Experimental studies of Generalized Parton Distributions

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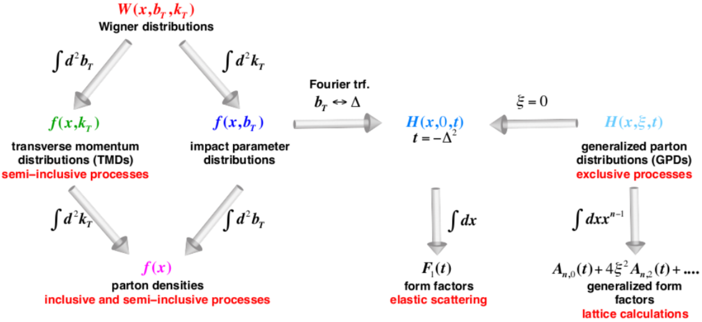
HADRON 2023

Generalized parton distributions

- GPDs encode correlations between longitudinal momentum and transverse position of partons in a hadron.
- For the nucleon, there are 8 GPDs at leading-twist that describe the various combinations between nucleon/quark helicity states.

		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\widetilde{H}_T + E_T$
	L		$\widetilde{H}$	$\widetilde{E}_T$
	T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$



Properties of GPDs

GPDs are well-constrained objects, making their modelisation challenging.

- 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.

Sum rules relate GPD to fundamental quantities:

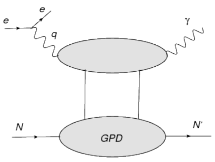
$$\begin{aligned} \int_{-1}^{1} x \left[H^f(x,\xi,t) + E^f(x,\xi,t)\right] \, dx &= J(t)^f \qquad \forall\xi \, . \\ \int_{-1}^{1} x H^f(x,\xi,t) \, dx &= M_2^f(t) + \tfrac{4}{5}\xi^2 d_1^f(t) \qquad \forall\xi \, . \end{aligned} \tag{1}$$

with:

- J(t) related to distribution of angular momentum. X. Ji, PRL 78 (1997) 610
- M_2(t) related to distribution of mass. M. Polyakov, PLB 555 (2003) 57
- d_1(t) related to the distribution of pressure and shear forces.

Several GPDs but a universality principle

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



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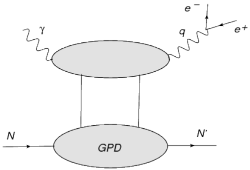

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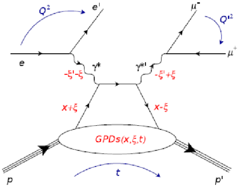
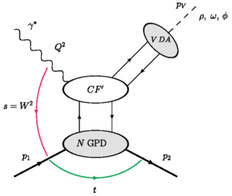
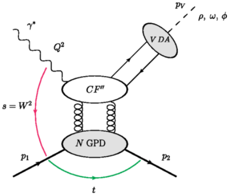
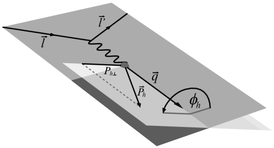








Factorization fully proven for DVCS/TCS/DDVCS whereas partial proof for DVMP only at LO for longitunally polarized photon.

The DA can conveniently be used for flavor separation or access to specific GPDs.

Quark transversity GPDs in π^0-electroproduction

In DVMP, the leading twist contribution is σ_L and σ_T should be suppressed by $1/Q^2$.

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

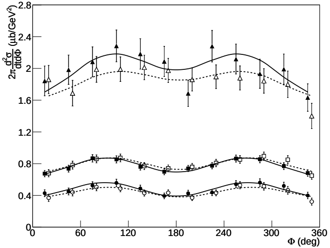
π^0-electroproduction was shown to be almost purely transverse.

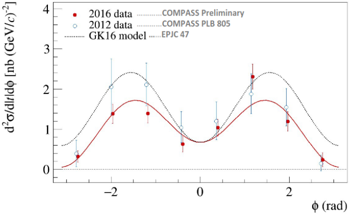
Coupling between twist-3 DAs and transversity GPDs:

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

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

Defurne *et al.*, Hall A coll., PRL 117, 262001





Top: Rosenbluth separation at Q^2=1.5, 1.75 and 2 GeV^2 and x_B=0.36.

Vector meson electroproduction

For VM, σ_L is related to H- and E-GPD. The L/T separation can be done by analyzing the VM decay, if conservation of the helicity in s-channel (SCHC).
For the small x_B/high W measurements:

- A similar origin from gluons indicated by cross sections ratio.
- SCHC is almost respected so L/T separation is valid.
- But the ratio $\frac{\sigma_L}{\sigma_T}$ is not $\propto Q^2$ and $\sigma_L \propto 1/Q^4$ instead of $1/Q^6$.

For large x_B/small W measurements (CLAS):

- ρ^0 and ω cross section much larger than expected.
- No SCHC therefore only a true Rosenbluth separation can separate σ_L/σ_T.
- ϕ-electroproduction is decreasing as expected from gluon dominance.

Favart *et al.*, EPJA 52-158 (2016)

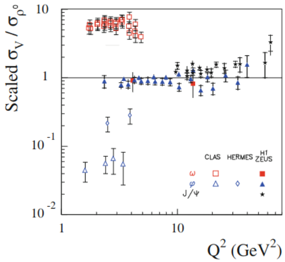
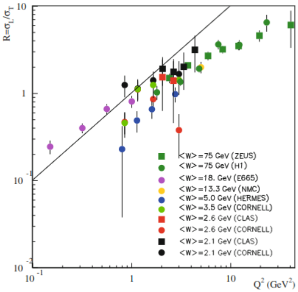


Fig. 9. Ratio of the cross sections: $9 \times \sigma_\omega/\sigma_{\rho^0}$, $9/2 \times \sigma_\phi/\sigma_{\rho^0}$ and $9/8 \times \sigma_{J/\Psi}/\sigma_{\rho^0}$ as a function of Q^2 for different W's.

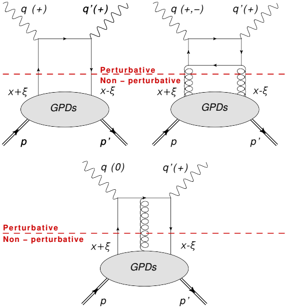


Short conclusion on DVMP

- Challenging theoretical description...
- ... but worth it as access to specific GPDs/flavor separation ...
- ... And analysis of the VM polarization is possible (spin density matrix element).
- Improvement of the description for both pseudo-scalar and vector meson production:
  $\rightarrow$ Transverse size effect of meson with transverse momentum of partons in subprocess. $\rightarrow$ with a coupling between twist-3 DAs and transversity GPDs for SDME.
- Still ρ^0 and ω to understand in the valence with CLAS12.

P. Kroll, S. Goloskokov, EPJA 47, 112 P. Kroll, S. Goloskokov, EPJC 74, 2725

Deeply virtual Compton scattering



- Like DVMP, DVCS is described with helicity amplitudes.
- Unlike DVMP, factorization is proven valid at any twist and order in perturbation theory.
- Unlike DVMP, σ_T is the leading-twist contribution.
- Main assumption: Only the helicity-conserved terms are considered
  $\rightarrow$ only H,E,$\tilde{H}$ and $\tilde{E}$-GPDs are probed.

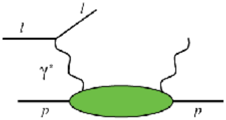
The GPDs enter the DVCS amplitude through a complex integral. This integral is called a *Compton form factor* (CFF).

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

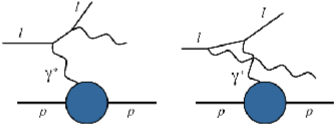
At leading order, $\text{Im}\mathcal{H}(\xi,t) \propto H(\xi,\xi,t) - H(-\xi,\xi,t)$.

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

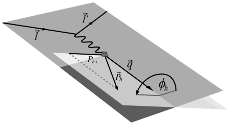


DVCS



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.

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

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

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

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

$$c_{1,UT}^{\mathcal{I}} \sim \quad \frac{t}{4M^2}\left(-F_1 \; Im\mathcal{E} + F_2 Im\mathcal{H}\right) ,$$

Asymetries are defined as:

$$A = \frac{\Delta^4\sigma}{d^4\sigma} \qquad (3)$$

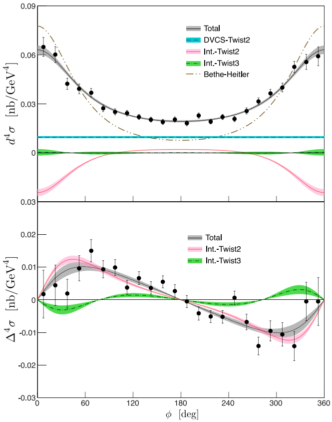
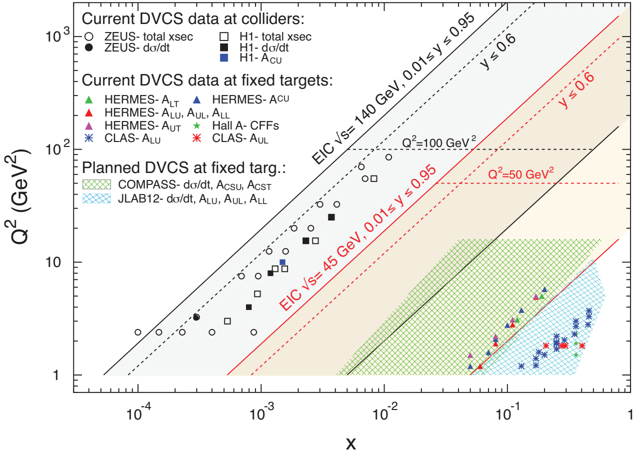


Figure: Unpolarized and beam-helicity cross sections at Q^2=2.3 GeV^2, x_B=0.36, t=-0.3 GeV^2 (Hall A).

HERA DVCS datasets

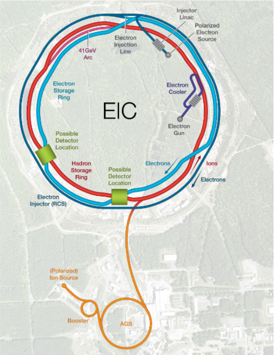
- Very small x_B-data collected by ZEUS and H1.
- One of the most complete set of observables from HERMES.

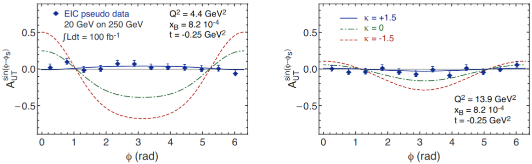


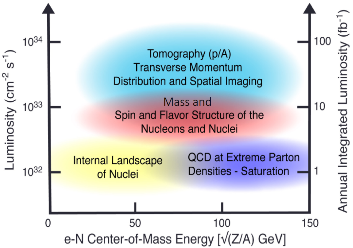
Accardi et al., EIC white paper

From HERA to Electron-Ion Collider

- Up to 18 GeV electrons will collide with 275 GeV protons.
- Longitudinal polarization of electrons.
- Transverse polarization of protons.
- From x_B=10^{-4} (gluons) to x_B=0.05 (gluons+sea quarks)
- $\mathcal{L}_{EIC} = 100 \times \mathcal{L}_{HERA}$.
  $\rightarrow$ Differential cross sections.







Accardi et al., EIC white paper

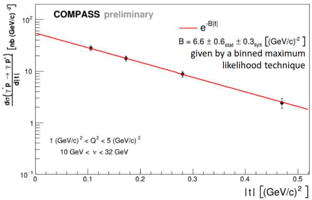
GPDs at medium-x_B: COMPASS

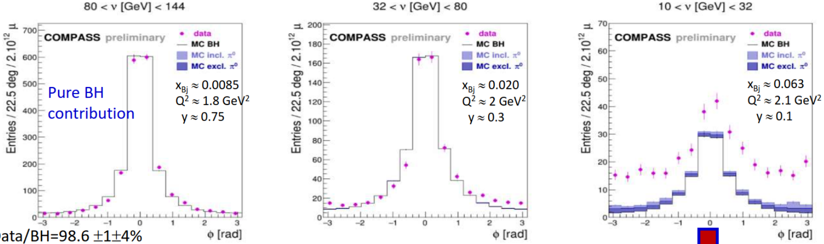
- Both $\overleftarrow{\mu^+}$ and $\overrightarrow{\mu^-}$ beams of 160 GeV/c.
- Two run periods in 2012 (1 month) and 2016 (12 months).

Assuming Im$\mathcal{H}$-dominance, proton radius can be estimated with:

$$\frac{d\sigma_{DVCS}}{dt} = \frac{1}{\Gamma(Q^2, x_B)} \int_{-\pi}^{\pi} \frac{d\sigma^T}{dQ^2 dx_B dt d\phi} - \frac{d\sigma_{BH}}{dQ^2 dx_B dt d\phi} d\phi \quad (4)$$

N. d'Hose, ECT* talk, Sepetember 2022





Data/BH=98.6 ±1±4%

MC: BH contribution evaluated for the integrated luminosity
π° background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)

DVCS above the BH contrib.

GPDs at large-x_B: Jefferson Lab

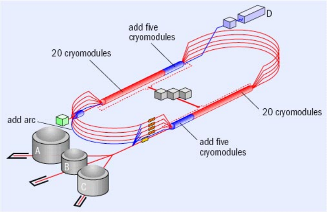
Unique in the world to probe the valence region at a very high luminosity.

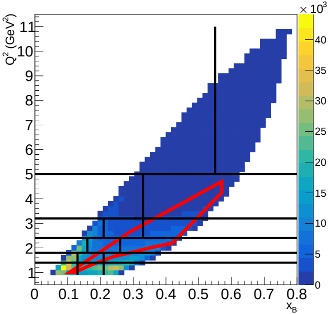
A 85%-longitudinally polarized electron beam is impinged on fixed targets in 3 experimental Halls:

- Hall A and Hall C were/are equiped with high-resolution/small acceptance spetrometers,
- Hall B hosted CLAS upgraded in CLAS12, a Large Acceptance Spectrometer.

Many results have been published from 6-GeV era. I will focus on 12-GeV era. An ambitious program has started:

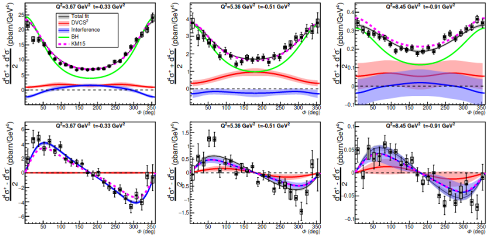
- unpolarized protons @ 6.6/7.5 and 10.6 GeV.
- unpolarized deuterium @ 10.4 GeV.
- with longitudinally/transversely polarized protons and longitudinally polarized neutrons @ 10.6 GeV.

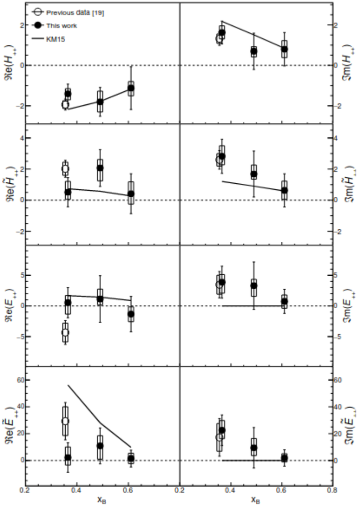




First results of 12GeV era from Hall A

- 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.
- Pioneers in CFF fit using kinematical corrections.
- All 24-helicity CFF are extracted from a fit at fixed x_B and t, over Q^2 and ϕ.



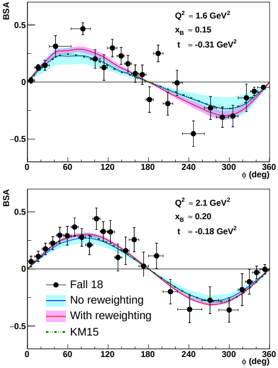


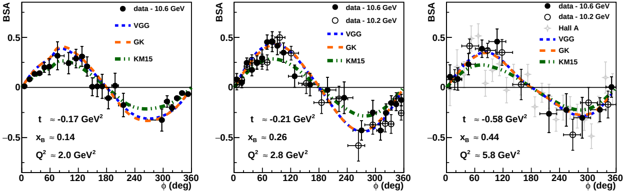
F. Georges *et al.*, Hall A collaboration, Phys. Rev. Lett. 128, 252002

Hall B 12GeV DVCS results

- Only 25% of the beam-time allocated to an unpolarized proton
- But already statistically competitive with 6 GeV program,
- 89% of the points in terra incognita,
- GPD models in fair agreement with the newly collected data
- More is to come as another 25% is being analyzed.

G. Christiaens *et al.*, CLAS collaboration, PRL 130, 211902

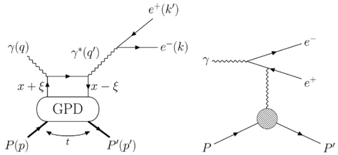


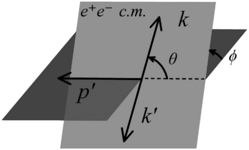


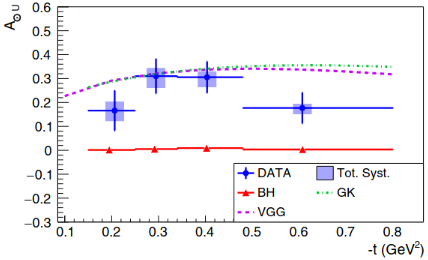
First ever TCS measurements with CLAS12

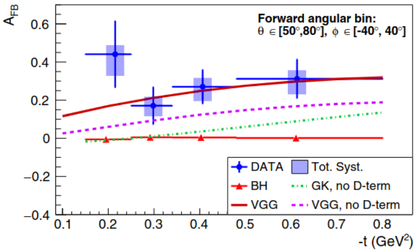
- TCS is a conjugate process of DVCS.
- Two observables were extracted.
- $A_{FB} = \frac{\sigma(\theta,\phi)-\sigma(180-\theta,\phi+180)}{\sigma(\theta,\phi)+\sigma(180-\theta,\phi+180)}$
- A_{FB} and $A_{\odot U}$ gives Re and Im of $F_1\mathcal{H} + \xi\,(F_1 + F_2)\,\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$
- Access to the D-term (pressure distributions) with the real part.

Chatagnon *et al.*, CLAS collaboration, PRL 127, 262501









Short-term future of DVCS results from Hall B and Hall C

Hall B

- Beam-spin asymetries for neutron are expected to be published this year/next year with data collected on unpolarized deuterium.
- Ongoing analysis for cross section extraction on proton.
- Until March 2023, data has been collected with a longitudinally polarized target of protons and neutrons (in deuterium).

Hall C

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

New observable to JLab set: DVCS with positron beam

- Proposal in Hall B and Hall C submitted this year to JLab PAC (Eric Voutier's talk in New facilities).
- Important: 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.

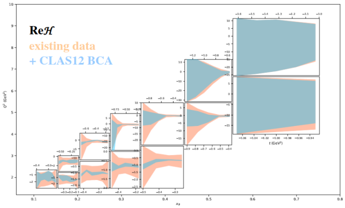
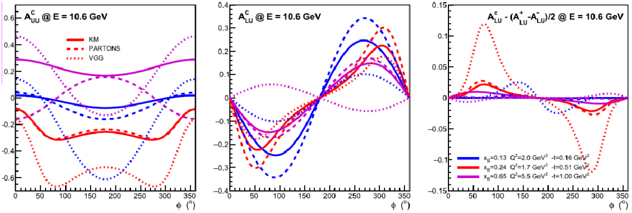


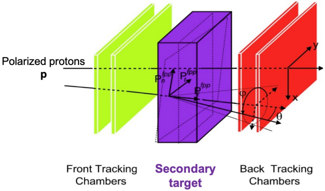
Figure: Bayesian reweighting with CLAS12 prediction. Dutrieux *et al*, EPJA 57

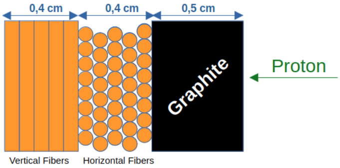


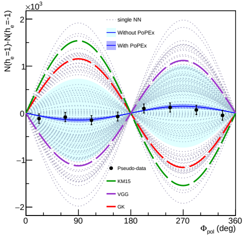
New observable to JLab set: DVCS recoil proton polarization

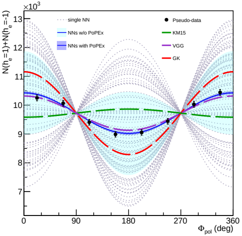
- Can only be done at JLab
- P_y (normal to the hadronic plane) to access E,
- P_x (in-plane and transverse to proton momentum) to $\widetilde{H}$.
- Cross section gives H.
- π^0-electroproduction done simultaneously.
- LoI submitted to JLab PAC51 for Hall C.

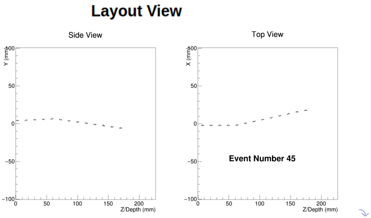
Bessidskaia Bylund *et al.*, Phys. Rev. D 107, 014020



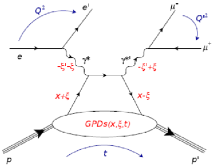


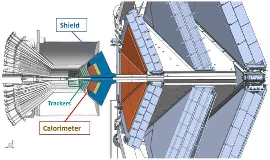


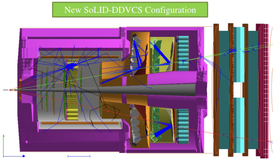




- Cross section much lower by a factor 300 than DVCS.
- But JLab High luminosity (10^{38}) with large acceptance of μCLAS12 or SoLID (Talk in New facilities :Nathan Baltzell/Zhihong Ye).
- DVCS and TCS limits of DVCS when Q^2 and Q'^2 at 0.
- Probing the GPD outside the diagonal $x = \xi$

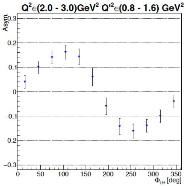


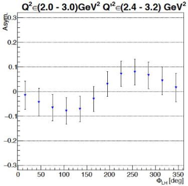




$$\mathcal{H}_{++}(\xi', \xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi' - x - i\epsilon} - \frac{1}{\xi' + x - i\epsilon} \right) dx \; .$$

At leading order, $\mathrm{Im}\mathcal{H}(\xi', \xi, t) \propto H(\xi', \xi, t) - H(-\xi', \xi, t)$.





Conclusion

Many GPD measurements have been left aside:

- Neutron GPDs: Measurements by Hall A and soon CLAS12. (Adam Hobart's talk)
- Transition GPDs: In DVMP, target and recoil hadron are not necessarily the same. (Stefan Diehl's talk)
- Nuclear GPDs: Dedicated run group in CLAS12 and an important research axis at EIC.
- Pion GPDs: Possibility to do Sullivan DVCS (DVCS on virtual pion cloud of the proton) at EIC.

Experimentalists cannot succeed to get the GPDs without theory/phenomenology support:

- Extraction: Huge phenomenological effort to develop a global fit procedure (PARTONS, Gepard, ...) that needs to go to NLO,
- Theory input/new ideas: Pion GPD model from Dyson-Schwinger equations for Sullivan DVCS.
- Complementarity/validation: lQCD is getting close to provide GPD predictions to be tested against the data or to suggest new measurements. (Constantia Alexandrou's talk)