The GPD program with CLAS12: highlights and perspectives

CLAS collaboration

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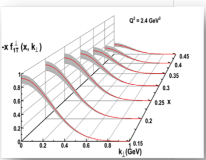
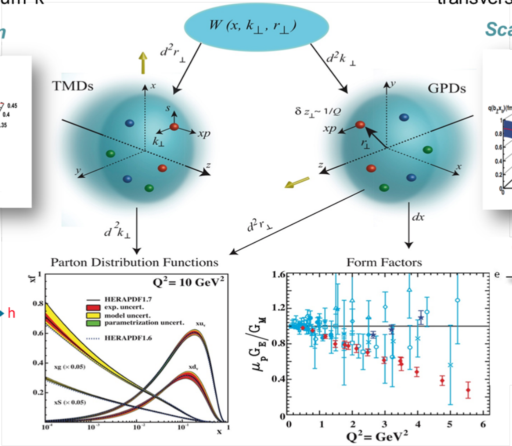
A set of distributions encoding the nucleon structure

TMDs: Fraction of longitudinal momentum x et transverse momentum k

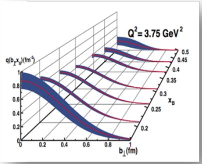
GPDs: Fraction of longitudinal momentum x et transverse position b

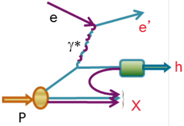
Scan in momentum

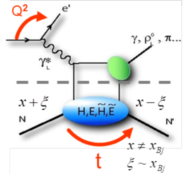




Scan in position







The generalized parton distributions and the nucleon

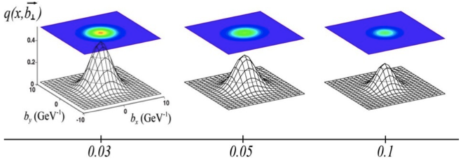
At leading twist there are 8 GPDs:

- 4 chiral-even GPDs: H, E, $\widetilde{H}$ and $\widetilde{E}$.
- 4 chiral-odd GPDs: H_T, E_T, $\widetilde{H}_T$ and $\widetilde{E}_T$.

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

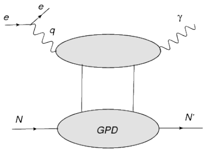
$$\int_{-1}^{1} x \left[H^f(x,\xi,0) + E^f(x,\xi,0) \right] \, dx = J^f \qquad \forall \xi \; .$$

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

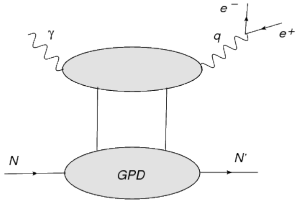


Several GPDs but a universality principle

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



(a)



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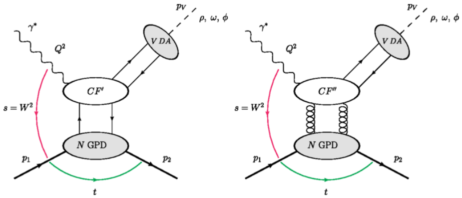


Deep virtual meson production has an additionnal non-perturbative part: The meson.
Although there is an additionnal “unknown”, it can conveniently be used for flavor separation or study of specific GPDs.

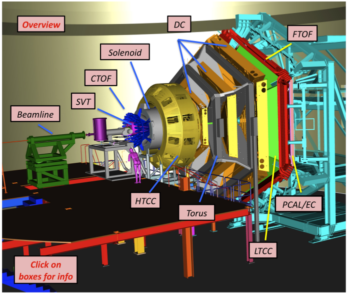
A spectrometer to get them all at once

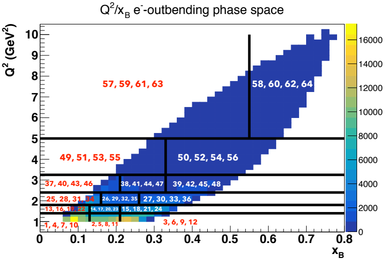
The deep exclusive processes are:

- associated with a low cross section => $10^{35}\ s^{-1}cm^{-2}$.
- diversifed with respect to their final state => RICH, LTCC, ToF.
- ... exclusive => Large acceptance with Central and Forward detectors.

CLAS12 spectrometer can simulatenously 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.

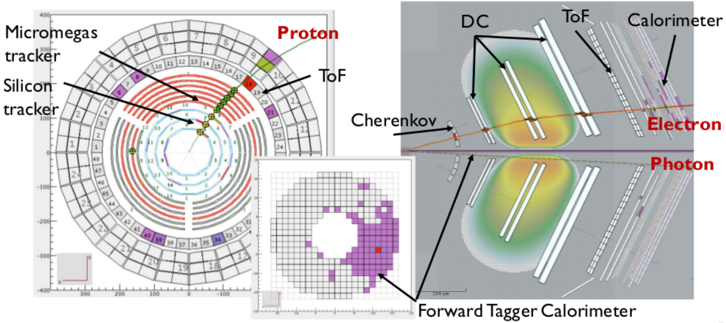




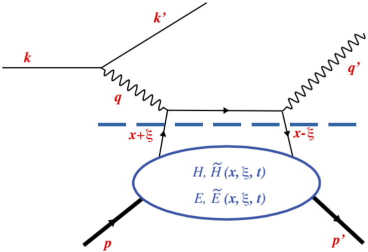
All detectors required for exclusive processes

A 10.6-GeV electron beam scatters off a 5-cm LH_2 target. The beam is ∼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 $PbWO_4$-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.

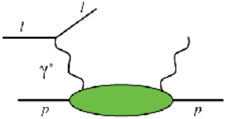
The GPDs enter the DVCS amplitude through a complex integral. This integral is called a *Compton form factor* (CFF).

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

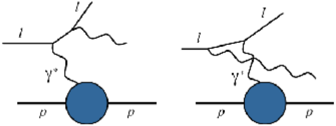
At leading order, $\mathrm{Im}\mathcal{H}(\xi, t) \propto (H(\xi, \xi, t) - H(-\xi, \xi, t))$.

Photon electroproduction

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

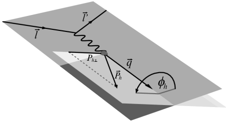


DVCS



Bethe-Heitler

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



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.

$$c_{0,UU}^{DVCS} \sim 4(1-x_B)\left(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right),$$

$$c_{1,UU}^{\mathcal{I}} \sim F_1\ Re\mathcal{H} + \xi(F_1+F_2)\ Re\widetilde{\mathcal{H}},$$

$$s_{1,LU}^{\mathcal{I}} \sim F_1\ Im\mathcal{H} + \xi(F_1+F_2)\ Im\widetilde{\mathcal{H}},$$

$$s_{1,UL}^{\mathcal{I}} \sim F_1\ Im\widetilde{\mathcal{H}} + \xi(F_1+F_2) Im\mathcal{H},$$

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

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

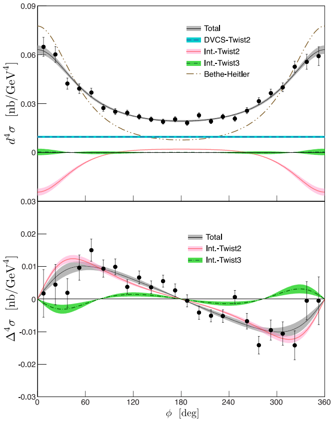
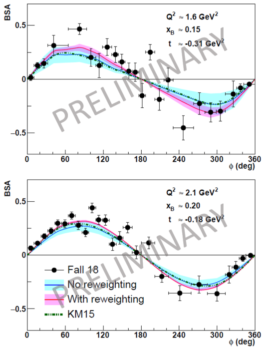
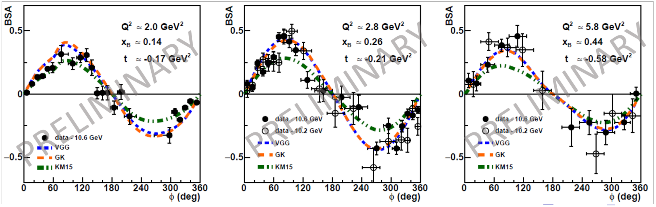


Figure: Unpolarized and beam-helicity cross sections at Q^2=2.3 GeV^2, x_B=0.36, t=-0.3 GeV^2 (Hall A).

DVCS: Unpolarized protons from LH2 at 10.6 GeV

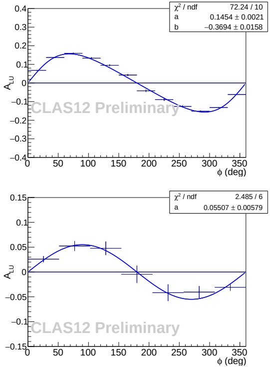
- $A_{LU} \propto Im\left[F_1\mathcal{H} + \xi\,(F_1 + F_2)\,\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$
- Performed by G. Christiaens, M. Defurne, D. Sokhan.
- Analysis note approved and article under Ad-Hoc review... Submission to PRL.
- Tested against ANNs fitted on 6 GeV data, new data significantly improved our knowledge of BSA.
- Comparisons with KM15 and VGG/GK models are performed as well.

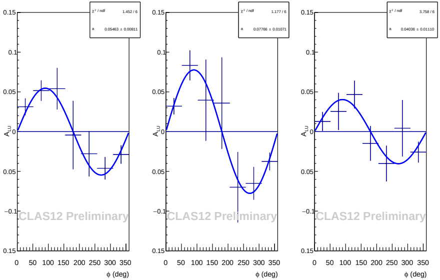




DVCS: Unpolarized protons/neutrons from LD2 at 10.2 GeV

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

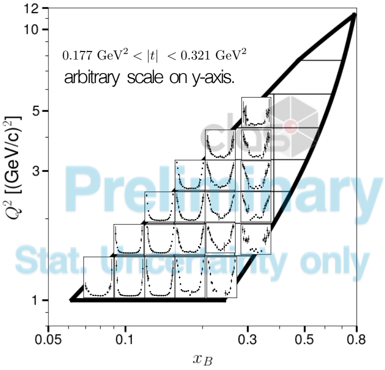




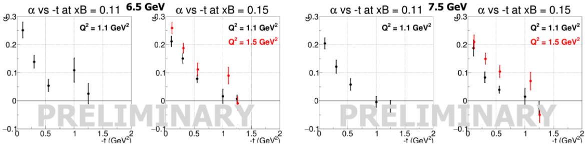
Top: pDVCS BSA integrated over all phase space. Bottom: nDVCS BSA integrated over all phase space.

DVCS: ongoing analysis on Unpolarized protons from LH2

- 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.

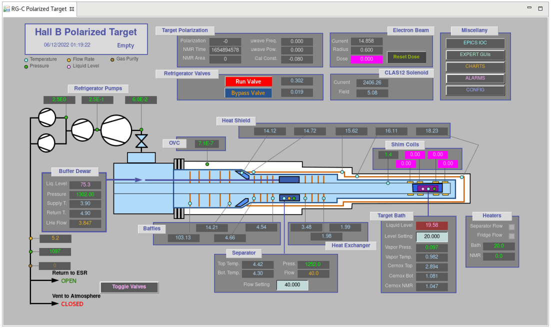


$$\mathrm{BSA}(\phi) \sim \frac{\alpha \sin\phi}{1+\beta\cos\phi}$$



DVCS: Data taking on longitudinally polarized target

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

$$\sigma(\lambda, \pm e) = \left|\mathcal{T}^{BH}\right|^2 + \left|\mathcal{T}^{DVCS}\right|^2 \mp \mathcal{I} \, ,$$

- $A^C_{UU} \propto Re\left[F_1\mathcal{H} + \xi\left(F_1 + F_2\right)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$
- The predictions for the charge asymmetry differ by much from one model to another.

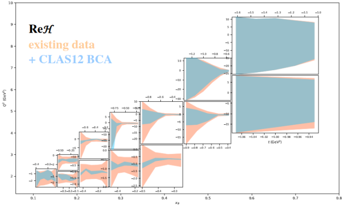
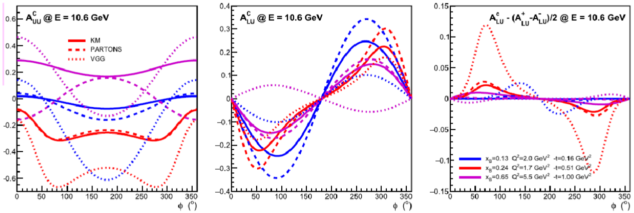
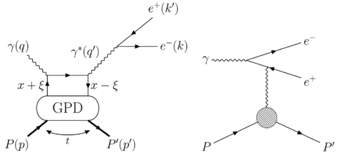


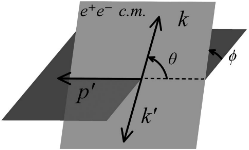
Figure: Bayesian reweighting with CLAS12 prediction. Dutrieux *et al*, EPJA 57, 8, 250.

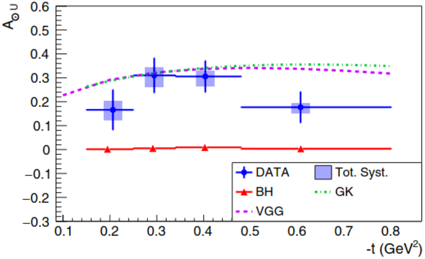


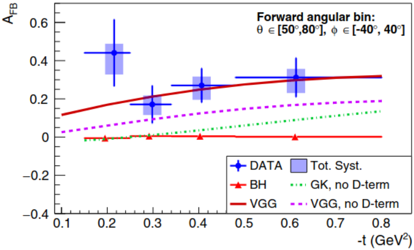
TCS: First measurement ever with CLAS12

- TCS is a conjuguate 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 $F_1\mathcal{H} + \xi\,(F_1 + F_2)\,\tilde{\mathcal{H}} - \frac{t}{4M^2} F_2\mathcal{E}$
- Published in PRL by P. Chatagnon and S. Niccolai (127, 262501).



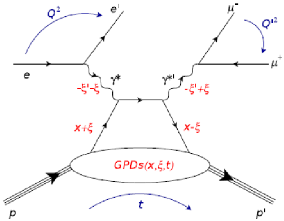


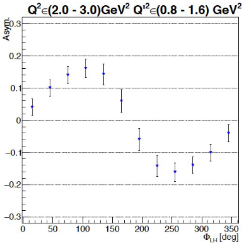


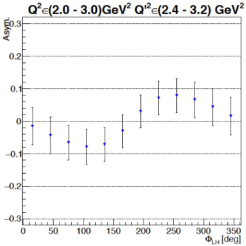


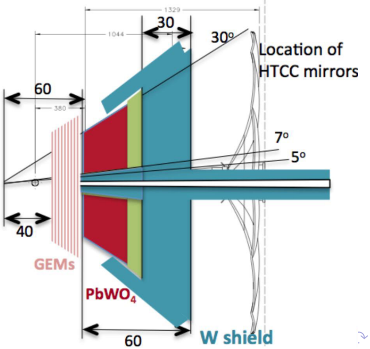
Perspectives: Double DVCS @ CLAS12

- 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.









π^0-electroproduction

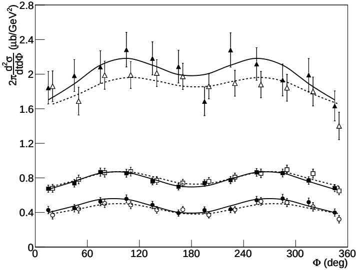
The π^0-electroproduction cross section can be written as the sum of structure functions corresponding to response to virtual photon polarization.

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

Assuming the factorization for transversely polarized photon:

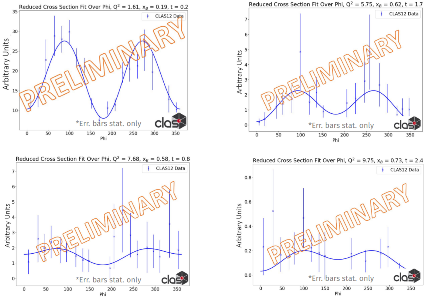
$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)|\mathcal{H}_T|^2 - \frac{t'}{8m^2}|2\widetilde{\mathcal{H}}_T + \mathcal{E}_T|^2\right], \quad (2)$$

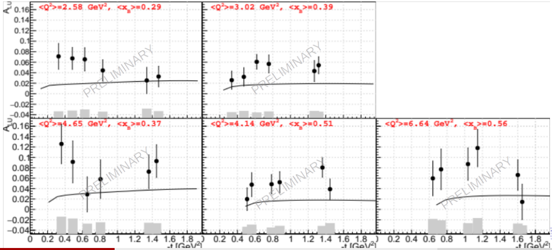
$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}|2\widetilde{\mathcal{H}}_T + \mathcal{E}_T|^2,$$



π^0-electroproduction: BSA and cross sections

- With the 10.6 GeV beam, new data at large Q^2 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.





Conclusion

- 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 π^0, including ϕ-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=ξ.

References

- H. Moutarde, P. Sznajder, and J. Wagner, Eur. Phys. J. C 79, 614 (2019), arXiv:1905.02089 [hep-ph].
- Kumericki, Kresimir and M uller, Dieter, EPJ Web of Conferences 112, 01012 (2016).
- S. V. Goloskokov and P. Kroll, The European Physical Journal C 65, 10.1140/epjc/s10052-009-1178-9 (2009)
- M. Vanderhaeghen, P. A. Guichon, and M. Guidal, Phys.Rev. D60, 094017 (1999), arXiv:hep-ph/9905372 [hep-ph].