Deep exclusive processes with CLAS12 at 10.6 GeV

Maxime DEFURNE
CEA/Saclay

On behalf of

Franck Sabatie (CEA/Saclay)
Latifa Elouadrhiri (Jefferson Lab)
F-X Girod (Jefferson Lab)
V. Kubarovsky (Jefferson Lab)
A. Kim (Uconn, Jefferson Lab)
The generalized parton distributions

• We want to understand the strong interaction. Lepton scattering experiments have proven to be a powerful tool to probe the inner structure of the nucleons. Form factors and Parton distributions functions give a very limited description of the behavior of confined partons.

• Generalized parton distributions encode the correlations between longitudinal momentum and transverse position of partons in the nucleon.

• GPDs are accessible through deep exclusive processes, thanks to the factorization theorem.
Accessing the GPDs

- Theoretical framework of GPDs is well-known:
  - Factorization proven for Deeply Virtual Compton Scattering (DVCS) at all-orders, Deep Virtual Meson Production (DVMP) for longitudinally polarized photons.
  - Kinematical power corrections to the DVCS amplitude.

- At leading-twist, there are 8 GPDs describing the nucleon per flavor.
  \( H, E, \tilde{H}, \tilde{E} \) are the chiral-even GPDs.
  \( H_T, E_T, \tilde{H}_T, \tilde{E}_T \) are the chiral-odd GPDs.

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- However, necessity to follow given constrains to have GPD-compatible and valuable measurements.
All amplitudes are convolution of GPDs and a kernel computed perturbatively.
Properties of measurements to have clean access to GPDs

• To have a minimal contribution from higher-twist effects, it is good to ensure $Q^2 \gg M^2$.

• Moreover, the squared momentum transfer $t$ must be rather small compared to $Q^2$ (In most phenomenological studies, $-t/Q^2 < 0.25$).

• The phenomenological analyses rely on harmonic analyses of the cross section/asymmetries: Good to ensure a good phi-coverage.

• Finally, measurements must be statistically-significant (tends to limit the maximal $Q^2$ values.)

Deep Virtual Meson Production

• The cross section of meson electroproduction can be written as the sum of 4-terms:

\[
\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_{TL}}{dt} \sqrt{2\varepsilon (1 + \varepsilon)} \cos(\Phi) + \frac{d\sigma_{TT}}{dt} \varepsilon \cos(2\Phi)
\]

With \(\sigma_T\) (resp. \(\sigma_L\)) response to a transversely or longitudinally polarized photon, \(\sigma_{TT}\) and \(\sigma_{TL}\) interference terms between the responses.

The term \(\varepsilon\) is the degree of longitudinal polarization of the virtual photon and is a kinematic term depending on \(Q^2\), \(x_B\) and the beam energy.

• For \(\varphi\), \(\eta\) and \(\pi^0\), the leading-twist term is \(\sigma_L\). In this term, one access chiral-even GPDs.

- \(\eta\) and \(\pi^0\) give different flavor combination for \(\tilde{H}, \tilde{E}\).
- \(\varphi\) give information about gluons inside the nucleon.
**φ electroproduction**

- The full separation of the cross section can be performed by looking at the φ-decay.

\[ \frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_{TL}}{dt} \sqrt{2\varepsilon (1 + \varepsilon)} \cos(\Phi) + \frac{d\sigma_{TT}}{dt} \varepsilon \cos(2\Phi) \]

- Through \( \gamma_L^* p \to p \phi_L \), we access the gluon GPDs.

\[ \frac{d\sigma_L}{dt} = \frac{\alpha_{em}}{Q^2} \frac{x_B^2}{1 - x_B} \left[ (1 - \xi^2) |\langle H_g \rangle|^2 + \text{terms in } \langle E_g \rangle \right] , \]

- It is well-described by GPD-model.

- This channel is very interesting to study the gluonic radius of the proton, extracted from the t-dependence of the cross sections. (Matter radius versus charge radius).

- There is also the question about an intrinsic strange sea (p=uud + uuds\(\bar{s}\) + \cdots)
The $\varphi$-meson will be detected thanks to:
- $K^+K^-$ pair from its decay (48.9%).
- $K_L^0 K_S^0 \rightarrow K_L^0 \pi^+ \pi^-$: Detect the two pions and cut on the missing mass to get the $K_L^0$ (34.2%).
Through the charged kaon pair, the phi-meson is well identified.

Courtesy F-X Girod
**φ-electroproduction acceptance**

Torus +100% Solenoid 100% : Blue
Torus +75% Solenoid 70% : Red
Torus -75% Solenoid 70% : Green
Torus -100% Solenoid 100% : Yellow

- Outbending (positive Torus polarity) gives better acceptance results compared to inbending.
- Significant improvements of acceptance at low $Q^2$/ low $x_B$.
- $T$-slope of cross sections should be published with 12 months.
Projected Results for Deep $\phi$ t-slopes

Left column: $\phi$ acceptances used for amplitude extraction in SCHC test

Right column: $\cos\theta_{CM}$ of meson decay allows separation of $\sigma_L$ and $\sigma_T$ under SCHC

Courtesy F-X Girod

$\sigma_L$ t-slopes extracted for different magnetic fields
Lower field and negative outbending torus are preferred
For the $\eta$ and $\pi^0$, the transverse-transverse interference was found surprisingly large, as well as $\frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt}$.

Liuti et al., Goloskokov et al. have assumed that chiral-odd GPDs might couple to twist-3 distribution amplitude of the pions, enhancing the T response.

$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_{TL}}{dt} \sqrt{2\varepsilon (1 + \varepsilon)} \cos(\Phi) + \frac{d\sigma_{TT}}{dt} \varepsilon \cos(2\Phi)$$

To perform a clean separation of the transverse and the longitudinal response for pseudo-scalar mesons, you must measure $\frac{d\sigma_T}{dt} + \varepsilon \frac{d\sigma_L}{dt}$ at fixed $Q^2$, $x_B$ but different beam energy to change $\varepsilon$.

This Rosenbluth separation was performed in Hall A and proved that $\frac{d\sigma_T}{dt} >> \frac{d\sigma_L}{dt}$. But we still need to test the $Q^2$-dependence of the two terms over the whole JLab phase space.

This data at 10.6 GeV will complete the CLAS data at 6 GeV. It is also part of a Rosenbluth proposal with CLAS12 (RG-K).

Preparing the upcoming data collection and analysis

- The cross section concentrates events at low $Q^2$/high xB. Missing mass and invariant mass have been successfully reconstructed.

Courtesy A. Kim
Photon electroproduction

- Compared to DVMP, photon electroproduction is considered as a golden channel to study the GPDs

- Indeed photon electroproduction arises from the interference between DVCS and the Bethe-Heitler.

  - Advantage: The interference term gives access to real part and imaginary part of CFFs. The latter gives the value of the GPD at $x=x_i$.

  - Be careful: Unlike DVMP, photon electroproduction is not always a pure GPD-information.

  => GPD information lies in the deviation from the Bethe-Heitler signal alone for the unpolarized cross sections.
Photon electroproduction

- Two observables will be studied:
  1) Beam spin asymmetries: Maximal polarization for the electron beam.
     - Asymmetries are very little sensitive to systematics compared to cross sections.

     It will be the first extracted observable, published within 12 months.
     (very pessimistic estimate taking into account very bad luck… but not an act of God).

  2) Unpolarized cross sections:
     - Much more delicate to extract because of systematics.
     - Need to identify all sources of systematics prior data taking.
     - Still prior data taking, try to minimize them and/or estimate them at best.

     First 20 days will be extremely useful to prepare the remaining data collection in 2018.

To have a complete picture of GPDs from DVCS, having both asymmetries and cross sections is essential!
Example of a photon electroproduction event

Identification of the process by detecting the 3-particle final states.

- DVCS Photon
- Recoil proton
- Scattered electron
- Internal Bremsstrahlung photon
GEMC Simulations to optimize running conditions

- GEMC v 4a.2.1
- COATJAVA 4.8.2
- Solenoid 80%
- Protons from EB
- Electrons from EB
- Photons by homemade ECAL algorithm. (so no FT-Cal)
- Inbending Torus is much efficient to get the recoil proton

-t>\text{t}_{\text{min}}\text{ and } -t<0.25 \ Q^2

Protons going at \(\theta_{\text{lab}} = 0^\circ\).

Courtesy G. Christiaens
What can we expect from 20 days of beam?

- To apply a binning similar to the proposal, the number of counts must be divided by at least a factor 10 => Instead of 1%, we will have 5%-measurements.

- To estimate these counts, we used the state-of-the-art of phenomenological fit (KM15), which cannot go above xB=0.5.

- Asymmetries of 0.10 and 0.20 depending on the bin, with 5%-accuracy.

With 20-days, enough statistics to challenge most fundamental assumptions of all phenomenological studies. M. Defurne et al., Accepted in Nature Communications. (Predictions)
Photon electroproduction GPD extraction

- Code including kinematical power corrections ready to extract CFFs from cross sections and asymmetries.
  
  \( M. \, \text{Defurne et al., Accepted in Nature Communications.} \)

- Release of PARTONS which can be embedded in fitting routine.

  \( B. \, \text{Berthou et al., } \text{https://arxiv.org/abs/1512.06174} \)
Manpower ressources

Maxime Defurne, Franck Sabatie, Francesco Bossu, Guillaume Christiaens (PhD/Glasgow), Noelie Cherrier (PhD) + 1 post-doc for 2 years.

CEA/Saclay

Latifa Elouadrhiri, Francois-Xavier Girod, Valery Kubarovsky
Jefferson Lab

Brandon Clary, Kyungseon Joo, Andrey Kim (Post-doc)
University of Connecticut

Rafayel Paremuzyan (Post-doc)
University of New Hampshire

Ivan Bedlinskiy
ITEP/Moscow

Joshua Artem Tan (Ph.D Student), Wooyoung Kim
Kyungpook National University, Taegu, Korea

All staff and post-docs have extensive experience from 6-GeV DVCS/DVMP experiments (Hall A/CLAS),
What remains to be done?

- Generators are ready for all channels with scripts to analyze the reconstructed files.
  1) Careful study of running conditions to maximize the low-\(t\) acceptance.
  2) Using the different generators, write and validate the analysis code for all observables (Generate pseudo-data).
  3) Estimate data analysis systematics for event selection:
      - Machine learning style.
      - Old school style (2 vs 3 particle coincidence.)
  4) Estimate systematics on observable extractions:
      - CLAS style.
      - Hall A style.

=> Challenge to keep systematics as low as possible, and to estimate them correctly.

- Points 1 and 2 are mandatory to ensure good understanding of detector performances and acceptances.
Timescales for high impact publications

- First observables which could be “easily” published are beam-spin asymmetries for $\pi^0$ electroproduction and photon electroproduction. Pessimistic estimate: 12-months after beginning of data collection.

- Then will come $\varphi$-electroproduction cross sections t-slope (12-months).

- Finally $\pi^0$ and photon electroproduction cross sections released almost simultaneously… but before needs to check normalization with elastic and DIS cross sections. (36-months)

- Considering the latest results from Hall A, we can expect CLAS12 data to unravel the exact nature of previous DVCS measurements.

Since having a 10.6 GeV beam “turn off” the Bethe-Heitler, we will measure quasi-pure DVCS.

We will finally determine if there are higher-twist or gluonic contributions.

We can aim at a Nature Physics paper! This data represents a giant leap for the GPD study.
Summary

• Physics of the first publications well defined.

• Tools in place for both simulations and reconstructions.

• Full simulations for all the physics reactions underway.

• Team in place, with weekly meeting, doing parallel analyses:
  • Within a month, Desired running conditions will be well-defined for all channels.
  • Then start generating pseudo-data and developing analysis code. (ex: Fine tuning of fiducial cuts, contamination subtraction,…)

• We have started a close collaboration with theorists and phenomenologists for GPD analysis of our measurements.
THANK YOU
Photon electroproduction

Bethe-Heitler is green curve.
Photon electroproduction and Bethe-Heilter

- \( Q^2 > 1 \text{ GeV}^2 \)  
- \( \theta_e > 8 \text{ degrees} \)  
- \( W > 2 \text{ GeV} \)  
- \( \theta_e < 35 \text{ degrees} \)

- \( E' > 1 \text{ GeV} \)

- \( -t_{\text{min}}/Q^2 \text{ (GeV}^2) \)

- \( \gamma \text{ at } x_B = 0.3, Q^2 = 4.5 \)

- \( \gamma^* \text{ direction} \)

- \( \text{increasing } t \)

- \( \text{increasing } \phi \)

- \( t_{\text{min}} = 0 \)

- \( \text{proton at } x_B = 0.3, Q^2 = 4.5 \)

- \( \text{proton at } x_B = 0.3, Q^2 = 4.5 \)

- \( \text{proton at } x_B = 0.3, Q^2 = 4.5 \)
Photon electroproduction

- At 10.6 GeV, a super-Rosenbluth separation opportunity for “low”-\(Q^2\) and high \(x_B\)
  \((Q^2 = 2\ \text{GeV}, \ x_B = 0.36, \ t = -0.3)\)

Finally, a validation of leading-twist/leading-order approximation for all 6-GeV data!
If sensitivity to gluon transversity GPDs is proven, a Nature Physics paper would be possible.

- Less straightforward for asymmetries but might be possible.