Nucleon Structure Studies at HERMES Experiment

V.A. Korotkov
(on behalf of the HERMES Collaboration)

Institute for High Energy Physics, Protvino, Russia

HSQCD 2016, Gatchina, 01.07.16

Outline

- Introduction
- Experiment HERMES
- Traditional Studies of the Nucleon Structure
  - $F_2(x, Q^2)$
  - g_1^p, g_1^d
  - g_2
- Modern Studies of the Nucleon Structure
  - TMDs
  - GPDs
- Summary

Motivation of the Experiment

1988 — SPIN CRISIS/PUZZLE — EMC measured $g_1^p(x)$

QPM: $g_1^p(x) = \frac{1}{2}\Sigma_q e_q^2 \Delta q(x)$, $\Delta q(x) = q^+(x) - q^-(x)$

Ellis-Jaffe sum rule: $\int_0^1 g_1^p(x)dx = 0.189 \pm 0.005$.

EMC: $\int_0^1 g_1^p(x)dx = 0.114 \pm 0.012(stat) \pm 0.026(syst)$.

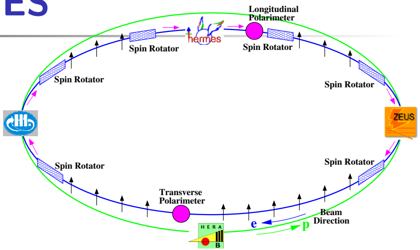
Using additional data from beta decay of neutrons and hyperons, EMC concluded:
Only $(14 \pm 9 \pm 21)\%$ of the proton spin is carried out by the spin of the quarks.

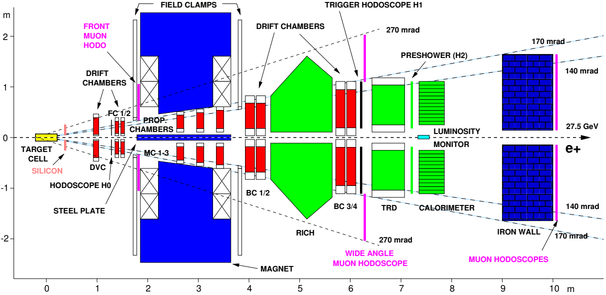
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_z^q + \Delta g + L_z^g$$

There was a necessity to measure the contribution of other constituents to spin of the proton.

Experiment HERMES

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





Internal gas Target:
polarized - $H^{\uparrow}$

Angular acceptance:
$40 < \theta < 220$ mrad

RICH: π / K / p

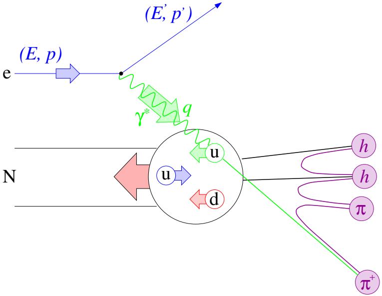
- e/h rejection: TRD, Preshower, Calorimeter, RICH
- magnetic spectrometer: $\Delta p/p < 2.5\%$ and $\Delta\theta < 0.6$ mrad

Experiment HERMES

HERMES Running History

- 1995: longitudinally polarized ^3He
- 1996 - 2000: longitudinally polarized hydrogen/deuteron;
  unpolarized nuclei from Hydrogen to Xenon.
- 2002 - 2005: transversally polarized hydrogen;
  unpolarized nuclei from Hydrogen to Xenon;
- 2006 - 2007: recoil detector with unpolarized target.
- 30.06.2007 - End of HERA running.

Deep-Inelastic Scattering



$Q^2 = -q^2 = -(k - k')^2$
$x_B = \frac{Q^2}{2P\cdot q}$
$y = \frac{P\cdot q}{P\cdot k}$
$W^2 = (P + q)^2$
$z = \frac{P\cdot P_h}{P\cdot q}$

inclusive DIS: detect scattered lepton
semi-inclusive DIS: detect scattered lepton and some fragments

$W^2 > 10$ GeV^2, $0.1 < y < 0.85$, $Q^2 > 1$ GeV^2, $0.2 < z < 0.7$

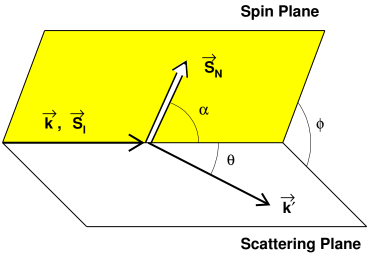
$< Q^2 >= 2.4$ GeV^2, $< x >= 0.09$, $< y >= 0.54$, $< z >= 0.36$, $P_{h\perp} = 0.41$ GeV^2

Inclusive DIS

Inclusive DIS

$$\frac{d^2\sigma(s,S)}{dxdQ^2} = \frac{2\pi\alpha^2 y^2}{Q^6} L_{\mu\nu}(s) W^{\mu\nu}(S)$$

Hadron Tensor $W^{\mu\nu}$
parametrized in terms of
Structure Functions



$$\frac{d^3\sigma}{dxdQ^2d\phi} = \frac{4\alpha^2}{Q^4} y \Bigg\{ \frac{y}{2} F_1(x,Q^2) + \frac{1-y-\gamma^2 y^2/4}{2xy} F_2(x,Q^2)$$
$$- P_l P_T \cos\alpha \left[\left(1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4}\right) g_1(x,Q^2) - \frac{\gamma^2 y}{2} g_2(x,Q^2) \right]$$
$$+ P_l P_T \sin\alpha \cos\phi \, \gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left(\frac{y}{2} g_1(x,Q^2) + g_2(x,Q^2) \right) \Bigg\}$$

Inclusive DIS

Extraction of $F_2(x, Q^2)$ requires good luminosity measurements (7.5%).

Extraction of $g_1(x, Q^2)$ requires measurement of asymmetries

$$A_{\parallel} = \frac{\sigma^{\overset{\rightarrow}{\Leftarrow}} - \sigma^{\overset{\rightarrow}{\Rightarrow}}}{\sigma^{\overset{\rightarrow}{\Leftarrow}} + \sigma^{\overset{\rightarrow}{\Rightarrow}}}$$

Extraction of $g_2(x, Q^2)$ requires measurement of asymmetries

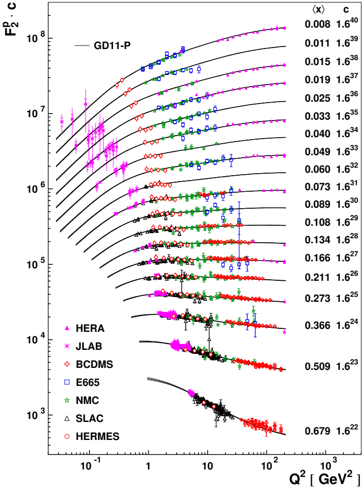
$$A_{\perp} = \frac{\sigma^{\rightarrow\Uparrow}(\phi) - \sigma^{\rightarrow\Uparrow}(\phi+\pi)}{\sigma^{\rightarrow\Uparrow}(\phi) + \sigma^{\rightarrow\Uparrow}(\phi+\pi)}$$

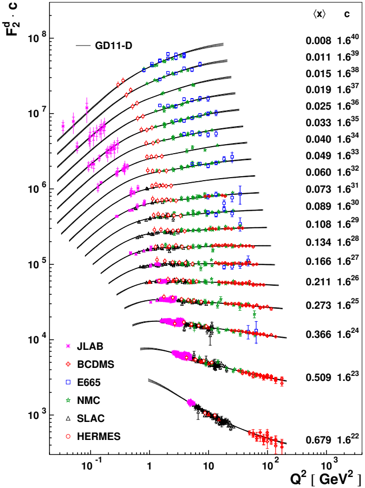
Extraction of each function requires

- independent knowledge of $R_{LT}(x, Q^2) = \sigma_L/\sigma_T$ (K.Abe et al. Phys.Lett. B 452 (1999) 194);
- unfolding of experimental data for QED radiative effects and experimental resolution.

$F_2^p(x, Q^2)$, $F_2^d(x, Q^2)$

HERMES collected about 58 million DIS events with (un)polarized hydrogen and deuterium targets (A.Airapetian et al. JHEP 05 (2011) 126)



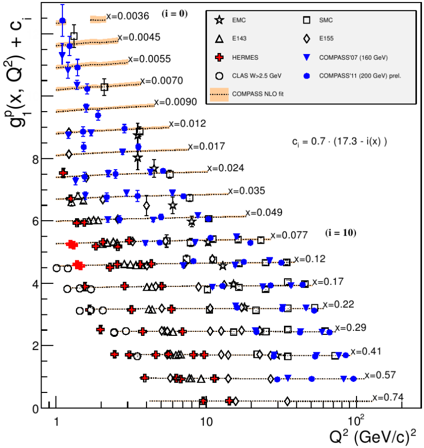


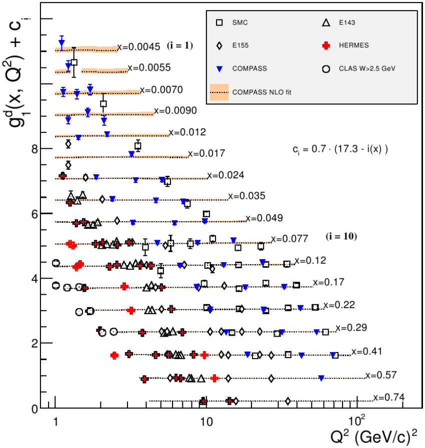
- New region covered by HERMES: $0.006 < x < 0.9$, $0.1\ \text{GeV}^2 < Q^2 < 20\ \text{GeV}^2$
- Agreement with world data in the overlap region

$g_1^p(x, Q^2)$, $g_1^d(x, Q^2)$

HERMES: A.Airapetian et al. Phys.Rev. D 75 (2007) 012007

COMPASS new data: C.Adolph et al. Phys.Lett. B 753 (2016) 18





$\Delta\Sigma = 0.330 \pm 0.011(theo) \pm 0.025(exp) \pm 0.028(evol)$ in the $\bar{MS}$ scheme at order $\mathcal{O}(\alpha_s^2)$ at $Q^2 = 5$ GeV^2.

$\delta s + \delta\bar{s} = -0.085 \pm 0.013(theo) \pm 0.008(exp) \pm 0.009(evol)$

$\delta u + \delta\bar{u} = 0.842 \pm 0.004(theo) \pm 0.008(exp) \pm 0.009(evol)$

$\delta b + \delta\bar{b} = -0.0427 \pm 0.004(theo) \pm 0.008(exp) \pm 0.009(evol)$

$A_2(x)$, $g_2(x)$

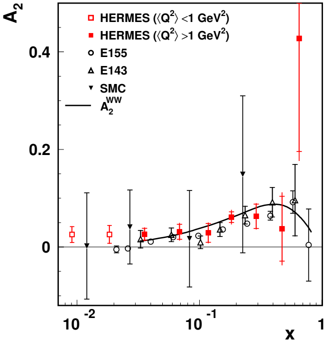
$$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2), \qquad g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_1(x,Q^2)$$

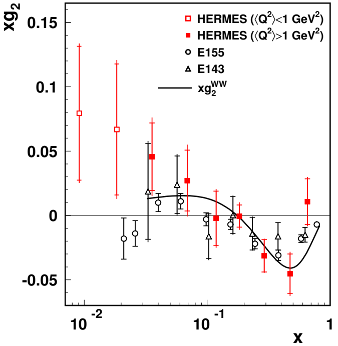
$d_2 = 3\int_0^1 x^2\,\bar{g}_2(x)\,dx$ — lattice QCD

$\int_0^1 g_2(x,Q^2)\,dx = 0$ — Burkhardt–Cottingham sum rule

A.Airapetian et al. Eur.Phys.J. C72 (2012) 1921

$0.004 < x < 0.9$, $0.18 < Q^2 < 20$ GeV^2, $W > 1.8$ GeV $\langle P_T \rangle \simeq 71\%$, $\langle P_b \rangle \simeq 34\%$ (HERA Run 1 $\langle P_b \rangle \geq 50\%$)





HERMES: $d_2 = 3\int_0^1 x^2\,\bar{g}_2(x)\,dx = 0.0148 \pm 0.0096 \pm 0.0048$

SLAC: $d_2 = 0.0032 \pm 0.0017$

HERMES: $\int g_2(x,Q^2)\,dx = 0.006 \pm 0.024 \pm 0.017$, $0.023 < x < 0.9$

SLAC: $\int g_2(x,Q^2)\,dx = -0.042 \pm 0.008$, $0.02 < x < 0.8$

Modern Views on the Nucleon Structure

There is one more, in addition to f_1 and g_1, twist-2 collinear quark distribution function $h_1(x)$ – transversity (J.P.Ralston and D.E.Soper, Nucl.Phys. B 152 (1979) 109)

Describes a distribution of transversely polarized quarks in a transversely polarized nucleon.

In non-relativistic limit h_1 coincides with $g_1(x)$.

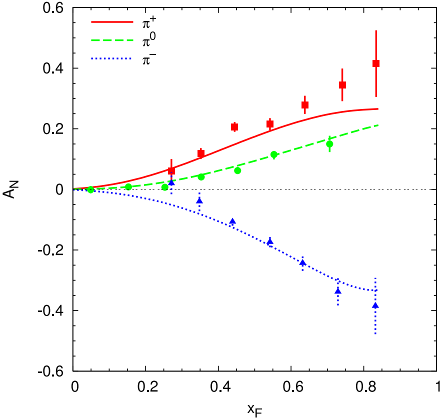
Generally, $h_1(x)$ is different from $g_1(x)$ because boosts and rotations do not commute.

Function h_1 is chiral-odd and can not be accessed in inclusive DIS.

For its measurement requires second chiral-odd function:
– Drell-Yan pp, $p\bar{p}$
– SIDIS, Colins fragmentation function.

Modern Views on the Nucleon Structure

D.L.Adams et al., E704 Coll., Phys.Lett. B261(1991)201; B264(1991)462; Z.Phys. C56(1992)181



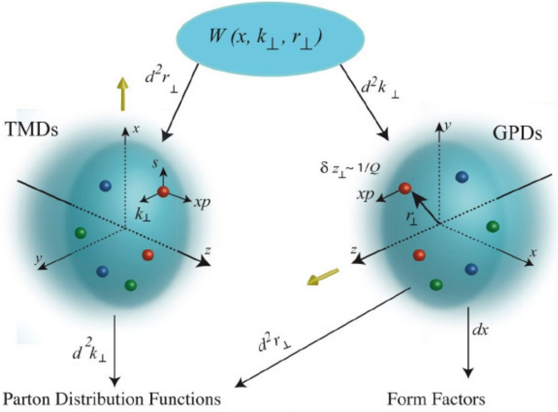
Fermilab, 200 GeV polarized proton beam.

Common belief – the asymmetry (polarization effects) is calculable perturbatively in QCD. The result is zero for $m_q = 0$ and is numerically small if we calculate $m_q/\sqrt{s}$ corrections for light quarks.
(G.L.Kane, J.Pumplin, W.Repko, Phys.Rev.Lett. 41(1978)1689)

The problem was that the conclusion was got in framework of the "collinear" QCD.

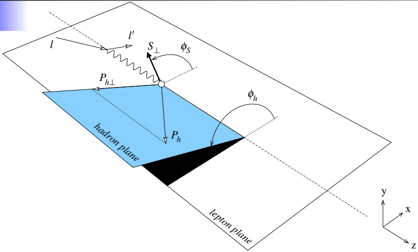
Modern Views on the Nucleon Structure

J.Dudek et al., EPJ A 48 (2012) 187



The Wigner $W(x, k_\perp, r_\perp)$ distribution yield a unified description of a nucleon in terms of the position $r_\perp$ and momenta $k_\perp$ of its constituents.

Quark Distributions



$$eN \to e' hX$$

A.Kotzinian, Nucl.Phys. B441 (1995) 234.

P.J.Mulders , R.D.Tangerman, Nucl.Phys. B461 (1996) 197; B484 (1997) 538.

A.Bacchetta et al., JHEP02 (2007) 093.

K.Goeke, A.Metz, M.Schlegel, Phys.Lett. B 618 (2005) 90

$$\begin{aligned}\Phi(x, p_T) = \frac{1}{2}\Big\{ & f_1\, \not{n}_+ - f_{1T}^\perp \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M}\, \not{n}_+ + g_{1s}\gamma_5\, \not{n}_+ \\ & + h_{1T}\frac{[\not{S}_T,\, \not{n}_+]\gamma_5}{2} + h_{1s}^\perp \frac{[\not{p}_T,\, \not{n}_+]\gamma_5}{2M} + i\, h_1^\perp \frac{[\not{p}_T,\, \not{n}_+]}{2M}\Big\} \\ + \frac{M}{2P^+}\Big\{ & e - i\, e_s\, \gamma_5 - e_T^\perp \frac{\epsilon_T^{\rho\sigma} p_{T\rho} S_{T\sigma}}{M} \\ & + f^\perp \frac{\not{p}_T}{M} - f_T'\, \epsilon_T^{\rho\sigma}\gamma_\rho S_{T\sigma} - f_s^\perp \frac{\epsilon_T^{\rho\sigma}\gamma_\rho p_{T\sigma}}{M} \\ & + g_T'\,\gamma_5\, \not{S}_T + g_s^\perp \gamma_5 \frac{\not{p}_T}{M} - g^\perp \gamma_5 \frac{\epsilon_T^{\rho\sigma}\gamma_\rho p_{T\sigma}}{M} \\ & + h_s \frac{[\not{n}_+,\, \not{n}_-]\gamma_5}{2} + h_T^\perp \frac{[\not{S}_T,\, \not{p}_T]\gamma_5}{2M} + i\, h \frac{[\not{n}_+,\, \not{n}_-]}{2}\Big\}. \end{aligned} \tag{1}$$

Quark Distributions

$$g_{1s}(x, p_T) = S_L g_{1L}(x, p_T^2) - \frac{p_T \cdot S_T}{M} g_{1T}(x, p_T^2)$$

$$h_{1s}(x, p_T) = S_L h_{1L}(x, p_T^2) - \frac{p_T \cdot S_T}{M} h_{1T}(x, p_T^2)$$

Eight distributions of twist two, and 16 distributions of twist three.

		Quark		
		U	**L**	**T**
Nucleon	**U**	f_1		$h_1^\perp$
	L		g_{1L}	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	g_{1T}	h_{1T}, $h_{1T}^\perp$

$f_1(x) = \int d^2\vec{p}_T f_1(x, p_T^2)$, $g_1(x) = \int d^2\vec{p}_T g_1(x, p_T^2)$, $h_1(x) = \int d^2\vec{p}_T \{h_{1T}(x, p_T^2) + \frac{p_T^2}{2M} h_{1T}^\perp(x, p_T^2)\}$

Fragmentation Functions

The fragmentation correlation function (for a spinless or an unpolarized hadron) can be parameterized as

$$\Delta(z, k_T) = \frac{1}{2}\left\{ D_1\, \not{n}_- + i H_1^{\perp} \frac{[\not{k}_T, \not{n}_-]}{2M_h} \right\} + \frac{M_h}{2P_h^-}\left\{ E + D^{\perp} \frac{\not{k}_T}{M_h} + i H \frac{[\not{n}_-, \not{n}_+]}{2} + G^{\perp} \gamma_5 \frac{\epsilon_T^{\rho\sigma}\gamma_\rho k_{T\sigma}}{M_h} \right\}$$

The functions on the r.h.s. depend on z and k_T^2.

Usual fragmentation function $D_1(z) = z^2 \int d^2\mathbf{k}_T D_1(z, k_T^2)$

SIDIS, $eN \rightarrow e'hX$

(A.Bacchetta et al., JHEP02 (2007) 093; JHEP08 (2008) 023)

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{x\,Q^2}\,\frac{y}{2\,(1-\varepsilon)}\left\{T_{UU} + \lambda_e\,T_{LU} + S_\parallel\,T_{UL} + S_\parallel\,\lambda_e\,T_{LL} + |\boldsymbol{S}_\perp|\,T_{UT} + |\boldsymbol{S}_\perp|\lambda_e\,T_{LT}\right\}$$

$$T_{UU} = F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}$$

$$T_{LU} = \sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$T_{UL} = \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}$$

$$T_{LL} = \sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}$$

$$T_{UT} = \sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\times F_{UT}^{\sin(3\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}$$

$$T_{LT} = \sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\times F_{LT}^{\cos(2\phi_h-\phi_S)}$$

$F_{XY,Z}$ – X - beam polarization, Y - target polarization, Z - virtual photon poalrization.
$X, Y = U, L, T$, $Z = L, T$.

ε is the ratio of longitudinal and transverse photon flux, $\varepsilon = \dfrac{1-y}{1-y+y^2/2}$.

SIDIS

(A.Bacchetta et al., JHEP02(2007)093; JHEP08(2008)023)

The following notations are introduced:

$$\mathcal{C}\left[w\,f\,D\right] = x \sum_a e_a^2 \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^{(2)}\left(\boldsymbol{p}_T - \boldsymbol{k}_T - \boldsymbol{P}_{h\perp}/z\right) w(\boldsymbol{p}_T, \boldsymbol{k}_T)\, f^a(x, p_T^2)\, D^a(z, k_T^2), \qquad (2)$$

where $w(\boldsymbol{p}_T, \boldsymbol{k}_T)$ is an arbitrary function and the summation runs over quarks and antiquarks and the unit vector

The expressions for the structure functions are:

$$F_{UU,T} = \mathcal{C}\left[f_1 D_1\right]$$

$$F_{UU,L} = 0$$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh\,H_1^{\perp} + \frac{M_h}{M}\,f_1\,\frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\,\frac{\tilde{H}}{z}\right)\right]$$

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

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp} + \frac{M_h}{M}\,f_1\,\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}D_1 + \frac{M_h}{M}\,h_1^{\perp}\,\frac{\tilde{E}}{z}\right)\right]$$

......

SIDIS

(A.Bacchetta et al., JHEP02(2007)093; JHEP08(2008)023)

The following notations are introduced:

$$\mathcal{C}\left[w f D\right] = x \sum_a e_a^2 \int d^2\boldsymbol{p}_T\, d^2\boldsymbol{k}_T\, \delta^{(2)}\left(\boldsymbol{p}_T - \boldsymbol{k}_T - \boldsymbol{P}_{h\perp}/z\right) w(\boldsymbol{p}_T, \boldsymbol{k}_T)\, f^a(x, p_T^2)\, D^a(z, k_T^2), \qquad (3)$$

where $w(\boldsymbol{p}_T, \boldsymbol{k}_T)$ is an arbitrary function and the summation runs over quarks and antiquarks and the unit vector $\hat{\boldsymbol{h}} = \boldsymbol{P}_{h\perp}/|\boldsymbol{P}_{h\perp}|$.

The expressions for the structure functions are:

$$F_{UU,T} = \mathcal{C}\left[f_1 D_1\right]$$

$$F_{UU,L} = 0$$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh\,H_1^\perp + \frac{M_h}{M}\,f_1\,\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\,\frac{\tilde{H}}{z}\right)\right]$$

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

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^\perp + \frac{M_h}{M}\,f_1\,\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\,\frac{\tilde{E}}{z}\right)\right]$$

$$F_{UL}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xh_L H_1^\perp + \frac{M_h}{M}\,g_{1L}\,\frac{\tilde{G}^\perp}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xf_L^\perp D_1 - \frac{M_h}{M}\,h_{1L}^\perp\,\frac{\tilde{H}}{z}\right)\right]$$

SIDIS

(A.Bacchetta et al., JHEP02(2007)093; JHEP08(2008)023)

$$F_{UL}^{\sin 2\phi_h} = \mathcal{C}\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{MM_h}h_{1L}^{\perp}H_1^{\perp}\right]$$

$$F_{LL} = \mathcal{C}\left[g_{1L}D_1\right]$$

$$F_{LL}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe_L H_1^{\perp}-\frac{M_h}{M}\,g_{1L}\frac{\tilde{D}^{\perp}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg_L^{\perp}D_1+\frac{M_h}{M}\,h_{1L}^{\perp}\frac{\tilde{E}}{z}\right)\right]$$

$$F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}f_{1T}^{\perp}D_1\right]$$

$$F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0$$

$$F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}h_1H_1^{\perp}\right]$$

$$F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{C}\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\boldsymbol{p}_T\cdot\boldsymbol{k}_T\right)+\boldsymbol{p}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)-4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)}{2M^2M_h}h_{1T}^{\perp}H_1^{\perp}\right]$$

$$F_{UT}^{\sin\phi_S} = \frac{2M}{Q}\,\mathcal{C}\left\{\left(xf_T D_1-\frac{M_h}{M}\,h_1\frac{\tilde{H}}{z}\right)-\frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(xh_T H_1^{\perp}+\frac{M_h}{M}g_{1T}\,\frac{\tilde{G}^{\perp}}{z}\right)-\left(xh_T^{\perp}H_1^{\perp}-\frac{M_h}{M}f_{1T}^{\perp}\,\frac{\tilde{D}^{\perp}}{z}\right)\right]\right\}$$

SIDIS

(A.Bacchetta et al., JHEP02(2007)093; JHEP08(2008)023)

$$F_{UT}^{\sin(2\phi_h-\phi_S)} = \frac{2M}{Q}\,\mathcal{C}\Big\{\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{2M^2}\left(xf_T^\perp D_1 - \frac{M_h}{M}\,h_{1T}^\perp\frac{\tilde{H}}{z}\right) - \frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(xh_T H_1^\perp + \frac{M_h}{M}g_{1T}\frac{\tilde{G}^\perp}{z}\right) + \left(xh_T^\perp H_1^\perp - \frac{M_h}{M}f_{1T}^\perp\frac{\tilde{D}^\perp}{z}\right)\right]\Big\}$$

$$F_{LT}^{\cos(\phi_h-\phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}g_{1T}D_1\right]$$

$$F_{LT}^{\cos\phi_S} = \frac{2M}{Q}\,\mathcal{C}\Big\{-\left(xg_T D_1 + \frac{M_h}{M}\,h_1\frac{\tilde{E}}{z}\right) + \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(xe_T H_1^\perp - \frac{M_h}{M}g_{1T}\frac{\tilde{D}^\perp}{z}\right) + \left(xe_T^\perp H_1^\perp + \frac{M_h}{M}f_{1T}^\perp\frac{\tilde{G}^\perp}{z}\right)\right]\Big\}$$

$$F_{LT}^{\cos(2\phi_h-\phi_S)} = \frac{2M}{Q}\,\mathcal{C}\Big\{-\frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)^2-\boldsymbol{p}_T^2}{2M^2}\left(xg_T^\perp D_1 + \frac{M_h}{M}\,h_{1T}^\perp\frac{\tilde{E}}{z}\right) + \frac{2\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)\,(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T)-\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(xe_T H_1^\perp - \frac{M_h}{M}g_{1T}\frac{\tilde{D}^\perp}{z}\right) - \left(xe_T^\perp H_1^\perp + \frac{M_h}{M}f_{1T}^\perp\frac{\tilde{G}^\perp}{z}\right)\right]\Big\}$$

Asymmetry A_{UT}

$$d\sigma = d\sigma_0 (1 + A_{UU}^{\cos\phi_h}\cos\phi_h + A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + |\boldsymbol{S}_\perp| \cdot \{A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) + A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) + A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) + A_{UT}^{\sin\phi_S}\sin\phi_S + A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\})$$

$$A_{UT}^{\sin(\phi_h-\phi_S)} \propto F_{UT,T}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M} f_{1T}^{\perp} D_1\right]$$ – Sivers asymmetry (PRL 103 (2009) 152002)

$$A_{UT}^{\sin(\phi_h+\phi_S)} \propto F_{UT}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h} h_1 H_1^{\perp}\right]$$ – Collins asymmetry (Phys.Lett. B693 (2010) 11)

$$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{C}\left[\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\boldsymbol{p}_T\cdot\boldsymbol{k}_T\right) + \boldsymbol{p}_T^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right) - 4\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)^2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)}{2M^2 M_h} h_{1T}^{\perp} H_1^{\perp}\right]$$

Other asymmetries are twist-3:

$$A_{UT}^{\sin(\phi_S)} \propto F_{UT}^{\sin(\phi_S)} = \frac{2M}{Q}\mathcal{C}\left\{\left(x f_T D_1 - \frac{M_h}{M} h_1 \frac{\tilde{H}}{z}\right) - \frac{\boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T}\frac{\tilde{G}^{\perp}}{z}\right) - \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp}\frac{\tilde{D}^{\perp}}{z}\right)\right]\right\}$$

$$F_{UT}^{\sin(2\phi_h-\phi_S)} \propto F_{UT}^{\sin(2\phi_h-\phi_S)} = \frac{2M}{Q}\mathcal{C}\left\{\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)^2 - \boldsymbol{p}_T^2}{2M^2}\left(x f_T^{\perp} D_1 - \frac{M_h}{M} h_{1T}^{\perp}\frac{\tilde{H}}{z}\right) - \frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right) - \boldsymbol{k}_T\cdot\boldsymbol{p}_T}{2MM_h}\left[\left(x h_T H_1^{\perp} + \frac{M_h}{M} g_{1T}\frac{\tilde{G}^{\perp}}{z}\right) + \left(x h_T^{\perp} H_1^{\perp} - \frac{M_h}{M} f_{1T}^{\perp}\frac{\tilde{D}^{\perp}}{z}\right)\right]\right\}$$

SIDIS: Extraction of the amplitudes, UT

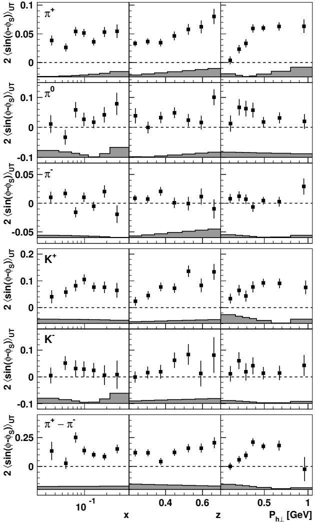
For each kinematic bin, the probability density function for hadron type h:
$F(2 < \sin(\phi + \phi_S) >^h_{UT},\ 2 < \sin(\phi - \phi_S) >^h_{UT},\ \ldots,\ S_\perp,\ \phi,\ \phi_S) =$

$$
\begin{aligned}
1 + S_\perp \cdot \Big(& 2 < \sin(\phi + \phi_S) >^h_{UT} \cdot \sin(\phi + \phi_S) + \\
& 2 < \sin(\phi - \phi_S) >^h_{UT} \cdot \sin(\phi - \phi_S) + \\
& 2 < \sin(3\phi - \phi_S) >^h_{UT} \cdot \sin(3\phi - \phi_S) + \\
& 2 < \sin(2\phi - \phi_S) >^h_{UT} \cdot \sin(2\phi - \phi_S) + \\
& 2 < \sin(2\phi + \phi_S) >^h_{UT} \cdot \sin(2\phi + \phi_S) + \\
& 2 < \sin(\phi_S) >^h_{UT} \cdot \sin(\phi_S) \Big)
\end{aligned}
$$

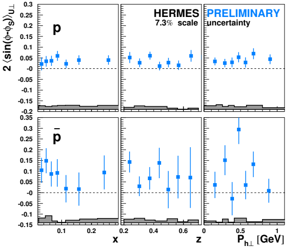
$< \sin(\phi + \phi_S) >^h_{UT}$ — signal for the Collins FF $H_1^\perp$ and the transversity DF h_1 :
$< \sin(\phi - \phi_S) >^h_{UT}$ — signal for the Sivers DF $f_{1T}^{\perp,q}$
$< \sin(3\phi - \phi_S) >^h_{UT}$ — signal for the pretzelosity DF $h_{1T}^{\perp,q}$

Sivers Asymmetry

PRL 103 (2009) 152002

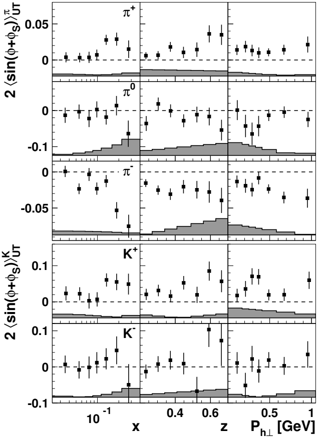


NEW

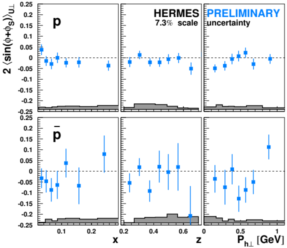


Collins Asymmetry

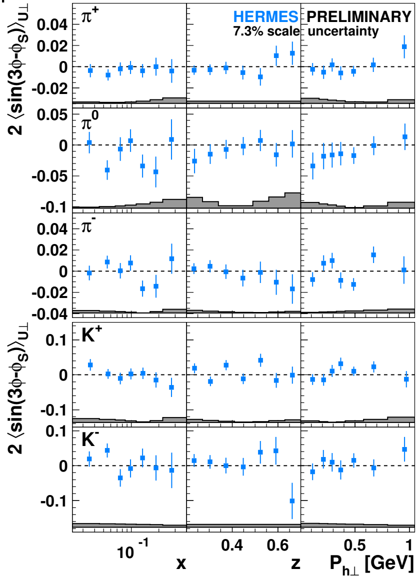
Phys.Lett. B693 (2010) 11



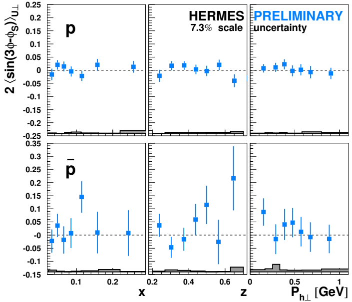
NEW



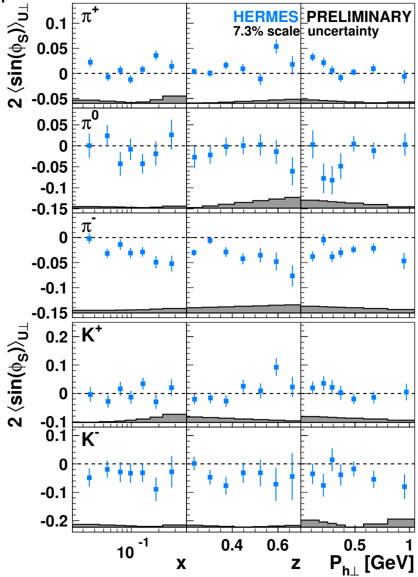
Pretzelosity $A_{UT}^{sin(3\phi-\phi_S)}$



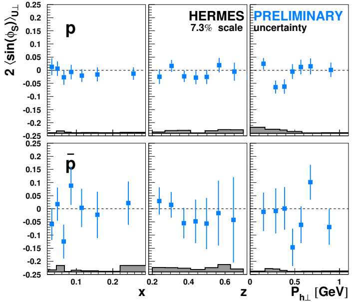
NEW



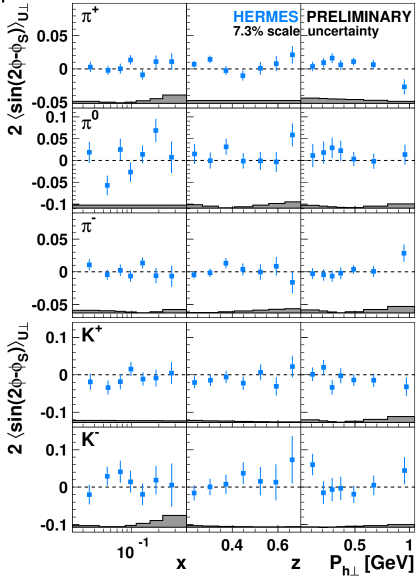
$A_{UT}^{sin(\phi_S)}$



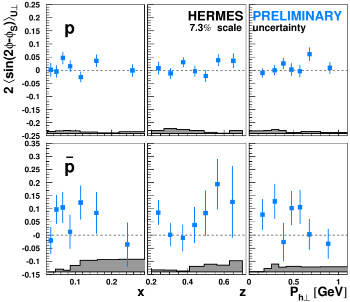
NEW



SIDIS: $A_{UT}^{\sin(2\phi-\phi_S)}$



NEW

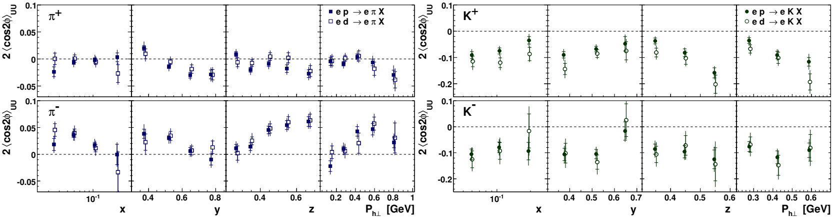


Asymmetry $A_{UU}^{\cos 2\phi}$

$$d\sigma = d\sigma_0 (1 + A_{UU}^{\cos\phi_h} \cos\phi_h + A_{UU}^{\cos 2\phi_h} \cos 2\phi_h)$$

$$F_{UU}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2\,(\hat{\boldsymbol{h}} \cdot \boldsymbol{k}_T)\,(\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T) - \boldsymbol{k}_T \cdot \boldsymbol{p}_T}{M M_h} h_1^\perp H_1^\perp \right]$$

Phys.Rev. D 87 (2013) 012010

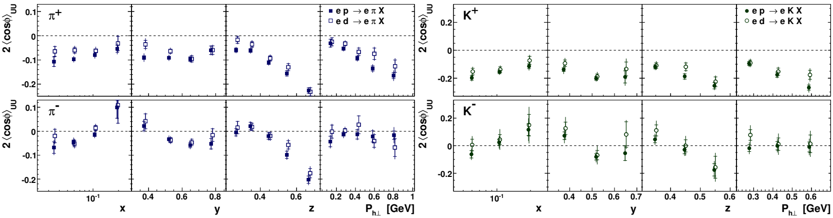


Twist-2 contribution Boer-Mulders DF $h_1^\perp$

Higher twist contribution from the Cahn effect.

Asymmetry $A_{UU}^{\cos\phi}$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h\, H_1^{\perp} + \frac{M_h}{M}\, f_1 \frac{\tilde{D}^{\perp}}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f^{\perp} D_1 + \frac{M_h}{M}\, h_1^{\perp}\frac{\tilde{H}}{z}\right)\right]$$



Twist-3 contributions from TMDs and twist-4 from Cahn effect.

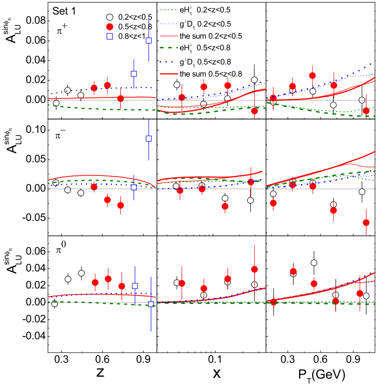
Asymmetry A_{LU}

$$d\sigma = d\sigma_0(1 + A_{UU}^{\cos\phi_h}\cos\phi_h + A_{UU}^{\cos 2\phi_h}\cos 2\phi_h + P_L \cdot A_{LU}^{\sin(\phi_h)})$$

$$A_{LU}^{\sin(\phi_h)} \propto F_{LU}^{\sin\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(xe\,H_1^{\perp} + \frac{M_h}{M}\,f_1\,\frac{\tilde{G}^{\perp}}{z}\right) + \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(xg^{\perp}\,D_1 + \frac{M_h}{M}\,h_1^{\perp}\,\frac{\tilde{E}}{z}\right)\right]$$

HERMES A.Airapetian et al., Phys.Lett., B648, 164 (2007)

Data of 1996–1997 years



$eH_1^{\perp}$ A.Efremov, K.Goeke, P.Schweitzer, Ph.Rev. D67, 114014(2003)

$h_1^{\perp}\tilde{E}$ F.Yuan. Ph.Lett. B589, 28(2004)

$g^{\perp}D_1$ A.Metz, M.Schlegel, EPJ A22, 489 (2004)

$g^{\perp}D_1$, $eH_1^{\perp}$ W.Mao, Z.Lu, EPJ C73, 2557 (2013)

Asymmetry A_{LT}

$$d\sigma = d\sigma_0 (1 + A_{UU}^{\cos\phi_h} \cos\phi_h + A_{UU}^{\cos 2\phi_h} \cos 2\phi_h + \lambda_e |\boldsymbol{S}_\perp| \cdot \{ A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) + A_{LT}^{\cos(2\phi_h - \phi_S)} \cos(2\phi_h - \phi_S) + A_{LT}^{\cos(\phi_S)} cos(\phi_S) \})$$

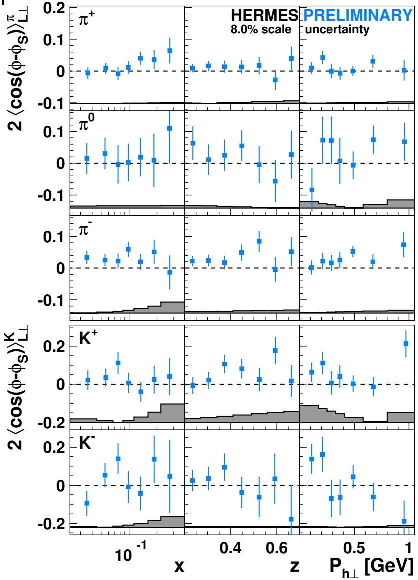
$$A_{LT}^{\cos(\phi_h - \phi_S)} \propto F_{LT}^{\cos(\phi_h - \phi_S)} = \mathcal{C}\left[\frac{\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T}{M} g_{1T} D_1 \right]$$

Other asymmetries are twist-3:

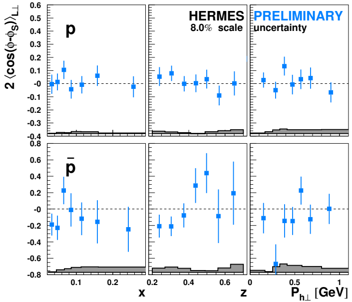
$$A_{LT}^{\cos\phi_S} \propto F_{LT}^{\cos\phi_S} = \frac{2M}{Q} \mathcal{C}\Big\{ -\Big(x g_T D_1 + \frac{M_h}{M} h_1 \frac{\tilde{E}}{z} \Big) + \frac{\boldsymbol{k}_T \cdot \boldsymbol{p}_T}{2MM_h} \Big[\Big(x e_T H_1^\perp - \frac{M_h}{M} g_{1T} \frac{\tilde{D}^\perp}{z} \Big) + \Big(x e_T^\perp H_1^\perp + \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{G}^\perp}{z} \Big) \Big] \Big\}$$

$$A_{LT}^{\cos(2\phi_h - \phi_S)} \propto F_{LT}^{\cos(2\phi_h - \phi_S)} = \frac{2M}{Q} \mathcal{C}\Big\{ -\frac{2\,(\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T)^2 - \boldsymbol{p}_T^2}{2M^2} \Big(x g_T^\perp D_1 + \frac{M_h}{M} h_{1T}^\perp \frac{\tilde{E}}{z} \Big) + \frac{2\,(\hat{\boldsymbol{h}} \cdot \boldsymbol{k}_T)\,(\hat{\boldsymbol{h}} \cdot \boldsymbol{p}_T) - \boldsymbol{k}_T \cdot \boldsymbol{p}_T}{2MM_h} \Big[\Big(x e_T H_1^\perp - \frac{M_h}{M} g_{1T} \frac{\tilde{D}^\perp}{z} \Big) - \Big(x e_T^\perp H_1^\perp + \frac{M_h}{M} f_{1T}^\perp \frac{\tilde{G}^\perp}{z} \Big) \Big] \Big\}$$

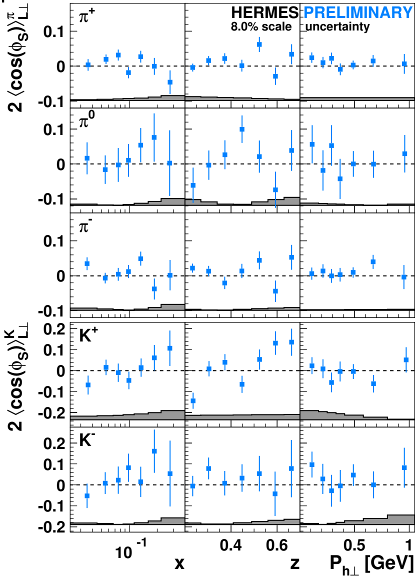
$A_{LT}^{cos(\phi-\phi_S)}$



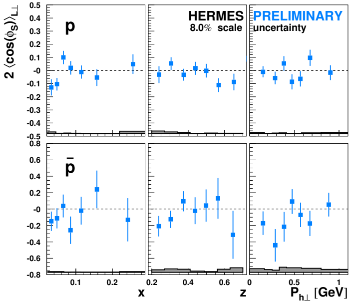
NEW



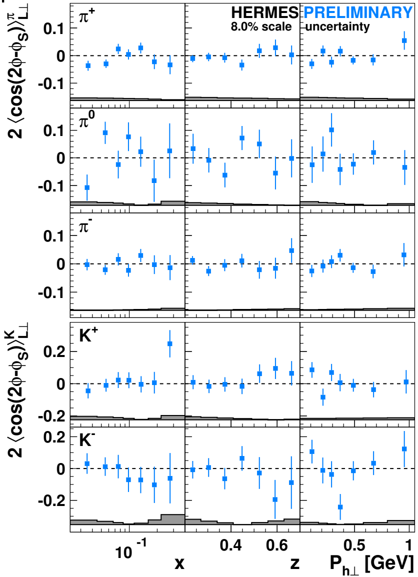
SIDIS: $\sigma_{LT}^{\cos(\phi_S)}$



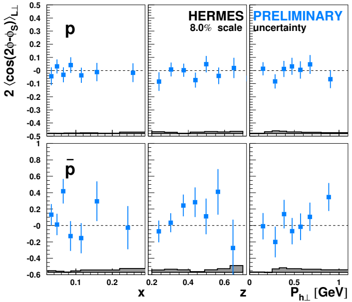
NEW



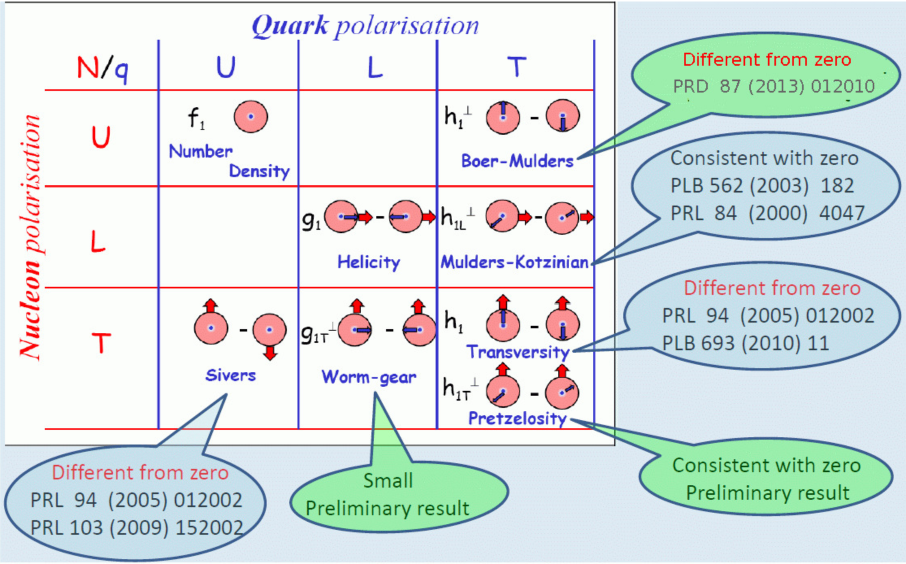
SIDIS: $\sigma_{LT}^{cos(2\phi-\phi_S)}$



NEW

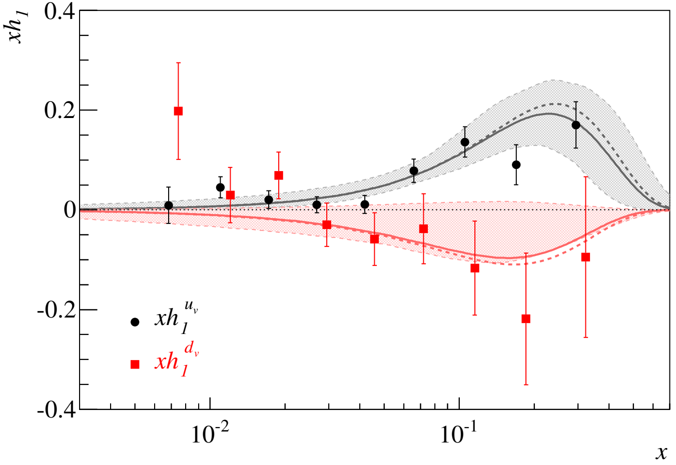


Leading-twist TMDs. Summary from HERMES



Valence Transversity Distribution

Valence transversity distribution at $Q^2 = 10$ GeV^2



Points — A.Martin, F.Bradamante,V.Barone, arXiv 1412.5946 Bands — M.Anselmino et al., Phys.Rev. D 87 (2013) 094019

Asymmetry A_{LU}

New analysis.

All data sets.

96–97 – threshold Čerenkov detector:
pions $4.5 < P < 13.5$ GeV

97–07 – dual radiator RICH detector:
pions, kaons $2.0 < P < 15.0$ GeV
(anti)protons $4.0 < P < 15.0$ GeV

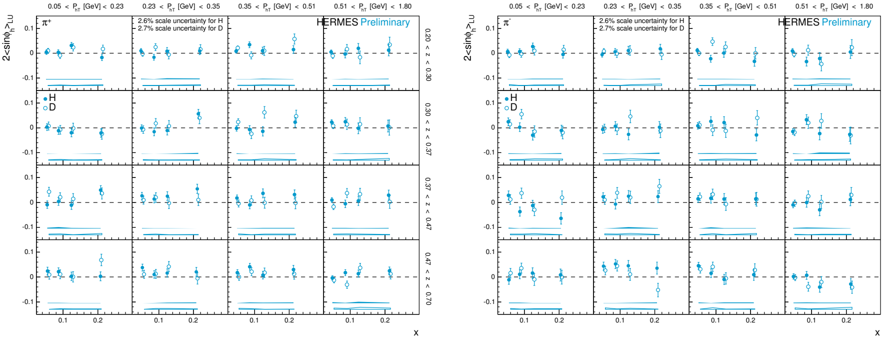
Hydrogen – 53 mln DIS events
Deuterium – 20 mln DIS events

1D and 3D analysis

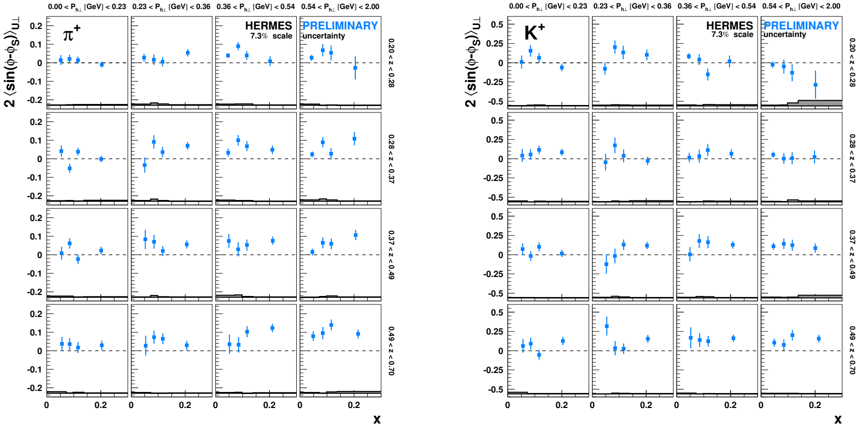
3D – kinematical range is separated in four x, four z, and four $P_{h\perp}$ bins.

The results are presented in 64 $(x, z, P_{h\perp})$ kinematical bins for each particle type.

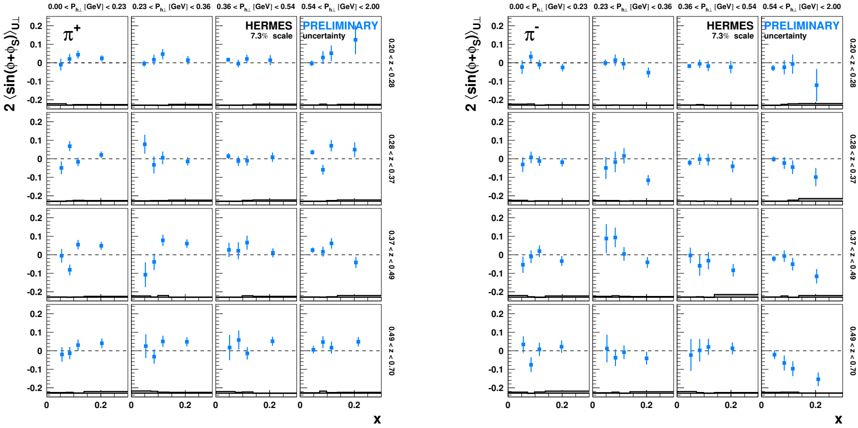
$A_{LU}^{sin(\phi)}$ vs. x, 3D



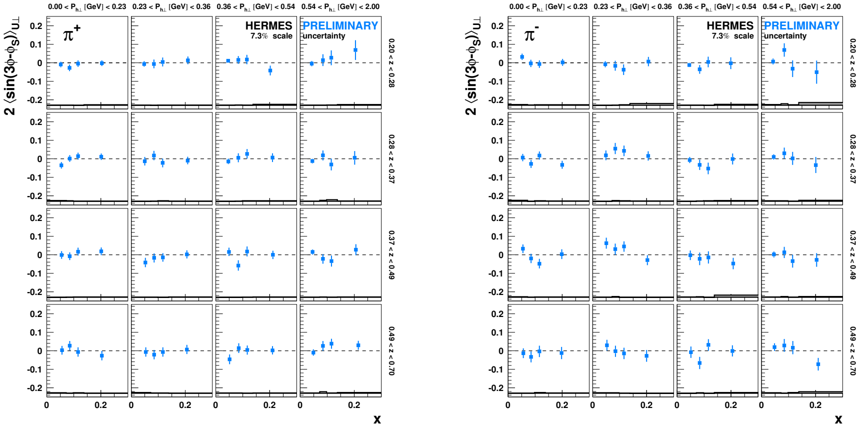
Sivers vs. x, 3D, π^+, K^+



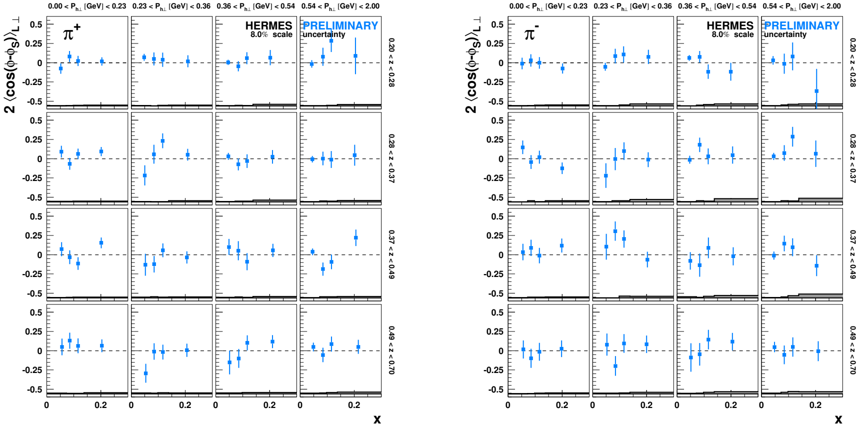
Collins vs. x, 3D, π^+, π^-



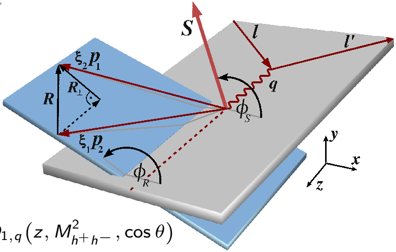
Pretzelosity vs. x, 3D, π^+, π^-



$A_{LT}^{cos(\phi-\phi_S)}$ vs. x, 3D, π^+, π^-



Dihadron Asymmetries



A.Bacchetta, M.Radici, Phys.Rev. D67(2003)094002; Phys.Rev. D69(2004)074026

$$\frac{d^7\,\sigma_{UU}}{d\cos\theta\; dM^2_{h^+h^-}\; d\phi_R\; dz\; dx\; dy\; d\phi_S} =$$

$$\frac{\alpha^2}{2\pi Q^2 y}\left(1-y+\frac{y^2}{2}\right)\times\sum_q e_q^2 f_1^q(x)\, D_{1,q}\big(z, M^2_{h^+h^-}, \cos\theta\big)$$

$$\frac{d^7\,\sigma_{UT}}{d\cos\theta\; dM^2_{h^+h^-}\; d\phi_R\; dz\; dx\; dy\; d\phi_S} =$$

$$\frac{\alpha^2}{2\pi Q^2 y}\, S_\perp\,(1-y)\times\sum_q e_q^2\,\frac{|\mathbf{p}_1-\mathbf{p}_2|}{2M_{h^+h^-}}\;\sin\theta\;\sin\phi_{RS}\; h_1^q(x)\, H^{\sphericalangle}_{1,q}\big(z, M^2_{h^+h^-}, \cos\theta\big)$$

$S_\perp$ – component of $\vec{S}$ perpendicular to the virtual photon direction.

θ – polar angle of positive hadron (in the dihadron rest frame) w.r.t. the dihadron boost axis.

$\phi_{RS} = \phi_R - \phi_{S'} = \phi_R + \phi_S - \pi$; ϕ_S – azimuthal angle of the initial nucleon spin;
$\phi_{S'}$ – azimuthal angle of the spin vector of the fragmenting quark with $\phi_{S'} = \pi - \phi_S$.

Dihadron Asymmetries

The number $N_{h^+h^-}$ of hadron pairs produced on a transversely polarised target can be written as

$$N_{h^+h^-}(x,\ y,\ z,\ M^2_{h^+h^-},\ \cos\theta,\ \phi_{RS})\ \propto \sigma_{UU}\left(1 + f(x,y)\, P_T\, D_{nn}(y)\, A_{UT}^{\sin\phi_{RS}} \sin\theta \sin\phi_{RS}\right)$$

$D_{nn}(y) = \frac{1-y}{1-y+y^2/2}$ the transverse-spin-transfer coefficient.

$f(x,y)$ is the target polarisation dilution factor

$$A_{UT}^{\sin\phi_{RS}} = \frac{|\mathbf{p}_1 - \mathbf{p}_2|}{2M_{h^+h^-}} \frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1,q}^{\sphericalangle}(z,\ M^2_{h^+h^-},\ \cos\theta)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1,q}(z,\ M^2_{h^+h^-},\ \cos\theta)}$$

Two-hadron fragmentation functions can be expanded in terms of Legendre polynomials in $\cos\theta$.
For the invariant mass range, typically covered by SIDIS experiments, only s and p partial waves contribute to the cross section:

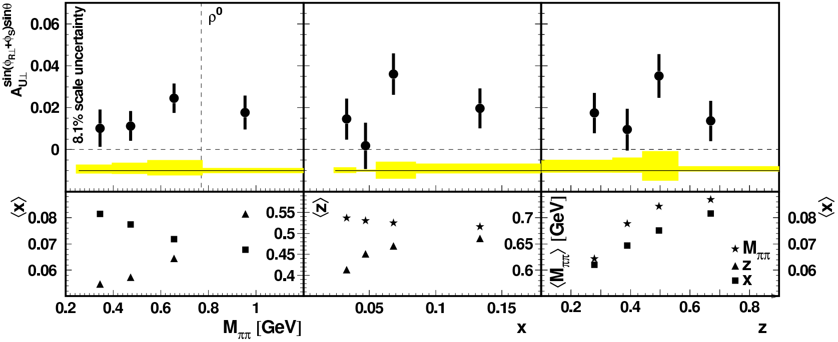
$$D_1(z, M^2_{hh}, \cos\theta) \simeq D_{1,q}(z, M^2_{hh}) + \cos\theta\, D_{1,q}^{sp}(z, M^2_{hh}) + \frac{1}{4}(3\cos^2\theta - 1)\, D_{1,q}^{pp}(z, M^2_{hh})$$

$$H_1^{\sphericalangle}(z, M^2_{hh}, \cos\theta) \simeq H_{1,q}^{\sphericalangle,sp}(z, M^2_{hh}) + \cos\theta H_{1,q}^{\sphericalangle,pp}(z, M^2_{hh})$$

Measurement of the σ_{UU} and σ_{UT} integrated over the θ, has the advantage that in the resulting cross sections the only FFs that appear are $D_{1,q}(z, M^2_{hh})$ and $H_{1,q}^{\sphericalangle,sp}(z, M^2_{hh})$.

Dihadron, HERMES

A.Airapetian et al., HERMES Coll., JHEP06 (2008) 017



First measurement of $A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}$.

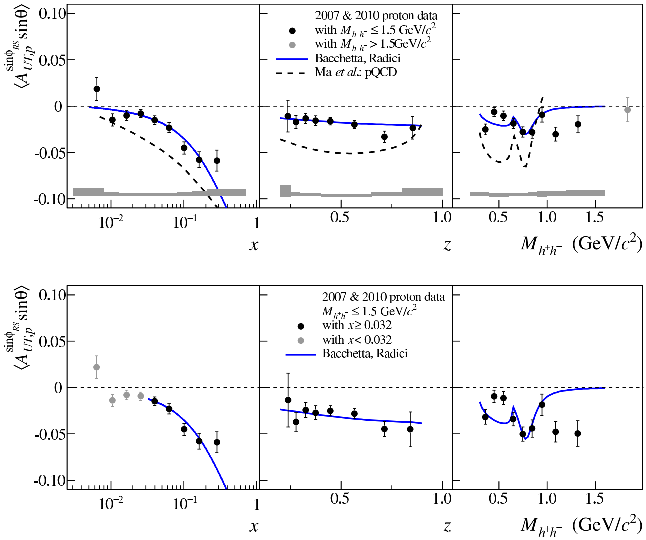
The asymmetry is non-zero – first evidence that dihadron fragmentation function $H_{1,q}^{\sphericalangle}$ iz non-zero.

The statistics is quite low.

HERMES – $A_{UT}^{\sin(\phi_R+\phi_S)\sin\theta}$ COMPASS – $A_{UT}^{\sin(\phi_R+\phi_S-\pi)\sin\theta}$

Dihadron, COMPASS

C.Adolph et al., COMPASS Coll., Phys.Lett. B736(2014)124



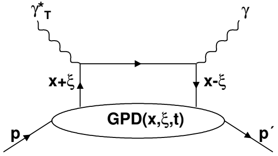
Exclusive Reactions

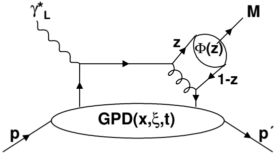
Motivation: Total Angular Momentum of Quarks

Ji's relation (1996):

$$J_{q,g} = \frac{1}{2} \int_{-1}^{1} dx \cdot x [H_{q,g}(x, \xi, 0) + E_{q,g}(x, \xi, 0)]$$

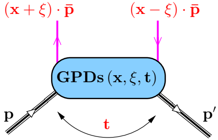
A measurement of Generalized Parton Distributions (GPD) H and E is required.
$\Longrightarrow$ Hard Exclusive reactions, e.g. DVCS, meson production





Motivation: Total Angular Momentum of Quarks

- twist-2 GPDs $H, E, \widetilde{H}, \widetilde{E}\,(x, \xi, t)$ for spin $1/2$ hadron



$x \pm \xi$: longitudinal momentum fractions of the partons,
ξ: fraction of the momentum transfer, $\xi \simeq \frac{x_B}{2-x_B}$,
t: invariant momentum transfer, $t \equiv (p - p')^2$.

GPDs ⇒ Form Factors:

$$\int_{-1}^{1} dx \cdot H_q(x, \xi, t) = F_1^q(t),$$
$$\int_{-1}^{1} dx \cdot E_q(x, \xi, t) = F_2^q(t),$$
$$\int_{-1}^{1} dx \cdot \tilde{H}_q(x, \xi, t) = G_A^q(t),$$
$$\int_{-1}^{1} dx \cdot \tilde{E}_q(x, \xi, t) = G_P^q(t).$$

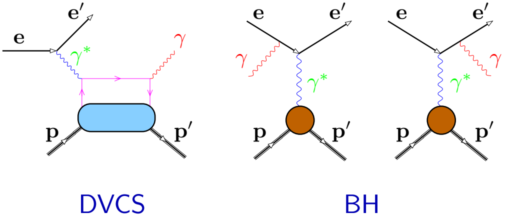
GPDs ⇒ PDFs :

$$H_q(x, 0, 0) = q(x)$$
$$\tilde{H}_q(x, 0, 0) = \Delta q(x)$$
$$H_g(x, 0, 0) = g(x)$$
$$\tilde{H}_g(x, 0, 0) = \Delta g(x).$$

DVCS depends on four GPDs $H, E, \widetilde{H}, \widetilde{E}$.
DVCS TTSA provides an access to GPD E without a kinematic suppression.

Exclusive production of vector mesons (ρ, ω, ϕ) depends on two GPDs, H and E.

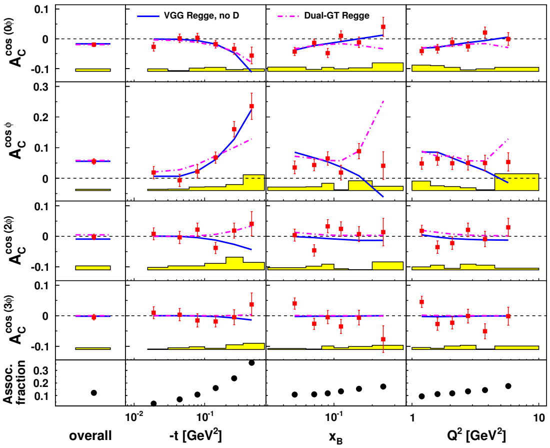
Deeply Virtual Compton Scattering



$$d\sigma \propto |\mathcal{T}_{BH}|^2 + |\mathcal{T}_{DVCS}|^2 + \underbrace{\mathcal{T}_{BH}\mathcal{T}^*_{DVCS} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}}_{\mathcal{I}}$$

- $\mathcal{T}_{BH}$ depends on known Dirac and Pauli FFs F_1, F_2
- $\mathcal{T}_{DVCS}$ depends on Compton FFs $\mathcal{H}$, $\mathcal{E}$, $\widetilde{\mathcal{H}}$, and $\widetilde{\mathcal{E}}$, which are convolutions of respective GPDs with hard-scattering kernels.
- At HERMES, $|\mathcal{T}_{BH}| \gg |\mathcal{T}_{DVCS}|$.
- $\mathcal{I}$ contains an information on the amplitudes and phases of the Compton FFs.

DVCS: Beam-Charge Asymmetry



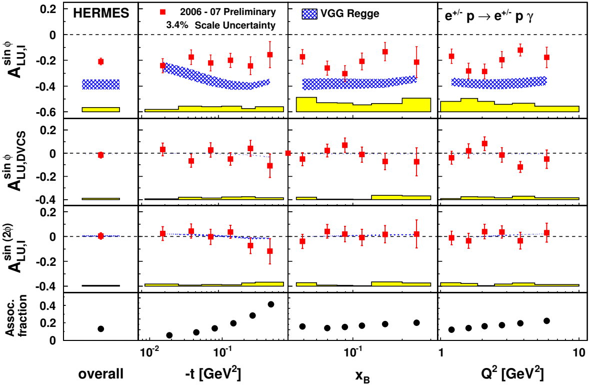
JHEP 11 (2009) 083

$A_C(\phi) \simeq \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi)$

- VGG model: Phys.Rev.D60(1999)094017, Prog.Nucl.Phys.47(2001)401
- Dual model: Phys.Rev.D74(2006)054027, Phys.Rev.D79(2009)017501

DVCS: Beam-Helicity Asymmetry

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

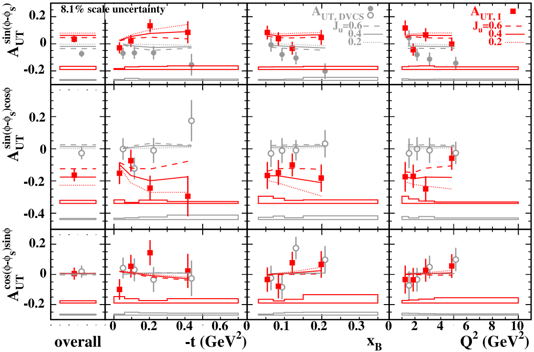


$\propto Im(\mathcal{H})$

- VGG overestimates the magnitude of the asymmetry amplitude

DVCS: Transverse-Target Spin Asymmetry

$$A_{UT}(\phi,\phi_S) = A_{UT}^{\sin(\phi-\phi_S)}\sin(\phi-\phi_S) + A_{UT}^{\sin(\phi-\phi_S)\cos(\phi)}\sin(\phi-\phi_S)\cos(\phi) + \ldots$$



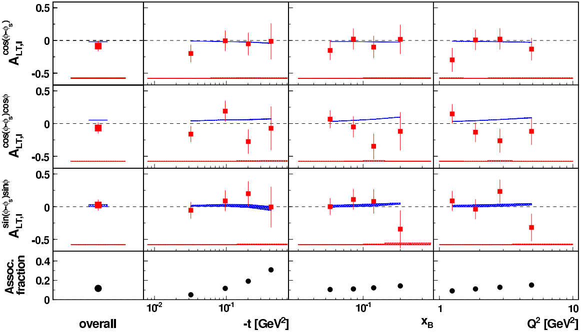
JHEP 06 (2008) 066

$\propto Im(F_2\mathcal{H} - F_1\mathcal{E})$

- $A_{UT}^{\sin(\phi-\phi_S)\cos(\phi)}$ sensitive to J_u, allows a model-dependent constraint

DVCS: Double-Spin Asymmetry

$$A_{LT}^{I}(\phi,\phi_S) = A_{LT,I}^{\sin(\phi-\phi_S)}\cos(\phi-\phi_S) + A_{LT,I}^{\cos(\phi-\phi_S)\cos(\phi)}\cos(\phi-\phi_S)\cos(\phi) + \ldots$$



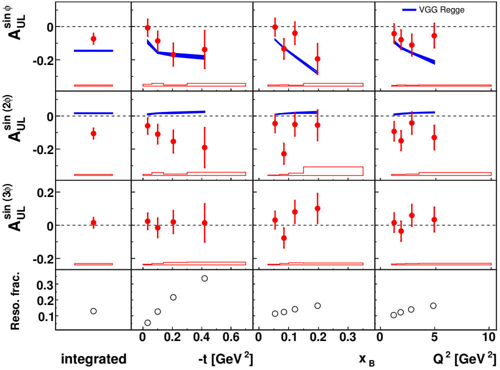
Phys.Lett.B704:15-23,2011

$\propto Re(F_2\mathcal{H} - (F_1 + \xi F_2)\mathcal{E})$

- Sensitivity to $J_u$suppressed by kinematic pre-factor

DVCS: LTSA, Proton

$A_{UL}(\phi) = \sum_{n=1}^{2} A_{UL}^{\sin(n\phi)} \sin(n\phi)$



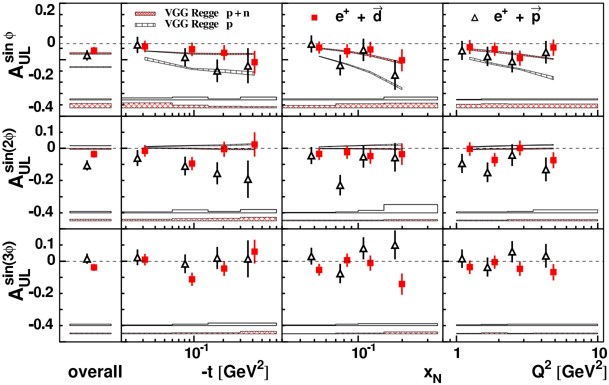
JHEP 06 (2010) 019

$\propto Im(\widetilde{\mathcal{H}})$

- Unexpectedly large $A_{UL}^{\sin(2\phi)}$ asymmetry amplitude

DVCS: LTSA, Deuteron

$$A_{UL}(\phi) = \sum_{n=1}^{2} A_{UL}^{\sin(n\phi)} \sin(n\phi)$$



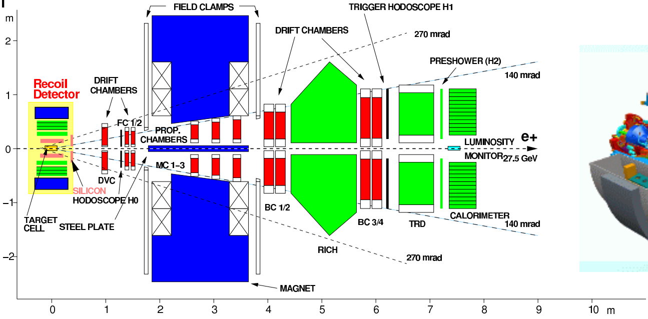
Nucl.Phys.B842:265,2011

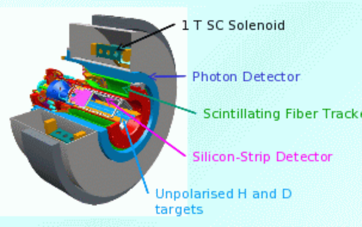
9 chiral-even GPDs in case of spin-1 target: $H_1, \ldots, H_5, \widetilde{H}_1, \ldots, \widetilde{H}_4$

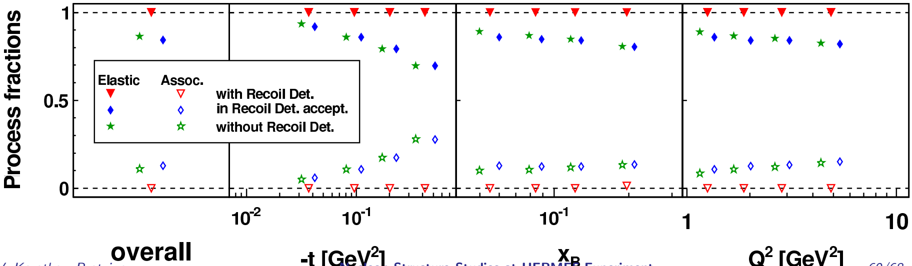
Search for coherent signature

- Results for deuteron are compatible with that for proton for leading amplitudes
- Different results for $A_{UL}^{\sin(2\phi)}$: compatible with zero for deuteron

DVCS: Recoil Detector

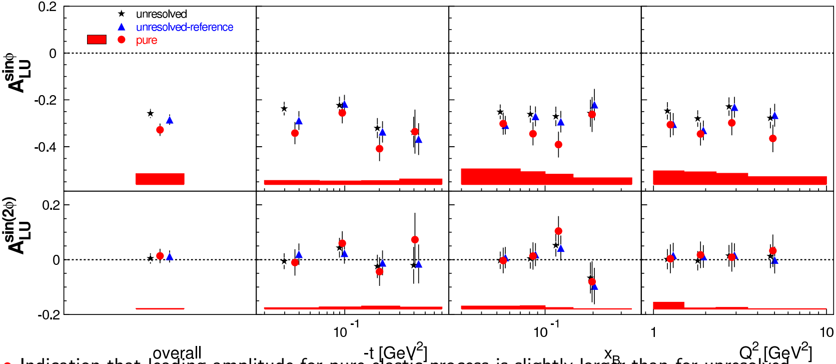






DVCS: A_{LU} with Recoil Detector

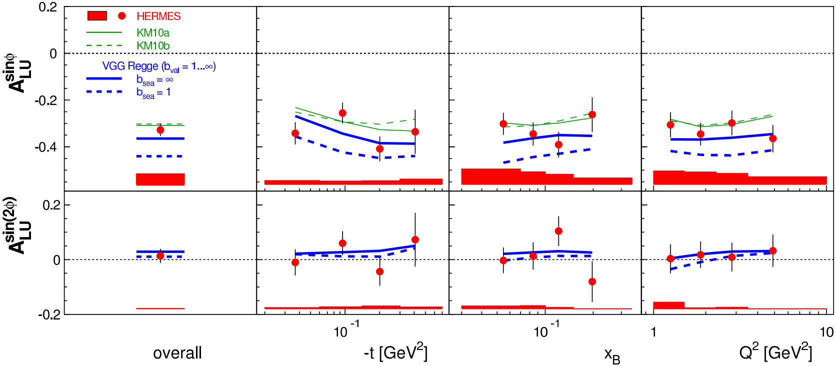
A.Airapetian et al, JHEP 1210 (2012) 042



- Indication that leading amplitude for pure elastic process is slightly larger than for unresolved signal (elastic + associated)

DVCS: A_{LU} with Recoil Detector

A.Airapetian et al, JHEP 1210 (2012) 042

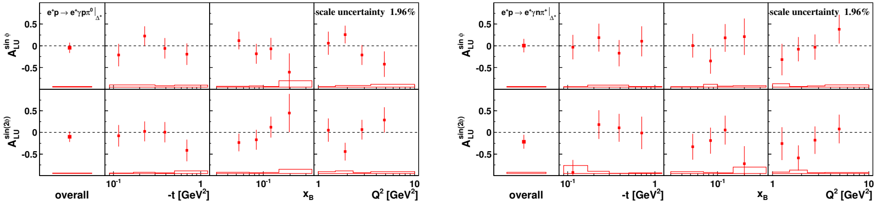


M.Vanderhaeghen, P.A.M.Guichon, M.Guidal, Phys.Rev. D60 (1999) 094017

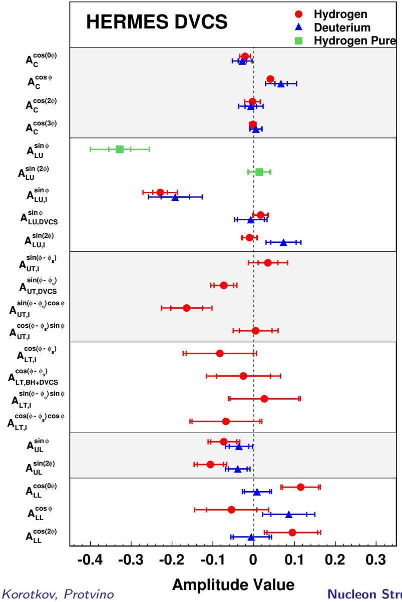
K. Kumericki, D. Mueller, Nucl.Phys. B841(2010)1.

DVCS: Recoil Detector $ep \to e\gamma\pi N$

JHEP 1401 (2014) 077



DVCS: HERMES Measurements Summary



- Beam charge asymmetry
- Beam helicity asymmetry

GPD *H* — PRL 87 (2001) 182001; PRD 75 (2007) 011103; JHEP 11 (2009) 083; Nucl.Phys. B 829 (2010) 1; JHEP 07 (2012) 032; JHEP 10 (2012) 042

- Transverse target-spin asymmetry

GPD *E* — JHEP 06 (2008) 066

- Transverse double-spin asymmetry

GPD *E* — Phys.Lett.B704(2011)15

- Longitudinal target-spin asymmetry

GPD $\tilde{H}$ — JHEP 06 (2010) 019; Nucl.Phys. B 842 (2011) 265

- Longitudinal double-spin asymmetry

GPD $\tilde{H}$ — Nucl.Phys. B 842 (2011) 265

Summary

• HERMES continues the study of the nucleon structire in SIDIS and in exclusive reactions

• Azimuthal asymmetries A_{LU}, A_{UT}, and A_{LT} in SIDIS production of (anti)protons have been evaluated.

• 3D analysis of the asymmetries in x, z, and $P_{h\perp}$ was carried out.
Each plot contains four x, four z, and four $P_{h\perp}$ bins, i.e. 64 bins in total.

• It is expected that the 3D asymmetries could be much more useful for a phenomenological analysis with a goal to constrain the TMDs. At the moment HERMES is able to present 18 3D plots for A_{LU} asymmetries, 90 3D plots for A_{UT} asymmetries, and 60 3D plots for A_{LT} asymmetries.

• HERMES measured the most complete set of the DVCS observables in one experiment.