Deeply virtual Compton scattering on Proton with CLAS12

CLAS collaboration

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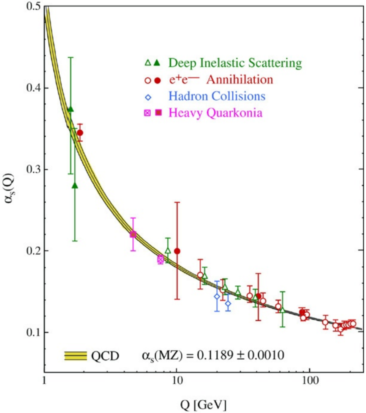
The nucleon: a formidable lab for QCD

- The nucleon is a dynamical object made of quarks and gluons.
- This dynamics is ruled by the strong interaction.
- A perturbative approach from first principles to unravel this dynamics is impossible due to the large size of the strong coupling constant.

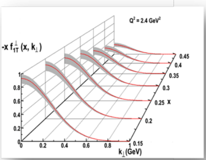


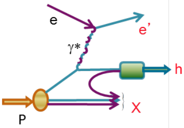
Although non-perturbative approaches (DSE, lattice QCD) starts making progress, the experimental approach remains more convenient to get complex information about this dynamics.

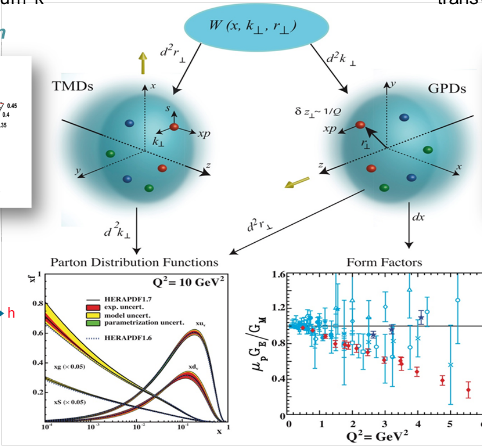
A set of distributions encoding the nucleon structure

TMDs: Fraction of longitudinal momentum x et transverse momentum k

Scan in momentum

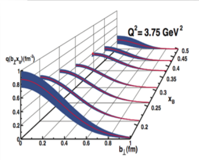


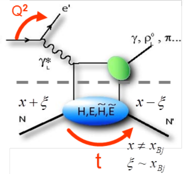




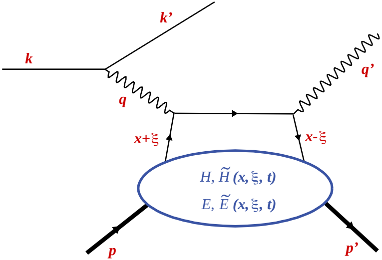
GPDs: Fraction of longitudinal momentum x et transverse position b

Scan in position





DVCS and GPDs



- $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi = \frac{x_B}{2 - x_B}$ 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).

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

The generalized parton distributions and the nucleon

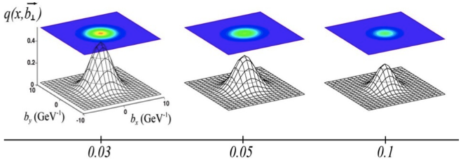
At leading twist there are 8 GPDs:

- 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.

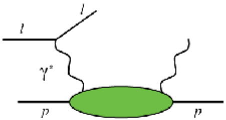
$$\int_{-1}^{1} x \left[H^f(x,\xi,0) + E^f(x,\xi,0) \right] \, dx = J^f \qquad \forall \xi \,.$$

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.

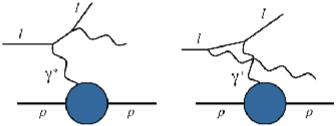


Photon electroproduction

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 $\gamma^* p \to \gamma p$.

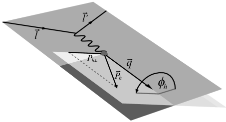


DVCS



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.

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

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

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

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

For these observables, at leading-order and leading-twist:

- there is only $c_{0,UU}^{DVCS}$ in $DVCS^2$.
- there are only $c_{1,UU}^{\mathcal{I}}$ and $s_{1,UL}^{\mathcal{I}}$ for $\mathcal{I}$.

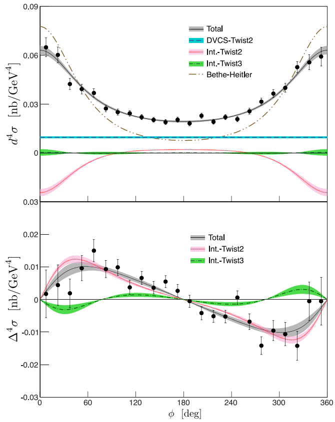
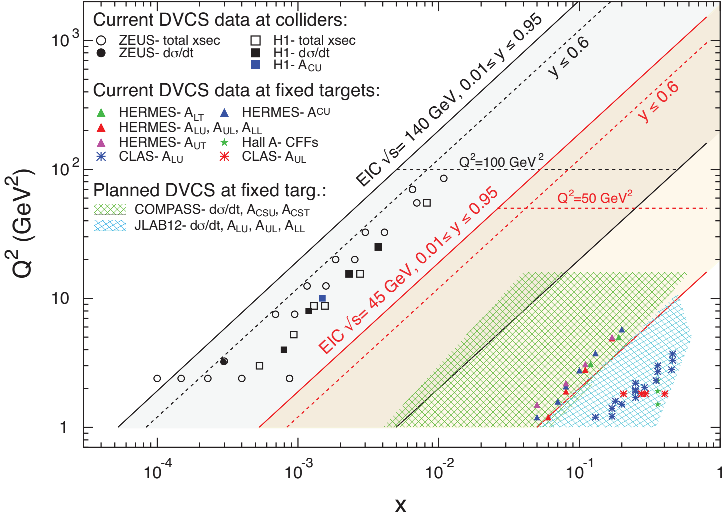


Figure: Unpolarized (top) and beam-helicity dependent cross sections at Q^2=2.3 GeV^2, x_B=0.36 and t=-0.3 GeV^2.

What have we collected so far?

Getting the GPDs: Cover the entire phase space with as many observables as possible!



CLAS12: A unique place to study GPDs

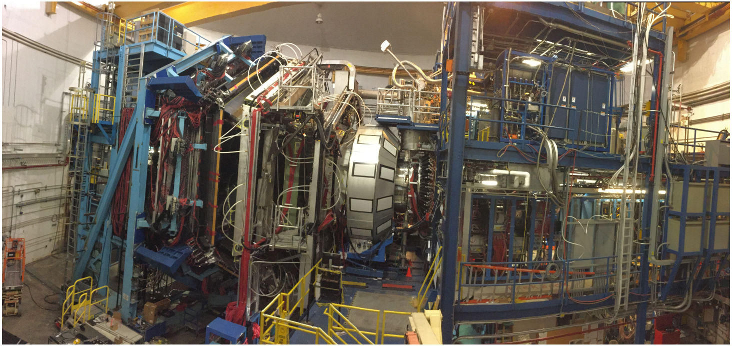
The 12-GeV upgrade of the accelerator opens an access to a terra incognita in Q^2/x_B.

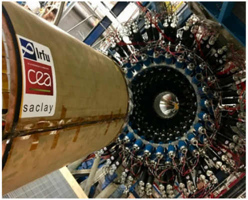
- CLAS to CLAS12 upgrade to reach higher luminosity and to explore the terra incognita!

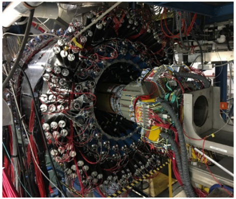
- Disentangle the different GPD contributions with :
  → Polarization of beam and targets for the different channels.
  RG-A/K (LU/Rosenbluth) , RG-C (Long. pol. target), RG-H (Trans. pol. target).
  → Neutron data:
  RG-B (See Silvia Niccolai's talk).
  → Have lepton/anti-lepton beam
  Proposal by Voutier, Niccolai *et al.*.

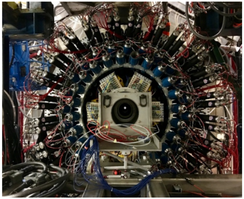
The most complete GPD experimental program ever run!

Focus on CLAS12: Beam from right to left.





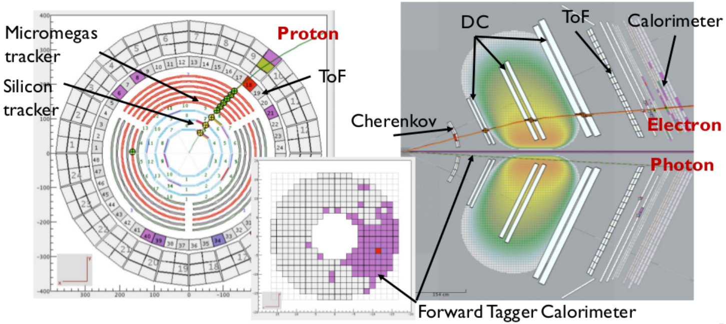




A typical DVCS event in CLAS12

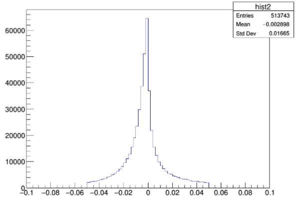
All CLAS12 detectors are necessary to reconstruct all particles of a DVCS final state:

- 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 Silicium and Micromegas detector.

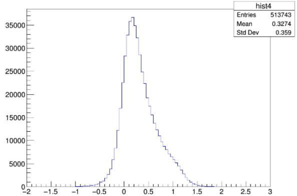


DVCS event selection

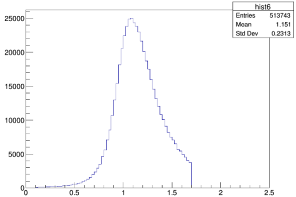
Exclusivity is enforced by cutting on 5 variables:



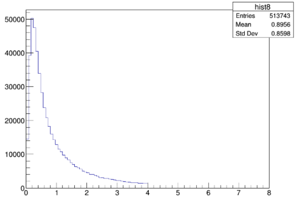
(a) Missing mass squared $ep \to ep\gamma X$ (GeV^2)



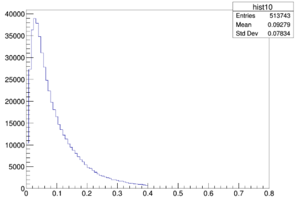
(b) Missing energy $ep \to ep\gamma X$ (GeV)



(c) Missing mass $ep \to e\gamma X$ (GeV)



(d) Photon cone angle (°)

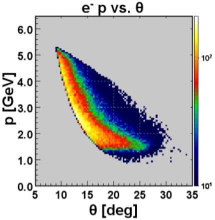


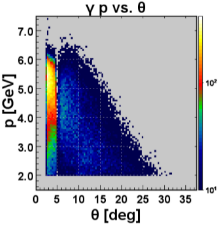
(e) Missing perpendicular momentum $ep \to ep\gamma X$ (GeV)

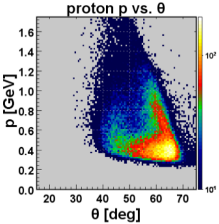
However some exclusive π^0's contaminate your DVCS sample.

Run group K: Unpolarized proton @ 7.5 GeV

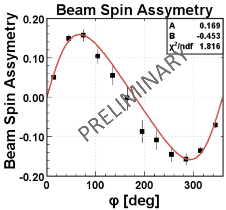
After exclusivity cuts, here are the momentum/angle distribution.







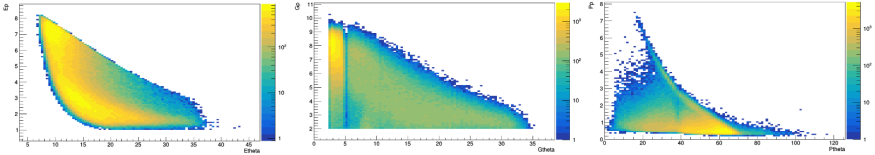
- Unpolarized protons with 7.5 GeV longitudinally polarized electron beam.
- π^0 subtraction not performed on this BSA.
- Stay tuned for next DNP results with pass-1.



Courtesy J. ARTEM TAN

Run group A: Unpolarized proton @ 10.6 GeV

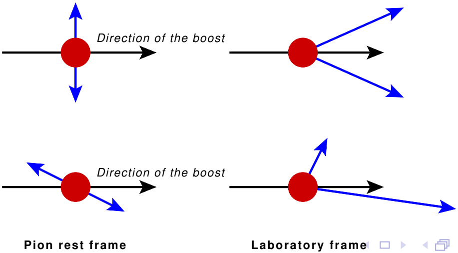
After exclusivity cuts, here are the momentum/angle distribution.



(a) Electrons (b) Photons (c) Protons

Figure 2: Momentum (GeV) vs θ angle ($^\circ$) for electrons, photons and protons after selection and exclusivity cuts

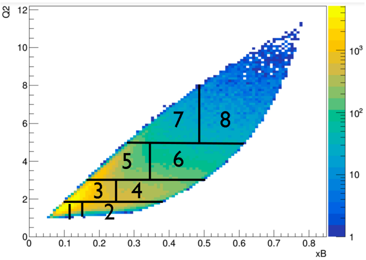
Some exclusive π^0's contaminate your DVCS sample.



Run group A: Unpolarized proton @ 10.6 GeV

The π^0-contamination has been studied and subtracted:

- BH/DVCS statistics is high for low Q^2 and low x_B.
- π^0 contamination grows larger with x_B.



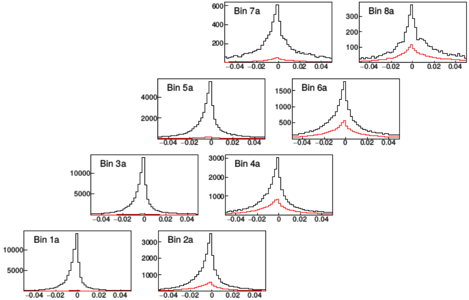


Figure 6: Missing mass squared $ep \to ep\gamma X$ for bins with $-t/Q^2 < 0.25$ and estimation of π^0 contamination.

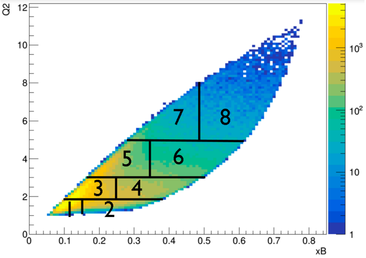
Courtesy G. CHRISTIAENS.

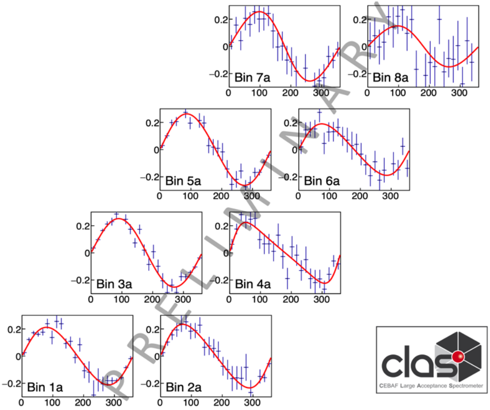
Run group A: Unpolarized proton @ 10.6 GeV

The asymmetry is fitted with the following functionnal form:

$$\mathcal{A}^{DVCS}(\phi_{Trento}) = \frac{1}{P_{el}} \frac{N^+/Q^+ - N^-/Q^-}{N^+/Q^+ + N^-/Q^-} = \frac{p_0 \sin\phi_{Trento}}{1 + p_1 \cos\phi_{Trento}} \qquad P_{el} \sim 85\% \qquad (1)$$

Courtesy G. CHRISTIAENS.





Conclusion

- The results in this presentation were shown at last DNP 2019.
- Pass-1 for RG-A data provides a much larger statistics... on-going analysis.
- π^0 subtraction procedure validated.
- Refining binning, computation of bin center and radiative corrections remain to be performed.
- CLAS12 may (will) carry out the most complete DVCS program ever.
- A great thanks to the PhD students leading the analysis effort:
  $\rightarrow$ Guillaume CHRISTIAENS (RGA/BSA),
  $\rightarrow$ Joshua ARTEM TAN (RGK),
  $\rightarrow$ Katheryne PRICE (RGB),
  $\rightarrow$ Sangbaek LEE (RGA/Cross sections),

Back-Up

Last but not least: The phenomenology

Many channels, many observables provided by different facilites and each of them holds a specific piece of the puzzle.
Need to work hand-by-hand with phenomenologists and theorists .

We will need to develop global analysis tools in order to:

- combine all data and thus strongly constrain fits or models.
- test systematically the impact of diverse assumptions:
  - LO, NLO, NNLO,...
  - the numbers of flavours,
  - the numbers of GPDs,

I want to use this opportunity to make some advertisement for a project of major importance.

GPD Computing made simple.

Differential studies: physical models and numerical methods.

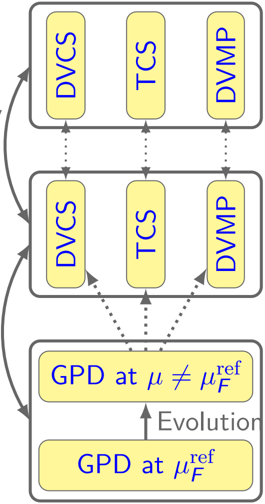
Phenomenology of Generalized Parton Distributions

PARTONS Project

Full processes
Experimental data and phenomenology

Small distance
Computation of amplitudes

Large distance
First principles and fundamental parameters



- Many observables.
- Kinematic reach.

- Perturbative approximations.
- Physical models.
- Fits.
- Numerical methods.
- Accuracy and speed.

What have we learned so far with data collected before 2016?

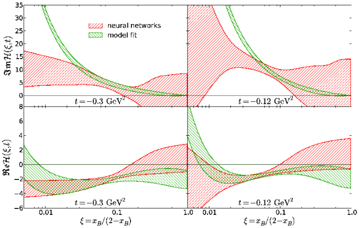
Several phenomenological fits of Compton Form factors has been performed at leading-twist:

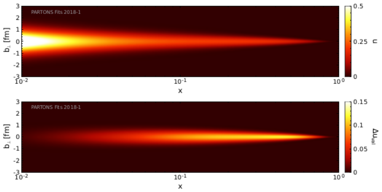
- Assuming that colliders are sensitive to gluons and fixed-target experiments to quarks.
- From either "empirical" models or Neural networks.

First sketch of proton profile is drawn, especially in the valence region.

Top: Kumericki *et al.*, JHEP07 (2011), 073

Bottom: Moutarde *et al.*, Eur.Phys.J.C78(2018)no.11,890





A glimpse of gluons through DVCS

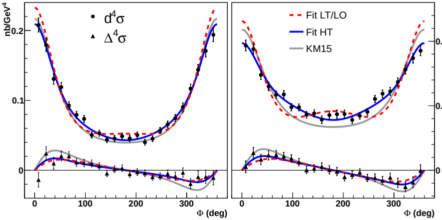
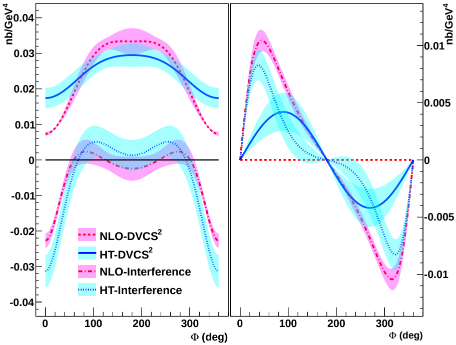


Figure: Q^2=1.75 GeV^2, -t=0.3 GeV^2. E=4.445 GeV (left) and E=5.55 GeV (right)



→ First data set at fixed kinematics but mutiple beam-energy.
→ First phenomenological analysis including kinematical power corrections.

- NLO: Gluon transversity GPDs.
- HT: Q-G-Q correlations.

M. Defurne *et al.*, Hall A collaboration, arXiv:1703.0944