton-deuteron asymmetry:

$$A_{d-p}^h \equiv \frac{M_d^h - M_p^h}{M_d^h + M_p^h}$$

Reflects different flavor content
Correlated systematics cancels

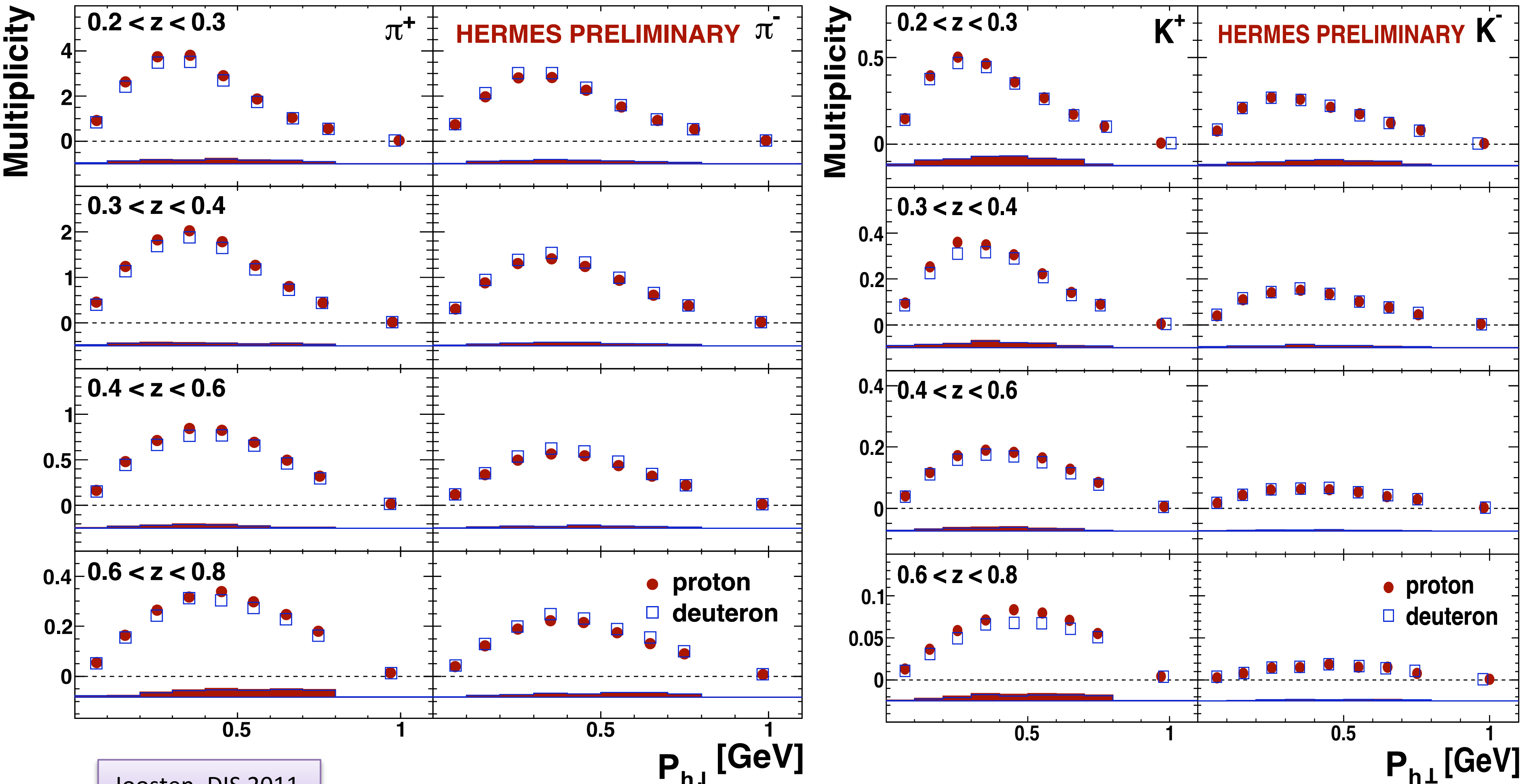




The $P_{h\perp}$–unintegrated Multiplicities $f_1 \otimes D_1$

Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark k_T and fragmentation p_T,

i.e. from gaussian anstaz $\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$



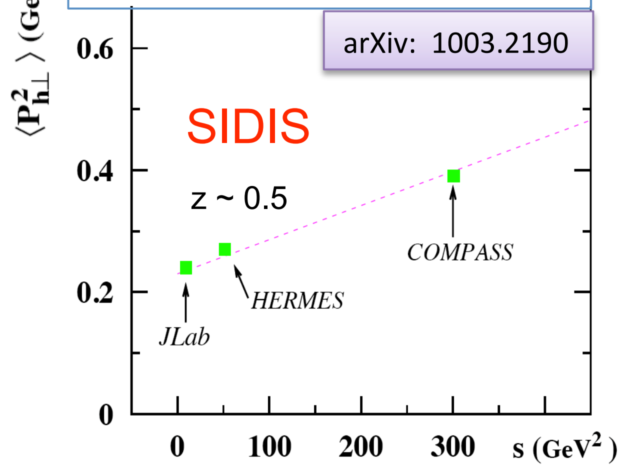
Joosten, DIS 2011

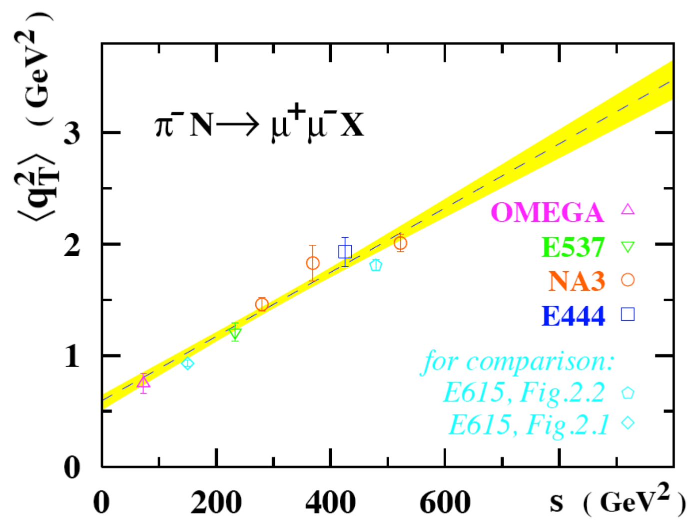
The Evolution

$f_1 \otimes D_1$

$$\frac{d\sigma_{UU}(P_{h\perp})}{dz\, dP^2_{h\perp}} = \frac{d\sigma_{UU}(0)}{dz\, dP^2_{h\perp}}\, e^{-P^2_{h\perp}/\overline{P^2_{h\perp}}}$$

arXiv: 1003.2190

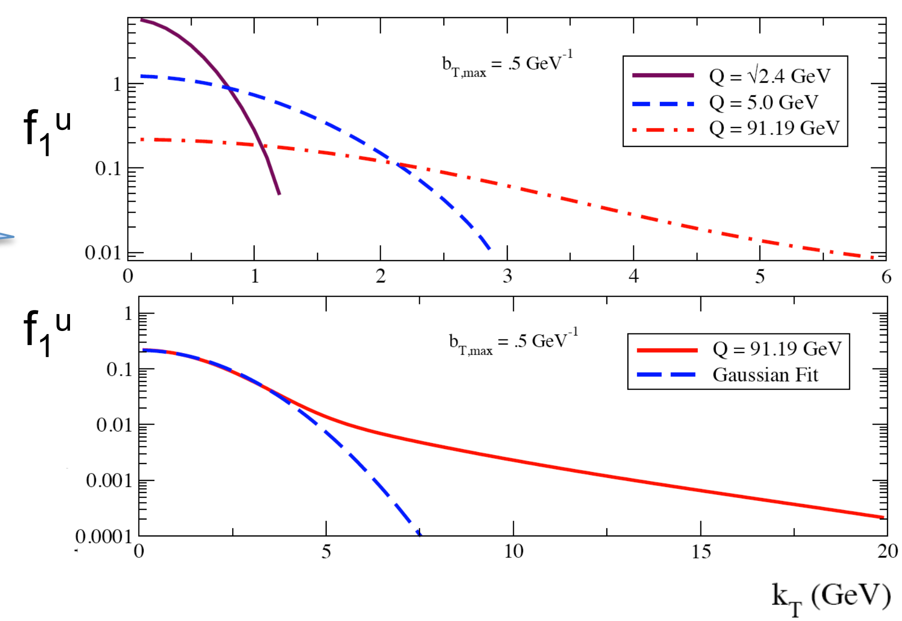




Indirect indication of a k_T and p_T broadening with c.m. energy:

TMD Q^2 evolution

arXiv: 1101.5057



Helicity

nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$ *Pretzelosity*

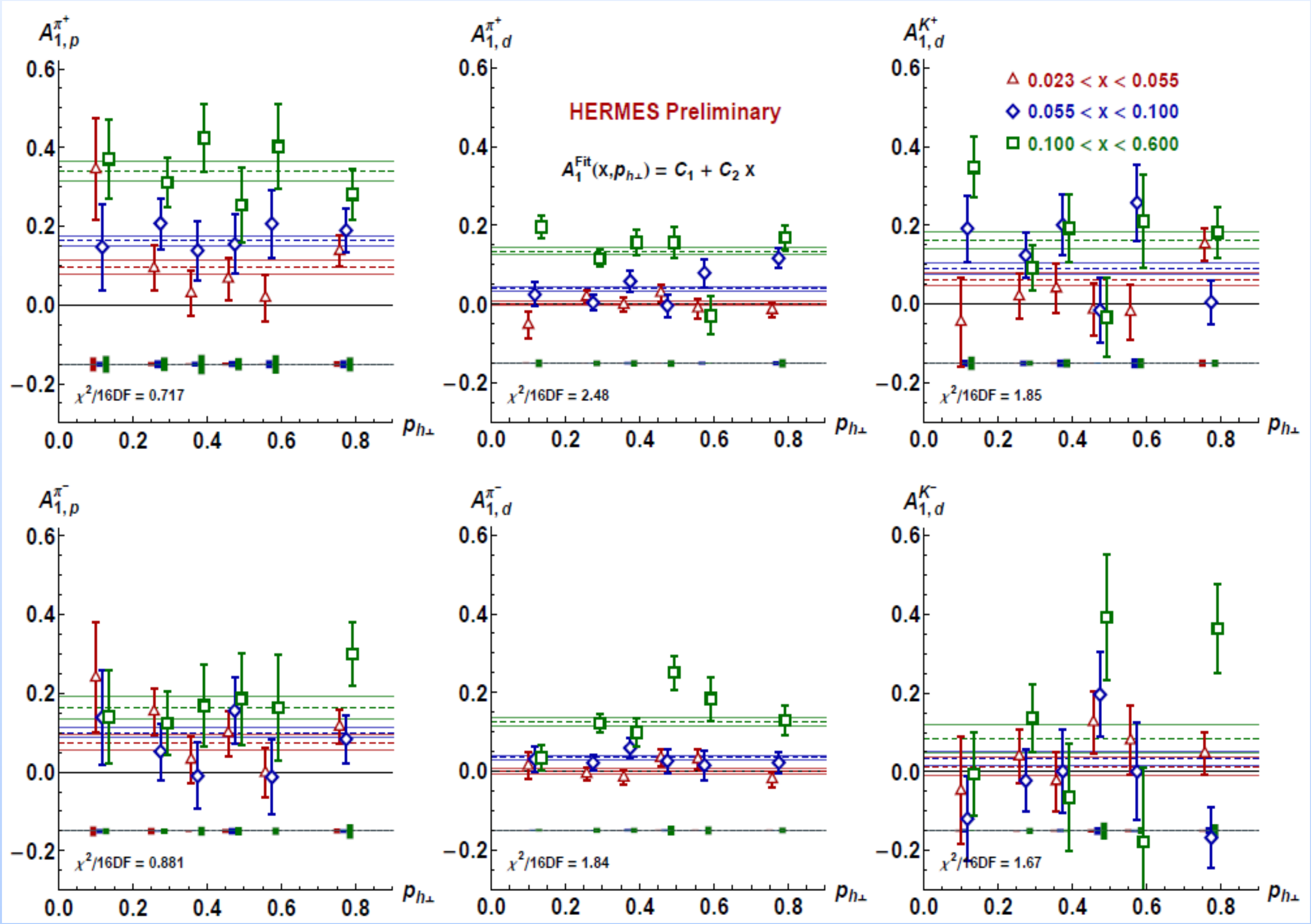
(The First Puzzle)

A_1 Double-spin Asymmetry

$g_1 \otimes D_1$

Refined studies extending the standard approach published *in Phys. Rev. Lett. 92 (2004) 012005*

$A_1(x, P_{h\perp})$ 2D - dependence

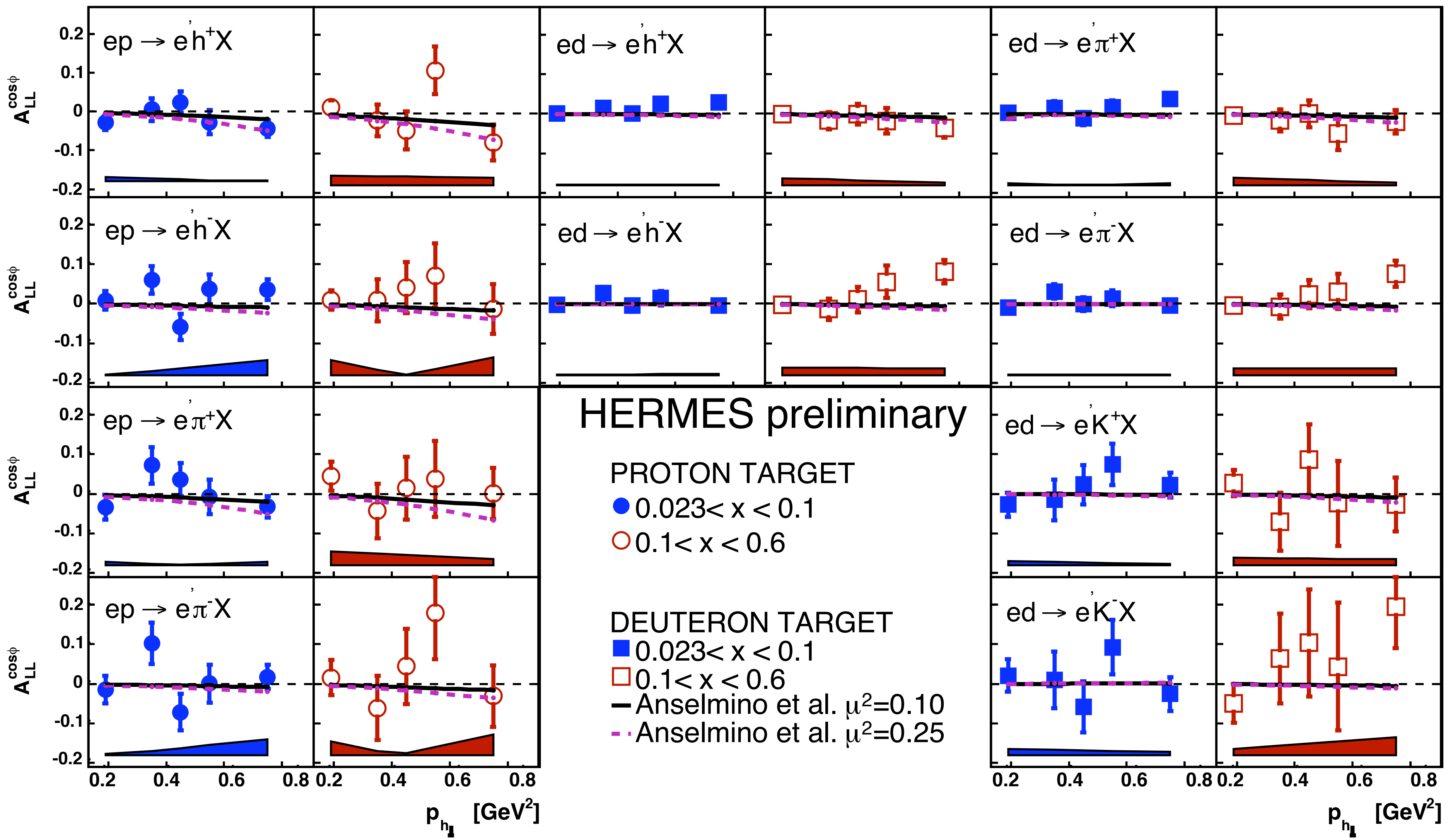


Sensitive to differences in transverse momentum dependence of g_1 and f_1

No significant $P_{h\perp}$ dependence observed

The $A_{LL}^{\cos(2\phi)}$ Asymmetry

$g_{1L} \otimes D_1$

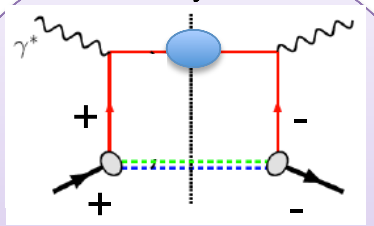


Transversity

nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ - *Boer-Mulders*
L		g_1 - *Helicity*	$h_{1L}^\perp$ - *Worm-gear*
T	$f_{1T}^\perp$ - *Sivers*	$g_{1T}^\perp$ - *Worm-gear*	h_1 - *Transversity* $h_{1T}^\perp$ - *Pretzelosity*

Chirally-odd



First evidence: 2005

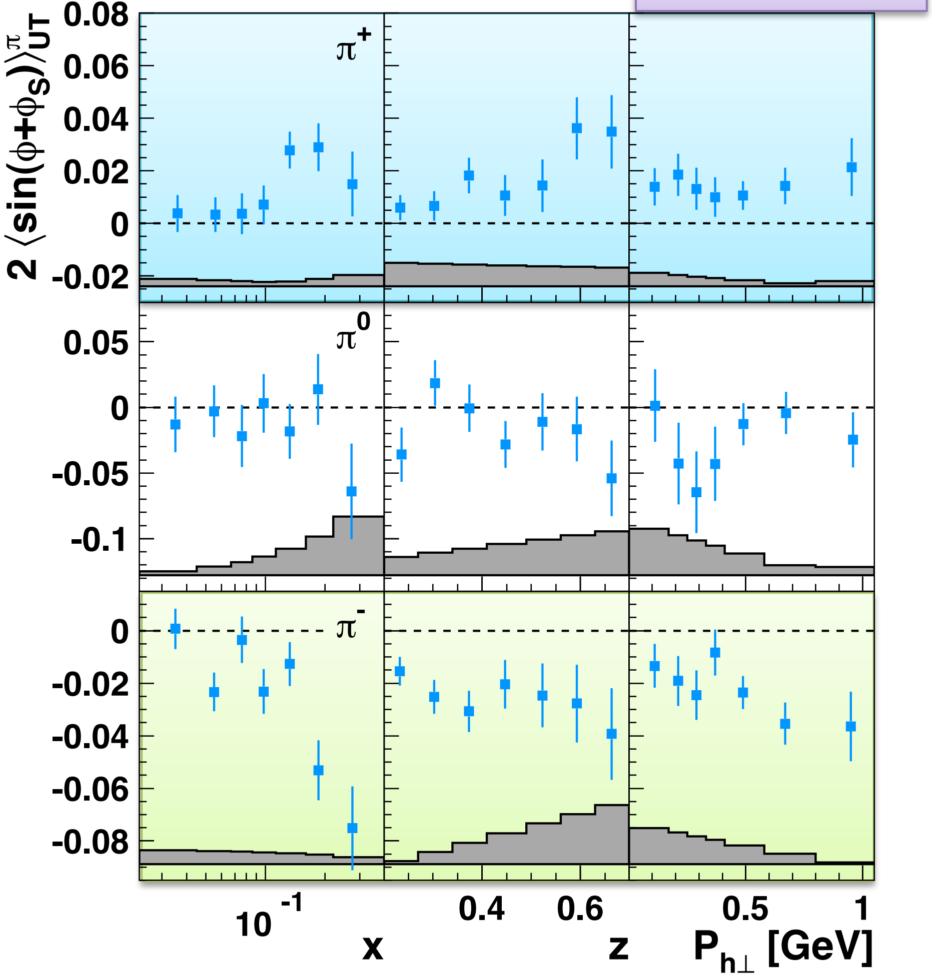
(The Collinear Missing Piece)

The Collins Amplitude

$h_1 \otimes H_1^{\perp}$

Pion signals fulfill isospin symmetry

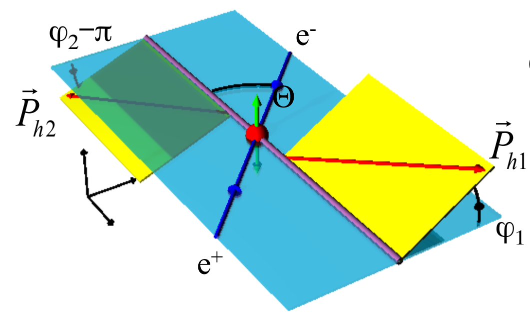
PLB 693 (2010) 11



Clear & opposite signals for charged pions:

With u-dominance: $\pi^+(u\bar{d})$ $\pi^-(\bar{u}d)$
opposite sign for favored and unfavored Collins

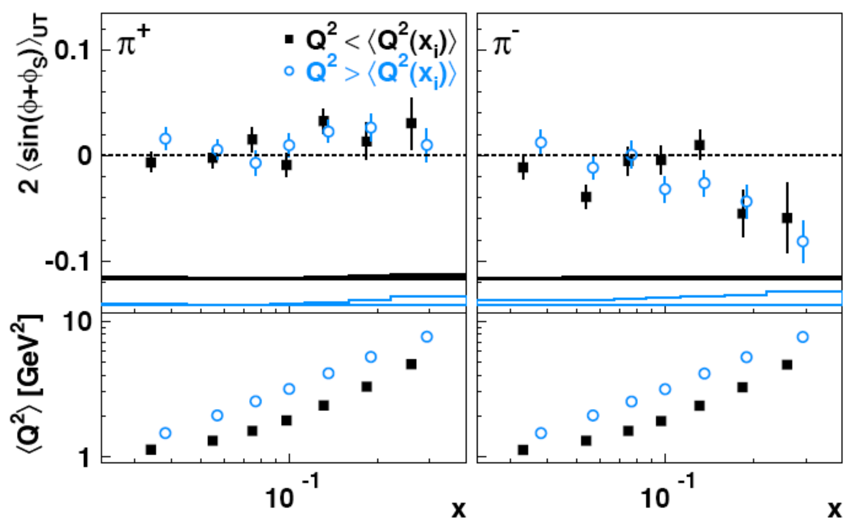
Not in contradiction with Collins at BELLE



$e^+e^- \rightarrow h_1h_2X$

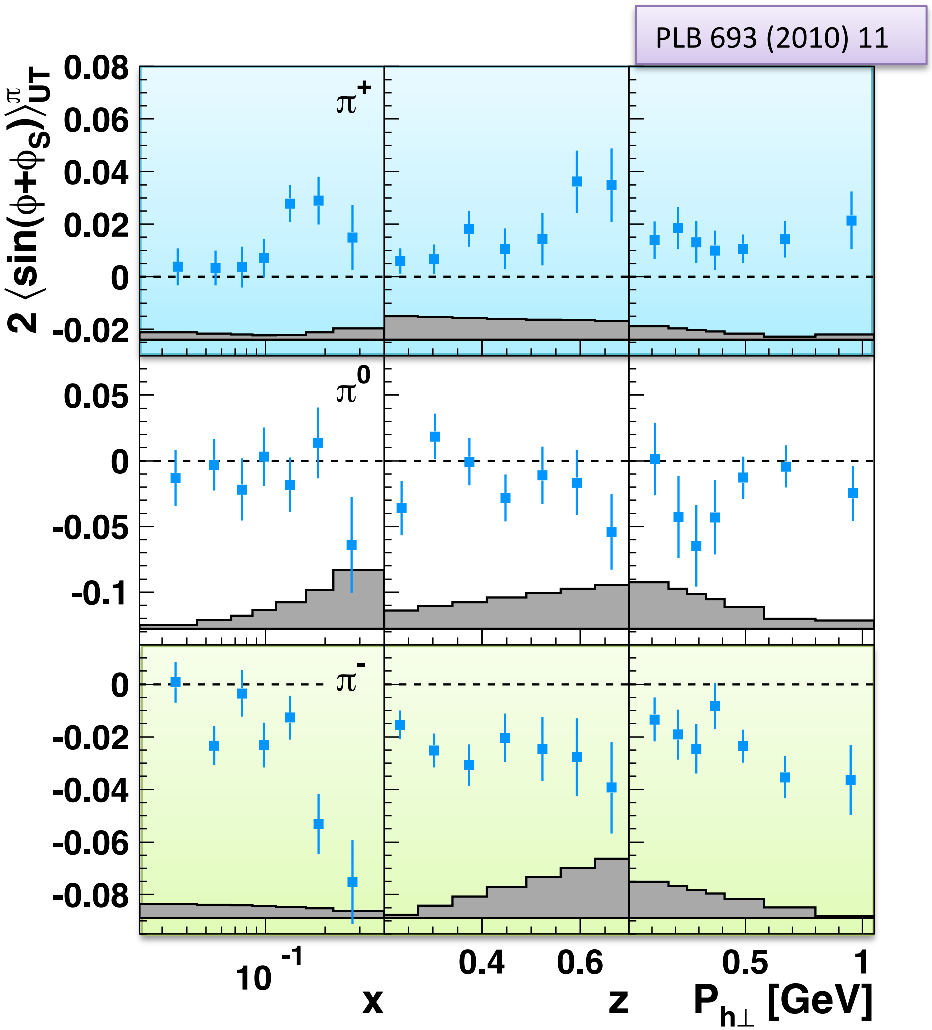
$A_{12} \propto H_1^{\perp} H_1^{\perp}$

Not enough statistics to exclude twist-4



The Collins Amplitude

$h_1 \otimes H_1^\perp$

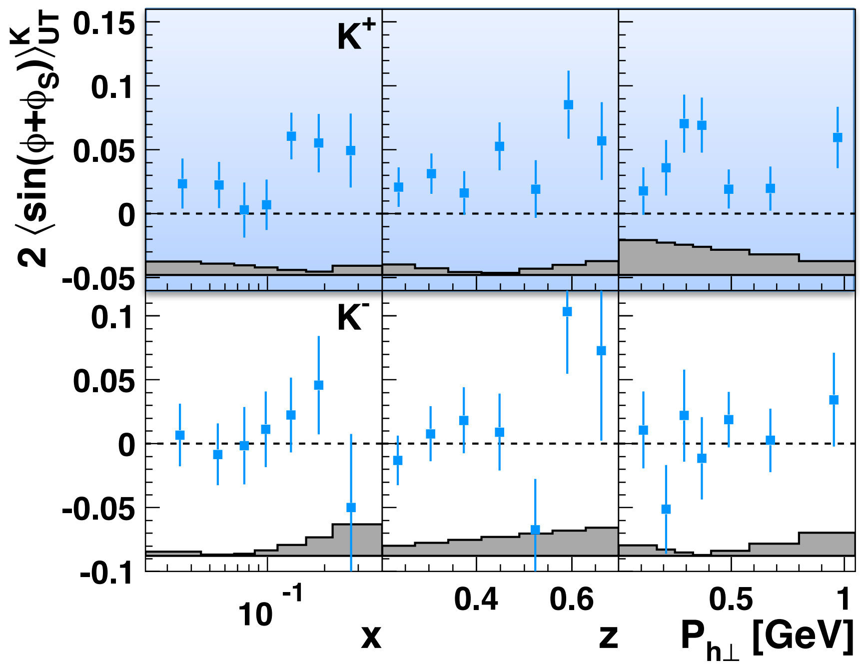


K+ signal larger than π+

- role of sea quarks
- k_T dependence in FFs
- higher twists effects

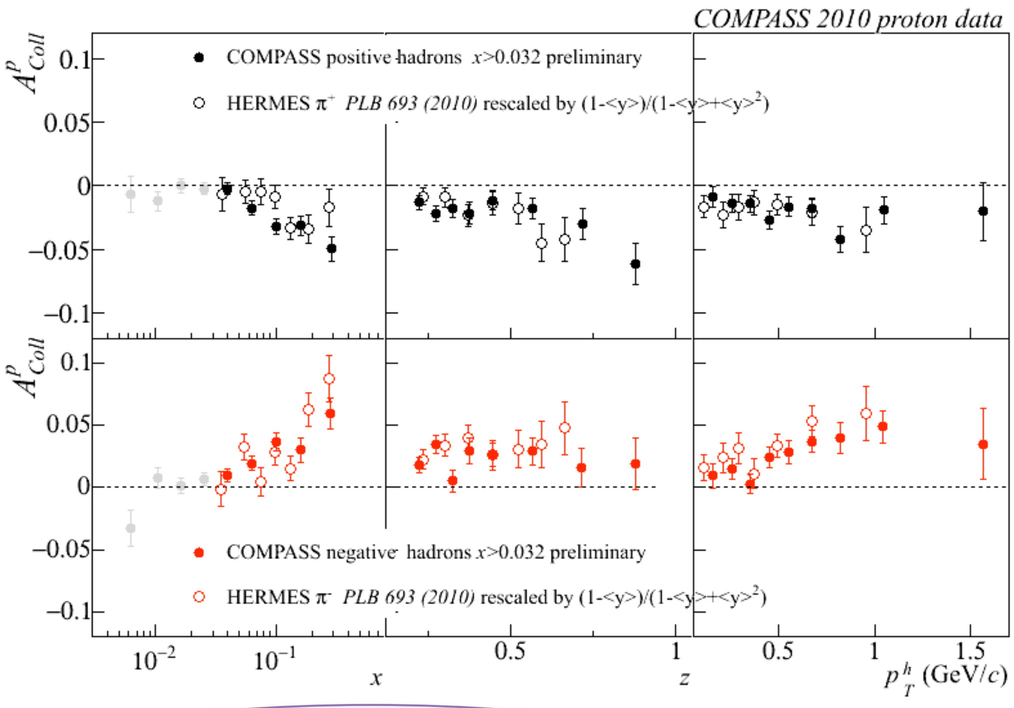
Peculiar K-

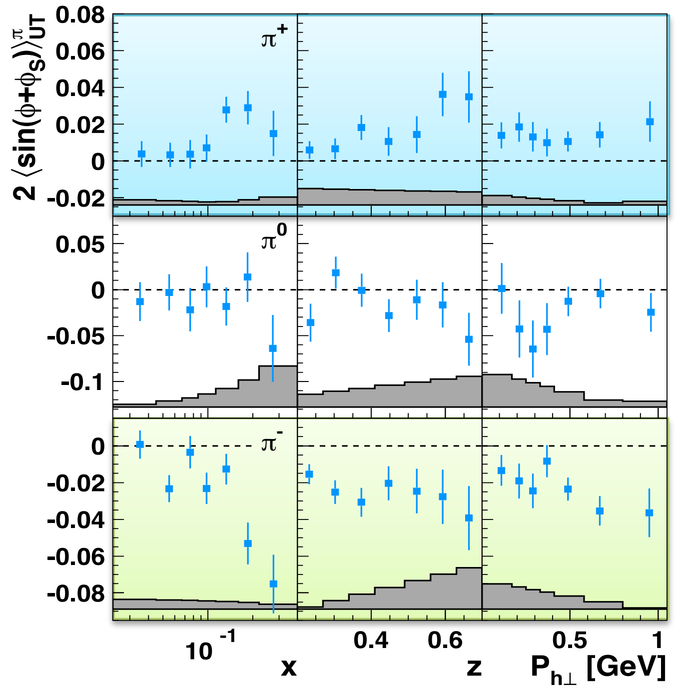
- no valence quark in common with proton



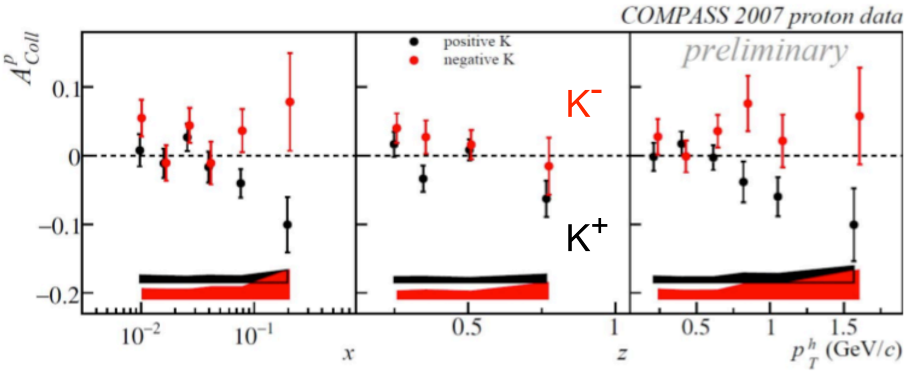
The Collins Amplitude

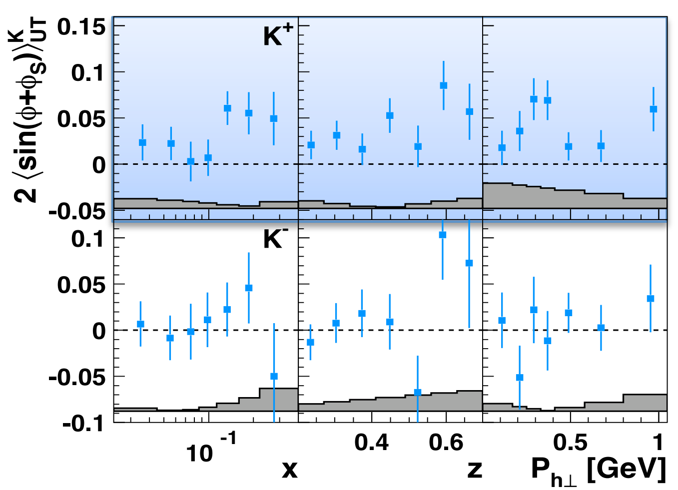
$h_1 \otimes H_1^{\perp}$





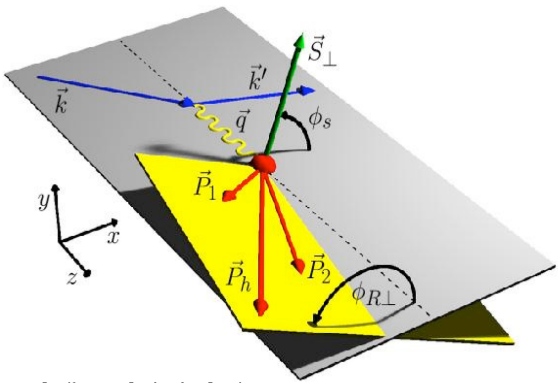
Consistent non-zero signals for charged hadrons, but K-

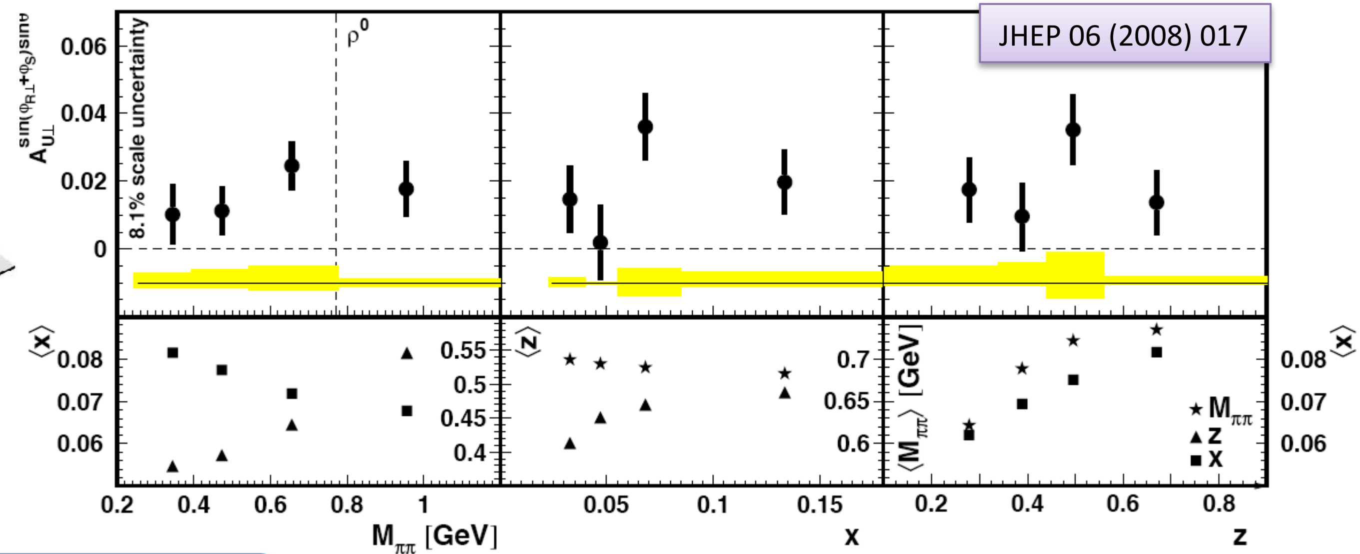




Two Hadron Asymmetries

$h_1 \otimes H_1^{\triangleleft}$

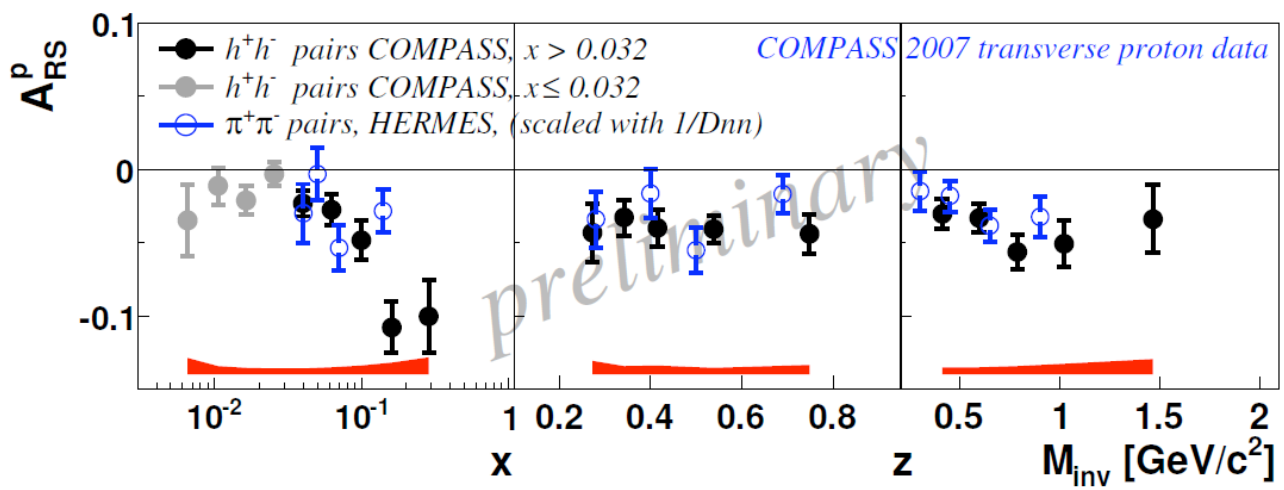




$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta} \propto \frac{\sum_q e_q^2 h_1(x,Q^2) H_1^{\triangleleft}(z,M_h^2,Q^2)}{\sum_q e_q^2 f_1(x,Q^2) D_1^{\triangleleft}(z,M_h^2,Q^2)}$$

Issue with unknown pp-terms in partial wave expansion

- Survives P_h integration
- Collinear factorization (simple product)
- DGLAP volution
- Universality



Transversity Signals

hermes: $lp \to l' hX$

COMPASS: $ld \to l' hX$

BELLE: $e^+e^- \to h_1 h_2 X$

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

hermes, COMPASS: $lp \to l'\pi^+\pi^- X$

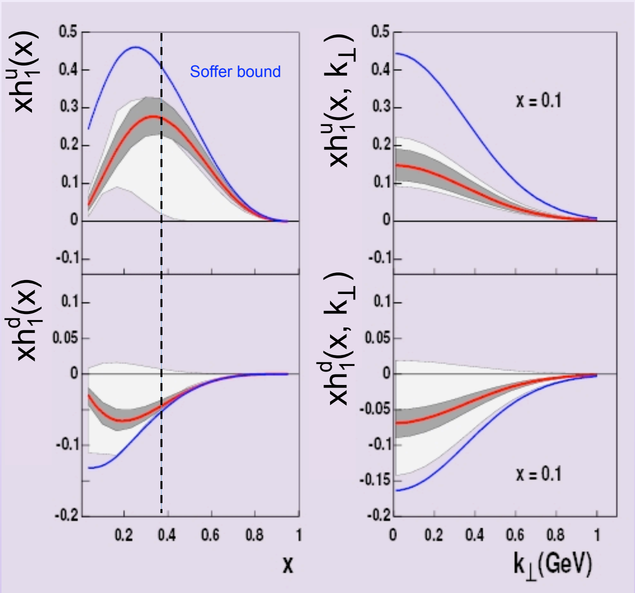
BELLE

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)} \propto \sin\vartheta\, h_1(x) \otimes H_1^{\sphericalangle q}(z)$$

Existing data limited to x < 0.3

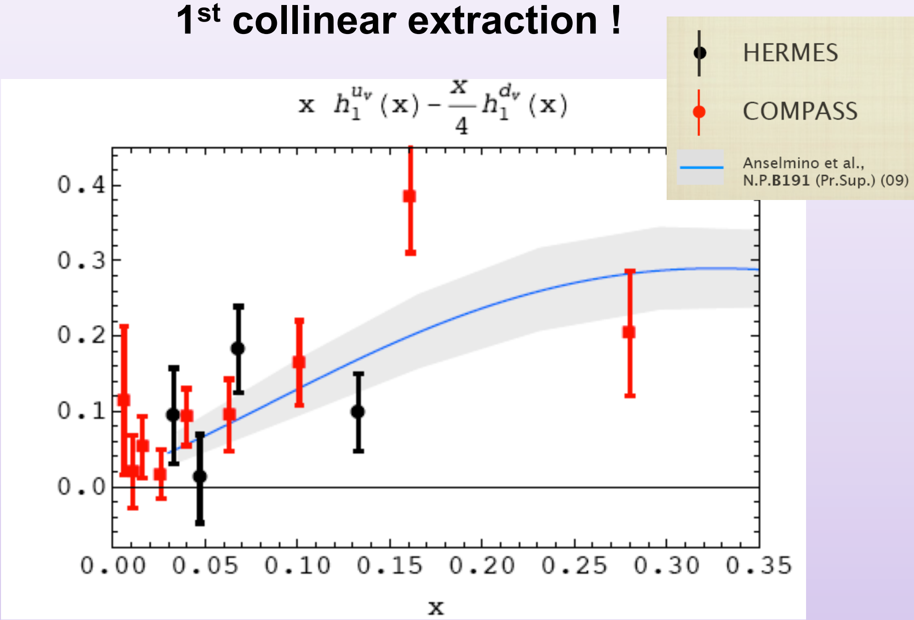
Evolution from high energy colliders

1st extraction of Transversity!



Anselmino et al. Phys. Rev. D 75 (2007)

1st collinear extraction !



Bacchetta et al., PRL 107 (2011)

Cahn & Boer-Mulders

nucleon polarisation

N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$ *Pretzelosity*

Naïve-T-odd
Chirally-odd
Spin effect in unpolarized reactions

(The Neglected Effects)

The Azimuthal Modulation

$h_1^\perp \otimes H_1^\perp$

$$\frac{d^5\sigma^{ep\to e'hX}}{dx\,dy\,dz\,d\phi\,dP_{h\perp}^2} \propto \{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \varepsilon s\cos(2\phi)F_{UU}^{\cos(2\phi)}\}$$

$\left(f_1 \otimes D_1\right)/Q$

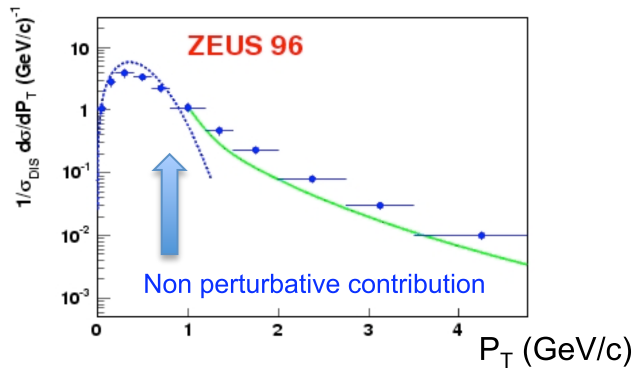
$h_1^\perp \otimes H_1^\perp$

Kinematical effect predicted since 1978
by Cahn due to non-zero intrinsic k_T

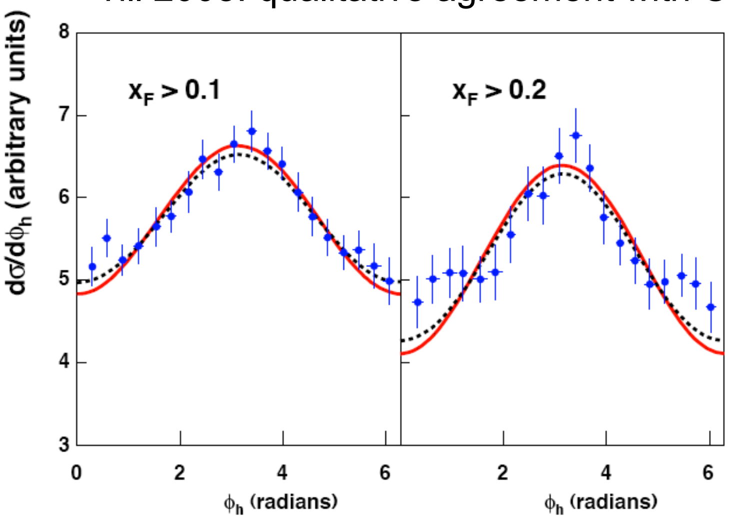
Cahn PLB 78 (1978)

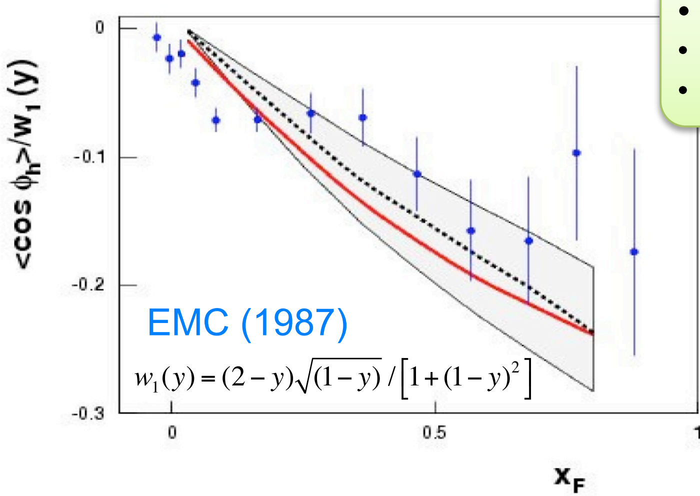
Leading-twist contribution introduced
by Boer & Mulders in 1998

Boer & Mulders PRD 57 (1998)



Till 2008: qualitative agreement with Cahn expectations





- No hadron identification
- No charge separation
- Poor statistics for cos2ϕ

Unpolarized Cross-section

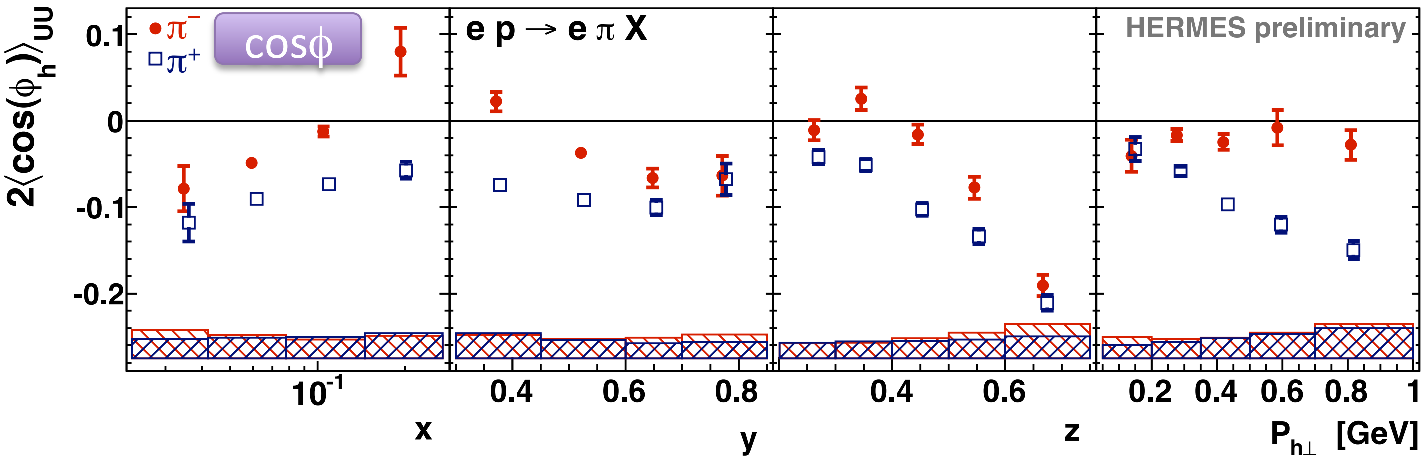
$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + \ldots \right] / Q$$

cosϕ large and negative !

Increasing with z and P_h

Large difference in hadron charge !

Larger in magnitude for π+



Unpolarized Cross-section

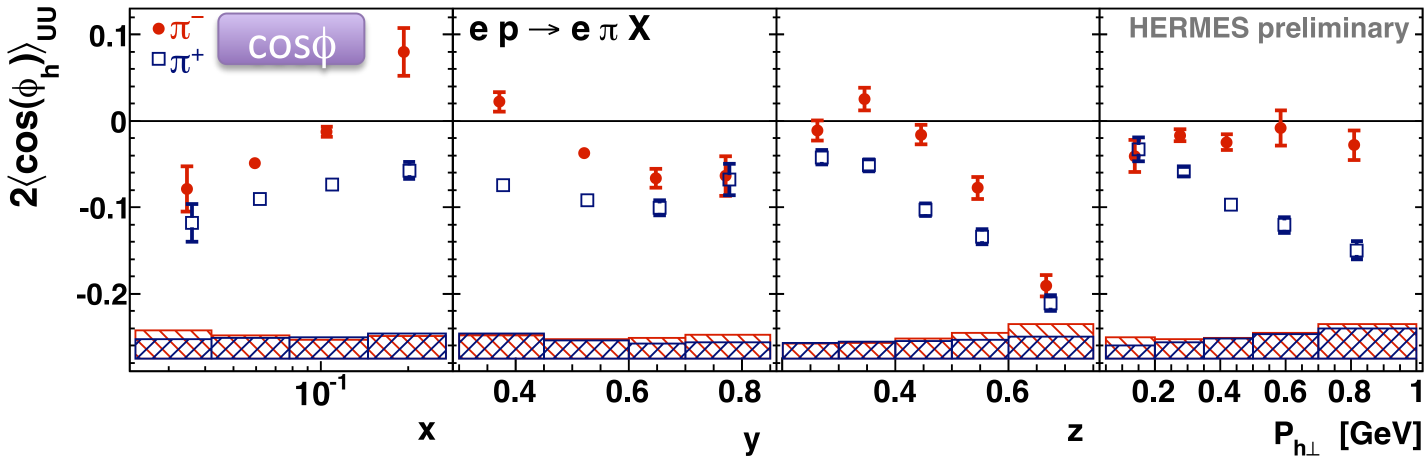
cosϕ large and negative !

$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + \ldots \right] / Q$$

Increasing with z and P_h

Large difference in hadron charge !

Larger in magnitude for π+



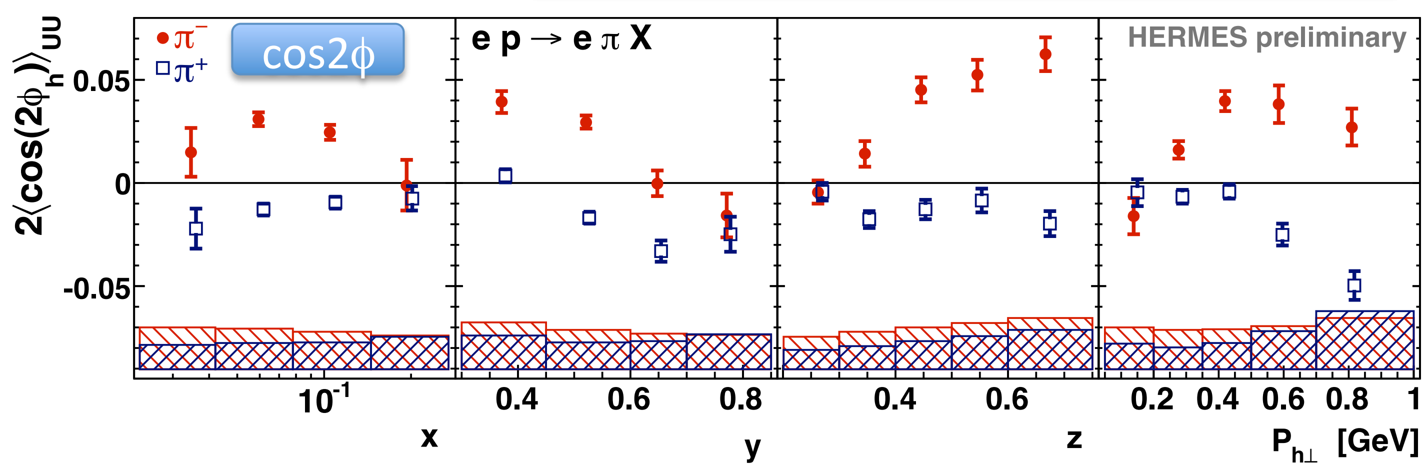
cos2ϕ non-zero !

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

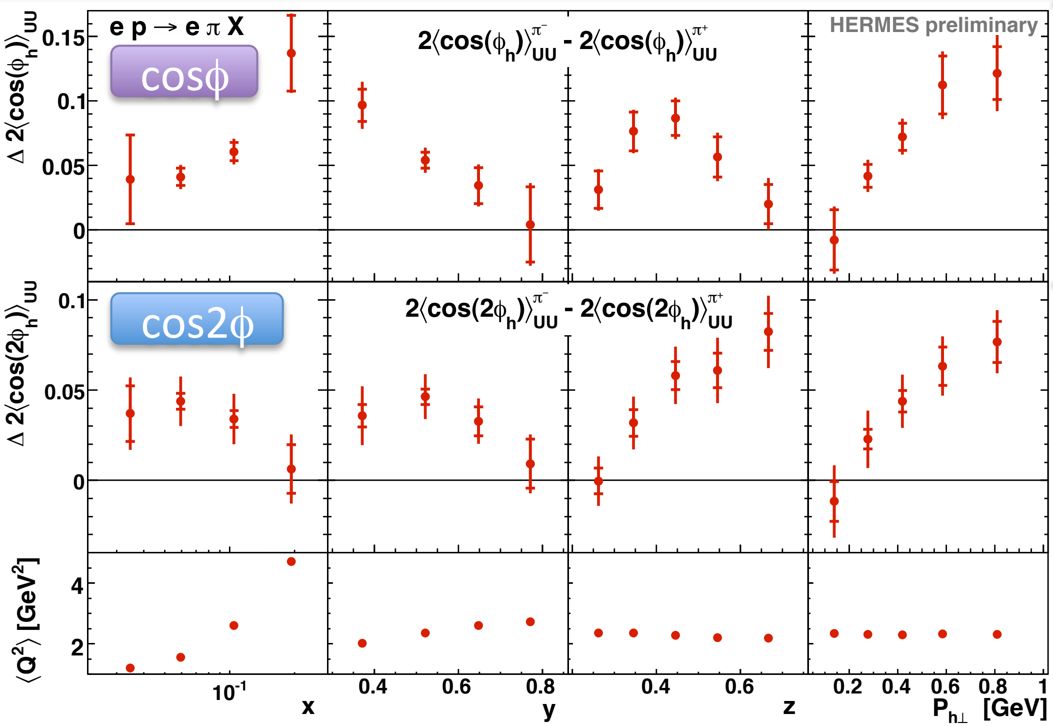
Difference in hadron charge !

Positive for π-

Negative for π+



Difference in pion charge



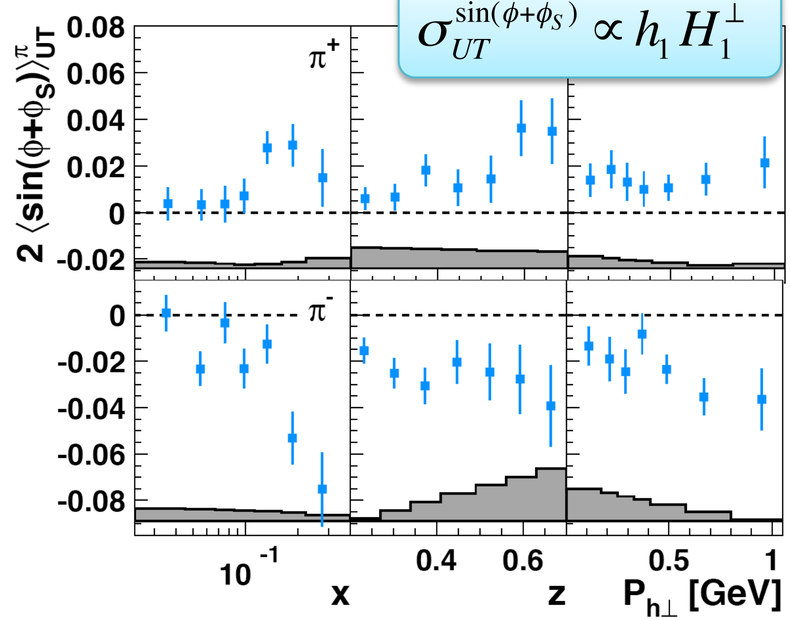
$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^{\perp} \otimes H_1^{\perp} + \ldots \right] / Q$$

$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

Mild flavor dependendence of k_T expected

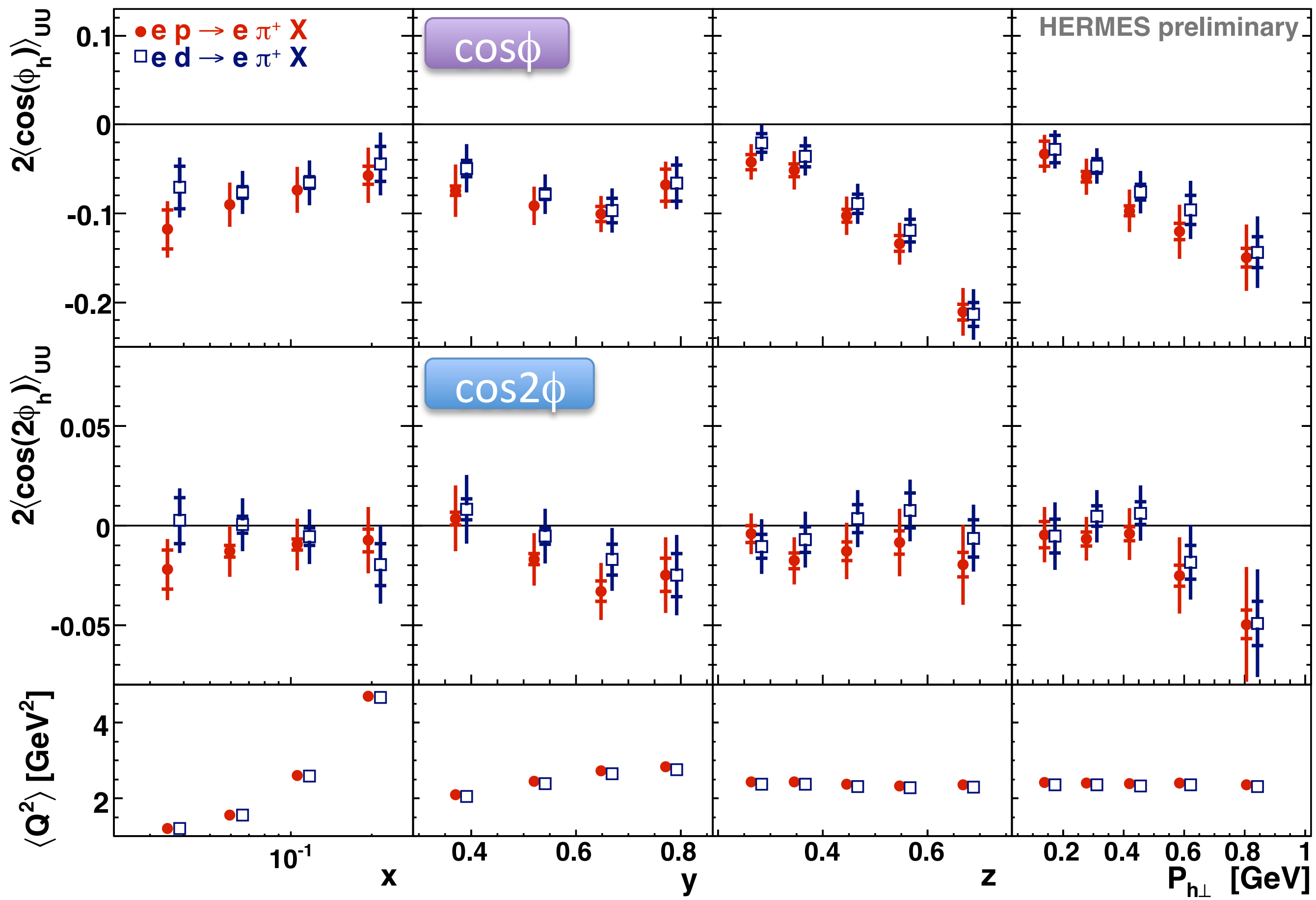
From A_{UT}: Collins favored (u → π+) and unfavored (u → π-) fragmentation opposite in sign

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^{\perp}$$



With u-dominance
Collins makes the difference !
Hint of non-zero Boer-Mulders

Proton vs Deuteron Target



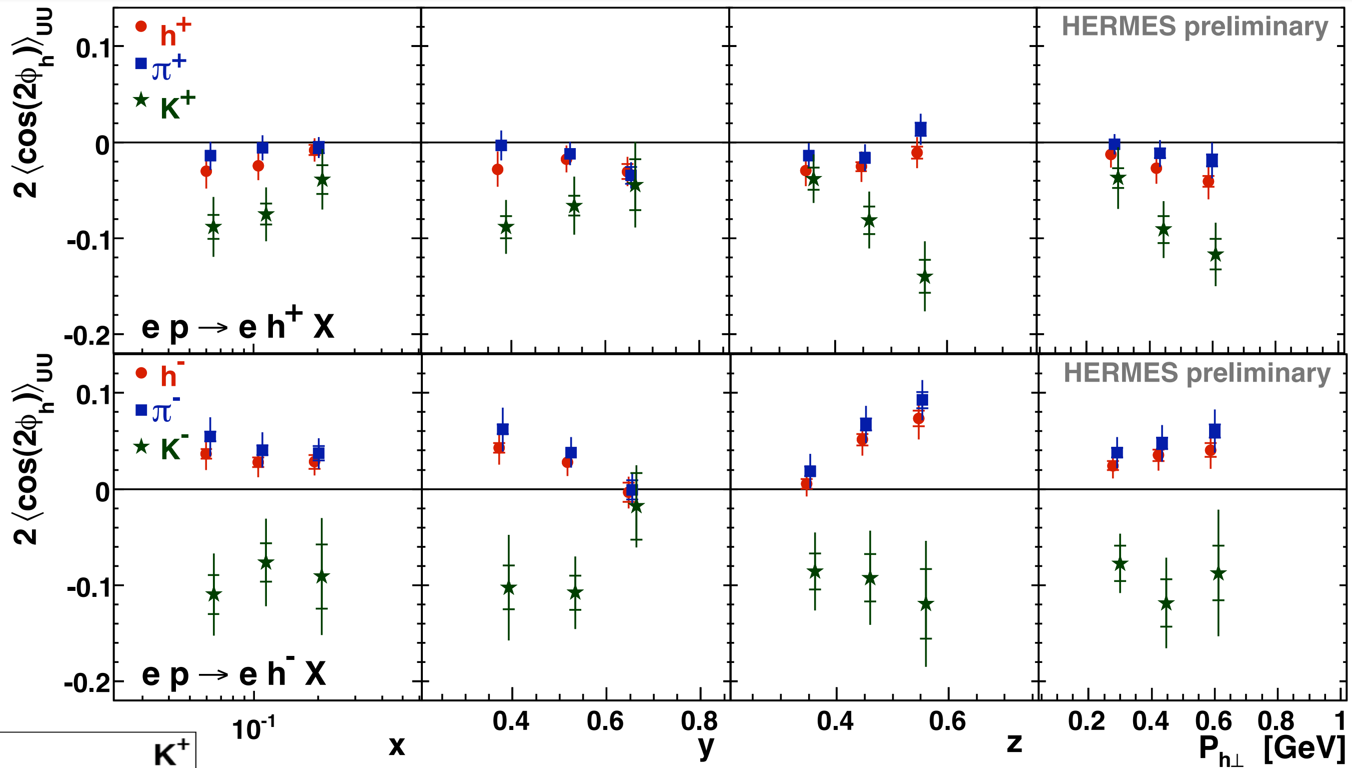
Quark d vs u contribution ?
DATA support Boer-Mulders of same sign for u and d

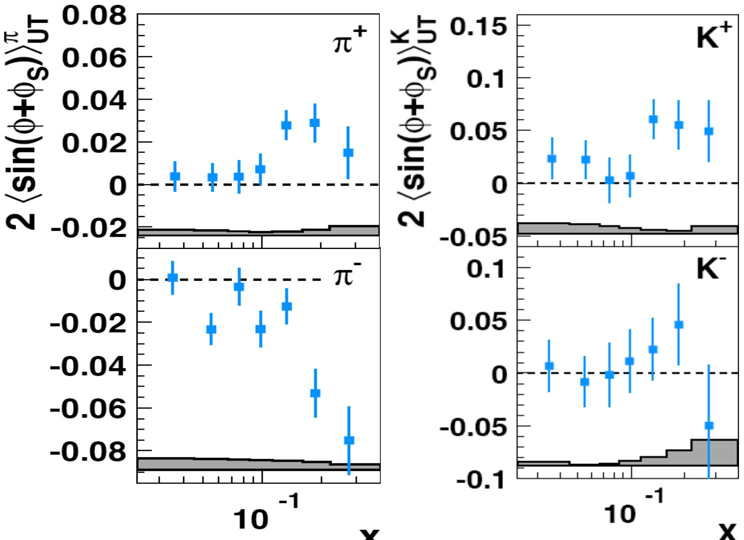
Kaon Signals

Striking difference versus pions !

- Role of the sea
- Strange Collins
- Sub-leading twists

$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 H_1^{\perp}$$





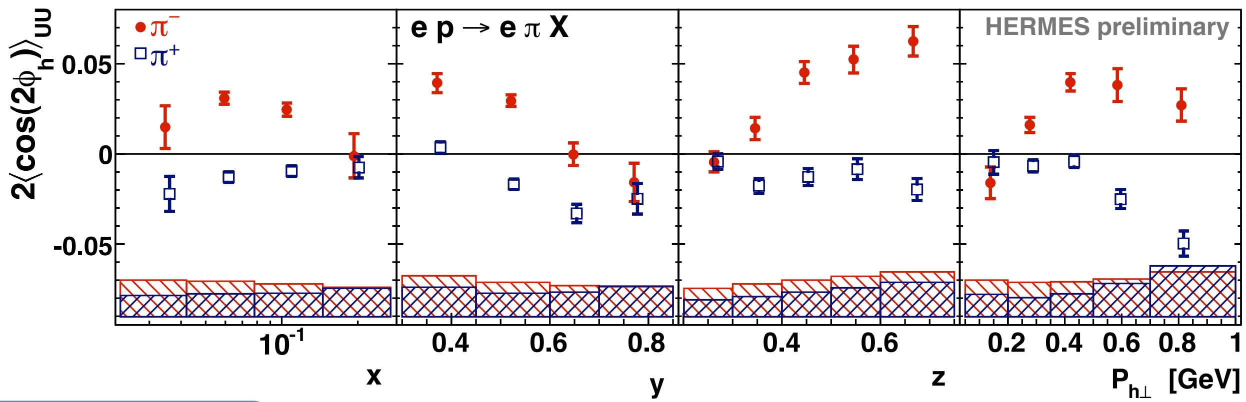
$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^{\perp} \otimes H_1^{\perp} + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$

Unpolarized cross-section:
any precision measurement
should account for these effects

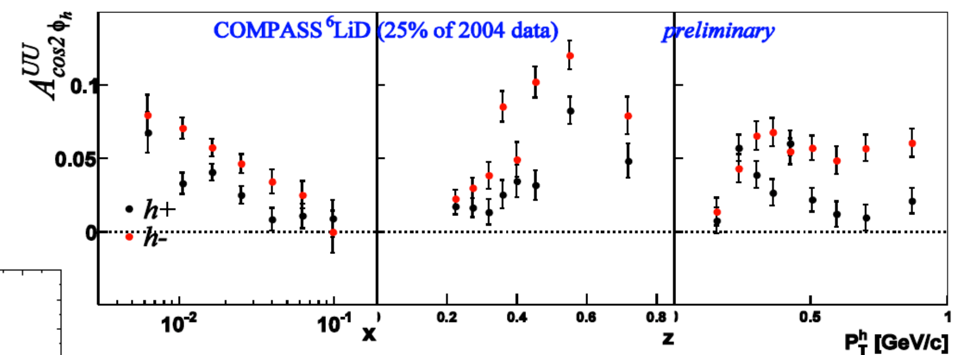
The SIDIS cos2ϕ Dependence

$h_1^\perp \otimes H_1^\perp$

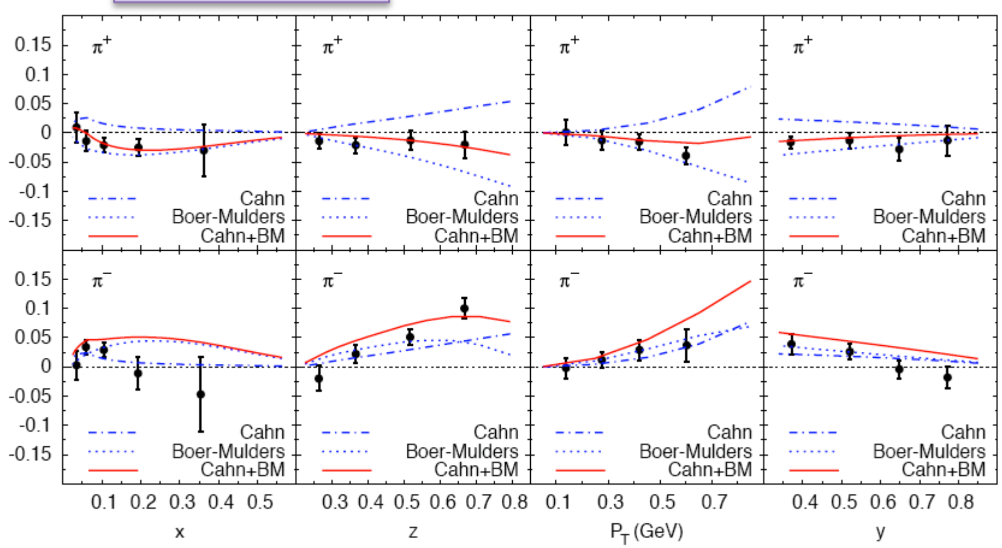
Issue: are π+ DATA consistent ??



$$\sigma_{UU}^{\cos(2\phi)} \propto h_1^\perp \otimes H_1^\perp + \left[f_1 \otimes D_1 + \ldots \right] / Q^2$$



arXiv: 0912.5194



Can be explained by large uncertainty on Cahn
- k_T evolution
- k_T cutoff

and neglected HT effects

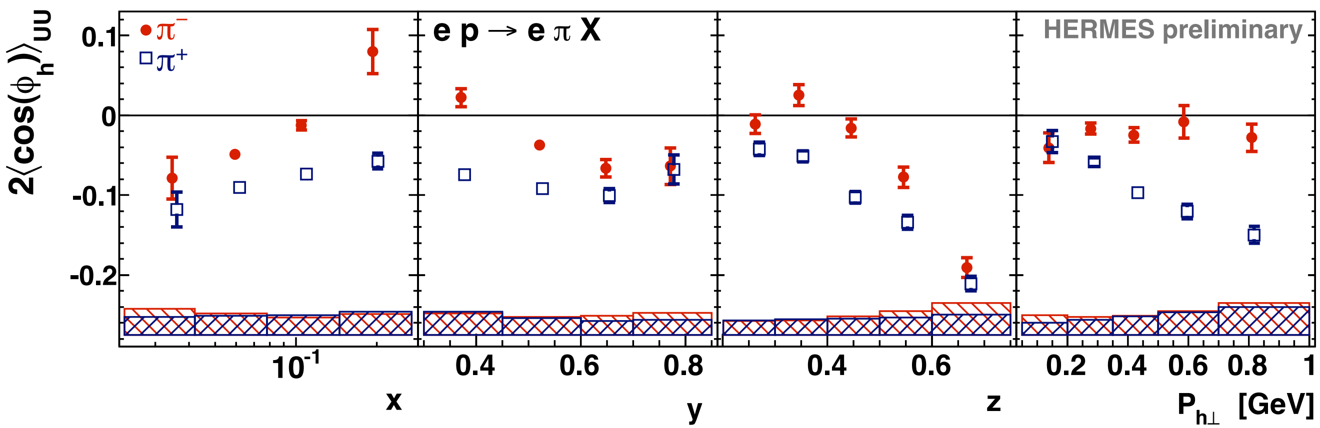
The SIDIS cosφ Dependence

$f_1 \otimes D_1$

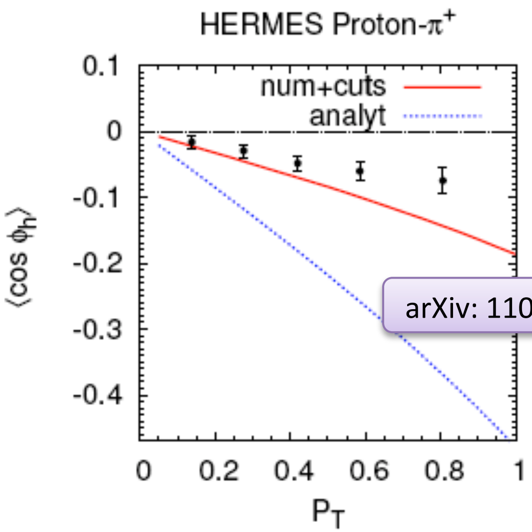
Significant difference in hadron charge might signal $h_1^\perp \otimes H_1^\perp$

$$\sigma_{UU}^{\cos(\phi)} \propto \left[f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp + \ldots \right] / Q$$

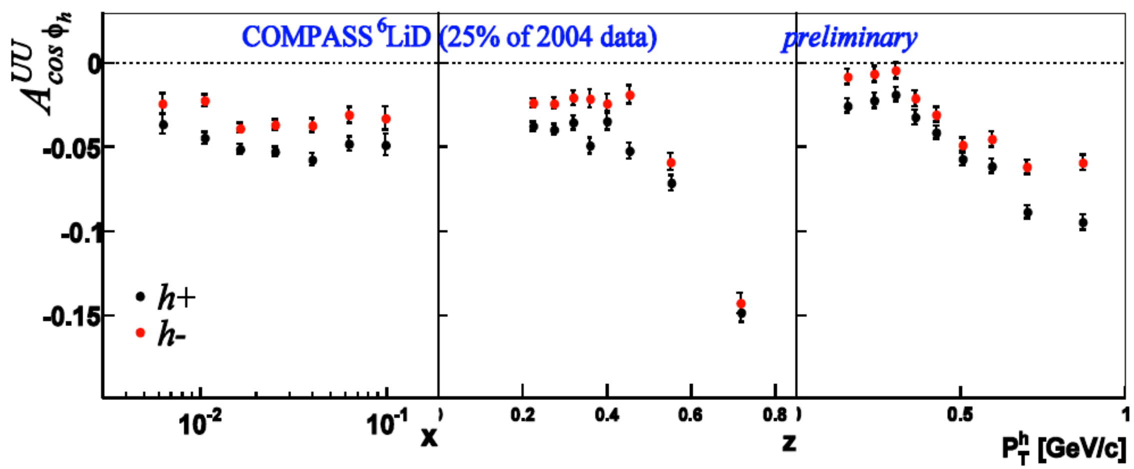
Issue: much lower than expected ??



Expectations largely sensitive on $\langle k_T \rangle$ and k_T cutoff



arXiv: 1106.6177

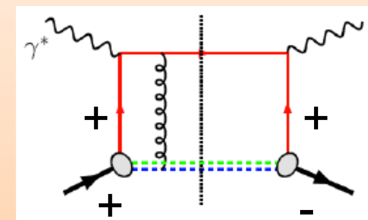


Sivers

N/q	U	L	T
U	f_1 *Number Density*		$h_1^{\perp}$ *Boer-Mulders*
L		g_1 *Helic*	*Worm-gear*
T	$f_{1T}^{\perp}$ *Sivers*	$g_{1T}^{\perp}$ *Worm-gear*	h_1 *Transversity* $h_{1T}^{\perp}$ *Pretzelosity*

nucleon polarisation

Naïve-T-odd
Non-trivial gauge link



Process dependence

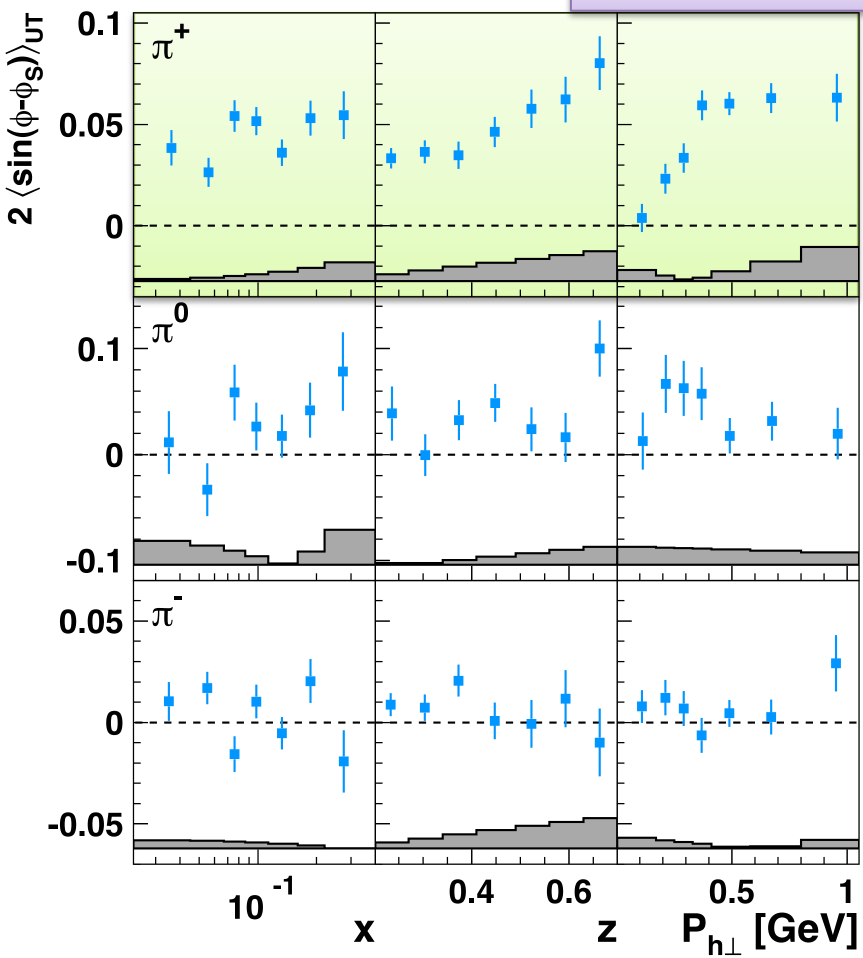
(The TMD Challenge)

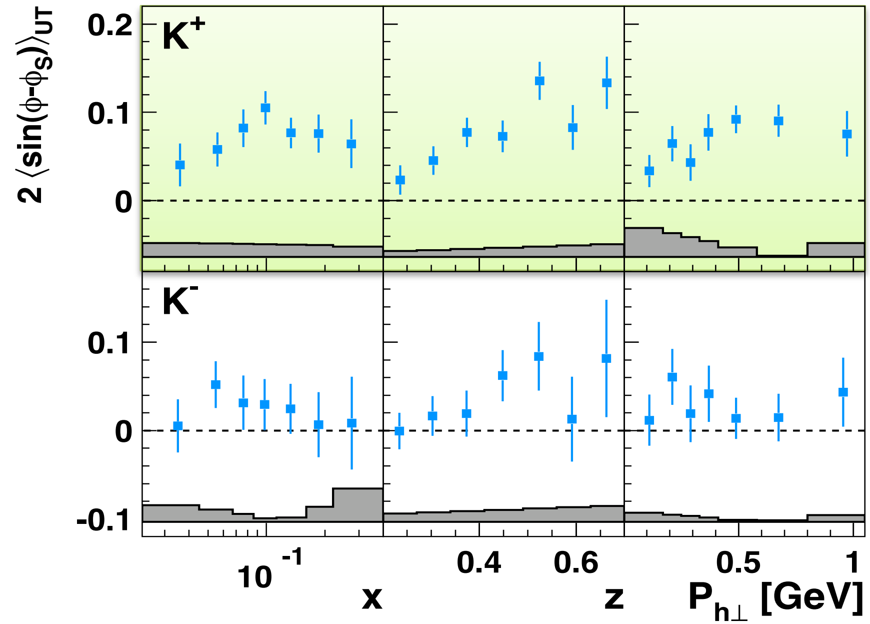
The Sivers Amplitude

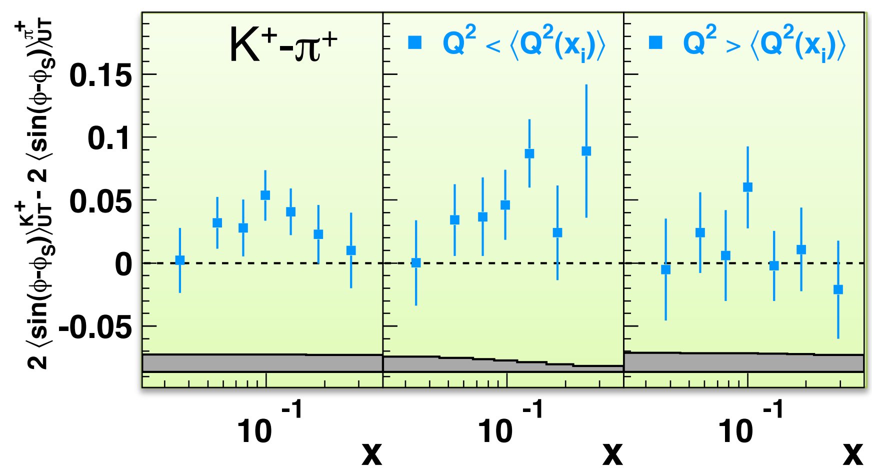
Pion electro-production on proton:

- ❖ Clear singal for π^+ and for pion difference
- ❖ Isospin symmetry fulfilled

PRL 103 (2009) 152002



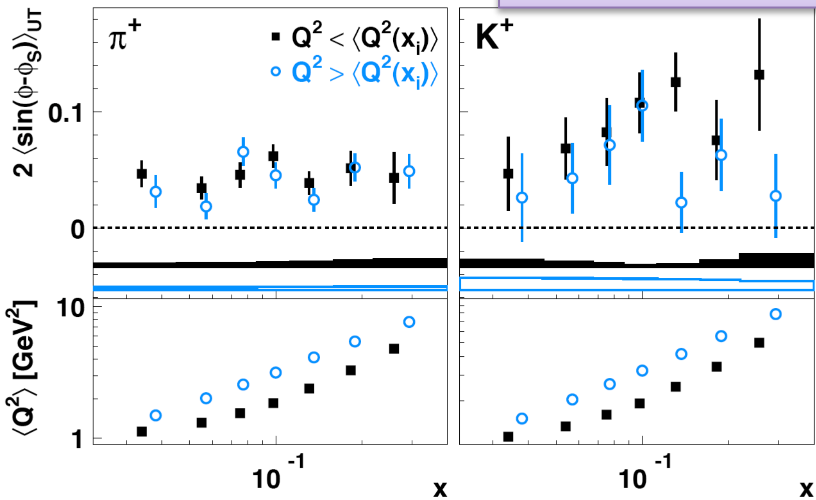


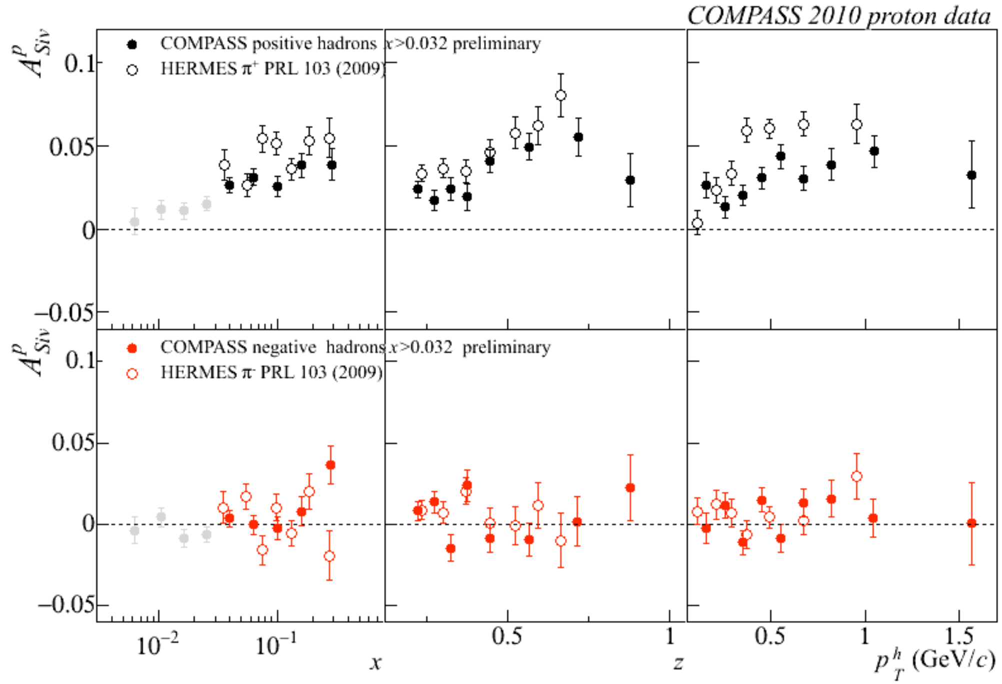


The Sivers Signals

$f_{1T}^{\perp} \otimes D_1$

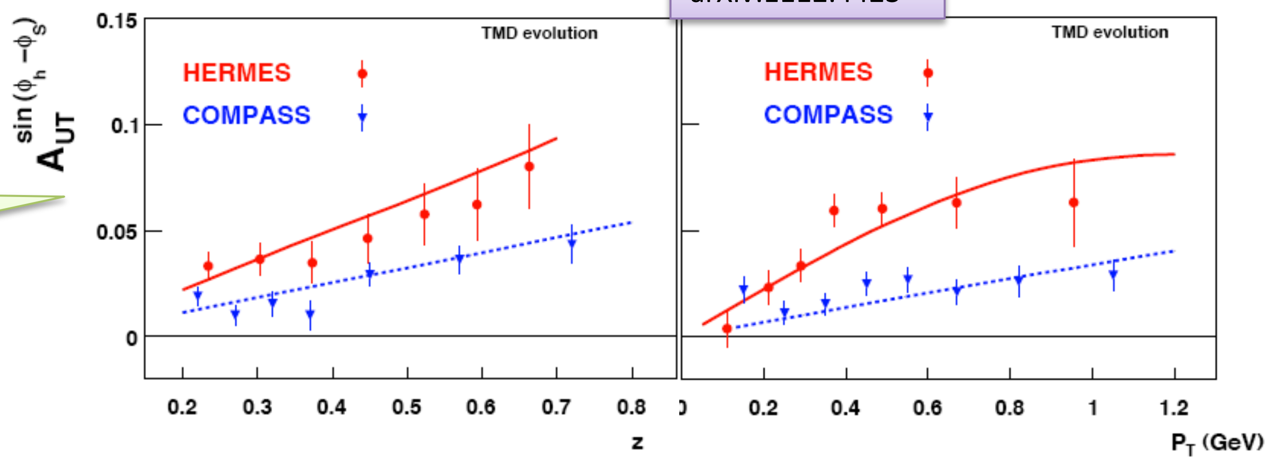
PRL 103 (2009) 152002





No evidence for twist-4 ($1/Q^2$) contribution

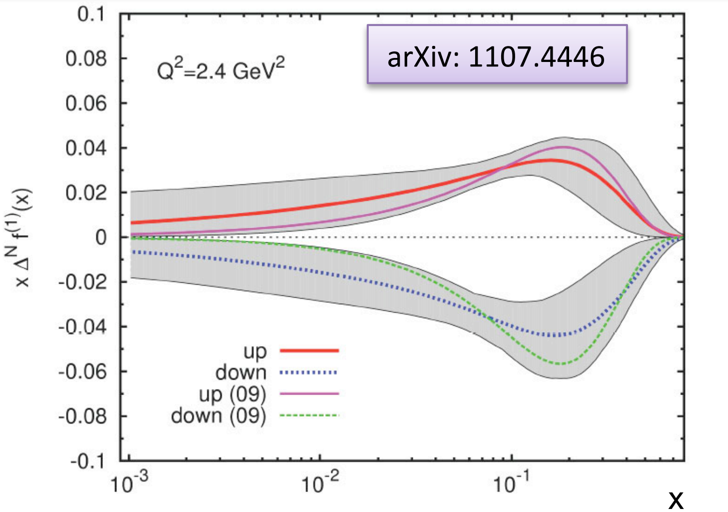
arXiv:1112.4423



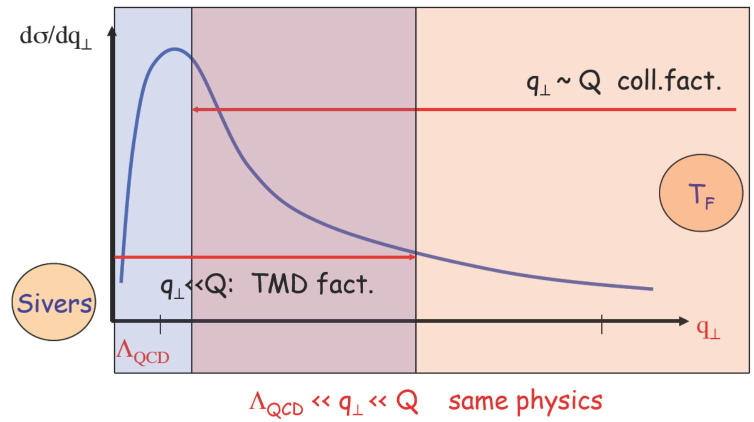
HERMES vs COMPASS comparison:
are data consistent ?

The Sivers Challenges

$f_{1T}^{\perp} \otimes D_1$



Coverage at large p_T and relation with twist-3 collinear approach

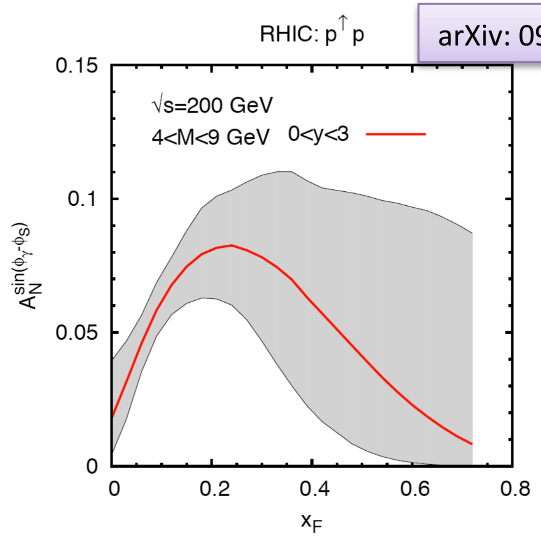


Sivers effect from SIDIS to Drell-Yan:

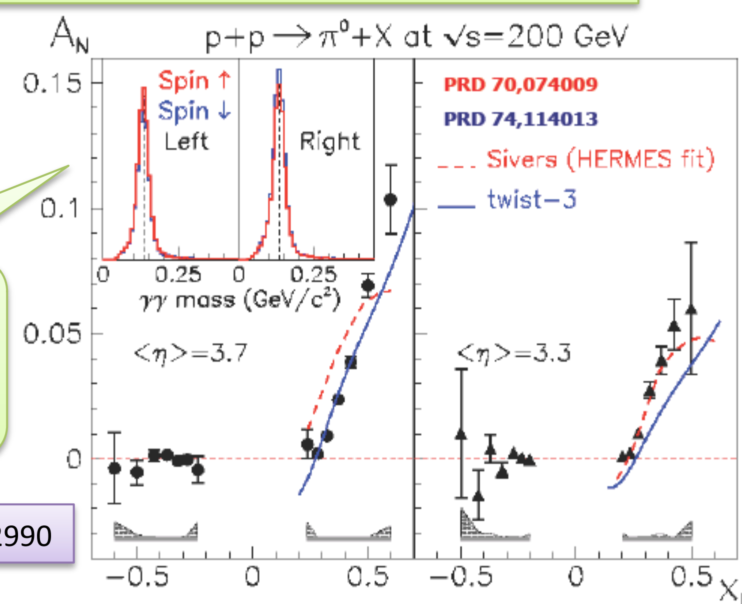
Sign change as a crucial test of TMDs factorization

Sivers effect from SIDIS to pp:

A possible candidate to explain SSA

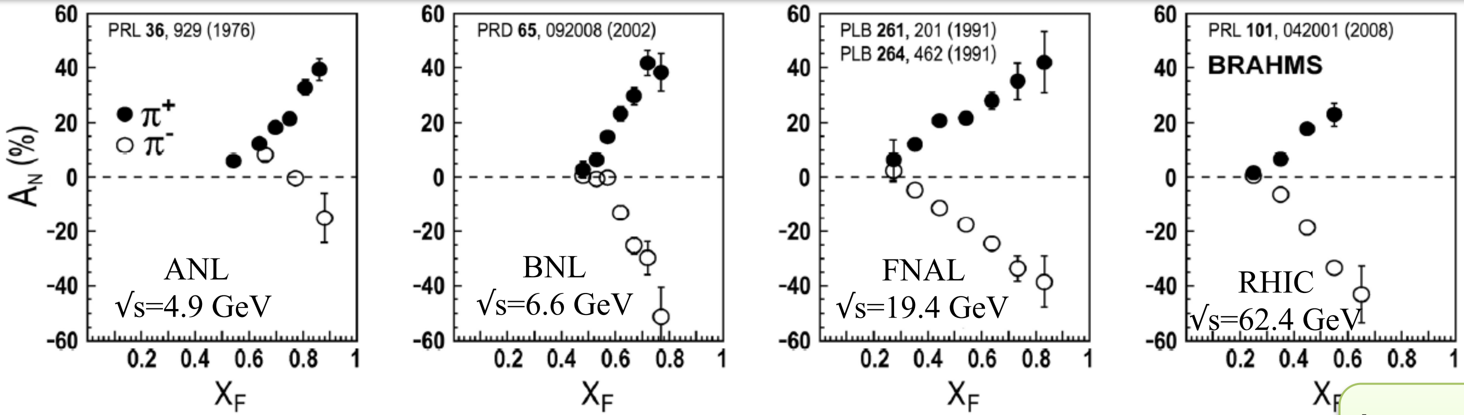


Sivers from SIDIS and collinear twist-3 as candidates for SSA explanation



arXiv: 0801.2990

The Inclusive Hadron SSA



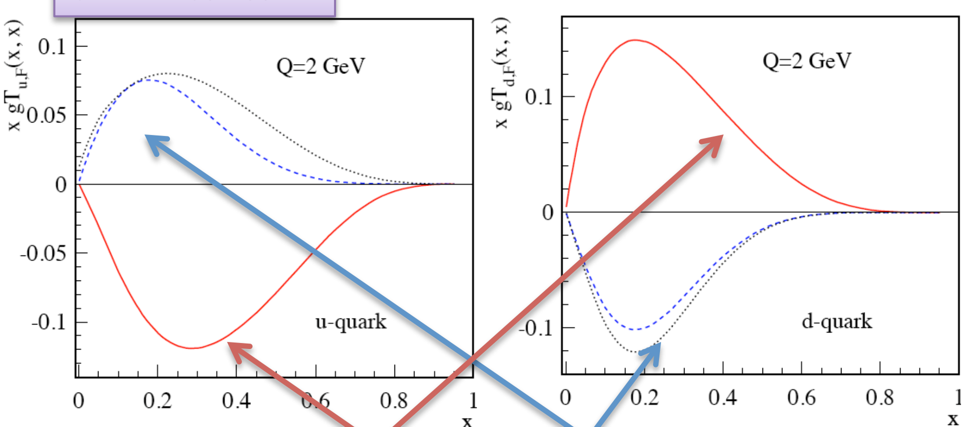
Persistent with energy

Sivers effect from SIDIS to pp:

Sign mismatch between SIDIS and pp SSA ?

$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\text{SIDIS}}$$

arXiv: 1103.1591

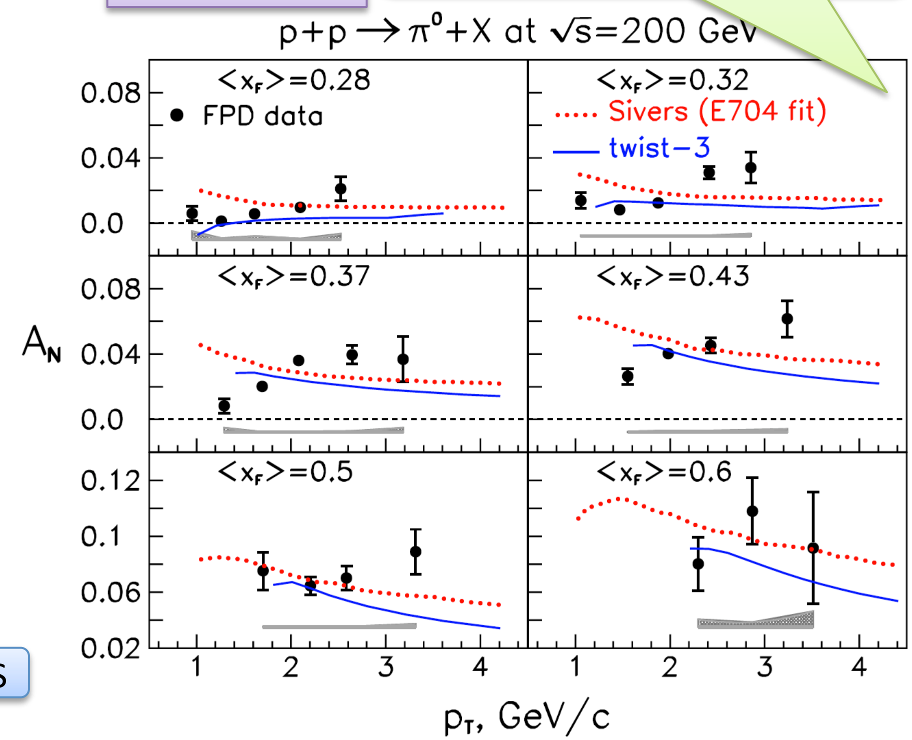


T3 correlator from pp

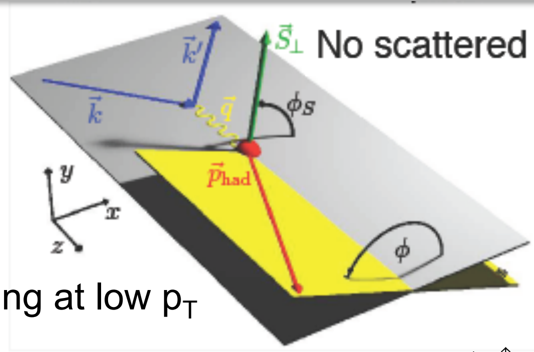
Sivers moment from SIDIS

arXiv: 0801.2990

Asymptotic $1/p_T$ not reached
Issues on factorization



Inclusive Hadron SSA in SIDIS



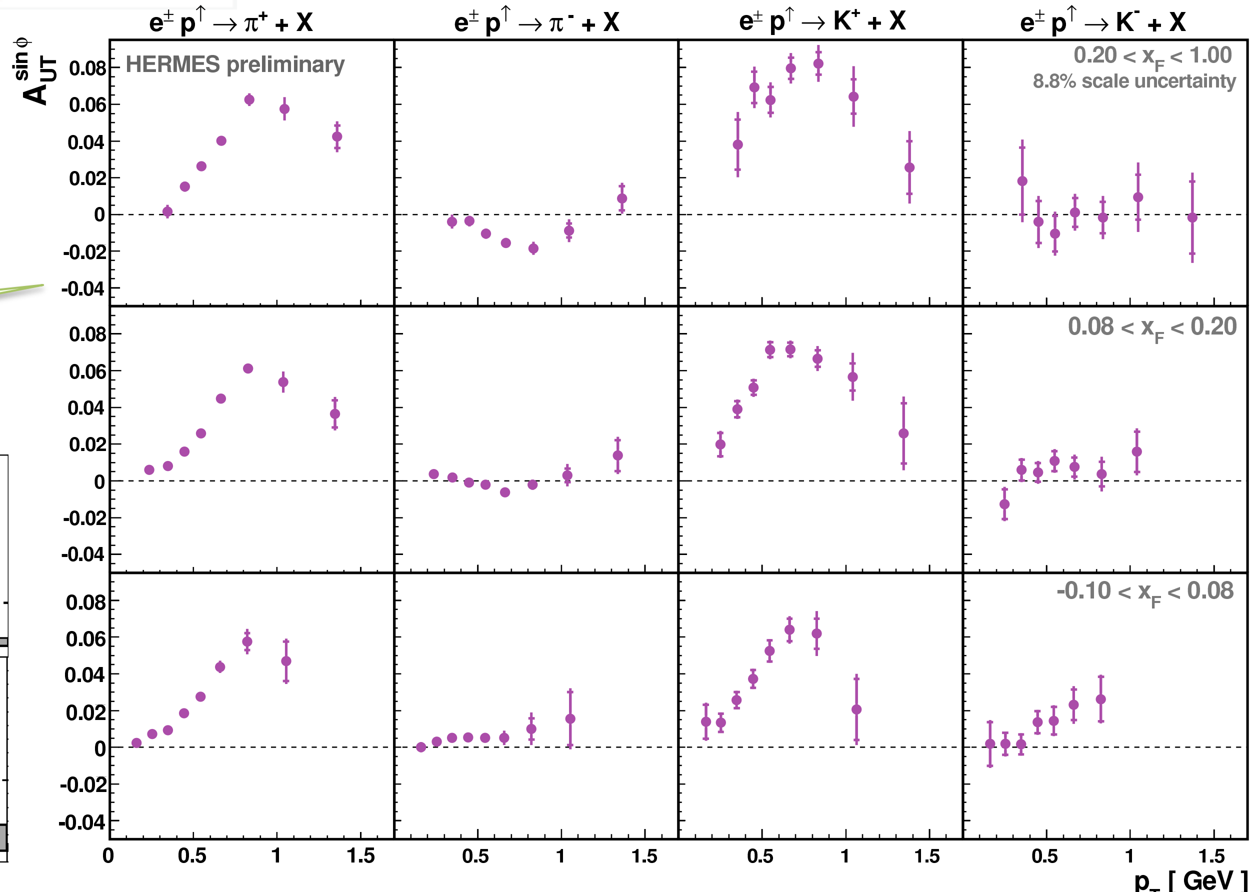
No scattered beam detected → **p_T, x_F** with respect to **e beam** (not q-vector)

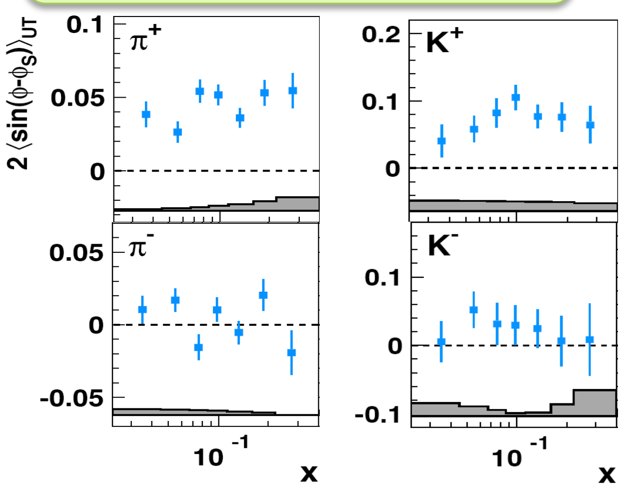
Sivers modulation $\sin(\phi-\phi_S)$ can survives as $\sin(\phi)$

$$A(x_F, p_T, \phi) = \frac{\sigma_{UT}(x_F, p_T, \phi)}{\sigma_{UU}(x_F, p_T)} = A_{UT}^{\sin\phi}(x_F, p_T)\sin\phi$$

- A_{UT} is vanishing at low p_T
- Q^2 increases with p_T approaching DIS regime
- Study transition from perturbative to non-perturbative regime

Non-zero signals for positive hadrons resembling Sivers





Pretzelosity

nucleon polarisation

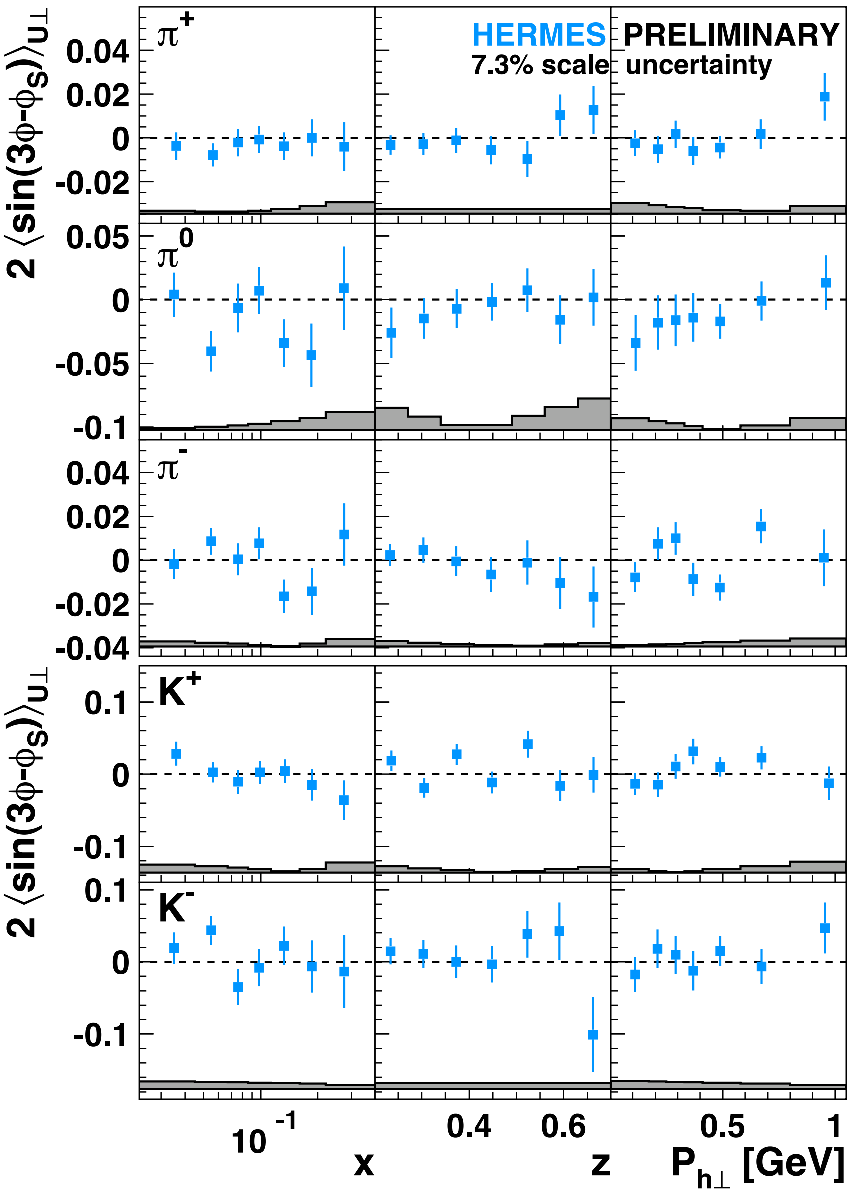
N/q	U	L	T
U	f_1 *Number Density*		$h_1^\perp$ *Boer-Mulders*
L		g_1 *Helicity*	$h_{1L}^\perp$ *Worm-gear*
T	$f_{1T}^\perp$ *Sivers*	$g_{1T}^\perp$ *Worm-gear*	h_1 *Transversity* $h_{1T}^\perp$ *Pretzelosity*

Sensitive to the D-wave component and the non spherical shape of the nucleon

(The D-Wave)

The Pretzelosity

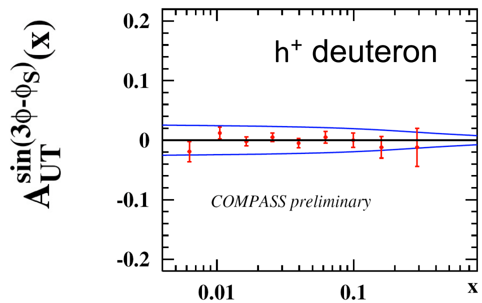
$h_{1T}^{\perp} \otimes H_1^{\perp}$

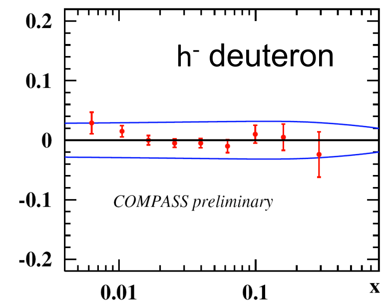


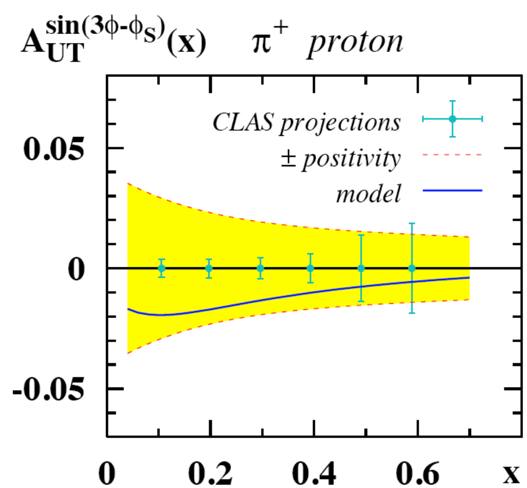
Statistical power of existing data is not enough to observe significant signals

$$h_{1T}^{\perp(1)q}(x) = g_1^q(x) - h_1^q(x)$$ no-gluon models

$$\left|h_{1T}^{\perp(1)q}(x)\right| + \left|h_1^q(x)\right| \le f_1^q(x)$$ positivity bound







Positivity bound

Avakian, PRD78

Covariant model

arXiv: 0812.3246

Worm Gear

nucleon polarisation

N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ - Boer-Mulders
L		g_1 - Helicity	$h_{1L}^\perp$ - Worm-gear
T	$f_{1T}^\perp$ - Sivers	$g_{1T}^\perp$ - Worm-gear	h_1 - Transversity $h_{1T}^\perp$ - Pretzelosity

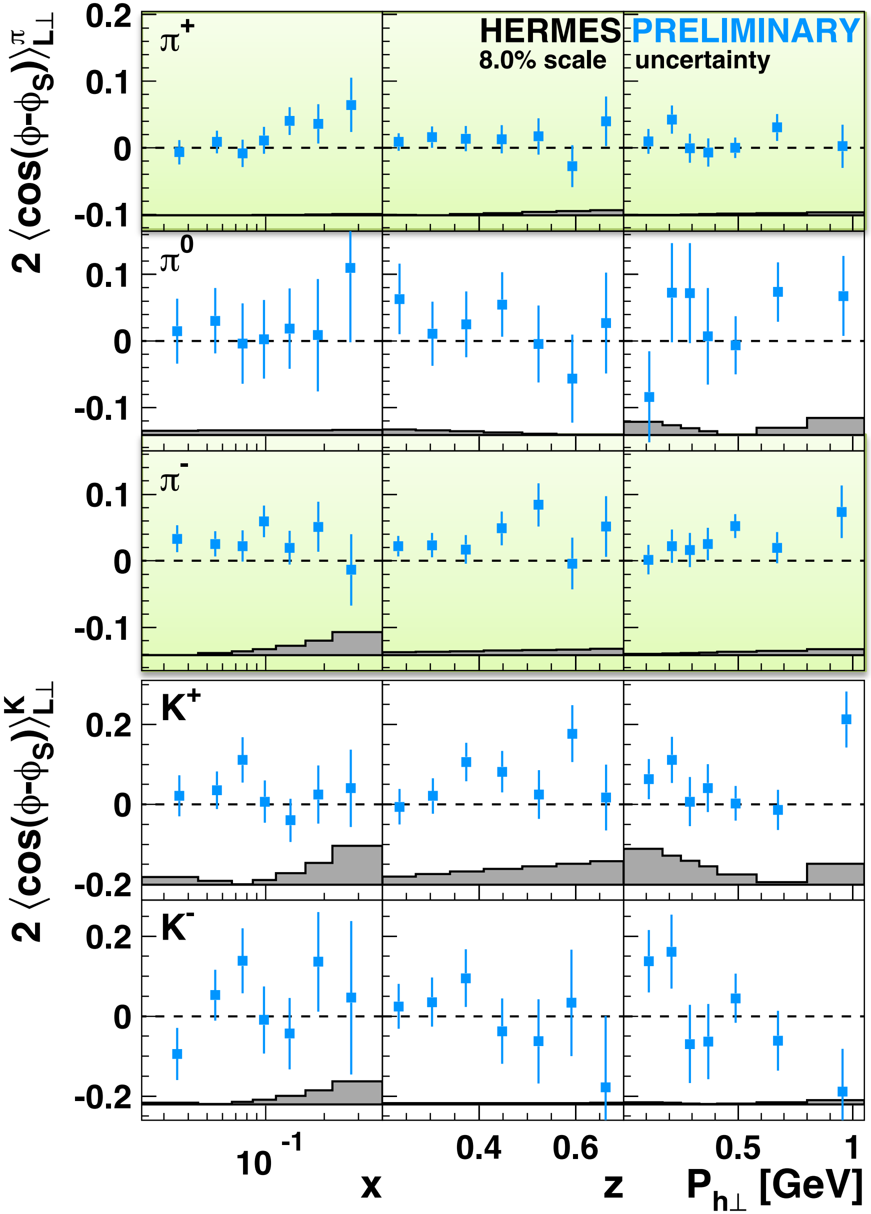
Proton wave-components with different OAM

The only T-even and chirally-even off-diagonal TMD

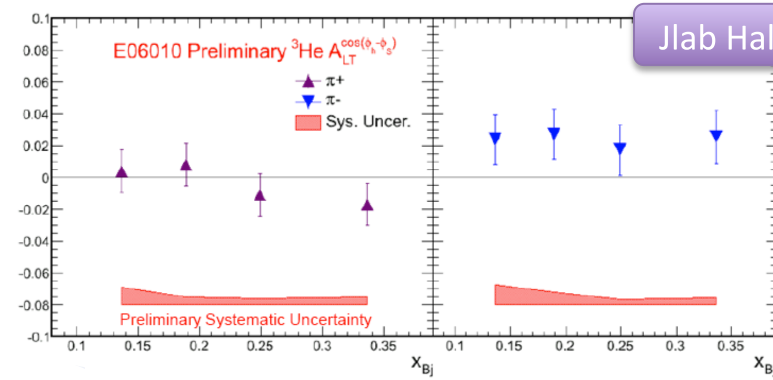
(The Standard OAM Effect)

The $A_{LT}^{\cos(\phi-\phi_S)}$ Asymmetry

$g_{1T}^{\perp} \otimes D_1$



Jlab Hall-A n



Hint of non-zero signals

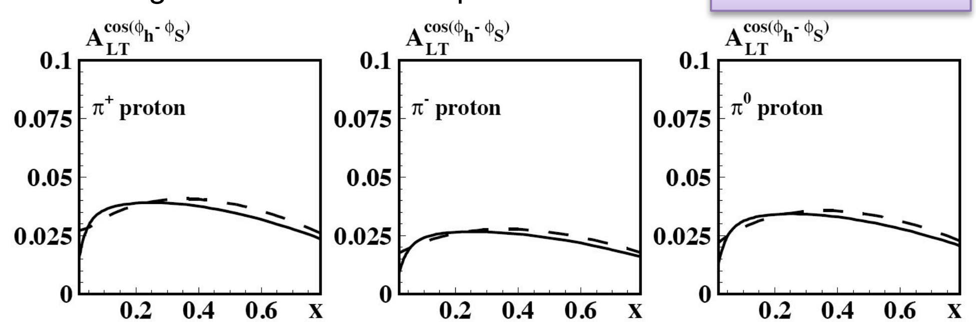
Statistics not enough to investigate relations supported by many theoretical models:

$$g_{1T}^{q} = -h_{1L}^{\perp q}$$ (supported by Lattice QCD and first data)

$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} g_1^q(y)$$ (Wandura-Wilczek type approximation)

From light-cone constituent quark model:

arXiv: 0903.1271

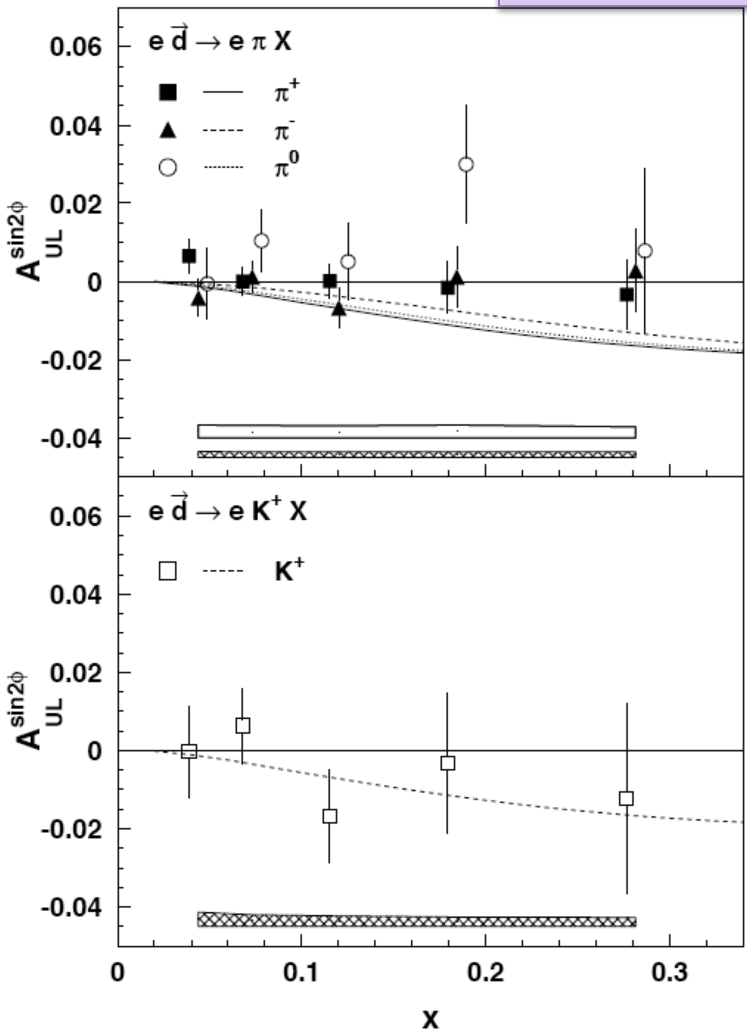


The $A_{UL}^{\sin(2\phi)}$ Asymmetry

$h_{1L}^{\perp} \otimes H_1^{\perp}$

Deuteron

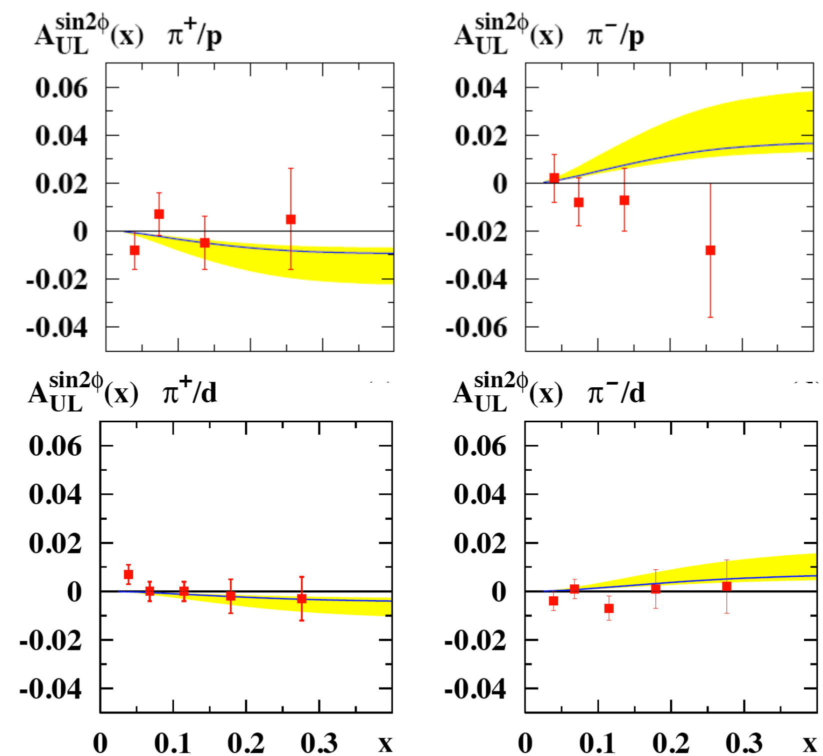
PLB 562 (2003) 182



Statistics not enough to investigate relations supported by many theoretical models:

$g_{1T}^{q} = -h_{1L}^{\perp q}$ (supported by Lattice QCD and first data)

$$h_{1L}^{q(1)}(x) \overset{WW-type}{\approx} -x^2 \int_x^1 \frac{dy}{y^2} h_1^q(y)$$ (Wandura-Wilczek type approximation)



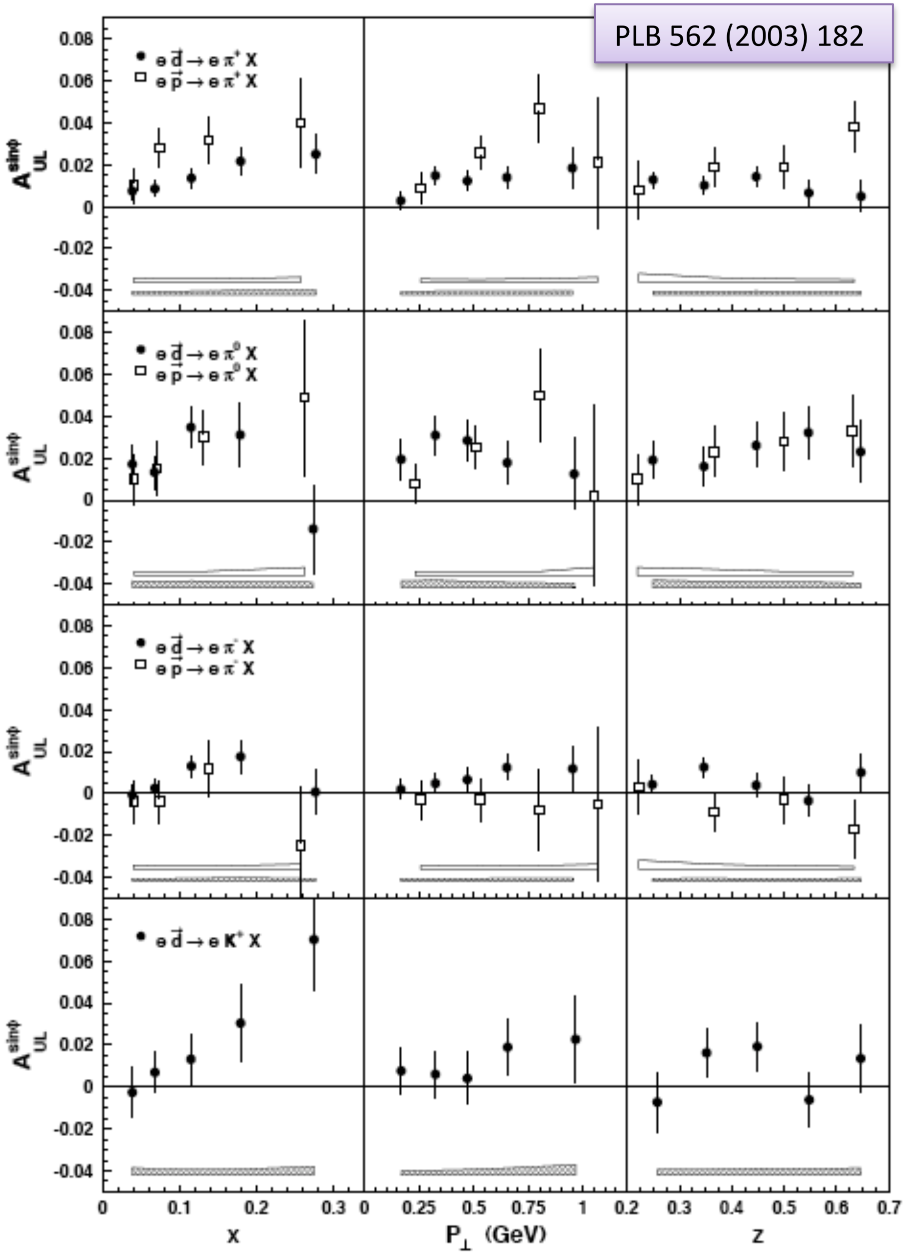
chiral quark soliton model

arXiv: 0902.0689

The $A_{UL}^{\sin(\phi)}$ Asymmetry

$h_L \otimes H_1^{\perp}$

PLB 562 (2003) 182



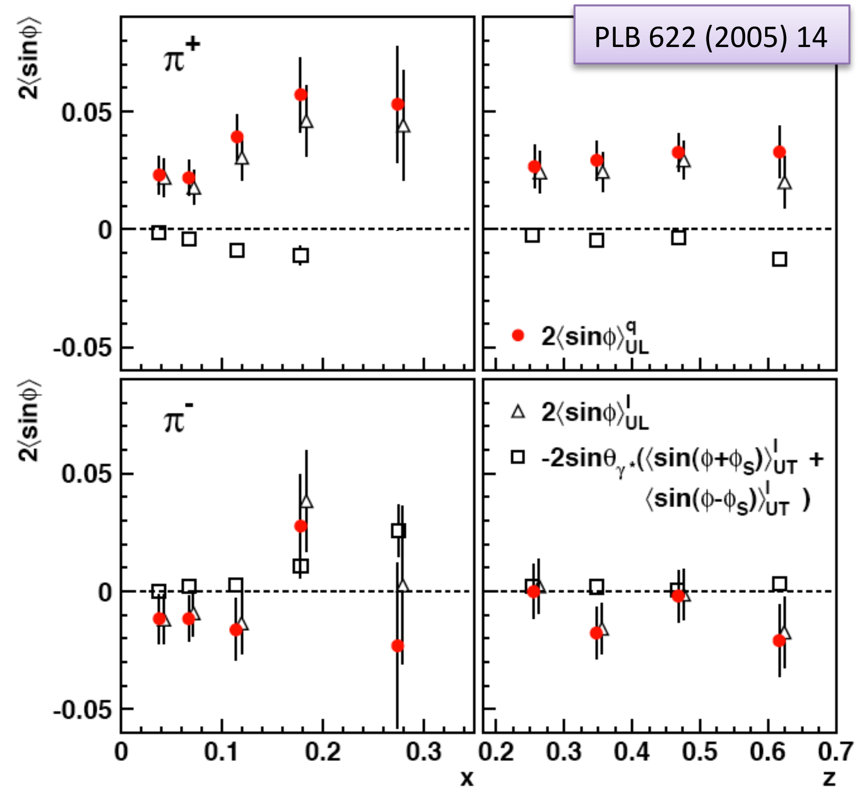
Non zero

Negligible contribution from transverse target spin (w.r.t. virtual photon):

$$F_{UL}^{\sin(\phi)} \overset{WW}{\propto} \left[h_{1L}^{\perp} \otimes H_1^{\perp} + g_{1L} \otimes H_1^{\perp} + \ldots \right] / Q$$

(Wandura-Wilczek type approximation)

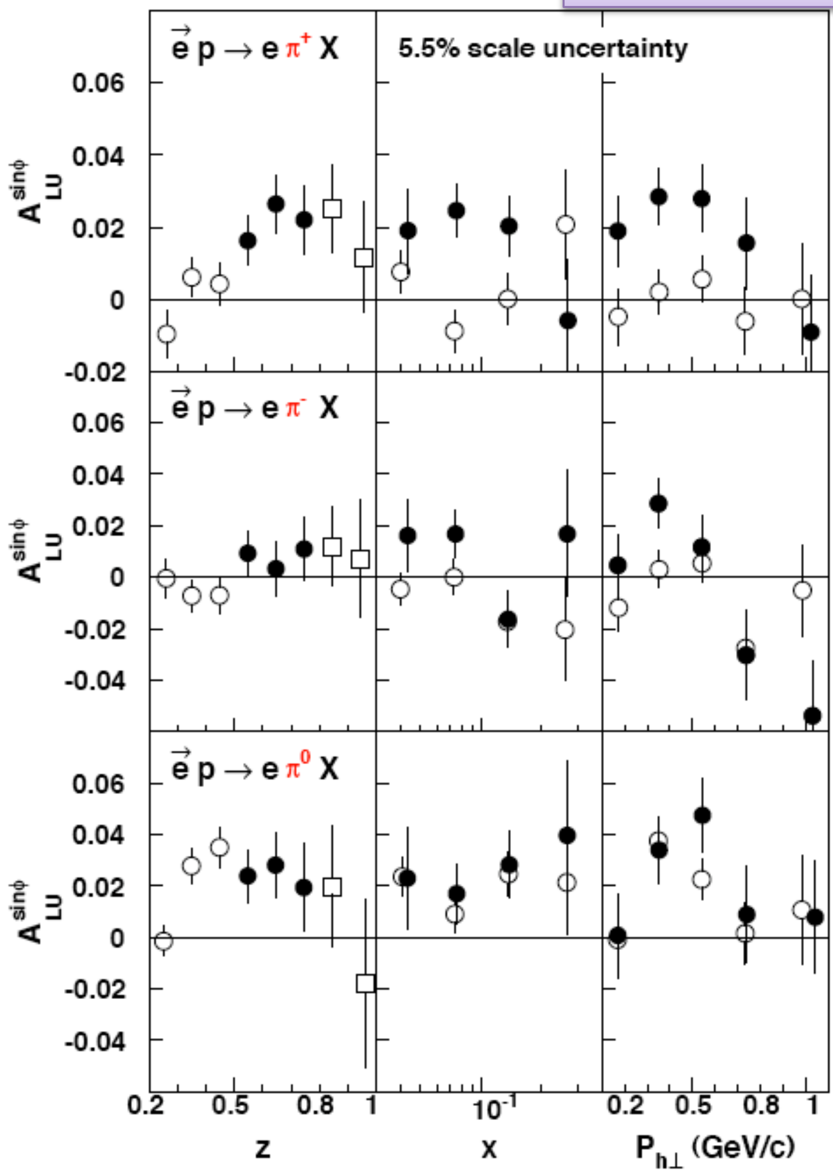
PLB 622 (2005) 14



The $A_{LU}^{\sin(\phi)}$ Asymmetry

$e \otimes H_1^{\perp}$

PLB 648 (2007) 164

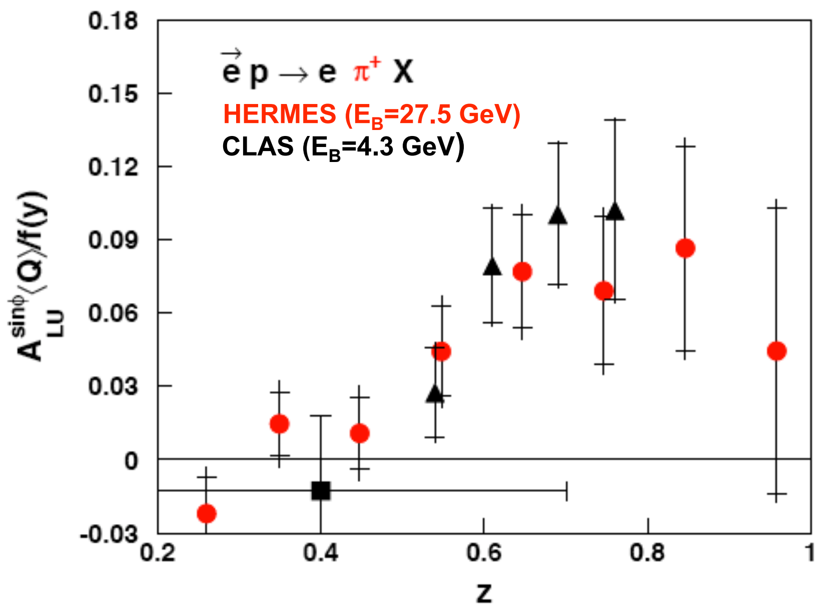


Non zero

Negligible contribution from transverse target spin (w.r.t. virtual photon):

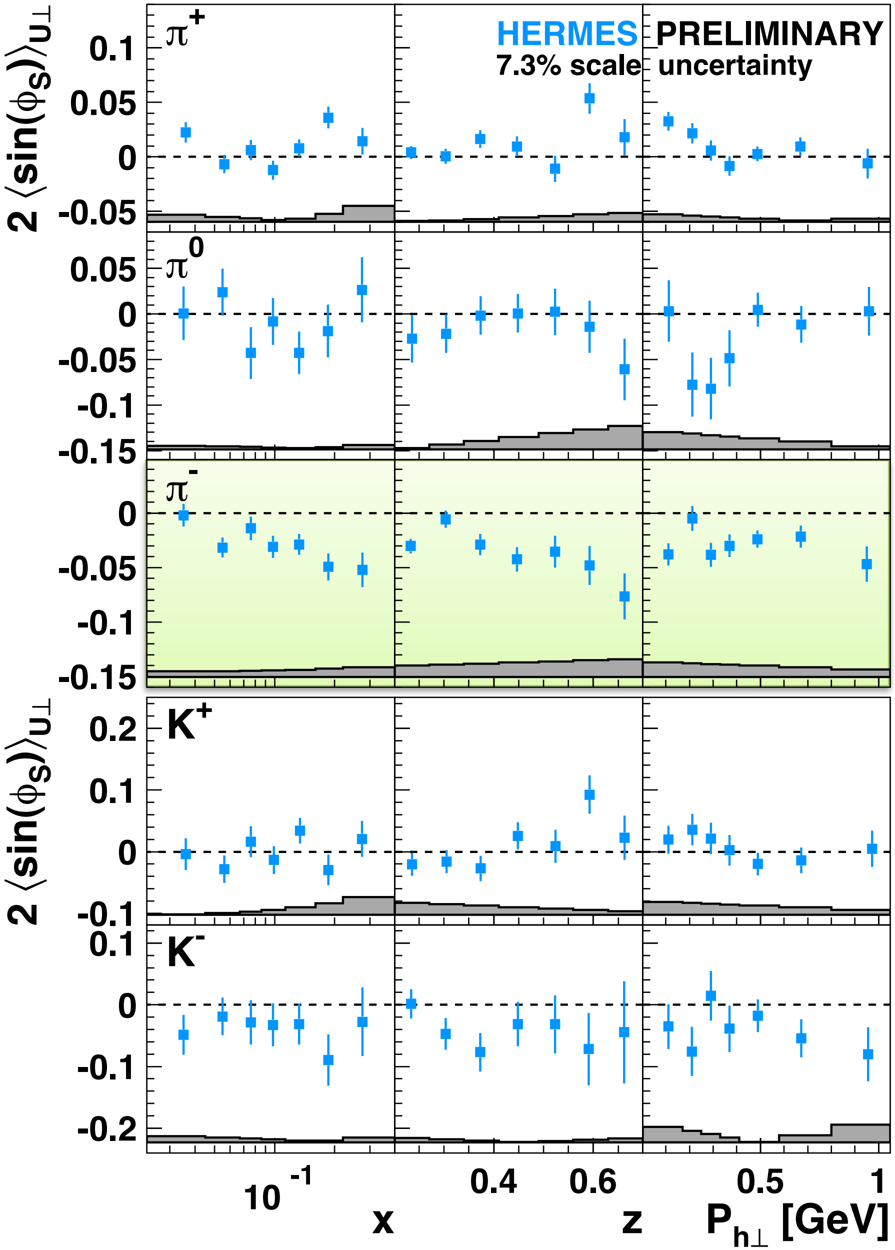
$$F_{UL}^{\sin(\phi)} \overset{WW}{\propto} \left[e \otimes H_1^{\perp} + \ldots \right] / Q$$

(Wandura-Wilczek type approximation)



The $A_{UT}^{\sin(\phi_S)}$ Asymmetry

$h_1 \otimes H_1^{\perp}$

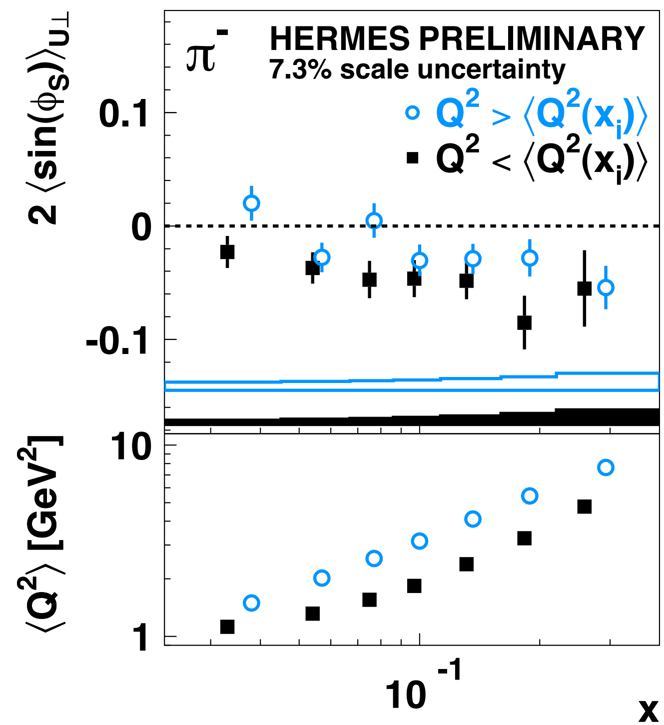


Non zero

Higher-twist term with manifest Q^2 dependence:

$$F_{UL}^{\sin(\phi)} \overset{WW}{\propto} \left[h_1 \otimes H_1^{\perp} + \ldots \right] / Q$$

(Wandura-Wilczek type approximation)



The SIDIS Cross-section

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \propto \left\{F_{UU,T} + \varepsilon F_{UU,L}\right\}$$

$$+ \quad \left\{\sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi)F_{UU}^{\cos(\phi)} + \varepsilon\cos(2\phi)F_{UU}^{\cos(2\phi)}\right\} + \lambda_\ell\left\{\sin(\phi)F_{LU}^{\sin(\phi)}\right\}$$

$$S_T\left\{\sin(\phi-\phi_S)(F_{UT,T}^{\sin(\phi-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi-\phi_S)}) + \varepsilon\sin(\phi+\phi_S)F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S)F_{UT}^{\sin(3\phi-\phi_S)}\right\} +$$

$$S_T\left\{\sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S)F_{UT}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S)F_{UT}^{\sin(2\phi-\phi_S)}\right\} +$$

$$S_T\lambda_e\left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)} + \left(\sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi_S)F_{LT}^{\cos(\phi_S)} + \cos(2\phi-\phi_S)F_{LT}^{\cos(2\phi-\phi_S)}\right)\right\}$$

$$+S_L\left\{\sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi)F_{UL}^{\sin(\phi)} + \varepsilon\sin(2\phi)F_{UL}^{\sin(2\phi)}\right\} + S_L\lambda_\ell\left\{\sqrt{1-\varepsilon^2}F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi)F_{LL}^{\cos(\phi)}\right\}$$

The Leading Terms

$$\frac{d^6\sigma}{dx\, dy\, dz\, d\phi_S d\phi\, dP_{h\perp}^2} \propto \left\{F_{UU,T} + \varepsilon F_{UU,L}\right\}$$

$F_{UU,T}$: $f_1 \otimes D_1$

$$+ \left\{\sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \varepsilon \cos(2\phi) F_{UU}^{\cos(2\phi)}\right\} + \lambda_\ell \left\{\sin(\phi) F_{LU}^{\sin(\phi)}\right\}$$

$F_{UU}^{\cos(2\phi)}$: $h_1^\perp \otimes H_1^\perp$

$$S_T \left\{\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \varepsilon \sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon \sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)}\right\} +$$

$F_{UT,T}^{\sin(\phi-\phi_S)}$: $f_{1T}^\perp \otimes D_1$; $F_{UT}^{\sin(\phi+\phi_S)}$: $h_1 \otimes H_1^\perp$; $F_{UT}^{\sin(3\phi-\phi_S)}$: $h_{1T}^\perp \otimes H_1^\perp$

$$S_T \left\{\sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\right\} +$$

$$S_T \lambda_e \left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \left(\sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\right)\right\}$$

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

$$+S_L \left\{\sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \varepsilon \sin(2\phi) F_{UL}^{\sin(2\phi)}\right\} + S_L \lambda_\ell \left\{\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\right\}$$

$F_{UL}^{\sin(2\phi)}$: $h_{1L}^\perp \otimes H_1^\perp$; F_{LL}: $g_{1L} \otimes D_1$

The Higher-twist Terms

$$\frac{d^6\sigma}{dx\,dy\,dz\,d\phi_S d\phi\,dP_{h\perp}^2} \propto \left\{F_{UU,T} + \varepsilon F_{UU,L}\right\}$$

$f_1 \otimes D_1 \ldots$ $f_1 \otimes D_1 \ldots$ $e \otimes H_1^{\perp} \ldots$

$$+ \left\{\sqrt{2\varepsilon(1+\varepsilon)}\cos(\phi) F_{UU}^{\cos(\phi)} + \varepsilon\cos(2\phi) F_{UU}^{\cos(2\phi)}\right\} + \lambda_\ell \left\{\sin(\phi) F_{LU}^{\sin(\phi)}\right\}$$

$$S_T \left\{\sin(\phi-\phi_S)\left(F_{UT,T}^{\sin(\phi-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi-\phi_S)}\right) + \varepsilon\sin(\phi+\phi_S) F_{UT}^{\sin(\phi+\phi_S)} + \varepsilon\sin(3\phi-\phi_S) F_{UT}^{\sin(3\phi-\phi_S)}\right\} +$$

$$S_T \left\{\sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi_S) F_{UT}^{\sin(\phi_S)} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi-\phi_S) F_{UT}^{\sin(2\phi-\phi_S)}\right\} +$$

$h_1 \otimes H_1^{\perp} \ldots$

$$S_T \lambda_e \left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S) F_{LT}^{\cos(\phi-\phi_S)} + \left(\sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi_S) F_{LT}^{\cos(\phi_S)} + \cos(2\phi-\phi_S) F_{LT}^{\cos(2\phi-\phi_S)}\right)\right\}$$

$h_L \otimes H_1^{\perp} \ldots$

$$+S_L \left\{\sqrt{2\varepsilon(1+\varepsilon)}\sin(\phi) F_{UL}^{\sin(\phi)} + \varepsilon\sin(2\phi) F_{UL}^{\sin(2\phi)}\right\} + S_L \lambda_\ell \left\{\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos(\phi) F_{LL}^{\cos(\phi)}\right\}$$

Summary

- HERMES has been a precursor experiment for TMDs and GPDs
- Many innovative results in both fields
- Data analysis still ongoing
- Several preliminary results close to be published
- New results on queque
  - beam spin asymmetry in the semi-inclusive kaon sector
  - semi-inclusive di-hadron analysis
  - exclusive reactions

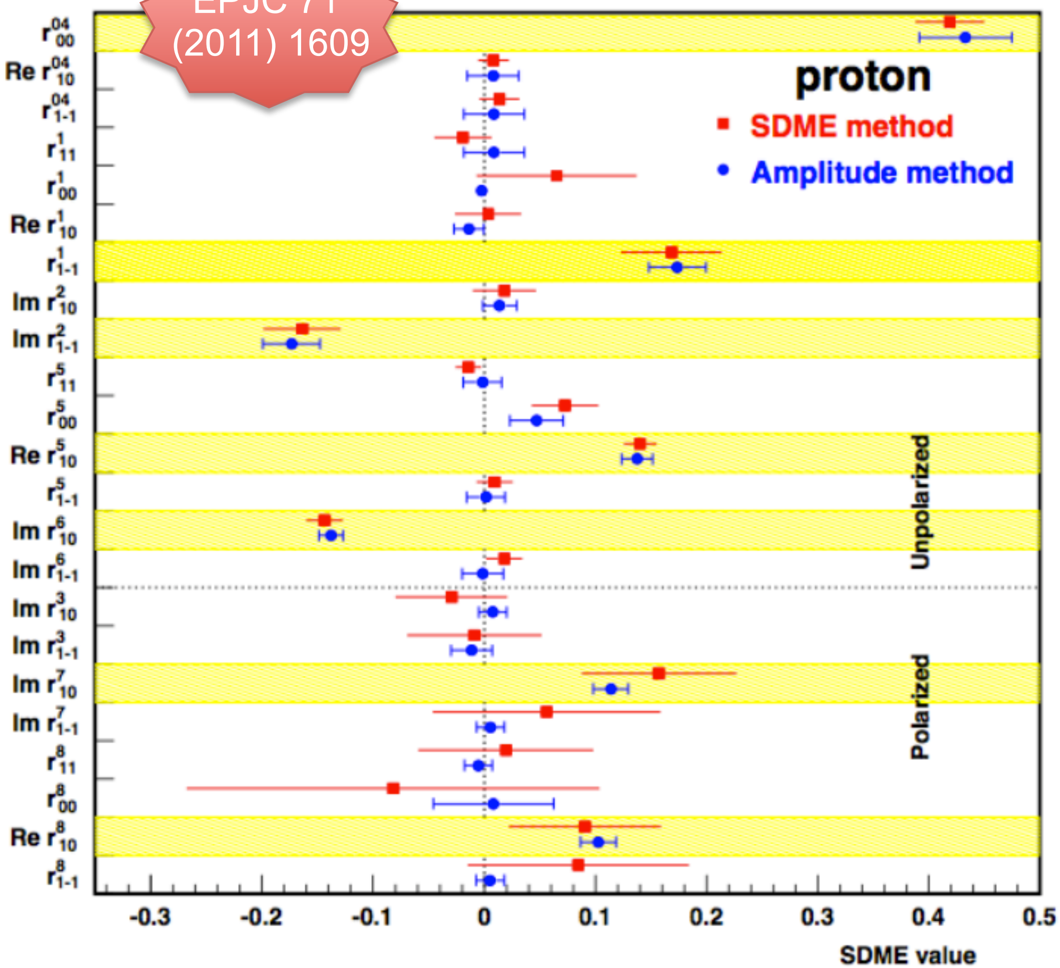
Hard Exclusive ρ^0 Meson Production

Meson SDMEs
EPJC 62 (2009) 659-694

Photon SDMEs

$$r^{\eta}_{\lambda_V \mu_V} = \frac{1}{2N} \sum_{\lambda_\gamma \mu_\gamma \lambda'_N \lambda_N} F_{\lambda_V \lambda'_N \lambda_\gamma \lambda_N} \Sigma^{\eta}_{\lambda_\gamma \mu_\gamma} F^{*}_{\mu_V \lambda'_N \mu_\gamma \lambda_N}$$

EPJC 71 (2011) 1609



Helicity Amplitudes

$$F_{\lambda_V \lambda_\gamma} = T_{\lambda_V \lambda_\gamma} + U_{\lambda_V \lambda_\gamma}$$

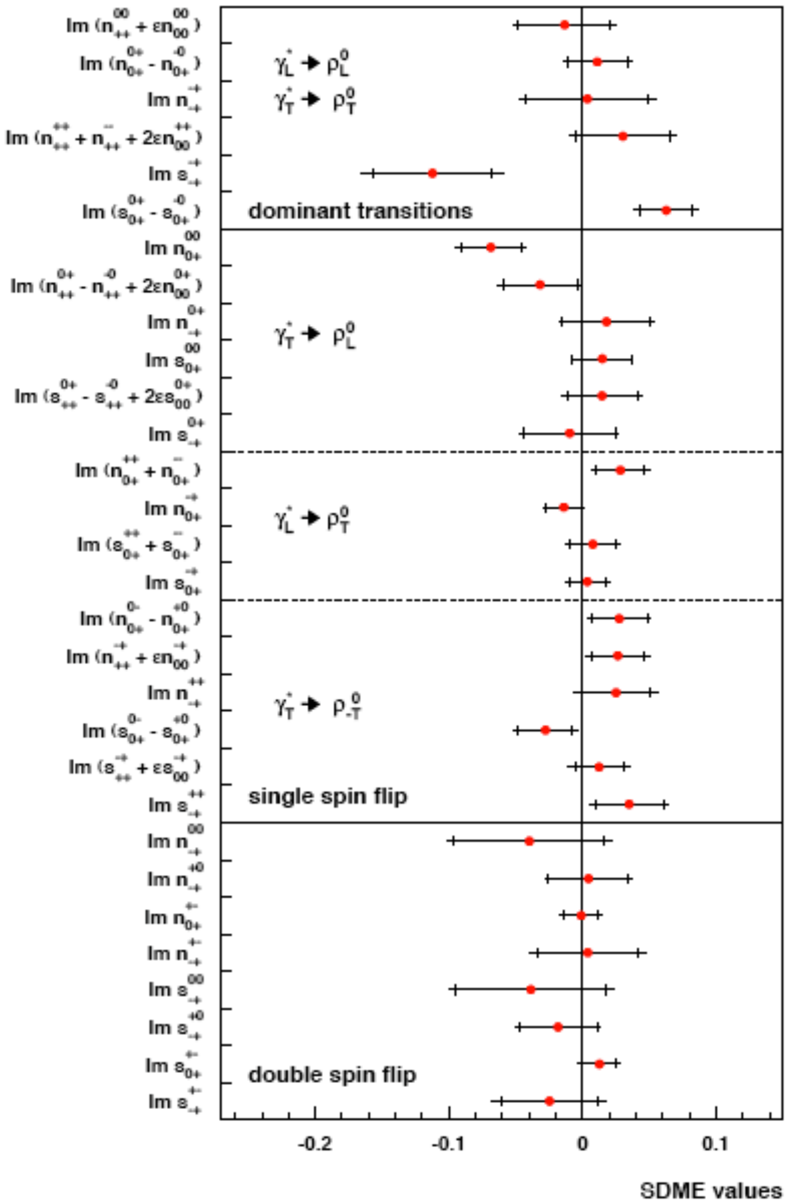
They form a basis for the SDMEs

Re-derived SDMEs consistent with published ones
[A. Airapetian et al. EPJC 62 (2009) 659)]

Enhanced sensitivity for polarized SDMEs

Helicity amplitudes are the fundamental quantities to be compared with theory

Hard Exclusive ρ^0 Meson Production



$$A_{UT}^{\gamma^*}(\phi,\phi_s) = \frac{\mathrm{Im}\, n_{00}^{00}}{u_{00}^{00}}$$

[PLB679(2009)