DVCS and DVMP: results from CLAS and the experimental program of CLAS12

- Accessing GPDs via DVCS and DVMP
- Recent results from Jefferson Lab
  - What we have learned
  - The JLab 12 GeV upgrade
- Upcoming CLAS12 experiments

Silvia Niccolai, IPN Orsay & CLAS Collaboration

INT-17 -3
29/8/2017, Seattle, WA (USA)
A complete picture of nucleon structure requires the measurement of all these distributions.
Exclusive reactions giving access to GPDs

- **DVCS**
- **DVMP**

\( Q^2 = -(k-k')^2 \)
\( x_B = Q^2/2Mv \quad v = E_e - E_e' \)
\( x + \xi, x - \xi \) long. mom. fract.
\( t = \Delta^2 = (p-p')^2 \)
\( \xi \approx x_B/(2-x_B) \)
Exclusive reactions giving access to GPDs

DVCS

Quark GPDs

Gluon GPDs

• $Q^2 = -(k-k')^2$
• $x_B = Q^2/2Mv$  $v = E_e - E_e'$
• $x + \xi, x - \xi$ long. mom. fract.
• $t = \Delta^2 = (p-p')^2$
• $\xi \approx x_B/(2-x_B)$

M. Defurne’s talk

M. Boer’s talk

(TCS), DDVCS

DVMP

Quark GPDs, Transversity GPDs

Gluon GPDs
Properties and “virtues” of GPDs

\[ \int H(x, \xi, t) dx = F_1(t) \quad \forall \xi \]
\[ \int E(x, \xi, t) dx = F_2(t) \quad \forall \xi \]
\[ \int \tilde{H}(x, \xi, t) dx = G_A(t) \quad \forall \xi \]
\[ \int \tilde{E}(x, \xi, t) dx = G_P(t) \quad \forall \xi \]

Link with FFs

Forward limit: PDFs

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

(not for E, \(\tilde{E}\))

Nucleon tomography

\[ q(x, b_\perp) = \int_0^\infty \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i \Delta_\perp b_\perp} H(x, 0, -\Delta_\perp^2) \]

\[ \Delta q(x, b_\perp) = \int_0^\infty \frac{d^2 \Delta_\perp}{(2\pi)^2} e^{i \Delta_\perp b_\perp} \tilde{H}(x, 0, -\Delta_\perp^2) \]

M. Burkardt, PRD 62, 71503 (2000)

Quark angular momentum (Ji’s sum rule)

\[ \frac{1}{2} \int_{-1}^{1} x dx (H(x, \xi, t = 0) + E(x, \xi, t = 0)) = J = \frac{1}{2} \Delta \Sigma + \Delta L \]


Nucleon spin: \( \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta L + \Delta G \)

Intrinsic spin of the quarks \( \Delta \Sigma \approx 25\% \)

Intrinsic spin on the gluons \( \Delta G \approx 0 \) (??)

Orbital angular momentum of the quarks \( \Delta L \)?
Deeply Virtual Compton Scattering and quark GPDs

\[ e' (Q^2) \]

\[ \gamma (x+\xi, x-\xi) \]

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

«Handbag» factorization valid in the Bjorken regime: high \( Q^2 \), \( v \) (fixed \( x_B \)), \( t \ll Q^2 \)

At leading order QCD, twist 2, chiral-even (quark helicity is conserved), quark sector → 4 GPDs for each quark flavor

Conserve nucleon spin

Vector: \( H (x, \xi, t) \)

Axial-Vector: \( \tilde{H} (x, \xi, t) \)

Flip nucleon spin

Tensor: \( E (x, \xi, t) \)

Pseudoscalar: \( \tilde{E} (x, \xi, t) \)
Accessing GPDs through DVCS

DVCS allows access to 4 complex GPDs-related quantities: **Compton Form Factors** \((\xi, t)\)

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

Only \(\xi\) and \(t\) are accessible experimentally

\[
Re \mathcal{H}_q = e_q^2 P \int_0^{+1} \left( H^q(x, \xi, t) - H^q(-x, \xi, t) \right) \left[ \frac{1}{\xi - x} + \frac{1}{\xi + x} \right] dx
\]

\[
Im \mathcal{H}_q = \pi e_q^2 \left[ H^q(\xi, \xi, t) - H^q(-\xi, \xi, t) \right]
\]

\[\sigma(eN \rightarrow eN\gamma) = |DVCS + BH|^2 \rightarrow Re(CFFs) \quad (also\ DSA)\]

\[\Delta \sigma = \sigma^+ - \sigma^- \propto I(DVCS \cdot BH) \rightarrow Im(CFFs)\]

\[A = \frac{\Delta \sigma}{2 \sigma} \propto \frac{I(DVCS \cdot BH)}{|BH|^2 + |DVCS|^2 + I}\]
Sensitivity to CFFs of DVCS spin observables

\[ A_{LU(UL)} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \propto \frac{s_{1,unp(UL)}^I \sin \phi}{c_{0,unp}^{BH} + c_{0,unp}^I + (c_{1,unp}^{BH} + c_{1,unp}^I) \cos \phi} \]

\[ A_{LL} = \frac{\sigma^{++} + \sigma^{+-} - \sigma^{-+} - \sigma^{--}}{\sigma^{++} + \sigma^{+-} + \sigma^{-+} + \sigma^{--}} \propto \frac{c_{0,LP}^{BH} + c_{0,LP}^I + (c_{1,LP}^{BH} + c_{1,LP}^I) \cos \phi}{c_{0,unp}^{BH} + c_{0,unp}^I + (c_{1,unp}^{BH} + c_{1,unp}^I) \cos \phi} \]

\( (\xi = x_B/(2-x_B) \quad k=-t/4M^2) \)

Polarized beam, unpolarized target:
\[ s_{1,unp}^I \sim \text{Im}\{F_1 \mathcal{H} + \xi(F_1+F_2)\mathcal{H} - k\mathcal{F}_2 \mathcal{E}\} \]

Unpolarized beam, longitudinal target:
\[ s_{1,UL}^I \sim \text{Im}\{F_1 \mathcal{H} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi k\mathcal{F}_2 \mathcal{E} + \ldots\} \]

Polarized beam, longitudinal target:
\[ c_{1,LP}^I \sim \text{Re}\{F_1 \mathcal{H} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) + \ldots\} \]

Unpolarized beam, transverse target:
\[ \Delta \sigma_{UT} \sim \sin(\phi_s-\phi)\text{Im}\{k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots\} \]

Proton \quad Neutron

\[ \text{Im}\{\mathcal{H}_p, \mathcal{F}_p, \mathcal{E}_p\} \quad \text{Im}\{\mathcal{H}_n, \mathcal{F}_n, \mathcal{E}_n\} \]

\[ \text{Im}\{\mathcal{H}_p, \mathcal{F}_p\} \quad \text{Im}\{\mathcal{H}_n, \mathcal{E}_n\} \]

\[ \text{Re}\{\mathcal{H}_p, \mathcal{F}_p\} \quad \text{Re}\{\mathcal{H}_n, \mathcal{E}_n\} \]

\[ \text{Im}\{\mathcal{H}_p, \mathcal{E}_p\} \quad \text{Im}\{\mathcal{H}_n\} \]
DVCS experiments worldwide

<table>
<thead>
<tr>
<th>JLAB</th>
<th>CLAS (Hall B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hall A</td>
<td>p-DVCS</td>
</tr>
<tr>
<td>p,n-DVCS (Bpol.) CS</td>
<td>BSA, ITSA, DSA, CS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DESY</th>
<th>CERN</th>
</tr>
</thead>
<tbody>
<tr>
<td>HERMES</td>
<td>CLAS (Hall A)</td>
</tr>
<tr>
<td>Hall A</td>
<td>HERMES</td>
</tr>
<tr>
<td>H1/ZEUS</td>
<td>COMPASS</td>
</tr>
<tr>
<td>p-DVCS</td>
<td>p-DVCS</td>
</tr>
<tr>
<td>BSA, BCA, tTSA, ITSA, DSA</td>
<td>CS, BSA, BCA</td>
</tr>
<tr>
<td>p-DVCS</td>
<td>p-DVCS</td>
</tr>
<tr>
<td>CS, BSA, BCA, tTSA, ITSA, DSA</td>
<td>CS, BSA, BCA</td>
</tr>
</tbody>
</table>

S. Stepanyan et al., PRL 87 (2001)

CLAS: first observation of DVCS-BH interference

Hall A: proof of scaling for DVCS

C.M. Camacho et al., PRL 97 (2006)

\[ Q^2 = 1.25 \text{ GeV}^2 \]
\[ \langle x_B \rangle = 0.19 \]
\[ \langle -t \rangle = 0.19 \text{ GeV}^2 \]

\[ \langle Q^2, -t \rangle = (2.3, -0.28) \text{ GeV}^2 \]
JLab@6 GeV

Hall C (SOS/HMS)

Hall B: CLAS
Large acceptance
Suited for multi-particle final states
L~10^{34}

Hall A: 2 HRS
High resolution
High luminosity (L~10^{37})
Limited coverage

Continuous Electron Beam Accelerator Facility

\[ E_{\text{max}} \sim 6.0 \text{ GeV} \]
- \[ I_{\text{max}} \sim 200 \text{ mA} \]
- Polarization 85%
- 3 x 499 MHz operation
- Simultaneous delivery to 3 halls
- Shutdown in May 2012
CLAS: unpolarized and beam-polarized cross sections

- Data taken in 2005, e1-dvcs
- Beam energy ~ 5.75 GeV
- Beam polarization ~ 80%
- Target LH$_2$
- Inner Calorimeter (IC)

21 $Q^2$-$x_B$ bins, 9 $t$ bins, 24 $\phi$ bins

H.S. Jo et al., PRL 115, 212003 (2015)

• Largest kinematic ever covered
• Two observables extracted

$\hat{e}p \rightarrow ep\gamma$

$\Delta \sigma_{LU} \sim \sin \phi \ Im \{ F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - kF_2E \} d\phi$

KM10 model fits Hall A 2006 data using « anomalous » $\mathcal{H}$
CLAS: DVCS on longitudinally polarized target

- Data taken in 2009, eg1-dvcs
- Beam energy ~5.9 GeV
- CLAS + IC to detect forward photons
- Target: longitudinally polarized NH$_3$ (P~80%)
- 3 DVCS observables

- 5 $Q^2$-x$_B$ bins
- 4 t bins
- 10 $\phi$ bins

S. Pisano et al., PRD 91, 052014 (2015)
CLAS: DVCS on longitudinally polarized target

- Data taken in 2009, eg1-dvcs
- Beam energy ~5.9 GeV
- CLAS + IC to detect forward photons
- Target: longitudinally polarized NH₃ (P~80%)
- 3 DVCS observables

[Diagram showing beam, target, and double asymmetry plots]

- 5 $Q^2$-$x_B$ bins
- 4 $t$ bins
- 10 $\phi$ bins

E. Seder et al., PRL 114 (2015) 032001

TSA ~ $\text{Im} \{ \mathcal{H}_p, \tilde{\mathcal{H}}_p \}$

CLAS: $<Q^2> = 2.4 \text{ (GeV/c)}^2$, $<x_B> = 0.31$
HERMES: $<Q^2> = 2.459 \text{ (GeV/c)}^2$, $<x_B> = 0.096$
CLAS2006: $<Q^2> = 1.82 \text{ (GeV/c)}^2$, $<x_B> = 0.28$

- Improved statistics x10 at low $-t$
- Extended kinematic coverage
CLAS: DVCS on longitudinally polarized target

- Data taken in 2009, eg1-dvcs
- Beam energy \( \sim 5.9 \) GeV
- CLAS + IC to detect forward photons
- Target: longitudinally polarized \( \text{NH}_3 \) (P~80%)
- 3 DVCS observables

\[ \text{DSA} \sim \text{Re} \{ \mathcal{H}_p, \tilde{\mathcal{H}}_p \} \]

- 5 \( Q^2\)-\( x_B \) bins
- 4 \( t \) bins
- 10 \( \phi \) bins

S. Pisano et al., PRD 91, 052014 (2015)
DVCS on the proton in Hall A

Significant deviation from Bethe-Heitler
Both $I(BH \cdot DVCS)$ and DVCS$^2$ contribute to the cross section
Twist-4 corrections (TMC) may be necessary to describe the data

New results from 2009 data: see M. Defurne’s talk
Extraction of Compton Form Factors from DVCS observables

GPDs cannot directly be extracted from DVCS observables, one can access Compton Form Factors:

\[
\begin{align*}
\text{Re}(\mathcal{H}) &= P \int_0^1 dx \left[ H(x, \xi, t) - H(-x, \xi, t) \right] C^+(x, \xi) \\
\text{Re}(\mathcal{E}) &= P \int_0^1 dx \left[ E(x, \xi, t) - E(-x, \xi, t) \right] C^+(x, \xi) \\
\text{Re}(\tilde{\mathcal{H}}) &= P \int_0^1 dx \left[ \tilde{H}(x, \xi, t) + \tilde{H}(-x, \xi, t) \right] C^-(x, \xi) \\
\text{Re}(\tilde{\mathcal{E}}) &= P \int_0^1 dx \left[ \tilde{E}(x, \xi, t) + \tilde{E}(-x, \xi, t) \right] C^-(x, \xi) \\
\text{Im}(\mathcal{H}) &= H(\xi, \xi, t) - H(-\xi, \xi, t) \\
\text{Im}(\mathcal{E}) &= E(\xi, \xi, t) - E(-\xi, \xi, t) \\
\text{Im}(\tilde{\mathcal{H}}) &= \tilde{H}(\xi, \xi, t) - \tilde{H}(-\xi, \xi, t) \\
\text{Im}(\tilde{\mathcal{E}}) &= \tilde{E}(\xi, \xi, t) - \tilde{E}(-\xi, \xi, t) \\
\text{with } C^\pm(x, \xi) &= \frac{1}{x - \xi} \pm \frac{1}{x + \xi}
\end{align*}
\]

M. Guidal: **Model-independent fit**, at fixed $Q^2$, $x_B$ and $t$ of DVCS observables
8 parameters (the CFFs), loosely bound (+/- 5 x VGG prediction)
Results for $H_{im}$ and $\tilde{H}_{im}$ from the fits of JLab 2015 data.

$H_{im}$ has steeper $t$-slope than $\tilde{H}_{im}$; the axial charge ($-\Delta u - \Delta d$) is more “concentrated” than the electric charge.

From CFFs to proton tomography

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

\[ A(\xi) = a_A (1 - \xi) / \xi \quad a_A = 0.36 \pm 0.06 \]

\[ B(\xi) = a_B \ln(1/\xi) \quad a_B = 1.07 \pm 0.26 \text{ GeV}^{-2} \]

\[ \langle b_\perp^2 \rangle = 0.43 \pm 0.01 \text{ fm}^2 \]

« Integrated » radius from elastic form factor $F_1$:
Summary of proton-DVCS spin observables and GPDs extraction

Beam charge asymmetry

Beam spin asymmetry

Transverse target spin asymmetry

Beam-spin and tr. target spin asymmetry

Longitudinal target spin asymmetry

Beam-spin and long. target spin asymmetry

Hall A (2015)  CLAS C.S.  CLAS C.S.  +TSA+DSA

Beam Charge Asymmetry: strong constraint for $H_{Re}$

N. d’Hose, S.N., A. Rostomyan, EPJA 52, 151 (2016)
DVCS on the neutron in Hall A

Proton and neutron GPDs (and CFFs) are **linear combinations** of quark GPDs

\[
\mathcal{H}_p(\xi, t) = \frac{4}{9} \mathcal{H}_u(\xi, t) + \frac{1}{9} \mathcal{H}_d(\xi, t)
\]

\[
\mathcal{H}_n(\xi, t) = \frac{1}{9} \mathcal{H}_u(\xi, t) + \frac{4}{9} \mathcal{H}_d(\xi, t)
\]

**A combined analysis** of DVCS observables for **proton and neutron targets** is necessary to perform a **quark-flavor separation** of the GPDs

- **E03-106**: First-time measurement of \( \Delta \sigma_{LU} \) for nDVCS, model-dependent extraction of \( J_u, J_d \)

- **E08-025**: Beam-energy « Rosenbluth » separation of nDVCS CS using an LD2 target
Deeply virtual meson production and GPDs

Different mesons → different sensitivity to GPDs

Vector mesons \((\rho, \omega, \phi)\)

Pseudoscalar mesons \((\pi, \eta)\)

<table>
<thead>
<tr>
<th>Meson</th>
<th>Quark Flavor Decomposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi^0)</td>
<td>(2\Delta u + \Delta d)</td>
</tr>
<tr>
<td>(\eta)</td>
<td>(2\Delta u - \Delta d)</td>
</tr>
<tr>
<td>(\rho^0)</td>
<td>(2u + d)</td>
</tr>
<tr>
<td>(\omega)</td>
<td>(2u - d)</td>
</tr>
<tr>
<td>(\rho^+)</td>
<td>(u - d)</td>
</tr>
</tbody>
</table>

Factorization proven only for **longitudinally polarized** virtual photons

Quark flavor decomposition accessible via meson production

\[
\mathcal{A}_L = -\frac{2ie}{9} \left( \int_0^1 dz \frac{\Phi(z)}{z} \right) \frac{4\pi\alpha_s(Q^2)}{Q} \int_{-1}^{+1} dx \left\{ \frac{1}{x - \xi + i\epsilon} + \frac{1}{x + \xi - i\epsilon} \right\} F(x, \xi, t)
\]

Complications: effective scale in the hard scattering process, meson distribution amplitude
Deeply virtual meson production at CLAS

**Vector mesons:** exclusive $\rho^0$, $\omega$, $\phi$ and $\rho^+$ electroproduction on the proton with CLAS

- K. Lukashin *et al.*, Phys. Rev. C 63, 065205, 2001 ($\phi@4.2$ GeV)
- C. Hadjidakis *et al.*, Phys. Lett. B 605, 256-264, 2005 ($\rho^0@4.2$ GeV)
- L. Morand *et al.*, Eur. Phys. J. A 24, 445-458, 2005 ($\omega@5.75$ GeV)
- J. Santoro *et al.*, Phys. Rev. C 78, 025210, 2008 ($\phi@5.75$ GeV)
- S. Morrow *et al.*, Eur. Phys. J. A 39, 5-31, 2009 ($\rho^0@5.75$ GeV)
- A. Fradi, Orsay Univ. PhD thesis ($\rho^+@5.75$ GeV)

**Pseudoscalar mesons:** exclusive $\pi^0$ and $\eta$ electroproduction on the proton with CLAS

- R. De Masi *et al.*, Phys. Rev. C 77, 042201(R), 2008 ($\pi^0@5.75$ GeV)
- K. Park *et al.*, Phys. Rev. C 77, 015208, 2008 ($\pi^+@5.75$ GeV)
- I. Bedlinskiy *et al.*, Phys. Rev. C 95, 035202 (2017) ($\eta@5.75$ GeV)
Comparison between vector mesons ($\sigma$)

![Graph showing comparison between vector mesons](image-url)
Comparison between vector mesons ($\sigma, \sigma_L$)

$\sigma_V(W, \mu_V^2) = a_1 W^{\delta_1(\mu_V^2)} + a_2 W^{\delta_2(\mu_V^2)}$

$\mu_V^2 = Q^2 + M_V^2$

The GPD models fail to reproduce $\sigma_L$ at low $W$ for $\rho^0$

L. Favart, M. Guidal, T. Horn, P. Kroll, EPJA 52, 158 (2016)
Chiral-odd GPDs

- 4 chiral-odd GPDs (parton helicity flip)
- Difficult to access (helicity flip processes are suppressed)
- Chiral-odd GPDs are very little constrained
- Anomalous tensor magnetic moment:

\[ \kappa_T = \int dx \bar{E}_T(x, \xi, t = 0) \quad \bar{E}_T = 2\tilde{H}_T + E_T \]

- Link to the transversity distribution: \( H_T^q(x, 0,0) = h_1^q(x) \)

Transverse Densities for u and d quarks in the nucleon

Distributions of unpolarized quarks in a transversely polarized nucleon, linked to \( E \)

Distribution of transversely polarized quarks in an unpolarized nucleon, linked to \( \bar{E}_T \)

Exclusive $\pi^0$ electroproduction

\[
\frac{d\sigma}{dQ^2dx_Bd\phi dt} = \Gamma(Q^2, x_B) \frac{1}{2\pi} \left( \sigma_T + \epsilon\sigma_L + \epsilon \cos 2\Phi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)} \cos \Phi \sigma_{LT} \right)
\]

**Leading twist:**  
\[
\sigma_L = \frac{4\pi\alpha_e}{k'Q^6} \left[ (1 - \xi^2) |< \tilde{H} >|^2 - 2\xi^2 \text{Re}(< \tilde{H} >^* < \tilde{E} >) - \frac{t'}{4m^2\xi^2} |< \tilde{E} >|^2 \right]
\]

**$\sigma_L$ is suppressed:**  
\[
\tilde{H}^\pi = \frac{1}{3\sqrt{2}} \left[ 2\tilde{H}^u + \tilde{H}^d \right]
\]

**Transversity GPD models:**  
- Goloskokov-Kroll  
- Liuti-Goldstein  
- $\sigma_L << \sigma_T$
Recent Hall A results for proton and neutron $\pi^0$ electroproduction → flavor separation of transversity GPDs (M. Defurne’s, T. Horn’s talks)

Goloskokov-Kroll model
Transversity GPDs
• Very little dependence on $x_B$ and $Q^2$
• Chiral-odd GPD models predict this ratio to be $\sim 1/3$ at CLAS kinematics
• Chiral-even GPD models predict this ratio to be around 1 (at low $-t$)

Potentially one can perform flavor separation of transversity GPDs combining $\pi^0$ and $\eta$
JLab upgrade to 12 GeV

E = 2.2, 4.4, 6.6, 8.8, 11 GeV for the Halls A, B, C
Beam polarization > 80%

Upgrade completed in 2014

The 12-GeV upgrade is well matched to studies in the valence-quark regime.

Study of high $x_B$ domain requires high luminosity
New capabilities in Halls A, B & C

High Resolution Spectrometer (HRS) pair and specialized large installation experiments

CLAS12: large acceptance, high luminosity

GPDs experiments at 11 GeV have been approved for each of these three halls. Complementary programs:
- different kinematic coverage
- different precisions/resolutions
- focus on different observables

M. Defurne and T. Horn will present Halls A and C
Hall B@12 GeV: CLAS12

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

Acceptance for charged particles:
- Central (CD), $40^\circ < \Theta < 135^\circ$
- Forward (FD), $5^\circ < \Theta < 40^\circ$

Acceptance for photons:
- Forward tagger T, $2^\circ < \Theta < 5^\circ$
- EC, $5^\circ < \Theta < 40^\circ$

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

+ FT, CND, MM, RICH
DVCS BSA and TSA with CLAS12 & 11 GeV beam

85 days of beam time
$P_{\text{beam}} = 85\%$
$L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
Statistical error: 1% to 10% on $\sin\phi$ moments
Systematic uncertainties: $\sim 6-8\%$

120 days of beam time
$P_{\text{beam}} = 85\%, P_{\text{target}} = 80\%$
$L = 2.10^{35} \text{ cm}^{-2}\text{s}^{-1}$
Statistical error: 2% to 15% on $\sin\phi$ moments
Systematic uncertainties: $\sim 6-8\%$

Impact of CLAS12 DVCS-BSA data on CFF fit

First CLAS12 experiment (December 2017)

Foreseen for the year 2020
CLAS12: p-DVCS *transverse* target-spin asymmetry

100 days of beam time
Beam pol. = 80% ; **target pol. (HDIce) = 60%** ; Luminosity = $5 \times 10^{33}$ cm$^{-2}$s$^{-1}$
$1 < Q^2 < 10$ GeV$^2$, $0.06 < x_B < 0.66$, $-t_{\text{min}} < -t < 1.5$ GeV$^2$

Transverse-target spin asymmetry for p-DVCS is **highly sensitive** to the **u-quark contributions** to proton spin.

Proposal conditionally approved by PAC39
Tests on HDIce target are ongoing
From CFFs to spatial densities

(M. Guidal, H. Moutarde, M. Vanderhagen, Rept.Prog.Phys. 76 (2013) 066202)
E12-11-003: BSA for DVCS on the neutron with CLAS12

\[ (H,E)_n(\xi,\xi,t) = \frac{9}{15}[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)] \]

\[ (H,E)_d(\xi,\xi,t) = \frac{9}{15}[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)] \]

\[ \Delta \sigma_{LU} \sim \sin \phi \mathbf{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi \]

The most sensitive observable to the GPD $E$

Installation in 3 weeks (IPN Orsay)

80 days of data taking

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

First-time measurement

JLab PAC: high-impact experiment
E12-11-003: BSA for DVCS on the neutron with CLAS12

$9^{-15}[4(H,E)_p(\xi,\xi,t)-H,E)_n(\xi,\xi,t)\]

$9^{-15}[4(H,E)_p(\xi,\xi,t)-H,E)_p(\xi,\xi,t)\]

$\Delta \sigma_{LU} \sim \sin \phi \ Im \{F_1 H + \xi(F_1 + F_2) H - kF_2 E\} d\phi$

The most sensitive observable to the GPD $E$

$ed \rightarrow e(p)n\gamma$

CLAS12 + Forward Calorimeter + Neutron Detector

80 days of data taking $L = 10^{35} \text{ cm}^{-2} \text{s}^{-1}/\text{nucleon}$

Model predictions (VGG) for different values of quarks’ angular momentum

First-time measurement

JLab PAC: high-impact experiment

$J_u=0.3, J_d=0.1$

$J_u=0.1, J_d=0.1$

$J_u=0.3, J_d=0.3$

$J_u=0.3, J_d=-0.1$
E12-06-109a: nDVCS, target-spin asymmetry

\[ \sigma_A = \frac{1}{P_t} \cdot \sqrt{\frac{(1 - P_t \cdot A)^2}{N}} \]

\[ \Delta \sigma_{UL} \sim \sin \phi \Im \{ F_1 \tilde{H} + \xi (F_1 + F_2) (\tilde{H} + x_B/2 \tilde{E}) - \xi kF_2 \tilde{E} + \ldots \} \]

L = 3/20 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}
Time = 50 days
\( P_t = 0.4 \)

\( eN_D \rightarrow e(p)n\gamma \)
CLAS12 +
Long. pol. target
Forward Calorimeter + Neutron Detector

- 4 bins in \( Q^2 \)
- 4 bins in \( -t \)
- 4 bins in \( x_B \)
- 12 bins in \( \phi \)
(Same as E12-11-003)

TSA \sim 0.2

First time measurement
E12-06-109a: nDVCS, double spin asymmetry

\[ \sigma_A = \frac{1}{P_b P_t} \cdot \frac{\sqrt{1 - P_b P_t \cdot A^2}}{\sqrt{N}} \]

\[ \Delta \sigma_{LL} \sim (A + B \cos \phi) \Re \{ F_1 \tilde{H} + \xi (F_1 + F_2)(\mathcal{H} + x_B/2 \mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}} + \ldots \} \]

L = 3/20 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}
Time = 50 days
P_t = 0.4; P_b = 0.85

\[ eND_3 \rightarrow e(p)n\gamma \]
CLAS12 +
Long. pol. target
Forward Calorimeter + Neutron Detector

- 4 bins in \( Q^2 \)
- 4 bins in \(-t\)
- 4 bins in \( x_B \)
- 12 bins in \( \phi \)
(Same as E12-11-003)

Green curves:
Bethe-Heitler

First time measurement

DSA up to 0.8
Combined analysis of all nDVCS CLAS12 projections

Extraction of neutron CFFs using M. Guidal’s fitting code. Fit of TSA, DSA (E12-06-109a) and BSA (E12-11-003)

7 CFFs as free fit parameters

$\text{Im} \widetilde{\mathcal{H}}_n = 0$
### DVCS on the nucleon: past, present, future

<table>
<thead>
<tr>
<th>Observable (target)</th>
<th>Target</th>
<th>Sensitivity to CFFs</th>
<th>Completed experiments</th>
<th>12-GeV experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \sigma_{beam}(p)$</td>
<td>Unpolarized hydrogen</td>
<td>$\Im m H^p$</td>
<td>Hall A, CLAS</td>
<td>Hall A, CLAS12, Hall C</td>
</tr>
<tr>
<td>BSA(p)</td>
<td>Unpolarized hydrogen</td>
<td>$\Im m H^p$</td>
<td>HERMES, CLAS</td>
<td>CLAS12</td>
</tr>
<tr>
<td>TSA(p)</td>
<td>Long. pol. NH3</td>
<td>$\Im m H^p, \Im m H_n^p$</td>
<td>HERMES, CLAS</td>
<td>CLAS12</td>
</tr>
<tr>
<td>DSA(p)</td>
<td>Long. pol. NH3</td>
<td>$\Re e H^p, \Re e H_n^p$</td>
<td>HERMES, CLAS</td>
<td>CLAS12</td>
</tr>
<tr>
<td>tTSA(p)</td>
<td>Transv. pol. protons</td>
<td>$\Im m H^p, \Im m E_p$</td>
<td>HERMES</td>
<td>CLAS12</td>
</tr>
<tr>
<td>$\Delta \sigma_{beam}(n)$</td>
<td>Unpolarized deuterium</td>
<td>$\Im m E_n$</td>
<td>Hall A</td>
<td></td>
</tr>
<tr>
<td>BSA(n)</td>
<td>Unpolarized deuterium</td>
<td>$\Im m E_n$</td>
<td></td>
<td>CLAS12</td>
</tr>
<tr>
<td>TSA(n)</td>
<td>Long. pol. ND3</td>
<td>$\Im m H_n$</td>
<td></td>
<td>CLAS12</td>
</tr>
<tr>
<td>DSA(n)</td>
<td>Long. pol. ND3</td>
<td>$\Re e H_n$</td>
<td></td>
<td>CLAS12</td>
</tr>
</tbody>
</table>

+ Timelike Compton Scattering @ CLAS12, DDVCS (SOLID? CLAS12?)…
CLAS12: projections for flavor separation ($\text{Im} \mathcal{H}$, $\text{Im} \mathcal{E}$)

\begin{align*}
(H,E)_u(\xi,\bar{\xi},t) &= \frac{9}{15} \left[ 4(H,E)_p(\xi,\bar{\xi},t) - (H,E)_n(\xi,\bar{\xi},t) \right] \\
(H,E)_d(\xi,\bar{\xi},t) &= \frac{9}{15} \left[ 4(H,E)_n(\xi,\bar{\xi},t) - (H,E)_p(\xi,\bar{\xi},t) \right]
\end{align*}

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

Fits done to all the projected observables for pDVCS (BSA, lTSA, lDSA, tTSA, CS, DCS) and nDVCS (BSA,lTSA, lDSA) of the CLAS12 program

\[ \int_0^1 d\xi (\mathcal{H}_x(\xi,t=0) + \mathcal{E}_x(\xi,t=0)) = J_x \]

Nucleon CFFs

Quark CFFs
DVMP @ CLAS12: exclusive $\phi$ electroproduction

- Differential c.s. $\rightarrow$ extraction of structure functions
- L-T separation from $\phi \rightarrow KK$ decay distributions
- $t$ dependence of $d\sigma_L/dt$

Transverse distribution of gluons in the proton
Conclusions

- GPDs are a unique tool to explore the **internal dynamics of the nucleon**:
  - **3D** quark/gluon **imaging** of the nucleon
  - **orbital angular** momentum carried by quarks

- Their extraction from experimental data is **very difficult**:
  - there are **4 GPDs for each quark flavor**
  - they depend on **3 variables**, only two (\(\xi, t\)) experimentally accessible via DVCS

- Recently-developed fitting methods allow to **extract CFFs from DVCS observables**. Need to measure several **p-DVCS** and **n-DVCS observables** over a **wide phase space**

- A wealth of **new results** on various DVCS observables is coming from recent **CLAS and Hall-A experiments** (on the proton, deuterium and \(^4\)He targets)

- First **tomographic interpretations** of the quarks in the **proton** from DVCS:
  - **valence quarks** are concentrated in its **center**, **sea quarks** at its **perifery**
  - **axial charge** more concentrated than the **electric** one

- Things are more complicate for **DVMP**: unexplained low-W behavior for light vector mesons, **transversity GPDs** dominance for pseudo-scalars

→ The 12-GeV-upgraded JLab is the **only facility** to perform GPD experiments **in the valence region**, for \(Q^2\) up to 11 GeV

→ DVCS and DVMP experiments on both **proton** and **neutron** (pol. and unpol.) are planned for 3 of the 4 Halls at JLab@12 GeV: quarks’ spatial densities, **flavor separation**, quarks’ **orbital angular momentum**, gluon densities,…