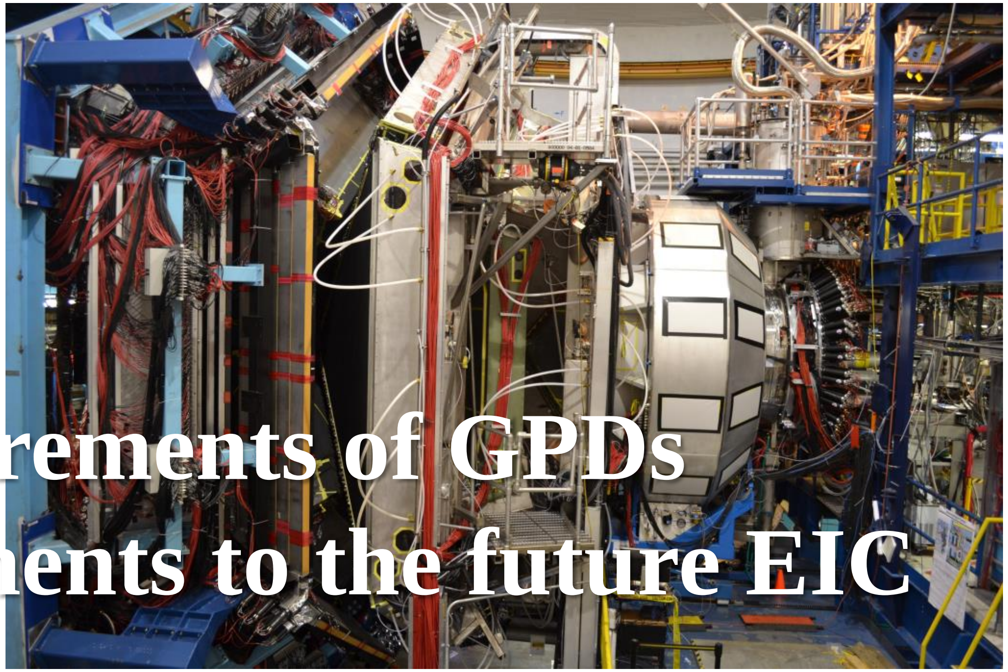


Experimental measurements of GPDs
From fixed target experiments to the future EIC

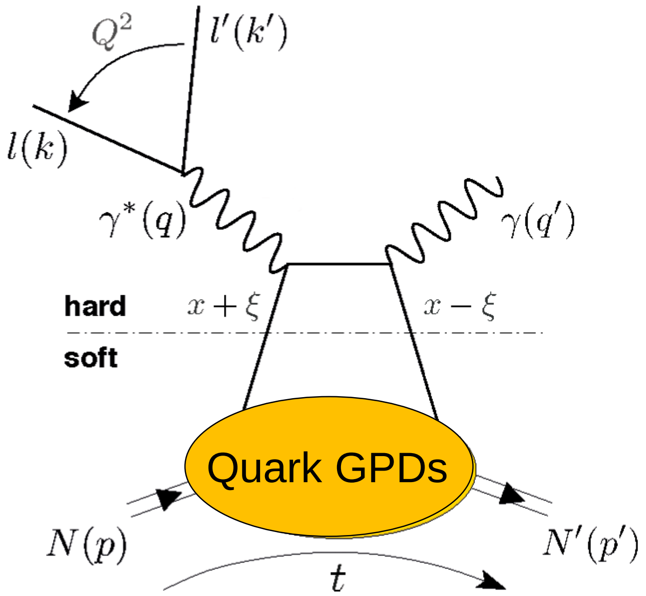
Silvia Niccolai, IJClab Orsay & CLAS Collaboration

EINN2023, Paphos, (Cyprus), 1/11/2023

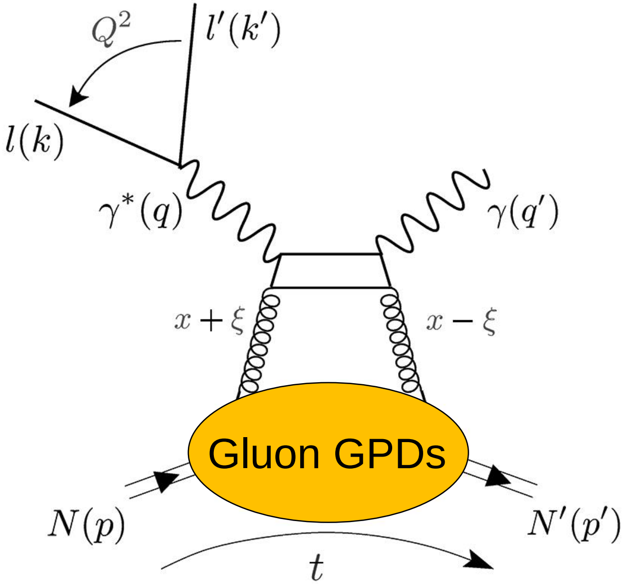
IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

clas
CEBAF Large Acceptance Spectrometer

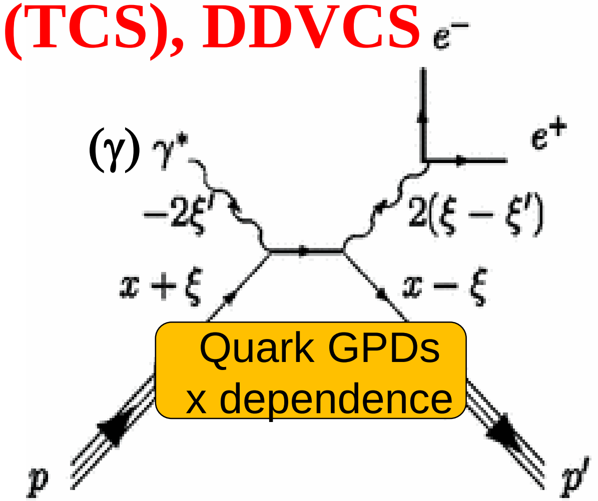
Exclusive reactions giving access to GPDs

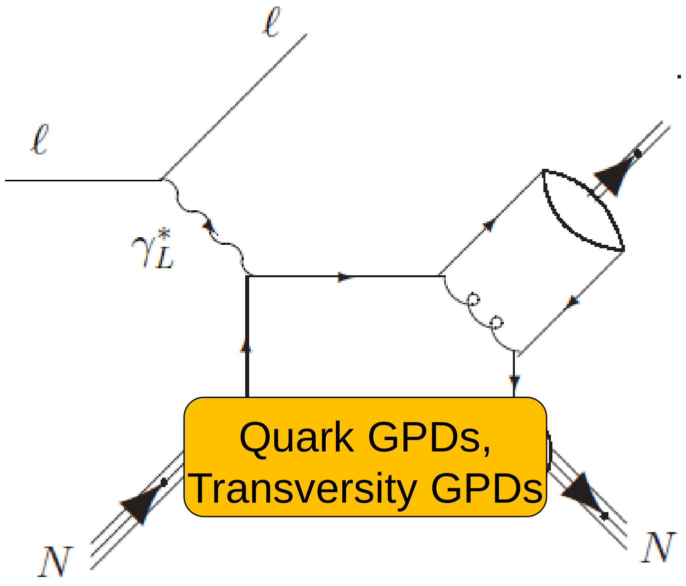


DVCS

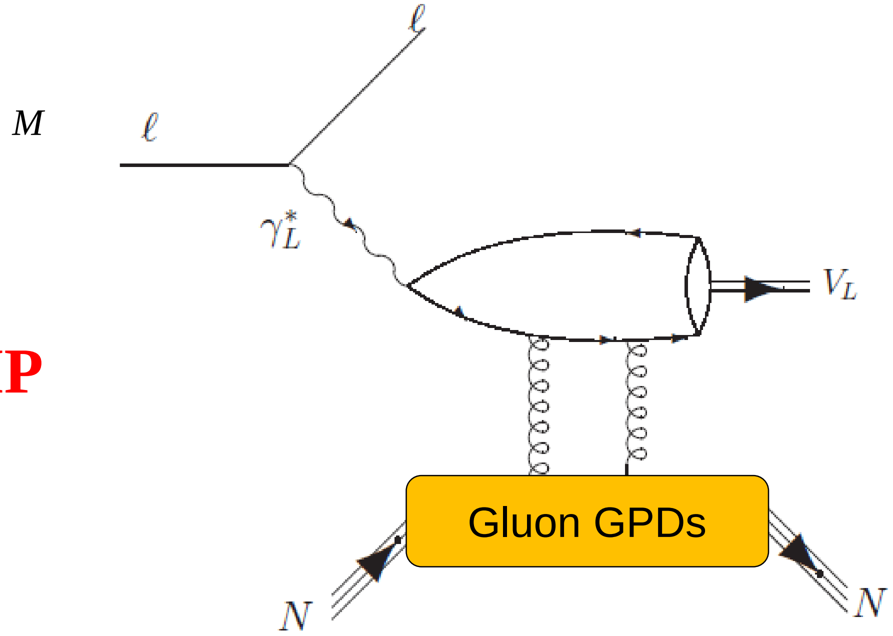


(TCS), DDVCS

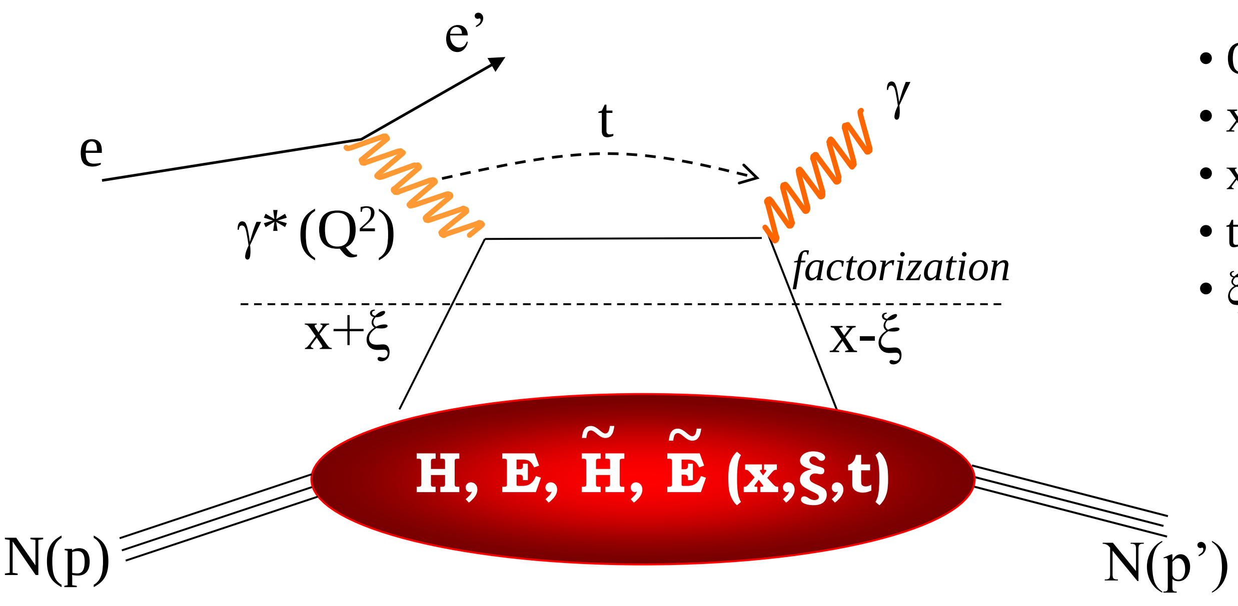




DVMP



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

Nucleon tomography

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

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

Quark angular momentum (Ji's sum rule)

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

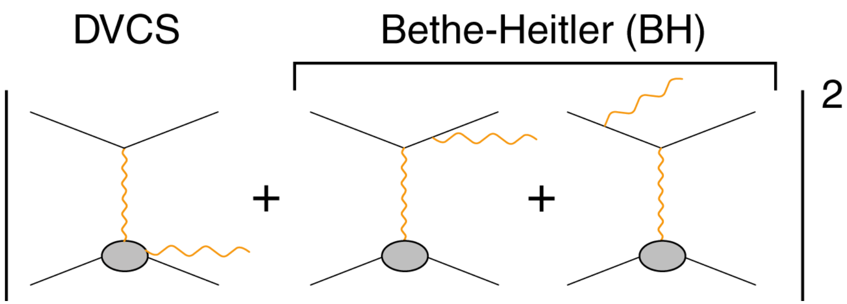
Accessing GPDs through DVCS

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

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

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

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



Proton Neutron

Polarized beam, unpolarized target:

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

Unpolarized beam, longitudinal target:

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

Polarized beam, longitudinal target:

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

Unpolarized beam, transverse target:

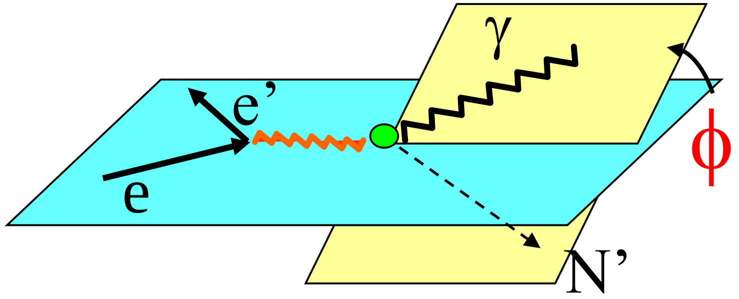
$\Delta\sigma_{UT} \sim \cos\phi\sin(\phi_s-\phi)\mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) +\ldots\}$ ⇒ $Im\{\mathcal{H}_p, \mathcal{E}_p\}$, $Im\{\mathcal{H}_n\}$

Unpolarized beam and target, different lepton charges:

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

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

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

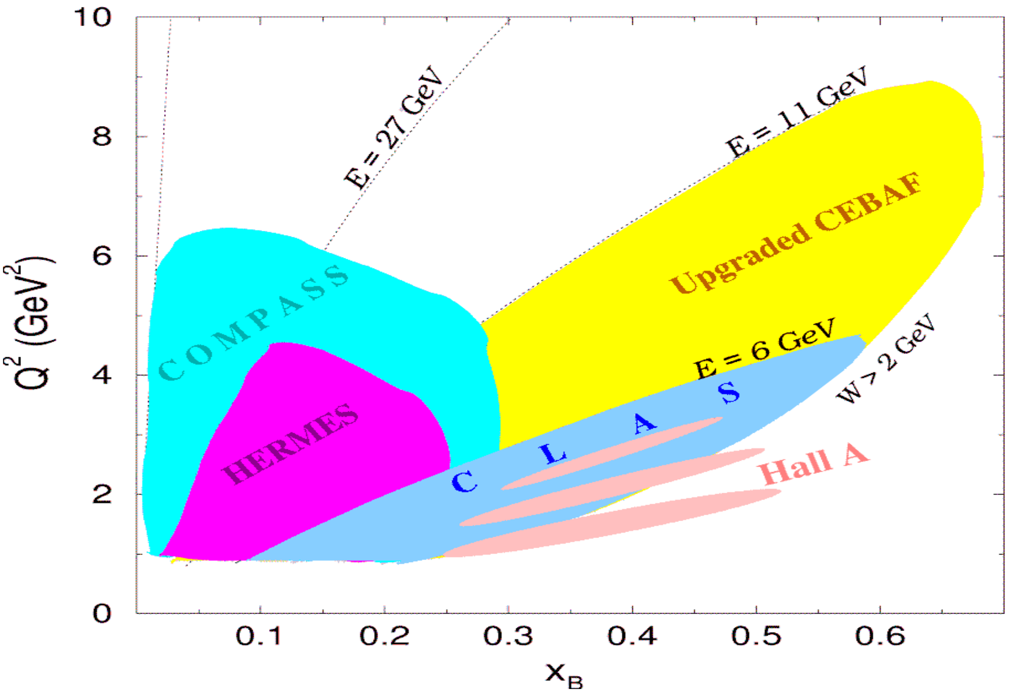


History of DVCS experiments worldwide

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

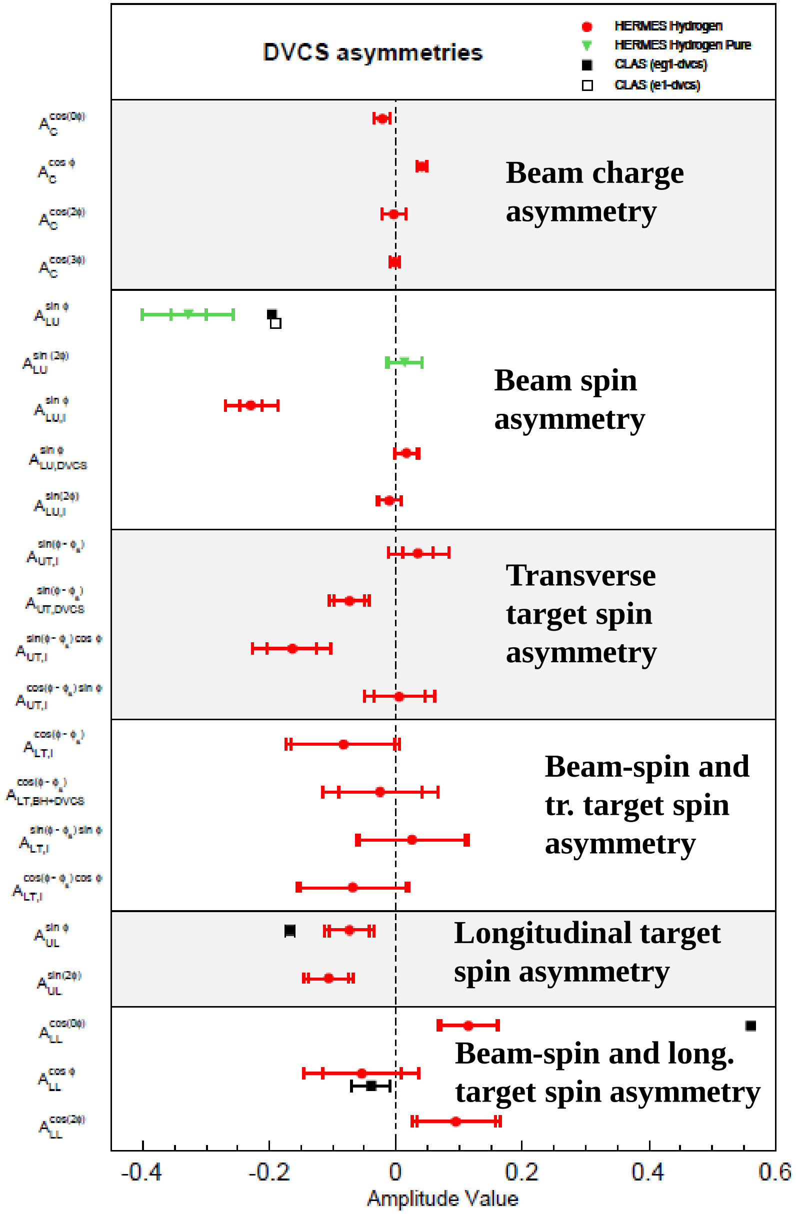
DESY	
HERMES	***H1/ZEUS***
p-DVCS,BSA,BCA, tTSA,lTSA,DSA	p-DVCS,CS,BCA

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



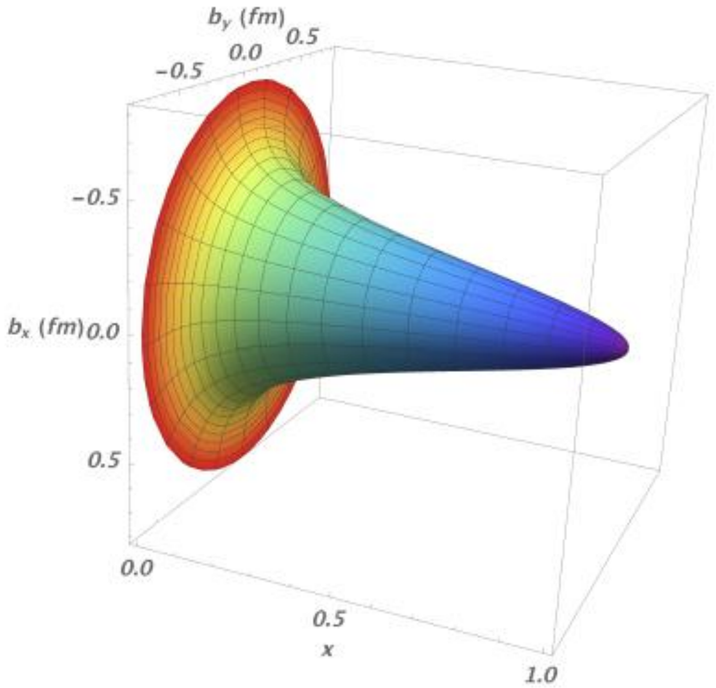
CLAS, HERMES: first observation of DVCS-BH interference in the beam-spin asymmetry (2001)

Hall A: test of scaling for DVCS (2006)



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

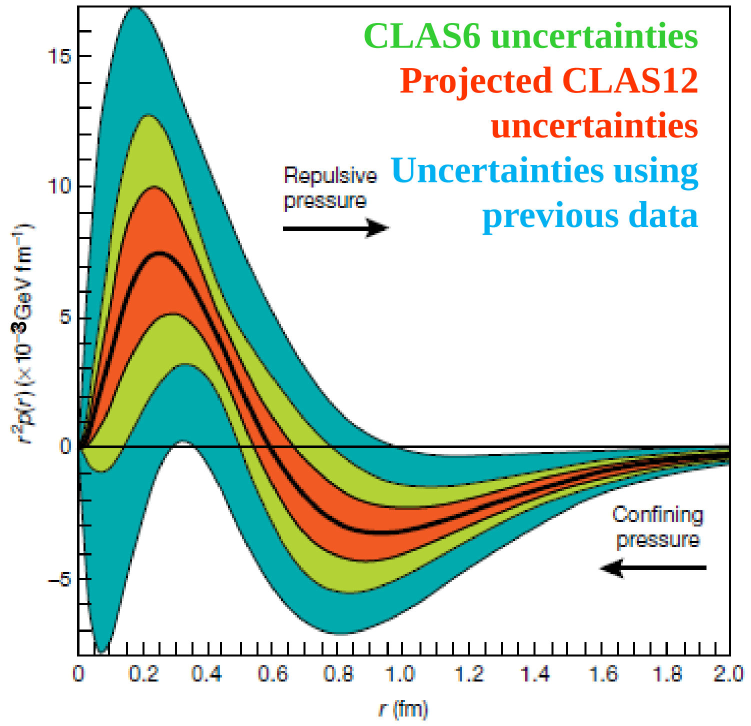
Proton tomography from *local fits* to HERMES, CLAS, and Hall-A data (**Im$\mathcal{H}$** + **model dependent** assumptions for x dependence)



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

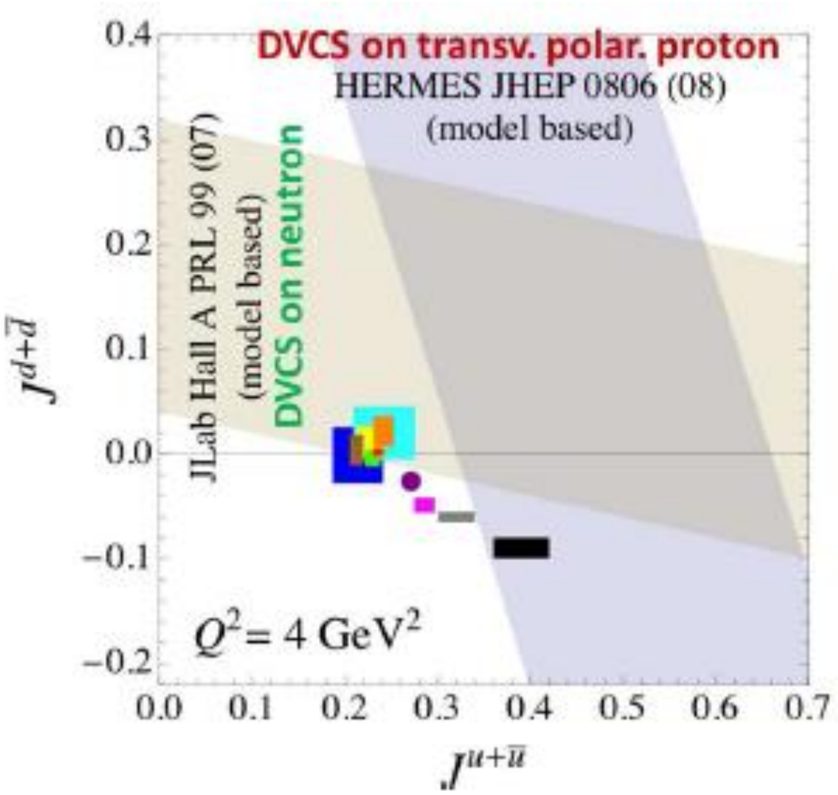
R. Dupré, M. Guidal, M.Vanderhaeghen, PRD95 (2017)

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**



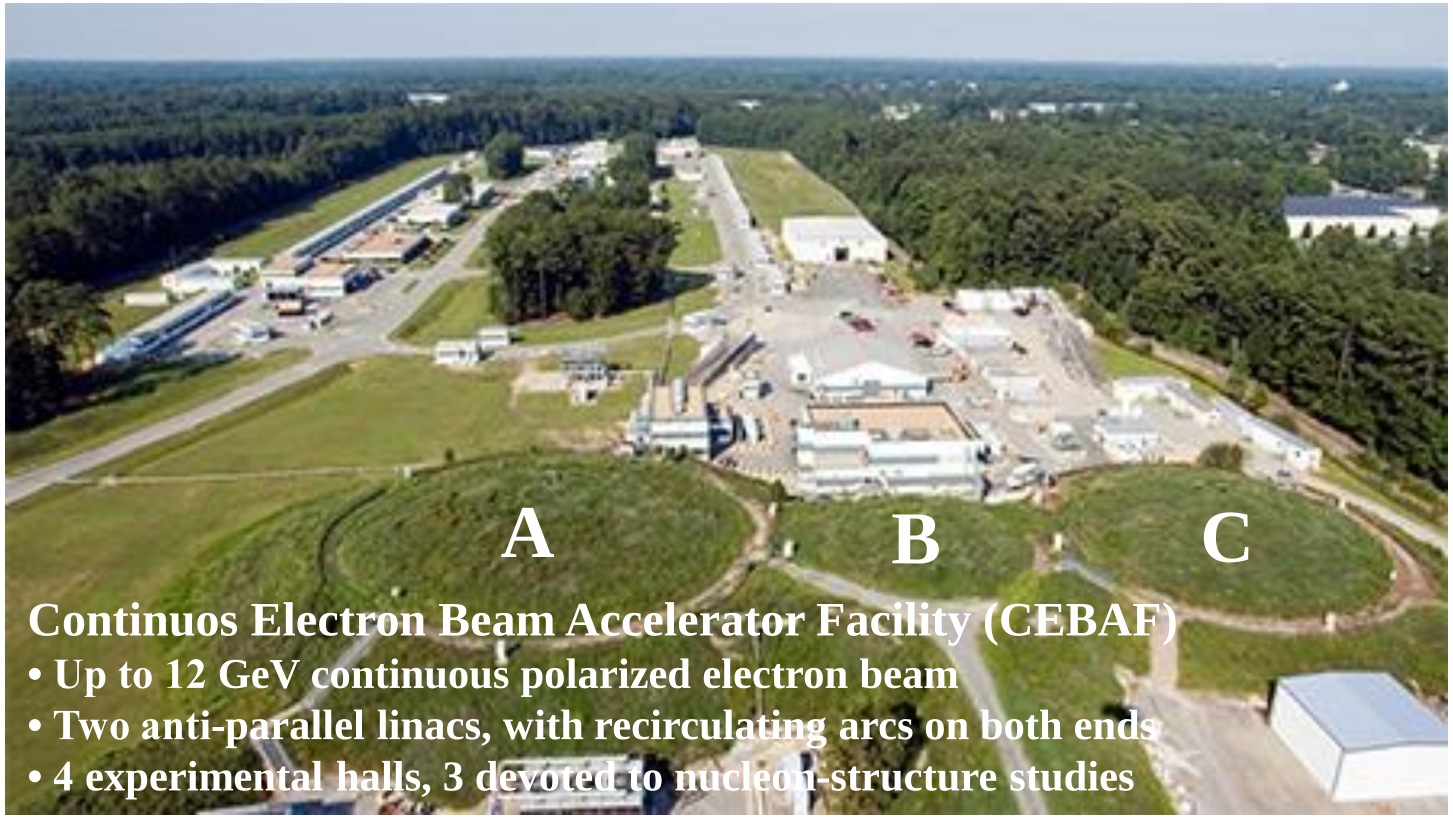
V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

Importance of **neutron-DVCS** and **transversely-polarized proton-DVCS** to **constrain J_u and J_d**



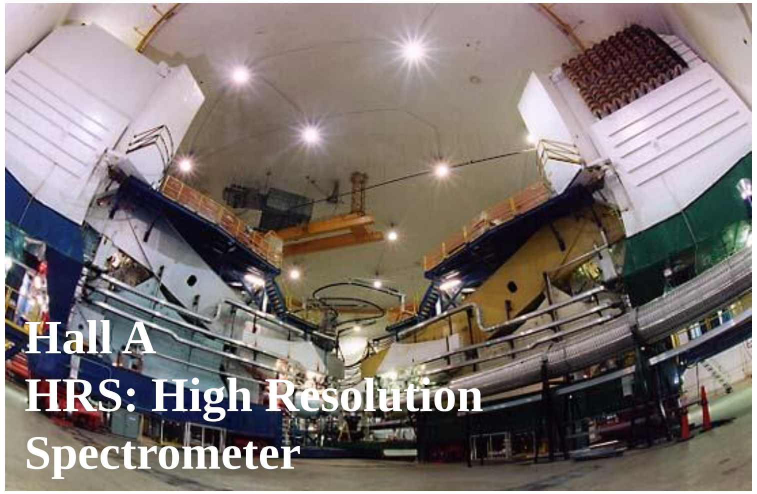
M. Mazouz et al., PRL 99 (2007) 242501

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**



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

JLab@12 GeV DVCS program

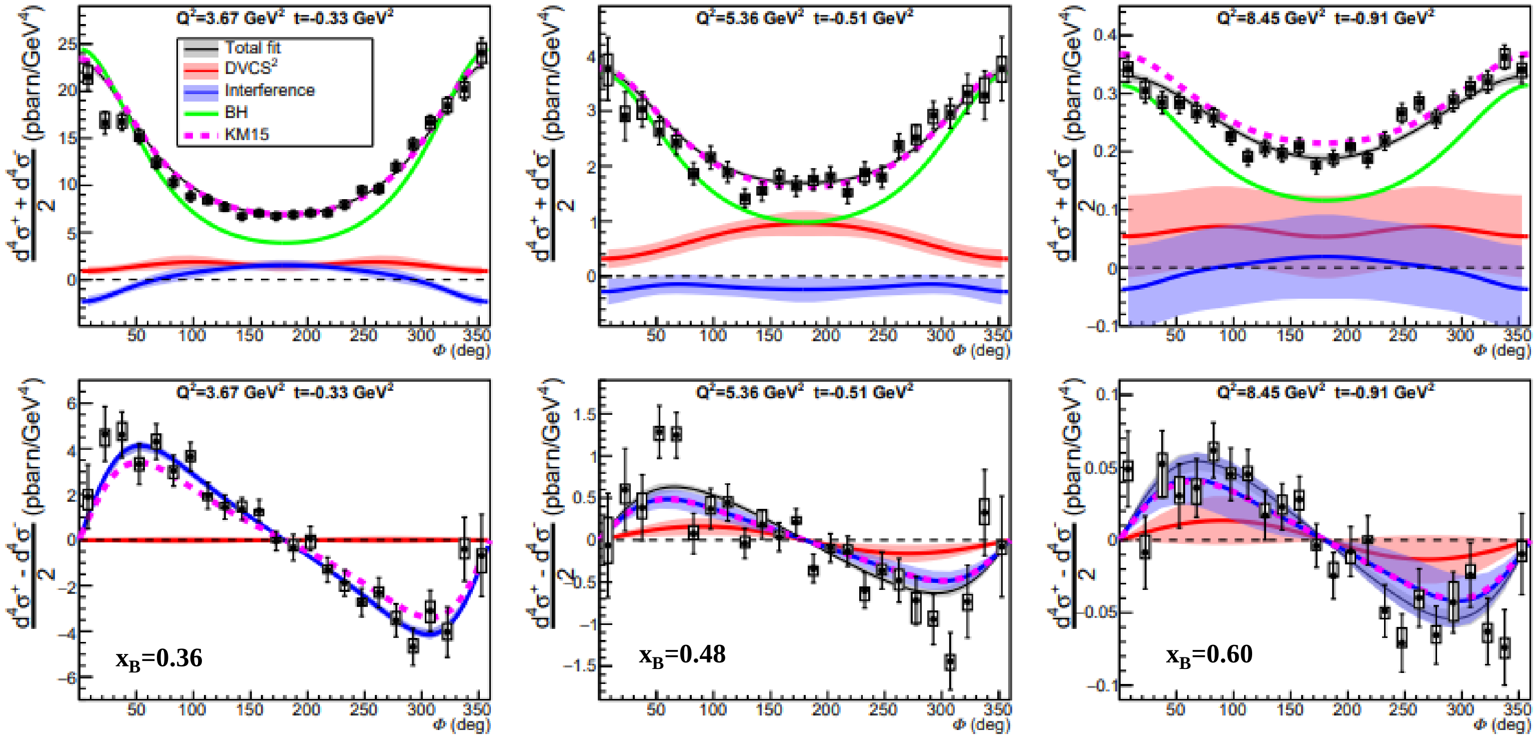
Observable (target)	**12-GeV experiments**	**CFF sensitivity**	**Status**
σ, $\Delta\sigma_{beam}$(p)	Hall A CLAS12 Hall C	Re$\mathcal{H}$(p), Im$\mathcal{H}$(p)	Data taken in 2016; Phys. Rev. Lett. 128 (2022) Data taken in 2018-2019; CS analysis under review Experiment ongoing
BSA(p)	CLAS12	Im$\mathcal{H}$(p)	Data taken in 2018-2019; Phys. Rev. Lett. 130 (2023)
lTSA(p), lDSA(p)	CLAS12	Im$\tilde{\mathcal{H}}$(p), Im$\mathcal{H}$(p), Re$\tilde{\mathcal{H}}$(p), Re$\mathcal{H}$(p)	Experiment recently completed
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 final steps of CLAS review
lTSA(n), lDSA(n)	CLAS12	Im$\mathcal{H}$(n), Re$\mathcal{H}$(n)	Experiment recently completed

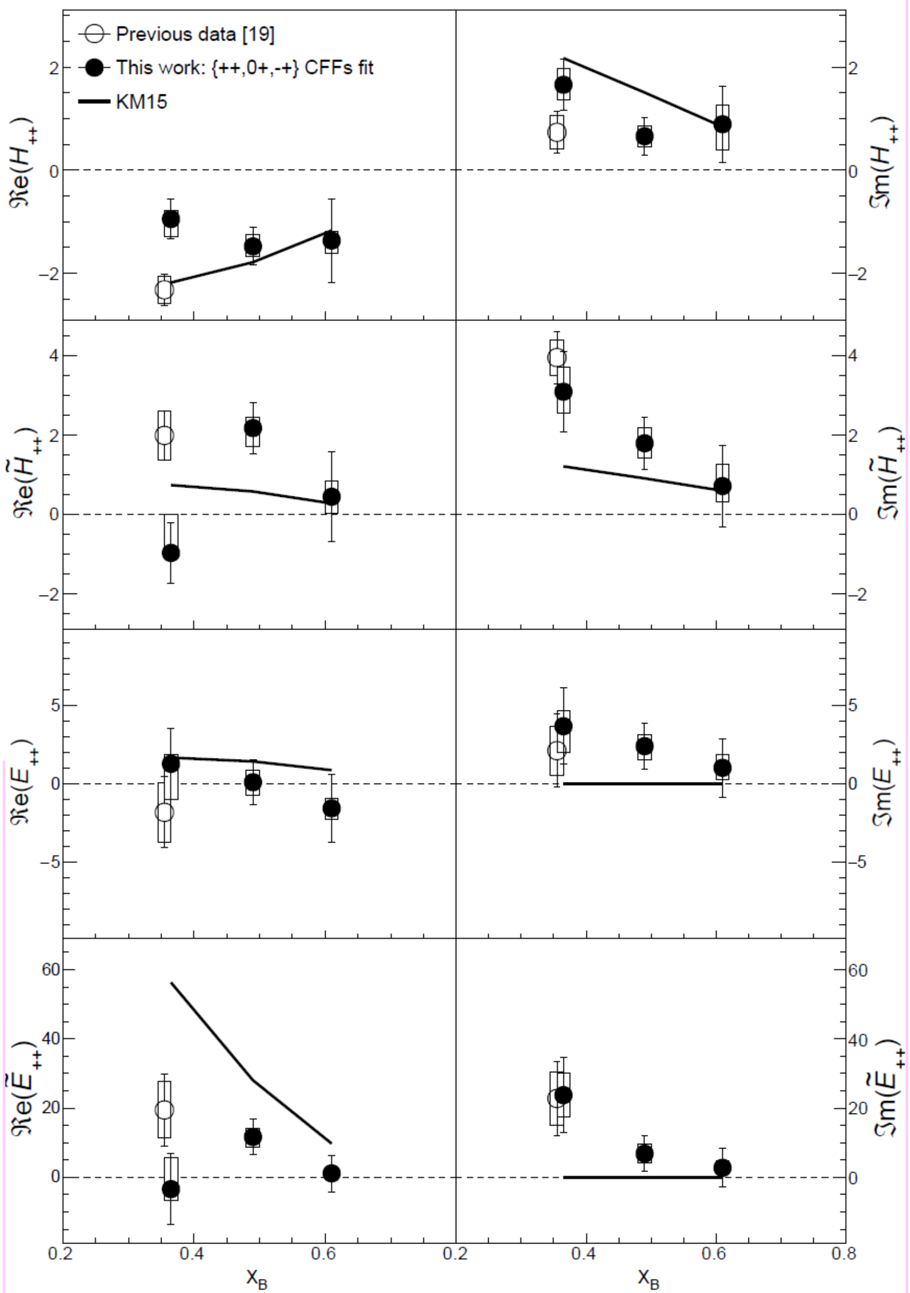
Complementarity of the experimental setups in the JLab Halls A/C and B

- 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@10.6 GeV: high-precision cross sections for DVCS on the proton

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



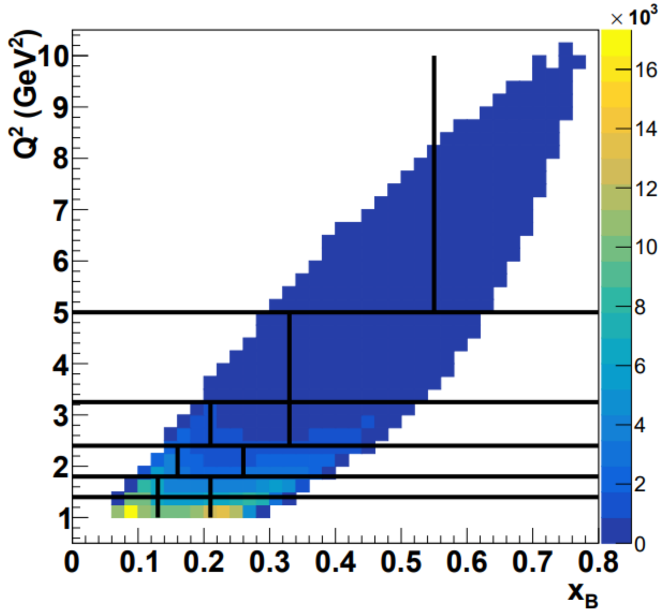


- High precision DVCS cross sections up to large x_B, for 3 beam energies
- Separation of Interference, BH, and DVCS^2 terms
- Sensitivity to all 4 Compton Form Factors
- BMMP (Braun-Manashov-Muller-Pirnay) formalism
- Kinematical power corrections ($\sim t/Q^2$, $\sim M/Q^2$) included in the analysis

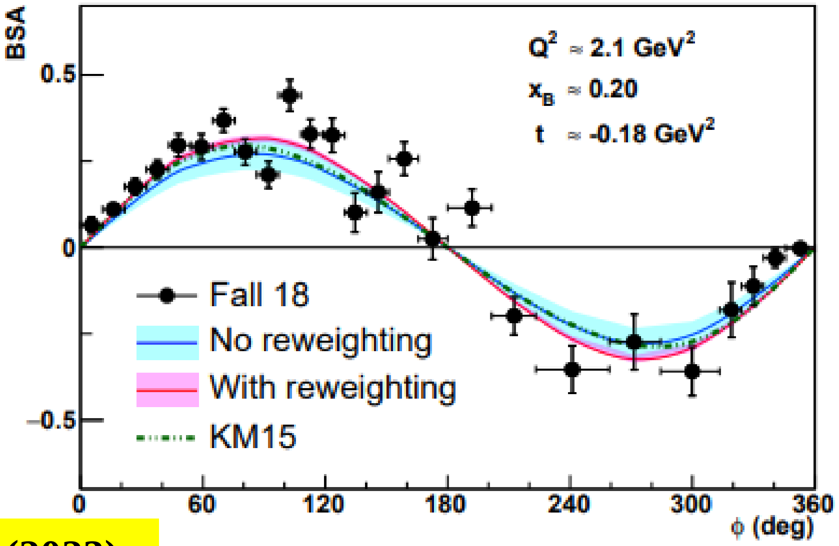
F. Georges et al., Phys. Rev. Lett. 128 (2022)

CLAS12: beam spin asymmetry for DVCS on the proton

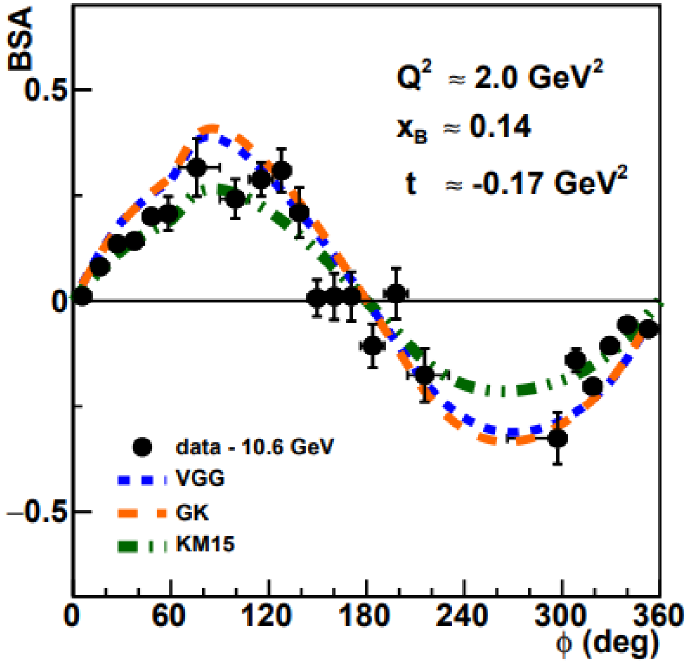
$\vec{e}p \rightarrow ep\gamma$

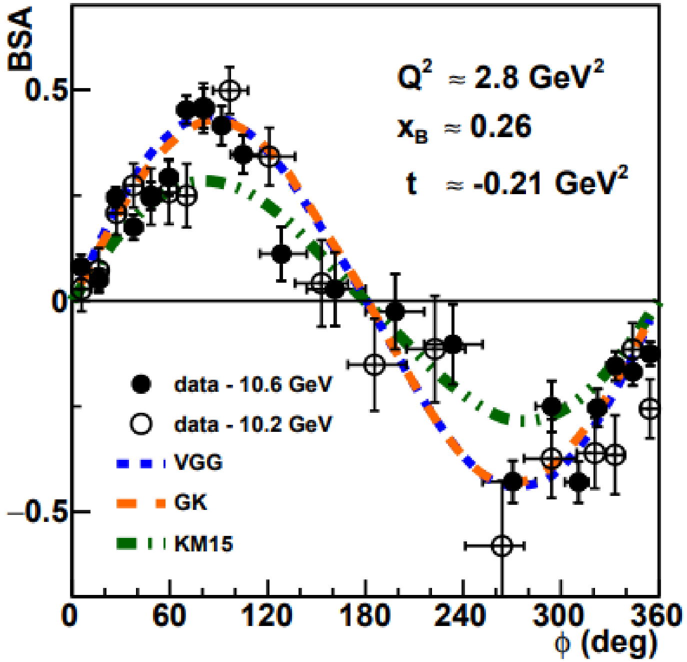


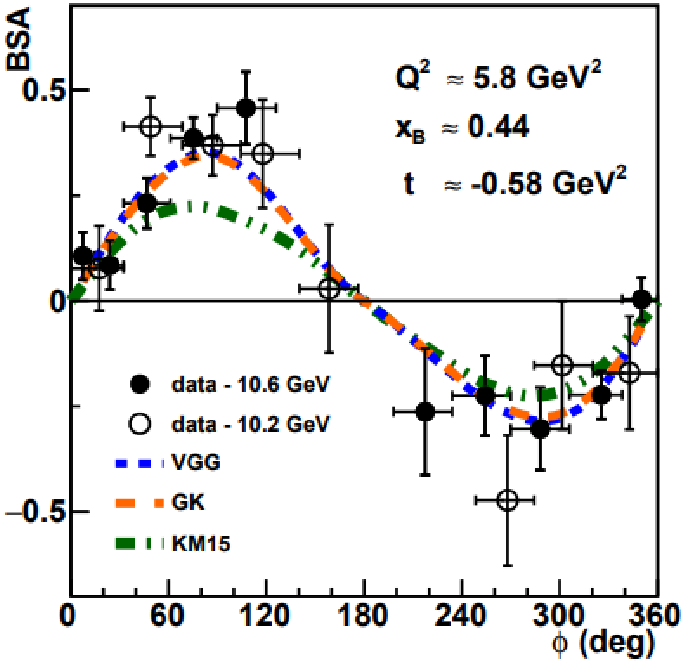
- Polarized beam (86%) with energy 10.6 GeV
- Unpolarized LH2 target
- 64 kinematical bins (Q^2, x_B, -t)
- Many kinematics never covered before
- In previously measured kinematics, the new data are shown to be in good agreement with existing data and improve the precision of GPD fits



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





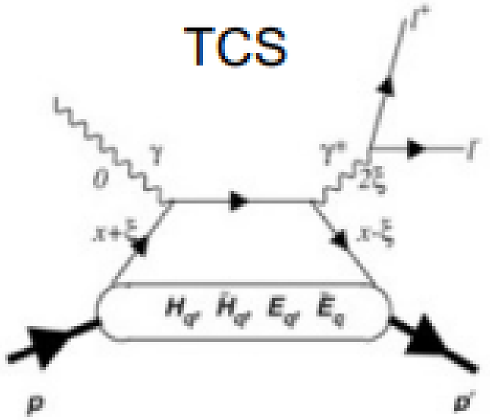


Examples of kinematics only accessible with ~10.6-GeV beam

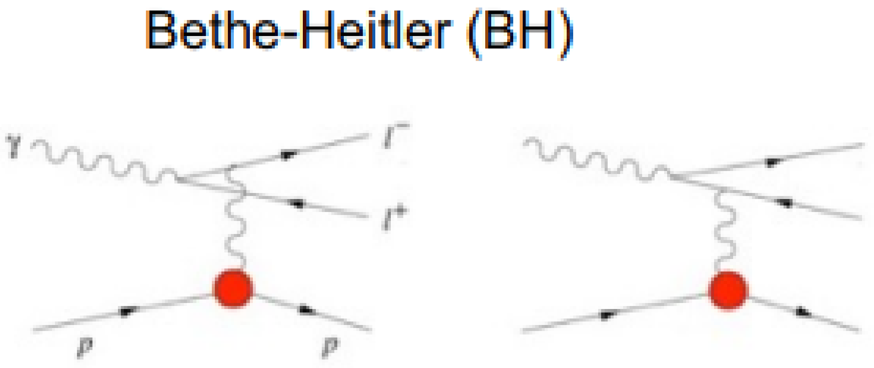
Beyond DVCS: Timelike Compton Scattering

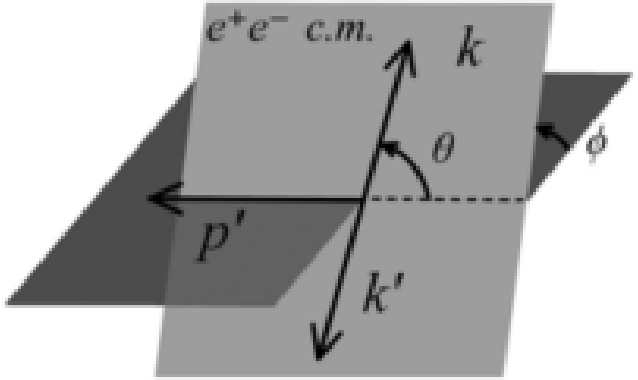
$\gamma p \rightarrow \gamma^* p$

TCS is the time-reversal symmetric process to DVCS:
The incoming photon is real, the outgoing photon is highly virtual and decays in a pair of leptons



+



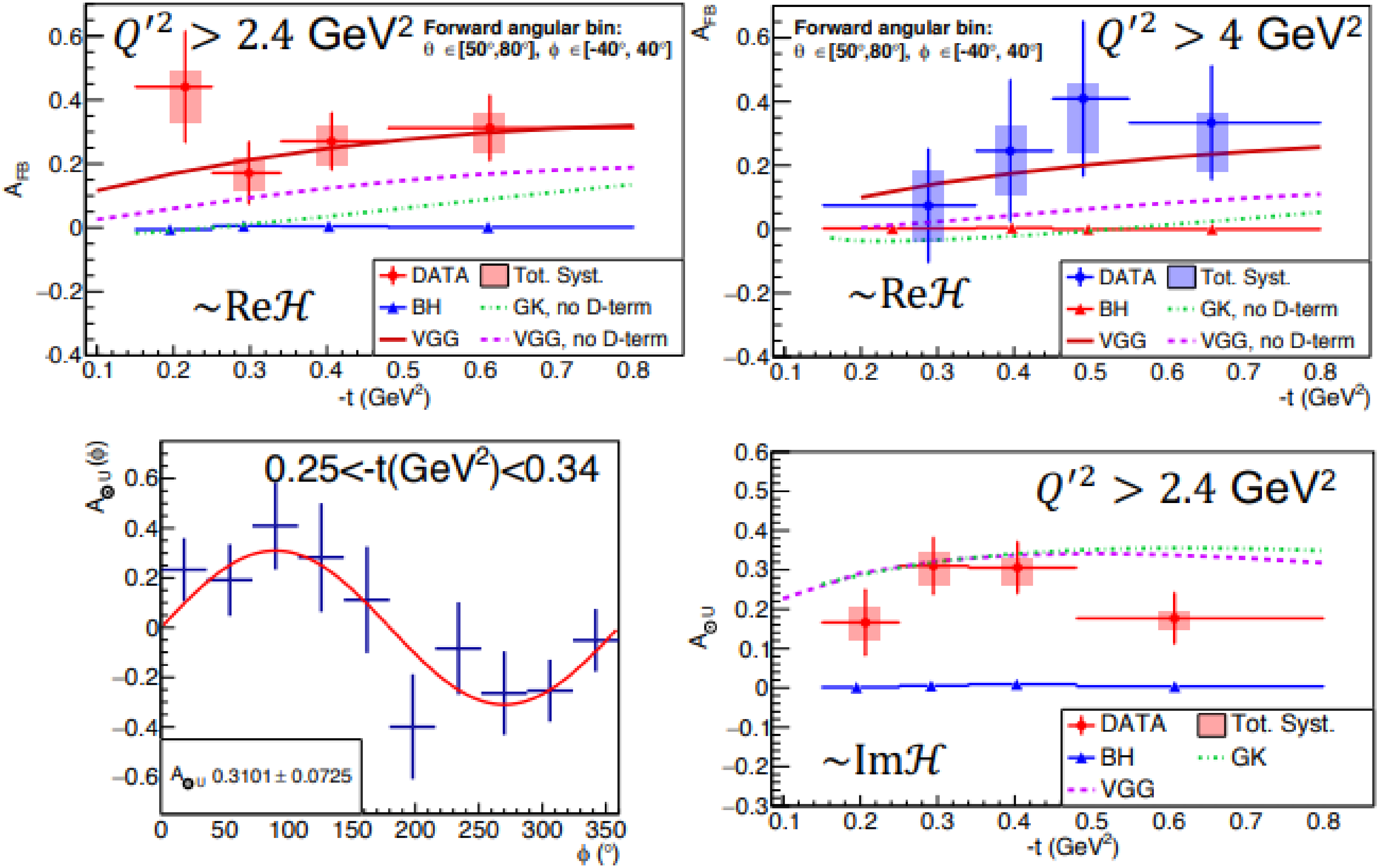


$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\cos\varphi\frac{1+\cos^2\theta}{\sin\theta}\mathrm{Re}\tilde{M}^{--}\right.$$
$$\left. -\cos 2\varphi\sqrt{2}\cos\theta\,\mathrm{Re}\tilde{M}^{0-}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

Incoming photon polarization

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

First-ever measurement of Timelike Compton Scattering (CLAS12)



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

$\gamma p \to \gamma^* p \to (e')e^+e^- p$

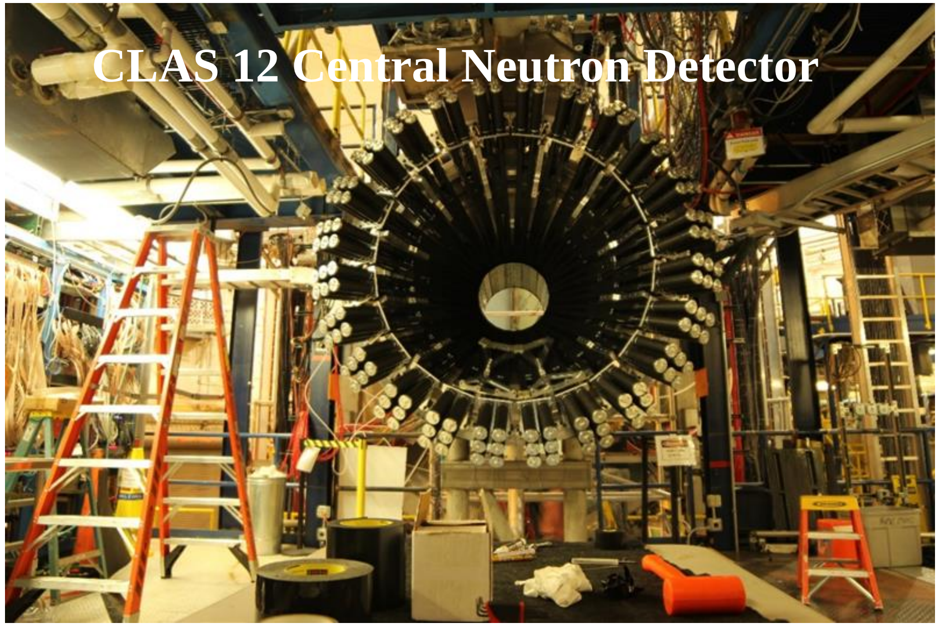
- Quasi-real photo-production (Q^2~0)
- The beam helicity asymmetry of TCS accesses the imaginary part of the CFF in the same way as in DVCS and probes the universality of GPDs
- The forward-backward asymmetry is sensitive to the real part of the CFF → direct access to the Energy-Momentum Form Factor $d_q(t)$ (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 more precise measurement
- Imminent doubling of statistics thanks to data reprocessing with improved reconstruction

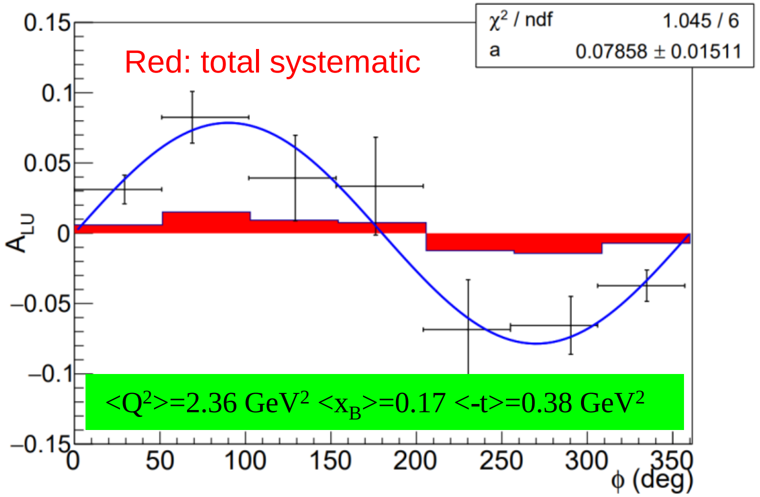
Preliminary CLAS12 results: Beam Spin Asymmetry for neutron DVCS

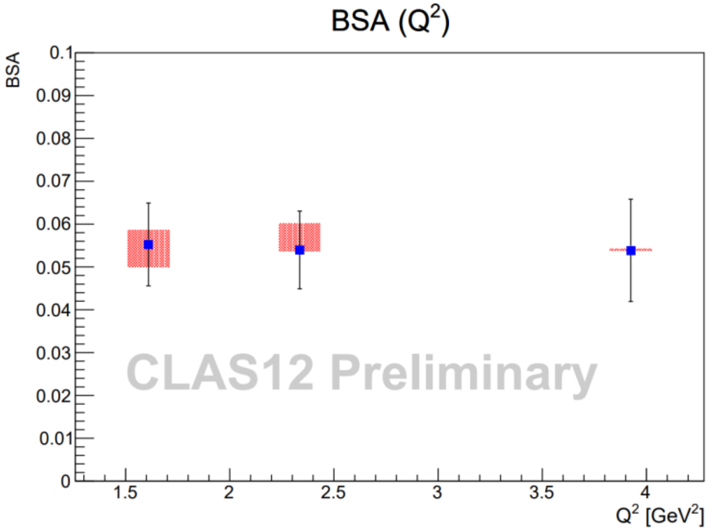
$\vec{e}d \rightarrow en\gamma(p)$

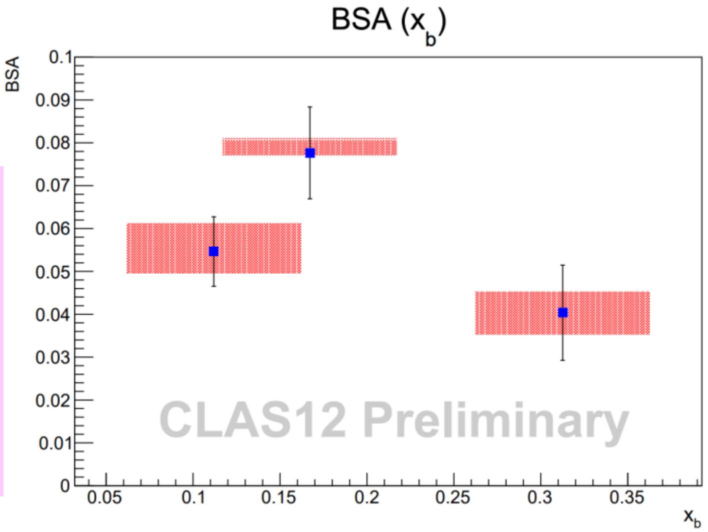
First-time measurement of nDVCS with detection of the active neutron

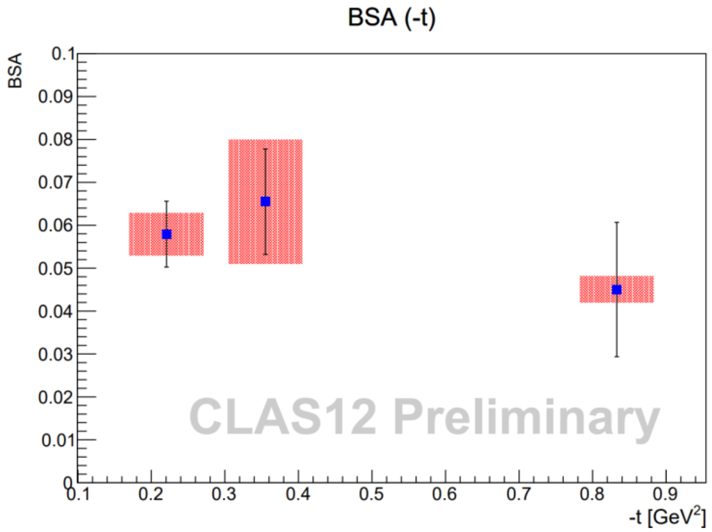
$$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - kF_2\mathcal{E}\}$$











- Scan of the BSA of nDVCS on a wide phase space
- Reaching the high Q^2- high x_B region of the phase space
- Exclusive measurement with the detection of the active neutron → small systematics
- Results of $ed \rightarrow ep\gamma(n)$ will also be released in parallel

See Adam Hobart's talk

CLAS12 data bring strong constraints for flavor separation on Im$\mathcal{H}$, Im$\mathcal{E}$, and Re$\mathcal{E}$

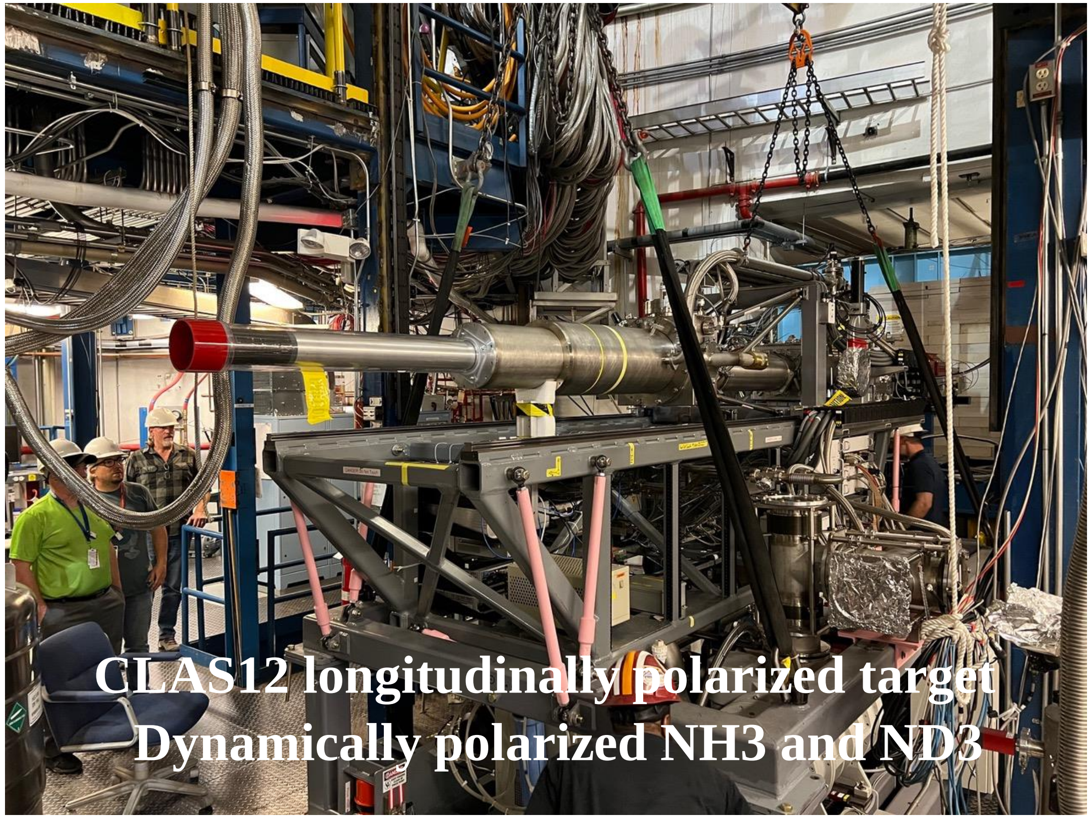
Recently run with CLAS12: DVCS (p, n) on longitudinally polarized target

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**



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

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

CLAS12 + Longitudinally polarized target + CND

Ran from June 2022 to March 2023

Transversely polarized target for CLAS12 in development

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

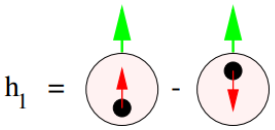
Chiral-odd GPDs

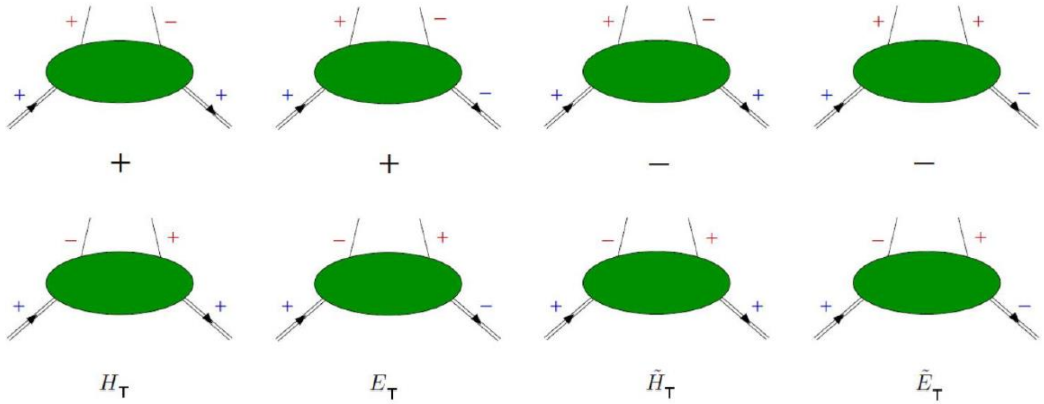
$H_T, \tilde{H}_T, E_T, \tilde{E}_T$

- 4 chiral-odd GPDs (parton helicity flip) at leading twist
- Difficult to access (helicity flip processes are **suppressed**)
- Chiral-odd GPDs are very **little constrained**
- Anomalous tensor magnetic moment:

$$\kappa_T = \int_{-1}^{+1} \mathrm{d}x\, \bar{E}_T(x,\xi,t=0) \qquad \bar{E}_T = 2\tilde{H}_T + E_T$$

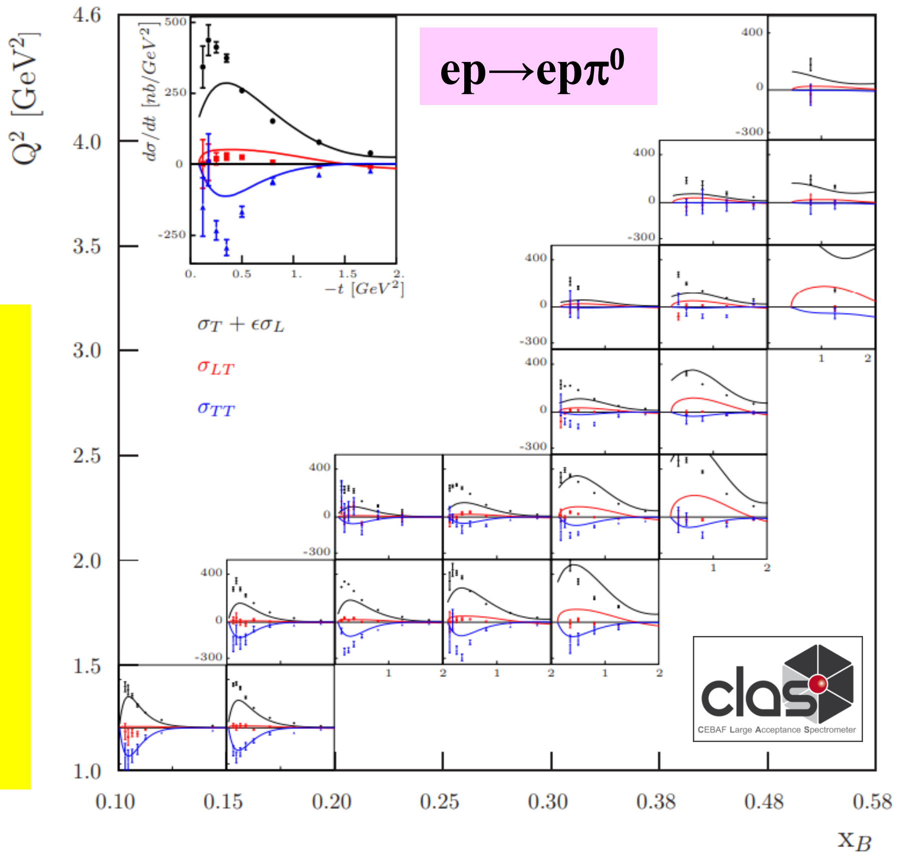
- Link to the **transversity** PDF: $H_T^q(x,0,0) = h_1^q(x)$



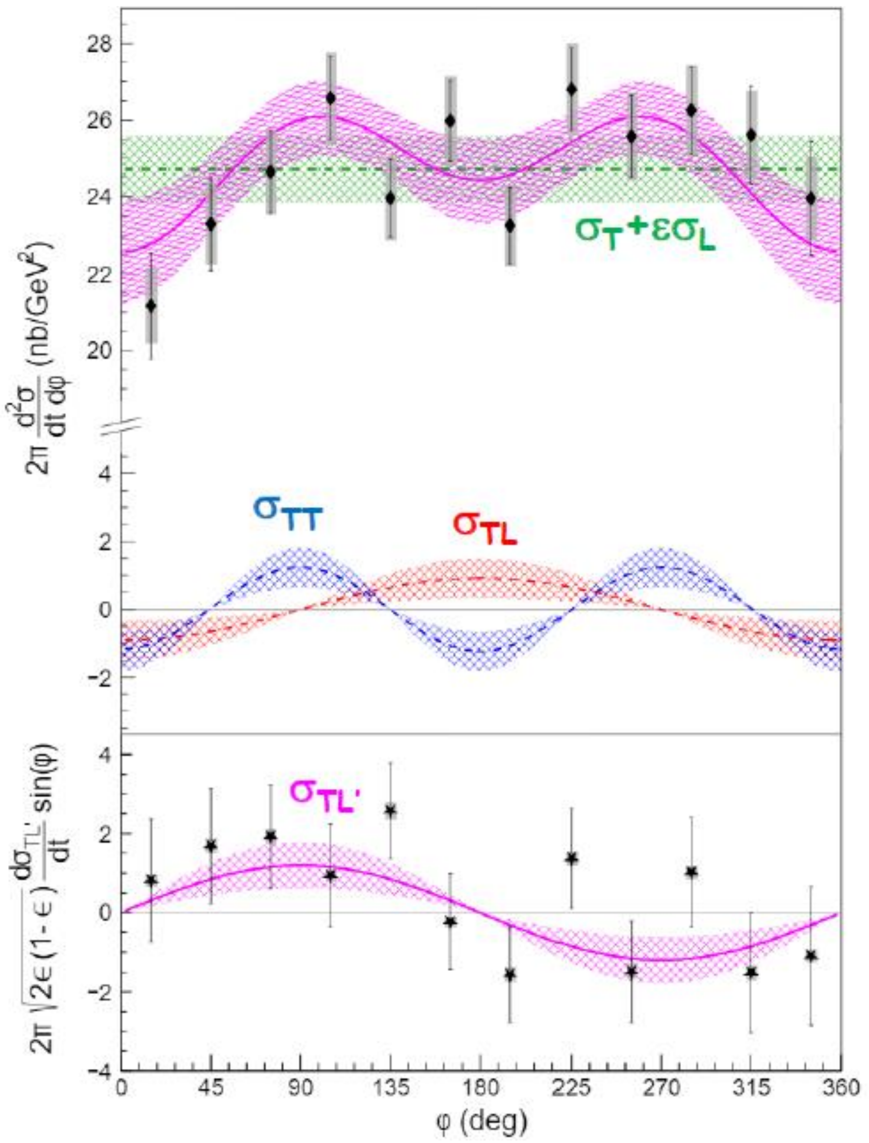


		Quark Polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	H		$2\tilde{H}_T + E_T$
	L		$\tilde{H}$	$\tilde{E}_T$
	T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

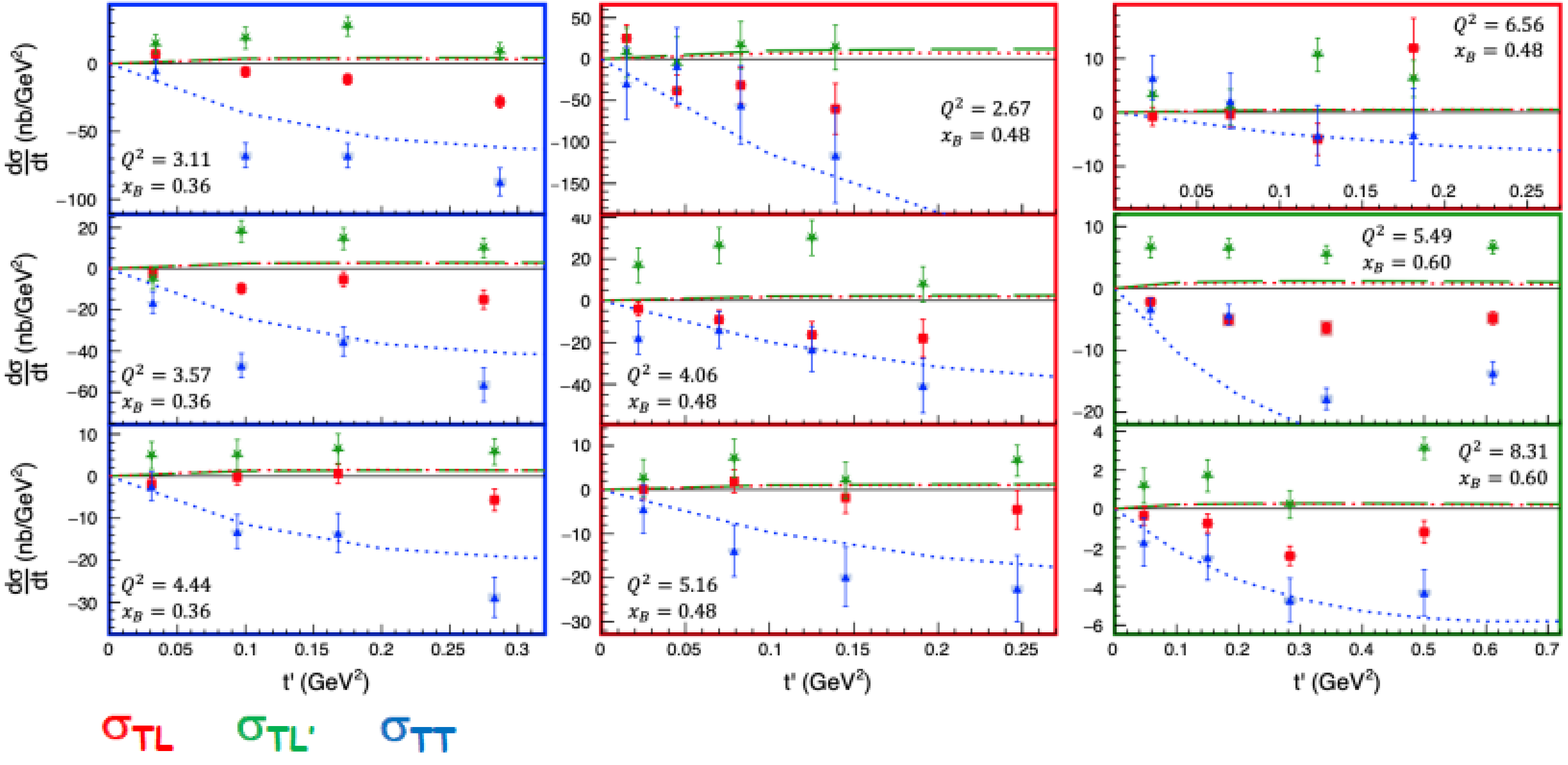
JLab data at 6 GeV (CLAS, Hall A) showed the first evidence of the sensitivity of *exclusive electroproduction of* ***pseudoscalar mesons*** to chiral-odd GPDs



Exclusive π^0 electroproduction in Hall A at 10.6 GeV



$Q^2 = 8.31$ GeV^2, $t' = t_{min} - t = 0.15$ GeV^2, $x_B = 0.60$



$\sigma_{TT} >> \sigma_{TL}, \sigma_{TL'}$ Indication of <u>significant transverse component</u>

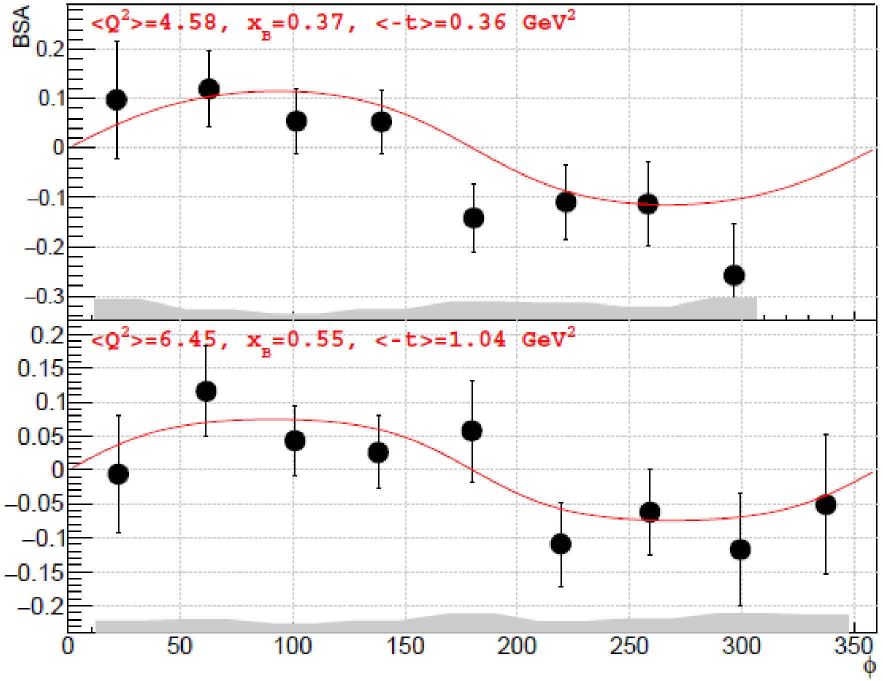
Confirmation of the trend observed in 6-GeV data
→ dominance of transversity GPDs

M. Dlamini et al., Phys. Rev. Lett. 127 (2021)

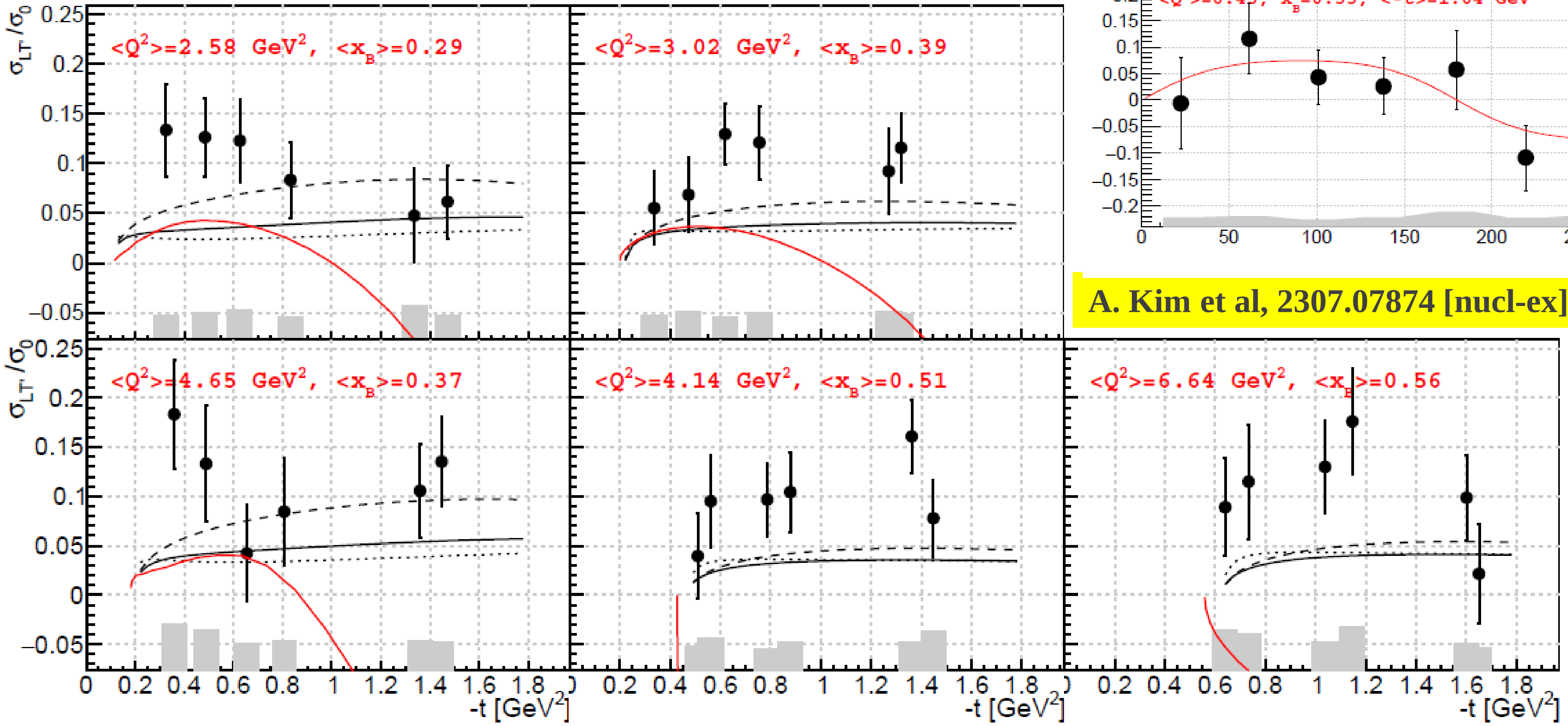
Beam Spin Asymmetry for Deeply Virtual π^0 production with CLAS12

$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi} \qquad \sigma_0 = \sigma_T + \epsilon\sigma_L$$

$$\sigma_{LT'} \sim \xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}Im[\langle\bar{E}_T\rangle^*\langle\tilde{H}\rangle + \langle H_T\rangle^*\langle\tilde{E}\rangle]$$ GK model

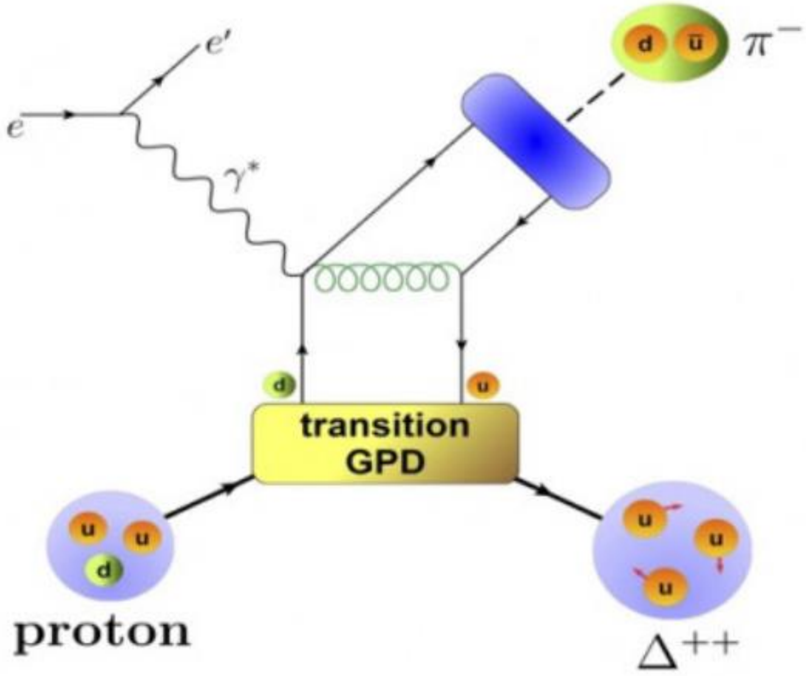


A. Kim et al, 2307.07874 [nucl-ex], submitted to PLB



- Multidimensional extraction of the BSA
- Comparison with model predictions (**GK** and JML) has been performed
- Models underestimate the data

$\pi^-\Delta^{++}$ electroproduction beam-spin asymmetries off the proton (CLAS12)



Transition GPDs:

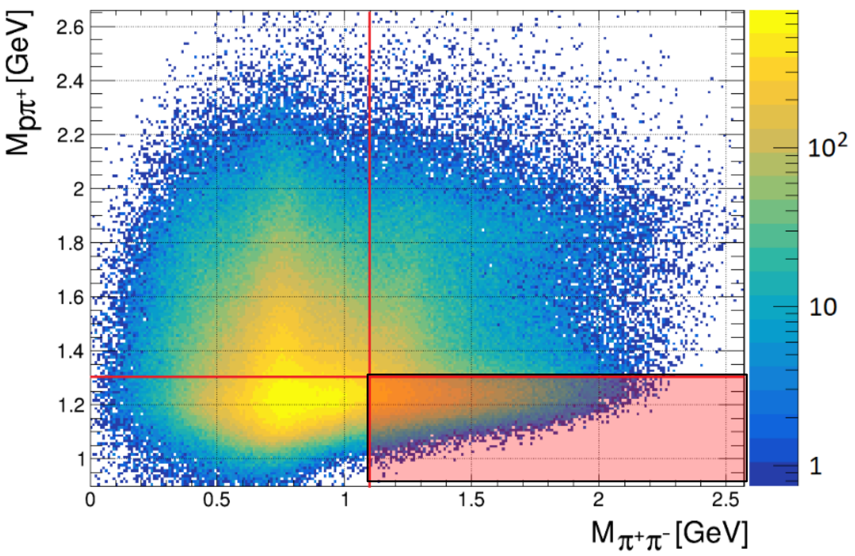
- 16 transition GPDs, generalizing the GPDs to p →Δ processes
- No experimental data yet
- Ongoing theoretical work inspired by this work

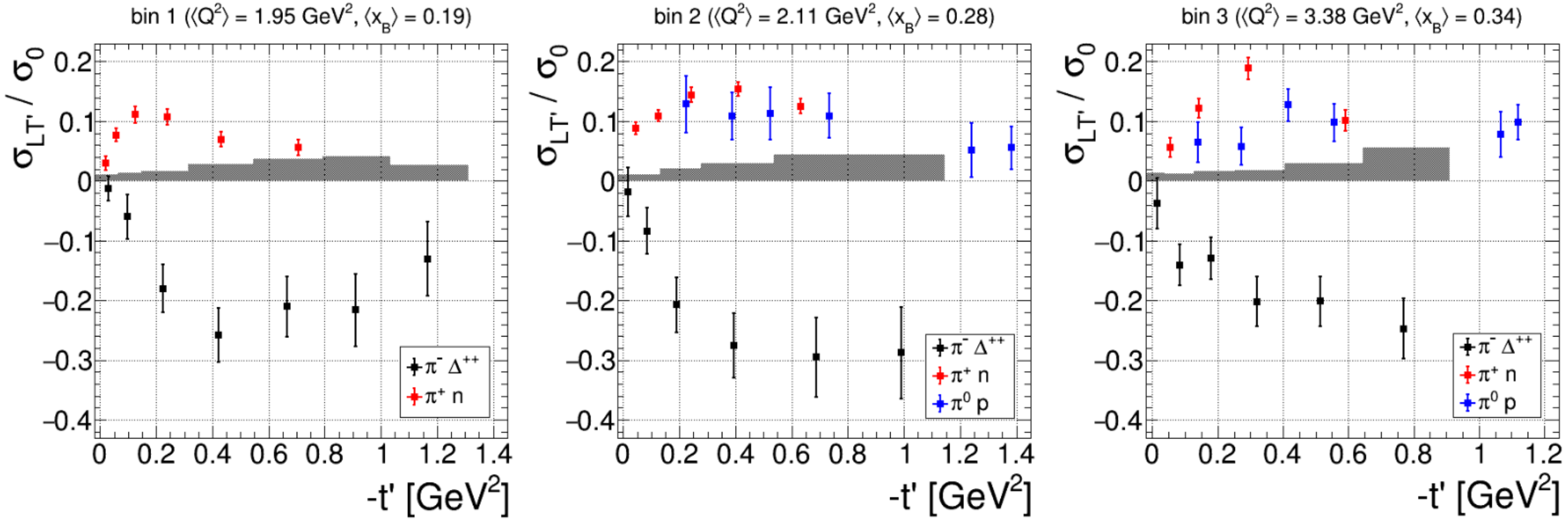
S. Diehl *et al.* PRL 131, 021901 (2023)

Analysis strategy and results:

- *ep→e'p π -(π +)*topology
- Avoid resonance region
- BSA fitted with a sin(φ) shape

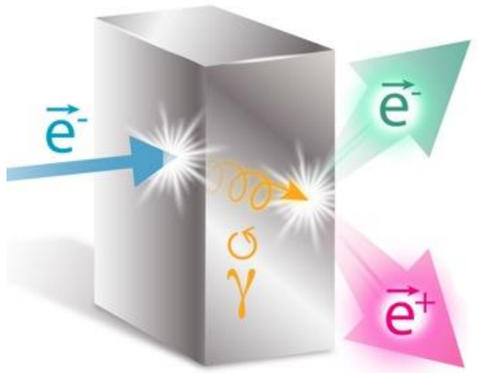
$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$





Perspectives: polarized positrons beam for Jefferson Lab

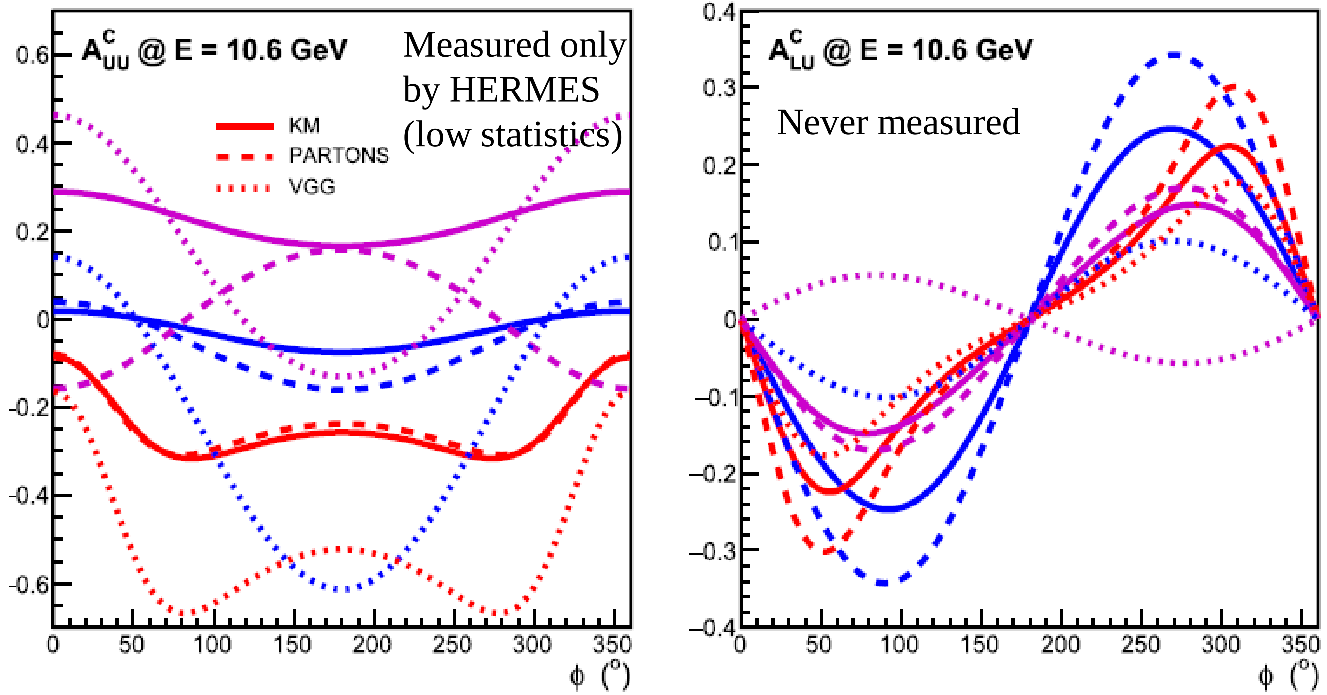
Physics Motivations:
- Two-photon physics
- **Generalized parton distributions**
- Neutral and charged current DIS
- Charm production
- Neutral electroweak coupling
- Light Dark Matter search
- Charged Lepton Flavor Violation



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

R&D ongoing
Possible timeline: >2030

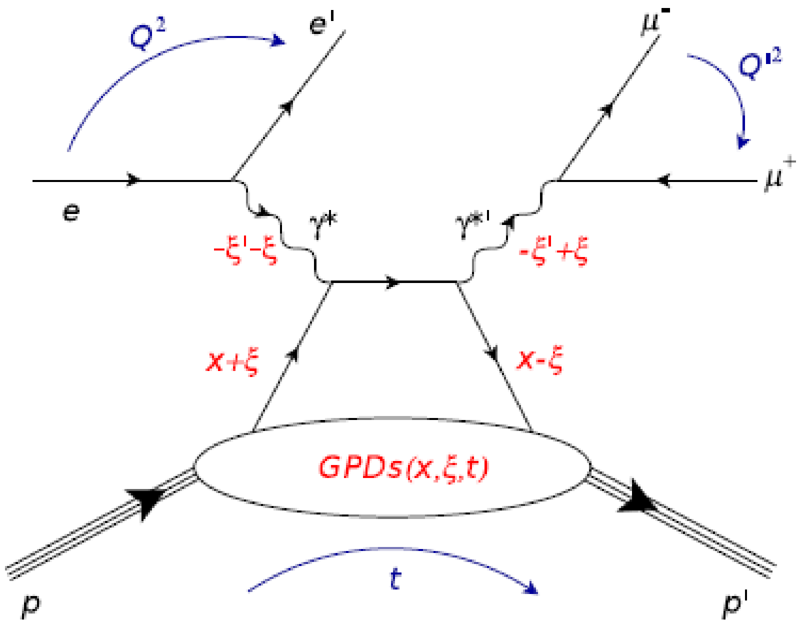
- Publication of the **EPJ A Topical Issue about "An experimental program with positron beams at Jefferson lab", Eur. Phys. J. A 58 (2022) 3, 45**
- 5 positron-based proposals, two of which on DVCS (CLAS12, Hall C) recently Conditionally Approved by JLab PAC51

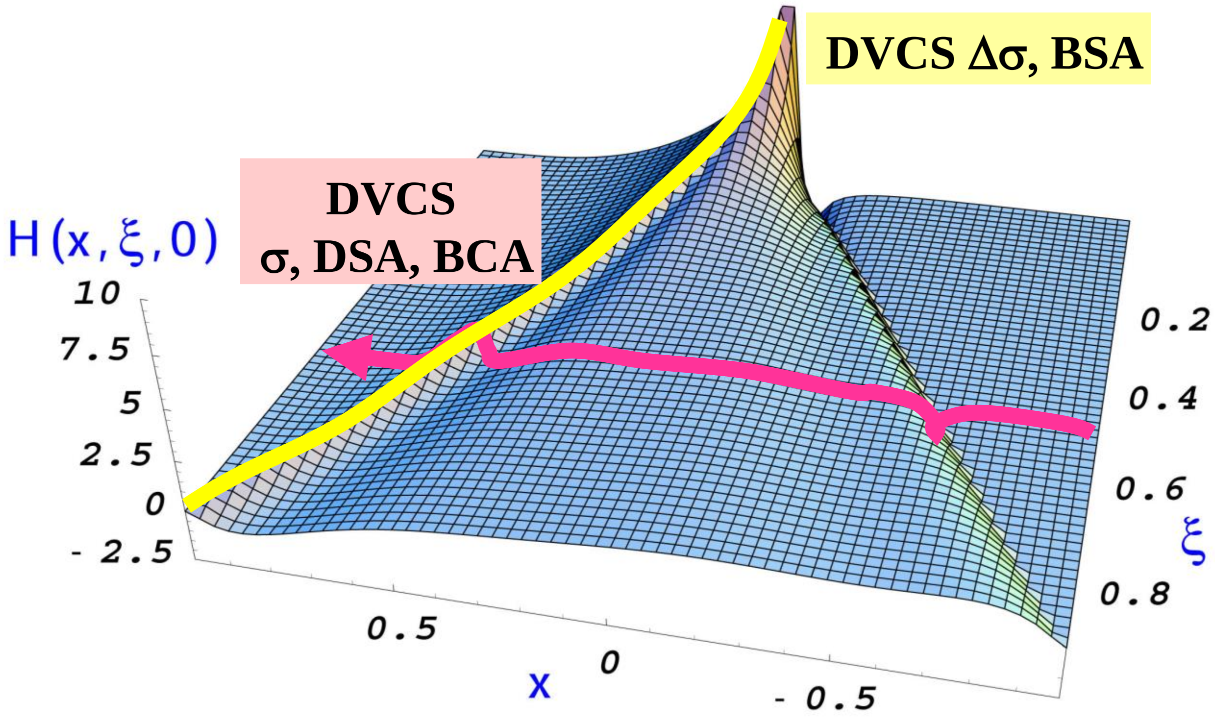


Model predictions for 2 out of the 3 proposed pDVCS observables
Impact of positron pDVCS projected data on the extraction of ReH via global fits: major reduction of relative uncertainties

See Eric Voutier's talk for more details

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 **$x \neq \pm\xi$**, which is fundamental for their modeling

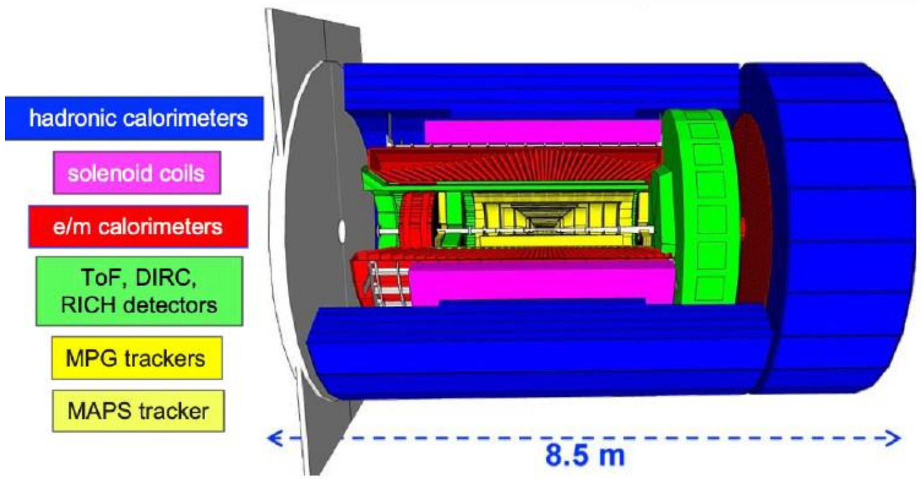
Experimental challenges:

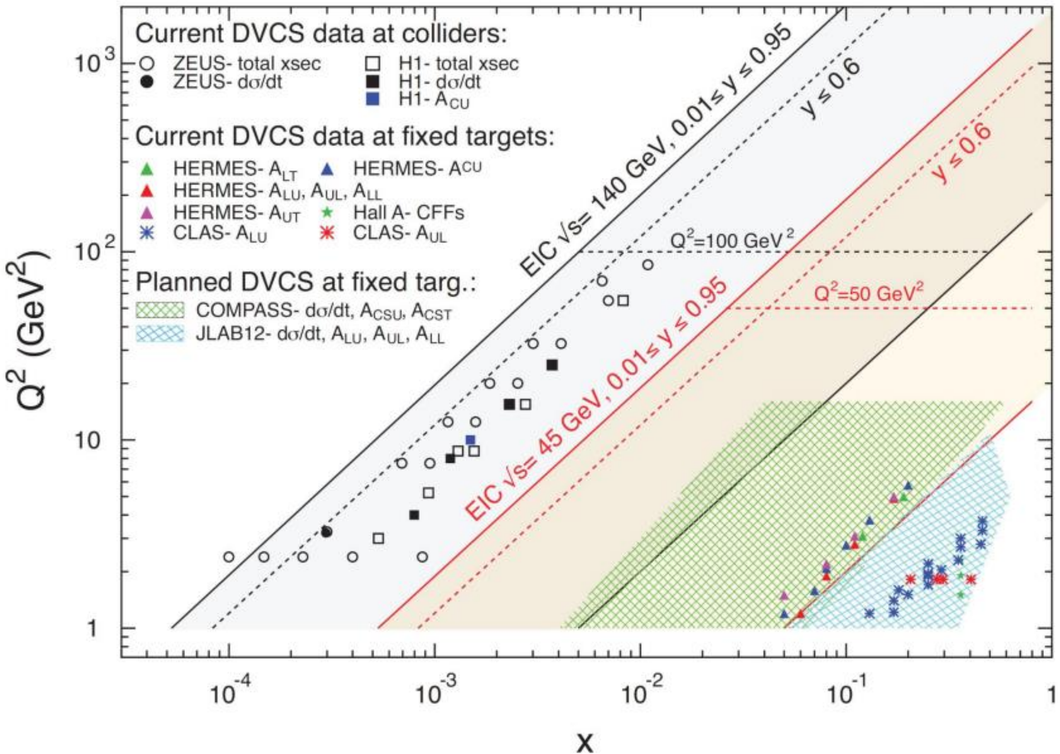
- Small cross section (300 times less than DVCS)
- Need to detect muons

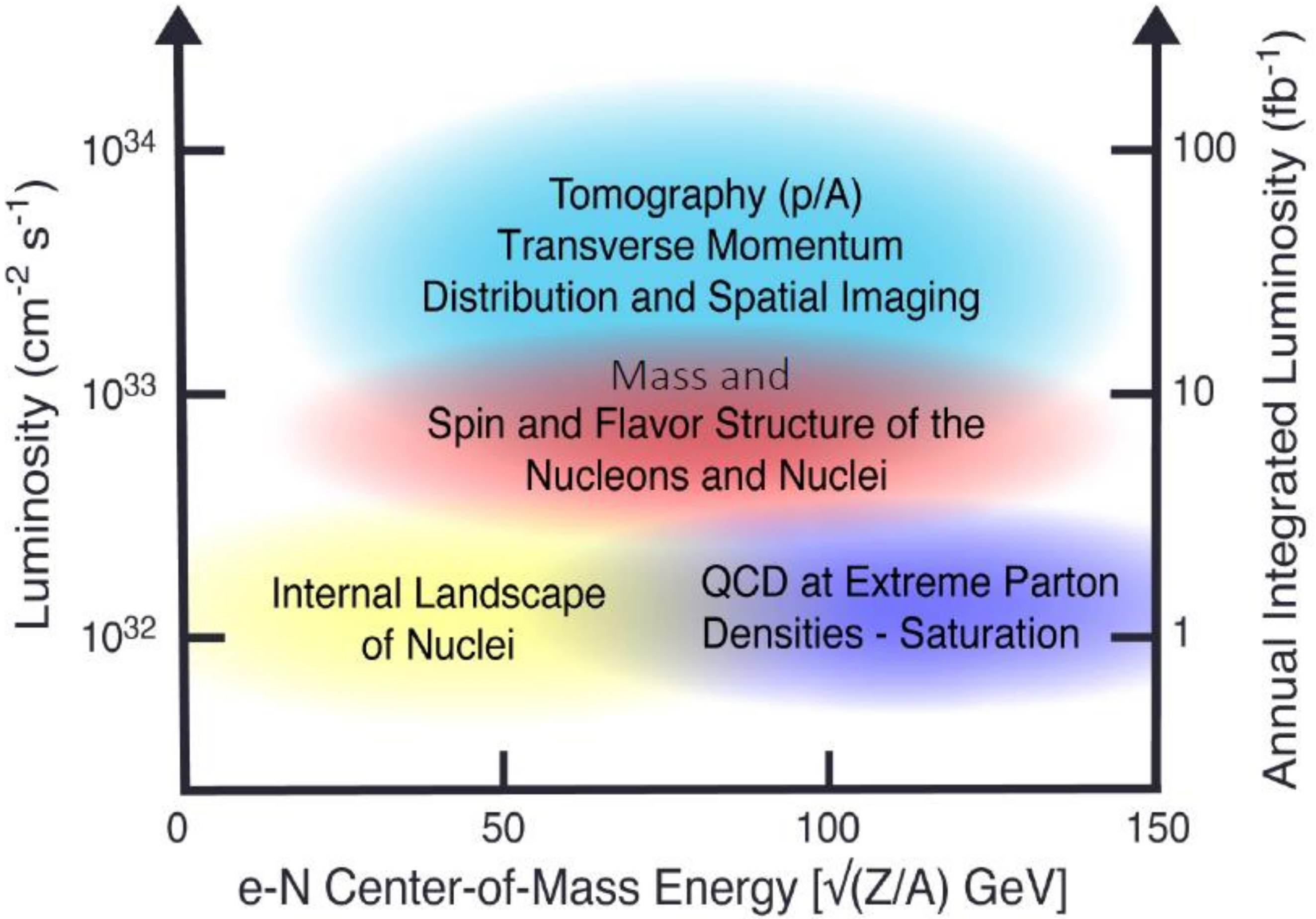
- **Possible CLAS12 upgrade (LOI): "μCLAS12" for DDVCS and J/ψ $ep \to e'p'\mu^+\mu^-$ at L~10^{37} cm^{-2}s^{-1} New tracker, calorimeter, shielding**

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

The future: GPDs with ePIC@EIC - sea quarks and gluons in 3D

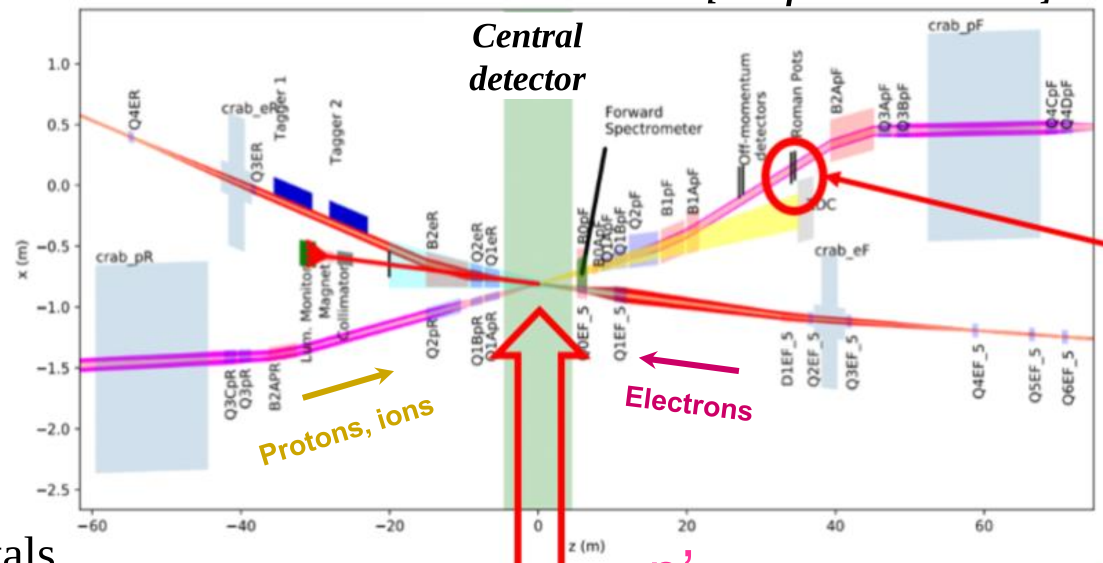






How to measure DVCS at EIC: EMCal, Roman Pots

[Far-forward detectors]

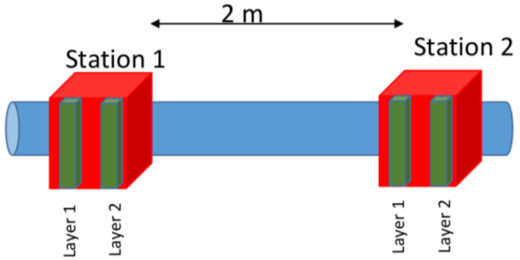


Roman Pots

protons / ions

Momentum & Timing

(25 – 30 m from IP)

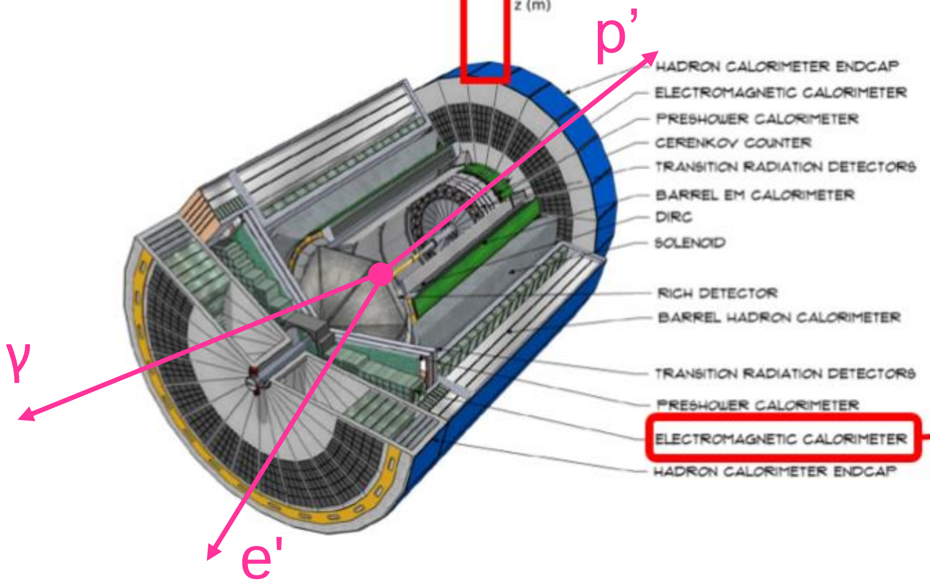


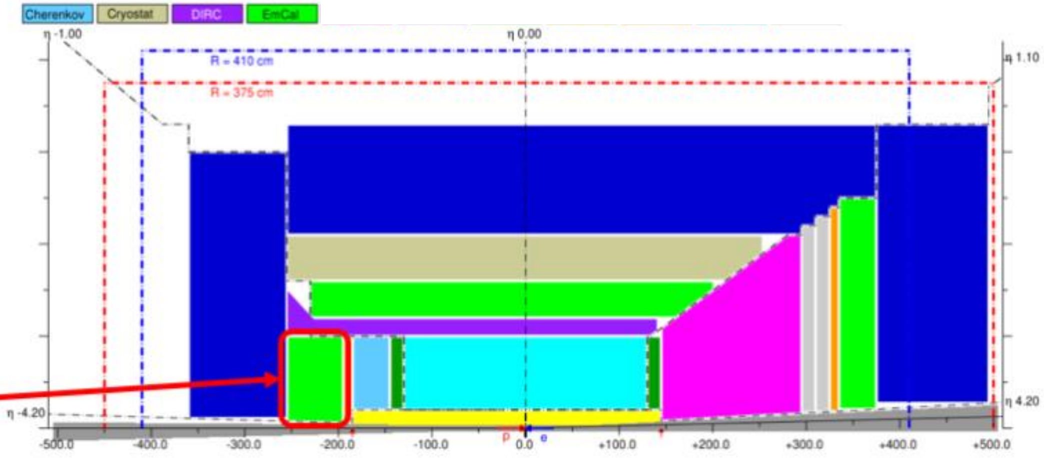
Technology :

- Ultra-fast silicon detectors (AC-LGADs)
- Readout ASIC to be developed

Technology :

- PbWO4 crystals
- SiPM readout (or APDs)





Calo. EM, e-End-Cap

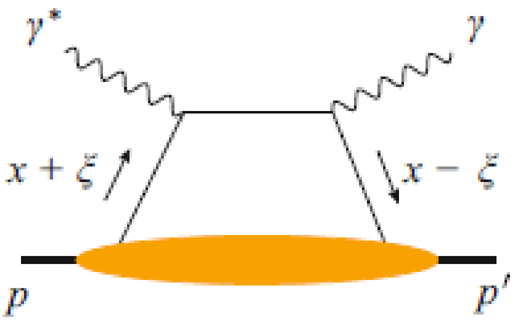
These are the R&D projects ongoing in my lab, IJCLab Orsay ☺

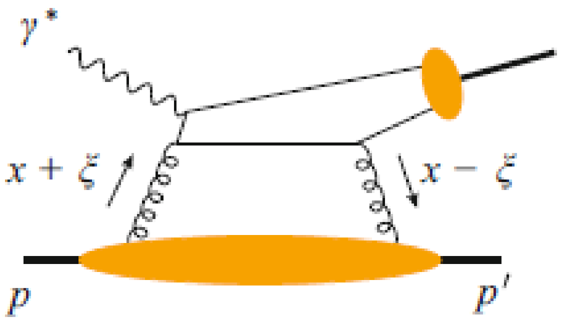
Work by P.K.Wang and N. Pilleux

GPDs with ePIC@EIC – DVCS and DVMP

From the EIC yellow report

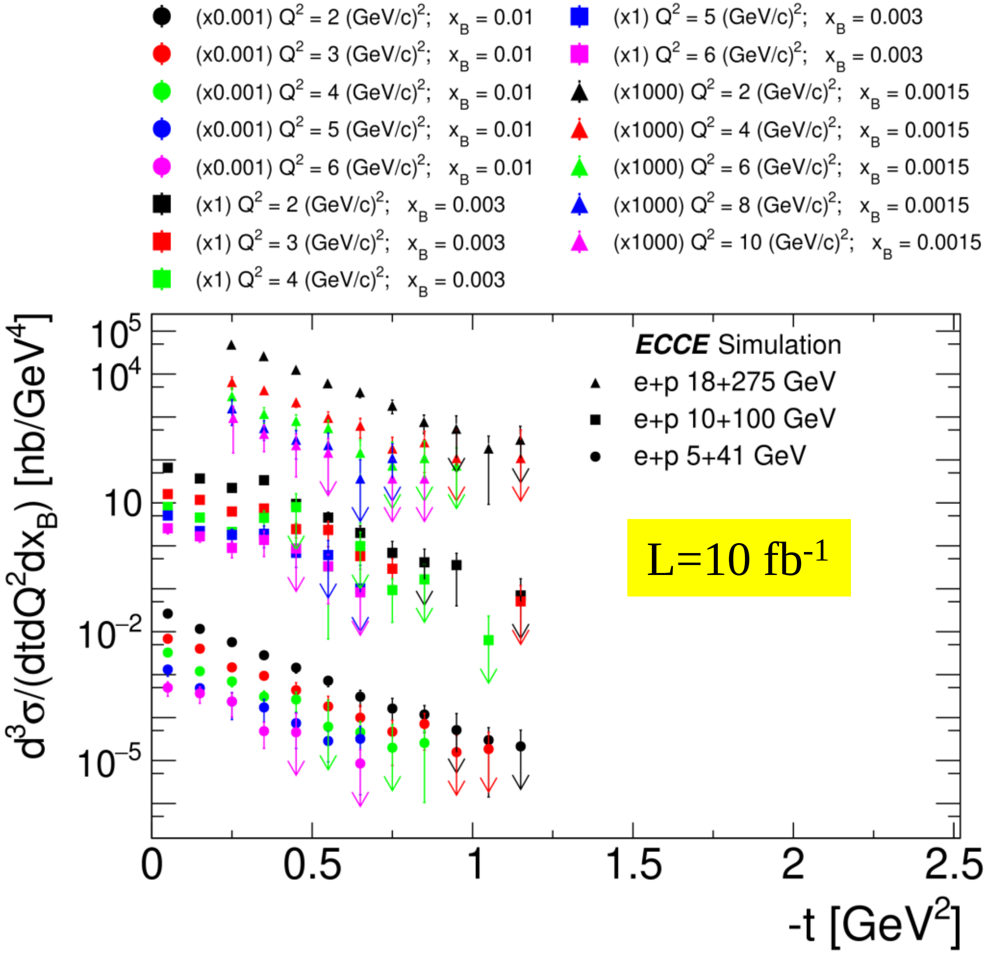
arXiv:2208.14575v2 (ECCE)

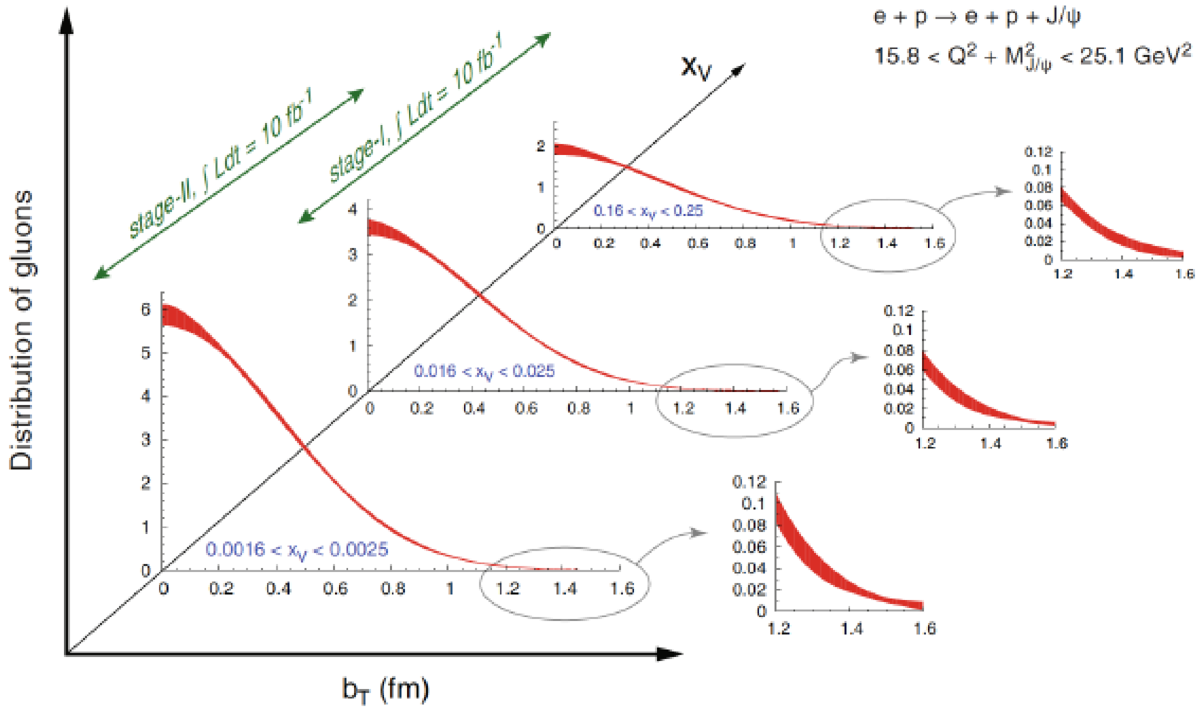




Gluon tomography

Projected EIC uncertainties for the gluon Impact Parameter Distribution from J/ψ production, for L= 10 fb^{-1}

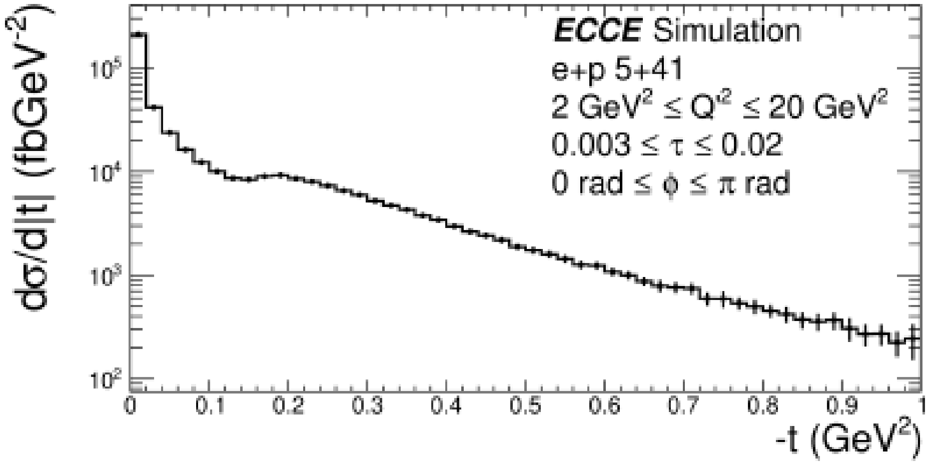


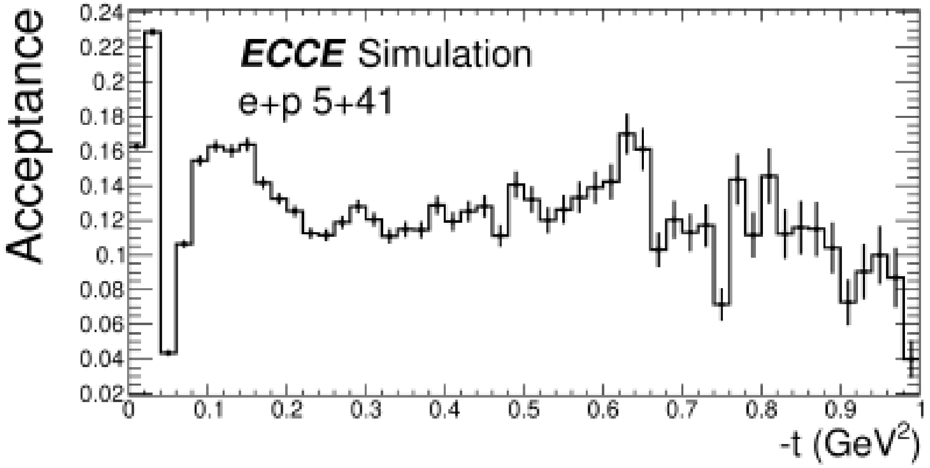


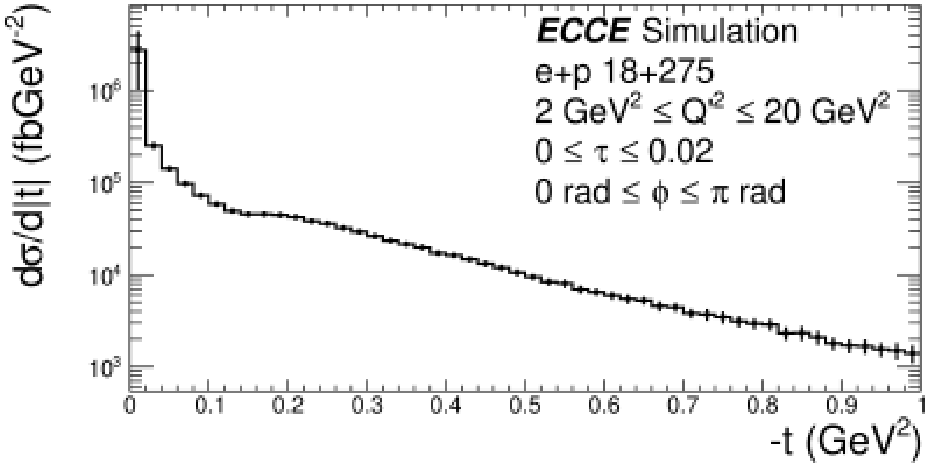
arXiv:2208.14575v2 (ECCE)

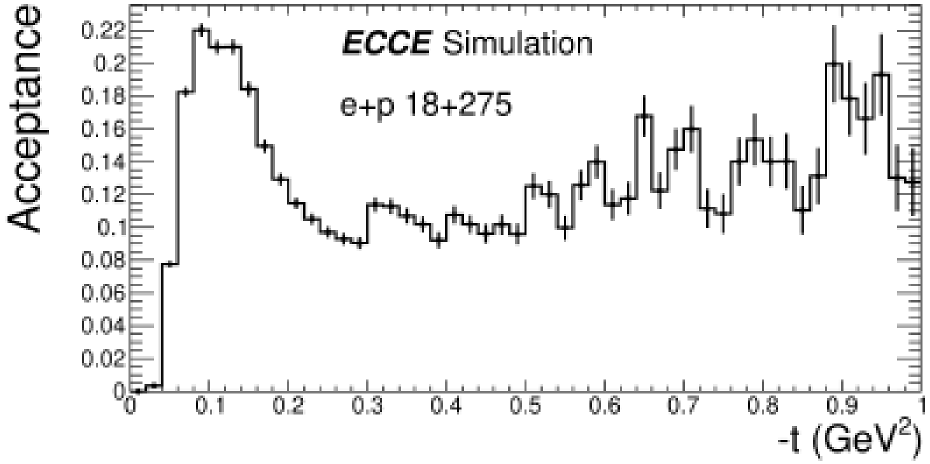
GPDs with ePIC@EIC – TCS

Work by K. Gates









Proton detection: B0 + Roman Pots
Decay leptons detection: EEMC, FEMC, and BECAL

Next steps: study the $\mu^+\mu^-$ decay mode, use the low-angle tagger for the scattered electron

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 distribution** 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** (polarized and unpolarized) are ongoing in **3 of the 4 Halls at JLab@12 GeV**, and **a wealth of results** are being released**:**

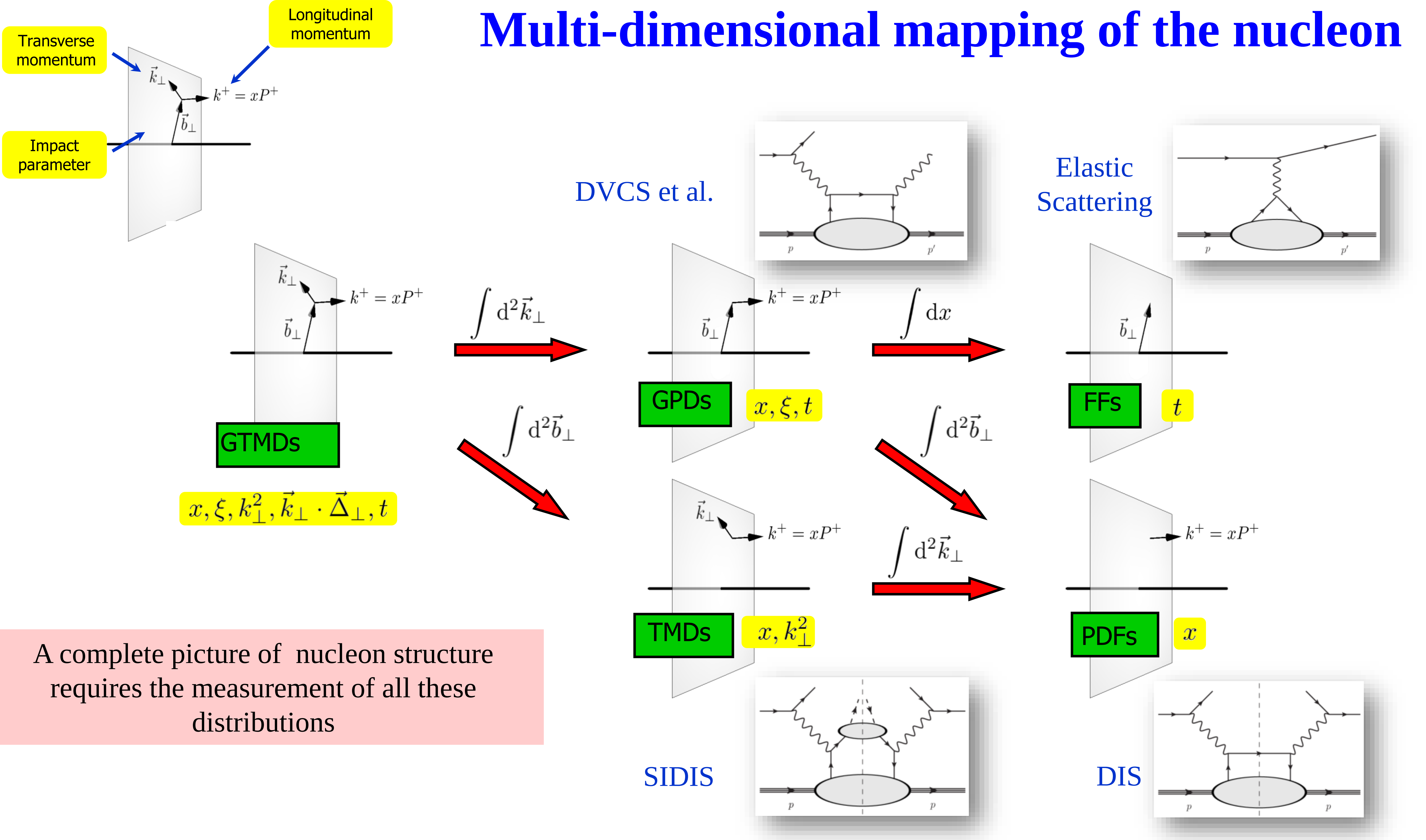
→ quarks' spatial densities, GPD flavor separation, <u>quarks' orbital angular momentum</u>, chiral-odd GPDs, transition GPDs,…

→ 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

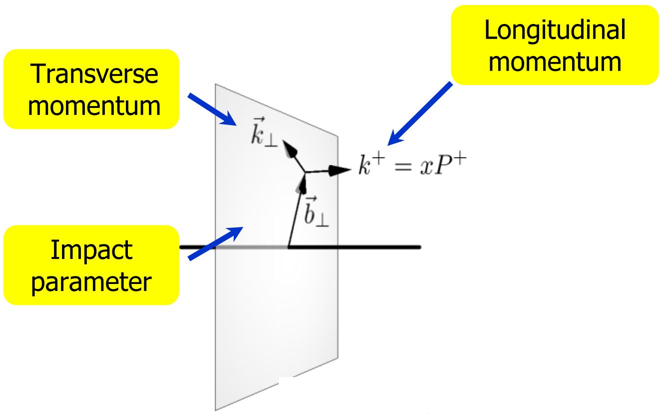
Back-up material

Multi-dimensional mapping of the nucleon

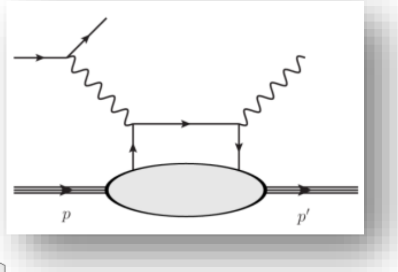


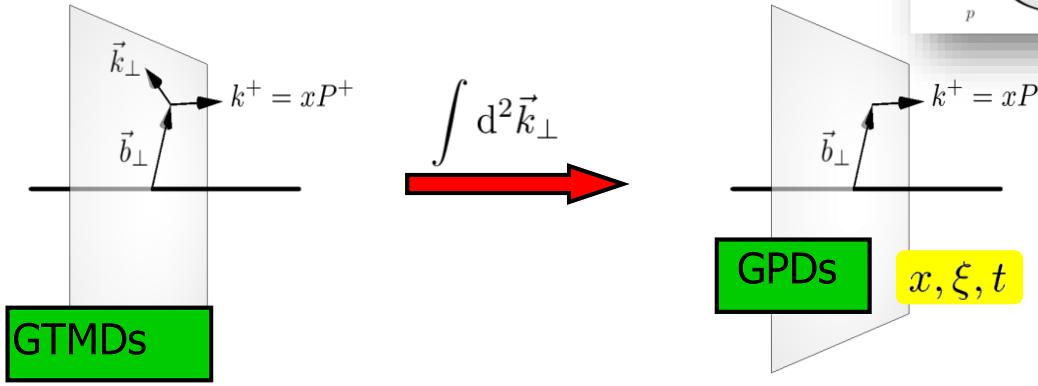
A complete picture of nucleon structure requires the measurement of all these distributions

Multi-dimensional mapping of the nucleon



DVCS et al.





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

Nucleon tomography

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

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

Generalized Parton Distributions:

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

✓ linked to **FFs** and **PDFs**

✓**Accessible in exclusive reactions**

Quark angular momentum (Ji's sum rule)

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

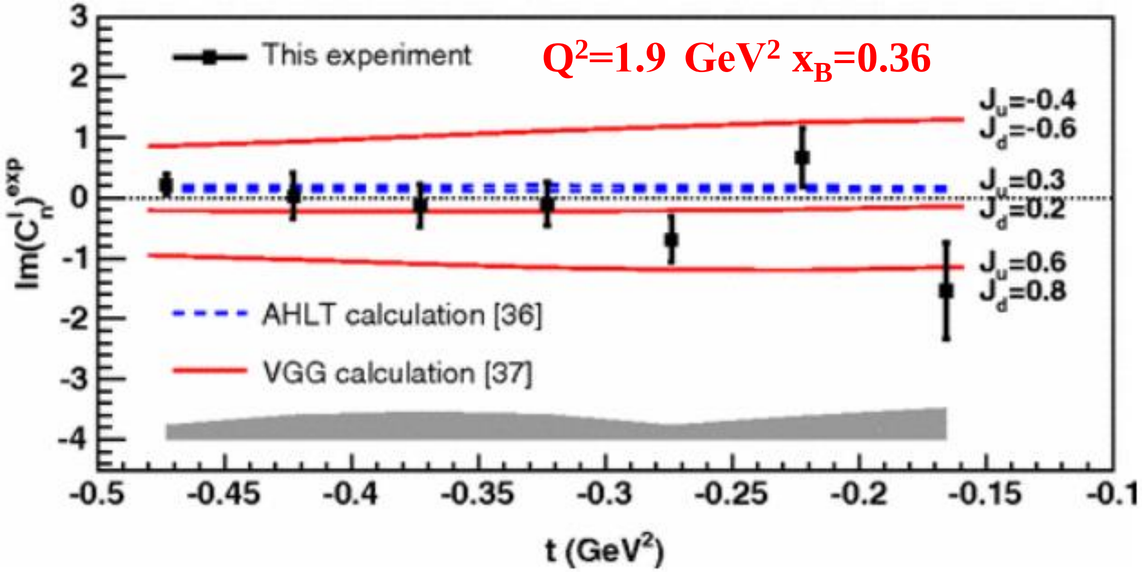
$\vec{e}d \to e\gamma(np)$

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

Hall-A experiment E08-025 (2010)

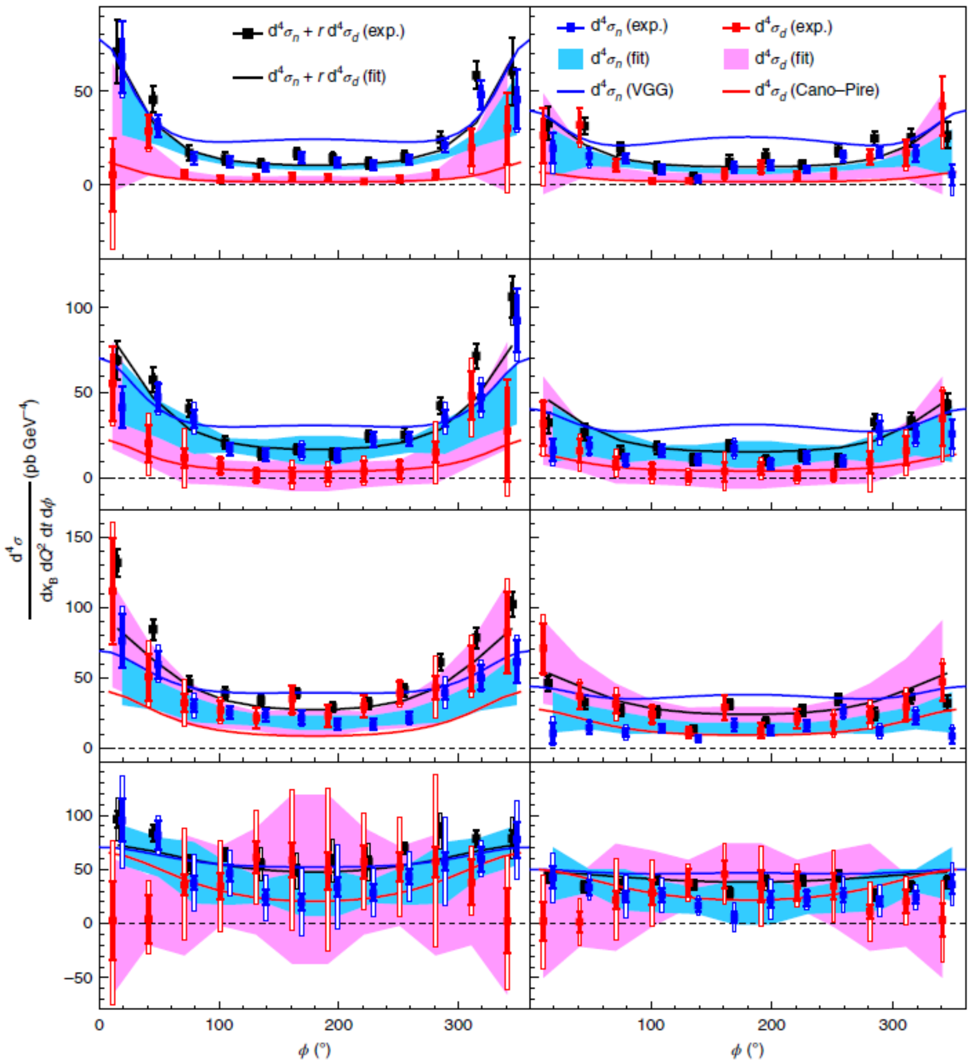
- Two beam-energies: « Rosenbluth » separation of nDVCS CS
- First observation of non-zero nDVCS CS

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



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

M. Benali et al., Nature 16 (2020)



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

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

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

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

Distribution of forces in the proton

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

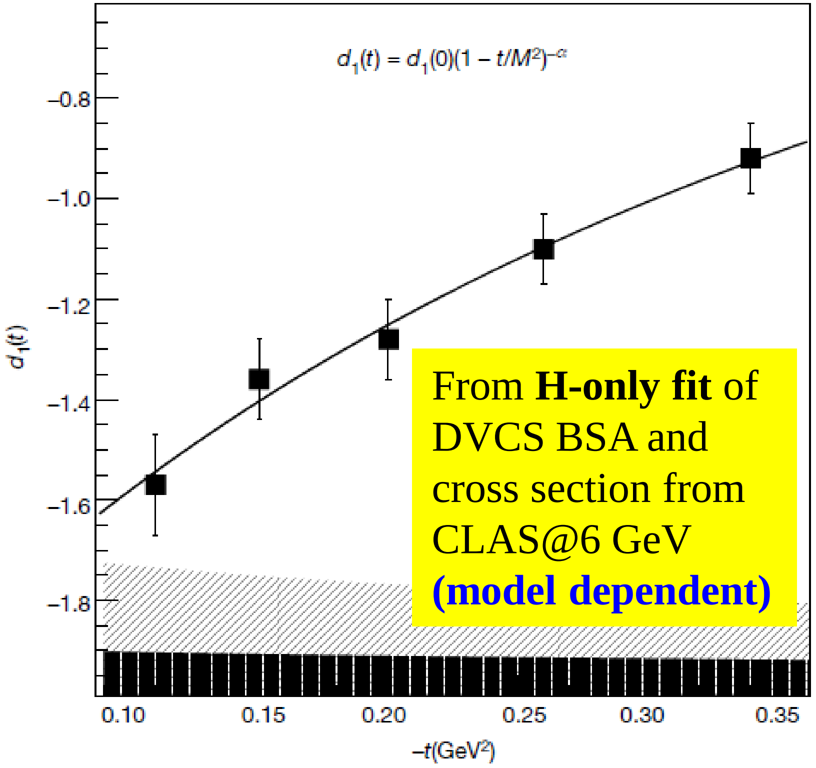
Second Mellin moment of H in x: **gravitational form factor** of the energy-momentum tensor → shear forces and pressure (d_1)

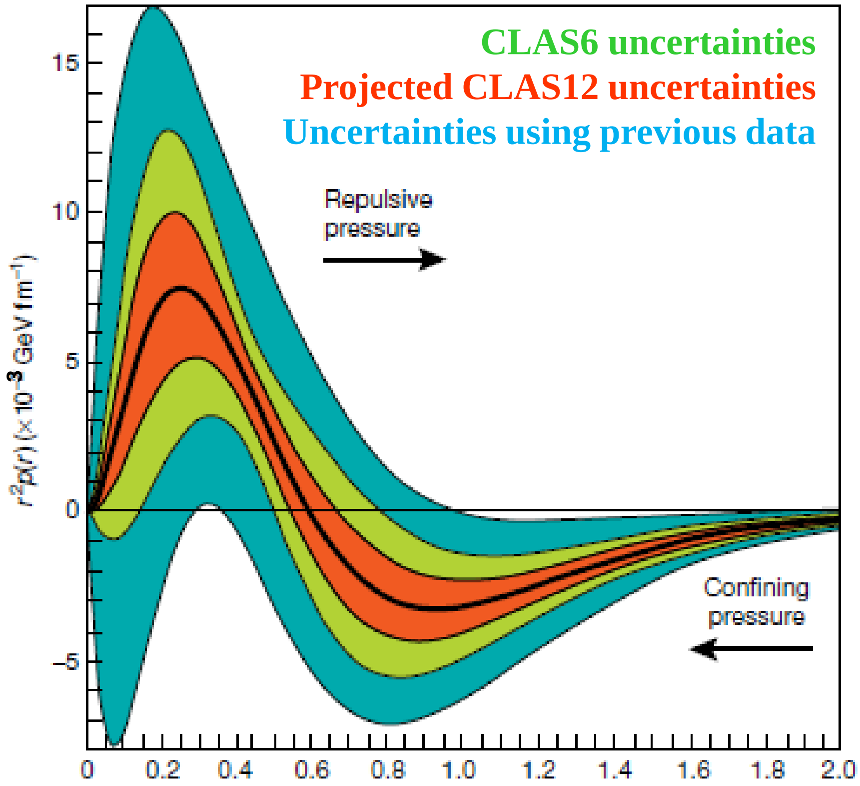
$$\mathrm{Re}\mathcal{H}(\xi,t) + i\mathrm{Im}\mathcal{H}(\xi,t) = \int_{-1}^{1}\mathrm{d}x\left(\frac{1}{\xi-x-i\epsilon} - \frac{1}{\xi+x-i\epsilon}\right)H(x,\xi,t) \quad (1)$$

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

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

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





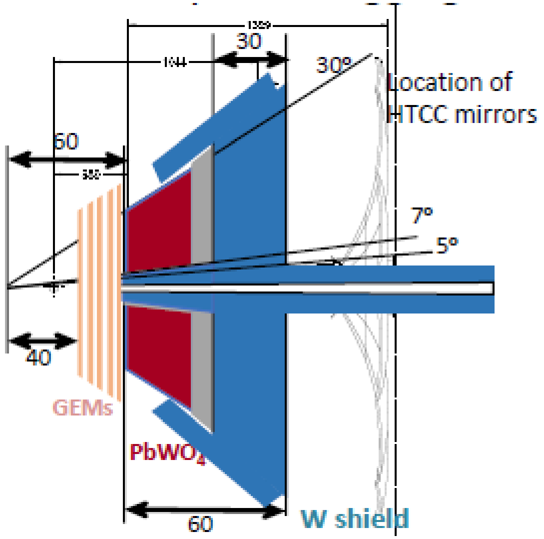
V. Burkert, L. Elouadrhiri, F.X. Girod, Nature 557, 396-399 (2018)

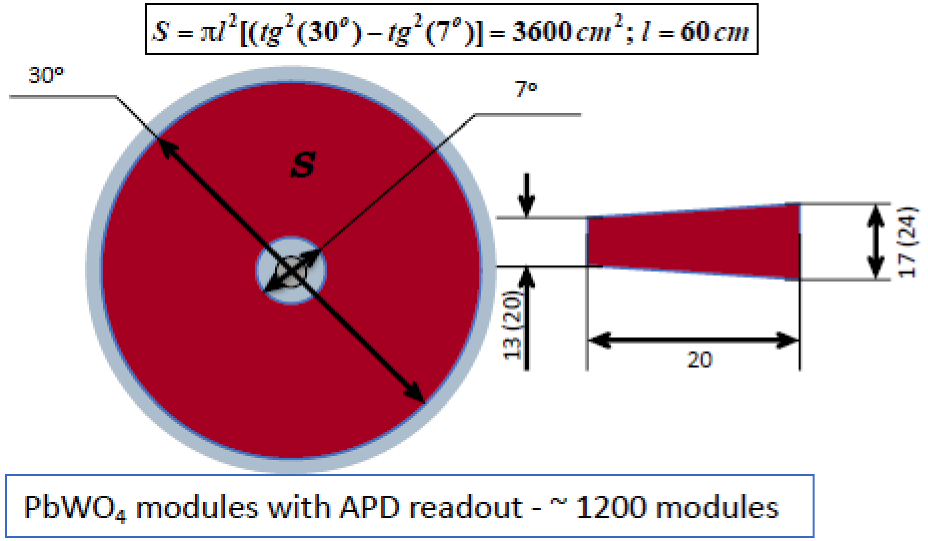
μCLAS12 for DDVCS and J/psi

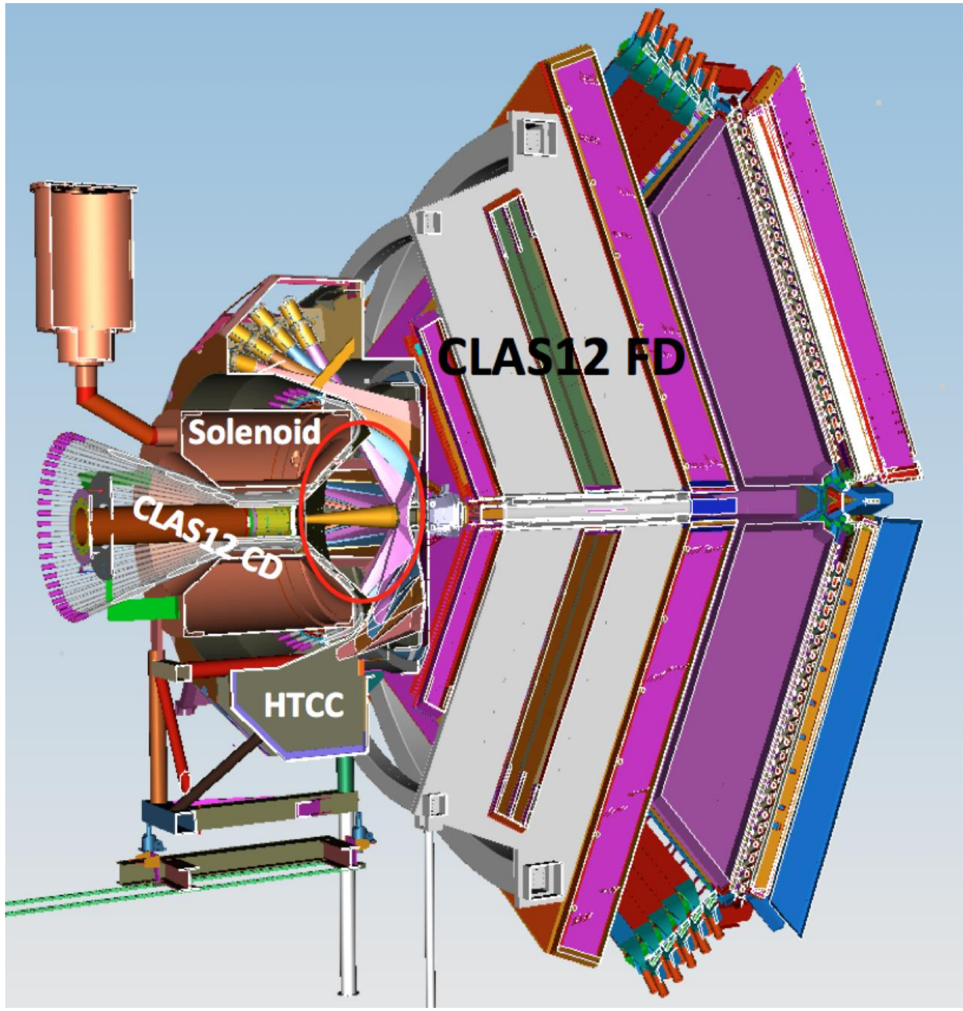
$ep \rightarrow e'p'\mu^+\mu^-$ at $L \sim 10^{37}\ cm^{-2}s^{-1}$

• 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





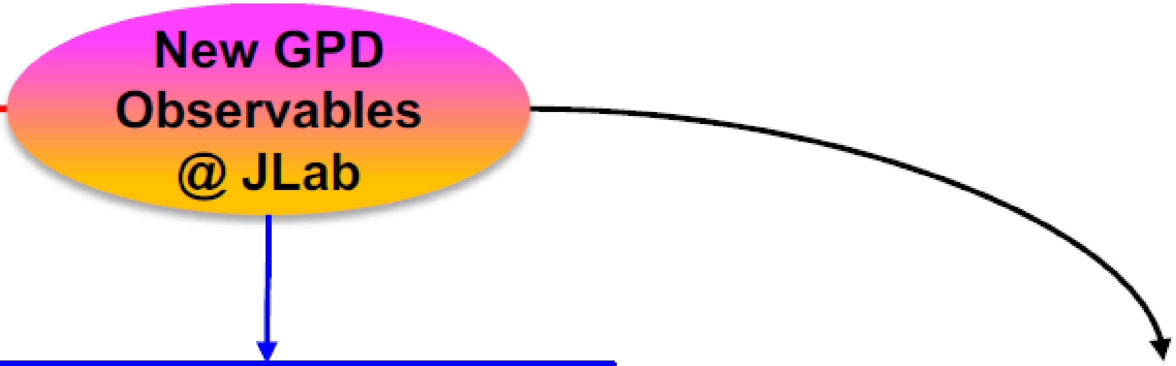


S. Stepanyan, LOI12-16-004

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



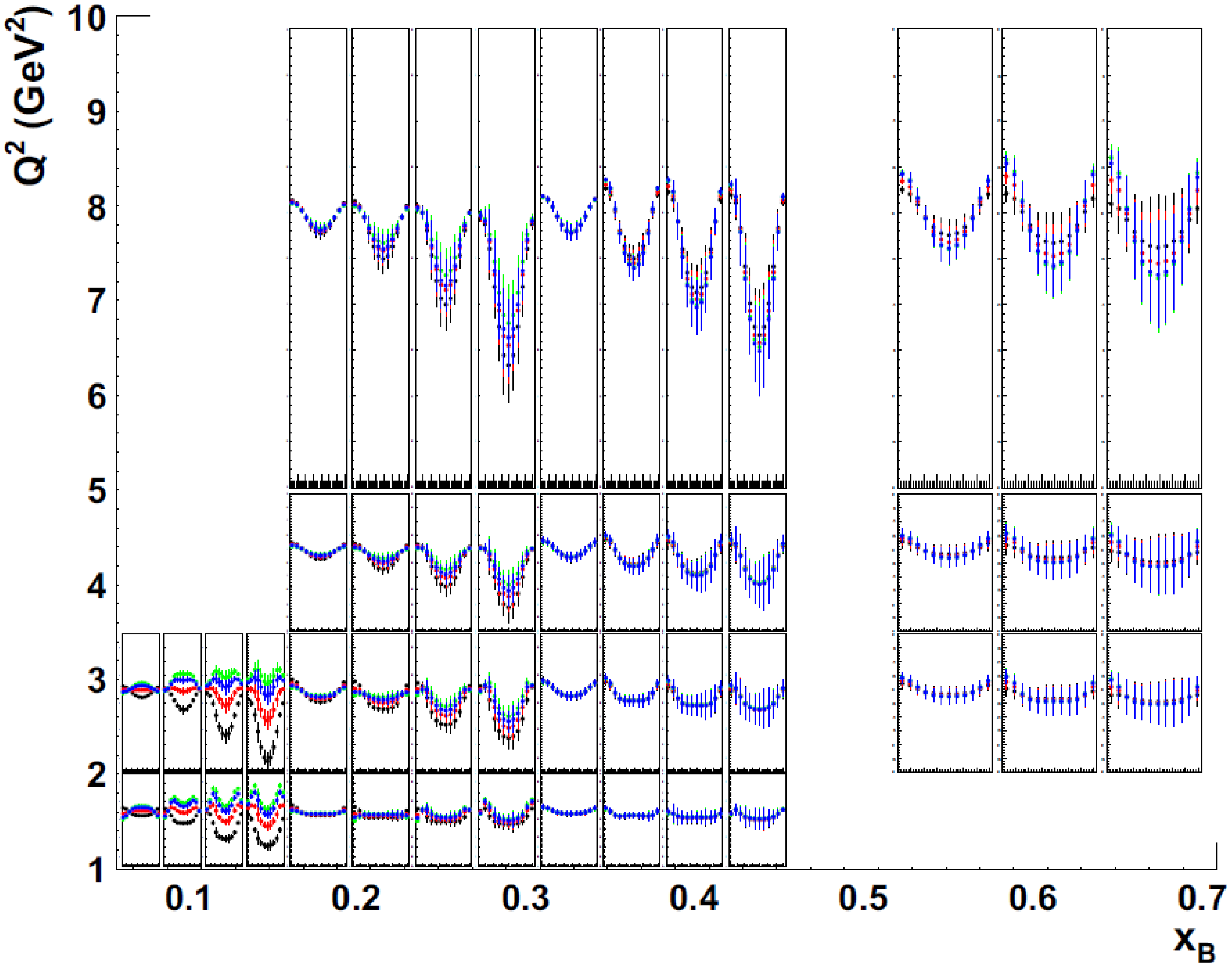
$$A^C_{UU} = \frac{(Y^+_+ + Y^+_-) - (Y^-_+ + Y^-_-)}{Y^+_+ + Y^+_- + Y^-_+ + Y^-_-} = \frac{\sigma_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

$$A^C_{LU} = \frac{(Y^+_+ - Y^+_-) - (Y^-_+ - Y^-_-)}{Y^+_+ + Y^+_- + Y^-_+ + Y^-_-} = \frac{\tilde{\sigma}_{INT}}{\sigma_{BH} + \sigma_{DVCS}}$$

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

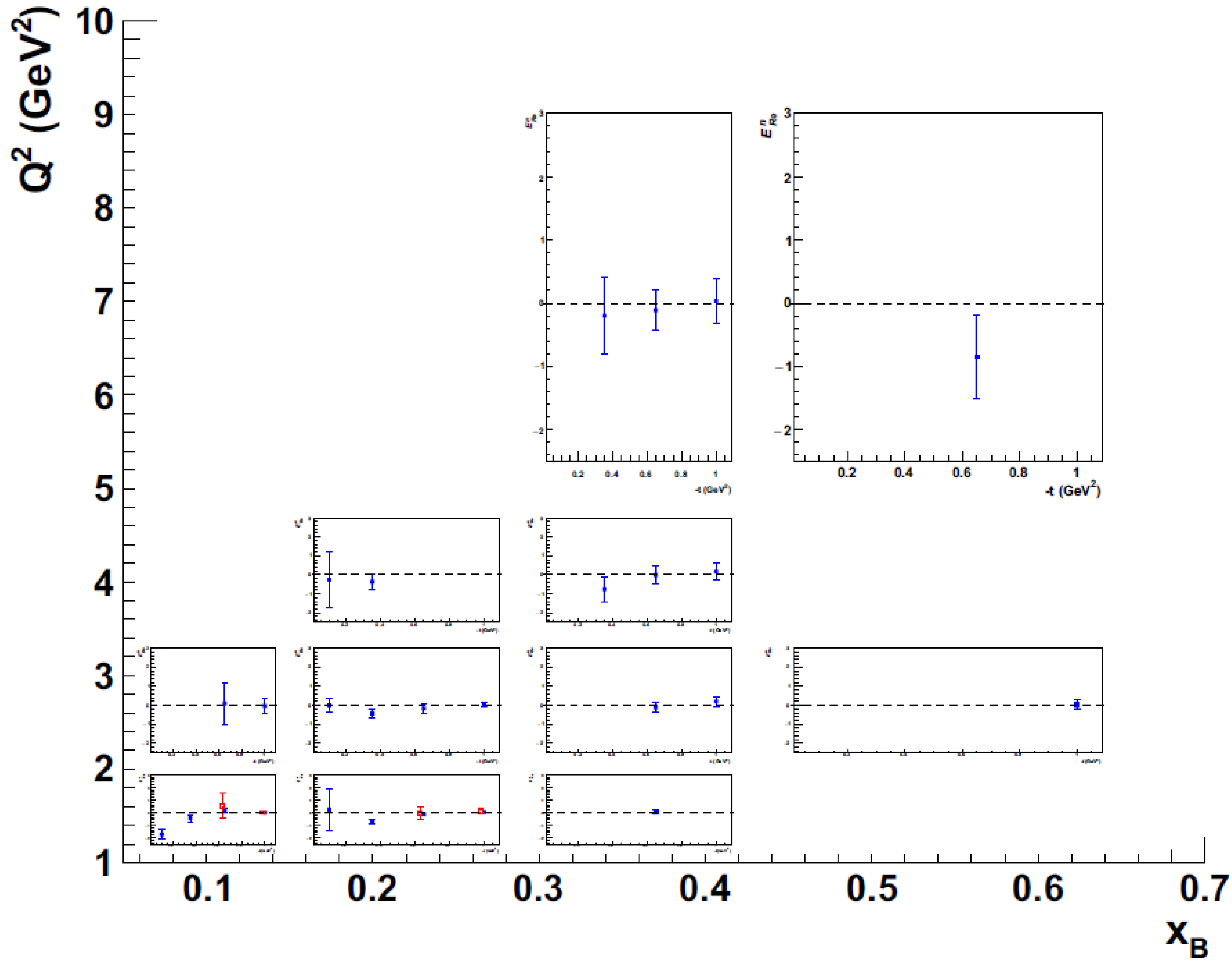
$$A^C_{LU} \neq A^{\pm}_{LU} = \frac{\pm(\tilde{\sigma}_{INT} \pm \tilde{\sigma}_{DVCS})}{\sigma_{BH} + \sigma_{DVCS} \pm \sigma_{INT}}$$

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



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

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

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)

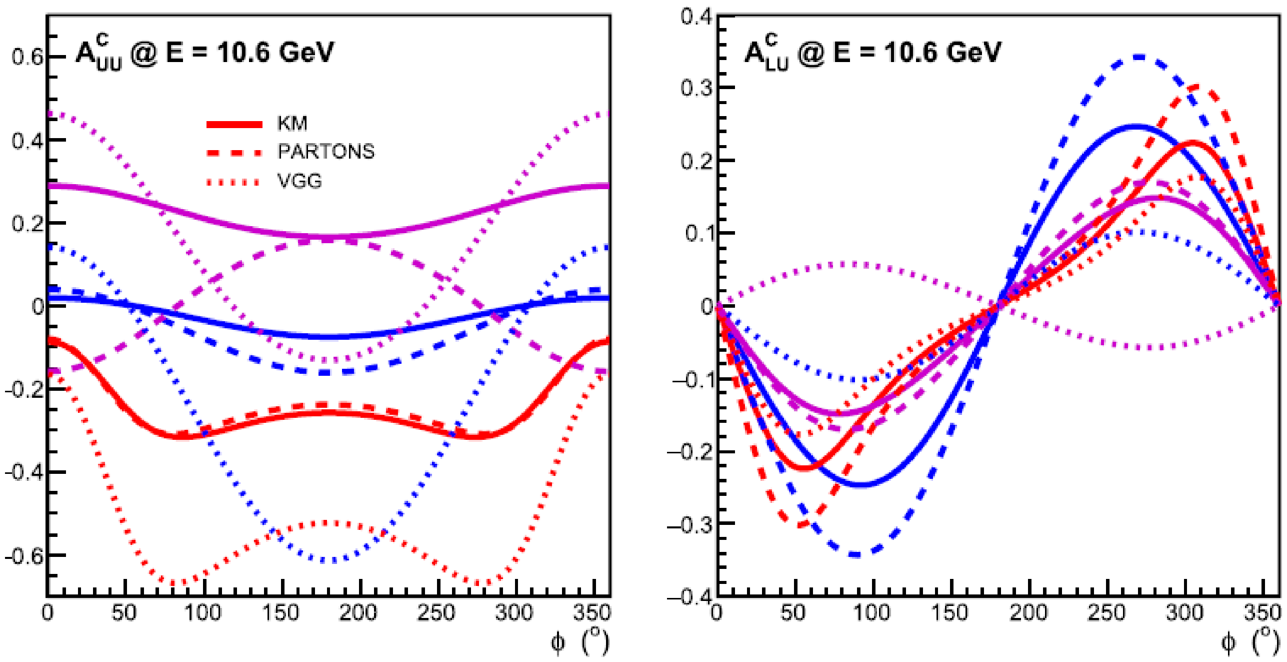
Nucleon spin: ½ = $\underbrace{½\ \Delta\Sigma + \Delta L}_{J}$ + ΔG

Intrinsic spin of the quarks ΔΣ ≈ 30%

Intrinsic spin on the gluons ΔG ≈ 20%

Orbital angular momentum of the quarks ΔL ?

pDVCS and nDVCS with polarized positrons beam at CLAS



Model predictions for 2 out of the 3 proposed pDVCS observables

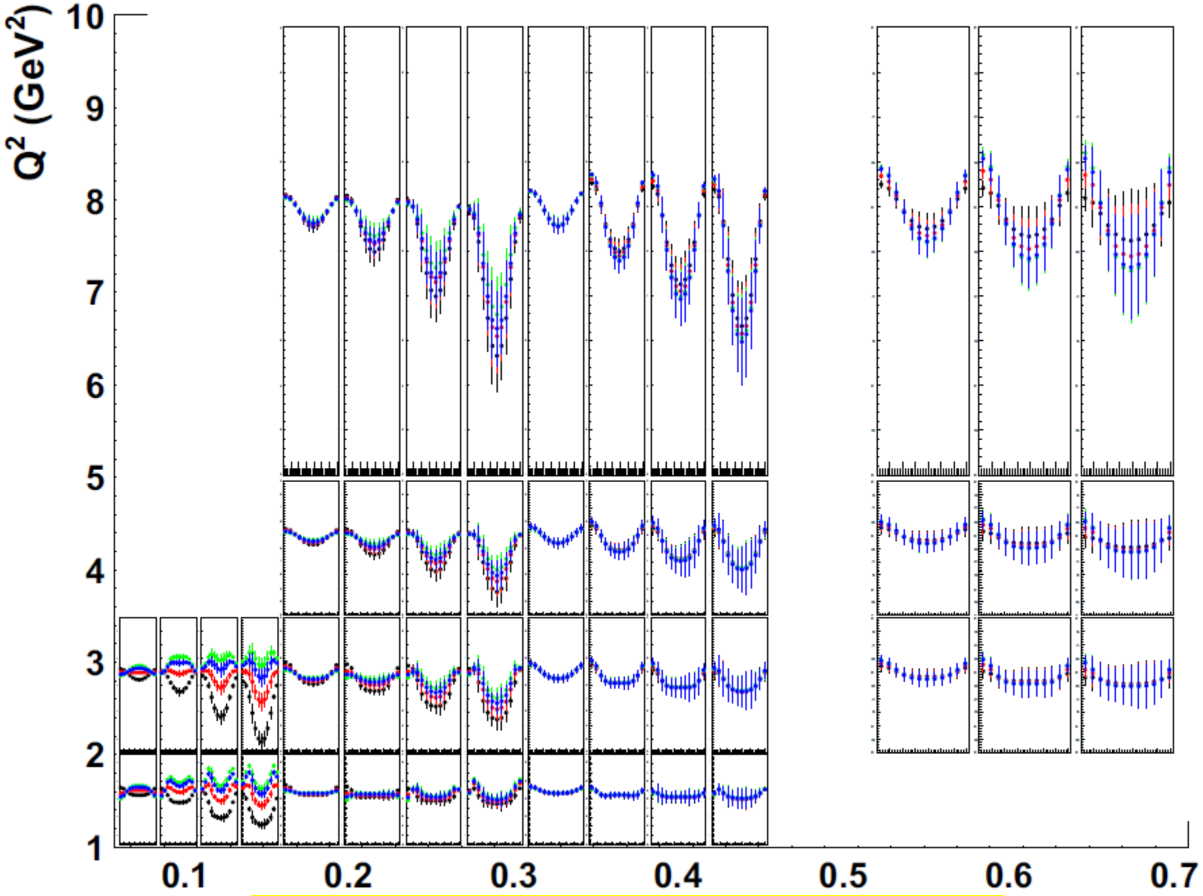
Impact of positron pDVCS projected data on the extraction of ReH via global fits: major reduction of relative uncertainties, especially at low -t

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