DVCS and GPDs at Jefferson Lab

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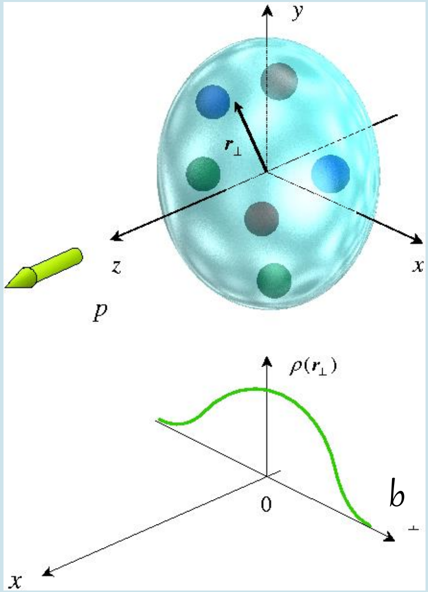
Outline

- Generalized parton distributions (GPDs)
- Deeply virtual Compton scattering (DVCS)
- DVCS at Jefferson Lab 6 GeV
- DVCS at Jefferson Lab 12 GeV
- Overview

Generalized parton distributions (GPDs)

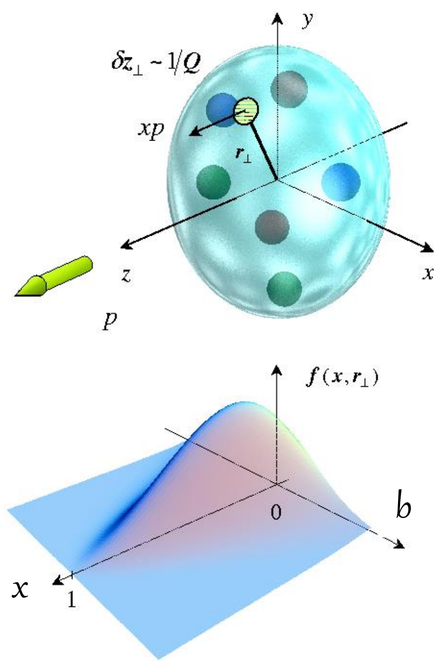


Form Factors (elastic scattering) :

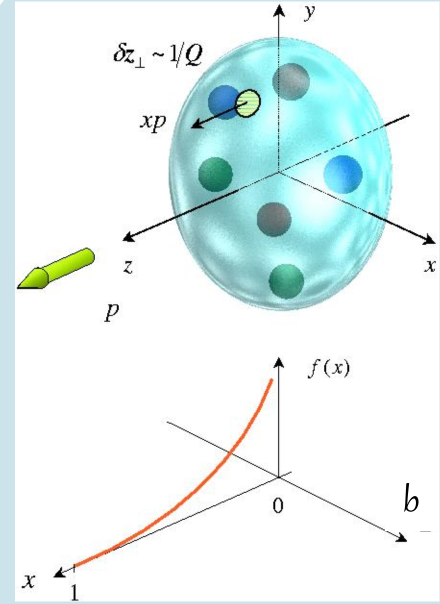
Transverse position of the quarks in the nucleon

GPDs, accessible via exclusive reactions, provide a **correlation** between the transverse position and the longitudinal momentum of the partons (quarks and gluons) in the nucleon

Nucleon tomography



Transverse position (b) as a function of longitudinal momentum fraction (x)



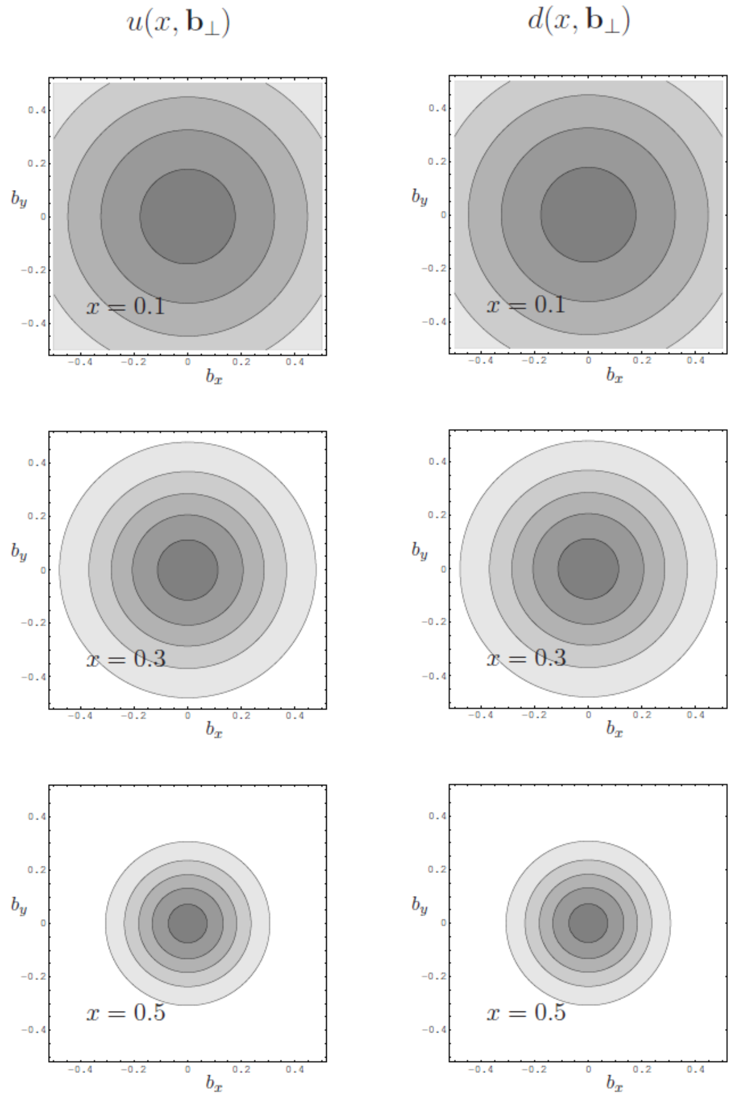
Parton Distribution Functions (deep inelastic scattering) :

Longitudinal momentum of the quarks in the nucleon

In this model, valence quarks (high x) are at the heart of the nucleon and sea quarks (low x) extend to its periphery

Interpretation of GPDs : impact parameter $b_\perp$ as a function of x

Transverse position $b_\perp$ of the quarks u and d inside the nucleon for different values of longitudinal momentum fraction x

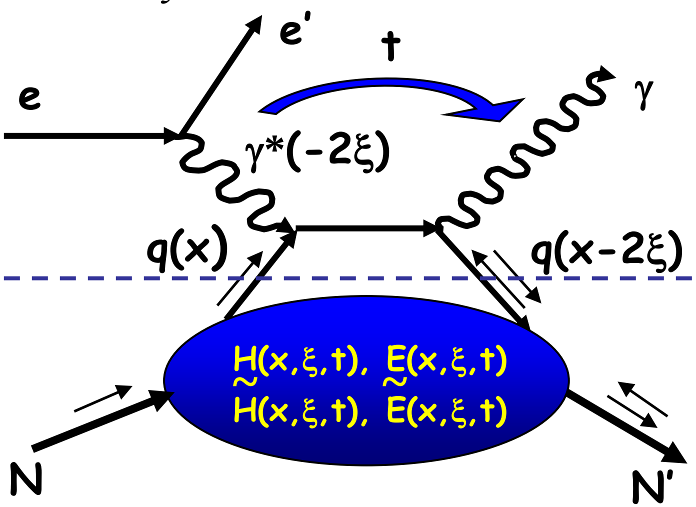


Deeply Virtual Compton Scattering (DVCS) and GPDs

High Q^2, small t

$$x_B = \frac{2\xi}{1+\xi}$$

DVCS



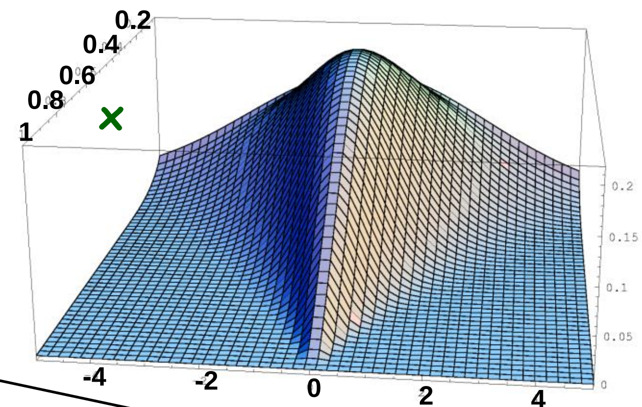
e N ⟶ e' N' γ

DVCS is the key reaction to access the GPDs as it offers the simplest interpretation in terms of GPDs

x longitudinal momentum fraction carried by the active quark.

$\xi \sim \frac{x_B}{2-x_B}$ the longitudinal momentum transfer.

$t = (p' - p)^2$ squared momentum transfer to the nucleon.



GPD(x,ξ,t)

$b_\perp$(GeV^{-1})

$b_\perp$: Fourier conjugate of t

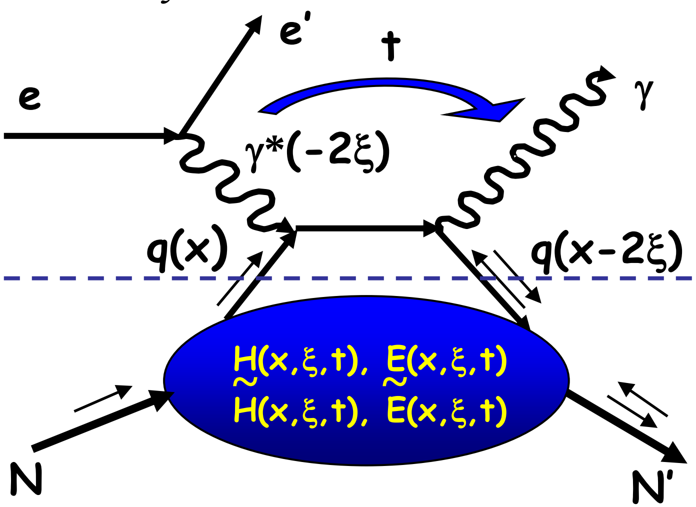
$$H^q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{i\mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp} H^q(x, \xi = 0, -\mathbf{\Delta}_\perp{}^2)$$

Deeply Virtual Compton Scattering (DVCS) and GPDs

High Q^2, small t

$$x_B = \frac{2\xi}{1+\xi}$$

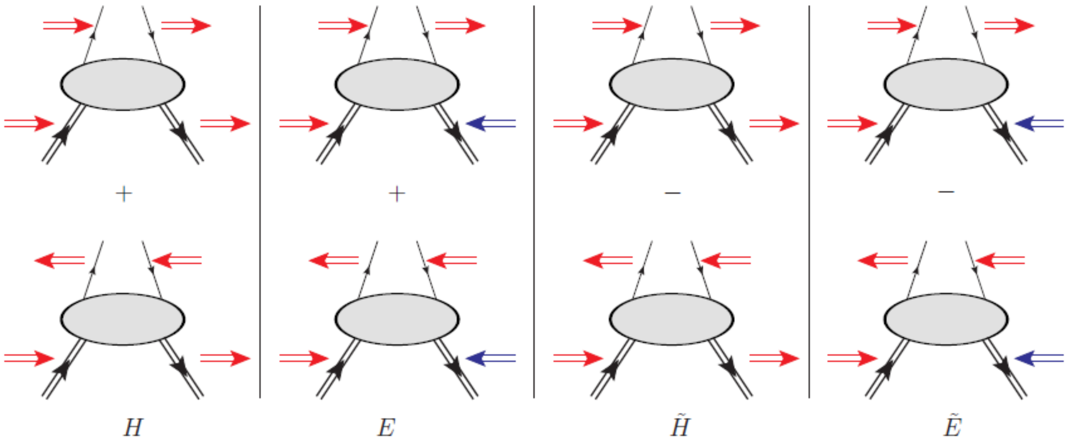
DVCS



$e\,N \longrightarrow e'\,N'\,\gamma$

DVCS is the key reaction to access the GPDs as it offers the simplest interpretation in terms of GPDs

At leading-order QCD, leading twist, there are 4 chiral-even (parton helicity is conserved) GPDs for each parton



$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*for sum over parton helicities*
$\widetilde{H}^{q,g}(x,\xi,t)$	$\widetilde{E}^{q,g}(x,\xi,t)$	*for difference over parton helicities*
nucleon helicity conserved	*nucleon helicity changed*	

GPDs and proton spin puzzle

Proton spin puzzle :
The origin of the proton spin is still unknown

$$\frac{1}{2} = \mathrm{J}^{q} + \mathrm{J}^{g} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Orbital angular momentum

GPDs H and E provide access to the total angular momentum of the partons in the nucleon

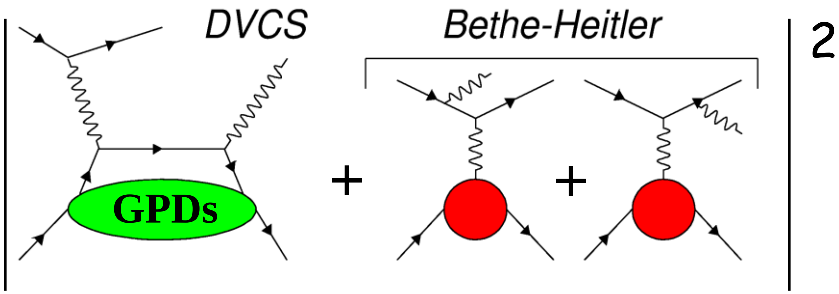
Ji's angular momentum sum rule:

$$\boxed{\mathrm{J}^{q,g} = \frac{1}{2}\int_{-1}^{1} x dx (\mathrm{H}^{q,g}(x,\xi,t=0) + \mathrm{E}^{q,g}(x,\xi,t=0))}$$

DVCS and Bethe-Heitler processes

BH fully calculable in QED

$\sigma(eN \to eN\gamma) =$



DVCS and Bethe-Heitler (BH) experimentally undistinguishable

interference between the 2 processes

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \sim \; P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$

Unpolarized Cross Section

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \approx \left|T^{DVCS} + T^{BH}\right|^2 = \left|T^{DVCS}\right|^2 + \left|T^{BH}\right|^2 + I$$

Beam-polarized Cross-Section difference

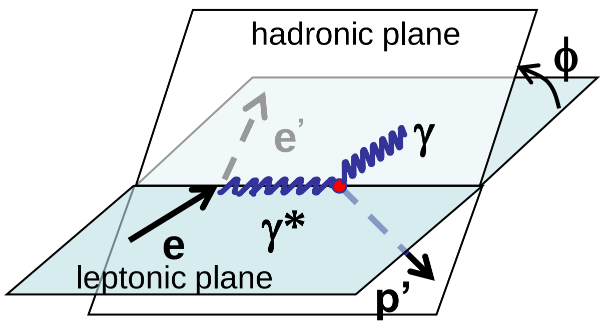
$$\frac{d^4\overrightarrow{\sigma}}{dQ^2 dx_B dt d\phi} - \frac{d^4\overleftarrow{\sigma}}{dQ^2 dx_B dt d\phi} \propto \mathrm{Im}(T_{DVCS}) \times T_{BH}$$

Compton Form Factors (CFFs) and DVCS observables

Compton Form Factors (CFFs)

$$\begin{cases} Re\mathcal{H}_q = e_q^2 P\int_0^{+1}\left(H^q(x,\xi,t)-H^q(-x,\xi,t)\right)\left[\frac{1}{\xi-x}+\frac{1}{\xi+x}\right]dx & \leftarrow \text{Integrals of GPDs over } x \\ Im\mathcal{H}_q = \pi e_q^2\left[H^q(\xi,\xi,t)-H^q(-\xi,\xi,t)\right] & \leftarrow \text{GPDs at } x=\pm\xi \end{cases}$$

Each DVCS observable is sensitive to a different combination of CFFs



$\xi = x_B/(2-x_B)$ $\quad k = t/4M^2$

		Proton Neutron
Polarized beam, unpolarized target: $\Delta\sigma_{LU} \sim \sin\phi\, Im\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$	$\Rightarrow$	$Im\{\boldsymbol{\mathcal{H}_p}, \widetilde{\mathcal{H}}_p, \mathcal{E}_p\}$ $Im\{\mathcal{H}_n, \widetilde{\mathcal{H}}_n, \boldsymbol{\mathcal{E}_n}\}$
Unpolarized beam, longitudinal target: $\Delta\sigma_{UL} \sim \sin\phi\, Im\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) - \xi kF_2\widetilde{\mathcal{E}}\}$	$\Rightarrow$	$Im\{\boldsymbol{\mathcal{H}_p}, \boldsymbol{\widetilde{\mathcal{H}}_p}\}$ $Im\{\boldsymbol{\mathcal{H}_n}, \mathcal{E}_n\}$
Polarized beam, longitudinal target: $\Delta\sigma_{LL} \sim (A+B\cos\phi)\, Re\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) + \ldots\}$	$\Rightarrow$	$Re\{\boldsymbol{\mathcal{H}_p}, \boldsymbol{\widetilde{\mathcal{H}}_p}\}$ $Re\{\boldsymbol{\mathcal{H}_n}, \mathcal{E}_n\}$
Unpolarized beam, transverse target: $\Delta\sigma_{UT} \sim \cos\phi \sin(\phi_s-\phi)\, Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$	$\Rightarrow$	$Im\{\boldsymbol{\mathcal{H}_p}, \boldsymbol{\mathcal{E}_p}\}$ $Im\{\boldsymbol{\mathcal{H}_n}\}$

Quark-flavor separation of GPDs

The extraction of the quark GPDs which requires a quark-flavor separation of GPDs can be done through a combined analysis of DVCS observables for the proton and the neutron (deuterium target)

$$(H,E)_u(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_p(\xi,\xi,t) - (H,E)_n(\xi,\xi,t)\right]$$
$$(H,E)_d(\xi,\xi,t) = {}^{9}\!/_{15}\left[4(H,E)_n(\xi,\xi,t) - (H,E)_p(\xi,\xi,t)\right]$$

Proton Neutron

Polarized beam, unpolarized target:

$$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\} \Rightarrow \begin{array}{l} Im\{\boldsymbol{\mathcal{H}_p}, \widetilde{\mathcal{H}}_p, \mathcal{E}_p\} \\ Im\{\mathcal{H}_n, \widetilde{\mathcal{H}}_n, \boldsymbol{\mathcal{E}_n}\} \end{array}$$

Unpolarized beam, longitudinal target:

$$\Delta\sigma_{UL} \sim \sin\phi\mathrm{Im}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\widetilde{\mathcal{E}}\} \Rightarrow \begin{array}{l} Im\{\boldsymbol{\mathcal{H}_p}, \boldsymbol{\widetilde{\mathcal{H}}_p}\} \\ Im\{\boldsymbol{\mathcal{H}_n}, \mathcal{E}_n\} \end{array}$$

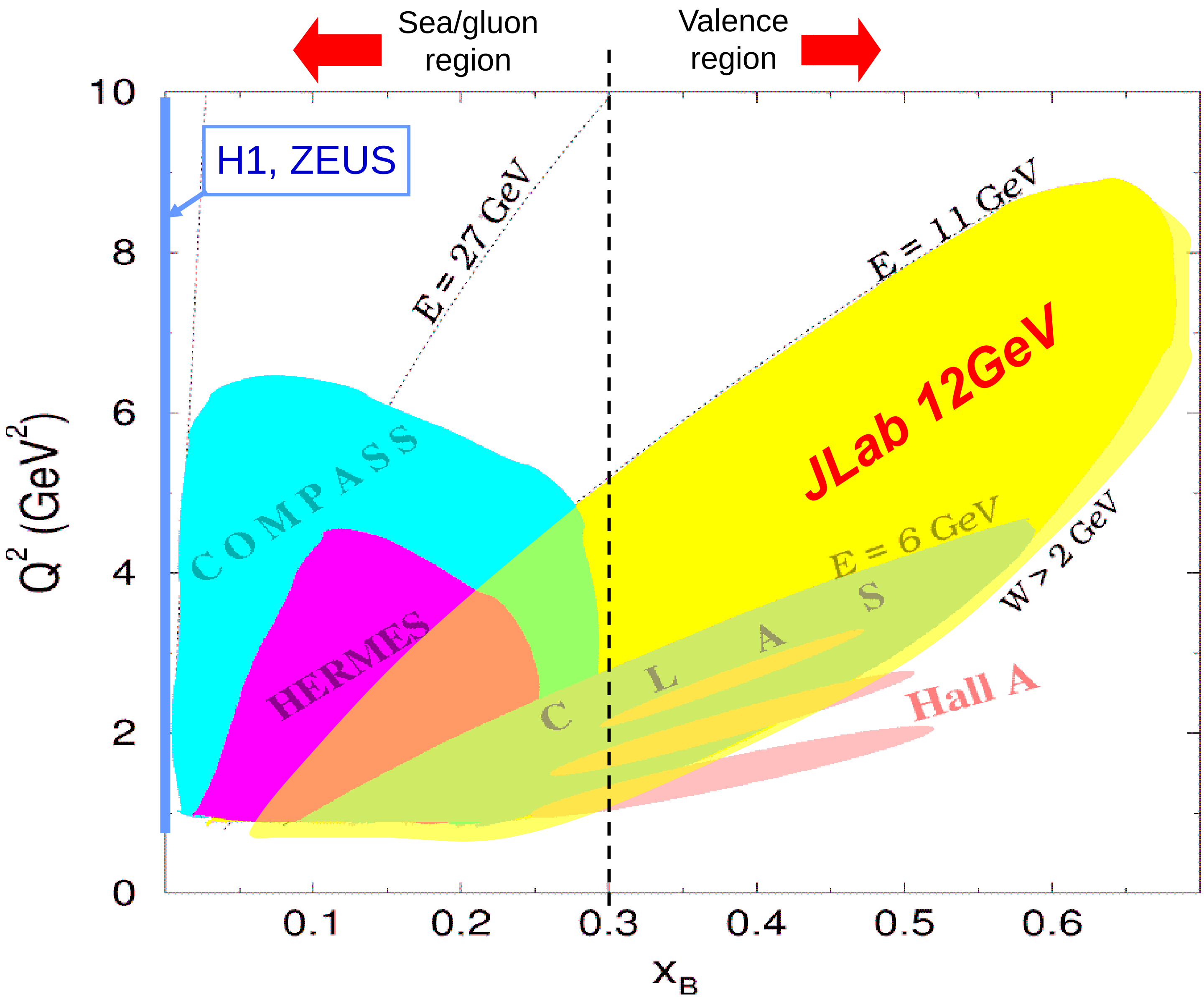
Polarized beam, longitudinal target:

$$\Delta\sigma_{LL} \sim (A+B\cos\phi)\mathrm{Re}\{F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) + \ldots\} \Rightarrow \begin{array}{l} Re\{\boldsymbol{\mathcal{H}_p}, \boldsymbol{\widetilde{\mathcal{H}}_p}\} \\ Re\{\boldsymbol{\mathcal{H}_n}, \mathcal{E}_n\} \end{array}$$

Unpolarized beam, transverse target:

$$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s - \phi)\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\} \Rightarrow \begin{array}{l} Im\{\boldsymbol{\mathcal{H}_p}, \boldsymbol{\mathcal{E}_p}\} \\ Im\{\boldsymbol{\mathcal{H}_n}\} \end{array}$$

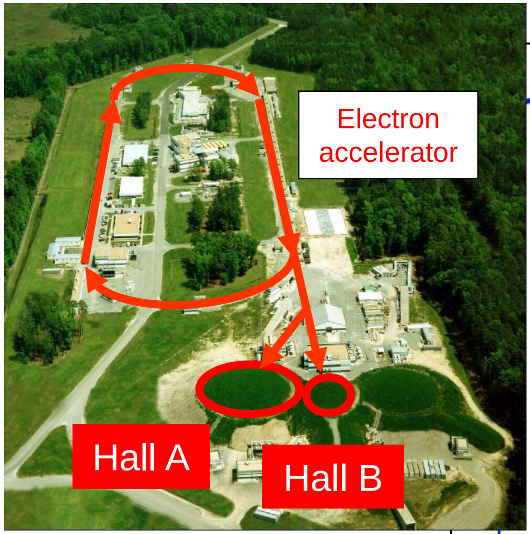
Kinematic coverage of the different experiments

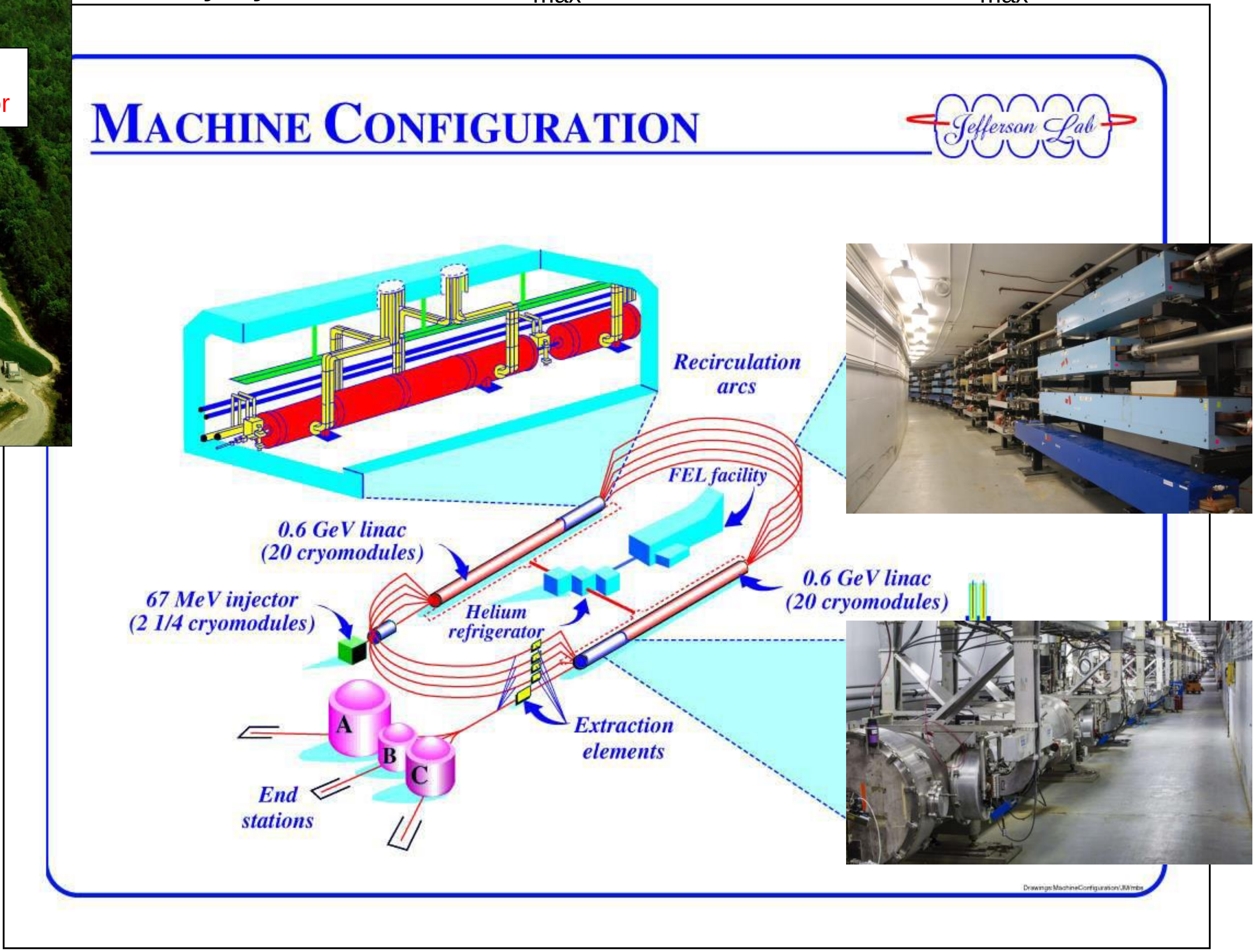


Jefferson Lab (Newport News, Virginia, USA)

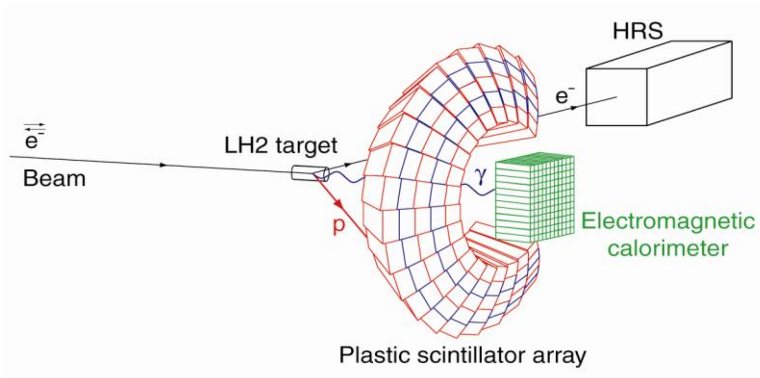
CEBAF : **C**ontinuous **E**lectron **B**eam **A**ccelerator **F**acility

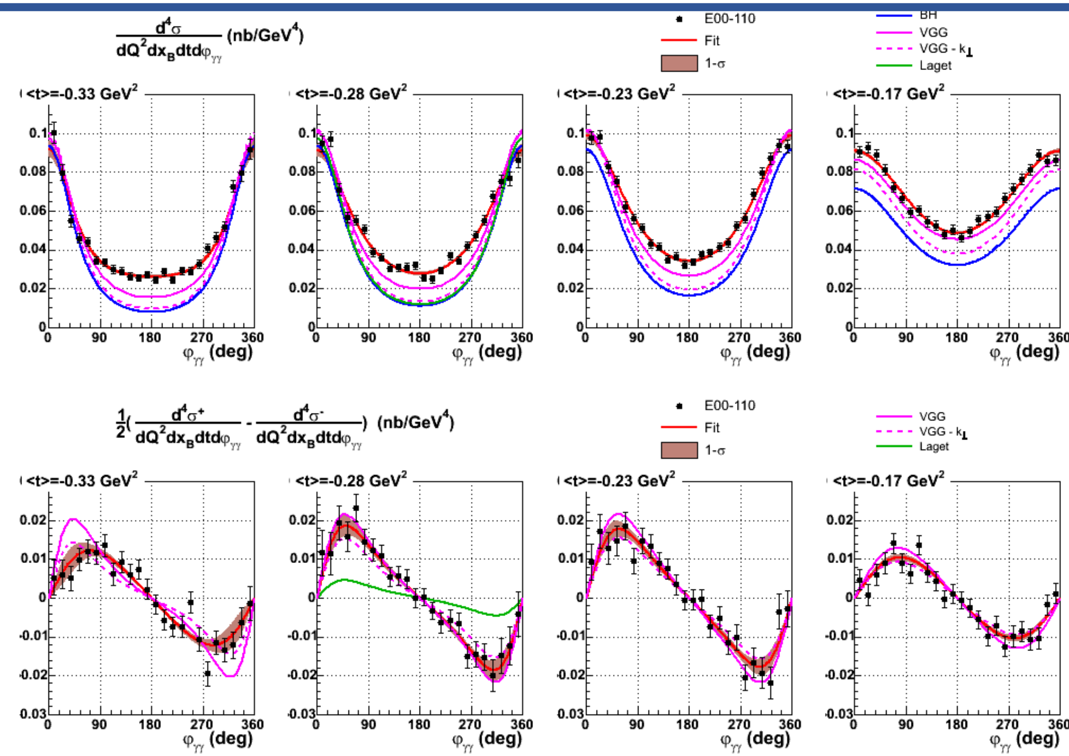
Duty cycle~100% E_{max}~6 GeV $\text{Polarization}_{max}$>80%





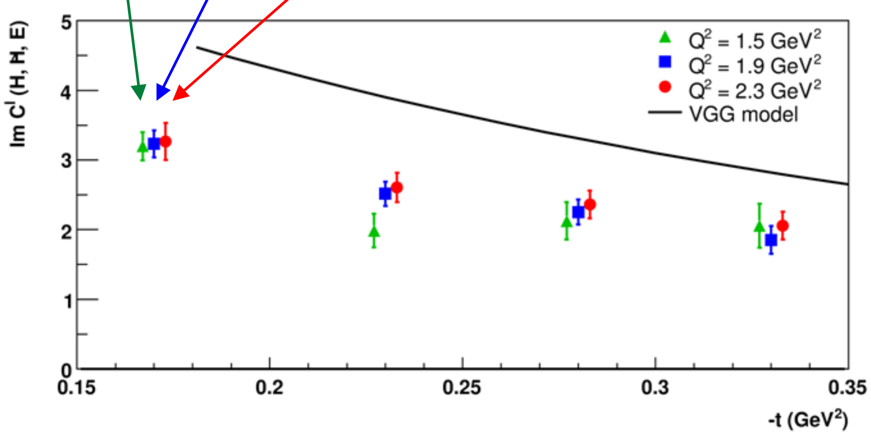
E00-110 experiment at Jefferson Lab 6 GeV in Hall A





$\boxed{\Delta\sigma_{LU}} \Rightarrow Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$

DVCS beam-polarized cross-section difference extracted for 3 different values of Q^2: 1.5 GeV^2, 1.9 GeV^2, 2.3 GeV^2

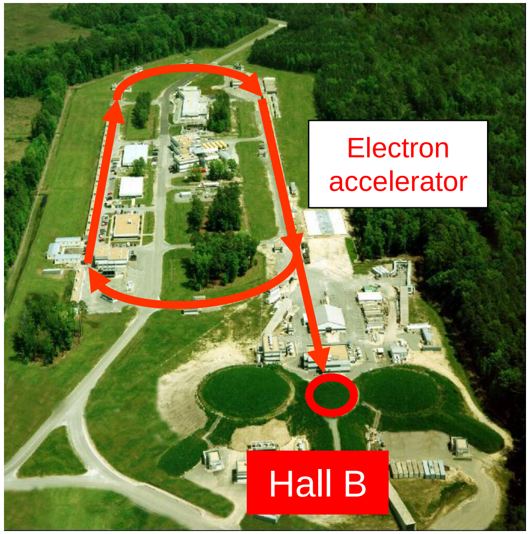


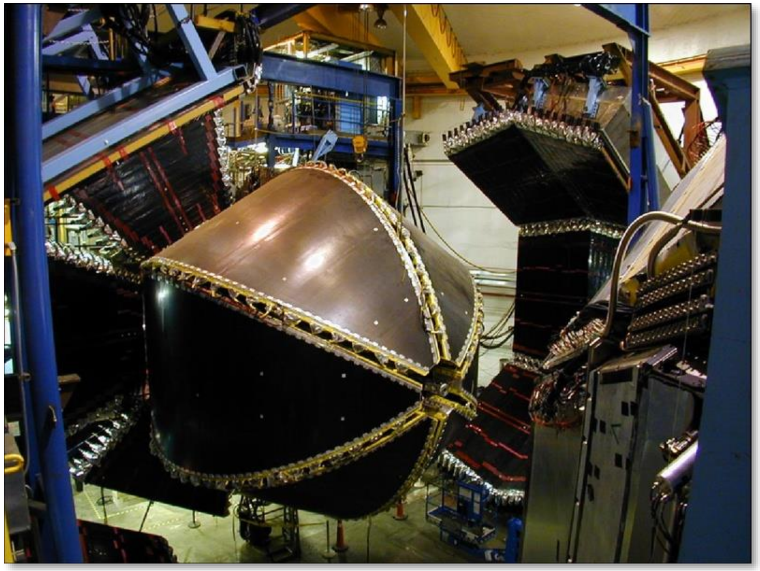
C. Munoz Camacho *et al.* (JLab Hall A Collaboration)
Phys. Rev. Lett. 97, 262002 (2006)

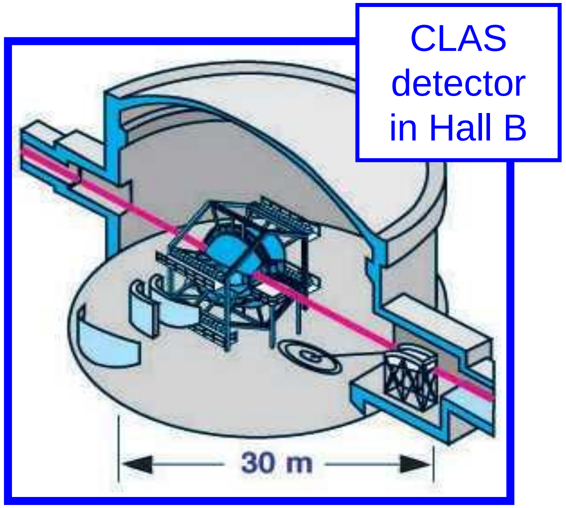
No Q^2 dependence: strong indication for scaling behavior and handbag dominance (but on a limited Q^2 range)

DVCS experiment at Jefferson Lab 6 GeV in Hall B with CLAS

Jefferson Lab

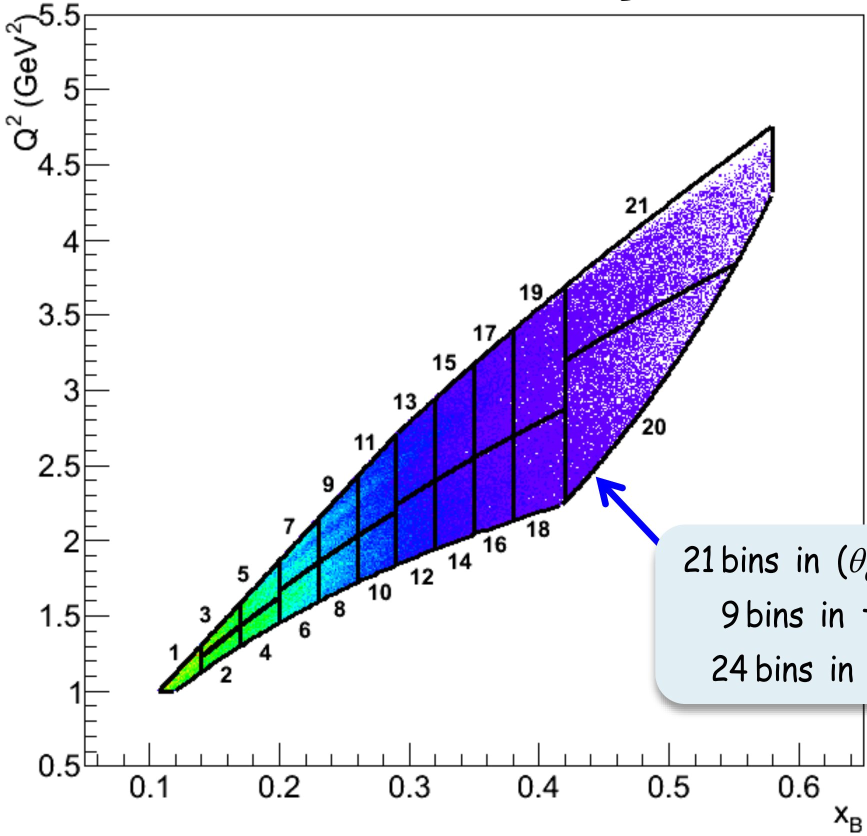




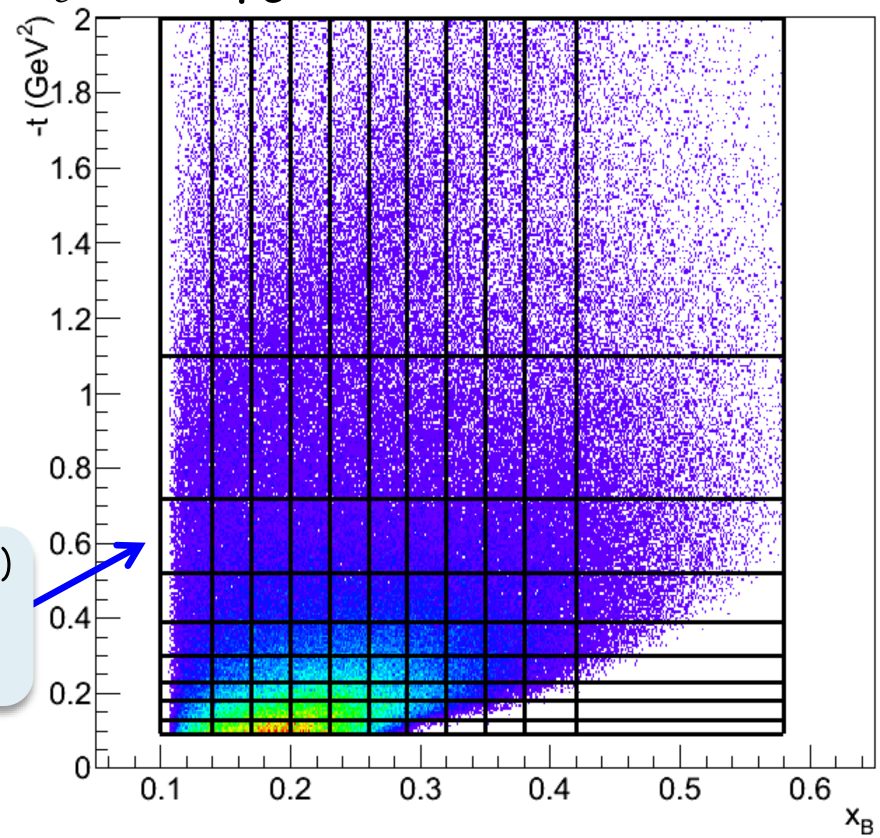


E1-DVCS experiment in Hall B : binning for cross sections analysis

$$Q^2 > 1,\ 0.1 < x_B < 0.58,\ 21 < \theta_e < 45,\ p_e > 0.8,\ W > 2$$



21 bins in (θ_e, x_B)
9 bins in t
24 bins in Φ



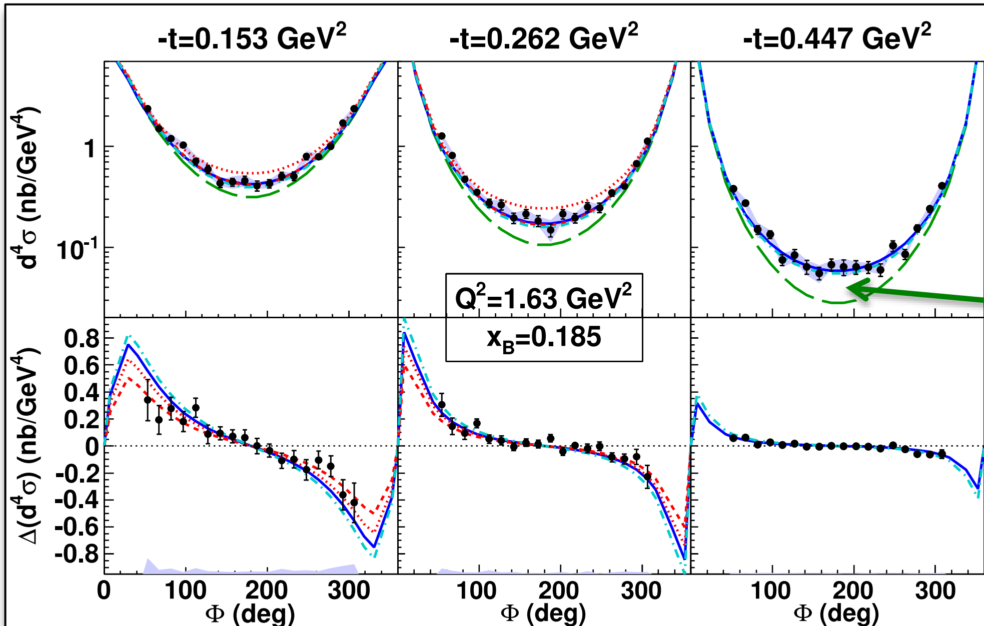
The cross section varies very quickly and is particularly sensitive to variations in x_B $\rightarrow$ very small bins in x_B

Extraction of 4-fold cross sections

$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} \qquad \frac{1}{2}\left(\frac{d^4\vec{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} - \frac{d^4\overleftarrow{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}\right)$$

Cross sections extracted for about **3000** (Q^2, x_B, t, ϕ) bins

DVCS unpolarized and beam-polarized cross sections from CLAS data

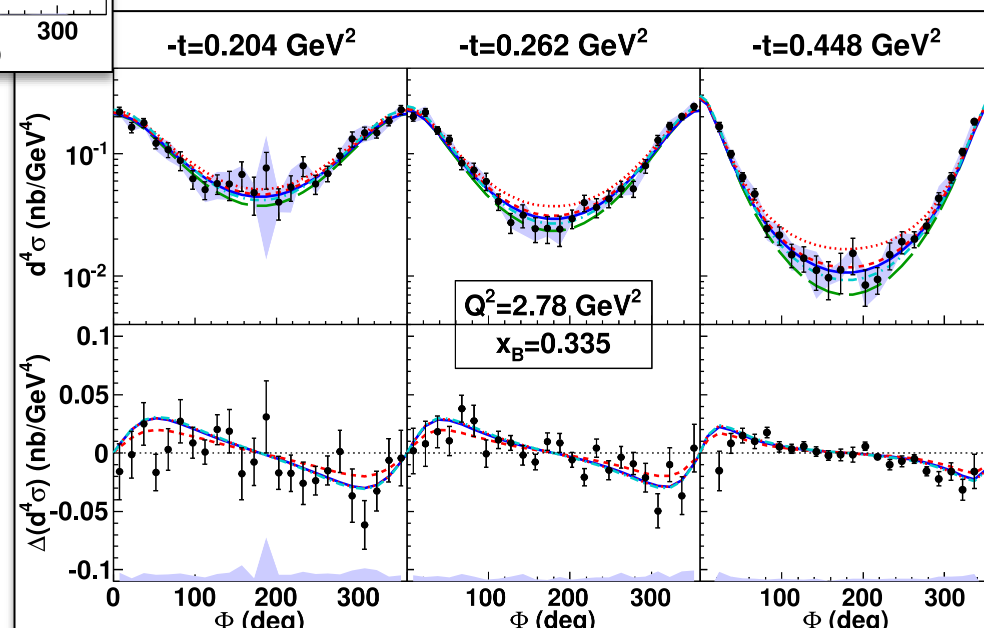


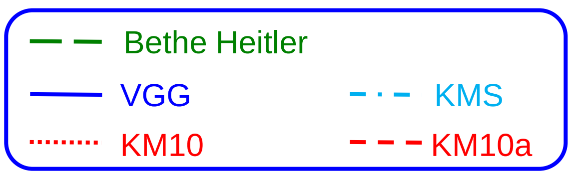
H.S. Jo *et al.* (CLAS Collaboration),
Phys. Rev. Lett. 115, 212003 (2015)

$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}(\mathrm{nb/GeV}^4)$$

DVCS + interference

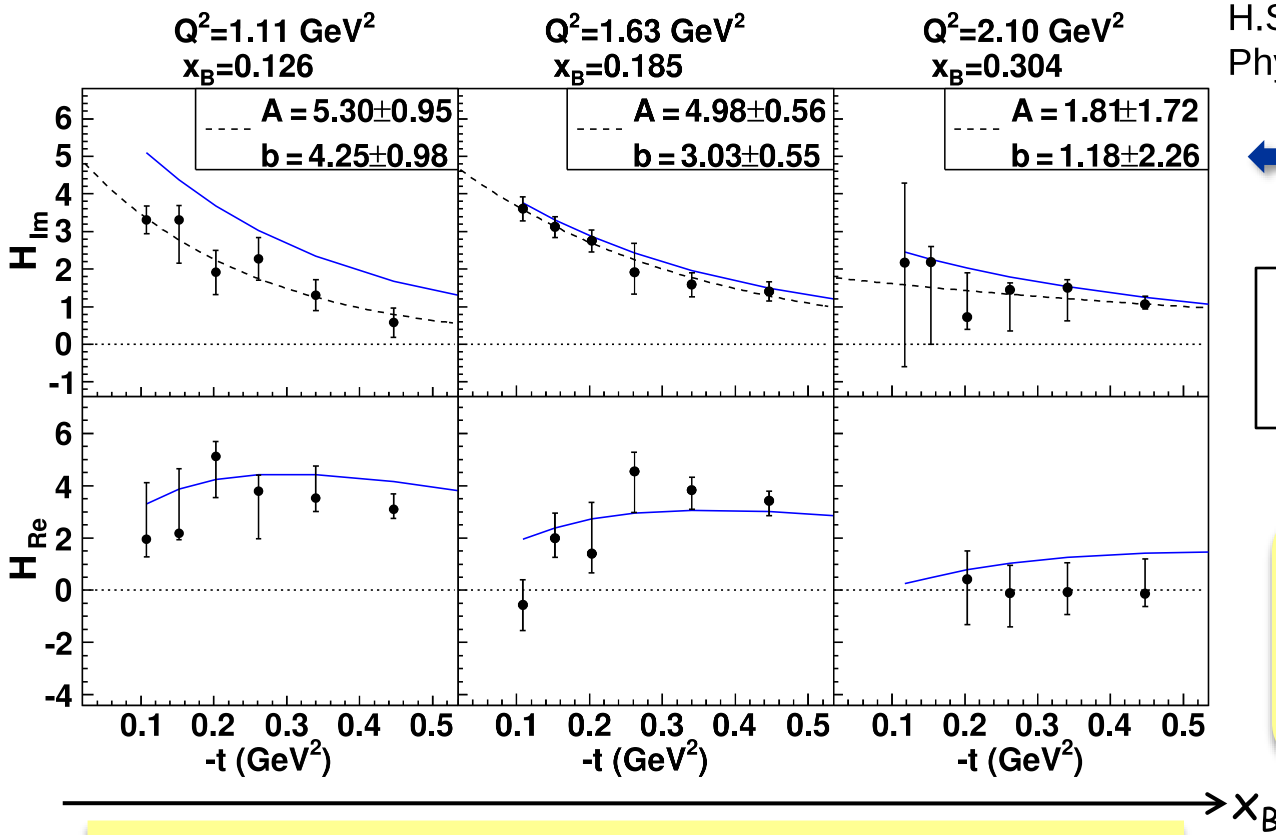
$$\frac{1}{2}\left(\frac{d^4\vec{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} - \frac{d^4\overleftarrow{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}\right)(\mathrm{nb/GeV}^4)$$





- Jefferson Lab's polarized electron beam (energy ~ 6 GeV, polarization ~ 80%) + LH_2 target
- Luminosity L = 2.10^{34} cm^{-2}s^{-1}

Interpretation of fit results obtained from the cross sections



H.S. Jo *et al.* (CLAS Collaboration), Phys. Rev. Lett. 115, 212003 (2015)

b : transverse position of the quarks in the nucleon

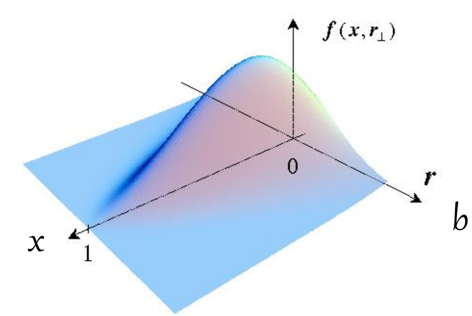
Fits with function Ae^{bt}

VGG predictions

The results tend to show that valence quarks (high x) are at the heart of the nucleon and sea quarks (low x) extend to its periphery

The transverse position *b* decreases with increasing x_B

The results suggest that the nucleon size decreases at higher parton-momentum values, thus revealing from the experiment a **first tomographic image of the nucleon**

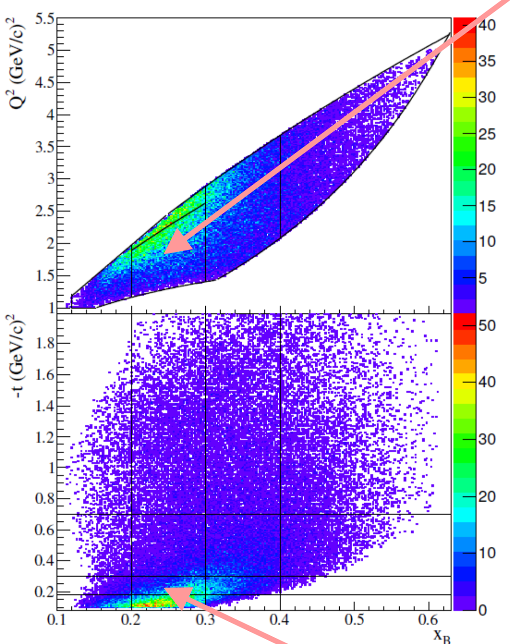


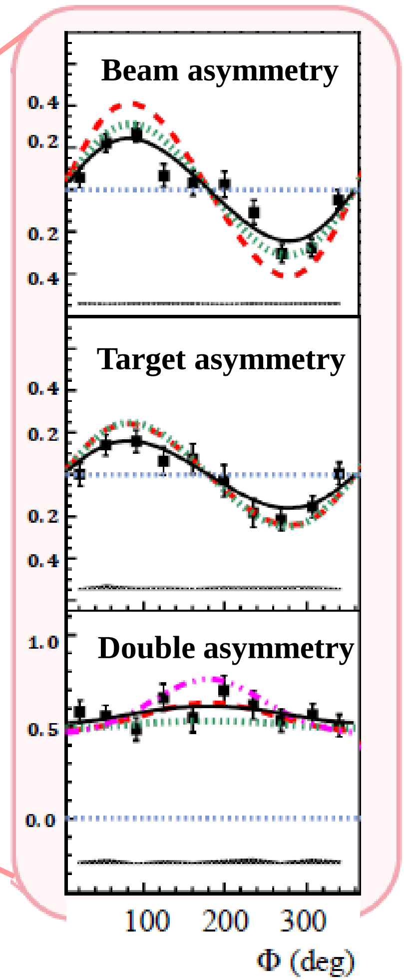
DVCS on longitudinally polarized target from CLAS 6 GeV data

- **eg1-dvcs experiment**
- Beam energy **~6 GeV**
- **CLAS + IC** to detect forward photons
- Target: **longitudinally polarized NH_3** (P~80%)
- **3 DVCS observables**

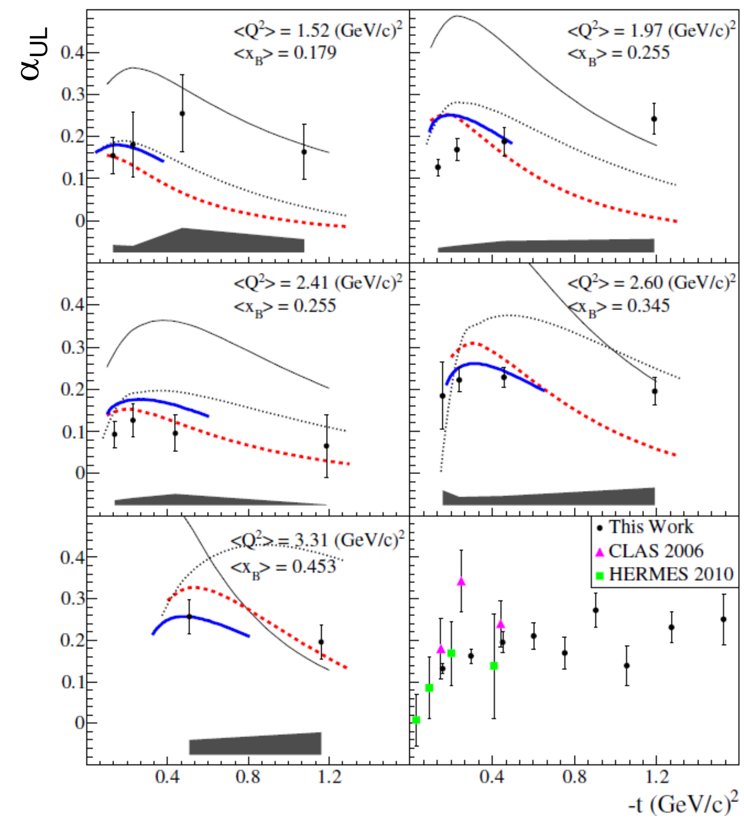
$\vec{e}\vec{p}\rightarrow ep\gamma$

$A_{UL} \sim Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$





- **5 (Q^2-x_B) bins**
- **4 t bins**
- **10 φ bins**



- Improved statistics ×10 at low $-t$
- Extended kinematic coverage

E. Seder *et al.* (CLAS Collaboration), Phys. Rev. Lett. 114, 032001 (2015)

DVCS on longitudinally polarized target from CLAS 6 GeV data

- **eg1-dvcs experiment**
- Beam energy **~6 GeV**
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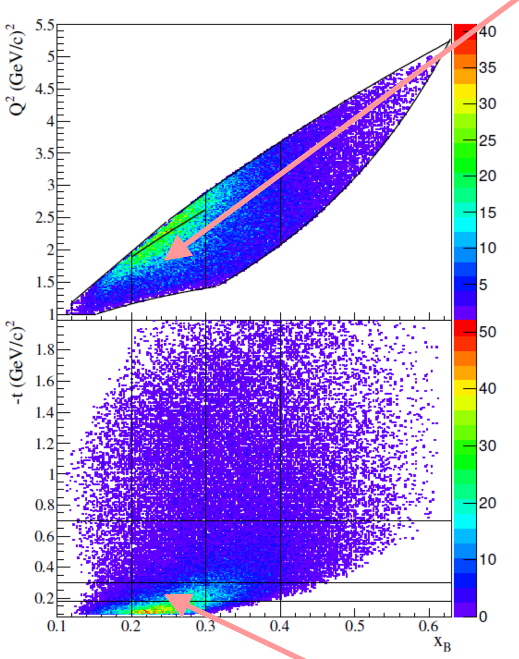
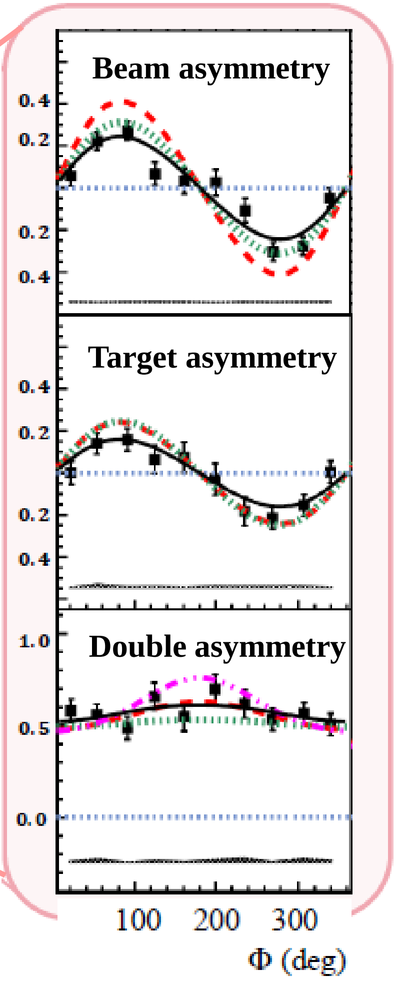
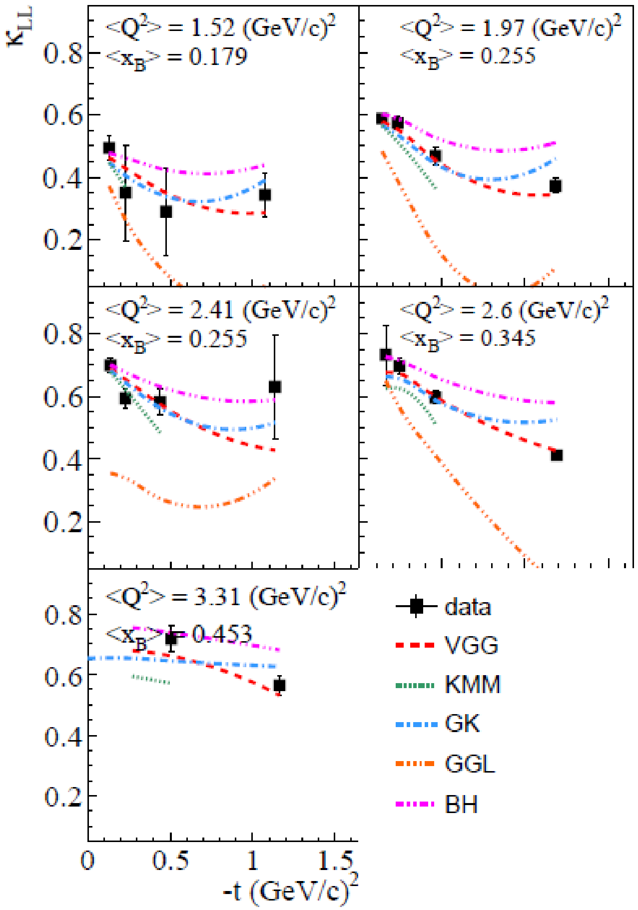
$\vec{e}\vec{p} \rightarrow ep\gamma$

$A_{LL} \sim Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$



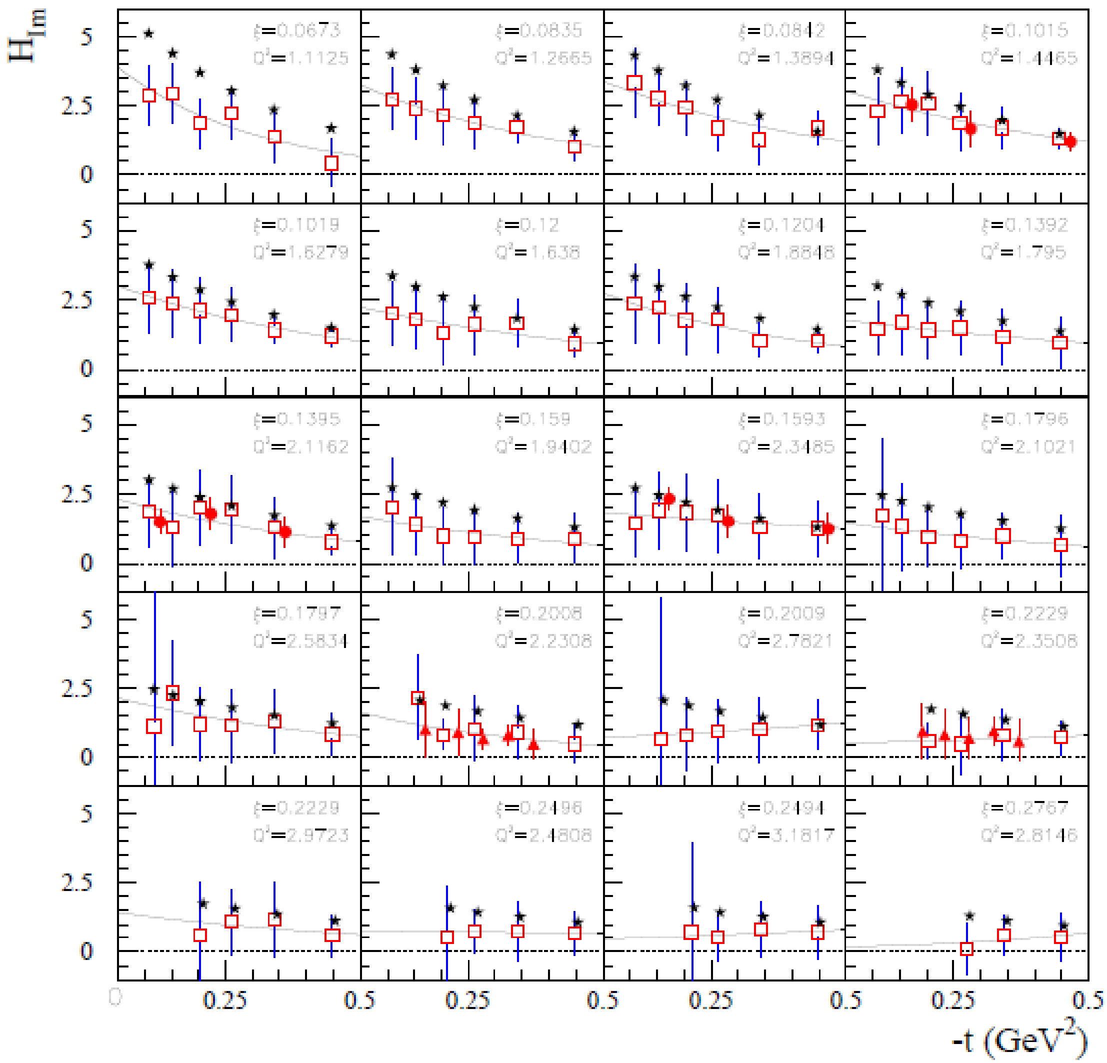




- **5 (Q^2-x_B) bins**
- **4 t bins**
- **10 ϕ bins**

S. Pisano *et al.* (CLAS Collaboration), Phys. Rev. D 91, 052014 (2015)

Extraction of H_{Im} from the fits of Jefferson Lab 6 GeV data



□ Fit to CLAS σ and Δσ

● Fit to CLAS σ, Δσ, A_{UL}, A_{LL}

▲ Fit to Hall A σ and Δσ

★ VGG model

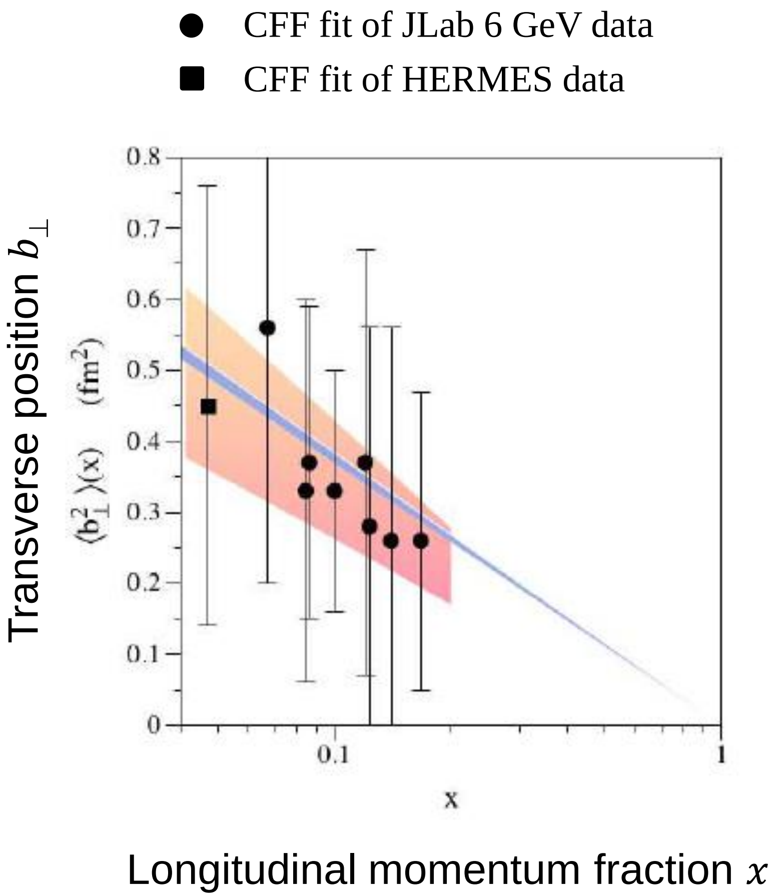
Fits in each (Q^2, x_B, t) bin of data

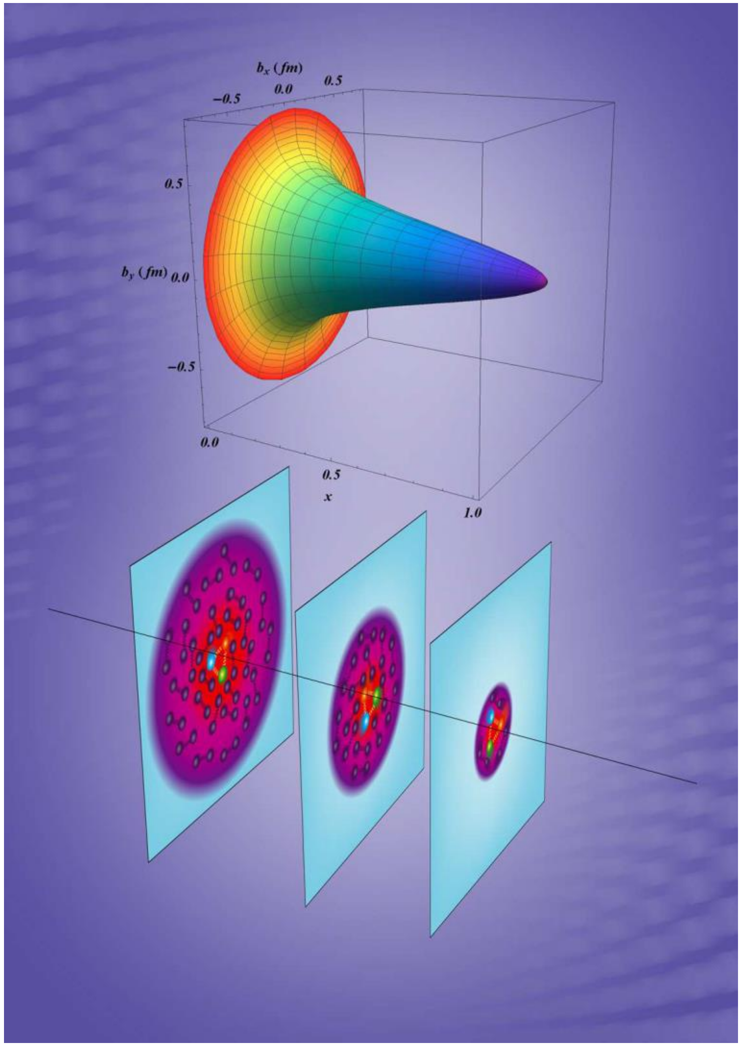
$$H_{Im}(\xi,t) = A(\xi)e^{b(\xi)t}$$

$$\xi \approx \frac{x_B}{2 - x_B}$$

R. Dupré, M. Guidal, S. Niccolai, and M. Vanderhaeghen, Eur. Phys. J. A 53, 171 (2017)

From CFFs to proton tomography





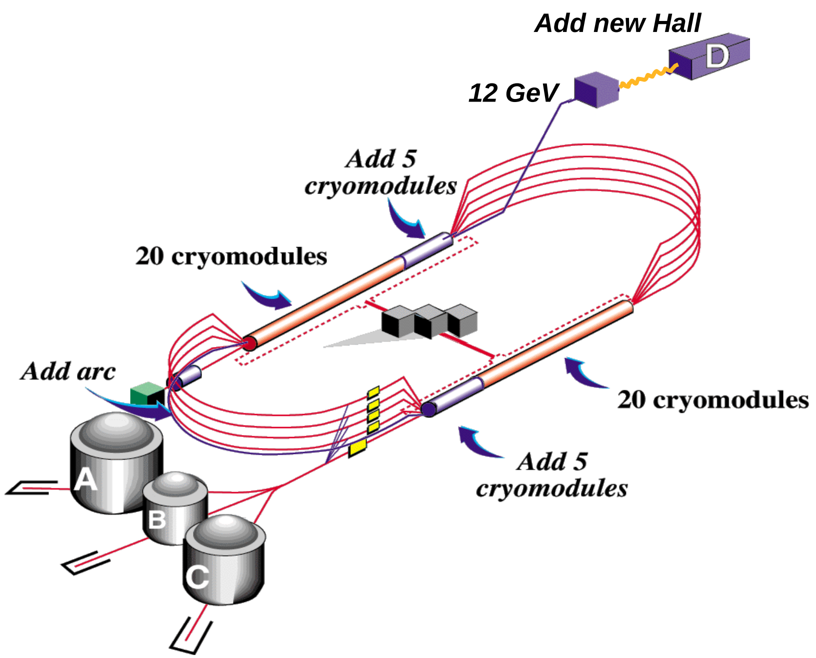
R. Dupré, M. Guidal, S. Niccolai, and M. Vanderhaeghen,
Eur. Phys. J. A 53, 171 (2017)

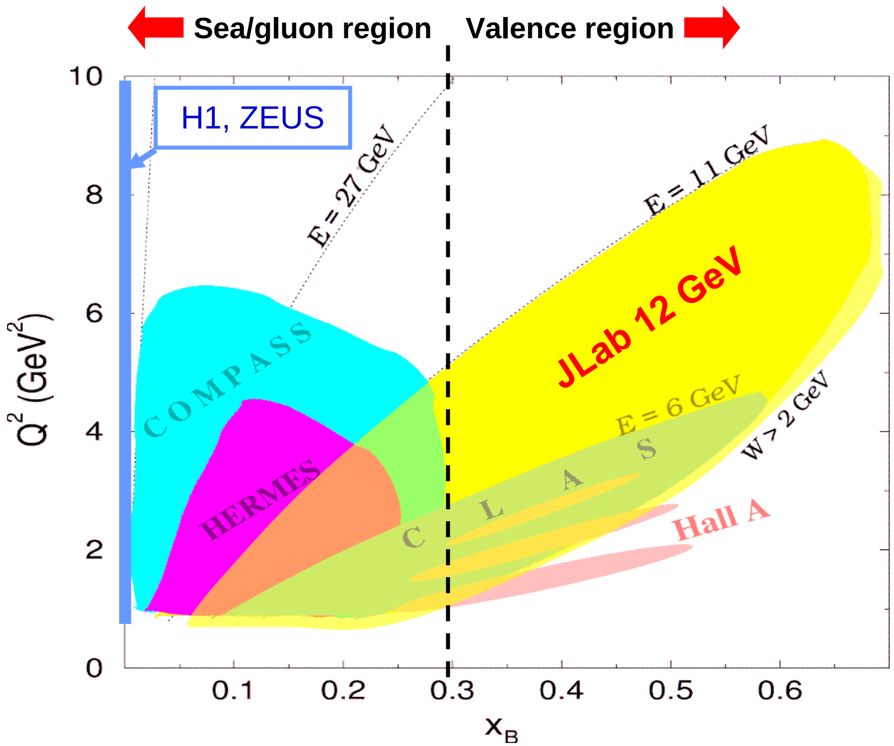
Jefferson Lab upgrade to 12 GeV

E= 2.2, 4.4, 6.6, 8.8, 11 GeV
for the Halls A, B, C

Beam polarization > 80%

Accelerator 12 GeV upgrade



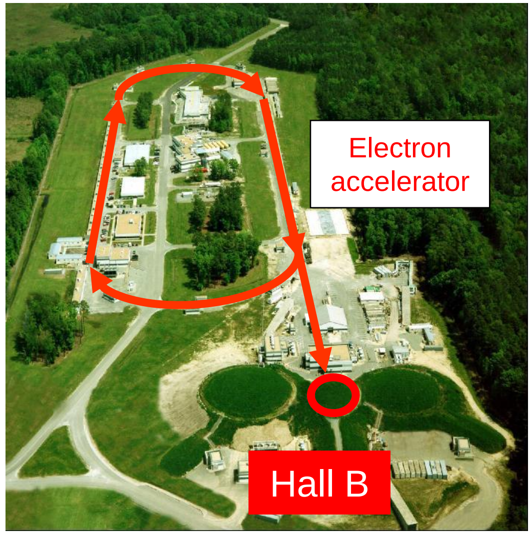


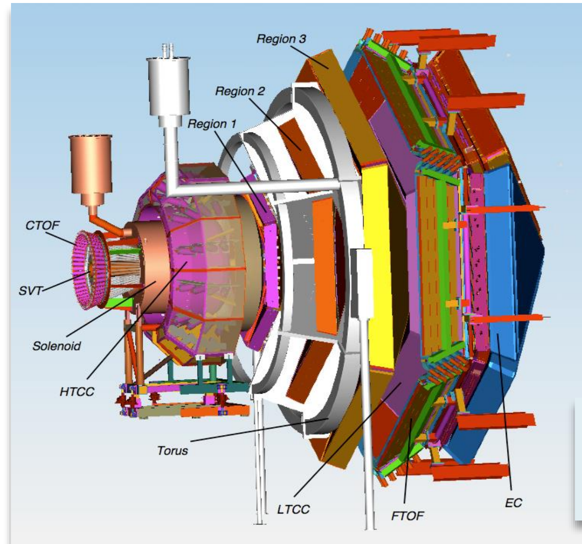
Study of high x_B domain requires high luminosity

The 12-GeV upgrade is well matched to studies in the valence-quark regime

Jefferson Lab 12 GeV and the CLAS12 detector

Jefferson Lab

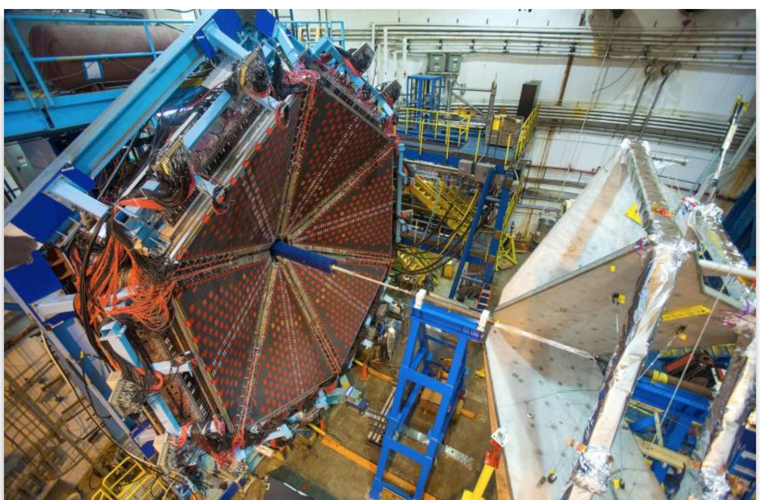




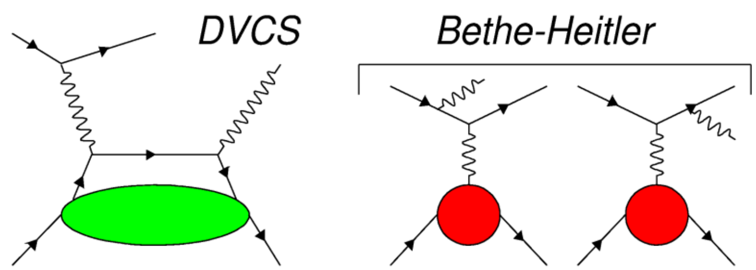
CLAS12 detector in Hall B

Luminosity
$L \sim 10^{35}\ cm^{-2}s^{-1}$

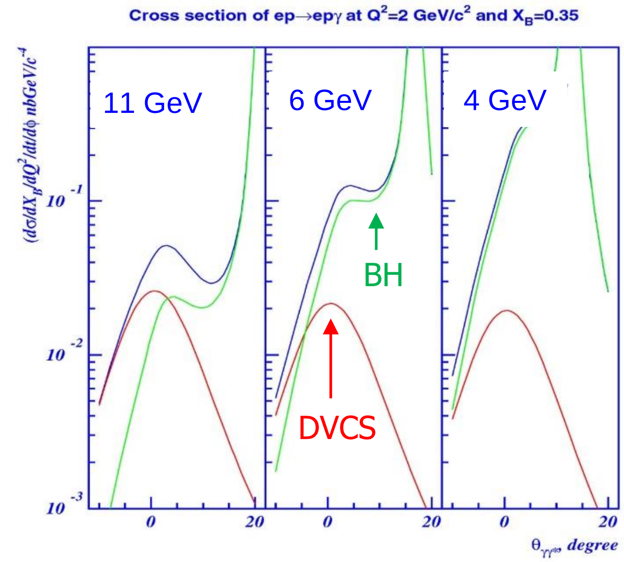
Data taking with the new CLAS12 detector started in 2018



Projected results for CFFs with CLAS12



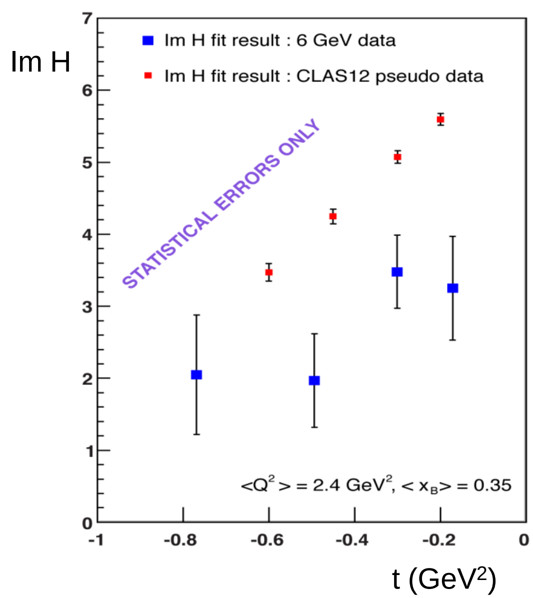
The contribution ratio from BH and DVCS to the ep→epγ cross section changes with the electron beam energy

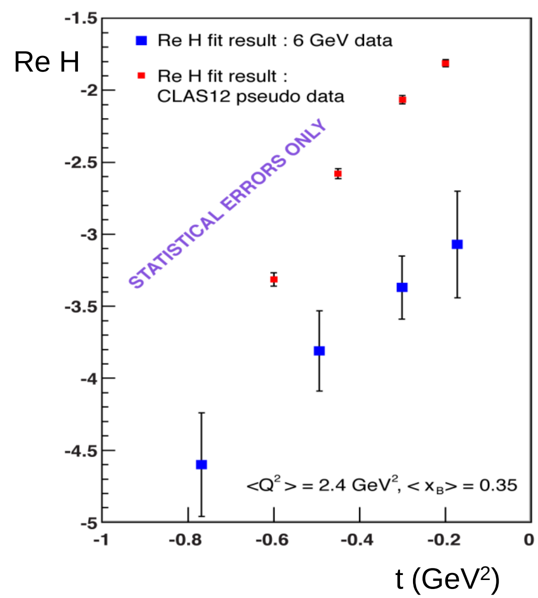


Impact of CLAS12 DVCS pseudo data on CFF fit

CLAS 6 GeV data

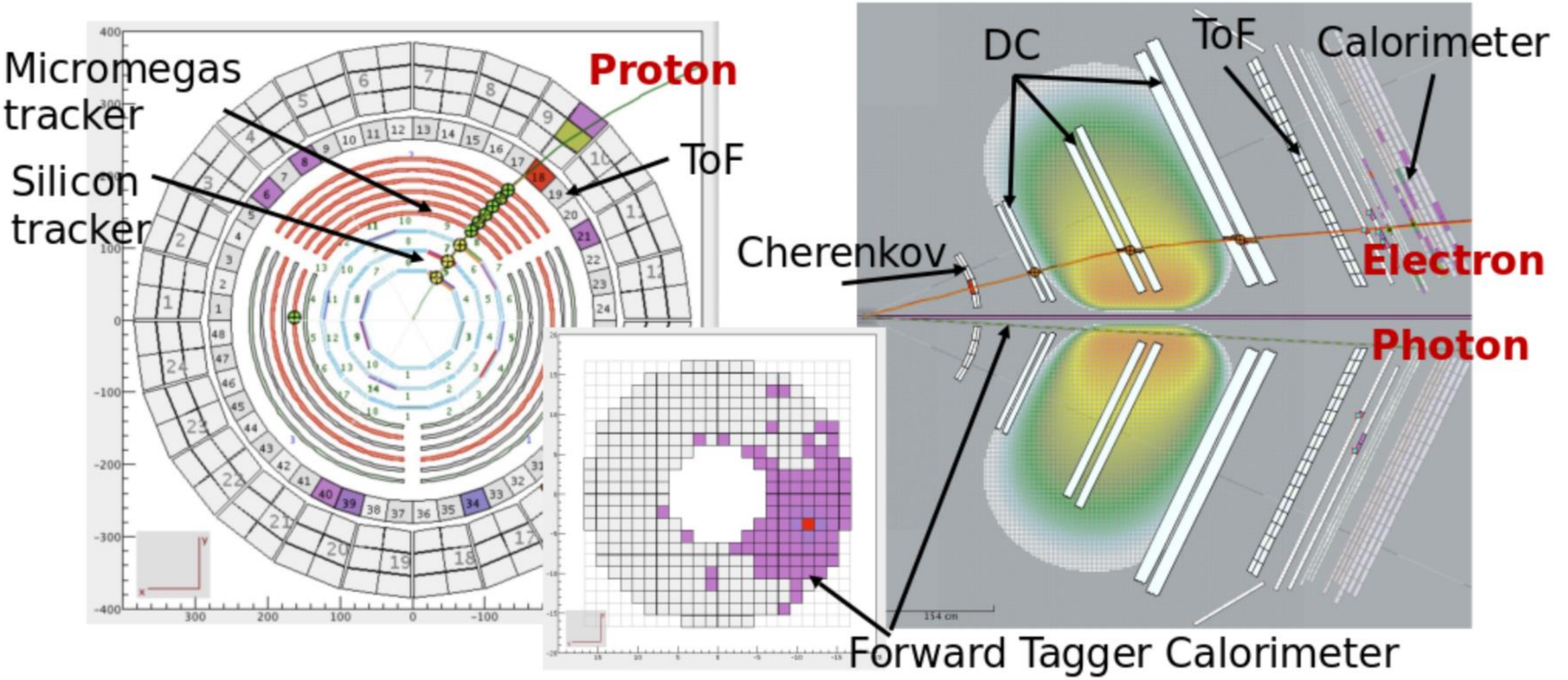
CLAS12 pseudo data





Typical DVCS event in CLAS12

- Electron: measured in the Forward Detector or in the Forward Calorimeter
- Photon: in the FT (or FD) calorimeter
- Proton: most often in the Central Detector



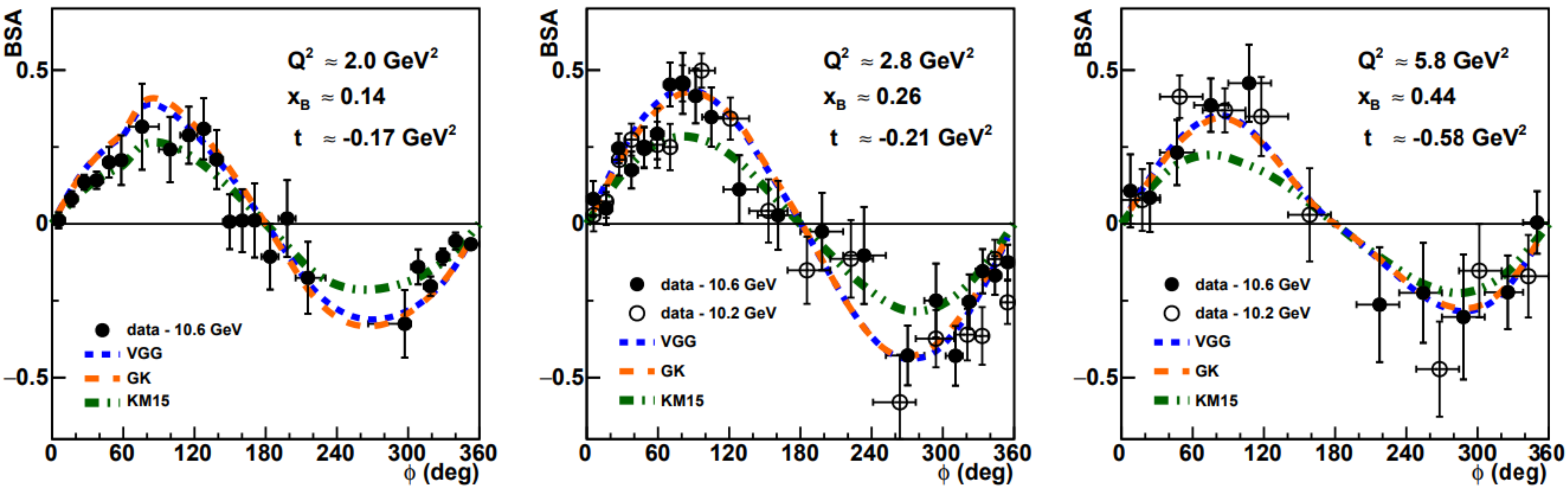
Proton DVCS A_{LU} with CLAS12

Beam spin asymmetry

$$A_{LU} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

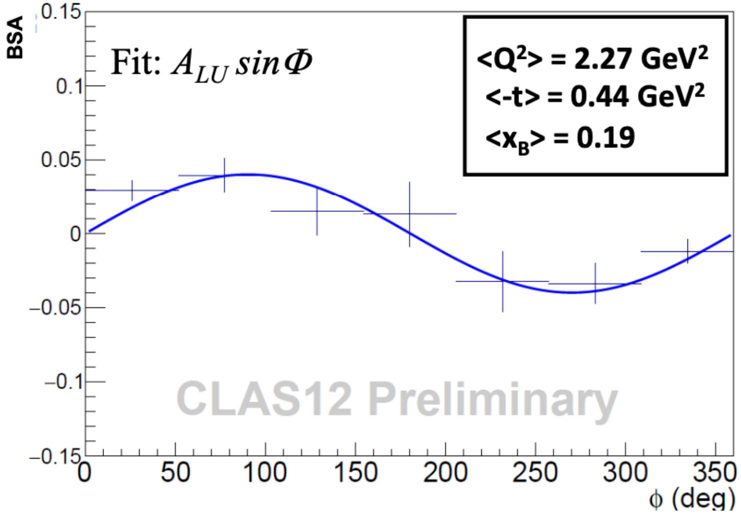
$$A_{LU} = \frac{1}{P} \frac{N^+(\phi_{Trento}) - N^-(\phi_{Trento})}{N^+(\phi_{Trento}) + N^-(\phi_{Trento})}$$

- P: electron polarization
- $N^{+(-)}$: number of photon electroproduction candidates with beam helicity +(-)

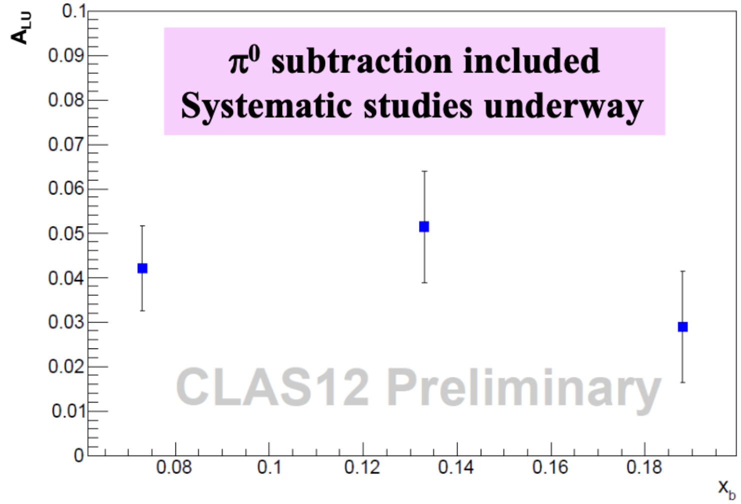


G. Christiaens *et al.* (CLAS Collaboration)
Phys. Rev. Lett. 130, 211902 (2023)

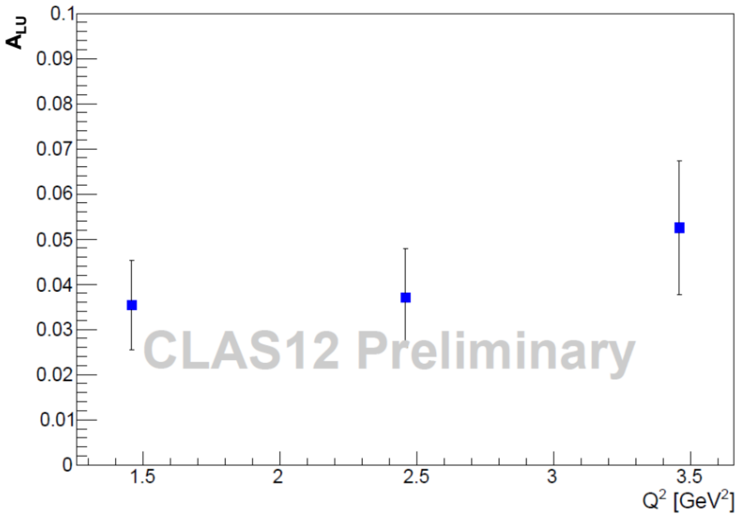
Preliminary neutron DVCS A_{LU} with CLAS12



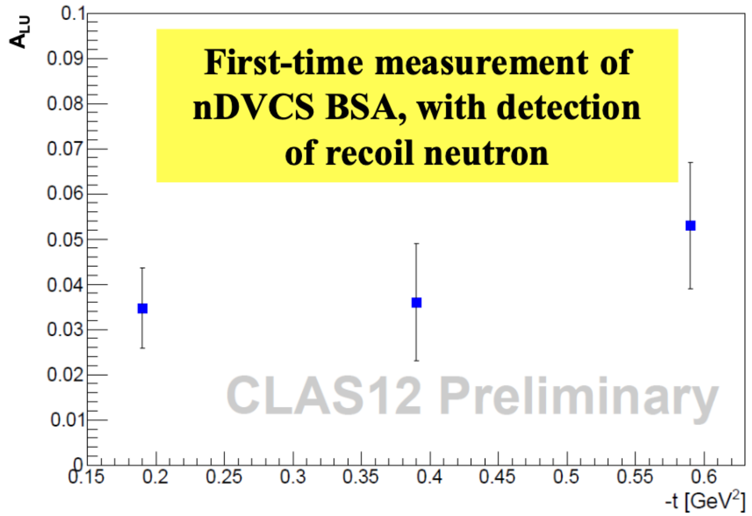
sinϕ amplitude vs x_B



sinϕ amplitude vs Q^2

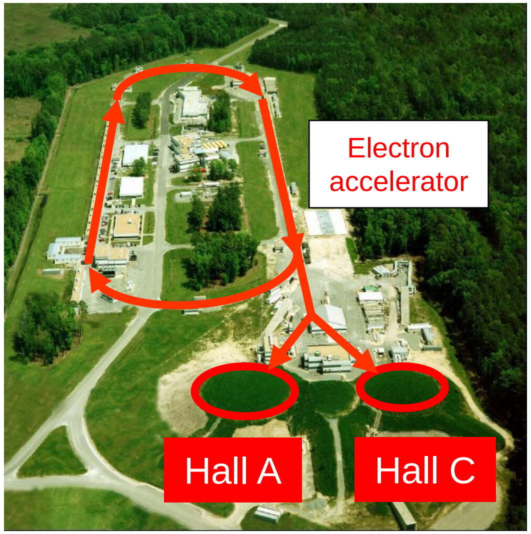


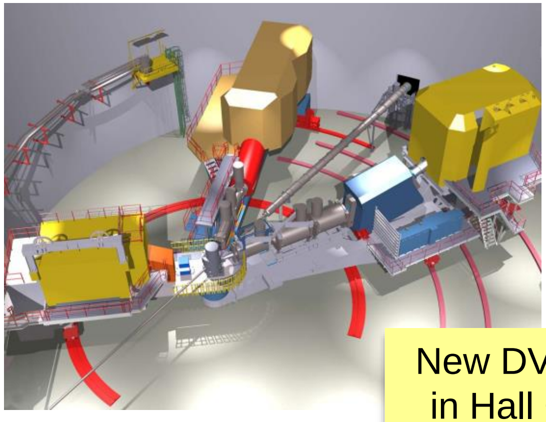
sinϕ amplitude vs -t



DVCS experiments in Hall A and Hall C of Jefferson Lab

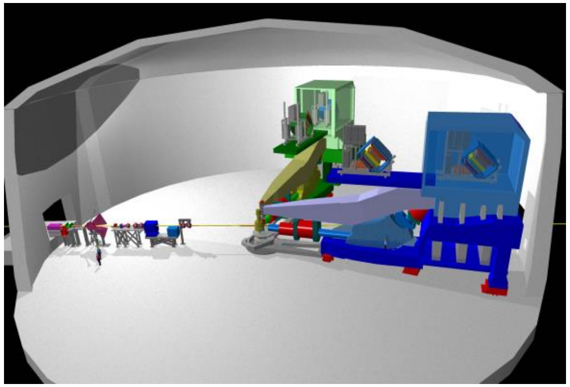
Jefferson Lab





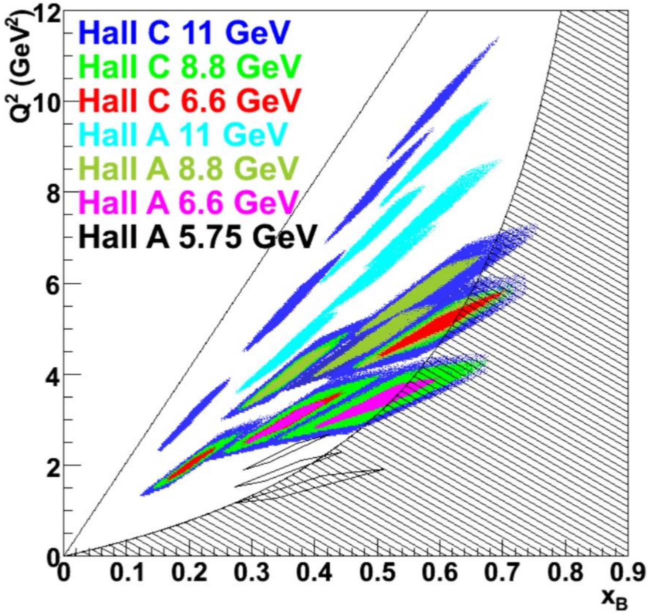
Hall C

New DVCS experiment in Hall C (2023-2024)



Hall A

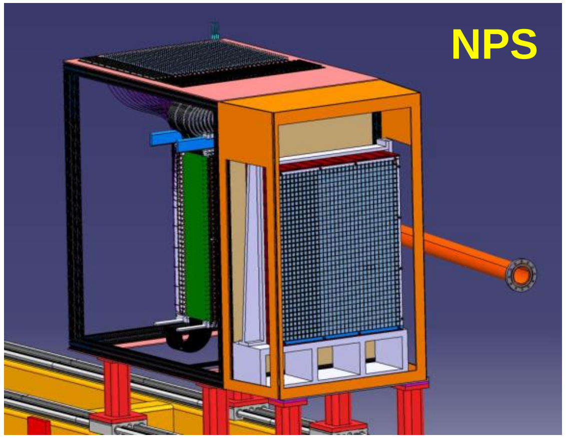
The analysis of the new Hall A data is underway

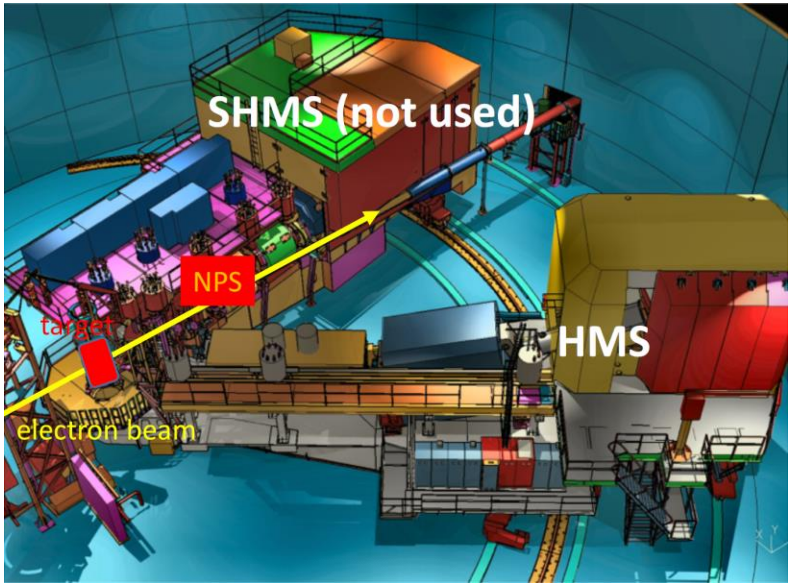


DVCS experiment in Hall C (2023-2024)

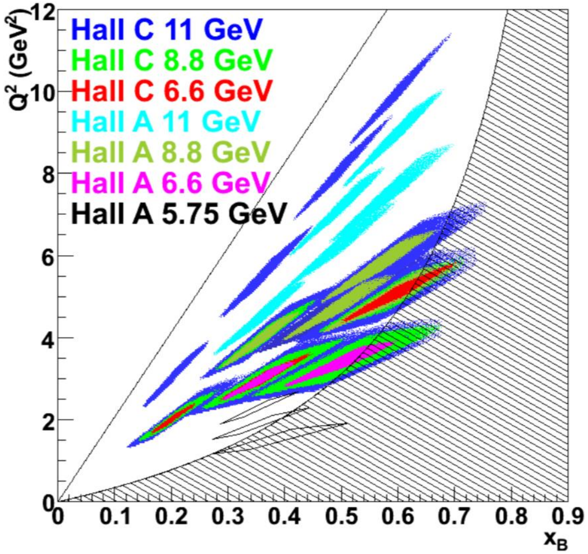
A new DVCS experiment will be carried in Hall C from 2023 to 2024

The new Neutral Particle Spectrometer (NPS) consisting of 1080 $PbWO_4$ crystals will be used to detect photons and π^0

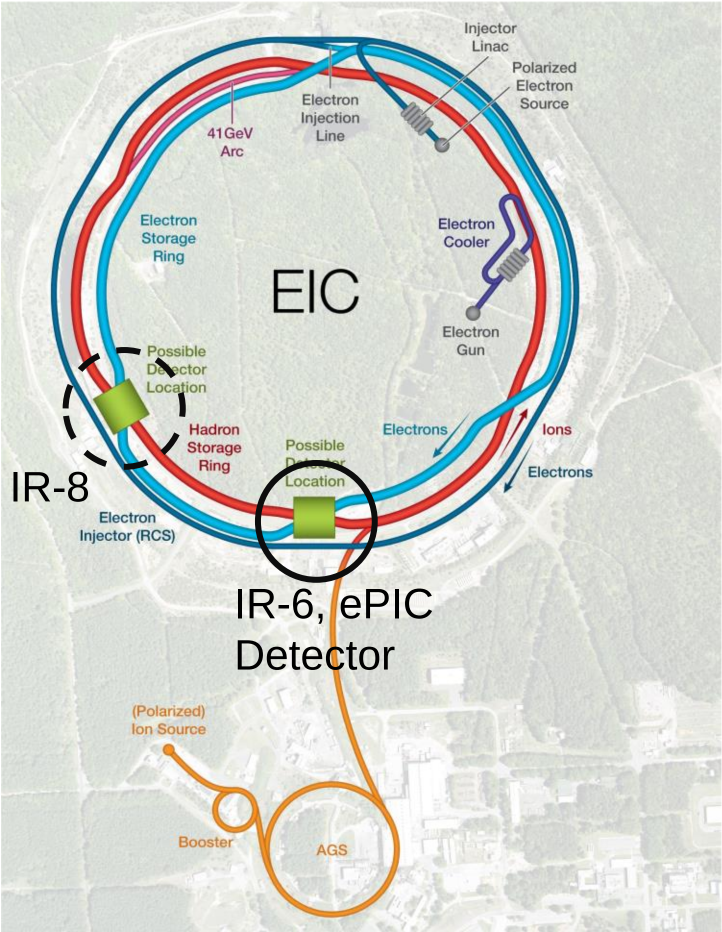




HMS : High Momentum Spectrometer



The Electron-Ion Collider (EIC) at BNL



Brookhaven National Laboratory (BNL)

A high luminosity ($10^{33} – 10^{34}$ cm^{-2}s^{-1}) polarized electron proton/ion collider

The EIC luminosity will be a factor 100 to 1000 higher than at HERA.

Both electrons and protons / light nuclei will be highly polarized (70%).

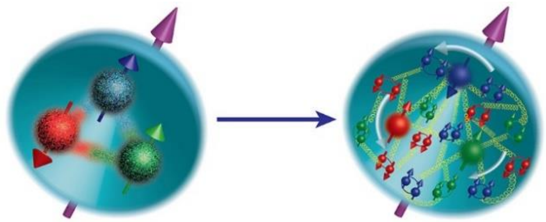
Science Program: An EIC can uniquely address three profound questions about nucleons - neutrons and protons - and how they are assembled to form the nuclei of atoms:

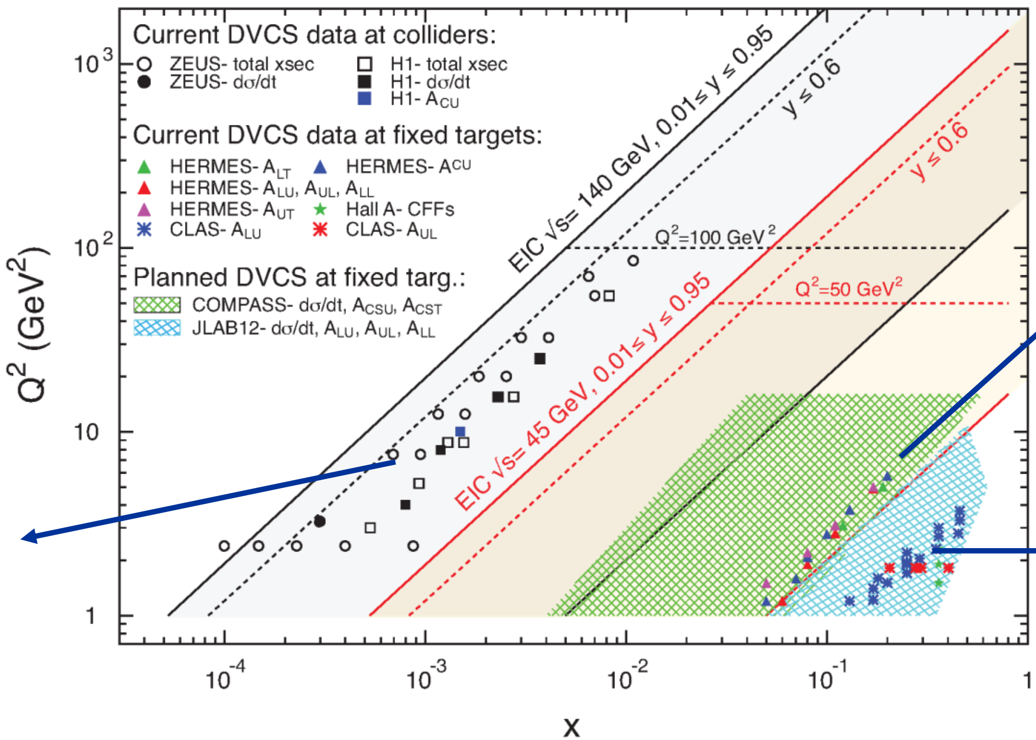
- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of high-density systems of gluons?

p/A beam		e beam	
41 GeV, 100 to 275 GeV	→	←	**5 GeV to 18 GeV**

DVCS at the Electron-Ion Collider (EIC): gluons and sea quarks

Nucleon tomography of the gluons and sea quarks (low momentum fraction x)





Overlap with H1 and ZEUS

Overlap with HERMES and COMPASS

Overlap with JLab 6 GeV and JLab 12 GeV

- Collision of polarized electrons with polarized protons, light and heavy nuclei
- High Luminosity : $L_{ep} \geq 10^{33\text{-}34}$ $cm^{-2}\, s^{-1}$ (100-1000 times HERA)

Overview

- Jefferson Lab 6 GeV data were used to extract promising results, including a first experimental result of nucleon tomography.

- Jefferson Lab 12 GeV data are providing new high-precision measurements covering a large unexplored kinematic domain at high x.

- Many ongoing studies show benefits of a luminosity and energy upgrade at Jefferson Lab.

- While Jefferson Lab is a unique facility to study the valence quarks, the future Electron-Ion Collider (EIC) will provide high-precision GPD measurements at low x, allowing us to perform nucleon tomography of the gluons and sea quarks.

Thank you