The Spin Nucleon Structure Investigation at HERMES: Recent Highlights.

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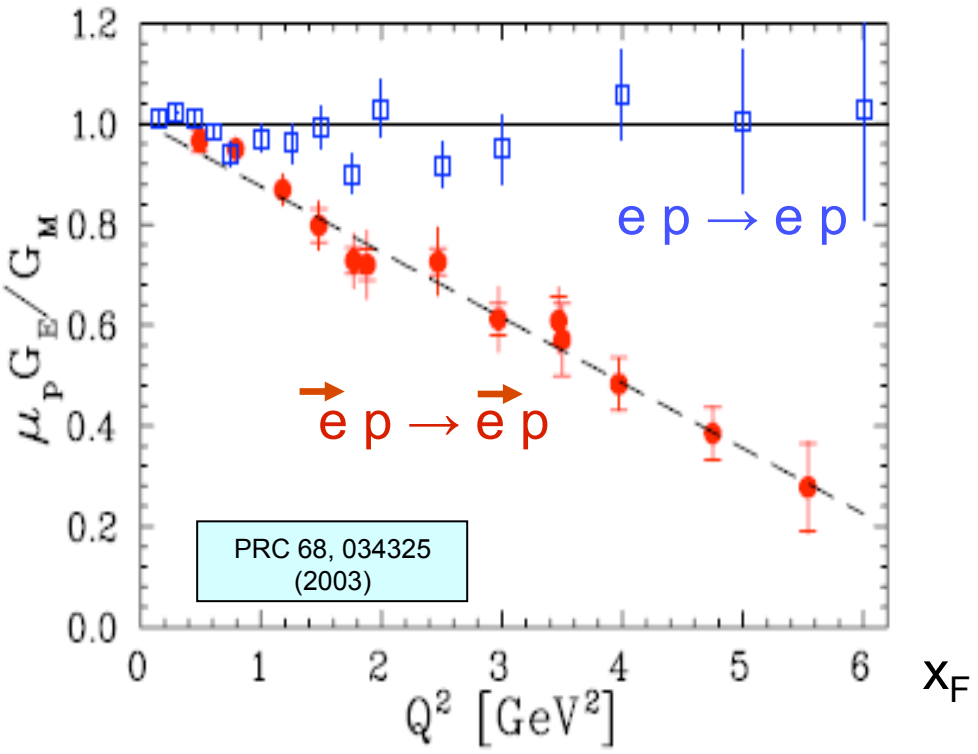
INFN Ferrara

Baryons2013 Conference
June 25th, 2013 Glasgow

The Spin Degree of Freedom

Spin degrees of freedom can explain otherwise surprising phenomena and bring new insights into nuclear matter structure

Fundamental: do not neglect it !!



Open Issues: Test Field for QCD

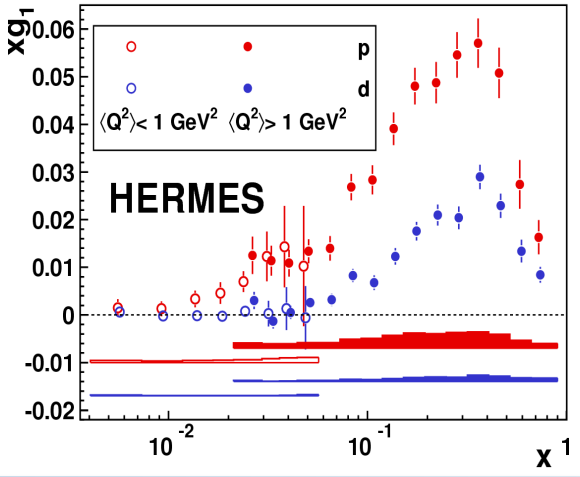
Proton spin budget: role of partonic orbital motion?

$\Delta\Sigma$=0.33±0.03
from DIS

ΔG~0.1 at 0.02<x<0.3
from DIS and pp scattering

$$\frac{1}{2} = \frac{1}{2}\sum_f (q_f^+ - q_f^-) + L_q + \Delta G + L_g$$

Phys Rev D75 (2007) 012007



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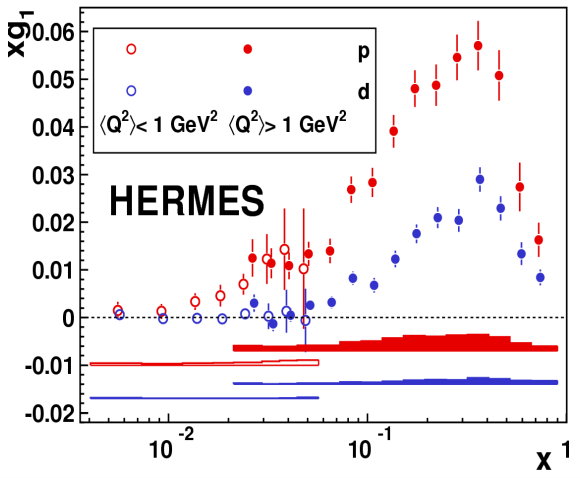
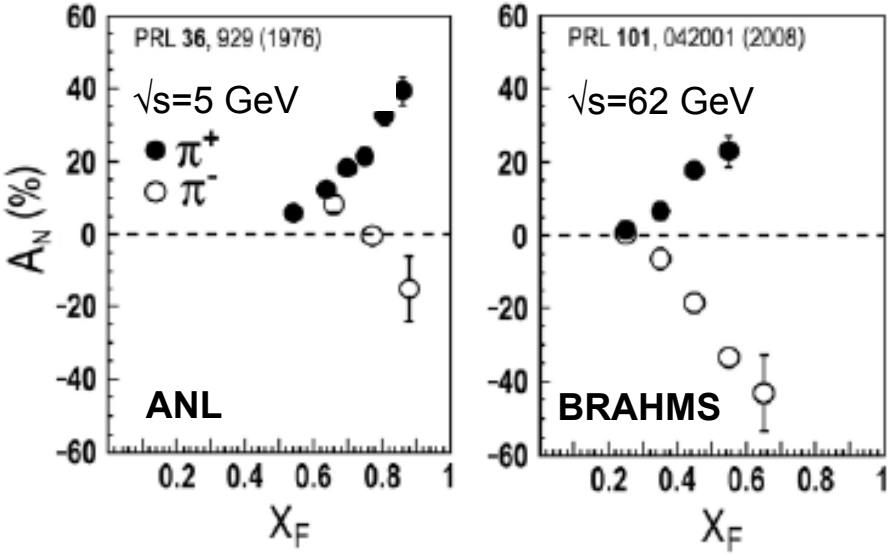
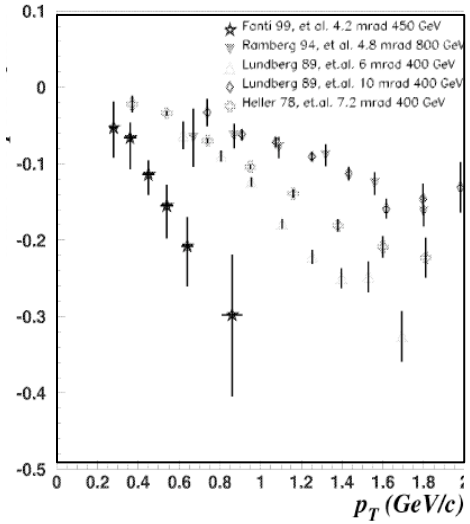


Single spin asymmetries: BIG (?!) although suppressed as m_q/Q^2 in pQCD

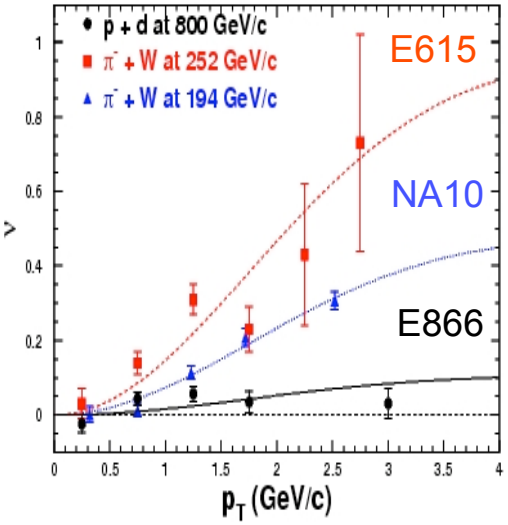
$p^\uparrow p \to \pi X$



$pp \to \Lambda^\uparrow X$



$\pi p \to \mu\mu X$

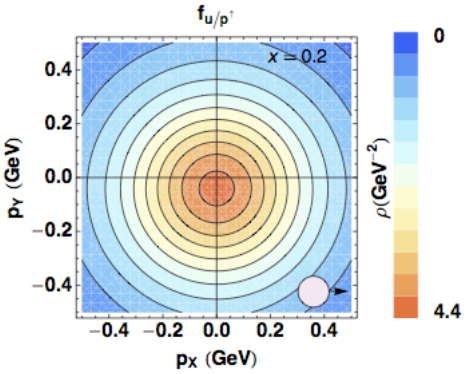


The Real Experience: 3D !

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

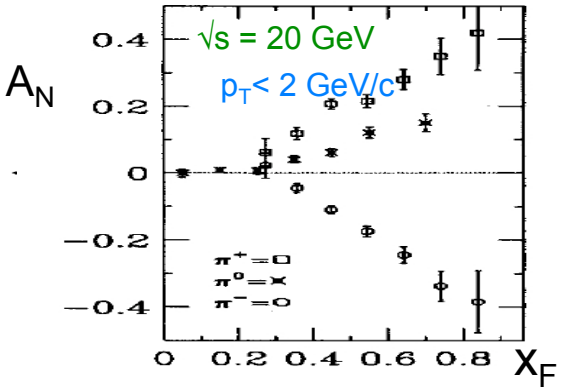
TMD PDFs: $f_p^u(x,k_T)$,…

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

d^2k_T

PDFs $f_p^u(x)$,…

May explain SSA & Lam-Tung



Quantum Phase-space Distributions of Quarks

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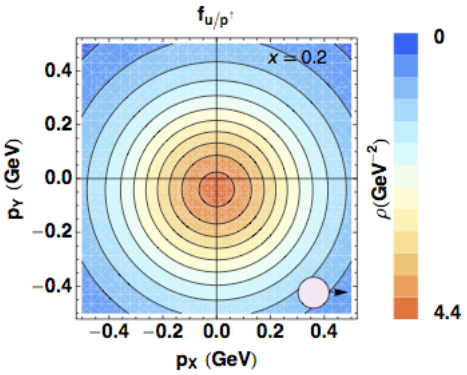
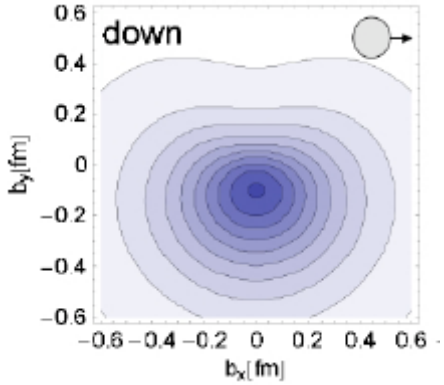


d^3r

d^2k_T (FT)



TMD PDFs: $f_p^u(x,k_T)$,…

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

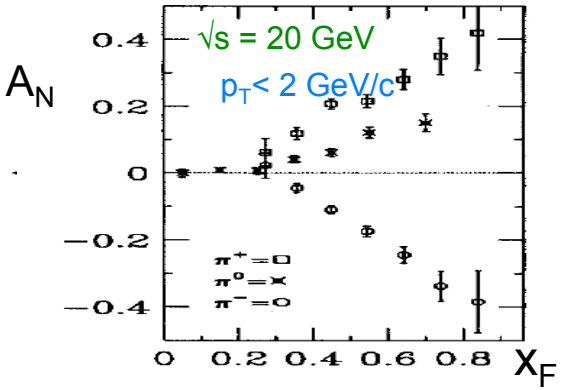
GPDs: $H_p^u(x,\xi,t)$, …

Exclusive Measurements
Momentum transfer to target
Direct info about spatial distribution

d^2k_T

$\xi=0,t=0$

May explain SSA & Lam-Tung



PDFs $f_p^u(x)$,…

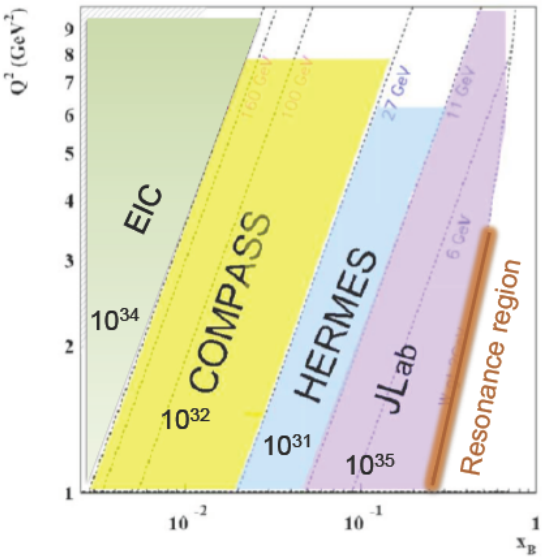
May solve
proton spin puzzle

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

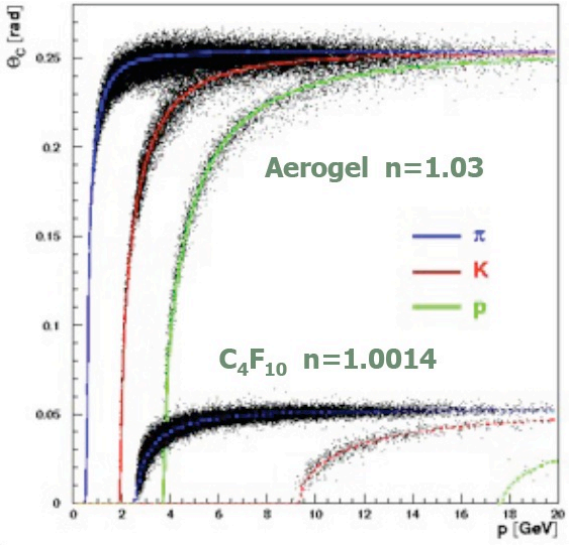
The HERMES Experiment

27.6 GeV e+/e- HERA beam

Valence and sea



Electron and Hadron ID

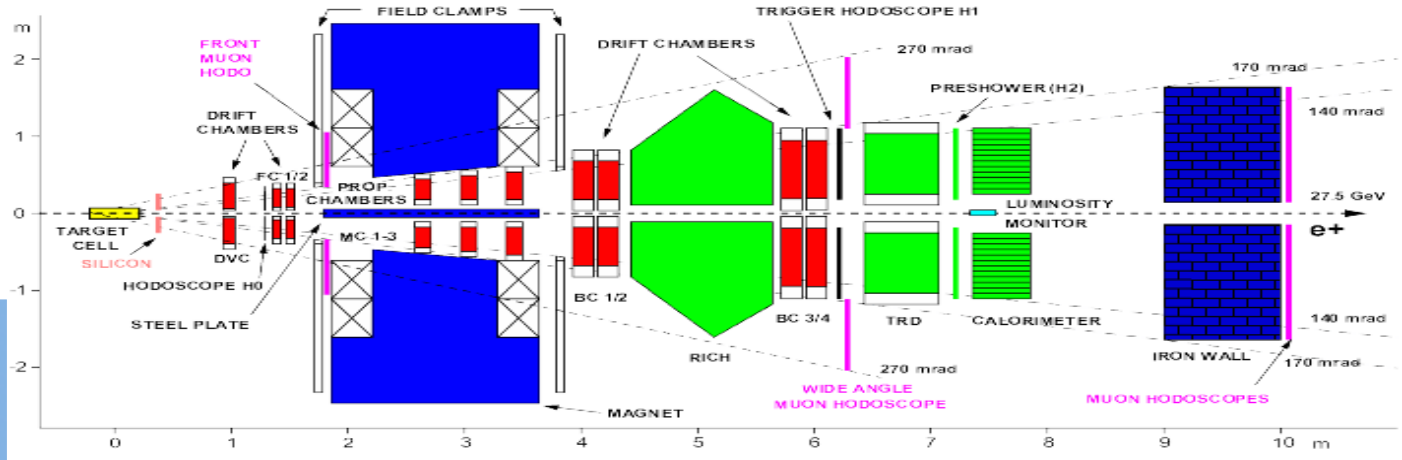


hermes

Data taking: 95-07

Internal gaseous target:

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



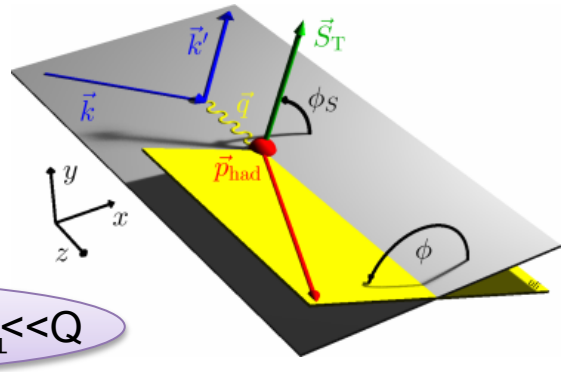
SIDIS for Transverse Momentum Dependence

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

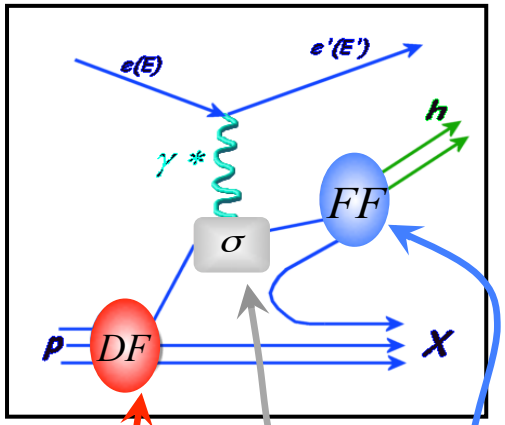
SIDIS cross section (transversely pol. target):



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

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

Involved phenomenology due to the convolution over transverse momentum



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

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

($h_1 \otimes H_1^\perp$; $f_{1T}^\perp \otimes D_1$; $h_{1T}^\perp \otimes H_1^\perp$)

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

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

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

Leading Twist TMDs

quark polarisation

nucleon polarisation

N/q	U	L	T
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Number density and helicity:

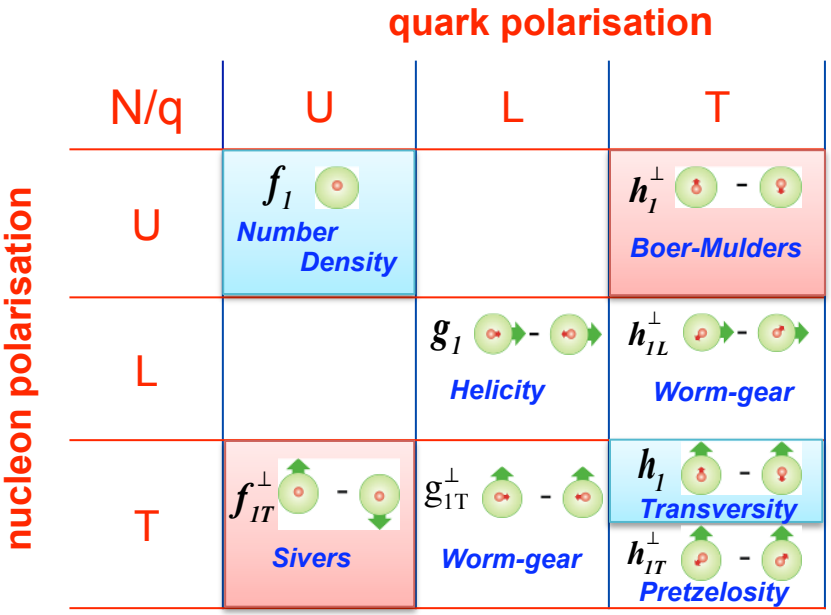
Focusing here in transverse momentum dependence

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

Leading Twist TMDs



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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 !

Leading Twist TMDs

quark polarisation

nucleon polarisation: N/q	U	L	T
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quark polarisation

nucleon polarisation: 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; $H_{1T}^\perp$

First TMD Evidences

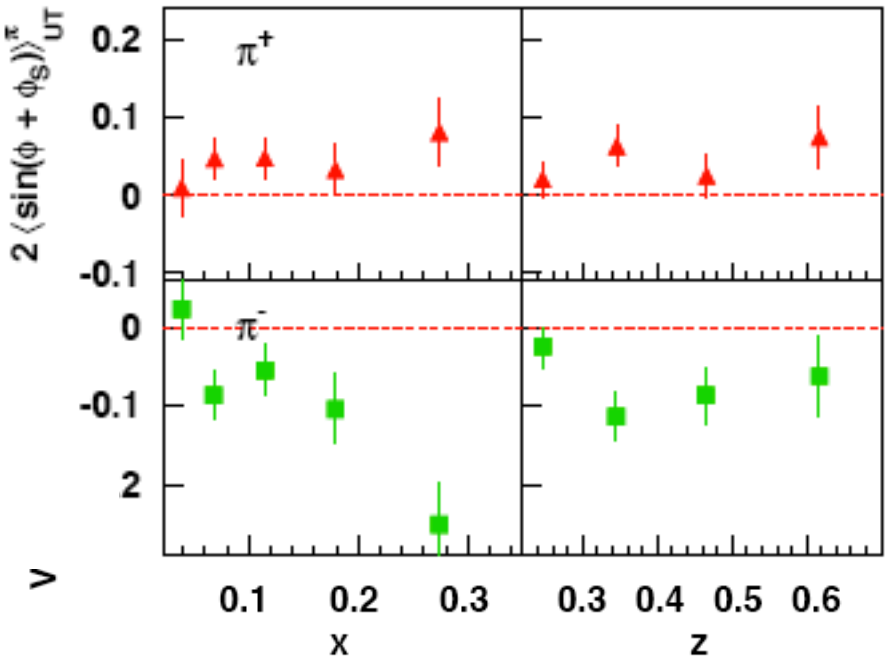
$$\sigma_{UT}^{\sin(\phi+\phi_S)} \propto h_1 \otimes H_1^{\perp}$$

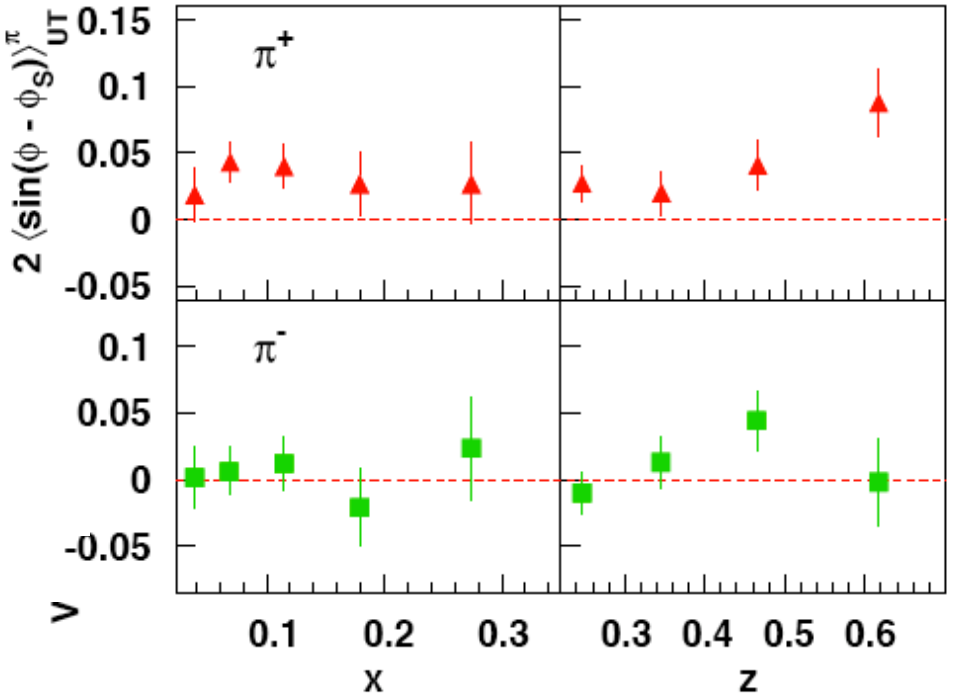
SIDIS:
ep → e'hX

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

2005: First evidence from HERMES measuring SIDIS on proton

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

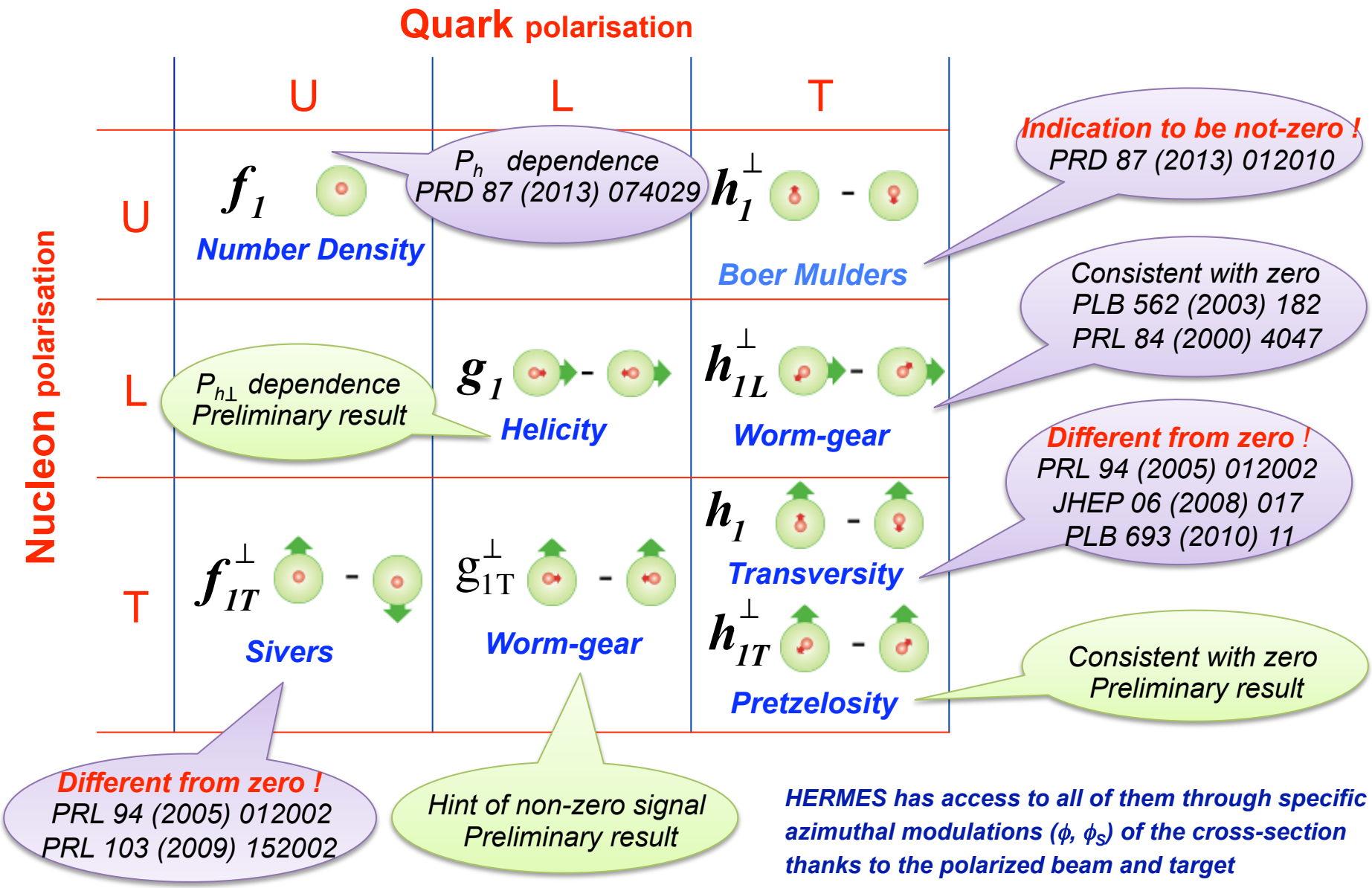




Non-zero transversity !!
Non-zero Collins function !!

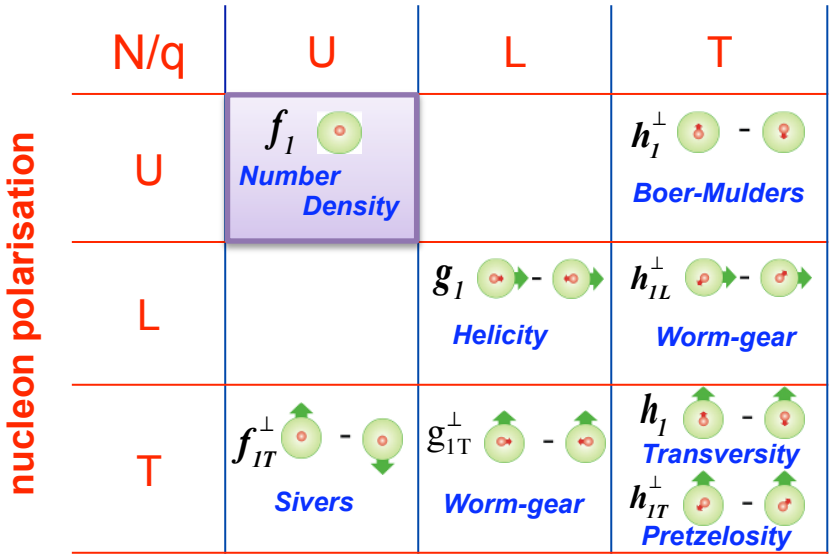
Non-zero Sivers function !!

Leading Twist TMDs



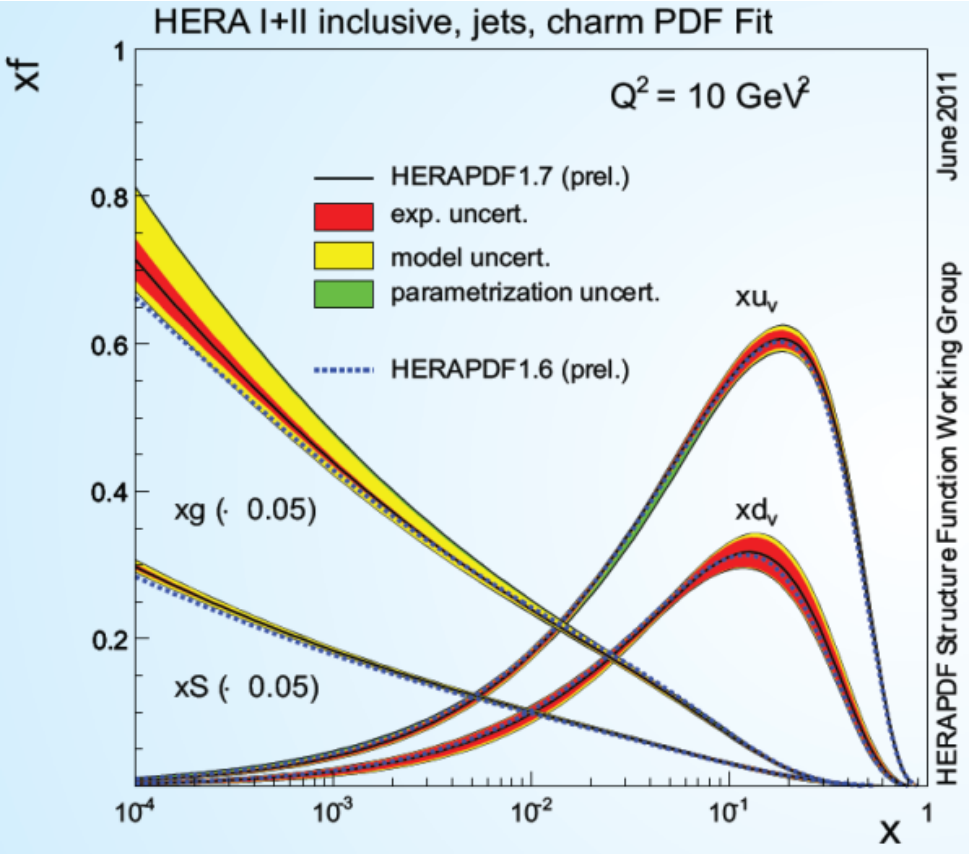
Parton Number Density

Number Density

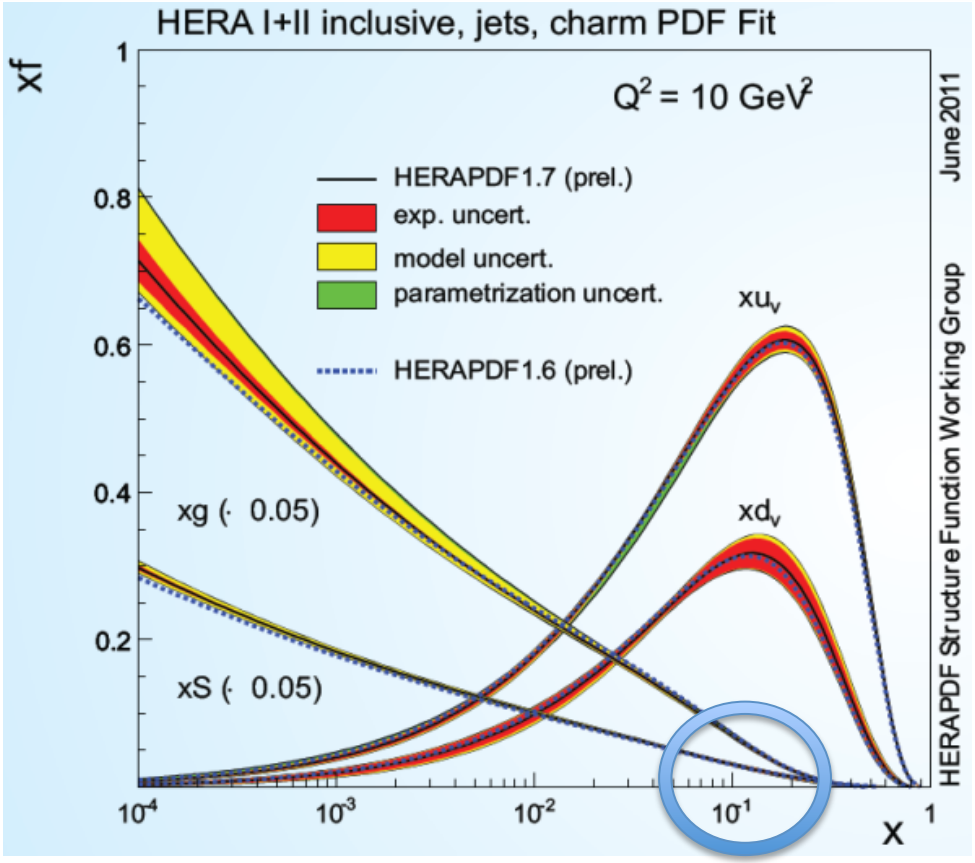


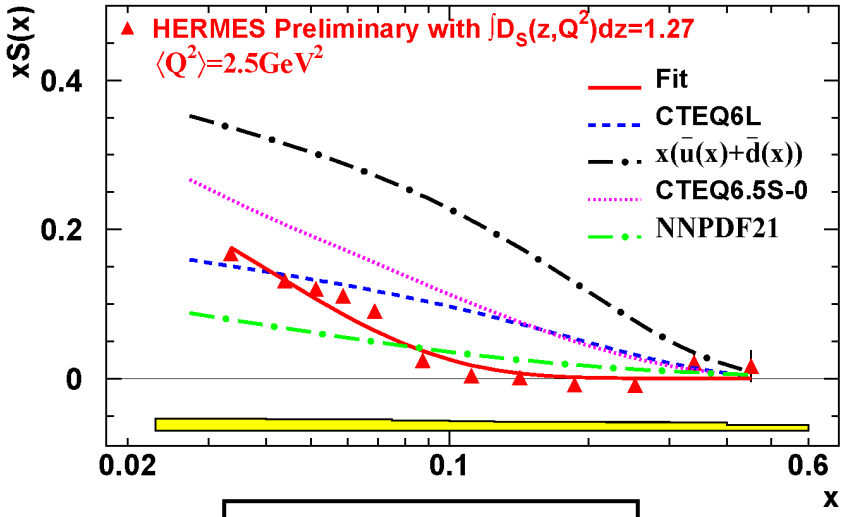
(The Baseline)

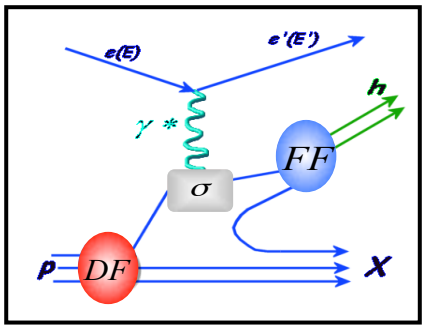
Parton Number Density



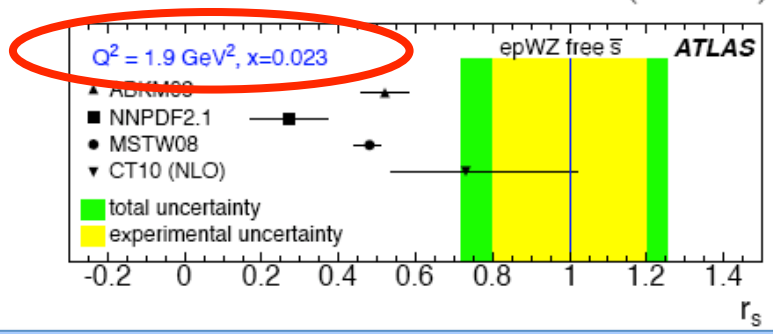
Parton Number Density

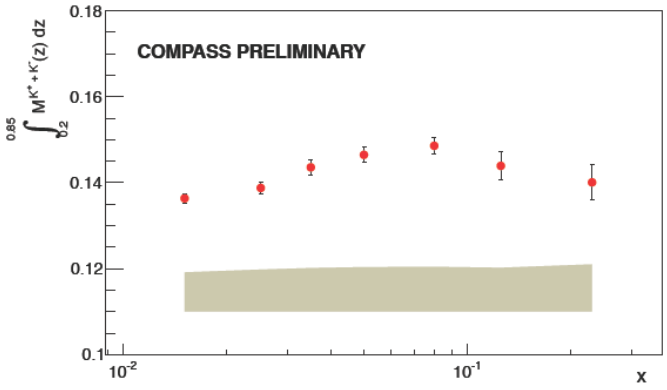






ATLAS: arXiv:1206.4051 $r_s = 0.5(s+\bar{s})/\bar{d}$





The Hadron Multiplicities

LO interpretation:

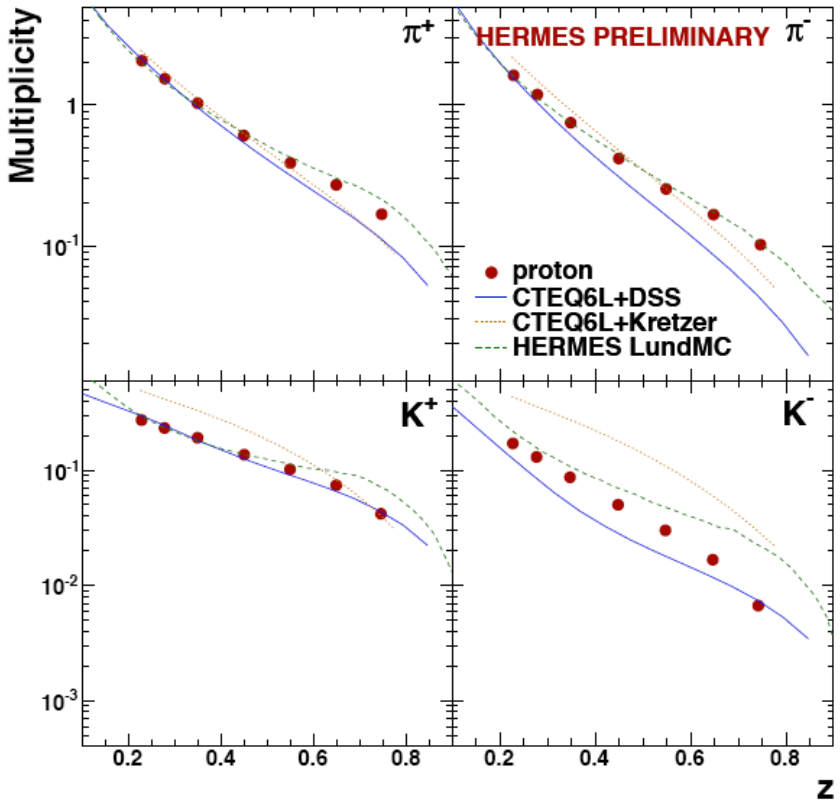
$$M_N^h = \frac{1}{N_N^{DIS}(Q^2)} \frac{dN_N^h(z,Q^2)}{dz} = \frac{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2) D_{1q}^h(z,Q^2)}{\sum_q e_q^2 \int dx\, f_{1q}(x,Q^2)}$$

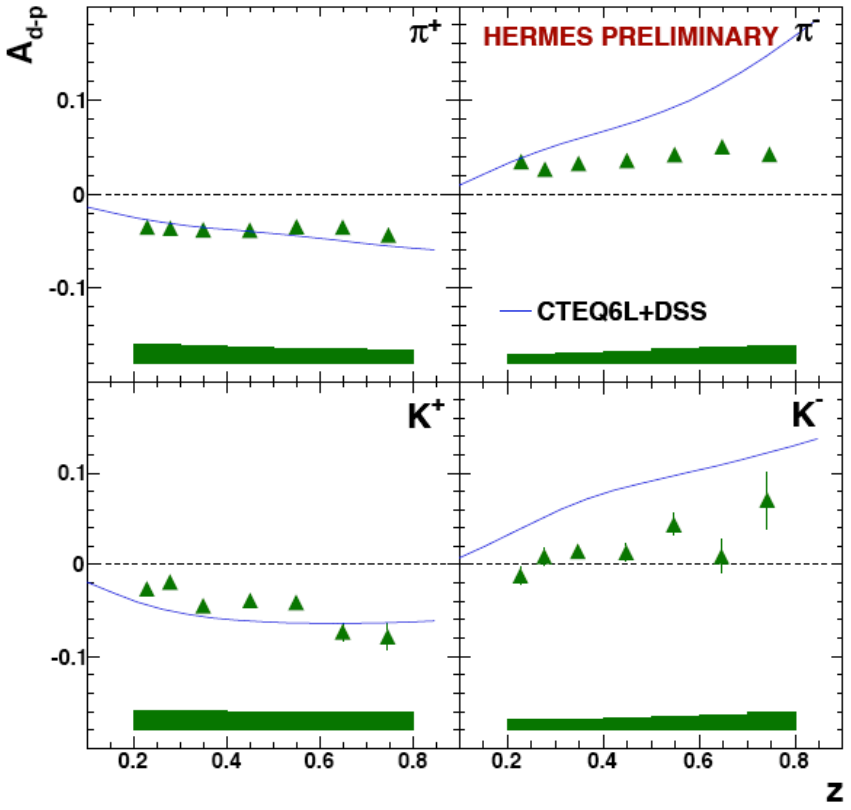
SIDIS data constrain fragmentation at low c.m. energy and bring enhanced flavor sensitivity

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



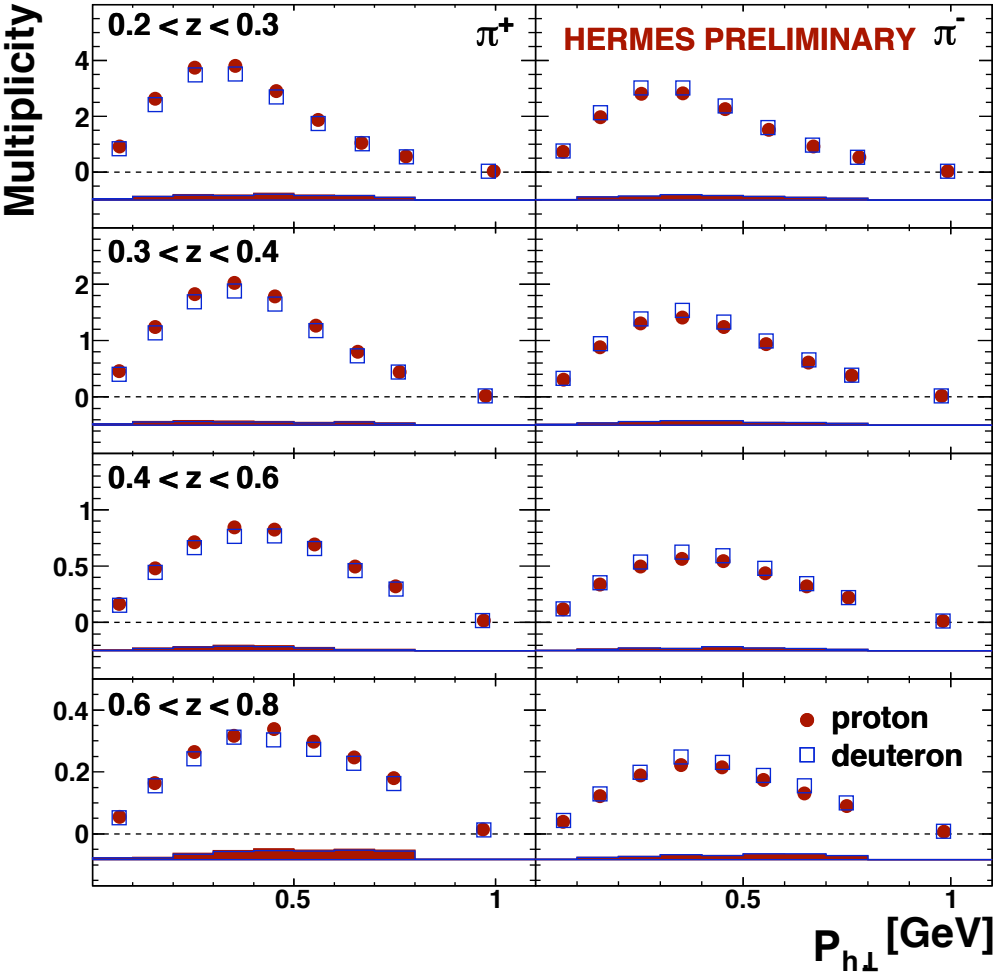


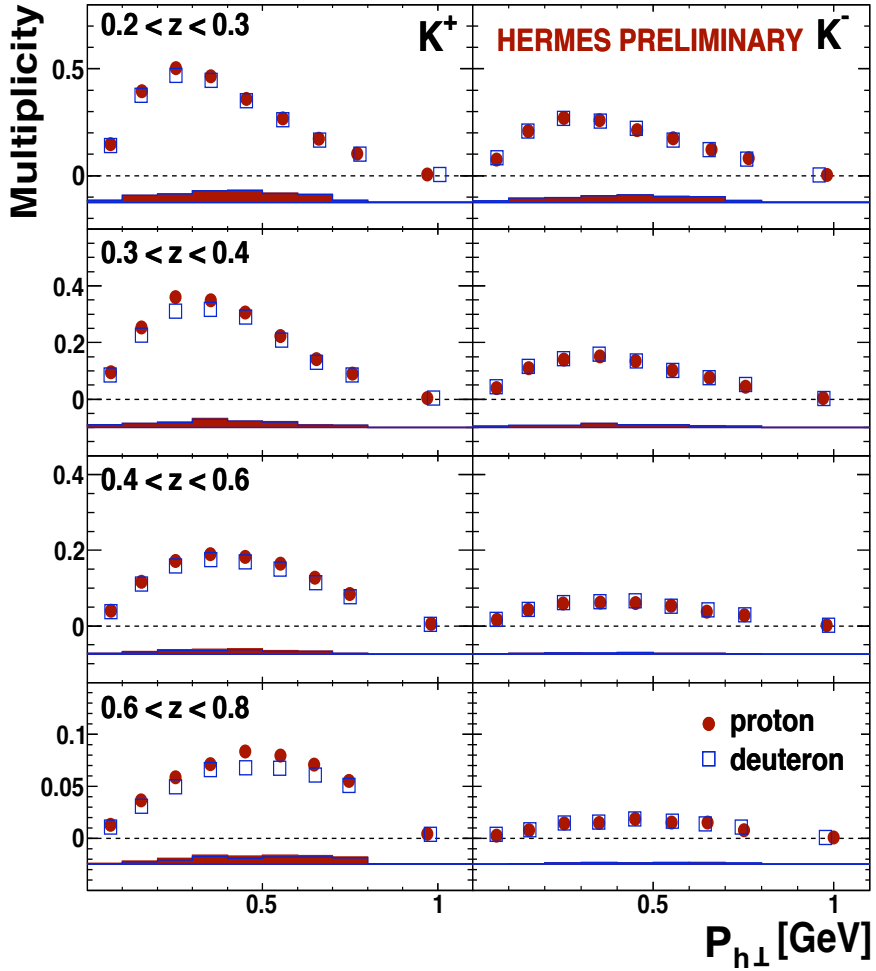
The $P_{h\perp}$ –unintegrated Multiplicities

$f_1 \otimes D_1$

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

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



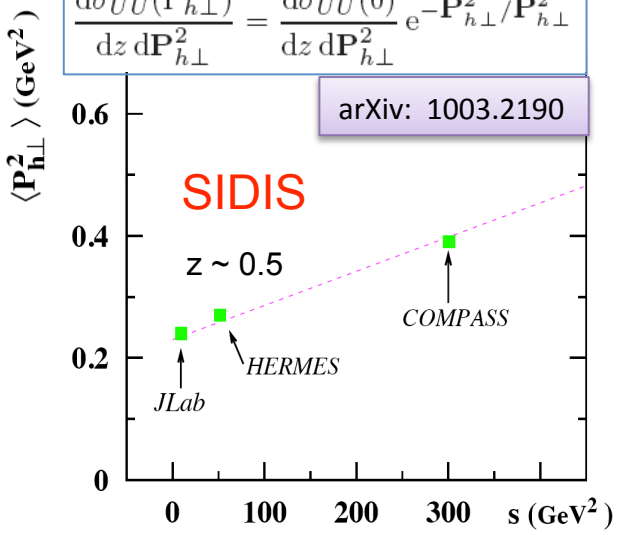


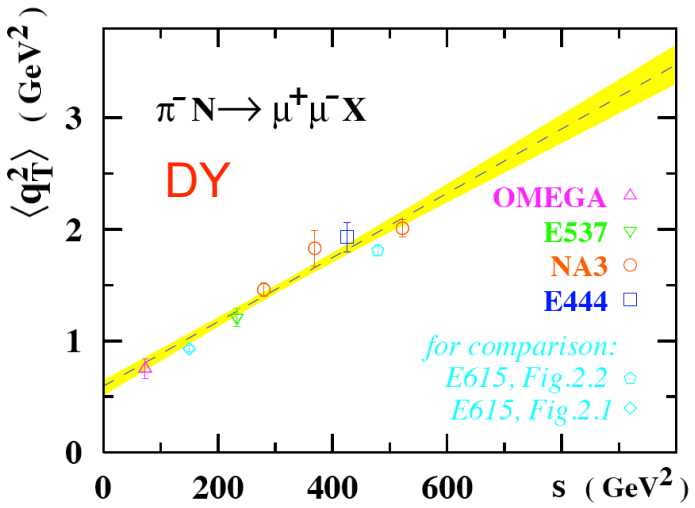
TMD Evolution

$f_1 \otimes D_1$

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

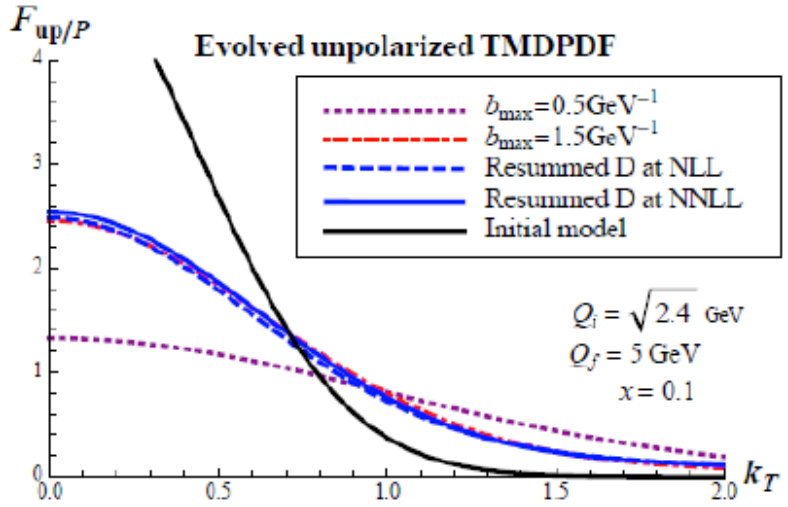
arXiv: 1003.2190

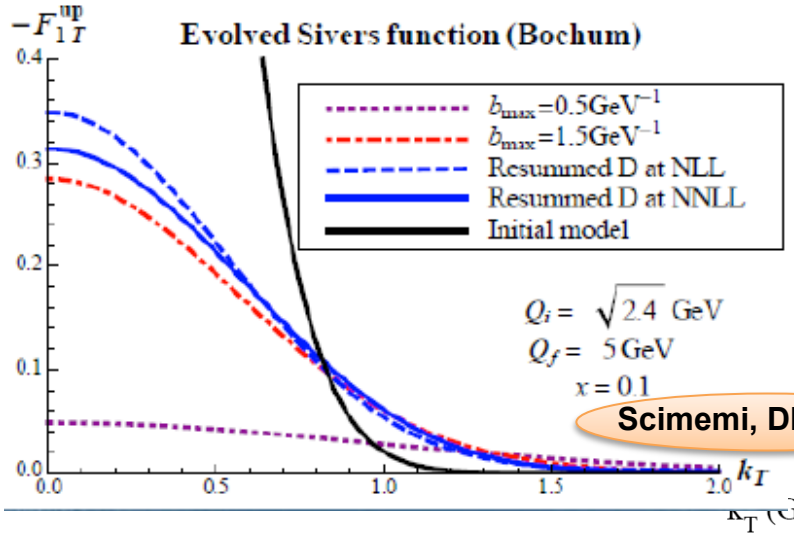




Indication of a k_T and p_T broadening with c.m. energy:

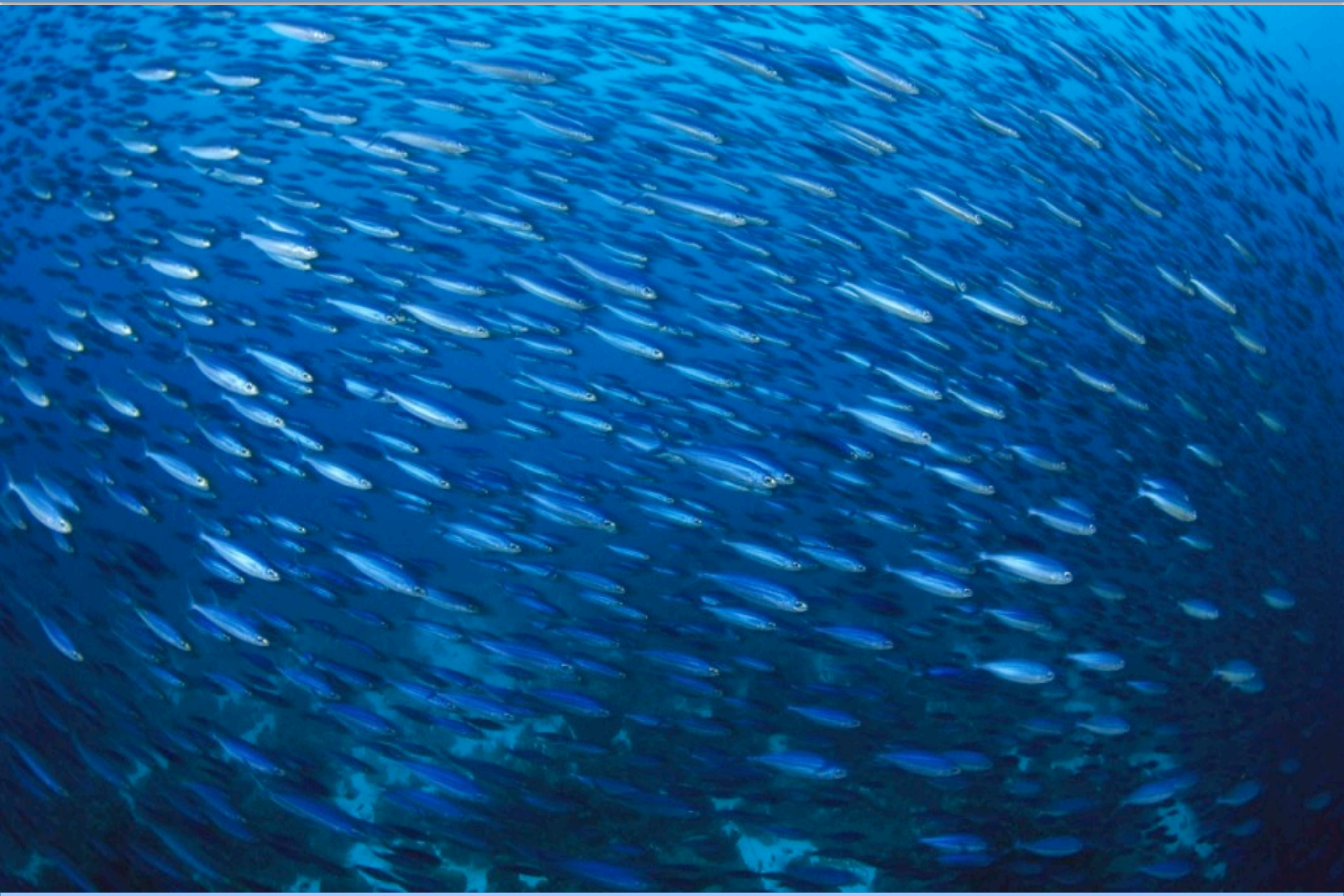
TMD Q^2 evolution ≠ DGLAP





Scimemi, DIS 2013

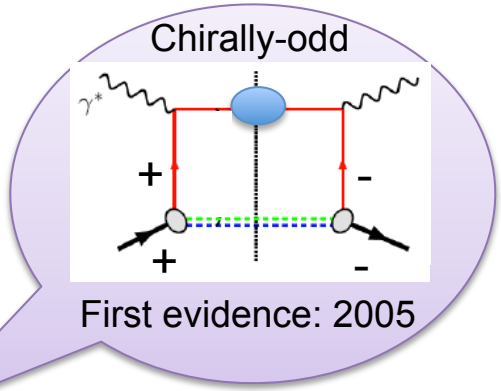
Parton Polarization



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*



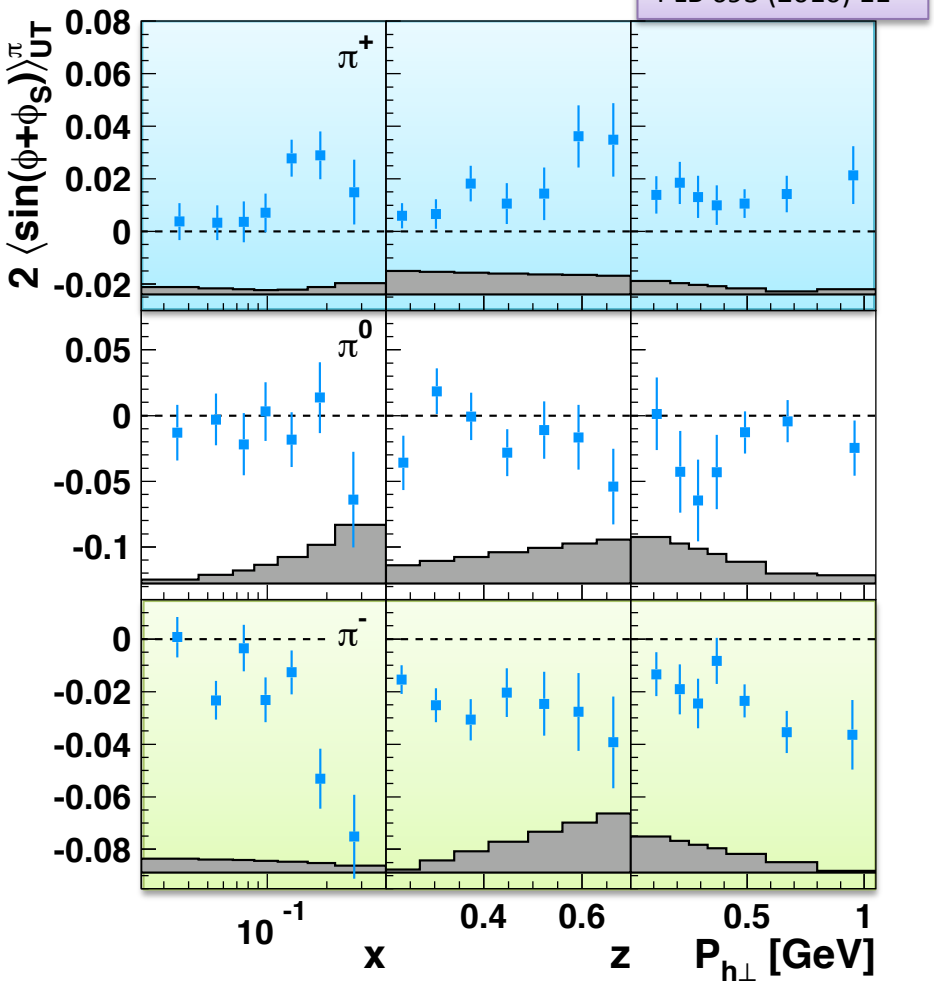
(THE COLLINEAR MISSING PIECE)

The Collins Amplitude

$h_1 \otimes H_1^{\perp}$

Non zero pion signals
Fulfill isospin symmetry

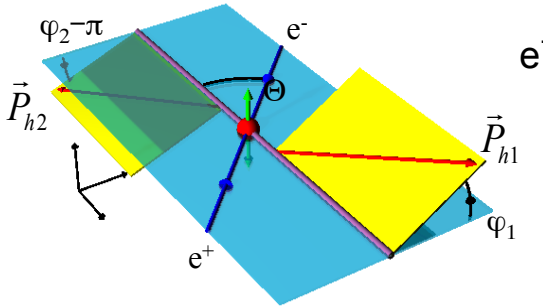
PLB 693 (2010) 11



Clear & opposite signals for charged pions:

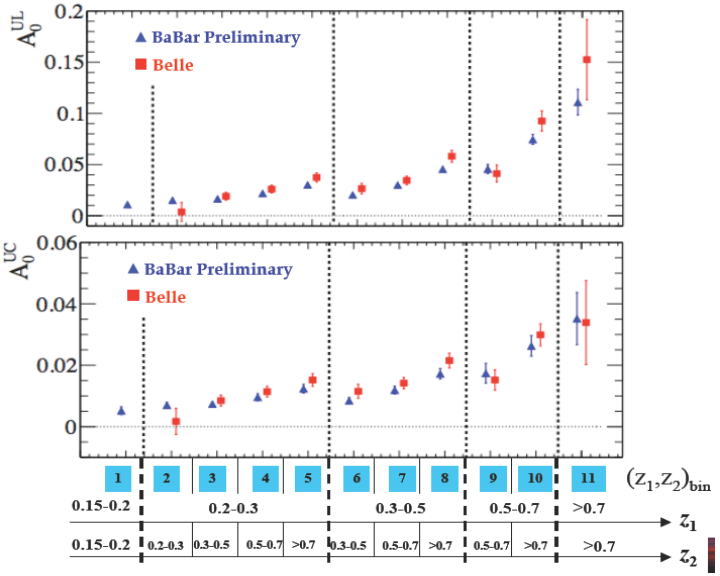
With u-dominance: $\pi^+(u\bar{d})$ $\pi^-(\bar{u}d)$
opposite sign for favored and unfavored Collins

Not in contradiction with Collins at BELLE



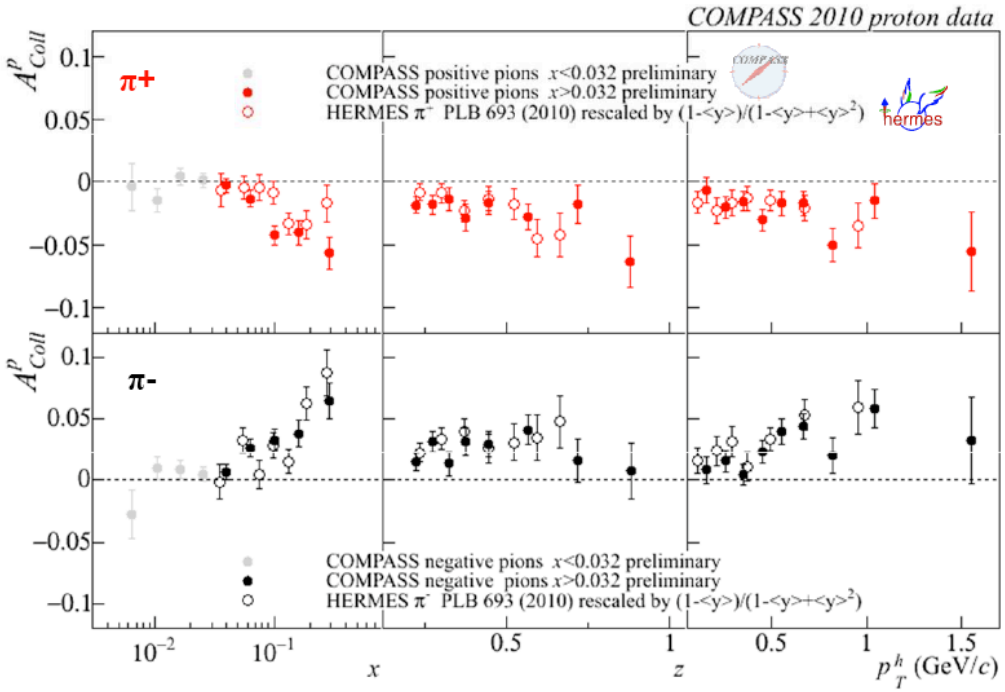
$e^+e^- \rightarrow h_1h_2X$

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

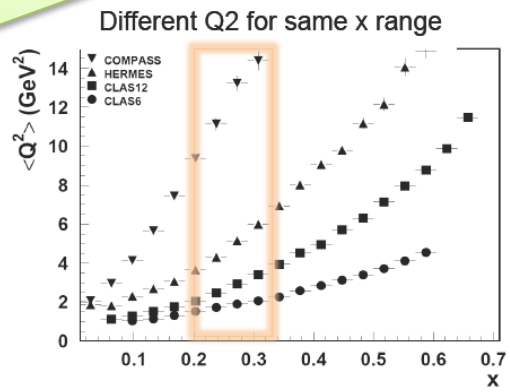


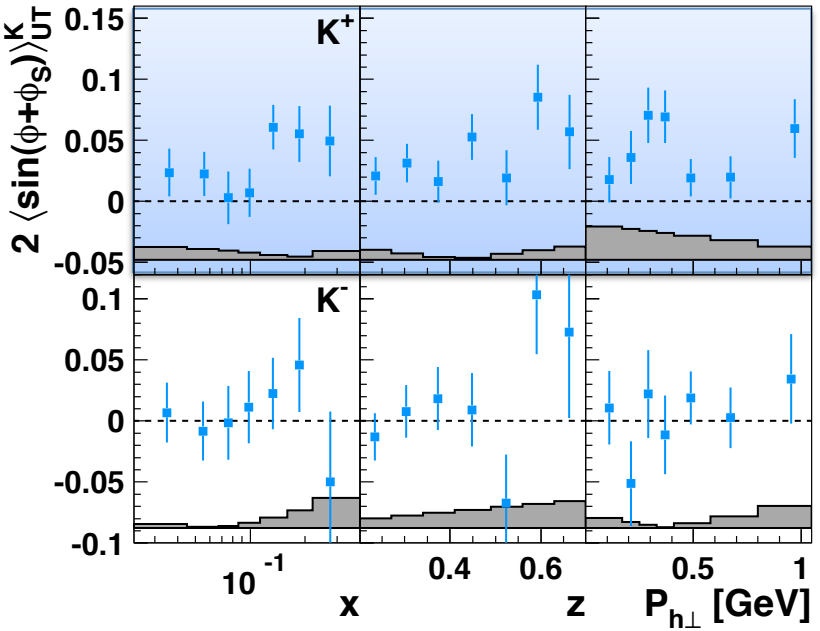
The Collins Amplitude

$h_1 \otimes H_1^{\perp}$



Consistent results at different Q^2
- → No higher twits
- → No strong evolution

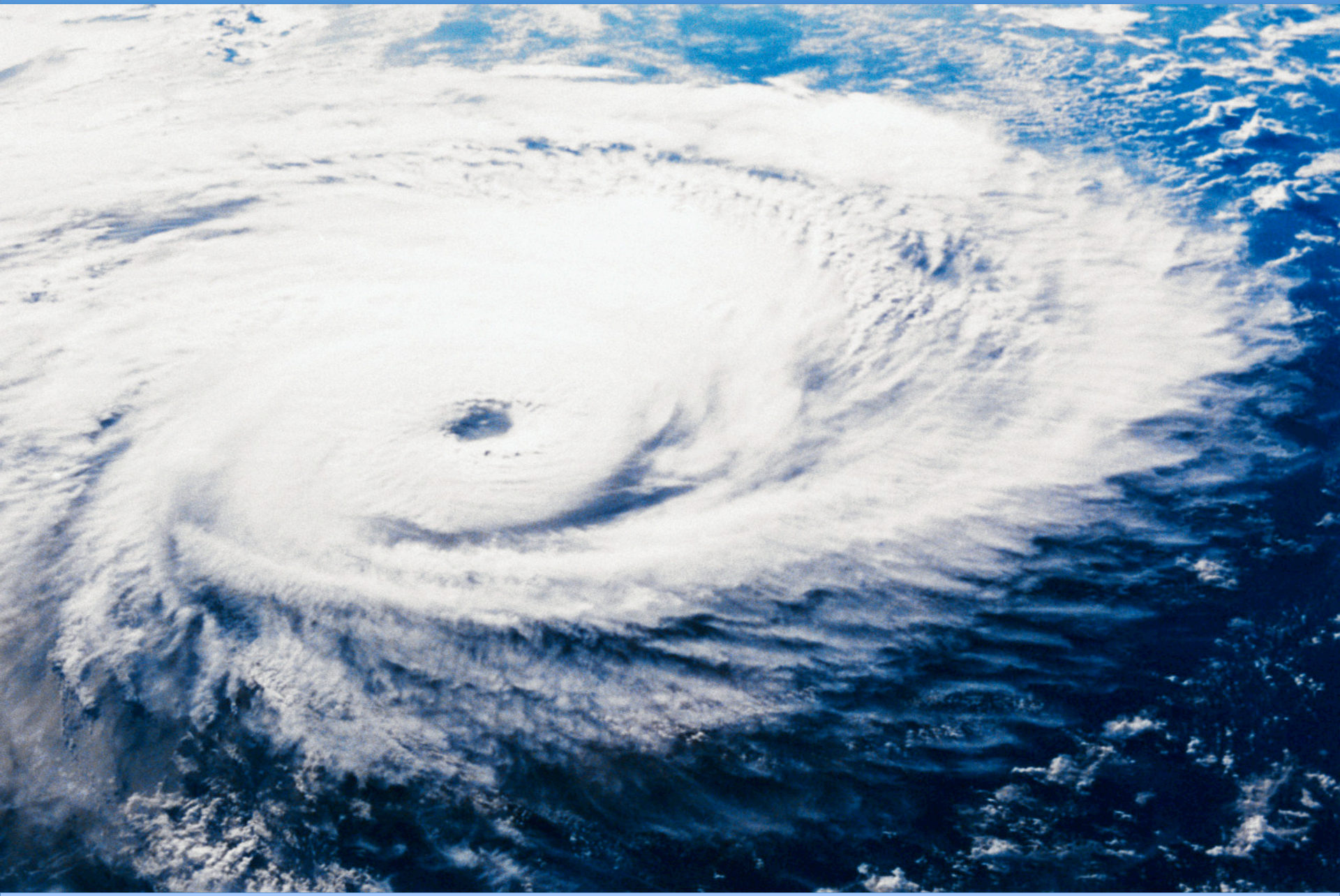




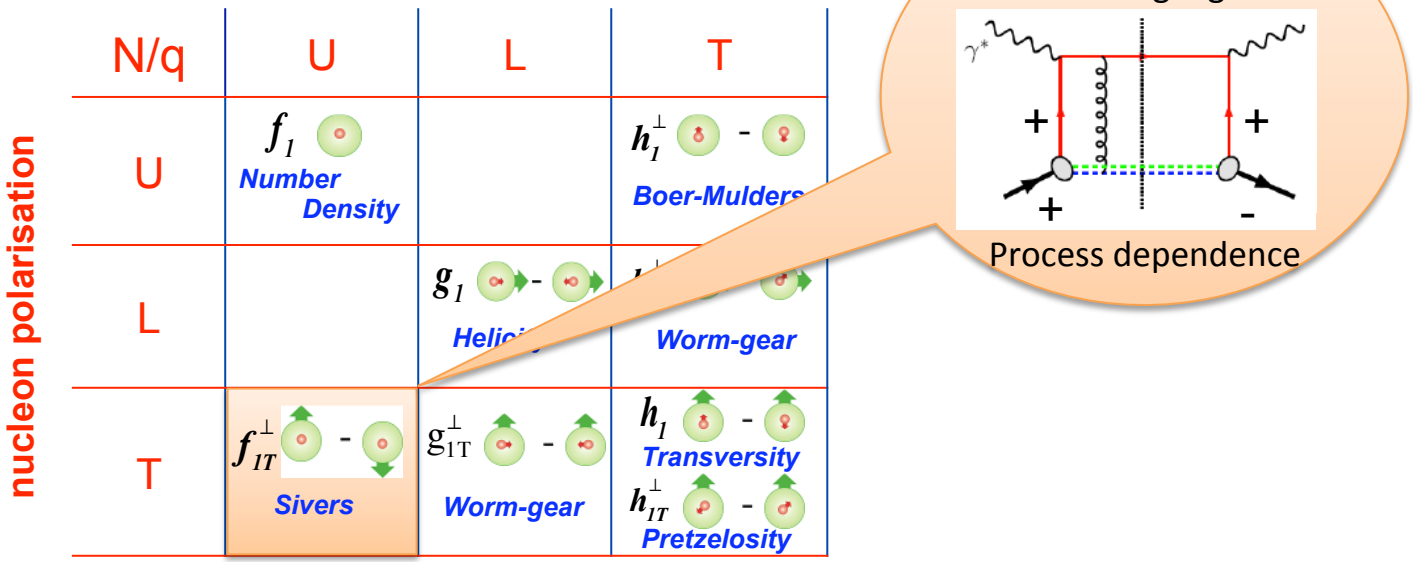
K^+ signal larger than π^+
- role of sea quarks
- k_T dependence in FFs
- higher twists effects

Peculiar K^-
- no valence quark in common with proton

Spin-Orbit Effects



SIVERS



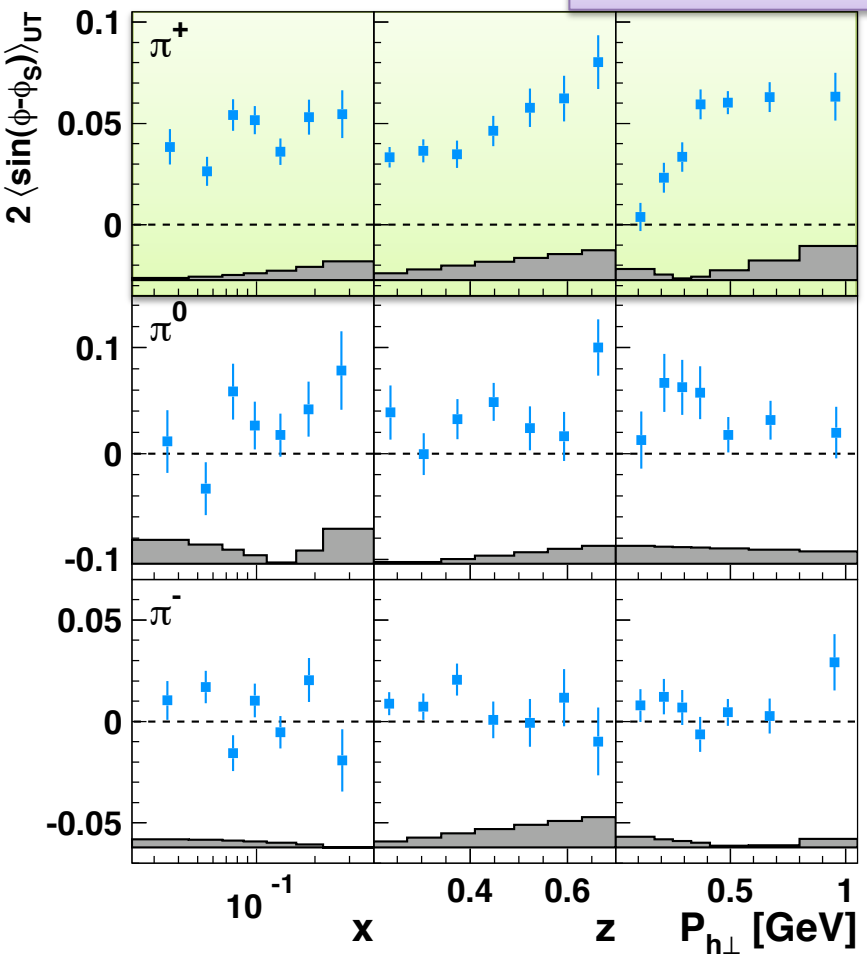
(THE TMD CHALLENGE)

The Sivers Amplitude @ HERMES

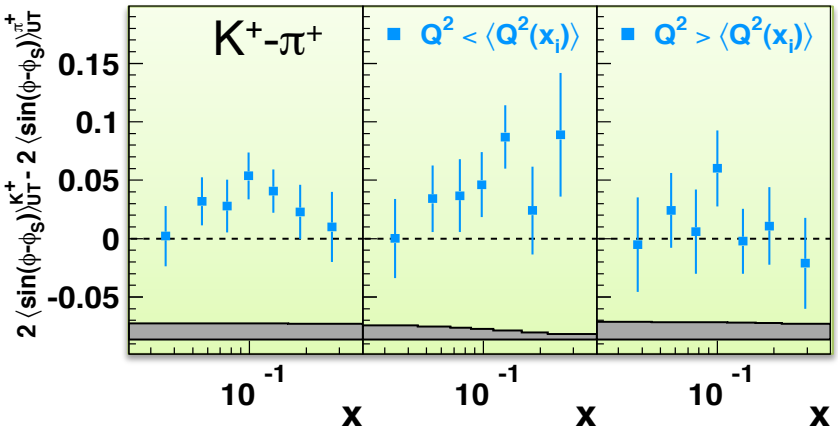
Pion electro-production on proton:

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

PRL 103 (2009) 152002

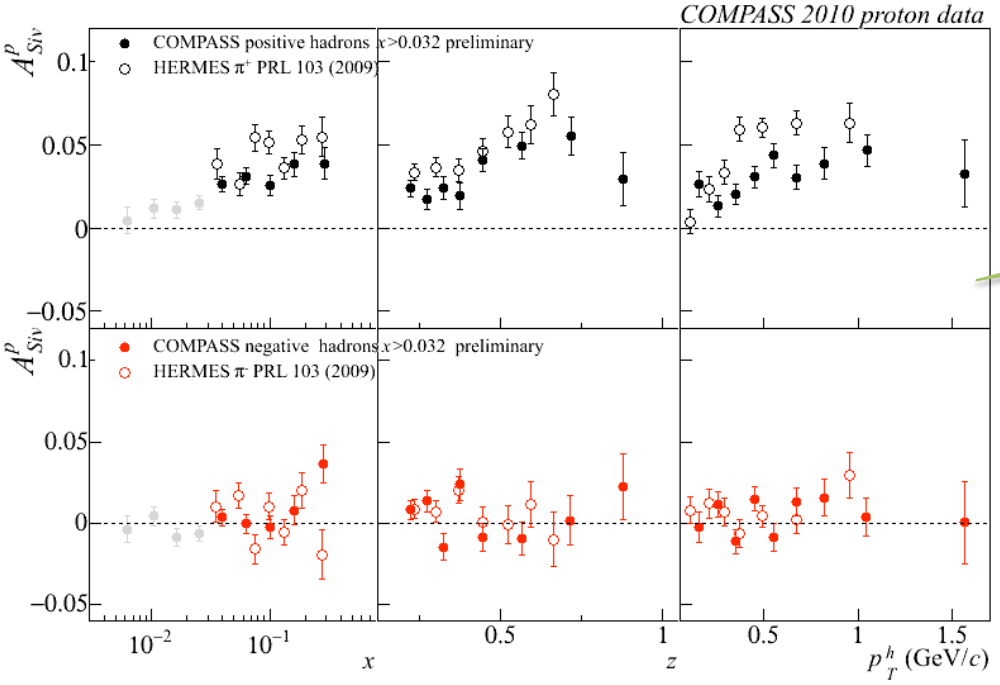


Peculiar kaon signals:



The Sivers Signals

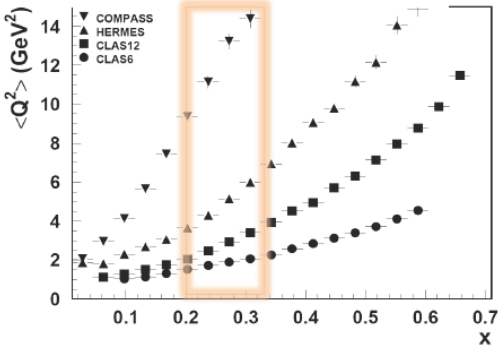
$f_{1T}^{\perp} \otimes D_1$



Signals of TMD evolution ?

HERMES vs COMPASS Comparison

Different Q2 for same x range



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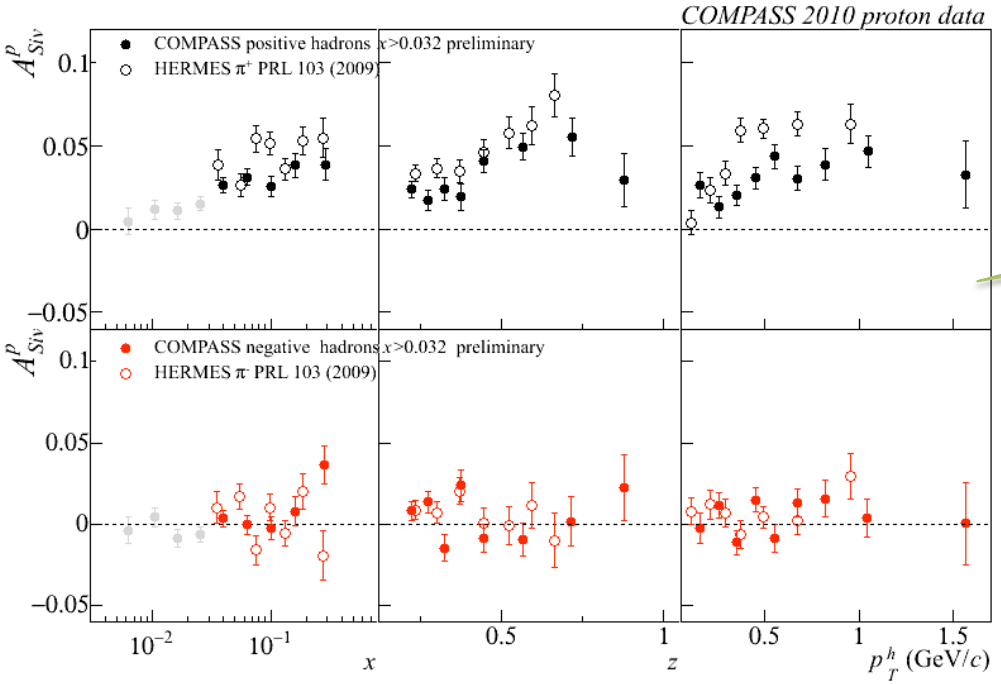
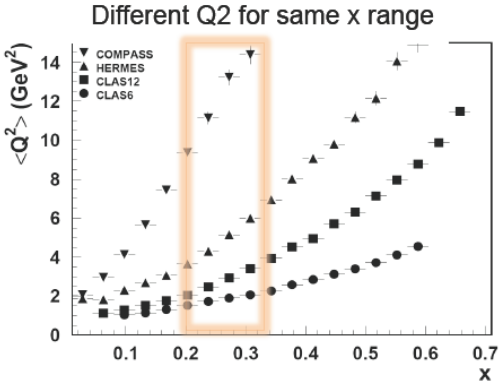
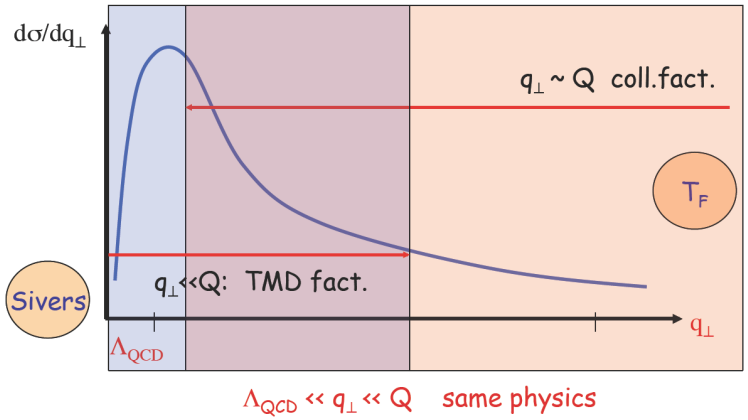


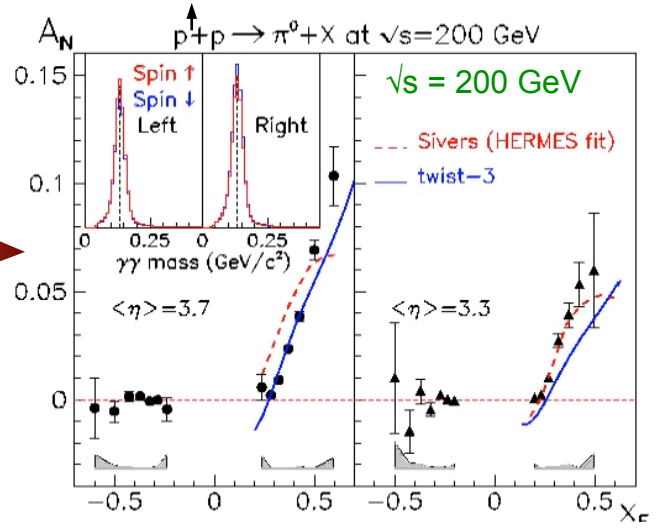
Signals of TMD evolution ?

HERMES vs COMPASS Comparison



From SIDIS to pp collisions:





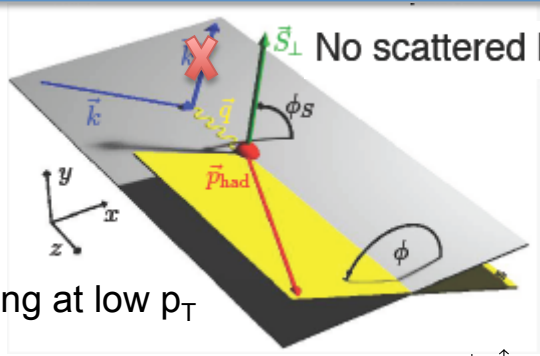
2 approaches:

TMDs fact.
$p_T << Q$

Collinear fact.
$M << p_T$

Sign mismatch !

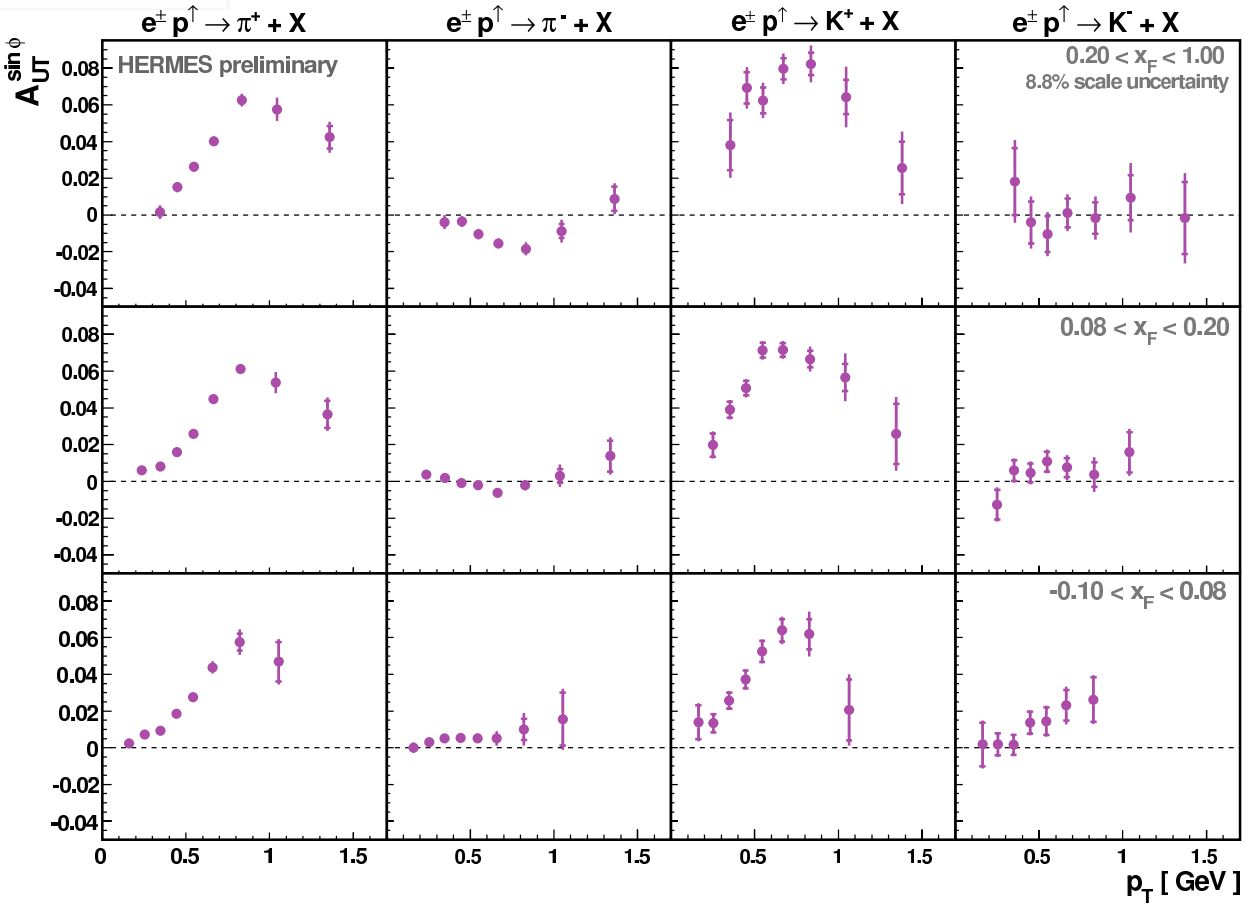
Inclusive Hadron SSA @ HERMES



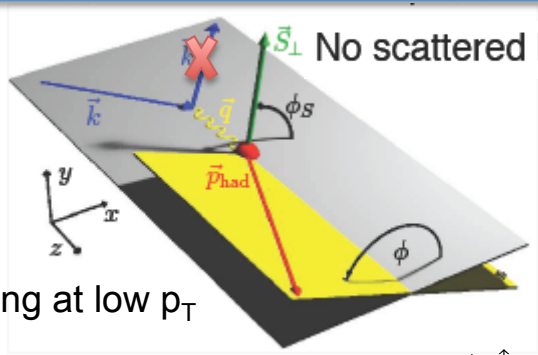
No scattered beam detected → p_T, x_F with respect to **e beam** (not q-vector)

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

- 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



Inclusive Hadron SSA @ HERMES



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
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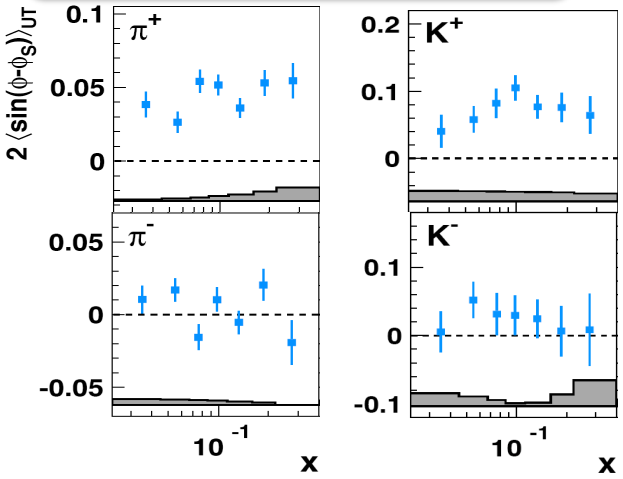
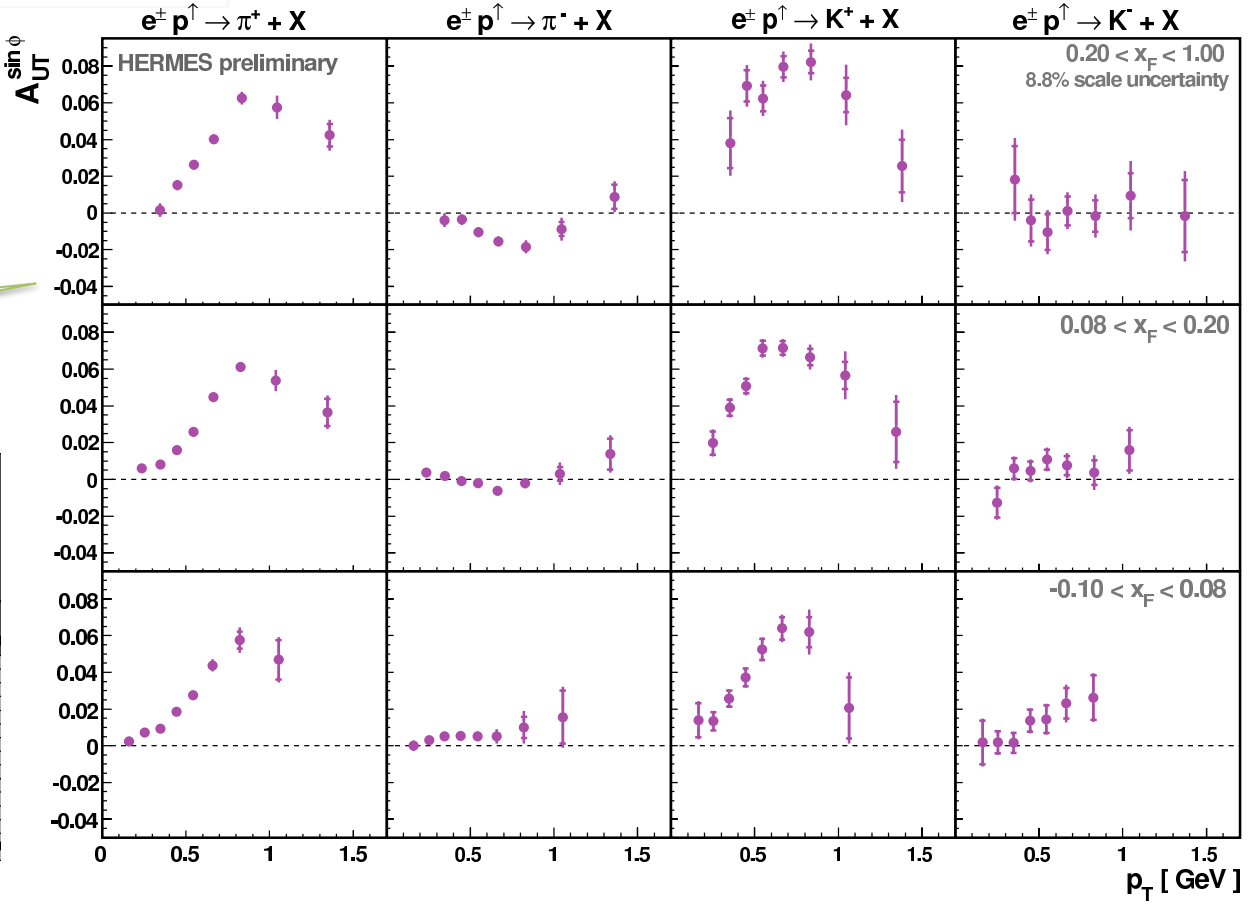
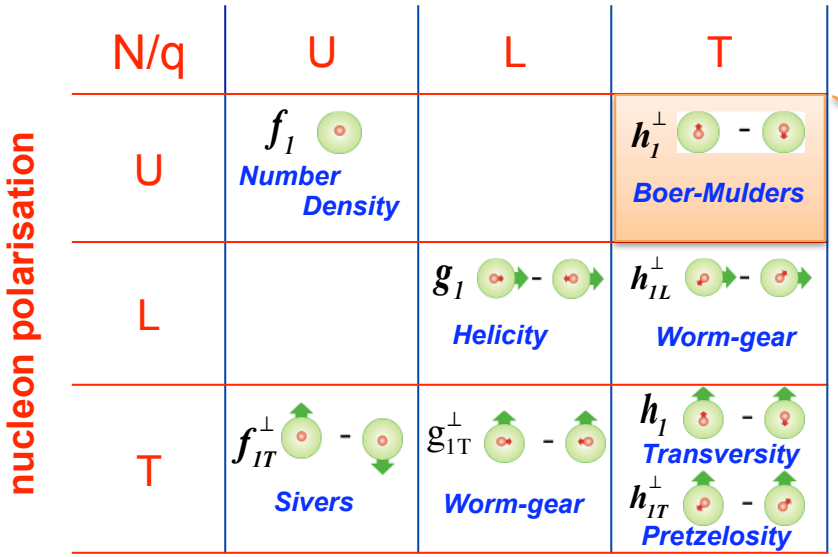
- Study transition from perturbative to non-perturbative regime

Non-zero signals for positive hadrons resembling Sivers





Cahn & Boer-Mulders



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

(The Neglected Effects)

The Azimuthal Modulation

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

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

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

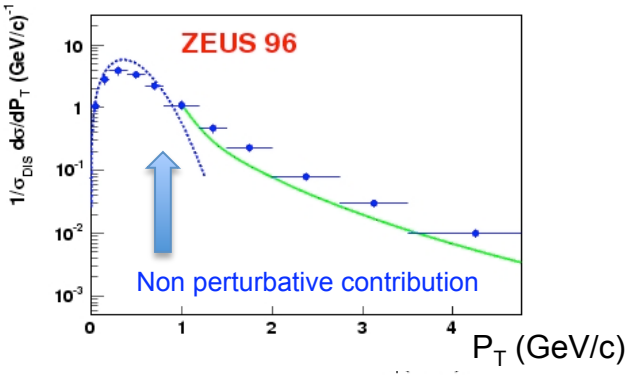
$h_1^\perp \otimes H_1^\perp$

Cahn PLB 78 (1978)

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

Boer & Mulders PRD 57 (1998)

Leading-twist contribution introduced by Boer & Mulders in 1998



The Azimuthal Modulation

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

$(f_1 \otimes D_1)/Q$

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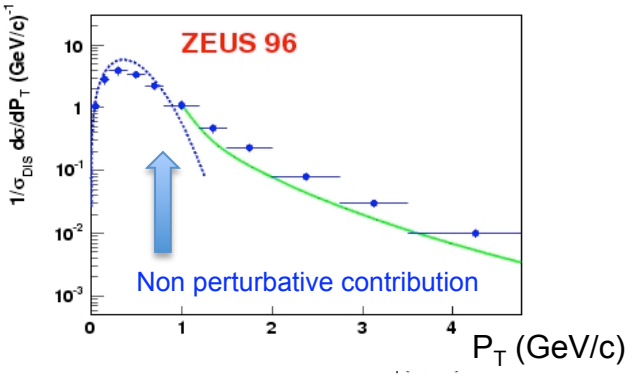
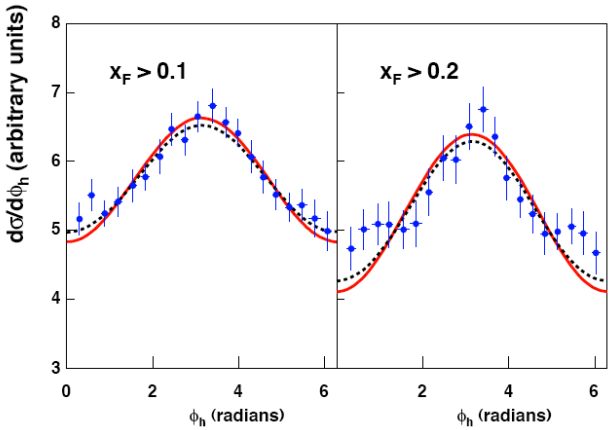
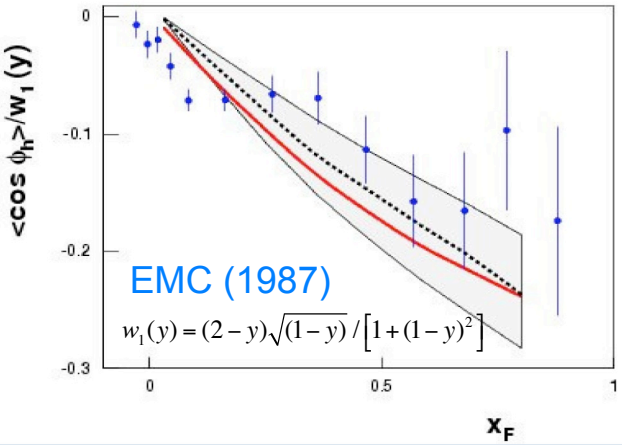


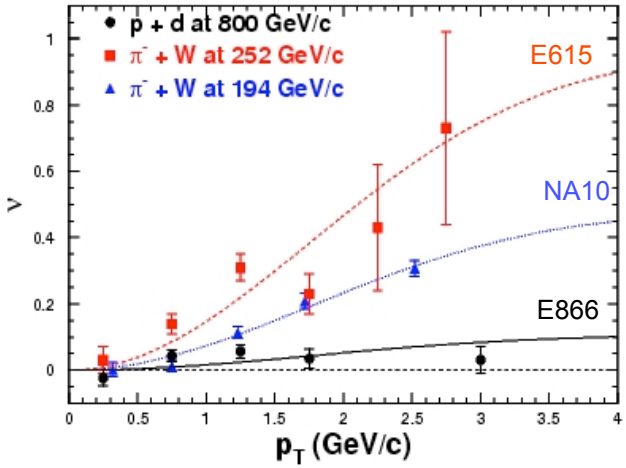
SIDIS: qualitative agreement with Cahn expectations till 2008

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

DY: violation of Lam-Tung relataion







Unpolarized Cross-section

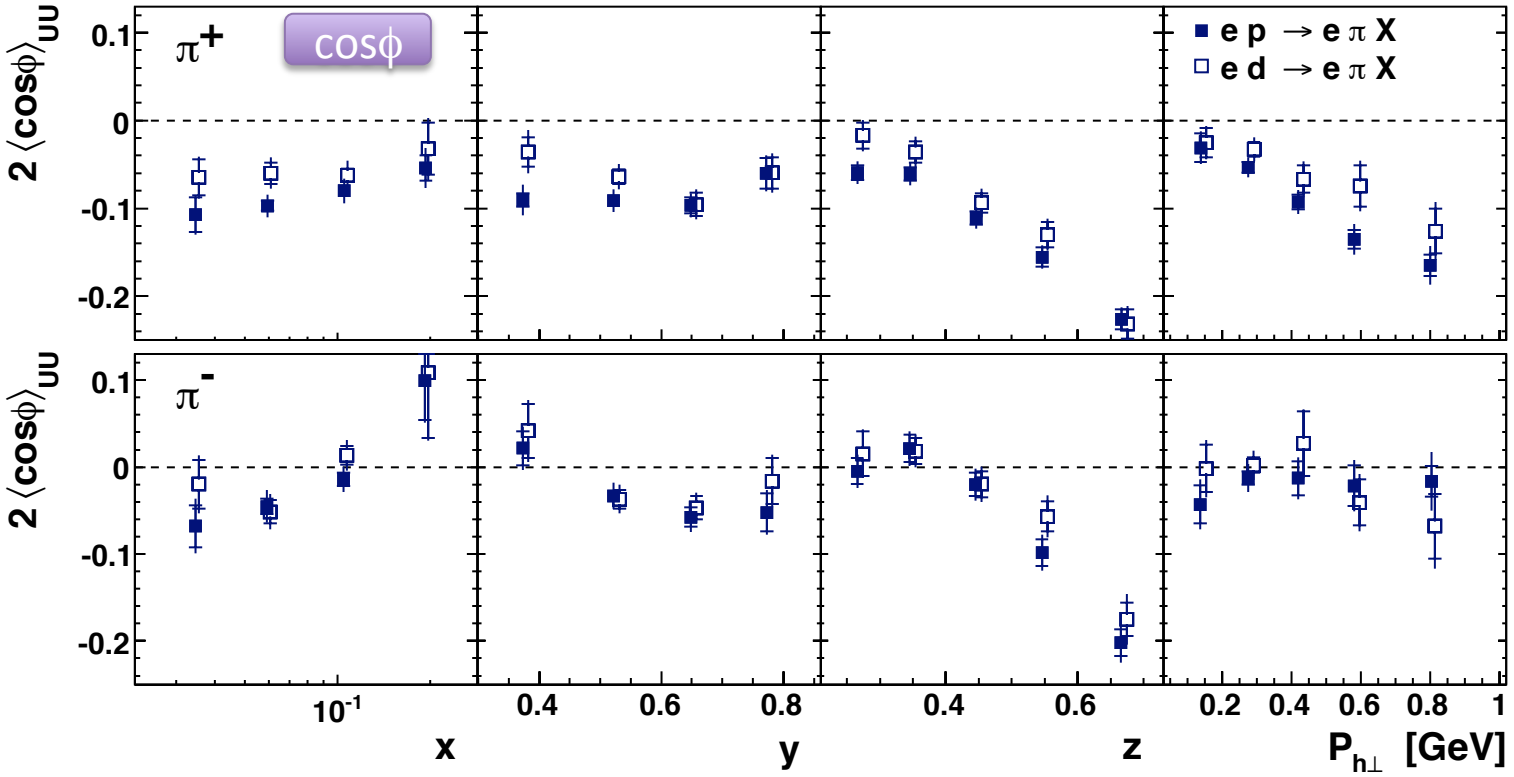
cosϕ large and negative !

Increasing with z and P_h

Large difference in hadron charge !

Larger in magnitude for π+

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



Unpolarized Cross-section

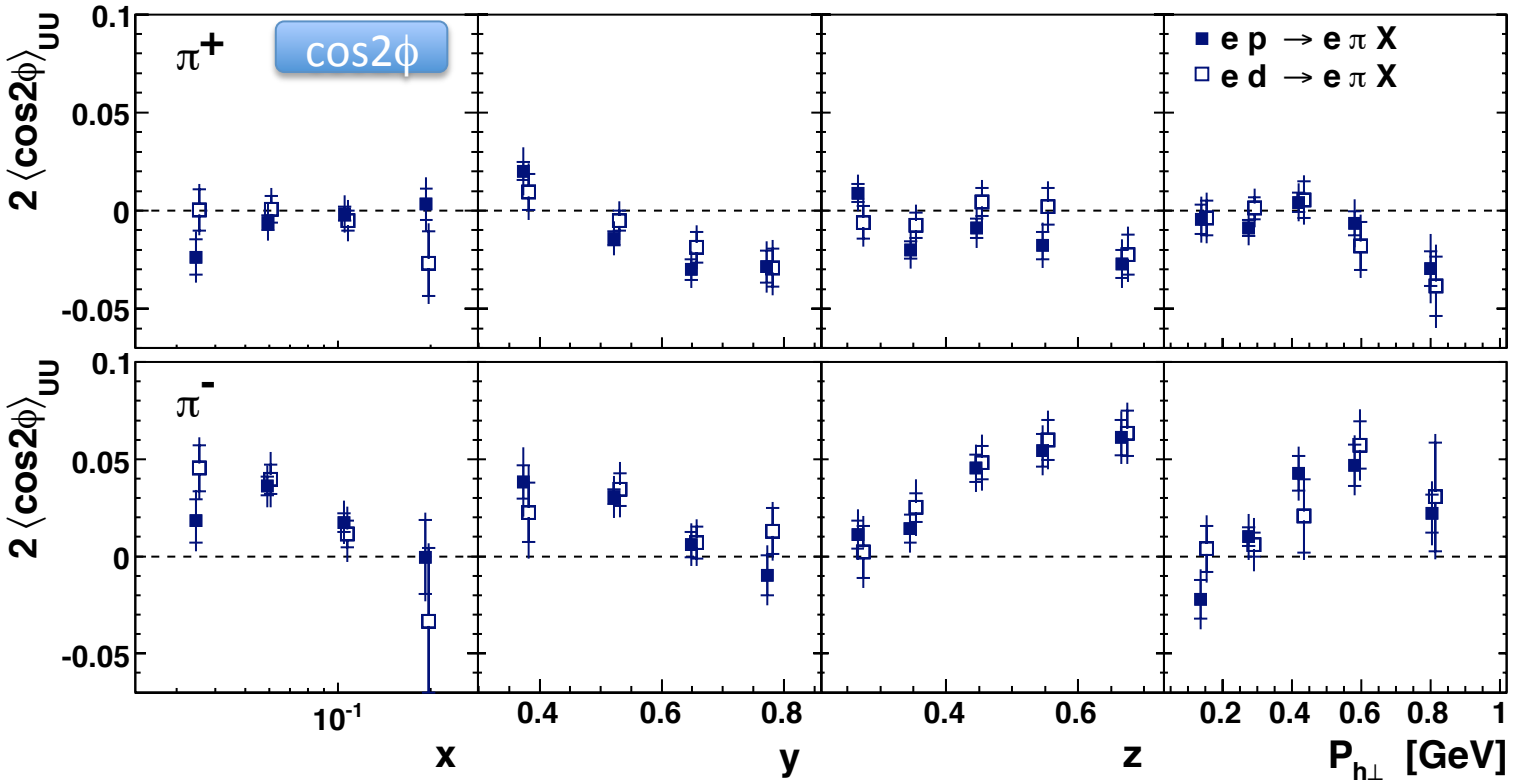
cos2ϕ non-zero !

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

Difference in hadron charge !

Positive for π-

Negative for π+



Unpolarized Cross-section

cos2ϕ non-zero !

Difference in hadron charge !

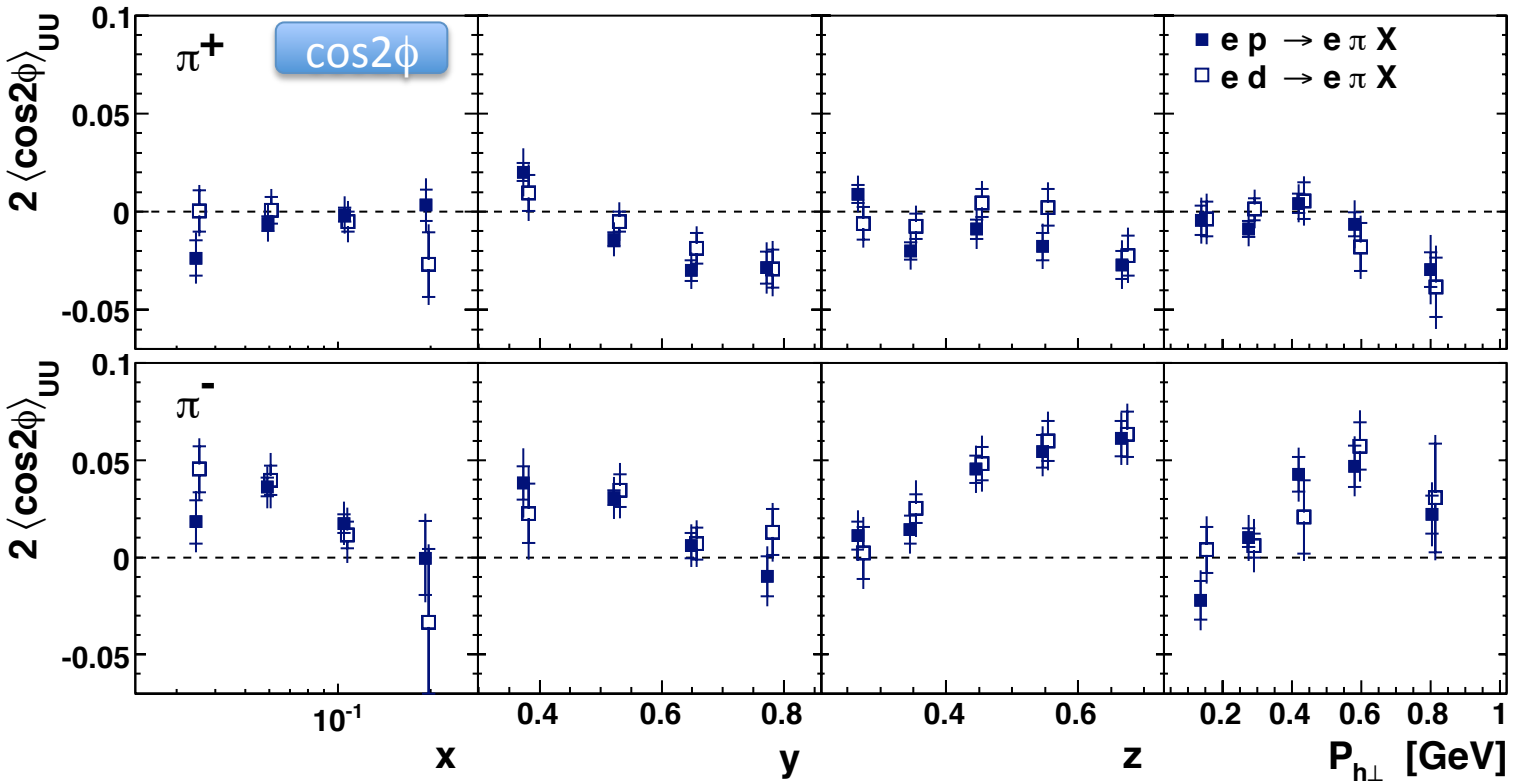
Positive for π-

Negative for π+

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

Mild flavor dependence of k_T expected
Hint of non-zero Boer-Mulders

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

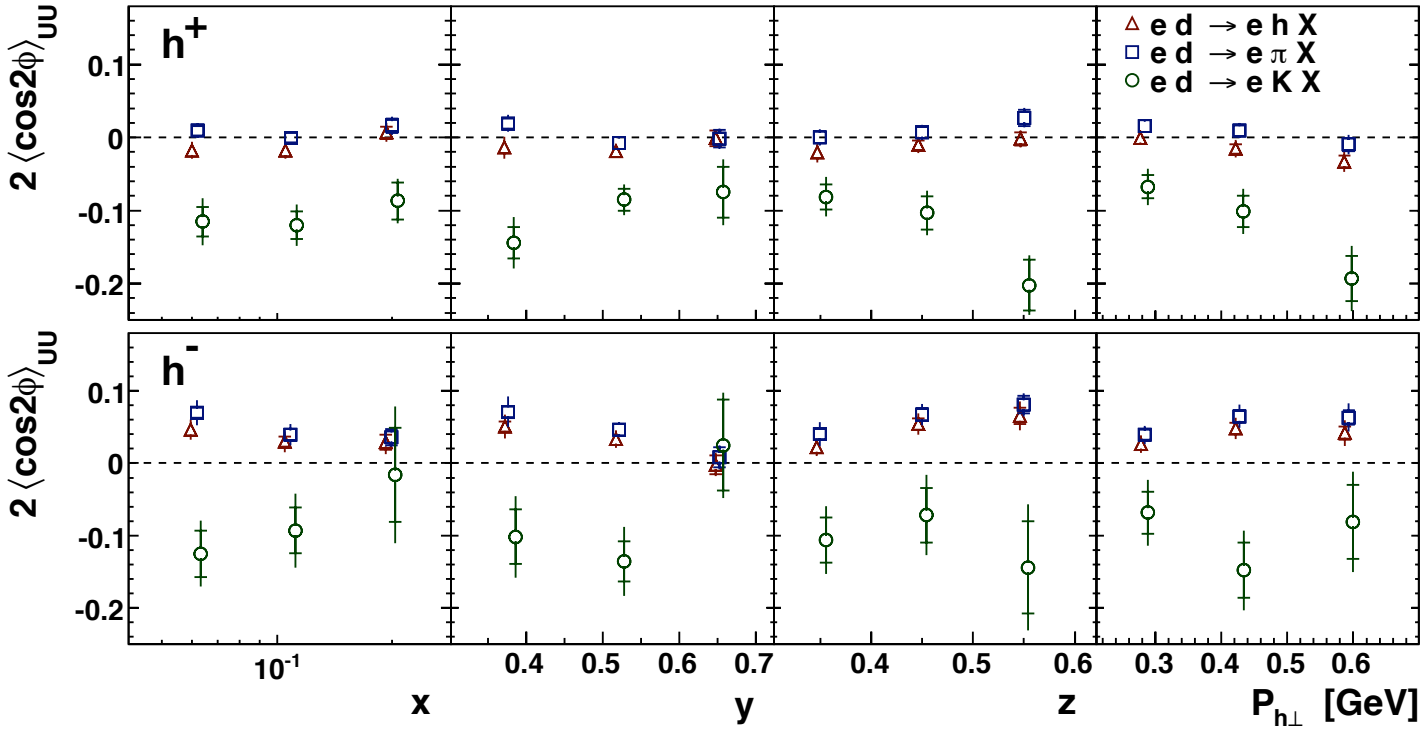


Kaon Signals

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

Striking difference versus pions !

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

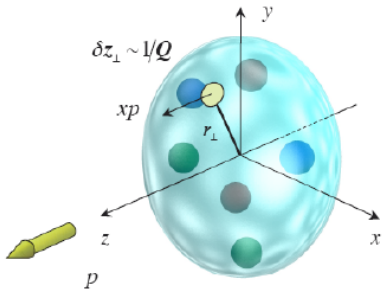


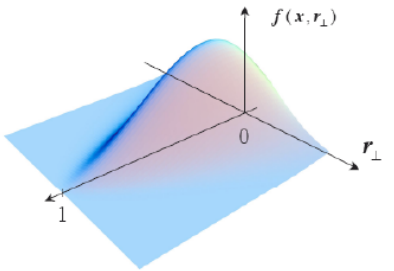
Unpolarized cross-section: any precision measurement should account for these effects

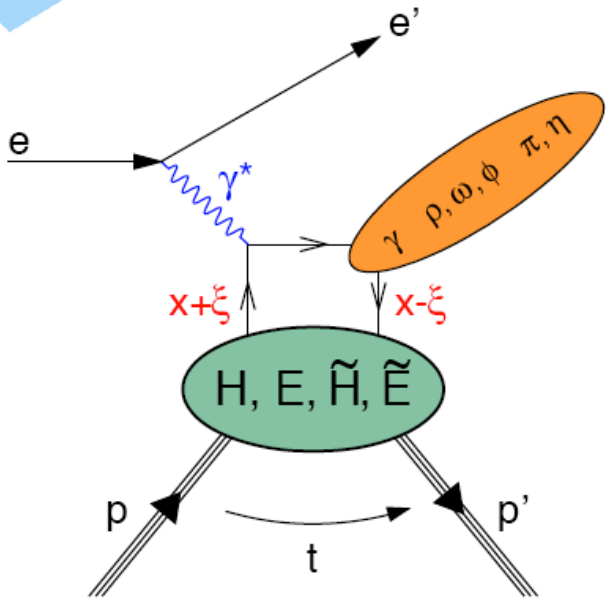
Exclusivity

Exclusive-DIS for Transverse Position Dependence

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

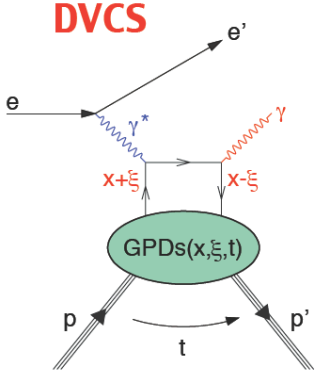
$$J_q = \lim_{t\to 0} \int_{-1}^{1} dx\, x\left[H_q(x,\xi,t) + E_q(x,\xi,t)\right]$$

- 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) → $\tilde{H}, \tilde{E}$

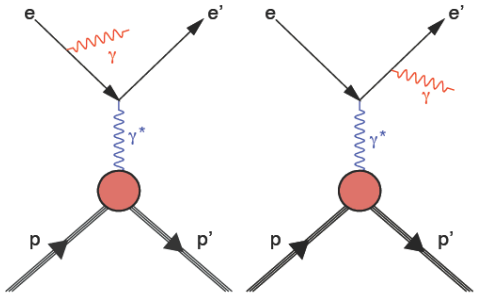
The DVCS Landscape

$\mathcal{H}$

DVCS

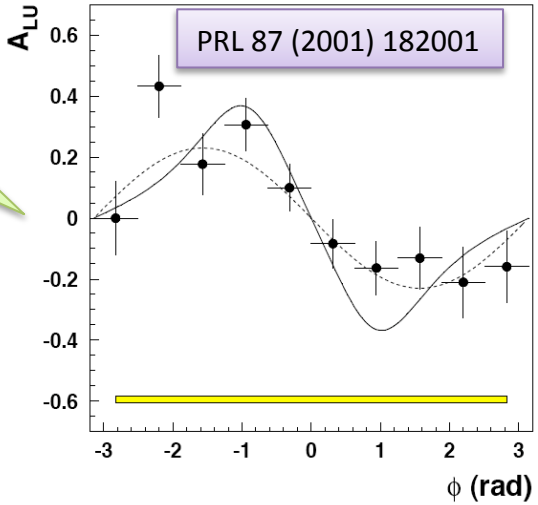


Bethe-Heitler



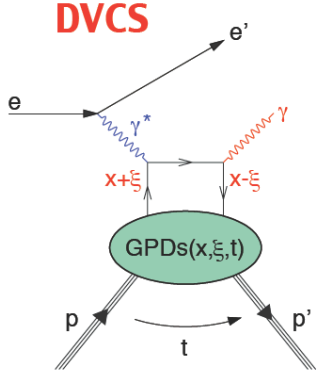
$$\frac{d^4\sigma}{dQ^2\, dx_B\, dt\, d\phi} \propto \left(|\mathcal{T}_{DVCS}|^2 + |\mathcal{T}_{BH}|^2 + \mathcal{I}\right)$$

First measurement of DVCS beam asymmetry Im(H)

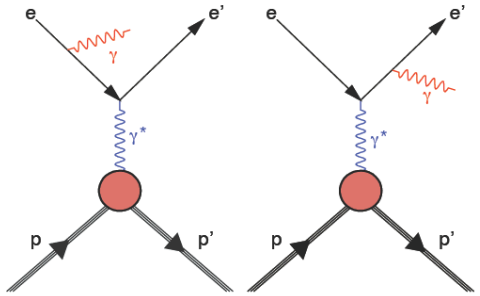


The DVCS Landscape

DVCS



Bethe-Heitler



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

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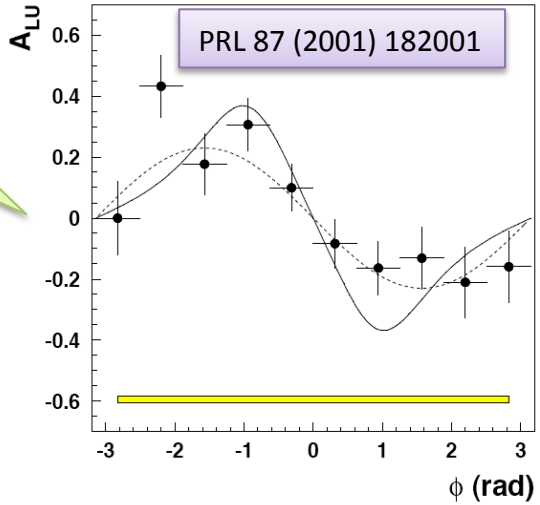
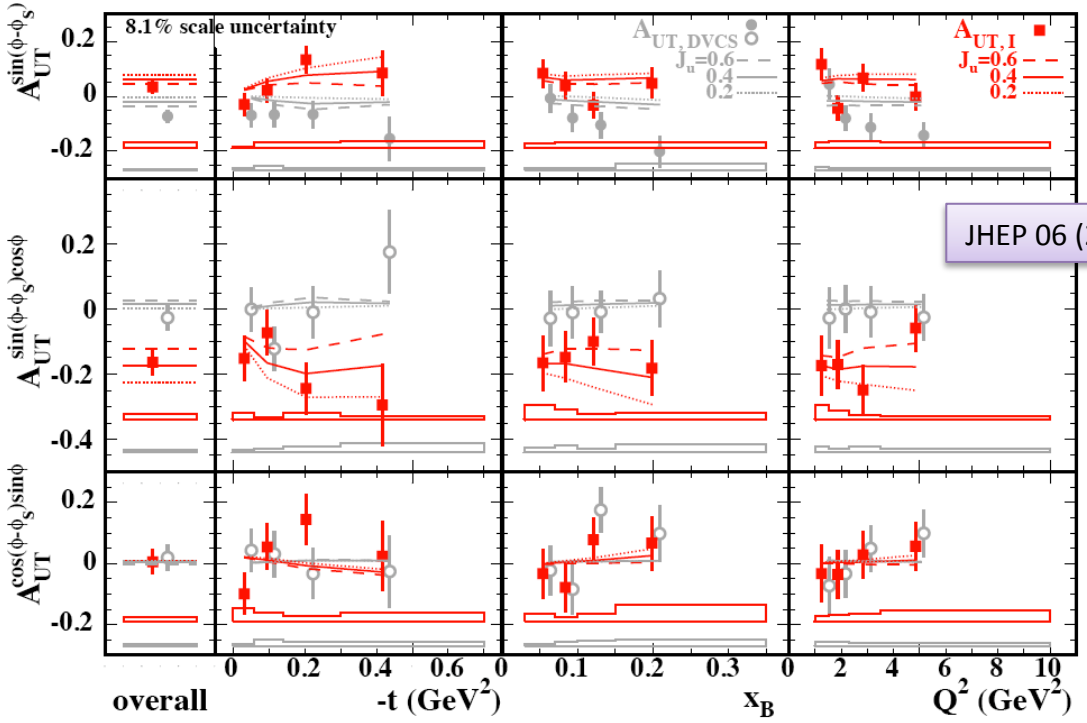


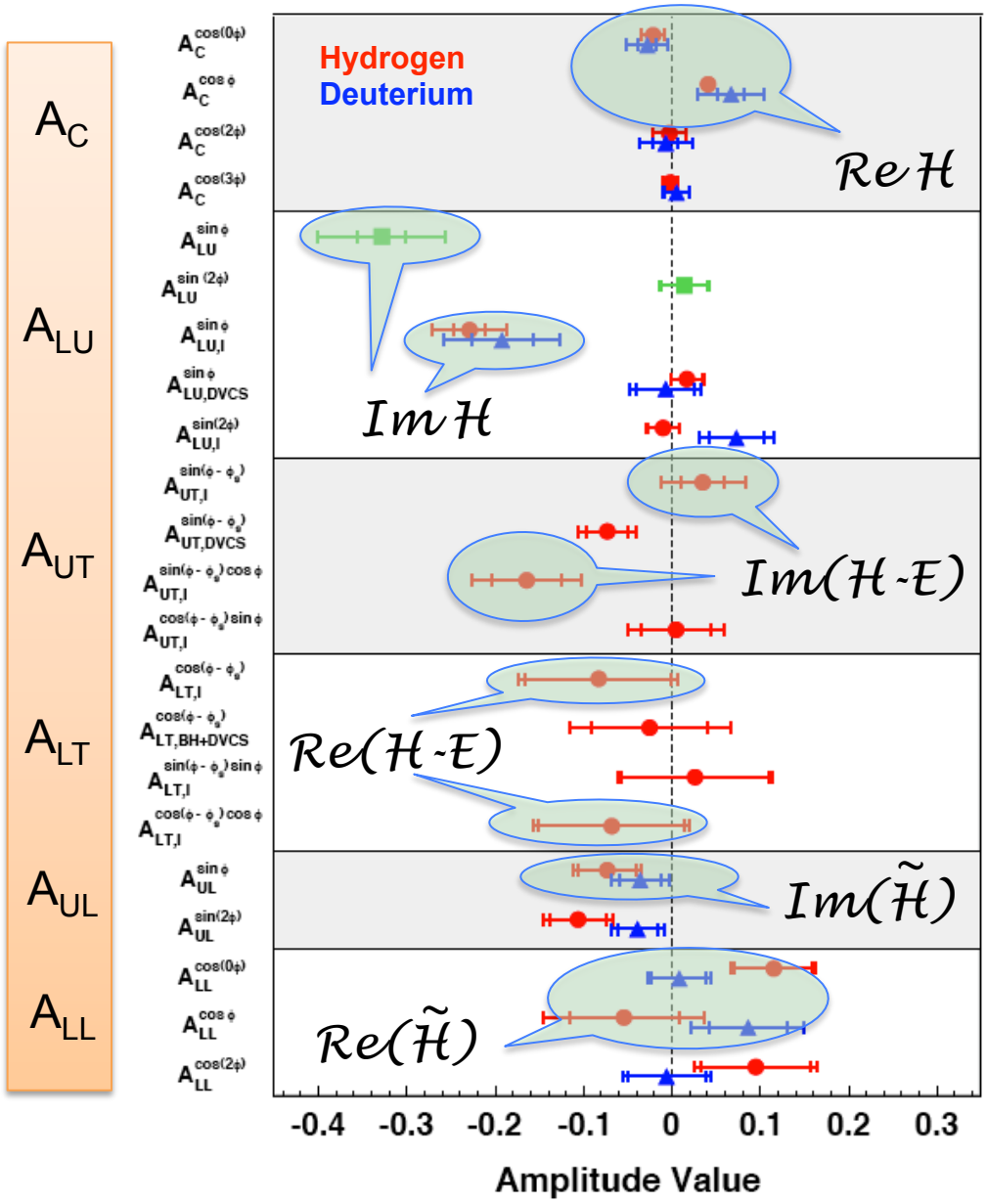
First measurement of DVCS asymmetry on a transverse target Im(H-E)

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



JHEP 06 (2008) 066

The HERMES DVCS Legacy



The most complete DVCS asymmetry measurement set:

A. Airapetian et al, JHEP 11 (2009)

A. Airapetian et al, JHEP10 (2012) 042

A. Airapetian et al, JHEP 07 (2012)

A. Airapetian et al, Nucl. Phys. B 829 (2010) 1-27

A. Airapetian et al, JHEP 06 (2008)

A. Airapetian et al, Phys. Lett. B 704 (2011)

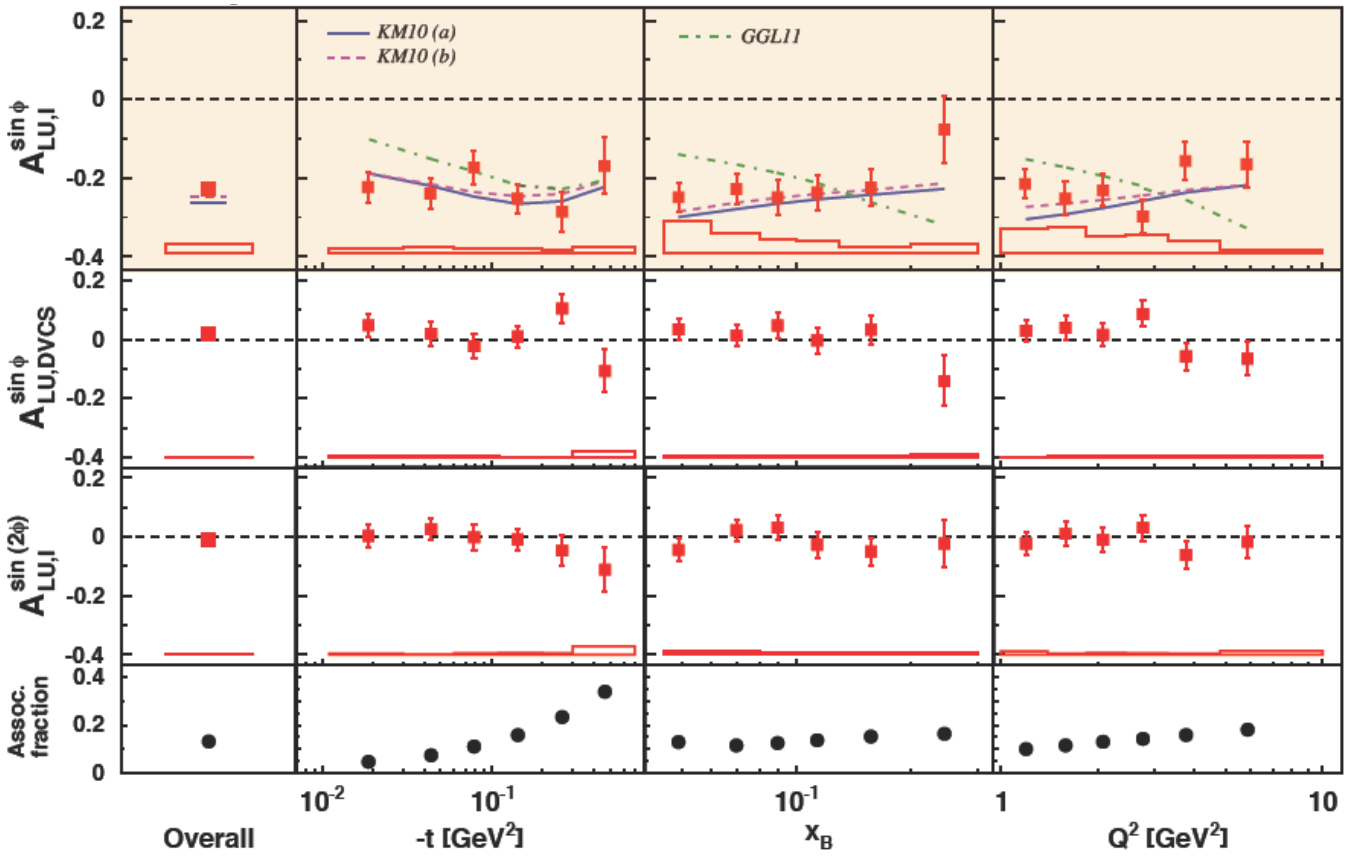
A. Airapetian et al, JHEP 06 (2010)

A. Airapetian et al, Nucl. Phys. B842 (2011)

DVCS on Proton @ HERMES

$\mathcal{H}$

A. Airapetian et al, JHEP 07 (2012) 032

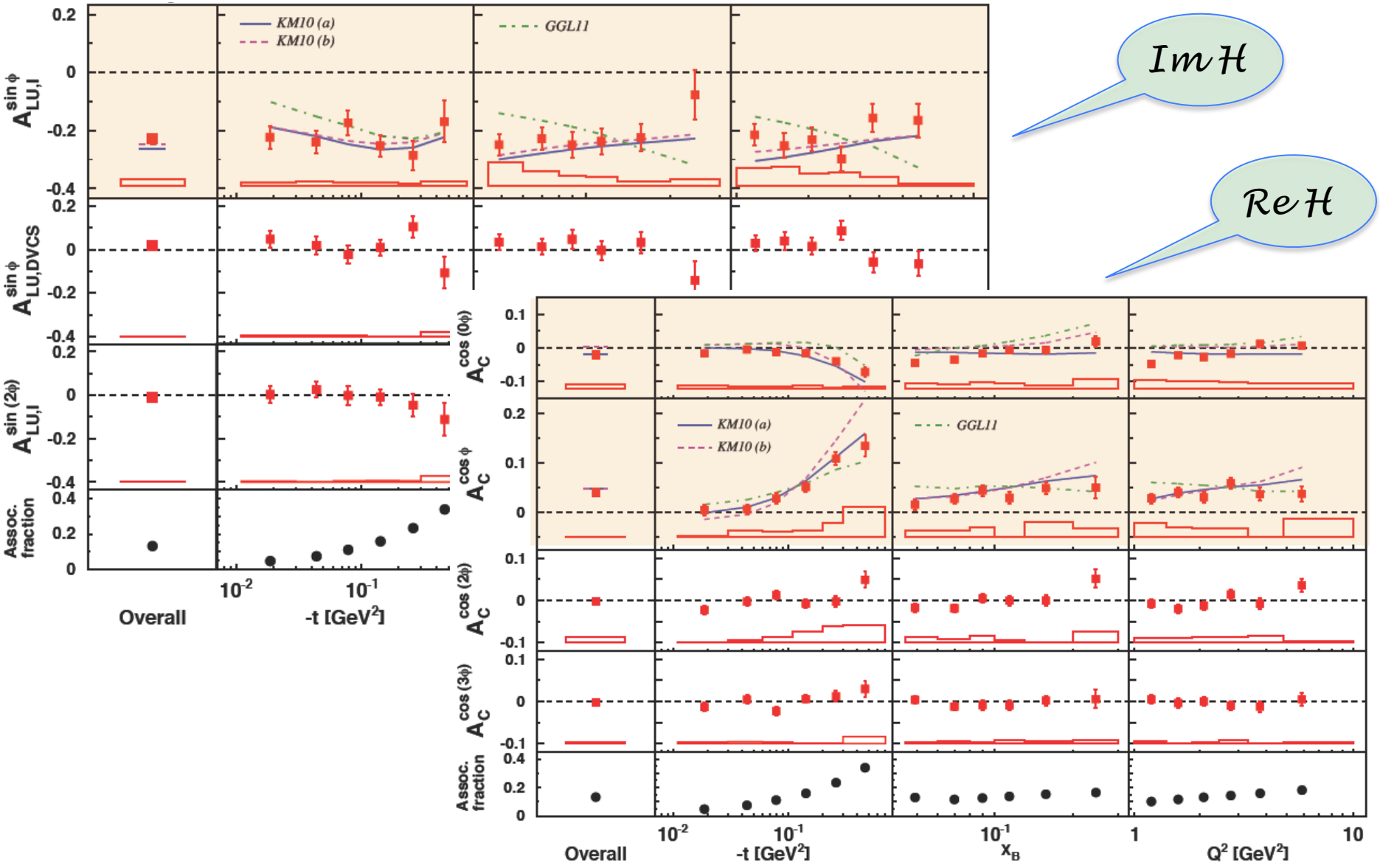


$Im\mathcal{H}$

DVCS on Proton @ HERMES

$\mathcal{H}$

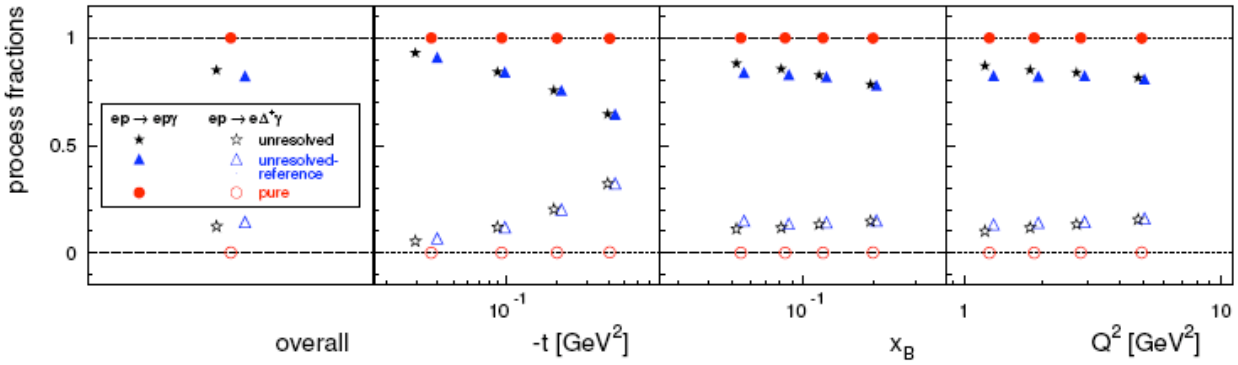
A. Airapetian et al, JHEP 07 (2012) 032

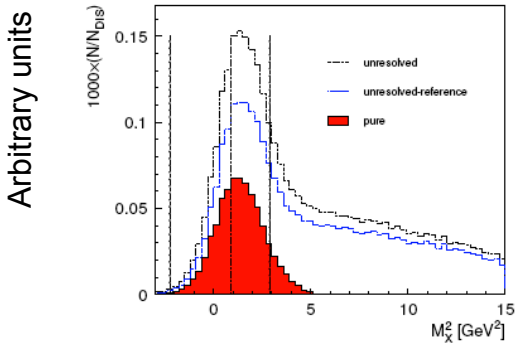


$Im\mathcal{H}$

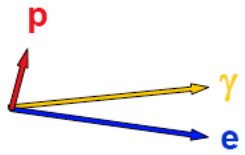
$Re\mathcal{H}$

Pure DVCS @ HERMES



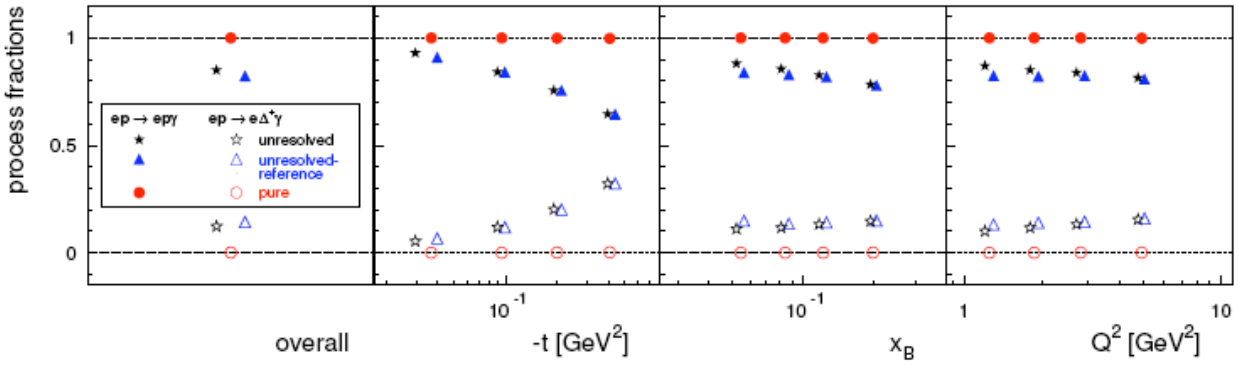


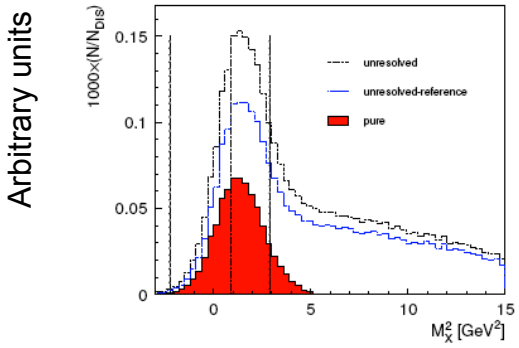
Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation



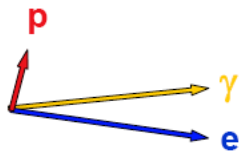
- **No requirement for Recoil**
- **Charged recoil track in acceptance**
- **Kinematic fit probability > 1 %**

Pure DVCS @ HERMES



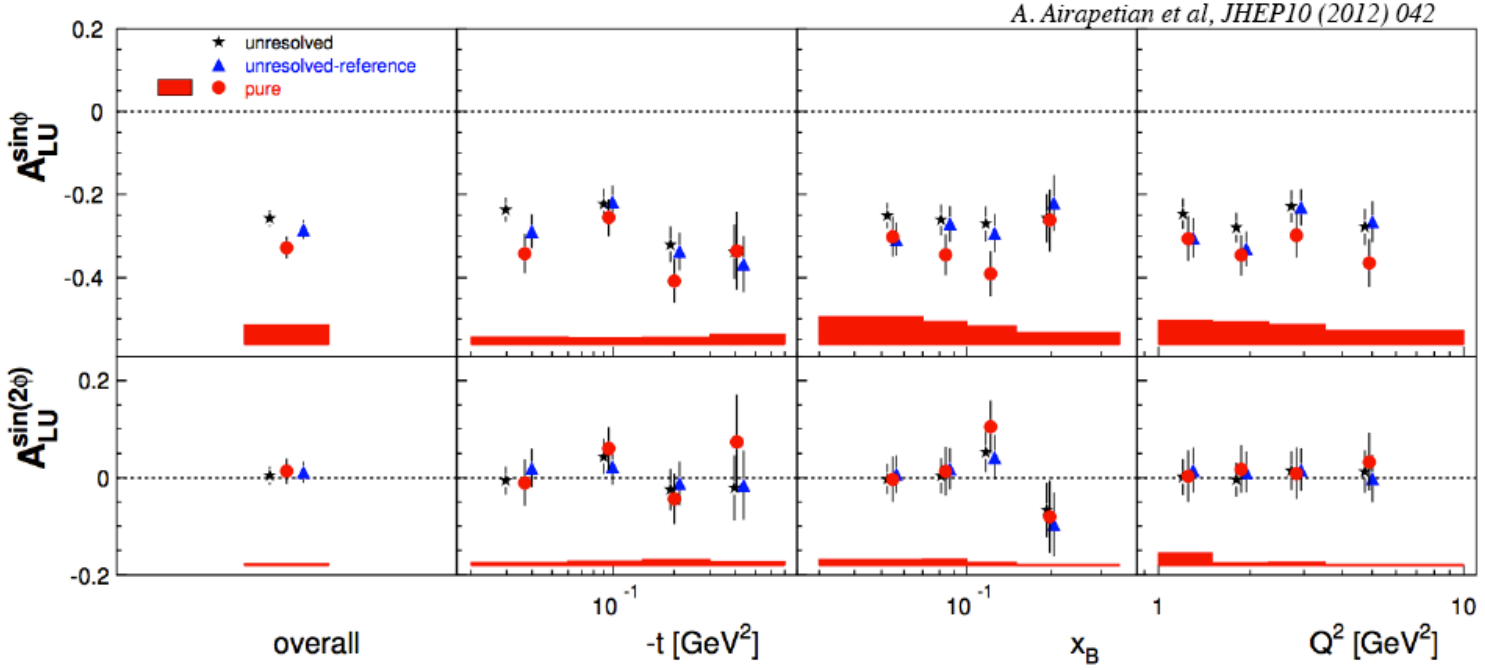


Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation

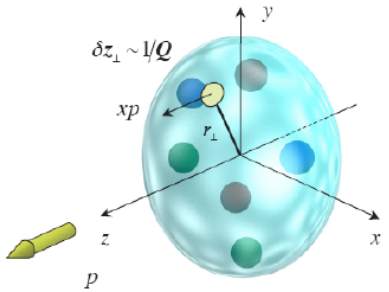


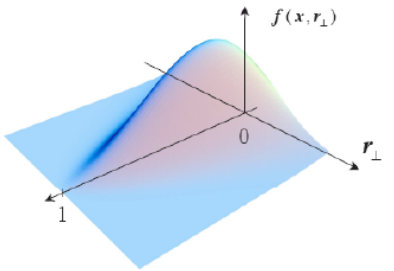
- **No requirement for Recoil**
- **Charged recoil track in acceptance**
- **Kinematic fit probability > 1 %**

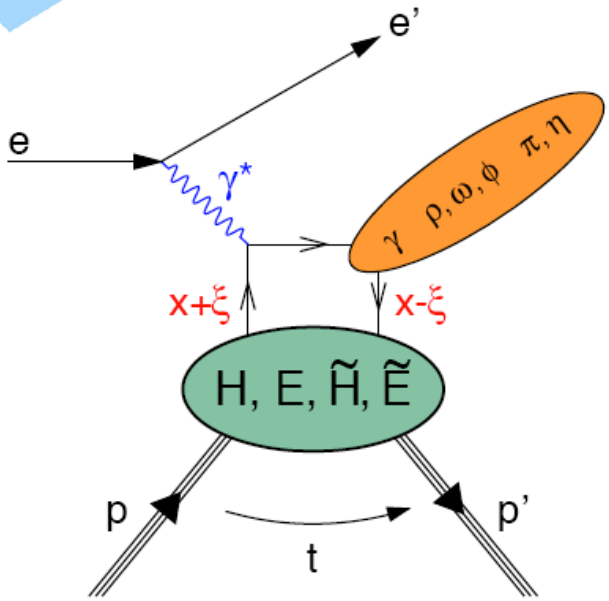
A. Airapetian et al, JHEP10 (2012) 042



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) → $\tilde{H}, \tilde{E}$

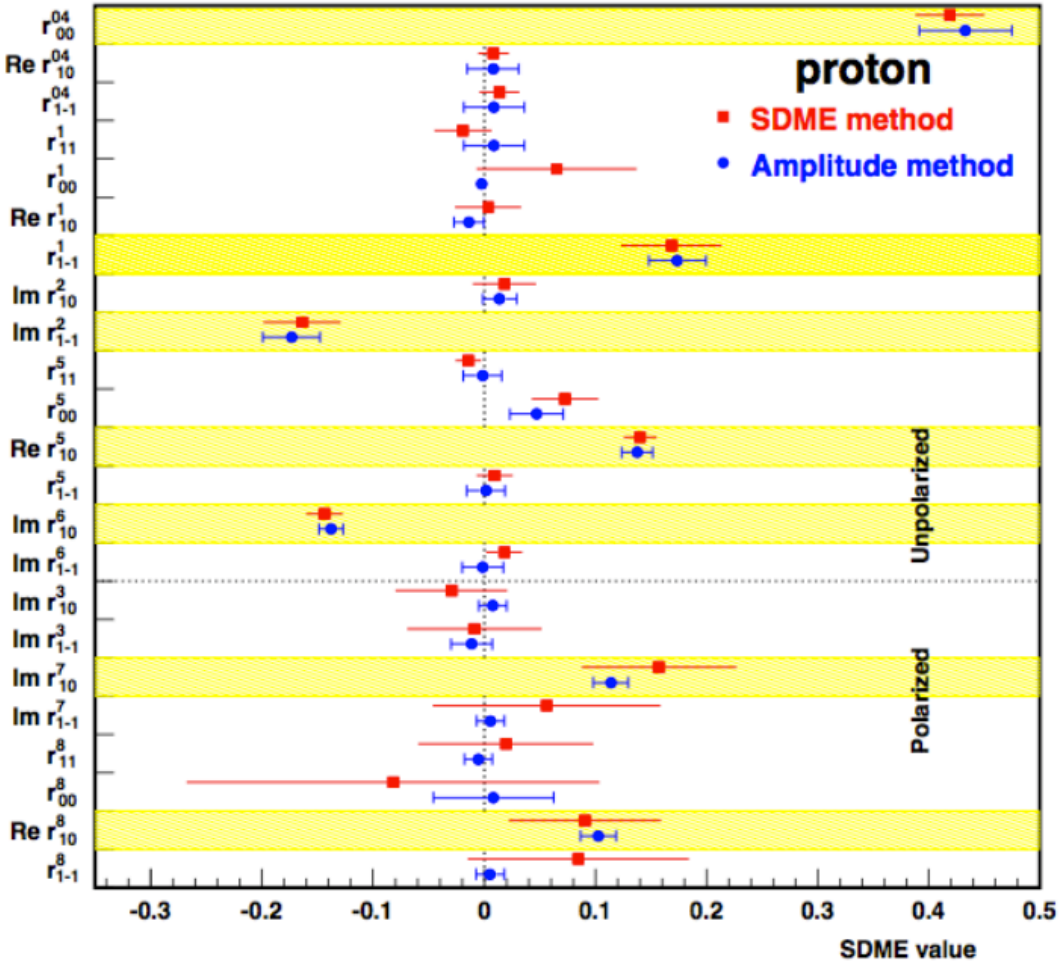
Hard Exclusive ρ^0 Meson Production

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

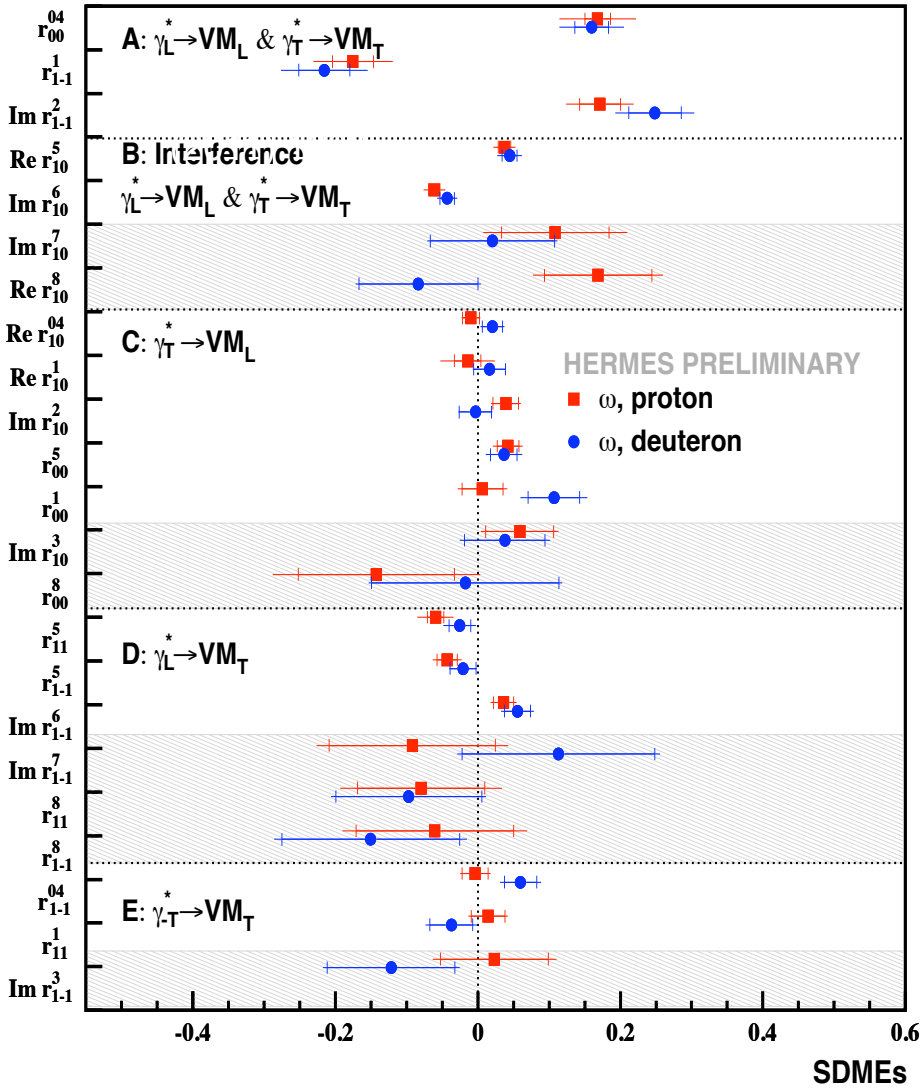
Re-derived SDMEs consistent with published ones
[A. Airapetian et al. EPJC 62 (2009) 659)]

Enhanced sensitivity for polarized SDMEs

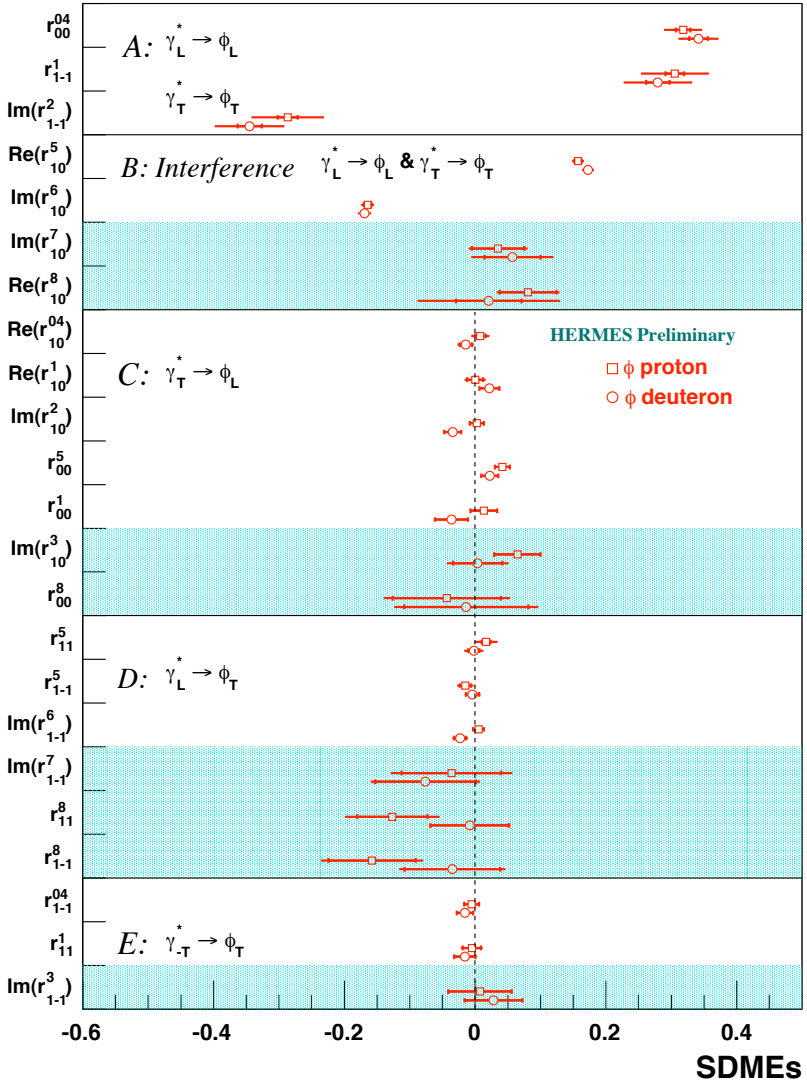
Helicity amplitudes are the fundamental quantities to be compared with theory

Hard Exclusive Meson Production

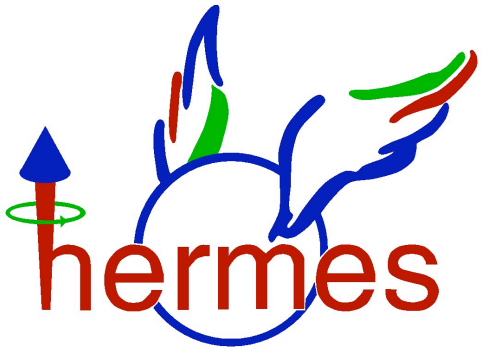
Omega SDMEs



Phi SDMEs



Summary



- HERMES has been a precursor experiment for TMDs and GPDs
- Data-taking closed in 2007 but analysis still ongoing
- Many innovative results in both fields and recently
  - Hadron multiplicities on a pure H target (→ I. Lehman)
  - Full-differential analysis of SIDIS unpolarized asymmetries (→ L. Pappalardo)
  - DVCS with recoil detection (→ I. Brodsky)
- Several preliminary results close to be published
  - Beam spin asymmetry in the semi-inclusive kaon sector (→ V. Zagrebelnyy)
  - Inclusive hadron and Semi-inclusive di-hadron analysis on a transverse target (→ L. Pappalardo)
  - Complete decomposition of the transverse target asymmetries (→ L. Pappalardo)
  - Associated DVCS (→ M. Murray)
  - Exclusive vector-meson production (→ A. Movsisyan)