The GPD program with CLAS12: highlights and perspectives

CLAS collaboration

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A set of distributions encoding the nucleon structure

**TMDs:** Fraction of longitudinal momentum \( x \) and transverse momentum \( k \)

**GPDs:** Fraction of longitudinal momentum \( x \) and transverse position \( b \)

**Scan in momentum**

**Scan in position**

Parton Distribution Functions

Form Factors
The generalized parton distributions and the nucleon

At leading twist there are 8 GPDs:
- 4 chiral-even GPDs: $H$, $E$, $\tilde{H}$ and $\tilde{E}$.
- 4 chiral-odd GPDs: $H_T$, $E_T$, $\tilde{H}_T$ and $\tilde{E}_T$.

Using the GPDs, we can determine the total angular momentum of quarks in the nucleon.

$$\int_{-1}^{1} x \left[ H^f(x, \xi, 0) + E^f(x, \xi, 0) \right] \, dx = J^f \quad \forall \xi .$$

By Fourier transform of the GPD $H$ at $\xi = 0$ (need extrapolation), we obtain the distribution in the transverse plane of the partons as a function of their longitudinal momentum.

![Diagram of GPDs](image)
Several GPDs but a universality principle

GPDs are universal: the same GPDs parameterize DVCS, DVMP, TCS, DDVCS,...

Deep virtual meson production has an additional non-perturbative part: The meson. Although there is an additional "unknown", it can conveniently be used for flavor separation or study of specific GPDs.
A spectrometer to get them all at once

The deep exclusive processes are:

- associated with a low cross section \( \Rightarrow 10^{35} \text{ s}^{-1} \text{cm}^{-2} \).
- diversified with respect to their final state \( \Rightarrow \) RICH, LTCC, ToF.
- ... exclusive \( \Rightarrow \) Large acceptance with Central and Forward detectors.

CLAS12 spectrometer can simultaneously look at all these processes. Collecting data since 2018 with a 85%-longitudinally polarized beam on:

- unpolarized protons @ 6.6/7.5 and 10.6 GeV.
- unpolarized deuterium @ 10.4 GeV.
- ... and today with longitudinally polarized protons and neutrons @ 10.6 GeV.
All detectors required for exclusive processes

A 10.6-GeV electron beam scatters off a 5-cm LH₂ target. The beam is \(\sim 85\%\) longitudinally polarized. All CLAS12 detectors are necessary to reconstruct all particles of a DVCS final state:

- The electron is going through Cerenkov detector, drift chambers and electromagnetic calorimeter.
- The photon is either detected in a sampling calorimeter or a small PbWO₄-calorimeter close to the beamline.
- The recoil proton goes in the Silicon and Micromegas detector.
**DVCS and GPDs**

\[ Q^2 = -q^2 = -(k - k')^2. \]

\[ x_B = \frac{Q^2}{2p \cdot q} \]

\( x \) average longitudinal momentum fraction carried by the active quark.

\[ \xi \sim \frac{x_B}{2 - x_B} \] the longitudinal momentum transfer.

\( t = (p' - p)^2 \) squared momentum transfer to the nucleon.

The GPDs enter the DVCS amplitude through a complex integral. This integral is called a Compton form factor (CFF).

\[
\mathcal{H}_{++}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left( \frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx.
\]

At leading order, \( \text{Im}\mathcal{H}(\xi, t) \propto (H(\xi, \xi, t) - H(-\xi, \xi, t)) \).
Photon electroproduction

We use leptons beam to generate the $\gamma^*$ in the initial state... not without consequences. Indeed, experimentally we measure the cross section of the process $ep \rightarrow ep\gamma$ and not strictly $\gamma^* p \rightarrow \gamma p$.

$$\frac{d^4\sigma(\lambda, \pm e)}{dQ^2 dx_B dt d\phi} = \frac{d^2\sigma_0}{dQ^2 dx_B} \frac{2\pi}{e^6} \times \left[ |T^{BH}|^2 + |T^{DVCS}|^2 \mp J \right],$$
Photon electroproduction and GPDs

The interference term allows to access the phase of the DVCS amplitude, i.e. allows to isolate imaginary and real parts of CFFs.

\[ c^{DVCS}_{0,UU} \sim 4(1-x_B) \left( \mathcal{H}\mathcal{H}^* + \mathcal{T}\mathcal{T}^* \right), \]

\[ c^{j}_{1,UU} \sim F_1 \text{Re}\mathcal{H} + \xi(F_1 + F_2) \text{Re}\mathcal{T}, \]

\[ s^{j}_{1,LU} \sim F_1 \text{Im}\mathcal{H} + \xi(F_1 + F_2) \text{Im}\mathcal{T}, \]

\[ s^{j}_{1,UL} \sim F_1 \text{Im}\mathcal{T} + \xi(F_1 + F_2) \text{Im}\mathcal{H}, \]

In the present talk, we will be interested in deriving the beam-spin asymmetry defined as:

\[ A = \frac{\Delta^4\sigma}{d^4\sigma} \tag{1} \]

Figure: Unpolarized and beam-helicity cross sections at \( Q^2 = 2.3 \text{ GeV}^2, \ x_B = 0.36, \ t = -0.3 \text{ GeV}^2 \) (Hall A).
DVCS: Unpolarized protons from LH2 at 10.6 GeV

\[ A_{LU} \propto \text{Im} \left[ F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \xi \right] \]

Performed by G. Christiaens, M. Defurne, D. Sokhan.

Analysis note approved and article under Ad-Hoc review... Submission to PRL.

Tested against ANNs fitted on 6 GeV data, new data significantly improved our knowledge of BSA.

Comparisons with KM15 and VGG/GK models are performed as well.
DVCS: Unpolarized protons/neutrons from LD2 at 10.2 GeV

- $A_{LU} \propto \text{Im} \left[ F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E} \right]$

- Performed by A. Hobart and S. Niccolai.

- Analysis note under review.

- Measuring the proton allows to check for nuclear effect on proton structure.

- With $F_2 >> F_1$, the neutron is more sensitive to $E$ than the proton.

Top: pDVCS BSA integrated over all phase space. Bottom: nDVCS BSA integrated over all phase space.
Cross sections must be measured to completely characterize DVCS.

S. Lee and R. Milner extracting cross section with 10.6 GeV data, shown @ DNP22.

Normalization is being carefully checked.

Data collected @ 6.5 and 7.5 GeV to separate DVCS and interference terms.

J. Tan and FX Girod currently finalizing the BSA analysis shown @ DNP22.
DVCS: Data taking on longitudinally polarized target

- \[ A_{UL} \propto \text{Im} \left[ F_1 \tilde{\mathcal{H}} + \xi (F_1 + F_2)(\mathcal{H} + x_B/2\tilde{E}) - \xi \frac{t}{4M^2} F_2 \tilde{E} \right] \]

- First electrons sent for RGC on Saturday evening to Hall B.
- Will continuously run until March 2023.
- Both NH\(_3\) and ND\(_3\) longitudinally polarized.
- NH\(_3\) polarized up to 90% last week in the Hall.
Perspectives: DVCS with positron beam

- Conditionally approved by the PAC.
- The most straightforward approach to separate DVCS and I.

\[ \sigma(\lambda, \pm e) = \left| J^{BH} \right|^2 + \left| J^{DVCS} \right|^2 \mp I, \]

\[ A_{UU}^C \propto Re \left[ F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \xi \right] \]

- The predictions for the charge asymmetry differ by much from one model to another.

**Figure:** Bayesian reweighting with CLAS12 prediction. Dutrieux et al, EPJA 57, 8, 250.
TCS: First measurement ever with CLAS12

- TCS is a conjugate process of DVCS.
- Two observables were extracted.
  \[ A_{FB} = \frac{\sigma(\theta,\phi) - \sigma(180-\theta,\phi+180)}{\sigma(\theta,\phi) + \sigma(180-\theta,\phi+180)} \]
- \( A_{FB} \) and \( A_{\odot U} \) gives Re and Im of 
  \[ F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \xi \]
- Published in PRL by P. Chatagnon and S. Niccolai (127, 262501).
Probing the GPD outside the diagonal $x = \xi$ unlike DVCS and TCS.

DVCS and TCS limits of DVCS when $Q^2$ and $Q'^2$ at 0.

But cross section much lower by a factor 300 than DVCS.

LOI12-16-004 for a HL-CLAS12 ($10^{37}$).

Predictions for 100 days run.
\[ \pi^0\text{-electroproduction} \]

The \( \pi^0 \)-electroproduction cross section can be written as the sum of structure functions corresponding to response to virtual photon polarization.

\[
\frac{d^4\sigma}{dtd\phi dQ^2 dx_B} = \frac{1}{2\pi} \Gamma_{\gamma^*}(Q^2, x_B, E_e) \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \frac{d\sigma_{TT}}{dt} \cos(2\phi) + \lambda_e \sqrt{2\epsilon(1-\epsilon)} \frac{d\sigma_{TL}'}{dt} \sin(\phi) + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{TL}}{dt} \cos(\phi) \right],
\]

Assuming the factorization for transversely polarized photon:

\[
\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'} \frac{\mu^2}{Q^8} \left[ (1 - \xi^2)|\mathcal{H}_T|^2 - \frac{t'}{8m^2} |2\tilde{\mathcal{H}}_T + \mathcal{E}_T|^2 \right],
\]

(2)

\[
\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{2k'} \frac{\mu^2}{Q^8} \frac{t'}{16m^2} |2\tilde{\mathcal{H}}_T + \mathcal{E}_T|^2,
\]
π⁰-electroproduction: BSA and cross sections

- With the 10.6 GeV beam, new data at large Q² but also Rosenbluth separation possible when compared to 6 GeV data.
- BSA analysis note under review submitted by A. Kim et al.
- Active work on cross-section extraction by R. Johnston shown @ DNP22.
The GPD experimental program with CLAS12 is one of the richest ever, thanks to the large acceptance of the spectrometer and the high luminosity.

Data was collected at multiple energies, on proton and neutron. And a longitudinally polarized target is in place as I speak.

Several analyses under review, becoming as many publications in the months to come.

Many ongoing analyses on DVMP in addition to $\pi^0$, including $\phi$-electroproduction by P. Moran on proton data and N. Ramasubramanian on deuterium data.

First TCS ever measurements published!

A positron beam would complete the set of DVCS observables collected by CLAS12, and unambiguously constrain the real part of CFF.

HL-CLAS12 would give us the opportunity to measure double DVCS for the first time, and constrain the GPDs away from the diagonal $x=\xi$. 
References

- Kumericki, Kresimir and Muller, Dieter, EPJ Web of Conferences 112, 01012 (2016).