Discussion for EIC EOI :

3D imaging of the Nucleon at the EIC

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Korea EIC Meeting

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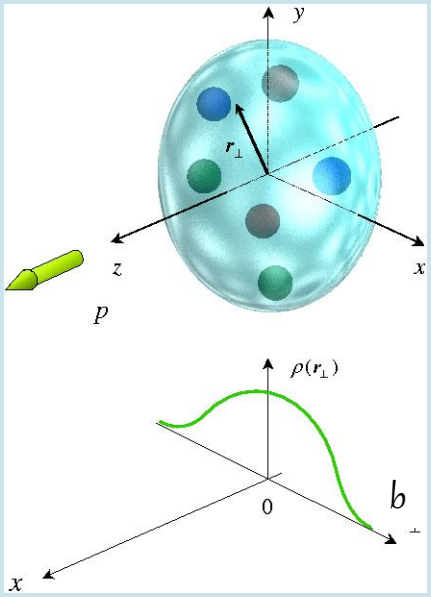
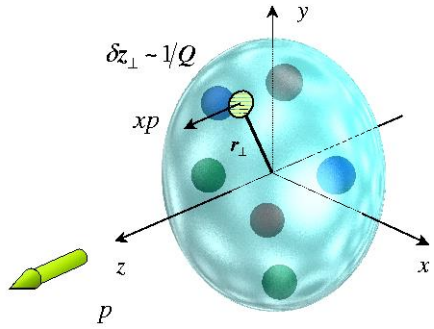
Generalized parton distributions (GPDs)

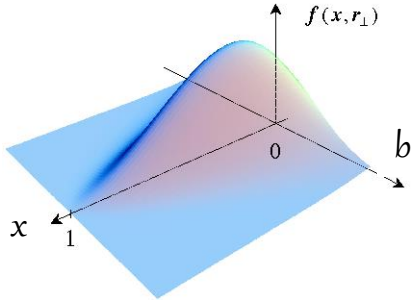
GPDs, accessibles via the measurement of exclusive reactions, provide a **correlation** between the transverse position and the longitudinal momentum of the quarks in the nucleon



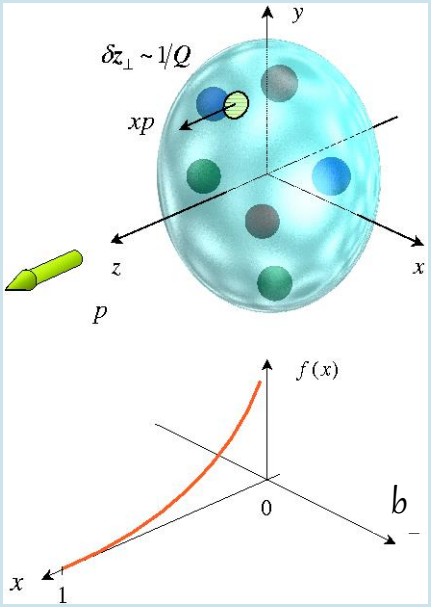
Form Factors (elastic scattering) :
Transverse position of the quarks in the nucleon

3D imaging of the Nucleon





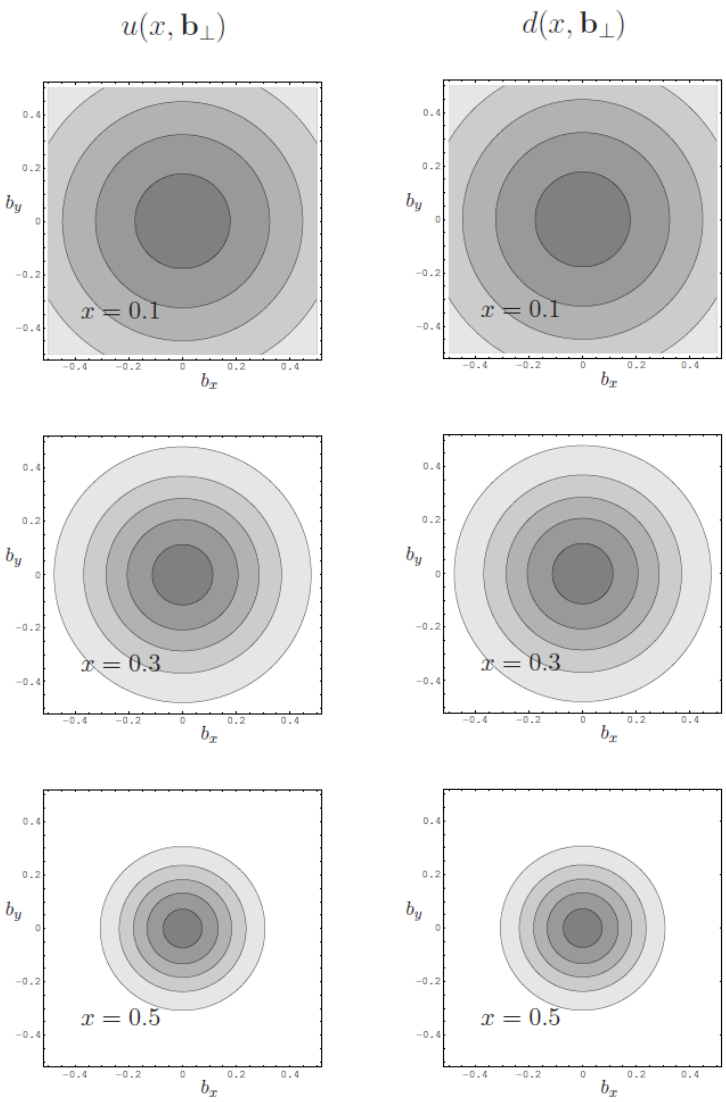
Transverse position (b) as a function of longitudinal momentum fraction (x)



Parton Distribution Functions (deep inelastic scattering) :
Longitudinal momentum of the quarks in the nucleon

In this model, valence quarks are at the heart of the nucleon and sea quarks extend to its periphery

Interpretation of GPDs : impact parameter as a function of x

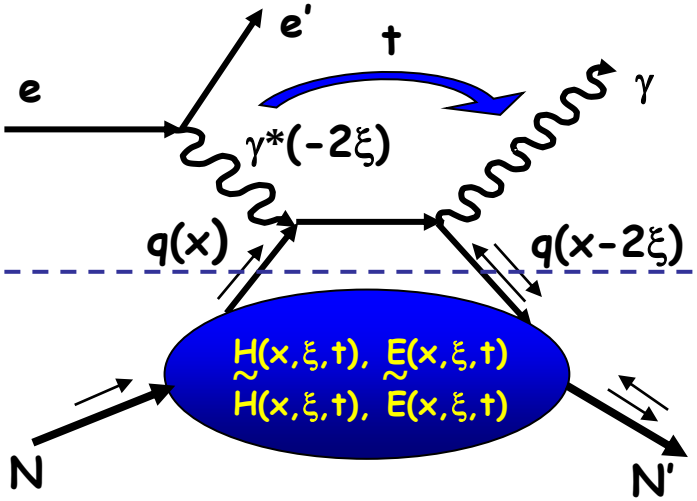


Deeply Virtual Compton Scattering (DVCS) and GPDs

high Q^2, small t, fixed x_B

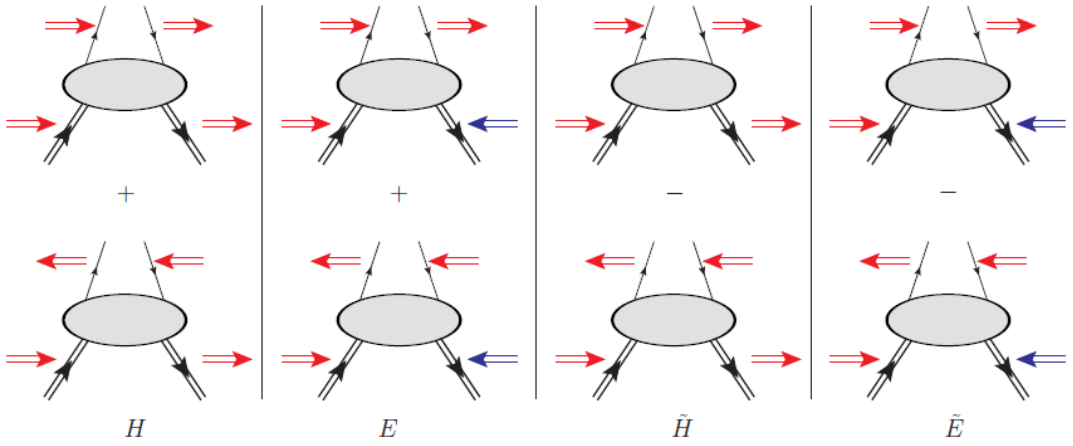
$$x_B = \frac{2\xi}{1+\xi}$$

DVCS



DVCS is the key reaction to access the GPDs → simplest interpretation in terms of GPDs

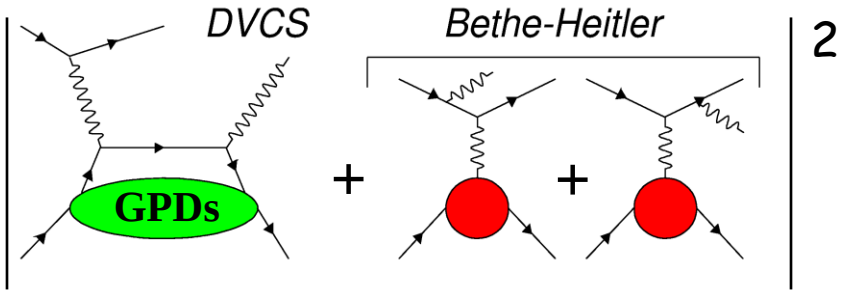
At leading-order QCD, leading twist, there are 4 chiral-even (parton helicity is conserved) GPDs for each parton



$H^{q,g}(x,\xi,t)$	$E^{q,g}(x,\xi,t)$	*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*	

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

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

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

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

GPDs and proton spin crisis

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

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

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

Ji's angular momentum sum rule :

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

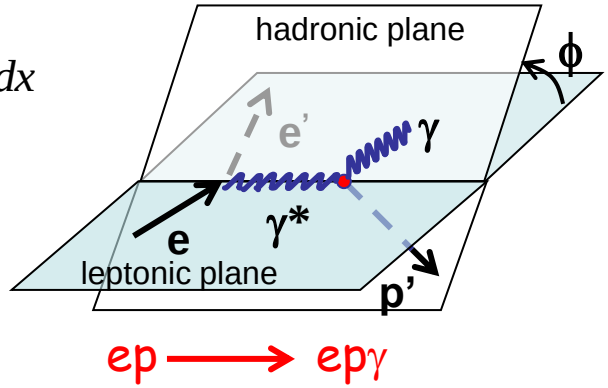
Extracting GPDs from DVCS observables

Compton Form Factors (CFFs)

$$Re\mathcal{H}_q = e_q^2 P \int_0^{+1} \left(H^q(x,\xi,t) - H^q(-x,\xi,t)\right)\left[\frac{1}{\xi - x} + \frac{1}{\xi + x}\right] dx$$

$$Im\mathcal{H}_q = \pi e_q^2 \left[H^q(\xi,\xi,t) - H^q(-\xi,\xi,t)\right]$$

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



Each DVCS observable is sensitive to a different combination of GPDs

- Polarized beam, Unpolarized target

$\Delta\sigma_{LU} \sim \sin\phi\ \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$

- Unpolarized beam, Longitudinally polarized target

$\Delta\sigma_{UL} \sim \sin\phi\ \mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi k F_2\,\tilde{\mathcal{E}} + \ldots\}d\phi$ ⇒ $Im\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$

- Unpolarized beam, Transversely polarized target

$\Delta\sigma_{UT} \sim \cos\phi\ \mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots..\}d\phi$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$

- Polarized beam, Longitudinally polarized target

$\Delta\sigma_{LL} \sim (A + B\cos\phi)\ \mathrm{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E})\ldots\}d\phi$ ⇒ $Re\{\mathcal{H}_p, \tilde{\mathcal{H}}_p\}$

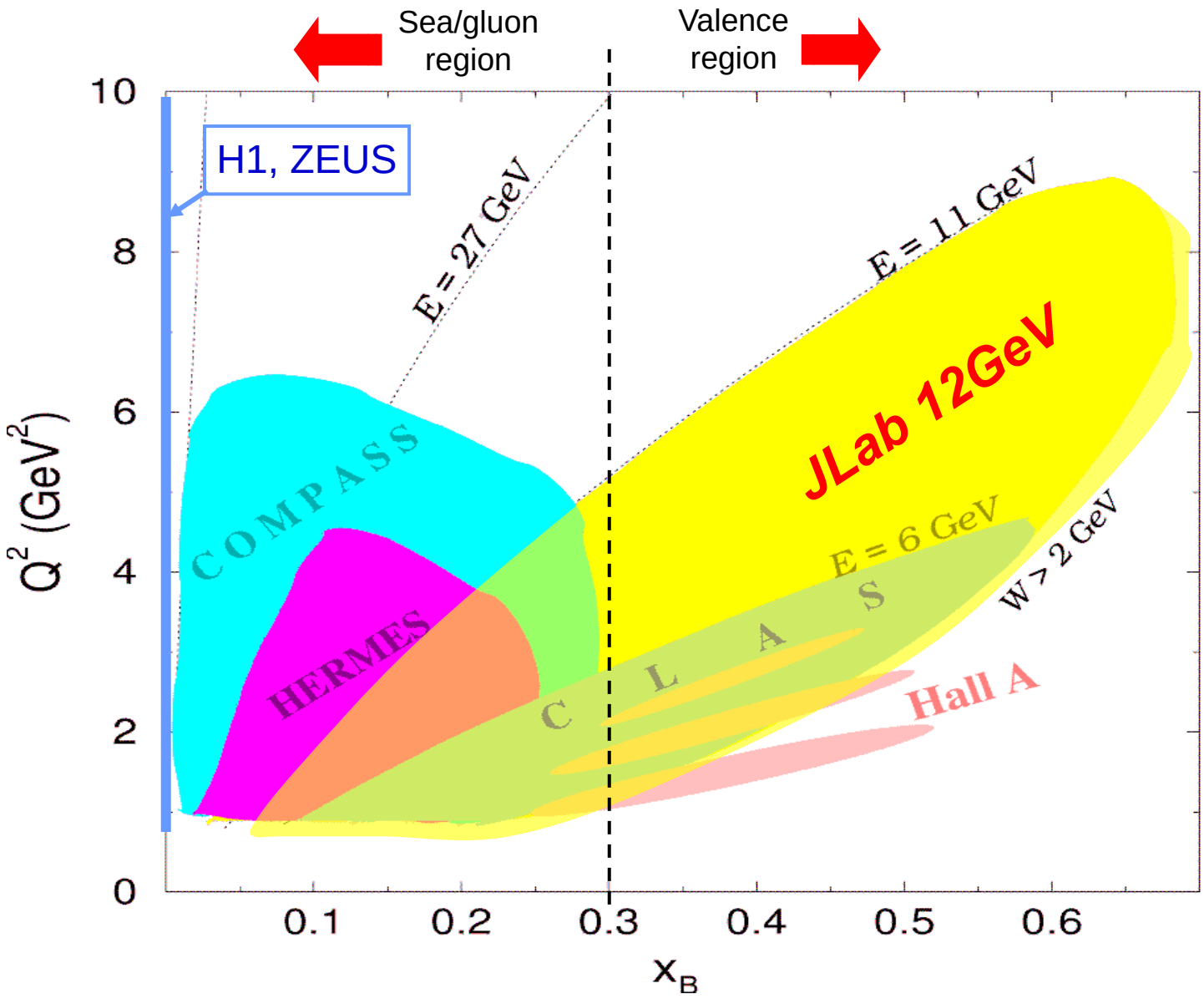
DVCS experiments

Jefferson Lab	
Hall A	***Hall B***

DESY	
HERMES	***H1/ZEUS***

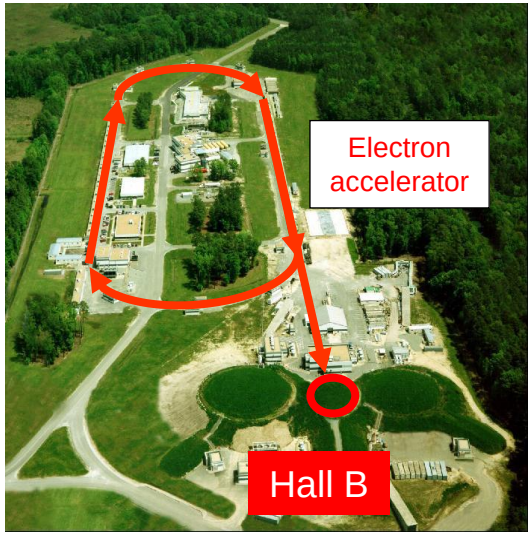
CERN
COMPASS

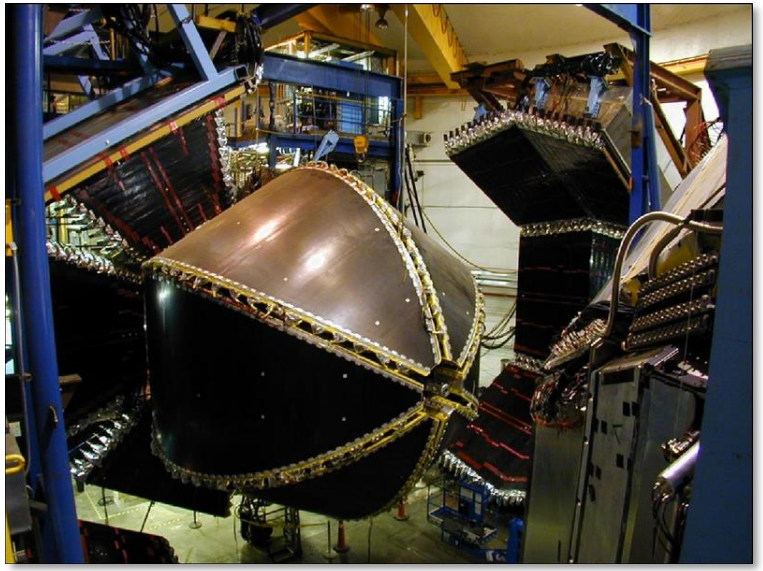
Kinematic coverage of the different experiments

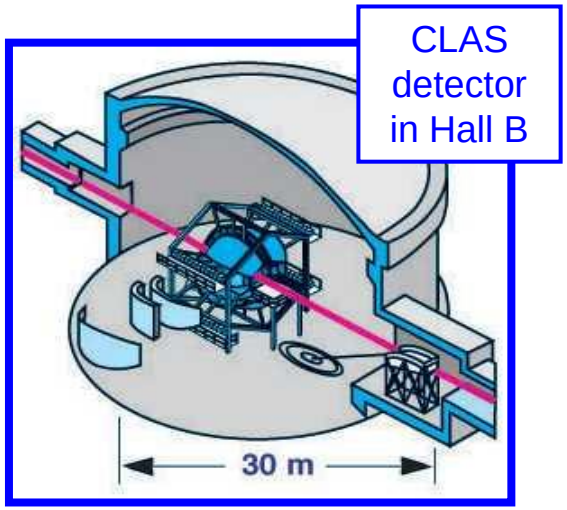


Jefferson Lab 6 GeV and the CLAS detector

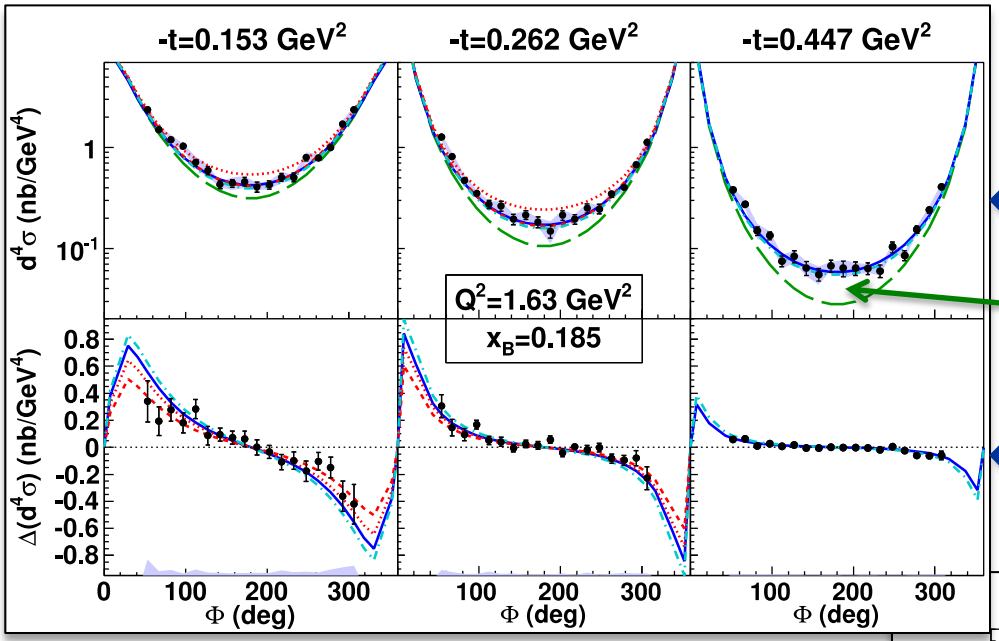
Jefferson Lab







Unpolarized and beam-polarized cross sections from CLAS data

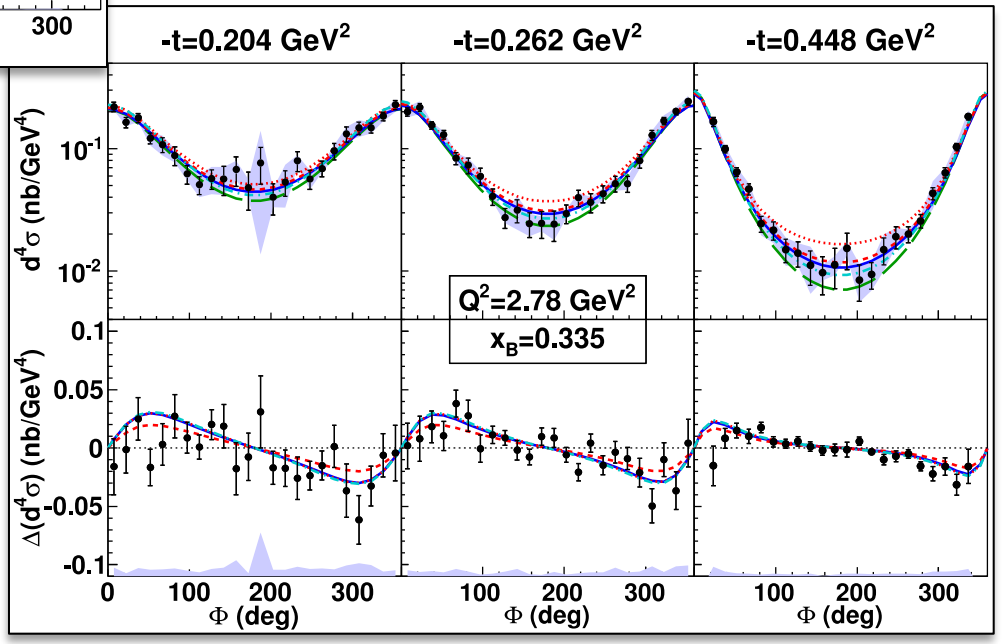


H.S. Jo *et al.* (CLAS Collaboration), Phys. Rev. Lett. 115, 212003 (2015)

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

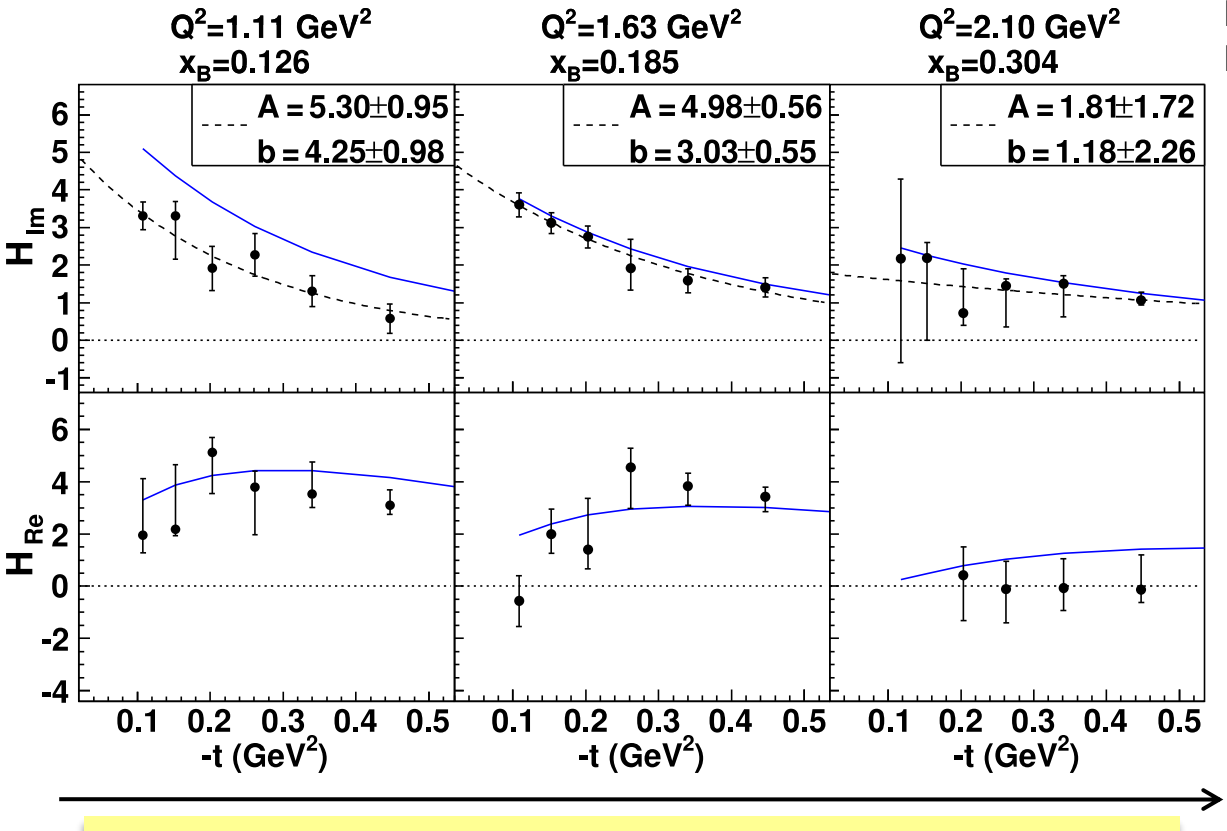
DVCS + interference

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



- CEBAF's polarized electron beam (E ~ 6 GeV, pol ~ 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)

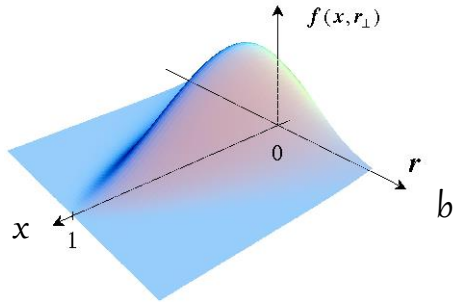
b : transverse position of the quarks in the nucleon

Fits with function Ae^{bt}

Model 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



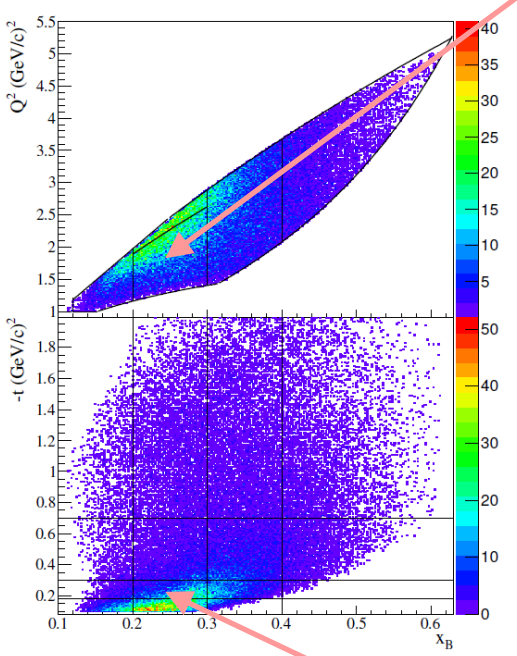
The results suggest that the nucleon size decreases at higher parton-momentum values, thus revealing from the experiment a **first tomographic image of the nucleon**

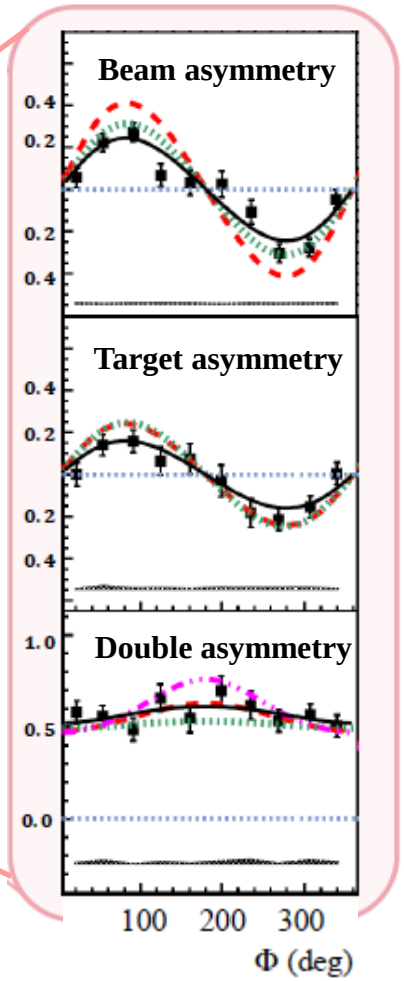
DVCS on longitudinally polarized target

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

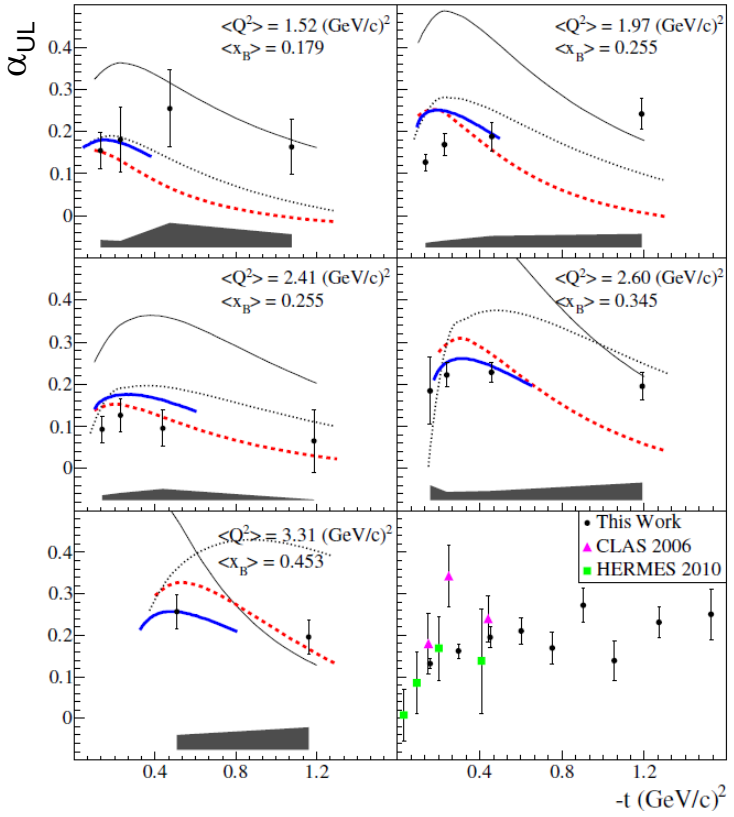
$\vec{e}\vec{p} \rightarrow ep\gamma$

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





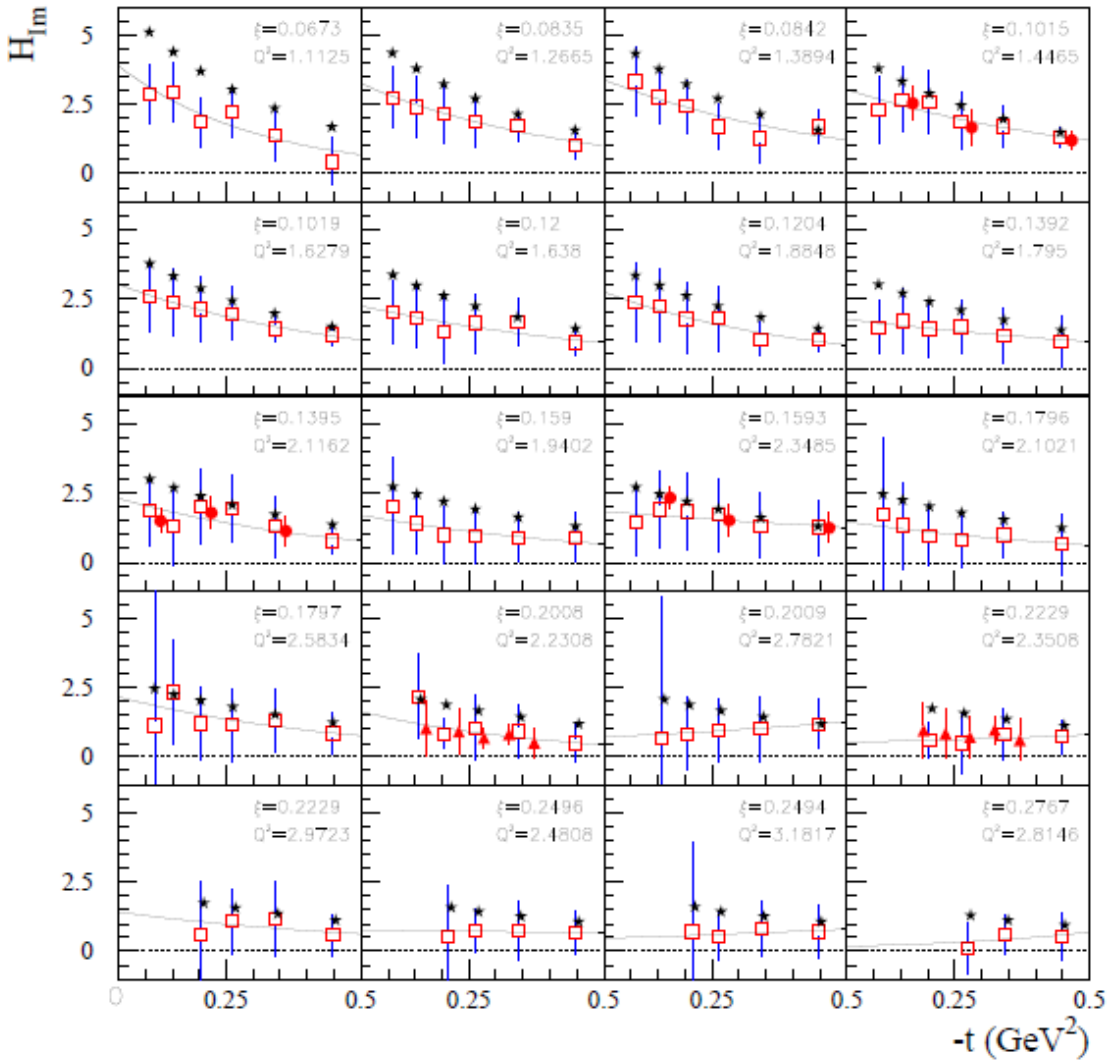
- **5 (Q^2-x_B) bins**
- **4 t bins**
- **10 ϕ bins**



- Improved statistics ×10 at low –*t*
- Extended kinematic coverage

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

Extraction of H_{Im} from the fits of JLab 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

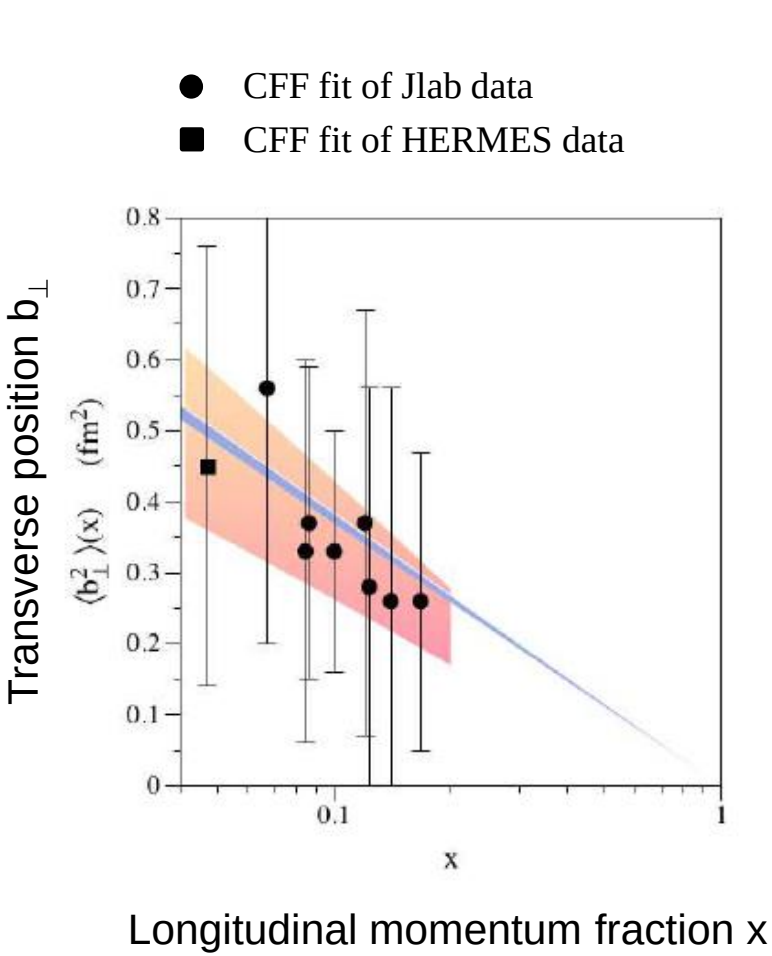
The majority of the results were obtained from the CLAS cross sections

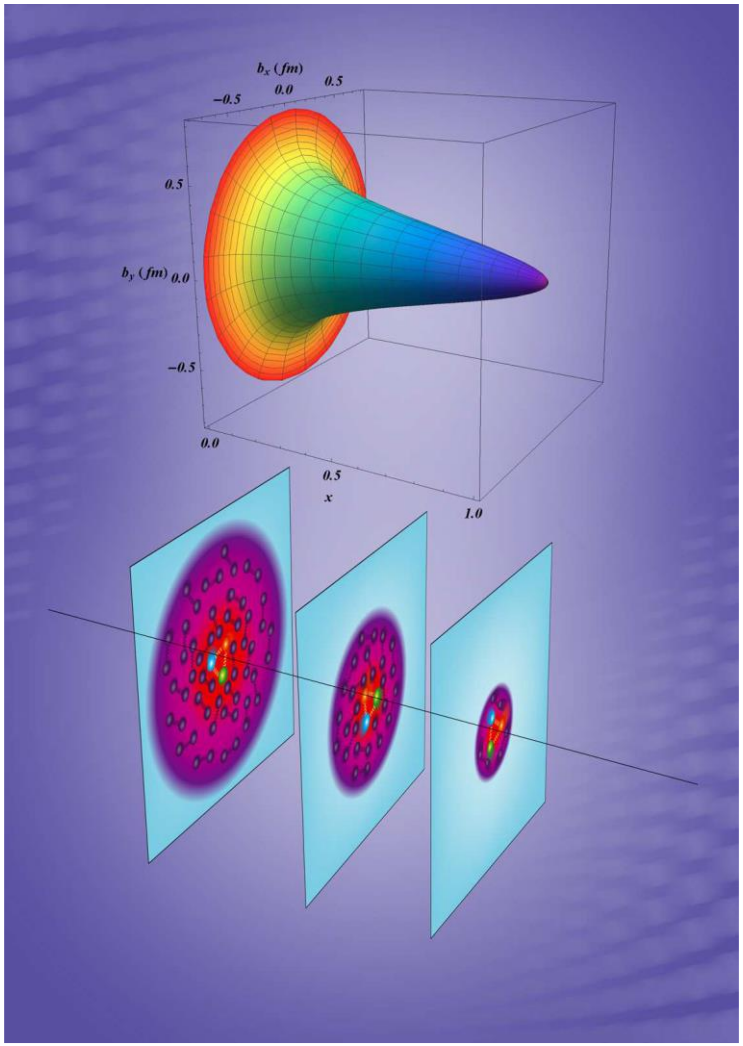
$$H_{Im}(\xi,t) = A(\xi)e^{b(\xi)t}$$

The slope in t becomes flatter with increasing ξ

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

From CFFs to proton tomography





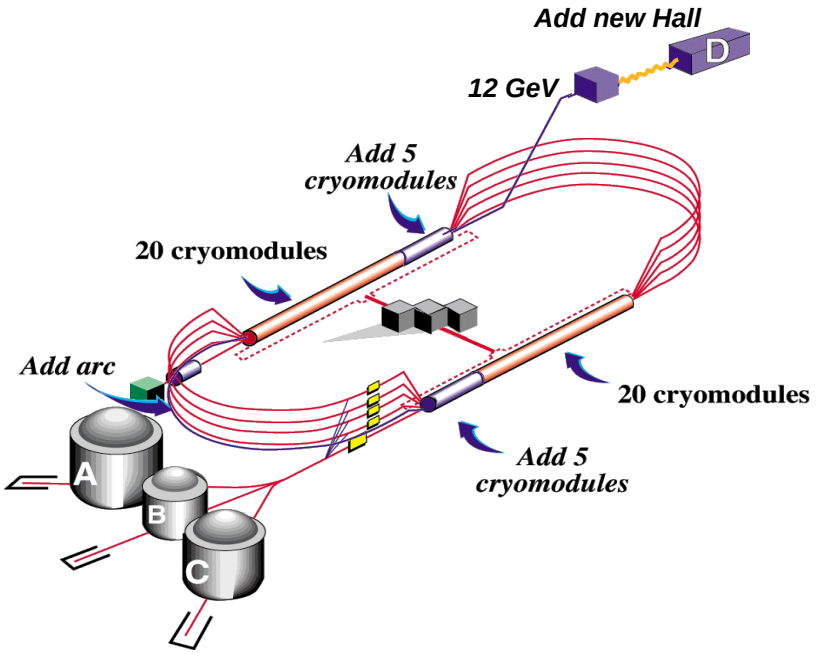
R. Dupré, M. Guidal, S. Niccolai, and M. Vanderhaeghen, Eur. Phys. J. A 53, 171 (2017)

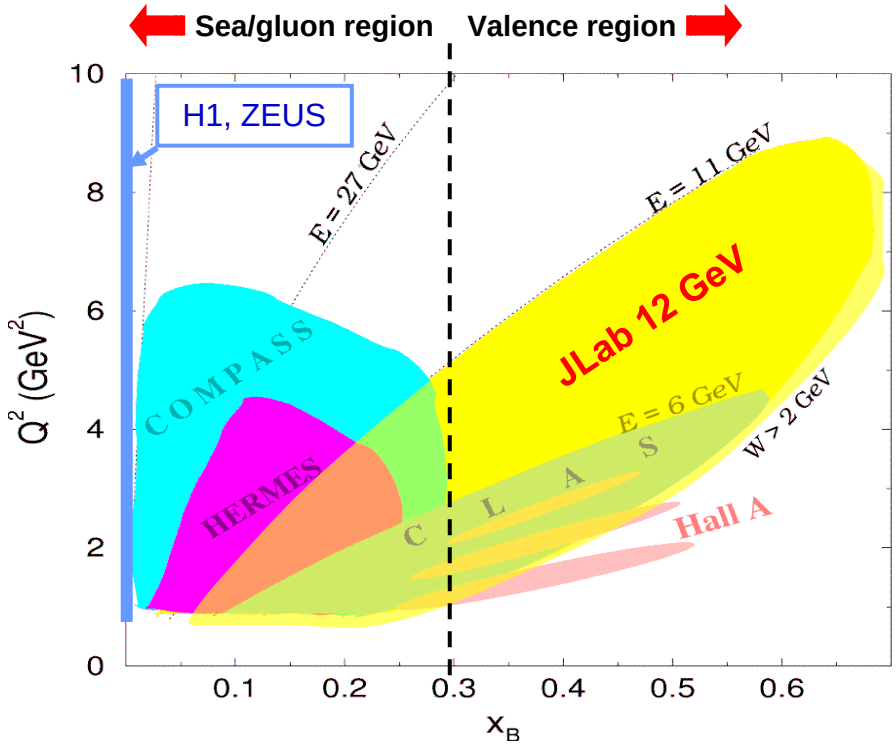
Jefferson Lab upgrade to 12 GeV

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

Beam polarization > 80%

Accelerator 12 GeV upgrade



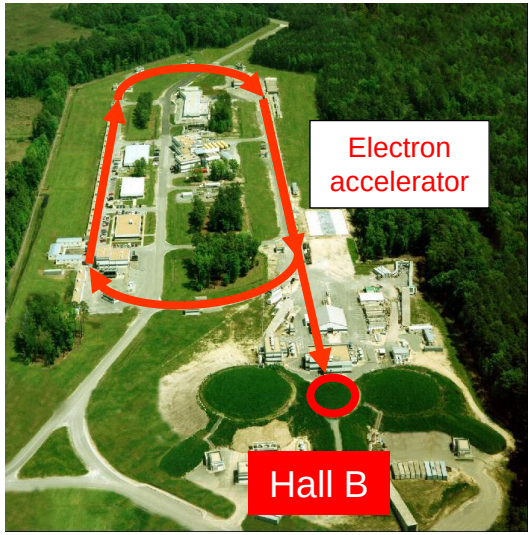


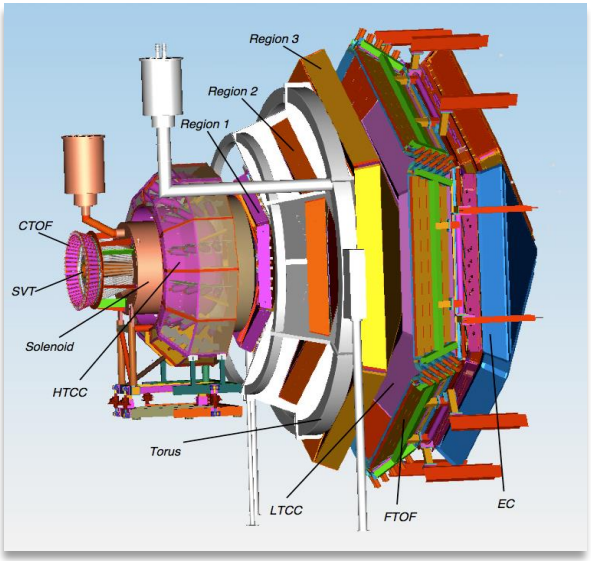
Study of high x_B domain requires high luminosity

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

Jefferson Lab 12 GeV and the new CLAS12 detector

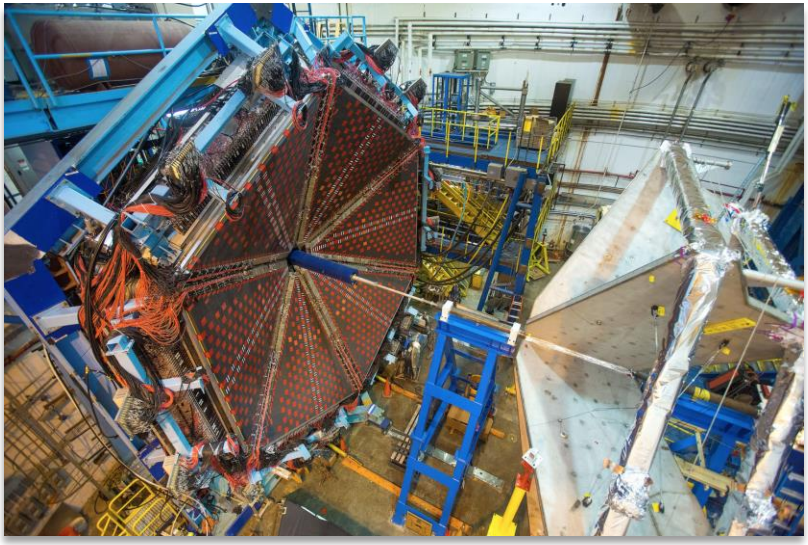
Jefferson Lab

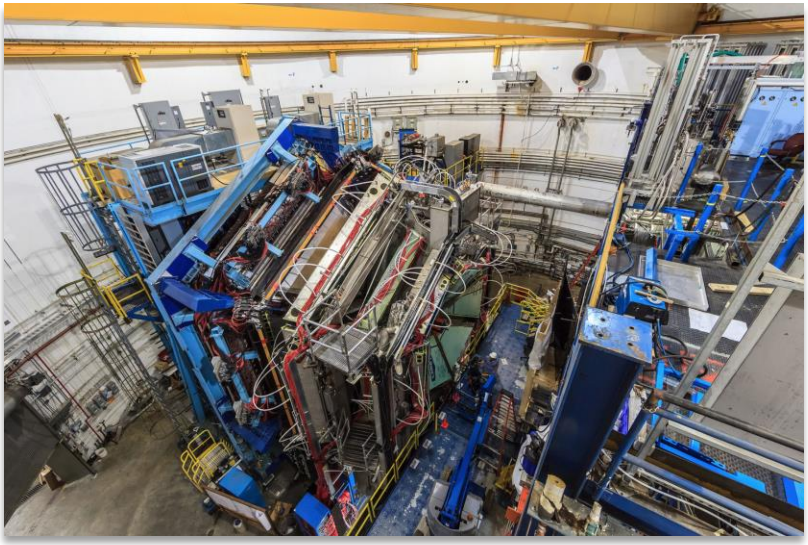




CLAS12 detector in Hall B

Data taking with the new CLAS12 detector started in 2018





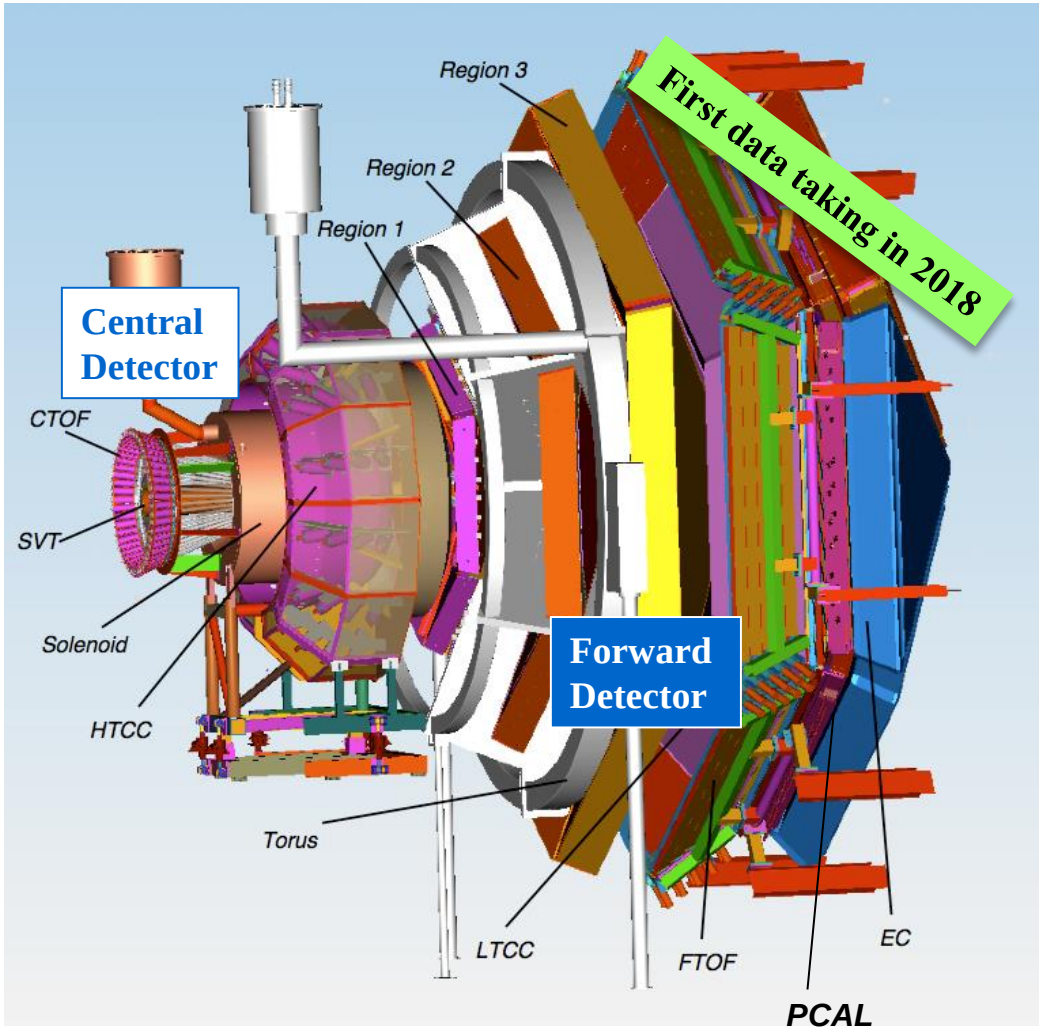
JLab 12 GeV : new CLAS12 detector in Hall B

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

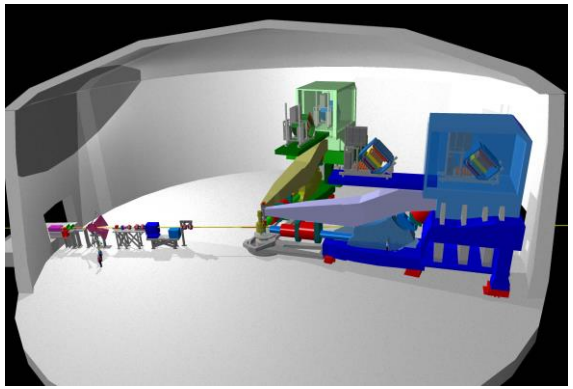
Acceptance for charged particles:
- **Central (CD), $40^o<\theta<135^o$**
- **Forward (FD), $5^o<\theta<40^o$**

Acceptance for photons:
- **Forward tagger, $2^o<\theta<5^o$**
- **EC, $5^o<\theta<40^o$**

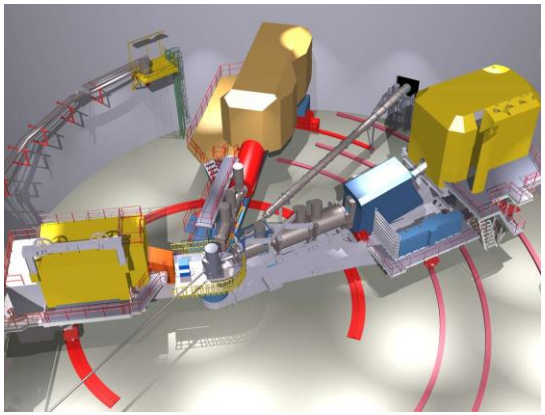
High luminosity & large acceptance:
Concurrent measurement of deeply virtual exclusive, semi-inclusive, and inclusive processes



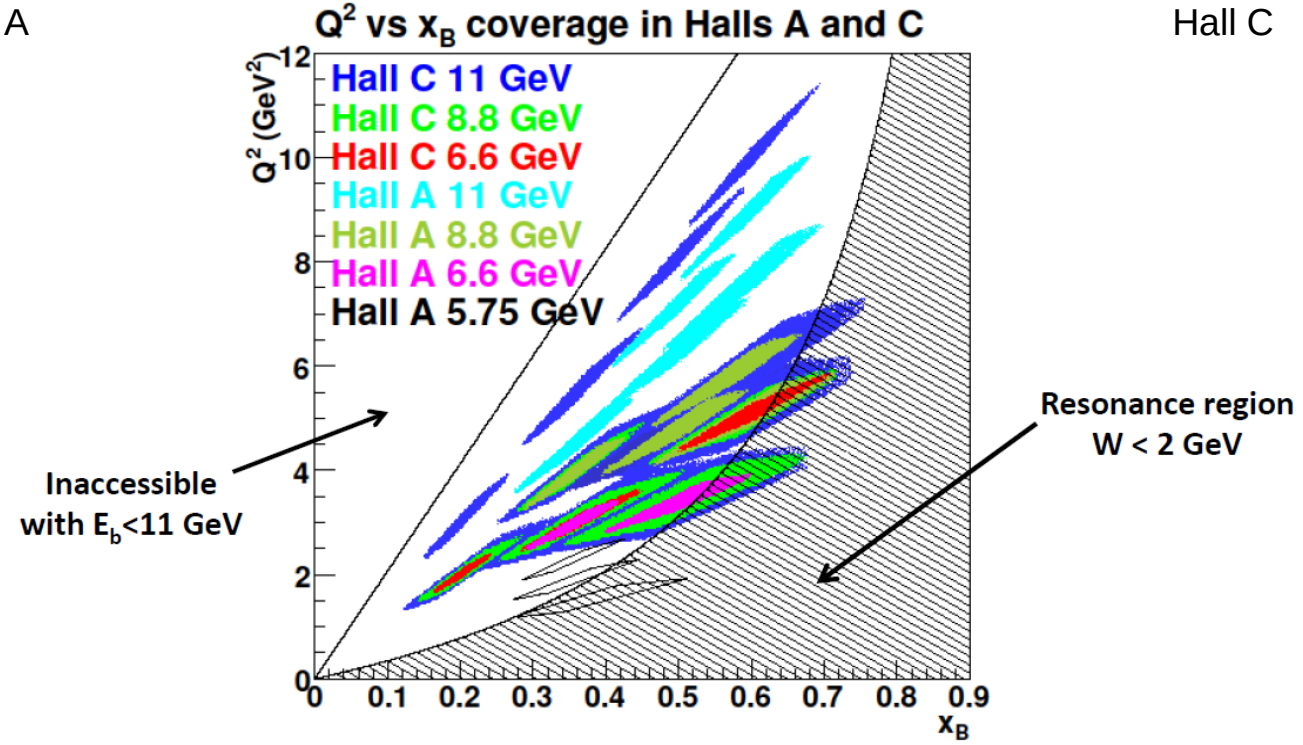
DVCS experiments also in Hall A and Hall C of Jefferson Lab



Hall A

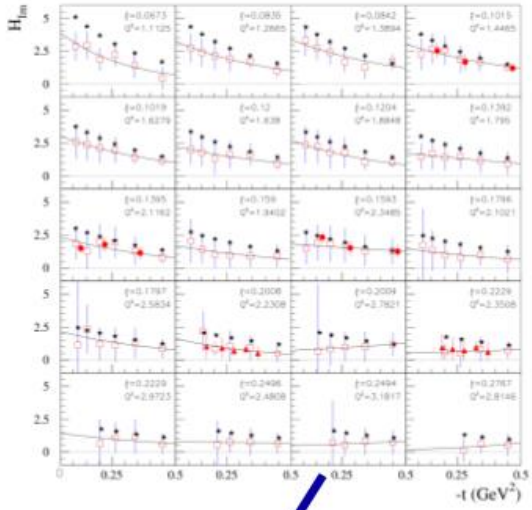


Hall C

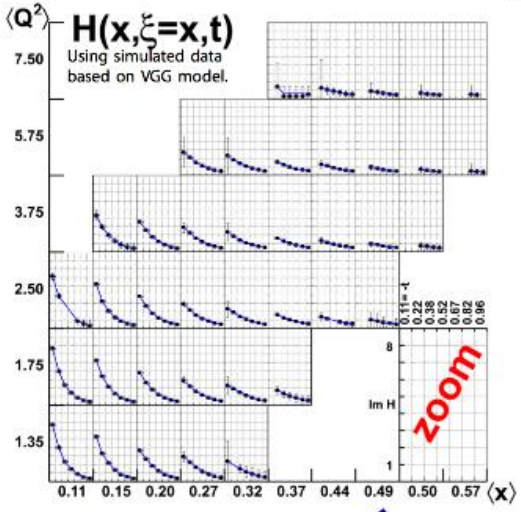


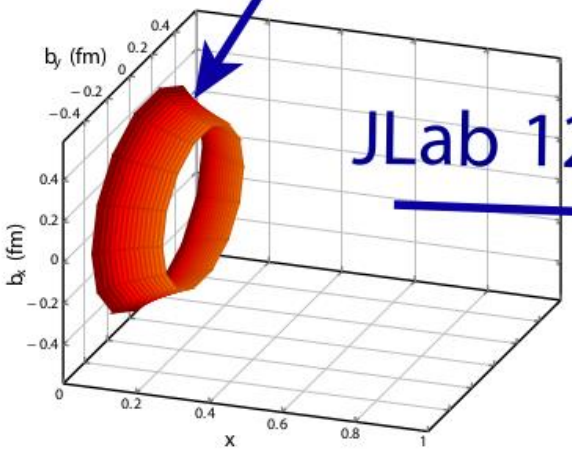
Proton tomography with CLAS12 projected data

Düpré-Guidal-Vanderhaeghen-PRD **95** 011501 (R) (2017)

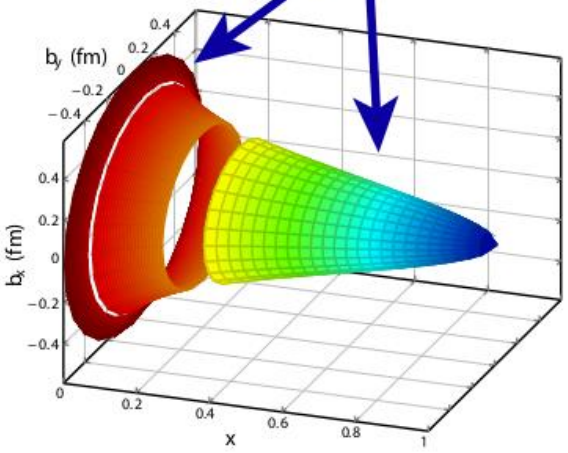


CLAS12 projections E12-06-119 with DVCS A_{UL} and A_{LU}



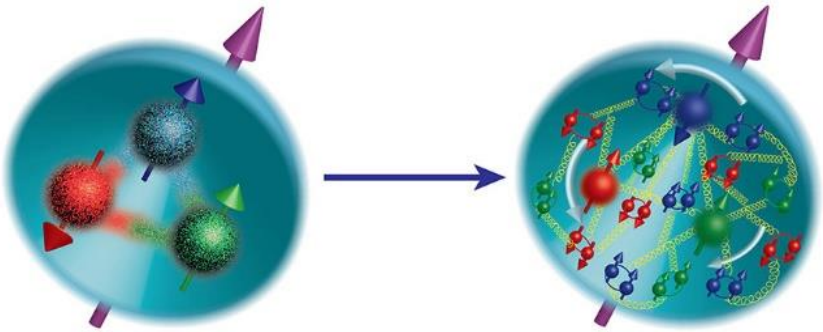


JLab 12 GeV

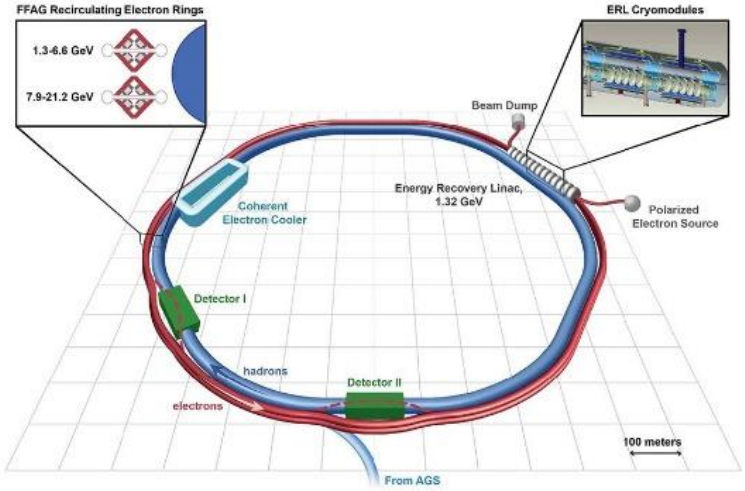


DVCS at the Electron-Ion Collider (EIC)

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

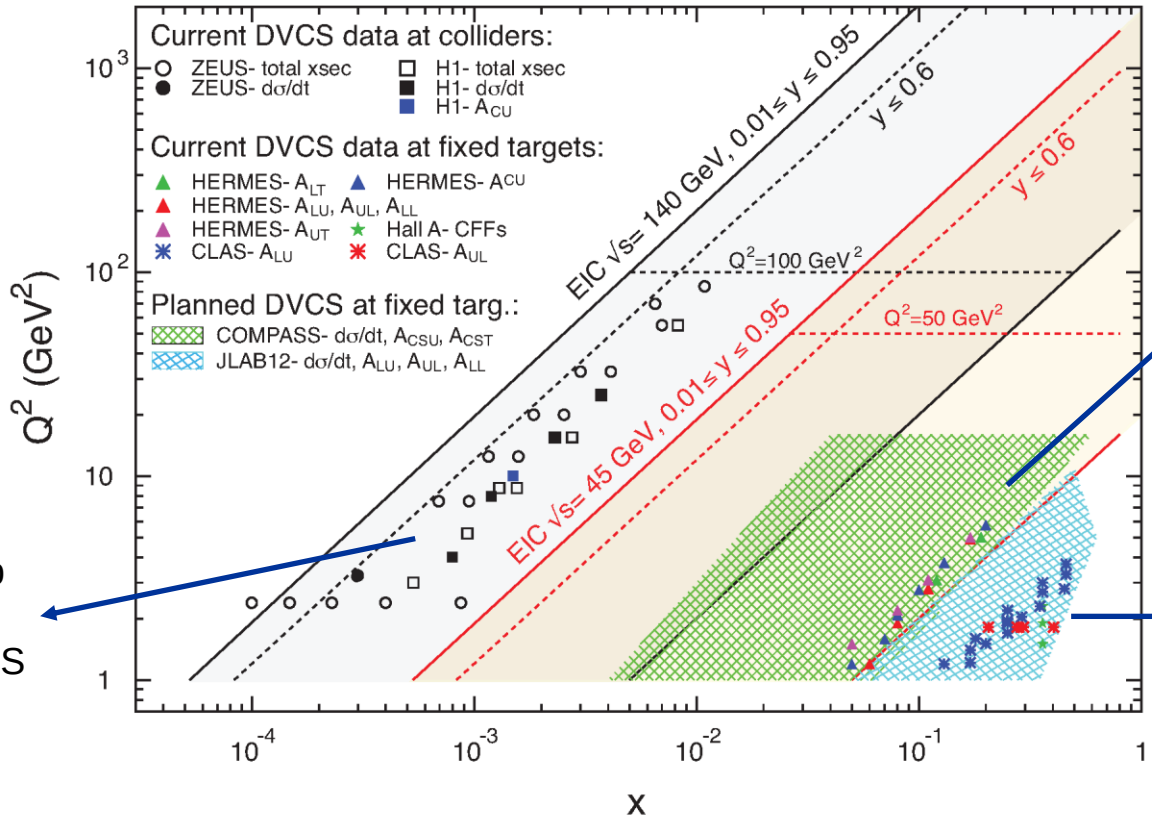


The Electron-Ion Collider (EIC) will be constructed at BNL



eRHIC design
(BNL)

DVCS at the EIC : gluons and sea quarks



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)
- Variable center-of-mass energy : 20-100(140) GeV

3D imaging of the Nucleon at the EIC

Unpolarized p

$\vec{p}$ along X