Overview of recent HERMES results

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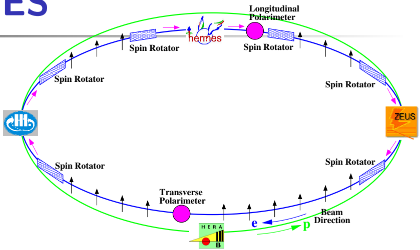
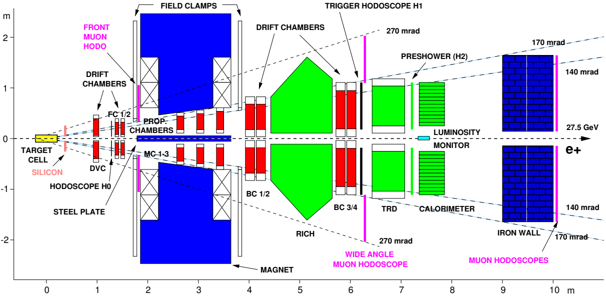
Outline

- Experiment HERMES
- Inclusive DIS
  - $F2(x)$
  - A_2, $g_2(x)$
- Semi-Inclusive DIS
  - Double-Spin Asymmetry A_1^h
  - Azimuthal Asymmetries in Unpolarized SIDIS
  - Azimuthal Asymmetries in Transversely polarized SIDIS
  - A_N asymmetry for the inclusive hadron production $lp^{\uparrow} \longrightarrow h + X$.
- Exclusive Reactions
  - DVCS
- Summary

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

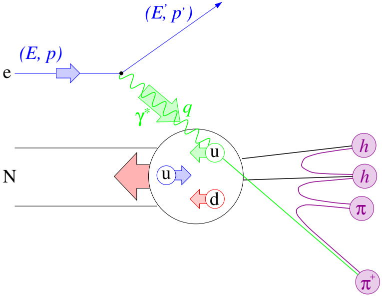
- e/h rejection: TRD, Preshower, Calorimeter, RICH
- magnetic spectrometer: $\Delta p/p < 2.5\%$ and $\Delta\theta < 0.6$ mrad

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

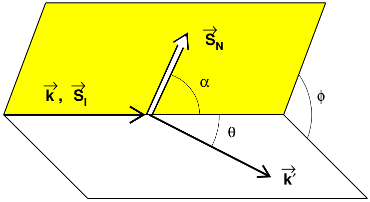
$W^2 > 10$ GeV^2, $0.1 < y < 0.85$, $Q^2 > 1$ GeV^2, $0.2 < z < 0.7$

$< Q^2 >= 2.4$ 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

$$\frac{d^3\sigma}{dxdyd\phi} \propto \frac{y}{2} F_1(x,Q^2) + \frac{1-y-\gamma^2 y^2/4}{2xy} F_2(x,Q^2)$$

$$-P_l P_T \cos\alpha \left[\left(1-\frac{y}{2}-\frac{\gamma^2 y^2}{4}\right) g_1(x,Q^2) - \frac{\gamma^2 y}{2} g_2(x,Q^2)\right]$$

$$+P_l P_T \sin\alpha\cos\phi\,\gamma\sqrt{1-y-\frac{\gamma^2 y^2}{4}}\left(\frac{y}{2} g_1(x,Q^2) + g_2(x,Q^2)\right)$$

$F_2(x)$, Proton, Deuteron

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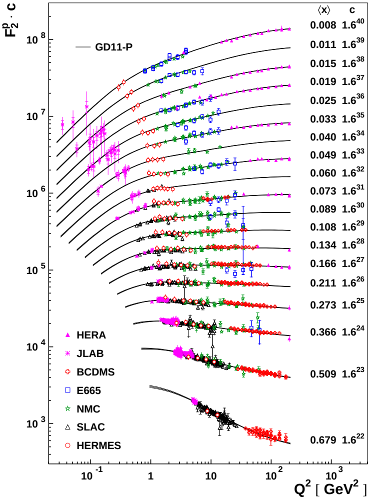
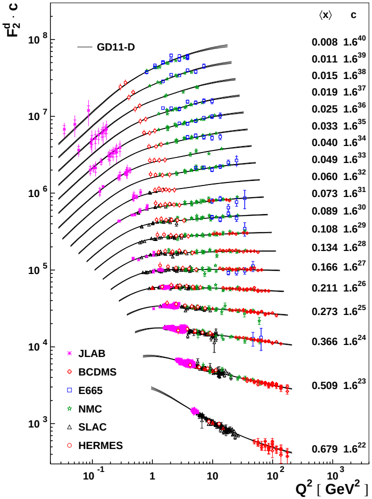




- New region covered by HERMES: $0.006 < x < 0.9$, $\quad 0.1\ \mathrm{GeV}^2 < Q^2 < 20\ \mathrm{GeV}^2$
- Agreement with world data in the overlap region

A_2, $g_2(x)$ *(Presented by A.Ivanilov)*

$e^{\leftrightarrow} + p^{\Updownarrow} \rightarrow e' + X$

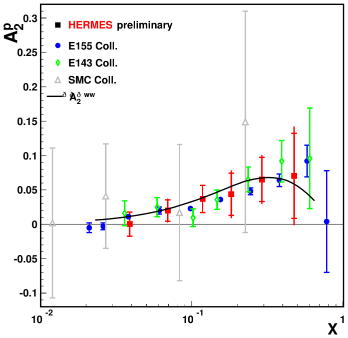
$\langle P_T \rangle \simeq 71\%$

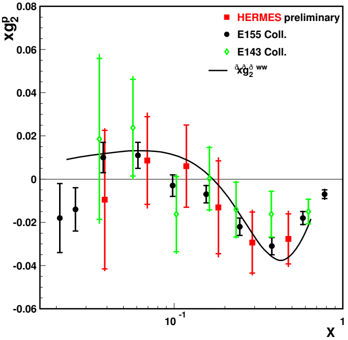
$\langle P_b \rangle \simeq 34\%$ (HERA Run 1 $\langle P_b \rangle \geq 50\%$)

$0.023 < x < 0.7$

$1 < Q^2 < 15 \quad GeV^2$

$W^2 > 4 \quad GeV^2$





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

Final publication: extended kinematic region; evaluation of $d_2 = 3 \int_0^1 x^2 \bar{g}_2(x)\, dx$;

evaluation of the BC integral $\int g_2(x, Q^2)\, dx$ in the measured region.

Semi-Inclusive DIS

SIDIS: Double-Spin Asymmetry A_1^h

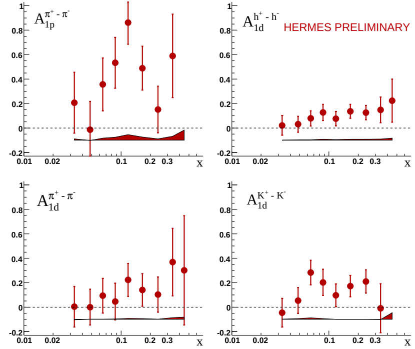
Charge conjugation symmetry for FF: $D_q^{h^+} = D_{\bar{q}}^{h-}$

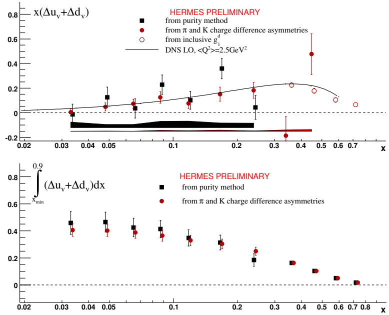
$$A_1^{h^+-h^-} = \frac{(\sigma_{\uparrow\downarrow}^{h^+} - \sigma_{\uparrow\downarrow}^{h^-}) - (\sigma_{\uparrow\uparrow}^{h^+} - \sigma_{\uparrow\uparrow}^{h^-})}{(\sigma_{\uparrow\downarrow}^{h^+} - \sigma_{\uparrow\downarrow}^{h^-}) + (\sigma_{\uparrow\uparrow}^{h^+} - \sigma_{\uparrow\uparrow}^{h^-})}$$

$$A_{1,p}^{\pi^+-\pi^-} = \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v}$$

For isoscalar target and $\Delta s = \Delta\bar{s}$:

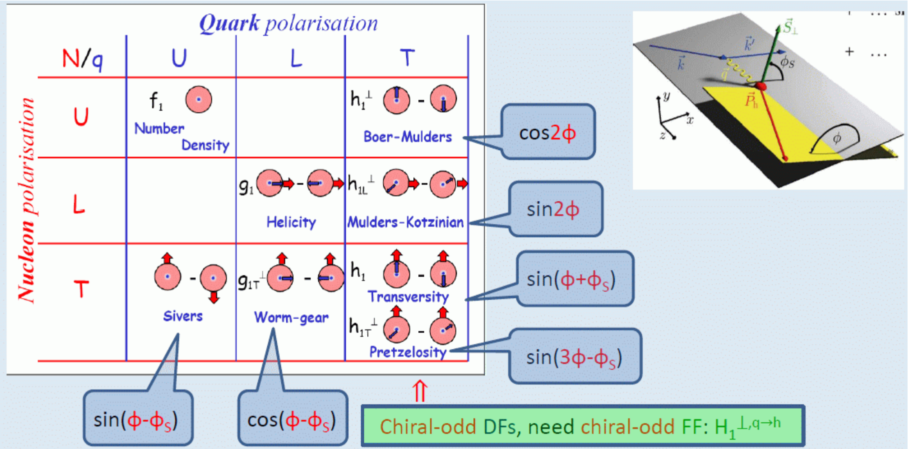
$$A_{1,d}^{\pi^+-\pi^-} = A_{1,d}^{K^+-K^-} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}$$



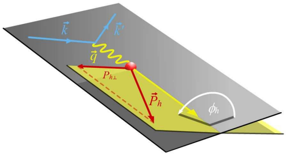


SIDIS: Leading-twist TMDs

- Nucleon structure described in leading-twist by 8 transverse-momentum dependent quark distributions (TMDs)
- HERMES has access to all of them through specific azimuthal modulations (ϕ, ϕ_S) of the cross-section due to the polarized beam and target.



Azimuthal Asymmetries in Unpolarized SIDIS



$$\frac{d^5\sigma_{UU}}{dx\,dy\,dz\,dP^2_{h\perp}\,d\phi_h} \propto \Big\{\mathcal{I}\big[R\, f_1 D_1\big] + \cos 2\phi_h \mathcal{I}\big[S\, h_1^{\perp} H_1^{\perp}\big] + \cos\phi_h \frac{2M}{Q}\mathcal{I}\big[T\, h_1^{\perp} H_1^{\perp} + U\, f_1 D_1 + \ldots\big]\Big\}$$

$\mathcal{I}\big[wfD\big]$ - convolution integral over initial (P_T^2) and final (k_T^2) quark transverse momenta.

$\cos 2\phi_h$ - solely due to Boer-Mulders $\otimes$ Collins term at twist-2. Cahn effect (a kinematic effect due to non-zero transverse quark momentum) contributes at twist-4.

$\cos\phi_h$ - due to the contributions from the Boer-Mulders and the Cahn effects at twist-3.

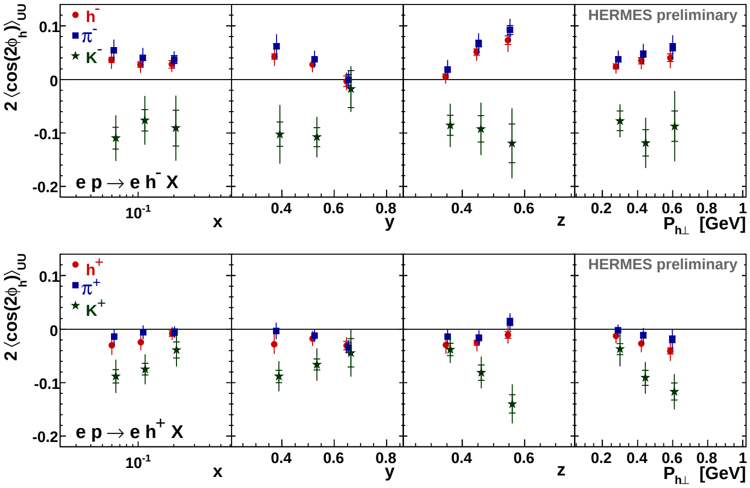
$$\langle \cos n\phi \rangle_{UU} = \frac{\int_0^{2\pi} \cos n\phi \, d\sigma_{UU}\, d\phi}{\int_0^{2\pi} d\sigma_{UU}\, d\phi}$$

To account for the experimental smearing and the QED radiative effects, the 5D unfolding procedure was applied.

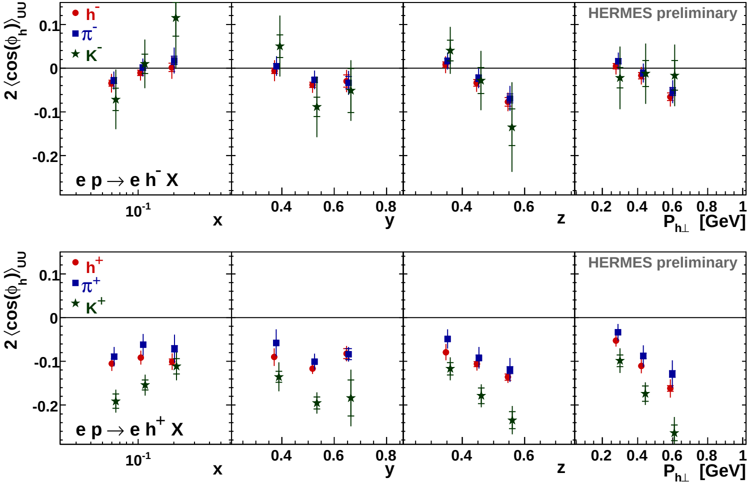
Finally, the 4D cosine moments in bins of x, y, z, and $P_{h\perp}$ were obtained.

Azimuthal Asymmetries in Unpolarized SIDIS

$$\sigma_{UU}^{cos2\phi} \propto h_1^{\perp,q} \otimes H_1^{\perp,q\to h}$$



Azimuthal Asymmetries in Unpolarized SIDIS



$$\propto \cos\phi_h \frac{2M}{Q} \mathcal{I}\left[T\, h_1^{\perp} H_1^{\perp} + U\, f_1 D_1 + \ldots \right]$$

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

SIDIS: $\sigma_{UT}^{sin(\phi-\phi_S)}$, $\sigma_{UT}^{sin(\phi+\phi_S)}$

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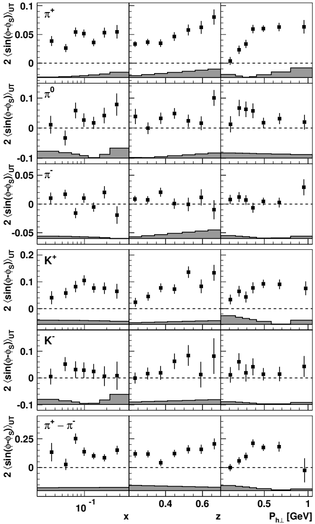

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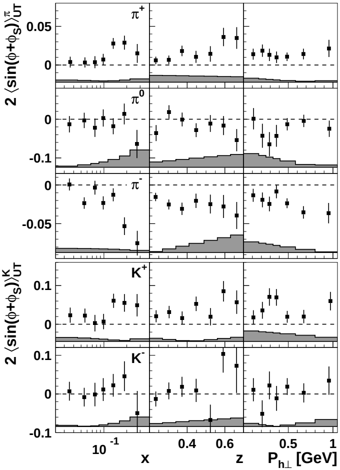
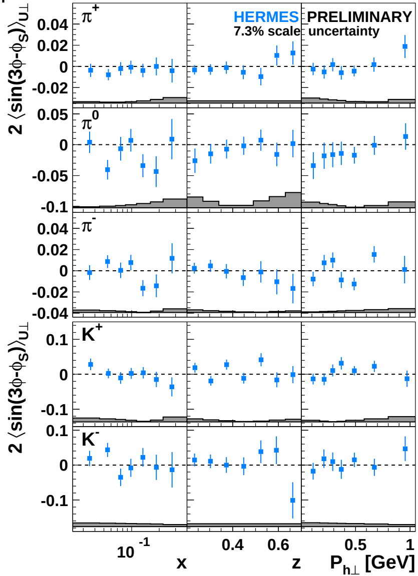
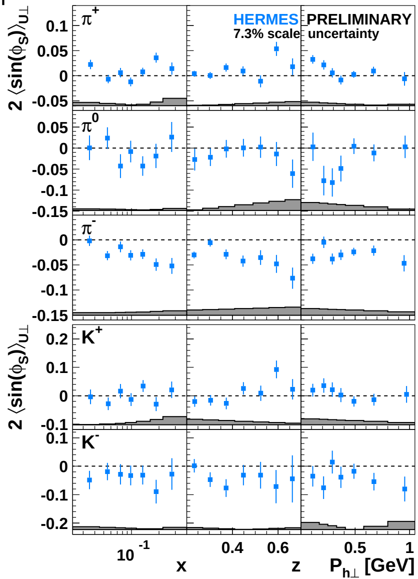


SIDIS: $\sigma_{UT}^{sin(3\phi-\phi_S)}$



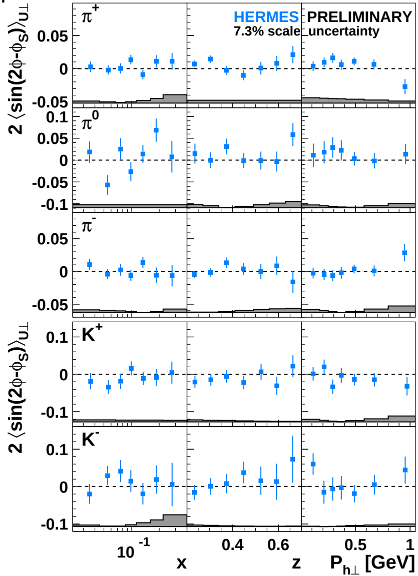
Consistent with zero.

SIDIS: $\sigma_{UT}^{sin(\phi_S)}$



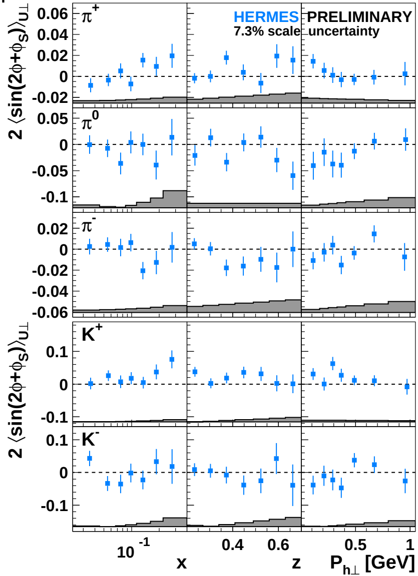
Negative for π^-
Positive for π^+
π^0, $K^{+,-}$ consistent with zero.

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



Consistent with zero.

SIDIS: $\sigma_{UT}^{sin(2\phi+\phi_S)}$



Consistent with zero.

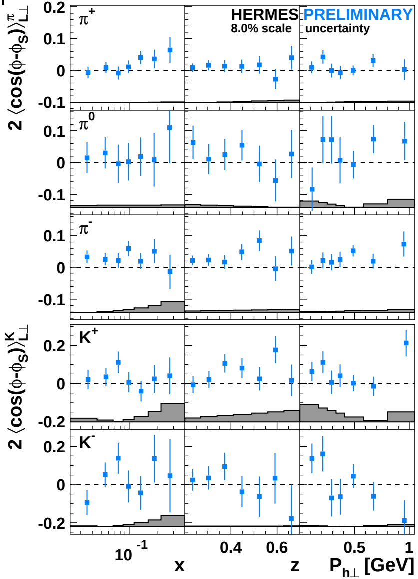
SIDIS: Extraction of the amplitudes, LT

$$F(2 < \sin(\phi+\phi_S) >^h_{UT},\ 2 < \sin(\phi-\phi_S) >^h_{UT},\ \ldots,\ \lambda_l,\ S_\perp,\ \phi,\ \phi_S) =$$

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

$< \cos(\phi-\phi_S) >^h_{LT}$ — signal for the worm-gear DF $g_{1T}^{\perp,q}$

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



$$\sigma_{LT}^{cos(\phi-\phi_S)} \propto g_{1T}^{\perp,q} \otimes D_1^{q\to h}$$

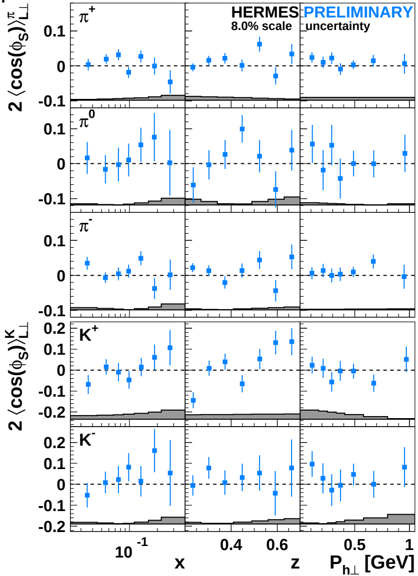
Worm-gear function: longitudinally polarized quarks in a transversely polarized nucleon

Positive amplitude for π^-

Hint of a positive signal for π^+ and K^+

Consistent with zero for π^0 and K^-

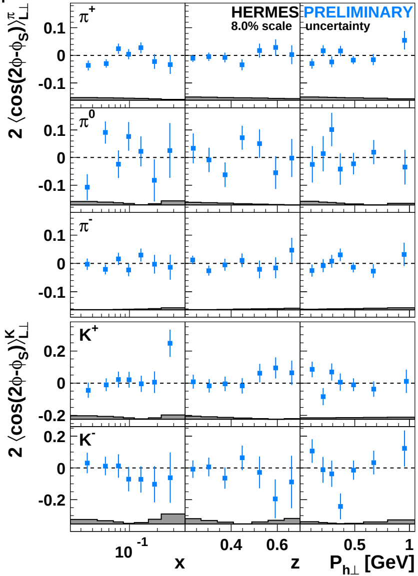
SIDIS: $\sigma_{LT}^{\cos(\phi_S)}$



Compatible with zero.

The amplitude involve a mixture of either twist-2 DF and twist-3 FF or twist-3 DF and twist-2 FF.

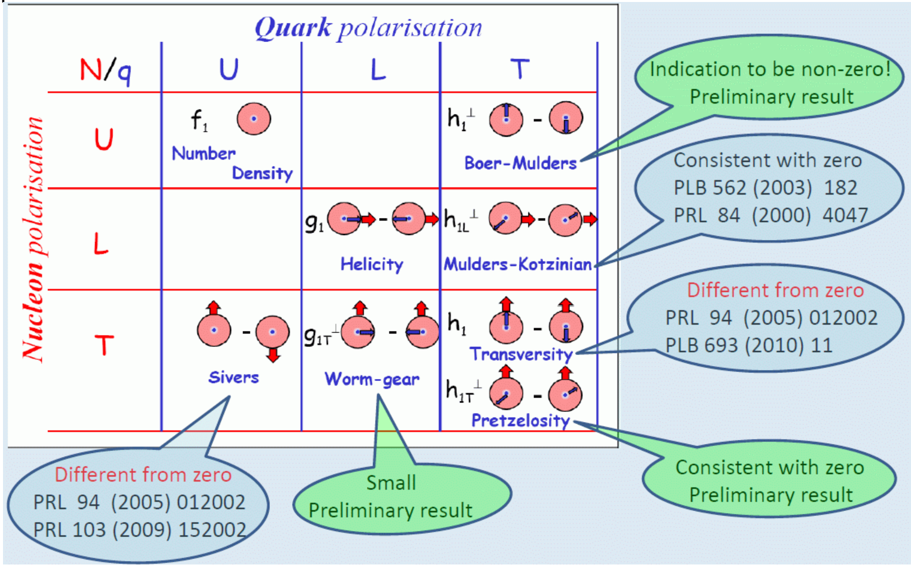
SIDIS: $\sigma_{LT}^{cos(2\phi - \phi_S)}$



Compatible with zero.

The amplitude involve a mixture of either twist-2 DF and twist-3 FF or twist-3 DF and twist-2 FF.

SIDIS: Leading-twist TMDs. Summary



Inclusive Hadrons

Non-zero left-right asymmetries A_N were observed in $p^{\uparrow}p \longrightarrow hX$.

A_N increased in magnitude with increasing of x_F.

It was suggested to investigate such asymmetry in inclusive electroproduction of hadrons $lp^{\uparrow} \longrightarrow hX$. (M.Anselmino et al., 2009)

This would allow a test of the validity of the TMD factorization for processes with only one large scale (p_T).

HERMES obtained first data on such single-spin asymmetries.

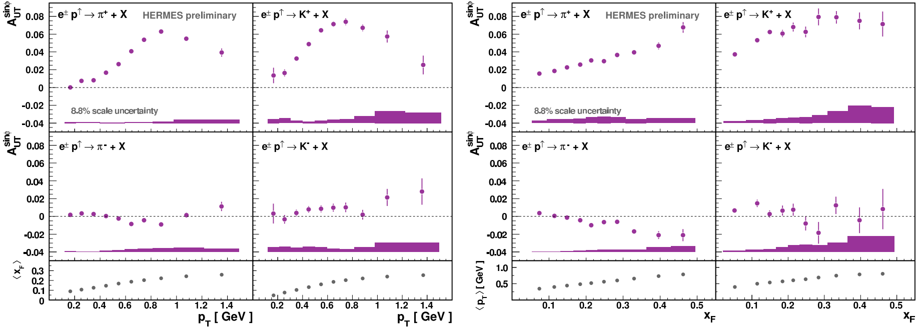
The following hadron variables were used:
p_T^h and $x_F \simeq 2p_L/\sqrt{s}$.

The asymmetry was defined as:

$$A_{UT}(p_T, x_F, \phi) = \frac{N^{\uparrow}/L_p^{\uparrow} - N^{\downarrow}/L_p^{\downarrow}}{N^{\uparrow}/L_p^{\uparrow} + N^{\downarrow}/L_p^{\downarrow}}$$

$A_{UT}^{\sin\phi}$ amplitudes were extracted with a fit of the form $p_1 \sin\phi + p_2$ to the measured asymmetry.

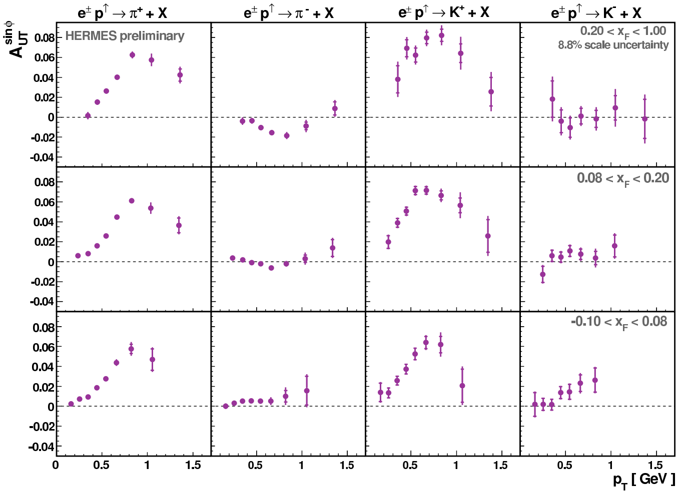
Inclusive Hadrons



Variables p_T^h and x_F are correlated in the HERMES acceptance.

One need study 2D dependencies.

Inclusive Hadrons



The data are in a good qualitive agreement with predictions of M.Anselmino et al. The P_T dependence is very similar to thr HERMES results for the Sivers asymmetry measured in SIDIS.

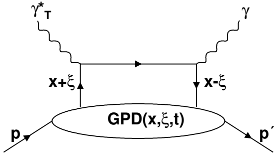
Exclusive Reactions

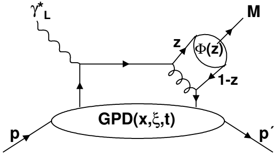
Motivation: Total Angular Momentum of Quarks

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

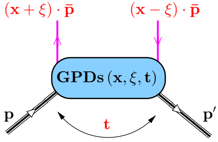




Motivation: Total Angular Momentum of Quarks

- 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:

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

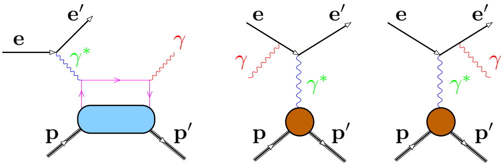
GPDs ⇒ PDFs :

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

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

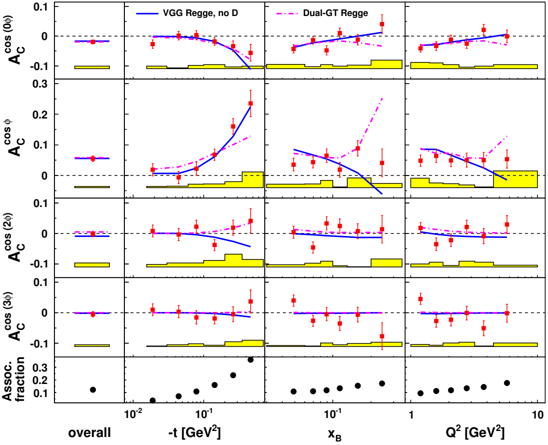


DVCS BH

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

- $\mathcal{T}_{BH}$ 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



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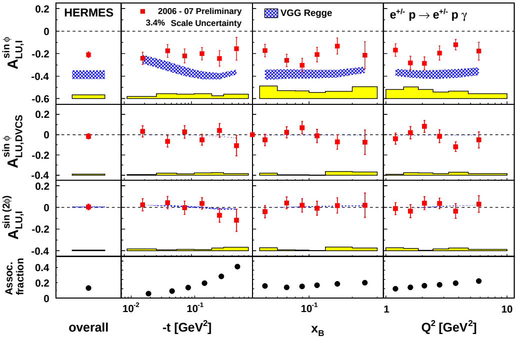
$A_C(\phi) \simeq \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi)$

- 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

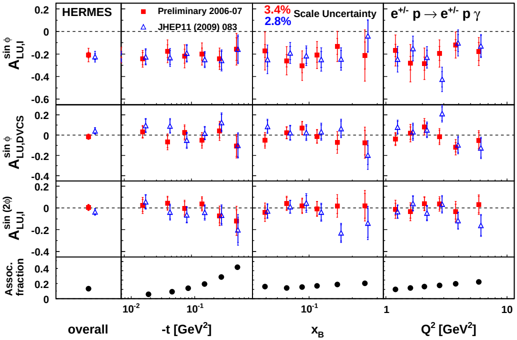
$$A_{LU,I}(\phi) \simeq \sum_{n=1}^{2} A_{LU,I}^{\sin(n\phi)} \sin(n\phi)$$



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

- VGG overestimates the magnitude of the asymmetry amplitude

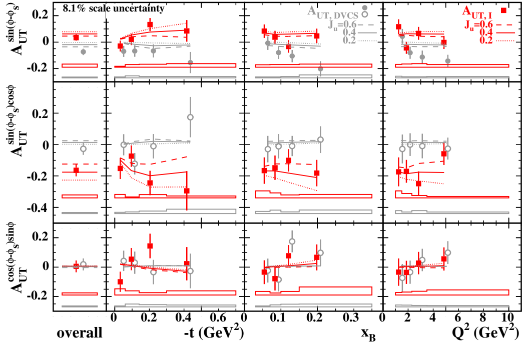
DVCS: Beam-Helicity Asymmetry (Comparison)



- New results are in agreement with published (JHEP 11 (2009) 083)

DVCS: Transverse-Target Spin Asymmetry

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

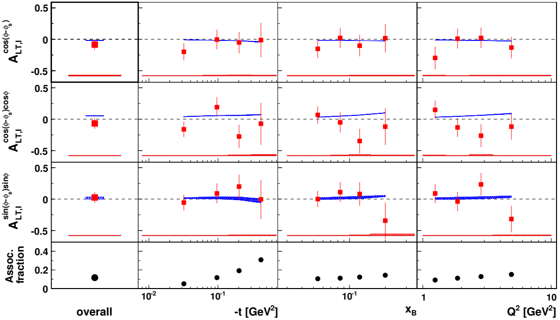


JHEP 06 (2008) 066
$\propto Im(F_2\mathcal{H} - F_1\mathcal{E})$

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

DVCS: Double-Spin Asymmetry

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



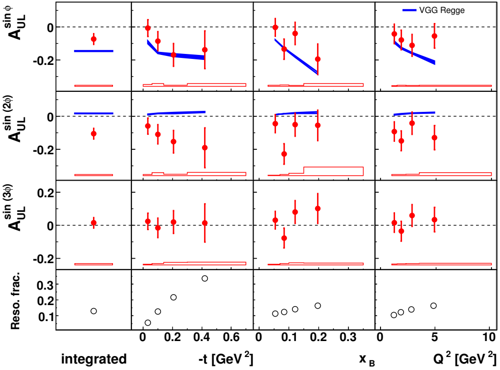
Phys.Lett.B704:15-23,2011

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

- Sensitivity to J_u suppressed by kinematic pre-factor

DVCS: LTSA, Proton

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

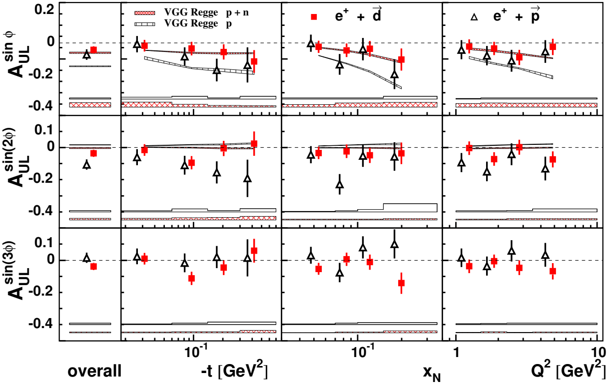


JHEP 06 (2010) 019
$\propto Im(\widetilde{\mathcal{H}})$

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

DVCS: LTSA, Deuteron

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



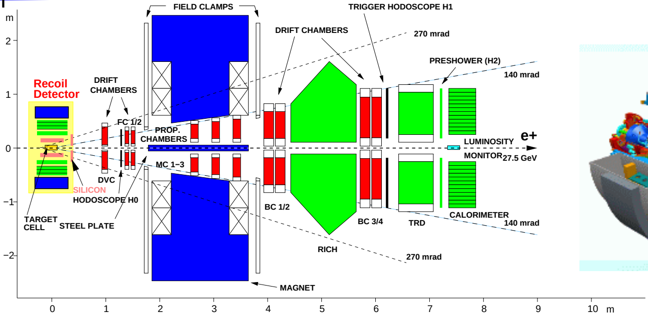
Nucl.Phys.B842:265,2011

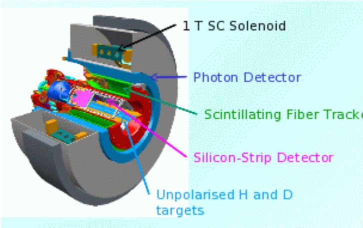
9 chiral-even GPDs in case of spin-1 target: $H_1, ..., H_5, \widetilde{H_1}, ..., \widetilde{H_4}$

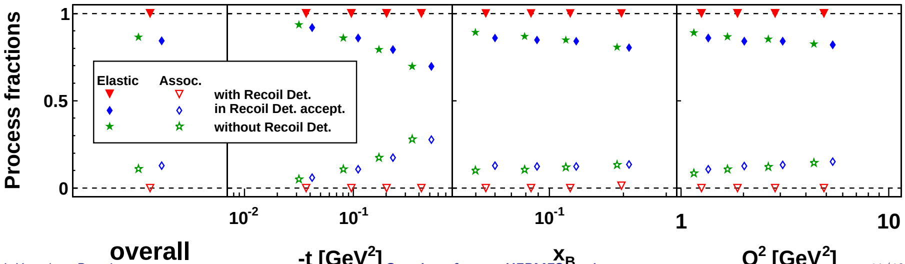
Search for coherent signature

- 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

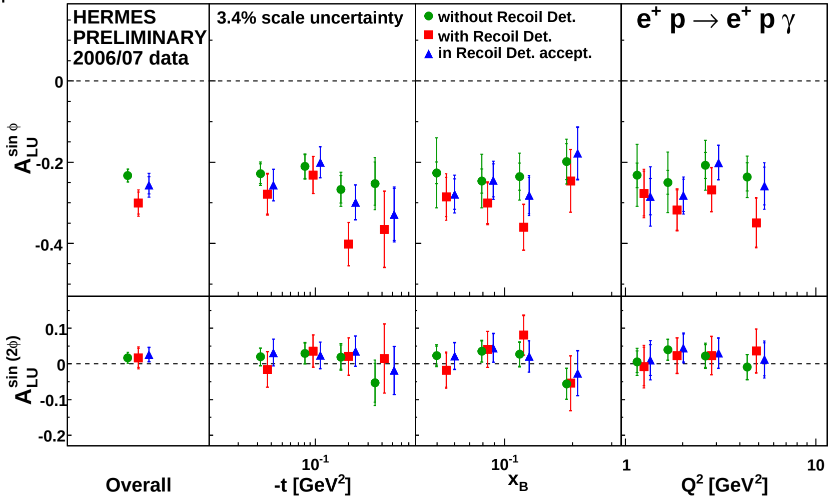
DVCS: Recoil Detector





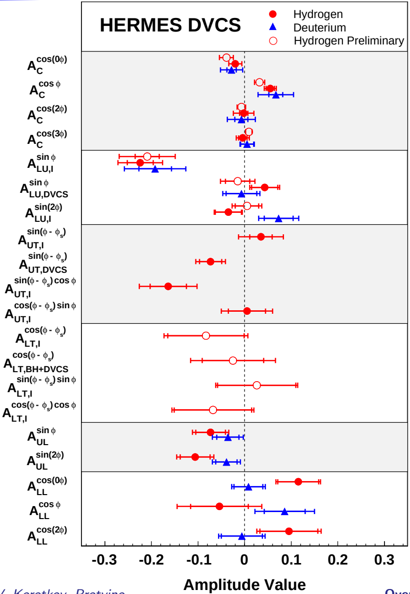


DVCS: Recoil Detector



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

DVCS: Summary



- Beam charge asymmetry
  GPD H PRL 87 (2001) 182001
  PRD 75 (2007) 011103
  JHEP 11 (2009) 083
  Nucl.Phys. B 829 (2010) 1
- Beam helicity asymmetry
  GPD H JHEP 11 (2009) 083
- Transverse target-spin asymmetry
  GPD E JHEP 06 (2008) 066
- Transverse double-spin asymmetry
  GPD E arXiv:1106.2990
- 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

• HERA was switched off more than 4 years ago, HERMES community still produces new interesting results.
• Structure functions $F_2(x, Q^2)$ and $g_2(x)$ are measured in new kinematic region.
• The Fourier amplitudes of various azimuthal asymmetries for pion/kaon production on the unpolarized and transversely polarized targets are extracted.
• Collins and Sivers amplitudes are well studied and the data have been published
• Contributions from other leading twist DF are investigated.
• Boer-Mulders DF is likely to be non-zero.
• Contributon from the pretzelosity DF $h_{1T}^{\perp,q}$ is compatible with zero.
• Amplitude $\sigma_{LT}^{cos(\phi-\phi_S)}$ is found to be positive for π^-. Hint of a positive signal for π^+ and K^+.
• Amplitude $\sigma_{UT}^{sin(\phi_S)}$ is found to be non-zero for π^- and π^+.
• First results were obtained for hadron asymmetry A_N in process $lp^\uparrow \longrightarrow h + X$.
• HERMES has obtained the most complete data set of various DVCS asymmetries.
• First results on the DVCS asymmetries using data from the recoil detector are obtained. Its using allows essentially increase the purity of the DVCS sample.