Overview of the HERMES Results

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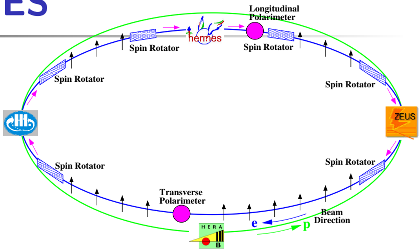
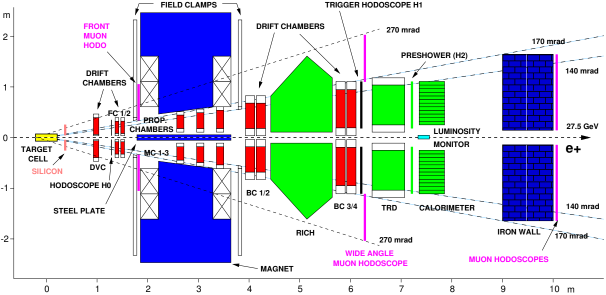
Outline

- Experiment HERMES
- Inclusive DIS
  - $F2(x)$
  - $g_1(x)$
  - A_2, $g_2(x)$
- Semi-Inclusive DIS
  - Azimuthal Asymmetries in Transversely polarized SIDIS
- Exclusive Reactions
  - DVCS
  - DVCS with Recoil Detector
- 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

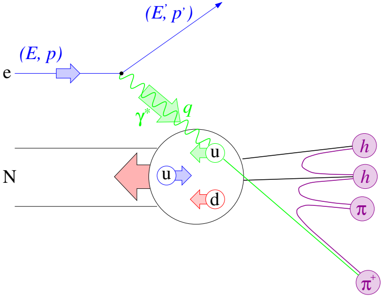
- e/h rejection: TRD, Preshower, Calorimeter, RICH
- magnetic spectrometer: $\Delta p/p < 2.5\%$ and $\Delta\theta < 0.6$ mrad

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

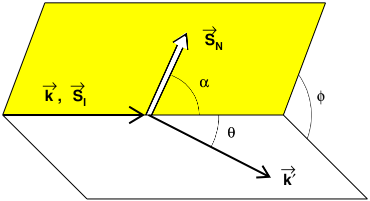
$W^2 > 10$ GeV^2, $0.1 < y < 0.85$, $Q^2 > 1$ GeV^2, $0.2 < z < 0.7$

$< Q^2 >= 2.4$ 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

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

$F_2(x)$, Proton, Deuteron

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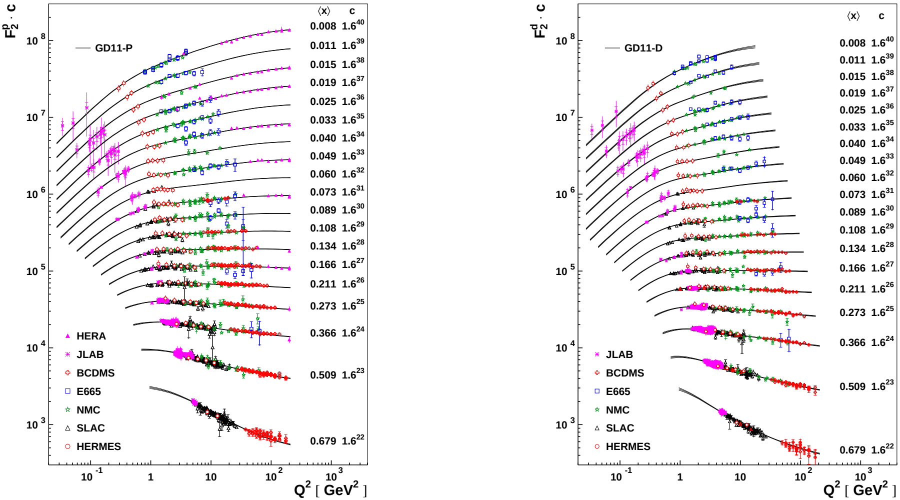
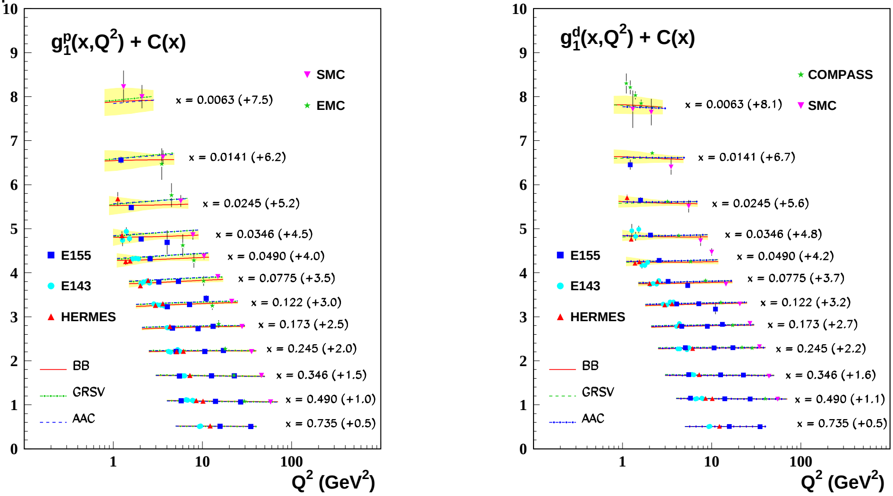


- New region covered by HERMES: $0.006 < x < 0.9, \quad 0.1\ \text{GeV}^2 < Q^2 < 20\ \text{GeV}^2$
- Agreement with world data in the overlap region

$g_1(x)$



Phys.Rev. D75 (2007) 012007

A_2, $g_2(x)$

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

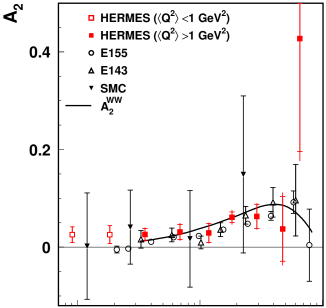
$\langle P_T \rangle \simeq 71\%$

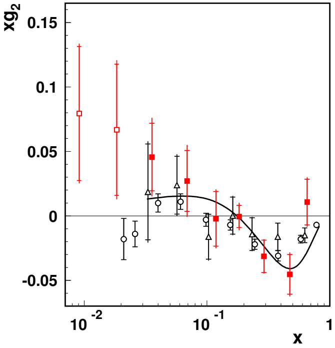
$\langle P_b \rangle \simeq 34\%$ (HERA Run 1 $\langle P_b \rangle \geq 50\%$)

$0.023 < x < 0.7$

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

$W^2 > 4$ GeV^2



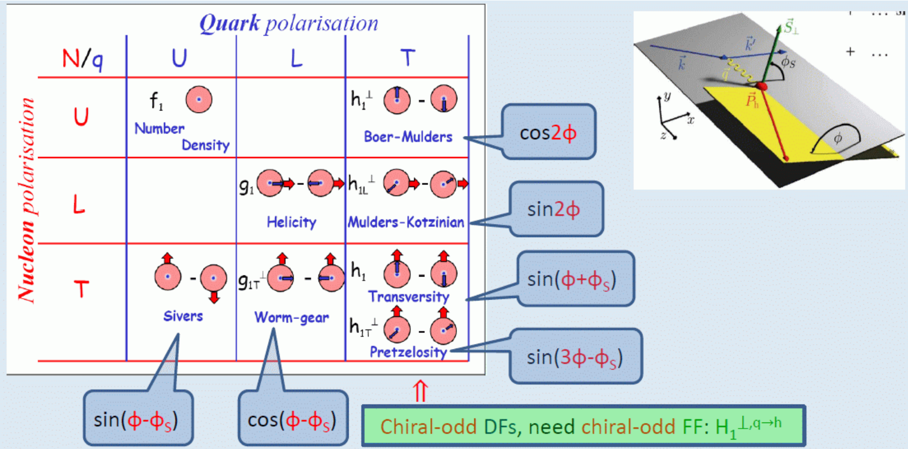


$g_2(x,Q^2) = g_2^{WW}(x,Q^2) + \bar{g}_2(x,Q^2)$, $\quad g_2^{WW}(x,Q^2) = -g_1(x,Q^2) + \int_x^1 \frac{dy}{y} g_1(x,Q^2)$

Eur.Phys.J. C72 (2012) 1921

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.



SIDIS: Extraction of the amplitudes, *UT*

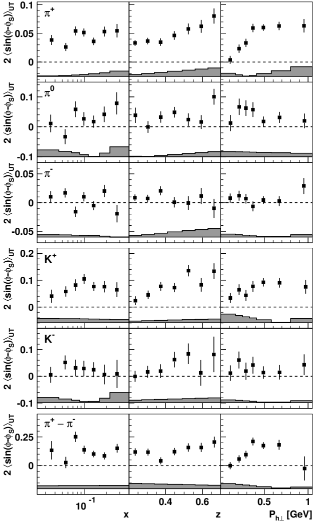
For each kinematic bin, the probability density function for hadron type h:
$F(2 < \sin(\phi+\phi_S) >^h_{UT},\ 2 < \sin(\phi-\phi_S) >^h_{UT},\ \ldots,\ S_\perp,\ \phi,\ \phi_S) =$

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

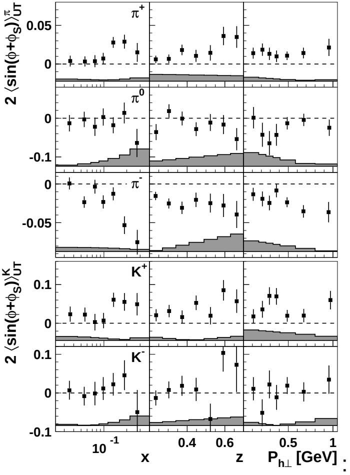
$< \sin(\phi+\phi_S) >^h_{UT}$ — signal for the Collins FF $H_1^\perp$ and the transversity DF h_1 :
$< \sin(\phi-\phi_S) >^h_{UT}$ — signal for the Sivers DF $f_{1T}^{\perp,q}$
$< \sin(3\phi-\phi_S) >^h_{UT}$ — signal for the pretzelosity DF $h_{1T}^{\perp,q}$

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

PRL 103 (2009) 152002



Phys.Lett. B693 (2010) 11



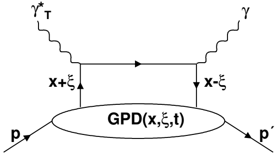
Exclusive Reactions

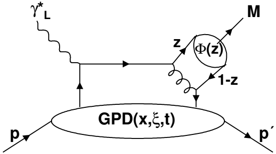
Motivation: Total Angular Momentum of Quarks

Ji's relation (1996):

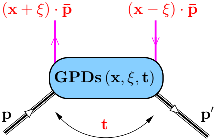
$$J_{q,g} = \frac{1}{2}\int_{-1}^{1} dx \cdot x[H_{q,g}(x,\xi,0) + E_{q,g}(x,\xi,0)]$$

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





- 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:

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

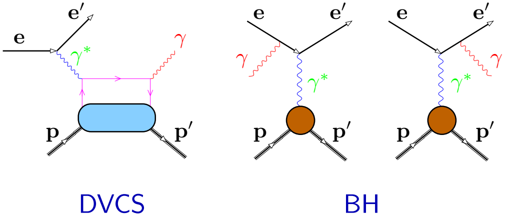
GPDs ⇒ PDFs :

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

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.

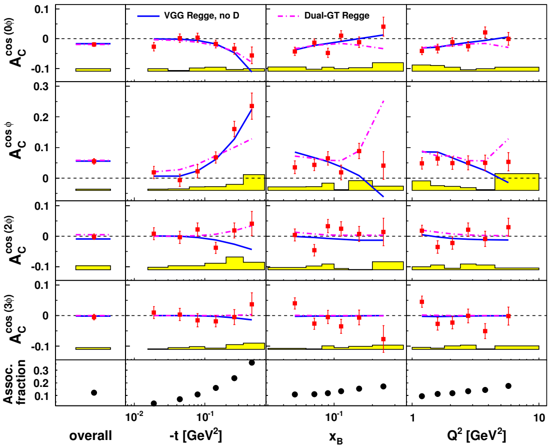
Deeply Virtual Compton Scattering



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

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



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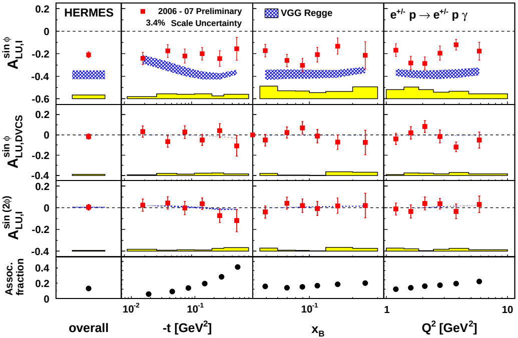
$A_C(\phi) \simeq \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi)$

- 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

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

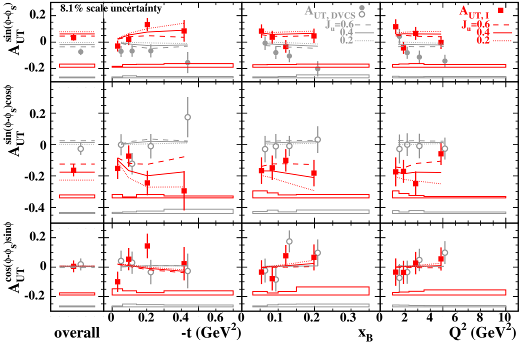


$\propto Im(\mathcal{H})$

- VGG overestimates the magnitude of the asymmetry amplitude

DVCS: Transverse-Target Spin Asymmetry

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

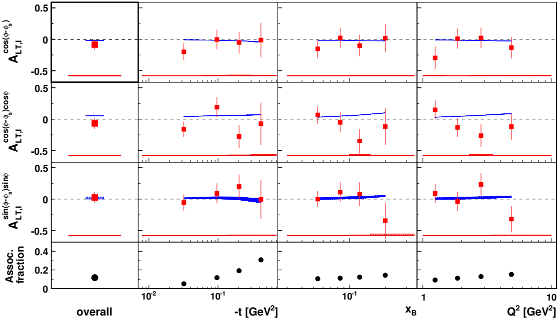


JHEP 06 (2008) 066
$\propto Im(F_2\mathcal{H} - F_1\mathcal{E})$

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

DVCS: Double-Spin Asymmetry

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



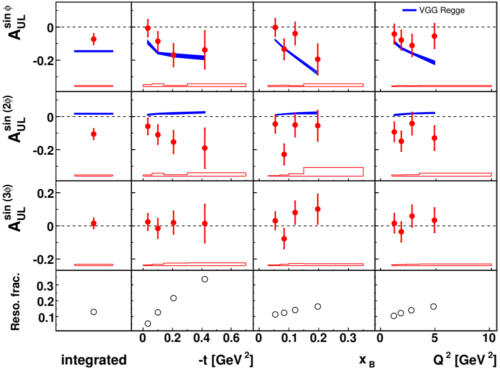
Phys.Lett.B704:15-23,2011

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

- Sensitivity to J_u suppressed by kinematic pre-factor

DVCS: LTSA, Proton

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



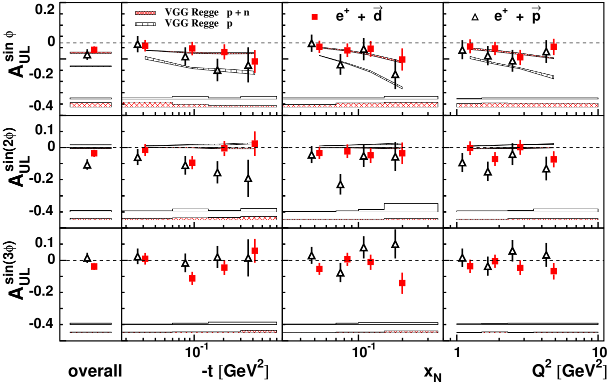
JHEP 06 (2010) 019

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

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

DVCS: LTSA, Deuteron

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



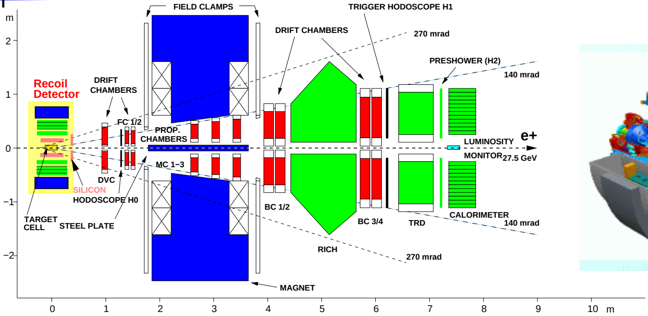
Nucl.Phys.B842:265,2011

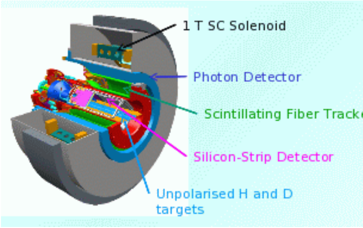
9 chiral-even GPDs in case of spin-1 target: $H_1, \ldots, H_5,\ \widetilde{H}_1, \ldots, \widetilde{H}_4$

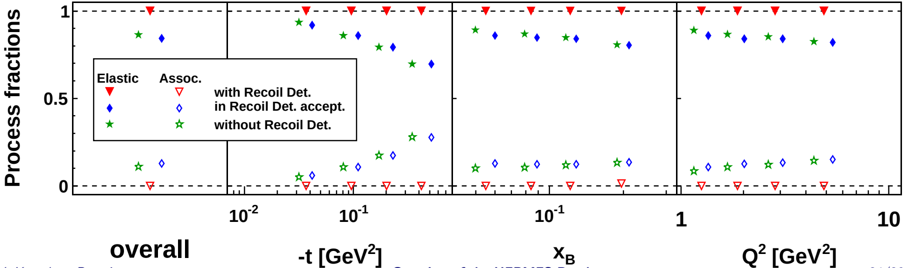
Search for coherent signature

- 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

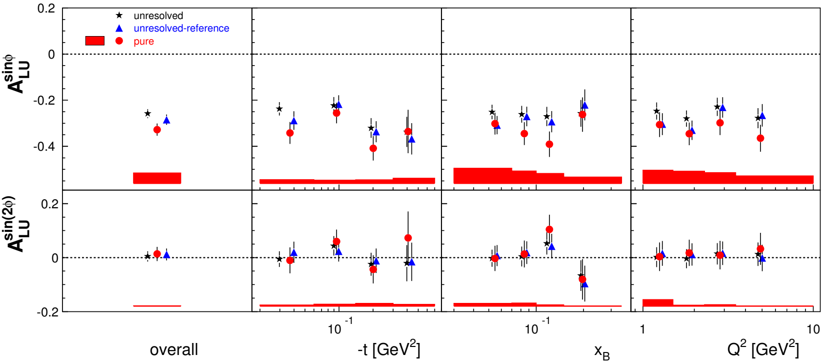
DVCS: Recoil Detector





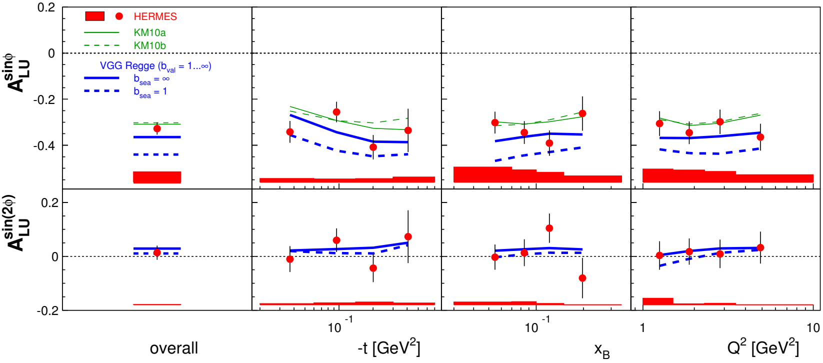


DVCS: Recoil Detector



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

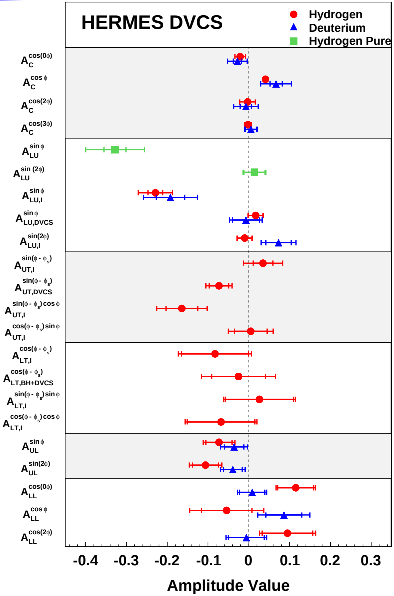
DVCS: Recoil Detector



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

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

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
  JHEP 07 (2012) 032
  JHEP 10 (2012) 042
- 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 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

• HERA was switched off more than 7 years ago, HERMES community still produces new interesting results.

• DIS: Structure functions $F_2(x, Q^2)$, $g_1(x, Q^2)$ and $g_2(x)$ are measured in new kinematic region.

• SIDIS: The Fourier amplitudes of various azimuthal asymmetries for pion/kaon production on the unpolarized and transversely polarized targets are extracted.

• Data on the Collins asymmetry were used by various theory groups to extract the transversity distribution.

• 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.

• Many other topics (hyperon production, quark hadronization inside nucleus, ...) are not covered in this talk.