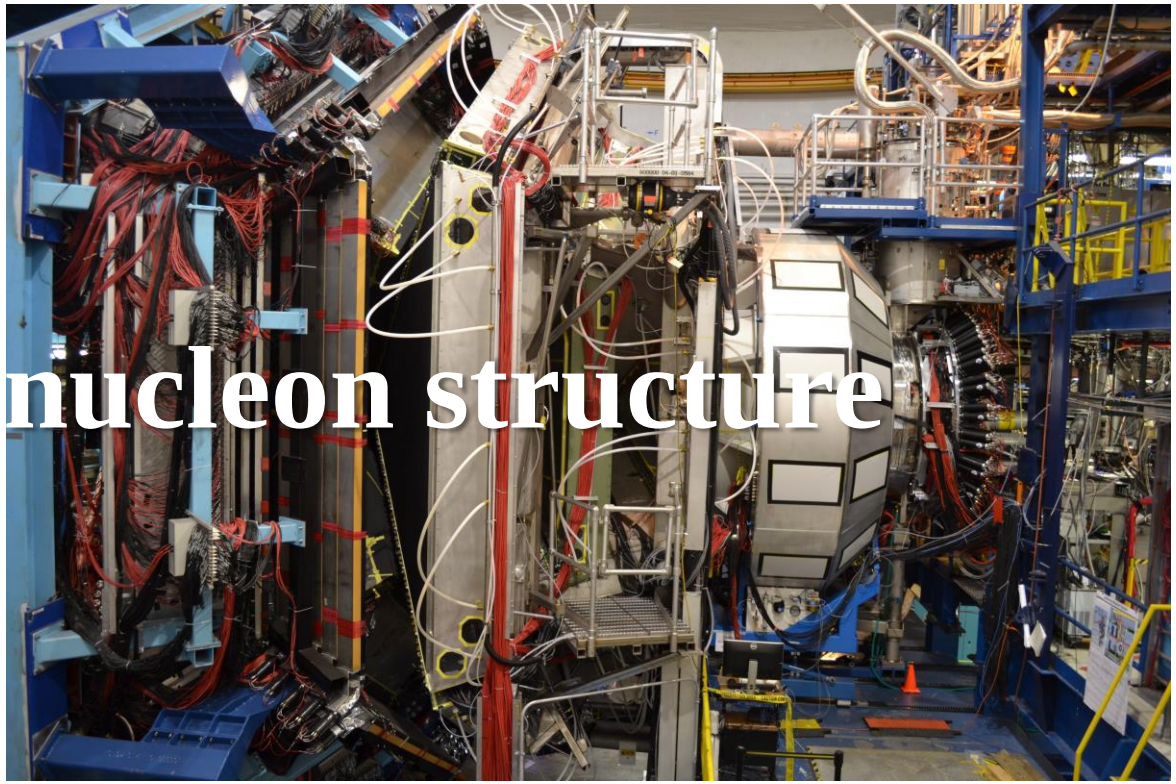
3D Investigation of nucleon structure



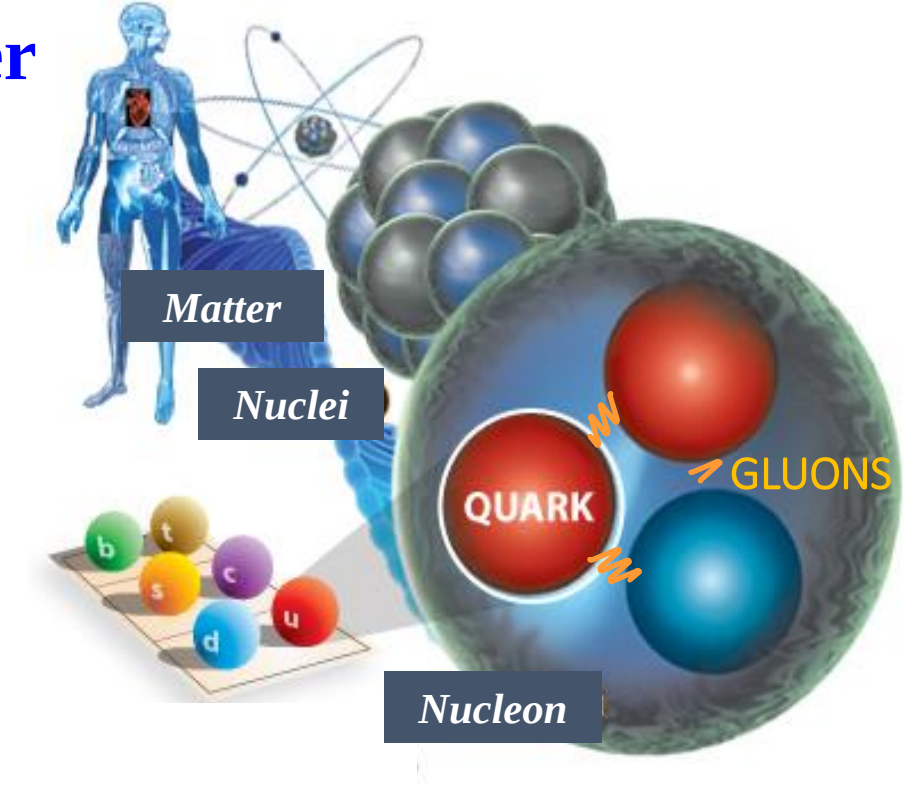
Silvia Niccolai, IJClab Orsay & CLAS Collaboration

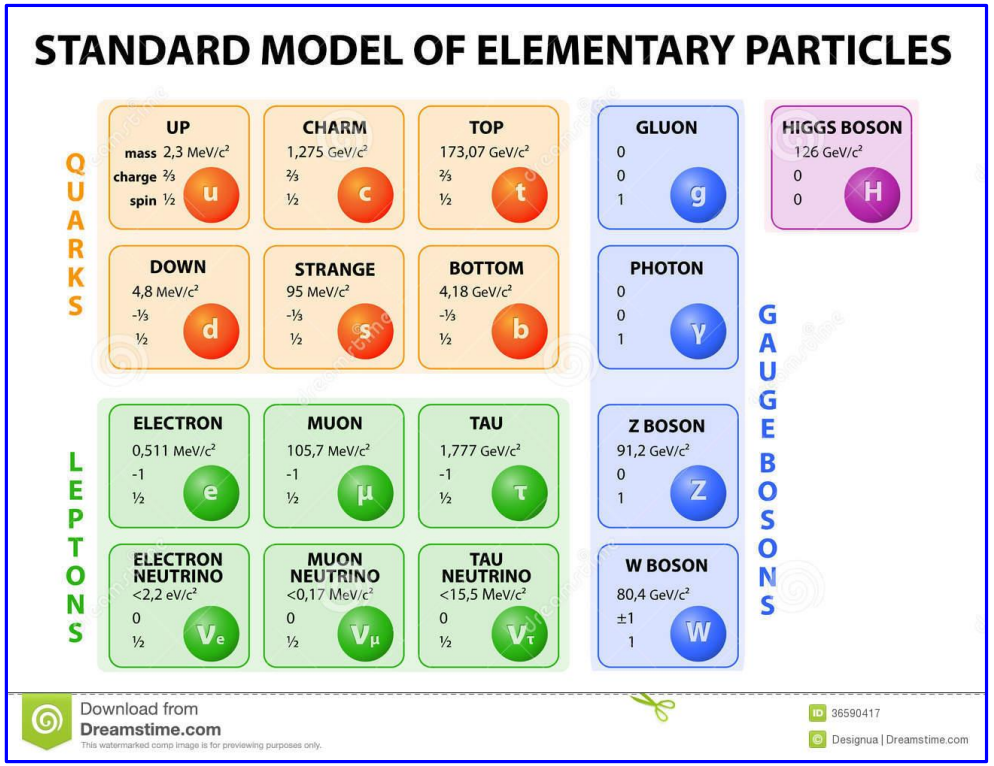
INPC2022, Cape Town (South Africa), 9/12/2022

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)**

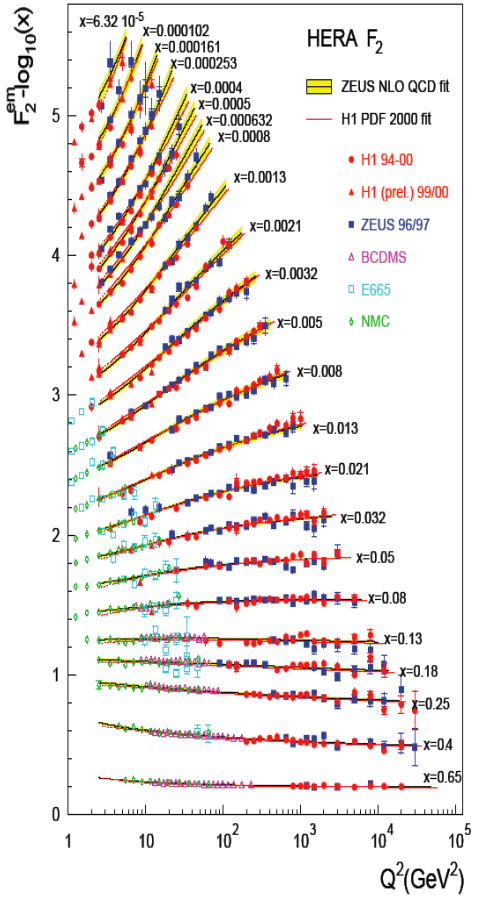




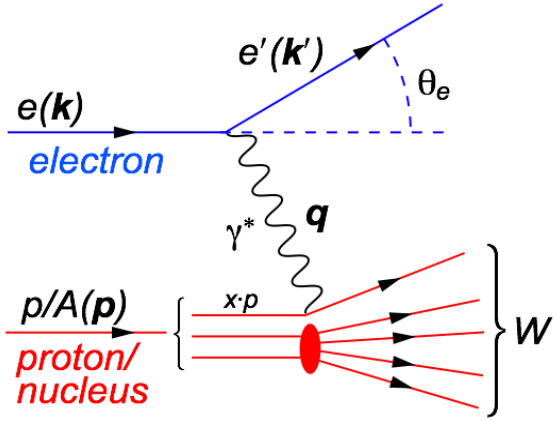
Properties of QCD:

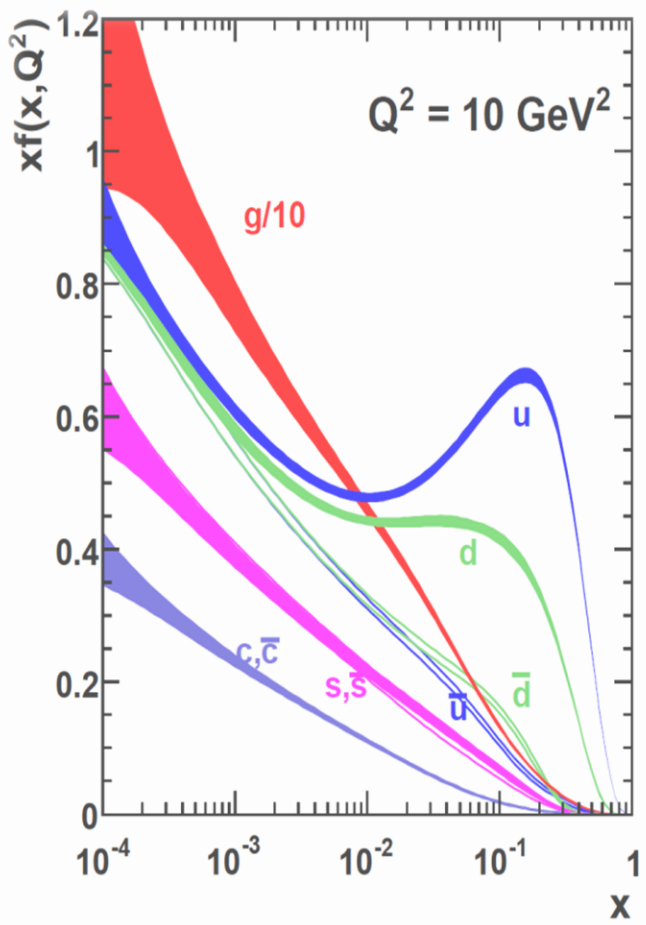
- **Confinement, at long distances:** unlike in QED, we cannot observe the individual constituents
- **Asymptotic freedom, at short distances**: the effective coupling constant α_s becomes very small (<1) at small distances (<0.2 fm)
- **Chiral simmetry breaking**: mass of the *u* and *d* quarks, very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

Successes of asymptotic QCD

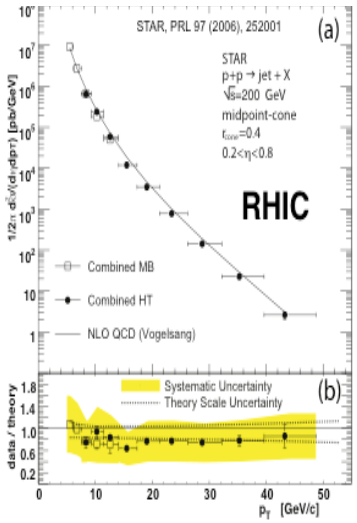


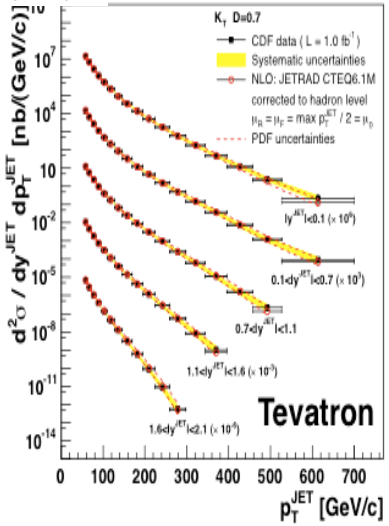
$$F_2 = \sum_q x\, q(x, Q^2)$$

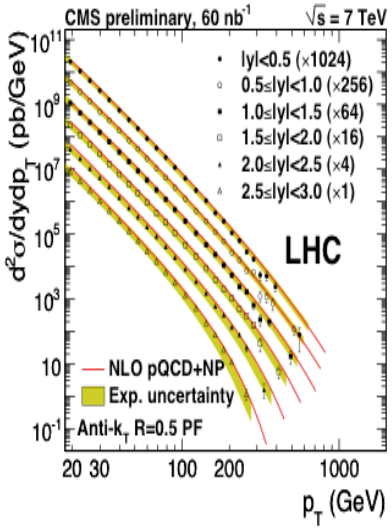




Measurements of F_2 in e-p at 0.3 TeV (HERA)
→ extraction quark and gluon PDFs
→ pQCD fits for p-p and p-$\bar{p}$ at 0.2, 1.96, and 7 TeV







BUT…

QCD is still unsolved in non-perturbative regions

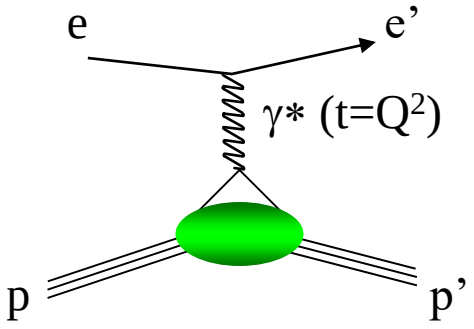
Insights into soft phenomena (hadron structure) through **models** and **numerical calculations** (lattice)

See C. Alexandrou's talk on lattice QCD on Thursday at 10AM

Electron scattering: the tool to study nucleon structure

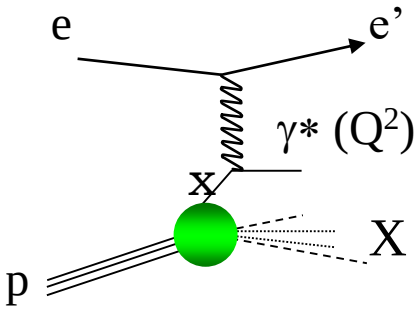
Electrons are **structureless** and interact only **electromagnetically**

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

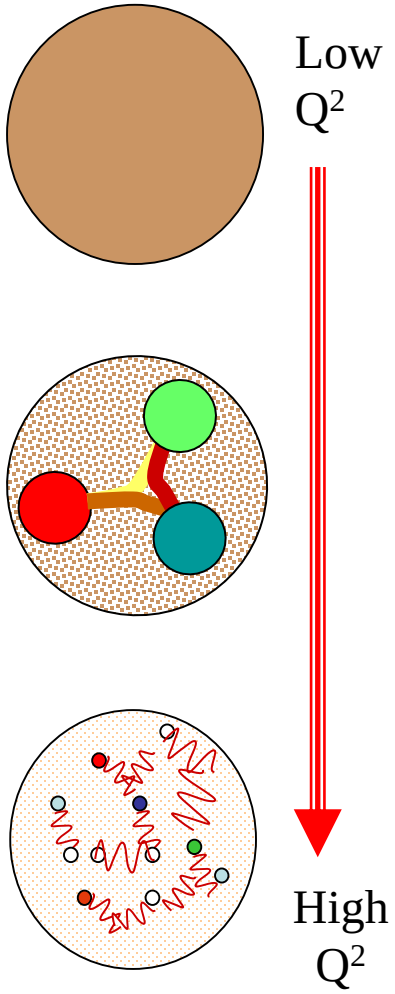


- The proton is **not a point-like object**
- Measurement of charge and current distributions of the proton: **Electromagnetic form factors $F_1(t)$, $F_2(t)$**

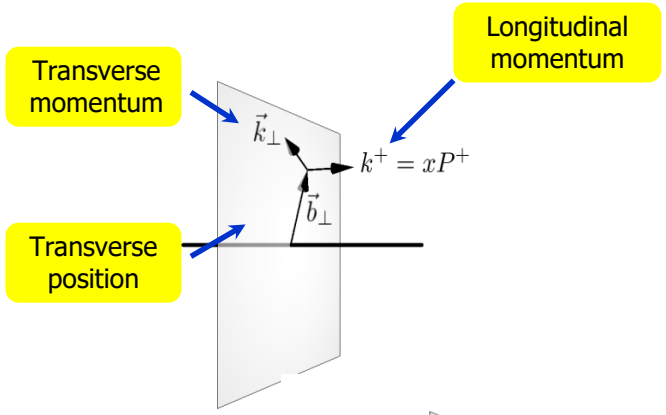
➢1967: **Deep inelastic scattering** (DIS) ep→e'X (Friedman, Kendall, Taylor, Nobel prize 1990)

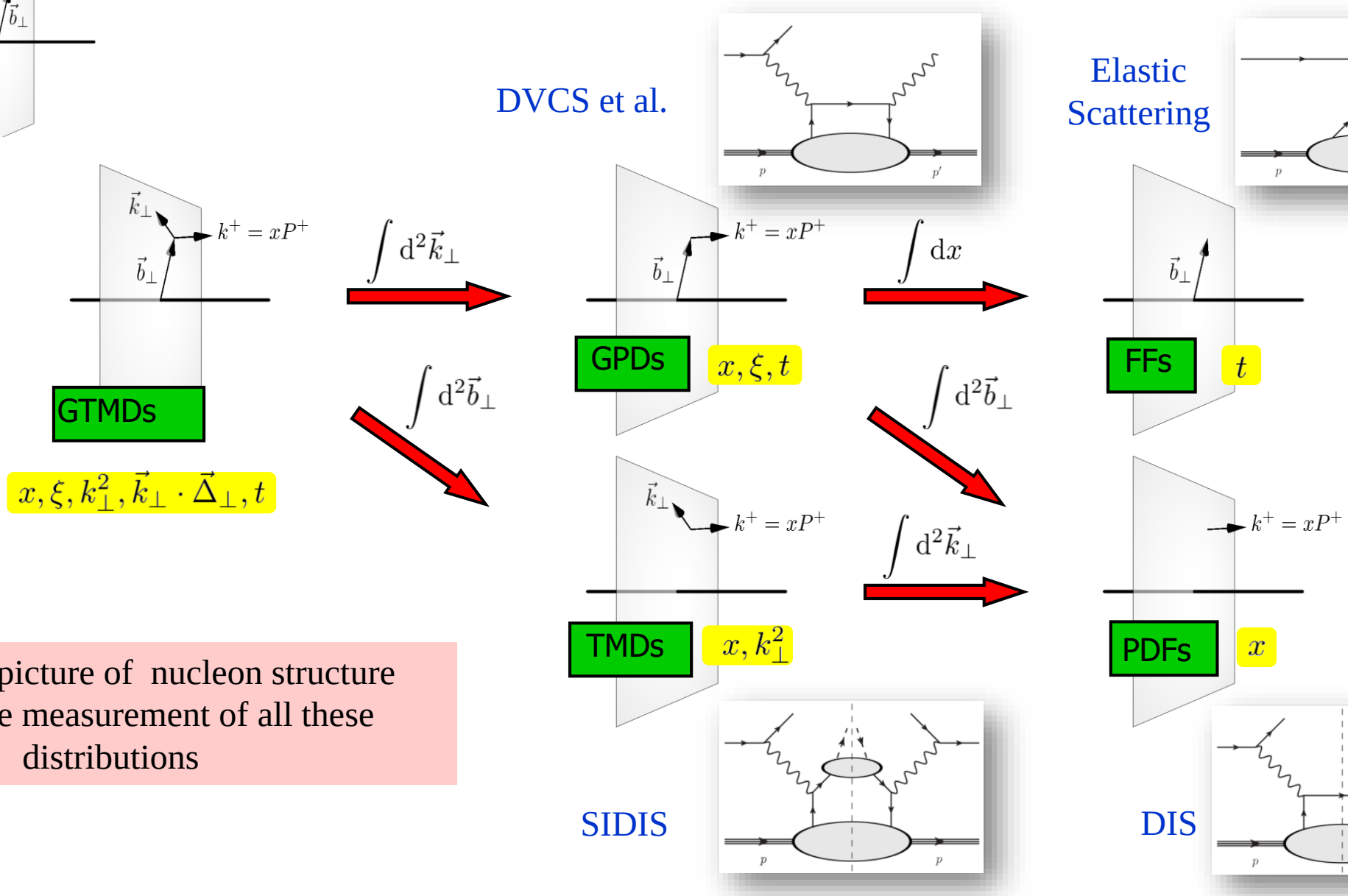


- Discovery of the **quarks** (or "partons")
- Measurement of the momentum and spin distributions of the partons: **Parton Distribution Functions (PDF) q(x), Δq(x)**



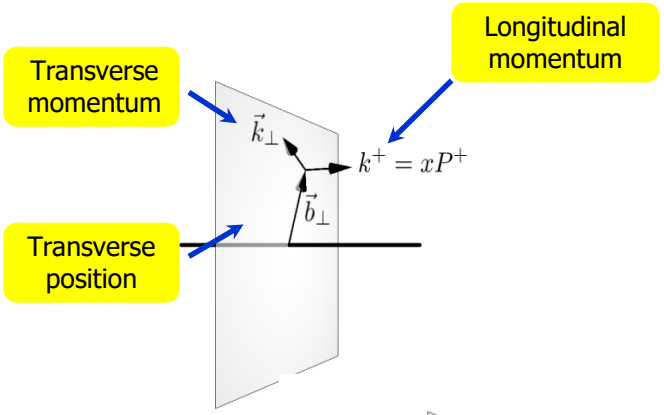
Multi-dimensional mapping of the nucleon

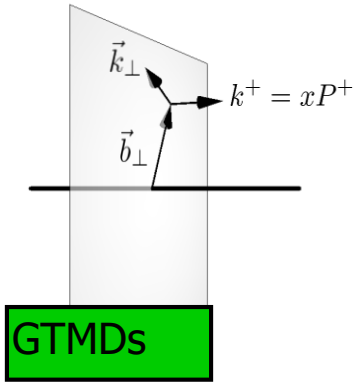




A complete picture of nucleon structure requires the measurement of all these distributions

Multi-dimensional mapping of the nucleon

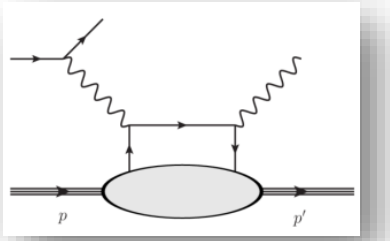


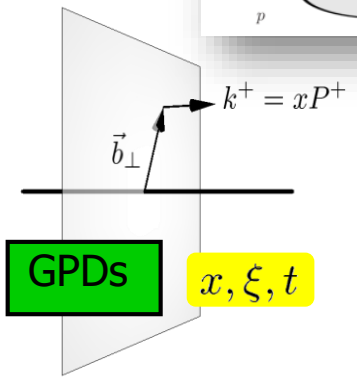


$x, \xi, k_\perp^2, \vec{k}_\perp \cdot \vec{\Delta}_\perp, t$

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

DVCS et al.

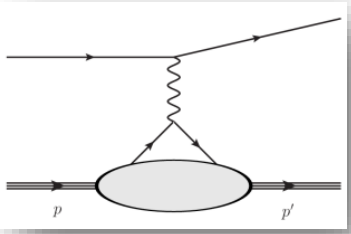


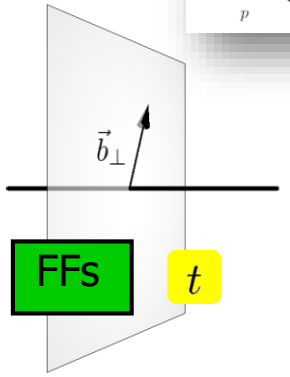


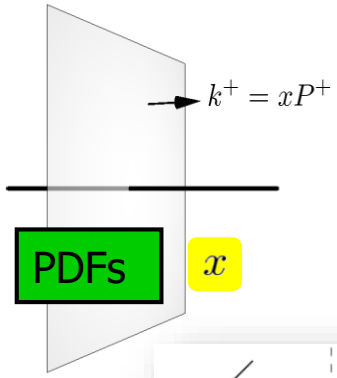
$\int dx$

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

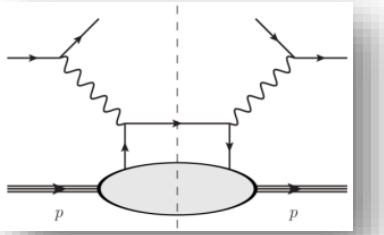
Elastic Scattering







DIS



Generalized Parton Distributions:

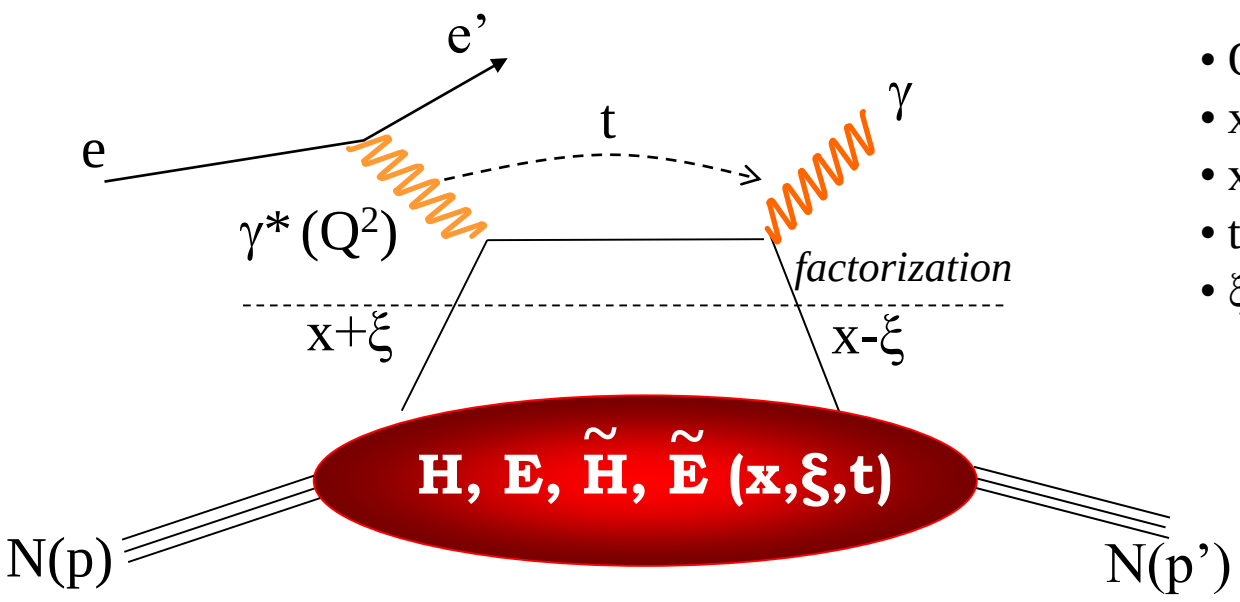
✓fully correlated parton distributions in both **coordinate** and **longitudinal momentum** space

✓ linked to **FFs** and **PDFs**

✓**Accessible in exclusive reactions**

To learn about TMDs and SIDIS, see D. Boer's talk, Wednesday 9:30AM

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
- $t = \Delta^2 = (p-p')^2$
- $\xi \cong x_B/(2-x_B)$

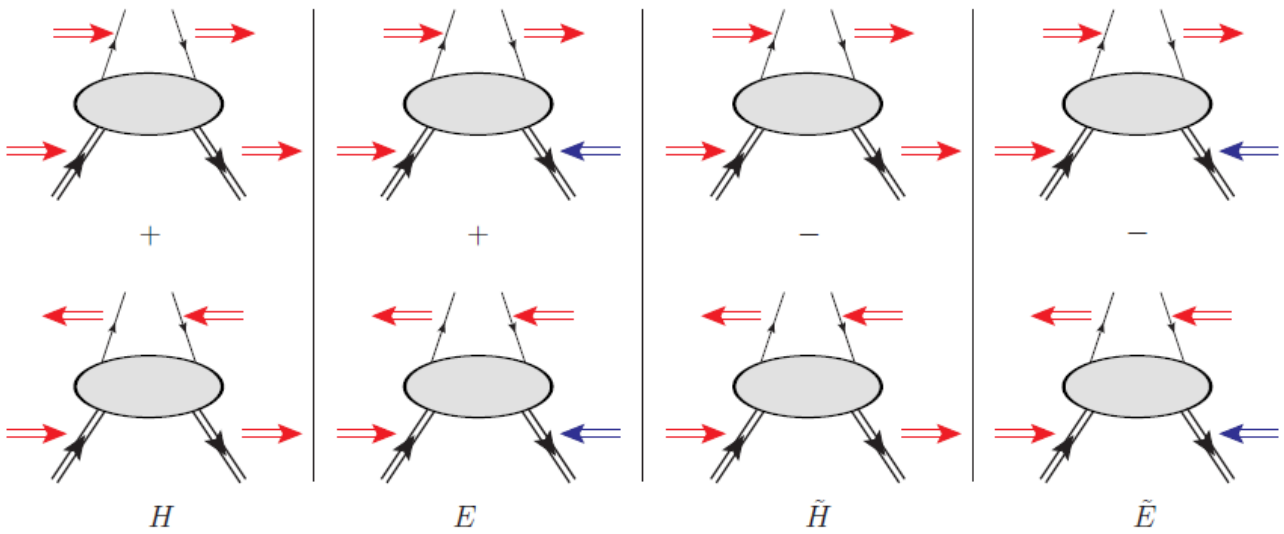
« **Handbag** » factorization, valid in the **Bjorken regime** (**high Q^2** and **ν**, fixed x_B), **$t \ll Q^2$**

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

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

conserve nucleon spin

flip nucleon spin



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

Properties and "virtues" of GPDs

$$\int H(x,\xi,t)dx = F_1(t) \quad \forall\xi$$
$$\int E(x,\xi,t)dx = F_2(t) \quad \forall\xi$$
$$\int \tilde{H}(x,\xi,t)dx = G_A(t) \quad \forall\xi$$
$$\int \tilde{E}(x,\xi,t)dx = G_P(t) \quad \forall\xi$$

Link with **FFs**

$$H(x,0,0) = q(x)$$
$$\tilde{H}(x,0,0) = \Delta q(x)$$

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

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: ½ = $\underbrace{\tfrac{1}{2}\Delta\Sigma + \Delta L}_{J}$ + ΔG

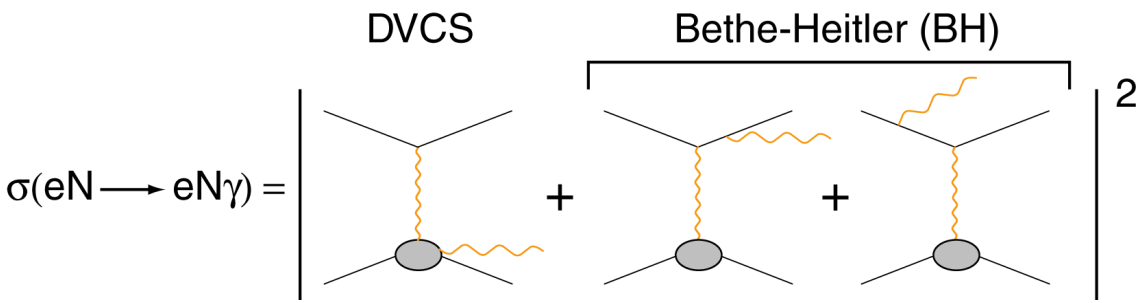
Intrinsic spin of the quarks ΔΣ ≈ 30%

Intrinsic spin on the gluons ΔG ≈ 20%

Orbital angular momentum of the quarks ΔL ?

Accessing GPDs through DVCS

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



Compton Form Factors (CFF)

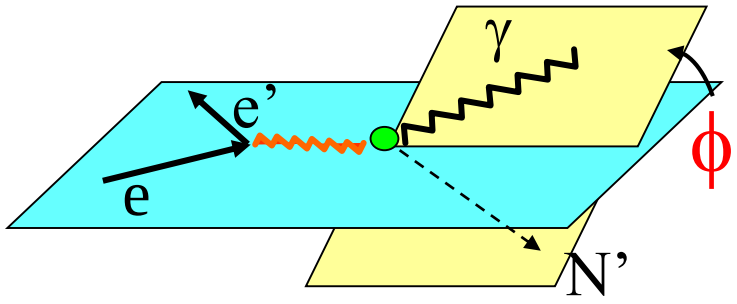
$$Re\mathcal{H}_q = e_q^2 P\int_0^{+1} \left(H^q(x,\xi,t) - H^q(-x,\xi,t)\right)\left[\frac{1}{\xi - x} + \frac{1}{\xi + x}\right] dx$$

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

$$\sigma \sim |T^{DVCS} + T^{BH}|^2 \sim Re\ (CFF)$$
$$\Delta\sigma = \sigma^+ - \sigma^- \propto I(DVCS \cdot BH) \sim Im\ (CFF)$$

Different spin asymmetries for different targets → different CFFs

Observable	Proton	Neutron
$\Delta\sigma_{LU}$	$\Im\{\boldsymbol{H_p}, \widetilde{H}_p, E_p\}$	$\Im\{H_n, \widetilde{H}_n, \boldsymbol{E_n}\}$
$\Delta\sigma_{UL}$	$\Im\{\boldsymbol{H_p}, \boldsymbol{\widetilde{H}_p}\}$	$\Im\{\boldsymbol{H_n}, E_n\}$
$\Delta\sigma_{LL}$	$\Re\{\boldsymbol{H_p}, \boldsymbol{\widetilde{H}_p}\}$	$\Re\{\boldsymbol{H_n}, E_n\}$
$\Delta\sigma_{UT}$	$\Im\{\boldsymbol{H_p}, \boldsymbol{E_p}\}$	$\Im\{\boldsymbol{H_n}\}$



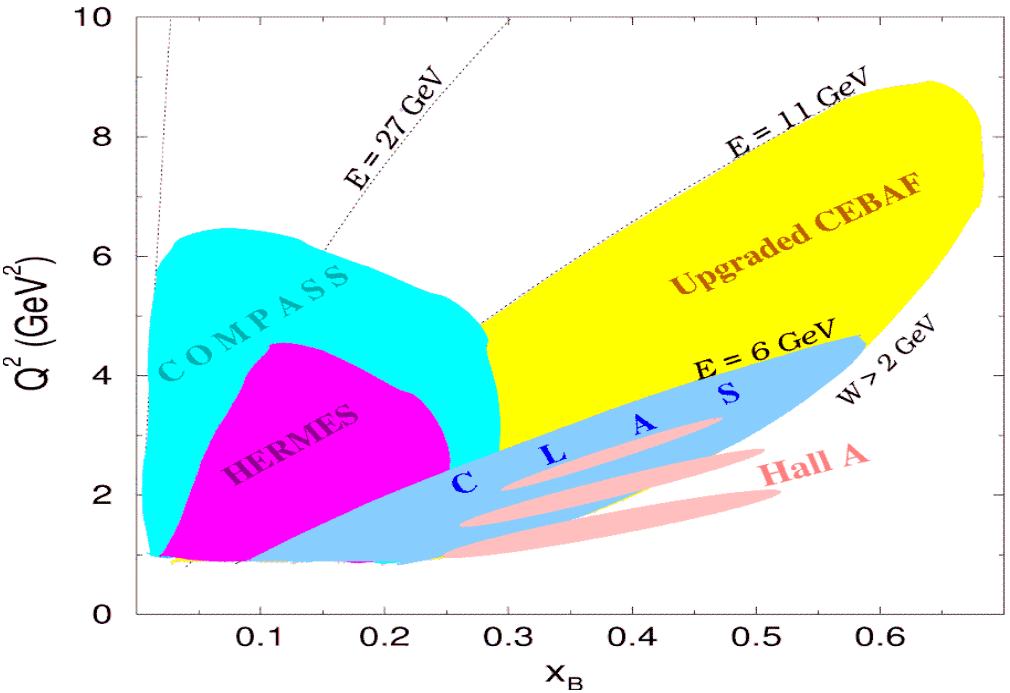
Different nucleon → different combinations of quark GPDs
proton + neutron DVCS → flavor separation of GPDs

History of DVCS experiments worldwide

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

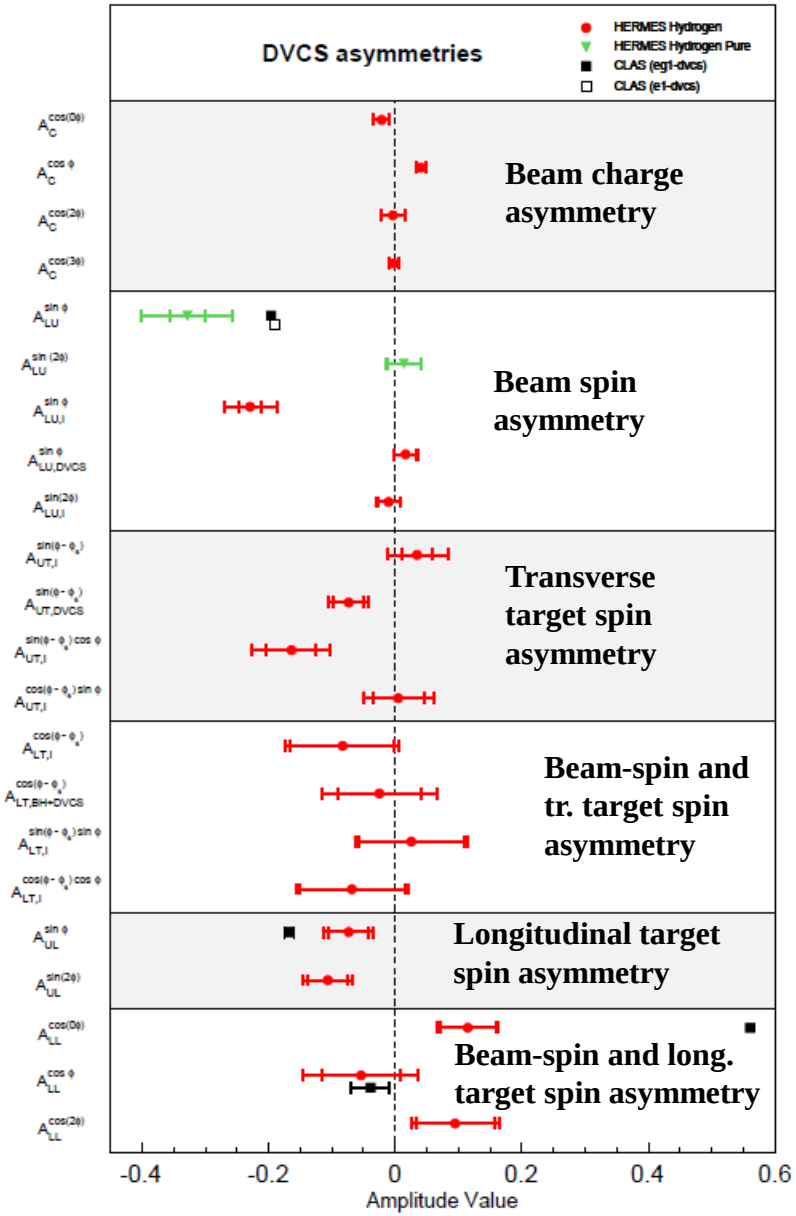
DESY	
HERMES	***H1/ZEUS***
p-DVCS,BSA,BCA, tTSA,lTSA,DSA	p-DVCS,CS,BCA

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



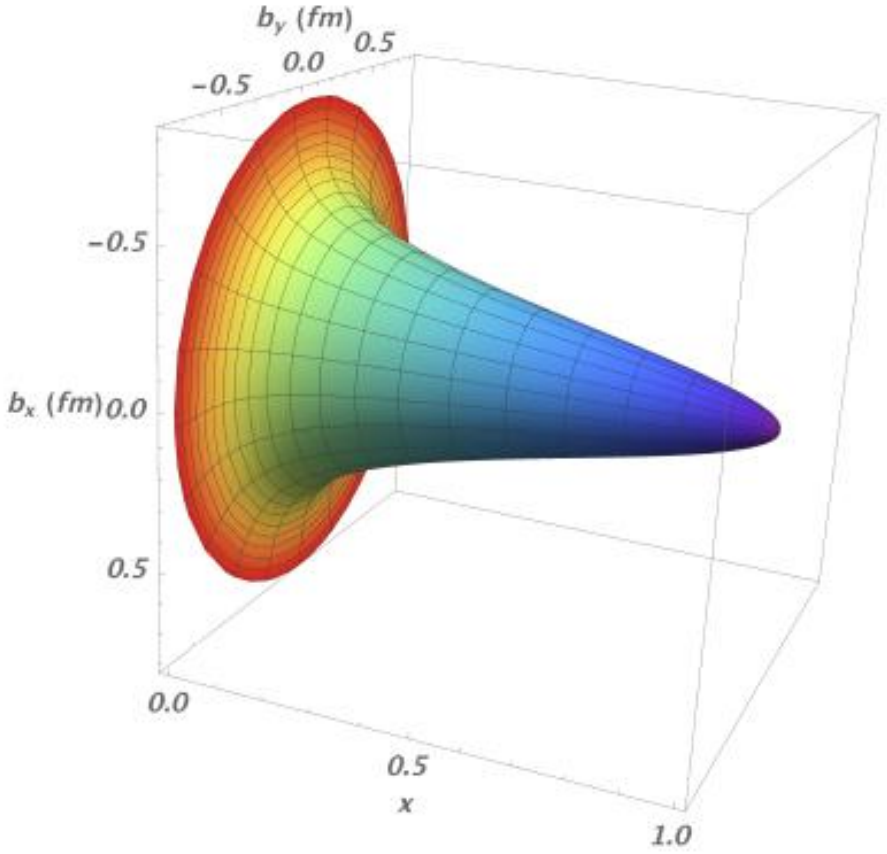
CLAS, HERMES: first observation of DVCS-BH interference in the beam-spin asymmetry (2001)

Hall A: test of scaling for DVCS (2006)



What have we learned from the first-generation of DVCS results?

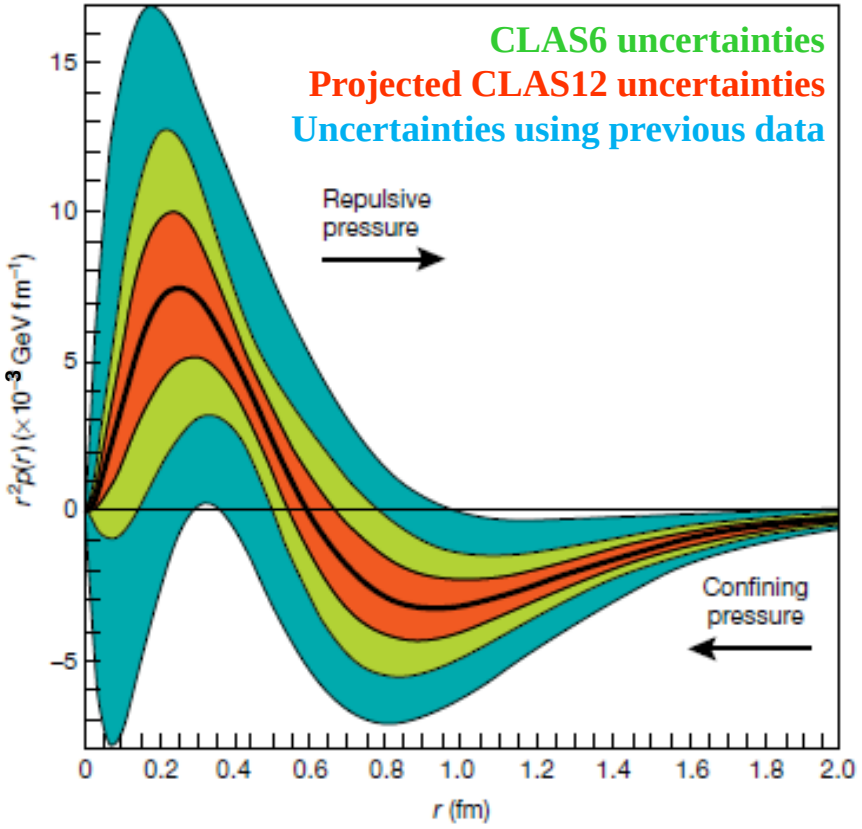
Proton tomography from *local fits* to HERMES, CLAS, and Hall-A data (**Im$\mathcal{H}$** + **model dependent** assumptions for x dependence)



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

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

From **$\mathcal{H}$-only fit** of DVCS BSA and cross section from CLAS@6 GeV **(model dependent)**: **an insight in the pressure distribution in the proton**

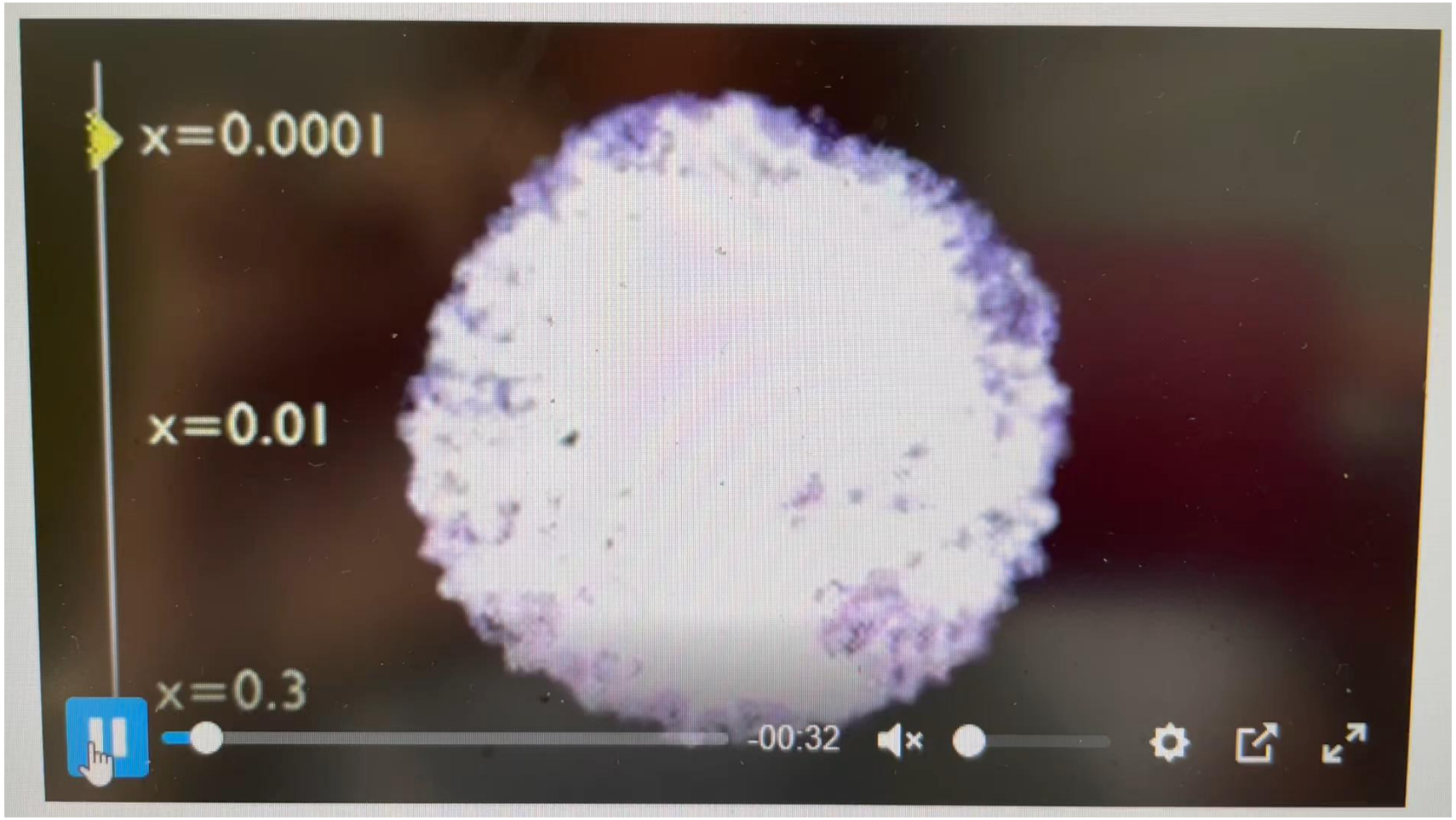


V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

YouTube video « Visualizing the proton »

(R. Milner, R. Ent, R. Yoshida)

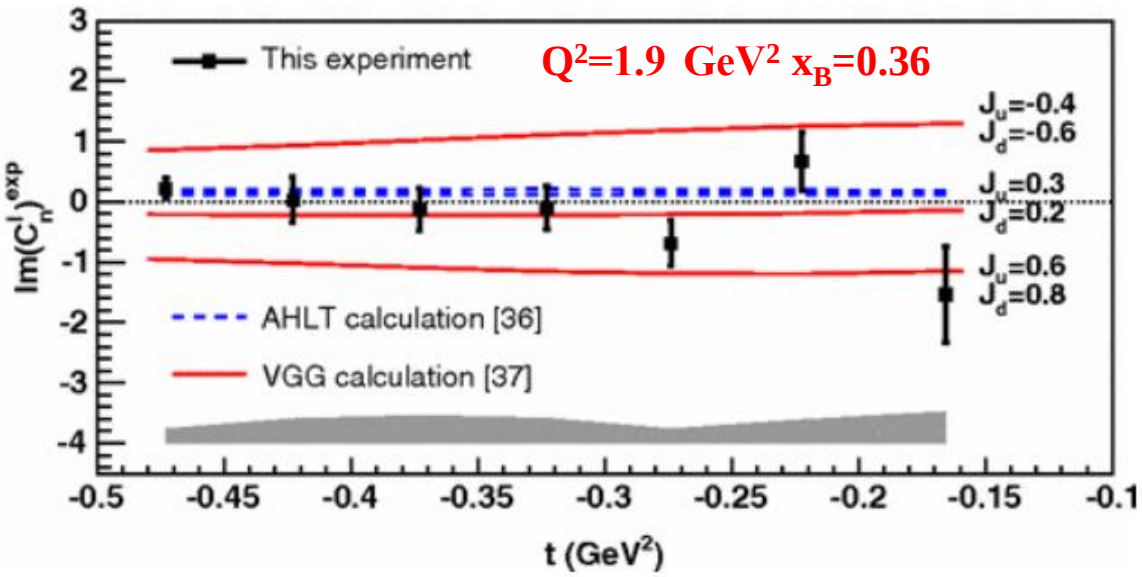
Filmmaking by Chris Boebel, Joe McMaster, and James LaPlante



https://www.youtube.com/watch?v=G-9I0buDi4s (published on April 13, 2022)

Interest of DVCS on the neutron: Hall A at 6 GeV

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



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

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

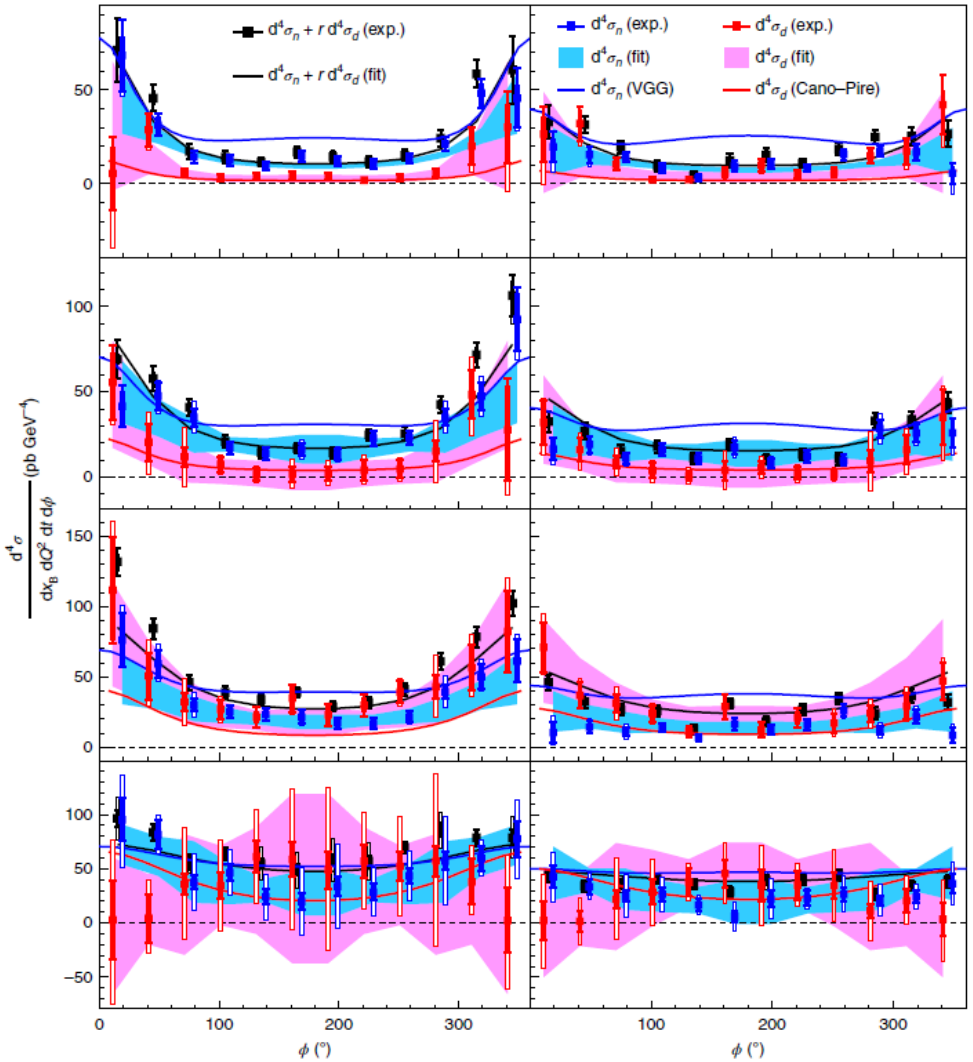
$$D(e,e'\gamma)X - H(e,e'\gamma)X = n(e,e'\gamma)n + d(e,e'\gamma)d + \ldots$$

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

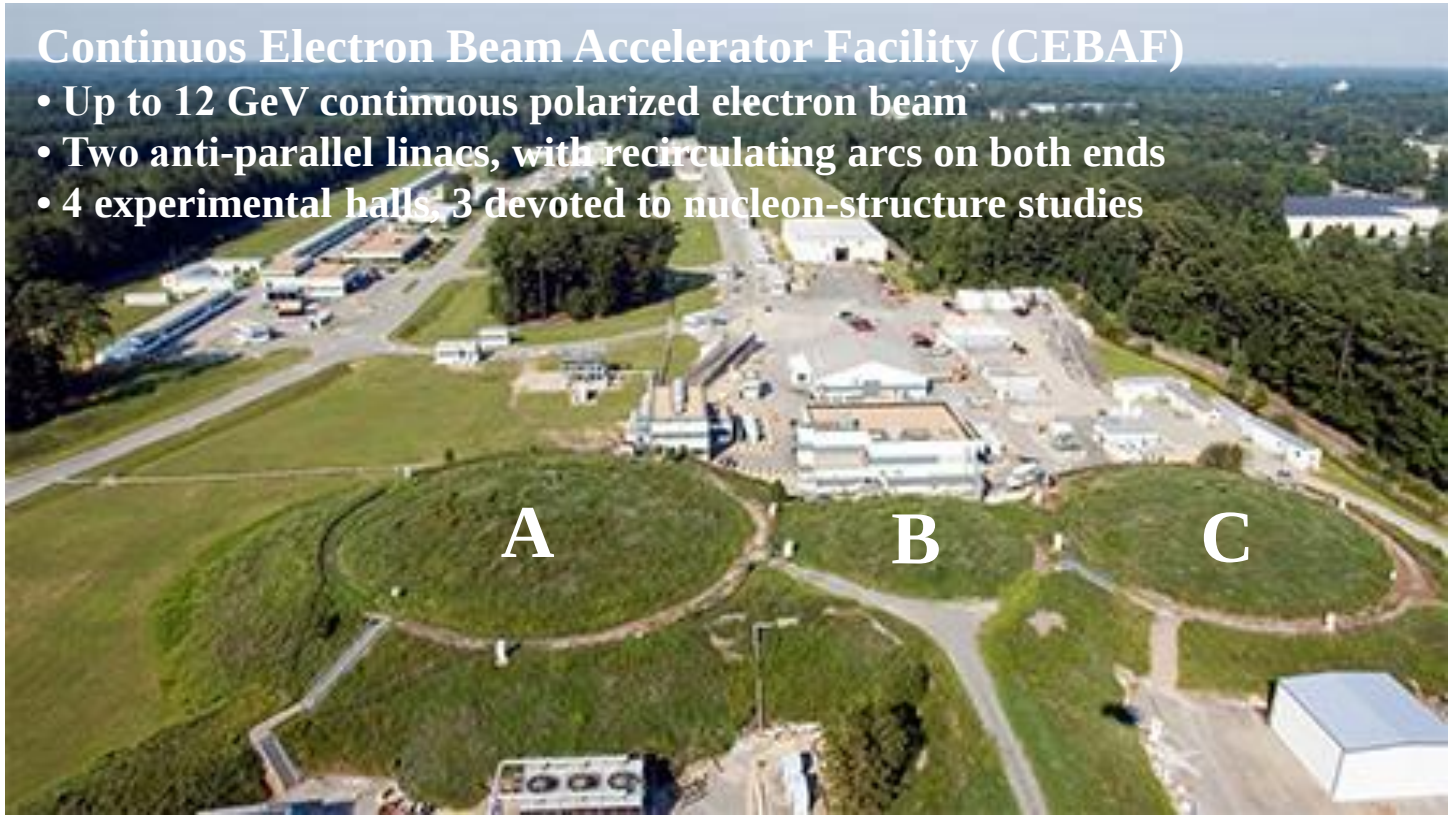
- large correlations at low –t
- good separation at larger -t

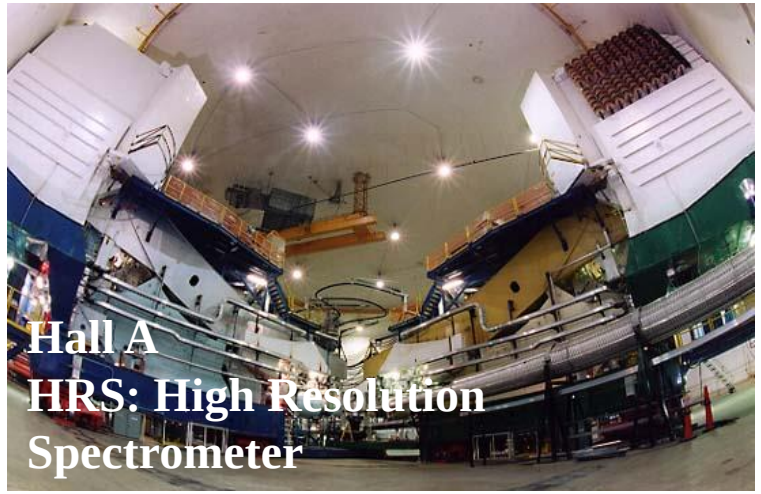
Hall-A experiment E08-025 (2010)

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



Jefferson Lab at 12 GeV



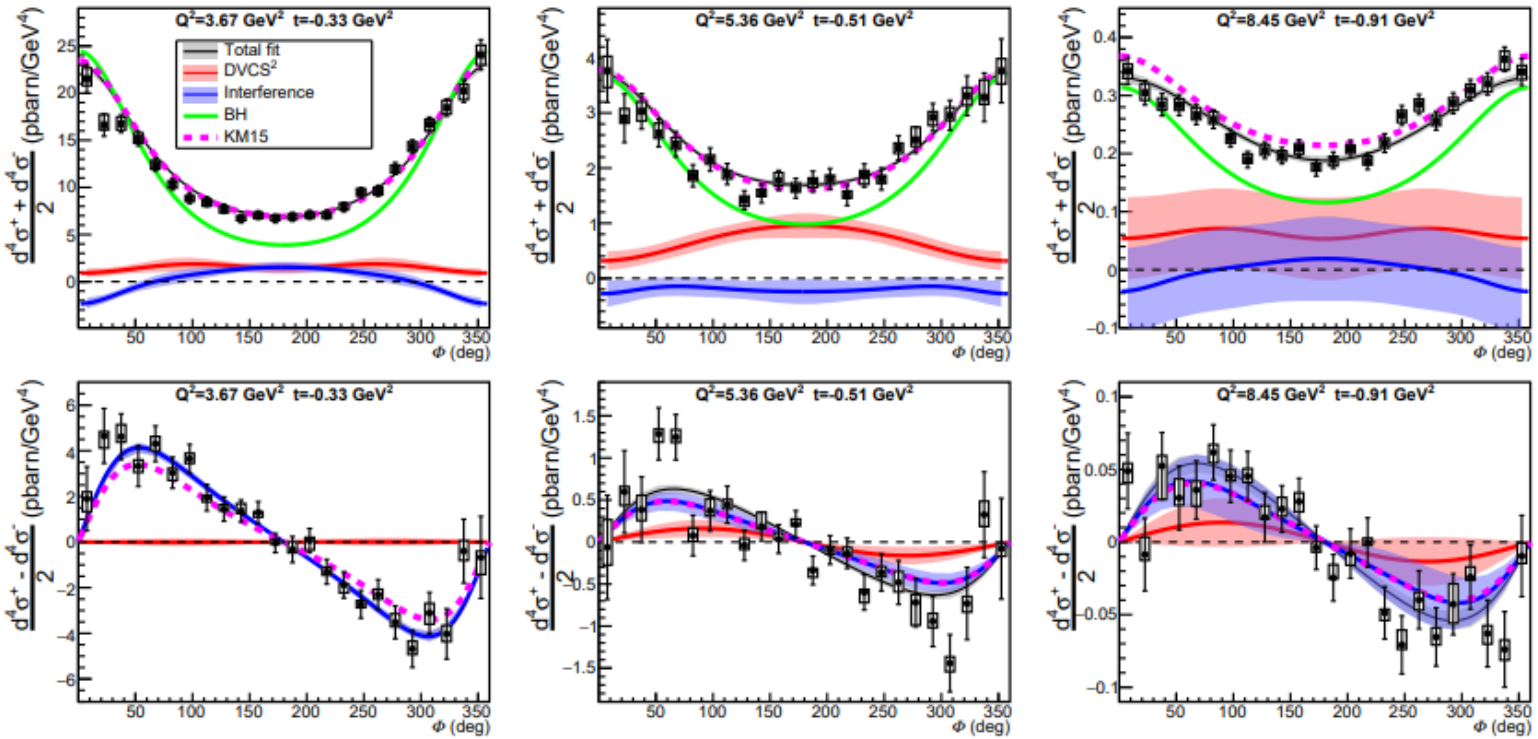


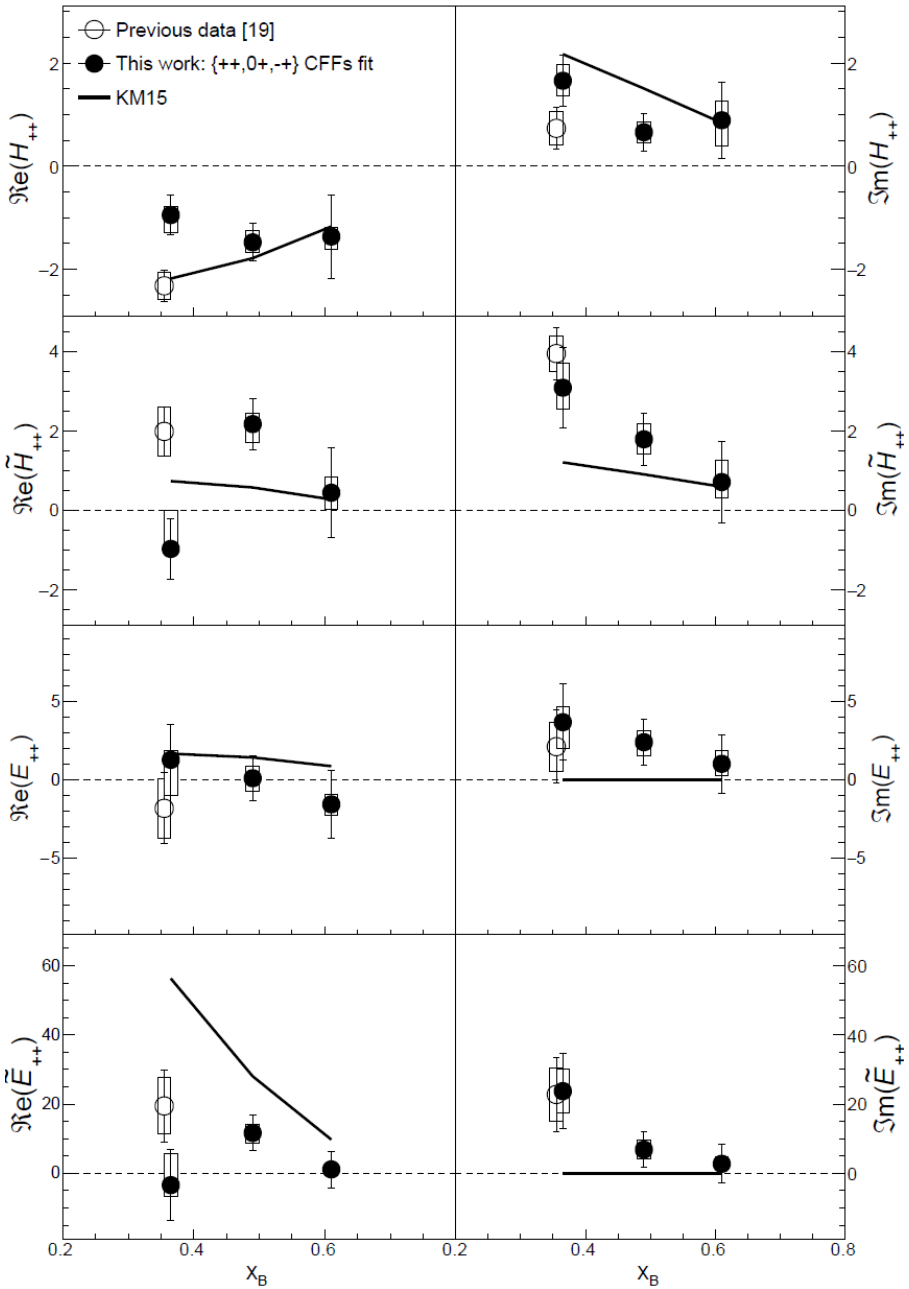
Complementarity of the setups in the Halls A/C and B

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

An extensive experimental program focused on DVCS and GPDs is underway

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





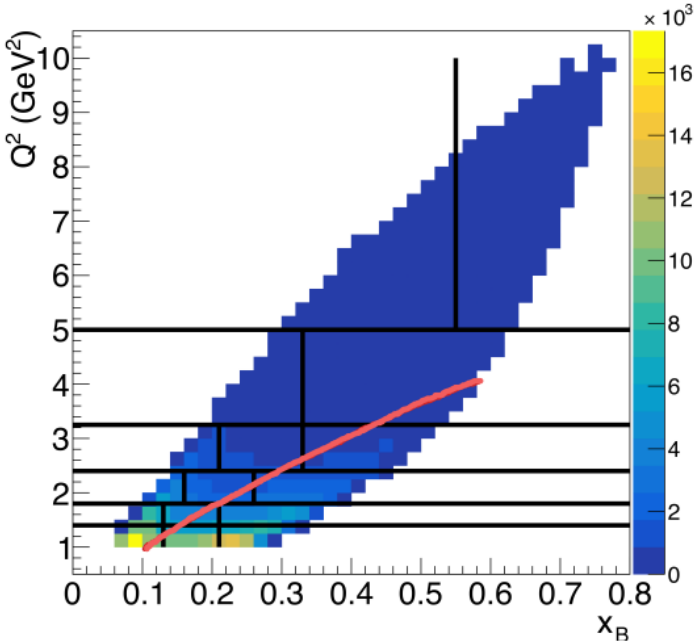
- Data taken in 2014 and 2016
- High precision DVCS cross sections up to large x_B, for 3 beam energies
- Sensitivity to all 4 Compton form factors

F. Georges et al., Phys. Rev. Lett. 128, 252002 (2022)

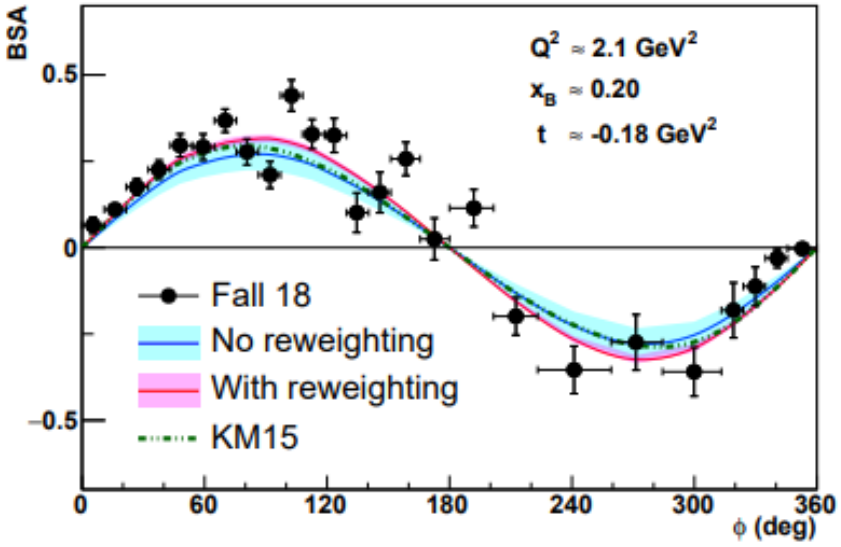
Other kinematics will be explored by the Hall-C NPS experiment (2023)

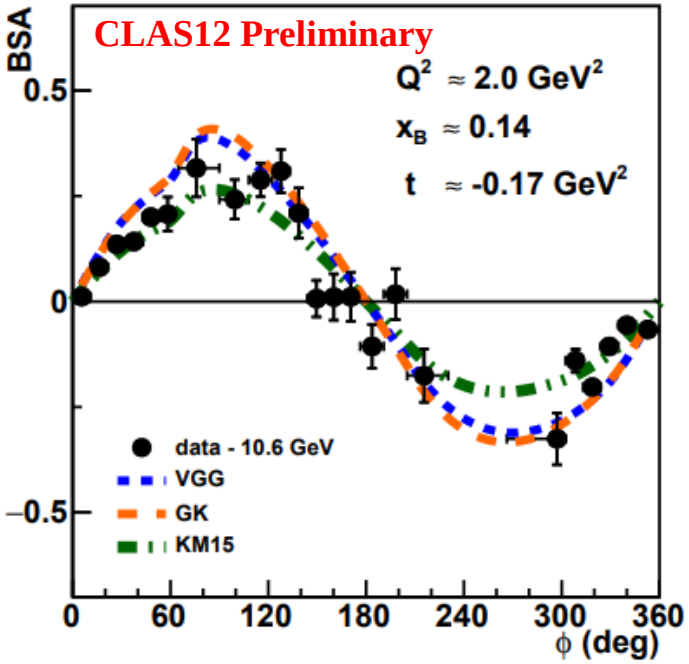
C. Munoz-Camacho's talk on Tuesday at 3:10PM, Hadron Structure

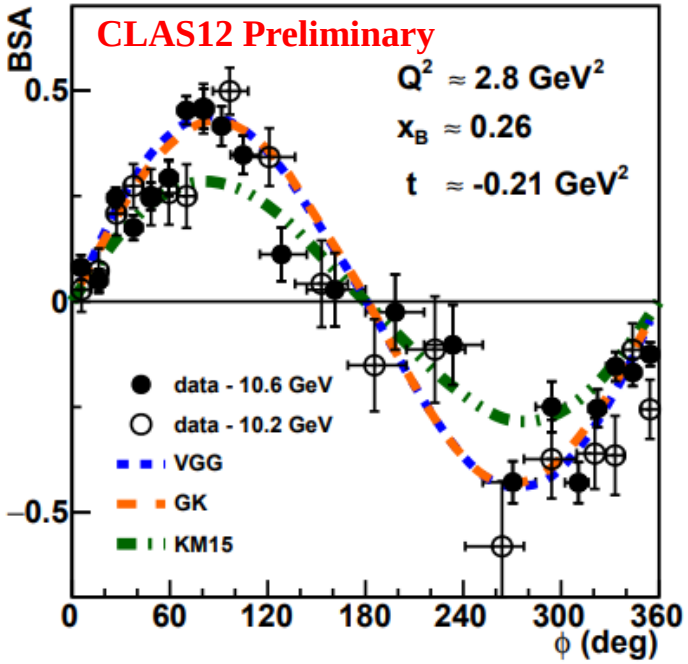
CLAS12: preliminary beam spin asymmetry for DVCS on the proton

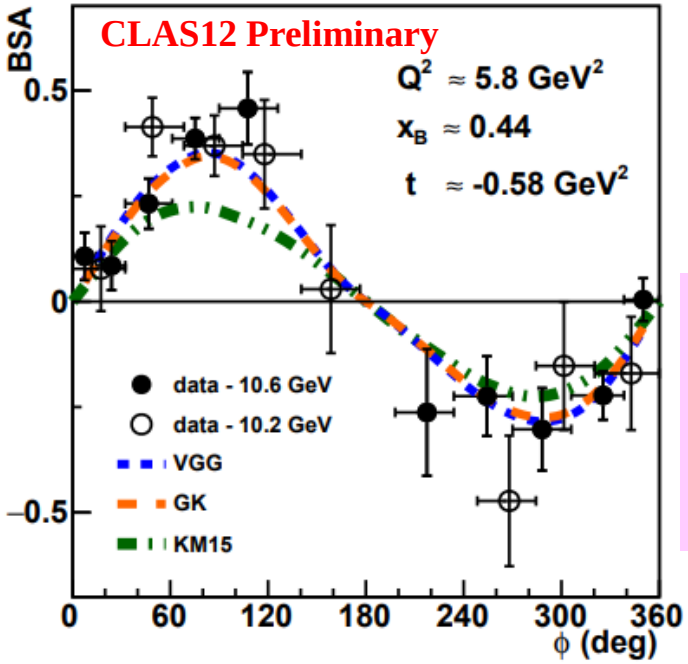


- Data taken in 2018
- Polarized beam (86%) with energy 10.6 GeV; unpolarized LH2 target
- 64 kinematical bins (Q^2, x_B, -t)
- Many kinematics never covered before
- In previously measured kinematics, the new data are shown to be in good agreement with existing data and improve the precision of GPD fits







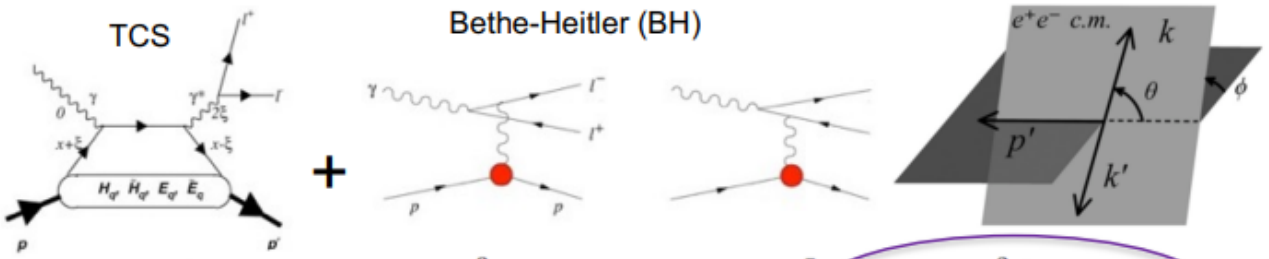


Examples of kinematics only accessible with ~10.6-GeV beam

Publication in mid October (final stage of Collaboration review)

First-ever measurement of Timelike Compton Scattering (CLAS12)

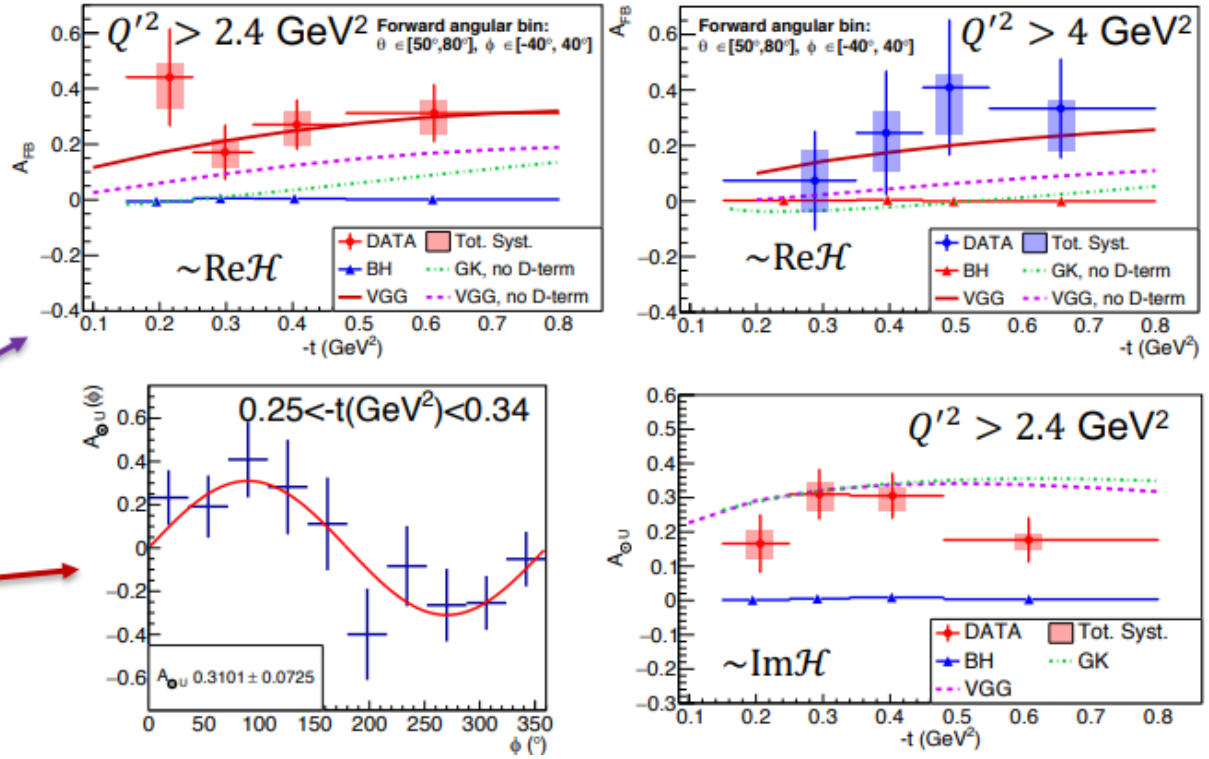
TCS – time-reversal symmetric process to DVCS:
incoming photon is real, and the outgoing photon has large time-like virtuality.



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

Incoming photon polarization

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



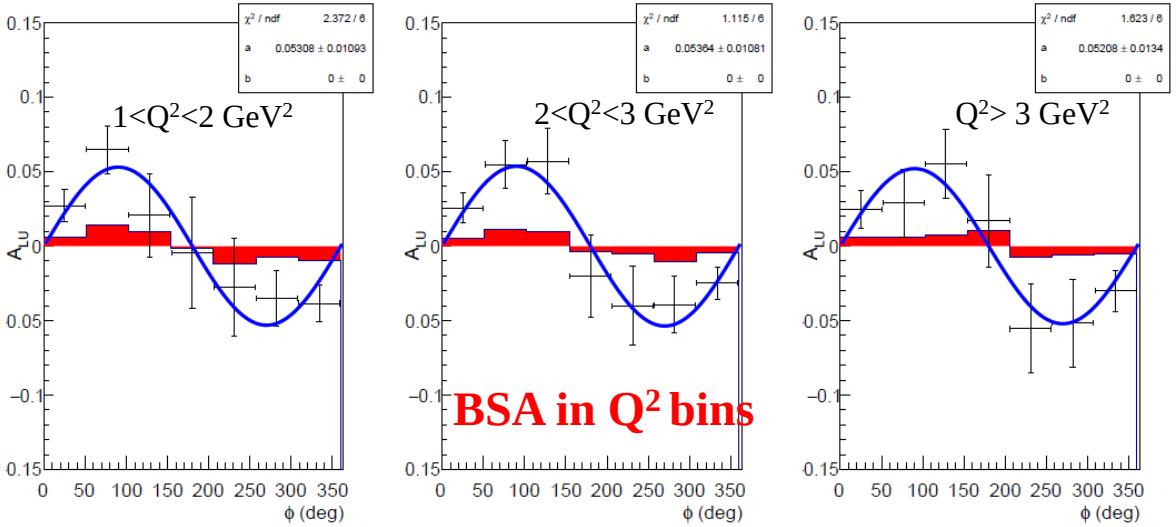
P. Chatagnon et al. (CLAS), Phys. Rev. Lett. 127, 262501 (2021)

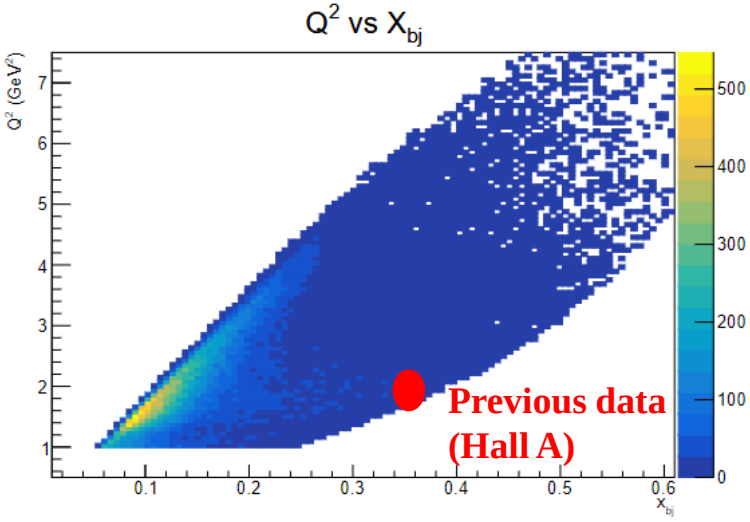
- The beam helicity asymmetry of TCS accesses the imaginary part of the CFF in the same way as in DVCS and **probes the universality of GPDs**
- The forward-backward asymmetry is sensitive to the real part of the CFF → direct access to the Energy-Momentum Form Factor $D_q(t)$ that relates to the **mechanical 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

Preliminary beam spin asymmetry for neutron DVCS (CLAS12)

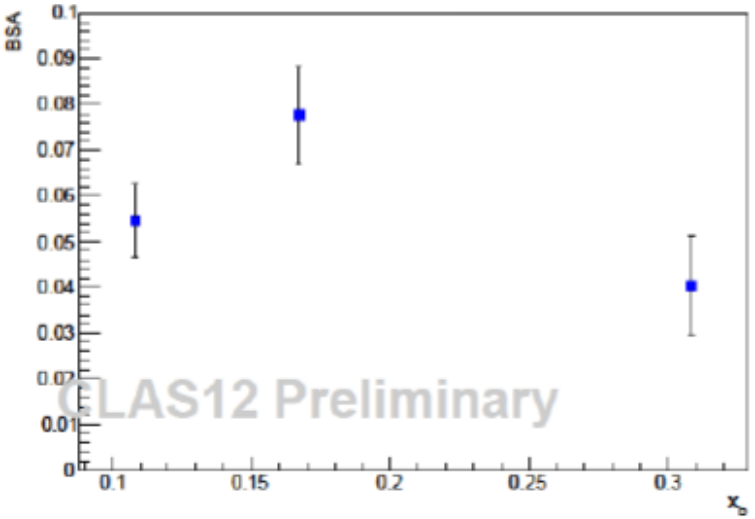
$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}$

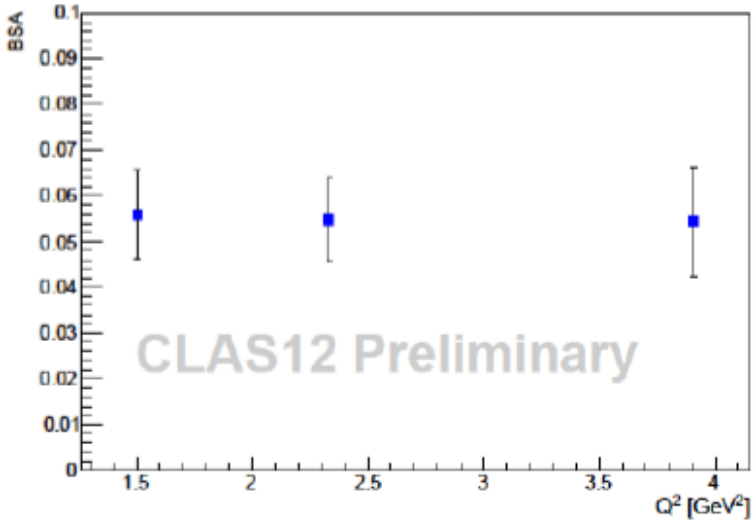
$\vec{e}d \rightarrow en\gamma(p)$

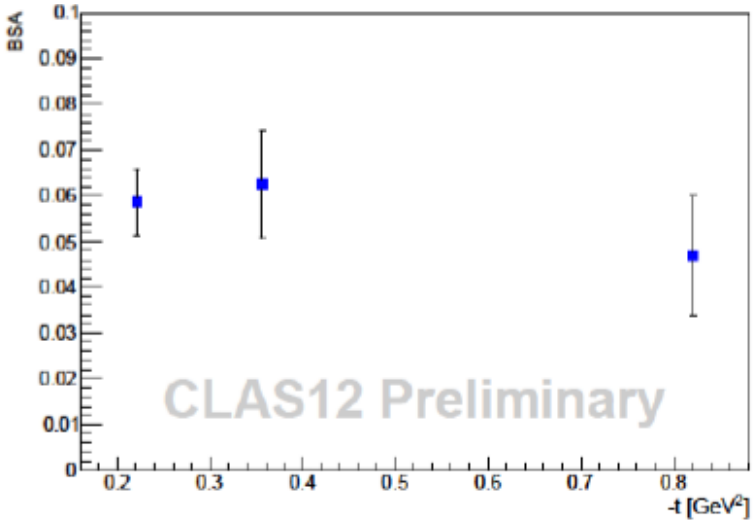




- Data taken in 2019/2020
- LD2 target, ~10.4 GeV beam energy
- Scan of the BSA on a wide phase space
- Reaching the high Q^2-high x_B region
- Exclusivity thanks to **detection of the active neutron** → small systematics
- Analysis undergoing internal review







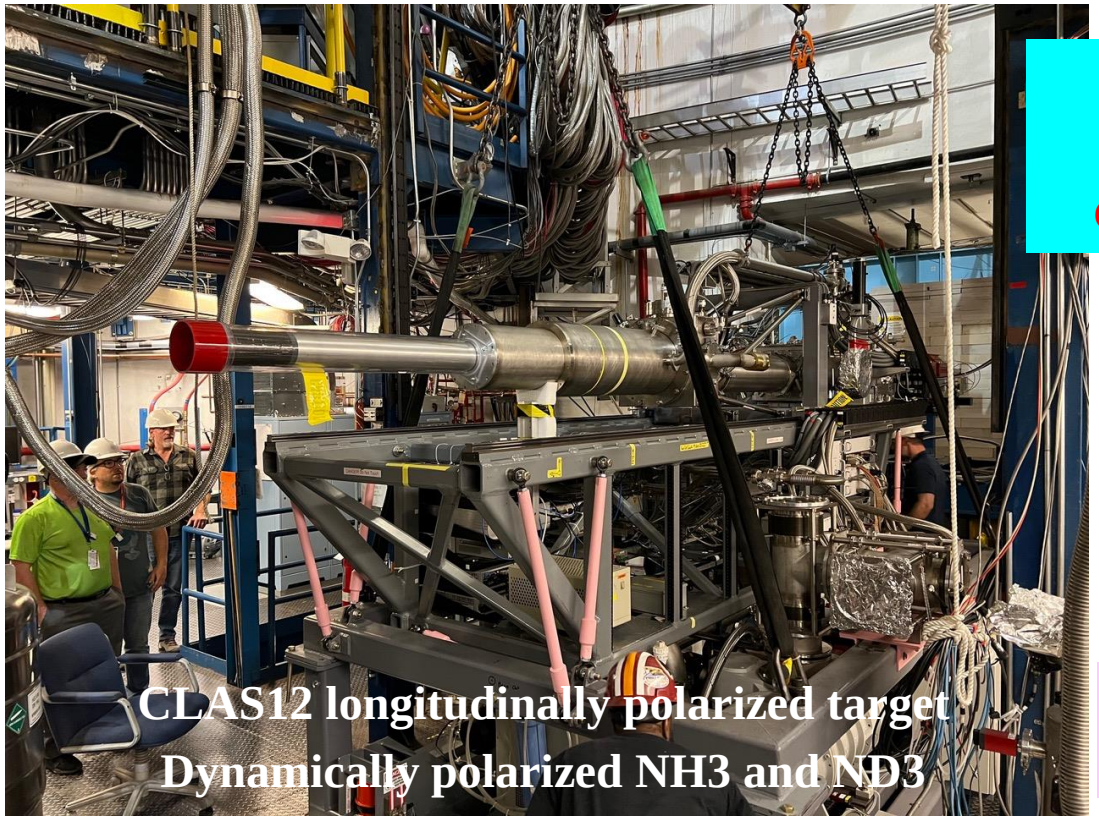
Ongoing at CLAS12: DVCS (p, n) on longitudinally polarized target

First-time measurement of longitidunal target-spin asymmetry and double (beam-target) spin asymmetry for nDVCS

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

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

→ 3 observables (including BSA), constraints on real and imaginary CFFs of various neutron GPDs



$ep \to ep\gamma$

$ed \to e(p)n\gamma$

CLAS12 + Longitudinally polarized target + CND

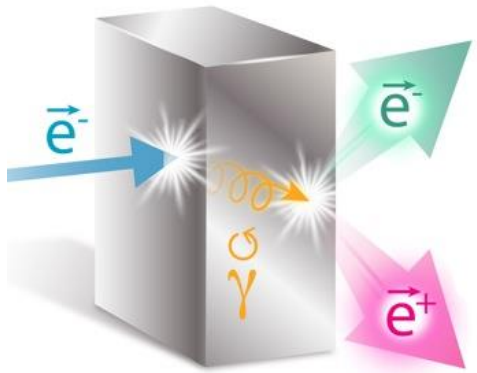
Running from June 2022 to March 2023

Transversely polarized target for CLAS12 in development → experiment ~2026

Ultimate goals: flavor separation of CFFs & Ji's sum rule

Perspectives: polarized positrons beam for Jefferson Lab

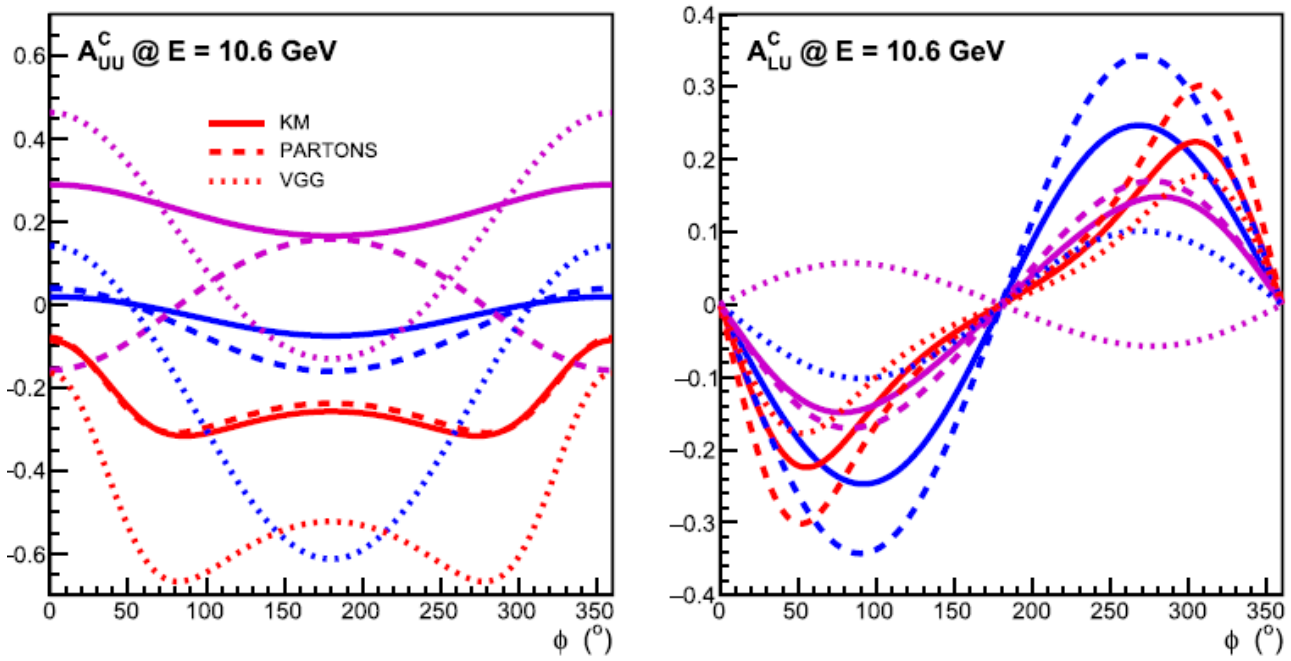
Physics Motivations:
- Two-photon physics
- **Generalized parton distributions**
- Neutral and charged current DIS
- Charm production
- Neutral electroweak coupling
- Light Dark Matter search
- Charged Lepton Flavor Violation



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

R&D ongoing
Possible timeline: ~2028-2030?

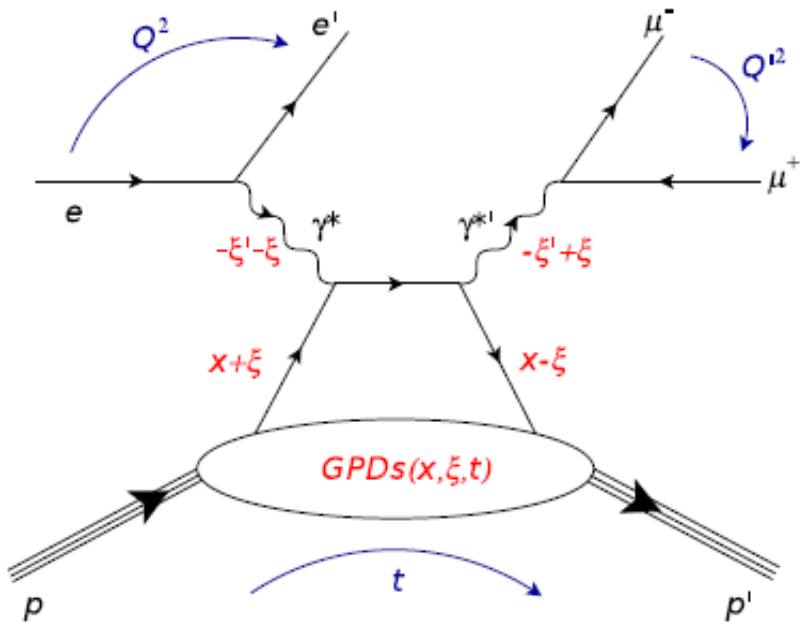
- Publication of the **EPJ A Topical Issue about "An experimental program with positron beams at Jefferson lab", Eur. Phys. J. A 58 (2022) 3, 45**
- Two DVCS-based proposals (CLAS12, Hall C) were submitted to JLab PAC48 and were Conditionally Approved

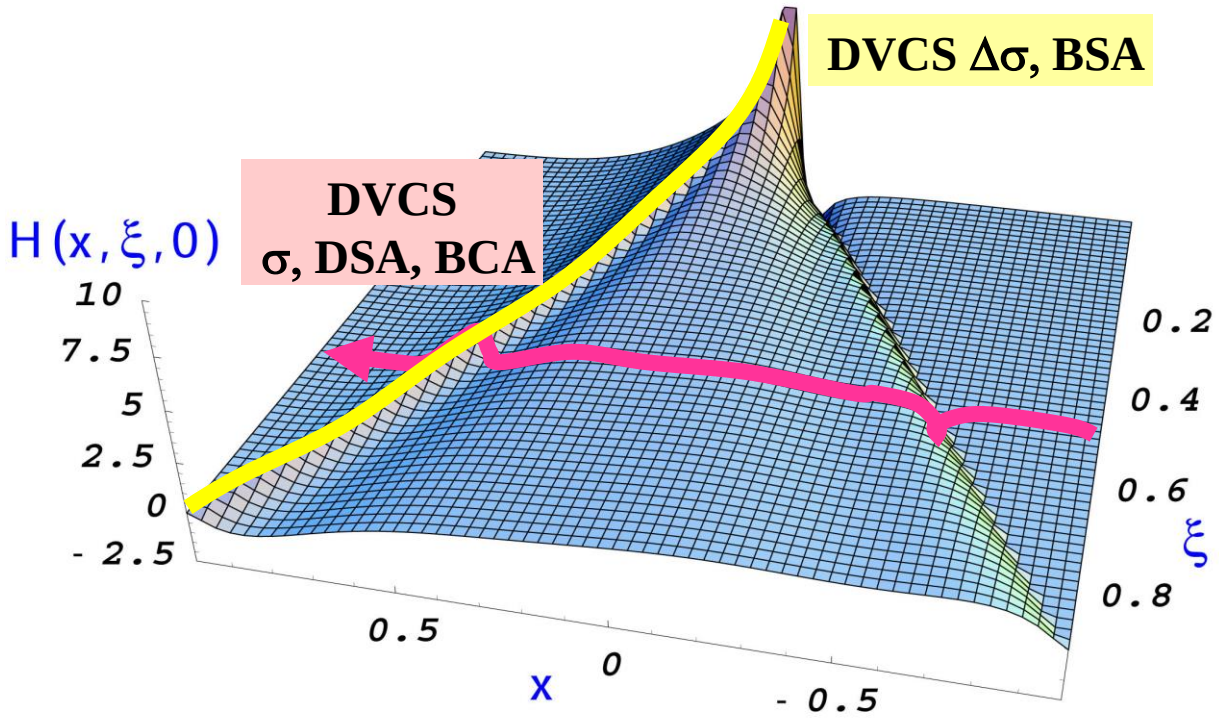


Model predictions for 2 out of the 3 proposed pDVCS observables

Impact of positron pDVCS projected data on the extraction of ReH via global fits: major reduction of relative uncertainties

DDVCS: the gateway to the full kinematic mapping of GPDs





Thanks to the virtuality of the final photon, Q'^{2}, **DDVCS** allows a unique direct access to GPDs at **x ≠ ±ξ**, which is fundamental for their modeling

Experimental challenges:

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

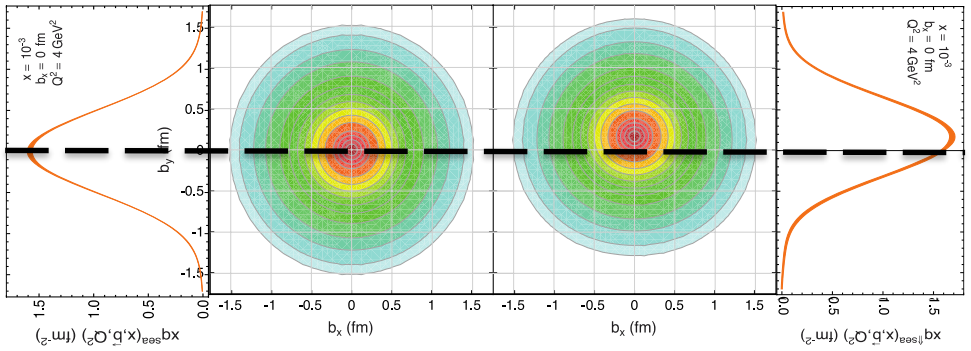
- **Possible CLAS12 upgrade (LOI): "μCLAS12" for DDVCS and J/ψ ep→e'p'μ+μ- at L~10^{37} cm^{-2}s^{-1} New tracker, calorimeter, shielding**

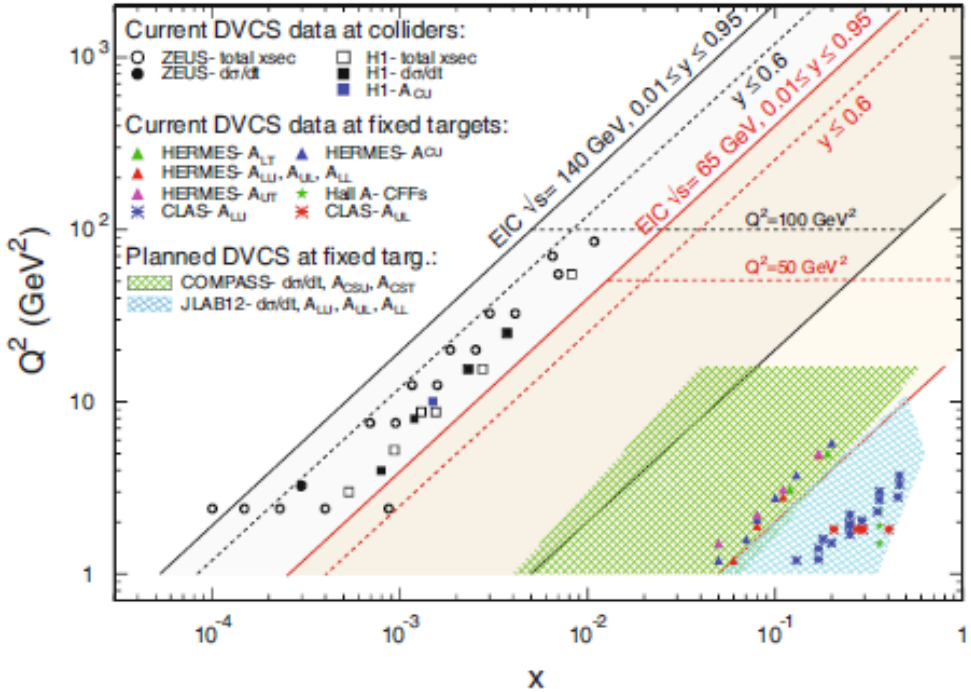
- **Possible DDVCS experiment with SOLID@HallA (LOI)**

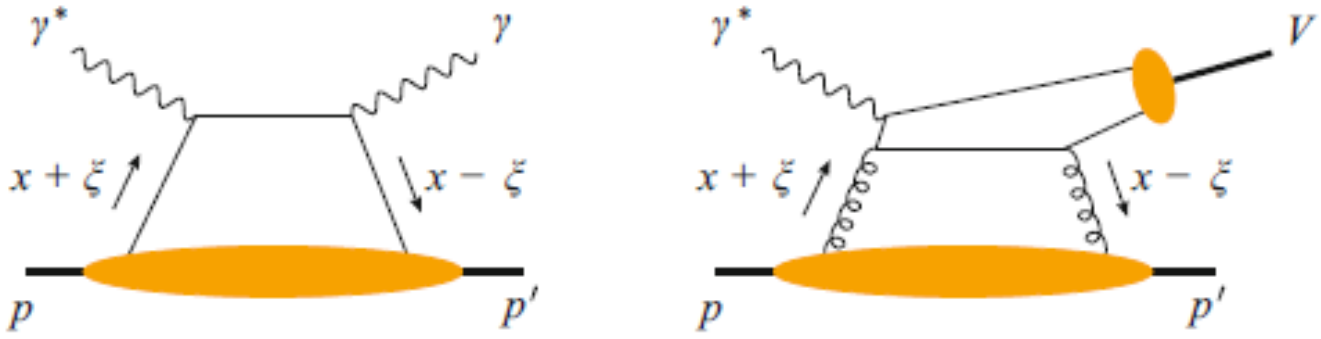
Nucleon structure with the EIC: sea quarks and gluons in 3D

Sea quarks

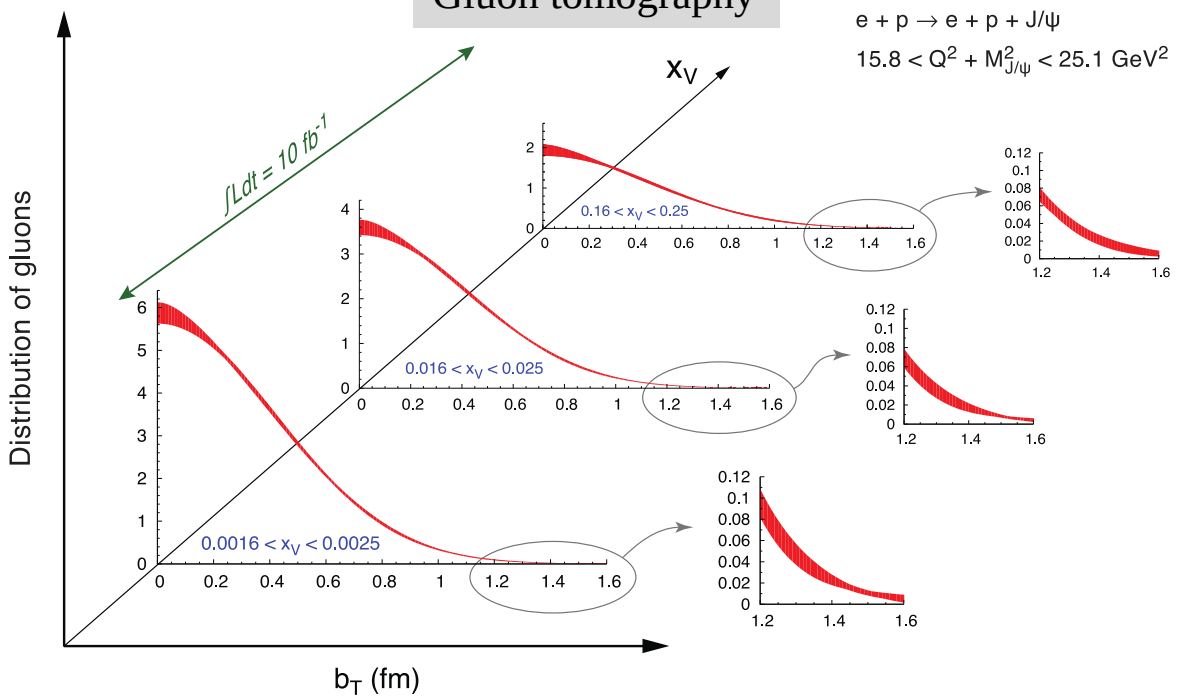
unpolarized polarized







Gluon tomography



For the EIC, see A. Deshpande's talk, Thursday at 9:30AM

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 **results** on proton-DVCS observables were obtained from **HERMES**, **CLAS** and **Hall-A** at 6 GeV

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

→ Insight in the **pressure distributions** in the proton

✓ 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, GPD flavor separation, <u>quarks' orbital angular momentum</u>, …**

→ 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

Back-up material

JLab@12 GeV DVCS program

Observable (target)	12-GeV experiments	CFF sensitivity	Status
σ, $\Delta\sigma_{beam}(p)$	Hall A CLAS12 Hall C	$\mathrm{Re}\mathcal{H}(p)$, $\mathrm{Im}\mathcal{H}(p)$	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	$\mathrm{Im}\mathcal{H}(p)$	BSA publication in Ad Hoc review stage
lTSA(p), lDSA(p)	CLAS12	$\mathrm{Im}\tilde{\mathcal{H}}(p)$, $\mathrm{Im}\mathcal{H}(p)$, $\mathrm{Re}\tilde{\mathcal{H}}(p)$, $\mathrm{Re}\mathcal{H}(p)$	Experiment just started! (will last 6 months)
tTSA(p)	CLAS12	$\mathrm{Im}\mathcal{H}(p)$, $\mathrm{Im}\mathcal{E}(p)$	Experiment foreseen for ~2025
BSA(n)	CLAS12	$\mathrm{Im}\mathcal{E}(n)$	Data taken in 2019-2020, BSA analysis undergoing CLAS review
lTSA(n), lDSA(n)	CLAS12	$\mathrm{Im}\mathcal{H}(n)$, $\mathrm{Re}\mathcal{H}(n)$	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

Distribution of forces in the proton

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

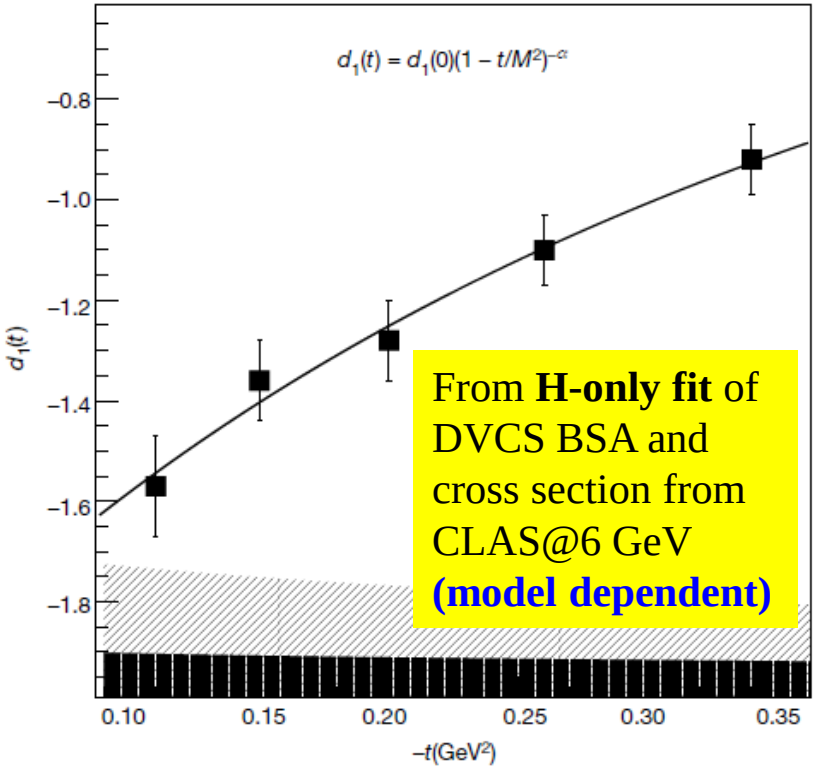
Second Mellin moment of H in x: **gravitational form factor** of the energy-momentum tensor → shear forces and pressure (d_1)

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

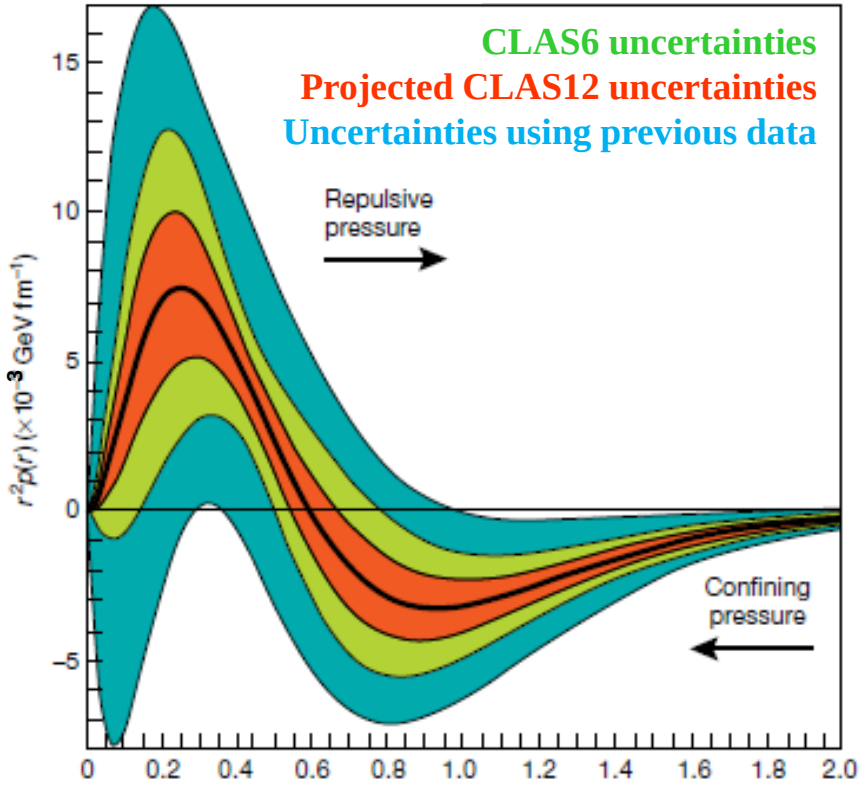
$$\mathrm{Re}\mathcal{H}(\xi,t) \overset{\mathrm{lo}}{=} D(t) + \mathcal{P}\int_{-1}^{1}\mathrm{d}x\left(\frac{1}{\xi-x} - \frac{1}{\xi+x}\right)\mathrm{Im}\mathcal{H}(x,t)$$

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

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



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

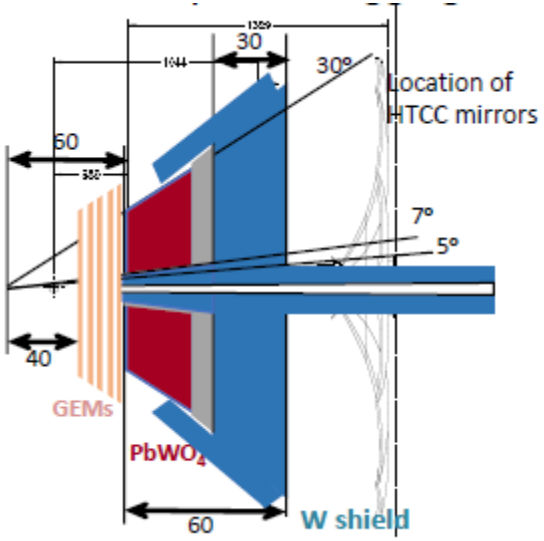


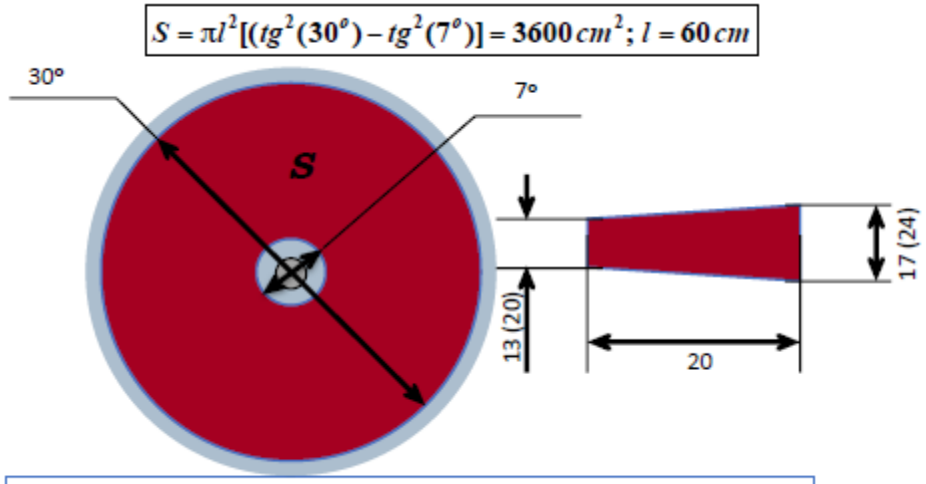
V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

μCLAS12 for DDVCS and J/psi

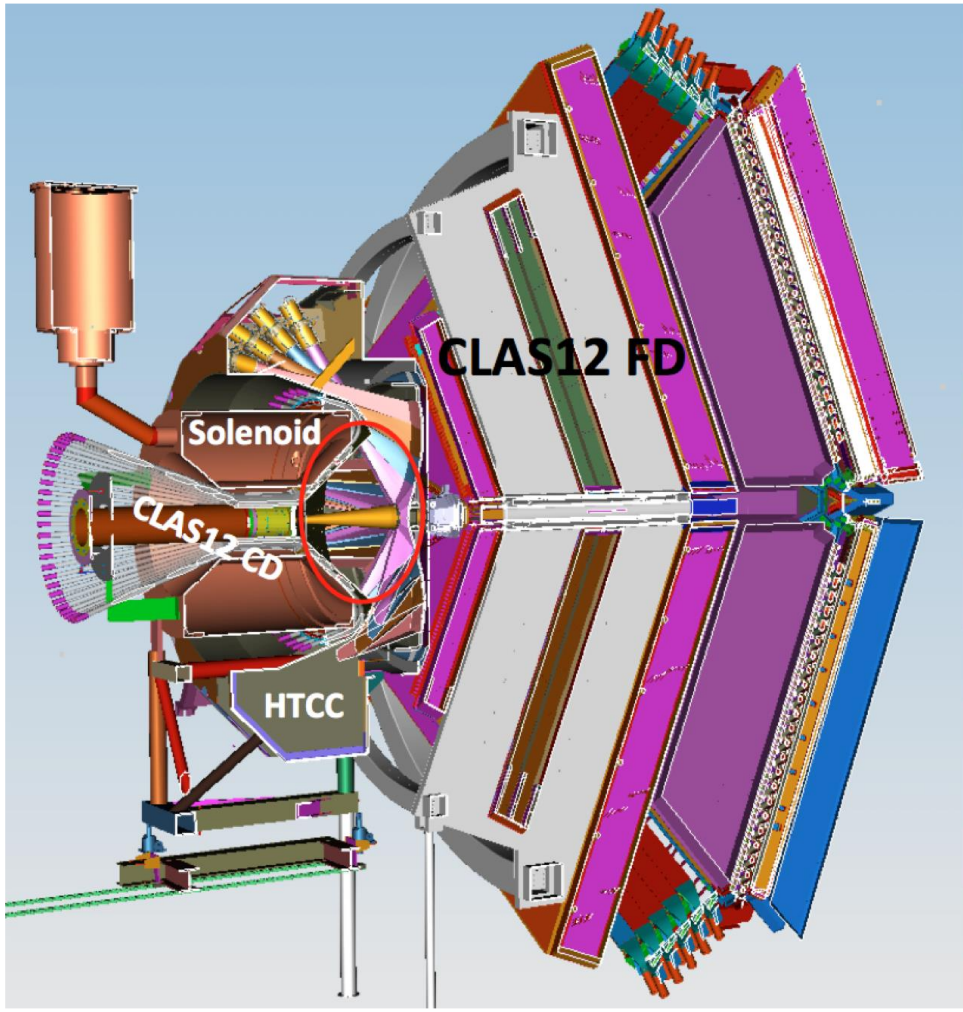
$ep \rightarrow e'p'\mu^+\mu^-$ at $L \sim 10^{37}\ cm^{-2}s^{-1}$

- 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



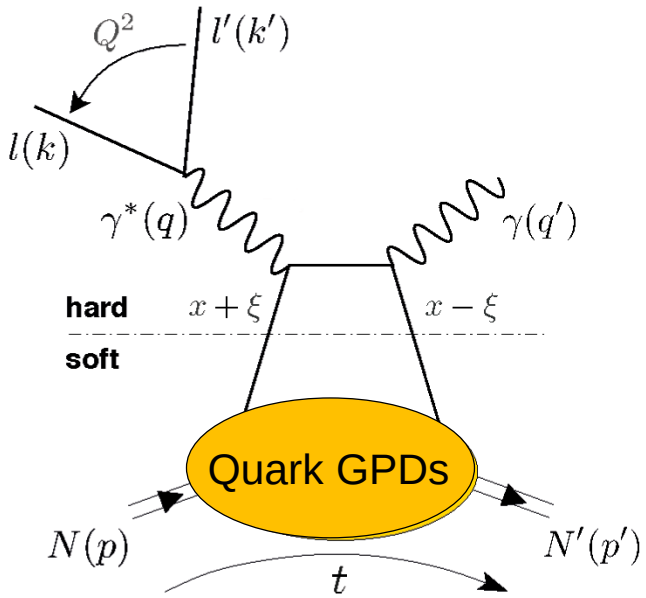


$PbWO_4$ modules with APD readout - ~ 1200 modules

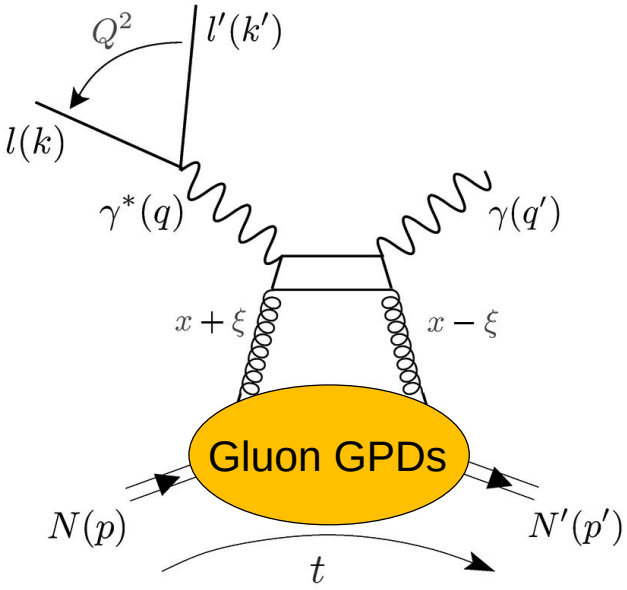


S. Stepanyan, LOI12-16-004

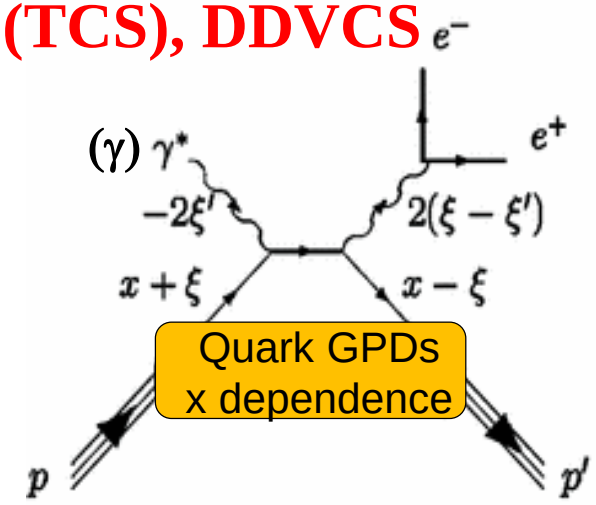
Exclusive reactions giving access to GPDs

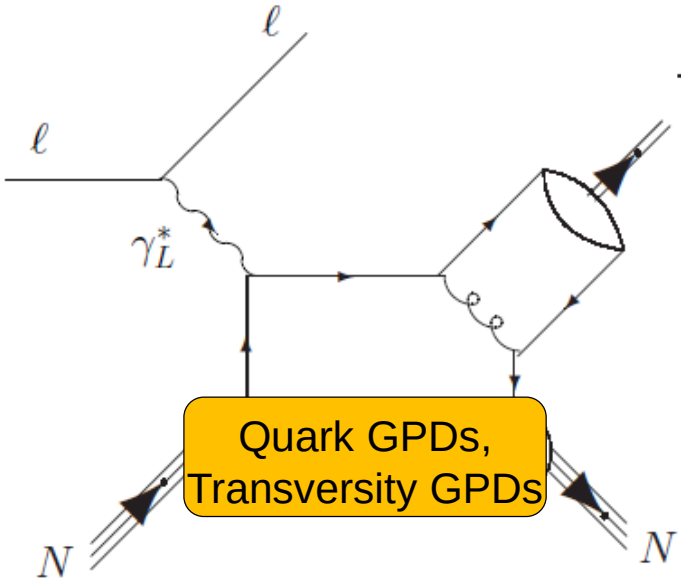


DVCS

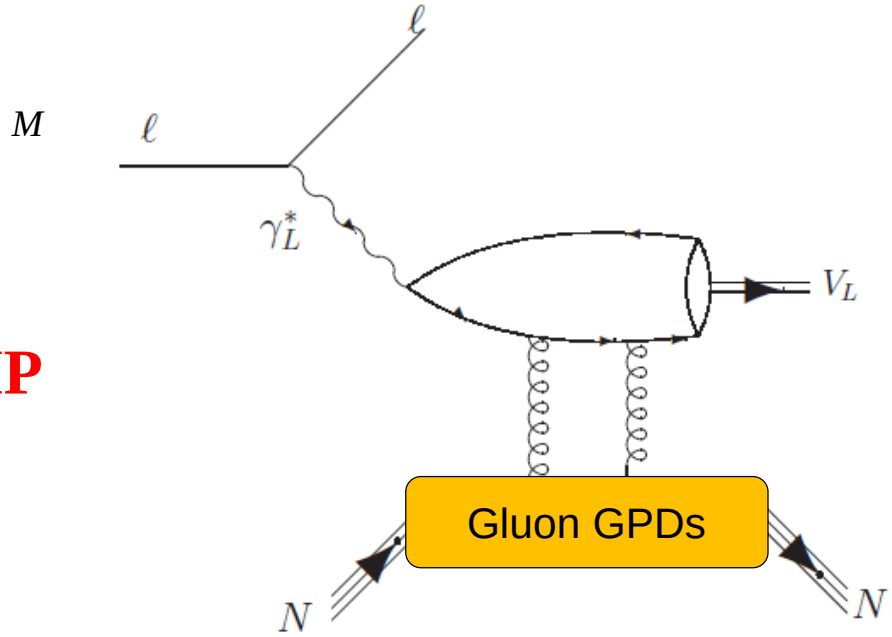


(TCS), DDVCS





DVMP



DVCS with polarized positrons beam at JLab

The important of beam-charge asymmetry for DVCS was highlighted by the pioneering HERMES experiment
Disposing of a polarized positron/electron beams at JLab → new observables = different sensitivities to GPDs
Beam Charge Asymmetries proposed to be measured at CLAS12:
- The unpolarized beam charge asymmetry A_C^{UU}, which is sensitive to the real part of the CFF → D-term, forces in the proton
- The polarized beam charge asymmetry A_C^{LU}, which is sensitive to the imaginary part of the CFF
- The neutral beam spin asymmetry A_0^{LU}, which is sensitive to higher twist effects

New GPD Observables @ JLab

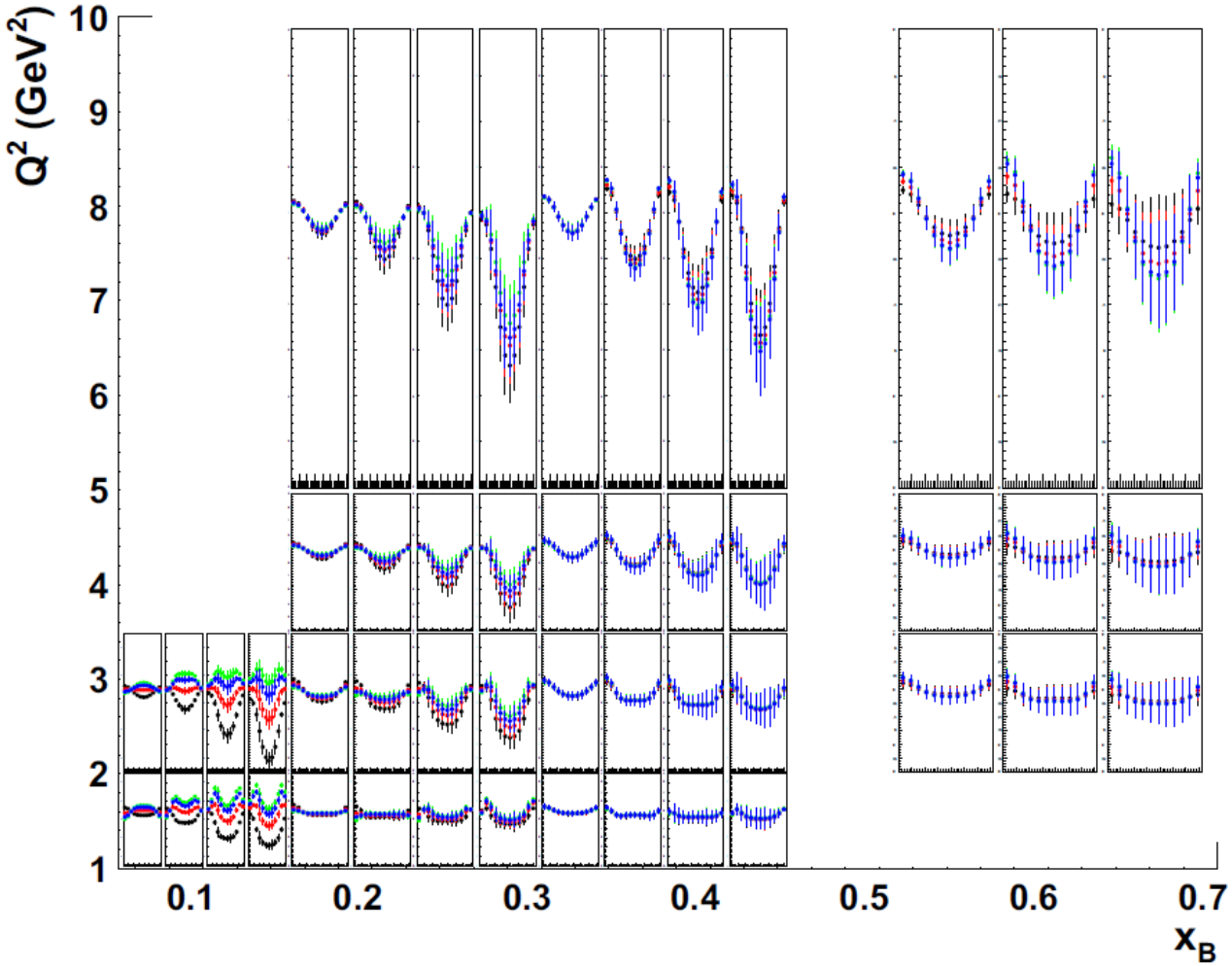
$$A_{UU}^{C} = \frac{(Y_+^+ + Y_-^+) - (Y_+^- + Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-} = \frac{\sigma_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A_{LU}^{C} = \frac{(Y_+^+ - Y_-^+) - (Y_+^- - Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-} = \frac{\tilde{\sigma}_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A_{LU}^{0} = \frac{(Y_+^+ + Y_+^-) - (Y_-^+ + Y_-^-)}{Y_+^+ + Y_-^+ + Y_+^- + Y_-^-} = \frac{\tilde{\sigma}_{DVCS}}{\sigma_{BH} + \sigma_{DVCS}}$$

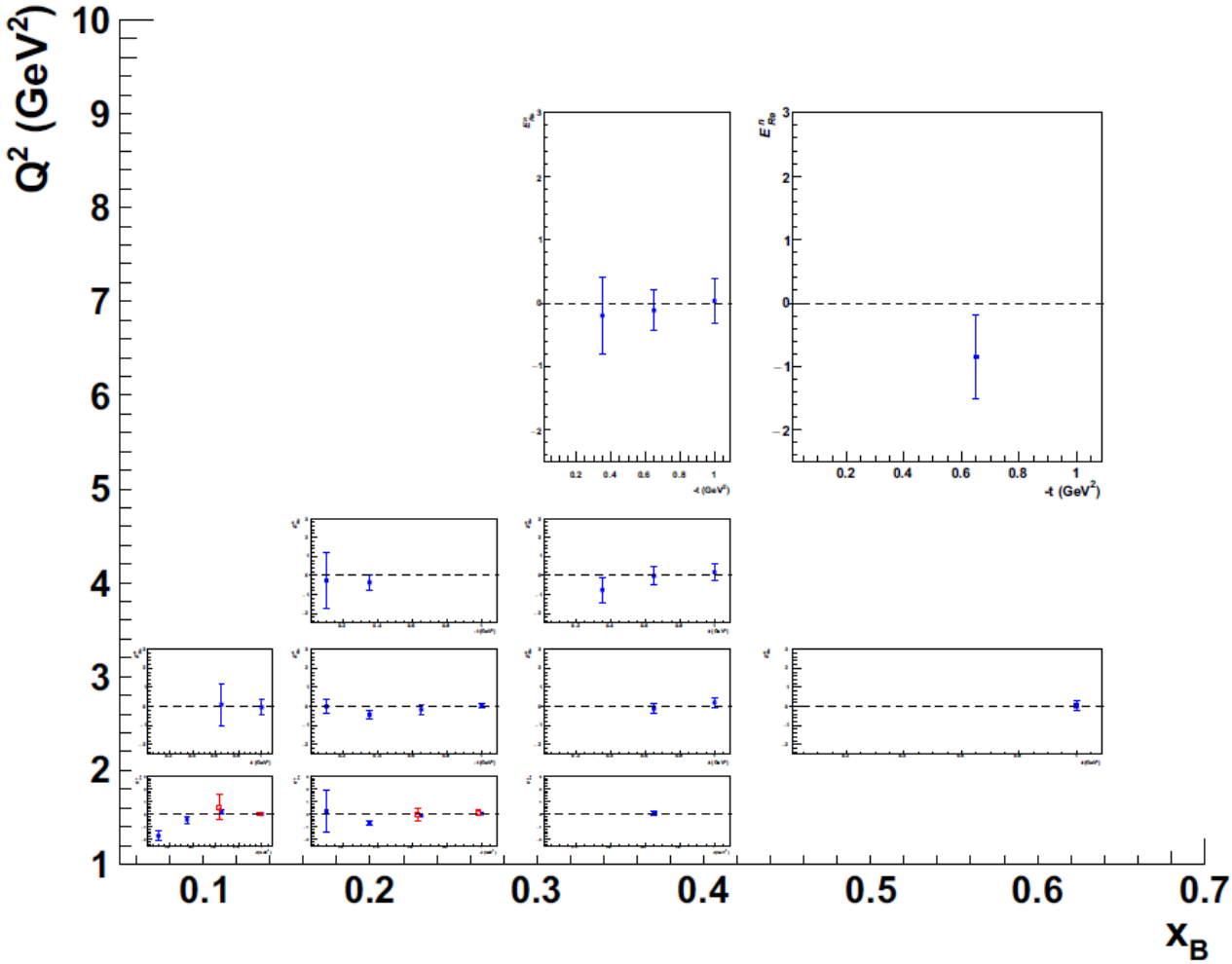
$$A_{LU}^{C} \neq A_{LU}^{\pm} = \frac{\pm(\tilde{\sigma}_{INT} \pm \tilde{\sigma}_{DVCS})}{\sigma_{BH} + \sigma_{DVCS} \pm \sigma_{INT}}$$

nDVCS with polarized positrons beam at CLAS12



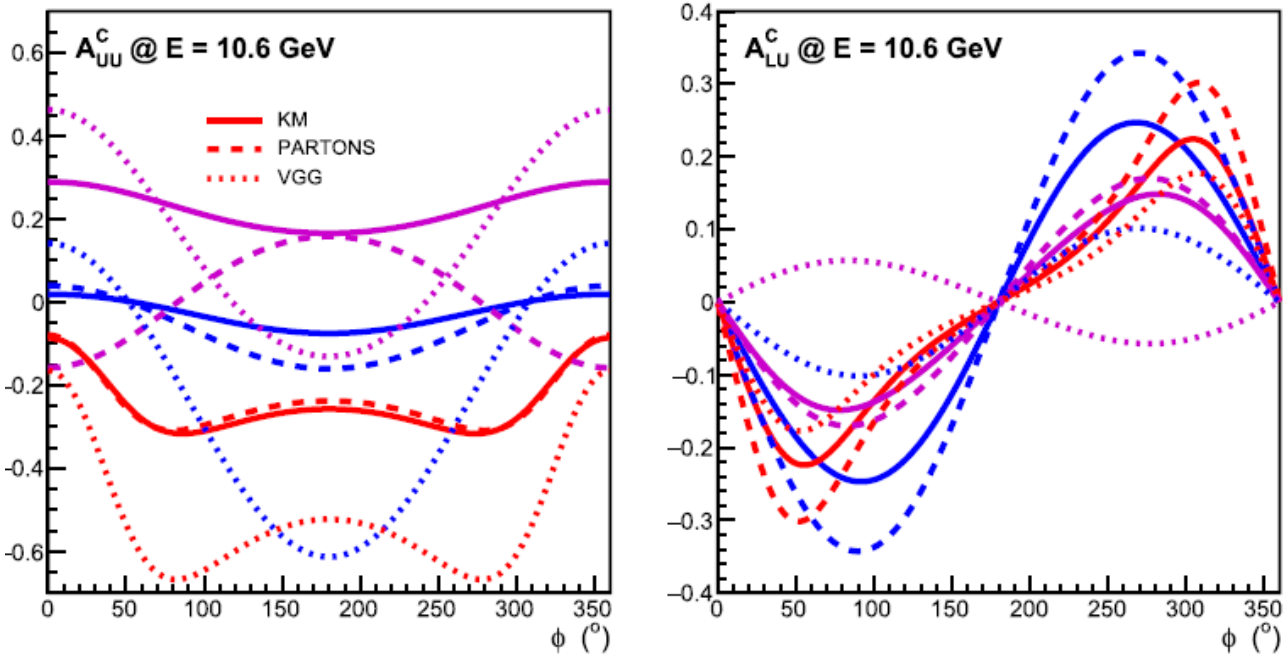
rojections (VGG) for the BCA, for various values of J_u, J_d
3, 0.1; 0.2/0.0; 0.1/−0.1; 0.3/−0.1

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



Impact on the extraction of Re$\mathcal{E}$ using local fits, using the projections of approved CLAS12 nDVCS measurements with and without BCA

pDVCS and nDVCS with polarized positrons beam at CLAS



Model predictions for 2 out of the 3 proposed pDVCS observables

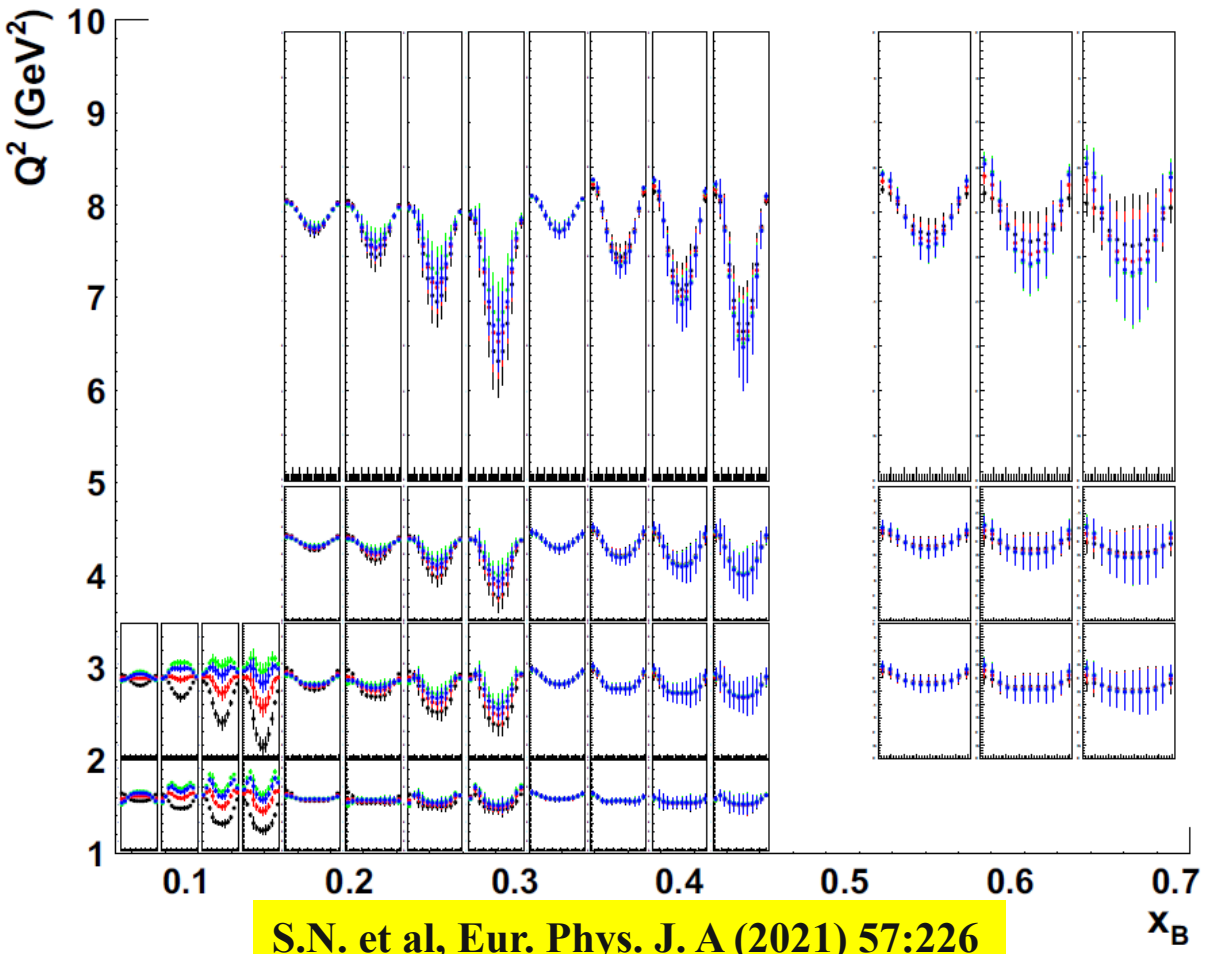
Impact of positron pDVCS projected data on the extraction of ReH via global fits: major reduction of relative uncertainties, especially at low -t

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