Accessing the generalized parton distributions in the valence region at Jefferson Laboratory

M. Defurne

CEA Saclay - IRFU/DPhN

June 2^{nd} 2018

Continuous Electron Beam Accelerator Facility

Longitudinally polarized electrons are accelerated using:

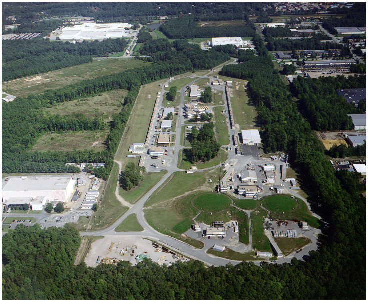
- Two linacs made of superconducting RF cavities,
- with recirculating arcs to be able to pass 5 times through the linacs.

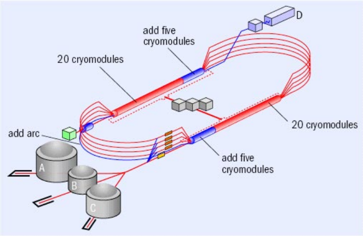
Two distinct era:

- 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.

First 4-Hall operation at 5-pass (maximal beam energy) early 2018!

The polarization of the beam is about 85%.





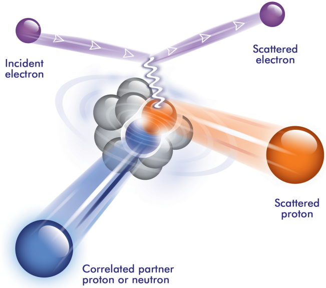
Its mission... to study the nature of matter

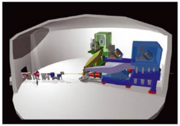
The electron beam is sent on fixed target inside the experimental Halls:

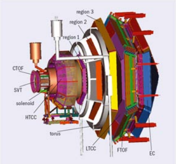
- Spectroscopy experiments,
- Partonic structure of nucleons and nuclei,
- Dark Matter, (Heavy Photon Search, DarkLight)
- Nuclear structure (Short Range correlations,...)

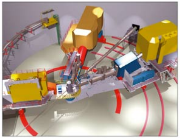
To address all these subjects, JLab's experimental Halls are equipped with dedicated experimental setup:

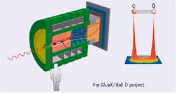
- A and C are equipped with small-acceptance (momentum/geometrical) spectrometers to run high-luminosity (10^{38}) experiments.
- B is equipped with a large acceptance spectrometer.
- D used a tagged-photon beam.











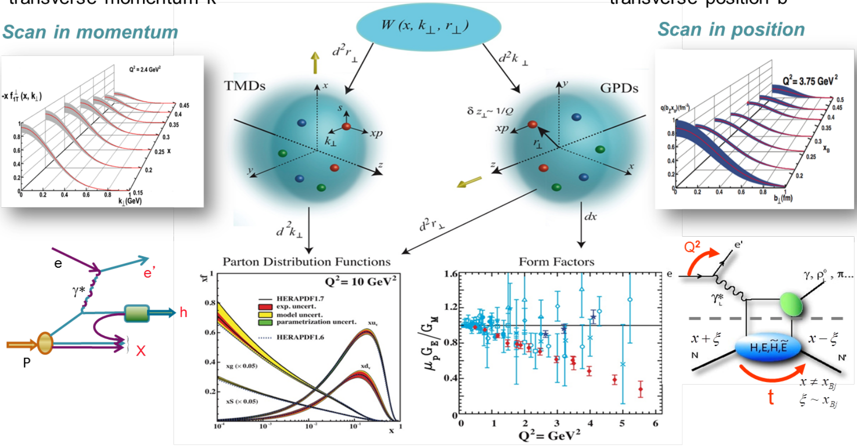
A set of distributions encoding the nucleon structure

TMDs: Fraction of longitudinal momentum x et transverse momentum k

Scan in momentum

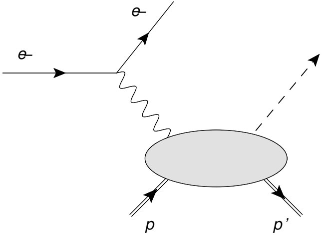
GPDs: Fraction of longitudinal momentum x et transverse position b

Scan in position



The deep exclusive processes

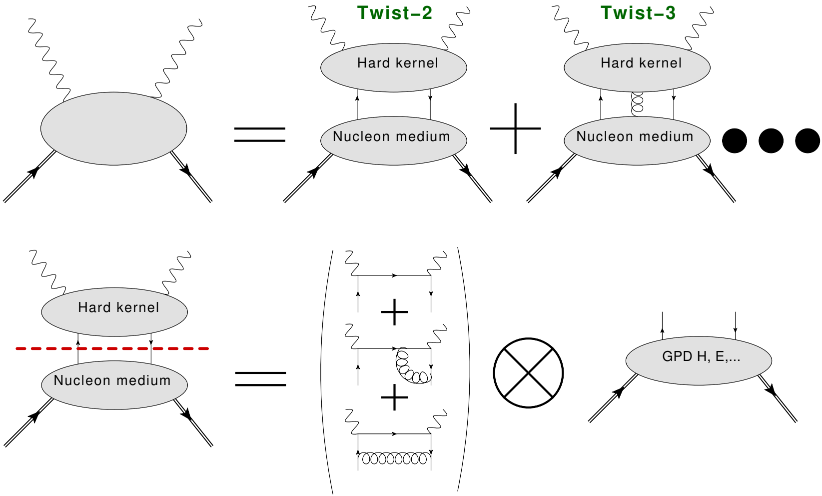
By measuring the cross section of deep exclusive processes, we get insights about the GPDs.



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

The link between these diagrams and the GPDs is guaranted by the factorization.

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.

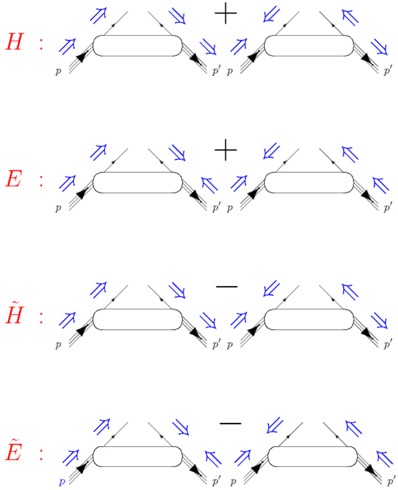
The generalized parton distributions

At leading twist there are 8 GPDs per quark flavor/gluon:

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

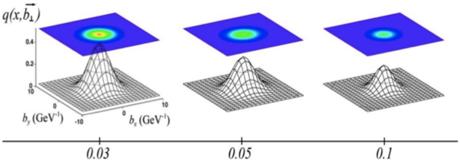
The number of GPDs come from the different combinations of helicity/spin state.

- The tilded GPDs are sensitive to the helicity of the active quarks.
- The E-GPDs describes processes with nucleon spin flip.
- The chiral-odd GPDs describe processes for which the active parton undergoes a helicity-flip.



Fun with GPDs

By Fourier transform of the GPD H, we obtain the distribution in the transverse plane of the partons as a function of their longitudinal momentum.



Sum rules relate GPD to fundamental quantities:

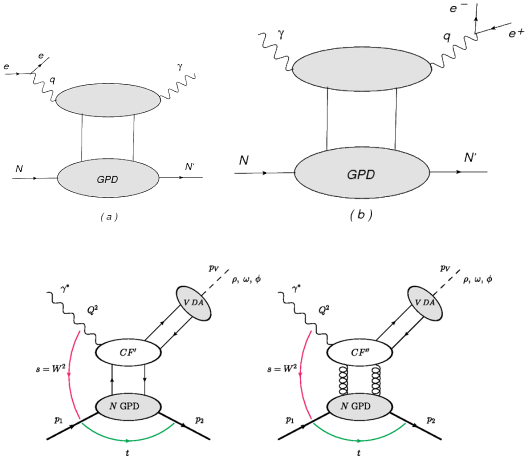
$$\int_{-1}^{1} x \left[H^f(x,\xi,t) + E^f(x,\xi,t) \right] \; dx = J(t)^f \qquad \forall \xi \; .$$
$$\int_{-1}^{1} x H^f(x,\xi,t) \; dx = M_2^f(t) + \frac{4}{5}\xi^2 d_1^f(t) \qquad \forall \xi \; . \tag{1}$$

with:

- J(t) related to distribution of angular momentum.
- M_2(t) related to distribution of mass.
- d_1(t) related to the distribution of pressure and shear forces.

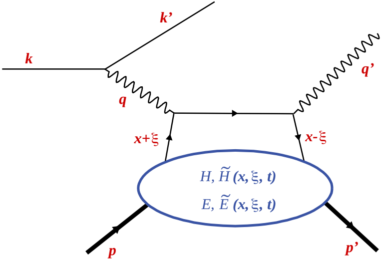
The GPD universality

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



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.

The golden channel for GPDs: Deeply virtual Compton scattering



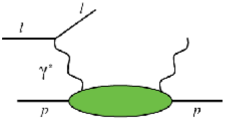
- $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi = \frac{x_B}{2-x_B}$ the longitudinal momentum transfer.
- $t = (p - p')^2$ squared momentum transfer to the nucleon.

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

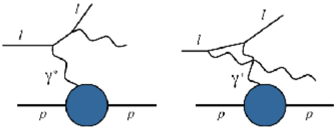
$$\mathcal{H}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx \,.$$

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

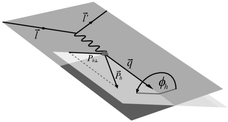


DVCS



Bethe-Heitler

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



Photon electroproduction and GPDs (PART II)

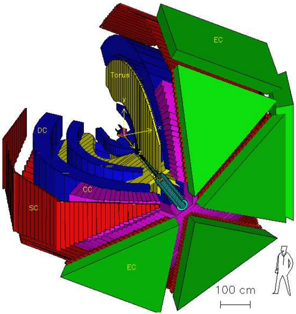
The interference term allows to access the phase of the DVCS amplitude, *i.e* allows to isolate imaginary and real parts of CFFs.
A few examples of harmonic coefficients and their sensitivity to CFFs:

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

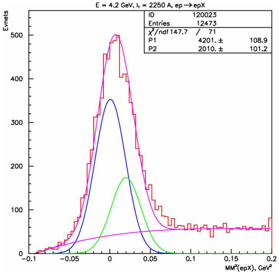
At leading-order, $Im\ \mathcal{H}(\xi,t) = \pi\left(H(-\xi,\xi,t) - H(\xi,\xi,t)\right)$.

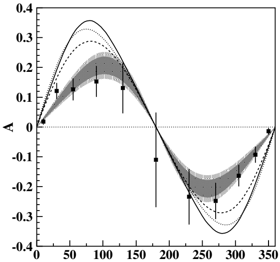
At leading-order, photon electroproduction offers a direct access to GPDs offered by beam-spin asymmetries.

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!



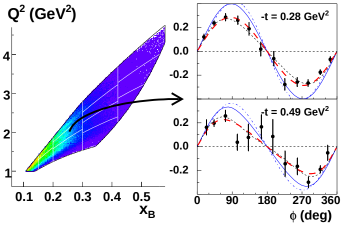


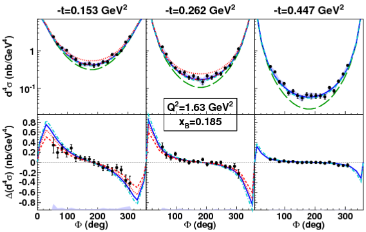
S. Stepanyan *et al.*, CLAS collaboration, Phys.Rev.Lett. 87 (2001) no.21, 182002

Then follows dedicated experiments with CLAS...

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

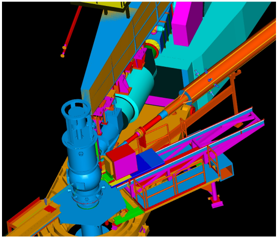
- Beam-spin asymmetries (A_{LU}).
  F-X. Girod *et al.*, Phys. Rev. Lett. 100, 162002
- Target-spin asymmetries (A_{UL}).
  E. Seder *et al.*, Phys.Rev.Lett. 114 (2015) no.3, 032001
- Double-spin asymmetries (A_{LL}).
  S. Pisano *et al.*, Phys.Rev. D91 (2015) no.5, 052014
- With unpolarized cross sections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



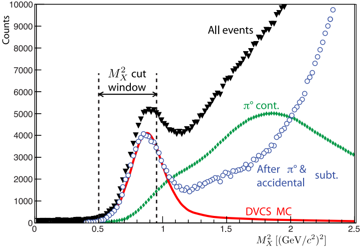


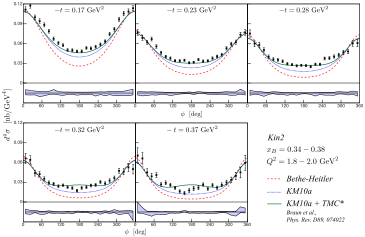
A complication with photon electroproduction is the dominance of Bethe-Heitler

High statistical results from Hall A to complement Hall B data



- Beam-helicity dependent and independent cross section
- At X_B=0.36, scaling test with Q^2= 1.5, 1.75, 1.9, 2 and 2.3 GeV^2.
- Hint that kinematical power corrections are needed.





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

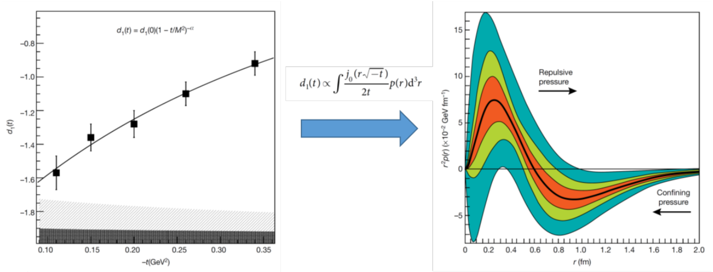
From the 6 GeV data, an interesting proof-of-principle...

At leading-order (simple handbag diagram with no gluon contributions), the imaginary and real part of a Compton Form Factor are related to each other through a dispersion relation:

$$Re\ \mathcal{H}(\xi,t) = D(t) + \mathcal{P}\int_{-1}^{1} dx \left(\frac{1}{\xi - x} - \frac{1}{\xi - x}\right) Im\ \mathcal{H}(x,t), \qquad (3)$$

where $D(t)$ encapsulates $d_1(t)$ describing the pressure and shear forces distribution in the nucleon.

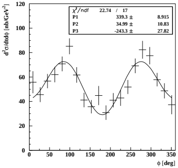
Keeping only H-GPD, CLAS6 beam-spin asymmetries and unpolarized cross sections have been fitted to get $d_1(t)$:



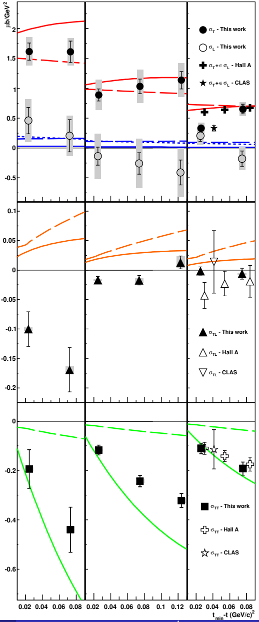
Burkert *et al.*, Nature, vol. 557, 17 May 2018

The unpolarized cross section can be written as the sum of responses according to the polarization of the virtual photon.

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



$ep \to ep\pi^0$ on the left (CLAS, PhysRevC.90.025205):
Striking evidence of higher-twist contributions because of ϕ-modulation.



Full L/T separation of π^0-electroproduction reveals $\sigma_T \gg \sigma_L$.

Defurne *et al.*, Hall A collaboration, Phys. rev. Lett. 117, 262001

... as well as in DVCS!

- Photon electroproduction cross section is given by:

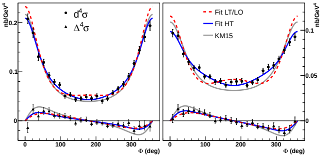
$$\frac{d^4\sigma(\lambda,\pm e)}{dQ^2 dx_B dt d\phi} = \frac{d^2\sigma_0}{dQ^2 dx_B}\frac{2\pi}{e^6}\times\left[\left|\mathcal{T}^{BH}\right|^2+\left|\mathcal{T}^{DVCS}\right|^2\mp\mathcal{I}\right]$$

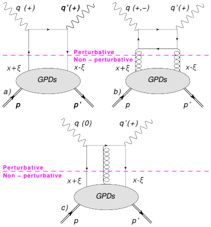
- To separate all terms, having no positron beam, Measurement of cross sections at different beam energies.

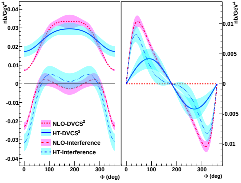
E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
(3.355 ; 5.55)	1.5	0.36	1.9
(4.455 ; 5.55)	1.75	0.36	2
(4.455 ; 5.55)	2	0.36	2.1

- First phenomenological analysis including kinematical corrections (t/Q^2 and M^2/Q^2-terms) indicates necessity of having higher-twist or gluon contributions.

M. Defurne *et al.*, Hall A collaboration, Nature Communications 8, 1408 (2017)



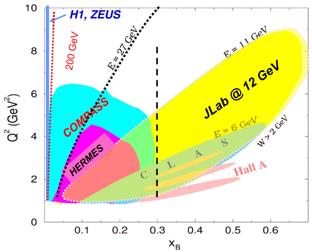




An exciting 12-GeV era has begun!

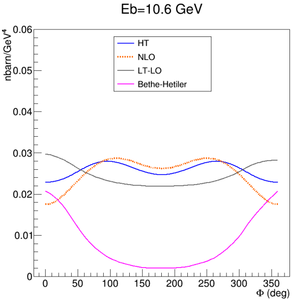
The increase in energy from 6 to 11 GeV as well as the upgrade of the experimental Halls will allow to:

- explore a *terra incognita* at high x_B and Q^2.
- collect high-statistics observables.

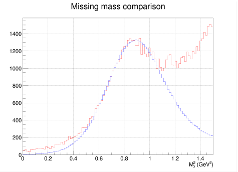


Reaching higher Q^2 will help getting cleaner results (less higher-twist contributions).

Covering the 6-GeV phase space at 12 GeV will bring new information concerning all the data collected so far!



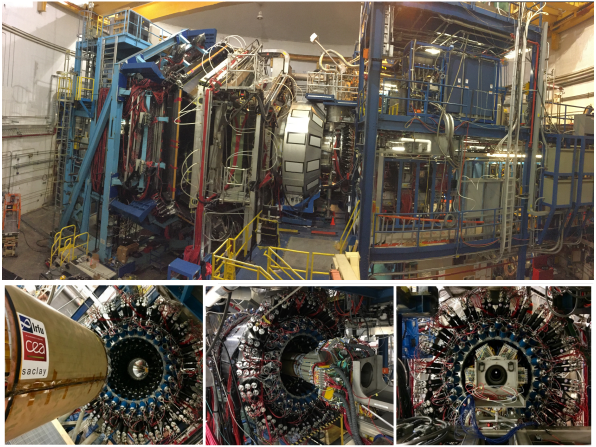
First DVCS experiment at 11 GeV started in 2014 in Hall A... Ongoing Analysis



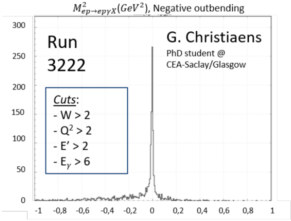
Ebeam = 8.521 GeV, Q2 = 5.541, xB = 0.6

Courtesy F. Georges, PhD student @ IPN Orsay

Since February 2018, Production data at 10.6 GeV with CLAS12 on unpolarized proton!



- 119 PAC days.
- 50 nA on 5-cm LH_2.
- Polarization: 85%.
- Goal: 1-2% BSA for DVCS



Conclusion

A lot of data on several channels collected during the 6-GeV era!

Under leading-twist and leading-order assumption, a GPD phenomenology well developped although higher-order contributions might be sizeable.

The 12-GeV program will give access to a terra incognita and much more information to fully understand 6-GeV data.

A complete GPD program will be covered by the 3 Halls (A,B and C):

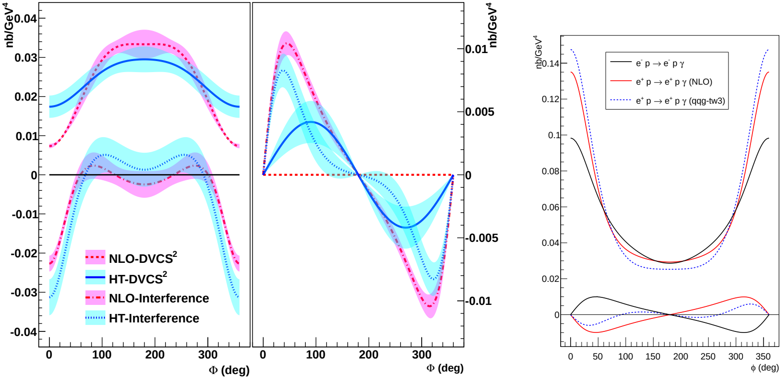
- longituinally polarized electron beam at multiple energy (6.6, 8.8, 11 GeV),
- proton and neutron target,
- unpolarized, longitudinally polarized, transversely polarized (HD-ice),
- to study DVCS and DVMP (π, ϕ, η).

Better than Christmas for the GPD business!

Much effort is now needed in phenomenology to analyze all upcoming data (multi-channels analysis, L0/NLO, NNLO,...).

the end

Despite an equally good fit, slight differences appear when separating the interference and DVCS term.

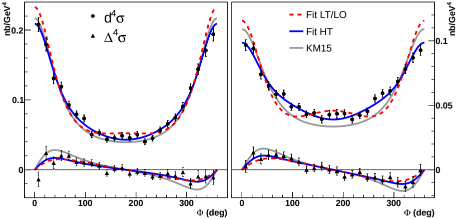


We can discriminate the two scenarii if we have a better grasp on the DVCS^2.

- The easiest path from a phenomenlogical point-of-view: The positron beam.
- Our best and closest hope: The data collected at 11 GeV.

A fit of CFFs including kinematical power corrections

Kinematical power corrections sizeable and changing the beam-energy dependences!



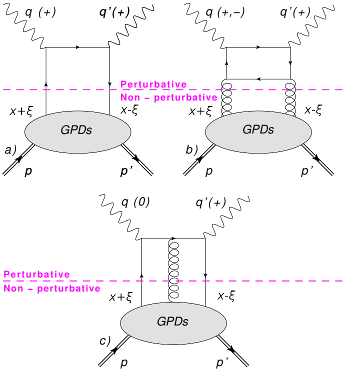
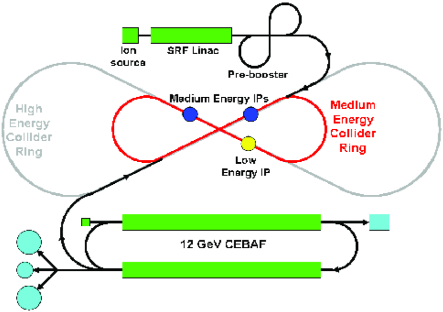


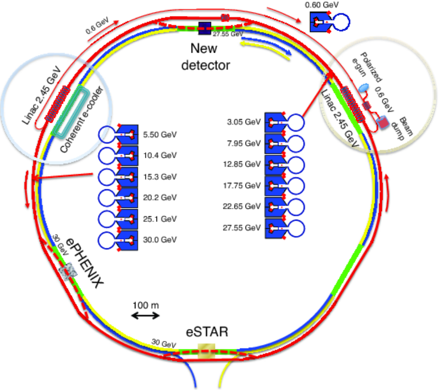
Figure: Q^2=1.75 GeV^2, -t=0.3 GeV^2. E=4.445 GeV (left) and E=5.55 GeV (right)

Parameterizing the observables with CFFs, equally good fit between the HT and NLO.
M. Defurne *et al.*, Hall A collaboration, Nature Communications 8, 1408 (2017)

- LT/LO: $\mathbb{H}_{++}, \mathbb{E}_{++}, \tilde{\mathbb{H}}_{++}, \tilde{\mathbb{E}}_{++}\ldots$ a)
- HT: $\mathbb{H}_{++}, \tilde{\mathbb{H}}_{++}, \mathbb{H}_{0+}, \tilde{\mathbb{H}}_{0+}\ldots$ c)
- NLO: $\mathbb{H}_{++}, \tilde{\mathbb{H}}_{++}, \mathbb{H}_{-+}, \tilde{\mathbb{H}}_{-+}\ldots$ b)

To study the sea-quarks and gluons:





Two designs at Jefferson Lab or at RHIC.
The Electron-Ion collider will complete the set of observables provided by the colliders and COMPASS. (polarizd beams, high luminosity)

What about the phenomenology?

Concerning DVCS, most phenomenologists sticks to extract CFFs:

- by doing local fits (each kinematical points are independent).
- by doing global fits (All kinemaical points are fitted using a parameterization for the CFFs).

But very few start from the GPDs. Modelling a GPD is very complex since it is a well constrained objects.

- Forward Limits: $H(x,0,0) \to q(x)$, $\widetilde{H}(x,0,0) \to \Delta q(x)$
- $\int_{-1}^{1} dx H^q(x,\xi,t) = F_1^q(t)$ and $\int_{-1}^{1} dx E^q(x,\xi,t) = F_2^q(t)$.
- Polynomiality: x^n Mellin moments of GPDs are polynomial in ξ with well-defined leading power.
- Positivity: Inequalities between a GPD and corresponding PDFs.