Status and Prospects of the Experimental Investigation on GPDs

Nicole d’Hose, CEA Université Saclay-Paris
Deeply virtual Compton scattering (DVCS) and DVMP

The variables measured in the experiment:

\( E_\ell, Q^2, x_B \sim 2\xi/(1+\xi), \) 
\( t \) (or \( \theta_{\gamma^*\gamma} \)) and \( \phi \) (\( \ell'\ell \) plane/\( \gamma^*\gamma \) plane)

The GPDs depend on the following variables:

- \( x \): average long. momentum
- \( \xi \): long. mom. difference \( \approx x_B/(2-x_B) \)
- \( t \): four-momentum transfer related to \( b_\perp \) via Fourier transform

DVCS: \( \ell p \rightarrow \ell' p' \gamma \) the golden channel because it interferes with the Bethe-Heitler process also meson production \( \ell p \rightarrow \ell' p' \pi, \rho \) or \( \phi \) or \( J/\psi \)...

GPDs and 3D imaging

M. Burkardt, PRD66(2002)

mapping in the transverse plane

Impact parameter distribution

Correlation between the spatial distribution of partons and the longitudinal momentum fraction
GPDs and Energy-Momentum Tensor and Confinement

GPDs can provide an experimental answer by exploiting their equivalence to the gravitational form factors of the nucleon energy-momentum-tensor (fundamental nucleon properties)

$$H^q(x, \xi, t) \xrightarrow{t \to 0} q(x) \text{ or } f_1(x)$$

“Elusive”

$$E^q(x, \xi, t) \xrightarrow{t \to 0} f_{1T}(x, k_T)$$

Sivers: quark $k_T$ & nucleon transv. spin

$$2J^q = \lim_{t \to 0} \int x (H^q(x, \xi, t) + E^q(x, \xi, t)) \, dx$$

Ji sum rule: PRL78 (1997) cited 1504 times

Relation to OAM

Lattice ArXiv:1706.02973
Alexandrou et al.

$$\frac{1}{2} \Delta \Sigma = 0.20$$

$$L^q = 0.21$$

$$J^g = 0.13$$

M. Polyakov, P. Schweitzer

mass & energy distribution

$$\int dx \, x H^q(x, \xi, t) = A^q(t) + \frac{4}{5} \xi^2 d_{1}^q(t)$$

$$\int dx \, x E^q(x, \xi, t) = B^q(t) - \frac{4}{5} \xi^2 d_{1}^q(t)$$

Angular momentum distribution

force & pressure distribution

Valence q (connected) + Sea q and g (disconnected)

Pressure Distribution
Deeply virtual Compton scattering (DVCS)

The amplitude DVCS at LT & LO in $\alpha_s$:

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

Real part

Imaginary part

$$ \text{Re } H(\xi, t) = \mathcal{P} \int dx \frac{\text{Im } H(x, t)}{x - \xi} $$

From Goeke, Polyakov, Vanderhaeghen, PPNP47 (2001)
The past and future DVCS experiments

- **Current DVCS data at colliders:**
  - ZEUS- total xsec
  - ZEUS- dσ/dt
  - H1- total xsec
  - H1- dσ/dt
  - H1- A_{UL}

- **Current DVCS data at fixed targets:**
  - HERMES- A_{UL}, A_{UL}, A_{LL}
  - HERMES- A_{UL}, A_{UL}, A_{LL}
  - HERMES- A_{UL}, A_{UL}, A_{LL}
  - HERMES- A_{UL}, A_{UL}, A_{LL}
  - CLAS- A_{UL}, A_{UL}, A_{LL}

- **Planned DVCS at fixed targets:**
  - COMPASS- dσ/dt, Σ_{CSU}, A_{CSU}, A_{CST}
  - JLAB12- dσ/dt, A_{UL}, A_{UL}, A_{LL}

- **Future colliders:**
  - **EIC...**

**Timeline:**
- **Start 2001**
- **After 2016**
- **After 2025**

**Q^2 [GeV^2]**

- Q^2 = 100 GeV^2
- Q^2 = 50 GeV^2
- Q^2 = 45 GeV

**X_B**

- 10^{-4} to 10^{-1}
- 10^{-3} to 10^{-2}
- 10^{-2} to 1

**X_B**

- 10^{-4} to 1
- 10^{-3} to 10^{-2}
- 10^{-2} to 1

**Legend:**
- Gluons
- Sea quarks
- Valence quarks
The past and present experiments

Collider mode e-p forward fast proton

HERA: H1 and ZEUS
Polarised 27 GeV e-/e+
Unpolarized 920 GeV proton
~ Full event reconstruction

Examples for EIC

Fixed target mode slow recoil proton

HERMES: Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector

Jlab: Hall A, C, CLAS
High lumi, polar. 6 & 12 GeV e-
Long, (Trans) polarised p, d target
Missing mass technique (A,C) and complete detection (CLAS)

COMPASS @ CERN: Polarised 160 GeV μ+/μ-
p target, (Trans) polarised target
with recoil detection

Rejection of background: SIDIS, exclusive π⁰/DVCS, dissociation of the proton
Exclusive Meson production for GPD models

\[ \rho^0 (\rightarrow \pi^+\pi^-) \] production at COMPASS with Transversely Polarized Target

GK Goloskokov, Kroll, EPJC42,50,53,59,65,74 GPD model constrained by HEMP at small \( x_b \) (or large \( W \))

dominant (longitudinal) \( \gamma^*_L p \rightarrow M p \) and transv. polar. \( \gamma^*_T p \rightarrow M p \)
quark and gluon contributions (GPDs \( H, E, H_T \)) and beyond leading twist
DVCS and Impact of the beam energy

$$d\sigma \propto |\mathcal{T}^{BH}|^2 + \text{Interference Term} + |\mathcal{T}^{DVCS}|^2$$

$E_\ell = 160$ GeV

Only for H1, ZEUS, COMPASS

DVCS dominates - Study of $d\sigma^{DVCS}/dt$

Jlab, HERMES, H1, COMPASS

DVCS ampl. via interference

Bethe-Heitler (BH)

Reference yield

BH dominates

Entries

$1000$

$500$

pure B.H contribution

$0.005 < x_B < 0.01$

$0.01 < x_B < 0.03$

$X_B > 0.03$
Study of $t$-dependence of the pure DVCS cross-section ($\gamma^* p \rightarrow \gamma p$)
Gluon imaging @ HERA

\[ \frac{d\sigma^{DVCS}}{dt} = e^{-B|t|} \]

B is related to the transversed size of the scattering objects

**DVCS**

Aaron et al., H1 Coll, PLB659 (2008)

\[
\sqrt{<r^2_\perp>} = 0.65 \pm 0.02 \text{ fm} \\
to be compared to \\
\sqrt{\frac{4}{dt} \frac{dP^t}{dt}} = 0.72 \pm 0.01 \text{ fm}
\]

not to

\[
\sqrt{\frac{4}{dt} \frac{dP^E}{dt}} = 0.67 \pm 0.01 \text{ fm}
\]

ZEUS-H1
Data collected 1995-2007

\[
W=82 \text{ GeV} \\
\langle Q^2 \rangle = 8 \text{ GeV}^2 \\
\langle x_B \rangle = 1.2 \times 10^{-3} \\
B = 5.45 \pm 0.19 \pm 0.34 \text{ GeV}^2
\]

PLB681 (2009)

W=82 GeV

\[
\langle Q^2 \rangle = 8 \text{ GeV}^2 \\
H1 \\
\langle x_B \rangle = 1.2 \times 10^{-3} \\
B = 5.45 \pm 0.19 \pm 0.34 \text{ GeV}^2
\]
Sea quark imaging @ COMPASS

HERA: $e^\pm p$ 27/920 GeV  
COMPASS: $\mu^\pm$ 200 GeV

$B = 4.31 \pm 0.62^{+0.09}_{-0.25}$ GeV$^{-2}$

$\frac{d\sigma^{DVCS}}{dt} = e^{-B|t|}$

$\langle r_{-}^2 (x_B) \rangle \approx 2B(x_B)$
Sea quark imaging @ COMPASS

HERA: $e^\pm p \ 27/920 \text{ GeV}$
COMPASS: $\mu^\pm 200 \text{ GeV}$

$$d\sigma^{\text{DVCS}}/dt = e^{-B|t|}$$

DVCS

Prediction at COMPASS for $2 \times 6$ months in 2016-17

$<r_{_2}^2(x_B)> \approx 2B(x_B)$

$\langle Q^2 \rangle$ = 1.8 (GeV/c)^2
$\langle Q^2 \rangle$ = 3.2 (GeV/c)^2
$\langle Q^2 \rangle$ = 4.0 (GeV/c)^2
$\langle Q^2 \rangle$ = 8.0 (GeV/c)^2
Study of DVCS-BH interference
A complete set of observables for DVCS

\[
\Re \left( F_1 H + \xi (F_1 + F_2) \tilde{H} + k F_2 E \right)
\]

\[
\Im \left( F_1 H + \xi (F_1 + F_2) \tilde{H} + k F_2 E \right)
\]

\[ k = \frac{t}{4M^2} \]

HERMES 27 GeV provided a complete set of observables

1995: start of data taking
2001: 1st DVCS publication as CLAS & H1
2007: end of data taking
2012: still important publications

\textit{JHEP} 07 (2012) 032 \( A_C A_{LU} \)

\textit{JHEP} 10(2012) 042 \( A_{LU} \)

with recoil detection (2006-7)


Very precise data
Beam Spin Sum and Diff of DVCS - CLAS

21 bins in $(x_B, Q^2)$ or 110 bins $(x_B, Q^2 t)$

Unpolarized cross section

Helicity Dependent cross section

models:

**VGG** Vanderhaeghen, Guichon, Guidal
1st model of GPDs constant evolution

**KMS12** Kroll, Moutarde, Sabatié, EPJC73 (2013)
using the **GK** model
Goloskokov, Kroll, EPJC42,50,53,59,65,74
for GPD adjusted on the hard exclusive meson production at small $x_B$

**KM10a - KM10** Kumericki, Mueller, NPB (2010) 841
Flexible parametrization of the GPDs based on both a Mellin-Barnes representation and dispersion integral which entangle skewness and $t$ dependences

Global fit on the world data ranging from H1, ZEUS to HERMES, JLab

"universality" of GPDs
Beam Spin Sum and Diff of DVCS - HallA

E00-110 pioneer experiment in 2004 with magnetic spectrometer

$x_B = 0.36$, $Q^2 = 1.5, 1.9, 2.3 \text{ GeV}^2$ Defurne et al. PRC92, 055202 (2015)

$x_B = 0.34, x_B = 0.39$, $Q^2 = 2.1 \text{ GeV}^2$

Unpolarized cross section

\[ \frac{d^2 \sigma}{d t d Q^2} \propto d\sigma^{BH} + d\sigma^{DVCS_{unpol}} + \text{Re } I \]

\[ \rightarrow d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi \]

Helicity Dependent cross section

\[ \frac{d^2 \sigma}{d t d Q^2} \propto d\sigma^{DVCS_{pol}} + \text{Im } I \]

\[ \rightarrow s_1^{DVCS} \sin \phi + s_2^{DVCS} \sin 2\phi \]

Further separation with different beam energies (2010 data)

2 solutions: higher-twist or next-to-leading order

arXiv:1703.09442 submitted to
Fit of 8 CFFs at L.O and L.T.

Dupré, Guidal, Vanderhaeghen, PRD95, 011501(R)(2017)

Fit $s_1^I = \text{Im} F_1 \mathcal{H}$

- CLAS $\sigma$ and $\Delta \sigma$
- HallA $\sigma$ and $\Delta \sigma$
- CLAS $A_{UL}$ and $A_{LL}$
- VGG model

Fit $A e^{-B'|t|}$

$\langle b_{\perp}^2 \rangle \approx 4 B'$

HERMES + 8 points from JLab

$\xi = x$ and $\xi \rightarrow 0$

Valence quark imaging at JLab and HERMES

Rept. Prog. Phys. 76 (2013)
Future Beam Spin Sum and Diff @JLab12

with high resolution magnetic spectrometer + Calorimeter in Halls A and C

Exp. 2010: run E07-007
2016-17: Hall A: E12-06-119
~2018: Hall C: E12-13-010

Different beam energies for a Rosenbluth-like DVCS²/Interf. separation

with CLAS12
In 2017

E12-06-119

LH₂ Target & Long. Pol. Target
Future Beam Spin Sum and Diff @ JLab12

Projected for JLab 12 GeV

Transverse profile

Pressure Distribution

World data model fit result
Predicted error band
χQSM
Stability requires forces compensate

Physics Opportunities with the 12 GeV Upgrade at Jefferson Lab

Dudek et al., EPJA48 (2012)
Predictions with VGG and D. Mueller KM10

\[ c_1^I = Re F_1 H \]

\[ 0.005 < x_{bj} < 0.01 \]

\[ 0.01 < x_{bj} < 0.02 \]

\[ 0.02 < x_{bj} < 0.03 \]

\[ 0.03 < x_{bj} < 0.07 \]

\[ 0.07 < x_{bj} < 0.15 \]

\[ 0.15 < x_{bj} < 0.30 \]

\[ Re H > 0 \] at H1

\[ < 0 \] at HERMES

Value of \( x_B \) for the node?

\[ E_{\mu} = 160 \text{ GeV} \]

\[ 1 < Q^2 < 8 \text{ GeV}^2 \]
Present knowledge of the GPD $H$ in global analysis

$\text{Im } H$ is rather well known

$\text{Re } H$ linked to the $d$ term is still poorly constrained

KM15 K Kumericki and D Mueller  \texttt{arXiv:1512.09014v1}

Present knowledge of the GPD $E$ in global analysis

$Im\ E$ is rather unknown

$Re\ E$ is rather unknown

Figure made by D. Mueller and K. Kumericki

$Q^2 = 2\ GeV^2$

$t = -0.3\ GeV^2$

KM15 K Kumericki and D Mueller arXiv:1512.09014v1

GPD E at Jlab 11 GeV with CLAS12

Exp E12-11-003: DVCS on the neutron

$$\Delta \sigma_{LU}^{\sin \phi} = \text{Im} \left( F_{1n} \mathcal{H} + \xi (F_{1n} + F_{2n}) \mathcal{H} + t/4m^2 F_{2n} E \right)$$

Exp E12-12-010: DVCS on a transversely polarized HD-Ice target

Pol H = 60% Pol D = 35%

$$\Delta \sigma_{UT}^{\sin(\phi - \phi_s) \cos \phi} = -t/4m^2 \text{Im} \left( F_{2p} \mathcal{H} - F_{1p} E \right)$$
$$\Delta \sigma_{LT}^{\sin(\phi - \phi_s) \cos \phi} = -t/4m^2 \text{Re} \left( F_{2p} \mathcal{H} - F_{1p} E \right)$$

90 days on LD2 target
Lumi = $10^{35}$ cm$^{-2}$ s$^{-1}$/nucleon

110 days on HD-Ice target
Lumi = $5 \times 10^{33}$ cm$^{-2}$ s$^{-1}$/nucleon

Model prediction using VGG

Neutron detector Efficiency ~ 10%

BOTH EXPERIMENTS FORESEEN IN 2019
From Pawel Sznajder
Using the PARTONS code
Formalism at LO

- GK and CFFs@LO
- Idem with GPDs E = 0
- VGG and CFFs@LO
- Idem with GPDs E = 0

GPD E at COMPASS 160 GeV with μ+ and μ-

$D_{CS,T} \equiv \sigma_T(\mu^+\downarrow) - \sigma_T(\mu^-\uparrow)$

$\propto \text{Im}(F_2H - F_1E) \sin(\phi - \phi_s) \cos \phi$

DVCS on a 1.2m long transversely polarized NH$_3$ target

2 years of data
$\epsilon_{\text{global}} = 10\%$

Accuracy $\pm 3\%$
GPD $E_{\text{gluon}}$ at RHIC in 2017 and 2023

2.3.1 Run-2017, Run-2023 and Opportunities with a Future Run at 500 GeV

Ultra Peripheral Collisions to access the Generalized Parton Distribution $E_{\text{gluon}}$

Two key questions, which need to be answered to understand overall nucleon properties like the spin structure of the proton, can be summarized as:

- How are the quarks and gluons, and their spins distributed in space and momentum inside the nucleon?
- What is the role of orbital motion of sea quarks and gluons in building the nucleon spin?

$Q^2$ of 9 GeV$^2$ and $10^{-4} < x < 10^{-1}$. A nonzero asymmetry would be the first signature of a nonzero GPD $E$ for gluons, which is sensitive to spin-orbit correlations and is intimately connected with the orbital angular momentum carried by partons in the nucleon and thus with the proton spin puzzle. Detecting one of the scattered polarized protons in “Roman Pots” (RP) ensures an elastic process.

$11k \ J/\psi \ in \ 2017 \ (p^\uparrow \ p \ @ \ 510 \ GeV) \ and \ 13k \ in \ 2023 \ (p^\uparrow \ Au \ @ \ 200 \ GeV)$

Important input for the photoproduction of $J/\psi$ at EIC
Stage 2
Ee=20 GeVEp=250 GeV

Stage 1
Ee=5 GeVEp=100 GeV

<table>
<thead>
<tr>
<th>Deliverables</th>
<th>Observables</th>
<th>What we learn</th>
<th>Requirements</th>
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</thead>
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<tr>
<td>GPDs of sea quarks and gluons</td>
<td>DVCS and J/ψ, ρ⁺, φ production cross section and polarization asymmetries</td>
<td>transverse spatial distrib. of sea quarks and gluons; total angular momentum and spin-orbit correlations</td>
<td>( \int dt L \sim 10 \text{ to } 100 \text{ fb}^{-1} ); Roman Pots; polarized e⁻ and ( p ) beams; wide range of ( x_B ) and ( Q^2 ); range of beam energies; ( e^+ ) beam valuable for DVCS</td>
</tr>
<tr>
<td>GPDs of valence and sea quarks</td>
<td>electroproduction of ( \pi^+, K ) and ( \rho^+, K^* )</td>
<td>dependence on quark flavor and polarization</td>
<td></td>
</tr>
</tbody>
</table>

**Key measurements for imaging partons with EIC**

**Exclusive J/ψ production**

**Gluon distribution**

**Transverse distance of the gluon from the center of the proton in femtometers**
DVCS publications and data taking over the years

**Jlab 12 GeV**
- E12-06-114: HallA DVCS diff energies
- E12-06-119: CLAS12 DVCS p, pol NH3
- E12-12-001: CLAS12 Time Like Compton and J/ψ
- E12-06-108: CLAS12 π⁰, η
- E12-11-003: CLAS12 DVCS n
- E12-12-007: CLAS12 φ meson
- C12-12-010: CLAS12 Hdice
- E12-13-010: HallC DVCS
- E12-16-010: CLAS12 DVCS 2 energies

**RHIC (STAR/sPHENIX)**
- not DVCS

**COMPASS**
- DVCS: 2x6 months

**FUTURE @ CERN**
- Compass DVCS: 4 weeks Pilot run
Conclusions

Jlab 12 GeV will perfectly investigate the valence quarks at large $x_B$

COMPASS with high energy muon beams at CERN and RHIC will provide first results of sea quarks and gluons at small $x_B$

All these facilities are physics opportunities prior EIC - to preserve knowledge on state of the art techniques - to prepare the next generation of leading new experiments at EIC
**Proton picture: 1D**  ➔  **1+2D**

**Parton Distribution Functions**

**PDFs** ($x$)

- **Longitudinal momentum**
  
  \[ q(x) \text{ or } f_1^q(x) \]

- **Longitudinal spin**
  
  \[ \Delta q(x) = \bar{q}(x) - \bar{\bar{q}}(x) \]

- **Transverse spin**
  
  \[ \Delta_T q \text{ or } h_1(x) \]

**Transverse momentum**

- 8 TMDs ($x, \mathbf{k}_\perp$)
  
  \[ \int d\mathbf{k}_\perp \]

**Transverse position**

- Impact param. $q(x, \mathbf{b}_\perp)$
  
  \[ \int d\mathbf{b}_\perp \]

**Form Factors**

- 8 GPDs ($x, \mathbf{b}_\perp, \mathbf{t}$)
  
  \[ \int dx \]

**Quantum tomography of the nucleon**

The Wigner functions offer unprecedented insight into confinement and chiral symmetry breaking.

**Theorems**

- Ji, PRL91 (2003), Belitsky, Ji, Yuan, PRD69 (2004)
- Lorcé et al, JHEP1105 (2011)

**Theorems**

- Ji, PRL91 (2003), Belitsky, Ji, Yuan, PRD69 (2004)
- Lorcé et al, JHEP1105 (2011)
Figure 2.2: Connections between different quantities describing the distribution of partons inside the proton. The functions given here are for unpolarized partons in an unpolarized proton; analogous relations hold for polarized quantities.
Exclusivity: $\ell p \rightarrow \ell + \gamma$ (or $\rho^0$) + p

\[ M_x^2 = (P_\ell + P_p - P_\ell - P_\gamma)^2 \]

$\Delta M_x^2$ increases with the beam energy!
Figure 2.22: Average values of $b_T^2$ obtained from the DVCS cross section in different bins of $x_B$ and $Q^2$. The assumed luminosity is as for the left panels of figure 2.21.