Exclusive Reactions at HERMES

or

The Spin Budget of the Proton

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Exp. Status on Parton Distribution Functions

Improvement over last 6 years:

- spin-independent & helicity PDFs:
  - COMPASS: $\Delta g$
  - HERMES: $\Delta u, \Delta d, \Delta s, \Delta g$
  - JLab: $\Delta u, \Delta d$ at large $x$

- transversity & friends:
  - HERMES: Sivers function
  - BELLE: Collins (fragm.) function

- Generalized Parton Distributions:
  - CLAS, HERMES, (H1/ZEUS):
    - first look on $H, \tilde{H}, E$

$\Rightarrow$ much more to come ...
3-dimensional Picture of the Proton

Nucleon momentum in Infinite Momentum Frame: \((p_{\gamma^*} + p_{\text{nucl}})_z \to \infty\)

- Form factor
- Parton density
- Generalized parton distribution at \(\eta=0\)

Nucleon’s transv. charge distribution given by 2-dim. Fourier transform of **Form Factor**:

\[ \Rightarrow \text{Parton’s transverse localization } b_{\perp} \]

Probability density to find partons of given long. mom. fraction \(x\) at resol. scale \(1/Q^2\)

\[ \Rightarrow \text{Parton’s longitudinal momentum distribution function (PDF) } f(x) \]

**GPDs** probe simultaneously transverse localization \(b_{\perp}\) for a given longitudinal momentum fraction \(x\)

2nd moment by Ji relation:

\[ J_{q,g} = \frac{1}{2} \lim_{t \to 0} \int x \, dx \left[ H_{q,g}(x, \xi, t) + E_{q,g}(x, \xi, t) \right] \]
Proton Spin Budget in a Nutshell

NO unique and gauge-invariant decomposition of the nucleon spin:

(A) ‘GPD-based’: \( \frac{1}{2} = J_q + J_g = \frac{1}{2} \Delta \Sigma + L_q + \hat{\Delta} g + L_g \)

- Total angular momenta of quarks \( J_q \) and gluons \( J_g \) are gauge-invariant and calculable in lattice gauge theory
- Intrinsic spin contribution and orbital angular momentum are gauge inv. for quarks \( \frac{1}{2} \Delta \Sigma \) and \( L_q \), but not for gluons \( \hat{\Delta} g \) and \( L_g \)
- Probabilistic interpretation only for \( \frac{1}{2} \Delta \Sigma \) (well measured)
- \( J_q \) accessible through exclusive lepton nucleon scattering
- \( J_g \) very difficult to access experimentally

(B) Light-cone gauge: \( \frac{1}{2} = J_q + J_g = \frac{1}{2} \Delta \Sigma + \mathcal{L}_q + \Delta g + \mathcal{L}_g \)

- All 4 terms have a probabilistic interpretation
- \( \Delta g \) is gauge invariant (being measured)

⇒ Results from both decompositions must not be mixed, as
\( \mathcal{L}_q \neq L_q, \Delta g \neq \hat{\Delta} g, \mathcal{L}_g \neq L_g, \) even \( J_g \neq J_g \)!
**DIS: Kinematics, Cross Sections, Asymmetry**

**Virtual-photon kinematics:**

\[ Q^2 = -q^2 \quad \nu = E - E' \]

Fraction of nucleon momentum carried by struck quark:

\[ x = \frac{Q^2}{2M\nu} \]

Fraction of virtual-photon energy carried by produced hadron \( h \):

\[ z = \frac{E_h}{\nu} \]

**Hadron transverse momentum:**

\[ P_{h\perp} \]

- **Unpolarized cross section:**

\[ \sigma_{UU} \equiv \frac{1}{2}(\sigma \leftarrow\rightarrow + \sigma \rightarrow\rightarrow) \]

- **Cross section (helicity) difference:**

\[ \sigma_{LL} \equiv \frac{1}{2}(\sigma \leftarrow\rightarrow - \sigma \rightarrow\rightarrow) \]

- **Double-spin asymmetry:**

\[ A_{||} \equiv \frac{\sigma_{LL}}{\sigma_{UU}} \sim \frac{g_1}{F_1} \quad \text{(neglecting small } g_2 \text{ contribution)} \]

- **Measured asymmetry:**

\[ A_{||} = \frac{1}{\langle P_T \rangle \langle P_B \rangle} \left( \frac{N}{L} \leftarrow\rightarrow - \frac{N}{L} \rightarrow\rightarrow \right) \left( \frac{N}{L} \leftarrow\rightarrow + \frac{N}{L} \rightarrow\rightarrow \right) \]
Direct determination of quark spin contribution \( \Delta \Sigma \)

Most precise \( g_1^d \) result: Hermes inclusive data [PRD75(2007)012007,hep-ex/0609039]:

\[
\Delta \Sigma = 0.330 \pm 0.011_{\text{theor.}} \pm 0.025_{\text{exp.}} \pm 0.028_{\text{evol.}}
\]

where ‘exp.’ includes stat., syst. and parameterization uncertainties

**Method:**

- NNLO leading twist analysis in \( \overline{\text{MS}} \) scheme
- assume \( \text{SU}_3 \) flavor symmetry in hyperon decay
- observe saturation of \( \Gamma_1 = \int dx \ g_1^d(x) \) for \( x < 0.04 \)
- assume no significant contribution of small-\( x \) region

**Data for \( Q^2 > 1 \text{ GeV}^2 \):** evaluate \( \Gamma_1^d(Q^2 = 5 \text{ GeV}^2) = 0.021 \int^{0.9} dx \ g_1^d(x) \)
Next-to-leading Order QCD Fits

Results by AAC [PRD74(2006)014015,hep-ph/0603213]: NLO in $\alpha_s$, $\overline{MS}$ scheme

Assumptions:
- Flavor-symmetric $\Delta q_{sea}$
- Integrals of $\Delta q^v_{u,d}$ fixed by weak decay constants $F$ and $D$

Input experimental data:
- $A_{1,p,d}^p$ from COMPASS,JLAB,HERMES
- $A_{u,d}^{\pi^0}$ from PHENIX

Results at $Q^2 = 1$ GeV$^2$:
- $\Delta\Sigma = 0.25 \pm 0.10$
- $\Delta G = 0.47 \pm 1.08$ (DIS alone)
- $\Delta G = 0.31 \pm 0.32$ (DIS+PHENIX)


<table>
<thead>
<tr>
<th>$\Delta g$</th>
<th>$\Delta \Sigma$</th>
<th>$\Delta s$</th>
<th>$\Delta g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; 0$</td>
<td>$0.207 \pm 0.040$</td>
<td>$-0.063 \pm 0.005$</td>
<td>$0.129 \pm 0.166$</td>
</tr>
<tr>
<td>$&lt; 0$</td>
<td>$0.243 \pm 0.065$</td>
<td>$-0.057 \pm 0.010$</td>
<td>$-0.200 \pm 0.414$</td>
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Determination of Gluon Contribution to Nucleon Spin

- Quasi-real photoprod. of high-$p_t$ hadron pairs or single hadrons: $\langle Q^2 \rangle \approx 0.1$ GeV$^2$
- Sensitivity through $\gamma^*g$ ‘direct’ hard scattering or ‘resolved-photon’ process

left graphs: direct processes; right graphs: resolved-photon processes [COMPASS analysis]

Extraction heavily relies on PYTHIA simulation (LO only !)

Hard scale $\mu^2 \approx 3$ GeV$^2$
only ‘loosely’ correlated with $x_g \left( \langle x_g \rangle \approx 0.1 \right)$

COMPASS: Open-charm production ($\gamma^*g \rightarrow c\bar{c}$) and hadron pairs
HERMES: Single high-$p_t$ hadrons. Pairs in old analysis (all $Q^2$, $\langle x_g \rangle \approx 0.17$

[PRL84 (2000) 2584] $\frac{\Delta g}{g} = 0.41 \pm 0.18_{\text{stat}} \pm 0.03_{\text{sys-exp (\pm unknown sys-Model)}}$

RHIC: $A_{LL}$ in inclusive direct $\gamma$ & $\pi^0$ production, inclusive jet production
Most precise results on $\frac{\Delta g}{g}(x)$:

**COMPASS high-$p_t$ hadron pairs:**

- $Q^2 < 1 \text{ GeV}^2$ ($\langle x \rangle \approx 0.085$): $\frac{\Delta g}{g} = 0.016 \pm 0.058_{\text{stat}} \pm 0.055_{\text{syst}}$
  [PLB 612,154 (2005)]

- $Q^2 > 1 \text{ GeV}^2$ ($\langle x_g \rangle \approx 0.13$) [prel.]: $\frac{\Delta g}{g} = 0.06 \pm 0.31_{\text{stat}} \pm 0.06_{\text{syst}}$

- Open charm ($\langle x_g \rangle \approx 0.15$) [prel.]: $\frac{\Delta g}{g} = -0.57 \pm 0.31_{\text{stat}}$

**HERMES high-$p_t$ single hadrons** [prel.]:

- $Q^2 \approx 0$; ($\langle x_g \rangle \approx 0.22$): $\frac{\Delta g}{g} = 0.071 \pm 0.034_{\text{stat}} \pm 0.010_{\text{syst}} - \text{exp} \pm 0.127_{0.105_{\text{sys - Models}}}$

**PHENIX:** Confidence limits for fits with different $\frac{\Delta g}{g}$ assumptions
Pure gas target: polarized H, D; unpolarized H, D, N, Ne, Kr, Xe

Forward spectrometer: 40 mrad $\leq \Theta \leq 220$ mrad

Tracking planes: $\mathcal{O}(50)$ per spectrometer half: $\delta p/p \sim 2\%$, $\delta \Theta \leq 1$ mrad

PID for $e^{\pm}$: TRD, Preshower, Calorimeter

PID for $\pi^{\pm}, K^{\pm}, p$: Dual-rad. Ring-imaging Cherenkov ($2 < p < 15$ GeV)

Recoil particle detection for data $\geq 2006$
Same final state in **DVCS** and **Bethe-Heitler** $\Rightarrow$ **Interference!**

$$d\sigma(eN \rightarrow eN\gamma) \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH}T_{DVCS}^* + T_{BH}^*T_{DVCS}$$

- $T_{BH}$ is parameterized in terms of Dirac and Pauli Form Factors $F_1, F_2$, calculable in QED.

- $T_{DVCS}$ is parameterized in terms of Compton form factors $\mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \tilde{\mathcal{E}}$ (which are convolutions of resp. GPDs $H, E, \tilde{H}, \tilde{E}$)

- (Certain Parts of) interference term can be filtered out by forming certain cross section differences (or asymmetries)

$\Rightarrow$ GPDs $H, E, \tilde{H}, \tilde{E}$ *indirectly* accessible via interference term $\mathcal{I}$
Azimuthal Asymmetries in DVCS

DVCS–Bethe-Heitler Interference term $\mathcal{I}$ induces azimuthal asymmetries in cross-section:

- **Beam-charge asymmetry** $A_C(\phi)$ [BCA]:
  $$d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto \text{Re}[F_1 \mathcal{H}] \cdot \cos \phi$$

- **Beam-spin asymmetry** $A_{LU}(\phi)$ [BSA]:
  $$d\sigma(\vec{e}, \phi) - d\sigma(\bar{\vec{e}}, \phi) \propto \text{Im}[F_1 \mathcal{H}] \cdot \sin \phi$$

- **Long. target-spin asymmetry** $A_{UL}(\phi)$:
  $$d\sigma(\vec{P}, \phi) - d\sigma(\bar{\vec{P}}, \phi) \propto \text{Im}[F_1 \bar{\mathcal{H}}] \cdot \sin \phi$$

- **Transverse target-spin asymmetry** $A_{UT}(\phi, \phi_S)$ [TTSA]:
  $$d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi) \propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}] \cdot \sin (\phi - \phi_S) \cos \phi$$
  $$+ \text{Im}[F_2 \bar{\mathcal{H}} - F_1 \xi \bar{\mathcal{E}}] \cdot \cos (\phi - \phi_S) \sin \phi$$

($F_1, F_2$ are the Dirac and Pauli elastic nucleon form factors)
Kinematic Coverage of DVCS Experiments

Fixed-target kinematics

Fixed-target experiments:
\[ x > 0.03, \quad Q^2 < 10 \ \text{GeV}^2 \]

- COMPASS: low + medium \( x_B \)
- HERMES: medium \( x_B \), higher \( Q^2 \)
- JLab: medium+large \( x_B \), lower \( Q^2 \)
- JLab 11 GeV: larger \( x_B \), higher \( Q^2 \)

Collider experiments H1+ZEUS:
\[ x_B < 0.01, \quad Q^2 : 5...100 \ \text{GeV}^2 : \]
- small skewness
\[ \Rightarrow \quad \text{almost forward GPDs} ! \]
\[ \Rightarrow \quad \text{fixed-target experiments essential to study non-forward region of GPDs} ! \]
\[ \Rightarrow \quad \text{only COMPASS can explore low-} x ! \]
Exclusive DVCS Events at HERMES

**REACTION**: \( e + p(d) \rightarrow e + \gamma ( + X ) \)

- \( 5 < \theta_{\gamma\gamma} < 45 \) mrad
- \(-t < 0.7 \) GeV
- \( 0.03 < x_B < 0.35 \)
- \( 1 < Q^2 < 10 \) GeV\(^2\)
- \( W > 3 \) GeV
- \( \nu < 22 \) GeV
- \(- (1.5)^2 < M_{X}^2 < (1.7)^2 \) GeV

- **absolute** normalization of data and Monte Carlo [solid line]
- elastic Bethe-Heitler process is main contribution in signal region
- associated Bethe-Heitler process is a small contribution
- semi-inclusive production is main background at higher \( M_{X}^2 \)
- as recoiling proton not (yet) detected, missing mass cut used instead
- \( t \) calculated under assumption of exclusivity, via scattered lepton kinematics
CLAS+HERMES: 1\textsuperscript{st} Beam-spin Asymmetries

\[
A_{LU}(\phi) = \frac{1}{\langle |P_B| \rangle} \cdot \frac{d\sigma_{\rightarrow}(\phi)-d\sigma_{\leftarrow}(\phi)}{d\sigma_{\rightarrow}(\phi)+d\sigma_{\leftarrow}(\phi)} \propto \text{Im} F_1 \mathcal{H} \cdot \sin \phi
\]

⇒ extract ‘amplitudes’ fitting per $\phi$-bin $A_{LU}(\phi) = c + A_{LU}^{\sin \phi} \sin \phi + A_{LU}^{\sin 2\phi} \sin 2\phi$

\[ \begin{align*}
\text{HERMES: 27.5 GeV p, } & P_B \approx 55\%. \text{ No recoil prot. detect. [PRL87(2001,182001]} \\
\text{CLAS: 4.25 GeV p, } & P_B \approx 70\%. \text{ No prod. gamma detect. [PRL87(2001,182002]} \\
\text{expected sin } \phi \text{ behaviour: } & \text{significant sin } \phi \text{ amplitudes on both targets} \\
\text{other harmonics don’t contribute significantly} & 
\end{align*} \]
HERMES Beam-charge Asy. vs. $\phi$ and $M_X^2$

$$A_C(\phi) = \frac{d\sigma^+(\phi) - d\sigma^-(\phi)}{d\sigma^+(\phi) + d\sigma^-(\phi)} \propto \text{Re } F_1 H \cdot \cos \phi$$

⇒ extract ‘azimuthal asymmetry amplitudes’ by fitting in every $\phi$-bin

$$A_C(\phi) = \text{const.} + A_C^{\cos \phi} \cos \phi + A_C^{\cos 2\phi} \cos 2\phi + A_C^{\cos 3\phi} \cos 3\phi$$

publ. results for *unpolarized proton* target [hep-ex/0605108, PRD75(2007)011103(R)]

use *symmetrization* ($\phi \rightarrow |\phi|$) to get rid of sinusoidal terms

$A_C^{\cos \phi} = 0.060 \pm 0.027$, other contributions insignificant (dashed = pure $\cos \phi$)

asymmetry only in exclusive and ‘associate’ $M_X^2$ region ($\rightarrow$ resol. smearing)

preliminary deuteron data (not shown) completely consistent
HERMES Beam-charge Asymmetry vs. \( t \)

BCA \( t \)-dependence can distinguish different GPD model versions:

\[ A_C^{\cos \phi} : \text{elastic + associated production} \]
\[ \Rightarrow \text{highest } t \text{-bin mostly affected} \]

- \( \text{GPD } H \text{ dominates, } \tilde{H} \text{ and } E \text{ suppr.} \)
  - Curves (code [Vanderh.,Guichon,Guidal]) calculated for 4 different param. sets

- BCA insensitive to profile fct. param.‘s

\[ \text{Only HERMES can measure BCA!} \]


- more precise HERA-II BCA results from ‘combined analysis’ with TTSA

- For all DVCS data: reduction of background & associated contribution in recoil detector data (2006+07)
HERMES Long. Target-spin Asymmetry vs. $\phi$

$$A_{UL}(\phi) = \frac{1}{\langle P_L \rangle} \cdot \frac{d\sigma^{\rightarrow}(\phi)-d\sigma^{\leftarrow}(\phi)}{d\sigma^{\rightarrow}(\phi)+d\sigma^{\leftarrow}(\phi)} \propto \text{Im} F_1 \widetilde{H} \sin \phi$$

$\Rightarrow$ extract ‘azimuthal asymmetry amplitudes’ by fitting per $\phi$-bin:

$$A_{UL}(\phi) = c + A_{UL}^{\sin \phi} \sin \phi + A_{UL}^{\sin 2\phi} \sin 2\phi$$

$\Leftarrow$ proton
deuteron $\Rightarrow$

- **FULL existing data set analyzed (1996-2000 data)**
- $s_1$ : expected $\sin \phi$ behaviour : $2\sigma$ (1.5$\sigma$) on p (d)
- $s_2$ : unexpected, sizeable ($> 3\sigma$) $A_{UL}^{\sin 2\phi}$ on p (1.7$\sigma$ on d) $\Rightarrow$ twist-3?
- final analysis tuning and paper in progress
Why TTSA Data Expected to be Sensitive to \( J_q \)?

\[ A_{UT}(\phi, \phi_S) \propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}] \sin(\phi - \phi_S) \cos \phi + \text{Im}[F_2 \mathcal{H} - F_1 \xi \tilde{\mathcal{E}}] \cos(\phi - \phi_S) \sin \phi \]

**ANSATZ:** spin-flip Generalized Parton Distribution \( E \) can be parameterized as follows:

- Factorized ansatz for spin-flip quark GPDs: \( E_q(x, \xi, t) = \frac{E_q(x,\xi)}{(1-t/0.71)^2} \)

- \( t \)-indep. part via double distr. ansatz: \( E_q(x, \xi) = E_{qDD}(x, \xi) - \theta(\xi - |x|) D_q \left( \frac{x}{\xi} \right) \)

  using double distr. \( K_q \): \( E_{qDD}(x, \xi) = \int_{-1}^{1} d\beta \int_{-1-|\beta|}^{1-|\beta|} d\alpha \delta(x - \beta - \alpha \xi) K_q(\beta, \alpha) \)

  with \( K_q(\beta, \alpha) = h(\beta, \alpha) e_q(\beta) \) and \( e_q(x) = A_q q_{val}(x) + B_q \delta(x) \) based on chiral QSM

  where coeff.s \( A, B \) constrained by Ji relation, and \( \int_{-1}^{+1} dx e_q(x) = \kappa_q \)

- \( A_u, A_d, B_u, B_d \) are functions of \( J_u, J_d \)

  \( \Rightarrow J_u, J_d \) are free parameters when calculating TTSA

- Sensitivity to \( J_u \) (with \( J_d = 0 \)) studied [EPJ C46, 729 (2006), hep-ph/0506264]
HERMES: First Measurement of TTSA

\[ A_{UT}(\phi, \phi_S) = A_{UT}^{\sin(\phi - \phi_S)} \cos \phi \cdot \sin(\phi - \phi_S) \cos \phi + A_{UT}^{\cos(\phi - \phi_S)} \sin \phi \cdot \cos(\phi - \phi_S) \sin \phi + \ldots \]
Model-dependent constraints on $J_u$ vs $J_d$

**HERMES analysis method:**

Unbinned maximum likelihood fit to all possible azimuthal asymmetry amplitudes at average kinematics: ⇒ ‘combined fit’ of HERMES BCA and TTSA data against various model calculations, leaving $J_u$ and $J_d$ as free parameters ⇒ model-dep. 1-$\sigma$ constraints on $J_u$ vs. $J_d$:

- **Double-distribution model:** [Vanderhaghen, Guichon, Guidal] $J_u + J_d/2.8 = 0.49 \pm 0.17 (\text{exp}_{\text{tot}})$
- **Dual model** [Guzey, Teckentrup]: $J_u + J_d/2.8 = -0.02 \pm 0.27 (\text{exp}_{\text{tot}})$
- **Lattice gauge theory:** QCDSF [Göckeler et al.], LHPC [Hägler et al.]  
- **DFJK model:** zero-skewness GPDs extracted from nuclear form factor data using valence-quark contributions only [Diehl et al.]
Summary and Outlook

- The HERMES experiment played a pioneering role exploring the potential of exclusive photon (also meson) production towards an interpretation of the data in terms of GPDs. Azimuthal asymmetries were measured with respect to beam spin and charge, and to longitudinal and transverse target polarization. Constraints on GPD models were obtained, in particular (model-dependent) constraints on the $u$ and $d$-quark total angular momenta. Presently the quality of the data is higher than that of the available models!

- At JLAB, many dedicated high-statistics DVCS measurements on various targets were/are/will be performed, which will have strong impact on constraining GPDs. Plans are being substantiated for measurements at 12 GeV that are hoped to become reality beyond 2012. At CERN, COMPASS prepares a proposal to measure DVCS with both beam charges after 2012. Exclusive reactions will hence presumably be mapped in the next decade, allowing the construction of precise GPD models which are expected to describe the 3-dimensional structure of the nucleon.