# CLAS12 GPD program

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TOWARDS IMPROVED HADRON TOMOGRAPHY WITH HARD EXCLUSIVE REACTIONS

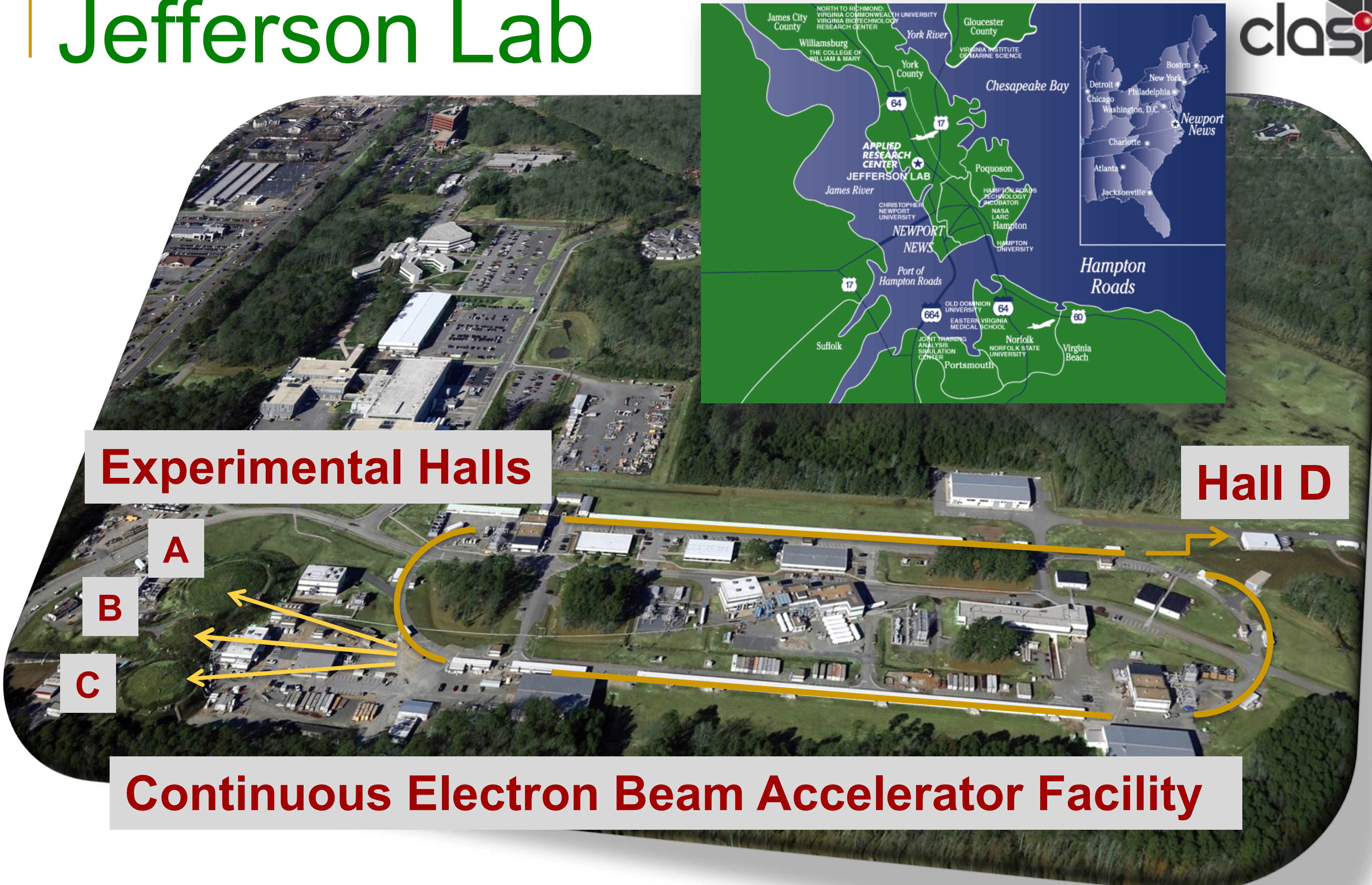
AUGUS 5-9, ECT*

TRENTO, ITALY

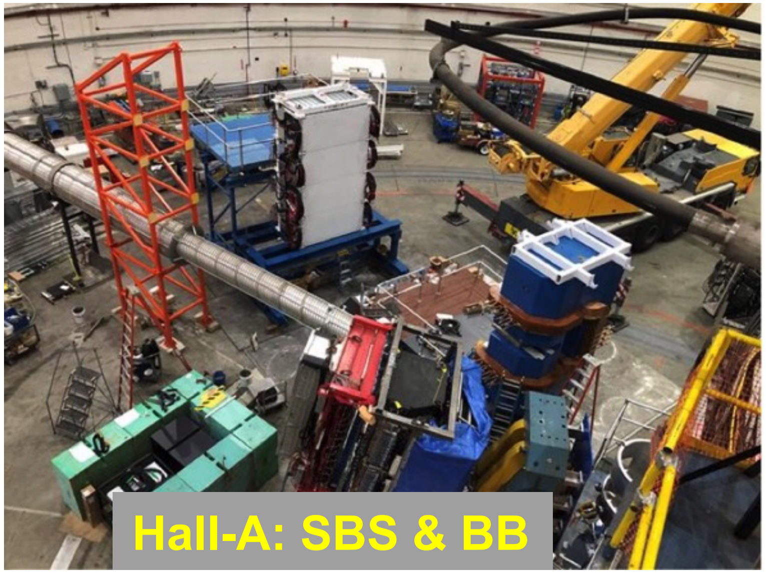
# Outline

- JLAB and 12 GeV physics program
- 3D structure of the nucleon and GPD framework
- Experimental observables and GPDs
- Deeply Virtual Exclusive Reactions with CLAS12
- Opportunities with high luminosity CLAS12
- Summary

# Jefferson Lab



# Experimental Setups

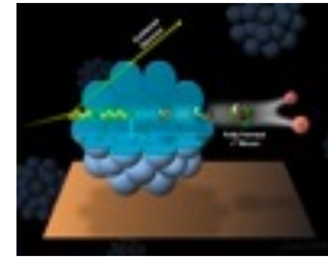




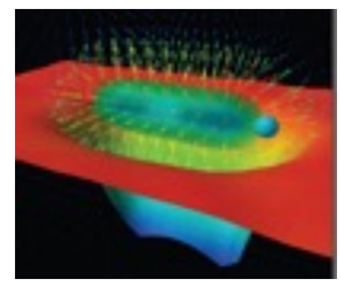

# JLAB Physics program

- Nucleon and nuclear structure studies, spatial and momentum tomography, form-factors …

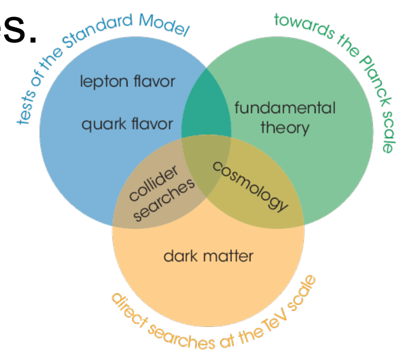
- Cold nuclear matter, NN correlations, hadronization, color transparency…



- Exploring origin of confinement – meson and baryon spectroscopy, exotics …



- Low-energy test of the Standard Model and fundamental symmetries, and search for Dark Matter particles.

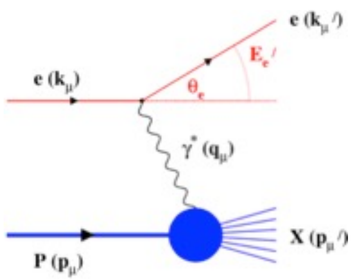



***Hall-B has a significant presence in all areas of JLAB physics.***

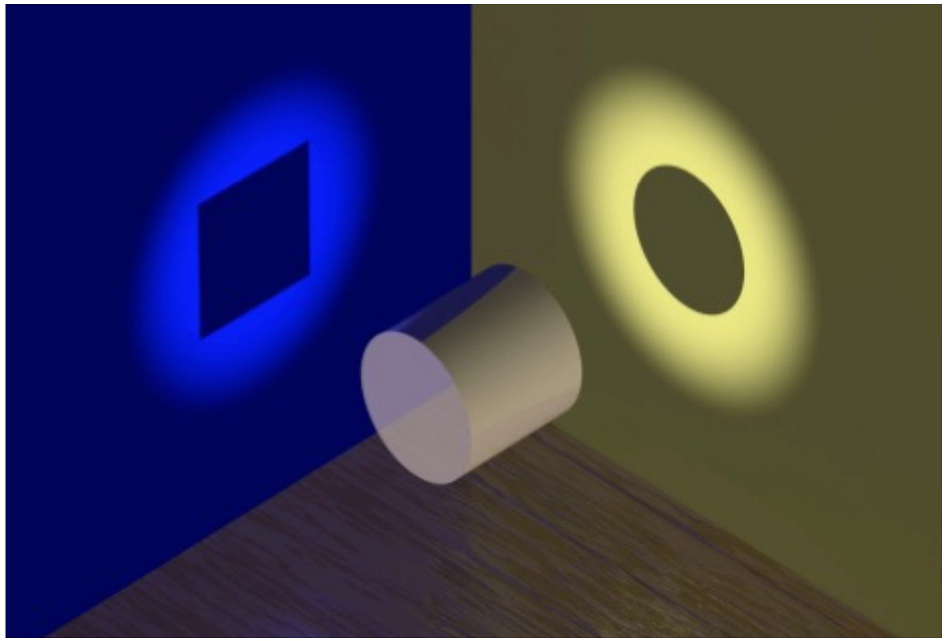
# Electron scattering for Nucleon Tomography

Elastic and deep inelastic scatterings give us two orthogonal projections.

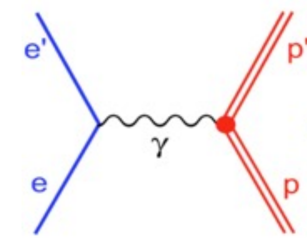
**DIS Parton Distribution Functions**




No information on the spatial location of the constituents



**Elastic Form Factors**

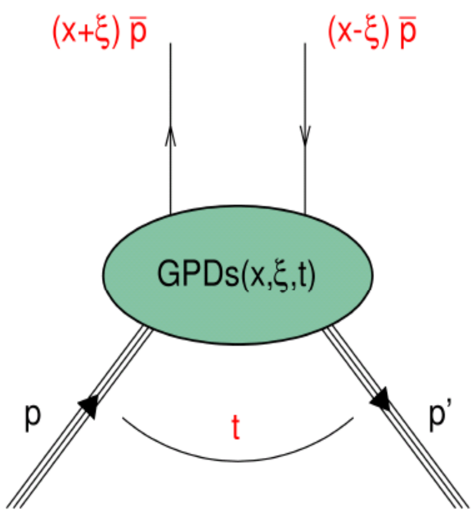



No information about the underlying dynamics of the system

*Over the past two decades, advances in theory – the development of the formalism of Generalized Parton Distributions (GPDs) and Transverse Momentum Distributions (TMDs) – have laid the path towards 3-D imaging of the nucleon's partonic structure and determination of nucleons' fundamental properties using deep exclusive and semi-inclusive reactions.*

# GPD framework

- GPDs, accessible in hard exclusive reactions (i.e., DVCS, TCS, DVMP), describe the internal dynamics of nucleon structure, forces inside, and its spin.
- They exhibit interesting properties, such as *polynomiality*, and are subject to several constraints:




At leading-twist, there are four chiral-even (parton helicity-conserving) GPDs:

$$H^q; E^q; \widetilde{H}^q; \widetilde{E}^q$$

- in the forward limit ($\xi \to 0, t \to 0$) $H$ and $\widetilde{H}$ GPD reduce to quark, anti-quark, and gluon PDFs

$$H^q(x,0,0) = q(x), -\bar{q}(-x)$$
$$\widetilde{H}^q(x,0,0) = \Delta q(x), \Delta\bar{q}(-x)$$

- and the first moments of quark GPDs are related to the Dirac, Pauli, axial, and pseudoscalar form factors

$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t) \quad \int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t)$$

$$\int_{-1}^{+1} dx \widetilde{H}^q(x,\xi,t) = g_A^q(t) \quad \int_{-1}^{+1} dx \widetilde{E}^q(x,\xi,t) = h_A^q(t)$$

# GPDs and the form factors of the QCD EMT

The Mellin moments of GPDs linked to the FF of the QCD energy-momentum tensor (EMT) of the nucleon, and to the nucleon spin:

$$\langle p', s'|\hat{T}^a_{\mu\nu}(x)|p, s\rangle = \bar{u}'\left[A^a(t)\,\frac{\gamma_{\{\mu}P_{\nu\}}}{2} + B^a(t)\,\frac{i\,P_{\{\mu}\sigma_{\nu\}\rho}\Delta^\rho}{4m} + D^a(t)\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{4m} + m\,\bar{c}^a(t)\,g_{\mu\nu}\right]u$$

$$\int_{-1}^{1} dx\; xH^a(x,\xi,t) = A^a(t) + \xi^2 D^a(t)$$

$$\int_{-1}^{1} dx\; xE^a(x,\xi,t) = B^a(t) - \xi^2 D^a(t)$$

$$a = q, g$$

$$\mathbf{J_q} = \frac{1}{2}\sum_q [A^q(0) + B^q(0)] = \frac{1}{2}\sum_q \int_{-1}^{1} dx\; x(H^q(x,\xi,0) + E^q(x,\xi,0))$$

Ji, Phys. Rev. Lett 77 / Phys. Rev. D 55, 1997.

The FF $D^a(t)$, or *D*-term (*M. Polyakov, C. Weiss, Phys. Rev. D 60, 114017*), characterizes the distribution of the shear forces, $s(r)$, and the pressure, $p(r)$, inside the nucleon:

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

*V.Burkert et al., Reviews of Modern Physics, volume 95, 2023.*

# From experimental observables to GPDs

- The experimental observables, for example, asymmetries and cross sections in DVCS/TCS, are parametrized by complex-valued CFF.

$$\mathcal{T}_{DVCS/TCS} \sim \mathcal{F}(\xi, t)$$

- The CFFs are expressed as convolutions of complex-valued hard-scattering coefficient functions with the real-valued GPDs.

$$Im\mathcal{F}(\xi, t) = i\pi \sum_a [F^a(\xi, \xi, t) - F^a(-\xi, \xi, t)]$$

$$Re\mathcal{F}(\xi, t) = P \int_{-1}^{1} dx \left( \frac{1}{\xi - x} \pm \frac{1}{\xi + x} \right) \sum_a [F^a(x, \xi, t) \mp F^a(-x, \xi, t)]$$

- Therefore, extracting information on GPDs from experimental observables is not straightforward and is a two-step process: from observables to CFFs, then to GPDs.

- And, of course, we have to disentangle different flavor ($\boldsymbol{a}$, gluon and quark) contributions.

# CLAS12 GPD program

- The subject of nuclear femtography is a central focus of the CLAS12 science program.
- Experiments, already underway, include the study of deeply virtual exclusive reactions using a variety of unpolarized and polarized targets and up to 11 GeV longitudinally polarized electron beams.
- These studies build on the successful GPD program at 6 GeV with CLAS on DVCS and DVMP and will provide many data points on cross sections and beam, target (L/T), and double spin asymmetries.
- The whole program is encapsulated in several Hall-B run groups and has more than 400 PAC-approved days of beam running.

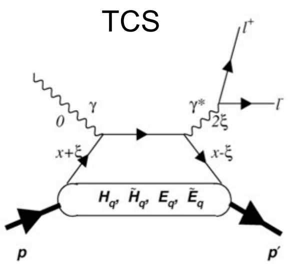
| Proposal | Physics | Contact | Rating | Days | Group | New equipment | Energy |
|---|---|---|---|---|---|---|---|
| **E12-06-108** | Hard exclusive electro-production of $\pi^0$, $\eta$ | Stoler | B | 80 | 139 | RICH (1 sector) Forward tagger | 11 |
| E12-06-108A | Exclusive N*->KY Studies with CLAS12 | Carman | | (60) | | | |
| E12-06-108B | Transition Form Factor of the $\eta'$ Meson with CLAS12 | Kunkel | | (80) | | | |
| **E12-06-112** | Proton's quark dynamics in SIDIS pion production | Avakian | A | 60 | | | |
| E12-06-112A | Semi-inclusive $\Lambda$ productiuon in target fragmentation region | Mirazita | | (60) | | | |
| E12-06-112B | Colinear nucleon structure at twist-3 | Pisano | | (60) | | | |
| E12-06-119(a) | Deeply Virtual Compton Scattering | Sabatie | A | 80 | | | |
| E12-09-003 | Excitation of nucleon resonances at high $Q^2$ | Gothe | B+ | 40 | | | |
| **E12-11-005** | Hadron spectroscopy with forward tagger | Battaglieri | A- | 119 | | | |
| E12-11-005A | Photoproduction of the very strangest baryon | Guo | | (120) | | | |
| E12-12-001 | Timelike Compton Scatt. & $J/\psi$ production in e+e- | Nadel-Turonski | A- | 120 | | | |
| E12-12-001A | Near Threshold $J/\psi$ photoproduction and study of LHCb pentquarks | Stepanyan | | (120) | | | |
| E12-12-007 | Exclusive $\varphi$ meson electroproduction with CLAS12 | Stoler, Weiss | B+ | 60 | | | |
| E12-07-104 | Neutron magnetic form factor | Gilfoyle | A- | 30 | 90 | Neutron detecto RICH (1 sector) Forward tagger | |
| E12-09-007(a) | Study of partonic distributions in SIDIS kaon production | Hafidi | A- | 30 | | | |
| **E12-09-008** | Boer-Mulders asymmetry in K SIDIS w/ H and D targets | Contalbrigo | A- | 56 | | | |
| E12-09-008A | Hadron production in target fragmentation region | Mirazita | | (60) | | | |
| E12-09-008B | Colinear nucleon structuer at twist-3 | Pisano | | (60) | | | |
| **E12-11-003** | DVCS on neutron target | Niccolai | A | 90 | | | |
| E12-11-003A | In medium structure functions, SRC, and the EMC effect | Hen | | (90) | | | |

| Proposal | Physics | Contact | Rating | Days | Group | Equipment | Energy (GeV) | Group | Target | Complete |
|---|---|---|---|---|---|---|---|---|---|---|
| E12-06-109 | Longitudinal Spin Structure of the Nucleon | Kuhn | A | 80 | ~~185~~ 120 | Longitudinally Polarized target RICH (1 sector) Forward tagger | 11 | **C** S. Kuhn | $NH_3$ $ND_3$ | |
| E12-06-109A | DVCS on the neutron with polarized deuterium target | Niccolai | | (60) | | | | | | |
| E12-06- 119(b) | DVCS on longitudinally polarized proton target | Sabatie | A | 120 | | | | | | |
| E12-07-107 | Spin-Orbit Correl. with Longitudinally polarized target | Avakian | A- | 103 | | | | | | |
| E12-09-007(b) | Study of partonic distributions using SIDIS K production | Hafidi | A- | 80 | | | | | | |
| E12-09-009 | Spin-Orbit correlations in K production w/ pol. targets | Avakian | B+ | 103 | | | | | | |
| E12-06-106 | Color transparency in exclusive vector meson production | Hafidi(El Fassi) | B+ | ~~60~~ 30 | 30 | | 11 | **D** | | |
| E12-06-106A | Nuclear TMDs in CLAS12 | Dupre | | (30) | | | | | | |
| E12-06-117 | Quark propagation and hadron formation | Brooks | A- | 60 | 60 | | 11 | **E** | Nuclear | |
| E12-06-113 | Free Neutron structure at large x | Bueltman | A | 42 | 42 | Radial TPC | 11 | **F** | Gas $D_2$ | 100% |
| E12-14-001 | EMC effect in spin structure functions | Brooks | B+ | 55 | 55 | Pol. target, Li | 11 | **G** | 6LiH/7LiD | |
| C12-11-111 | SIDIS on transverse polarized target | Contalbrigo | A | 110 | 110 | Transversely polarized target | 11 | **H** | HD | |
| C12-12-009 | Transversity w/ di-hadron on transvere target | Avakian | A | 110 | | | | | | |
| C12-12-010 | DVCS with transverse polarized target in CLAS12 | Elouadrhriri | A | 110 | | | | | | |

| Proposal | Physics | Contact | Rating | Days app. | Group | Equipment | Energy (GeV) | Group | Target | Completed |
|---|---|---|---|---|---|---|---|---|---|---|
| E12-16-010 | A search for Hybrid Baryons in Hall B with CLAS12 | D'Angelo | A- | 100 | **100** | Forward Tagger | 6.6, 8.8 | **K** Confinement & Strong QCD | **LH2** | **12%** |
| E12-16-010A | Nucleon Resonances in exc. KY electroproduction | Carman | A- | (100) | | | | | | |
| E12-16-010B | DVCS with CLAS12 at 6.6 and 8.8 GeV | Elouadrhiri | A- | (100) | | | | | | |
| E12-17-012 | Partonic Structure of Light Nuclei | Meziani | A- | 55 | **55** | ALERT detector | 11 | **L** | **High pressure gas H, D, 4He** | |
| E12-17-012A | Tagged EMC measurements on Light Nuclei | Dupre | | | | | | | | |
| E12-17-012B | Spectator-Tagged DVCS on Light Nuclei | Armstrong | | | | | | | | |
| E12-17-012C | Other Physics Opportunities with ALERT | Hafidi | | | | | | | | |

# Time-like Compton Scattering

TCS + Bethe-Heitler (BH)

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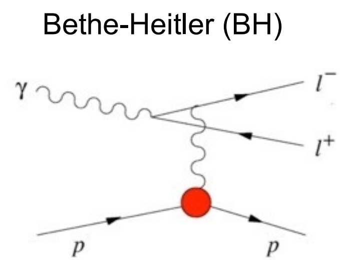
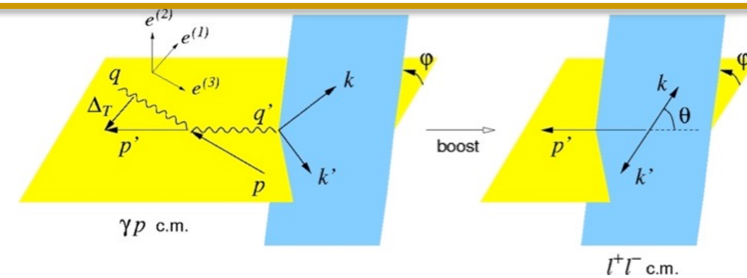



$$\frac{d^4\sigma}{dx_B dQ^2 dt d\phi} \propto |T^{BH}|^2 + T^{BH} \bullet \mathrm{Re}(T^{VCS}) + \lambda T^{BH} \bullet \mathrm{Im}(T^{VCS}) + |T^{VCS}|^2$$

CLAS12 measures the reaction:

$$ep \to l^+ l^- p'(X)$$

*where the scattered electron escapes the detection and is identified in the missing momentum analysis,* $X \equiv e'$.

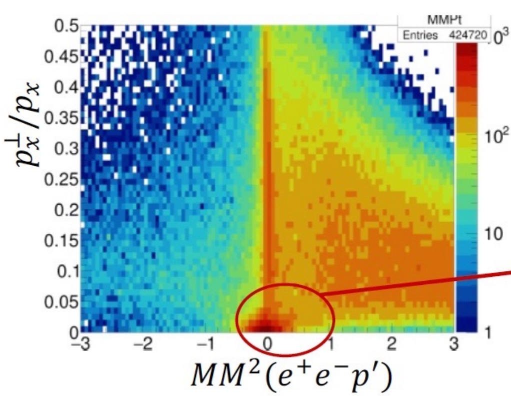


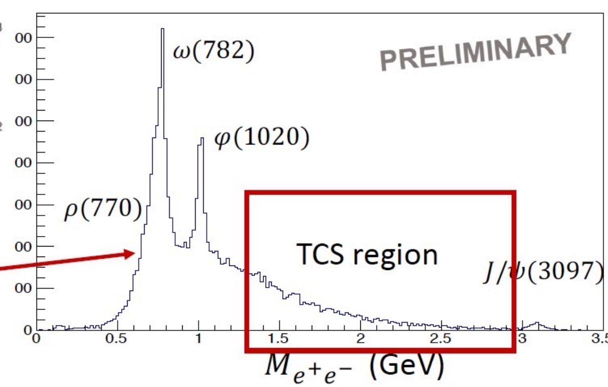

$$\frac{d\sigma_{INT}}{dQ'^2\,dt\,d(\cos\theta)\,d\varphi} = -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\left[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\tilde{M}^{--} - \cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\tilde{M}^{0-} +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

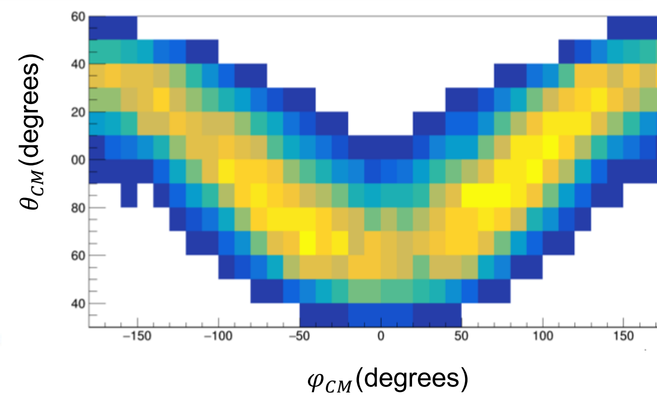
Photon polarization

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

$$\tilde{M}^{--} = \frac{2\sqrt{t_0-t}}{M}\frac{1-\xi}{1+\xi}\left[F_1(t)\mathcal{H} - \xi\left(F_1(t)+F_2(t)\right)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2(t)\mathcal{E}\right]$$



# First experimental results on TCS

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

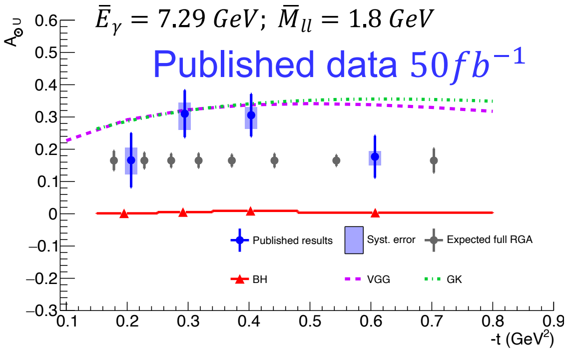
Two observables:

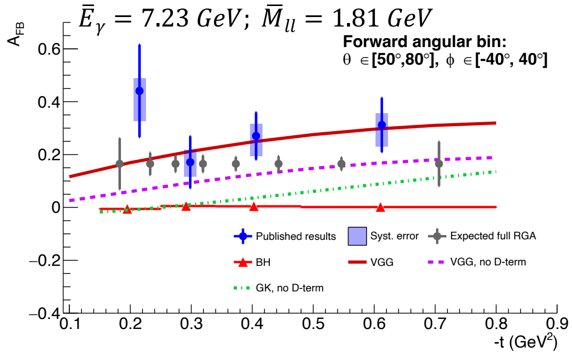
- Photon helicity asymmetry, accessing the imaginary part of the CFF (similar to BSA in DVCS) – testing the universality of GPDs:

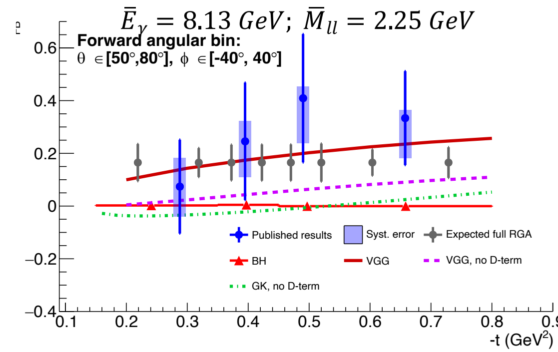
$$A_{\odot U} = \frac{1}{P_b}\frac{N^+ - N^-}{N^+ + N^-} = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\sin\phi\frac{(1+\cos^2\theta)}{\sin(\theta)}\mathrm{Im}\tilde{M}^{--}}{d\sigma_{BH}}$$

- Forward-backward asymmetry, accessing the real part of the CFF – extracting the *D*-term (QCD EMT FF $D^Q(t)$):

$$\mathbf{A_{FB}}(\theta_0,\phi_0) = \frac{\mathbf{d}\sigma(\theta_0,\phi_0) - \mathbf{d}\sigma(\pi-\theta_0,\pi+\phi_0)}{\mathbf{d}\sigma(\theta_0,\phi_0) + \mathbf{d}\sigma(\pi-\theta_0,\pi+\phi_0)} = \frac{-\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{m_p}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\cos\phi_0\frac{(1+\cos^2\theta_0)}{\sin(\theta_0)}\mathrm{Re}\tilde{M}^{--}}{\mathbf{d}\sigma_{BH}(\theta_0,\phi_0) + \mathbf{d}\sigma_{BH}(\pi-\theta_0,\pi+\phi_0)}$$




- The currently available data for analysis is about $155fb^{-1}$ .
- The expected full data set will be $760fb^{-1}$ (grey predictions on the plots).



Jefferson Lab
Thomas Jefferson National Accelerator Facility

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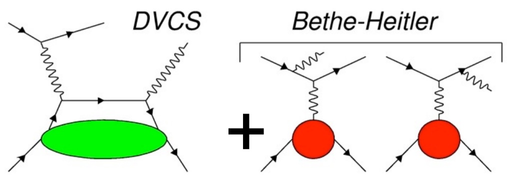
# Proton DVCS: BSA

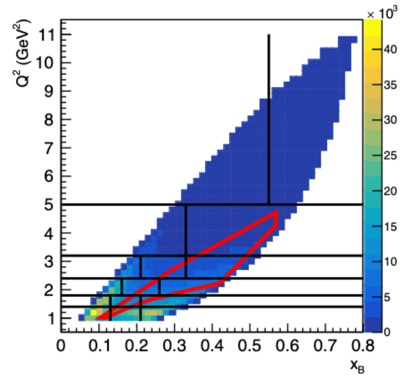
*G. Christiaens, et al., CLAS Collaboration, Phys. Rev. Lett. 130, 211902 (2023).*

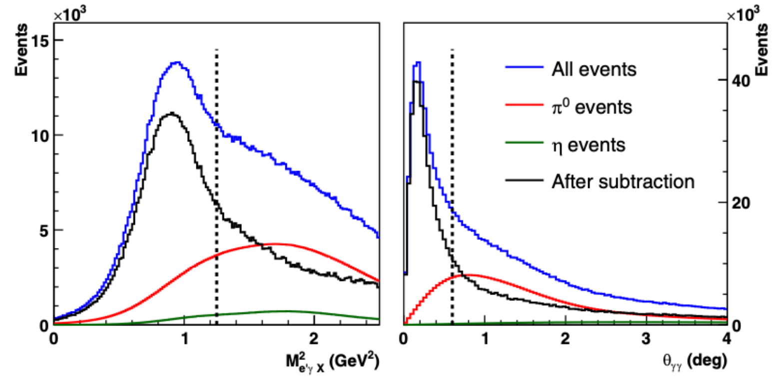



$$\sigma(ep \to e'p'\gamma) = \sigma_{BH} + \sigma_{DVCS} + \sigma_{INT}$$

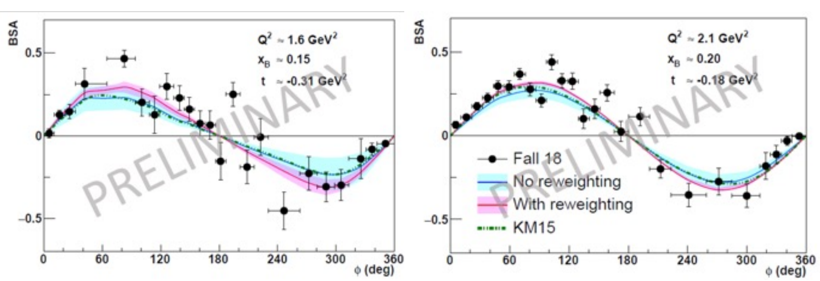
$$A_{\mathrm{LU}}(\phi) \sim \frac{s^{\mathcal{I}}_{1,\mathrm{unp}} \sin\phi}{c^{\mathrm{BH}}_{0,\mathrm{unp}} + (c^{\mathrm{BH}}_{1,\mathrm{unp}} + c^{\mathcal{I}}_{1,\mathrm{unp}} + \cdots)\cos\phi \cdots}$$

$$s^{\mathcal{I}}_{1,\mathrm{unp}} \propto \Im\mathrm{m}\left[F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}\right]$$

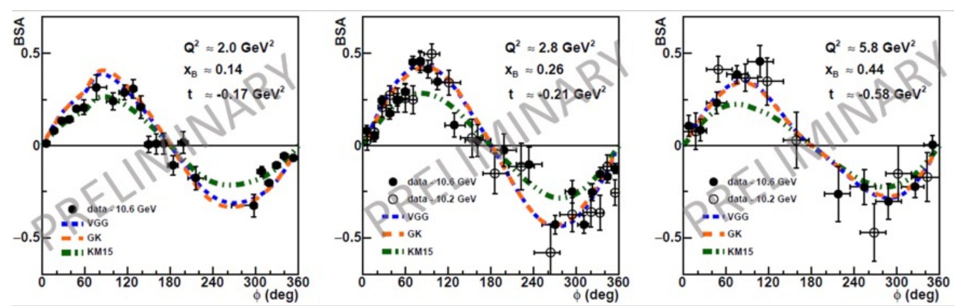



- Large phase space, total of 64 bins in $Q^2$, $x_B$, and $t$;
- Exclusivity is ensured by application of cuts on $\vartheta_{\gamma\gamma}$, $E_{miss}$, $P^T_{miss}$, and $M^2_{e'\gamma X}$.




- The kinematic region overlaps with previously published CLAS data.
- KM15 parameters and AAN training use the available world dataset on DVCS.




- Kinematic bins that are reachable only with a ~10 GeV electron beam.
- Comparisons with KM15, VGG, and GK models.
- A reasonable description of data in the unexplored region of phase space by VGG and GK.

# Neutron DVCS

*A. Hobart et al., CALS collaboration, arxiv:2406.15539 (submitted to PRL).*

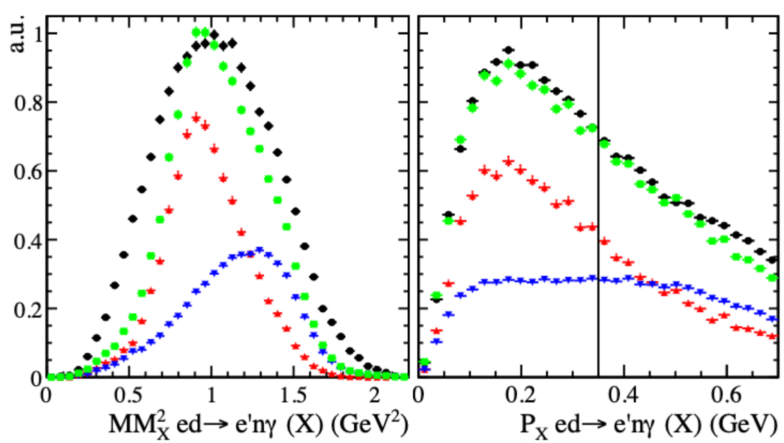
- The first measurement of BSA for nDVCS in a fully exclusive reaction.

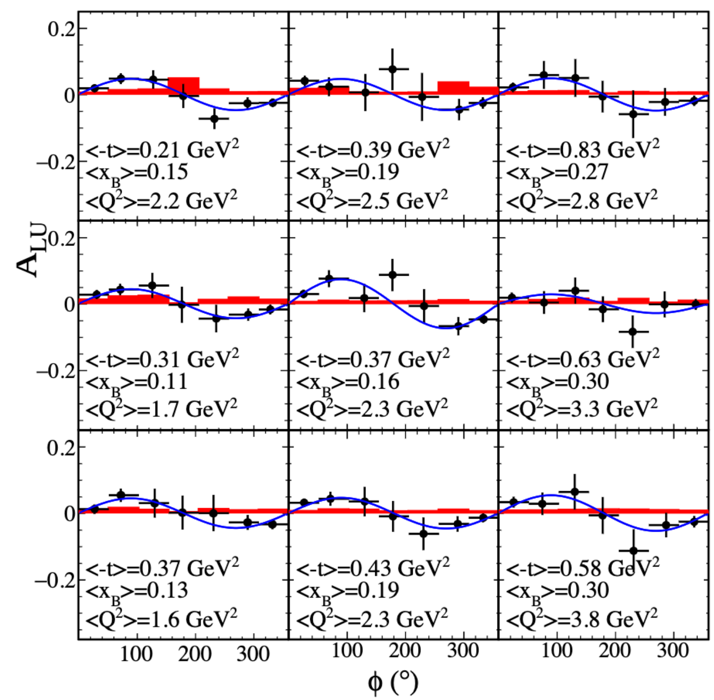
$$ed \rightarrow e'n\gamma(p)$$

- An important reaction for the flavor separation of GPDs.
- BSA is most sensitive to the CFF $\mathcal{E}$ and provides access to the GPD *E*, one of the ingredients in Ji's spin sum rule.

$$A_{LU} = \frac{1}{P}\frac{N^+ - N^-}{N^+ + N^-}$$

$$A_{LU} \propto \sin\phi \, \Im m(F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4M^2}\mathcal{E})$$



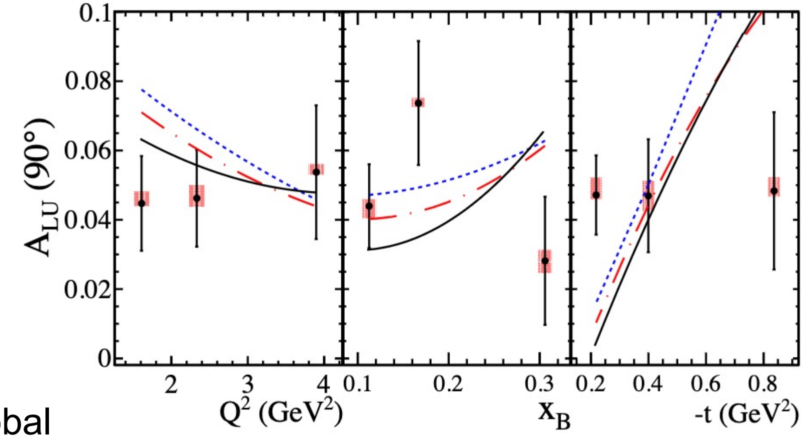

Exclusivity cuts include $\vartheta_{\gamma\gamma}$, $P_X$, $M^2_{e'nX}$, and $M^2_{e'n\gamma X}$.

About 80k $e'\gamma n(p)$ events were identified in a wide kinematic phase space.

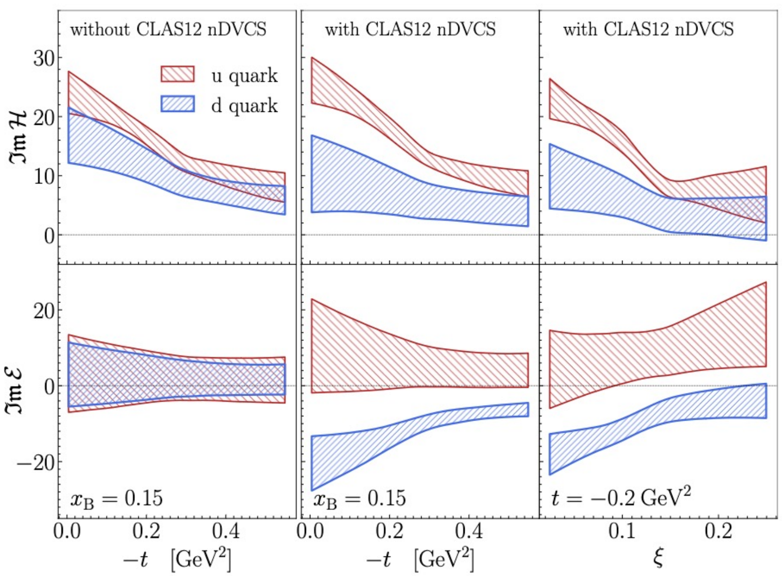
# Neutron DVCS: BSA

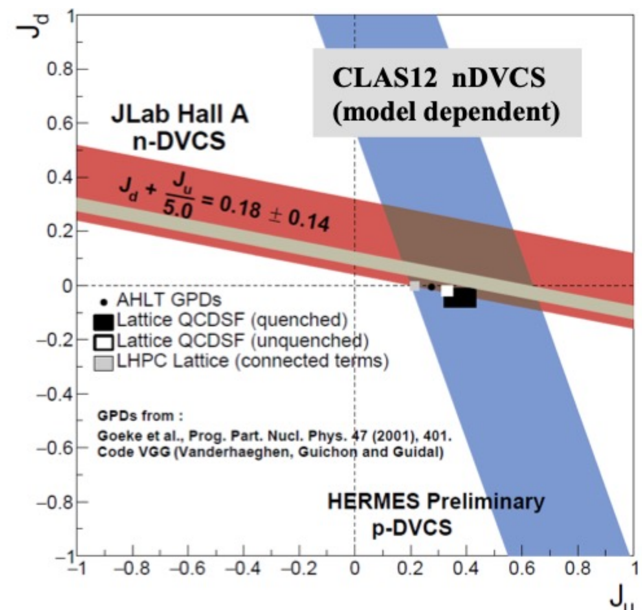
Fits to the $Q^2, x_B$, and $t$ dependencies of $A_{LU}(90^o)$ with the VGG model. The best fits yielded:

$$J_u = 0.35, J_d = 0.05,$$
$$J_u = -0.2, J_d = 0.15$$
$$J_u = -0.45, J_d = 0.2$$




The flavor separation of both $Im\mathcal{H}$ and $Im\mathcal{E}$ in global fits of CFF using neural networks (K. Kumericki et al.)

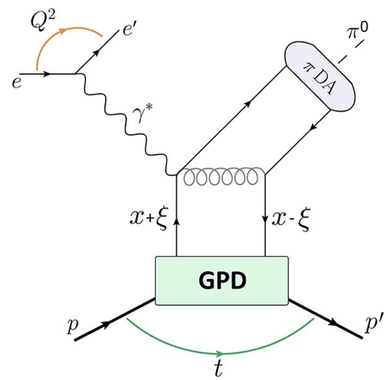



*Credit to S.Niccolai*

# DVMP and transversity GPDs

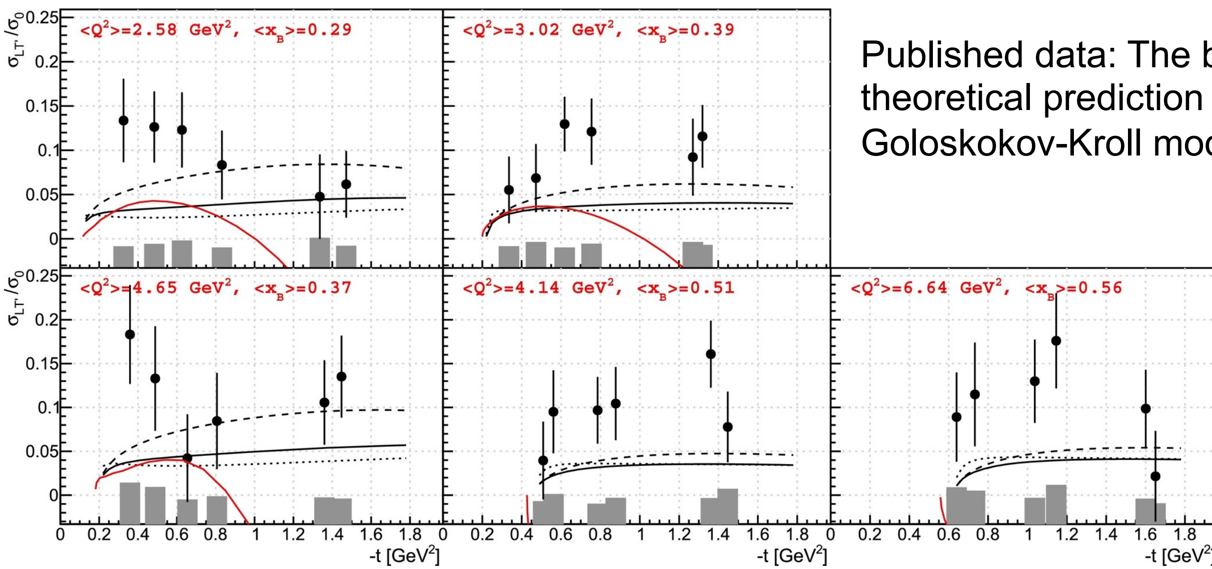
*A. Kim et al., CLAS collaboration, Phys. Lett. B 849 (2024) 138459.*




- Deeply virtual exclusive production of $\pi^0$ has an increased sensitivity to chiral-odd GPD, $\bar{E}_T = 2\widetilde{H}_T + E_T$.
- The $\sin\phi$ moment of BSA projects out $\sigma_{LT'}/\sigma_0$:

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

$$\frac{\sigma_{LT'}}{\sigma_0} \sim \frac{Im[\langle\bar{E}_T\rangle^*\langle\widetilde{H}\rangle + \langle H_T\rangle^*\langle\widetilde{E}\rangle]}{(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2 + \epsilon\sigma_L}.$$




Published data: The black curves show the theoretical prediction from the GPD-based Goloskokov-Kroll model. The other curves are:

- The black dashed lines show the effect of the GPD $\tilde{E}_T$ multiplied by a factor of 0.5,
- the black dotted lines show the effect of the GPD $H_T$multiplied by a factor 0.5.
- The red curve shows the theoretical predictions from the Regge-based JML model.

# DVCS with longitudinally polarized targets

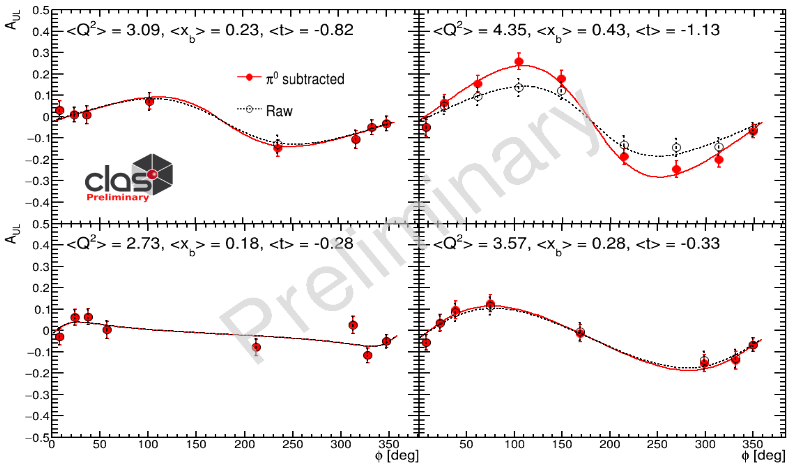
- The longitudinal target-spin asymmetry ($A_{UL}$) gives access to the imaginary part of a combination of the CFF $\mathcal{H}$ and $\widetilde{\mathcal{H}}$. Double spin asymmetry ($A_{LL}$) allows access to the real part of Compton amplitude.
- The experiment, CLAS12 RGC, collected 70% of the expected data. Part of the data is analyzed with preliminary results on $A_{UL}$ and $A_{LL}$ in a new kinematic domain.
- Asymmetries for proton ($NH_3$) and neutron ($ND_3$) targets has been measured and will be studied in a wide range of kinematics.

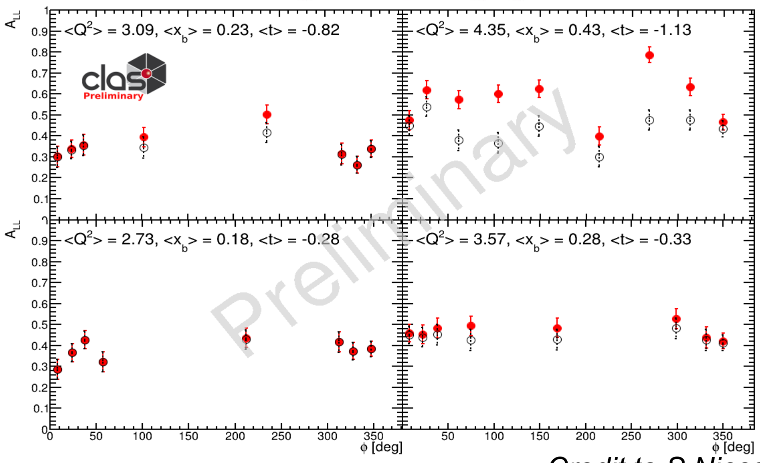
$$A_{\mathrm{UL}}(\phi) \sim \frac{s^{\mathcal{I}}_{1,\mathrm{LP}} \sin\phi}{c^{\mathrm{BH}}_{0,\mathrm{unp}|} + (c^{\mathrm{BH}}_{1,\mathrm{unp}} + c^{\mathcal{I}}_{1,\mathrm{unp}} + \cdots)\cos\phi + \cdots},$$

$$s_{1,\mathrm{LP}} \propto \Im\mathrm{m}\Big[F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\Big(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\Big) + - \xi\Big(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\Big)\tilde{\mathcal{E}}\Big].$$

$$A_{\mathrm{LL}}(\phi) \sim \frac{c^{\mathrm{BH}}_{0,\mathrm{LP}} + c^{\mathcal{I}}_{0,\mathrm{LP}} + (c^{\mathrm{BH}}_{1,\mathrm{LP}} + c^{\mathcal{I}}_{1,\mathrm{LP}})\cos\phi}{c^{\mathrm{BH}}_{0,\mathrm{unp}} + (c^{\mathrm{BH}}_{1,\mathrm{unp}} + c^{\mathcal{I}}_{1,\mathrm{unp}} + \cdots)\cos\phi \cdots}$$

$$c^{\mathcal{I}}_{0,\mathrm{LP}}, c^{\mathcal{I}}_{1,\mathrm{LP}} \propto \Re\mathrm{e}\Big[F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)\Big(\mathcal{H} + \frac{x_B}{2}\mathcal{E}\Big) + - \xi\Big(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2\Big)\tilde{\mathcal{E}}\Big],$$

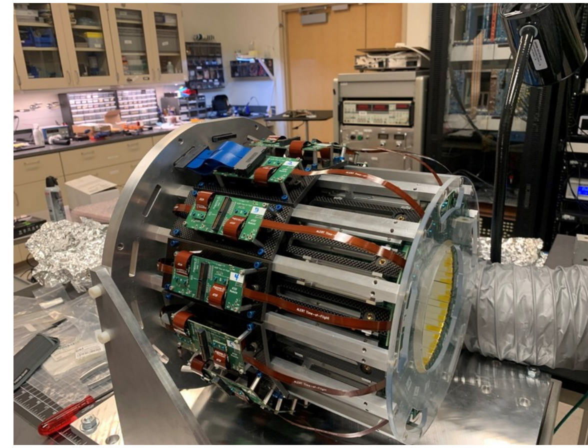



*Credit to S.Niccolai*

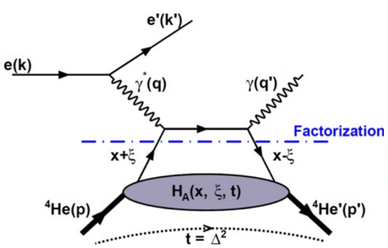
# Nuclear DVCS: ALERT program

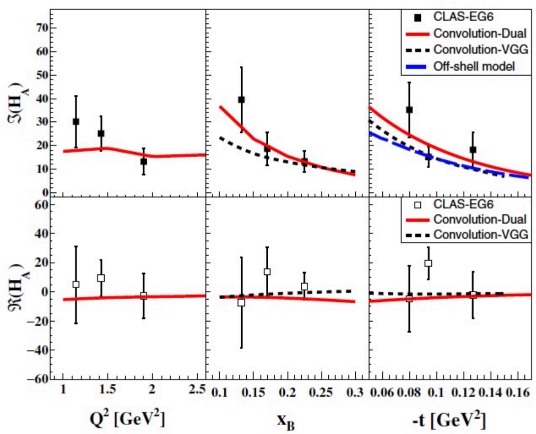
- Building on the successful program of studying coherent and incoherent DVCS using $^{4}He$ gaseous target with CLAS (EG6), ALERT will expand measurements to larger kinematical phase space and to tagged final states.
- Other physics targets include near-threshold J/ψ production, aiming to study the gluing structure of light nuclei.
- The experiment is scheduled to run next year.



*6 GeV CLAS results*

$e^4He \rightarrow e'^4He'\gamma$

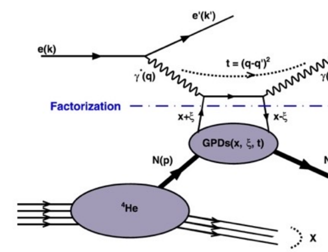


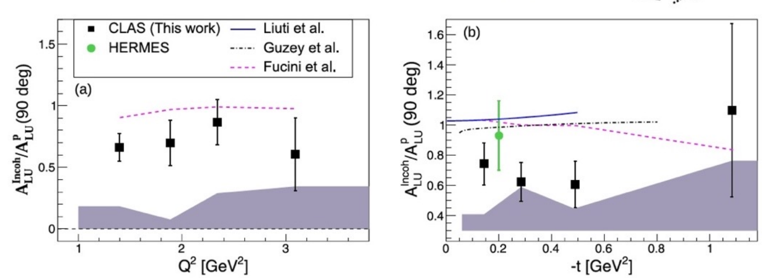




$$A_{LU} = \frac{\alpha_0(\phi)\mathcal{I}_A}{\alpha_1(\phi) + \alpha_2(\phi)\mathcal{R}_A + \alpha_3(\phi)(\mathcal{R}_A^2 + \mathcal{I}_A^2)}$$

M. Hattawy *et al., Phys. Rev. Lett.* 119, 202004 (2017)

$e^4He \rightarrow e'p'\gamma X$

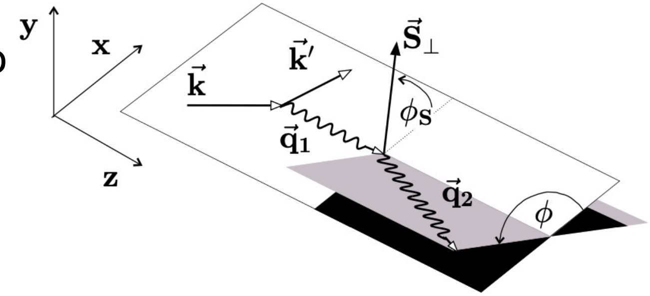



M. Hattawy *et al.*, Phys. Rev. Lett. 123, 032502 (2019)

# DVCS with transversely polarized target

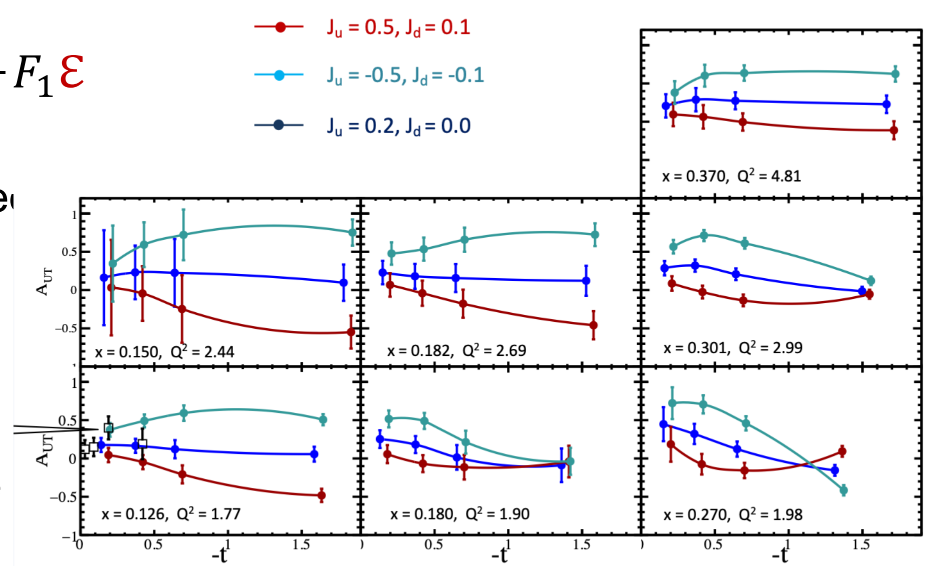
- Combinations of harmonics of $\phi$ and $\phi_S$ of single target spin (UT) and double spin (LT) asymmetry give access to imaginary and real parts of CFFs.
- High sensitivity to the CFF $\mathcal{E}$ and allows access to the GPD$-E$ of the proton. Together with neutron DVCS, this experiment will provide data for flavor separation of GPD$-E$.




$$A_{UT}^{\sin(\phi_S-\phi)} \propto \cos\phi\, \Im m(C_{TP}^I) \qquad A_{LT}^{\sin(\phi_S-\phi)} \propto \sin\phi\, \Re m(C_{TP}^I)$$

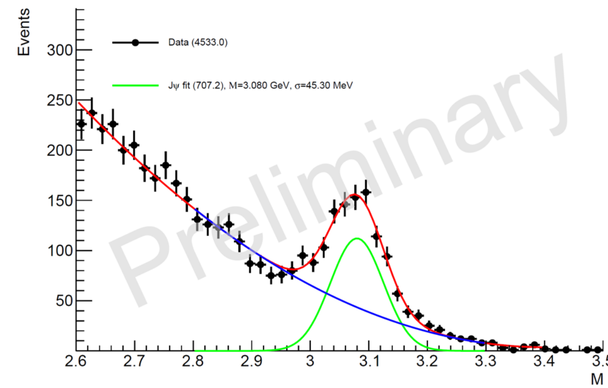
$$C_{TP}^I \propto \frac{1-x_B}{2-x_B}\frac{t}{m^2}F_2\mathcal{H} + (2-x_B)\frac{t}{4m^2}F_1\mathcal{E}$$

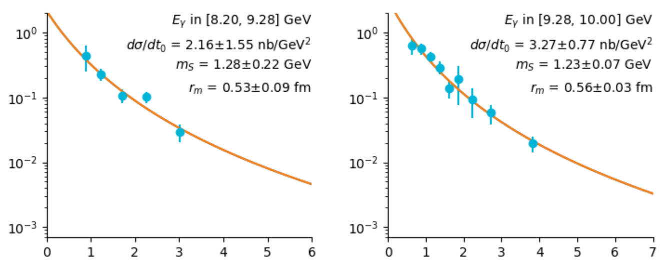
- The experiment is conditionally approved for 110 days of beam time.
- Since 2021, collaboration has adopted dynamically polarized NH3 technology for the target.
- Complications with the background due to the 5T field of the target magnet.

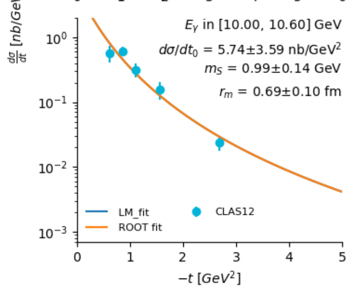


# Proton gluonic structure

- Charmonium production near-threshold region offers unique access to the gluonic structure of the nucleon.
- Model-dependent approaches have been proposed to relate the near-threshold photoproduction of heavy quarkonium to gluonic FF of QCD EMT and the origin of the proton mass. (K.A. Mamo and I. Zahed, PRD (2022), Y. Guo, X. Ji, and Y. Liu, PRD (2021), *D. E. Kharzeev, PRD (2021)*)
- CLAS12 has comparable statistics to GlueX and J/ψ-007 and will soon release complementary results to those already published by JLAB experiments.

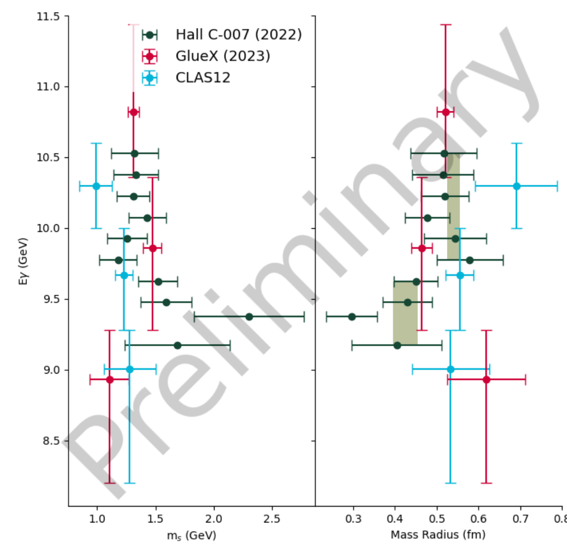



$$\frac{d\sigma}{dt} = \frac{d\sigma}{dt}\Big|_0 \cdot \frac{1}{(1-t/m_S^2)^4}$$

$$\sqrt{\langle r_m^2 \rangle} = \frac{\sqrt{12}}{ms}$$




*Credit to P.Chatagnon*



OFFICE OF SCIENCE

Jefferson Lab
Thomas Jefferson National Accelerator Facility

# Closing the loop on virtual Compton scattering

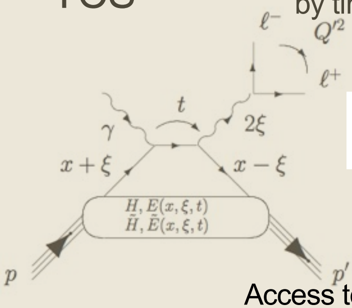
**JLAB Flagship program – accessing GPDs through measurements of beam/target asymmetries and the cross sections of Compton processes (TCS and DVCS)**

First experimental measurement with CLAS12 PRL 127, 262501 (2021)

Started in 2001, PRL 87, 182002. Now is the flagship physics program

## TCS

Hard scale is defined by time-like photons



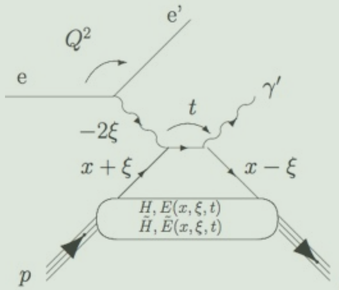

$$Re\ \mathcal{H}(\xi,t) = PV \int_{-1}^{1} dx\, C^{-}(\xi,x) H(x,\xi,t)$$

$$Im\ \mathcal{H}(\xi,t) = i\pi H(\xi,\xi,t)$$

Access to the Re-part of the Compton amplitude

## DVCS

Hard scale is defined by space-like photon

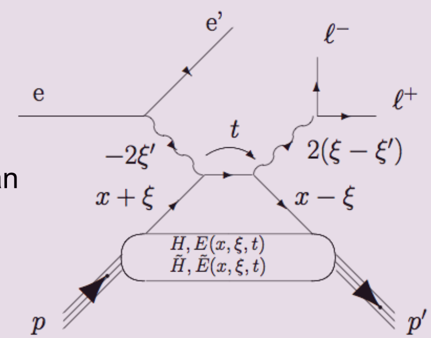



**Jefferson Lab at the luminosity frontier is the only place in the world DDVCS can be measured!**

**μCLAS12 in Hall B and SoLID in Hall A are the two proposed facilities capable of carrying out such measurements.**

## DDVCS

Both space-like and time-like photons can set the hard scale




$$\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-(2\xi'-\xi)+i\epsilon} + \ldots$$

$$H(2\xi'-\xi,\xi,t) + H(-(2\xi'-\xi),\xi,t)$$

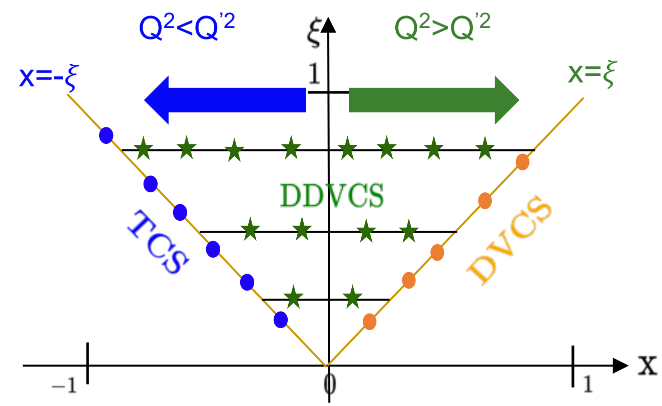
***σ-DDVCS is three orders of magnitude smaller than σ-DVCS***

# CFFs and GPDs in Virtual Compton Scattering

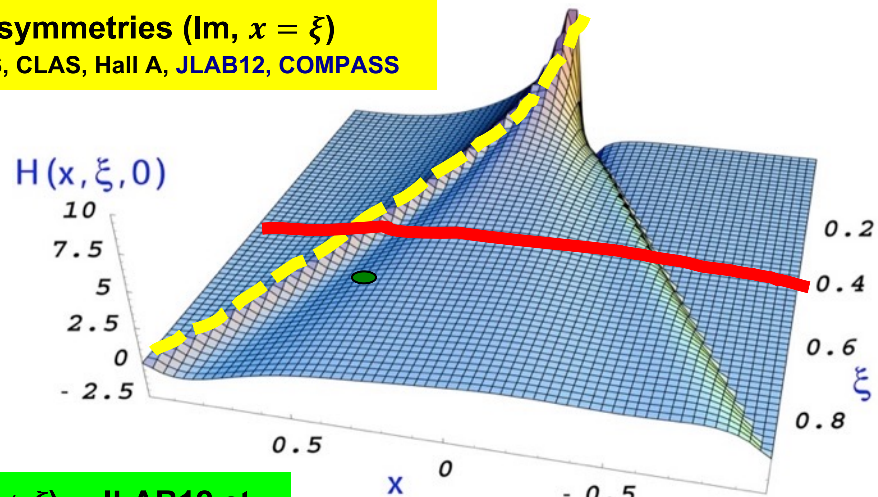
$$\mathcal{T}_{DVCS} \sim CFF\ \ \mathcal{H}(\xi,t) \propto i\pi[H(\xi,\xi,t) - H(\xi,\xi,t)] + P\int_{-1}^{+1} dx\left(\frac{1}{x-\xi} \pm \frac{1}{x+\xi}\right)[H(x,\xi,t) \mp H(x,\xi,t)]$$

*(the same for TCS)*

$$\mathcal{T}_{DDVCS} \sim CFF\ \ \mathcal{H}(\xi,\xi',t) \propto i\pi[H(2\xi'-\xi,\xi,t) - H(-2\xi'+\xi,\xi,t)] + P\int_{-1}^{+1} dx\left(\frac{1}{x-(2\xi'-\xi)} \pm \frac{1}{x+(2\xi'-\xi)}\right)[H(x,\xi,t) \mp H(x,\xi,t)]$$




**Spin asymmetries (Im, $x = \xi$)**
**HERMES, CLAS, Hall A, JLAB12, COMPASS**




**Angular asymmetry in TCS (|Re|)**
**JLAB12**

**Charge asymmetry in DVCS (|Re|)**
**HERMES, COMPASS, JLAB12**

**DVCS Cross sections (|Re|$^2$)**
**H1, Hall A, JLAB12, COMPASS**

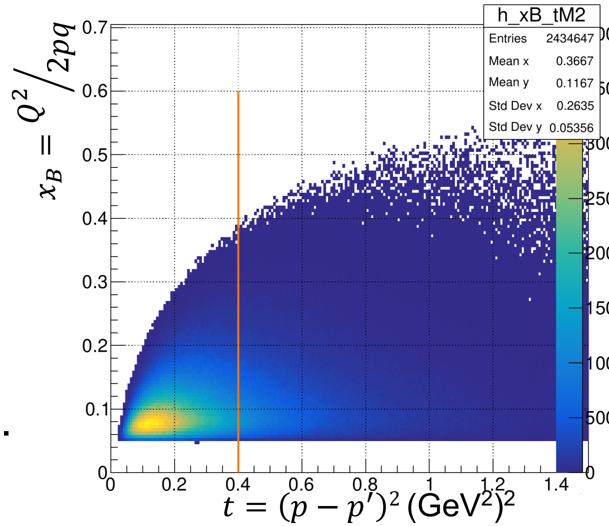
**DDVCS (Im, $x \neq \xi$) – JLAB12 at *$L \geq 10^{37}$ $cm^{-2}$ $sec^{-1}$***

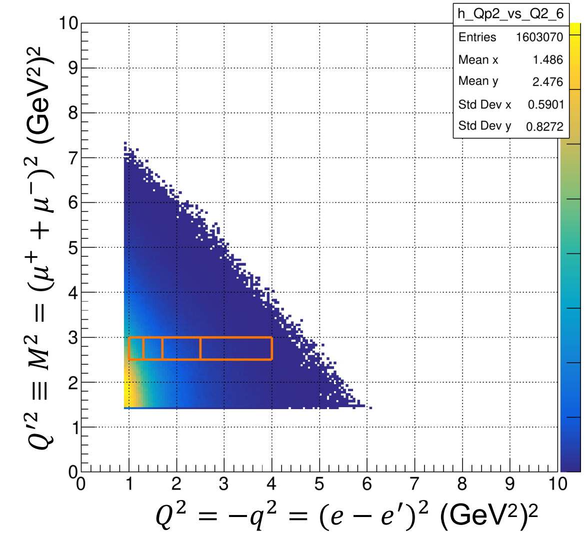
*Re* part of CFFs provides a direct measurement of the D-term and access to the mechanical properties of the proton

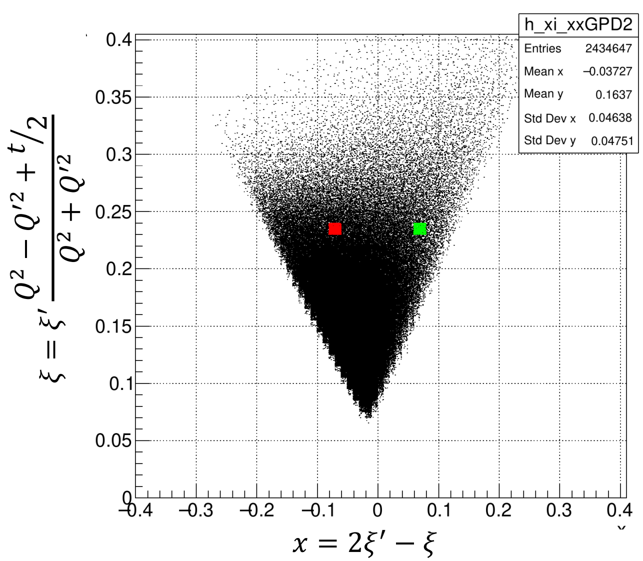
# Kinematical coverage at 11 GeV

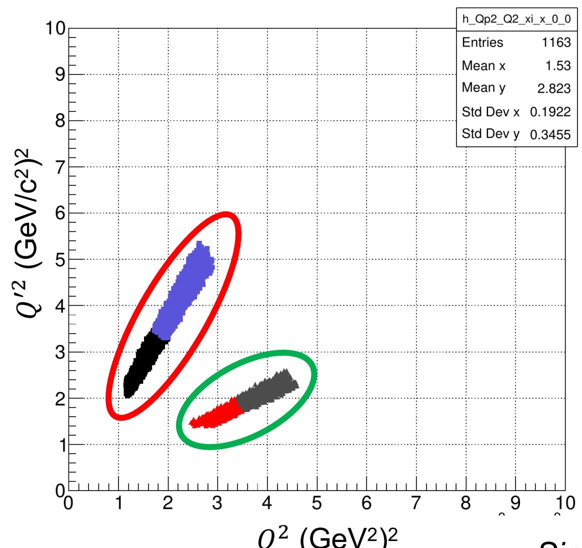
$$ep \to e'p'\mu^+\mu^-$$

- GRAPE event generator, BH only.
- The whole region is measured simultaneously.
- At 11 GeV, the interesting region is $Q'^2 > 2$ (GeV/c$^2$)$^2$.




$$x_B = \frac{Q^2}{2pq} \qquad \xi' = \frac{Q^2 + Q'^2}{2Q^2/x_B - Q^2 - Q'^2 + t}$$

- ξ - x bin fixes the ratio $Q'^2/Q^2$ while their values are unconstrained.
- For each ξ - x bin asymmetry can be measured at different $Q'^2$ and $Q^2$, can be a scaling test for GPDs.

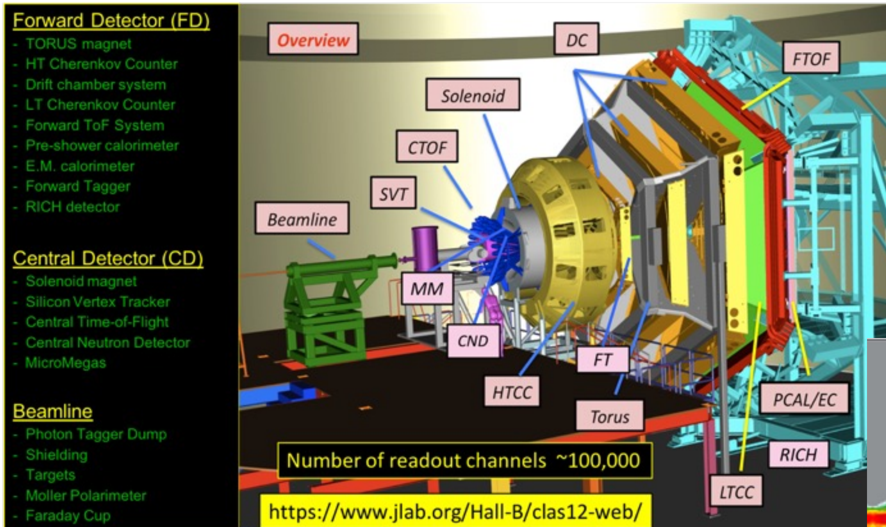
*Simulations from R. Paremuzyan*

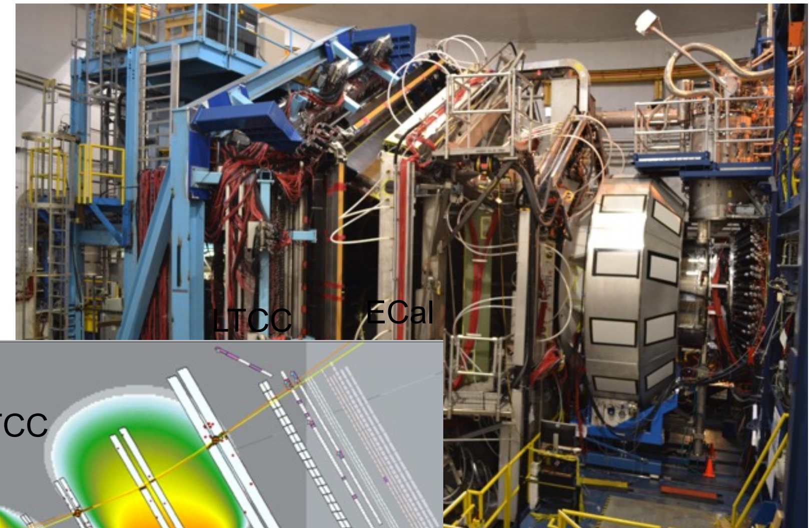
# Summary

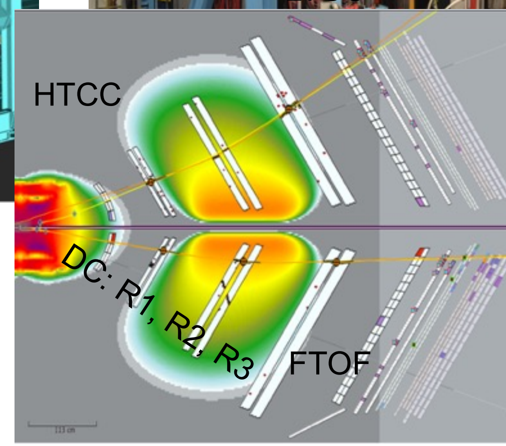
- The description of the partonic structure of hadronic matter is a major thrust of the JLAB 12 GeV.
- A comprehensive program of studying GPDs using deeply virtual exclusive processes is underway in Hall B using the CLAS12 detector and up to 11 GeV polarized electron beams.
- The first results, using only a fraction of the available data, are out and include the first-time measurement of TCS, DVCS BSA on the proton and the neutron in new, uncharted kinematic regions, and BSA in deeply virtual $\pi^0$ production.
- More results, including data from polarized targets, on the nuclear DVCS and near-threshold charmonium production will be available soon.
- These data are crucially important yet limited for inferring information on GPDs from experimental observables.
- The collaboration is working on the luminosity upgrade to measure the Double DVCS process, which allows the mapping of GPDs in the $x$-space.

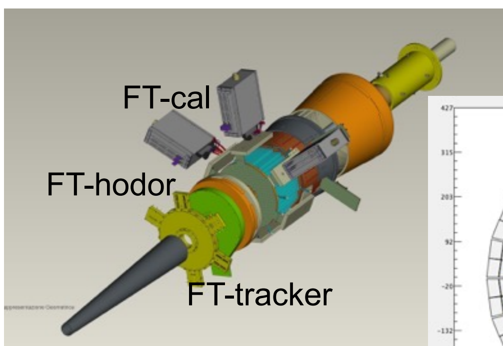
# CLAS12 in Hall-B at JLAB

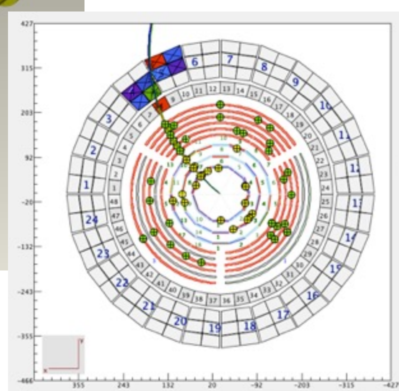
Designed luminosity $10^{35} \mathrm{cm}^{-2} \mathrm{sec}^{-1}$



Physics targets:
- $LH_2$, $LD_2$, LHe, LAr, D, $^4He$
- $^{12}C$ to $^{208}Pb$
- Polarized $NH_3$, $ND_3$