Generalized Parton Distributions at Jefferson Lab

Carlos Muñoz Camacho

Institut de Physique Nucléaire, CNRS/IN2P3 (France)

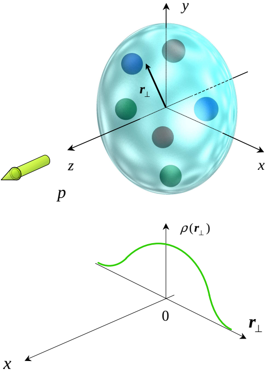
2018 European Nuclear Physics Conference
Bologne (Italy)

Outline

1. Introduction
2. Nucleon 3D-imaging & Generalized Parton Distributions (GPDs)
3. Deeply Virtual Compton Scattering (DVCS): $ep \to ep\gamma$
   - Results on both proton and neutron (preliminary)
4. Exclusive π^0 electroproduction (DVMP): $eN \to eN\pi^0$
   - Also: proton + neutron ⇒ *flavor separation*
5. Plans at 12 GeV
6. Summary

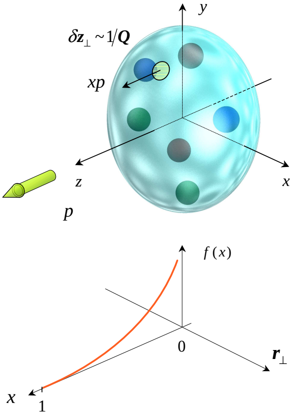
Studying the structure of the nucleon experimentally

Elastic scattering



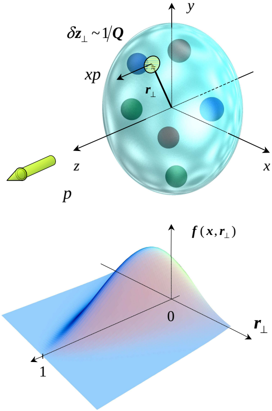
Form factors

Deeply Inelastic Scattering



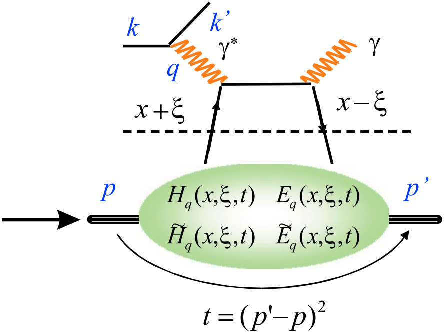
Parton distributions

Hard exclusive processes



Generalized Parton Distributions (GPDs)

Deeply Virtual Compton Scattering (DVCS): $\gamma^* \, p \to \gamma \, p$



Handbag diagram

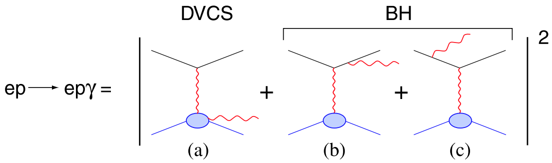
High Q^2
Perturbative QCD

Non-perturbative
GPDs

Bjorken limit :

$$\left.\begin{array}{rcl} Q^2 = & -q^2 \to & \infty \\ & \nu \to & \infty \end{array}\right\} \quad x_B = \frac{Q^2}{2M\nu} \text{ fixed}$$

DVCS experimentally: interference with Bethe-Heitler



At leading order in $1/Q$ (leading twist) :

$$d^5 \overrightarrow{\sigma} - d^5 \overleftarrow{\sigma} = \Im m \left(T^{BH} \cdot T^{DVCS}\right)$$

$$d^5 \overrightarrow{\sigma} + d^5 \overleftarrow{\sigma} = |BH|^2 + \Re e \left(T^{BH} \cdot T^{DVCS}\right) + |DVCS|^2$$

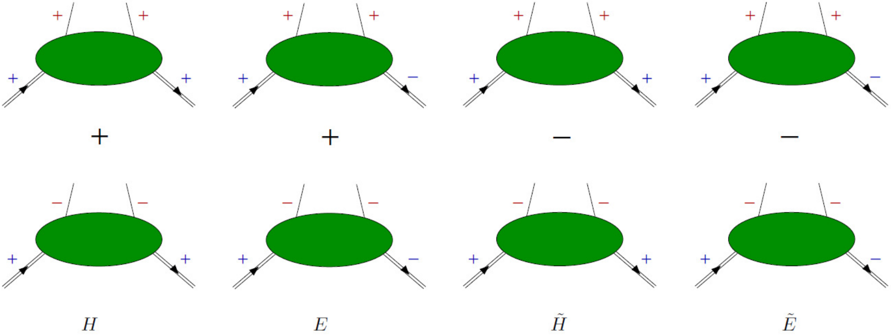
$$\mathcal{T}^{DVCS} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x - \xi + i\epsilon} + \cdots =$$

$$\underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}} \quad - \quad \underbrace{i\pi\, H(x=\xi,\xi,t)} \quad + \ldots$$

Access in helicity-independent cross section — Access in helicity-dependent cross-section

Leading twist GPDs

8 GPDs related to the different combination of quark/nucleon helicities

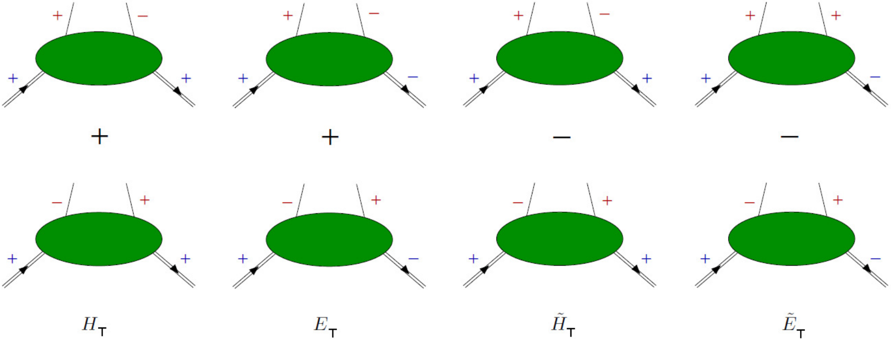


4 chiral-even GPDs: conserve the helicity of the quark

Access through DVCS (and DVMP)

Leading twist GPDs

8 GPDs related to the different combination of quark/nucleon helicities



4 chiral-odd GPDs: flip helicity of the quark

"transversity GPDs"

Experimental access more complicated (π^0 electroproduction?)

Accessing different GDPs

Polarized beam, unpolarized target (BSA)

$$d\sigma_{LU} = \sin\phi \cdot \mathcal{I}m\{F_1\mathcal{H} + x_B(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$$

Unpolarized beam, longitudinal target (lTSA)

$$d\sigma_{UL} = \sin\phi \cdot \mathcal{I}m\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E}) - x_B kF_2\tilde{\mathcal{E}}\dots\}d\phi$$

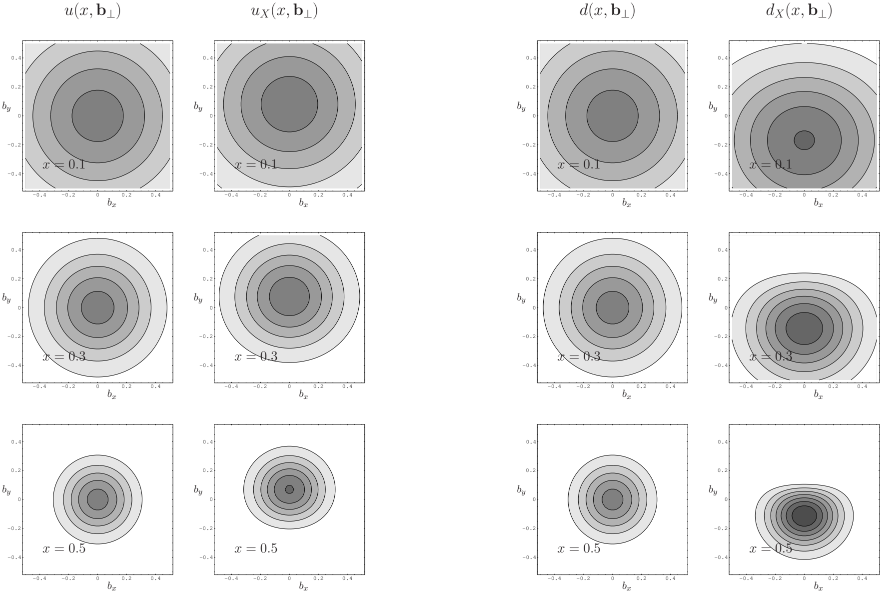
Polarized beam, longitudinal target (BlTSA)

$$d\sigma_{LL} = (A + B\cos\phi) \cdot \mathcal{R}e\{F_1\tilde{\mathcal{H}} + x_B(F_1+F_2)(\tilde{\mathcal{H}} + x_B/2\mathcal{E})\dots\}d\phi$$

Unpolarized beam, transverse target (tTSA)

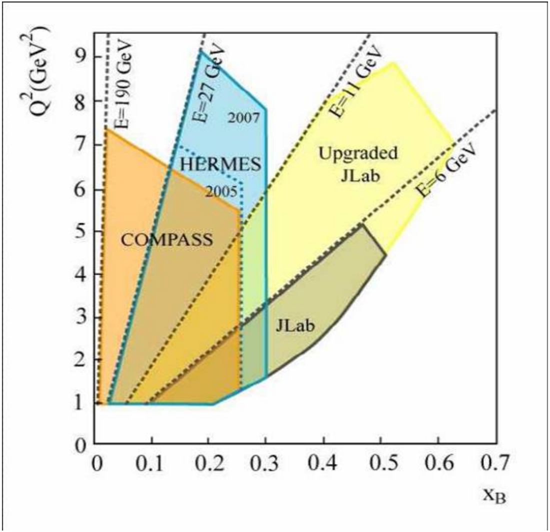
$$d\sigma_{UT} = \cos\phi \cdot \mathcal{I}m\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \dots\}d\phi$$

Impact-parameter interpretation of GPDs



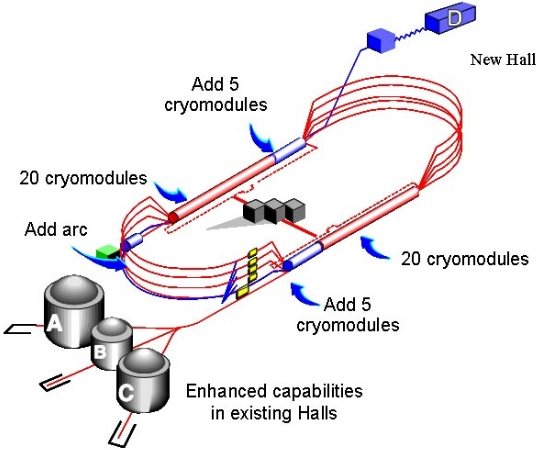
Kinematic coverage

Kinematic complementarity between different facilities:



Jefferson Lab: upgraded to 12 GeV

- 6-12 GeV longitudinally polarized (>85%) continuous electron beam
- High intensity (>100 μA): luminosities $> 10^{38}$ s^{-1} cm^{-2}
- 3 experimental Halls (A, B, C) w/ fixed target and dedicated detectors



The GPD experimental program at Jefferson Lab

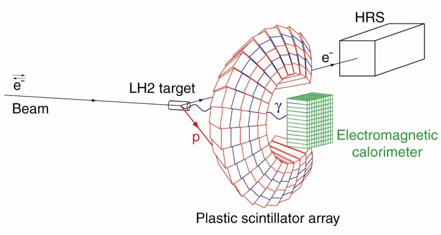
- Hall A: high accuracy, limited kinematic coverage
- Hall B: wide kinematic range, limited precision
- Hall C: high precision program at 11 GeV

Partially overlapping, partially complementary programs
with different experimental setups

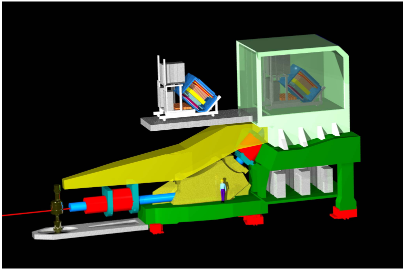
The roadmap:

- Early results (2001) from non-dedicated experiment (CLAS)
- 1^{st} round of dedicated experiments in Halls A/B in 2004/5
- 2^{nd} round on 2008–2010: precision tests + more spin observables
- Compeling DVCS experiments in Halls A+B+C at 11 GeV ($\gtrsim$2016)

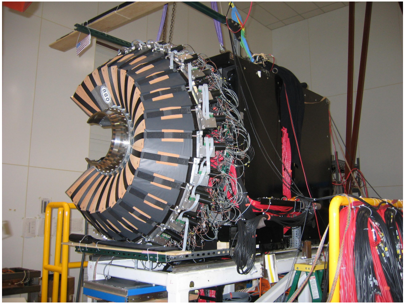
Experimental setup



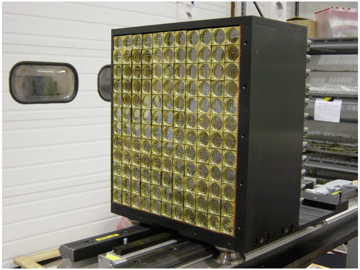
High Resolution Spectrometer



100-channel scintillator array

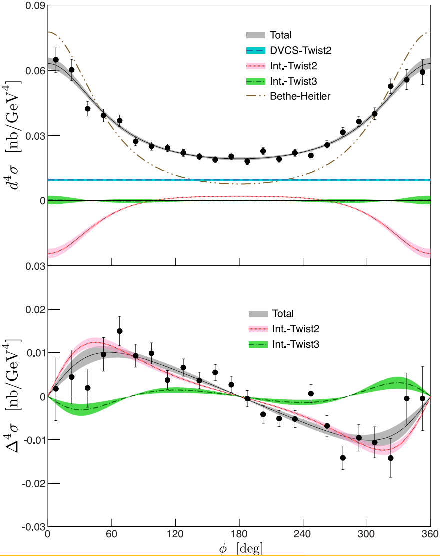


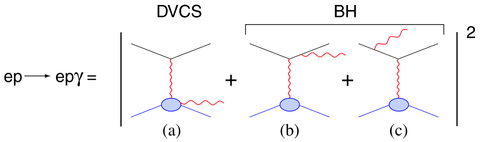
132-block PbF_2 electromagnetic calorimeter



DVCS cross sections: azimuthal analysis

$Q^2 = 2.36$ GeV^2, $x_B = 0.37$, $-t = 0.32$ GeV^2





$$d^4\sigma = \mathcal{T}_{\mathsf{BH}}^2 + \mathcal{T}_{\mathsf{BH}}\mathcal{R}e(\mathcal{T}_{\mathsf{DVCS}}) + \mathcal{T}_{\mathsf{DVCS}}^2$$

$$\mathcal{R}e(\mathcal{T}_{\mathsf{DVCS}}) \sim c_0^{\mathcal{I}} + c_1^{\mathcal{I}}\cos\phi + c_2^{\mathcal{I}}\cos 2\phi$$

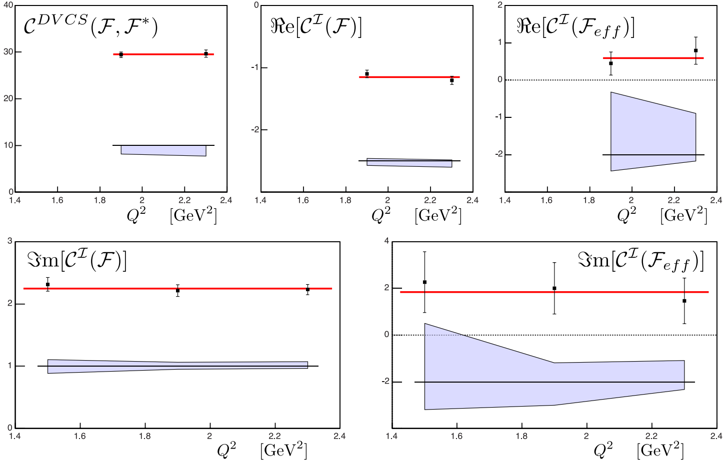
$$\mathcal{T}_{\mathsf{DVCS}}^2 \sim c_0^{\mathsf{DVCS}} + c_1^{\mathsf{DVCS}}\cos\phi$$

$$\Delta^4\sigma = \frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{2} = \mathcal{I}m(\mathcal{T}_{\mathsf{DVCS}})$$

$$\mathcal{I}m(\mathcal{T}_{\mathsf{DVCS}}) \sim s_1^{\mathcal{I}}\sin\phi + s_2^{\mathcal{I}}\sin 2\phi$$

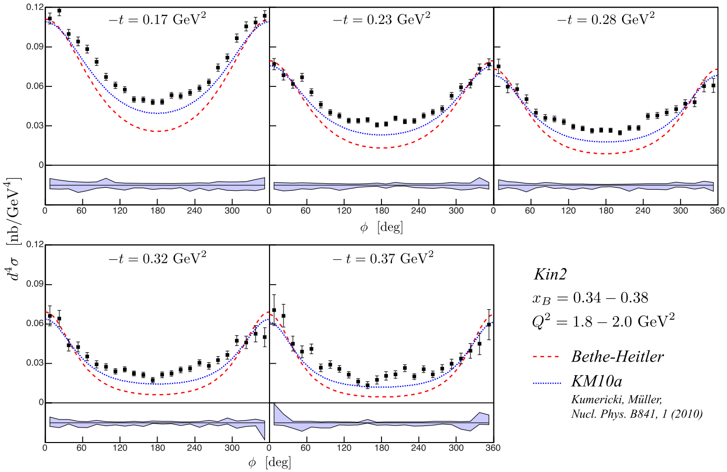
M. Defurne *et al.* Phys. Rev. C 92, 055202

DVCS cross sections: Q^2–dependance



No Q^2-dependance within limited range $\Rightarrow$ leading twist dominance

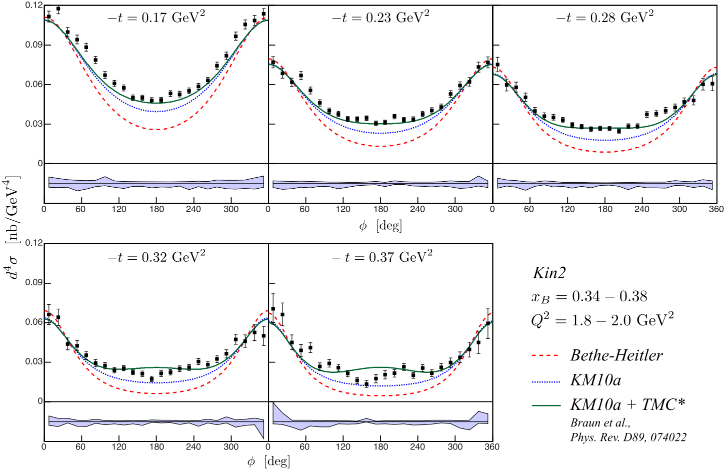
DVCS cross sections: kinematical power corrections



- KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries

Kumericki and Mueller (2010)

DVCS cross sections: kinematical power corrections



- KM10a: global fit to HERA x-sec & HERMES + CLAS spin asymmetries

  Kumericki and Mueller (2010)

- Target-mass corrections (TMC): $\sim \mathcal{O}(M^2/Q^2)$ and $\sim \mathcal{O}(t/Q^2)$

  Braun, Manashov, Mueller and Pirnay (2014)

Rosenbluth-like separation of the DVCS cross section

$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$

$$\mathcal{I} \propto 1/y^3 = (k/\nu)^3,$$
$$\left|\mathcal{T}^{DVCS}\right|^2 \propto 1/y^2 = (k/\nu)^2$$

BKM-2010 – at leading twist $\to$ 7 independent GPD terms:

$$\left\{\Re\text{e}, \Im\text{m}\left[\mathcal{C}^{\mathcal{I}}, \mathcal{C}^{\mathcal{I},V}, \mathcal{C}^{\mathcal{I},A}\right](\mathcal{F})\right\}, \quad \text{and} \quad \mathcal{C}^{DVCS}(\mathcal{F}, \mathcal{F}*).$$

φ-dependence provides 5 independent observables:

$$\sim 1, \sim \cos\varphi, \sim \sin\varphi, \sim \cos(2\varphi), \sim \sin(2\varphi)$$

The measurement of the cross section at two or more beam energies for exactly the same Q^2, x_B, t kinematics, provides the additional information in order to extract all leading twist observables independently.

DVCS process: leading twist ambiguity

- DVCS defines a preferred axis: light-cone axis
- At finite Q^2 and non-zero t, there is an ambiguity:
  1. Belitsky et al. ("BKM", 2002–2010): light-cone axis in plane (q,P)
  2. Braun et al. ("BMP", 2014): light-cone axis in plane (q,q')
     easi*er* to account for kin. corrections $\sim \mathcal{O}(M^2/Q^2)$, $\sim \mathcal{O}(t/Q^2)$

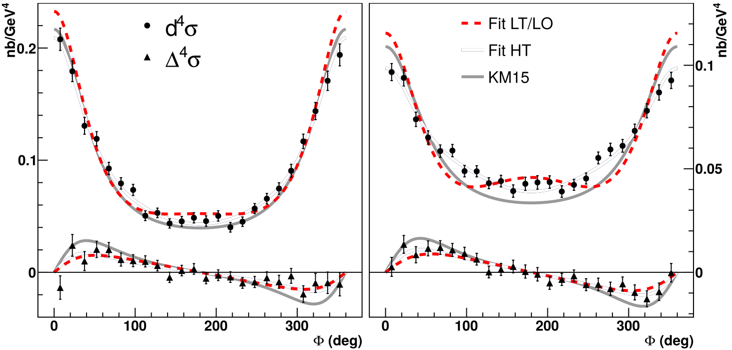
$$\left.\begin{aligned} \mathcal{F}_{++} &= \mathbb{F}_{++} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+} \\ \mathcal{F}_{-+} &= \mathbb{F}_{-+} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+} \\ \mathcal{F}_{0+} &= -(1+\chi)\mathbb{F}_{0+} + \chi_0\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] \end{aligned}\right\} \xrightarrow[\mathbb{F}_{0+}=0]{\mathbb{F}_{-+}=0} \left\{\begin{aligned} \mathcal{F}_{++} &= (1+\tfrac{\chi}{2})\mathbb{F}_{++} \\ \mathcal{F}_{-+} &= \tfrac{\chi}{2}\mathbb{F}_{++} \\ \mathcal{F}_{0+} &= \chi_0 \mathbb{F}_{++} \end{aligned}\right.$$

(eg. $\chi_0 = 0.25$, $\chi = 0.06$ for $Q^2 = 2$ GeV^2, $x_B = 0.36$, $t = -0.24$ GeV^2)

E07-007: DVCS beam-energy dependence

- Cross section measured at 2 beam energies and constant Q^2, x_B, t

$E = 4.5$ GeV $E = 5.6$ GeV



- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data

Light-cone axis in the (q,q') plane **(Braun et al.)**: $\mathbb{H}_{++}$, $\widetilde{\mathbb{H}}_{++}$, $\mathbb{E}_{++}$, $\widetilde{\mathbb{E}}_{++}$

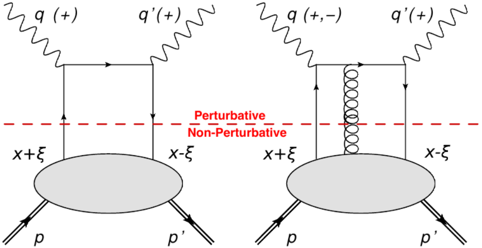
Beyond Leading Order (LO) and Leading Twist (LT)

Two fit-scenarios:

Light-cone axis in the (q,q') plane (Braun et al.)

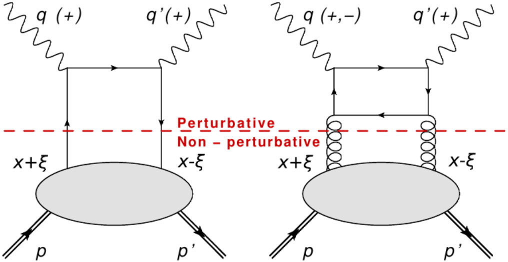
LO/LT + HT

$\mathbb{H}_{++}$, $\widetilde{\mathbb{H}}_{++}$, $\mathbb{H}_{0+}$, $\widetilde{\mathbb{H}}_{0+}$



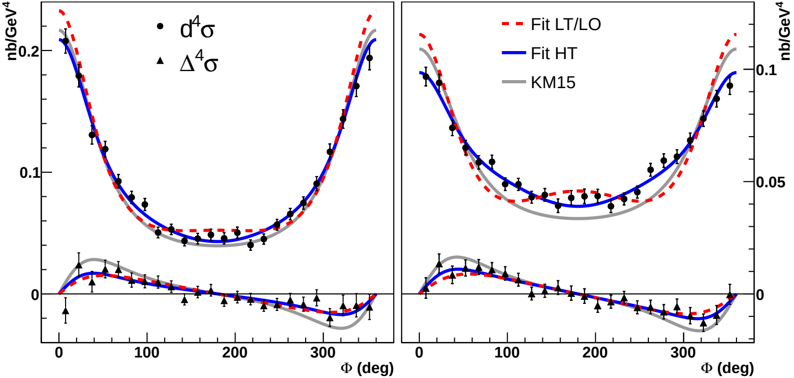
LO/LT + NLO

$\mathbb{H}_{++}$, $\widetilde{\mathbb{H}}_{++}$, $\mathbb{H}_{-+}$, $\widetilde{\mathbb{H}}_{-+}$



E07-007: DVCS beam-energy dependence

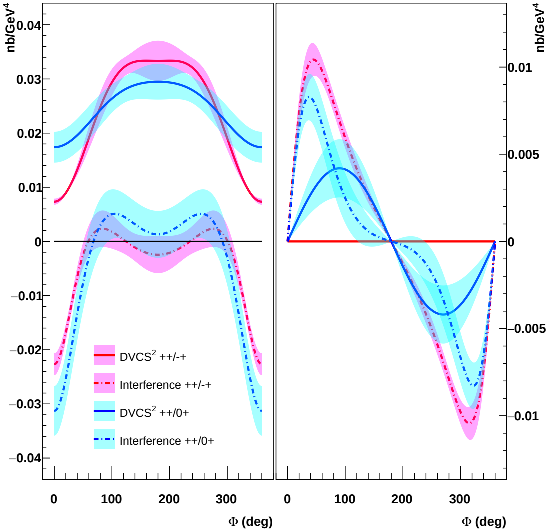
- Cross section measured at 2 beam energies and constant Q^2, x_B, t



- Leading-twist and LO simultaneous fit of both beam energies (dashed line) does not reproduce the data
- Including either NLO or higher-twist effects (dark solid line) satisfactorily reproduce the angular dependence

DVCS^2 and $\mathcal{I}$(DVCS·BH) separation

DVCS^2 and $\mathcal{I}$(DVCS·BH) separated in NLO and higher-twist scenarios

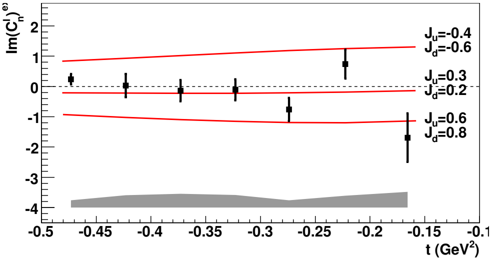


- DVCS^2 & $\mathcal{I}$ significantly different in each scenario
- Sizeable DVCS^2 contribution in the higher-twist scenario in the helicity-dependent cross section

Nature Commun. 8, 1408 (2017)

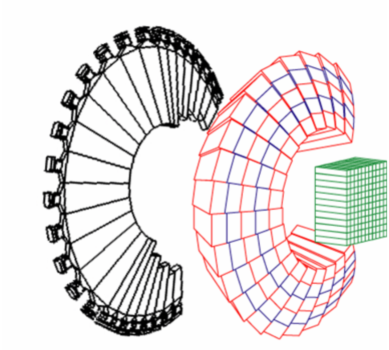
DVCS on the neutron: experiment E03-106 at JLab

LD_2 target $(F_2^n(t) \gg F_1^n(t)$!)



$$\sigma^{\rightarrow} - \sigma^{\leftarrow} = \Gamma(A \sin\varphi + \dots)$$

Charged particle veto
in front of scintillator array

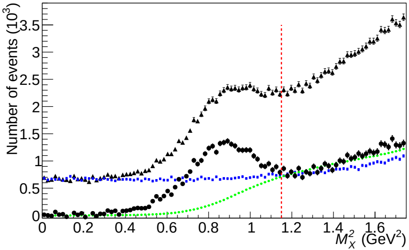


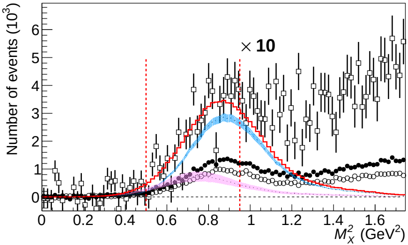
$$A = F_1(t)\mathcal{H} + \frac{x_B}{2 - x_B}[F_1(t) + F_2(t)]\tilde{\mathcal{H}} - \underbrace{\frac{t}{4M^2} \cdot F_2(t) \cdot \mathcal{E}}_{\text{Main contribution for neutron}}$$

E08-025: DVCS off the neutron at different beam energies

- LD_2 as a target ($Q^2 = 1.75$ GeV^2, $x_B = 0.36$)
- Quasi-free p evts subtracted using the (normalized) data from E07-007
- Concurrent running: switching LD2/LD2 $\rightarrow$ minimize uncertainties

$$D(e, e\,\gamma)X - p(e, e\,\gamma)p = n(e, e\,\gamma)n + d(e, e\,\gamma)d$$





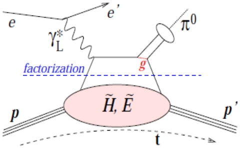
The average momentum transfer to the target is much larger than the np relative momentum, justifying this **impulse approximation**

Preliminary DVCS cross sections off the n & d

DVCS^2/Interference separation off the neutron

Potential flavor separation of CFFs combining these data with DVCS off the proton. . .

π^0 electroproduction ($ep \to ep\pi^0$)



At leading twist:

$$\frac{d\sigma_L}{dt} = \frac{1}{2}\Gamma \sum_{h_N, h_{N'}} |\mathcal{M}^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6} \qquad \sigma_T \propto \frac{1}{Q^8}$$

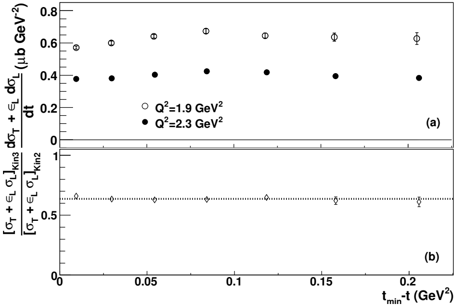
$$\mathcal{M}^L \propto \left[\int_0^1 dz \frac{\phi_\pi(z)}{z}\right] \int_{-1}^1 dx \left[\frac{1}{x-\xi} + \frac{1}{x+\xi}\right] \times \left\{\Gamma_1 \widetilde{H}_{\pi^0} + \Gamma_2 \widetilde{E}_{\pi^0}\right\}$$

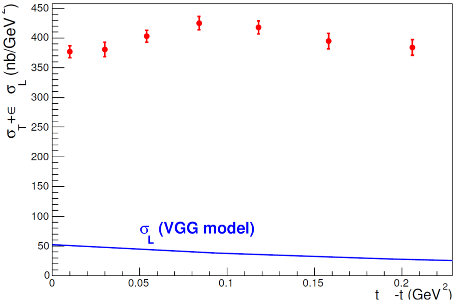
Different quark weights: flavor separation of GPDs

$$|\pi^0\rangle = \frac{1}{\sqrt{2}}\{|u\bar{u}\rangle - |d\bar{d}\rangle\} \qquad \widetilde{H}_{\pi^0} = \frac{1}{\sqrt{2}}\left\{\frac{2}{3}\widetilde{H}^u + \frac{1}{3}\widetilde{H}^d\right\}$$

$$|p\rangle = |uud\rangle \qquad H_{DVCS} = \frac{4}{9}H^u + \frac{1}{9}H^d$$

Exclusive π^0 electroproduction cross-sections – Hall A





- $\sigma_T + \epsilon_L \sigma_L \sim Q^{-5}$
  (similar to $\sigma_T(ep \to ep\pi^+)$ measured in Hall C)
- GPDs predict $\sigma_L \sim Q^{-6}$
- σ_T likely to dominate at these Q^2,
  but L/T separation necessary ($\to$ new experiment. . .)

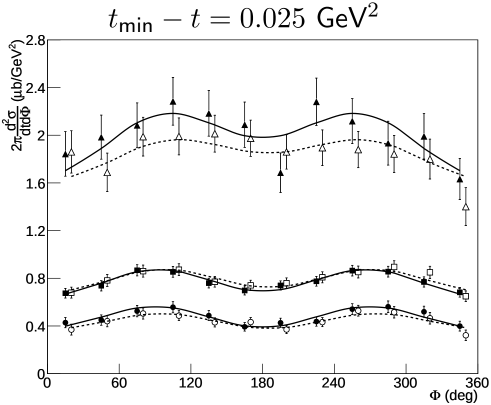
E. Fuchey et al., Phys. Rev. C83 (2011), 025125

Rosenbluth separation

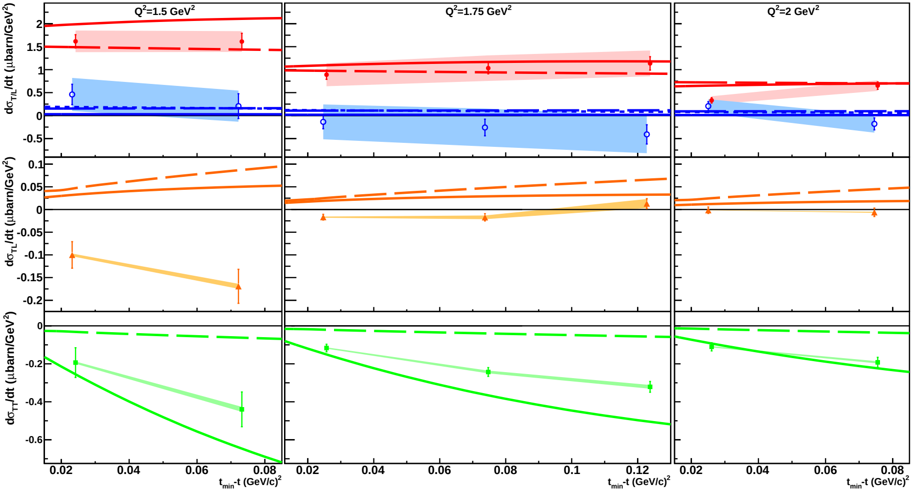
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi}\Gamma(Q^2, x_B, E)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}\cos\phi + \epsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi\right]$$

Kinematics

Setting	Q^2 (GeV^2)	x_B	E^{beam} (GeV)	ϵ
Kin1	1.50	0.36	3.355	0.52
			5.55	0.84
Kin2	1.75	0.36	4.455	0.65
			5.55	0.79
Kin3	2.00	0.36	4.455	0.53
			5.55	0.72



π^0 separated response functions



Goloskokov, Kroll (2011)

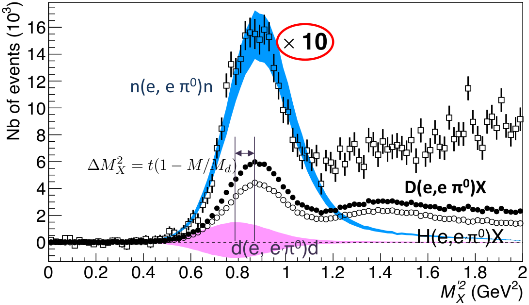
Goldstein, Hernandez, Liuti (2011)

Vanderhaeghen, Guichon, Guidal (1999)

E08-025: DVCS and π^0 off quasi-free neutrons

- LD_2 as a target
- Quasi-free p evts subtracted using the (normalized) data from E07-007
- Concurrent running: switching LD2/LD2 $\rightarrow$ minimize uncertainties

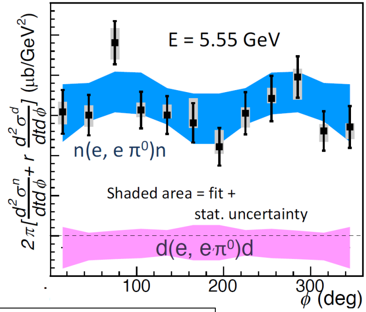
$$D(e, e\,\pi^0)X - p(e, e\,\pi^0)p = n(e, e\,\pi^0)n + d(e, e\,\pi^0)d$$

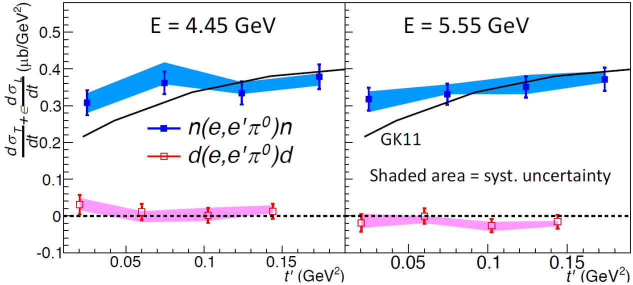


The average momentum transfer to the target is much larger than the np relative momentum, justifying this **impulse approximation**

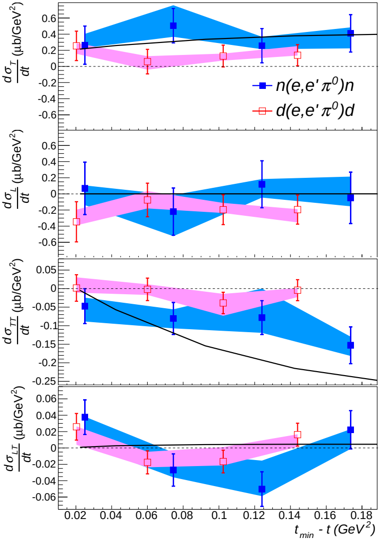
π^0 electroproduction cross section off the neutron

- Cross section off coherent d found negligeable within uncertainties
- Very low E_{beam} dependence of the n cross section $\rightarrow$ dominance of σ_T





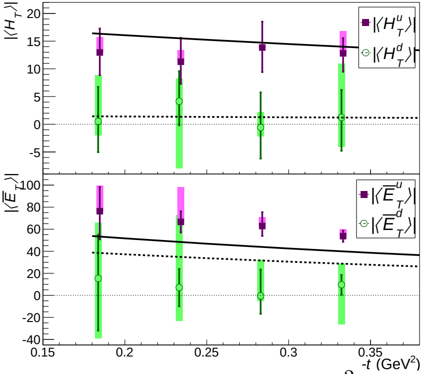
Separated π^0 cross section off the neutron



M. Mazouz et al, Phys.Rev.Lett. 118 (2017)

In the modified factorization approach (KG):

- $d\sigma_T \propto \left[\left(1-\xi^2\right)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8M^2}\left|\langle \bar{E}_T\rangle\right|^2\right]$
- $d\sigma_{TT} \propto \frac{t'}{8M^2}\left|\langle \bar{E}_T\rangle\right|^2$

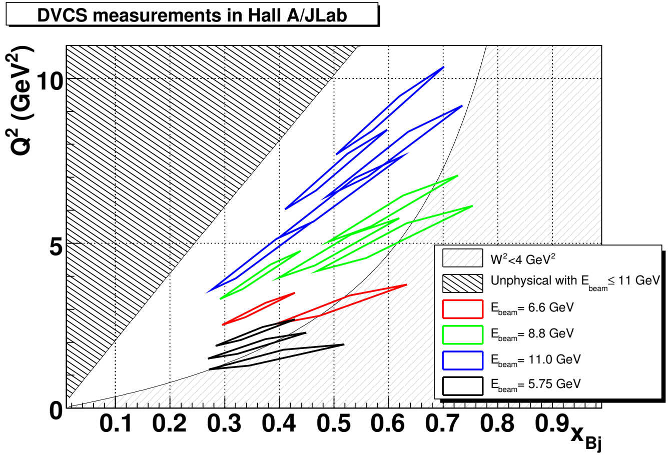


$$\left|\langle H_T^{p,n}\rangle\right|^2 = \frac{1}{2}\left|\frac{2}{3}\left\langle H_T^{u,d}\right\rangle + \frac{1}{3}\left\langle H_T^{d,u}\right\rangle\right|^2$$

E12-06-114: JLab Hall A at 11 GeV

JLab12 with 3, 4, 5 pass beam

(6.6, 8.8, 11.0 GeV beam energy)



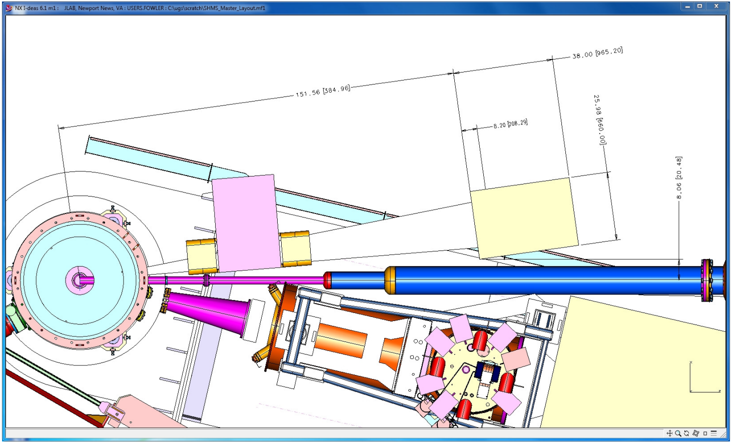
88 days

250k events/setting

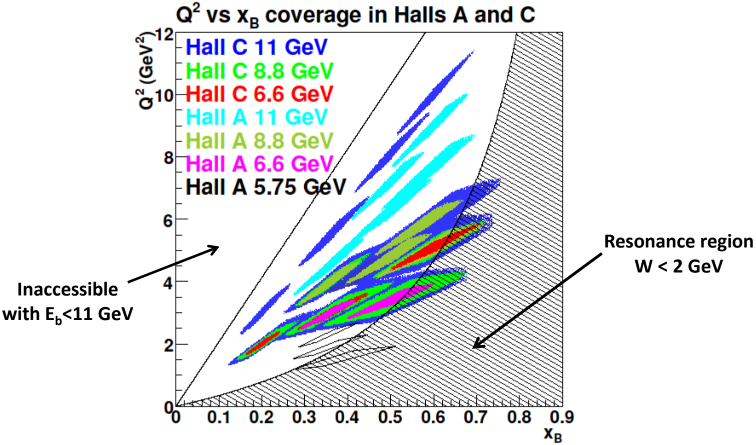
1 year of operations in JLab/Hall A

E12-13-010: DVCS in Hall C

- HMS ($p < 7.3GeV$): scattered electron
- $PbWO_4$ calorimeter: γ/π^0 detection
- Sweeping magnet

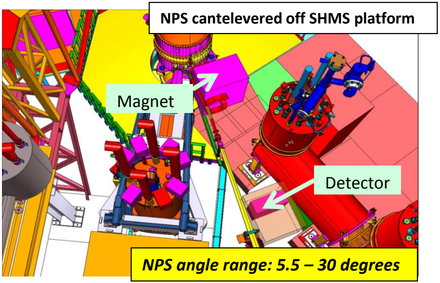


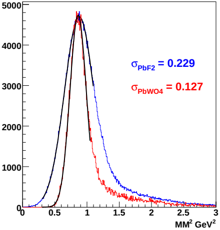
E12-13-010: beam energy separation in Hall C



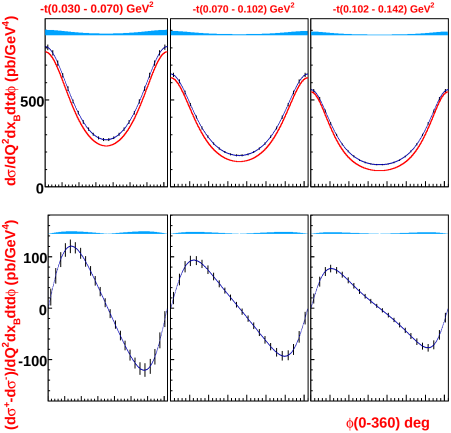
Approved by the PAC, possible running in $\gtrsim 2021$

Projections





- $PbF_2 \rightarrow PbWO_4$
- Improved E resolution wrt Hall A



Summary

- Recent high precision DVCS cross sections from Hall A at JLab
- Need of higher twist and/or NLO contributions to fully describe the data (eg. in global GPD fits)
- First separation of DVCS^2 and BH-DVCS interference in the $eN \to e\gamma N$ cross section, off the proton and neutron
- L/T separation of π^0 electroproduction cross section off neutron: dominance of σ_T measured
- Flavor separation of transversity GPD convolutions within the modified factorization approach
- Approved program of experiments in Hall A and C to continue these high precision DVCS measurements at 12 GeV

Back-up