

Deeply Virtual Compton Scattering at Jefferson Lab

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Outline

- ① Introduction
- ② Nucleon 3D-imaging & Generalized Parton Distributions (GPDs)
- ③ Deeply Virtual Compton Scattering (DVCS): $ep \rightarrow ep\gamma$
- ④ Experimental program at Jefferson Lab
 - Recent results
 - Experiments at 12 GeV
- ⑤ Summary

The proton: QCD at work!

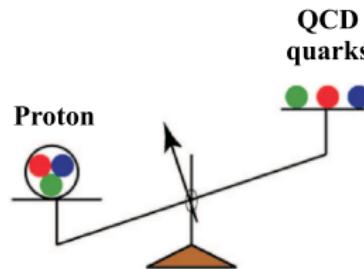
What we know...

- 2 up quarks ($q_u = 2/3 e$) + 1 down quark ($q_d = -1/3 e$)
- any number of quark-antiquark pairs & any number of gluons

$$|p\rangle = |uud\rangle + |uudq\bar{q}\rangle + |uudg\rangle + \dots$$

Fundamental questions

- Origin of proton mass?



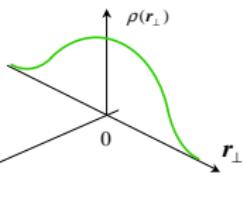
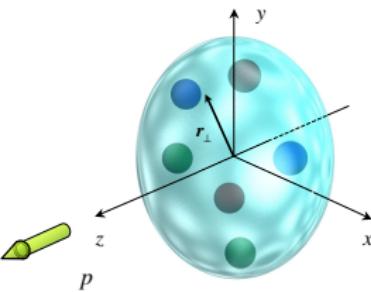
- Most of it comes from the motion of quarks & gluons
- Only a small fraction comes from *quark masses*

- Origin of proton spin?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z$$

Studying the structure of the nucleon experimentally

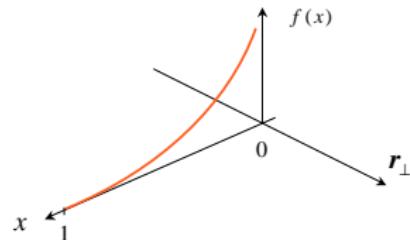
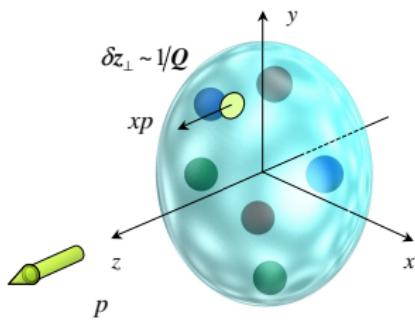
Elastic scattering



Form factors

Nobel prize, 1961

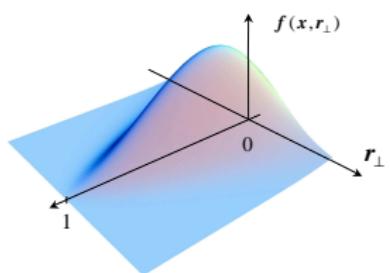
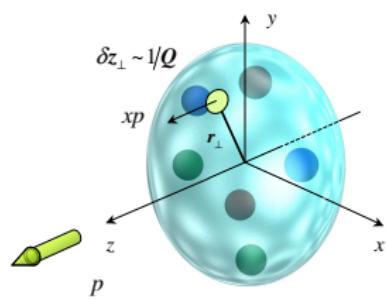
Deeply Inelastic Scattering



Parton distributions

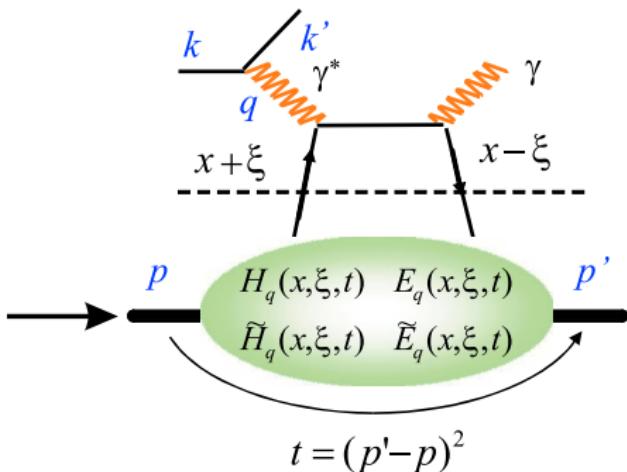
Nobel prize, 1969
Nobel prize, 1990

Hard exclusive processes



Generalized Parton
Distributions (GPDs)

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



Handbag diagram

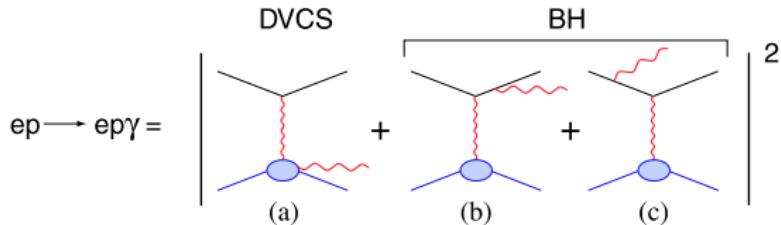
Bjorken limit :

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

High Q^2
Perturbative QCD

Non-perturbative
GPDs

DVCS experimentally: interference with Bethe-Heitler



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

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

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

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

$$\underbrace{\mathcal{P} \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi}}_{\text{Access in helicity-independent cross section}} - \underbrace{i\pi H(x = \xi, \xi, t)}_{\text{Access in helicity-dependent cross-section}} + \dots$$

Access in helicity-independent cross section

Access in helicity-dependent cross-section

Accessing different GDPs

Polarized beam, unpolarized target (**BSA**)

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

Unpolarized beam, longitudinal target (**ITSA**)

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

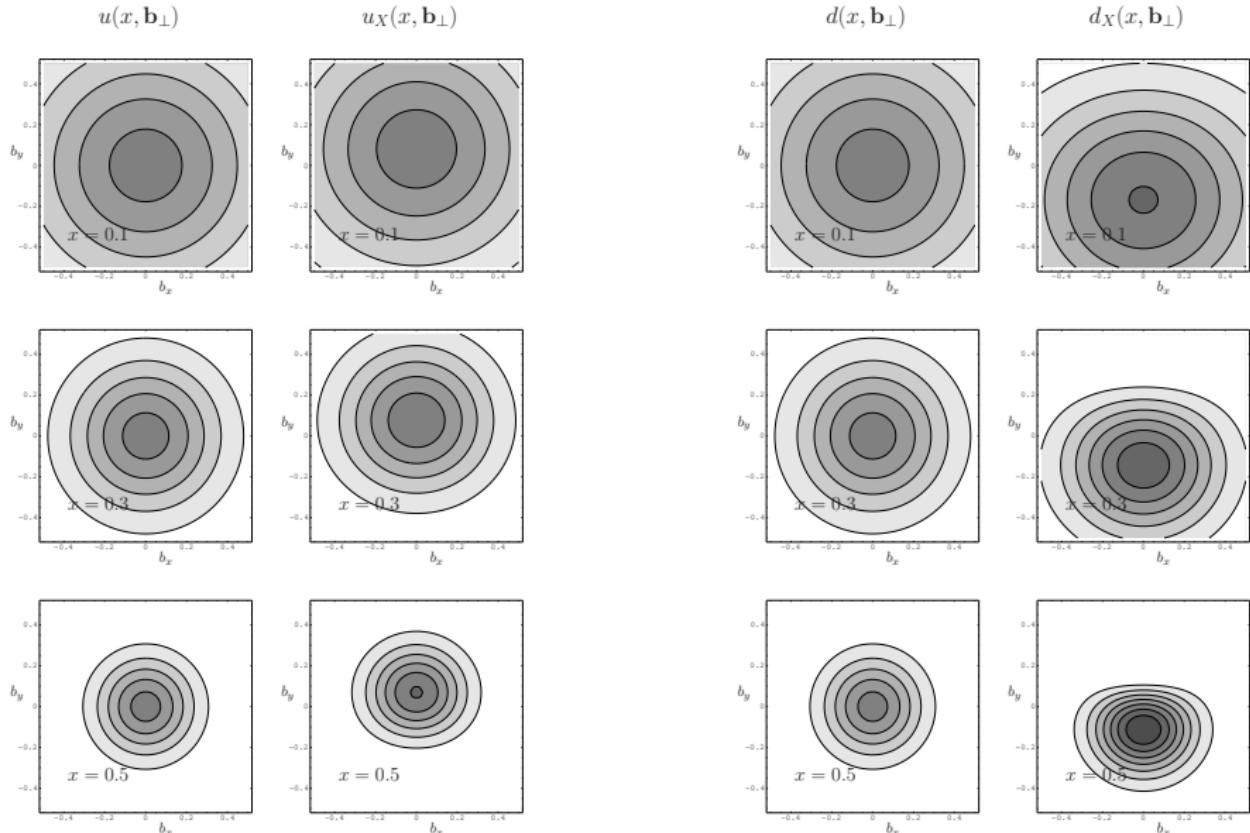
Polarized beam, longitudinal target (**BITSA**)

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

Unpolarized beam, transverse target (**tTSA**)

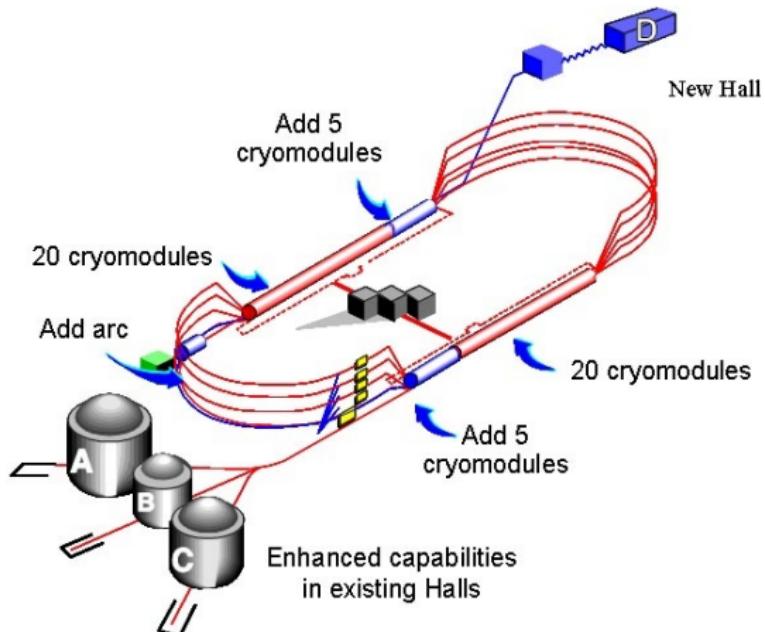
$$d\sigma_{UT} = \cos \phi \cdot \mathcal{Im}\{k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \dots\} d\phi$$

Impact-parameter interpretation of GPDs



Jefferson Lab: upgraded to 12 GeV

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



The GPD experimental program at Jefferson Lab

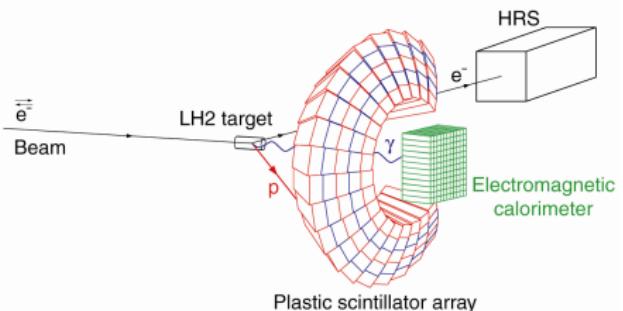
- Hall A: high accuracy, limited kinematic coverage
- Hall B: wide kinematic range, limited precision
- Hall C: high precision program at 11 GeV

Partially overlapping, partially complementary programs
with different experimental setups

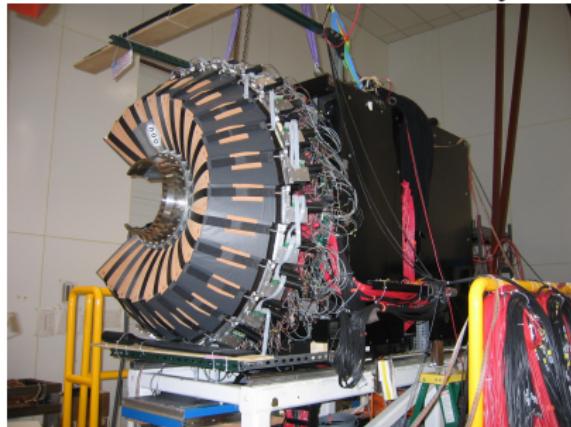
The roadmap:

- Early results (2001) from non-dedicated experiment (CLAS)
- 1st round of dedicated experiments in Halls A/B in 2004/5
- 2nd round on 2008–2010: precision tests + more spin observables
- Compelling DVCS experiments in Halls A+B+C at 11 GeV (\gtrsim 2017)

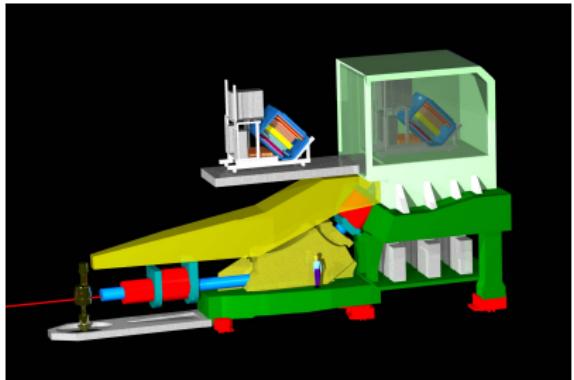
Experimental setup



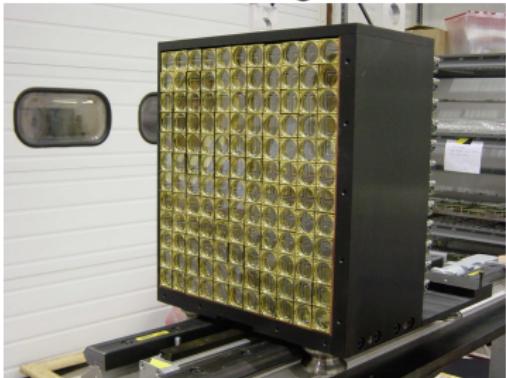
100-channel scintillator array



High Resolution Spectrometer

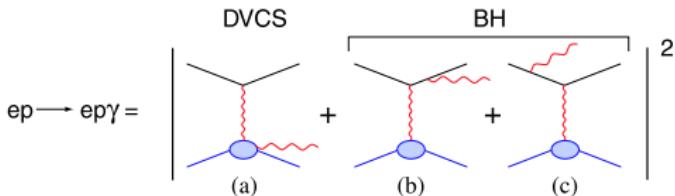
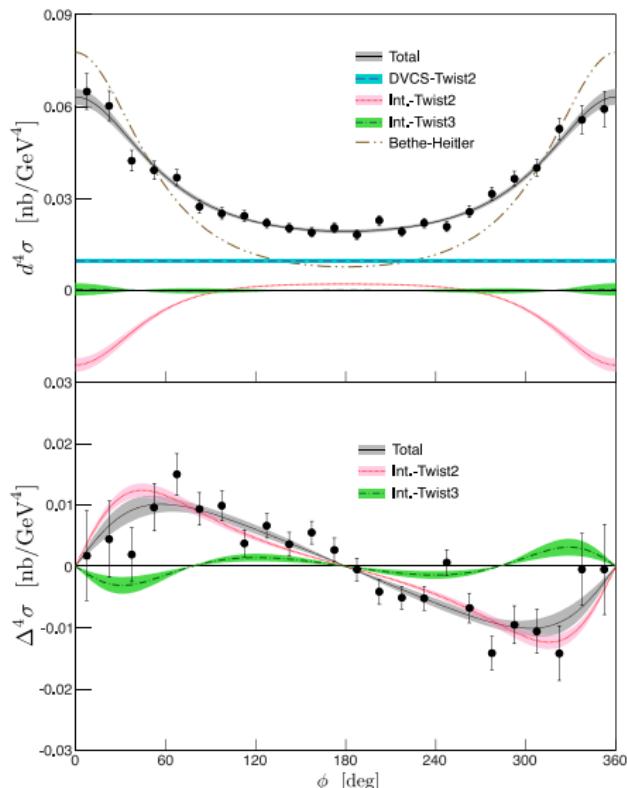


132-block PbF₂ electromagnetic calorimeter



DVCS cross sections: azimuthal analysis

$$Q^2 = 2.36 \text{ GeV}^2, x_B = 0.37, -t = 0.32 \text{ GeV}^2$$



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

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

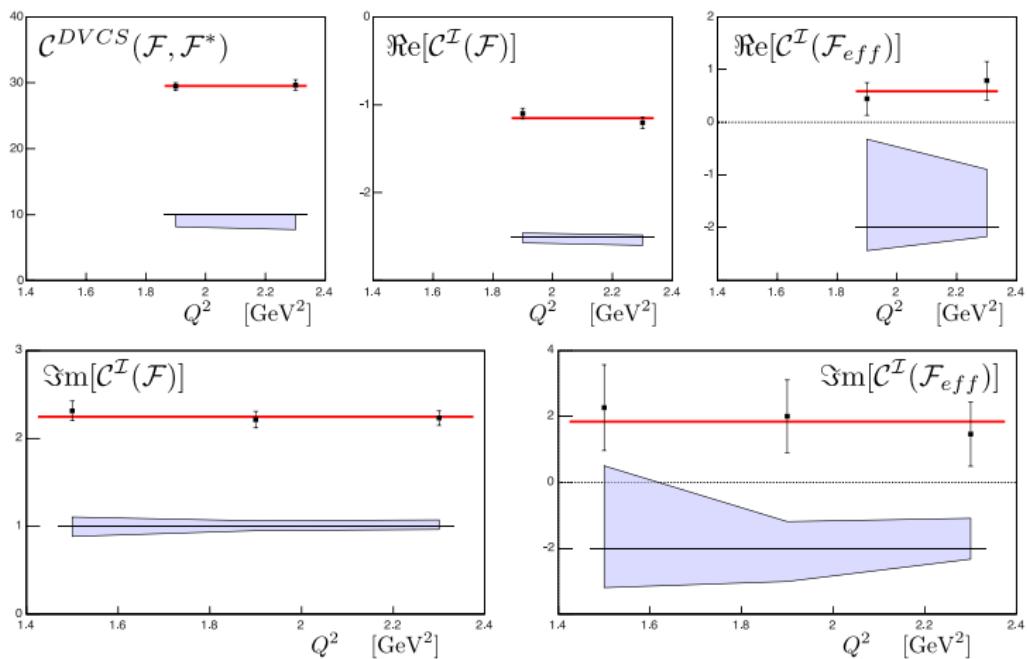
$$\mathcal{T}_{\text{DVCS}}^2 \sim c_0^{\text{DVCS}} + c_1^{\text{DVCS}} \cos \phi$$

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

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

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

Rosenbluth-like separation of the DVCS cross section

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

$$\mathcal{I} \propto 1/y^3 = (k/\nu)^3,$$

$$|\mathcal{T}^{DVCS}|^2 \propto 1/y^2 = (k/\nu)^2$$

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

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

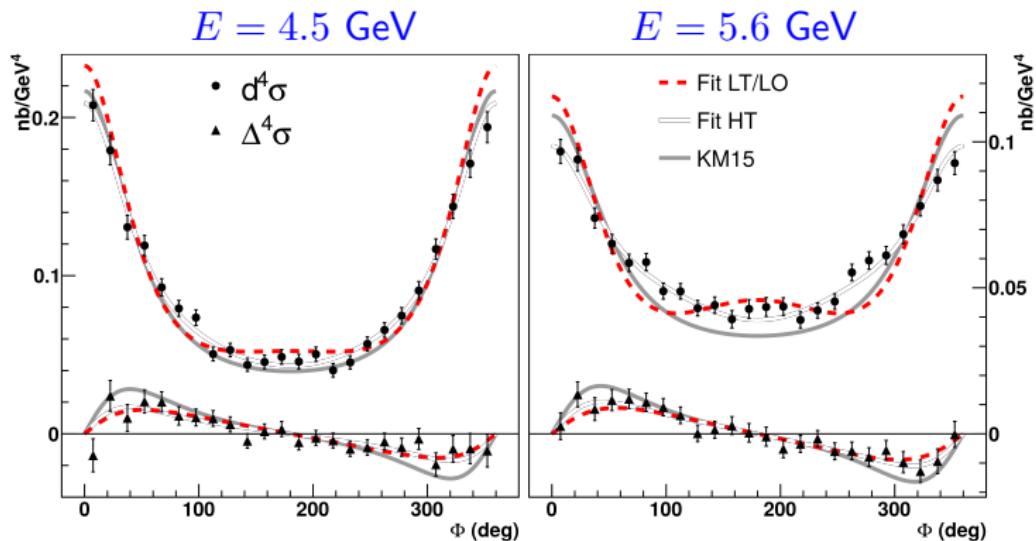
φ -dependence provides 5 independent observables:

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

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.

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

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

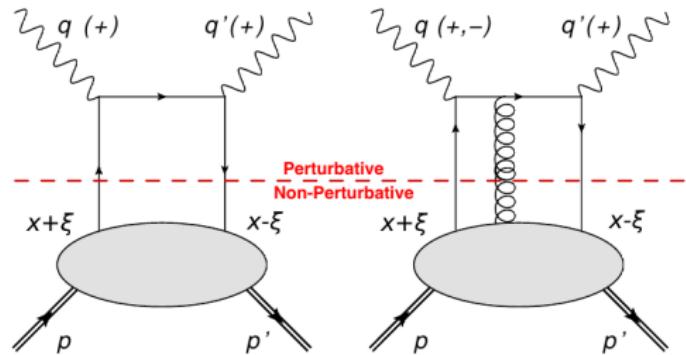
Beyond Leading Order (LO) and Leading Twist (LT)

Two fit-scenarios:

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

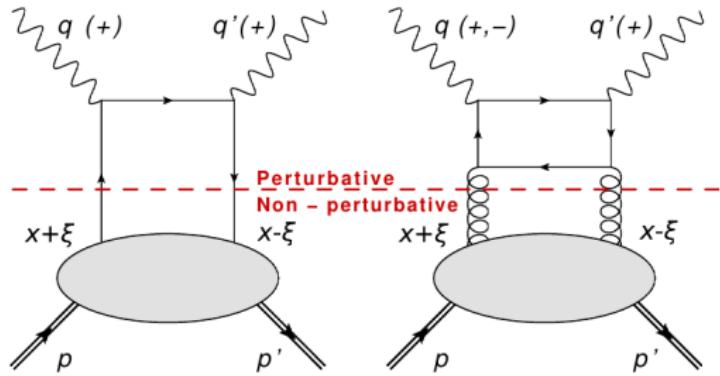
LO/LT + HT

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



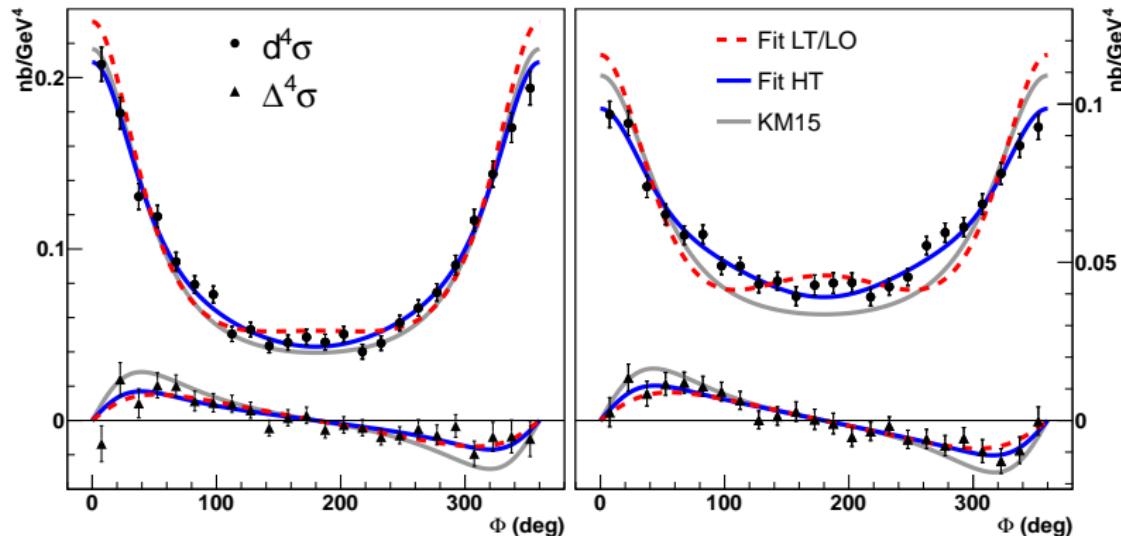
LO/LT + NLO

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



E07-007: DVCS beam-energy dependence

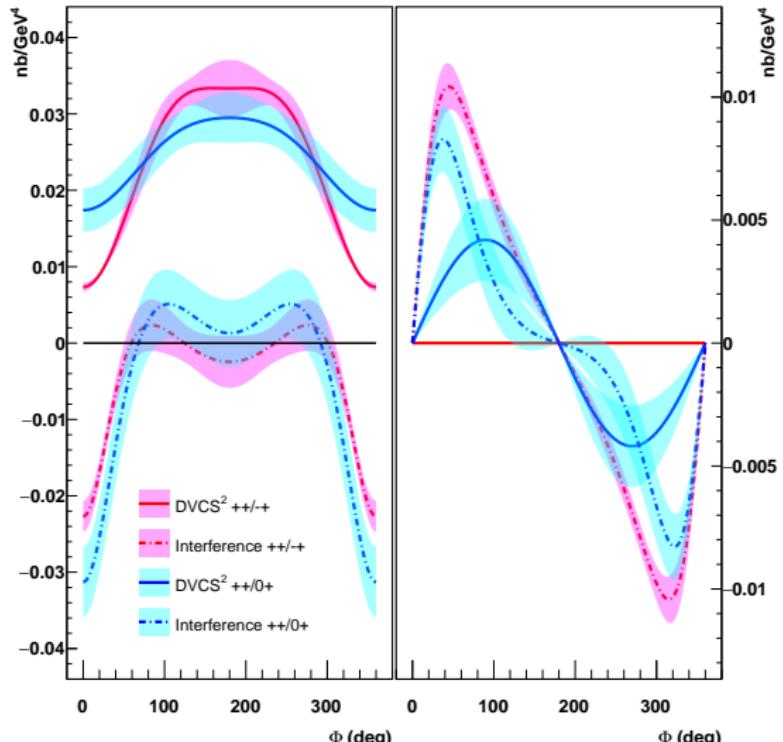
- Cross section measured at 2 beam energies and constant Q^2 , x_B , t



- 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

DVCS² and \mathcal{I} (DVCS·BH) separation

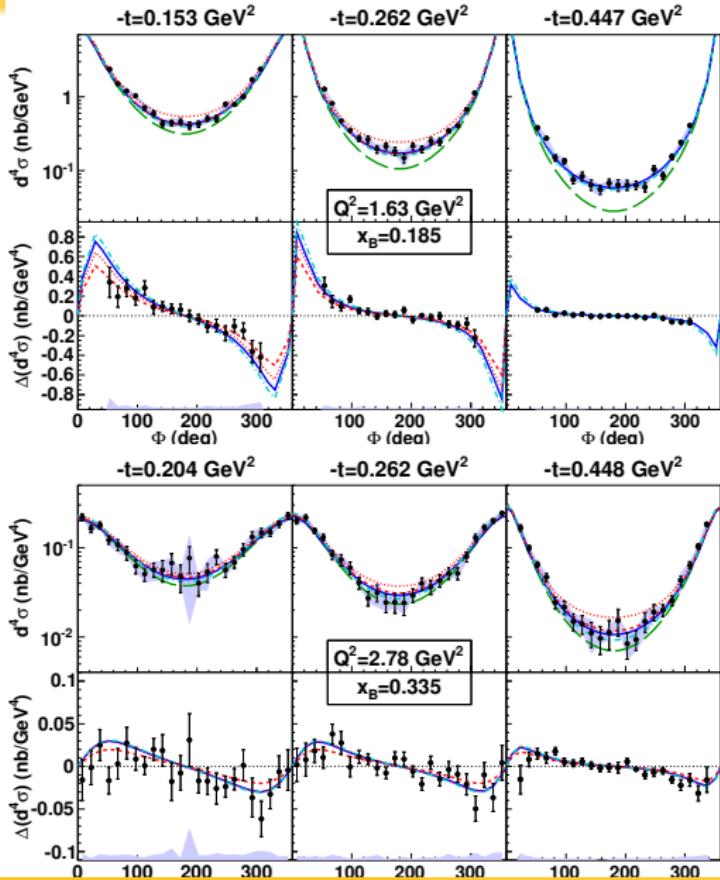
DVCS² and \mathcal{I} (DVCS·BH) separated in NLO and higher-twist scenarios



- DVCS² & \mathcal{I} significantly different in each scenario
- Sizeable DVCS² contribution in the higher-twist scenario in the helicity-dependent cross section

Nature Commun. 8, 1408 (2017)

Hall B DVCS cross-section measurements



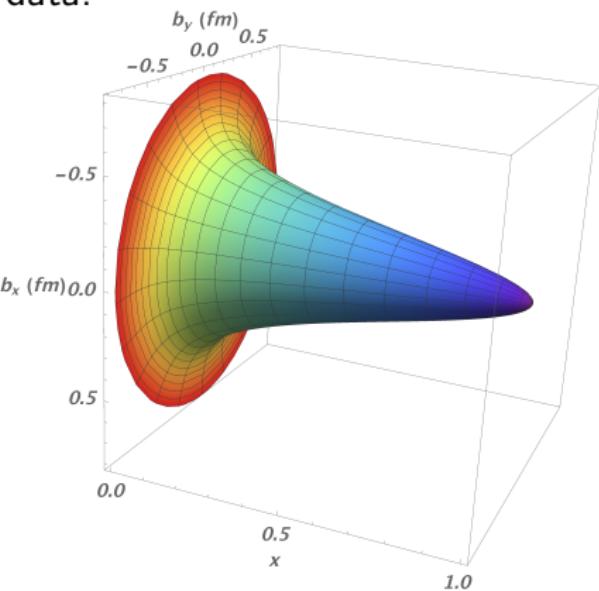
- Larger kinematic range covered:
110 (Q^2 , x_B , t) bins
- Compatible with Hall A results in overlap region
- Leading twist models describe the data within uncertainties

H.S. Jo *et al.* PRL 115, 212003 (2015)

First 3D-imaging of the proton from DVCS

From a simultaneous fit of JLab DVCS data:

- Fast-moving partons localized in the center of the proton
- Low energy and sea quarks mostly in the outer region



Much more results to come with JLab12 data:
neutron, polarized protons...

Phys. Rev. D95, 011501 (2017)

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

At leading twist:

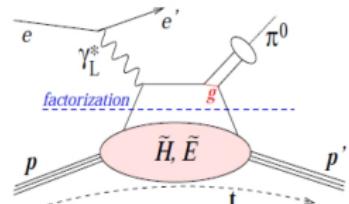
$$\frac{d\sigma_L}{dt} = \frac{1}{2}\Gamma \sum_{h_N, h_{N'}} |\mathcal{M}^L(\lambda_M = 0, h'_N, h_N)|^2 \propto \frac{1}{Q^6} \quad \sigma_T \propto \frac{1}{Q^8}$$

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

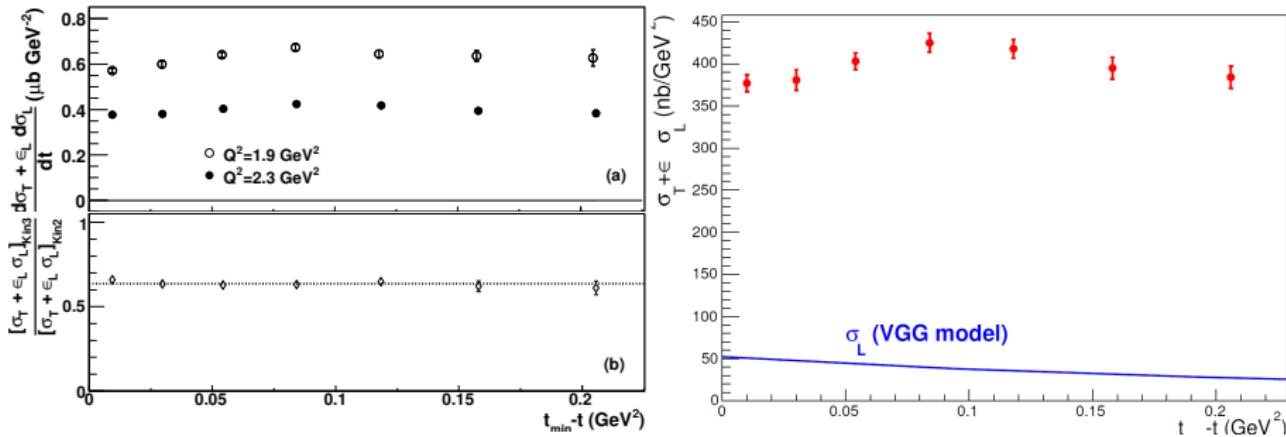
Different quark weights: flavor separation of GPDs

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

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



Exclusive π^0 electroproduction cross-sections – Hall A



- $\sigma_T + \epsilon_L \sigma_L \sim Q^{-5}$
(similar to $\sigma_T(ep \rightarrow ep\pi^+)$ 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 (\rightarrow new experiment...)

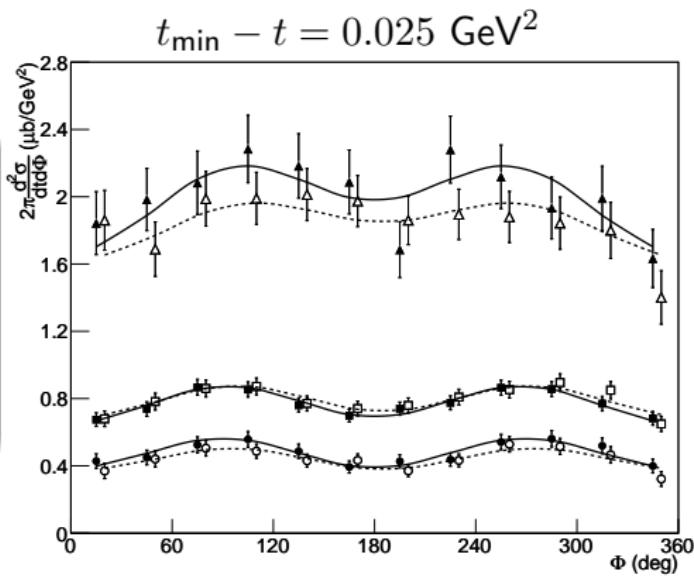
E. Fuchey et al., Phys. Rev. C83 (2011), 025125

Rosenbluth separation

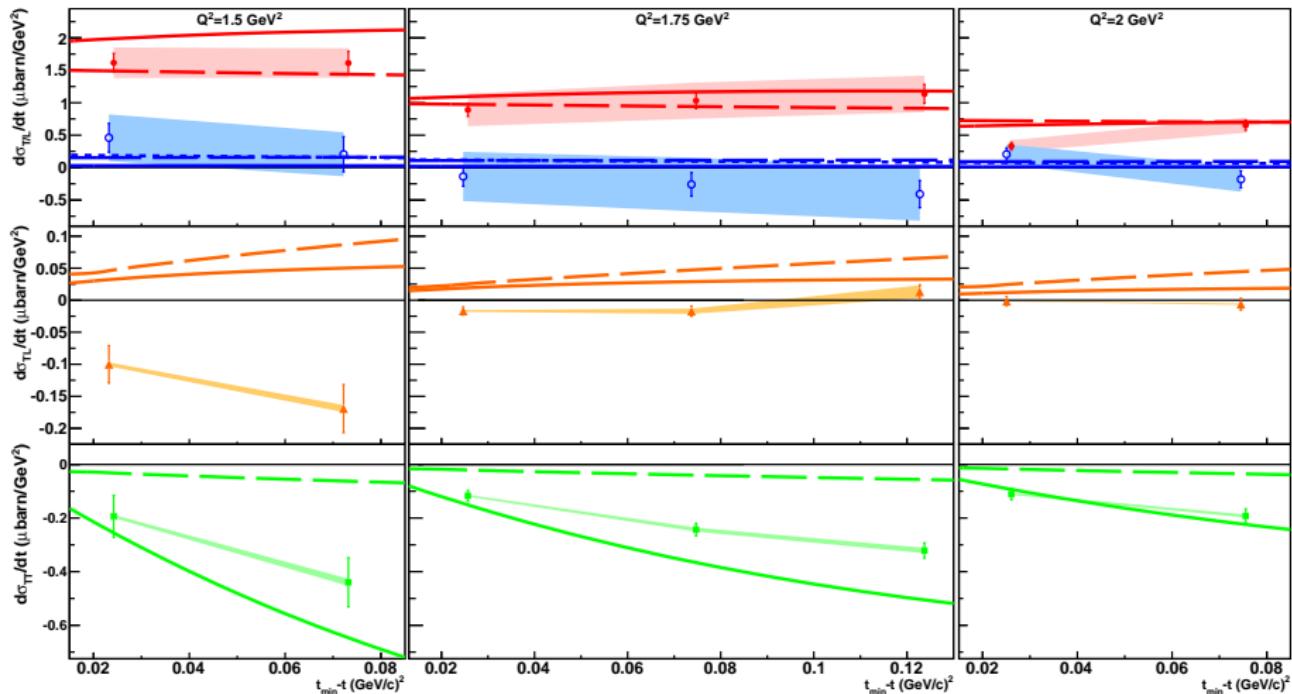
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} = \frac{1}{2\pi} \Gamma(Q^2, x_B, E) \left[\frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)} \frac{d\sigma_{TL}}{dt} \cos\phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos^2\phi \right]$$

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)

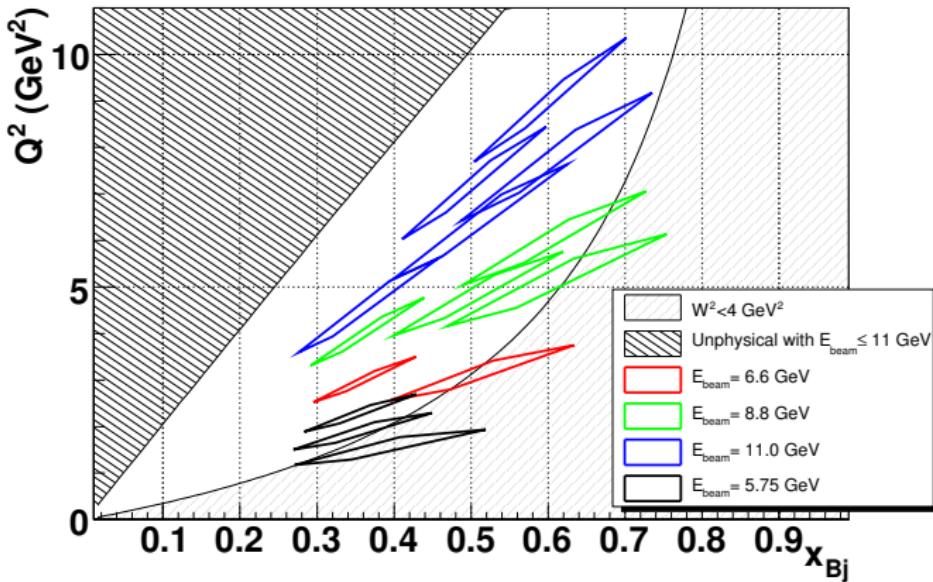
- - - - Vanderhaeghen, Guichon, Guidal (1999)

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)

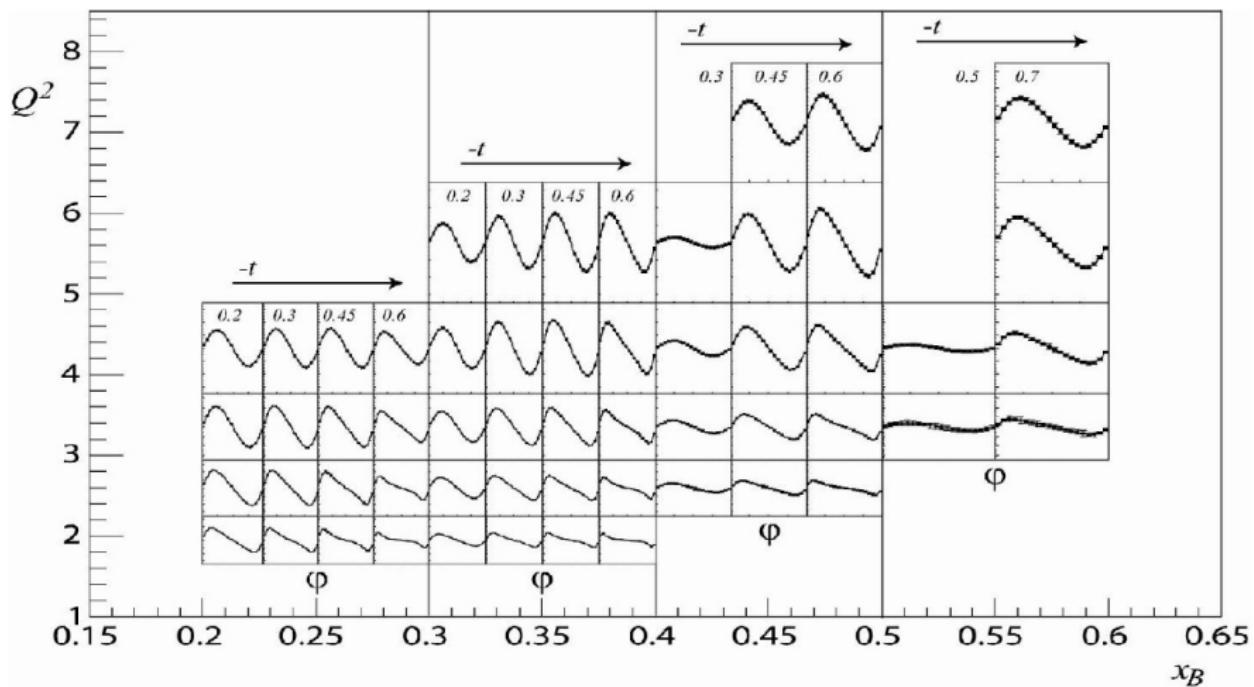
DVCS measurements in Hall A/JLab



88 days
250k events/setting

1 year of operations in JLab/Hall A

E12-06-119: DVCS on the proton with CLAS12



Summary

- DVCS golden channel to access GPDs experimentally, but also accessible in:
 - Deep meson production
 - Time-like Compton Scattering, Double DVCS...
- Large and accurate set of data (cross-sections and asymmetries) is now available in the valence region
 - Dominance of leading twist, but...
 - Necessity of higher twist corrections to explain high precision data
- Compelling GPD program in the future at Jefferson Lab 12 GeV in all 3 electron Hall A, B & C.