The DVCS experimental program @ JLab

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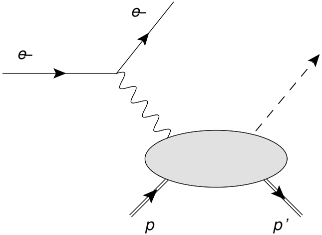
The deep exclusive processes

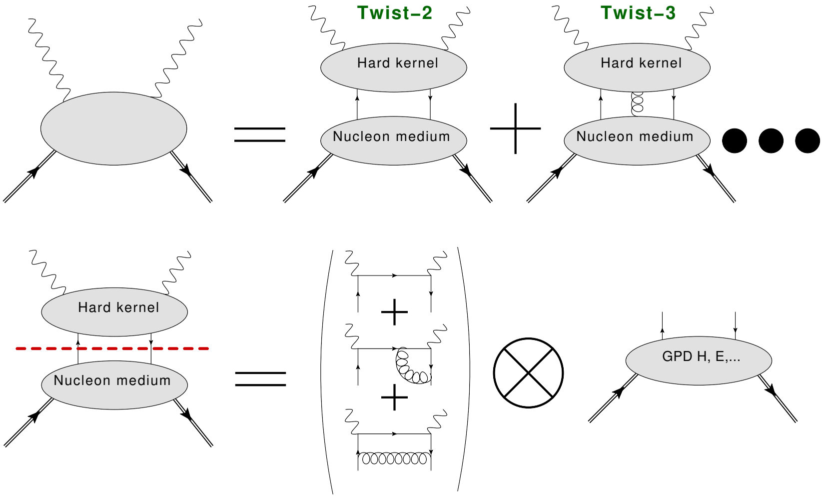
By measuring the cross section of deep exclusive processes, we get insights about the GPDs.



1. The electron interacts with the proton by exchanging a hard virtual photon with transverse and longitudinal polarization.
2. The proton emits a particle (γ, π^0, ρ,...)

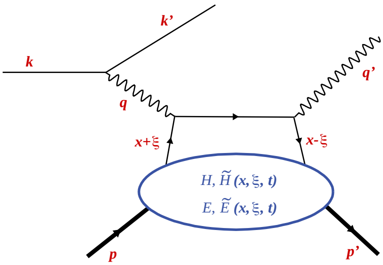
The link between these diagrams and the GPDs is guaranted by the factorization (Proven for DVCS for all polarization, only longitudinal for DVMP).

Factorization and GPDs



The amplitudes at twist-$(n+1)$ are suppressed by a factor $\frac{1}{Q}$ with respect to the twist-n amplitudes, with Q the virtuality of the photon.

DVCS and GPDs



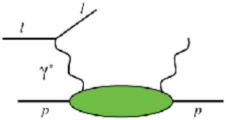
- $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi = \frac{x_B}{2 - x_B}$ the longitudinal momentum transfer.
- $t = (p - p')^2$ squared momentum transfer to the nucleon.

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

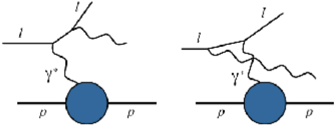
$$\mathcal{H}_{++}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx \, .$$

Photon electroproduction and GPDs (PART I)

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

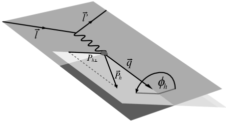


DVCS



Bethe-Heitler

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

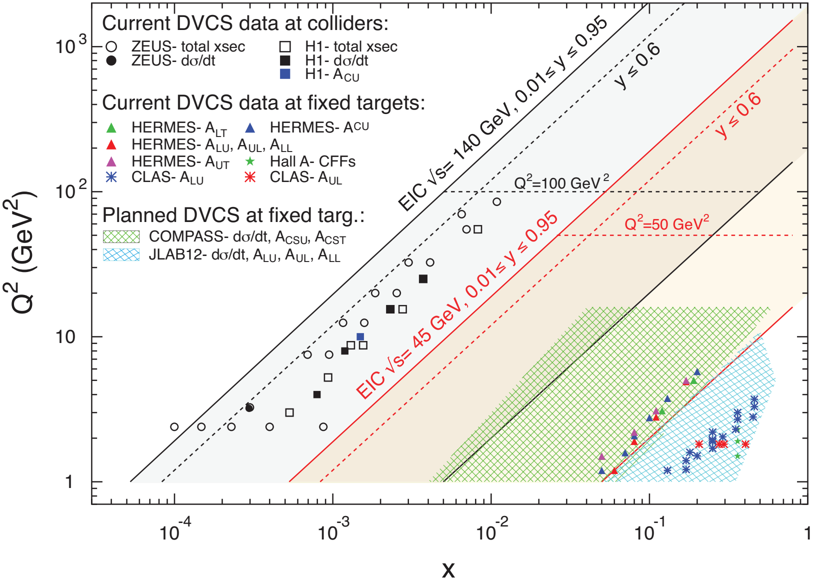


The interference term allows to access the phase of the DVCS amplitude, *i.e* allows to isolate imaginary and real parts of CFFs.
A few examples of harmonic coefficients and their sensitivity to CFFs:

$$
\begin{aligned}
c_{0,UU}^{DVCS} &\propto \quad 4(1-x_B)\left(\mathcal{H}\mathcal{H}^* + \widetilde{\mathcal{H}}\widetilde{\mathcal{H}}^*\right) + \cdots \\
c_{1,UU}^{\mathcal{I}} &\propto \quad F_1 \, Re\mathcal{H} + \xi(F_1+F_2)\, Re\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \, Re\mathcal{E}\,, \\
s_{1,LU}^{\mathcal{I}} &\propto \quad F_1 \, Im\mathcal{H} + \xi(F_1+F_2)\, Im\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \, Im\mathcal{E}\,, \\
s_{1,UL}^{\mathcal{I}} &\propto \quad F_1 \, \widetilde{\mathcal{H}} + \xi(F_1+F_2)\, \left(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\right) - \xi\left(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\right)\, \widetilde{\mathcal{E}}\,,
\end{aligned} \tag{1}
$$

At leading-order, the imaginary part of CFFs gives access to the GPD value on the diagonal x=ξ.

Various facilites to cover the entire phase space



Continuous Electron Beam Accelerator Facility

Longitudinally polarized electrons are accelerated using:

- Two linacs made of superconducting RF cavities,
- with recirculating arcs to be able to pass 5 times through the linacs.

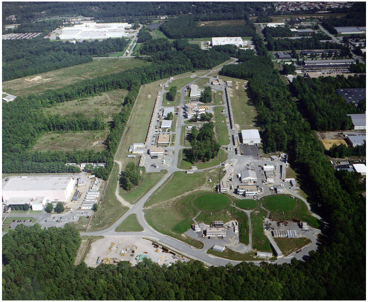
Two distinct era:

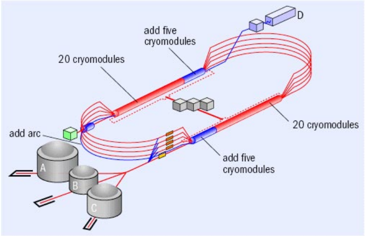
- 1994-2012: 6-GeV beam with three experimental Halls.
- 2014-...: 12-GeV beam with upgraded B and C Halls in addition to a brand new Hall D.

The polarization of the beam is about 85%.

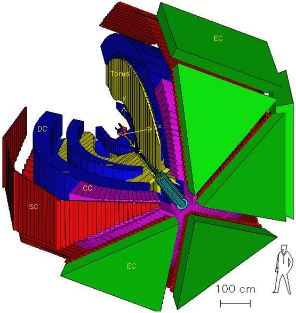
Unique in the world to study the valence region

Reaching L=10^{38}cm^{-2}s^{-1} to study very low cross section processes in detail

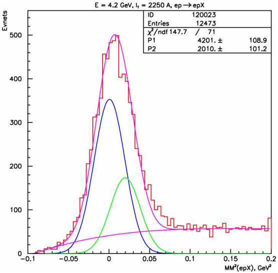


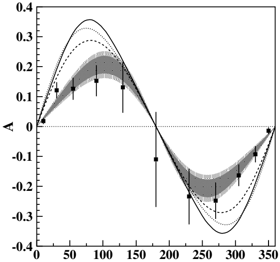


The adventure starts in Hall B with CLAS in 1999



CLAS=Cebaf Large acceptance spectrometer.
Very large beam-spin asymmetries measured, arising from the interference between DVCS and BH.
→ Straightforward conclusion: Access to the GPDs at JLab!



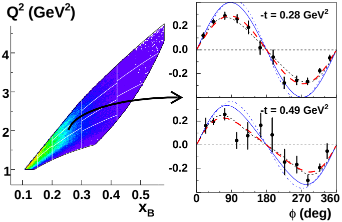


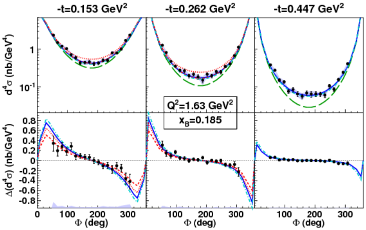
S. Stepanyan *et al.*, CLAS collaboration, Phys.Rev.Lett. 87 (2001) no.21, 182002

Then follows dedicated experiments with CLAS...

The CLAS collaboration has a impressive DVCS data set. First came:

- Beam-spin asymmetries (A_{LU}).
  F-X. Girod *et al.*, Phys. Rev. Lett. 100, 162002
- Target-spin asymmetries (A_{UL}).
  E. Seder *et al.*, Phys.Rev.Lett. 114 (2015) no.3, 032001
- Double-spin asymmetries (A_{LL}).
  S. Pisano *et al.*, Phys.Rev. D91 (2015) no.5, 052014
- With unpolarized cross sections (V-shape of Bethe-Heitler) (2015).





H.S. Jo *et al.*, Phys.Rev.Lett. 115 (2015) no.21, 212003

Hall A 6GeV experimental program

Two experimental campaign were run in Hall A:

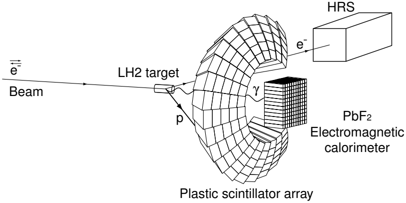
- 2004: Check scaling of CFF to establish if LT/LO-approximation is valid.

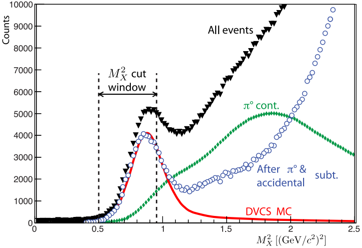
Setting	E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
2004-Kin1	5.7572	1.5	0.36	1.9
2004-Kin2	5.7572	1.9	0.36	2.06
2004-Kin3	5.7572	2.3	0.36	2.23

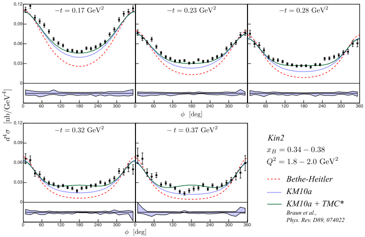
- 2010: Change the beam energy to separate interference and DVCS^2 contributions.

Setting	E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
2010-Kin1	(3.355 ; 5.55)	1.5	0.36	1.9
2010-Kin2	(4.455 ; 5.55)	1.75	0.36	2
2010-Kin3	(4.455 ; 5.55)	2	0.36	2.1

2004: Dedicated DVCS experiment in Hall A for high statistical unpolarized cross sections







- Beam-helicity dependent and independent cross section
- Large DVCS^2 contribution!
- Kinematical power corrections seems to explain the gap.

M. Defurne *et al.*, Hall A collaboration, Phys.Rev. C92 (2015) no.5, 055202

Last results from 6 GeV: A glimpse of gluons through DVCS

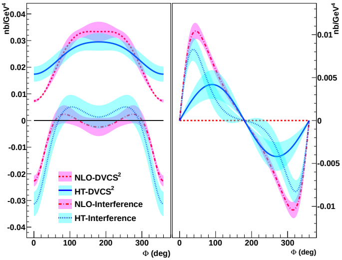
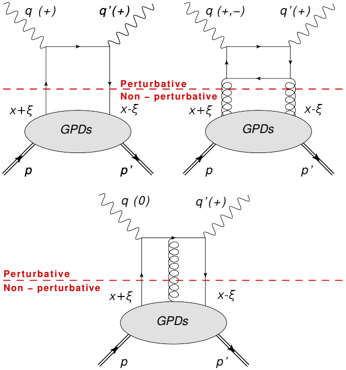


Figure: Q^2=1.75 GeV^2, -t=0.3 GeV^2. E=4.445 GeV (left) and E=5.55 GeV (right)



→ First data set at fixed kinematics but mutiple beam energies.
→ Separation of interference and $DVCS^2$.

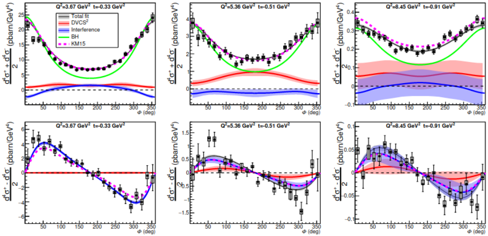
- NLO: Gluon transversity GPDs.
- HT: Q-G-Q correlations.

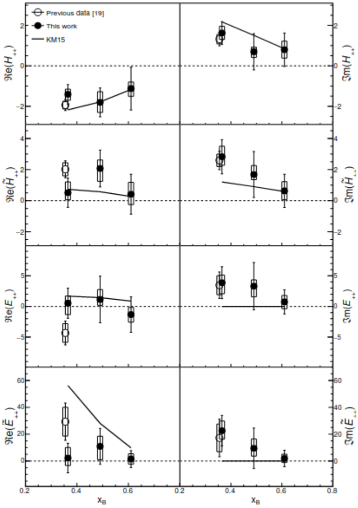
M. Defurne *et al.*, Hall A collaboration, Nat. comms.8, 1408 (2017)

First results of 12GeV era from Hall A

- New Q^2 points at x_B=0.36: 3.2, 3.6 and 4.47 GeV^2.
- Exploring new x_B-values:
  $\rightarrow x_B$=0.48 with Q^2 from 2.7 / 4.37 / 5.33 and 6.9 GeV^2.
  $\rightarrow x_B$=0.6 with Q^2 from 5.54 and 8.4 GeV^2.
- All 24-helicity CFF are extracted from a fit at fixed x_B and t, over Q^2 and ϕ.

F. Georges *et al.*, Hall A collaboration, Phys. Rev. Lett. 128, 252002





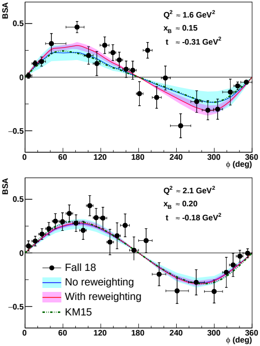
Hall B 12GeV results

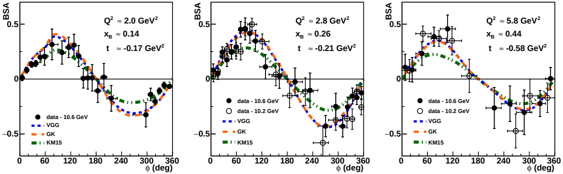
- Deriving the mean and standard deviation of a 100 ANN-predictions produced by a global fit, the new data are shown to be in good agreement. Called reweighting technique, a weight ω_k for the k^{th}-ANN is computed:

$$\omega_k = \frac{1}{Z} \chi_k^{n-1} e^{-(\chi_k^2/2)} , \qquad (2)$$

  A weighted mean and standard deviation of the 100 ANNs show the impact of the newly collected data.

- Comparisons with KM15 and VGG/GK models are performed as well. (see last slide for references)





G. Christiaens *et al.*, CLAS collaboration, soon on arXiv

Short-term future in Hall B and Hall C

Hall B

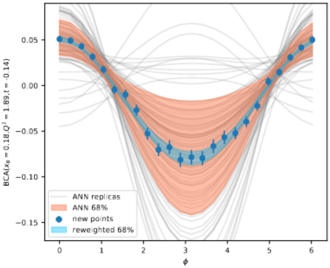
- This year, until March 2023, data is being collected in the Hall B with a longitudinally polarized target of protons and neutrons (in deuterium).
- Analysis of DVCS cross section on unpolarized protons is well advanced.

Hall C

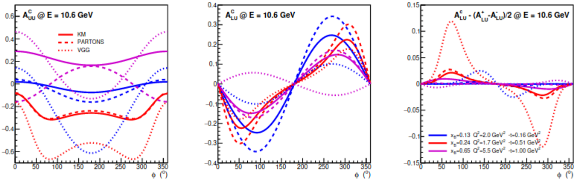
- Complementary to Hall A measurements in order to access higher Q^2 and perform Rosenbluth separation.
- Data taking will start in July 2023 until March 2024 (including data on deuterium).

The future at JLab: a Positron beam at JLab for DVCS

- Idea to produce a beam of polarized positrons by sending the initial electron beam in a radiator.
- Proposals already submitted for Hall B and Hall C to collect data with a positron beam.
- Much efficient to separate DVCS[2] and interference contribution.
- Reweighting analysis shows the importance of such measurements to access real parts of CFFs.



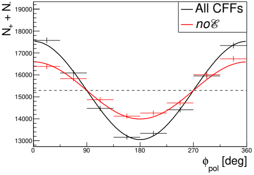
H. Dutrieux *et al.*, Eur.Phys.J.A 57

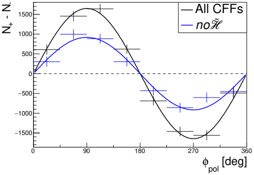


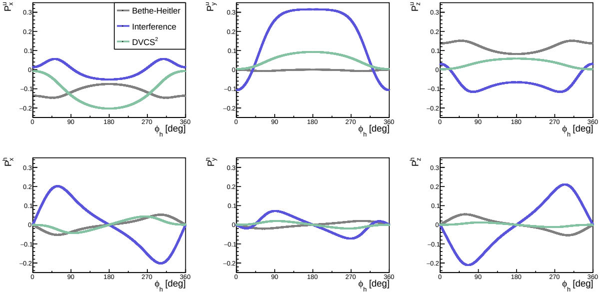
V. Burkert *et al.*, Eur.Phys.J.A 57

The future at JLab: Polarization of recoil proton in DVCS

- Idea: The polarization of the recoil proton can provide similar information to polarized target.
- P_y (normal to the hadronic plane) mostly sensitive to E and H ,
  P_x (in-plane and transverse to proton momentum) to $\widetilde{H}$.
  O. Bessidskaia-Bylund, arXiv:2209.04313
- Proposal or letter of intent to be submitted to next JLab PAC.







Prediction	P^m_x	P^m_y
GK	-0.33	0.41
VGG	0.32	0.17
KM15	-0.44	-0.04

Conclusion

- Jefferson Lab: The only facility to study the valence region where many questions must still be answered.
- data at 12 GeV are published with an unprecedented statistical precision, and add even more constrains: It is time to re-run all global fits (KM, Partons Neural Networks,...).
- Not really mentionned but there are experiments on deuterium for neutron GPDs and on Helium-4 for nuclear GPD.
- A lot of thinking and effort to constrain real part of CFFs (positron beam) or elusive GPDs such as E (measuring the polarization of recoil protons).

It is a great time to join the GPD adventure.