Nucleon structure in 3D: experimental status and perspectives

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An abridged history of nucleon structure

1960s: the Quark Model. Nucleons are composed of three valence quarks! Gell-Mann (Nobel Prize 1969), Zweig.


1972: Theory of QCD developed.

21st Century: High-precision imaging of quarks and gluons. 3D tomography of the nucleon: spatial and momentum distributions inside it, mechanical properties of the nucleon, ...


1970s-1990s: Deep Inelastic Scattering reveals a rich structure: quark-gluon sea, flavour distributions, puzzles of spin and mass... what you see depends on how closely you look!
A constructivist view of the nucleon

Wigner distributions

\[ \rho(x, k_T, b_T) \]

intuitive relation to experimental observables

Longitudinal momentum

\[ k^+ = xP^+ \]

\( x \): longitudinal momentum fraction carried by struck parton
Wigner function: full phase space parton distribution of the nucleon

Generalised Transverse Momentum Distributions (TMDs)

\[ \int d^2 k_T \]

\[ \int d^2 b_T \]

Generalised Parton Distributions (GPDs)

\[ \int dx \]

\[ \int d^2 b_T \]

Form Factors e.g. \( G_E, G_M \)

\[ \int d^2 k_T \]

Parton Distribution Functions (PDFs)

Transverse Momentum Distributions (TMDs)
Wigner function: full phase space parton distribution of the nucleon

Generalised Transverse Momentum Distributions (TMDs)

\[ \int d^2k_T \]

Transverse Momentum Distributions (TMDs)

Generalised Parton Distributions (GPDs)

\[ \int dx \]

G. Renee Guzlas, artist.

Form Factors eg: \( G_E, G_M \)

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\[ \int d^2b_T \]
Wigner function:
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Generalised Transverse Momentum Distributions (GTMDs)

\[ \int d^2k_T \]

It’s a Wall!

Generalised Parton Distributions (GPDs)

\[ \int dx \]

G. Renee Guzlas, artist.

Parallel session 6 on Tuesday

Parallel session 6 on Saturday

Parallel session 6 on Sunday
Generalised Parton Distributions

- can be interpreted as relating, in the infinite momentum frame, transverse position of partons (impact parameter $b_\perp$) to longitudinal momentum fraction ($x$).

**Tomography** of the nucleon: transverse spatial distributions of quarks and gluons in longitudinal momentum space.

* Information on the orbital angular momentum contribution to nucleon spin: the spin puzzle.

$$J_N = \frac{1}{2} = \frac{1}{2} \sum_q + L_q + J_g$$

Ji's relation:

$$J^q = \frac{1}{2} - J^g = \frac{1}{2} \int_{-1}^{1} x dx \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\}$$

* Indirect access to mechanical properties of the nucleon: possibilities of extracting pressure distributions within the nucleon.

* Combine with TMDs to access spin-orbit correlations of quarks and gluons, study non-perturbative interactions of partons.
Experimental processes for accessing GPDs

Accessible in *exclusive* processes, where all final state particles are determined:

- Deeply Virtual Compton Scattering (DVCS)
- Deeply Virtual Meson Production (DVMP) / Hard Exclusive Meson Production (HEMP)
- Time-like Compton Scattering (TCS)
- Double DVCS
- Production of a meson-photon pair, ...

Relies on *factorisation* of the process amplitude into a hard, perturbative part and the soft non-perturbative part containing GPD information.
Deeply Virtual Compton Scattering

the “golden channel” for GPD extraction

\[ Q^2 = - (k - k')^2 \quad t = (p'_n - p_n)^2 \]

**Bjorken variable:** \( x_B = \frac{Q^2}{2 p_n \cdot q} \)

\( x \pm \xi \) longitudinal momentum fractions of the struck parton

Skewness: \( \xi \equiv \frac{x_B}{2 - x_B} \)

\* At high exchanged \( Q^2 \) and low \( t \) access to four parton helicity-conserving, chiral-even GPDs:

\[ E^q, \tilde{E}^q, H^q, \tilde{H}^q(x, \xi, t) \]

\* Can be related to PDFs:

\[ H(x, 0, 0) = q(x) \quad \tilde{H}(x, 0, 0) = \Delta q(x) \]

and form factors:

\[ \int_{-1}^{+1} H \, dx = F_1 \quad \int_{-1}^{+1} \tilde{H} \, dx = G_A \]

\( (\text{Dirac and Pauli}) \)

\[ \int_{-1}^{+1} E \, dx = F_2 \quad \int_{-1}^{+1} \tilde{E} \, dx = G_P \]

\( (\text{axial and pseudo-scalar}) \)

\* Small changes in nucleon transverse momentum allows mapping of transverse structure at large distances.
Measuring DVCS

Process measured in experiment:

\[ d\sigma \propto |T_{DVCS}|^2 + |T_{BH}|^2 + T_{BH}T_{DVCS}^* + T_{DVCS}T_{BH}^* \]

- Amplitude calculable from elastic Form Factors and QED
- Amplitude parameterised in terms of Compton Form Factors

Interference term

\[ |T_{DVCS}|^2 \ll |T_{BH}|^2 \]
Compton Form Factors in DVCS

Experimentally accessible in DVCS cross-sections and spin asymmetries, eg:

\[ A_{LU} = \frac{d\sigma - d\bar{\sigma}}{d\sigma + d\bar{\sigma}} = \frac{\Delta\sigma_{LU}}{d\sigma + d\bar{\sigma}} \]

At leading twist, leading order:

\[ T_{DVCS}^{\perp} \sim \int_{-1}^{1} \frac{GPDs(x, \xi, t)}{x \pm \xi + i\epsilon} \, dx + \ldots \sim P \int_{-1}^{1} \frac{GPDs(x, \xi, t)}{x \pm \xi} \, dx \pm i\pi GPDs(\pm \xi, \xi, t) + \ldots \]

Only $\xi$ and $t$ are accessible experimentally!

To get information on $x$ need extensive measurements in $Q^2$.

Need measurements off proton and neutron to get flavour separation of CFFs in DVCS.
Nucleon at different scales

Valence quarks

Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$

Parton Distribution Function

$Q^2 = 10 \text{ GeV}^2$

$\frac{xf(x,Q^2)}{Q^2}$

$\frac{xS(x)}{Q^2}$

$\frac{xd(x)}{Q^2}$

$\frac{xg(x)}{Q^2}$

$\frac{ux_u}{Q^2}$
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**Jefferson Lab**: fixed-target electron scattering

\[ 0.1 < x_B < 0.7 \]

**Sea quarks**

**HERMES**: fixed gas-target electron/positron scattering

\[ 0.02 < x_B < 0.3 \]
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COMPASS: fixed-target muon scattering

\[ 0.01 < x_B < 0.1 \]
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The glue

ZEUS/H1: electron/positron-proton collider

\[10^{-4} < x_B < 0.02\]
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Electron-ion collider: \( 10^{-4} < x_B < 10^{-1} \)

Luminosity 100 - 1000 times that of HERA
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Luminosity 100 - 1000 times that of HERA

See EIC talks in parallel session 6 on Tuesday 14.00:

EicC: Y. Liang
US EIC: Z. Kang

Derek Leinweber
Kinematic landscape

Image from Po-Ju Lin, IWHSS 2019
Jefferson Lab: 6 GeV era

CEBAF: Continuous Electron Beam Accelerator Facility.

- Energy up to $\sim 6$ GeV
- Energy resolution $\delta E/E_e \sim 10^{-5}$
- Longitudinal electron polarisation up to $\sim 85\%$

Hall A:
- High resolution ($\frac{\delta p}{p} = 10^{-4}$) spectrometers, very high luminosity.

Hall B: CLAS
- Very large acceptance, detector array for multi-particle final states.

Hall C:
- Two movable spectrometer arms, well-defined acceptance, high luminosity
JLab @ 12 GeV

Hall A

High resolution ($\frac{\delta p}{p} = 10^{-4}$) spectrometers, very high luminosity, large installation experiments.

Hall B: CLAS12

Very large acceptance, high luminosity.

Hall C

Two movable high momentum spectrometers, well-defined acceptance, very high luminosity.

GlueX

Hall D

9 GeV tagged polarised photons, full acceptance
High resolution ($\delta p/p = 10^{-4}$) spectrometers, very high luminosity, large installation experiments.

**Hall B: CLAS12**

Very large acceptance, high luminosity.

**Hall C**

Two movable high momentum spectrometers, well-defined acceptance, very high luminosity.
CLAS12

Design luminosity
$L \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

High luminosity & large acceptance: Concurrent measurement of exclusive, semi-inclusive, and inclusive processes

Acceptance for photons and electrons:
• $2.5^\circ < \theta < 125^\circ$

Acceptance for all charged particles:
• $5^\circ < \theta < 125^\circ$

Acceptance for neutrons:
• $5^\circ < \theta < 120^\circ$
DVCS in Hall A

- 15 cm long liquid $H_2$ target
- E00-110 experiment (2004): 5.75 GeV polarised electron beam
- E07-004 experiment (2010):
  - Luminosity = $10^{37}$ cm$^{-2}$s$^{-1}$
  - Energy scan for fixed $x_B$, $Q^2$:

<table>
<thead>
<tr>
<th>$Q^2$ (GeV$^2$)</th>
<th>$x_B$</th>
<th>$E^{\text{beam}}$ (GeV)</th>
<th>$-t$ (GeV$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.50</td>
<td>0.36</td>
<td>3.355</td>
<td>0.18, 0.24, 0.30</td>
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<td>5.55</td>
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<tr>
<td>1.75</td>
<td>0.36</td>
<td>4.455</td>
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<td>2.00</td>
<td>0.36</td>
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<tr>
<td></td>
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</tbody>
</table>

[Image of DVCS reaction and experimental setup]
High-precision cross-sections: Hall A

- High precision cross-section measurement in a small kinematic region: Generalised Rosenbluth separation of the DVCS\(^2\) (scales as \(E_e^2\)) and the BH-DVCS interference (scales as \(E_e^3\)) terms. NLO and/or higher-twist improve model agreement.

- Significant differences between pure DVCS and interference contributions.

- If NLO: sensitivity to gluons.

- Separation of HT and NLO effects requires scans across wider ranges of \(Q^2\) and beam energy: JLab12.

\[Q^2: 1.5, 1.9, 2.3 \text{ GeV}^2 \text{ at fixed } x_B 0.36\]
\[-t: 0.18, 0.24, 0.30\]

\(E_e\): 4.5, 5.6 GeV.

Large kinematic coverage: CLAS

* Unpolarised DVCS cross-sections and helicity-dependent cross-section differences in a wide kinematic range:

- CFFs extracted in a VGG fit.
  \[ F_{Im}(\xi, t) = F(\xi, \xi, t) \mp F(-\xi, \xi, t) \]

- VGG (Vanderhaeghen, Guichon, Guidal)
- \( A e^{bt} \) prediction

* Dominance of GPD \( H \) in unpolarised cross-section.

* \( H_{Im} \) slope in \( t \) becomes flatter at higher \( x_B \)

Valence quarks at centre, sea quarks spread out towards the periphery.

N. Hirlinger Saylor et al (CLAS), *PRC* 98 (2018) 045203
DVCS asymmetries @ CLAS

High statistics, large kinematic coverage, strong constraints on fits, simultaneous fit of BSA, TSA and DSA at common kinematics from the same dataset:

\[ \Delta \sigma_{LU} \sim \sin \phi \Im(F_1 \tilde{H} + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E) \, d\phi \]

\[ \Delta \sigma_{UL} \sim \sin \phi \Im(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) - \xi \frac{t}{4M^2} F_2 \tilde{E} + ...) \, d\phi \]

\[ \Delta \sigma_{LL} \sim (A + B \cos \phi) \Re(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) + ... ) \, d\phi \]

\( F_1, F_2: \) Dirac, Pauli form factors

Constraints on CFFs \( H \) and \( \tilde{H} \)

E. Seder et al (CLAS), PRL 114 (2015) 032001
S. Pisano et al (CLAS), PRD 91 (2015) 052014
F.-X. Girod et al (CLAS), PRL 100 (2008) 162002
What can we learn from the asymmetries?

- Information on relative distributions of quark momenta (PDFs) and quark helicity, $\Delta q(x)$. 

$$H(x, 0, 0) = q(x) \quad \tilde{H}(x, 0, 0) = \Delta q(x)$$

- Indications that axial charge is more concentrated than electromagnetic charge.

$$\int_{-1}^{+1} H \, dx = F_1$$

$$\int_{-1}^{+1} \tilde{H} \, dx = G_A$$

Answers will hinge on a global analysis of all available data: eg: PARTONS framework.

GPDs and nucleon spin

\[ J_N = \frac{1}{2} = \frac{1}{2} \Sigma_q + L_q + J_g \]

\* Ji’s relation:

\[ J^q = \frac{1}{2} - J^g = \frac{1}{2} \int_{-1}^{1} x dx \left\{ H^q(x, \xi, 0) + E^q(x, \xi, 0) \right\} \]

\* \( H^q \) in DVCS off the proton, first experimental constraint on \( E^q \) from neutron-DVCS beam-spin asymmetry.

M. Mazouz et al, PRL 99 (2007) 242501

\* Gives constraints on orbital angular momentum of quarks: the spin puzzle.

\* Rosenbluth separation of interference & DVCS terms underway in neutron-DVCS cross-sections: \( E_e = 4.5 \) and 5.5 GeV (experiment E08-025).

\( LD_2 \) target \quad \langle Q^2 \rangle = 1.75 \text{ GeV}^2 \quad \langle x_B \rangle = 0.36
Towards nucleon tomography: local fits

Quasi model-independent extraction of CFFs based on a local fit:

- Set 8 CFFs as free parameters to fit, at each \((x_B, t)\) point, the available observables.
- Limits imposed within +/- 5 times the VGG model predictions (Vanderhaeghen-Guichon-Guidal).
- Leading-twist DVCS amplitude parametrisation based on Double Distributions.

The best constraints in fits to CLAS data were obtained on \(H_{Im}\).

Parametrise its dependence on \(t\):

\[
H_{Im}(\xi, t) = A(\xi) e^{B(\xi)t}
\]

Relates to quark density

Inverse relation to spatial distribution

Towards nucleon tomography: local fits

Relating the impact parameter to helicity-averaged transverse distribution:

\[ \rho^q(x, b_\perp) = \int \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{-ib_\perp \cdot \Delta_\perp} H^q(x, 0, -\Delta_\perp^2) \]

\[ H^q(x, 0, t) \equiv H^q(x, 0, t) + H^q(-x, 0, t) \]

Transverse four-momentum transfer to nucleon

Assuming leading-twist and exponential dependence of GPD on $t$, using models to extrapolate to the zero skewness point $\xi = 0$ and assuming similar behaviour for $u$ and $d$ quarks there:

\[ \langle b^2 \rangle^q(x) = -4 \frac{\partial}{\partial \Delta_\perp^2} \ln H^q(x, 0, -\Delta_\perp^2) \bigg|_{\Delta_\perp = 0} \]

Tentative hints of 3D distributions are emerging. 

*We need more data from JLab @ 11 GeV!*

Towards nucleon tomography: global fits

PARTONS framework: global fits and neural networks to minimise model-dependence in the extraction of CFFs.

Inclusion of other channels into PARTONS underway.

Framework in place: more data needed!

Image from Pawel Sznajder, IWHSS 2019
Imaging pressure within the nucleon

- GPDs provide indirect access to mechanical properties of the nucleon (encoded in the gravitational form factors, GFFs, of the energy-momentum tensor).
  - M. Polyakov, PLB 555, 57-62 (2016)

- Three scalar GFFs, functions of $t$: encode pressure and shear forces ($d_1(t)$), mass ($M_2(t)$) and angular momentum distributions ($J(t)$).

- Can be related to GPDs via sum rules:
  $$\int x [H(x, \xi, t) + E(x, \xi, t)] \, dx = 2J(t)$$
  $$\int xH(x, \xi, t) \, dx = M_2(t) + \frac{4}{5} \xi^2 d_1(t)$$

- Model-dependent extraction

- Neural net analysis, however: $d$-term almost unconstrained and consistent with zero

  Possibility of extracting pressure distributions! But more data needed.

Detect electron with (Super) High Momentum Spectrometer, (S)HMS.

Detect photon in PbWO$_4$ calorimeter.

Sweeping magnet to reduce backgrounds in calorimeter.

Reconstruct recoiling proton through missing mass.
DVCS in Hall C

Detect electron with (Super) High Momentum Spectrometer, (S)HMS.

Detect photon in PbWO₄ calorimeter.

Sweeping magnet to reduce backgrounds in calorimeter.

Reconstruct recoiling proton through missing mass.

See talk in parallel session 6 on Tuesday 8.55am:

DVCS in Hall C: Ho San Ko
11 GeV era DVCS Cross-sections: Halls A and C

Experiments:
**E12-06-114** (Hall A, 100 days),
**E12-13-010** (Hall C, 53 days)
C. Muñoz Camacho et al.,
C. Hyde et al.

Unpolarised liquid H$_2$ target:
- Beam energies: 6.6, 8.8, 11 GeV
- Scans of $Q^2$ at fixed $x_B$.
- Hall A: aim for absolute cross-sections with 4% relative precision.

- Azimuthal, energy and helicity dependencies of cross-section to separate $|T_{DVCS}|^2$ and interference contributions in a wide kinematic coverage.
- Separate $Re$ and $Im$ parts of the DVCS amplitude.
11 GeV era: DVCS with CLAS12

**E12-06-119:** Unpolarised liquid H$_2$ target
Beam-spin asymmetry $\rightarrow \text{Im}(H_p)$

**First experiment with CLAS12!** Almost complete

**E12-16-010:** Unpolarised liquid H$_2$ target
Beam energy: 6.6 GeV, 8.8 GeV Almost complete

**E12-11-003:** Unpolarised liquid D$_2$ target
$$e + d \rightarrow e' + \gamma + n + (p_s)$$
Beam-spin asymmetry $\rightarrow \text{Im}(E_n)$ Running this year!

**E12-12-010:** Transversely polarised HD target.
Target-spin asymmetries $\rightarrow \text{Im}(E_p)$

~2023?

**E12-06-109:** Longitudinally polarised NH$_3$ and ND$_3$ targets

- Dynamic Nuclear Polarisation (DNP) of target material, cooled in a He evaporation cryostat.
- $P_{\text{proton}} = 80\%$, $P_{\text{deuteron}}$ up to 50\%

Target-spin asymmetry in proton- and neutron-DVCS $\rightarrow \text{Im}(\tilde{H}_p), \text{Im}(H_n)$

~ 2021

- $P_{\text{beam}} = 85\%$
- $L = 10^{35}$ cm$^{-2}$s$^{-1}$
- $1 < Q^2 < 10$ GeV$^2$
- $0.1 < x_B < 0.65$
- $-t_{\text{min}} < -t < 2.5$ GeV$^2$
DVCS with CLAS12

**E12-06-119**: Unpolarised liquid H$_2$ target

Beam-spin asymmetry $\rightarrow \text{Im}(H_p)$

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Raw Beam-Spin Asymmetry $ep \rightarrow ep\gamma$

No background subtraction

Guillaume Christiaens
Neutron DVCS @ 11 GeV: sensitivity to $J_q$

$E_e = 11$ GeV

$A_{LU}$ vs $\phi$ ($^\circ$)

VGG (calculations by M. Guidal)

Fixed kinematics: $x_B = 0.17 \quad Q^2 = 2$ GeV$^2 \quad t = -0.4$ GeV$^2$

- $J_u = 0.3, J_d = -0.1$  
- $J_u = 0.3, J_d = 0.1$
- $J_u = 0.1, J_d = 0.1$
- $J_u = 0.3, J_d = 0.3$
- $J_u = 0.3, J_d = -0.1$

- At 11 GeV, beam spin asymmetry ($A_{LU}$) in neutron DVCS is very sensitive to $J_u, J_d$
- Dedicated neutron detector added to CLAS12: Central Neutron Detector
DVCS on $^4$He: CLAS12 with ALERT

Experiment E12-17-012: Measurement of BSA in coherent DVCS from a $^4$He target: partonic structure of nuclei.

- Spin 0 target, so at leading twist only one chiral-even GPD: $H_A$.

11 GeV beam, 80% polarised. Gas target straw @ 3 atm $L = 6 \times 10^{34}$ nucleon cm$^{-2}$s$^{-1}$ with 1000 nA beam.

CLAS12 + ALERT: central recoil detector

Experiment E12-17-012B

W. Armstrong et al.

Incoherent, spectator-tagged DVCS on $^4$He and $d$. 
COMPASS @ Cern (SPS)

Compact Muon and Proton Apparatus for Structure and Spectroscopy

**COMPASS-II:**
2012 - 2021

Forward particles: two-stage large angle, wide momentum range spectrometer (tracking, muon filters, calorimeters).

**2.5m liquid H₂ target**
Upgrades: new scintillator ToF CAMERA for recoil proton detection & new EM calorimeter.

- 160 GeV 80% polarised $\mu^+ / \mu^-$
- $\sim 4 \times 10^8 \mu/\text{spill}$, 9.6s/40s duty cycle

**Data:**
- 2008 & 2009: two very short test runs, 40 cm $LH_2$ target.
- COMPASS-II: 1 month in 2012, 6 months in 2016 & 2017 each (GPD $H$).
- 2022+: transversely pol. $NH_3$ target (GPD $E$). LOI stage...

**DVCS:** $\mu^+ p \rightarrow \mu^0 p \gamma$
DVCS @ COMPASS (2012 run)

- DVCS dominates at these kinematics.
- Bethe-Heitler dominates at very low $x_B$.
- $0.005 < x_B < 0.01$
- $x_B > 0.03$

Slide mash-up from N. d’Hose and A. Ferrero
$d\sigma^{DVCS}/dt = e^{-B|t|}$

$\langle x_{Bj} \rangle = 0.056$
$\langle Q^2 \rangle = 1.8 \text{ (GeV/c)}^2$
$\langle W \rangle = 5.8 \text{ GeV/c}^2$

$B = 4.31 \pm 0.62^{+0.09}_{-0.25} \text{ (GeV/c)}^{-2}$

$1 \text{ (GeV/c)}^2 < Q^2 < 5 \text{ (GeV/c)}^2$
$10 \text{ GeV} < \nu < 32 \text{ GeV}$

arXiv:1802.02739 [hep-ex]
**Tomography of sea quarks**

Heră

10 times more stats in 2016-17 runs

Integrated luminosity: $42.4 \text{ pb}^{-1}$

\[ 1 < Q^2 < 5 \text{ GeV}^2 \]
\[ \langle Q^2 \rangle = 1.8 \text{ GeV}^2 \]
\[ \langle x_B \rangle = 0.056 \]

\[ B = (4.31 \pm 0.62_{\text{stat}} \pm 0.09_{\text{sys}}) \text{ (GeV/c)}^{-2} \]

\[ \sqrt{\langle r_{\perp}^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \pm 0.01_{\text{sys}} \pm 0.04_{\text{model}}) \text{ fm} \]

at average $x_B = 0.056$
Tomography of sea quarks

See talk in parallel session 6 on Tuesday 8.30am: GPDs @ COMPASS: Po-Ju Lin

\[ B = (4.31 \pm 0.62_{\text{stat}} \pm 0.09_{\text{sys}})(\text{GeV}/c)^{-2} \]

\[ \sqrt{\langle r_{\perp}^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \pm 0.01_{\text{sys}} \pm 0.04_{\text{model}}) \text{fm} \]

at average \( x_B = 0.056 \)

\[ 1 < Q^2 < 5 \text{ GeV}^2 \]

\[ \langle Q^2 \rangle = 1.8 \text{ GeV}^2 \]

\[ \langle x_B \rangle = 0.056 \]

Integrated luminosity:

42.4 pb\(^{-1}\)

10 times more stats in 2016-17 runs

\[ \langle r_{\perp}^2(x_B) \rangle \approx 2B(x_B) \]

for small \( x_B \)
Deeply Virtual Meson Production

- Amplitude depends on convolution of GPDs and meson Distribution Amplitudes (DA).
- At leading order & twist, access to the four chiral-even (parton helicity-conserving) GPDs:
  - Pseudo-scalar mesons: $\tilde{H}^q, \tilde{E}^q(x, \xi, t)$
  - Vector mesons: $H^q, E^q, H^g, E^g(x, \xi, t)$

DVMP enables flavour decomposition of quark GPDs and gives access to gluon GPDs

Caveats:
- factorisation established only for longitudinal photons,
- factorisation sets in at a higher scale than in DVCS,
- DA not entirely understood

Extracting GPDs from DVMP is hard!
DVMP Cross-section

Virtual photon flux

\[
\frac{2\pi}{\Gamma} \frac{d^4 \sigma}{dQ^2 dx_B dt d\phi_{meson}} = \sigma_T + \epsilon \sigma_L + \epsilon \sigma_{TT} \cos 2\phi + \sqrt{\epsilon(1+\epsilon)} \sigma_{LT} \cos \phi
\]

\[
+ P_b \sqrt{\epsilon(1-\epsilon)} \sigma_{LT} \sin \phi
\]

\[
+ P_{tg} \left( \sqrt{\epsilon(1+\epsilon)} \sigma_{UL}^{\sin \phi} \sin \phi + \epsilon \sigma_{UL}^{\sin 2\phi} \sin 2\phi \right)
\]

\[
+ P_b P_{tg} \left( \sqrt{1-\epsilon^2} \sigma_{LL} + \sqrt{\epsilon(1-\epsilon)} \sigma_{LL}^{\cos \phi} \cos \phi \right)
\]

\(\epsilon\): ratio of the fluxes of longitudinally (L) and transversely (T) polarised virtual photons.

\(\sigma_i\): structure functions, related to scattering amplitudes \((i = L, T, LT, \ldots)\), eg:

\[
\frac{d\sigma_L}{dt} = \frac{4\pi \alpha}{k'} \frac{1}{Q^6} \left\{ (1 - \xi^2) |\langle \tilde{H} \rangle|^2 - 2\xi^2 \text{Re}[\langle \tilde{H}^* \rangle \langle \tilde{E} \rangle] - \frac{t'}{4m^2} \xi^2 |\langle \tilde{E} \rangle|^2 \right\}
\]

where \(\langle F \rangle \equiv \sum_\lambda \int_{-1}^1 dx \mathcal{H}_{\mu'\lambda'\mu\lambda} F \)
Transversity GPDs

For pseudo-scalar mesons, access four chiral-odd (parton helicity-flipping) transversity GPDs (via convolutions of leading-twist GPDs with twist-3 meson DA):

\[ E_T^q, \tilde{E}_T^q, H_T^q, \tilde{H}_T^q(x, \xi, t) \]

Appear in DVMP amplitude when virtual photon has transverse polarisation — not accessible at LT in DVCS.

\( \tilde{E}_T \) can be related to the transverse anomalous magnetic moment:

\[ \kappa_T = \int_{-1}^{+1} \tilde{E}_T(x, \xi, t = 0) \, dx \]

and \( H_T \) to the transversity distribution:

\[ H_T(x, 0, 0) = h_1(x) \]

which describes distribution of transverse partons in a transverse nucleon

The combination \( \bar{E}_T = 2\tilde{H}_T + E_T \)

is related to spatial density of transversely polarised quarks in an unpolarised nucleon.
Vector mesons:

- L/T contributions to cross-sections separated by using helicity conservation between virtual photon and meson: strong deviations from leading-twist GPD formalism (higher-twist? evolution effects? meson-size corrections?)

- Gluonic GPD $H_g$ dominates at small $x$: gluonic radius.

  GPD extraction much cleaner for heavier quarks: $J/\Psi$

Too close to threshold @ JLab12, ideal for the Electron-Ion Collider!

Pseudo-scalar mesons:

- Separation of L/T contributions to cross-sections through Rosenbluth-like techniques / simultaneous fits at different kinematics.

- Strong transverse contribution observed in charged and neutral pion / $K+$ cross-sections: possible access to transversity GPDs.

- Attempt at GPD flavour-separation using $\pi^0$ and $\eta$ BSA.

M. Defurne et al, PRL 117 (2016) 262001
Meson production at JLab 12 GeV

Cross-sections and spin asymmetries in the 11 GeV kinematics:

- Hard exclusive electroproduction of $\eta$ and $\pi^0$ (E12-06-108, CLAS12)
- Exclusive $\phi$ meson electroproduction (E12-12-007, CLAS12)
- DVCS and neutral pion cross-sections (E12-13-010, Hall C)
- Scaling study of the L-T separated pion electroproduction cross-section (E12-07-105, Hall C)
- Studies of the L-T separated kaon electroproduction cross-section from 5-11 GeV (E12-09-011, Hall C)
- Near-threshold electroproduction of $J/\Psi$ (E12-12-006, Hall A)
- Time-like Compton scattering and $J/\Psi$ electroproduction (E12-12-001, CLAS12)
Meson production at COMPASS

Unpolarised target:

\[ e^+ p \rightarrow e^- \pi^0 p \]

Transversely-polarised target: \( \rho^0 \) and \( \omega \)

Sensitivity to \( H_T \)

hep-ex: 1903.12030

Slide from Po-Ju Lin, IWHSS 2019
Meson production at COMPASS

Unpolarised target:

\[ e^+ p \to e^- \pi^0 p \]

Transversely-polarised target: \( \rho^0 \) and \( \omega \)

Sensitivity to \( H_T \)

See talk in parallel session 6 on Tuesday 8.30am:

GPDs @ COMPASS: Po-Ju Lin

hep-ex: 1903.12030
Summary

- Valence quark region at Jefferson Lab, sea quarks at Hermes and COMPASS. Very low-x gluons await the Electron-Ion Collider.
- Factorisation appears to be applicable at JLab kinematics for DVCS, situation for HEMP/DVMP not so straight-forward.
- Constraints for GPD models, most strongly for H and $\tilde{H}$
- First attempts at tomography -- framework in place, more data needed!
- Possibility of extracting pressure distributions of the nucleon.
- GPDs in the nuclear medium.
- Need measurements across a wide range of channels: DVCS, Double-DVCS, TCS, HEMP/DVMP, meson-photon production, ...
Thank you!
Back-up
Order and Twist

Twist: powers of $\frac{1}{\sqrt{Q^2}}$ in the DVCS amplitude. Leading-twist (LT) is twist-2.

Order: introduces powers of $\alpha_s$

Leading Order (LO) requires $Q^2 >> M^2$ ($M$: target mass)
DVCS with transversely polarised target @ COMPASS

\[ \mathcal{D}_{CS,T} = \Delta \sigma_{T}(\mu^{+}) - \Delta \sigma_{T}(\mu^{-}) \]
\[ \rightarrow \text{Im}(F_2 \mathcal{H} - F_1 \mathcal{E}) \sin(\phi - \phi_s) \cos \phi \]

\[ A \sin(\phi - \phi_s) \cos \phi \]

1.2m long transv. polarized NH$_3$ target

Indications of statistical accuracy.

Slide from: N. d’Hose @ Getting to Grips with QCD, Primosten 2018
Detect electron in the Left High Resolution Spectrometer (HRS-L): 0.01% momentum resolution

Detect photon in PbF$_2$ calorimeter: < 3% energy resolution

Detect recoil proton in plastic scintillator array.
Large kinematic coverage: CLAS

- Unpolarised DVCS cross-sections and helicity-dependent cross-section differences in a wide kinematic range:

- Widest phase space coverage in valence quark region: CFF constraints.

N. Hirlinger Saylor et al (CLAS), PRC 98 (2018) 045203
Which DVCS experiment?

Real parts of CFFs accessible in cross-sections, beam-charge and double polarisation asymmetries,

imaginary parts of CFFs in single-spin asymmetries.

For example:

\[ \Delta \sigma_{LU} \sim \sin \phi \Im \left( F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E \right) d\phi \]

\[ \Delta \sigma_{UL} \sim \sin \phi \Im \left( F_1 \tilde{H} + \xi G_M \left( H + \frac{x_B}{2} E \right) - \xi \frac{t}{4M^2} F_2 \tilde{E} + \ldots \right) d\phi \]

\[ \Delta \sigma_{UT} \sim \cos \phi \Im \left( \frac{t}{4M^2} (F_2 H - F_1 E) + \ldots \right) d\phi \]

\[ \Delta \sigma_{LL} \sim (A + B \cos \phi) \Re \left( F_1 \tilde{H} + \xi G_M \left( H + \frac{x_B}{2} E \right) + \ldots \right) d\phi \]

<table>
<thead>
<tr>
<th>Proton</th>
<th>Neutron</th>
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<tbody>
<tr>
<td>( \text{Im} {H_p, \tilde{H}_p, E_p} )</td>
<td>( \text{Im} {H_n, H_n, E_n} )</td>
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<tr>
<td>( \text{Im} {\tilde{H}_p} )</td>
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<tr>
<td>( \text{Re} {\tilde{H}_p} )</td>
<td>( \text{Re} {H_n, E_n, \tilde{E}_n} )</td>
</tr>
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</table>
What do GPDs tell us?

- **Tomography** of the nucleon: transverse spacial distributions of quarks and gluons in longitudinal momentum space.

- For small $x$ can image the pion cloud: chiral symmetry breaking.

- Provide information on the orbital angular momentum contribution to nucleon spin: the spin puzzle.

- Using transversely polarised targets can map transverse shift of partons due to the polarisation: combine with TMDs to access spin-orbit correlations of quarks and gluons, study non-perturbative interactions of partons.

- Indirect access to mechanical properties of the nucleon: possibilities of extracting pressure distributions within the nucleon.
Beam-spin Asymmetry ($A_{LU}$)

Follows first CLAS measurement: S. Stepanyan et al (CLAS), *PRL* 87 (2001) 182002

$A_{LU}$ from fit to asymmetry:

$$A_i = \frac{\alpha_i \sin \phi}{1 + \beta_i \cos \phi}$$

$A_{LU}$ characterised by imaginary parts of CFFs via:

$$F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} E$$

Qualitative agreement with models, constraints on fit parameters.

Target-spin Asymmetry ($A_{UL}$)

Follows first CLAS measurement:
S. Chen et al (CLAS),
PRL 97 (2006) 072002

$A_{UL}$ from fit to asymmetry:

$$A_i = \frac{\alpha_i \sin \phi}{1 + \beta_i \cos \phi}$$

$A_{UL}$ characterised by imaginary parts of CFFs via:

$$F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) - \frac{\xi t}{4M^2} F_2 \tilde{E} + ...$$

High statistics, large kinematic coverage, strong constraints on fits, simultaneous fit with BSA and DSA from the same dataset.

E. Seder et al (CLAS), PRL 114 (2015) 032001
S. Pisano et al (CLAS), PRD 91 (2015) 052014
Beam- and target-spin asymmetries

\[ A = \frac{\alpha \sin \phi}{1 + \beta \cos \phi} \]

KMM: Kumericki, Mueller, Murray
GK: Kroll, Moutarde, Sabatié
GGL: Goldstein, Gonzalez, Liuti
VGG: Vanderhaeghen, Guichon, Guidal

TSA shows a flatter distribution in \( t \) than BSA.

S. Pisano et al (CLAS), *PRD* 91 (2015) 052014
E. Seder et al (CLAS), *PRL* 114 (2015) 032001
Double-spin asymmetry

At leading twist, double-spin asymmetry (DSA) can be expressed as:

$$A_{LL}(\phi) \sim \frac{c_{0,LP}^{BH} + c_{1,LP}^{T} + (c_{1,LP}^{BH} + c_{1,LP}^{T}) \cos \phi}{c_{0,unp}^{BH} + (c_{1,unp}^{BH} + c_{1,unp}^{T} + \ldots) \cos \phi \ldots}$$

$$c_{0,LP}^{T}, c_{1,LP}^{T} \propto \Re[F_1 \tilde{H} + \xi(F_1 + F_2)(\mathcal{H} + \frac{x_B}{2} \mathcal{E}) - \xi(\frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2) \tilde{\mathcal{E}}]$$

At CLAS kinematics, leading-twist dominance of these CFFs

* Fit function for the phi-dependence of the asymmetry:

$$\frac{\kappa_{LL} + \lambda_{LL} \cos \phi}{1 + \beta \cos \phi}$$

Shares denominator with BSA and TSA!
If measurements at same kinematics, can do a simultaneous fit.
Double-spin Asymmetry ($A_{LL}$)

$A_{LL}$ from fit to asymmetry:
\[
\frac{\kappa_{LL} + \lambda_{LL} \cos \phi}{1 + \beta \cos \phi}
\]

$A_{LL}$ characterised by real parts of CFFs via:
\[
F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) + \ldots
\]

- Fit parameters extracted from a simultaneous fit to BSA, TSA and DSA.
- Constant term dominates and is almost entirely BH.


CFF extraction from three spin asymmetries at common kinematics.
Projected sensitivities to $\text{Im}(H)$ CFF

$Q^2 = 2.6 \text{ GeV}^2, x_B = 0.23$

$\text{Im}(H): p$

$\text{Im}(H): n$

$Q^2 = 5.9 \text{ GeV}^2, x_B = 0.35$

$\text{Im}(H): p$

$\text{Im}(H): n$

$\text{Im}(H): d$

$\text{Im}(H): u$

Projections for $\text{Im}(H)$ neutron and proton and up and down CFFs extracted from approved CLAS12 experiments.

VGG fit (M. Guidal)
Projected sensitivities to $\text{Im}(E)$ CFF

$Q^2 = 2.6 \text{ GeV}^2$, $x_B = 0.23$

$\text{Im}(E)$: $p$
$\text{Im}(E)$: $n$

$Q^2 = 5.9 \text{ GeV}^2$, $x_B = 0.35$

$\text{Im}(E)$: $p$
$\text{Im}(E)$: $n$

Projections for $\text{Im}(E)$ neutron and proton and up and down CFFs extracted from approved and conditionally-approved CLAS12 experiments.

$Q^2 = 2.6 \text{ GeV}^2$, $x_B = 0.23$

$\text{Im}(E)$: $u$
$\text{Im}(E)$: $d$

$Q^2 = 5.9 \text{ GeV}^2$, $x_B = 0.35$

$\text{Im}(E)$: $u$
$\text{Im}(E)$: $d$

VGG fit (M. Guidal)
DVCS on the bound proton

• Beam spin asymmetry in DVCS from bound protons in $^4$He.

$A_{L/L}^{\text{coh}}/A_{L/L}^{\text{free}}$ vs $-t$ [GeV$^2$]

25% - 40% lower asymmetries for bound proton compared to free, no strong dependence on $t$.

Medium-modification effects, initial/final state interactions?

M. Hattawy et al, arXiv:1812.07628
Nuclear GPDs: coherent DVCS on $^{4}$He

$^{4}$He is spin-0, so only one GPD at leading twist, $H_{A}$.

$$\mathcal{R}e(H_{A}) = \mathcal{P} \int_{0}^{1} dx [H_{A}(x, \xi, t) - H_{A}(-x, \xi, t)] C^{+}(x, \xi)$$

$$\mathcal{S}m(H_{A}) = -\pi (H_{A}(\xi, \xi, t) - H_{A}(-\xi, \xi, t))$$

Beam spin asymmetry in coherent DVCS from $^{4}$He: CLAS and a radial time projection chamber (RTPC) for detection of recoiling helium, data taken in 2009.

Paves the way for measurements at 11 GeV.

First DVCS cross-sections in valence region

- E00-110: Hall A, ran in 2004, high precision, narrow kinematic range.
- Luminosity $= 10^{37}$ cm$^{-2}$s$^{-1}$.
- Measure $Q^2$-dependence ($Q^2: 1.5, 1.9, 2.3 \text{ GeV}^2$) of DVCS-BH cross-sections at fixed $x_B$ (0.36).
- Also $x_B$ dependence at constant $Q^2$.
- CFFs show scaling in DVCS: leading twist (twist-2) dominance at this moderate $Q^2$.

$x_B = 0.36, Q^2 = 2.3 \text{ GeV}^2, -t = 0.32 \text{ GeV}^2$

- Strong deviation of unpolarised DVCS cross-section from BH: extraction of $|T_{\text{DVCS}}|^2$ amplitude as well as interference terms.
First DVCS cross-sections in valence region

High precision of the data: sensitivity to subtle differences in model predictions.

- **VGG model**: Vanderhaeghen, Guichon, Guidal
- **KMS model**: Kroll, Moutarde, Sabatié
- **KM model**: Kumericki, Mueller

**TMC**: kinematic twist-4 target-mass and finite-$t$ corrections, calculated for proton DVCS and estimated for KMS12.

**KMS parameters** tuned on very low $x_B$ meson-production data: not adapted to valence quarks.

**TMC*: TMC extracted from the KMS12 model and applied to KM10a.**

**TMC** improve agreement for KM10a model, especially at $\phi = 180^\circ$. Higher-twist effects?

The devil is in the detail…

$x_B = 0.36$, $Q^2 = 1.9 \text{ GeV}^2$, $-t = 0.32 \text{ GeV}^2$

Here comes the twist…

Twist: powers of $\frac{1}{\sqrt{Q^2}}$ in the DVCS amplitude. Leading-twist (LT) is twist-2.

Order: introduces powers of $\alpha_s$

LO requires $Q^2 \gg M^2$ ($M$: target mass)

*Bold assumption for JLab 6 GeV kinematics!*

CFFs can be classified according to real and virtual photon helicity:

- Helicity-conserved CFFs $-\mathcal{F}_{++}$
- Helicity-flip (transverse) $-\mathcal{F}_{-+}$
- Longitudinal to transverse flip $-\mathcal{F}_{0+}$

CFFs contributing to the scattering amplitude:

- LT in LO: only $\mathcal{F}_{++}$
- LT in NLO: both $\mathcal{F}_{++}$ and $\mathcal{F}_{-+}$
- Twist-3: $\mathcal{F}_{0+}$
*At finite $Q^2$ and non-zero $t$ there’s ambiguity in defining the light-cone axis:*

Traditional GPD phenomenology uses the Belitsky convention, in plane of $q$ and $P$:

New, Braun definition using $q$ and $q’$:
more natural.
V. Braun *et al*, *Phys. Rev. D89* (2014), 074022

Reformulating CFFs in this frame absorbs most kinematic power corrections (TMC):

\[
\begin{align*}
\mathcal{F}_{++} &= \mathcal{F}_{++} + \frac{x}{2} \left[ \mathcal{F}_{++} + \mathcal{F}_{-+} \right] - \chi_0 \mathcal{F}_{0+} \\
\mathcal{F}_{-+} &= \mathcal{F}_{-+} + \frac{x}{2} \left[ \mathcal{F}_{++} + \mathcal{F}_{-+} \right] - \chi_0 \mathcal{F}_{0+} \\
\mathcal{F}_{0+} &= - \left( 1 + \chi \right) \mathcal{F}_{0+} + \chi_0 \left[ \mathcal{F}_{++} + \mathcal{F}_{-+} \right]
\end{align*}
\]

Assuming LO and LT in the Braun frame:

\[
\begin{align*}
\mathcal{F}_{++} &= (1 + \frac{x}{2}) \mathcal{F}_{++} \\
\mathcal{F}_{-+} &= \frac{x}{2} \mathcal{F}_{++} \\
\mathcal{F}_{0+} &= \chi_0 \mathcal{F}_{++}
\end{align*}
\]

HT/HO contributions in the Belitsky frame, scaled by kinematic factors $\chi$ and $\chi_0$ .

Non-negligible at the $Q^2$ and $x_B$ of the Hall A cross-section measurement:

$\chi_0 = 0.25$, $\chi = 0.06$ for $Q^2 = 2$ GeV$^2$, $x_B = 0.36$, $t = -0.24$ GeV$^2$

M. Defurne *et al*, *Nature Communications 8* (2017) 1408
Including either higher order or higher twist effects (HT) improves the match with data:

\[ E_e = 4.5 \text{ GeV} \]
\[ E_e = 5.6 \text{ GeV} \]

Wider range of beam energy needed to identify the dominant effect

Rosenbluth separation of DVCS$^2$ and BH-DVCS terms

- Generalised Rosenbluth separation of the DVCS$^2$ (scales as $E_e^2$) and the BH-DVCS interference (scales as $E_e^3$) terms in the cross-section is possible but NLO and/or higher-twist required: experiment E07-007 @ two beam energies: 4.5 and 5.6 GeV.

- Significant differences between pure DVCS and interference contributions.

- Helicity-dependent cross-section has a sizeable DVCS$^2$ contribution in the higher-twist scenario.

- Separation of HT and NLO effects requires scans across wider ranges of $Q^2$ and beam energy: JLab12!

CLAS unpolarised cross-sections

- Widest phase space coverage in valence quark region: CFF constraints.
- Dominance of GPD $H$ in unpolarised cross-section.

\[
\frac{d^4\sigma_{ep\rightarrow ep\gamma}}{dQ^2\,dx_B\,dt\,d\Phi} \quad \quad \frac{1}{2} \left( \frac{d^4\sigma_{ep\rightarrow ep\gamma}}{dQ^2\,dx_B\,dt\,d\Phi} - \frac{d^4\sigma_{ep\rightarrow ep\gamma}}{dQ^2\,dx_B\,dt\,d\Phi} \right)
\]
Nucleon Tomography from GPDs

* At a fixed $Q^2$, $x_B$, slope of GPD with $t$ is related, via a Fourier Transform, to the transverse spatial spread.

Formally, the radial separation, $b$, between the struck parton and the centre of momentum of the remaining spectators.

* Experimentally, fit the $t$-dependence of structure functions or CFFs with an exponential.

\[ \text{eg: } \frac{d\sigma_U}{dt} = Ae^{B_1t} \]
GPDs and nucleon spin

\[ J_N = \frac{1}{2} = \frac{1}{2} \sum_q + L_q + J_g \]

* Ji’s relation: \[ J^q = \frac{1}{2} - J^g = \frac{1}{2} \int_{-1}^{1} x dx \left\{ H^q(x, \xi, 0) + E^q(x, \xi, 0) \right\} \]

Second Mellin moments of the GPDs contain information on the total angular momentum carried by quarks.

Note that the contribution from GPD \( H \) is given by the quark momentum, already known from PDFs:

\[ 2J^q = \int_{0}^{1} dx \ x [q(x) + \bar{q}(x)] + \int_{-1}^{+1} dx \ x E^q(x, 0, 0) \]
Compton Form Factors in DVCS

Experimentally, DVCS amplitude is proportional to Compton Form Factors (CFFs) — sums of GPD integrals over $x$:

$$\int_{-1}^{1} dx F(\mp x, \xi, t) \left[ \frac{1}{x - \xi + i\epsilon} \pm \frac{1}{x + \xi - i\epsilon} \right]$$

GPD

Plus sign for unpolarised GPDs, minus for polarised.

Can be decomposed into real and imaginary parts:

$$\Re F = \mathcal{P} \int_{-1}^{1} dx \left[ \frac{1}{x - \xi} \mp \frac{1}{x + \xi} \right] F(x, \xi, t)$$

Cauchy's principal value integral

$$\Im F(\xi, t) = -\pi [F(\xi, \xi, t) \mp F(-\xi, \xi, t)]$$

Both parts are accessible in different experimental observables
Other reactions to get at GPDs

**Time-like Compton scattering**: virtual photon is time-like. At leading order, access same integrals of GPDs. At higher orders, they differ.

**Double Deeply Virtual Compton scattering**: two virtual photons: the second vertex provides a second variable $Q'^2$. This allows direct access to $x$, but cross-sections are suppressed by another factor of $\alpha$.

**Deeply Virtual Meson Production**: the meson vertex provides flavour information. Amplitude now depends on GPDs and the meson Distribution Amplitudes. In light mesons, more sensitive to higher order and higher twist.

In vector mesons, gluon GPDs appear at lowest order!
Flavour separation is possible in DVCS using different targets (proton and neutron), and in DVMP with different mesons.

For example, compare measurements of $\pi^0$ and $\eta$ DVMP:

$$H_T^{\pi^0} = \left( e_u H_T^u - e_d H_T^d \right) / \sqrt{2}, \quad H_T^\eta = \left( e_u H_T^u + e_d H_T^d \right) / \sqrt{6},$$

$$E_T^{\pi^0} = \left( e_u E_T^u - e_d E_T^d \right) / \sqrt{2}, \quad E_T^\eta = \left( e_u E_T^u + e_d E_T^d \right) / \sqrt{6}.$$ (Goloskokov-Kroll model)

Different GPDs represent different aspects of the parton distributions: EM charge, axial charge, transversity, etc....

Sensitivity to gluon distributions through gluon GPDs. Particularly cleanly accessible for heavier $q$: $J/\Psi$
Extracting asymmetries

Number of DVCS/BH events for each kinematic bin:

\[ N^{bt} = (1 - B^{bt}_{\pi^0}) \cdot \frac{N^{bt}_{ep\gamma}}{FC^{bt}} \]

- Polarisation state of beam, target
- Background due to \( \pi^0 \) contamination
- Normalisation by beam current (in Faraday Cup)

\* Beam-spin asymmetry:

\[ A_{LU} = \frac{P_t^- (N^{++} - N^{-+}) + P_t^+ (N^{++} - N^{--})}{P_b (P_t^- (N^{++} + N^{-+}) + P_t^+ (N^{++} + N^{--}))} \]

- Correction for electron / virtual photon axes

\* Target-spin asymmetry:

\[ A_{UL} = A_{UL}^{lab} + c_{AUT} \]

- Dilution factor due to unpolarised background

\* Double-spin asymmetry:

\[ A_{LL} = A_{LL}^{lab} + c_{ALT} \]

\[ A_{LL}^{lab} = \frac{N^{++} + N^{--} - N^{++} - N^{--}}{P_b \cdot D_f (P_t^- (N^{++} + N^{-+}) + P_t^+ (N^{++} + N^{--}))} \]
The DVCS/BH amplitude

\[ \mathcal{T}^2 = |\mathcal{T}_{\text{BH}}|^2 + |\mathcal{T}_{\text{DVCS}}|^2 + \mathcal{I} \]

\[ |\mathcal{T}_{\text{BH}}|^2 = \frac{e^6}{x_B y^2 (1 + e^2)^2 t \mathcal{P}_1(\phi) \mathcal{P}_2(\phi)} \left[ c_0^{\text{BH}} + \sum_{n=1}^{2} c_n^{\text{BH}} \cos n\phi + s_1^{\text{BH}} \sin \phi \right] \]

\[ |\mathcal{T}_{\text{DVCS}}|^2 = \frac{e^6}{y^2 Q^2} \left[ c_0^{\text{DVCS}} + \sum_{n=1}^{2} c_n^{\text{DVCS}} \cos n\phi + s_n^{\text{DVCS}} \sin n\phi \right] \]

\[ \mathcal{I} = \frac{e^6}{x_B y^3 t \mathcal{P}_1(\phi) \mathcal{P}_2(\phi)} \left[ c_0^{\mathcal{I}} + \sum_{n=1}^{3} c_n^{\mathcal{I}} \cos n\phi + s_n^{\mathcal{I}} \sin n\phi \right] \]
From asymmetries to CFFs

At leading twist, beam-spin asymmetry (BSA) can be expressed as:

\[ A_{LU}(\phi) \sim \frac{s_{1,unp}^T \sin \phi}{c_{0,unp}^B + (c_{1,unp}^B + c_{1,unp}^T + \ldots) \cos \phi} \quad \text{higher-twist terms...} \]

The leading coefficient is related to the imaginary part of the Compton Form Factors:

\[ s_{1,unp}^T \propto \Im[F_1 \hat{H} + \xi(F_1 + F_2)\tilde{H} - \frac{t}{4M^2}F_2\mathcal{E}] \]

At CLAS kinematics, this dominates

Likewise, for the target-spin asymmetry (TSA):

\[ A_{UL}(\phi) \sim \frac{s_{1,LP}^T \sin \phi}{c_{0,unp}^B + (c_{1,unp}^B + c_{1,unp}^T + \ldots) \cos \phi + \ldots} \]

\[ s_{1,LP} \propto \Im[F_1 \hat{H} + \xi(F_1 + F_2)(\hat{H} + \frac{x_B}{2}\mathcal{E}) - \xi(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2)\tilde{E}] \]

At CLAS kinematics, these CFFs dominate

\[ * \text{Obtain coefficients from fitting the phi-dependence of the asymmetry:} \]

\[ A_i = \frac{\alpha_i \sin \phi}{1 + \beta_i \cos \phi} \]
Impact of CLAS12 unpolarised target proton-DVCS data on the extraction of \( \text{Re}(H) \) and \( \text{Im}(H) \).

**Proton DVCS @ 11 GeV**

\( \text{Re}(H) \)

\( \text{Im}(H) \)

(CLAS 6 GeV extraction H. Moutarde)
Scheduled experiments to measure cross-sections and spin asymmetries with unpolarised and longitudinally polarised liquid $H_2$ and $D_2$ targets using CLAS12. \( \text{Im}(E_n), \text{Im}(H_p), \text{Im}(\widetilde{H}_p), \text{Re}(H_p) \)

- Dynamic Nuclear Polarisation (DNP) of target material, cooled in a $^4\text{He}$ evaporation cryostat.
- $P_{\text{proton}} = 80\%$
- $P_{\text{deuteron}}$ up to 50\%

Measurements of cross-sections at 10.6, 8.8 and 6.6 GeV (allows separation of pure DVCS amplitude and the DVCS/Bethe-Heitler interference terms) in Halls A, B and C.

Transversely-polarised target (HD) for use with electron beams is under development (Hall B). \( \text{Im}(E_p) \)

Measurement of beam-spin asymmetry in coherent DVCS from a \(^4\text{He}\) target (CLAS12 + recoil detector ALERT): partonic structure of nuclei. \( \text{Im}(H_A) \)
JLab 6 GeV era DVCS X-sections: kinematics


Hall A

Proton DVCS @ 11 GeV

Experiment E12-06-119
_F. Sabatié et al._

- $P_{\text{beam}} = 85\%$
- $L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
- $1 < Q^2 < 10 \text{ GeV}^2$
- $0.1 < x_B < 0.65$
- $-t_{\text{min}} < -t < 2.5 \text{ GeV}^2$

**Kinematics similar for all proton DVCS @ 11 GeV with CLAS12 experiments**

**Unpolarised liquid H$_2$ target:**

- Statistical error: 1% - 10% on $\sin \varphi$ moments
- Systematic uncertainties: ~ 6 - 8%

$A_{LU}$ characterised by imaginary parts of CFFs via:

$$F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} E$$

- $\text{Im}(H_p)$

First experiment with CLAS12

Started this February!
DVCS at lower energies with CLAS12

Experiment E12-16-010B
F.-X. Girod et al.

Unpolarised liquid H\textsubscript{2} target:

- Beam energies: 6.6, 8.8 GeV
- Simultaneous fit to beam-spin and total cross-sections.

- Rosenbluth separation of interference and $|T_{DVCS}|^2$ terms in the cross-section

- Scaling tests of the extracted CFFs

- Model-dependent determination of the D-term in the Dispersion Relation between $Re$ and $Im$ parts of CFFs: sensitivity to Gravitational Form Factors.

Compare with measurements from Halls A and C: cross-check model and systematic uncertainties.
DVCS at lower energies with CLAS12

Projected extraction of CFFs (red) compared to generated values (green). Three curves on the $Re(H)$ show three different scenarios for the D-term.
Neutron DVCS @ 11 GeV

Experiment E12-11-003
S. Niccolai, D. Sokhan et al.

\[ \Delta \sigma_{LU} \sim \sin \phi \text{Im}\{F_1 H + \xi (F_1 + F_2)^{\widetilde{H}} - k F_2 E\} \, d\phi \]

Simulated statistical sample:

\[ \text{Im } (E_n) \text{ dominates.} \]

L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}/\text{nucleon}

\[ e + d \rightarrow e' + \gamma + n + (p_s) \]

CLAS12 +
Forward Tagger +
Neutron Detector

Scheduled: 2019
Proton DVCS with a longitudinally polarised target

Experiment E12-06-119  
F. Sabatié et al.

Longitudinally polarised NH$_3$ target:

• Dynamic Nuclear Polarisation (DNP) of target material, cooled to 1K in a He evaporation cryostat.
• $P_{\text{proton}} > 80\%$
• Statistical error: 2% - 15% on sin$\phi$ moments
• Systematic uncertainties: ~ 12%

A$_{UL}$ characterised by imaginary parts of CFFs via:

$$F_1 \tilde{H} + \xi G_M(H + \frac{x_B}{2} E) - \frac{\xi t}{4M^2} F_2 \tilde{E} + ...$$

Tentative schedule: 2020

Im($\tilde{H}_p$)

Target cryostat
Neutron DVCS with a longitudinally polarised target

Experiment E12-06-109A.
S. Niccolai, D. Sokhan et al.

Longitudinally polarised ND$_3$ target:
- Dynamic Nuclear Polarisation (DNP) of target material in a cryostat shared with the NH$_3$ target.
- $P_{\text{deuteron}}$ up to 50%
- Systematic uncertainties: ~ 12%

$A_{UL}$ characterised by imaginary parts of CFFs via:
\[
F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) - \frac{\xi t}{4M^2} F_2 \tilde{E} + \ldots
\]

\[\text{Im}(H_n)\]

In combination with pDVCS, will allow flavour-separation of the $H_q$ CFFs.

Tentative schedule: 2020
Proton DVCS with transversely polarised target at CLAS12

C12-12-010: with transversely polarised HD target (conditionally approved).

\[ \Delta \sigma_{UT} \sim \cos \phi \, \text{Im} \{ k(F_2H - F_1E) + \ldots \} \, d\phi \]

Sensitivity to \( \text{Im}(E) \) for the proton.

VGG extraction (M. Guidal)

\[ \langle x \rangle = 0.2, \langle Q^2 \rangle = 2.5 \text{ GeV}^2 \]

\[ \langle x \rangle = 0.33, \langle Q^2 \rangle = 2.5 \text{ GeV}^2 \]