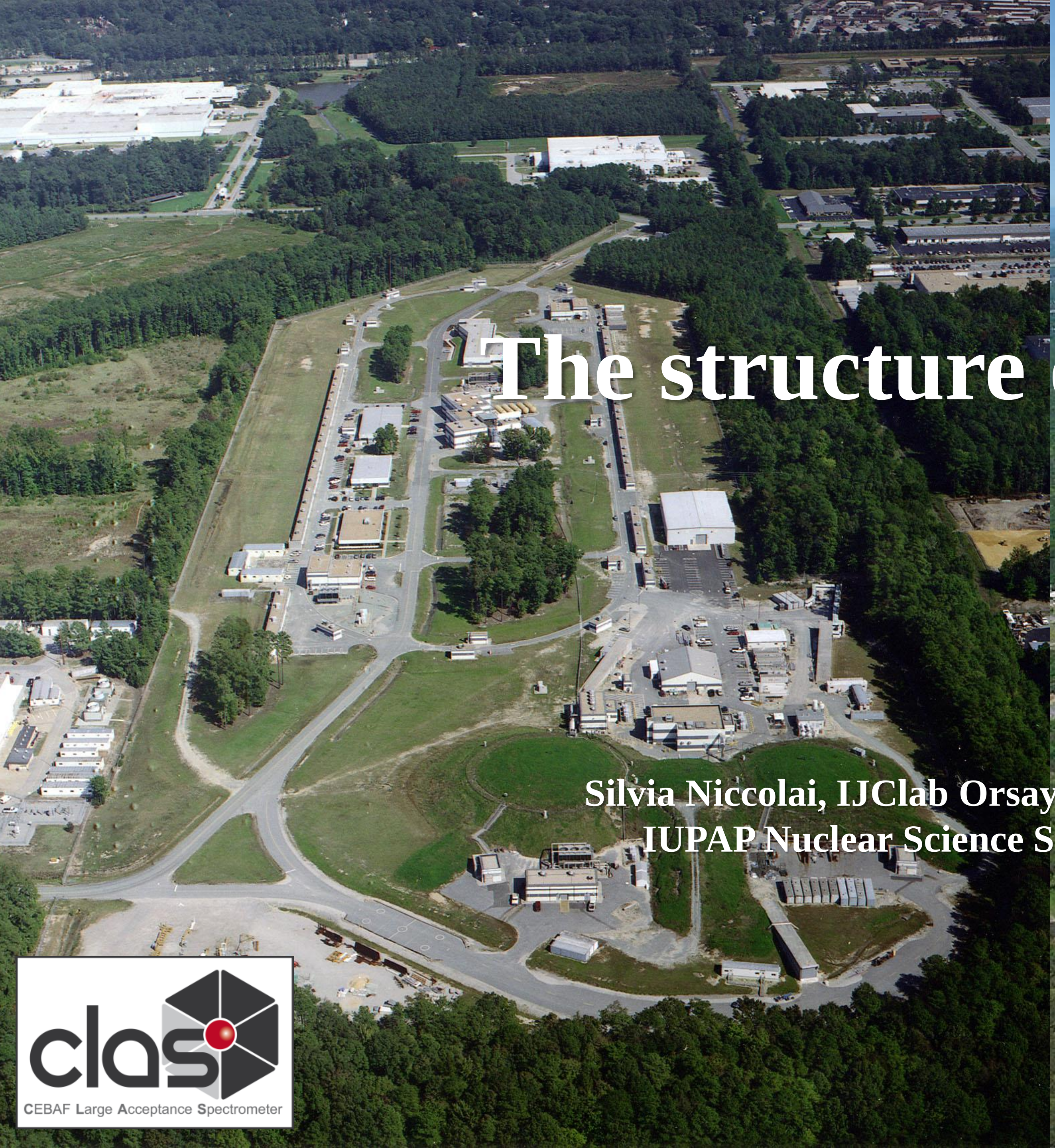


The structure of the nucleon

Silvia Niccolai, IJClab Orsay & CLAS Collaboration
IUPAP Nuclear Science Symposium, 6/14/2022

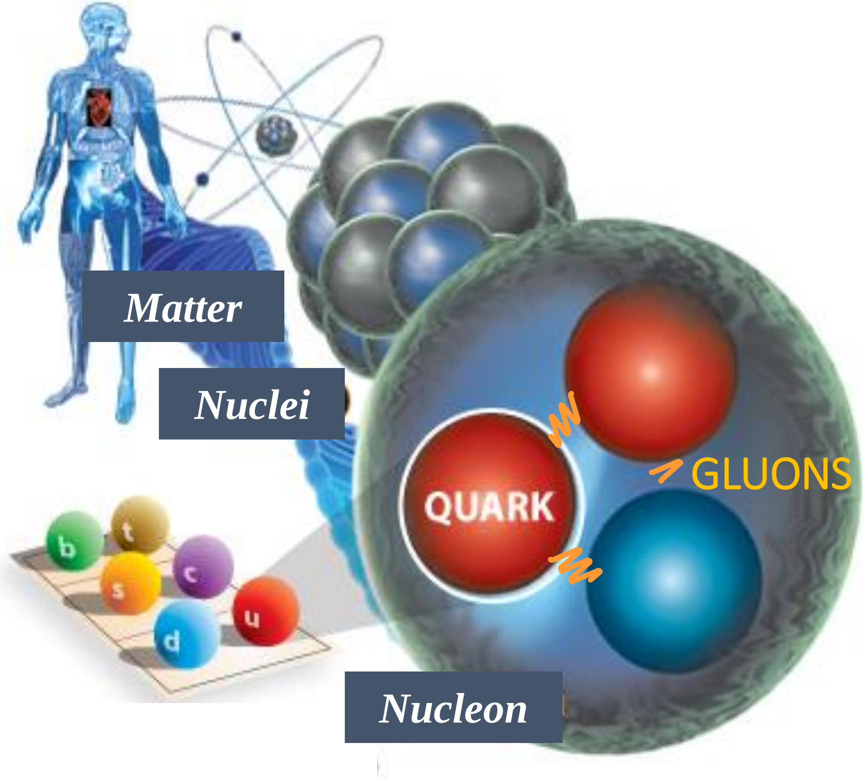
clas
CEBAF Large Acceptance Spectrometer

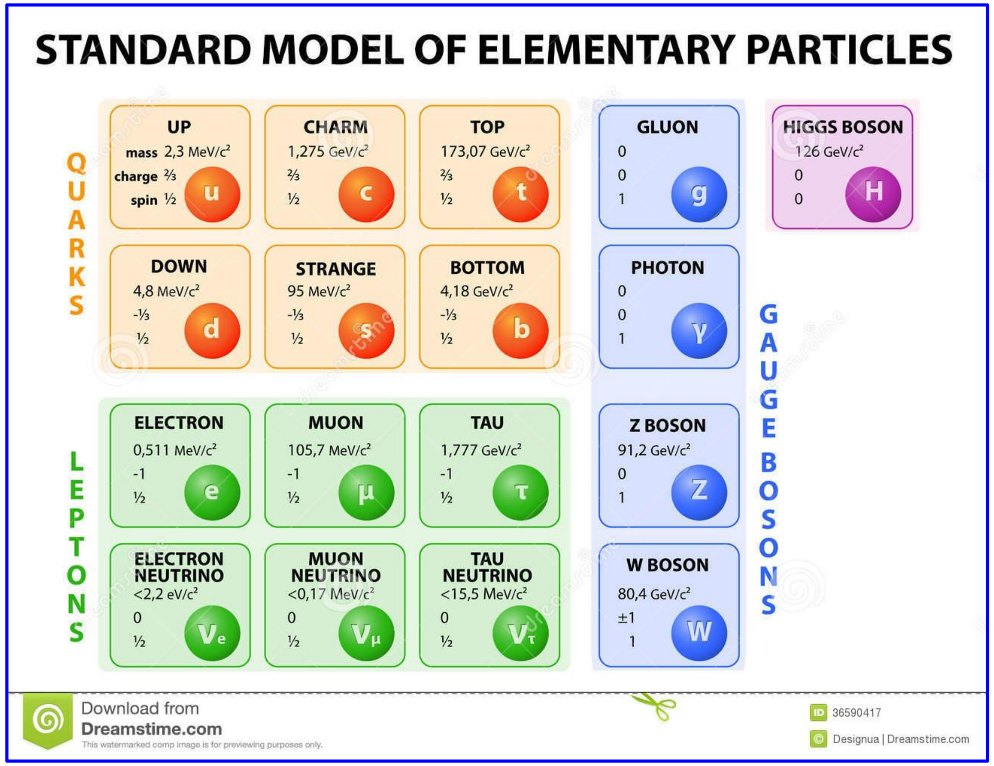
IJCLab
Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

QCD at the heart of matter

- **Protons and neutrons** are the building blocks of atomic **nuclei**
- **Nucleons** provide **~99% of the mass** of the visible universe
- **~99% of nucleon mass** arises from the **dynamics** and **interactions** between its constituents (**quarks** and **gluons**)

→ **Quantum Chromodynamics (QCD)**





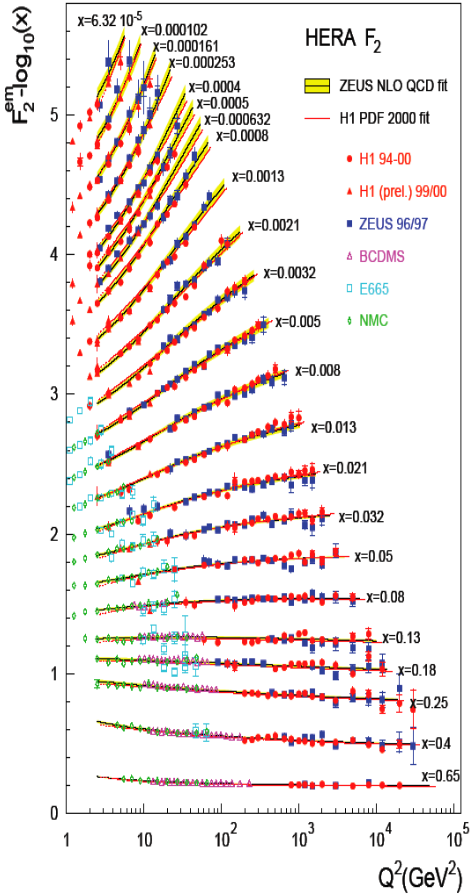
STANDARD MODEL OF ELEMENTARY PARTICLES

QUARKS	UP mass 2,3 MeV/c^2 charge ⅔ spin ½ u	CHARM 1,275 GeV/c^2 ⅔ ½ c	TOP 173,07 GeV/c^2 ⅔ ½ t	GLUON 0 0 1 g	HIGGS BOSON 126 GeV/c^2 0 0 H
	DOWN 4,8 MeV/c^2 -⅓ ½ d	STRANGE 95 MeV/c^2 -⅓ ½ s	BOTTOM 4,18 GeV/c^2 -⅓ ½ b	PHOTON 0 0 1 γ	GAUGE BOSONS
LEPTONS	ELECTRON 0,511 MeV/c^2 -1 ½ e	MUON 105,7 MeV/c^2 -1 ½ μ	TAU 1,777 GeV/c^2 -1 ½ τ	Z BOSON 91,2 GeV/c^2 0 1 Z	
	ELECTRON NEUTRINO <2,2 eV/c^2 0 ½ ν_e	MUON NEUTRINO <0,17 MeV/c^2 0 ½ ν_μ	TAU NEUTRINO <15,5 MeV/c^2 0 ½ ν_τ	W BOSON 80,4 GeV/c^2 ±1 1 W	

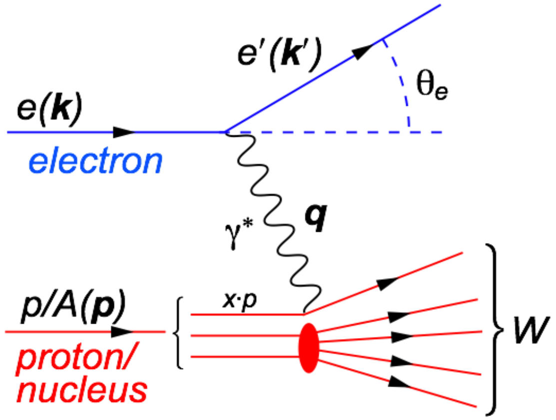
Properties of QCD:

- **Confinement, at long distances:** unlike in QED, we cannot observe the individual constituents
- **Asymptotic freedom, at short distances**: the effective coupling constant α_s becomes very small (<1) at small distances (<0.2 fm)
- **Chiral simmetry breaking**: mass of the *u* and *d* quarks, very small → generates nucleon mass
- **Non-linearity**: **self-interaction of gluons**

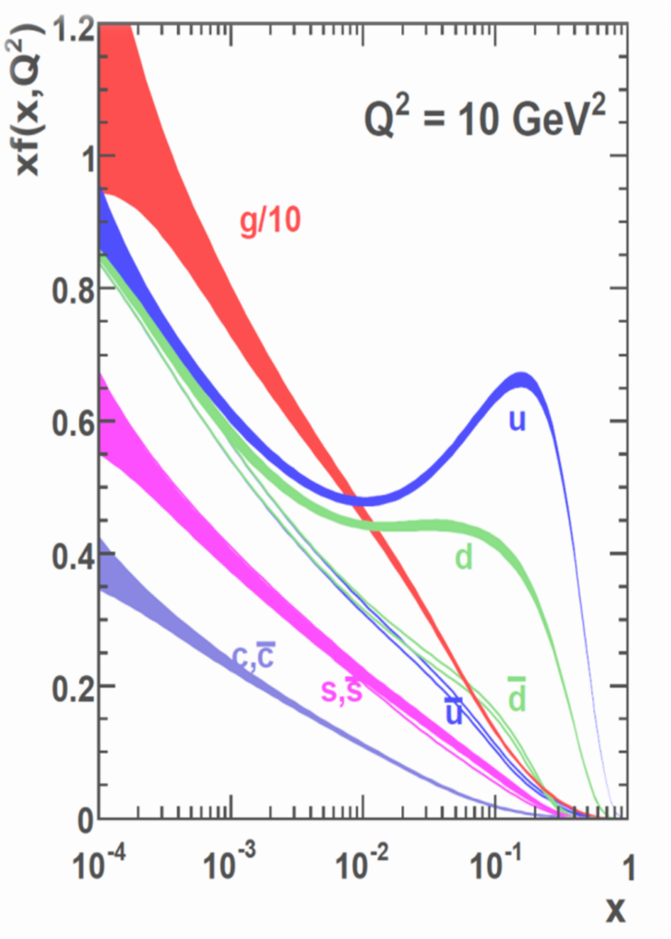
Successes of asymptotic QCD

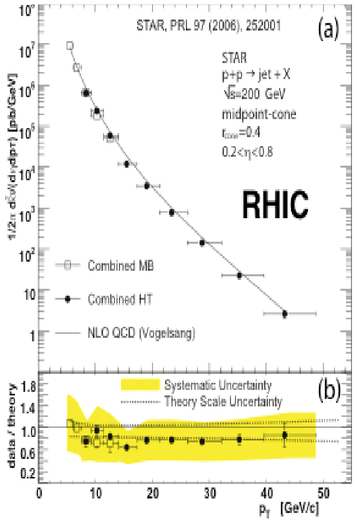


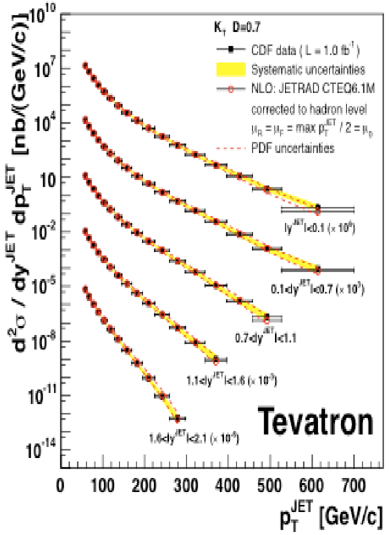
$$F_2 = \sum_q x\, q(x,Q^2)$$

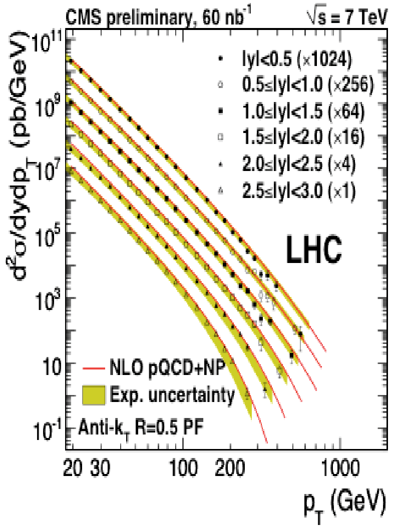


Measurements of F$_2$ in e-p at 0.3 TeV (HERA)
→ extraction quark and gluon PDFs
→ pQCD fits for p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV









BUT…

QCD is still unsolved in non-perturbative regions

Insights into soft phenomena exist through qualitative **models** and quantitative **numerical calculations** (lattice)

The proton: QCD at work!

What we know about the content of the proton:

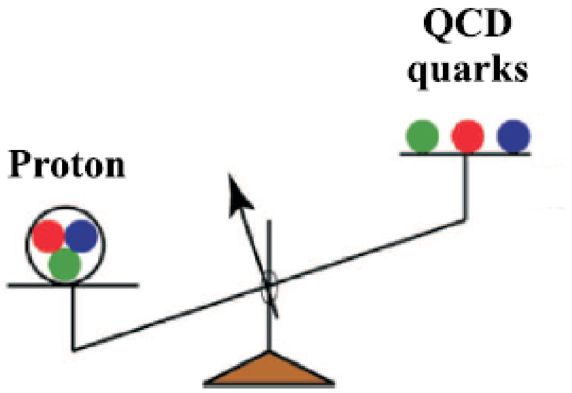
- 2 *up* quarks ($q_u = 2/3\, e$) + 1 *down* quark ($q_d = -1/3\, e$)
- Any number of quark-antiquark pairs (sea)
- Any number of gluons

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

Fundamental questions:

- Origin of proton **mass**?

→ Only a small fraction comes from the actual quark masses
→ Most of it comes from the ***motion of quarks and gluons***



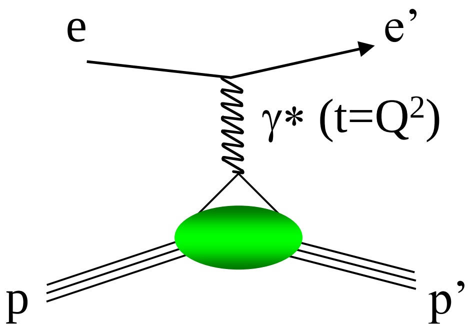
- Origin of proton **spin**?

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

Electron scattering: the ideal tool to study nucleon structure

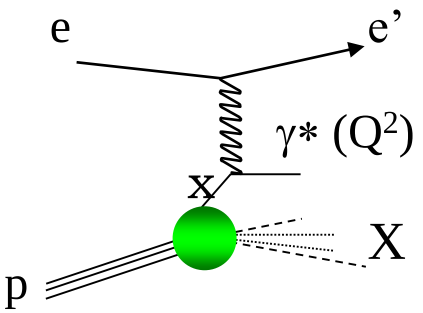
Electrons are **structureless** and interact only **electromagnetically**

- 1950: **Elastic scattering** ep→e'p' (Hofstadter, Nobel prize 1961)

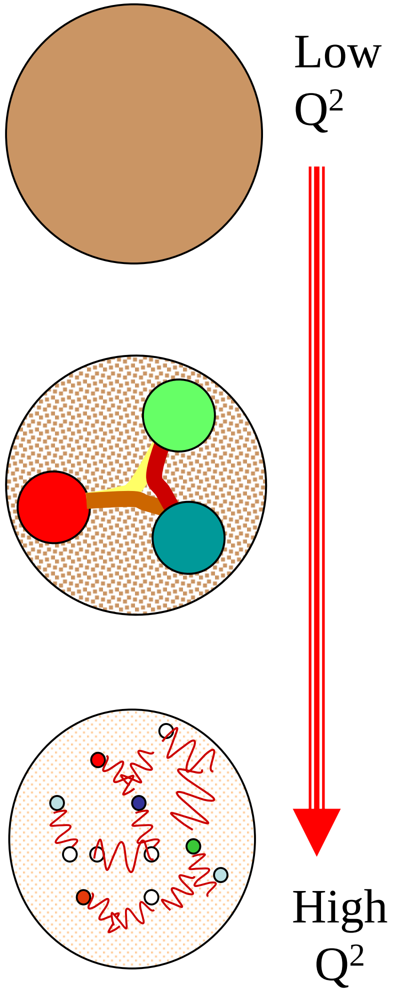


- The proton is **not a point-like object**
- Measurement of charge and current distributions of the proton: **Electromagnetic form factors $F_1(t)$, $F_2(t)$**

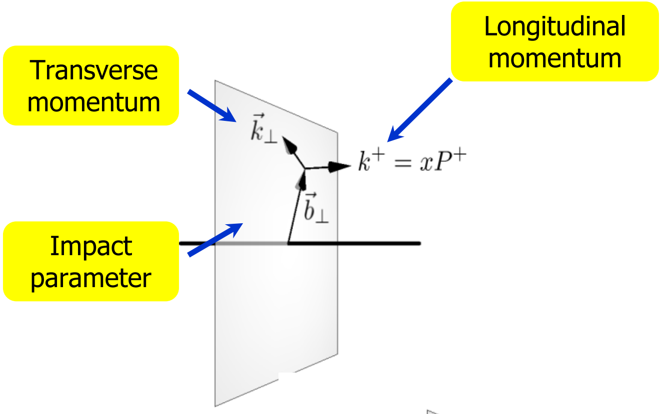
- 1967: **Deep inelastic scattering** (DIS) ep→e'X (Friedman, Kendall, Taylor, Nobel prize 1990)



- Discovery of the **quarks** (or "partons")
- Measurement of the momentum and spin distributions of the partons: **Parton Distribution Functions (PDF) $q(x)$, $\Delta q(x)$**



Multi-dimensional mapping of the nucleon


Transverse momentum

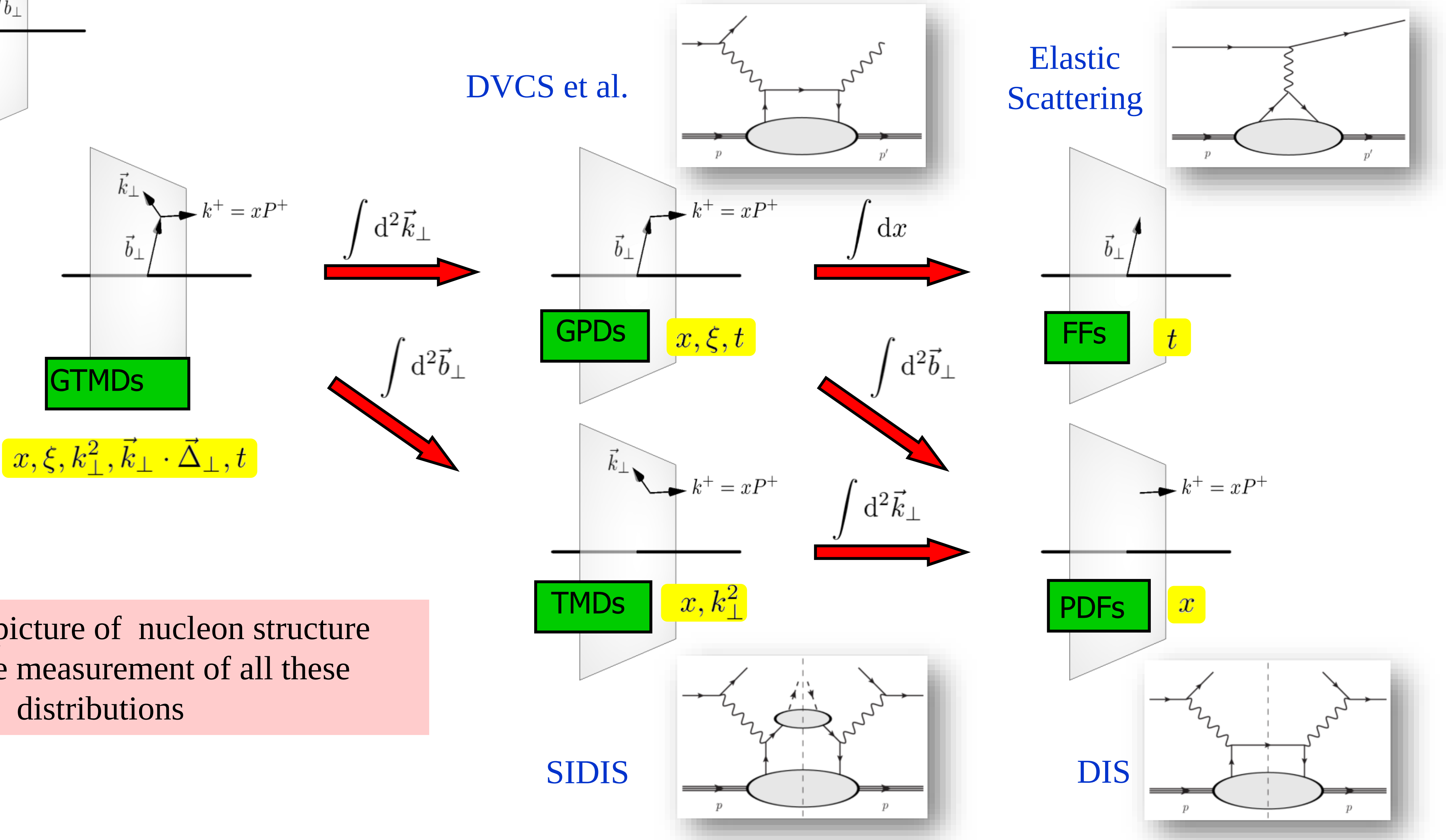
Longitudinal momentum

Impact parameter

$\vec{k}_\perp$

$k^+ = xP^+$

$\vec{b}_\perp$


DVCS et al.

Elastic Scattering

$\int \mathrm{d}^2\vec{k}_\perp$

$\int \mathrm{d}x$

$\int \mathrm{d}^2\vec{b}_\perp$

$\int \mathrm{d}^2\vec{b}_\perp$

$\int \mathrm{d}^2\vec{k}_\perp$

GTMDs

$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$

GPDs x, ξ, t

FFs t

TMDs $x, k_\perp^2$

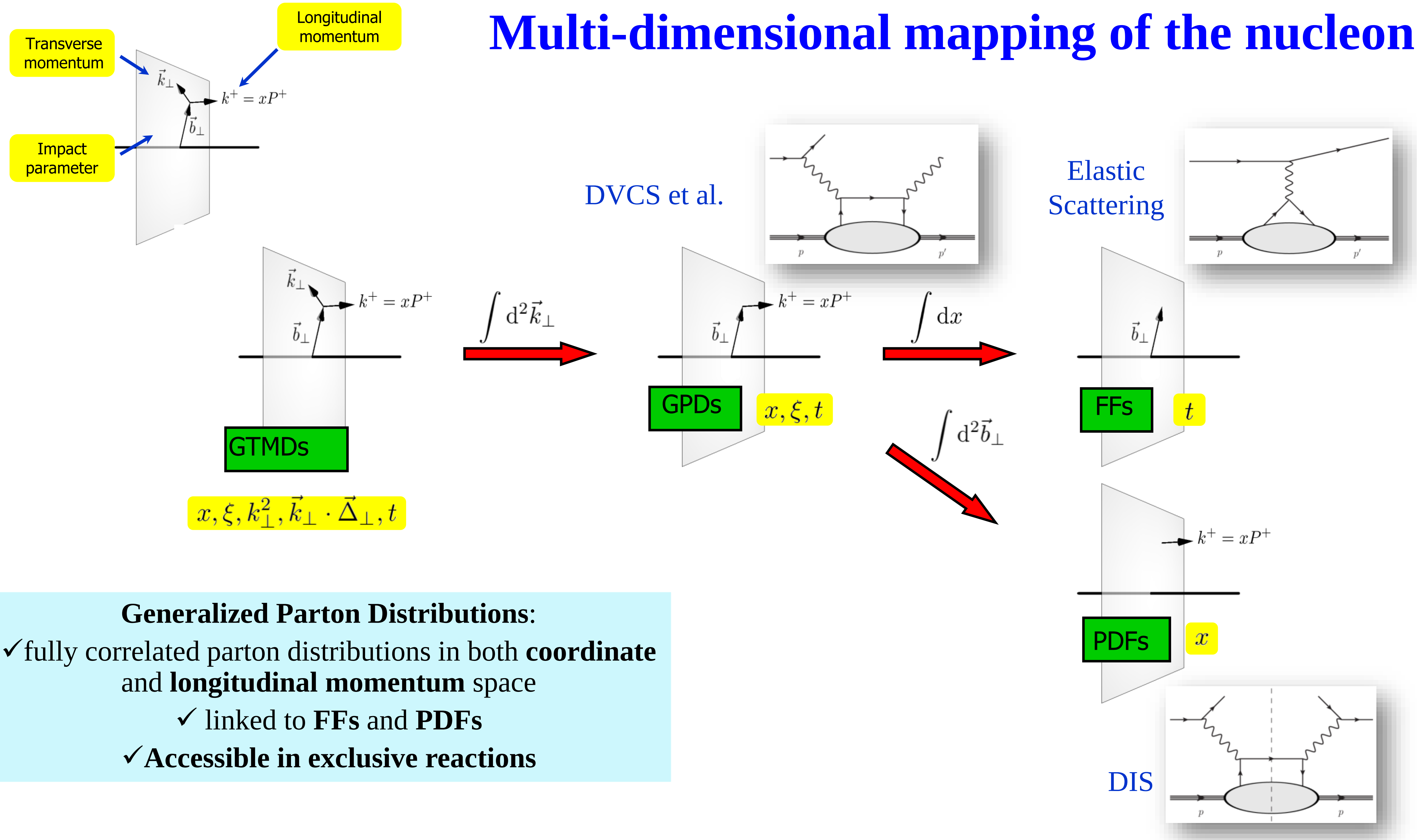
PDFs x

SIDIS

DIS

A complete picture of nucleon structure requires the measurement of all these distributions

Multi-dimensional mapping of the nucleon



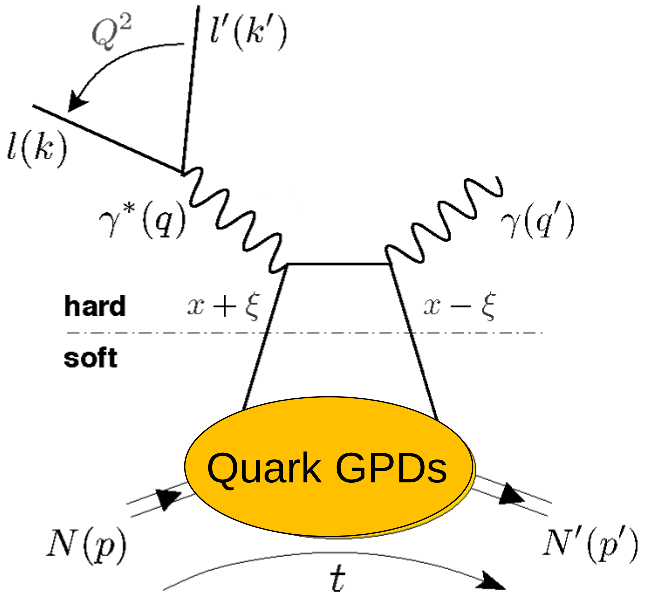
Generalized Parton Distributions:

✓fully correlated parton distributions in both **coordinate** and **longitudinal momentum** space

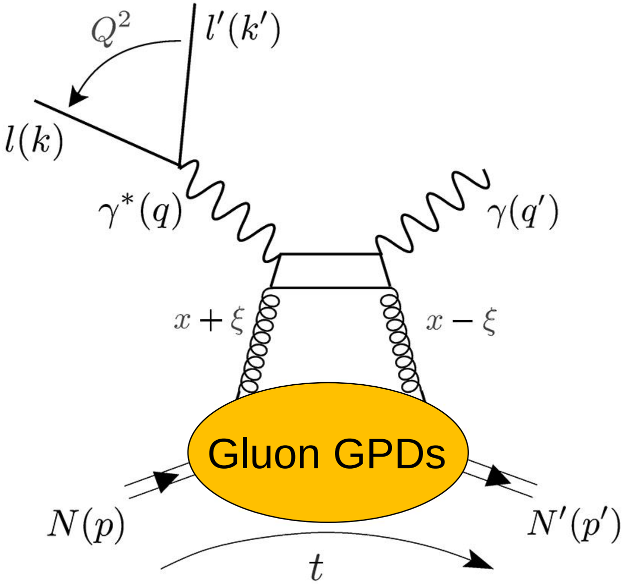
✓ linked to **FFs** and **PDFs**

✓**Accessible in exclusive reactions**

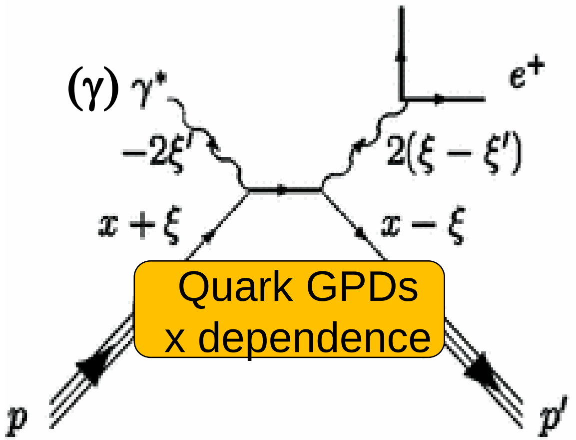
Exclusive reactions giving access to GPDs

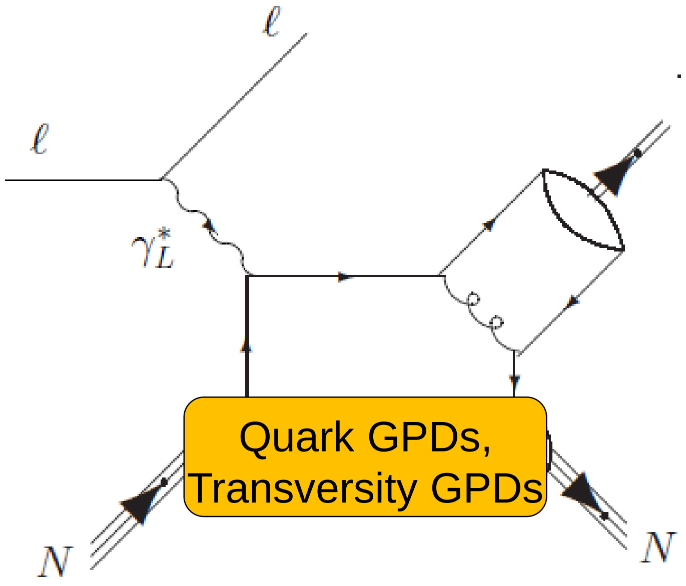


DVCS

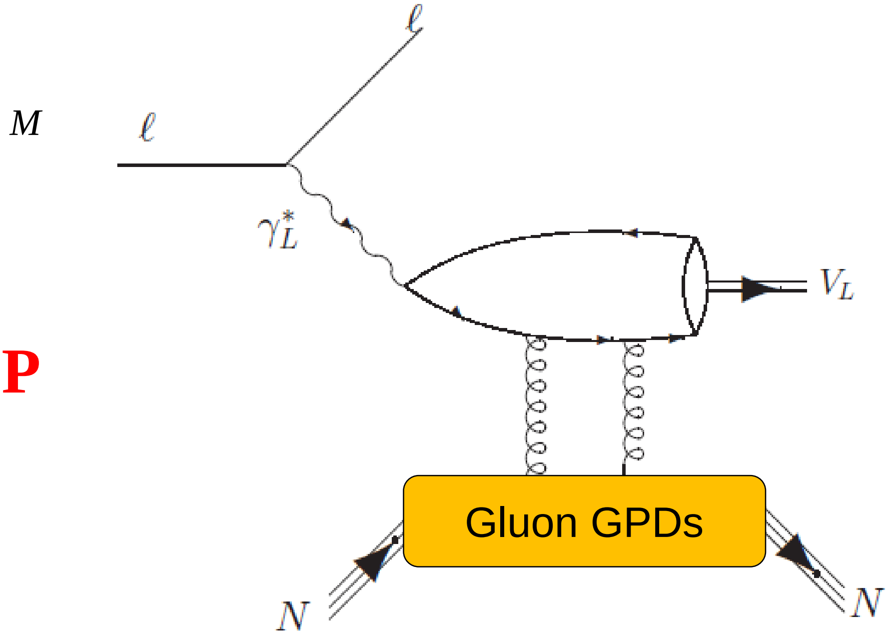


(TCS), DDVCS

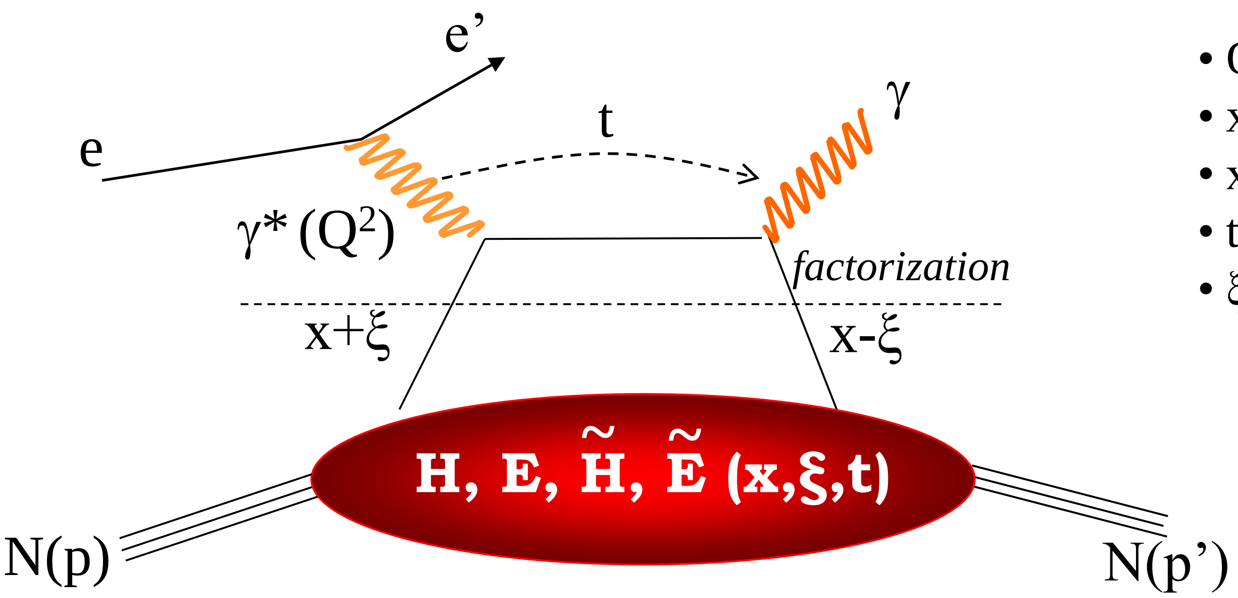




DVMP



Deeply Virtual Compton Scattering and GPDs



- $Q^2 = -(e-e')^2$
- $x_B = Q^2/2M\nu \quad \nu = E_e - E_{e'}$
- $x+\xi$, $x-\xi$ longitudinal momentum fractions
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

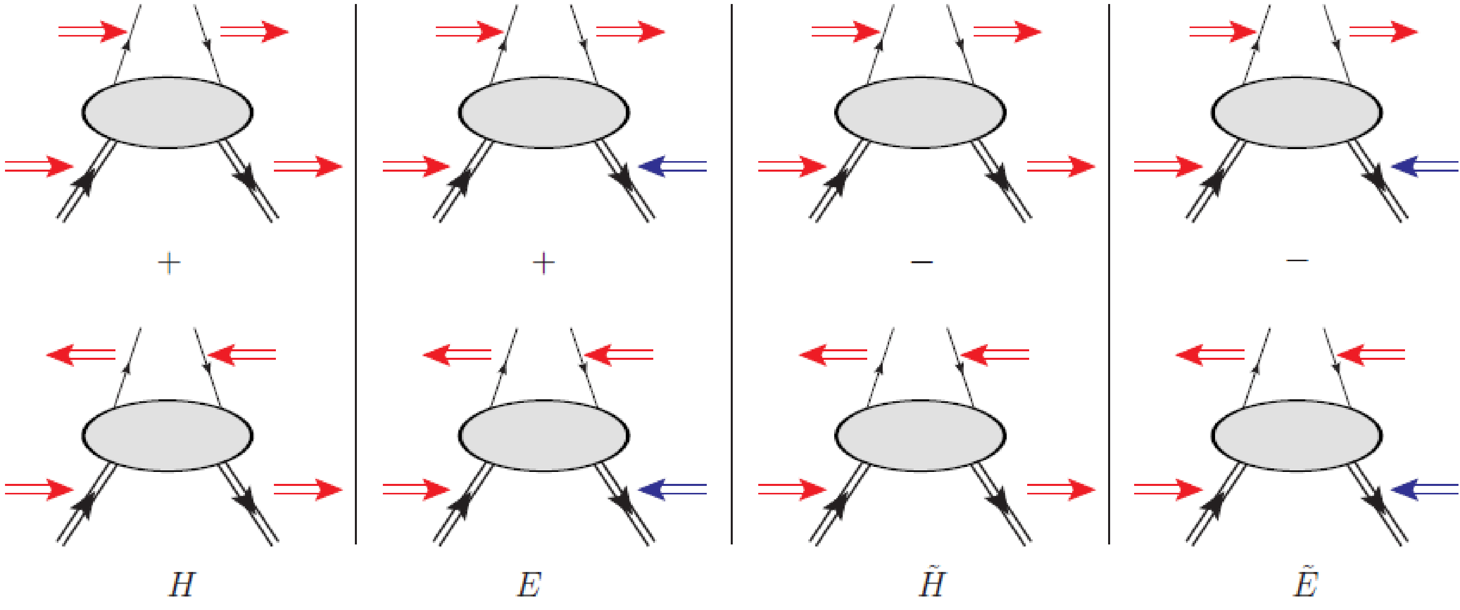
« **Handbag** » factorization, valid in the **Bjorken regime** (**high Q^2** and **ν,** fixed x_B)**, $t \ll Q^2$**

*GPDs: Fourier transforms of **non-local**, **non-diagonal** QCD operators*

4 GPDs for each quark flavor
(leading-order, leading twist, quark-helicity conservation)

conserve nucleon spin

flip nucleon spin



Vector **Tensor** **Axial-vector** **Ps.scalar**

Properties and “virtues” of GPDs

$$\left.\begin{aligned}
&\int H(x,\xi,t)\,dx = F_1(t) \quad \forall\xi \\
&\int E(x,\xi,t)\,dx = F_2(t) \quad \forall\xi \\
&\int \tilde{H}(x,\xi,t)\,dx = G_A(t) \quad \forall\xi \\
&\int \tilde{E}(x,\xi,t)\,dx = G_P(t) \quad \forall\xi
\end{aligned}\right\}$$

Link with **FFs**

$$\left.\begin{aligned}
&H(x,0,0) = q(x) \\
&\tilde{H}(x,0,0) = \Delta q(x)
\end{aligned}\right\}$$

Forward limit: **PDFs**
(not for E, $\tilde{\mathrm{E}}$)

Nucleon tomography

$$q(x,\mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} H(x,0,-\Delta_\perp^2)$$

$$\Delta q(x,\mathrm{b}_\perp) = \int_0^\infty \frac{d^2\Delta_\perp}{(2\pi)^2} e^{i\Delta_\perp \mathrm{b}_\perp} \tilde{H}(x,0,-\Delta_\perp^2)$$

M. Burkardt, PRD 62, 71503 (2000)

Quark angular momentum (Ji’s sum rule)

$$\frac{1}{2}\int_{-1}^{1} x\,dx\,(H(x,\xi,t=0) + E(x,\xi,t=0)) = J = \frac{1}{2}\Delta\Sigma + \Delta L$$

X. Ji, Phy.Rev.Lett.78,610(1997)

Nucleon spin: $\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + \Delta L}_{\mathbf{J}} + \Delta G$

Intrinsic spin of the quarks ΔΣ ≈ 30%

Intrinsic spin on the gluons ΔG ≈ 20%

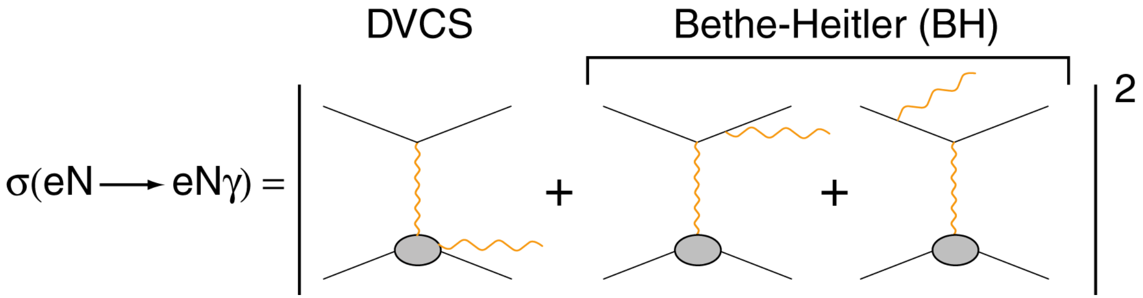
Orbital angular momentum of the quarks ΔL ?

Accessing GPDs through DVCS

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

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

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



Proton Neutron

Polarized beam, unpolarized target:

$\Delta\sigma_{LU} \sim \sin\phi\ Im\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$

$Im\{\boldsymbol{\mathcal{H}}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$

$Im\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \boldsymbol{\mathcal{E}}_n\}$

Unpolarized beam, longitudinal target:

$\Delta\sigma_{UL} \sim \sin\phi Im\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\mathcal{E}) - \xi kF_2\tilde{\mathcal{E}}\}$

$Im\{\boldsymbol{\mathcal{H}}_p, \boldsymbol{\tilde{\mathcal{H}}}_p\}$

$Im\{\boldsymbol{\mathcal{H}}_n, \mathcal{E}_n\}$

Polarized beam, longitudinal target:

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

$Re\{\boldsymbol{\mathcal{H}}_p, \boldsymbol{\tilde{\mathcal{H}}}_p\}$

$Re\{\boldsymbol{\mathcal{H}}_n, \mathcal{E}_n\}$

Unpolarized beam, transverse target:

$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s - \phi)Im\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}$

$Im\{\boldsymbol{\mathcal{H}}_p, \boldsymbol{\mathcal{E}}_p\}$

$Im\{\boldsymbol{\mathcal{H}}_n\}$

Unpolarized beam and target, different lepton charges:

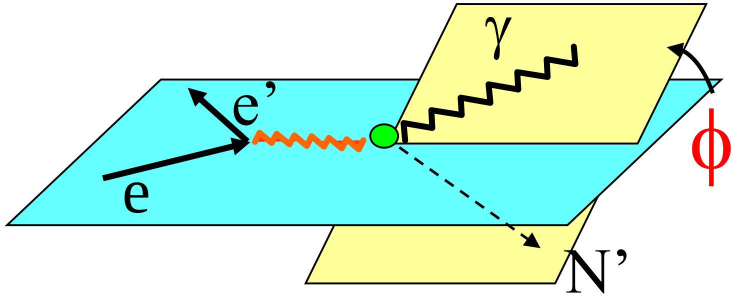
$\Delta\sigma_C \sim \cos\phi\ Re\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E} + \ldots\}$

$Re\{\boldsymbol{\mathcal{H}}_p, \tilde{\mathcal{H}}_p, \mathcal{E}_p\}$

$Re\{\mathcal{H}_n, \tilde{\mathcal{H}}_n, \boldsymbol{\mathcal{E}}_n\}$

$$\sigma \sim \left|T^{DVCS} + T^{BH}\right|^2$$

$$\Delta\sigma = \sigma^+ - \sigma^- \propto I(DVCS \cdot BH)$$

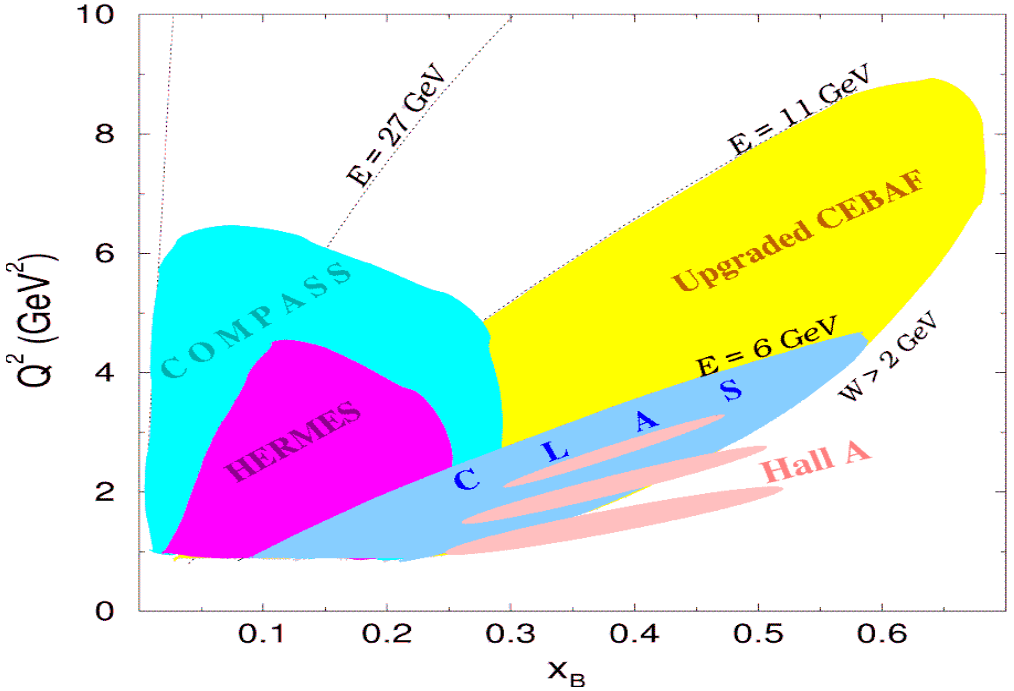


DVCS experiments worldwide

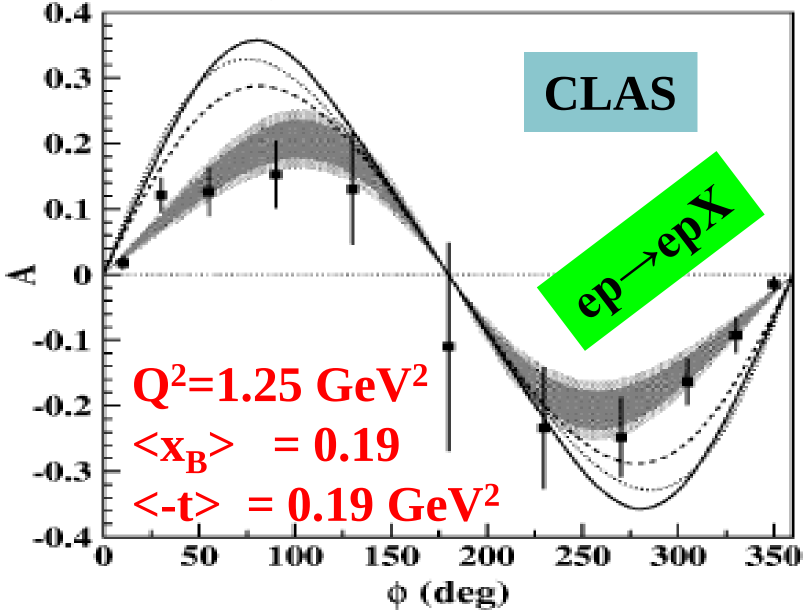
JLAB	
Hall A	***CLAS (Hall B)***
p,n-DVCS, Beam-pol. CS	p-DVCS, BSA,lTSA,DSA,CS

DESY	
HERMES	***H1/ZEUS***
p-DVCS,BSA,BCA, tTSA,lTSA,DSA	p-DVCS,CS,BCA

CERN
COMPASS
p-DVCS CS,BSA,BCA, tTSA,lTSA,DSA



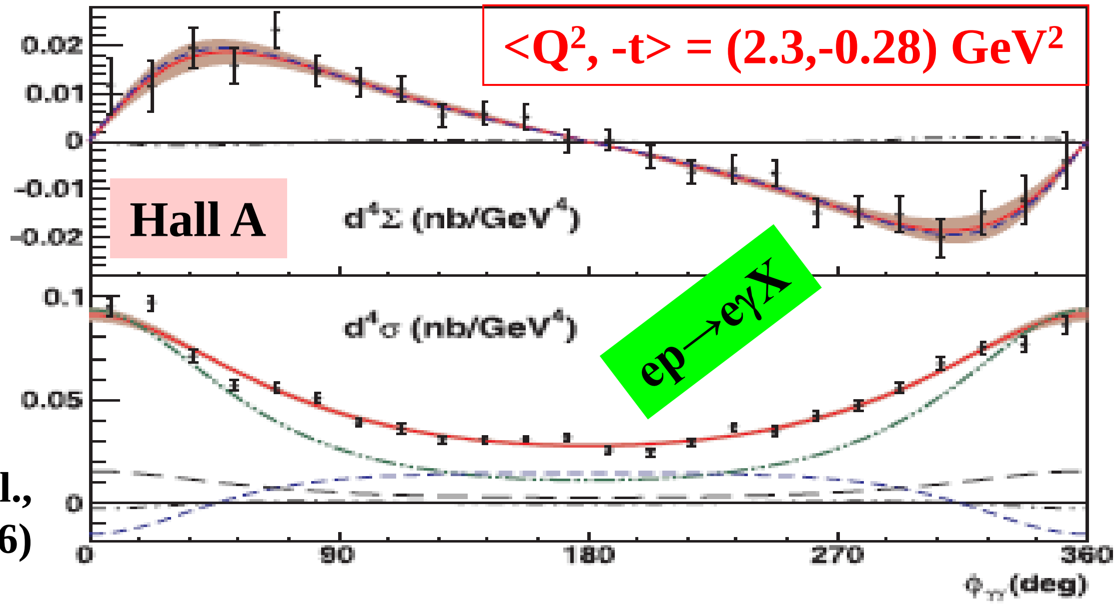
S. Stepanyan et al., PRL 87 (2001)



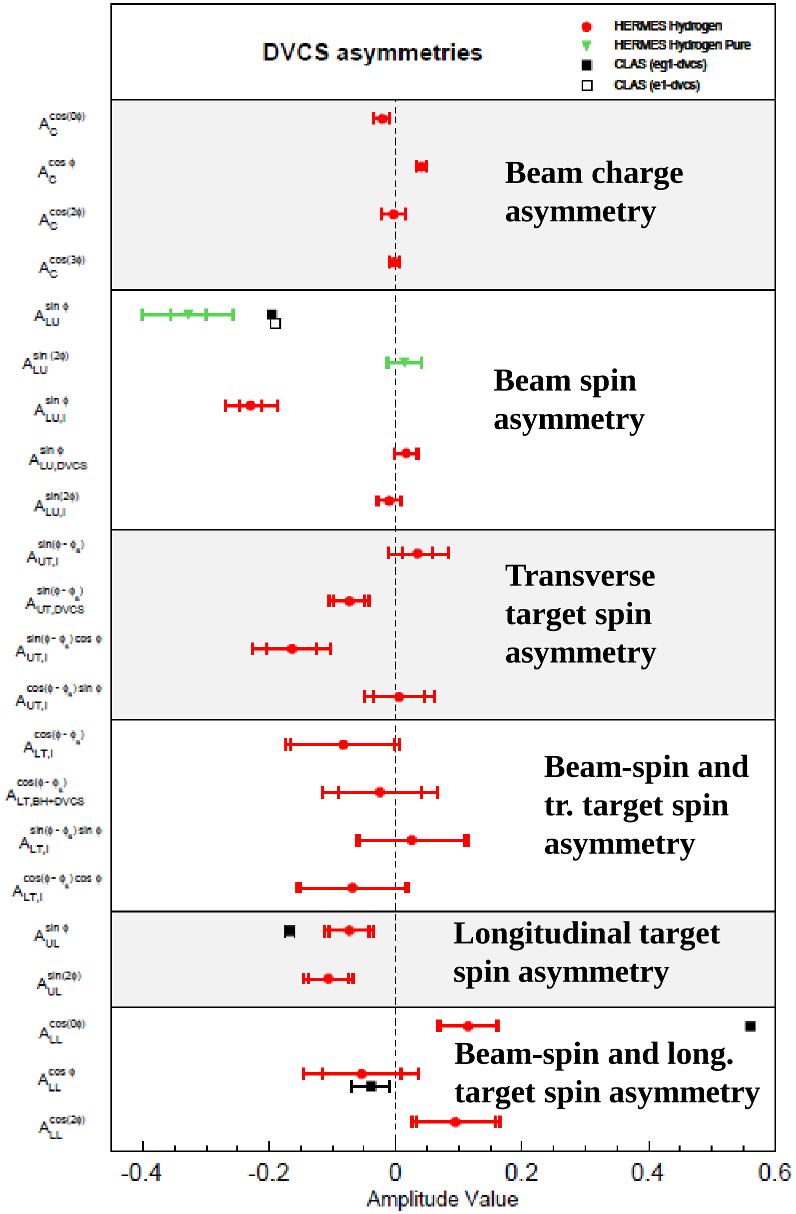
CLAS, HERMES: first observation of DVCS-BH interference

Hall A: proof of scaling for DVCS

C.M. Camacho et al., PRL 97 (2006)

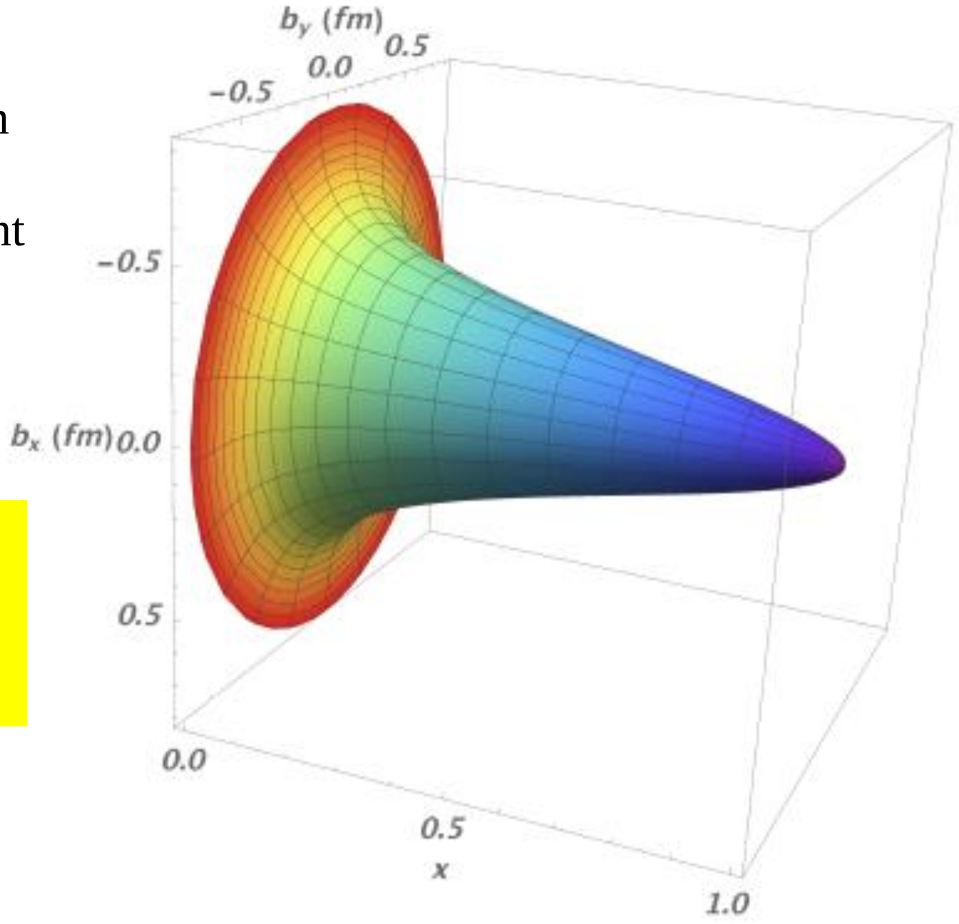


Measured p-DVCS observables and proton tomography



Proton tomography obtained from *local fits* to HERMES, CLAS, and Hall-A data (Im$\mathcal{H}$ + model dependent assumptions for x dependence)

High-momentum quarks (valence) are at the core of the nucleon, low-momentum quarks (sea) are at its periphery



R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95, 011501 (2017)

YouTube video on proton structure: https://www.youtube.com/watch?v=G-9I0buDi4s

Distribution of forces in the proton

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t) + \frac{4}{5}\xi^2 d_1(t)$$

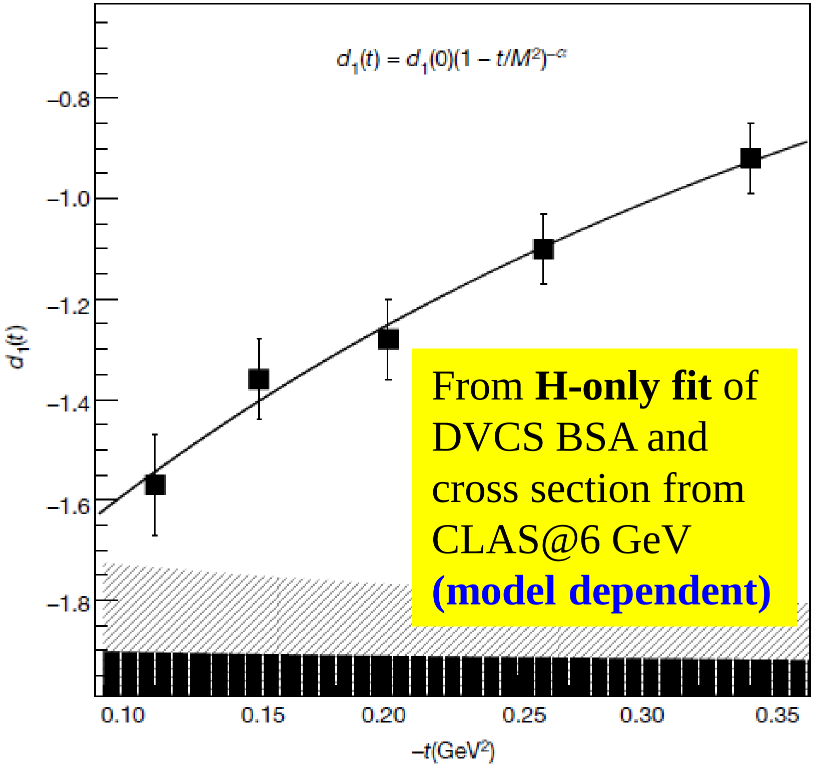
Second Mellin moment of H in x: **gravitational form factor** of the energy-momentum tensor → shear forces and pressure (d_1)

$$\mathrm{Re}\mathcal{H}(\xi,t) + i\mathrm{Im}\mathcal{H}(\xi,t) = \int_{-1}^{1}\mathrm{d}x\left(\frac{1}{\xi-x-i\epsilon}-\frac{1}{\xi+x-i\epsilon}\right)H(x,\xi,t)\ (1)$$

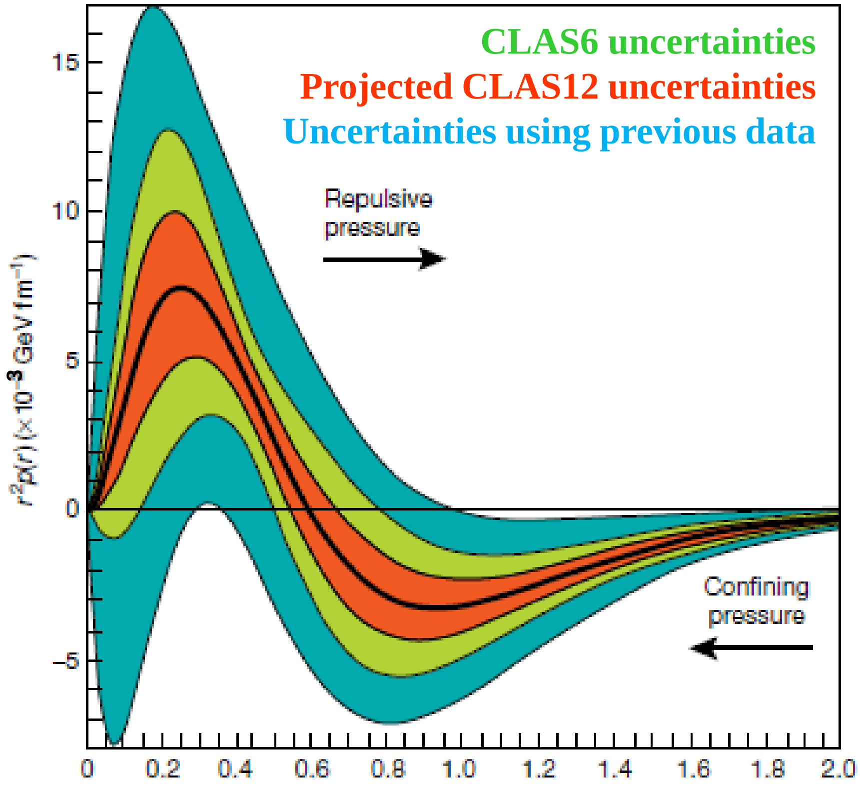
$$\mathrm{Re}\mathcal{H}(\xi,t) \overset{\mathrm{lo}}{=} D(t) + \mathcal{P}\int_{-1}^{1}\mathrm{d}x\left(\frac{1}{\xi-x}-\frac{1}{\xi+x}\right)\mathrm{Im}\mathcal{H}(x,t)$$

$$D(t) = \frac{1}{2}\int_{-1}^{1}\frac{D(z,t)}{1-z}\mathrm{d}z \qquad D(z,t) = (1-z^2)[d_1(t)C_1^{3/2}(z)+\cdots]$$

$$d_1(t) \propto \int \frac{j_0(r\sqrt{-t})}{2t}p(r)\mathrm{d}^3r$$



From **H-only fit** of DVCS BSA and cross section from CLAS@6 GeV **(model dependent)**



V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

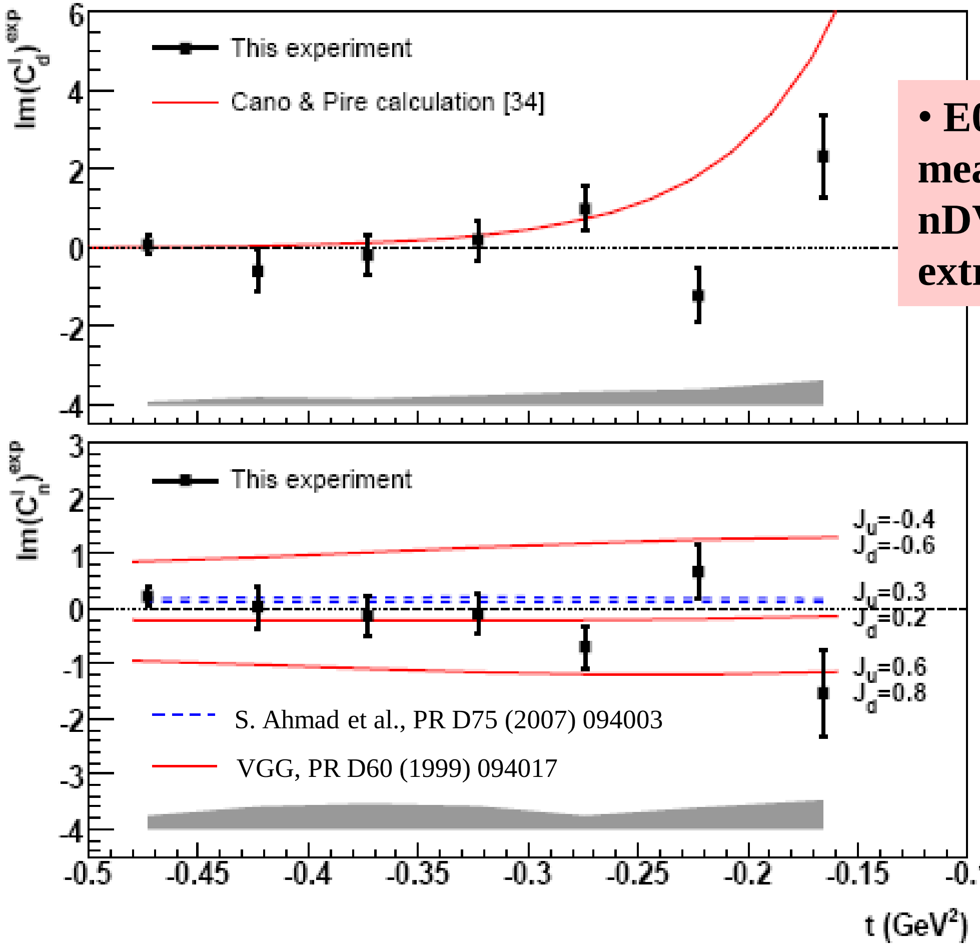
$\vec{e}d \to e\gamma(np)$

DVCS on the neutron in Hall A at 6 GeV

$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \dots$$

Q^2=1.9 GeV^2 x_B=0.36

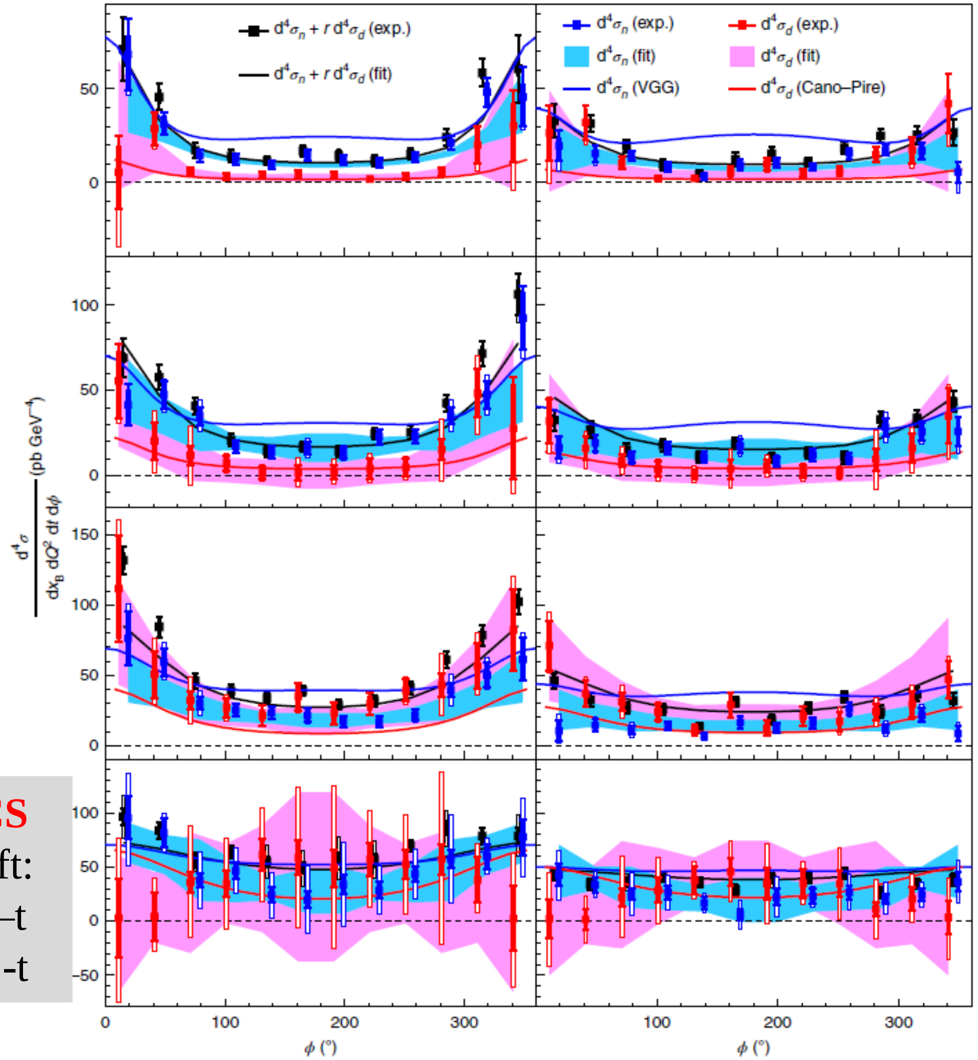
$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}$



- **E03-106**: **First-time measurement of $\Delta\sigma_{LU}$ for nDVCS, model-dependent extraction of J_u, J_d**

nDVCS and coherent **dDVCS** separated through MM^2_X shift:

- large correlations at low –t
- good separation at larger -t

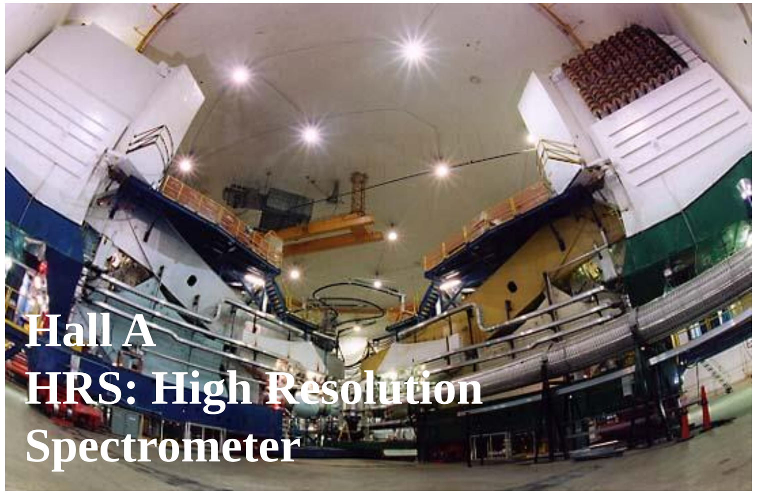


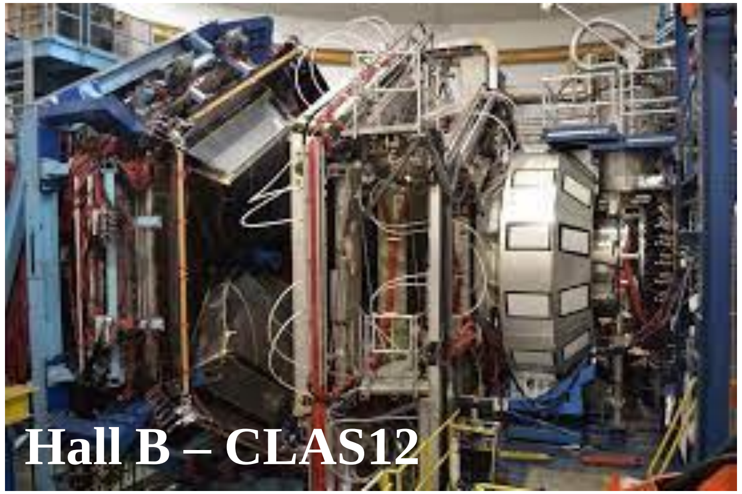
M. Mazouz et al., PRL 99 (2007) 242501

Hall-A experiment E08-025 (2010)

- Beam-energy « Rosenbluth » separation of nDVCS CS (two beam energies)
- First observation of non-zero nDVCS CS
- **M. Benali et al., Nature 16 (2020)**

Jefferson Lab at 12 GeV





Continuos Electron Beam Accelerator Facility (CEBAF)

- Up to 12 GeV continuous polarized electron beam
- Two anti-parallel linacs, with recirculating arcs on both ends
- 4 experimental halls, 3 devoted to nucleon-structure studies

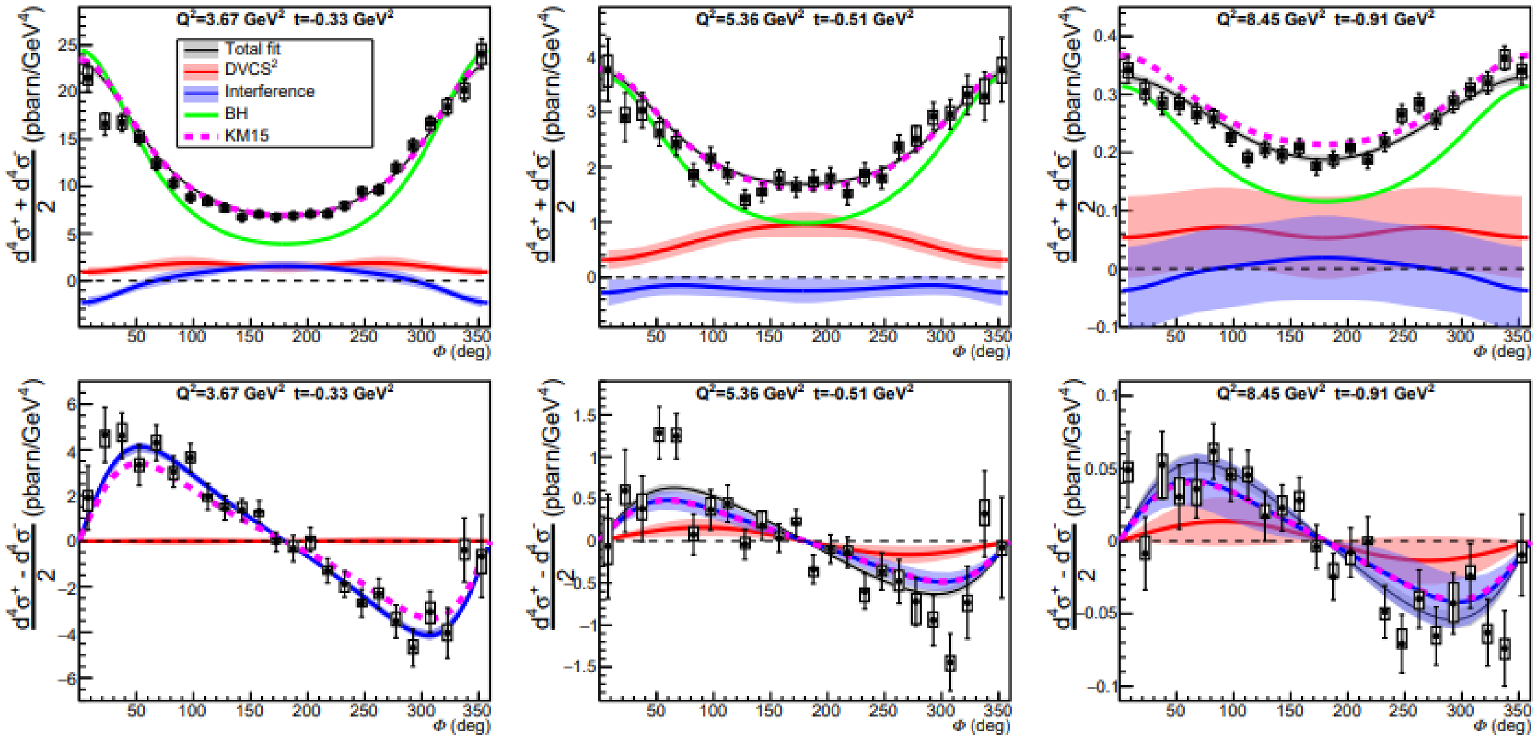
JLab@12 GeV DVCS program

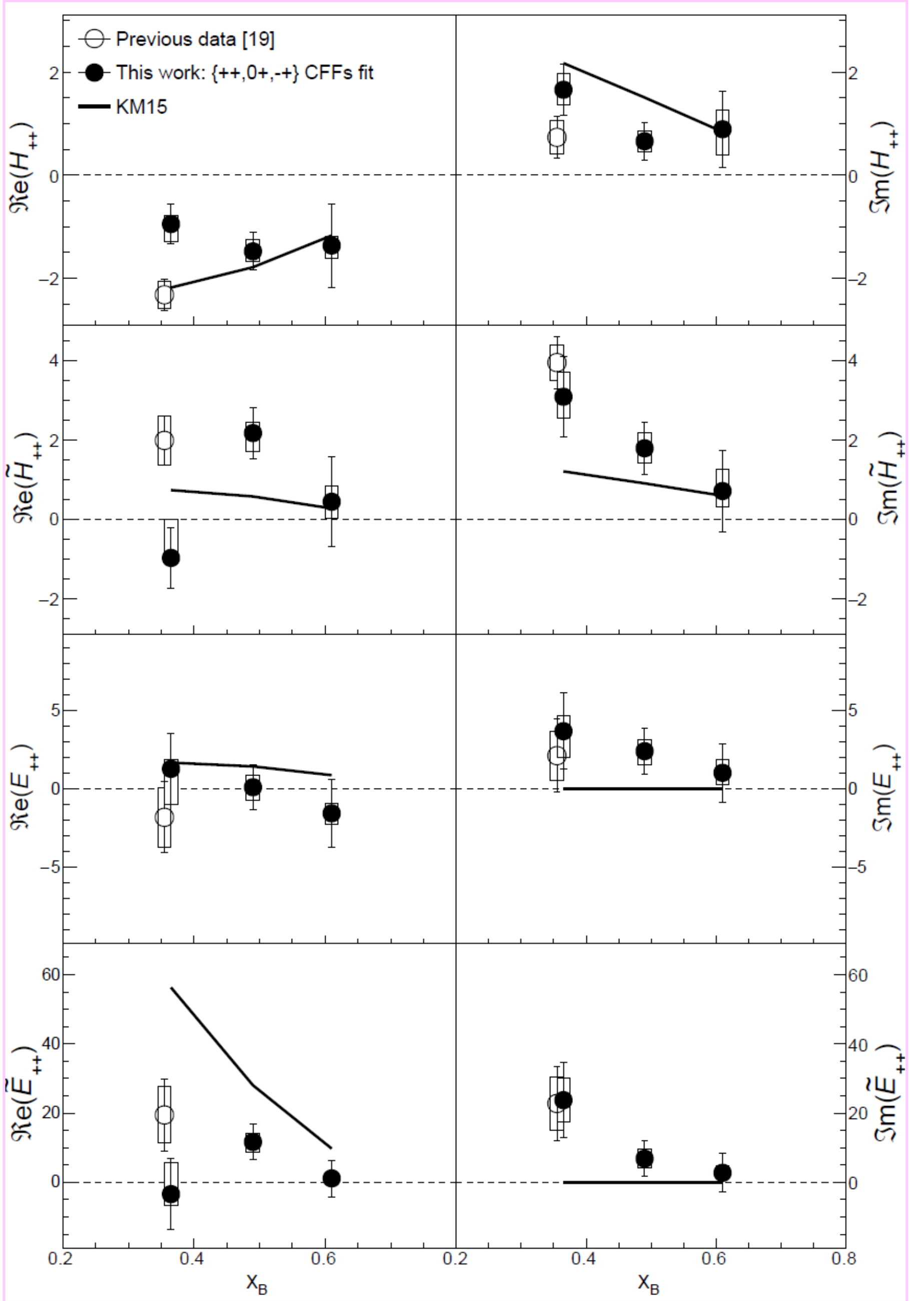
Observable (target)	**12-GeV experiments**	**CFF sensitivity**	**Status**
σ, $\Delta\sigma_{\text{beam}}$(p)	Hall A CLAS12 Hall C	Re$\mathcal{H}$(p), Im$\mathcal{H}$(p)	Hall A: data taken in 2016; e-Print: 2201.03714 [hep-ph] CLAS12: data taken in 2018-2019; CS analysis in progress Hall C: experiment planned for 2023-2024
BSA(p)	CLAS12	Im$\mathcal{H}$(p)	BSA publication in Ad Hoc review stage
lTSA(p), lDSA(p)	CLAS12	Im$\tilde{\mathcal{H}}$(p), Im$\mathcal{H}$(p), Re$\tilde{\mathcal{H}}$(p), Re$\mathcal{H}$(p)	Experiment just started! (will last 6 months)
tTSA(p)	CLAS12	Im$\mathcal{H}$(p), Im$\mathcal{E}$(p)	Experiment foreseen for ~2025
BSA(n)	CLAS12	Im$\mathcal{E}$(n)	Data taken in 2019-2020, BSA analysis undergoing CLAS review
lTSA(n), lDSA(n)	CLAS12	Im$\mathcal{H}$(n), Re$\mathcal{H}$(n)	Experiment just started! (will last 6 months)

Complementarity of the experimental setups in the JLab Halls A/C and B

- Hall A/C: high luminosity → precision, small kinematic coverage, eγ topology
- Hall B (CLAS12): lower luminosity, large kinematic coverage, fully exclusive final state

Hall-A@11 GeV: high-precision cross sections for DVCS on the proton

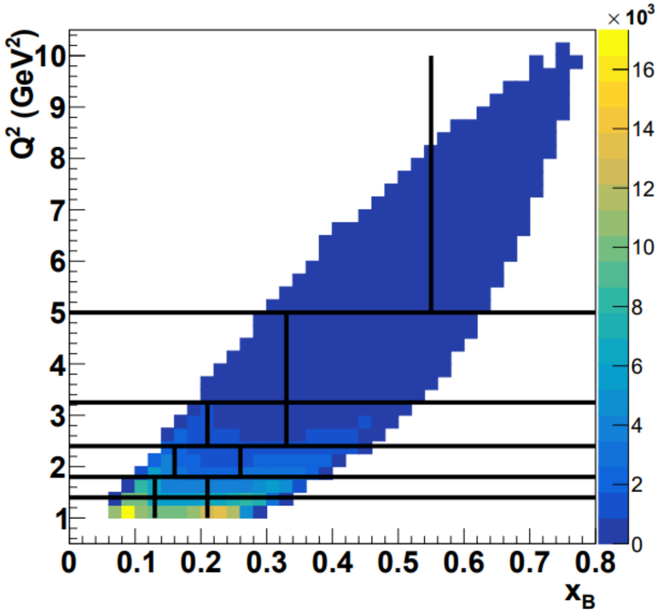




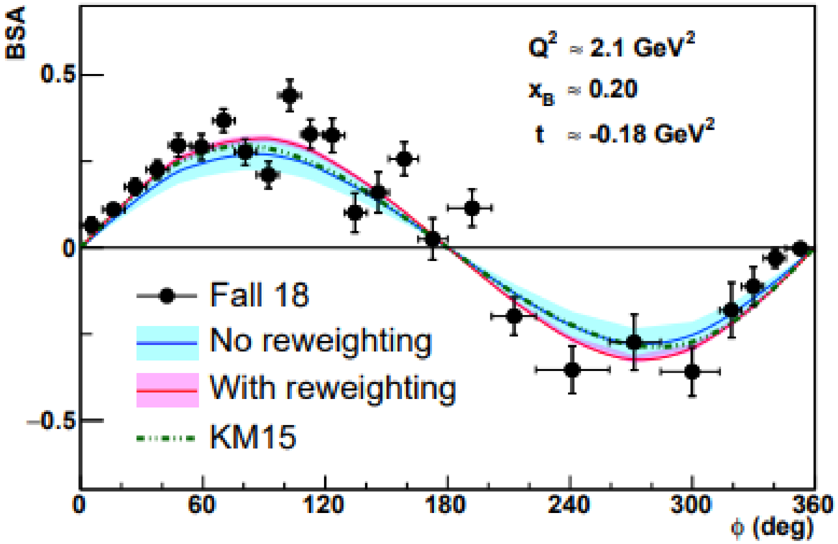
- High precision DVCS cross sections up to large x_B, for 3 beam energies
- Sensitivity to all 4 Compton form factors
- Kinematical power corrections ($\sim t/Q^2$, $\sim M/Q^2$) included in the analysis

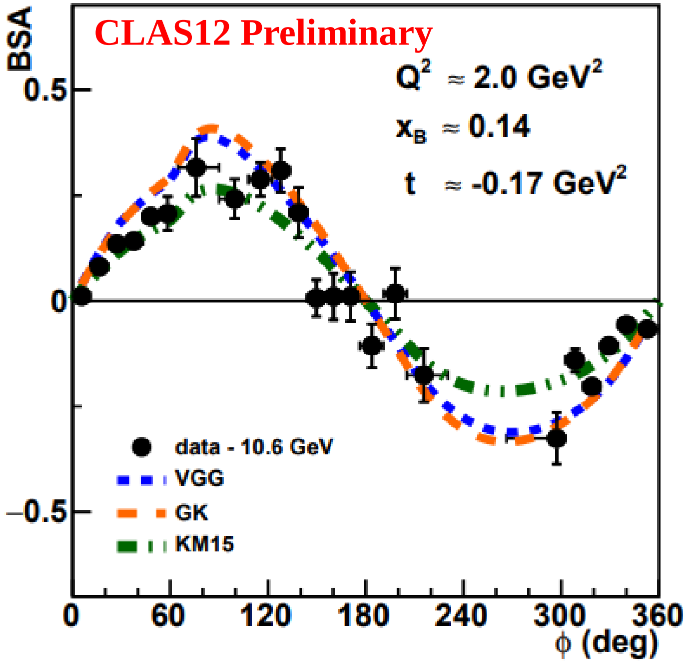
Results submitted to Phys. Rev. Lett.
https://arxiv.org/abs/2201.03714

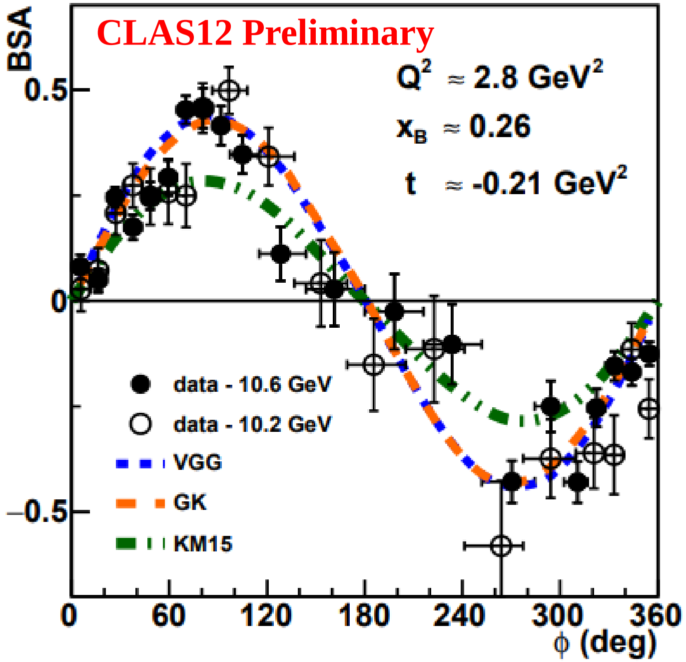
CLAS12: preliminary beam spin asymmetry for DVCS on the proton

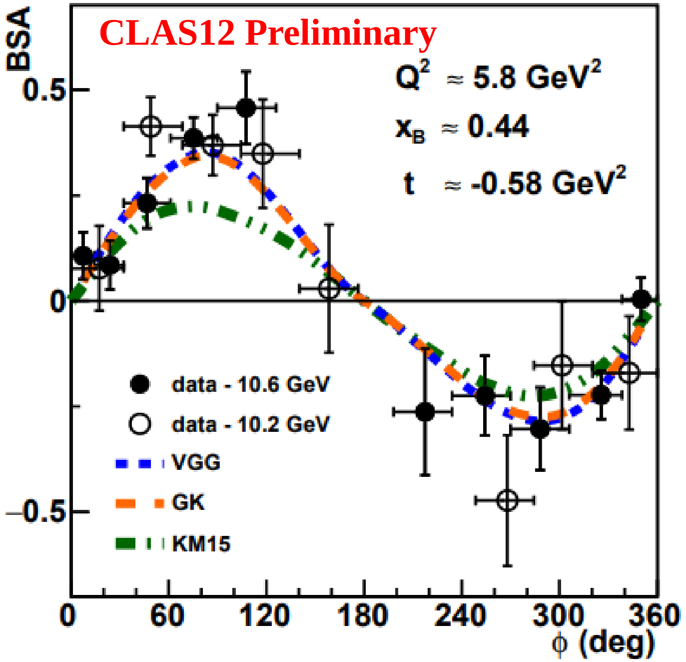


- Polarized beam (86%) with energy 10.6 GeV
- Unpolarized LH2 target
- 64 kinematical bins (Q^2, x_B, $-t$)
- Many kinematics never covered before
- In previously measured kinematics, the new data are shown to be in good agreement with existing data and improve the precision of GPD fits







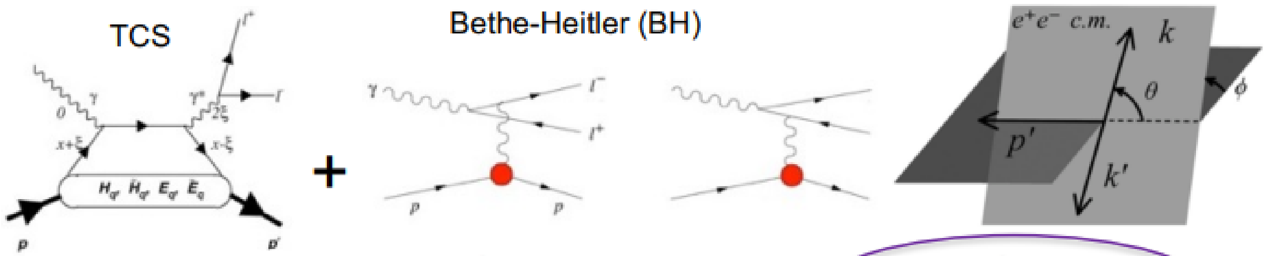


Examples of kinematics only accessible with ~10.6-GeV beam

First-ever measurement of Timelike Compton Scattering (CLAS12)

- The beam helicity asymmetry of TCS accesses the imaginary part of the CFF in the same way as in DVCS and probes the universality of GPDs
- The forward-backward asymmetry is sensitive to the real part of the CFF → direct access to the Energy-Momentum Form Factor $D_q(t)$ (linked to the D-term) that relates to the mechanical properties of the nucleon (quark pressure distribution)
- This measurement proves the importance of TCS for GPD physics.
- Limits: very small cross section → high luminosity is necessary for a precise measurement

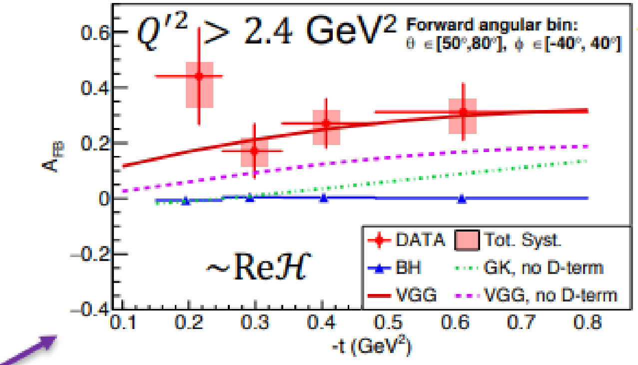
TCS – time-reversal symmetric process to DVCS:
incoming photon is real, and the outgoing photon has large time-like virtuality.

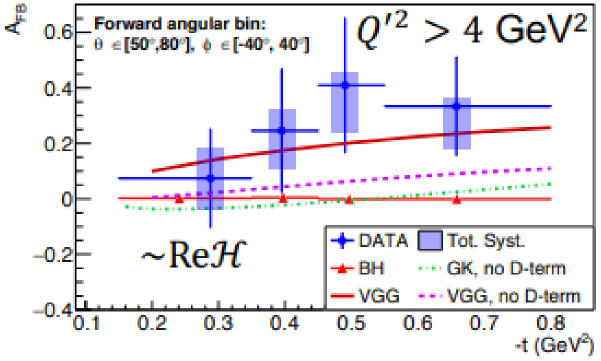


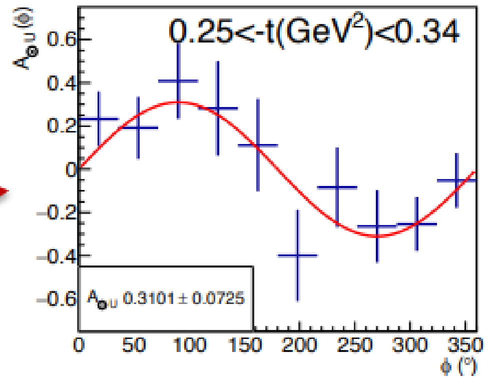
$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\,\frac{1}{-t}\,\frac{M}{Q'}\,\frac{1}{\tau\sqrt{1-\tau}}\,\frac{L_0}{L}\left[\boxed{\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\tilde{M}^{--}}\right.$$
$$\left. -\cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\tilde{M}^{0-} + \cos 3\varphi\,\sin\theta\,\mathrm{Re}\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right)\right]$$

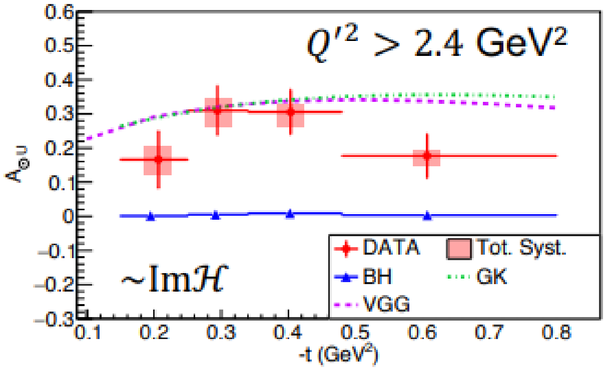
Incoming photon polarization

$$\boxed{-\lambda}\,\frac{\alpha_{em}^3}{4\pi s^2}\,\frac{1}{-t}\,\frac{M}{Q'}\,\frac{1}{\tau\sqrt{1-\tau}}\,\frac{L_0}{L}\left[\boxed{\sin\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Im}\tilde{M}^{--}}\right.$$
$$\left. -\sin 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Im}\tilde{M}^{0-} + \sin 3\varphi\,\sin\theta\,\mathrm{Im}\tilde{M}^{+-} + O\left(\frac{1}{Q'}\right)\right].$$







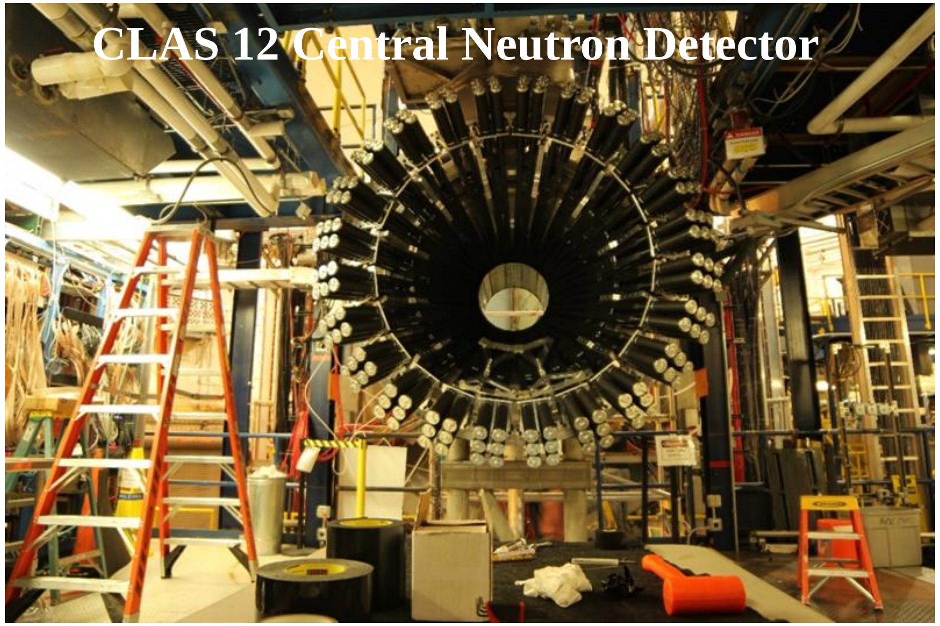


P. Chatagnon et al. (CLAS), Phys. Rev. Lett. 127, 262501 (2021)

Preliminary CLAS12 results: Beam Spin Asimmetry for neutron DVCS

$\vec{e}d \rightarrow en\gamma(p)$

First-time measurement of nDVCS with detection of the active neutron

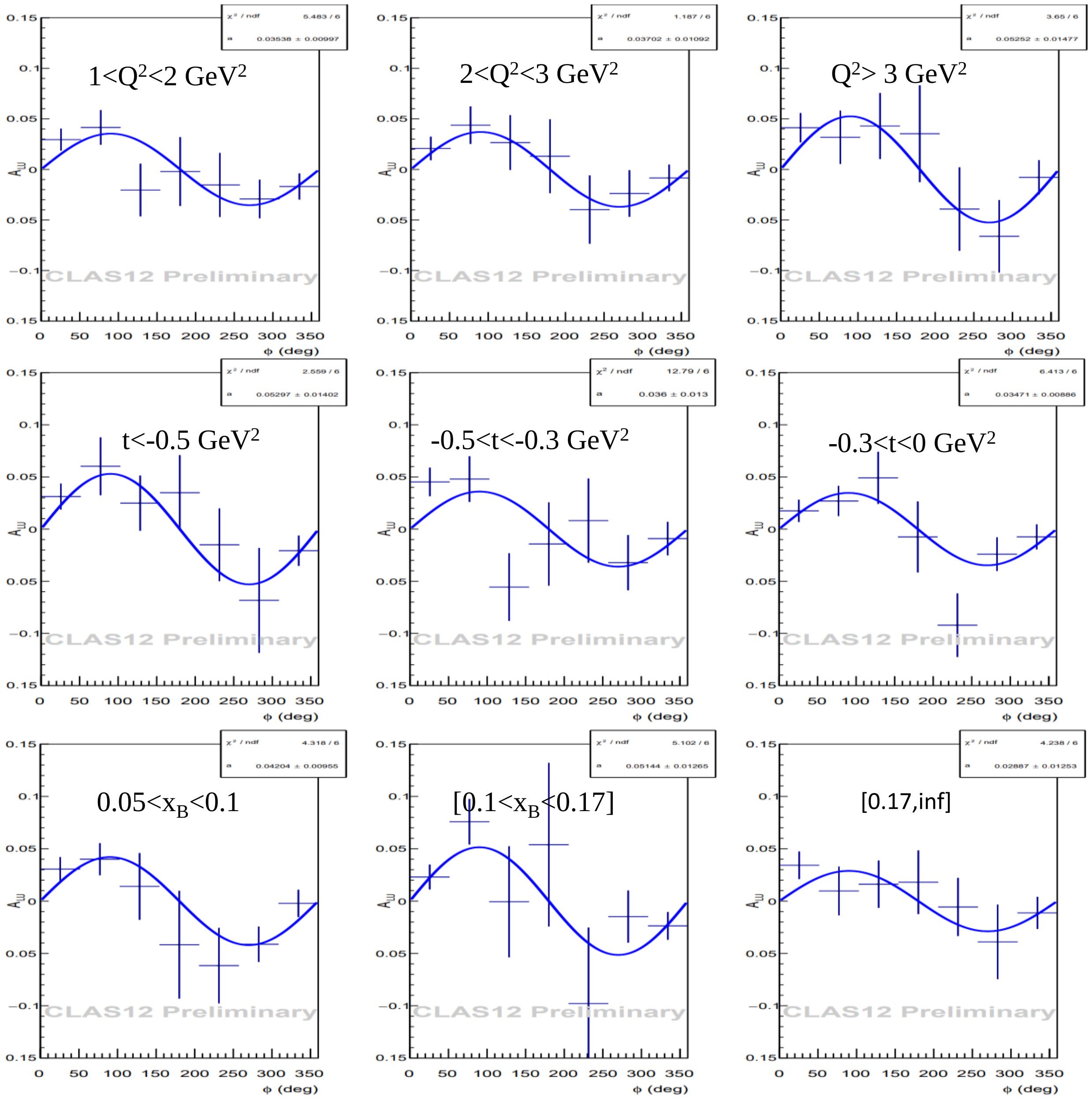

CLAS 12 Central Neutron Detector

- Scan of the BSA of nDVCS on a wide phase space
- Reaching the high $Q2$- high xb region of the phase space
- Exclusive measurement with the detection of the active neutron → small systematics

Q^2 bins

t bins

x_B bins



Recap: what have we learned so far

- ImH well constrained, in CLAS (and soon CLAS12) kinematics → proton tomography
- ReH constrained mainly by Hall A measurements in selected kinematics; important for D-term and distribution of forces
- Initial constraints on $\tilde{\mathcal{H}}$ from longitudinally polarized target experiments, more data coming soon
- Potential of TCS for Re$\mathcal{H}$, D-term, universality of GPDs
- Importance of nDVCS for E_n sensitivity and flavor separation, but low statistics
- pDVCS on transverse target is vital to constrain E_p
- Still no information on x dependence of GPDs
- DVMP: only pseudo-scalars had until now a « succesful » GPD interpretation (transversity) → higher Q^2 may be necessary

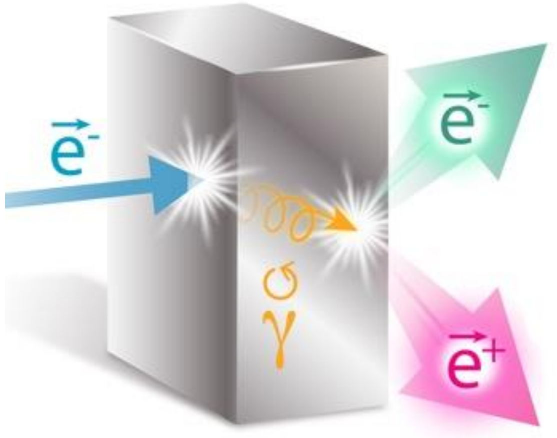
Perspectives beyond the approved 12-GeV JLab program

- **Upgrades for JLab** under discussion:
  - ✓ Polarized positrons beam
  - ✓ Higher luminosity for CLAS12
  - ✓ Double CEBAF beam energy
- **Electron-Ion Collider (EIC)**

Polarized positrons beam for Jefferson Lab

Physics Motivations:

- Two-photon physics
- **Generalized parton distributions**
- Neutral and charged current DIS
- Charm production
- Neutral electroweak coupling
- Light Dark Matter search
- Charged Lepton Flavor Violation



PePPO: proof-of-principle for a polarized positron beam
PRL 116 (2016) 214801

- Publication of the **EPJ A Topical Issue about "An experimental program with positron beams at Jefferson lab"** gathering about 250 physicists from 75 institutions around a several-years-long experimental program.
- Two DVCS-based proposals were submitted to JLab PAC48 and were Conditionally Approved

An Experimental Program with Positron Beams at Jefferson Lab

A. Accardi[1,39], A. Afanasev[3], I. Albayrak[41], S.F. Ali[56], M. Amaryan[17], J.R.M. Annand[37], J. Arrington[11], A. Asaturyan[59], H. Avakian[1], T. Averett[57], C. Ayerbe Gayoso[15], L. Barion[32], M. Battaglieri[1,9], V. Bellini[28], F. Benmokhtar[48], V. Berdnikov[56], J.C. Bernauer[20,22], A. Bianconi[27,45], A. Biselli[31], M. Boer[29], M. Bondi[9], K.-T. Brinkmann[34], W.J. Briscoe[3], V. Burkert[1], T. Cao[39], A. Camsonne[1], R. Capobianco[21], L. Cardman[1], M. Carmignotto[1], M. Caudron[2], L. Causse[2], A. Celentano[9], P. Chatagnon[2], T. Chetry[15], G. Ciullo[32,33], E. Cline[20], P.L. Cole[24], M. Contalbrigo[32], G. Costantini[27,45], A. D'Angelo[52,53], D. Day[5], M. Defurne[35], M. De Napoli[28], A. Deur[1], R. De Vita[9], N. D'Hose[35], S. Diehl[21,34], M. Diefenthaler[1], B. Dongwi[39], R. Dupré[2], D. Dutta[15], M. Ehrhart[2], L. El-Fassi[15], L. Elouadrhiri[1], R. Ent[1], J. Erler[13,14], I.P. Fernando[39], A. Filippi[55], D. Flay[1], T. Forest[49], E. Fuchey[21], S. Fucini[18], Y. Furletova[1], H. Gao[7], D. Gaskell[1], A. Gasparian[38], T. Gautam[39], F.-X. Girod[21], J. Grames[1], P. Gueye[30], M. Guidal[2], S. Habet[2], D.J. Hamilton[37], O. Hansen[1], D. Hasell[4], M. Hattawy[17], D.W. Higinbotham[1], A. Hobart[2], T. Horn[56], C.E. Hyde[17], H. Ibrahim[36], A. Italiano[28], K. Joo[21], S.J. Joosten[11], N. Kalantarians[50], G. Kalicy[56], D. Keller[5], C. Keppel[1], M. Kerver[17], A. Kim[21], J. Kim[11], P.M. King[23], E. Kinney[26], V. Klimenko[21], H.-S. Ko[2], M. Kohl[39], V. Kozhuharov[8,54], V. Kubarovsky[1], T. Kutz[3,4], L. Lanza[52,53], M. Leali[27,45], P. Lenisa[32,33], N. Liyanage[5], Q. Liu[12], S. Liuti[5], J. Mammei[58], S. Mantry[6], D. Marchand[2], P. Markowitz[44], L. Marsicano[9,10], V. Mascagna[27,45], M. Mazouz[16], M. McCaughan[1], B. McKinnon[37], D. McNulty[49], W. Melnitchouk[1], Z.-E. Meziani[11], M. Mihovilovič[43], R. Milner[4], A. Mkrtchyan[59], H. Mkrtchyan[59], A. Movsisyan[32], M. Muhoza[56], C. Muñoz Camacho[2], J. Murphy[23], P. Nadel-Turoński[20], J. Nazeer[39], S. Niccolai[2], G. Niculescu[40], R. Novotny[34], M. Paolone[42], L. Pappalardo[32,33], R. Paremuzyan[29], E. Pasyuk[1], T. Patel[39], I. Pegg[56], C. Peng[11], D. Perera[5], M. Poelker[1], K. Price[2], A.J.R. Puckett[21], M. Raggi[8,19], N. Randazzo[28], M.N.H. Rashad[17], M. Rathnayake[39], B. Raue[44], P.E. Reimer[11], M. Rinaldi[18], A. Rizzo[52,53], J. Roche[23], O. Rondon-Aramayo[5], F. Sabatié[35], G. Salmè[51], E. Santopinto[9], R. Santos Estrada[21], B. Sawatzky[1], A. Schmidt[3], P. Schweitzer[21], S. Scopetta[18], V. Sergeyeva[2], M. Shabestari[46], A. Shahinyan[59], Y. Sharabian[1], S. Širca[43], E. Smith[1], D. Sokhan[37], A. Somov[1], N. Sparveris[47], M. Spata[1], S. Stepanyan[1], P. Stoler[21], I. Strakovsky[3], R. Suleiman[1], M. Suresh[39], H. Szumila-Vance[1], V. Tadevosyan[59], A.S. Tadepalli[1], M. Tiefenback[1], R. Trotta[56], M. Ungaro[1], P. Valente[19], L. Venturelli[27,45], H. Voskanyan[59], E. Voutier[2], B. Wojtsekhowski[1], S. Wood[1], J. Xie[11], Z. Ye[25], M. Yurov[5], H.-G. Zaunick[34], S. Zhamkochyan[59], J. Zhang[5], S. Zhang[1], S. Zhao[2], Z.W. Zhao[7], X. Zheng[5], C. Zorn[1]

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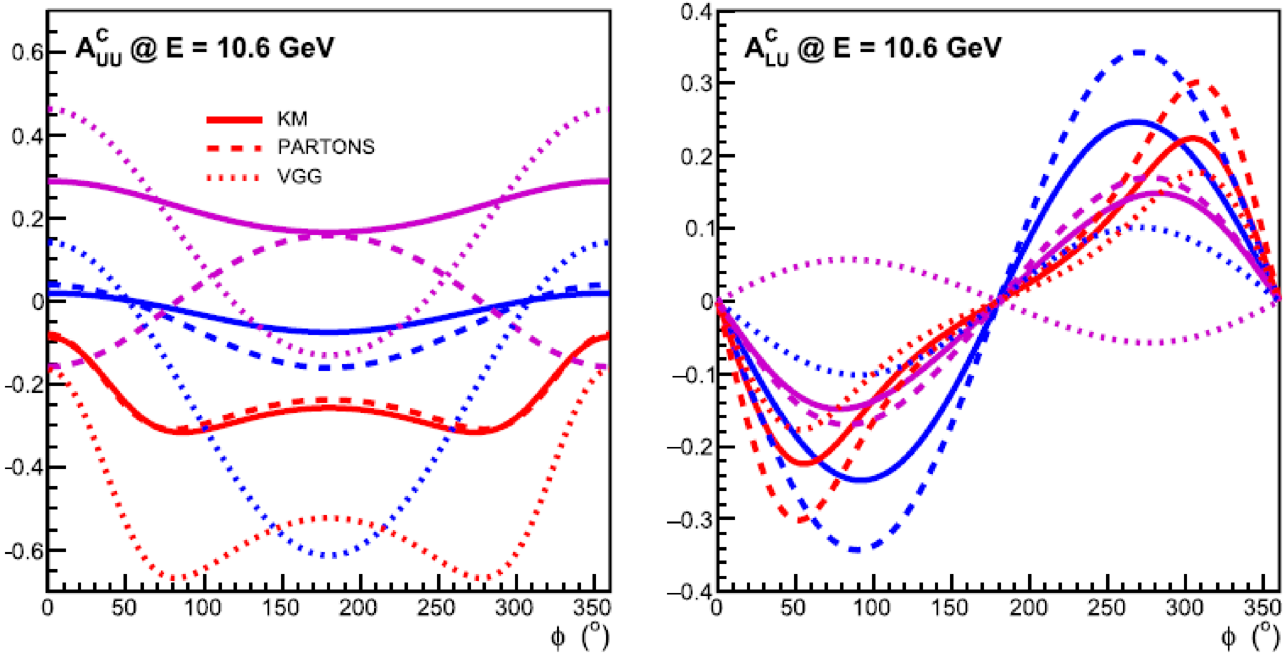
Eur. Phys. J. A 58 (2022) 3, 45

- The ongoing R&D aims to identify the most appropriate implementation of PEPPo at CEBAF, taking into account the many constraints and technological challenges towards the development of a prototype and a CDR
- ***Possible timeline: ~2028-2030? Discussions ongoing at JLab***

pDVCS and nDVCS with polarized positrons beam at CLAS



Model predictions for 2 out of the 3 proposed pDVCS observables

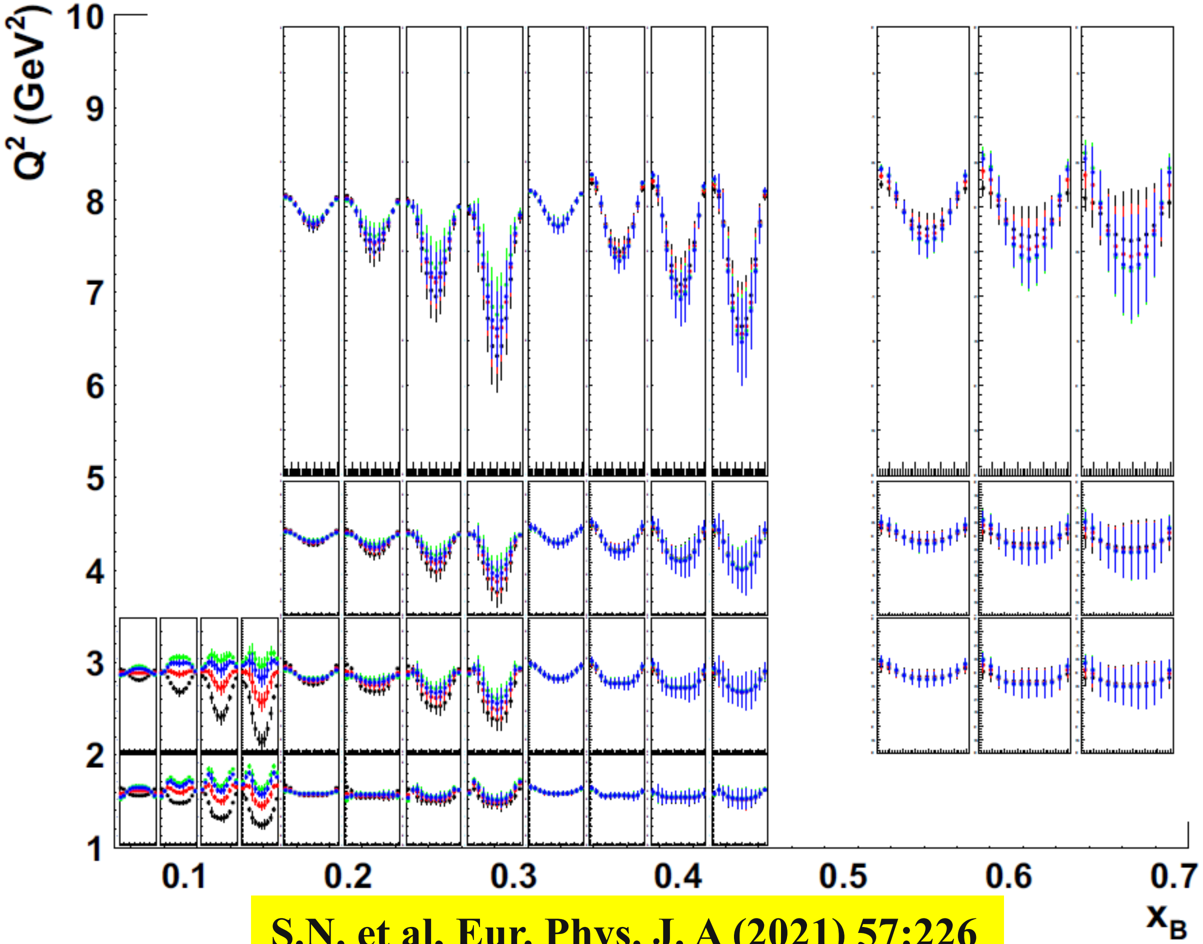
Impact of positron pDVCS projected data on the extraction of ReH via global fits: major reduction of relative uncertainties, especially at low -t

V. Burkert et al., Eur. Phys. J. A (2021) 57

nDVCS Beam-charge asymmetry (BCA):
This observables has a strong impact on the extraction of Re$\mathcal{E}$. This was verified via local fits to the projections of approved CLAS12 nDVCS measurements with and without BCA

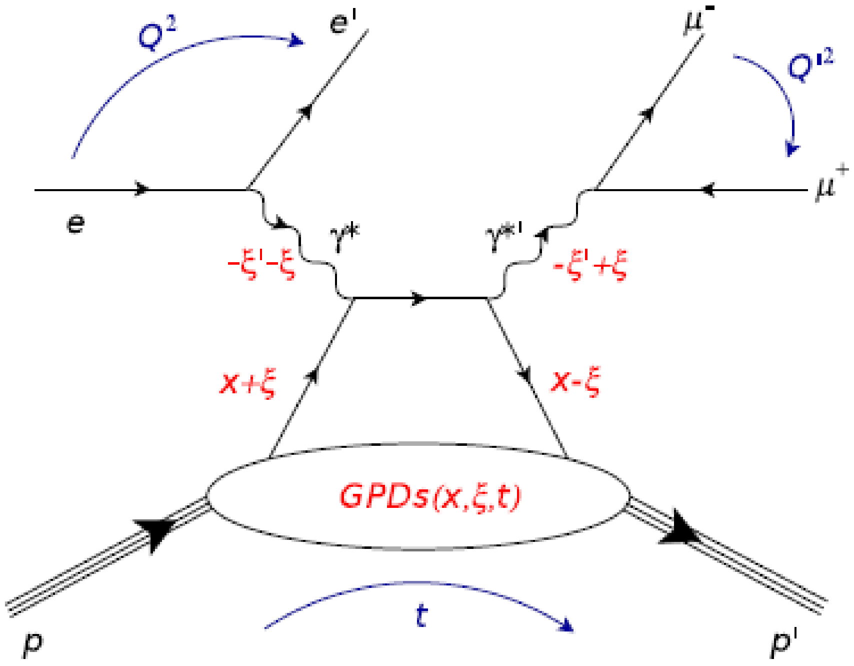
Projections (VGG) for the BCA, for various values of J_u, J_d

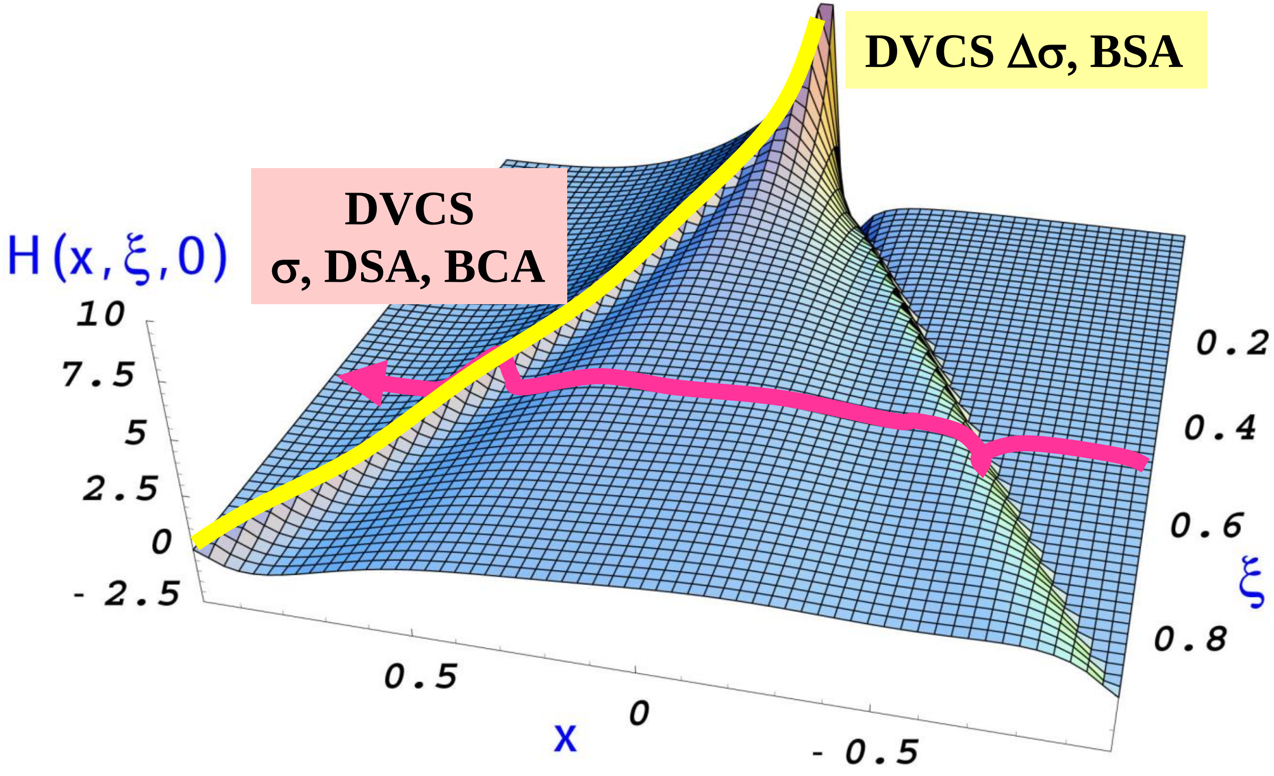
0.3, 0.1; 0.2/0.0; 0.1/−0.1; 0.3/−0.1



S.N. et al, Eur. Phys. J. A (2021) 57:226

DDVCS: the gateway to the full kinematic mapping of GPDs




DVCS Δσ, BSA

DVCS
σ, DSA, BCA

Thanks to the virtuality of the final photon, Q'^2, **DDVCS** allows a unique direct access to GPDs at **$x \neq \pm\xi$** (within $0 < 2\xi' - \xi < \xi$), which is fundamental for their modeling

Experimental challenges:

- Small cross section (300 times less than DVCS)
- Need to detect muons

μCLAS12 for DDVCS and J/psi

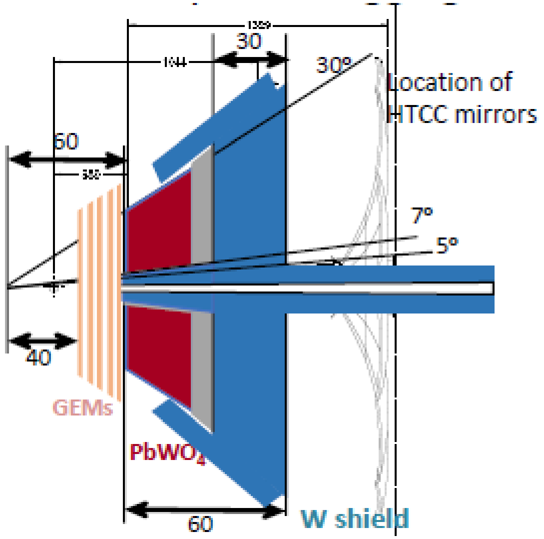
$ep \rightarrow e'p'\mu^+\mu^-$ at $L \sim 10^{37}\ cm^{-2}s^{-1}$

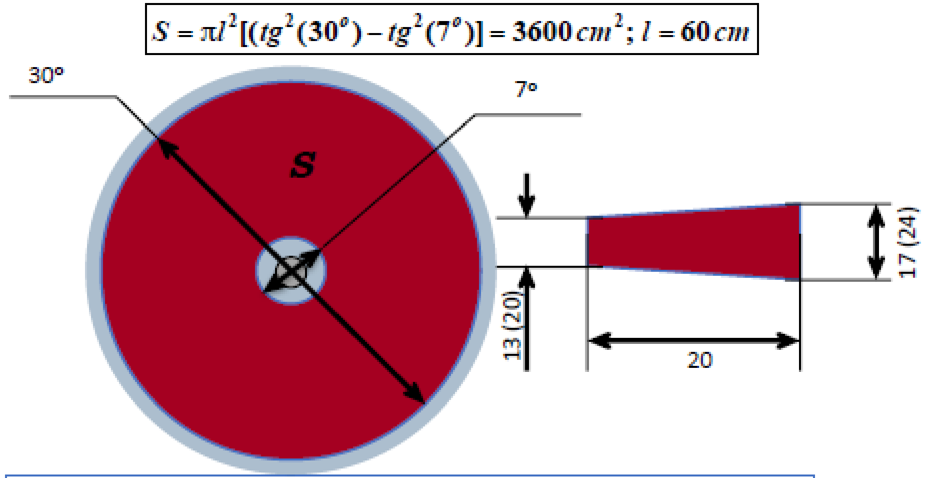
- Remove HTCC and install in the region of active volume of HTCC

- a new Moller cone that extends up to 7°

- a new PbWO4 calorimeter that covers 7° to 30° polar angular range with 2π azimuthal coverage.

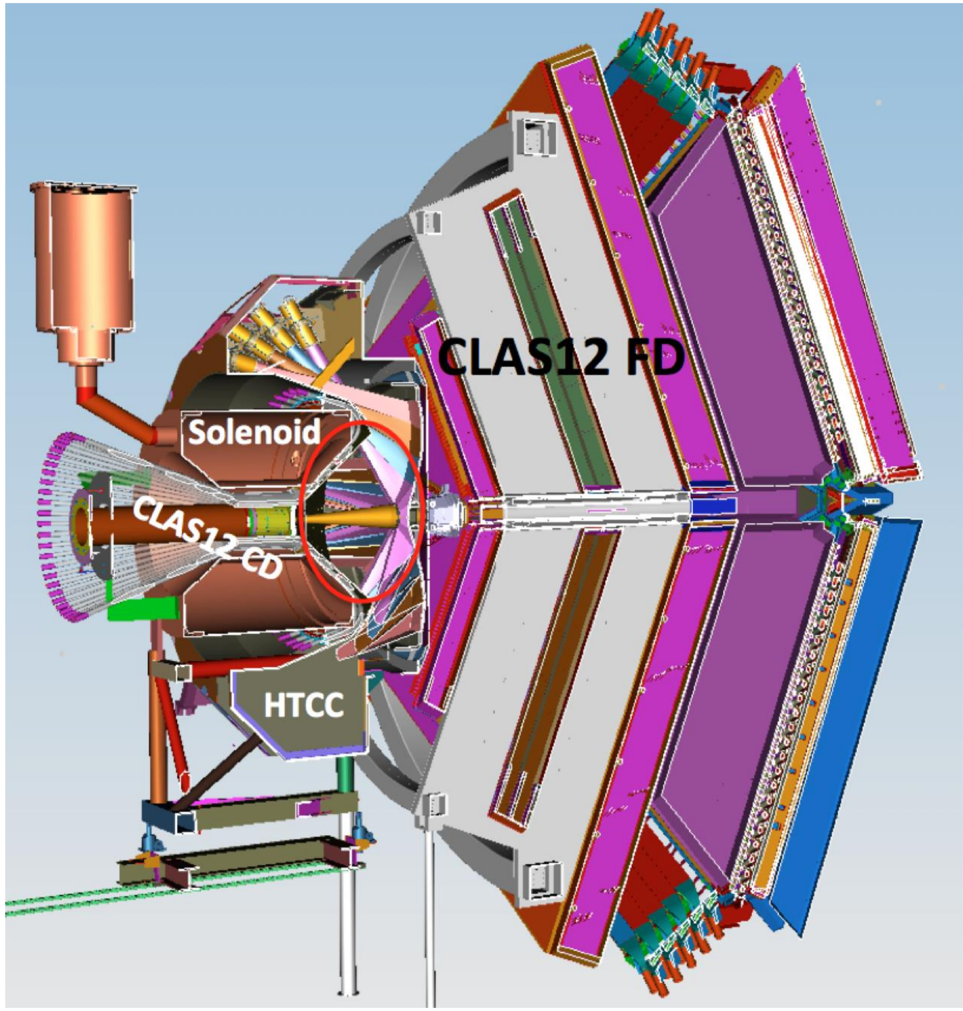
- Behind the calorimeter, a 30-cm-thick tungsten shield covers the whole acceptance of the CLAS12 FD
- MPGD tracker in front of the calorimeter for vertexing and inside the solenoid for recoil proton tagging





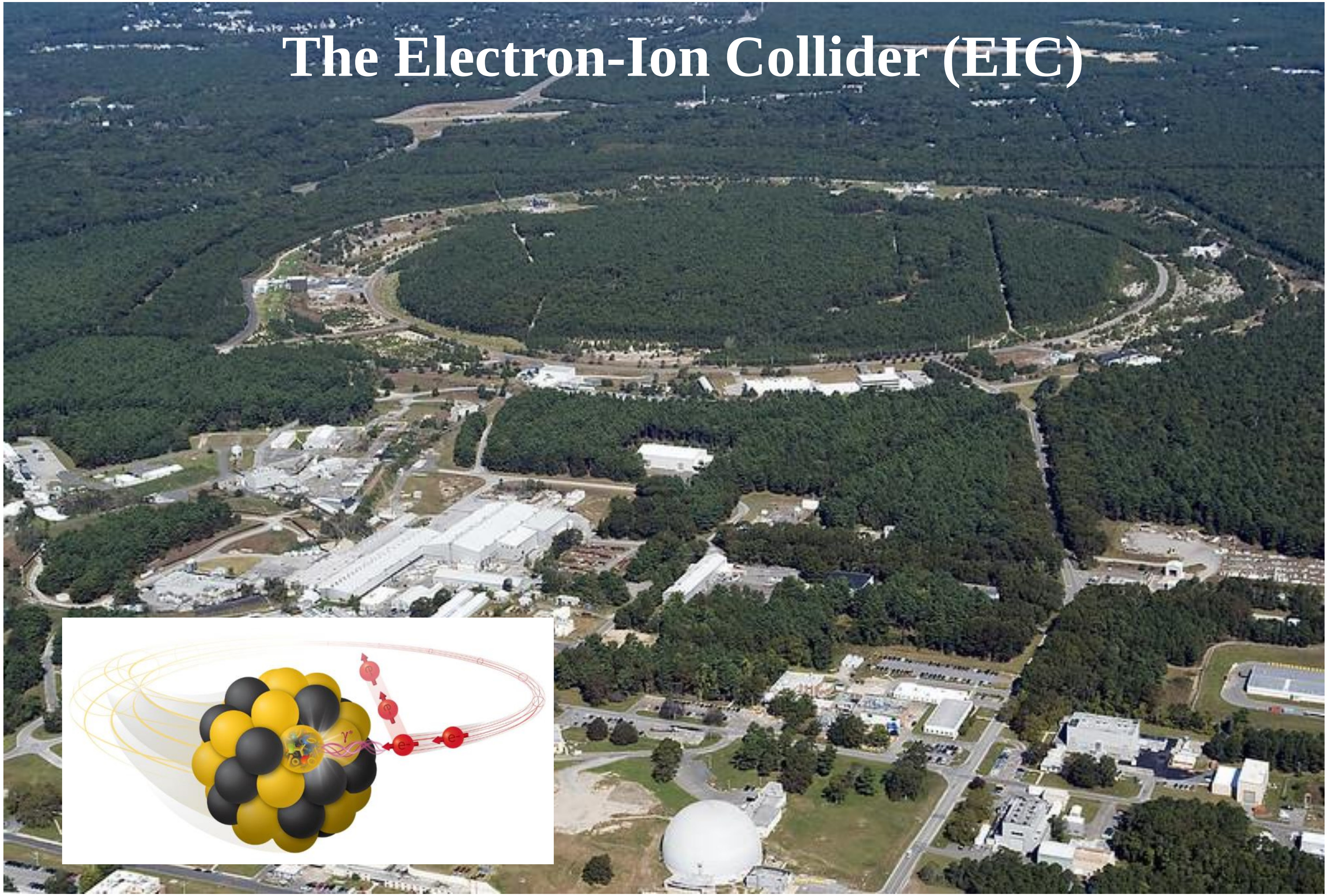
$$S = \pi l^2[(tg^2(30^o) - tg^2(7^o)] = 3600\,cm^2;\ l = 60\,cm$$

$PbWO_4$ modules with APD readout - ~ 1200 modules



S. Stepanyan, LOI12-16-004

The Electron-Ion Collider (EIC)

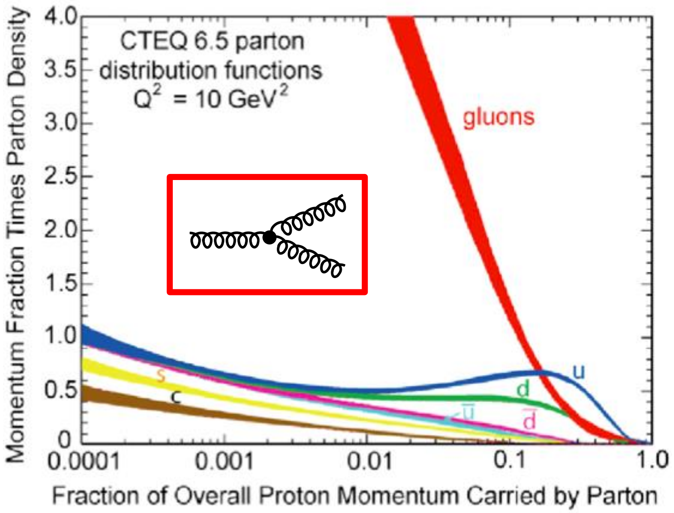


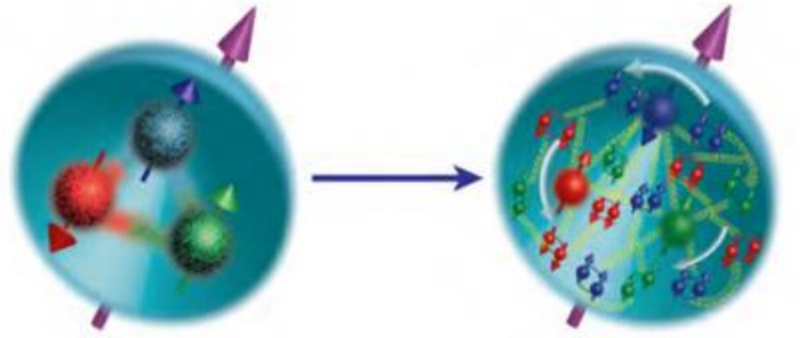
EIC: the answer to many open questions in QCD

Saturation: a new state of hadronic matter?

What happens to the **gluon density** in nuclei at high energies? It cannot grow infinetely…

Is there a **saturation** in some sort of gluonic matter with universal properties (« color glass condensate »)?





Exploring the partonic structure of nucleons and nuclei

How do the **spin** and the **mass** of the nucleon emerge from the dynamics of its constituents?

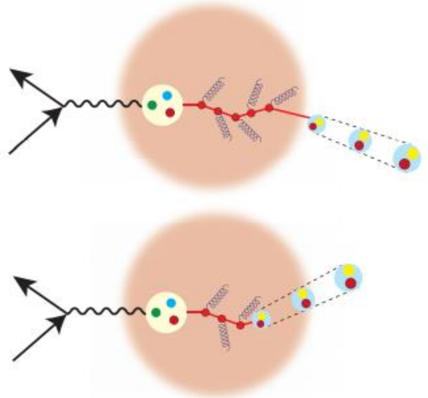
What are the position, momentum and spin distributions of **sea quarks and gluons** in the nucleon and in light nuclei?

What is the role of orbital momentum?

The role of gluons in nuclear medium

How do gluons and sea quarks contribute to nucleon-nucleon force? How does nuclear matter react when a colored charge passes through it?

How does nuclear matter affect quark and gluon distributions and their interactions in nuclei?



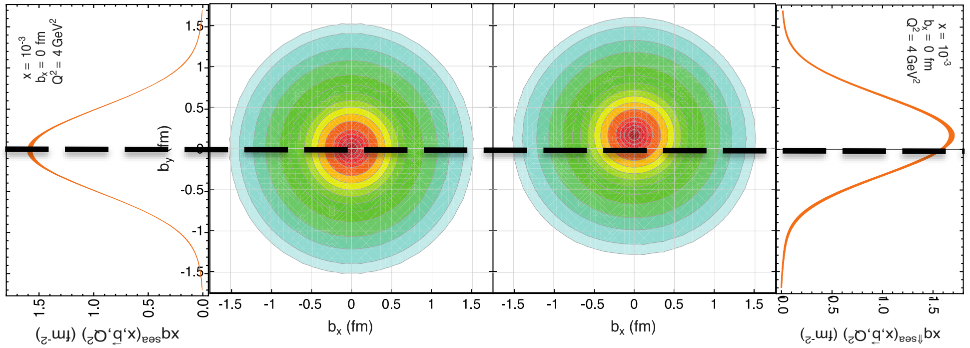
Multi-D partonic image of the nucleon with the EIC

Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum)

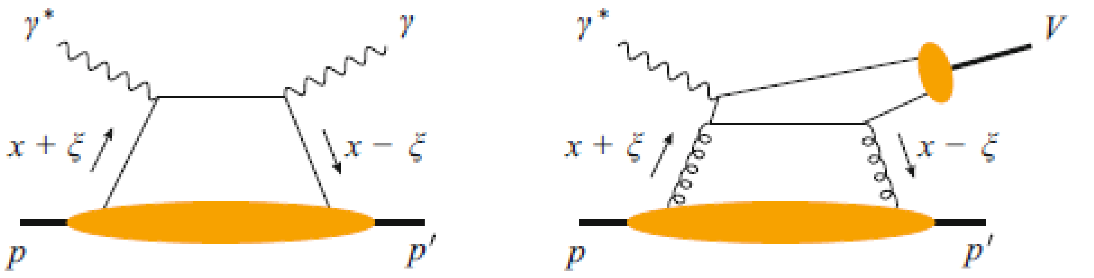
Measurable via **exclusive scattering**

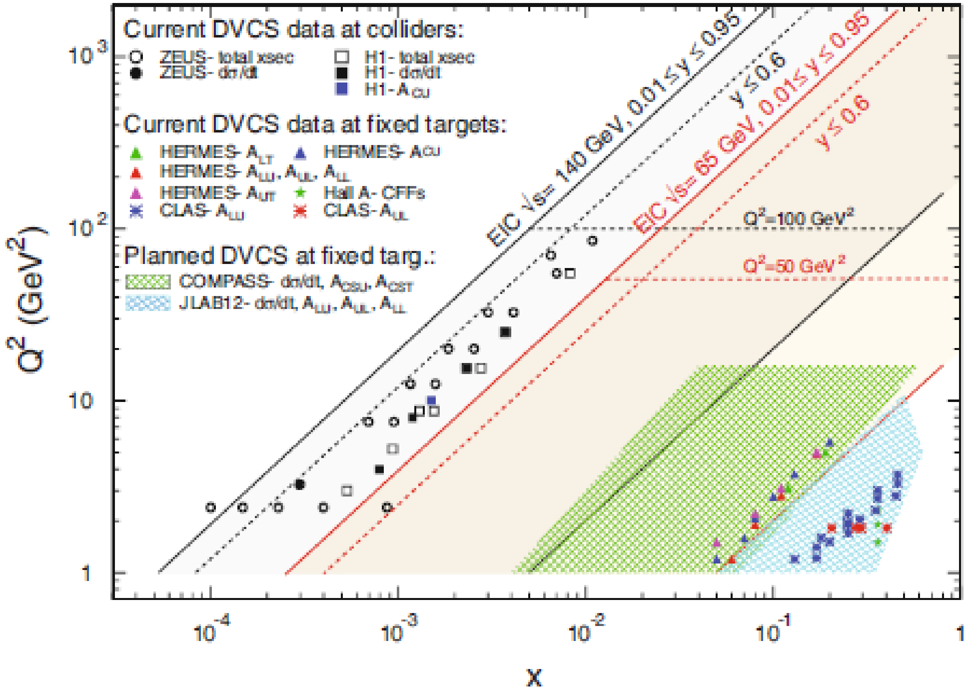
Sea quarks

unpolarized polarized

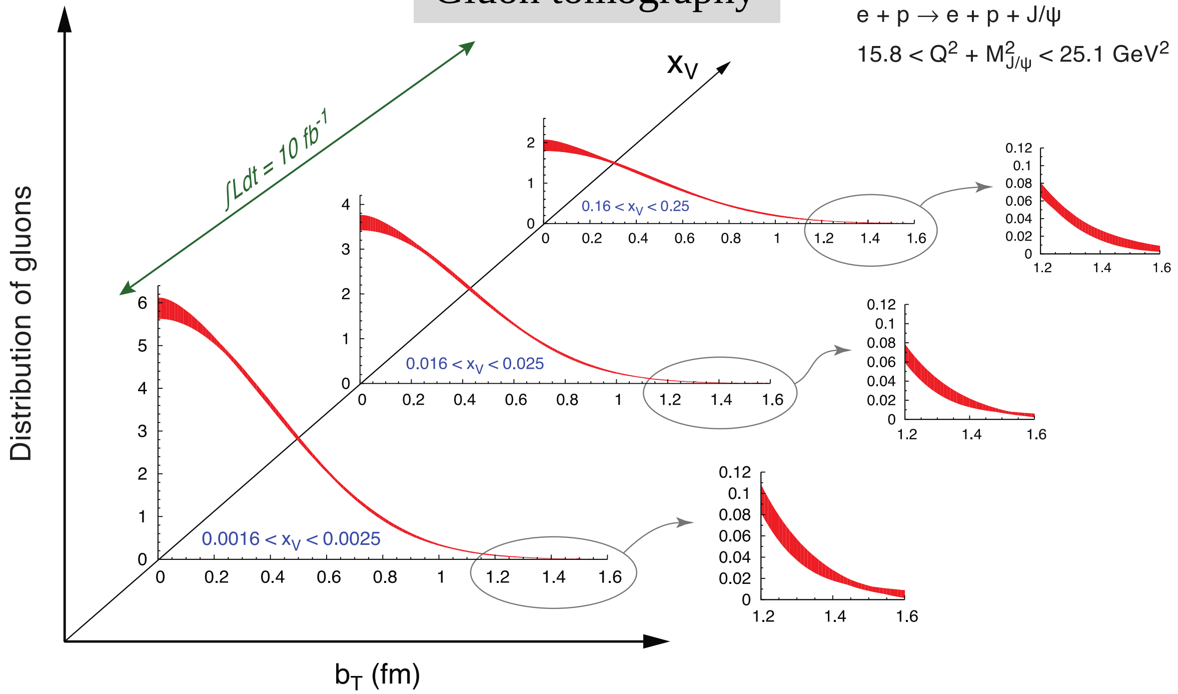


Generalized Parton Distributions





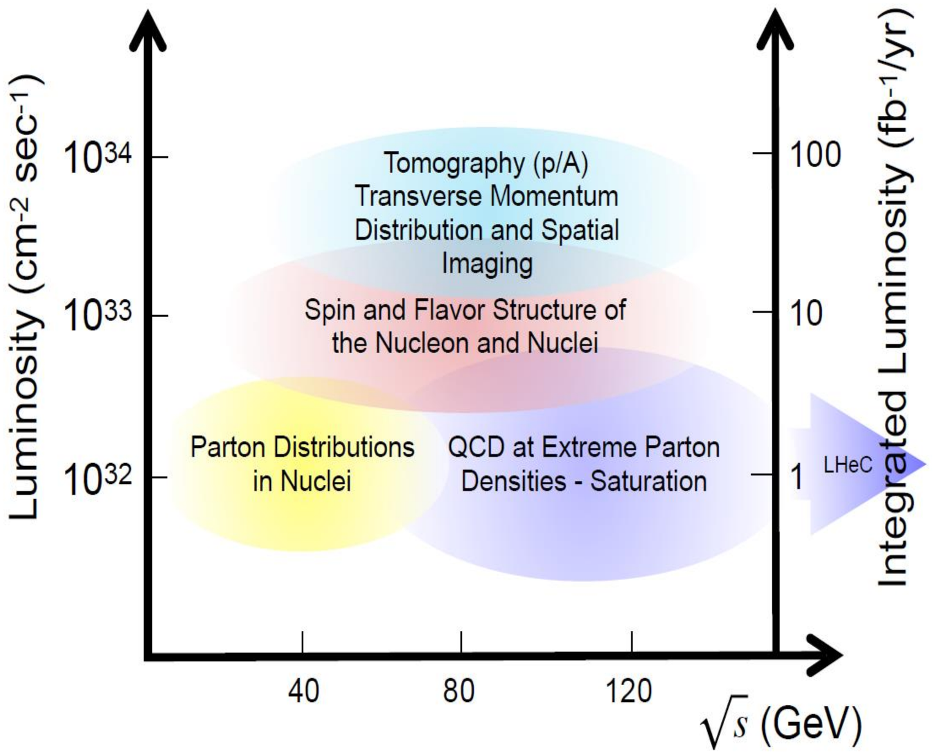
Gluon tomography

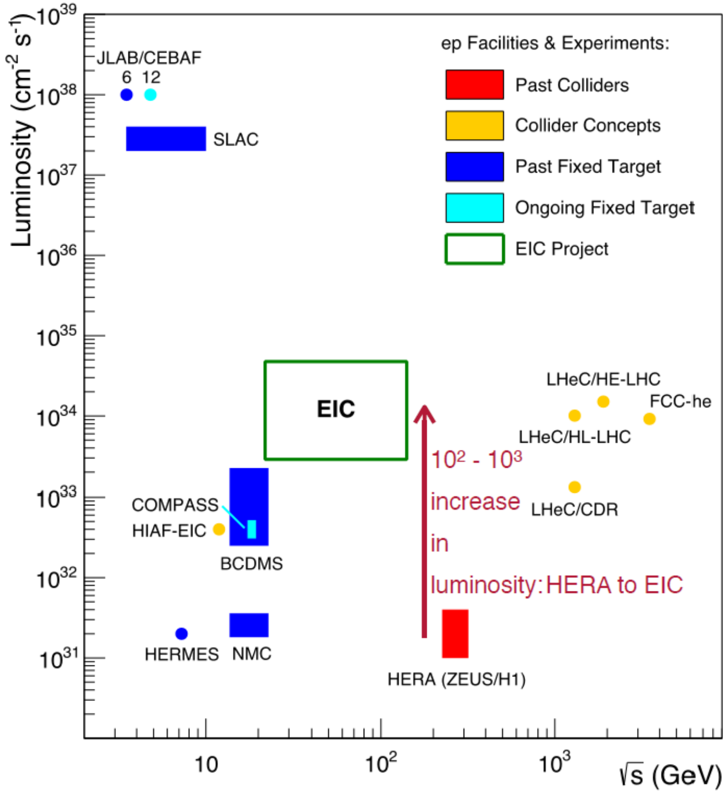


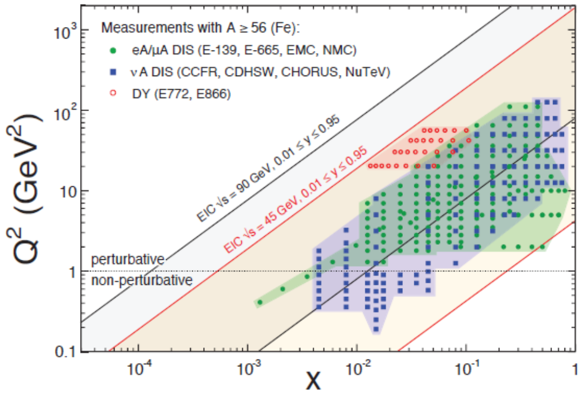
e + p → e + p + J/ψ

$15.8 < Q^2 + M^2_{J/\psi} < 25.1$ GeV^2

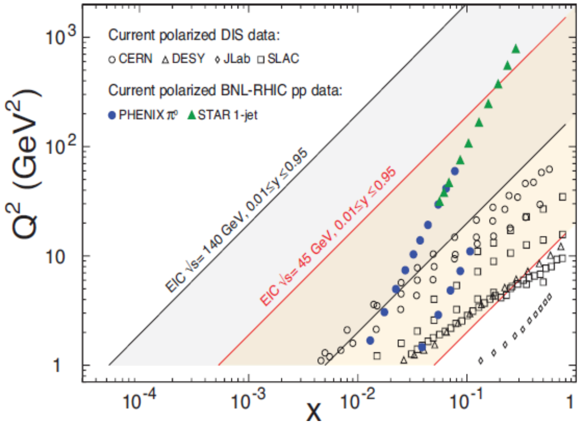
EIC: Luminosity and kinematic coverage







eA



ep

EIC facility @ BNL

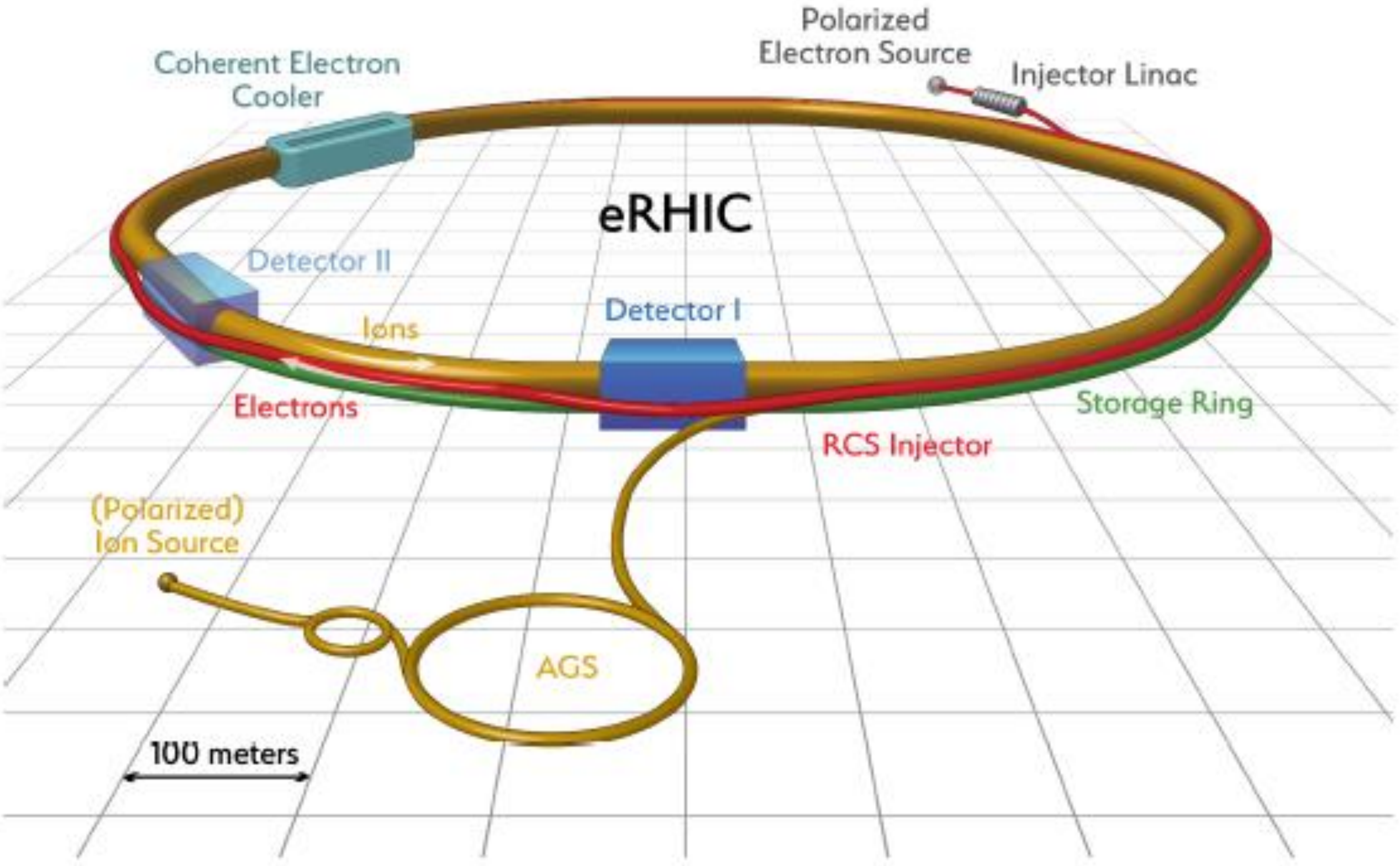
The EIC will be built at BNL by adding an electron storage ring to the existing RHIC facility:

- ➢ Highly polarized electron / Highly polarized proton and lights ions / Unpolarized heavy ions
- ➢ CME: ~ 20 – 100 GeV
- ➢ Luminosity: ~ $10^{33\text{-}34}\text{cm}^{-2}\text{s}^{-1}$

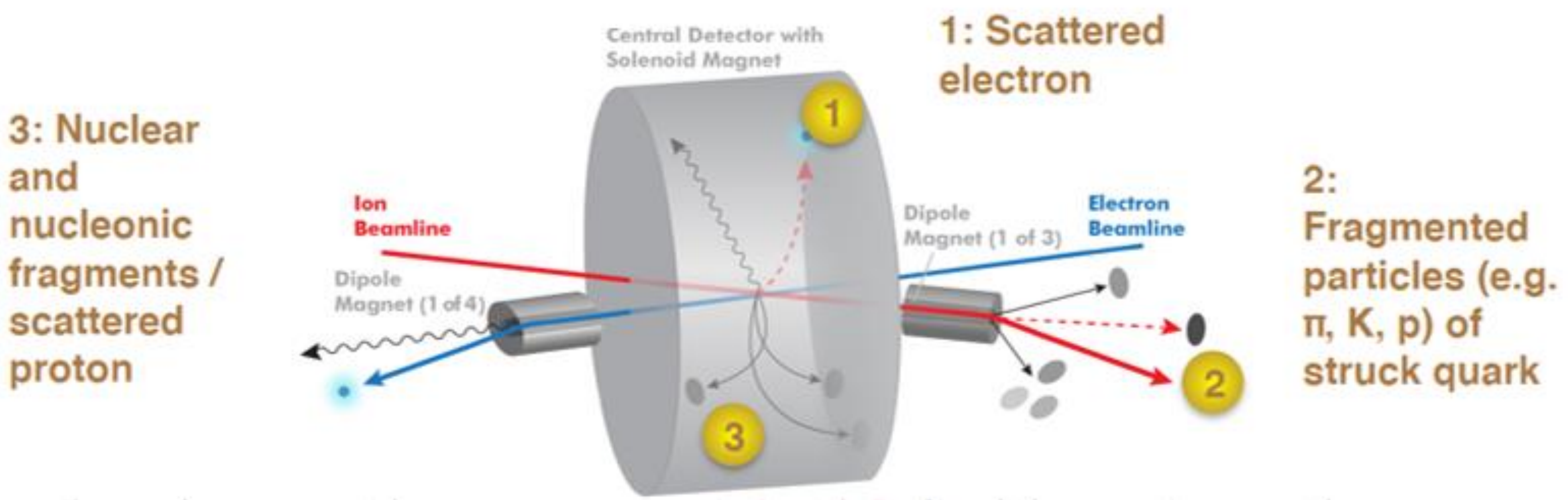
- ❑ Polarized electron source and 400 MeV injector linac
- ❑ Polarized proton beams and ion beams based on existing RHIC facility
- ❑ 2 detector interaction points capability in the design

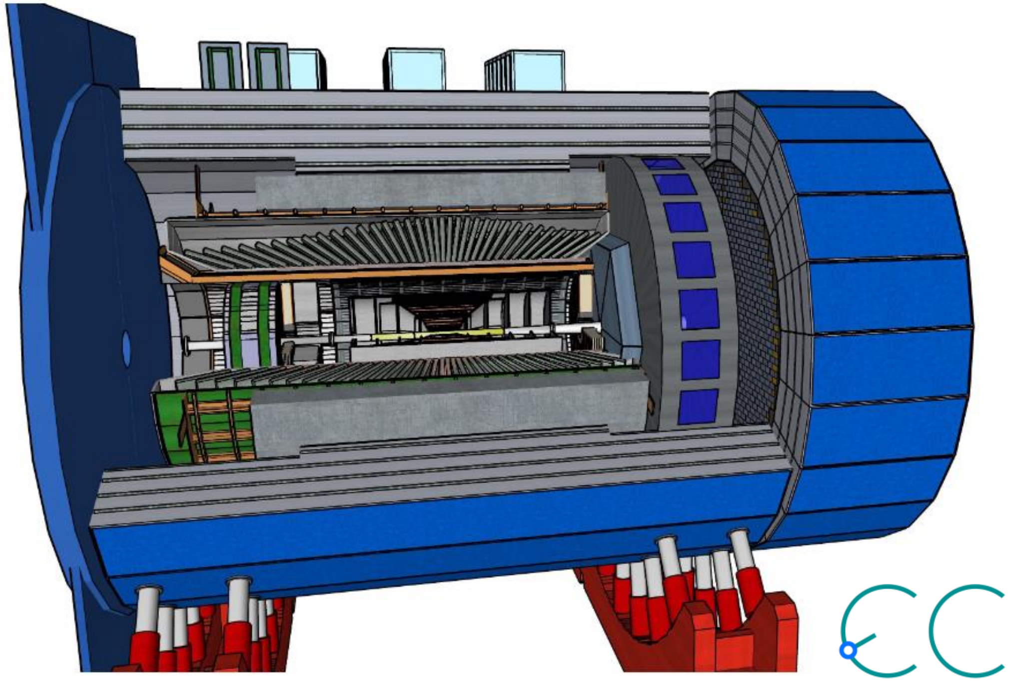
Project status:

- ▪ Awarded CD-0, CD-1 and site selection
- ▪ Lots of recent and future activities towards CD-2/3
- ▪ EIC facility completion in roughly a decade from now



The ECCE detector (« Detector 1 »)





Characteristics of ECCE:

- Reuse of the 1.4 T BaBar solenoid and sPHENIX barrel HCAL
- Limited number of technologies
- Tracking: hybrid Si tracker
- PID: hpDIRC + dRICH + mRICH + TOF (AC-LGADs)
- Calorimetry: homogeneous ECAL (back+barrel) + scintillating Pb (ECAL) + steel/W (HCAL) in forward endcap.
- *No HCAL in back-endcap*

ECCE

The ECCE detector concept was chosen by the Detector Proposal Advisory Panel (March 2022)

Conclusions/outlook

✓ GPDs are a unique tool to explore **the structure of the nucleon**:

- **3D** quark/gluon **imaging** of the nucleon
- **orbital angular** momentum carried by quarks
- **pressure** distribution

✓ Fitting methods allow to **extract CFFs (→ GPDs) from DVCS** observables → several **p-DVCS** and **n-DVCS observables** are needed, covering a **wide phase space**

✓A lot of **recent results** on DVCS observables were obtained from **CLAS** and **Hall-A** at 6 GeV

→ First **tomographic interpretations** of the quarks in the **proton** from DVCS

✓ JLab@12 GeV is **the optimal facility** to perform GPD experiments **in the valence region**

→ DVCS and DVMP experiments on both **proton** and **neutron** (pol. and unpol.) are ongoing in **3 of the 4 Halls at JLab@12 GeV: quarks' spatial densities, flavor separation, quarks' orbital angular momentum, …**

→ **JLab upgrade perspectives (positron beam, higher luminosity and energy) pave the road to the completion of the GPD program in the valence regime**

→ **Longer-term future: EIC, to study the gluonic structure of the nucleon and gluon GPDs**