Overview of TMD Measurements

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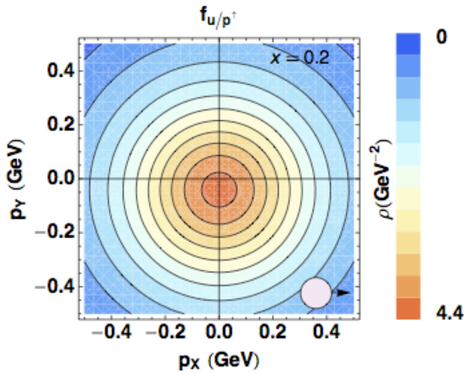
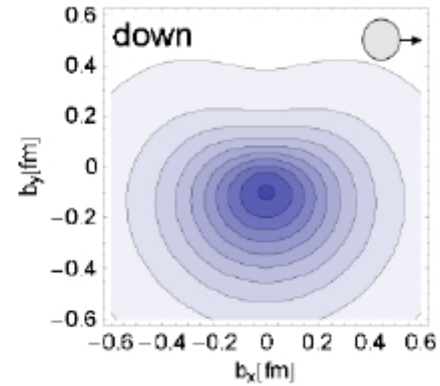
Partons in Nucleons and Nuclei
September 30, 2011 Marrakech

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: $H_p^u(x,\xi,t)$, …

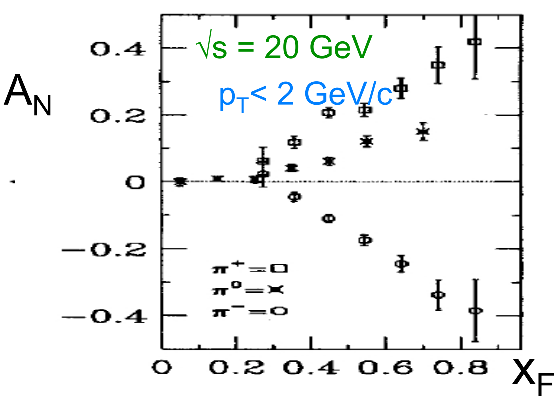
Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

d^2k_T

$\xi=0, t=0$

PDFs $f_p^u(x)$,…

May explain SSA & Lam-Tung



May solve
proton spin puzzle

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

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

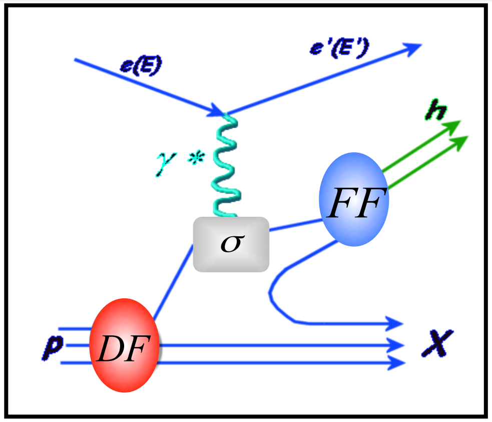
- universality of TMDs

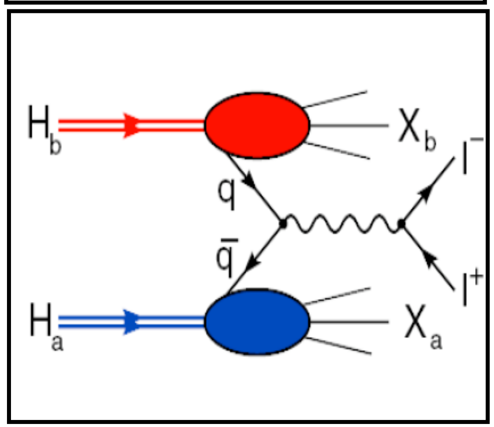
Strict prediction from TMDs + QCD !

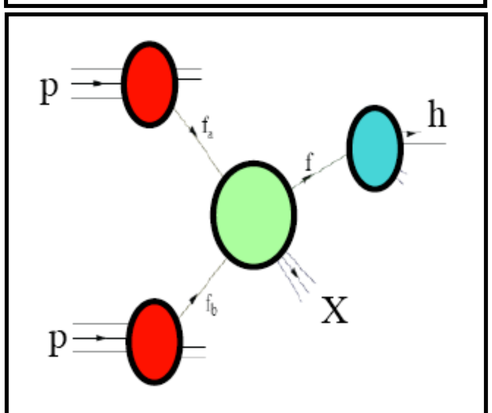
quark polarisation (columns) / nucleon polarisation (rows)

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

Physics reactions







SIDIS: rich phenomenology, the most explored so far

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

e⁺e⁻: B-factories as powerful fragmentation laboratories

e⁺e⁻ $$\sigma^{pp\to eeX} = \sum_q \sigma^{qq\to ee} \otimes FF \otimes FF$$

DY: challenging for experiments (only unpolarized so far)

DY $$\sigma^{pp\to eeX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to ee}$$

Hadron reactions: challenging for theory (ISI + FSI)

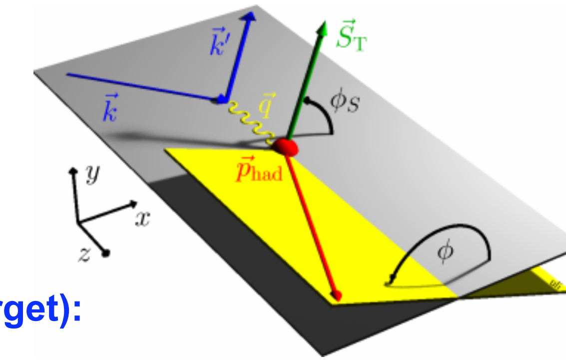
pp $$\sigma^{pp\to hX} = \sum_q DF \otimes DF \otimes \sigma^{qq\to qq} \otimes FF$$

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 polarized target):



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

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

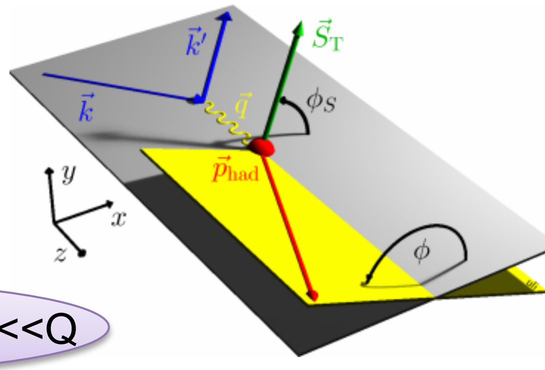
$$+S_T\lambda_e\left\{\sqrt{1-\varepsilon^2}\cos(\phi-\phi_S)F_{LT}^{\cos(\phi-\phi_S)}\right\}+\ldots$$

The SIDIS case

quark polarisation / **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

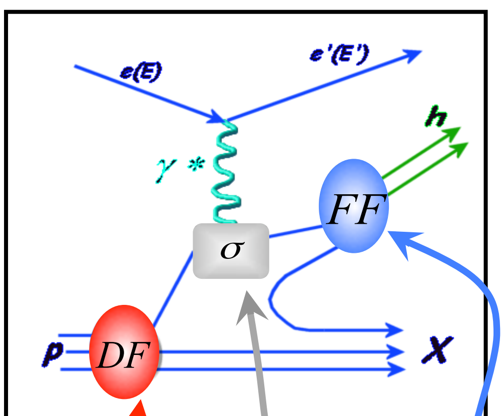
SIDIS cross section (transversely pol. target):



TMD factorization for P_T<<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



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

$h_1 \otimes H_1^\perp$

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

$f_{1T}^\perp \otimes D_1$ $h_{1T}^\perp \otimes H_1^\perp$

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

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

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

First evidences

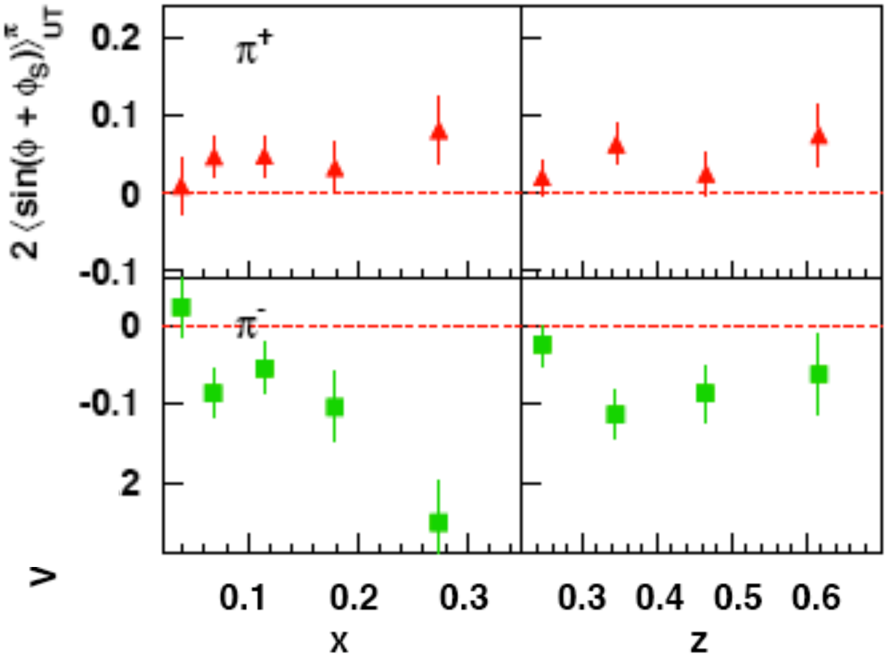
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

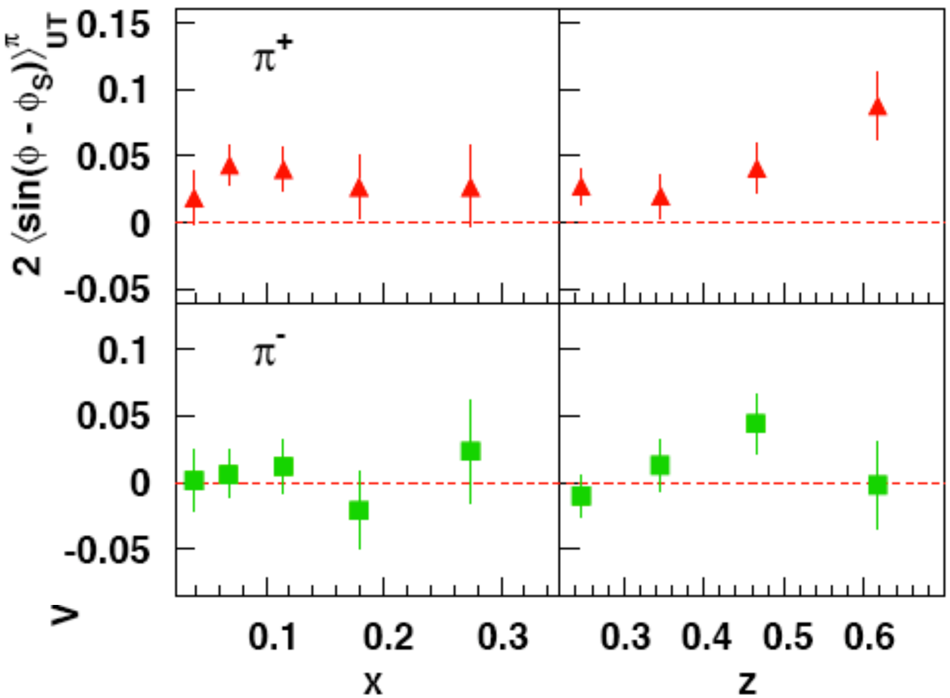
SIDIS:
ep → e'hX

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

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 !!

Number Density & 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 Baseline)

The hadron multiplicities

$f_1 \cdot D_1$

LO interpretation:

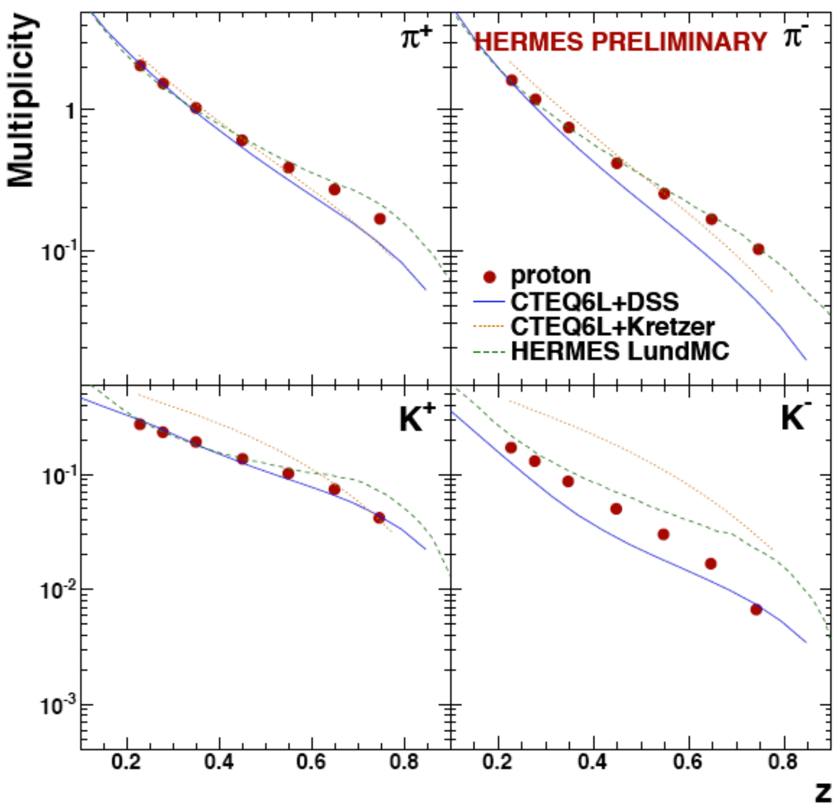
$$M_N^h = \frac{1}{N_N^{DIS}(Q^2)} \frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2)}$$

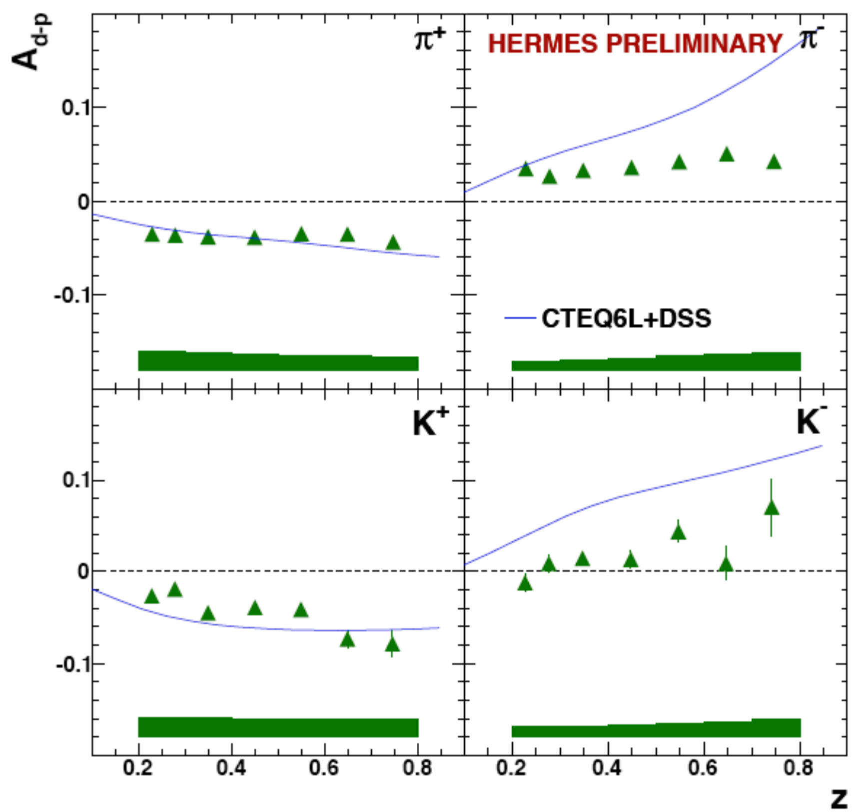
SIDIS data constrain fragmentation at low c.m. energy and bring enhanced flavor sensitivity

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

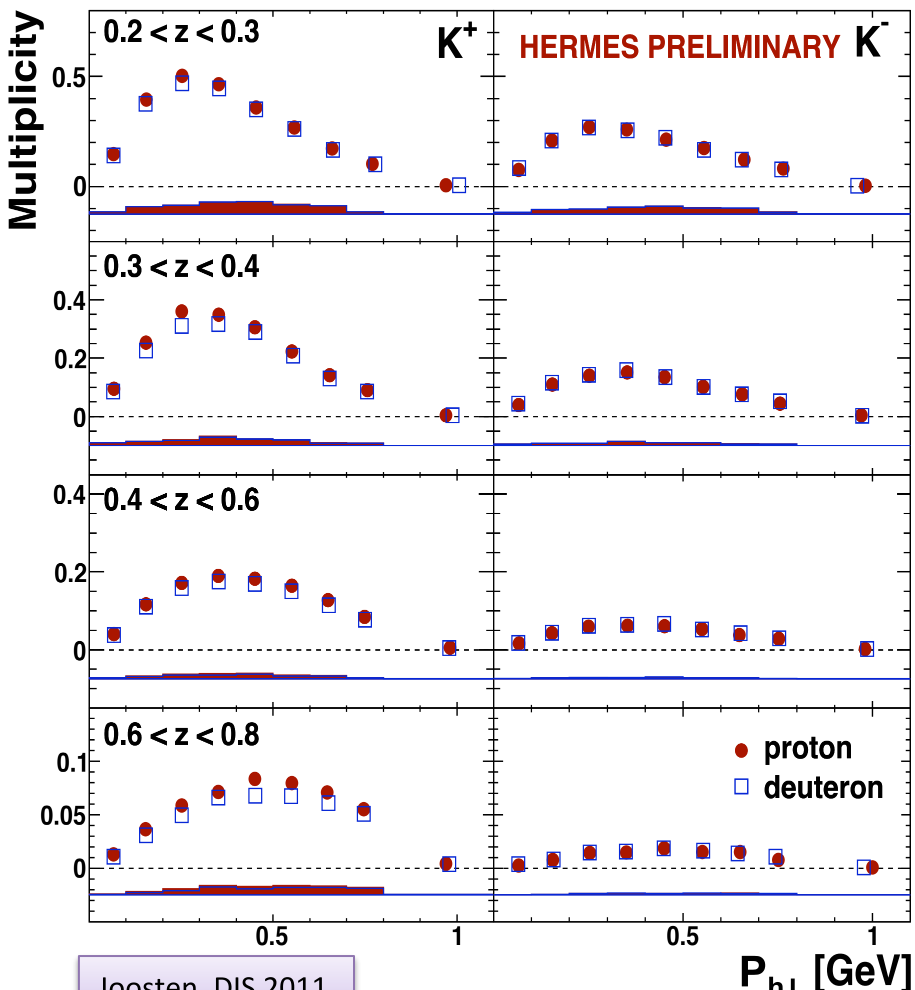




The $P_{h\perp}$-unintegrated multiplicities $f_1 \otimes D_1$

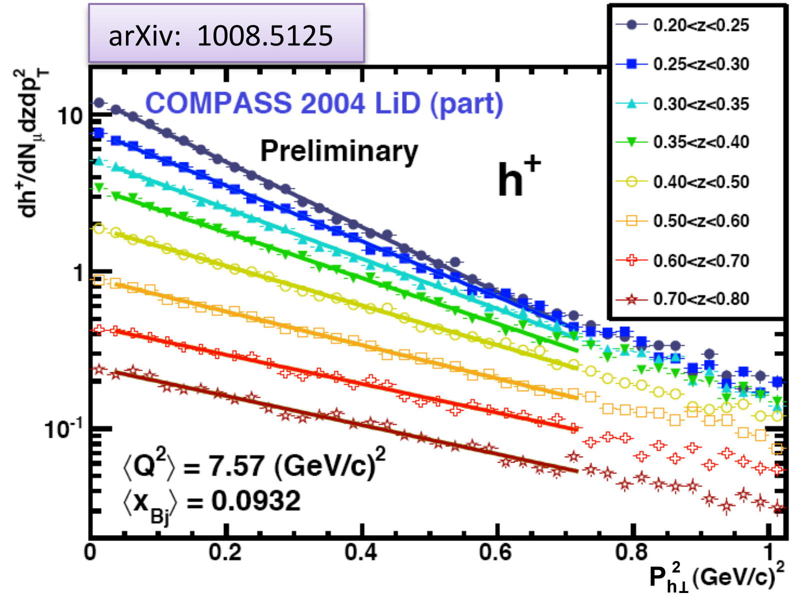
Disentanglement of z and $P_{h\perp}$: access to the transverse intrinsic quark k_T and fragmentation p_T,

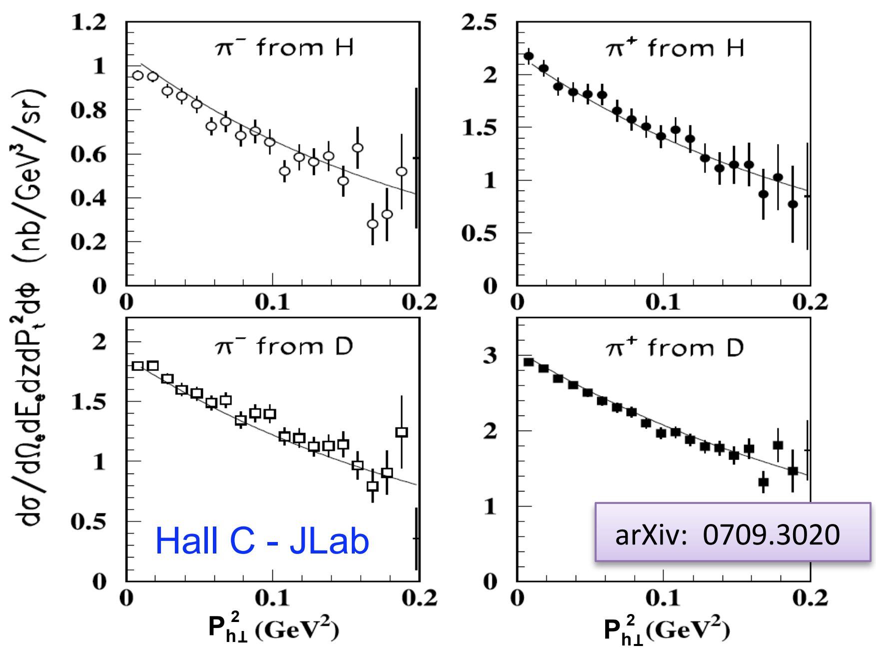
i.e. from gaussian anstaz $$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$



Joosten, DIS 2011

arXiv: 1008.5125



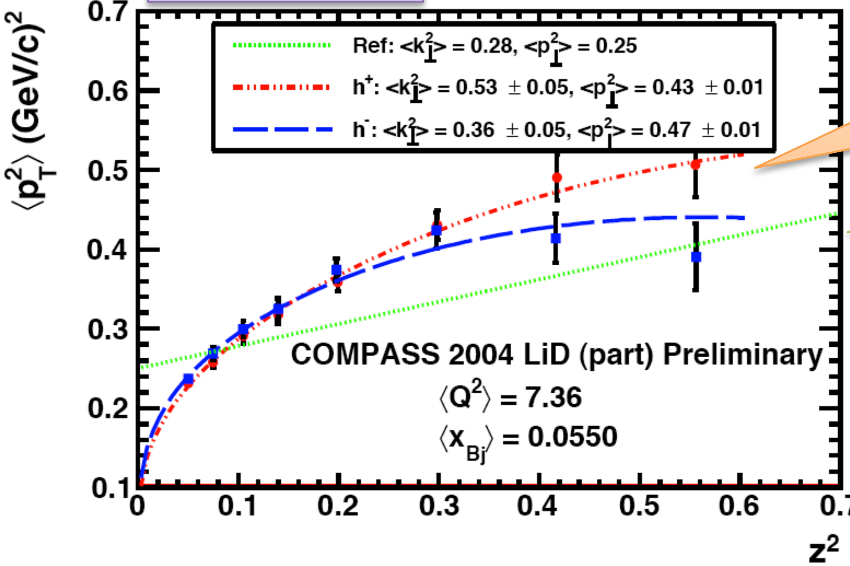


arXiv: 0709.3020

The evolution

$f_1 \otimes D_1$

arXiv: 1008.5125

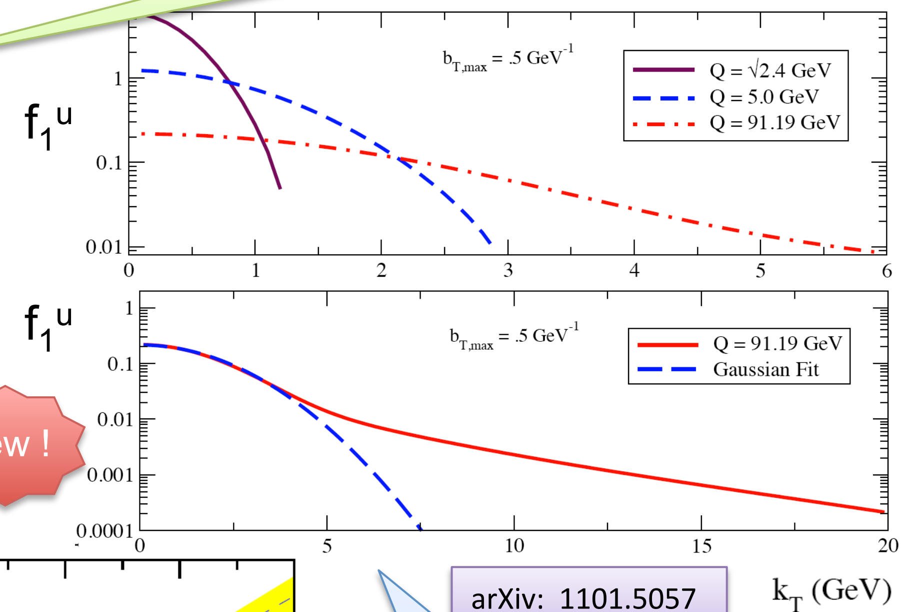


Is p_T independent of z ?

$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + z^\alpha (1-z)^\beta \langle p_T^2 \rangle$$

Gaussian ansatz

$$\langle P_{h\perp}^2 \rangle = z^2 \langle k_T^2 \rangle + \langle p_T^2 \rangle$$

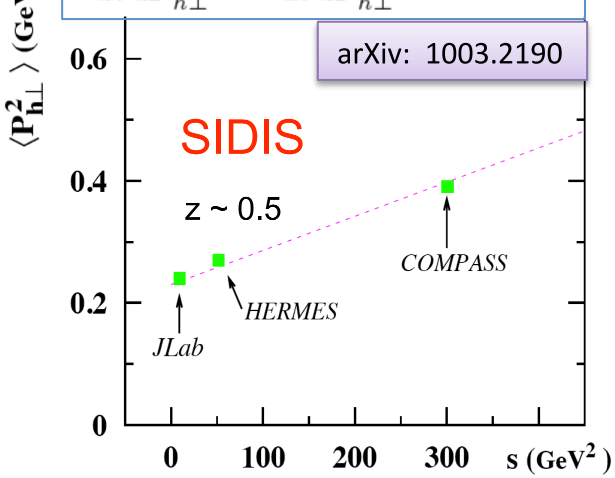


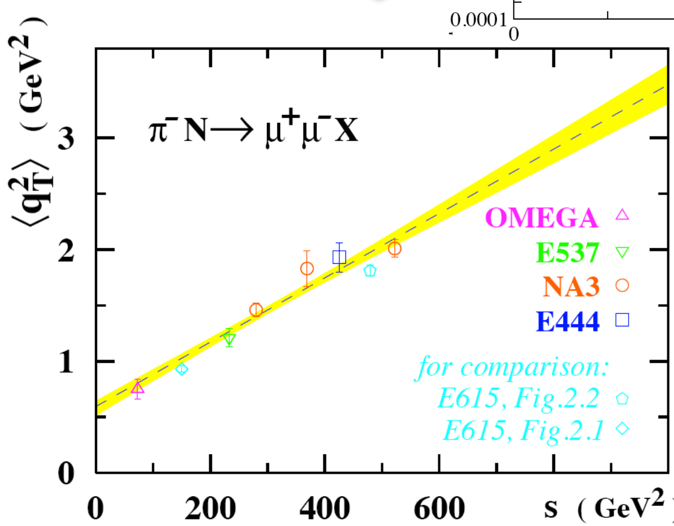
New !

arXiv: 1101.5057

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

arXiv: 1003.2190





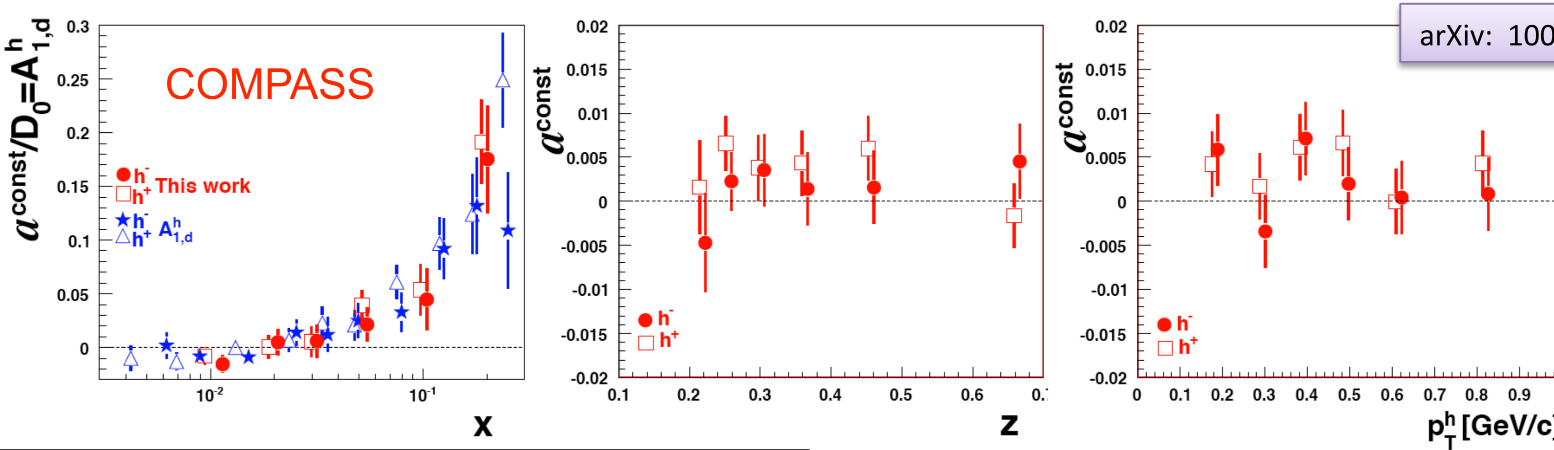
Indirect indication of a k_T and p_T broadening with c.m. energy:

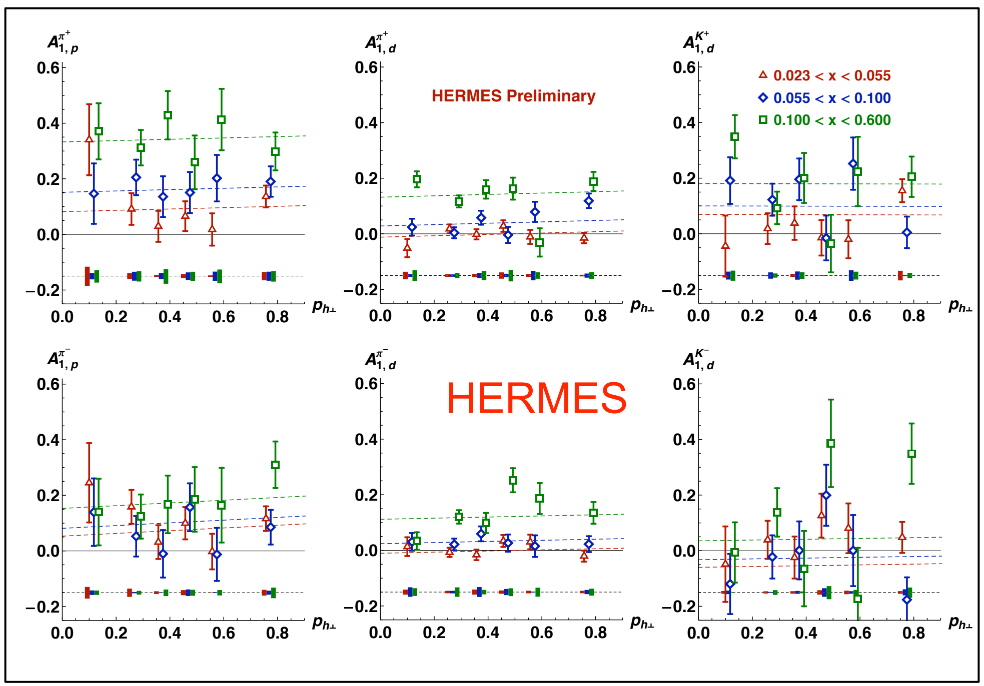
TMD Q^2 evolution

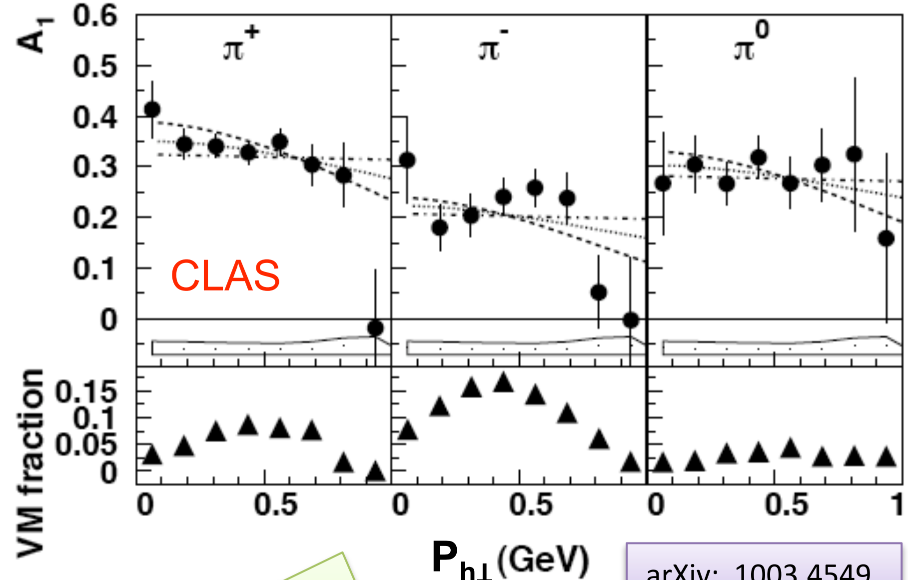
The A_{LL} Asymmetry

$g_1 \otimes D_1$

arXiv: 1007.1562







arXiv: 1003.4549

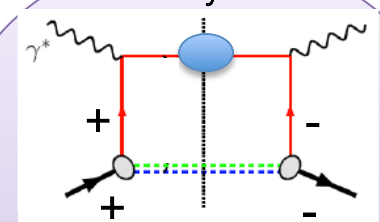
Hint of different transverse momentum widths for helicity vs number density

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 fragmentation

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

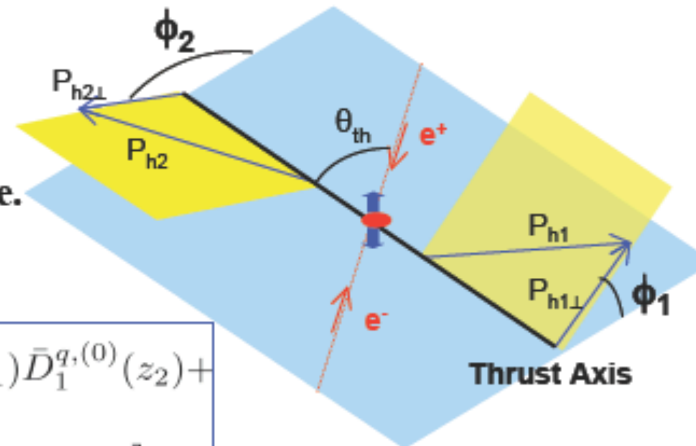
$e^+e^- \rightarrow h\,h\,X$

Correlation between quark polarization and observed hadron transverse momentum

$\phi_1+\phi_2$ or Thrust RF

θ: angle between the e^+e^- axis and the thrust axis;
$\phi_{1,2}$: azimuthal angles between $P_{h1(h2)}$ and the scattering plane.

All quantities in e+e- center of mass



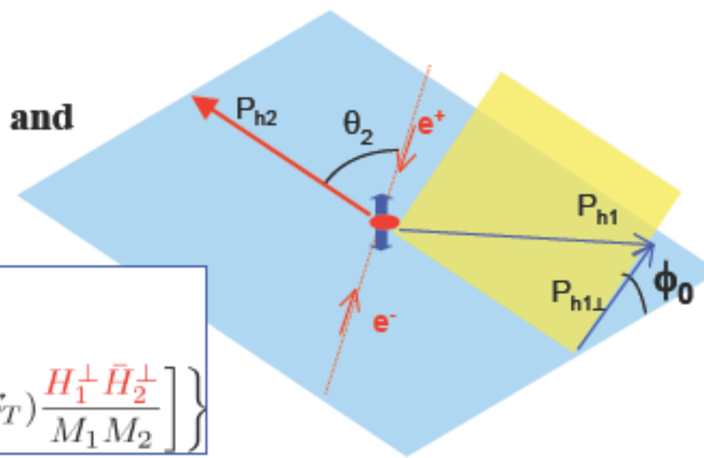
$$\frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2 d\phi_1 d\phi_2} = \sum_{q,\bar{q}} \frac{3\alpha^2}{Q^2}\frac{e_q^2}{4} z_1^2 z_2^2 \left[(1+cos^2\theta) D_1^{q,(0)}(z_1)\bar{D}_1^{q,(0)}(z_2) + sin^2(\theta) cos(\phi_1+\phi_2) H_1^{\perp,(1),q}(z_1)\bar{H}_1^{\perp,(1),q}(z_2)\right]$$

Daniel Boer
Nucl. Phys. B 806,23-67(2009)
[arXiv:0804.2408v2]

$2\phi_0$ or P_{h2} RF

θ_2: angle between the e^+e^- axis and P_{h2};
ϕ_0: angle between the plane spanned by P_{h2} and the e^+e^- axis, and the direction of P_{h1} perpendicular to P_{h2}.

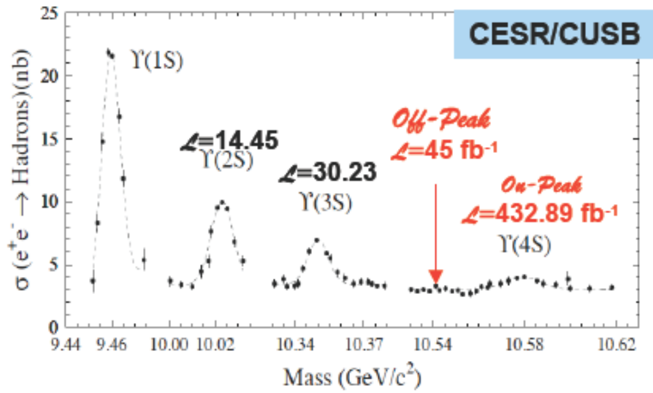
All quantities in e+e- center of mass



$$\frac{d\sigma(e^+e^- \rightarrow h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2\vec{q}_T} = \frac{3\alpha^2}{Q^2} z_1^2 z_2^2 \left\{ A(y)\mathcal{F}[D_1\bar{D}_2] + B(y) cos(2\phi_0) \mathcal{F}\left[(2\hat{h}\cdot\vec{k}_T \hat{h}\cdot\vec{p}_T - \vec{k}_T\cdot\vec{p}_T)\frac{H_1^{\perp}\bar{H}_2^{\perp}}{M_1 M_2}\right]\right\}$$

The Collins fragmentation

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



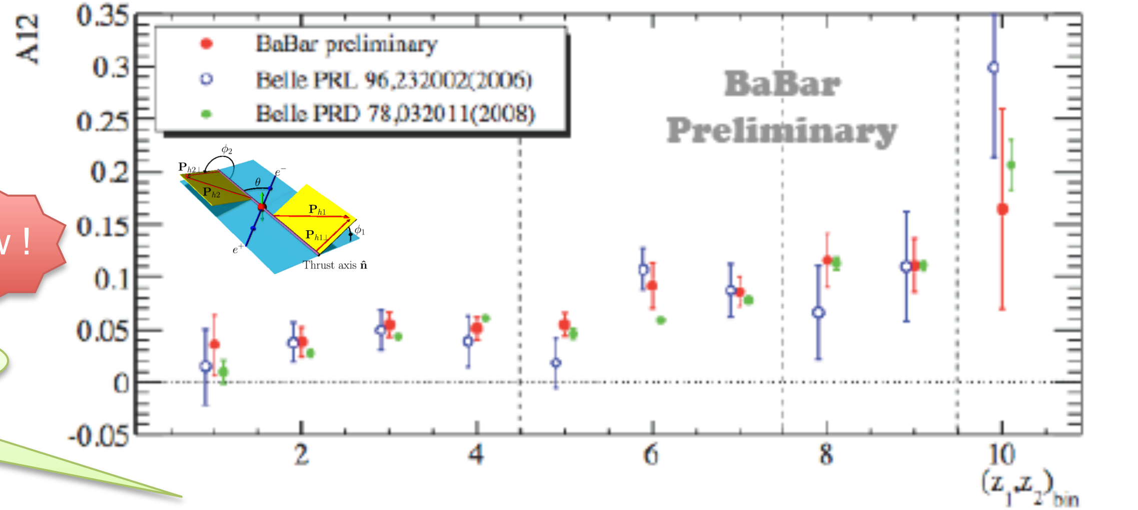
Different from zero signal!

BaBar preliminary: $\mathcal{L}\approx 45\ fb^{-1}$

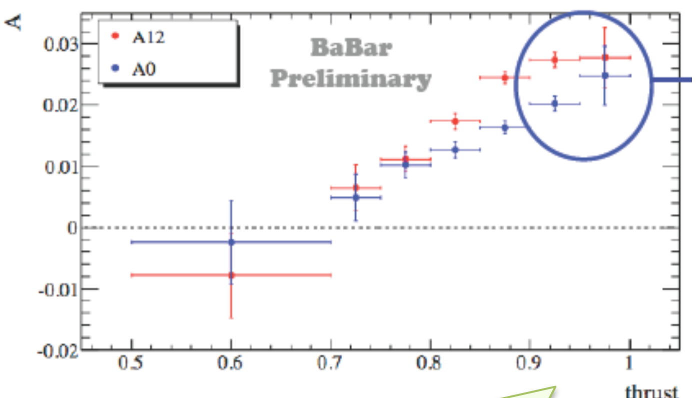
Belle Off-peak: $\mathcal{L}\approx 29\ fb^{-1}$

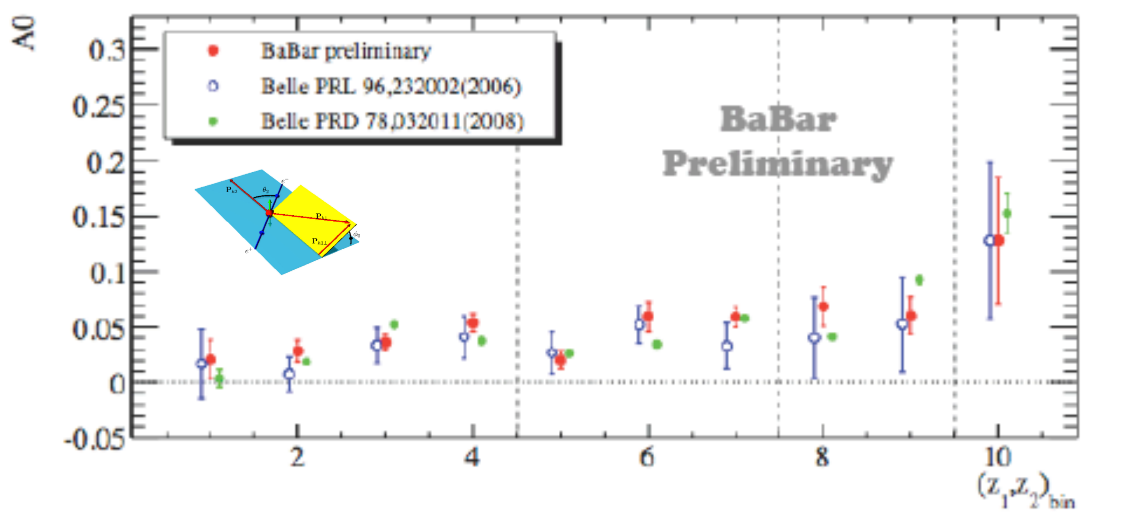
Belle full statistics (supersede previous results) $\mathcal{L}\approx 547\ fb^{-1}$

New !



At low z little memory of the struck quark





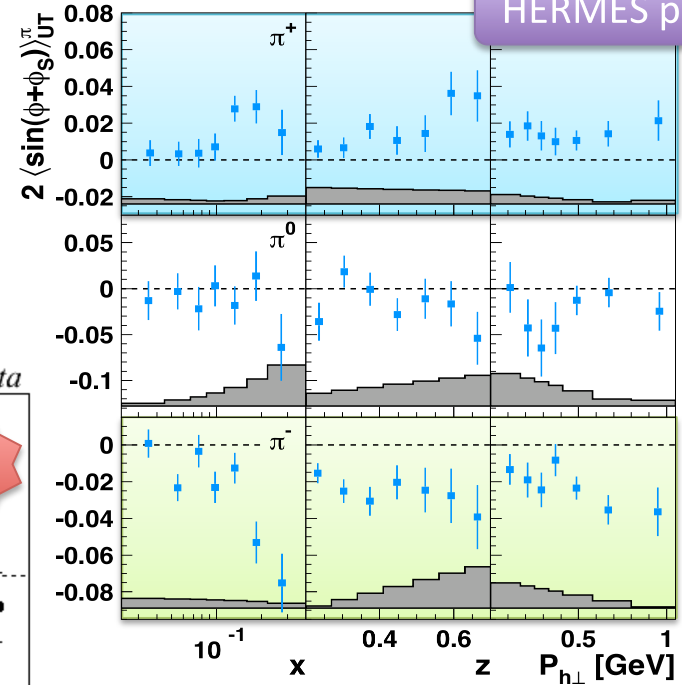
At low thrust spherical events and gluon emission

The Collins SIDIS amplitude

$h_1 \otimes H_1^{\perp}$

$$A_{UT}^{\sin(\phi+\phi_S)} \propto \frac{\sum_q e h_1^q(x,p_T^2) \otimes_\omega H_1^{q,\perp}(z,k_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,k_T^2)}$$

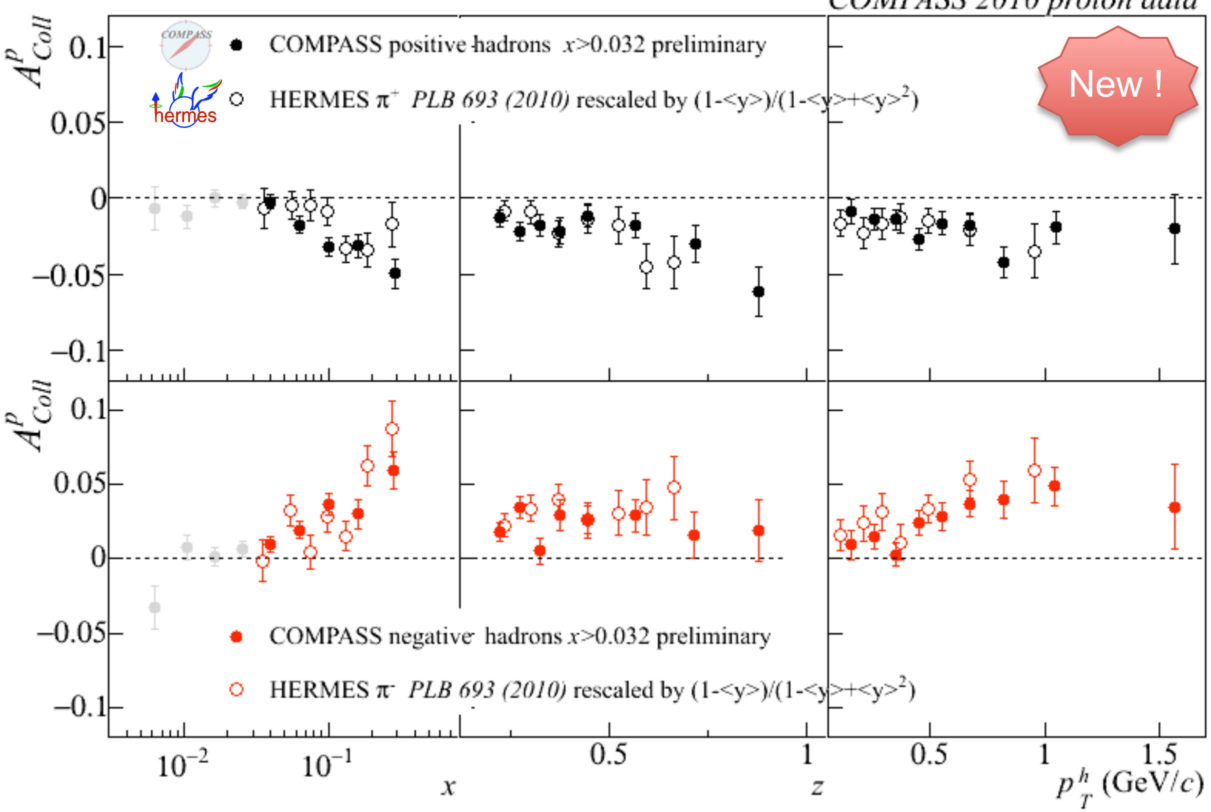
HERMES p



Opposite sign for pions reveals Collins features

COMPASS 2010 proton data

New !



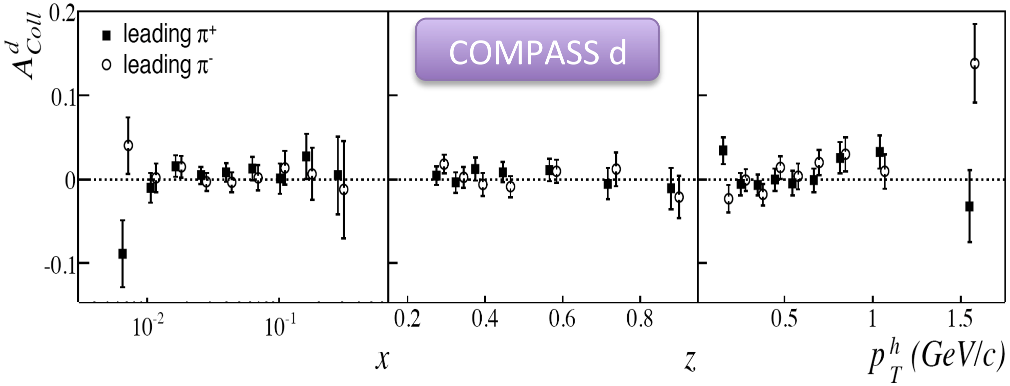
Consistent non-zero signals for charged pions

The Collins SIDIS amplitude

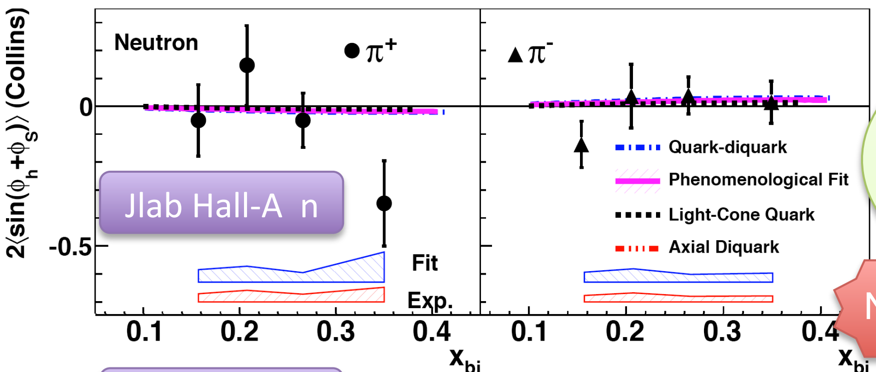
$h_1 \otimes H_1^{\perp}$

Flavor separation with various targets and detected hadrons

COMPASS d

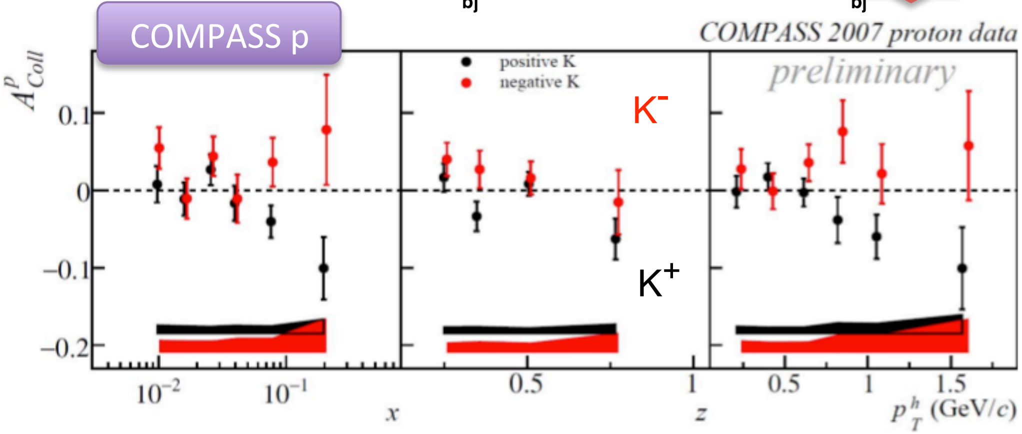


Jlab Hall-A n

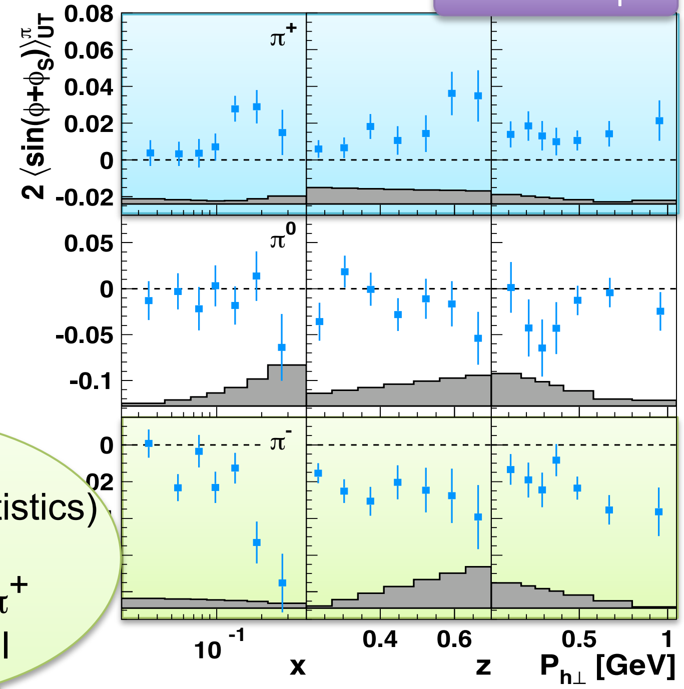


New !

COMPASS p



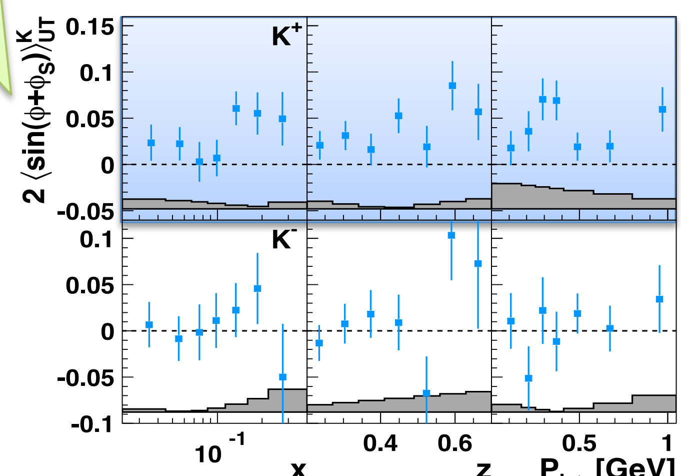
HERMES p



Puzzle in (low-statistics) kaon amplitudes:

K^+ larger than π^+

K^- controversial



Transversity signals

$h_1 \otimes H_1^{\perp}$

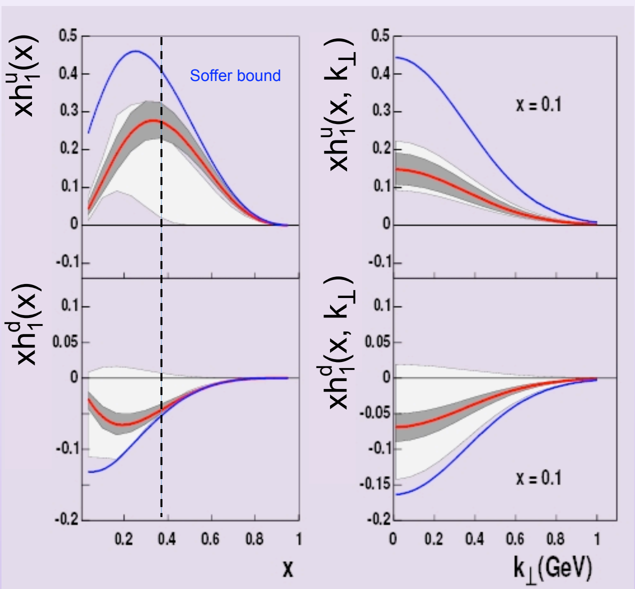
$lp \rightarrow l'hX$

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

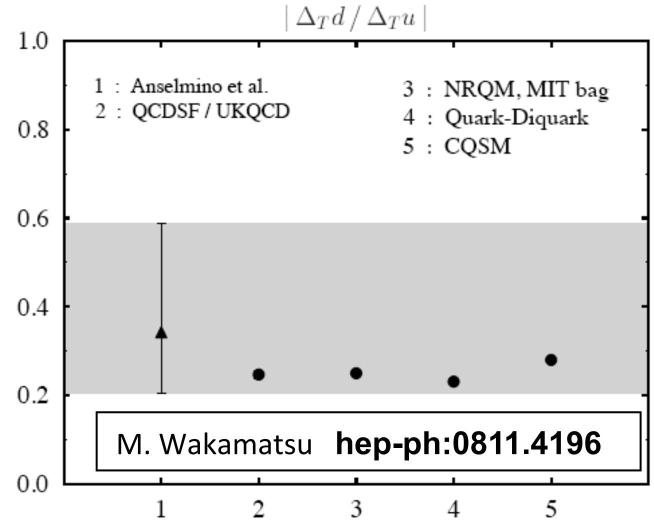
$ld \rightarrow l'hX$

$e^+e^- \rightarrow h_1 h_2 X$

First extraction of Transversity!



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



M. Wakamatsu **hep-ph:0811.4196**

Tensor charge

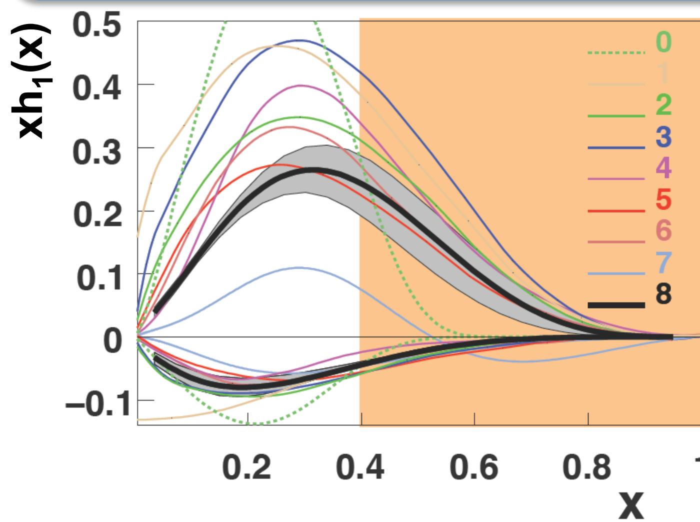
$$\int_0^1 dx\left[h_1^q(x) - \bar{h}_1^q(x)\right] = \delta q$$

$$\delta u = 0.54^{+0.09}_{-0.22}$$

$$\delta d = -0.23^{+0.09}_{-0.16}$$

M. Anselmino et al **hep-ph:0812.4366**

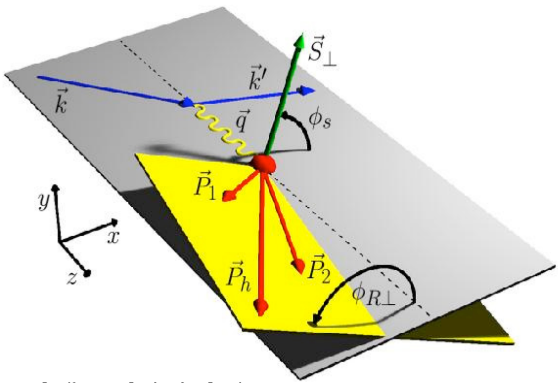
- Existing data limited to x < 0.3
- Gaussian ansatz
- Evolution from high energy colliders

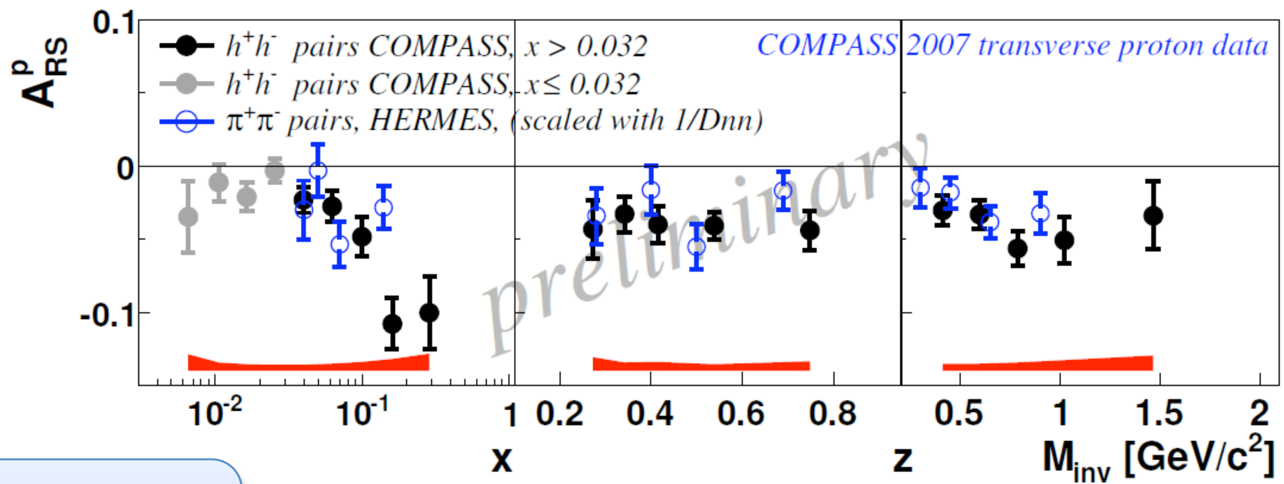


0. chiral color-dielectric model [Barone et al. PLB 390 (97)]
1. Soffer bound [Soffer et al. PRD 65 (02)]
2. $h_1 = g_1$ [Korotkov et al. EPJC 18 (01)]
3. chiral quark-soliton model [Schweitzer et al., PRD 64 (01)]
4. chiral quark-soliton model [Wakamatsu, PLB 509 (01)]
5. light-cone constituent quark model [Pasquini et al., PRD 72 (05)]
6. quark-diquark model [Cloet, Bentz, Thomas, PLB 659 (08)]
7. quark-diquark model [Bacchetta, Conti, Radici, PRD 78 (08)]
8. parametrization [Anselmino et al., arXiv:0807.0173]

Two hadron asymmetries

$h_1 \otimes H_1^{\triangleleft}$



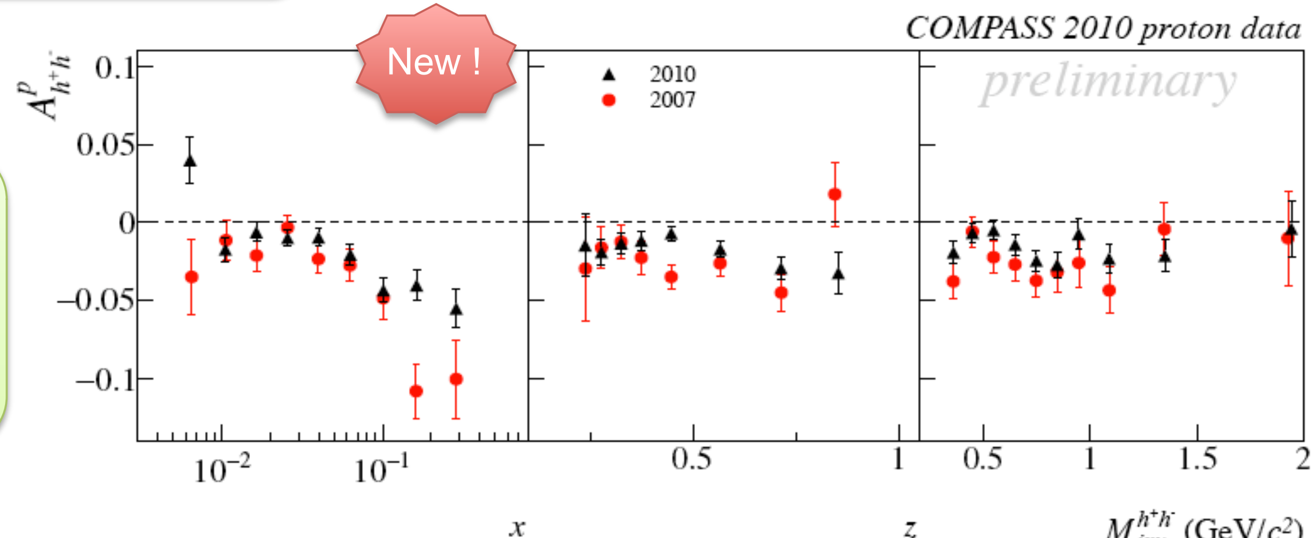


$$A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta} \propto \frac{\sum_q e_q^2 h_1(x,Q^2) H_1^{\triangleleft}(z,M_h^2,Q^2)}{\sum_q e_q^2 f_1(x,Q^2) D_1^{\triangleleft}(z,M_h^2,Q^2)}$$

Issue with unknown pp-terms in partial wave expansion

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

New !



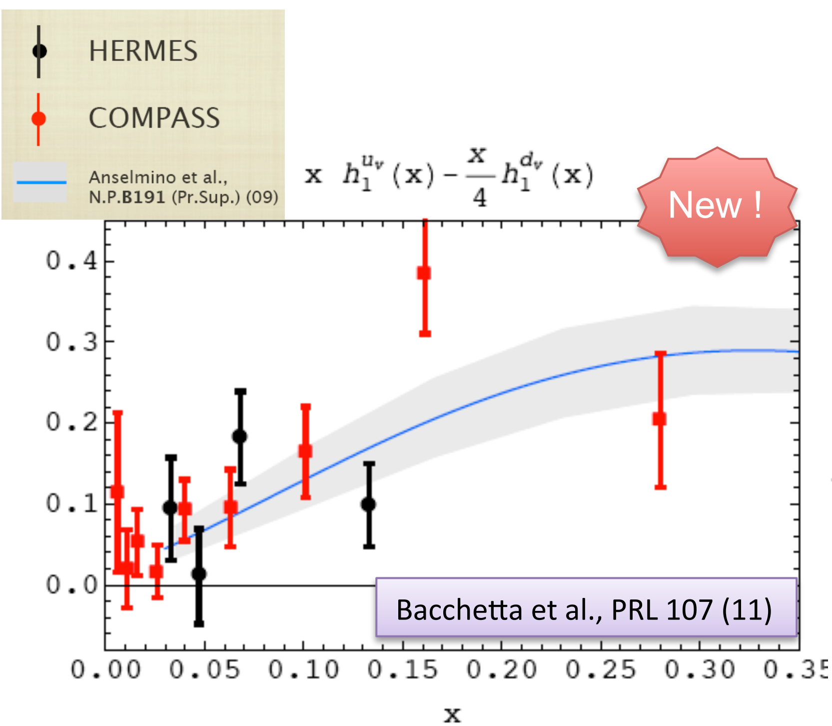
Transversity signals

$h_1 \otimes H_1^{\triangleleft}$

$lp \to l'\pi^+\pi^- X$

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

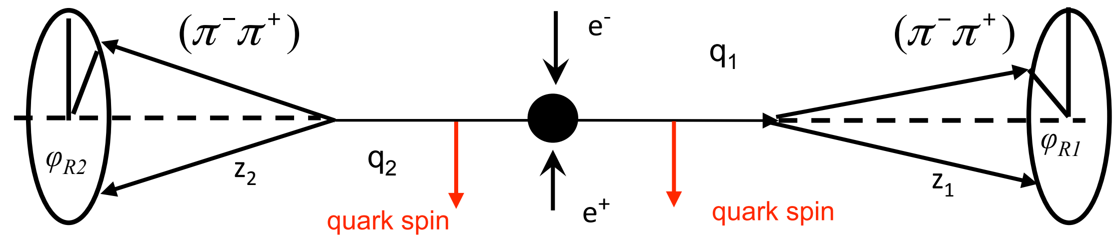
1st collinear extraction !

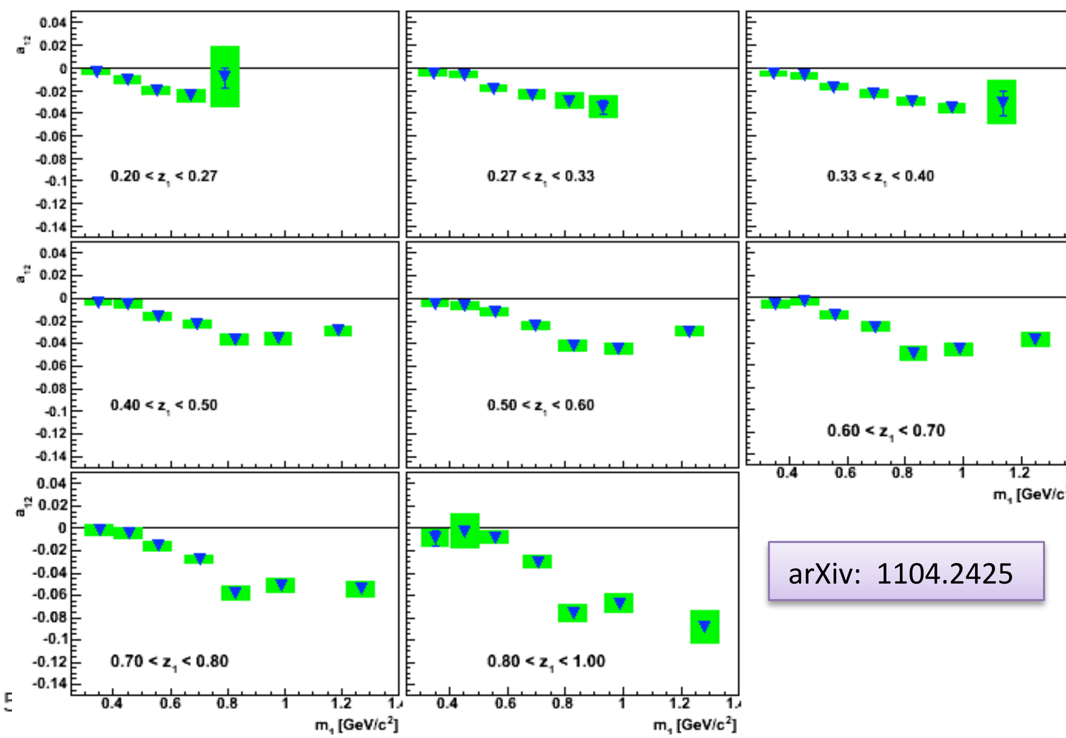


Bacchetta et al., PRL 107 (11)

$e^+e^- \to (\pi^+\pi^-)(\pi^+\pi^-)X$

Different from zero correlations !

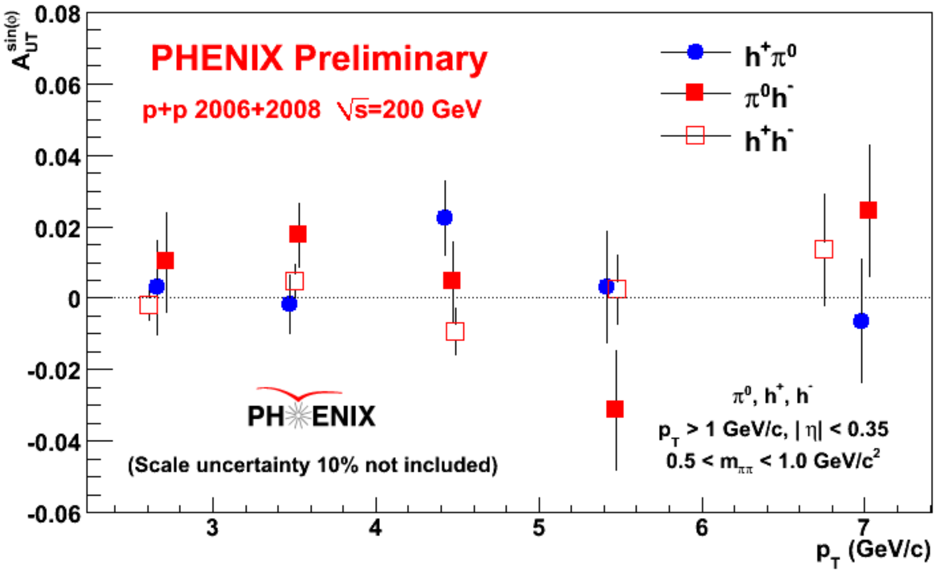




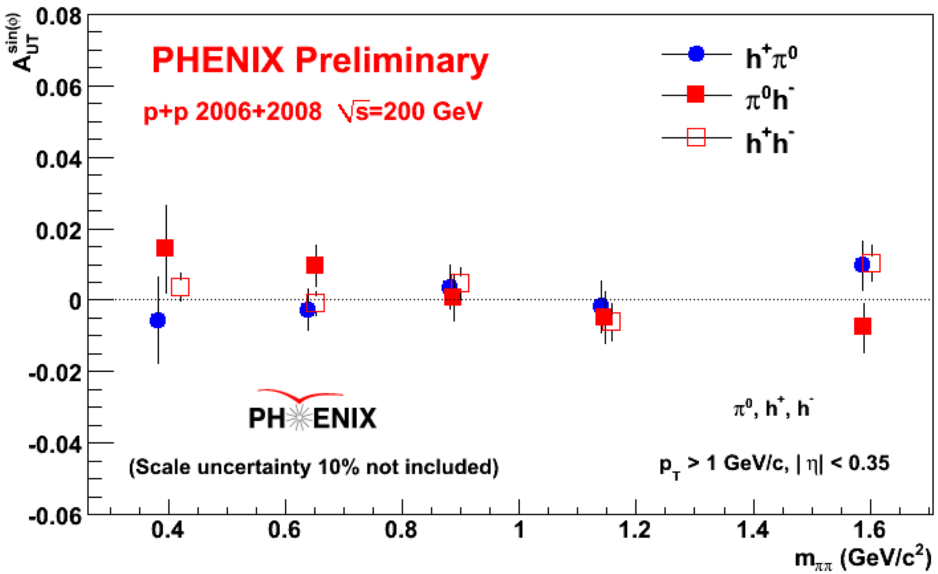
arXiv: 1104.2425

Transversity signals

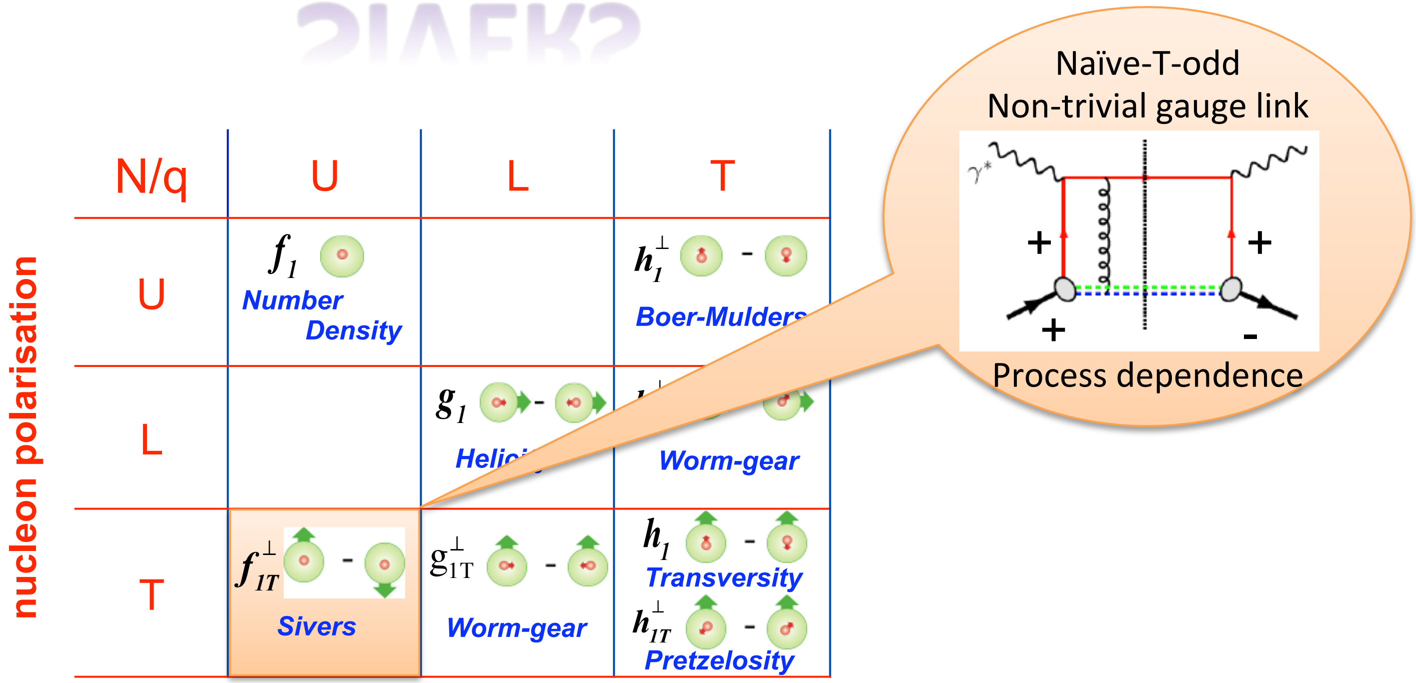
$h_1 \otimes H_1^{\triangleleft}$



No significant asymmetries seen in pp reactions at mid-rapidity.



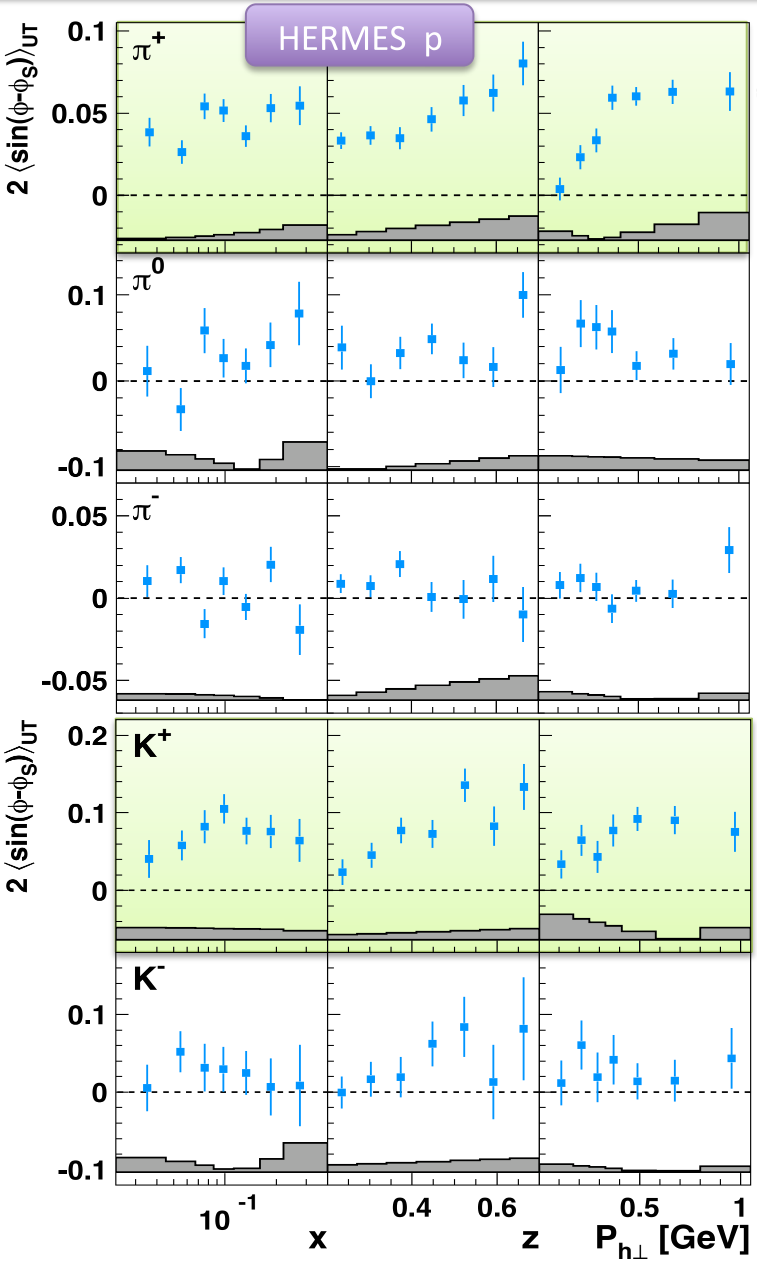
Sivers

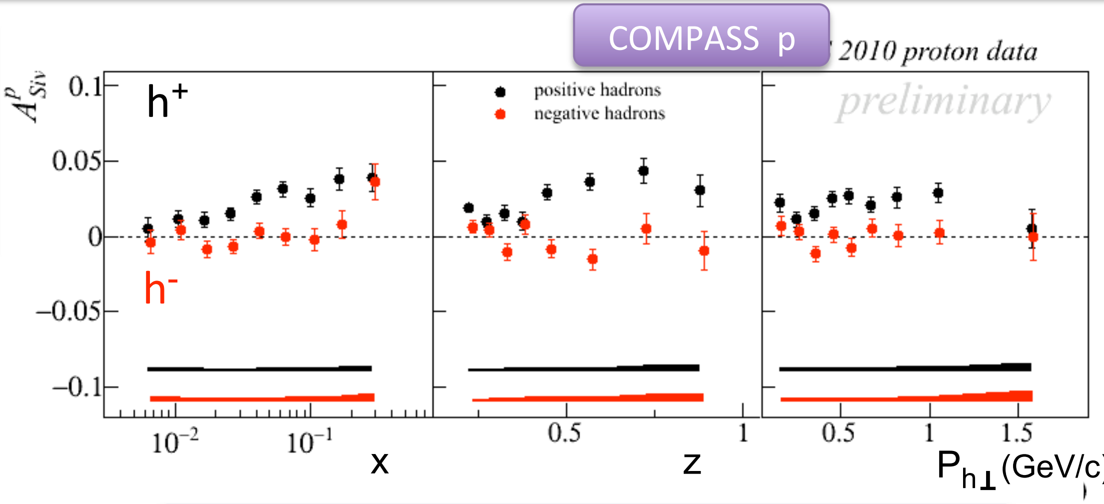


(The TMD Challenge)

The Sivers signals

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

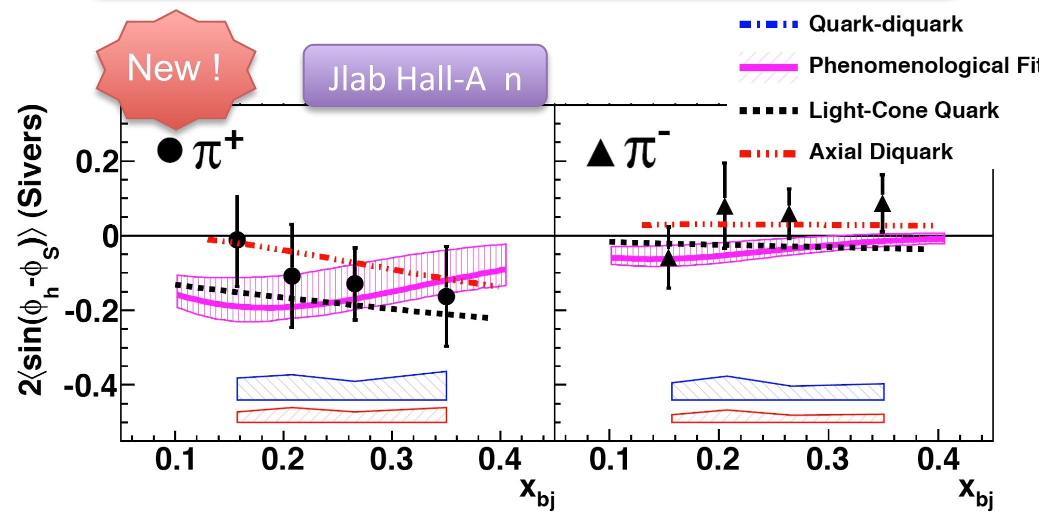




Non zero ! for positive hadrons on proton

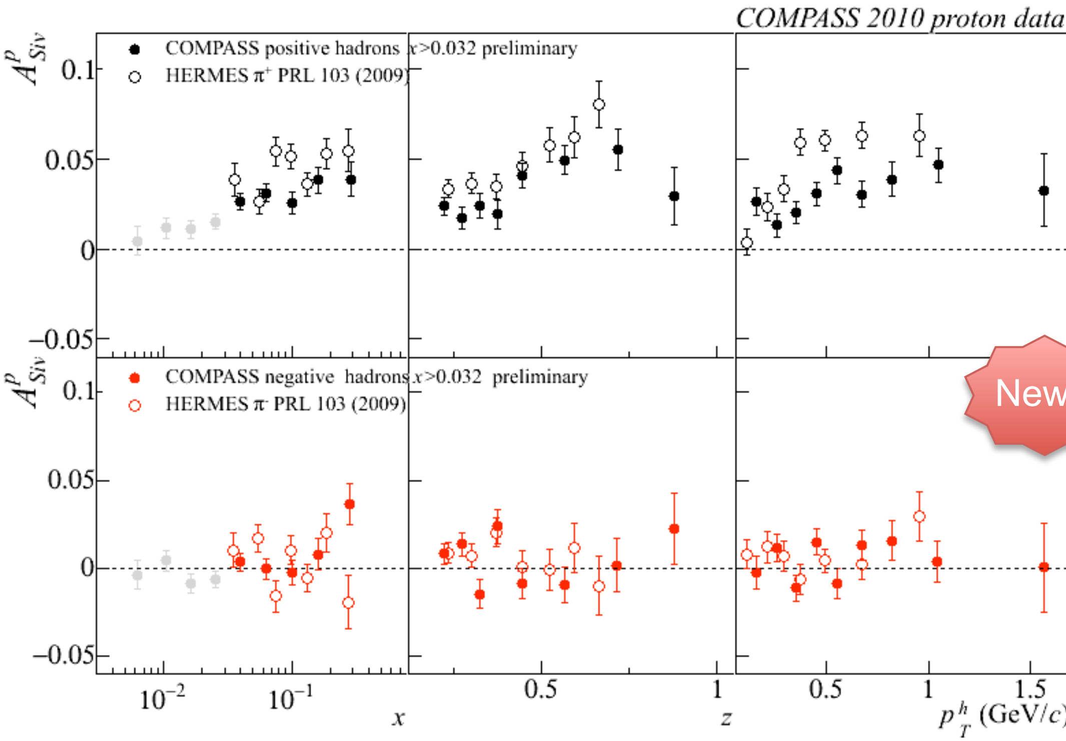
Flavor tagging: K^+ signals larger than π^+

No signal on deuteron target



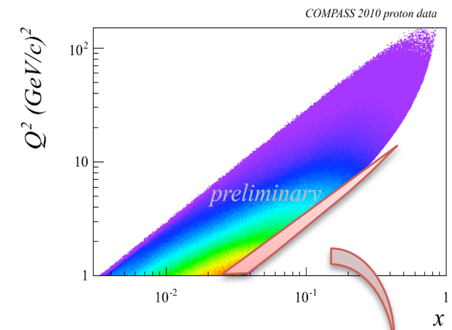
The Sivers signals

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

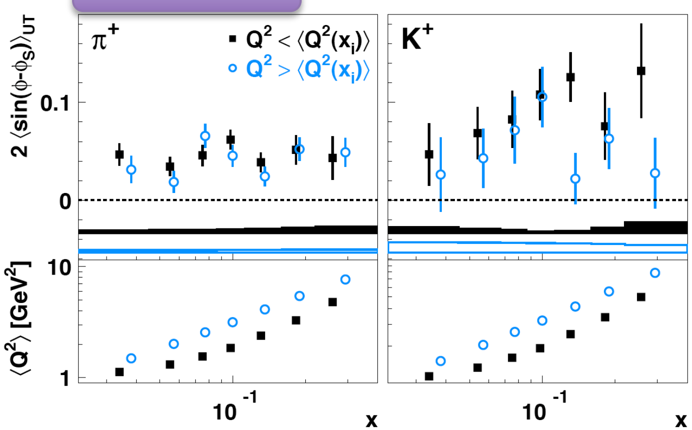


HERMES vs COMPASS comparison:
are data consistent ?

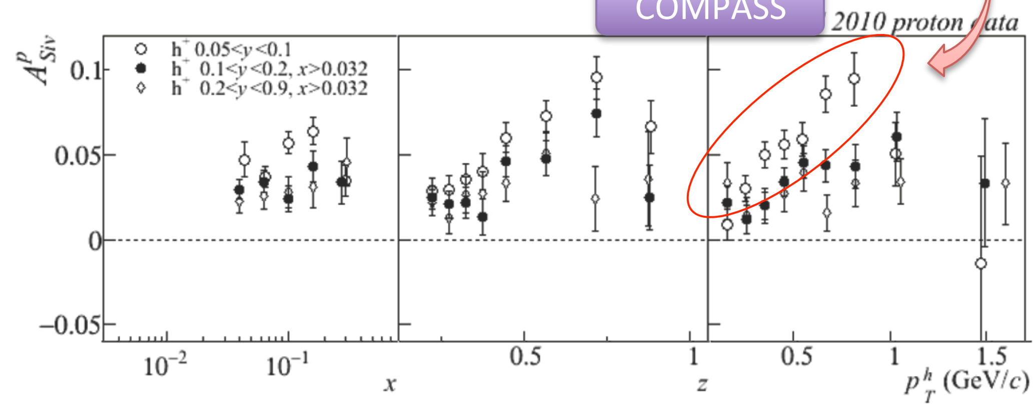
New !



HERMES

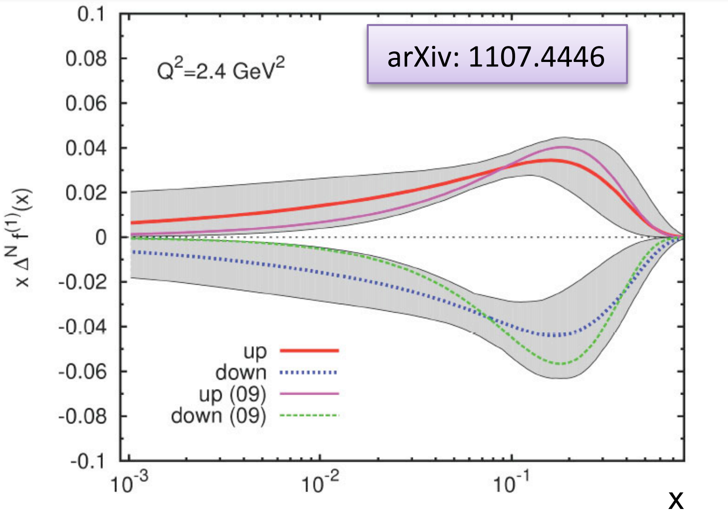


COMPASS

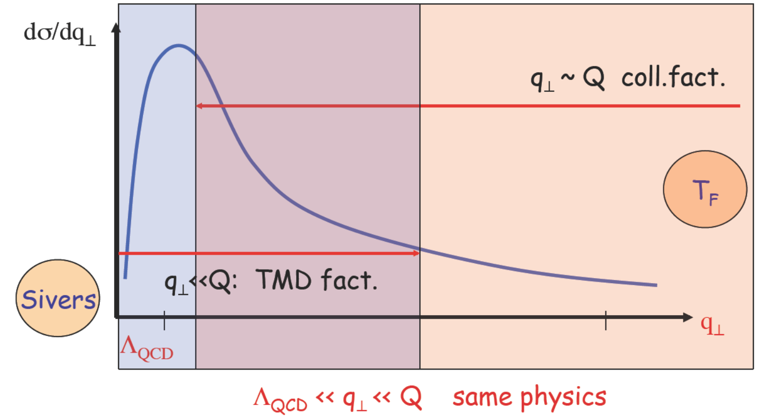


The Sivers challenges

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



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

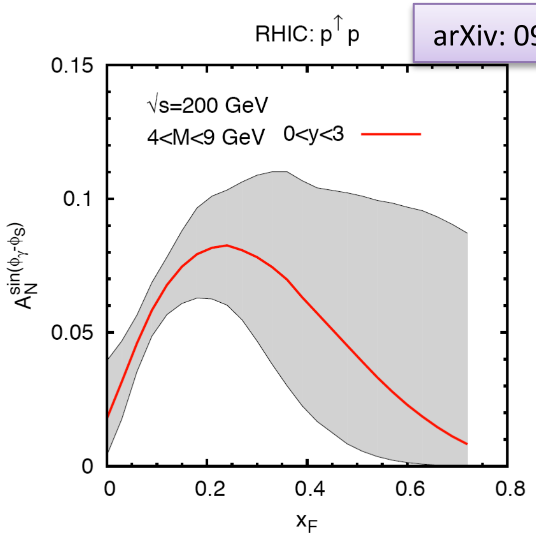


Sivers effect from SIDIS to Drell-Yan:

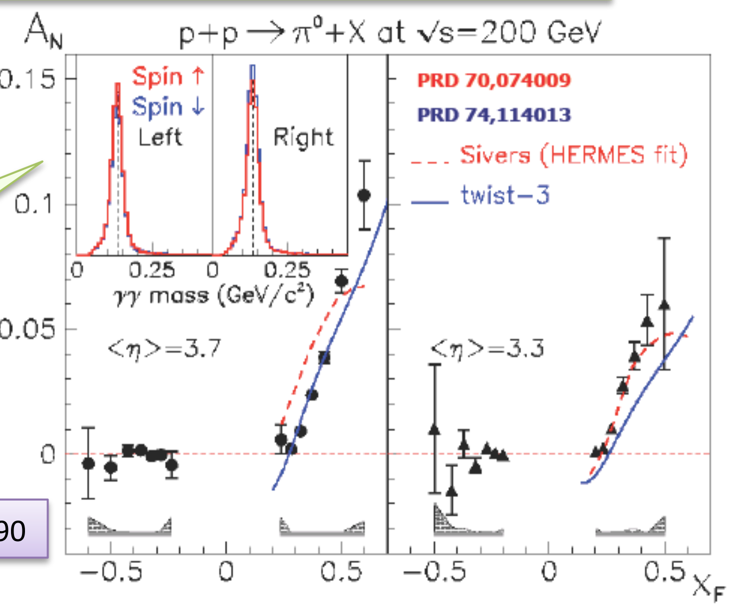
Sign change as a crucial test of TMDs factorization

Sivers effect from SIDIS to pp:

A possible candidate to explain SSA



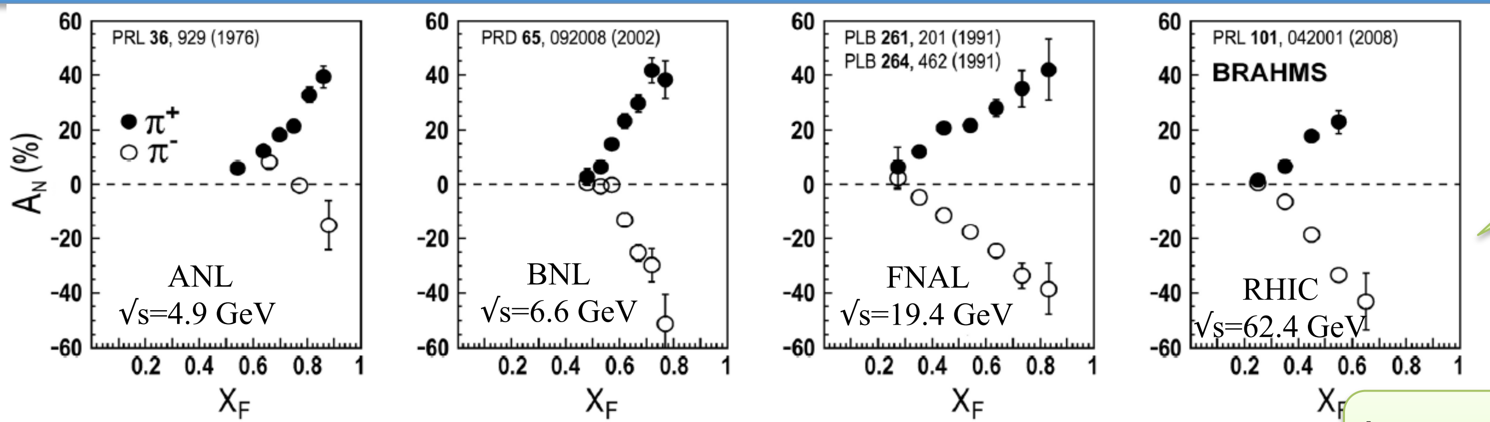
Sivers from SIDIS and collinear twist-3 as candidates for SSA explanation



arXiv: 0801.2990

The inclusive hadron SSA

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



Persistent with energy

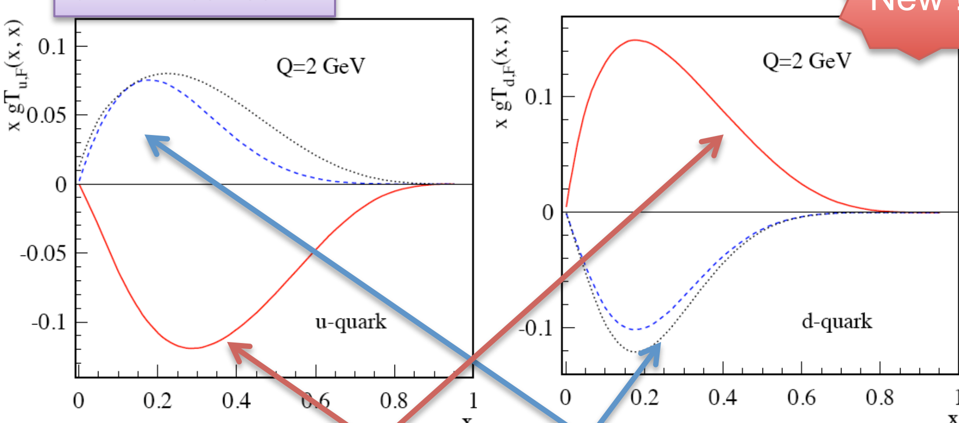
Sivers effect from SIDIS to pp:

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

New !

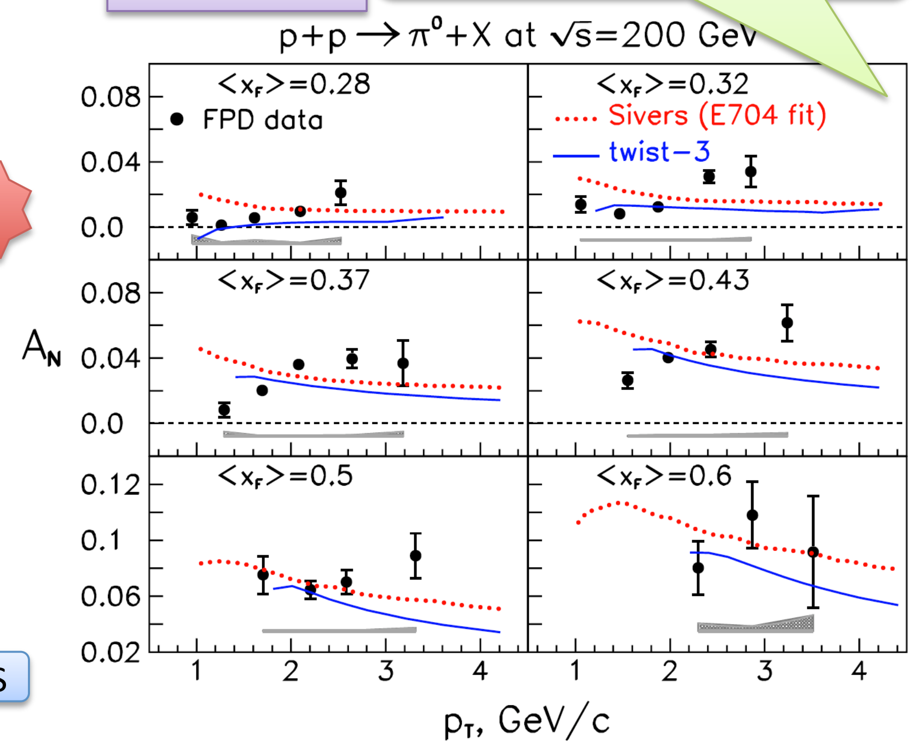


T3 correlator from pp

Sivers moment from SIDIS

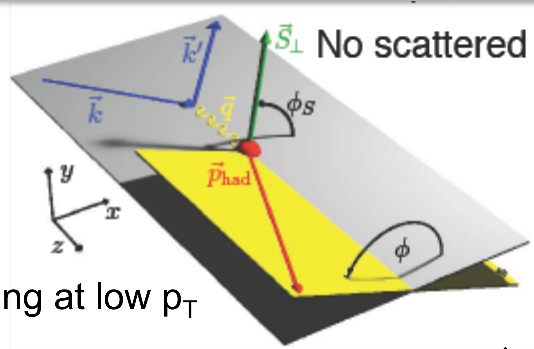
arXiv: 0801.2990

Asymptotic $1/p_T$ not reached
Issues on factorization



Inclusive hadron SSA in SIDIS

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



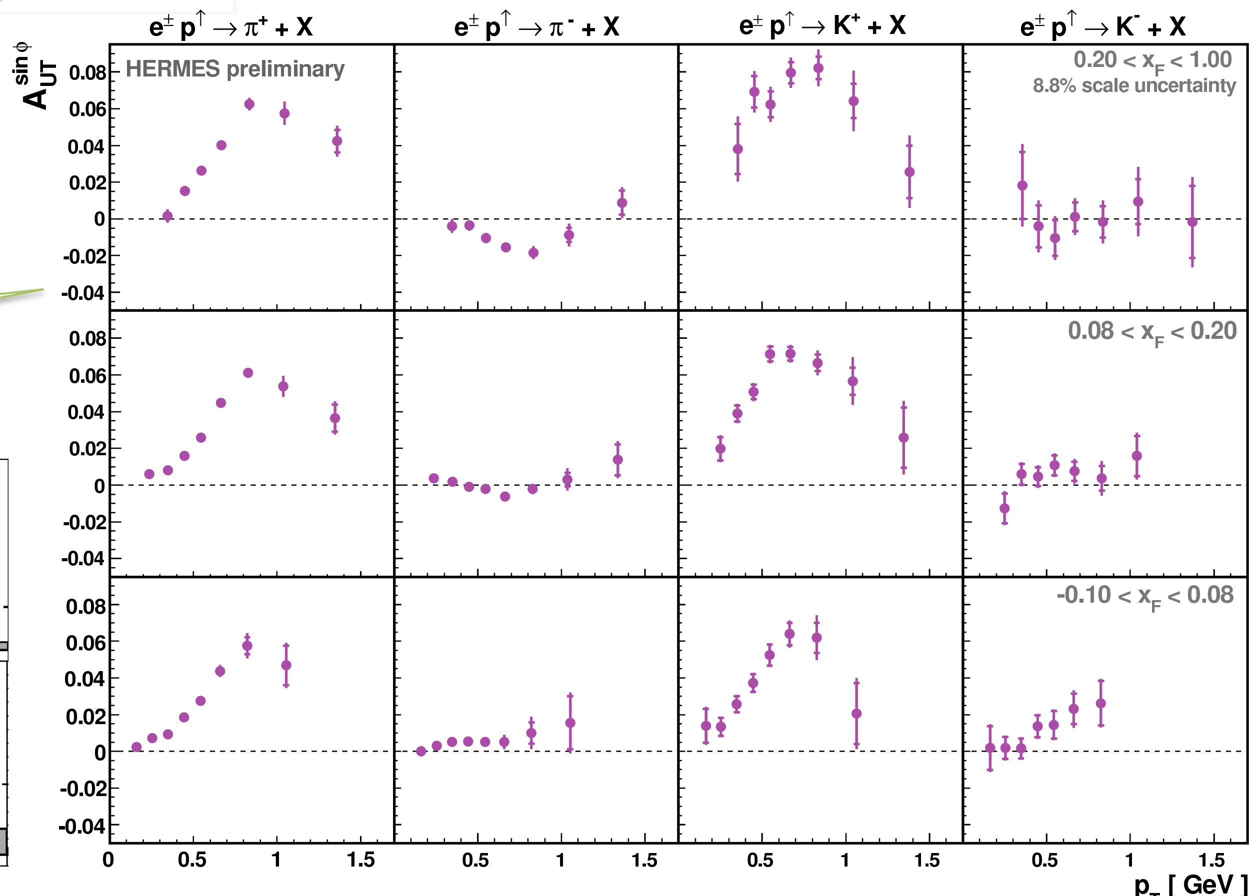
No scattered beam detected → **p_T, x_F** with respect to **e beam** (not q-vector)

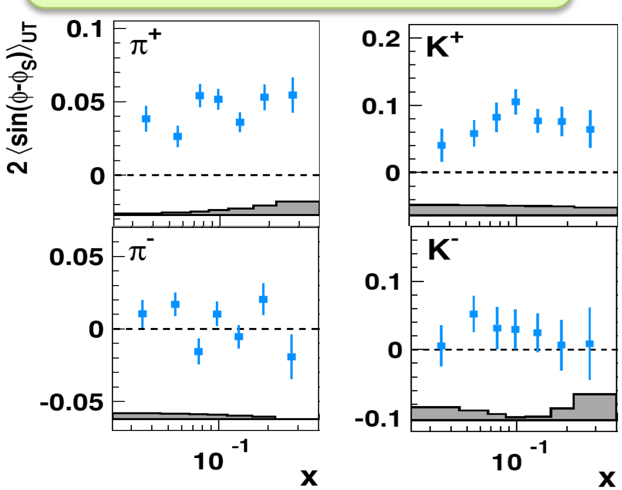
Sivers modulation $\sin(\phi-\phi_S)$ can survives as $\sin(\phi)$

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

- 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





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 Lam-Tung relation

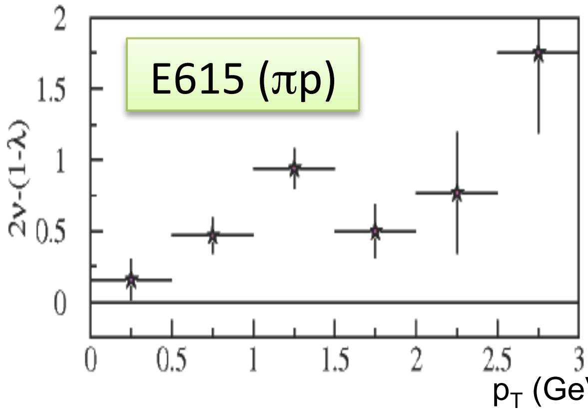
$h_1^\perp \otimes h_1^\perp$

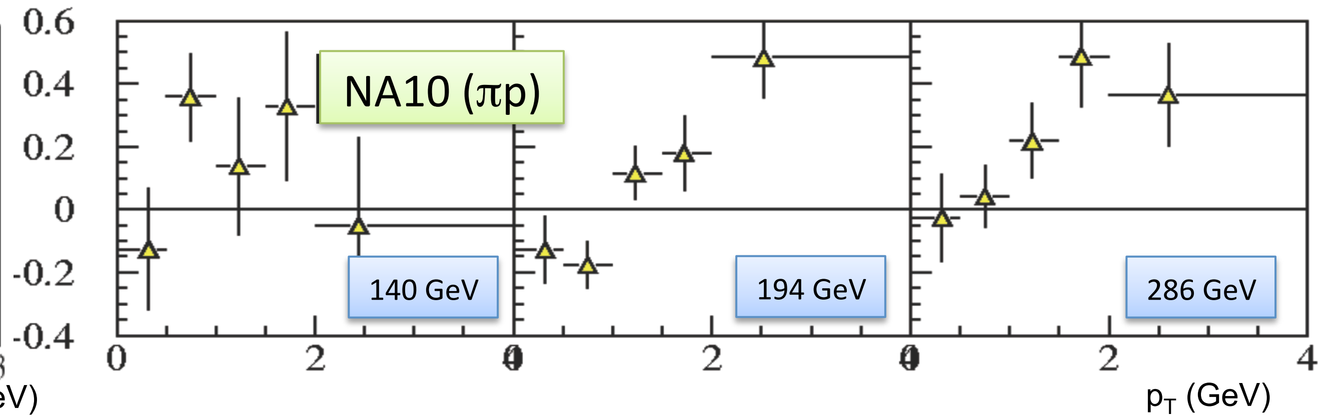
$$\frac{d\sigma^{hp\to eeX}}{d\Omega} \propto 1+\lambda\cos^2\theta+\mu\sin 2\theta\cos\phi+\frac{\nu}{2}\sin^2\theta\cos 2\phi$$

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

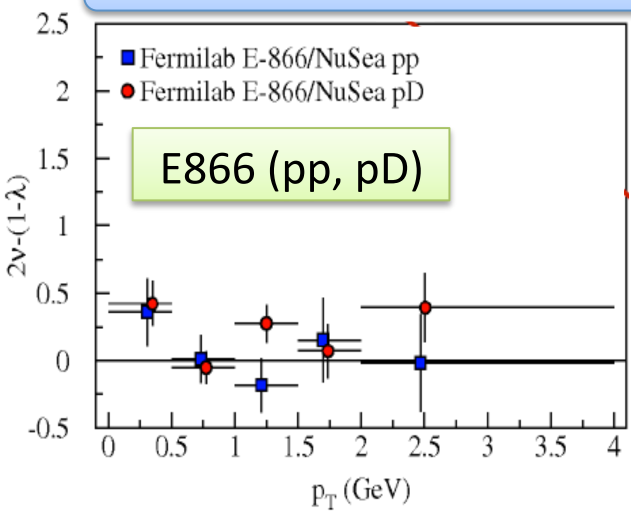
$$(1-\lambda)=2\nu$$

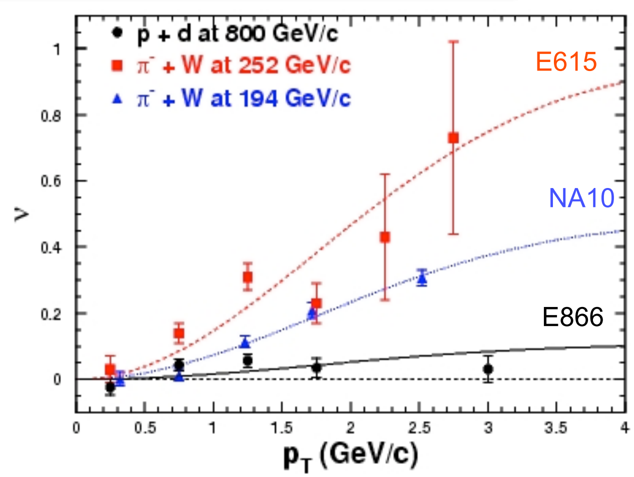
Preserved by NLO and resummation
Analogous of SIDIS Callan-Gross

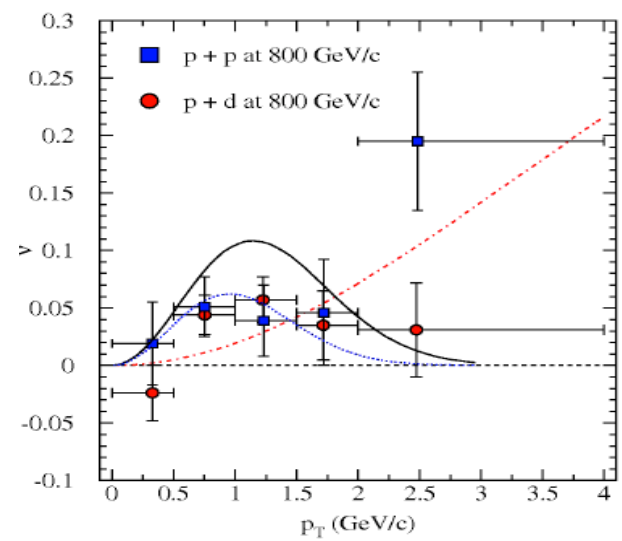




Boer-Mulders offers a possible explanation $\nu \approx h_{1q}^\perp \times h_{1\bar{q}}^\perp$







The azimuthal modulation $h_1^\perp \otimes H_1^\perp$

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

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

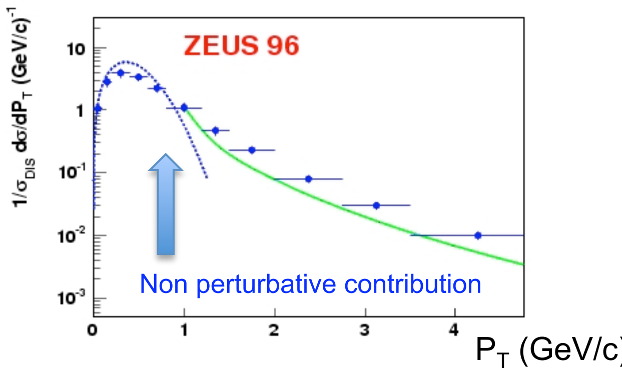
$h_1^\perp \otimes H_1^\perp$

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

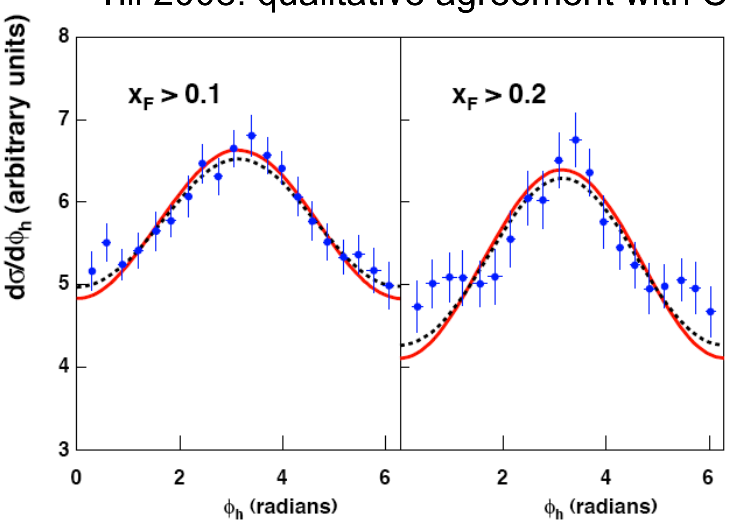
Cahn PLB 78 (1978)

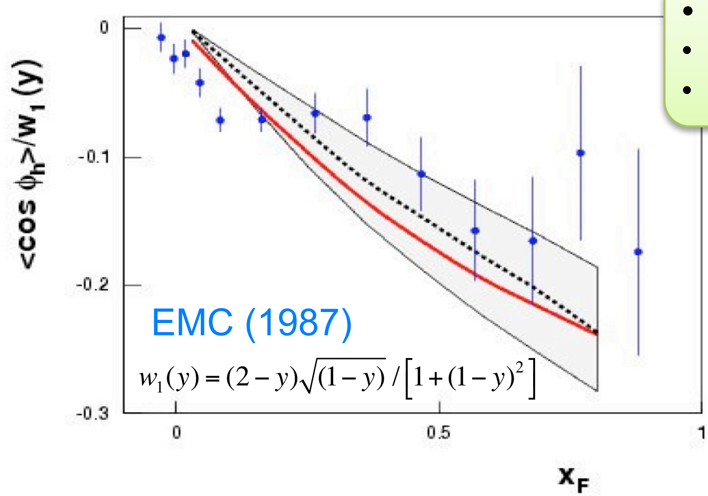
Leading-twist contribution introduced by Boer & Mulders in 1998

Boer & Mulders PRD 57 (1998)



Till 2008: qualitative agreement with Cahn expectations





- No hadron identification
- No charge separation
- Poor statistics for $\cos 2\phi$

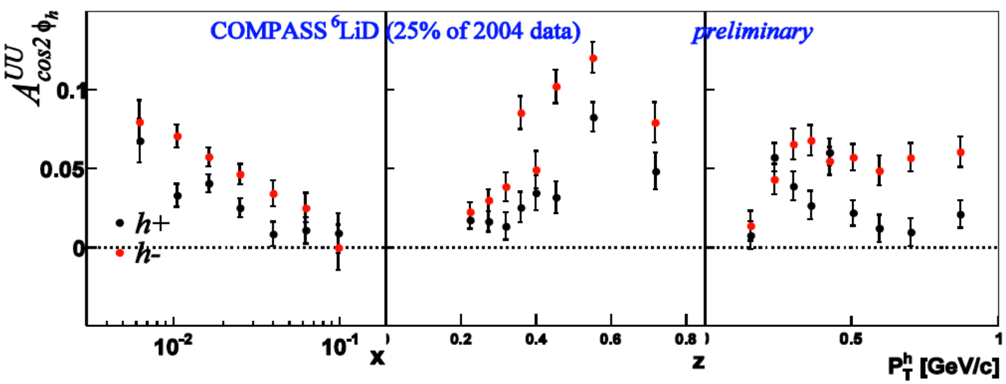
The SIDIS cos2ϕ dependence

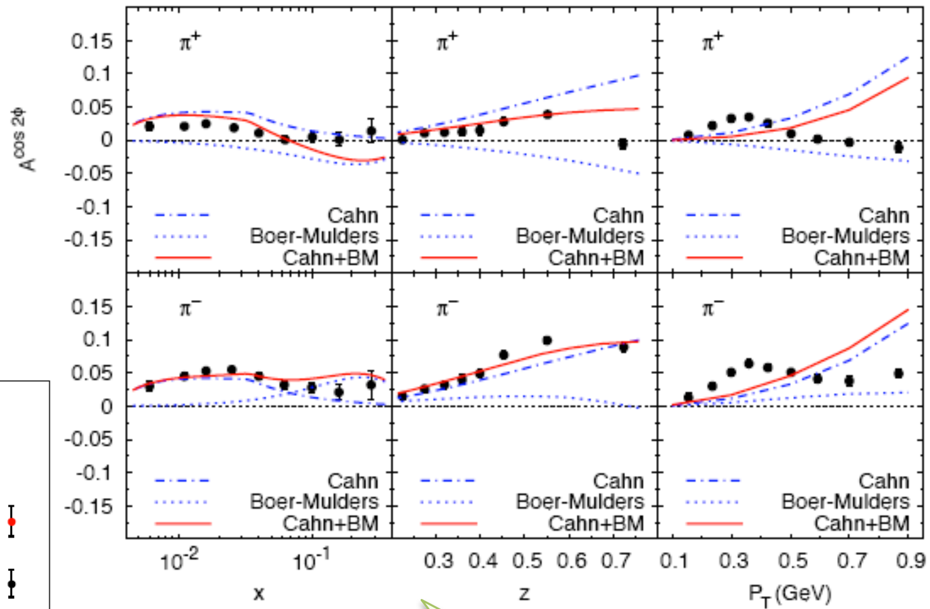
$h_1^\perp \otimes H_1^\perp$

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

Non-zero !

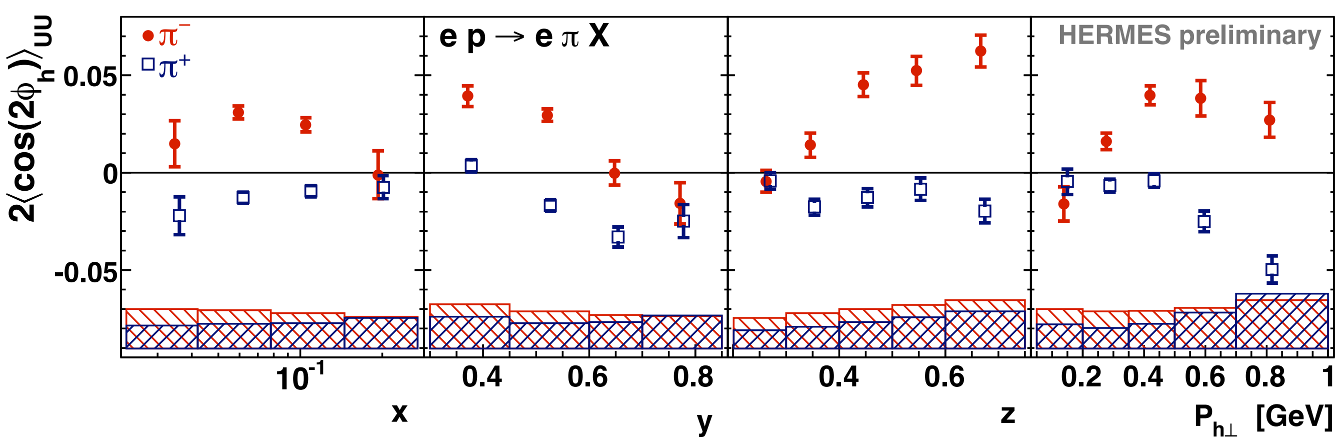
Issue on DATA consistency





arXiv: 0912.5194

Can be explained by large uncertainty on Cahn and neglected HT effects



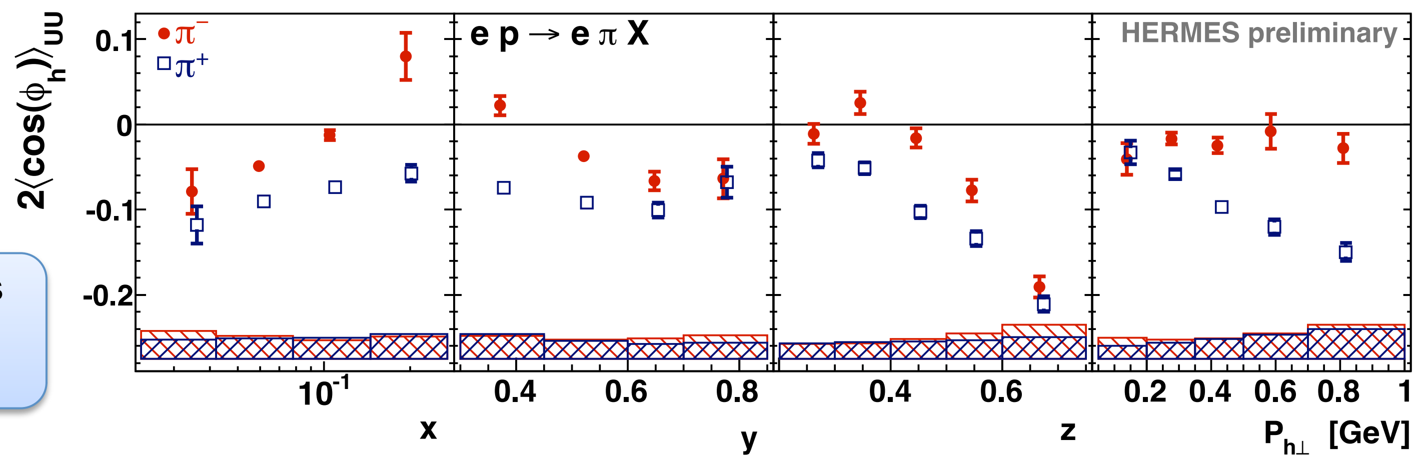
The SIDIS cosϕ dependence

$f_1 \otimes D_1$

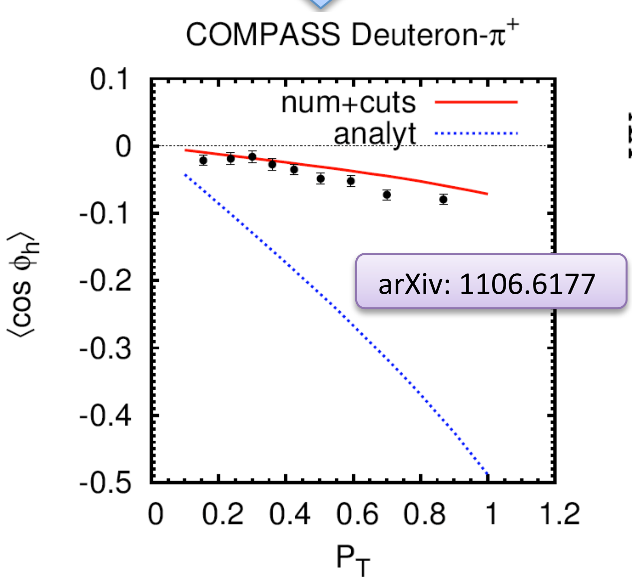
Significant difference in hadron charge might signal $h_1^{\perp} \otimes H_1^{\perp}$

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

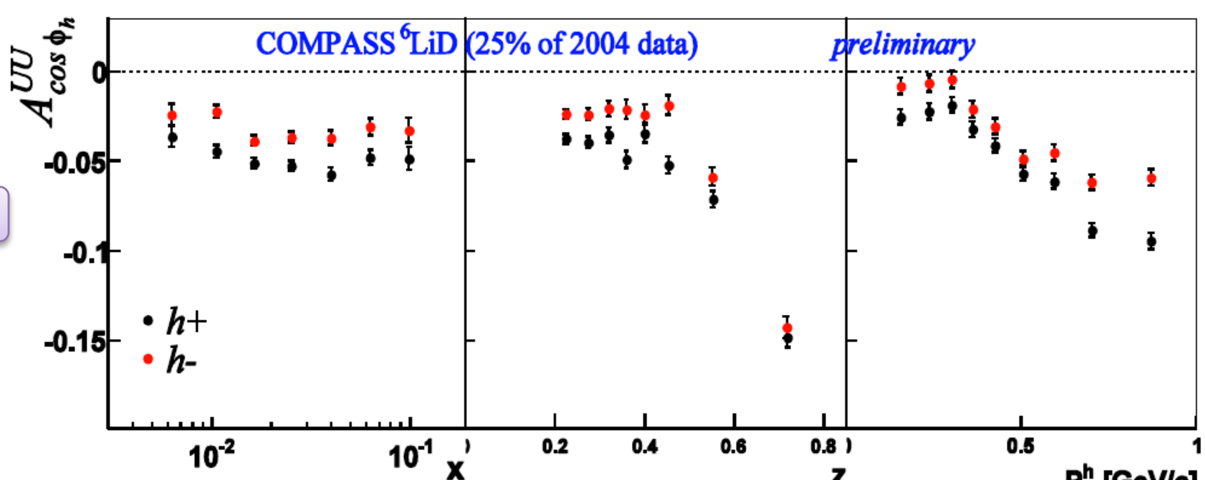
Large and negative increasing with z and P_h



Much larger expectations but largely sensitive on $<k_T>$ and k_T cutoff



arXiv: 1106.6177



Summary

TMDs describe a new class of phenomena
providing novel insights into the rich nuclear structure

SIDIS and e^+e^- experiments provide evidence of non-zero TMDs

First generation experiments provide promises but also open questions

- Full coverage of valence region not achieved
- Limited knowledge on transverse momentum dependences
- Role of the higher twist to be quantified
- Evolution properties to be defined
- Flavor decomposition to be refined
- Universality ⟷ Fundamental test of QCD

The TMDs Landascape

A very active field to explore for various upcoming experiments !

The 3D description of the nucleon

Distribution Functions (DF)

nucleon \ quark	U	L	T
U	q		$h_1^{\perp}$
L		Δq	$h_{1L}^{\perp}$
T	$f_{1T}^{\perp}$	$g_{1T}^{\perp}$	δq, $h_{1T}^{\perp}$

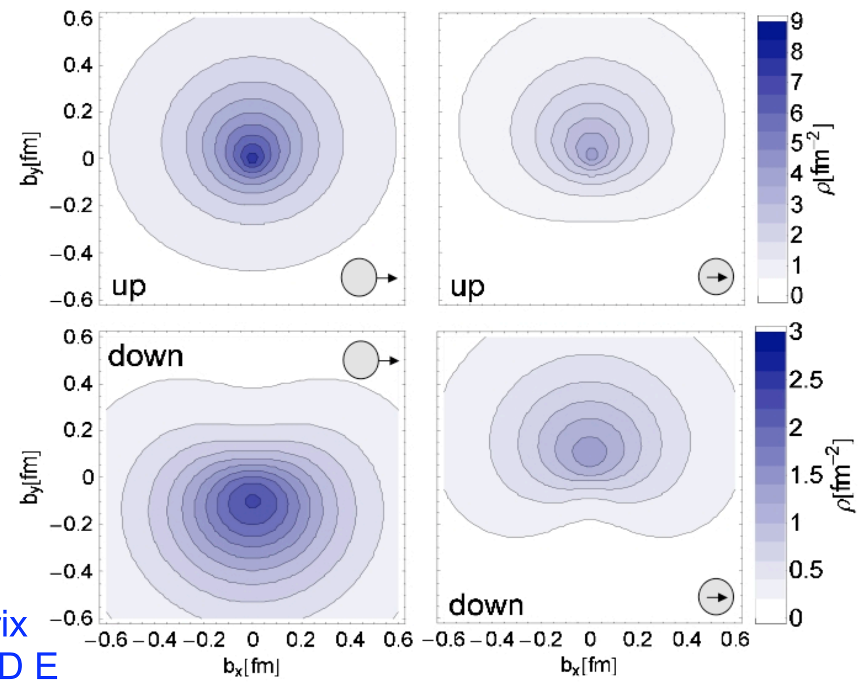
BOER-MULDERS

Spin orbit effect

$$h_1^{\perp q} \sim -\kappa_T^q$$

Impact parameter space

Deformations by

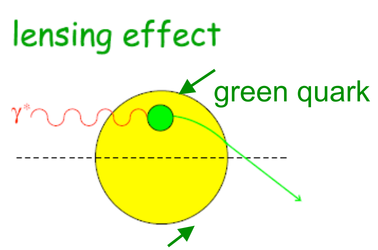


SIVERS

Quark orbital angular momentum

$$f_{1T}^{\perp q} \sim -\kappa^q$$

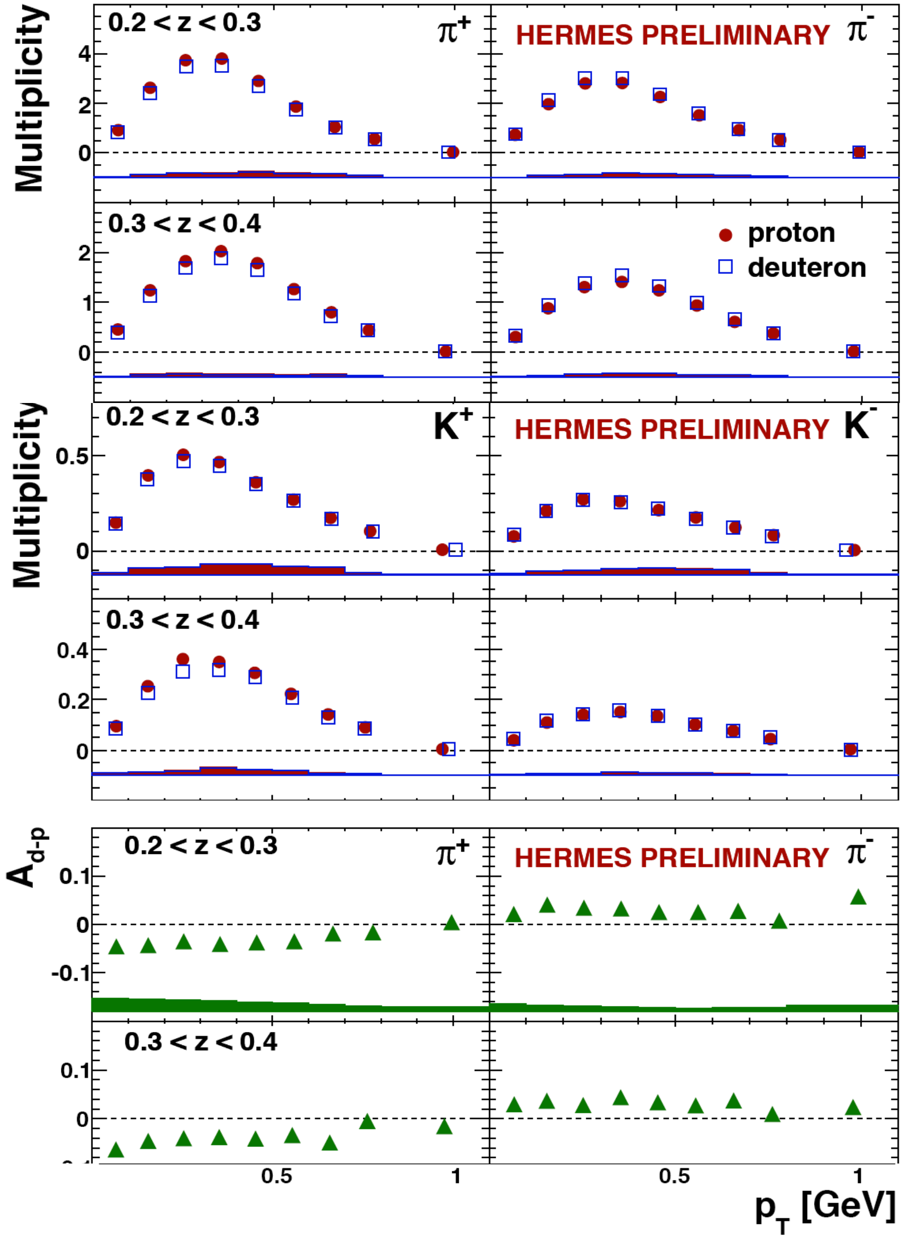
3-momentum space



i.e. Sivers: spin-orbit correlations with same matrix element of anomalus magnetic moment, and GPD E

The hadron multiplicities

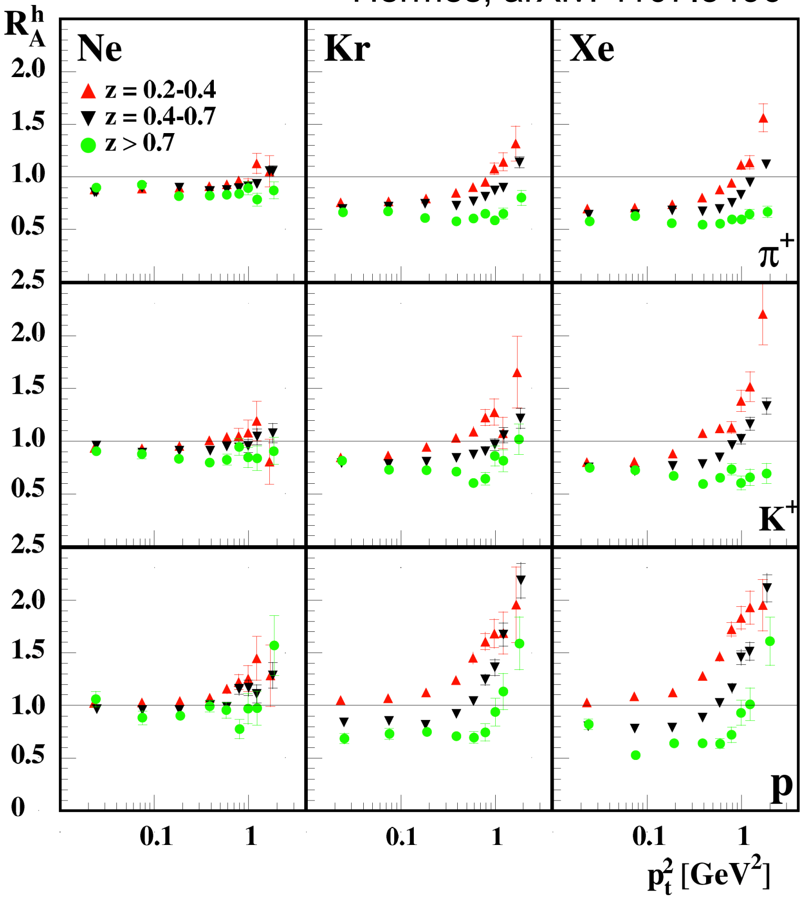
$f_1 \otimes D_1$



Seek for flavor dependences

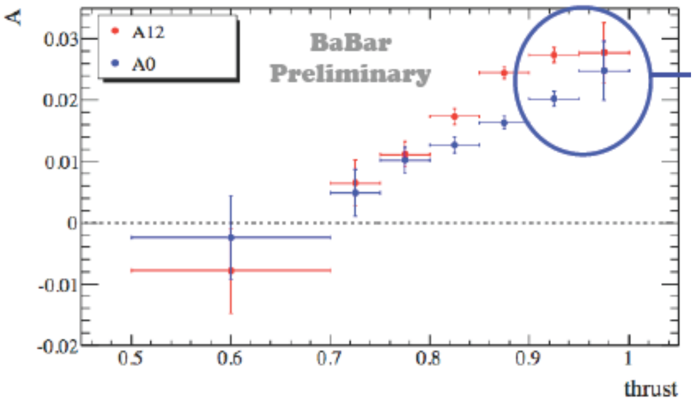
Nuclear effects should be taken into account for not pure targets

Hermes, arXiv: 1107.3496

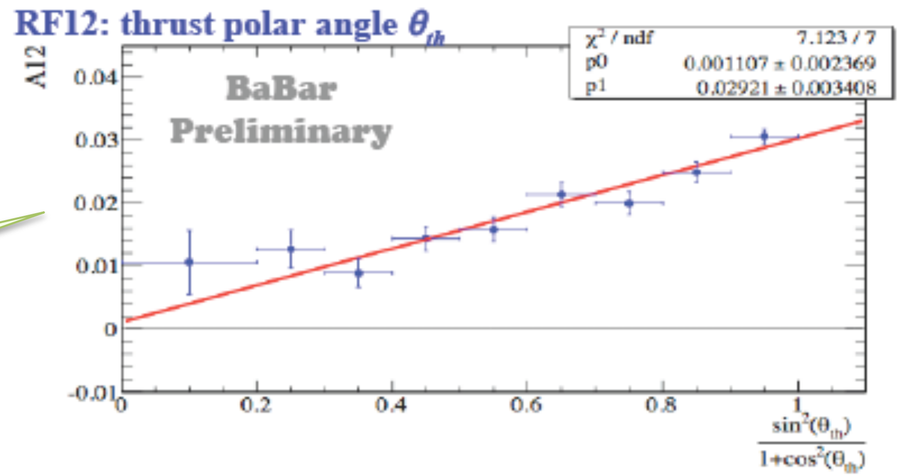


The Collins fragmentation

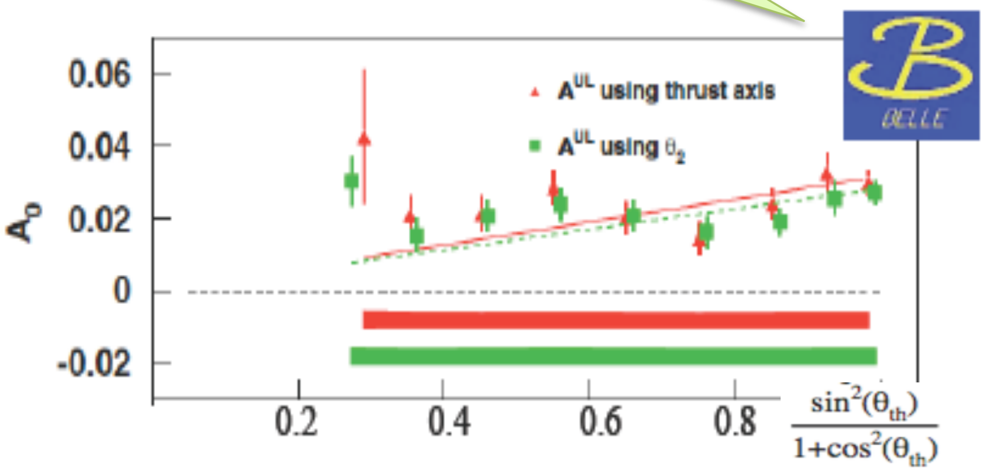
$H_1^{\perp} \otimes H_1^{\perp}$

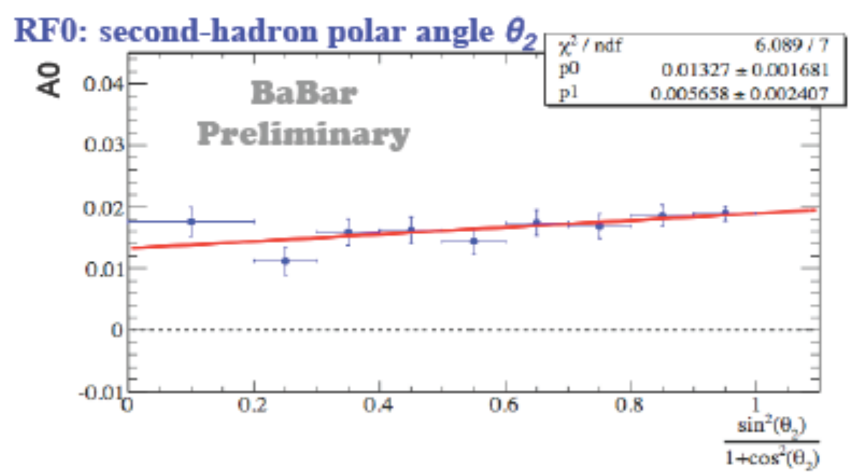


At low thrust spherical events and gluon emission



Asymmetry expected to go As $\sin^2(\theta)/(1+\cos^2(\theta))$





Pretzelosity

nucleon polarisation

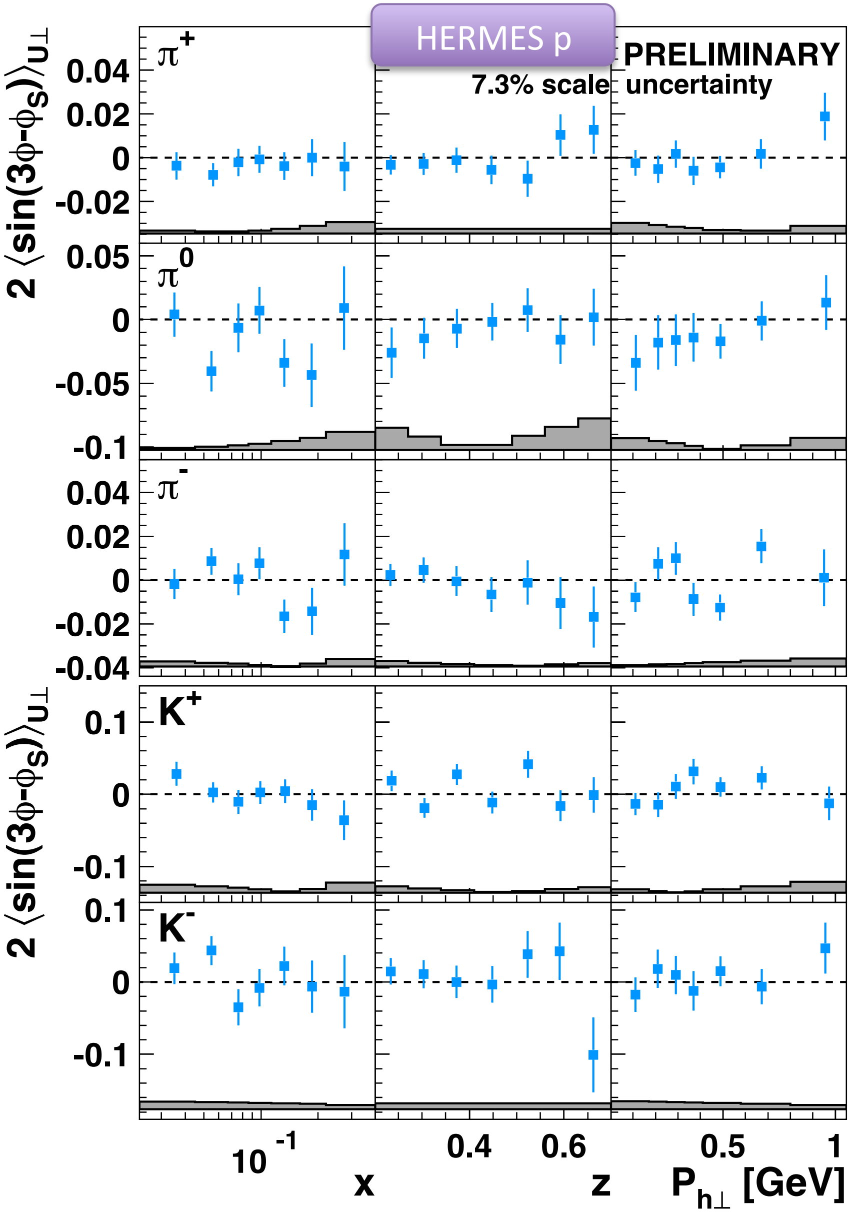
N/q	U	L	T
U	f_1 Number Density		$h_1^\perp$ - Boer-Mulders
L		g_1 - Helicity	$h_{1L}^\perp$ - Worm-gear
T	$f_{1T}^\perp$ - Sivers	$g_{1T}^\perp$ - Worm-gear	h_1 - Transversity $h_{1T}^\perp$ - Pretzelosity

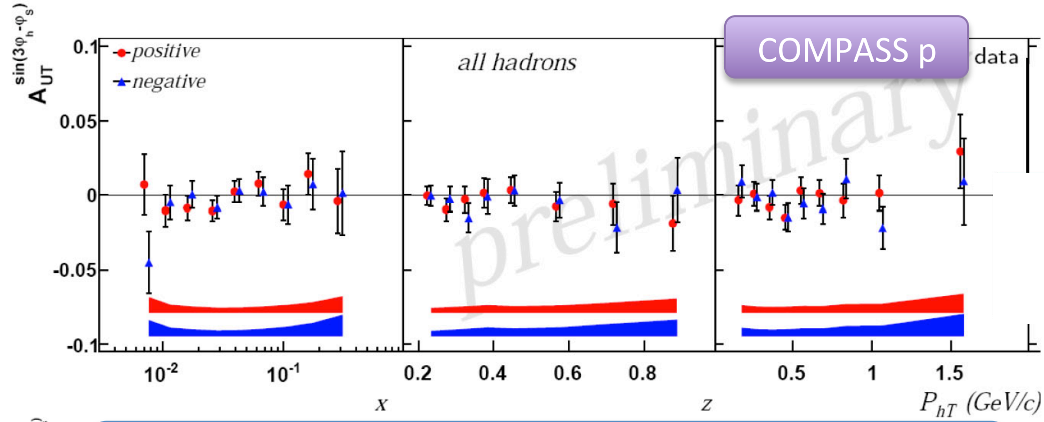
Sensitive to the D-wave component and the non spherical shape of the nucleon

(The D-Wave)

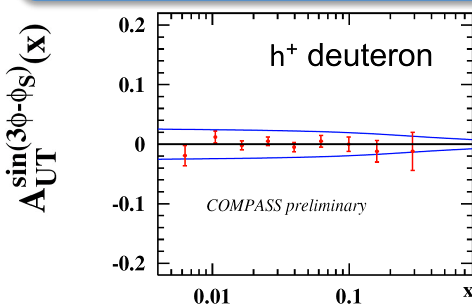
The Pretzelosity

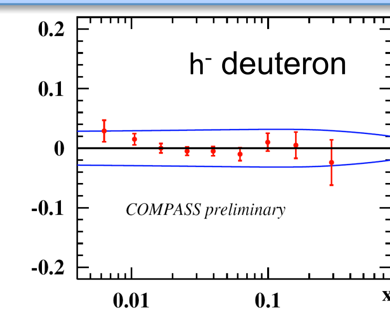
$h_{1T}^{\perp} \otimes H_1^{\perp}$





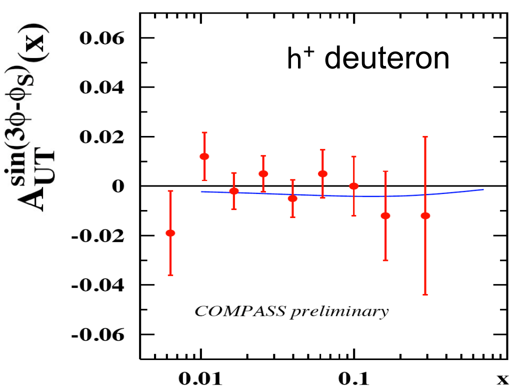
Statistical power of existing data is not enough to observe significant signals





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

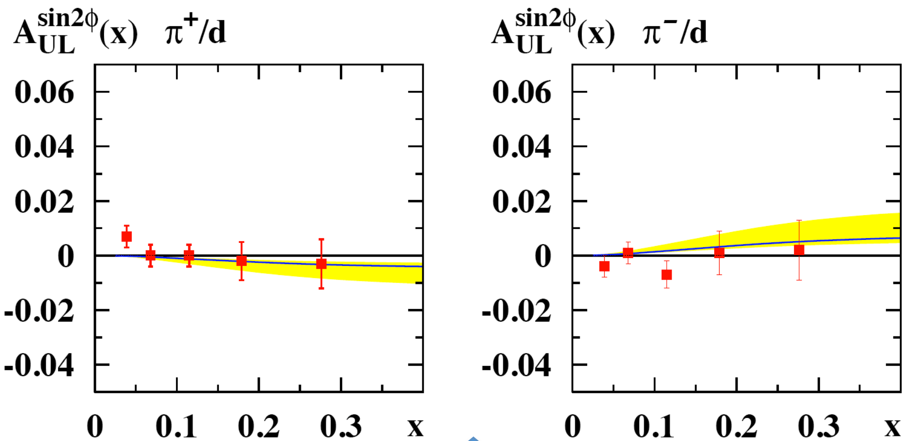
The only T-even and chirally-even off-diagonal TMD

(The Standard OAM Effect)

The A_{UL} Asymmetry

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

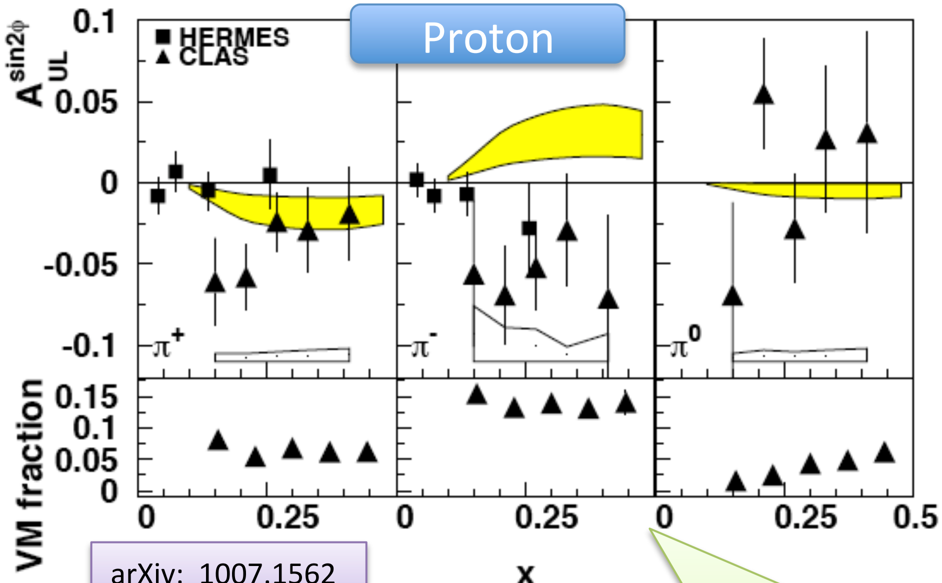
$$A_{UT}^{\sin(\phi-\phi_S)} \propto \frac{\sum_q e_q^2 f_1^{\perp,q}(x,p_T^2) \otimes_\omega D_1^q(z,K_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,K_T^2)}$$



Deuteron

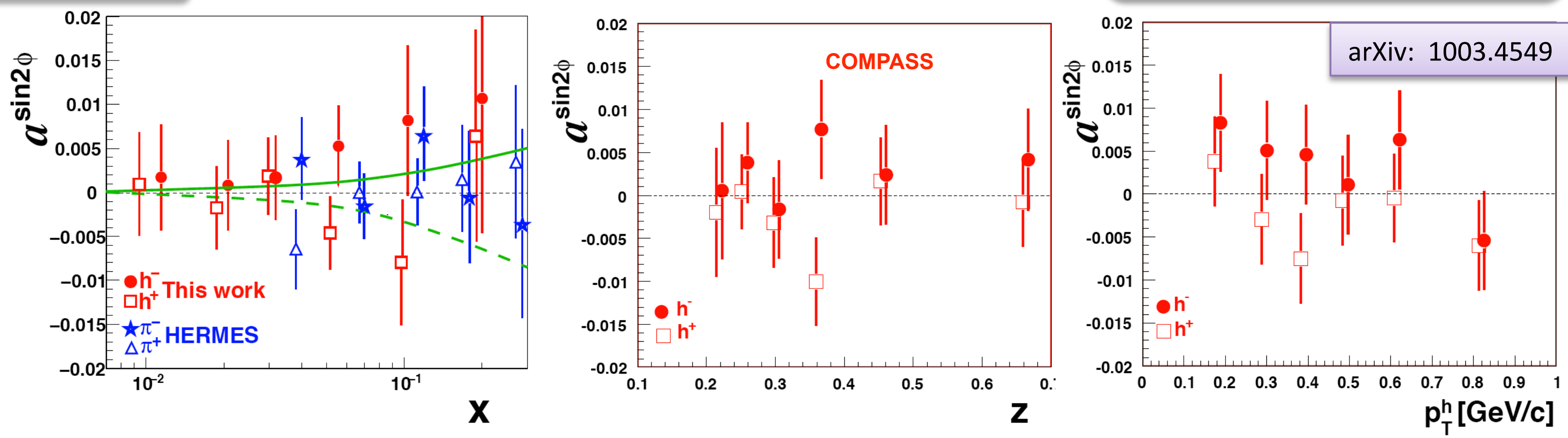
arXiv: 0902.0689

Proton



arXiv: 1007.1562

Unexpected pattern needs more statistics to be verified

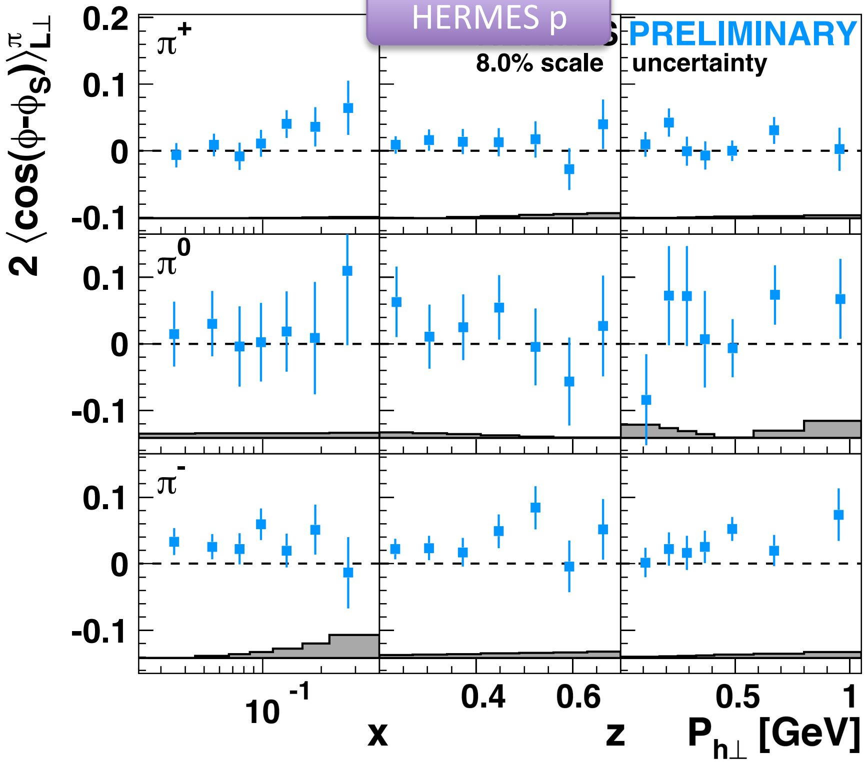


arXiv: 1003.4549

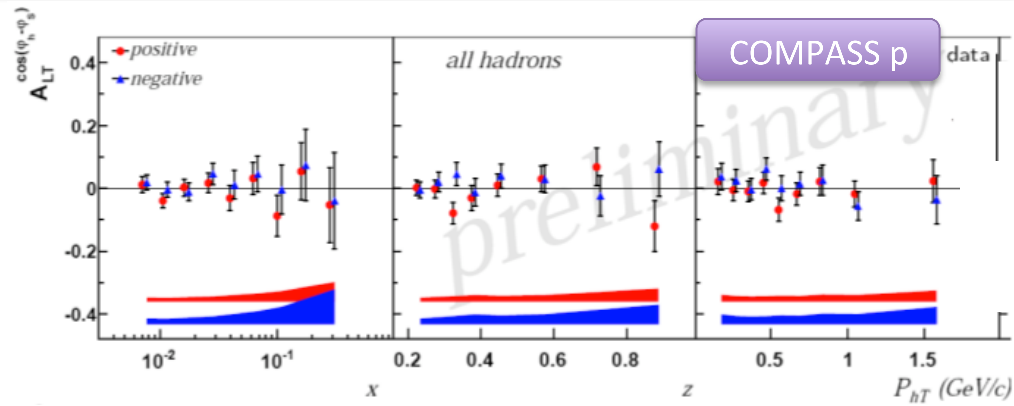
The A_{LT} Asymmetry

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

HERMES p



COMPASS p

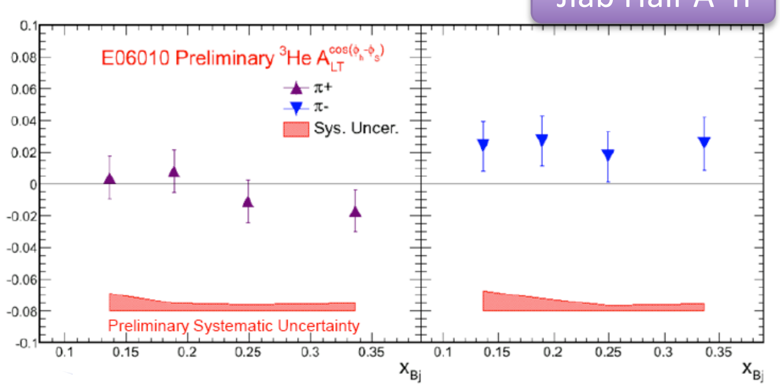


Statistics not enough to investigate relations supported by many theoretical models:

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

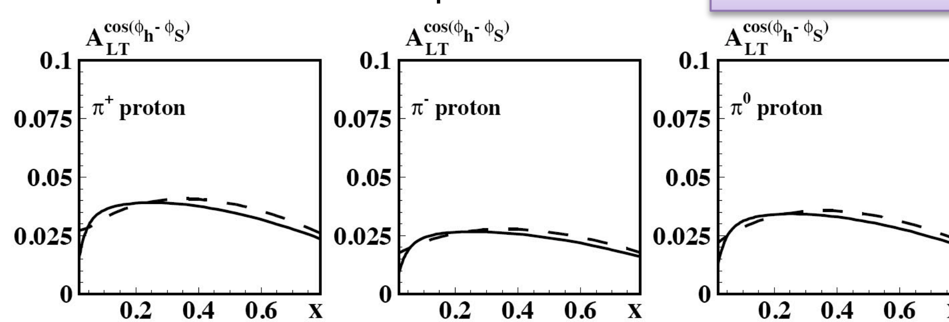
$$g_{1T}^{q(1)}(x) \overset{WW-type}{\approx} x \int_x^1 \frac{dy}{y} g_1^q(y)$$ (Wandura-Wilczek type approximation)

Jlab Hall-A n



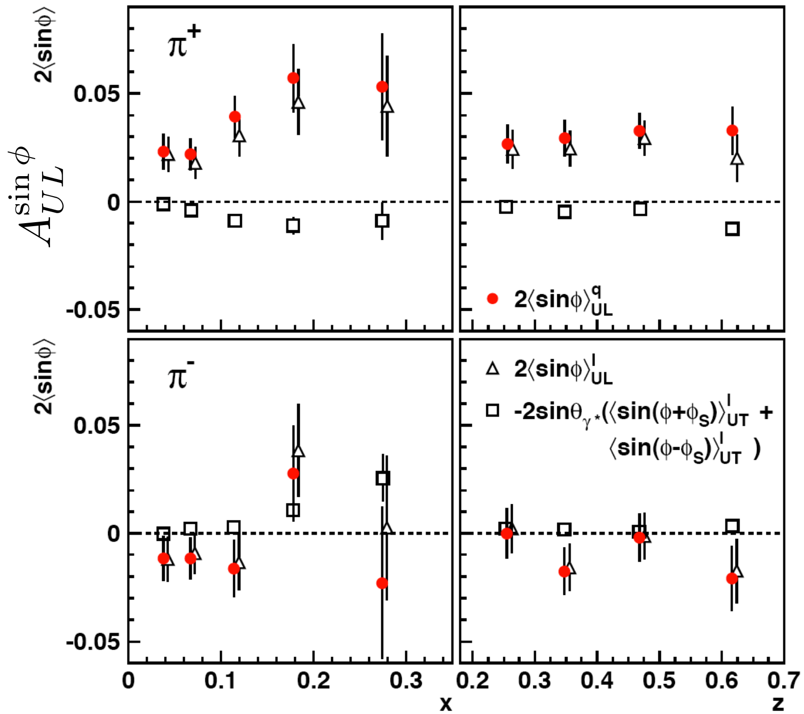
From constituent quark model:

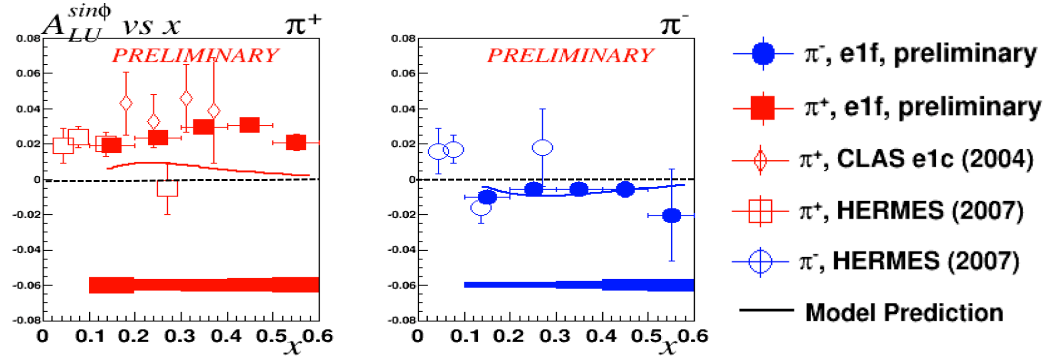
arXiv: 0903.1271

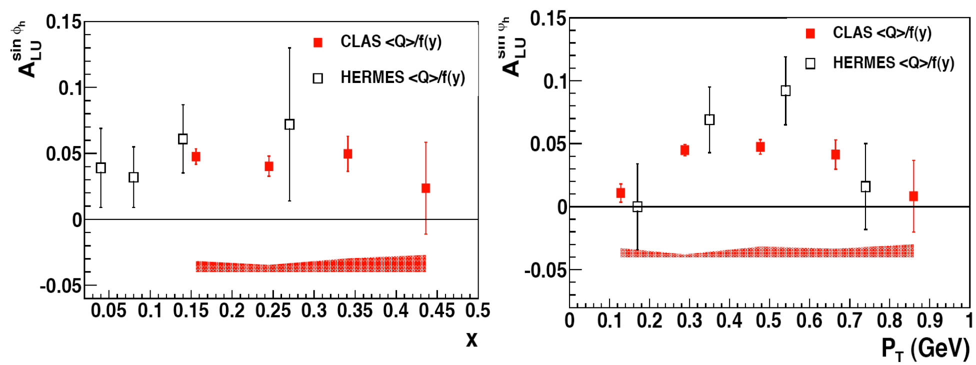


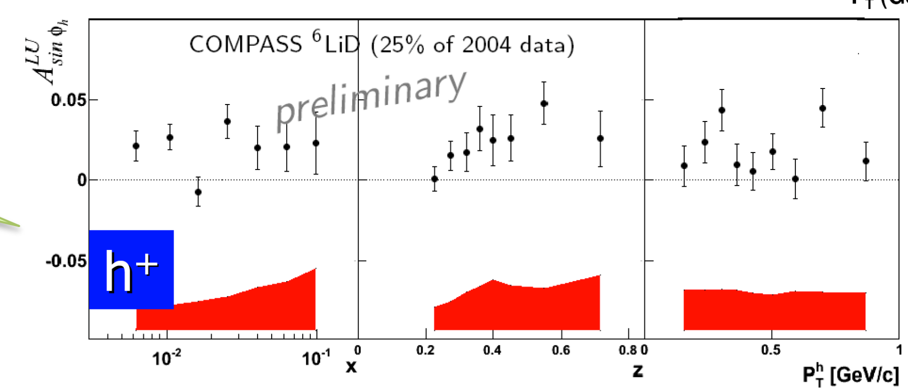
Higher-twist effects

$$\sigma_{UL}^{\sin(\phi)} \propto \left[h_L \otimes H_1^{\perp} + f_L^{\perp} \otimes D_1 + \ldots \right] / Q \qquad \sigma_{LU}^{\sin(\phi)} \propto \left[e \otimes H_1^{\perp} + g^{\perp} \otimes D_1 + \ldots \right] / Q$$









Non zero up to the COMPASS energies