Experimental results on DVCS and HEMP for Generalized Parton Distributions

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Accessing GPDs

Physics goals:
- 3D mapping of Nucleon
- Sensitivity to Orbital Angular Momentum

Deeply Virtual Compton Scattering (DVCS)

Deeply Virtual Meson Production (DVMP)

+ Clean process
- Only sensitive to chiral even GPDs

+ Enables Flavour decomposition of GPDs
+ Access to transversity degrees of freedom described by chiral-odd GPDs
- Distribution Amplitude (DA) is involved as additional soft non pert. quantity
<table>
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<tr>
<th>HERMES at DESY</th>
<th>COMPASS at CERN</th>
<th>JLab</th>
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<tbody>
<tr>
<td><strong>27 GeV e^+ &amp; e^-</strong> Longit. polarized ~ 54% Gaseous intern. polar target 1995 to 2007</td>
<td><strong>160-200 GeV</strong> Polarized muon beam <strong>DIS</strong> Pion beam: Drell-Yan, J/ψ Long solid polarized targets</td>
<td><strong>6 GeV → 12 GeV</strong> Polarized CW e^- beam Pol=85%, High luminosity</td>
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and pioneering work at H1 and ZEUS.
Want to determine Re and Im parts of 8 GPDs: \( H, E, \tilde{H}, \tilde{E} \) and the 4 ‘transverse’ ones via ‘exclusive’ processes: DVCS (\( \gamma \)) and HEMP (\( \rho, \omega, \phi \)).

**DVCS interferes with Bethe-Heitler process**

→ Can use interference terms (e.g. at Jlab) or pure DVCS production (e.g. at COMPASS).

**Method:**

- Collect very large sample of data, numerous observables (cross sections and asymmetries) in 4 kinematic variables
- Global analyses to extract 8x2 (Re and Im) Compton Form Factors CFFs
- Deconvolutions to finally access GPDs.
Results on Deep Virtual Compton Scattering - DVCS

e p → e' p' γ

DVCS mostly sensitive to:

<table>
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<tr>
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<th>Im DVCS</th>
<th>Re DVCS</th>
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<tbody>
<tr>
<td>$\mathcal{H}$</td>
<td>$A_{LU}, A_C$</td>
<td>$\sigma, A_{UU}$</td>
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<tr>
<td>$\mathcal{H}$</td>
<td>$A_{UL}$</td>
<td></td>
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<tr>
<td>$\mathcal{E}$</td>
<td>$A_{UT}$</td>
<td>$A_{LL}, A_{LT}$</td>
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U, L, T indexes refer to beam and target polarization.

$\mathcal{H}$ sensitive to OAM, need transversely polarized target.

Easiest

All demanding in luminosity.
HERMES- Summary of results

Gunnar Schnell at IWHSS-22, sept.2022

Beam-charge asymmetry: 
- \( A_{LU} \) & \( A_{LT} \) & \( A_{UL} \) & \( A_{LL} \) for \( e^+ \) & \( e^- \) beams

Beam-helicity asymmetry: 
- \( A_{LU} \) \\
- \( A_{LT} \) \\
- \( A_{UL} \) \\
- \( A_{LL} \) \\

Transverse target spin asymmetries: 
- \( A_{LU} \) & \( A_{LT} \) for GPD E from proton target

Longitudinal target spin asymmetry: \( A_{UL} \) & \( A_{LL} \) for GPD \( \tilde{H} \)

Double-spin asymmetry: \( A_{LL} \) for GPD \( \tilde{H} \)
DVCS – Jlab CLAS proton target, e H $\rightarrow$ e’p γ

$d^4 \sigma(x, Q^2, t, \phi)$ and $\Delta (d^4 \sigma)$ beam spin difference, sensitive to $Im[H] \sim e^{-b(x) t}$

$b$ related to proton transverse size

Assuming one GPD, fit to CFF at 3 x values:

- $Q^2=1.11$ GeV$^2$
  - $x_B=0.126$
  - $A=5.30 \pm 0.95$
  - $b=4.25 \pm 0.98$

- $Q^2=1.63$ GeV$^2$
  - $x_B=0.185$
  - $A=4.98 \pm 0.56$
  - $b=3.03 \pm 0.55$

- $Q^2=2.10$ GeV$^2$
  - $x_B=0.304$
  - $A=1.81 \pm 1.72$
  - $b=1.18 \pm 2.26$

$b$ decreases as $x_B$ increases

$\rightarrow$ proton shrinking with $x_B$
DVCS- t-slope of Cross-section (COMPASS)

Combining data from $\mu^+$ and $\mu^-$ beams (beam spin & charge sum), measure t-slope of DVCS cross section

\[ \sigma^{DVCS}/dt \sim \exp^{-B|t|} \]

\[ B(x_B) = \frac{1}{2} \langle r_{\perp}^2 (x_B) \rangle \]

Measurement of proton transverse size vs $x_B$

New prelim. COMPASS result:

2016 data: prelim. result
3 x more stat. expected from 2017 data
Flavour separation of CFFs

JLab Hall-A neutron and proton DVCS

Cross sections measured with LH$_2$ & LD$_2$ targets

- DVCS$^2$ and interference extracted simultaneously
- curves: predictions of diquark model Goldstein et al.

Note larger scale for E

u and d flavour separation for 3 CFFs

Benali, Desnault, Mazouz et al., Nature Physics 16 (2020) 191-198
DVCS – Jlab CLAS $\vec{p}$ target, $e \vec{p} \rightarrow e' (p) \gamma$

$A_{UL}(x,Q^2,t,\phi)$ sensitive to $\text{Im}(\tilde{H})$

Possibility to access spatial distribution of quark helicity

S. Pisano et al., CLAS, PRD 91 (2015) 5, 052014
First results 12 GeV beam

Data 12 GeV, with curves based on earlier results obtained with 6 GeV beam data

Towards higher $Q^2$ : very promising results – only 25% of stat used here
DVCS – Jlab CLAS $^4$He target, $e^4$He $\rightarrow$ $e'$ $\gamma$ $\alpha$

$A_{LU}(x,Q^2,t,\phi)$
sensitive to $\text{Im}(H)$

At LO- LT, only one GPD, fit to $\text{Re}$ and $\text{Im}[H(t)]$

+ radial TPC for recoil $\alpha$, $\phi=16$ cm

M. Hattawy et al., CLAS, PRL 119 (2017)

Promising $^4$He study
Hard Exclusive Meson Production - HEMP

- Enables flavour decomposition of GPDs
- Access to transversity degrees of freedom described by chiral-odd GPDs
- Distribution Amplitude (DA) is involved as additional soft non pert. quantity
Mesons, DVMP – JLab, $e\, H \rightarrow e'\,(p)\, \pi^0 / \eta$

**First clear separation of $\sigma_T$ and $\sigma_L$ (Rosenbluth)**

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$\pi^0$

- $Q^2 = 1.5\,\text{GeV}^2$
- $Q^2 = 1.75\,\text{GeV}^2$
- $Q^2 = 2.0\,\text{GeV}^2$

$\sigma_T(t)$

$\sigma_L(t)$

---

$\eta$

- $Q^2 = 1.38\,\text{GeV}^2$
- $Q^2 = 2.21\,\text{GeV}^2$

**M. Defurne et al., Hall A, PRL 117 (2016) 262001**

**I. Bedlinskiy et al., CLAS, PRC 95 (2017)**
Beam spin asymmetry $\pi^+$

S. Diehl et al., PRL125, 182001 (2020)

New: CLAS12 first results

$ep \rightarrow ep\pi^0$

$$\sigma_{LT} = \xi \sqrt{1 - \xi^2} \frac{-t}{2m} \times \text{Im} \left[ \langle H_T \rangle^* \langle E \rangle + \langle E_T \rangle^* \langle H \rangle \right]$$

$ep \rightarrow en\pi^+$

CLAS12 prelim, K. Joo, IWHSS 22, Sept. 2022
CLAS12 exclusive $\pi^+$, $\pi^-$ and $\pi^0$ production

$\langle Q^2 \rangle = 2.48 \text{ GeV}^2$, $\langle x_B \rangle = 0.27$

$\sigma / \sigma_0$

$\pm \pi^0$, $\pi^+$ n, $\pi^-$, $\Delta^{++}$

$-t [\text{GeV}^2]$

ep $\rightarrow$ ep $\pi^- \Delta^{++}$

BSA ($\phi$) in 7 t bins

$BSA = \frac{1}{P_e} \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-}$
COMPASS exclusive \( \pi^0 \) production

\[ \mu^+/ - \ p \rightarrow \mu^- \ p \ \pi^0 \]

- recoil proton detection + ECALs

Only 25% of available stat. used

Preliminary result on \( \pi^0 \) production at \( x_B \sim 0.1 \)

\( \rightarrow \) input for models as Goloskokov Kroll, Goldstein Liuti, etc.
COMPASS HEMP of $\rho^0$ and $\omega$

$\mu^+/ \mu^- p \rightarrow \mu^- p \rho^0/\omega$

Transversely polarized target

Sensitivity to GPD $E$

However, $E^u$ and $E^d$ of opposite sign

$\rho^0 \rightarrow \pi^+\pi^-$

$E_{\rho^0} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^u + \frac{1}{3} E^d + \frac{3}{4} E_d \right)$

$\omega \rightarrow \pi^+\pi^- \pi^0$

$E_{\omega} = \frac{1}{\sqrt{2}} \left( \frac{2}{3} E^u - \frac{1}{3} E^d + \frac{1}{4} E_d \right)$

→ $\omega$ promising despite $\pi^0$ pole contribution

Acces to GPDs $E_T$, $H_T$ ...

GK Goloskokov, Kroll, EPJC42,50,53,59,65,74 GPD model constrained by HEMP at small $x$

longitudinal $\gamma^*_L p \rightarrow M p$ and transv. polar. $\gamma^*_T p \rightarrow M p$

quark and gluon contributions (GPDs $H, E, H_T, E_T$) and beyond leading twist
If SCHC (s channel helicity conservation):

\[ r_{10}^L + \text{Im}\{r_{10}^T\} = 0 \]
\[ \text{Re}\{r_{10}^L\} + \text{Im}\{r_{10}^T\} = 0 \]
\[ \text{Im}\{r_{10}^L\} - \text{Re}\{r_{10}^T\} = 0 \]

All the other SDME in classes C, D, E should be 0

not observed for class C

From Goloskokov and Kroll, EPJC74 (2014) 2725

\( F_0 = 2/3 F_u - 1/3 F_d \)

Both 2 terms are important

\( (H_u, H_d) \) of same sign
\( (\overline{E}_u, \overline{E}_d) \) of same sign
\( (H_u, \overline{H}_d) \) of opposite sign
\( (E_u, \overline{E}_d) \) of opposite sign
COMPASS $\rho^0$ SDME (prelim.)

If SCHC ($\lambda_\gamma = \lambda_\nu$)

\[ r_{1-1}^l + \text{Im}\{r_{7-1}^l\} = 0 \]
\[ \text{Re}\{r_{10}^l\} + \text{Im}\{r_{10}^l\} = 0 \]
\[ \text{Im}\{r_{10}^l\} - \text{Re}\{r_{10}^l\} = 0 \]

measurements:

\[ = 0.000 \pm 0.005 \pm 0.003, \]
\[ = 0.011 \pm 0.002 \pm 0.002. \]
\[ = 0.009 \pm 0.014 \pm 0.028. \]

All the other SDME in classes C,D, E should be 0, not observed for class C.

From Goloskokov and Kroll, EPJC74 (2014) 2725

\[ F\rho^0 = 2/3 F^n + 1/3 F^d \]

The first term dominates and $r_{00}^5$ probes $E_T$.

$(H^n, H^d)$ of same sign
$(\bar{E}^n, \bar{E}^d)$ of same sign
$(H^e, H^{\bar{e}})$ of opposite sign
$(E^n, E^d)$ of opposite sign

COMPASS to be submitted

\(<Q^2> = 2.4 \text{ GeV}^2\)
\(<W> = 9.9 \text{ GeV} \)
\(<p_T^2> = 0.18 \text{ GeV}^2\)
CLAS12 $\rho^0$ exclusif prelim.

\[ r_{00}^1 \sigma_0 \sim |E_T|^2 \]
\[ r_{00}^5 \sigma_0 \sim \text{Re} \left[ \langle E_T \rangle \langle H \rangle + \langle H_T \rangle \langle E \rangle \right] \]
\[ r_{00}^8 \sigma_0 \sim \text{Im} \left[ \langle E_T \rangle \langle H \rangle + \langle H_T \rangle \langle E \rangle \right] \]

\[ \sigma_{LT'} \sim r_{00}^8 \sim \text{Im} \left[ \langle H_T \rangle^* \langle E \rangle + \langle E_T \rangle^* \langle H \rangle \right] \]

\[ BSA = \frac{A_L^1 \sin \phi \sin \phi}{1 + A_U^0 \cos \phi \cos \phi + A_U^0 \cos(2\phi) \cos(2\phi)} \]

Impressive statistics on $\rho^0$ + ongoing work on $\omega$, $\phi$, $\Delta^{++}$
TCS - CLAS12 first measurements

TCS = ‘mirror’ of DVCS

\[ \sigma(\gamma p \rightarrow p' e^+ e^-) = \sigma_{BH} + \sigma_{TCS} + \sigma_{INT} \]

Bethe-Heitler (BH)

\[ A_{\text{BH}} \sim \sin \varphi \text{Im} M^{--}, \text{universality of GPDs} \]

\[ A_{FB} \sim \cos \varphi \text{Re} M^{--}, \text{access to the EM FF } D^0(t) \text{ (D-term).} \]

Beam helicity asymmetry ~ Im CFF

Forward backward asymmetry ~ Re CFF

CLAS12, P. Chatagnon et al., PRL127, 262501 (2021)

F. Kunne
CFFs from globat fits of DVCS data

Example: ‘PARTON’ fit at LO/LT DVCS proton, Including Jlab, HERMES and COMPASS data
2600 / 3970 points
with constraints on GPDs (PDFs, elastic Form Factors, limits at $x \to 1$...)


Position of up quarks in a proton:

See talk by J. Wagner
Future US Electron Ion Collider

- Hadrons up to 275 GeV
  existing RHIC complex, incl. polarized p
- Electrons up to 18 GeV
  Storage ring, polarized e⁻

→ $\sqrt{s} = 20 - 140$ GeV
→ Design to reach $10^{34} \text{ cm}^{-2}\text{sec}^{-1}$
Conclusion

• Plenty of results on DVCS & HEMP (Jlab 6GeV, COMPASS, HERMES) Measurements are difficult, demanding in precision and luminosity.

• Data from Jlab 12 GeV coming

• Global analyses preparing for CFF extractions
GPDs - Definitions

Definition of variables:
- $q$ ... four-momentum
- $x$ ... average longitudinal momentum fraction of initial and final parton (NOT accessible)
- $\xi$ ... difference of longitudinal-momentum fraction between initial and final parton $\approx x_B/(2 - x_B)$
- $t$ ... four-momentum transfer

- 4 chiral-even GPDs (parton helicity conserved)
- 4 chiral-odd (or transversity) GPDs (parton helicity flipped)

<table>
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<tr>
<th>Nucleon Polarisation</th>
<th>Quark Polarisation</th>
<th>Unpolarised $(U)$</th>
<th>Longitudinally polarised $(L)$</th>
<th>Tranversely polarised $(T)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$H$</td>
<td>$E_T$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>$\tilde{H}$</td>
<td>$\tilde{E}_T$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$E$</td>
<td>$H_T$, $\tilde{H}_T$</td>
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GPDs enter the exclusive processes through Compton Form Factors (CFF)

$$\mathcal{H}(\xi, t) = \mathcal{P} \int_{-1}^{1} dx \frac{H(x, \xi, t)}{x - \xi} + i\pi H$$

F. Kunne
HEMP – sensitivity to CFFs and q/g contrib.

Hard Exclusive Meson Production:

- Flavour separation for specific GPDs due to different partonic content of mesons
- Gluon and quark contributions at the same order in $\alpha_s$ for vector mesons
- DVCS sensitive to $H^f$, $E^f$, $\tilde{H}^f$, and $\tilde{E}^f$
- At the leading twist:
  - Vector meson production sensitive to $H^f$, and $E^f$
  - Pseudoscalar mesons production is described by GPDs $\tilde{H}^f$, and $\tilde{E}^f$
- Both vector meson and pseudoscalar mesons (as the $\pi_0$ presented in this talk) are also sensitive to $E_T^f = 2\tilde{H}_T^f + E_T^f$, and $H_T^f$
### HEMP cross section

\[
\frac{d^2 \sigma_{\gamma^* p}}{dt d\phi} = \frac{1}{2\pi} \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cos(2\phi) \frac{d\sigma_{TT}}{dt} + \sqrt{\epsilon(1 + \epsilon)} \cos \phi \frac{d\sigma_{LT}}{dt} \right]
\]

### GPDs in exclusive $\pi^0$ production

- \[ \frac{d\sigma_L}{dt} \propto \left[ (1 - \xi^2) \left| \langle \bar{H}\rangle \right|^2 - 2\xi^2 \text{Re} (\langle \bar{H}\rangle^* \langle \bar{E}\rangle) - \frac{t'}{4M^2} \xi^2 |\langle \bar{E}\rangle|^2 \right] \]
- \[ \frac{d\sigma_T}{dt} \propto \left[ (1 - \xi^2) \left| \langle H_T\rangle \right|^2 - \frac{t'}{8M^2} |\langle \bar{E}_T\rangle|^2 \right] \]
- \[ \frac{d\sigma_{TT}}{dt} \propto t' |\langle \bar{E}_T\rangle|^2 \]
- \[ \frac{d\sigma_{LT}}{dt} \propto \xi \sqrt{1 - \xi^2} \sqrt{-t'} \text{Re} (\langle H_T\rangle^* \langle \bar{E}\rangle) \]

### Impact of $\bar{E}_T$

Should be visible in $\frac{d\sigma_{TT}}{dt}$, and also a dip at small $t$ of $\frac{d\sigma_T}{dt}$.

\[ t' = t - t_{min}, \quad t_{min} \text{ is the minimum value of } |t| \]
Compton Scattering and GPDs

TCS

Hard scale is defined by time-like photons

\[ \text{Re } \mathcal{H}(\xi, t) = PV \int_{-1}^{1} dx C^{-}(\xi, x) H(x, \xi, t) \]

\[ \text{Im } \mathcal{H}(\xi, t) = i\pi H(\xi, \xi, t) \]

Access to the Re-part of the Compton amplitude

DVCS

Hard scale is defined by space-like photon

DDVCS

Both space-like and time-like photons can set the hard scale

\[ \int_{-1}^{1} dx \frac{H(x, \xi, t)}{x - (2\xi' - \xi) + i\epsilon + \ldots} \]

\[ H(2\xi' - \xi, \xi, t) + H(-(2\xi' - \xi), \xi, t) \]

\(\sigma\)-DDVCS is three orders of magnitude smaller than \(\sigma\)-DVCS

The main driver of the high luminosity upgrade

First experimental measurement with CALS12
PRL 127, 262501 (2021)

Started in 2001, PRL 87, 182002
Is the large part of the CLAS12 physics program

CLAS12 GPD studies

\(\mu\)CLAS12, one of two proposed facilities capable of measuring

S. Stepanyan, IWHSS2022
BHA  Beam Helicity Asymmetry

\[ A_{\otimes U} = \frac{1}{P_b} \frac{N^+ - N^-}{N^+ + N^-} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{-\frac{\alpha^3_{em}}{4\pi s^2} \frac{1}{t} \frac{m_p}{Q'} \frac{1}{\tau \sqrt{1-\tau}} \frac{L_0}{L} \sin \phi \frac{(1+\cos^2 \theta)}{\sin(\theta)} \text{Im} \tilde{M}^{--}}{d\sigma_{BH}} \]

FB  Forward Backward Asymmetry

\[ A_{FB}(\theta_0, \phi_0) = \frac{d\sigma(\theta_0, \phi_0) - d\sigma(\pi - \theta_0, \pi + \phi_0)}{d\sigma(\theta_0, \phi_0) + d\sigma(\pi - \theta_0, \pi + \phi_0)} = \frac{-\frac{\alpha^3_{em}}{4\pi s^2} \frac{1}{t} \frac{m_p}{Q'} \frac{1}{\tau \sqrt{1-\tau}} \frac{L_0}{L} \cos \phi_0 \frac{(1+\cos^2 \theta_0)}{\sin(\theta_0)} \text{Re} \tilde{M}^{--}}{d\sigma_{BH}(\theta_0, \phi_0) + d\sigma_{BH}(\pi - \theta_0, \pi + \phi_0)} \]