Studying GPDs at Jefferson Lab

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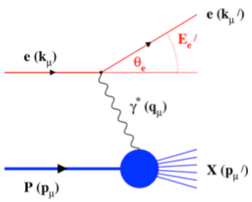
6th Workshop of the APS Topical Group on Hadronic Physics
April 8-10, 2015, Baltimore, Maryland

- 3-D picture of the nucleon and GPDs
- Extracting GPDs from experimental observables
- DVCS experiments with JLAB-6 GeV
- Future plans with upgraded JLAB-12 GeV
- Summary

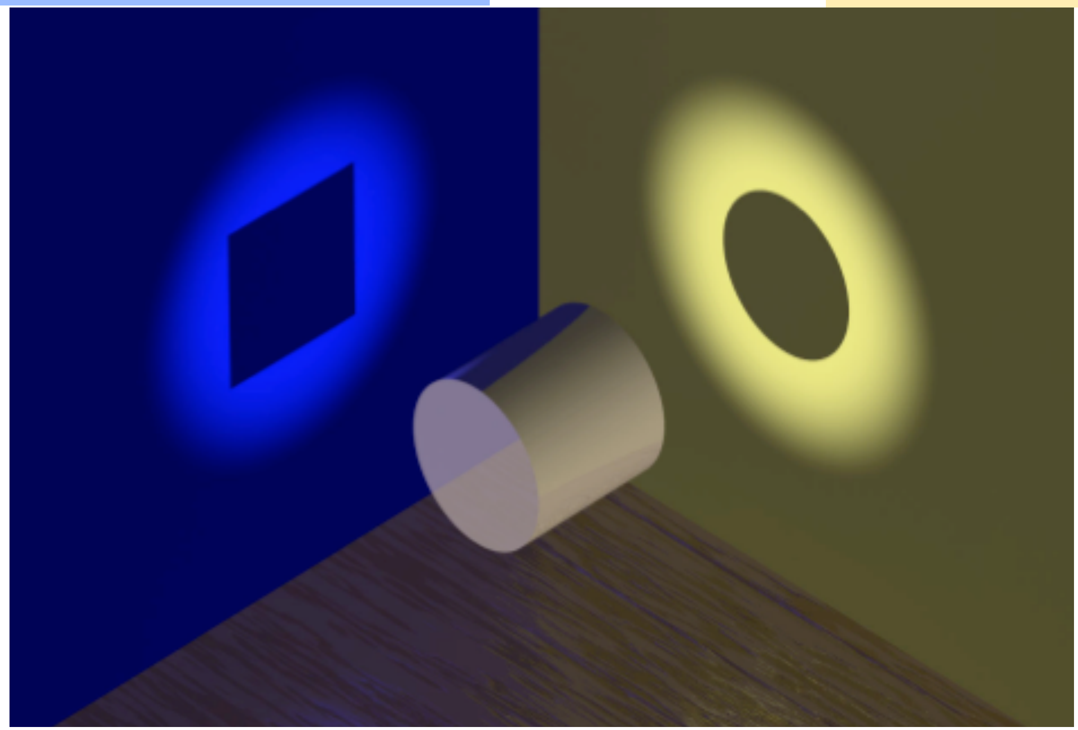
3-D Picture of the Nucleon

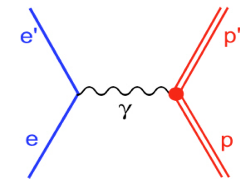
DIS Parton Distribution Functions

Elastic Form Factors



No information on the spatial location of the constituents

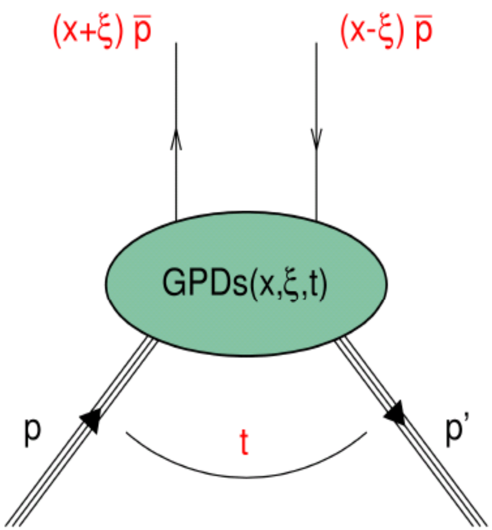




No information about the underlying dynamics of the system

Transverse Momentum Distributions & Generalized Parton Distributions
3-D imaging of the nucleon, the correlation of quark/antiquark transverse spatial and longitudinal momentum distributions, and on the quark angular momentum distribution

GPDs, PDFs, FFs



- GPDs → PDFs (in the limite t → 0)

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

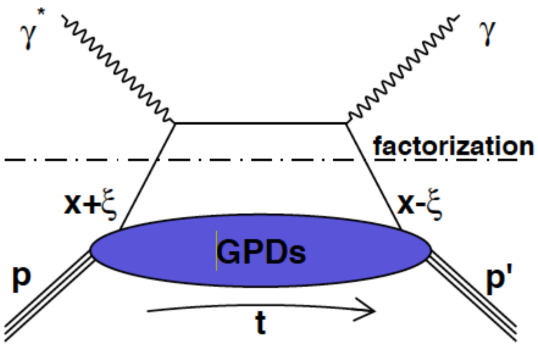
- GPDs → FFs (first moments of GPDs)

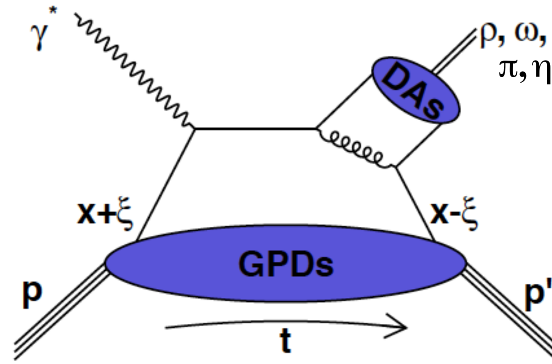
$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t) \quad \int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t)$$
$$\int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t) \quad \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

Four chiral-even GPDs:

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

Deep-exclusive reactions and GPD





DVCS

	$\mathcal{I}m$	$\mathcal{R}e$
$\mathcal{H}$	A_{LU}	σ
$\tilde{\mathcal{H}}$	A_{UL}	A_{LL}, A_{LT}
$\mathcal{E}$	A_{UT}	

DVMP

	Meson	Flavor
$\mathcal{H}_T, \mathcal{E}_T$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	g

A global analysis is needed to fully disentangle GPDs

Disentangling GPDs – model simulations

Global fit to the DVCS data, using models of GPDs - M. Guidal, Eur.Phys.J. **A37**, p319 (2008)

8 independent quantities to be fit -

$$\mathrm{Im}(\mathbf{H});\ \mathrm{Im}(\mathcal{E});\ \mathrm{Im}(\tilde{\mathbf{H}});\ \mathrm{Im}(\tilde{\mathcal{E}})$$

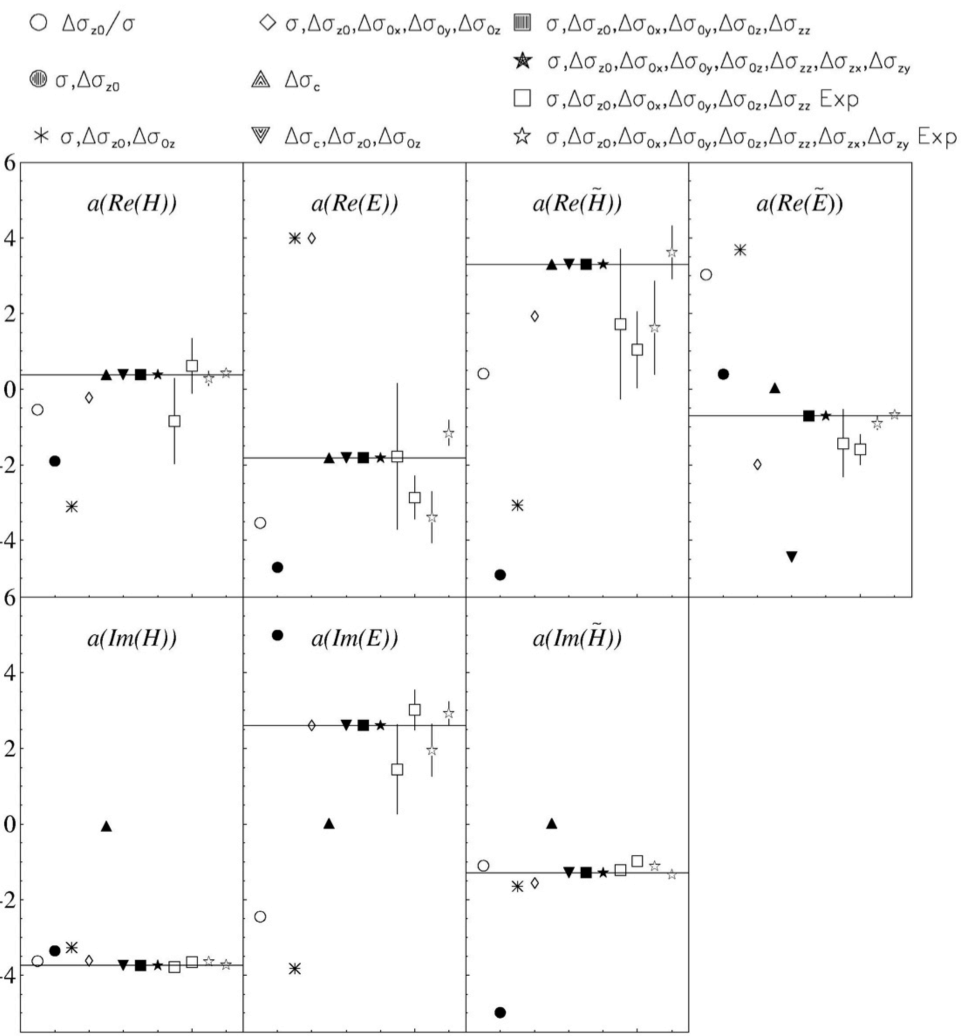
$$\mathrm{Re}(\mathbf{H});\ \mathrm{Re}(\mathcal{E});\ \mathrm{Re}(\tilde{\mathbf{H}});\ \mathrm{Re}(\tilde{\mathcal{E}})$$

Using 9 independent observables -

$$\sigma;\ \Delta\sigma_{z0};\ \Delta\sigma_{0x};\ \Delta\sigma_{0y};\ \Delta\sigma_{0z};$$

$$\Delta\sigma_{zx};\ \Delta\sigma_{zy};\ \Delta\sigma_{zz};\ \Delta\sigma_{c};$$

Assumption - $\mathrm{Im}(\tilde{\mathcal{E}}) = 0$



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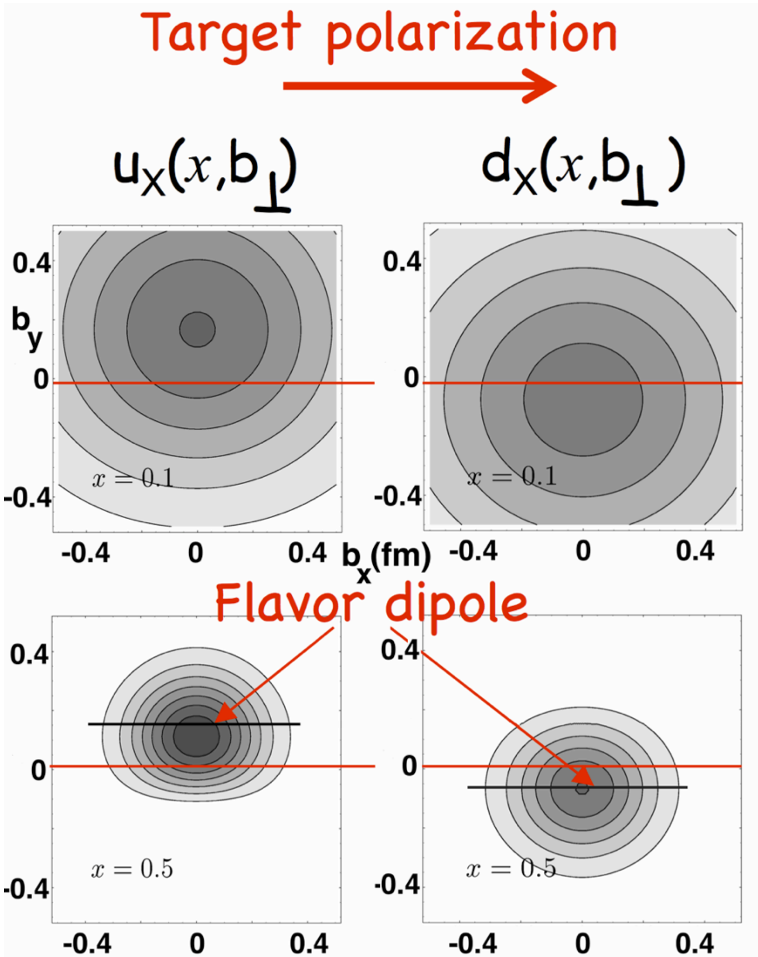
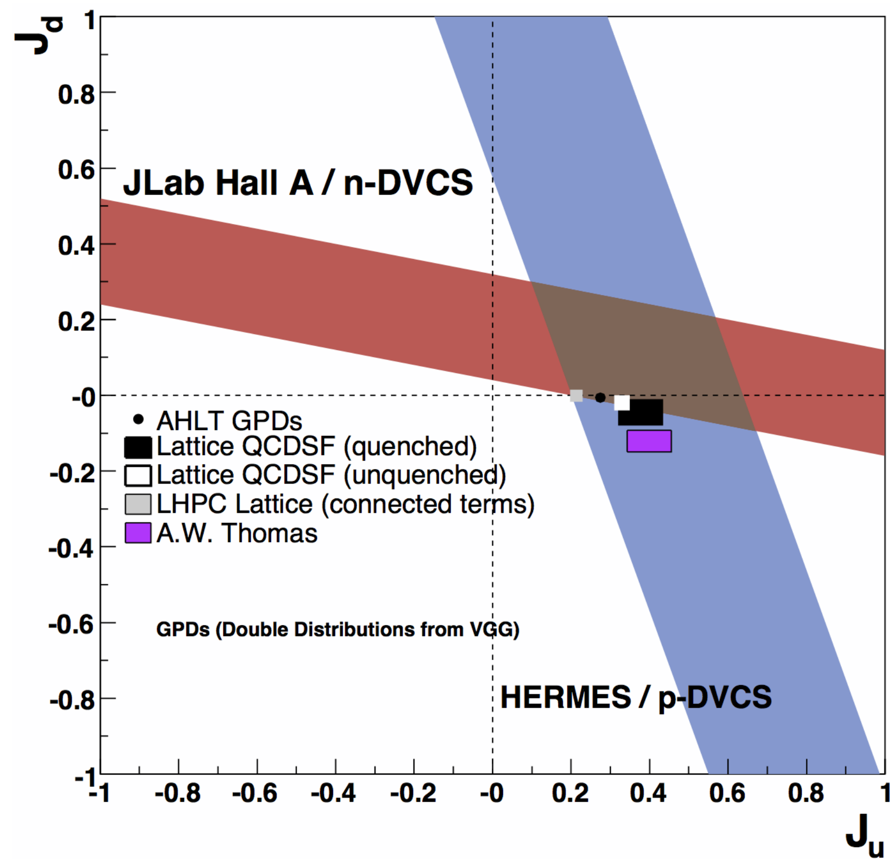
Angular momentum and Transverse Imaging



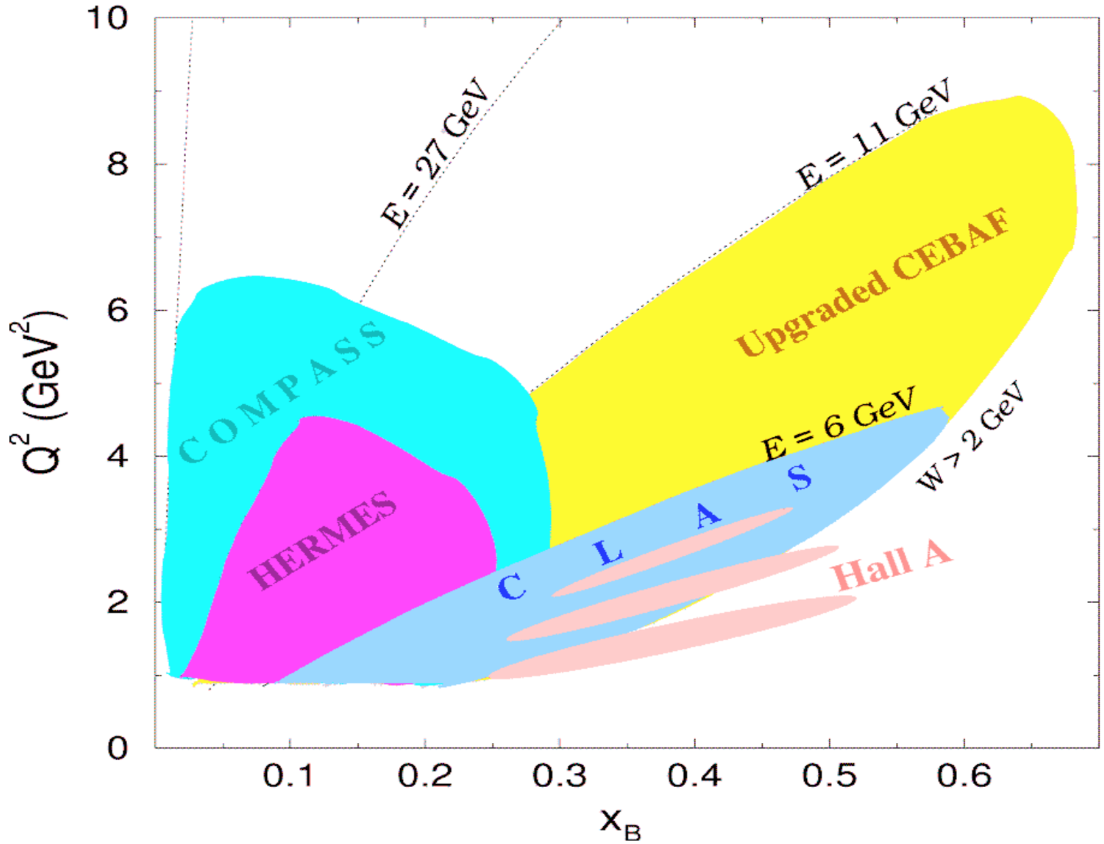
$$J_q = \frac{1}{2}\Delta\Sigma + L_q = \lim_{t\to 0}\int_{-1}^{+1} dx\, x\left[H^q(x,\xi,t) + E^q(x,\xi,t)\right]$$



M. Burkardt, Int.J.Mod.Phys.A18:173-208,2003

M. Mazouz et al., Phys.Rev.Lett.99:242501,2007

JLAB kinematic and experimental reach



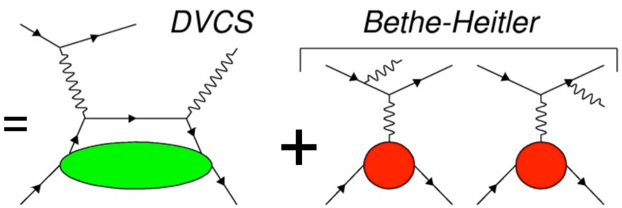
Target Polarization

Beam Polarization

	U	L	T
U			
L			

Reaction	γ	$\pi^+/\pi^-/\pi^0$	η	ρ/ω/ϕ
Deeply exclusive (GPDs)				

Accessing GPDs experimentally - DVCS

ep→epγ = 

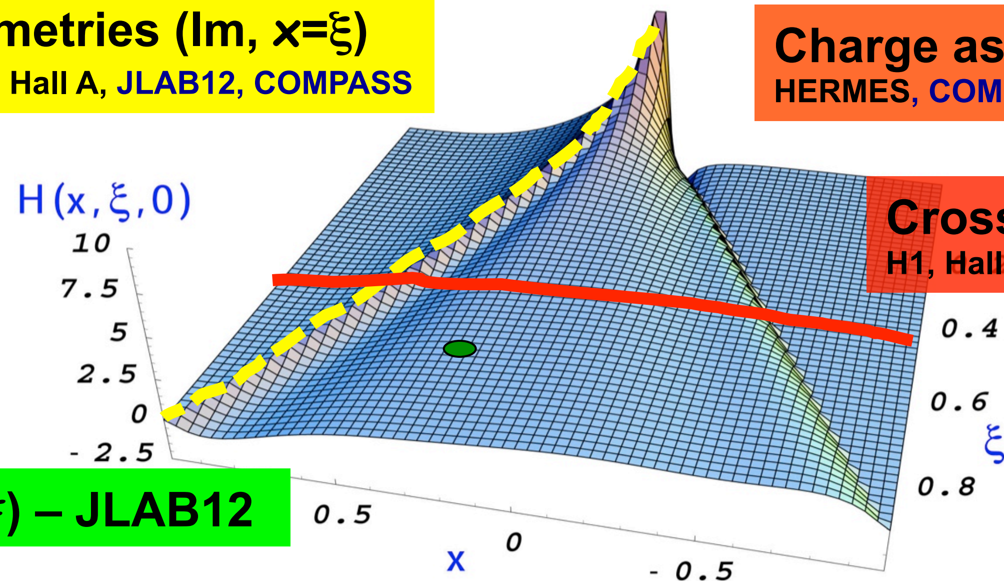
$$\mathcal{T}^2 = \left|\mathcal{T}_{BH}\right|^2 + \left|\mathcal{T}_{DVCS}\right|^2 + \mathcal{T}^*_{DVCS}\mathcal{T}_{BH} + \mathcal{T}^*_{BH}\mathcal{T}_{DVCS}$$

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

Spin asymmetries (Im, x=ξ)
HERMES, CLAS, Hall A, JLAB12, COMPASS

Charge asymmetry (|Re|)
HERMES, COMPASS

Cross sections (|Re|²)
H1, Hall A, JLAB12, COMPASS



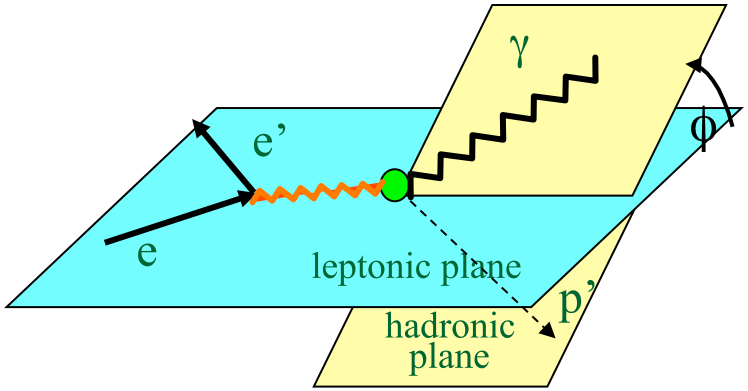
DDVCS ($x \neq \xi$) – JLAB12

GPDs and DVCS spin observables

Polarized beam, unpolarized proton target:

$$\Delta\sigma_{LU} \propto \sin\phi \bullet \mathrm{Im}\{F_1^p H_p + \xi(F_1^p + F_2^p)\tilde{H}_p + kF_2^p E_p\}d\phi$$

Kinematically suppressed



Unpolarized beam, longitudinal proton target:

$$\Delta\sigma_{UL} \propto \sin\phi \bullet \mathrm{Im}\{F_1^p \tilde{H}_p + \xi(F_1^p + F_2^p)(H_p + ...)\}d\phi$$

Unpolarized beam, transverse proton target:

$$\Delta\sigma_{UT} \propto \sin\phi \bullet \mathrm{Im}\{k(F_1^p H_p - F_1^p E_p) + ...\}d\phi$$

Polarized beam, unpolarized neutron target:

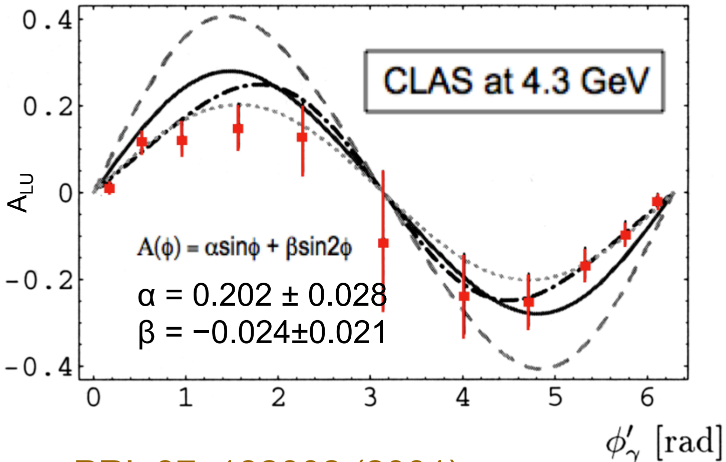
$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

$$\Delta\sigma_{LU} \propto \sin\phi \bullet \mathrm{Im}\{F_1^n H_n + \xi(F_1^n + F_2^n)\tilde{H}_n + kF_2^n E_n\}d\phi$$

$$H_p(\xi, \xi, t) = 4/9\, H_u(\xi, \xi, t) + 1/9\, H_d(\xi, \xi, t)$$
$$H_n(\xi, \xi, t) = 1/9\, H_u(\xi, \xi, t) + 4/9\, H_d(\xi, \xi, t)$$

Experiments for all combinations of polarized and unpolarized beam and target have been approved by JLAB PAC

First DVCS measurements

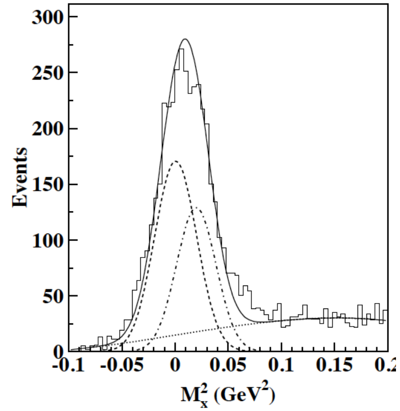


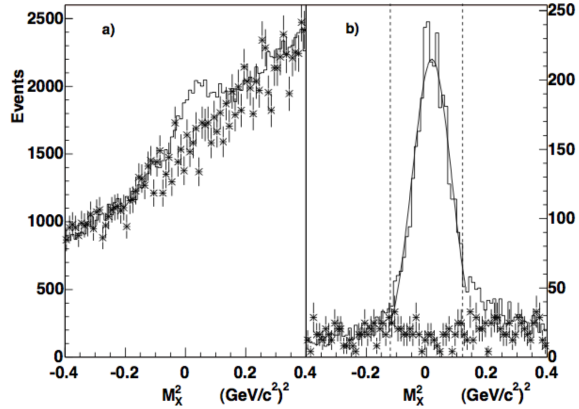
PRL 87, 182002 (2001)

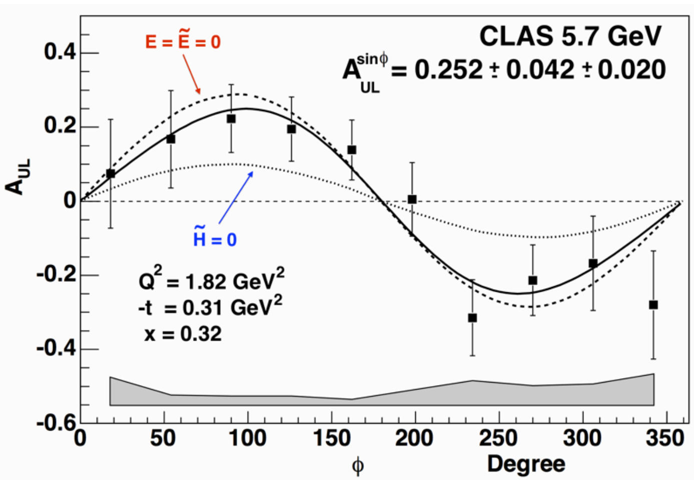
Analysis of existing CLAS data

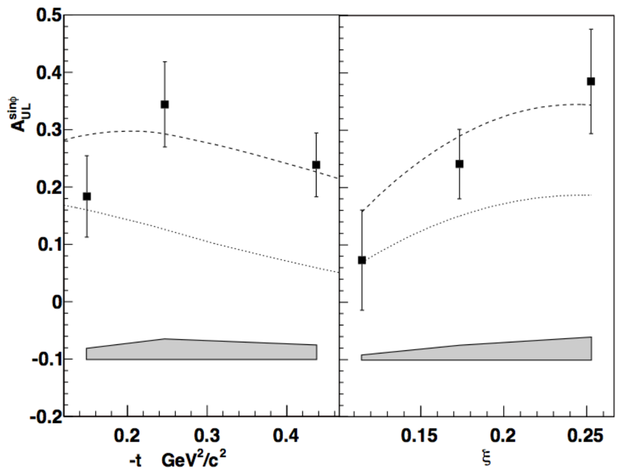
Reaction: $ep \to e'p'X$

Missing momentum analysis $X \approx \gamma$







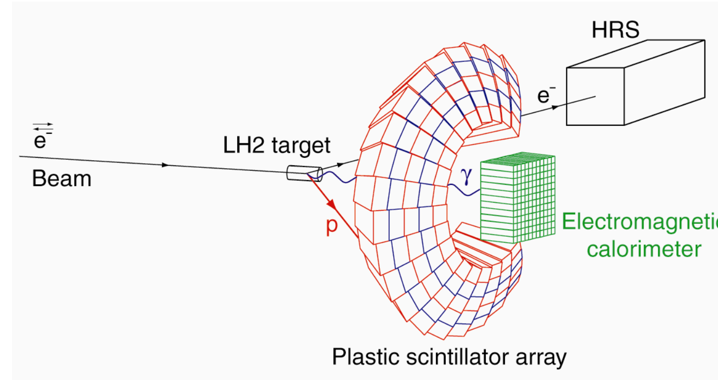


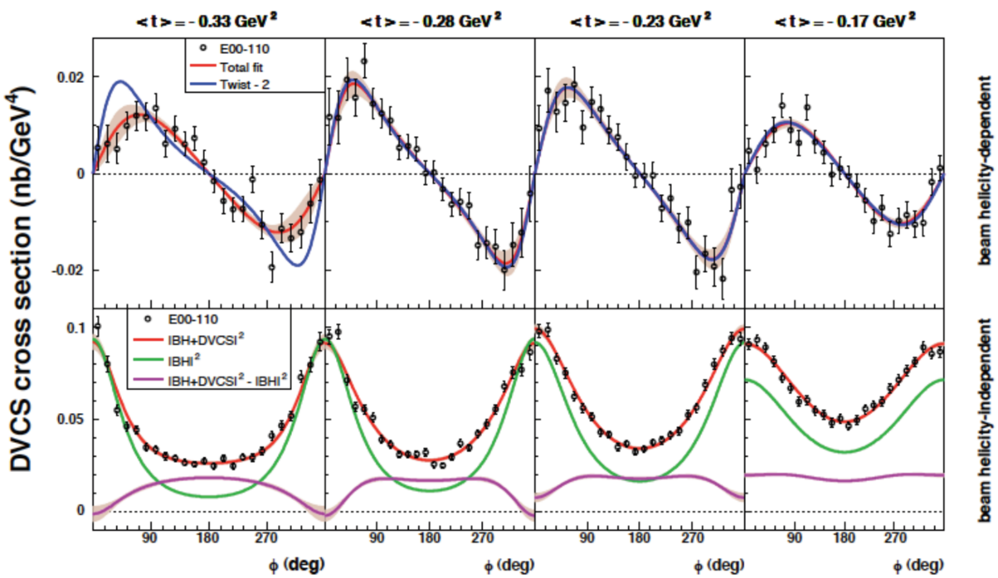
$$A_{UL}(\phi) = \frac{N^{\Uparrow}(\phi) - N^{\Downarrow}(\phi)}{f(P_t^{\Downarrow} N^{\Uparrow}(\phi) + P_t^{\Uparrow} N^{\Downarrow}(\phi))}$$

PRL 97, 072002 (2006)

Hall-A DVCS measurements

- Helicity-dependent cross section ($\vec{\sigma} - \overleftarrow{\sigma}$) at Q^2 = 1:5,1.9 and 2.3 GeV^2
- Helicity-independent cross section ($\vec{\sigma} + \overleftarrow{\sigma}$) at Q^2=2.3 GeV^2
- Twist-2 dominance is observed

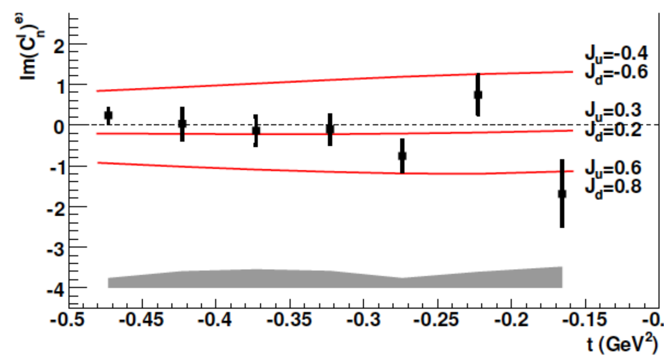




Phys. Rev. Lett. 97, 262002 (2006)

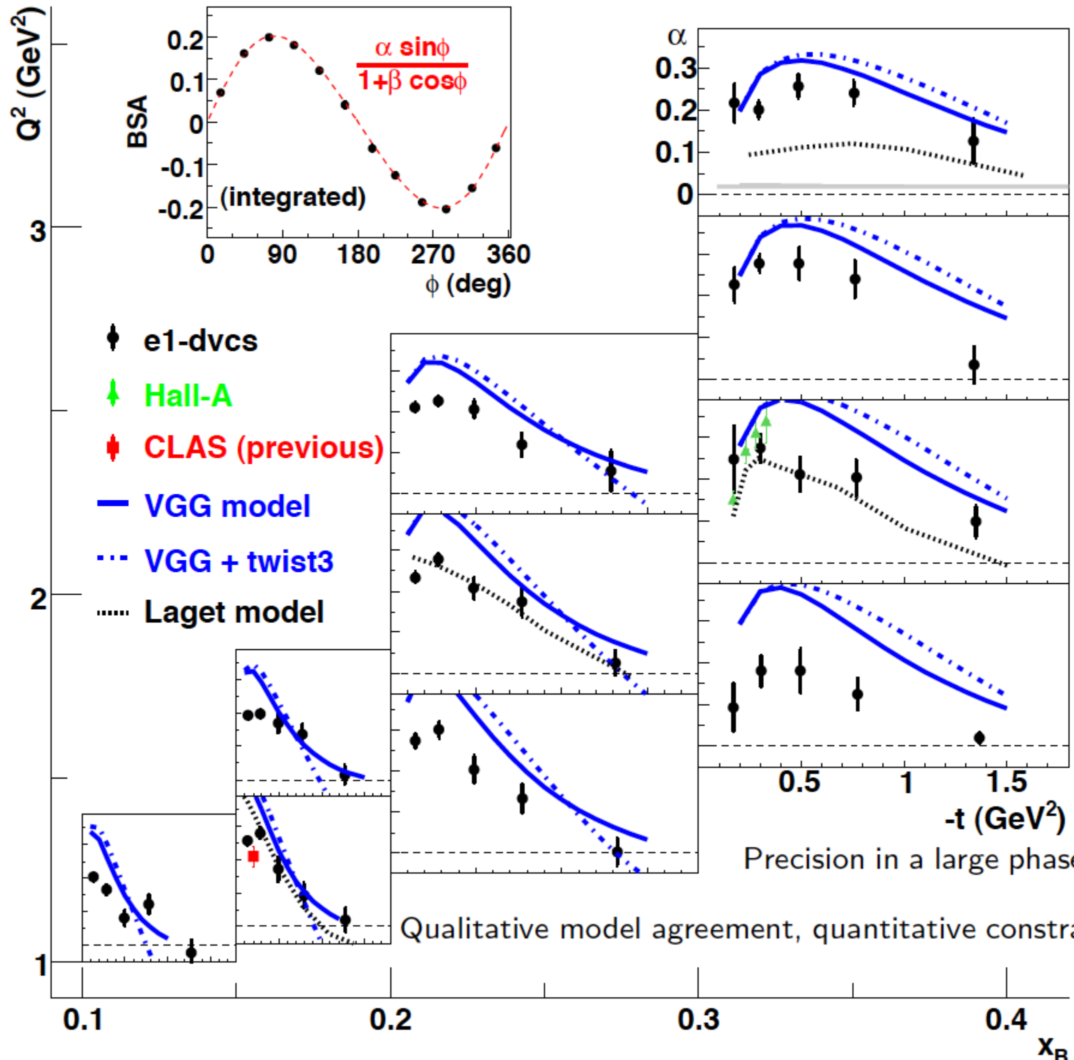
With an additional charged particle veto in front of the proton detector DVCS on neutron has been measured, where the main contribution is from GPD $\mathcal{E}$

$$\text{LD}_2 \text{ target } (F_2^n(t) \gg F_1^n(t)\ !)$$



$$\sigma^{\rightarrow} - \sigma^{\leftarrow} = \Gamma(A \sin\varphi + \ldots)$$

CLAS DVCS beam spin asymmetry



Precision in a large phase-space (x_B, Q^2, t)

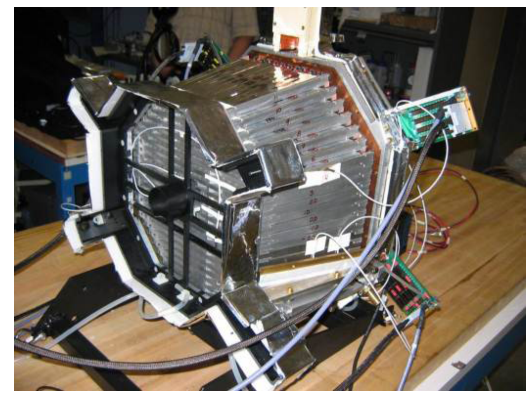
Qualitative model agreement, quantitative constraints on parameters

F.-X. G. *et al.*, PRL **100** (2008) 162002

The first most extensive set of DVCS data with CLAS

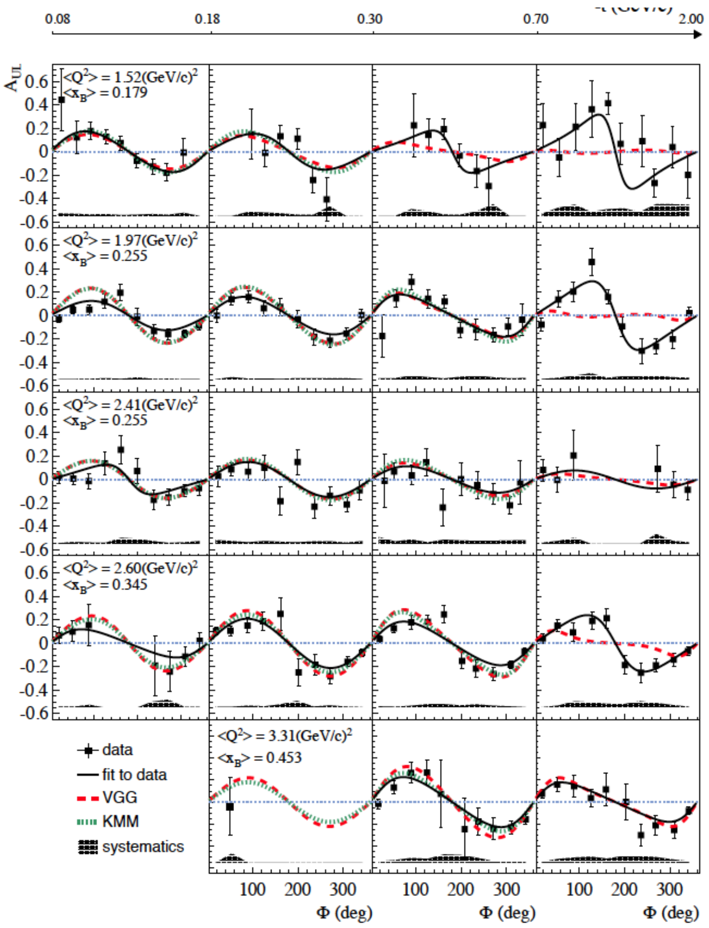
Fully excusive final state

$$ep \rightarrow e'p'\gamma$$

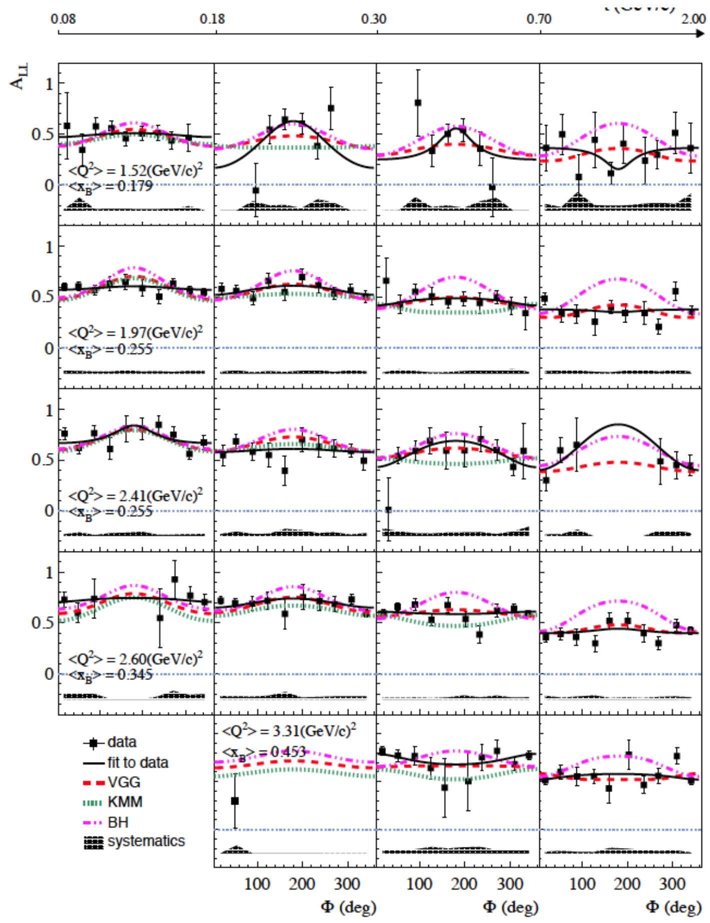


CLAS target and double spin asymmetry

$A_{UL} \propto F_1 \mathcal{I}m \tilde{\mathcal{H}}$



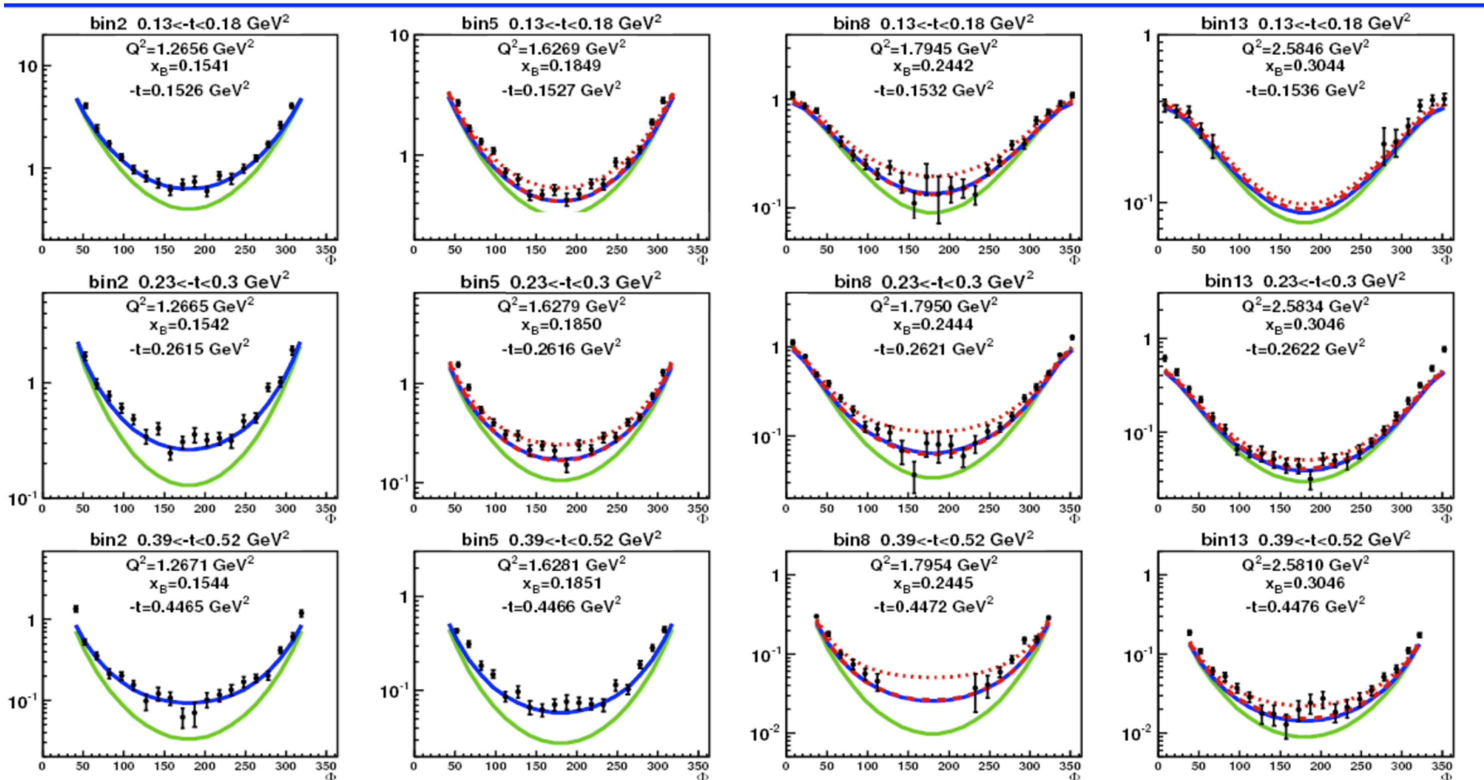
$A_{LL} \propto F_1 \mathcal{R}e \tilde{\mathcal{H}}$



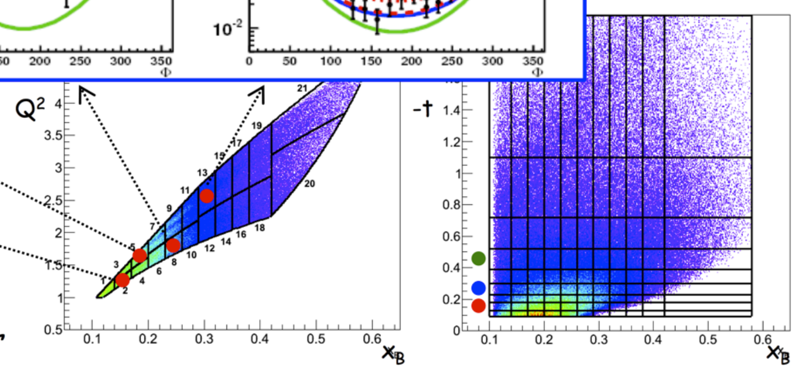
E. Seder et al., Phys. Rev. Lett. 114, 032001 (2015)

S. Pisano et al., Phys. Rev. D 91, 052014

CLAS DVCS cross sections



- • $\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}$ (nb/GeV^4)
- BH
- VGG (H only)
- KM10
- KM10a



VGG : Vanderhaeghen, Guichon, Guidal *KM : Kumericki, Mueller*

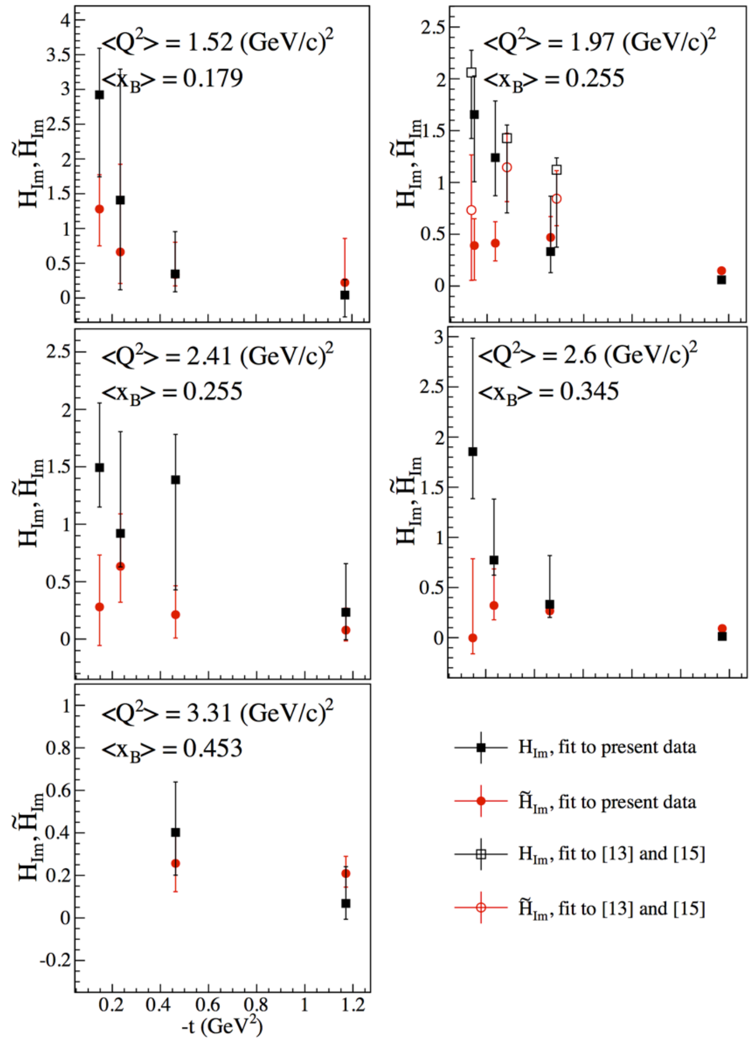
Extracting Compton form-factors

- The three sets of asymmetries (BSA, TSA and DSA) for all kinematic bins were processed using the local fitting procedure to extract the Compton FF
- In the fit $\tilde{E}_{\mathrm{Im}}$ is set to zero, as $\tilde{E}$ is assumed to be purely real
- Thus seven out of the eight real and imaginary parts of the CFFs are left as free parameters in the fit

$$F_{\mathrm{Re}}(\xi,t) = \Re\mathrm{e}\mathcal{F}(\xi,t)$$

$$F_{\mathrm{Im}}(\xi,t) = -\frac{1}{\pi}\Im\mathrm{m}\mathcal{F}(\xi,t) = [F(\xi,\xi,t) \mp F(-\xi,\xi,t)]$$

- Two out of seven have been reasonably constrained by the fit

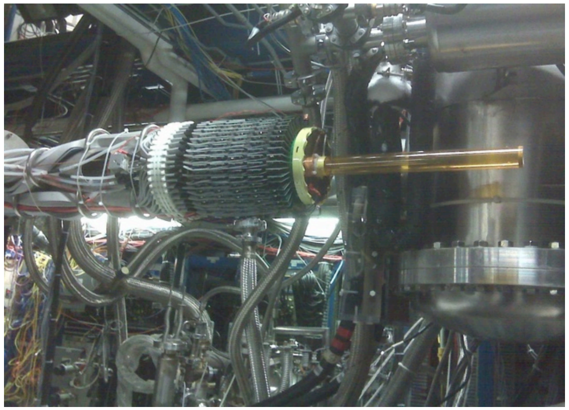


S. Pisano et al., Phys. Rev. D 91, 052014

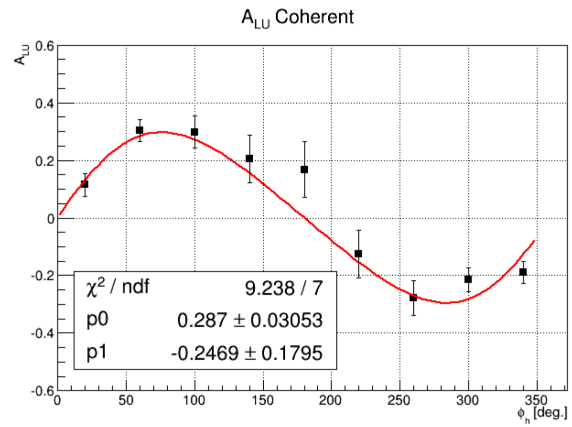
Nuclear GPDs – ^{4}He (CLAS)

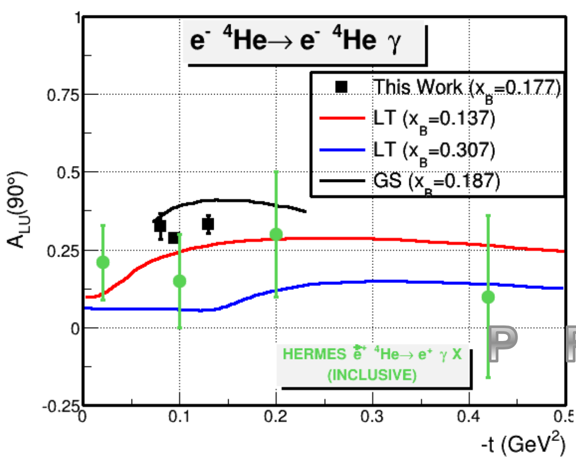
SPIN ZERO target → ONE GPD IS NEEDED $H_A(x,\xi,t)$

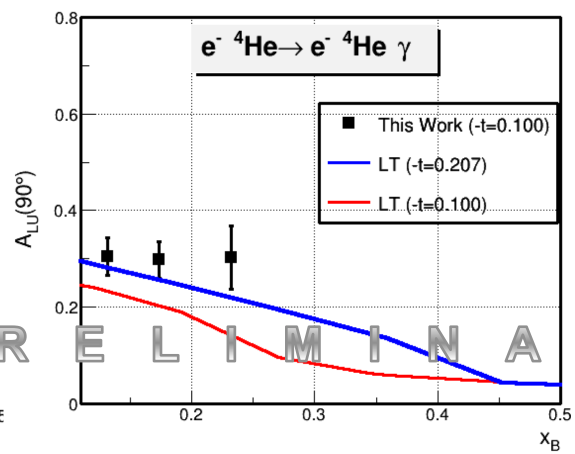
$$A_{LU} = \frac{\alpha_0(\phi) * \mathcal{H}_{Im}}{\alpha_1(\phi) + \alpha_2(\phi)\mathcal{H}_{Re} + \alpha_3(\phi)(\mathcal{H}_{Im}^2 + \mathcal{H}_{Re}^2)}$$

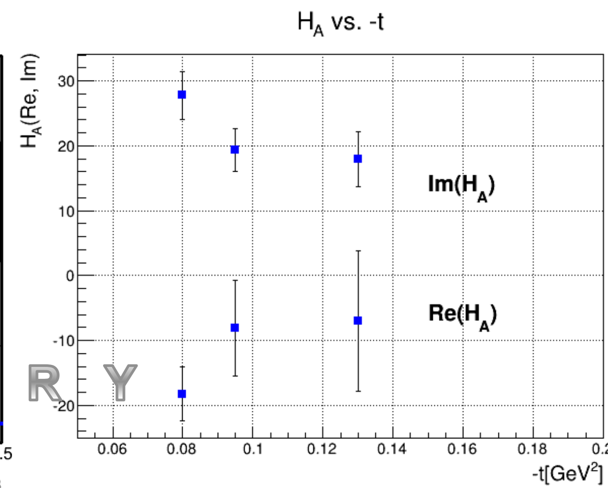


GEM based low energy recoil detector
Gaseous target at 6 atm, cell 6 mm ID, 27 μm wall thickness



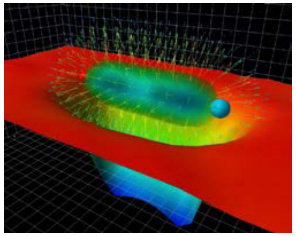


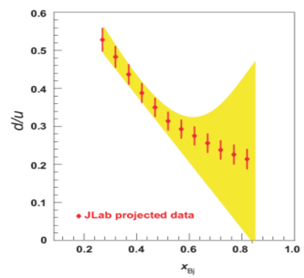


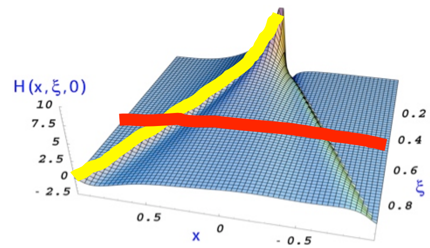


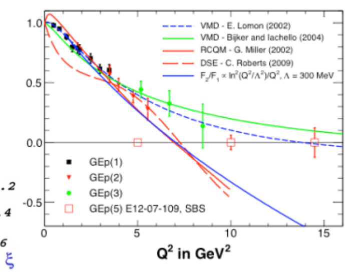
The JLab 12 GeV Upgrade - Major Programs in Six Areas

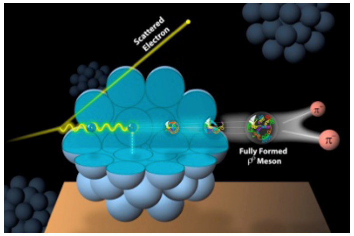
- The Hadron spectra as probes of QCD (GluEx and CLAS12, heavy baryon and meson spectroscopy)
- The transverse structure of hadrons (Elastic and transition Form Factors)
- The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)
- **The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)**
- Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, few-body experiments)
- Low-energy tests of the Standard Model and Fundamental Symmetries (Møller, PVDIS, PRIMEX, Heavy Photons)

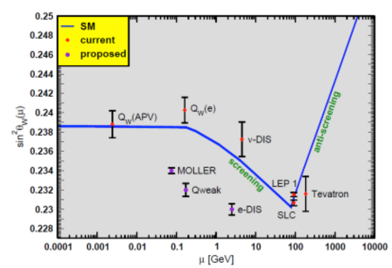












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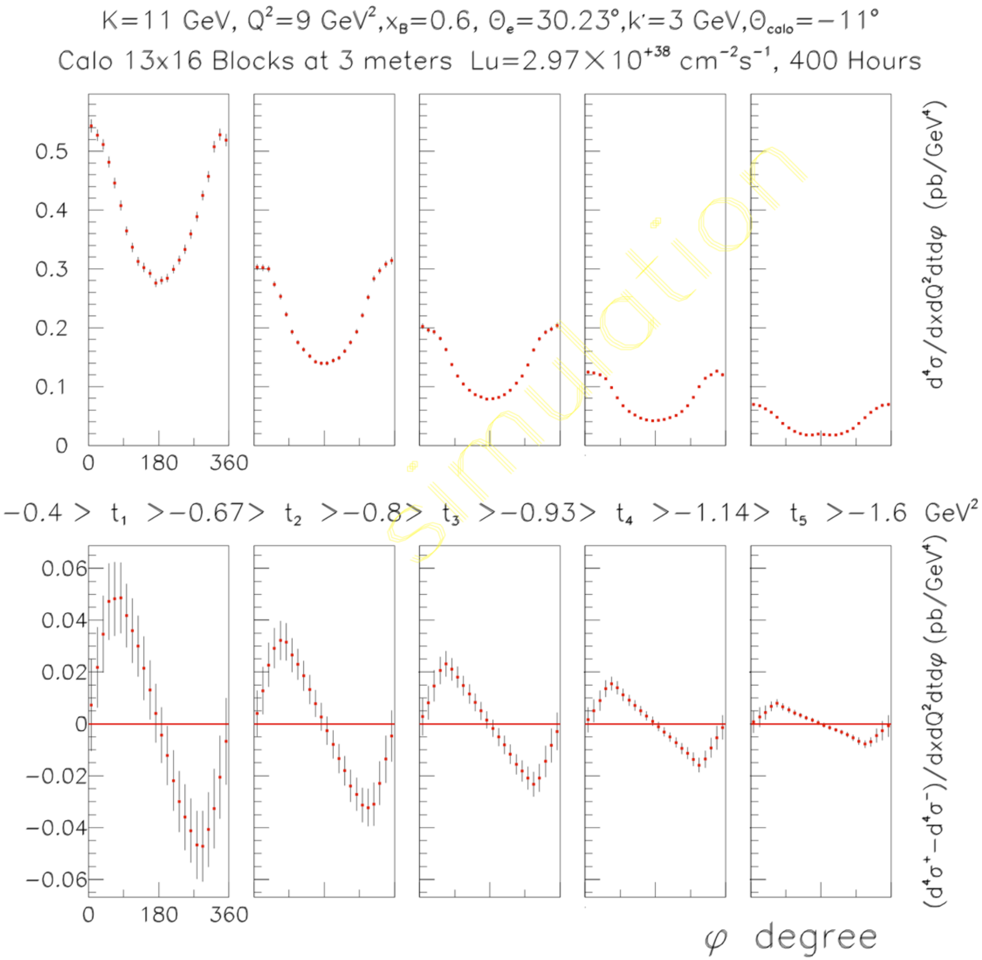
Hall-A DVCS



- Q^2 up to 9 GeV2, only highest Q^2 shown, long lever arm
- Three Different beam energies for Rosenbluth separation of I and $DVCS^2$
- High-precision scaling test on both Re and Im
- Combined with measurements in Hall-C at higher Q^2 and lower x_B will cover significant parameter space

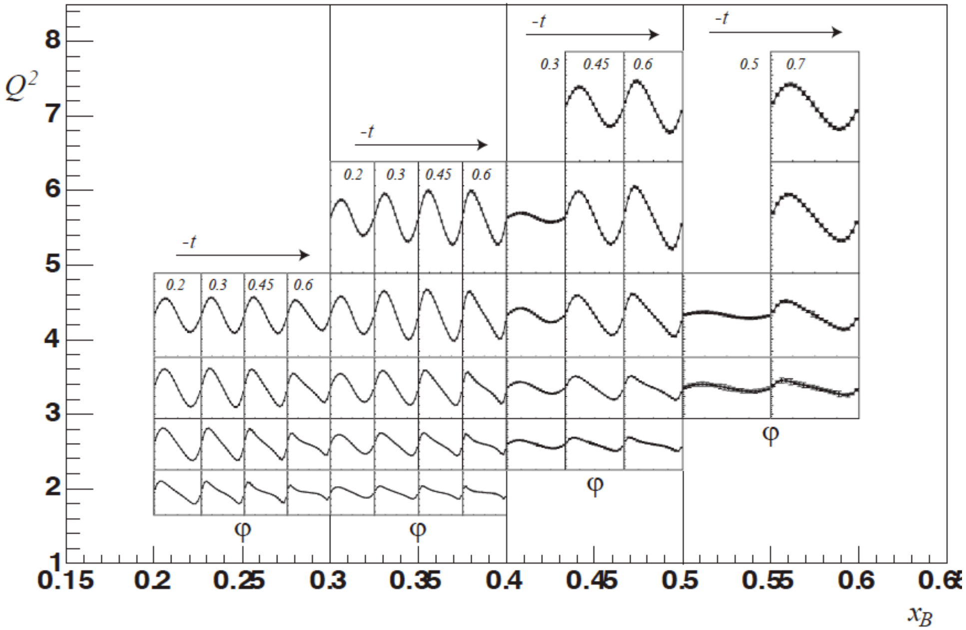
CLAS12 DVCS - longitudinally polarized beam

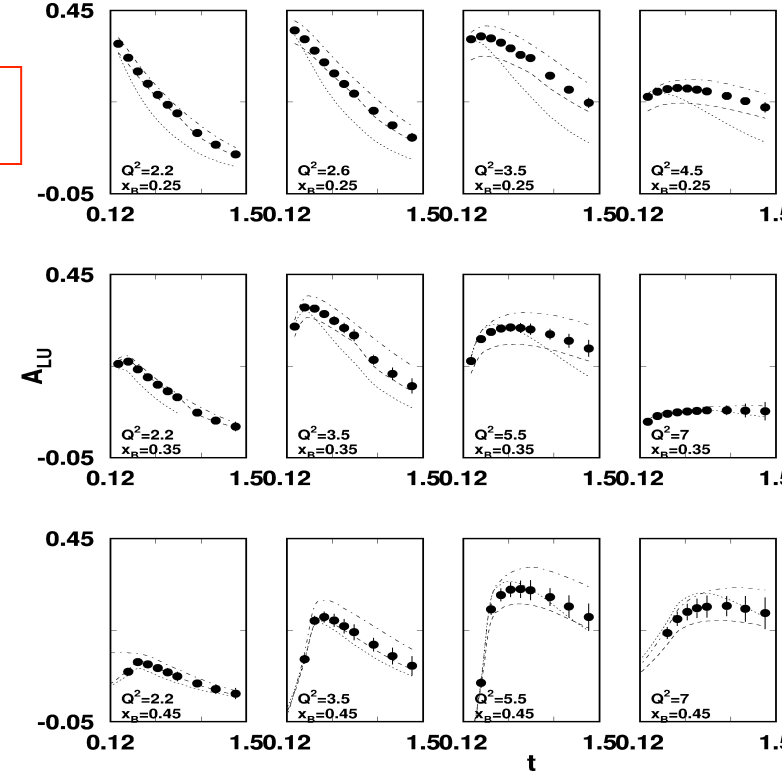
$$\vec{e}\,p \rightarrow ep\gamma$$

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{\Delta\sigma}{2\sigma}$$

Extract $H(\xi,t)$

$\Delta\sigma_{LU} \sim \sin\phi\{F_1 H + ..\}d\phi$





Large coverage in x_B, Q^2, and t with high statistical precision

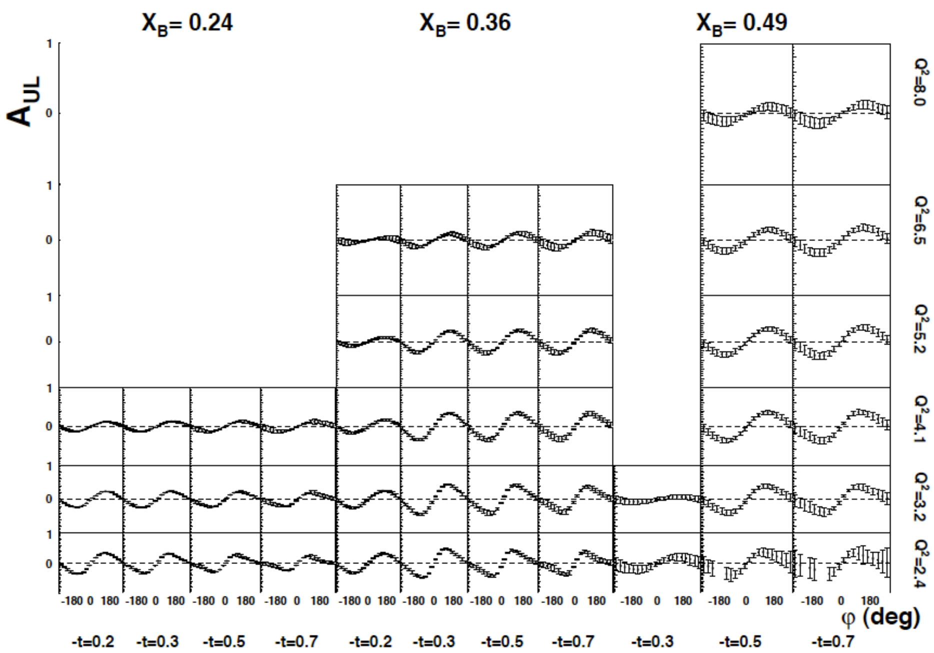
CLAS12 DVCS with polarized targets

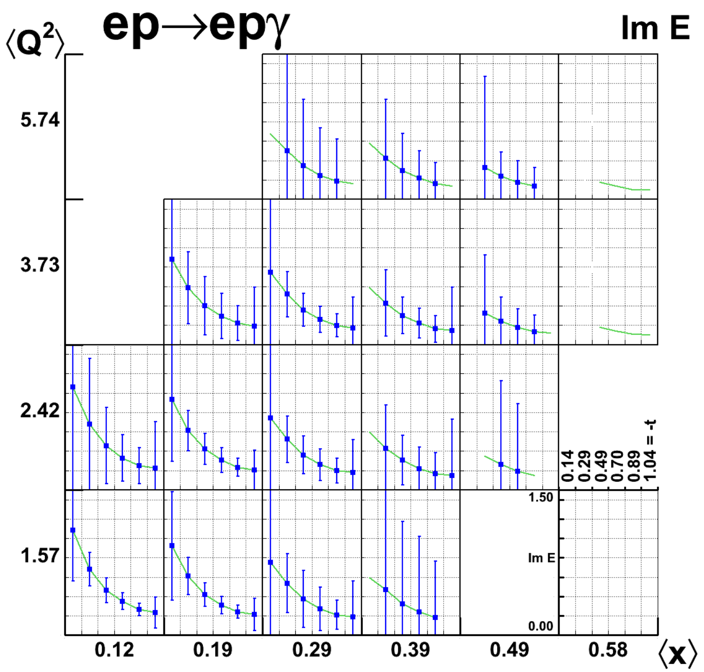
$$A_{UL} = \frac{\sigma^{\Rightarrow} - \sigma^{\Leftarrow}}{\sigma^{\Rightarrow} + \sigma^{\Leftarrow}}$$

$$A_{UT} = \frac{\sigma^{\Downarrow} - \sigma^{\Uparrow}}{\sigma^{\Downarrow} + \sigma^{\Uparrow}}$$

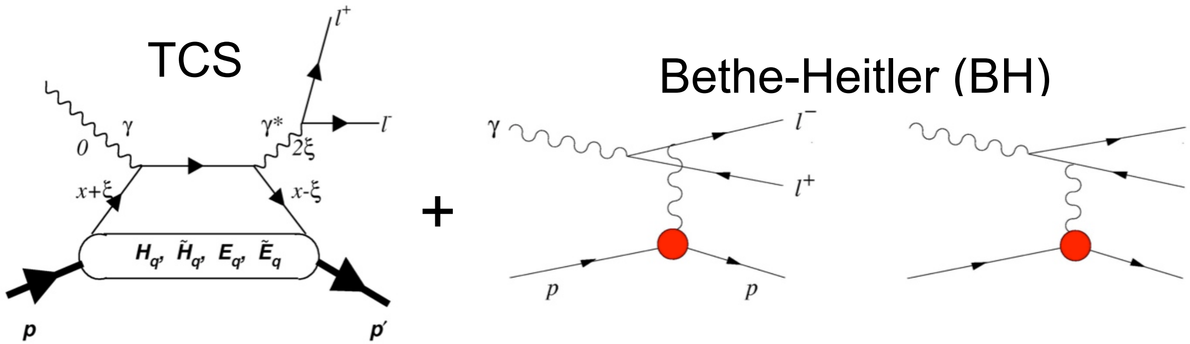
$\Delta\sigma_{UL} \sim \sin\phi \, \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + \ldots\}d\phi$

$\Delta\sigma_{UT} \sim \sin\phi \, \mathrm{Im}\{k(F_2H - F_1E) + \ldots\}d\phi$





Time-like Compton Scattering (TCS)



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

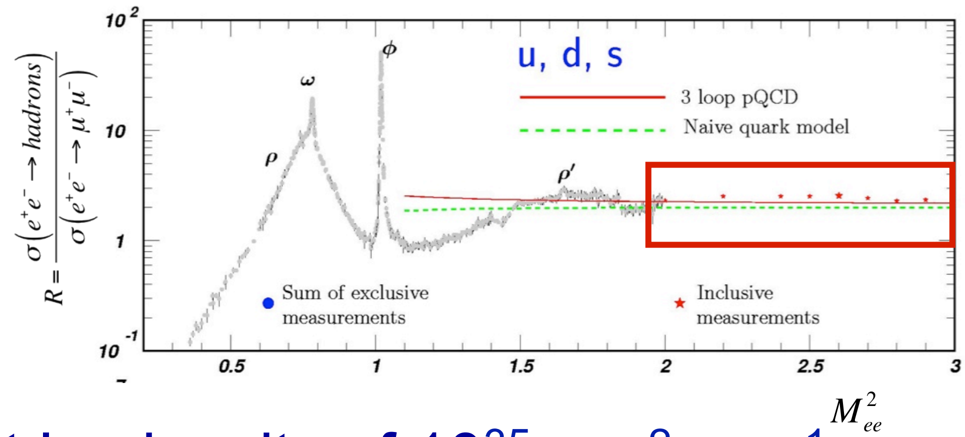
$$\begin{aligned}\frac{d\sigma_{INT}}{dQ'^2\, dt\, d(\cos\theta)\, d\varphi} = & -\frac{\alpha_{em}^3}{4\pi s^2}\frac{1}{-t}\frac{M}{Q'}\frac{1}{\tau\sqrt{1-\tau}}\frac{L_0}{L}\Big[\cos\varphi\,\frac{1+\cos^2\theta}{\sin\theta}\,\mathrm{Re}\tilde{M}^{--} \\ & -\cos 2\varphi\,\sqrt{2}\cos\theta\,\mathrm{Re}\tilde{M}^{0-}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

Universality of GPDs

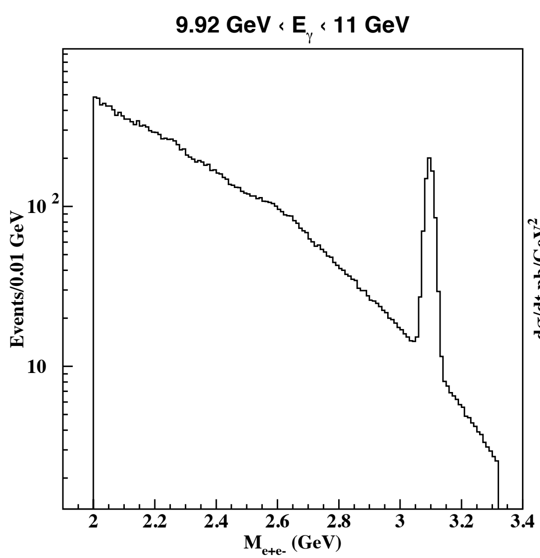
$$\tilde{M}^{--} = \frac{2\sqrt{t_0 - t}}{m}\frac{1-\eta}{1+\eta}\Big[F_1\mathcal{H} - \eta(F_1+F_2)\tilde{\mathcal{H}} - \frac{t}{4m^2}F_2\mathcal{E}\Big]$$

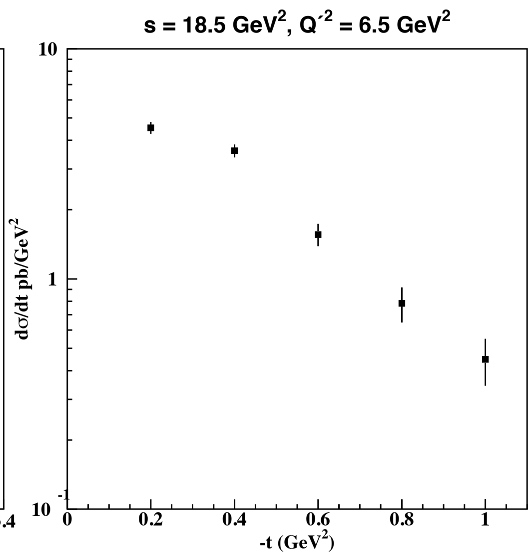
TCS with 11 GeV electron beam

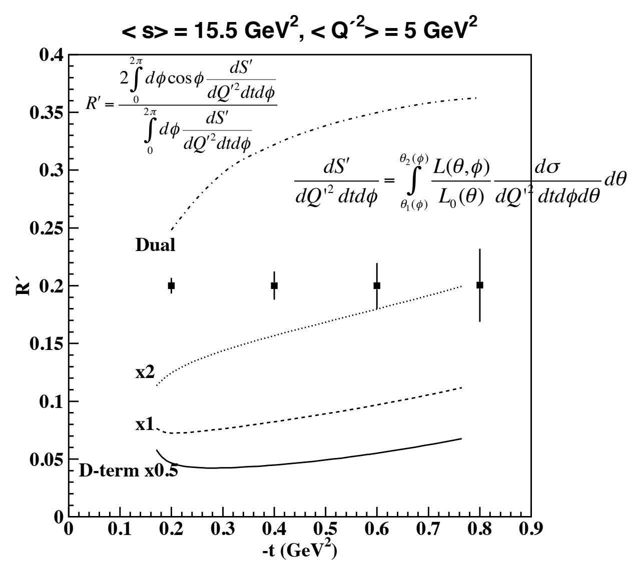
Lepton pair production will be studied in the range of outgoing photon virtualities $M_{ee}^2 \equiv Q'^2$ from 4 GeV^2 to 9 GeV^2 (above the light-quark meson resonances and below charm threshold)



100 days of running at luminosity of 10^{35} cm^{-2} sec^{-1}







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Summary

- DVCS clearly is the best channel to study GPDs
- After the first proof-of-principal BSA and TSA results in DVCS from CLAS data mining efforts, JLAB made significant investment in dedicated experiments where BSA and TSA on proton and neutron targets were explored
- The new set of data initiated new theoretical approaches for extracting GPDs from experimental observables
- The 12 GeV Upgrade will greatly enhance the scientific “reach” of JLAB facility
- Detectors in experimental halls are well suited to carry out vigorous program for studying the nucleon structure in terms of GPDs
- Experimental program includes DVCS measurements with polarized beams and targets on the proton and the neutron, as well as Deeply Virtual Meson Production, and Time-like Compton Scattering – not all approved experiment have been covered in this talk
- Solid and CLAS12 collaborations exploring possibilities of Double DVCS measurements with improved detector in near future