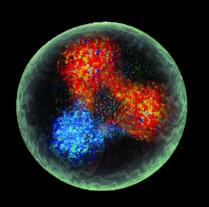
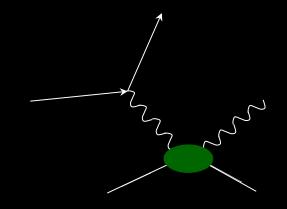




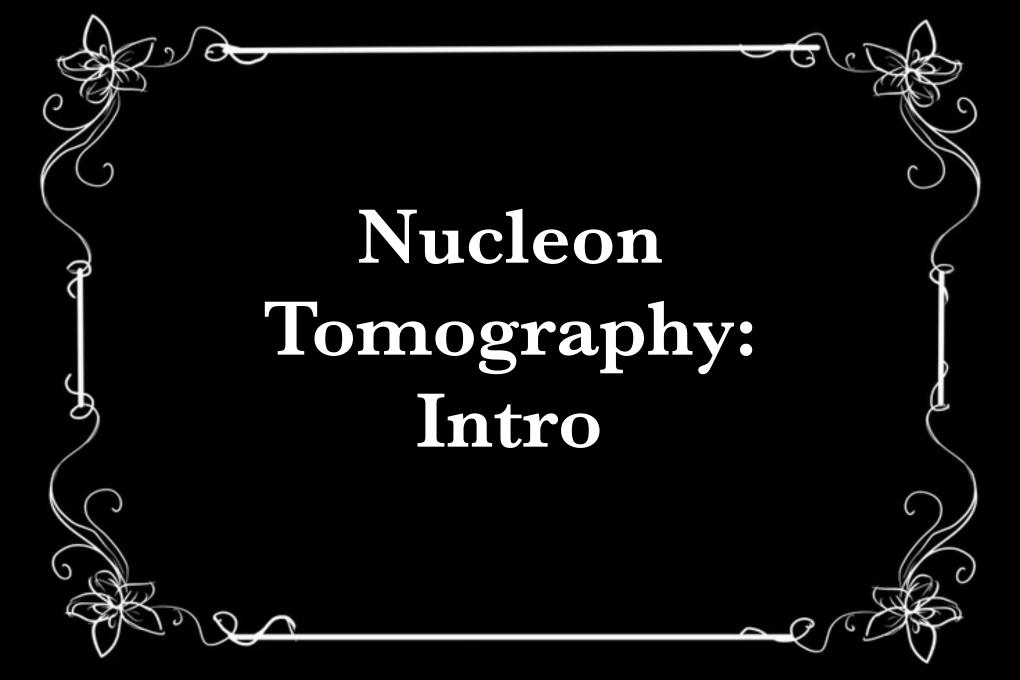
Deeply Virtual Compton Scattering at JLab



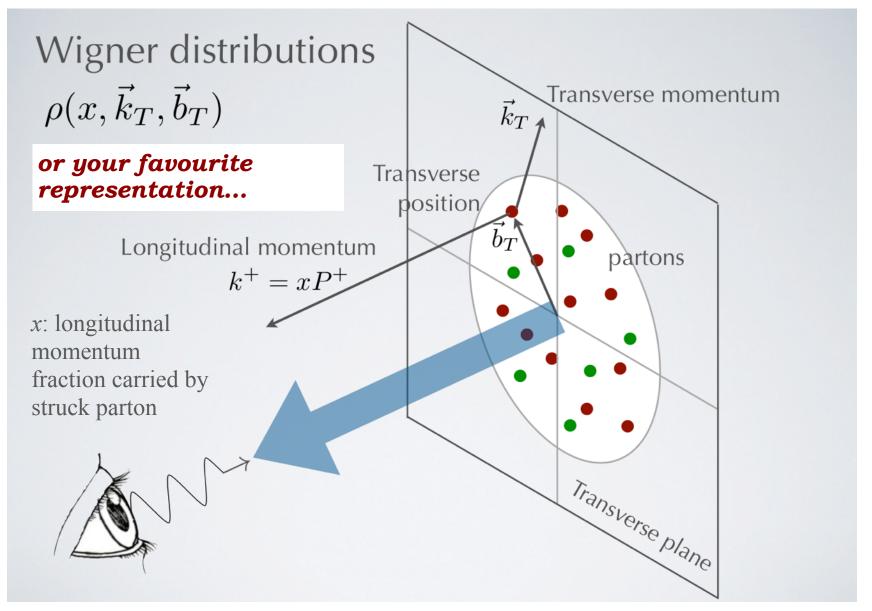
Daria Sokhan
University of Glasgow,
Scotland



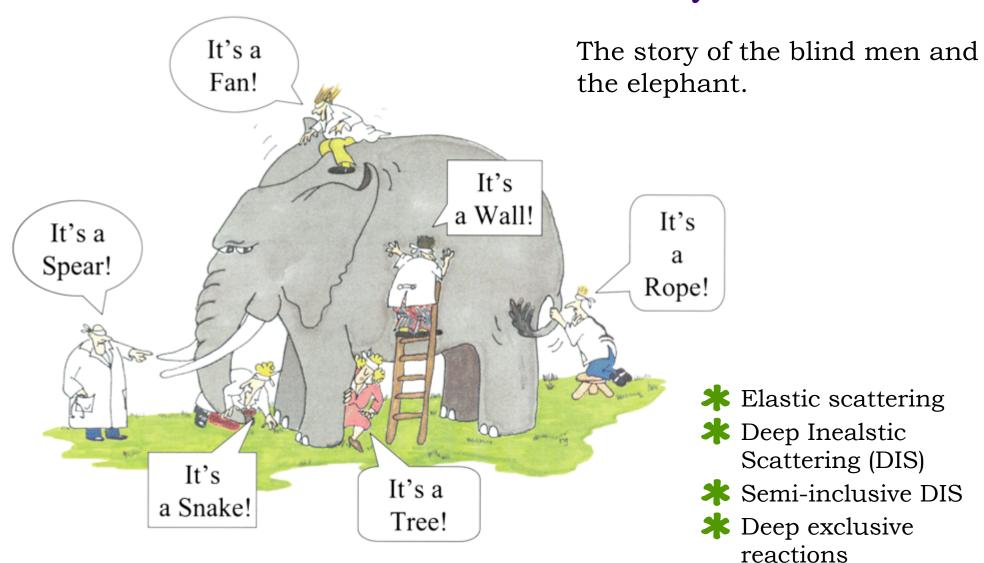
6th International Workshop on Non-perturbative Aspects of Quantum Field Theories Tuxtla Gutierrez, Chiapas, Mexico — 26th April 2017



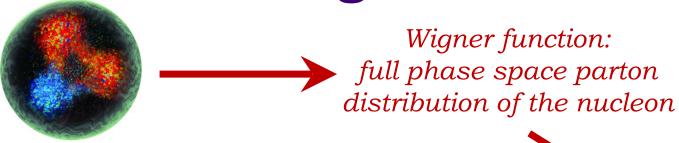
A full knowledge of the nucleon...



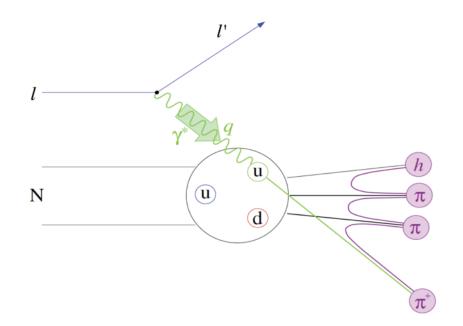
... is hard to come by



G. Renee Guzlas, artist.



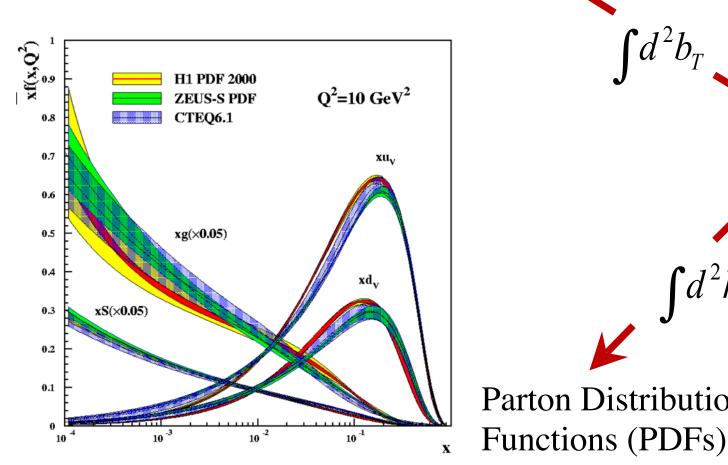
* Semi-inclusive DIS

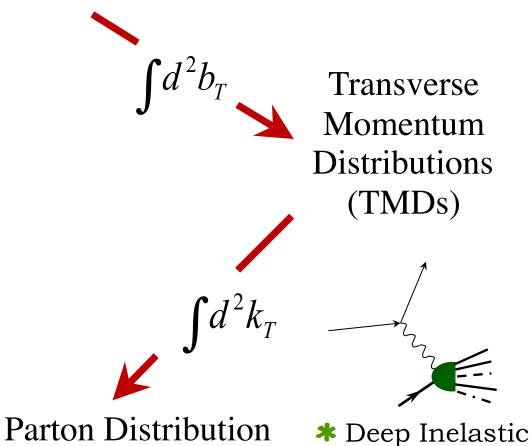


 $\int d^2b_T$ Transverse Momentum Distributions

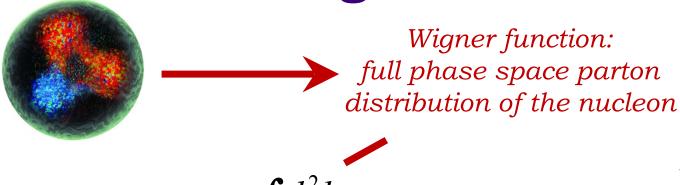
(TMDs)

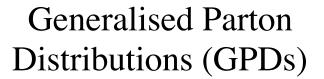




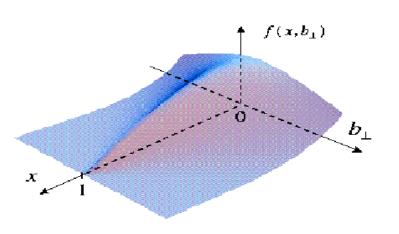


Scattering

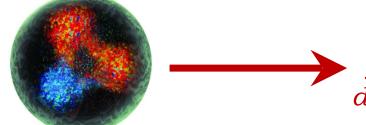




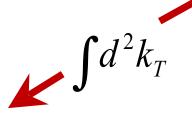
• relate, in the infinite momentum frame, transverse position of partons (b_{\perp}) to longitudinal momentum (x).



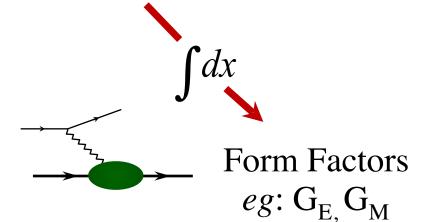
* Deep exclusive reactions, e.g.: Deeply Virtual Compton Scattering, Deeply Virtual Meson production, ...



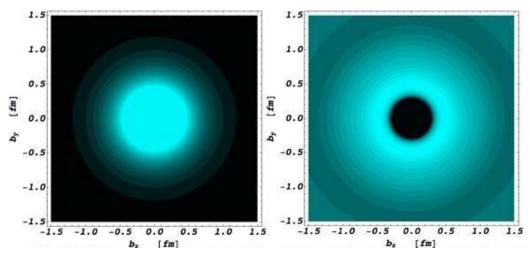
Wigner function: full phase space parton distribution of the nucleon



Generalised Parton Distributions (GPDs)



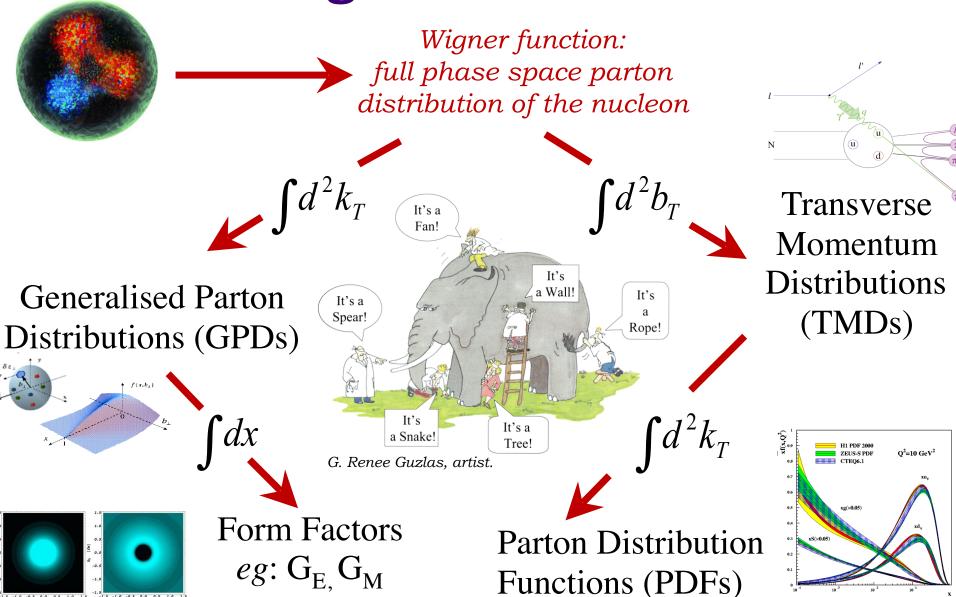
Fourier Transform of electric Form Factor: transverse charge density of a nucleon

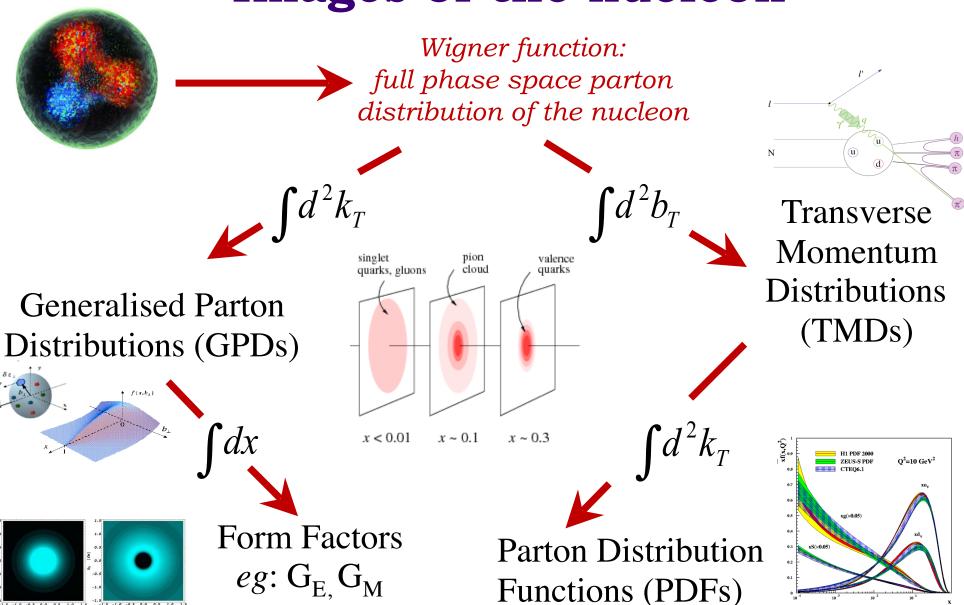


proton

neutron

C. Carlson, M. Vanderhaeghen PRL 100, 032004 (2008)

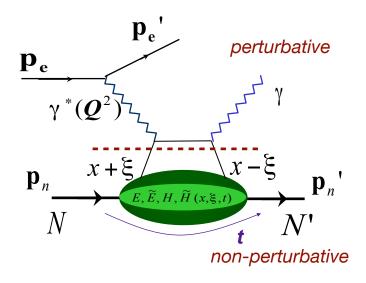






GPDs and DVCS

***Deeply Virtual Compton Scattering:** golden channel for the extraction of GPDs.



$$Q^2 = -(\mathbf{p}_e - \mathbf{p}_e')^2$$
 $t = (\mathbf{p}_n - \mathbf{p}_n')^2$

Bjorken variable:
$$x_B = \frac{Q^2}{2\mathbf{p_n} \cdot \mathbf{q}}$$

$$x \pm \xi$$
 longitudinal momentum fractions of the struck parton

$$\xi \cong \frac{x_B}{2 - x_B}$$

* At high exchanged Q^2 and low t access to four chiral-even GPDs:

$$E^q, \tilde{E}^q, H^q, \tilde{H}^q(x, \xi, t)$$

* Can be related to PDFs:

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

and form factors:

$$\int_{-1}^{+1} H dx = F_1 \qquad \int_{-1}^{+1} \tilde{H} dx = G_A$$
$$\int_{-1}^{+1} E dx = F_2 \qquad \int_{-1}^{+1} \tilde{E} dx = G_P$$

*Small changes in nucleon transverse momentum allows mapping of transverse structure at large distances: **confinement**.

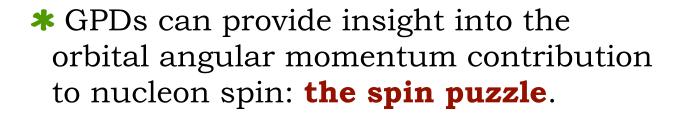
GPDs and nucleon spin

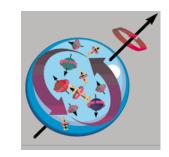
$$J_N = \frac{1}{2} = \frac{1}{2} \Sigma_q + L_q + J_g$$

* Ji's relation:
$$J^q = \frac{1}{2} - J^g = \frac{1}{2} \int_{-1}^1 x dx \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\}$$

H accessible in DVCS off the proton, first experimental constraint on *E*, through neutron-DVCS:

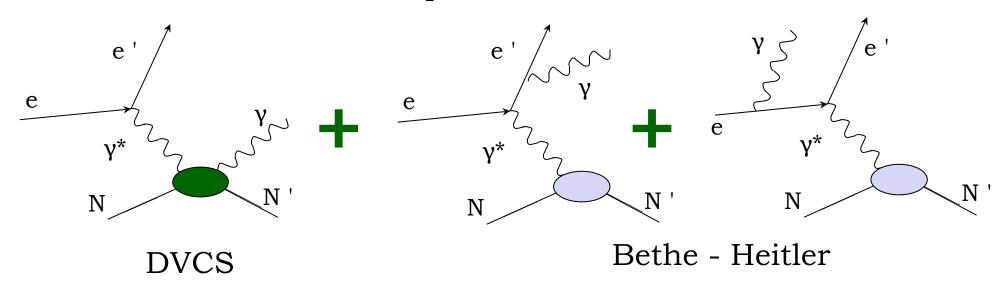
M. Mazouz et al, PRL 99 (2007) 242501





Measuring DVCS

* Process measured in experiment:



$$d\sigma \propto \left|T_{DVCS}\right|^2 + \left|T_{BH}\right|^2 + \left|T_{BH}T^*_{DVCS} + T_{DVCS}T^*_{BH}\right|$$
Amplitude Amplitude calculable Interference term

Amplitude parameterised in terms of Compton Form Factors

Amplitude calculable from elastic Form Factors and QED

 $\left|T_{DVCS}\right|^2 \ll \left|T_{BH}\right|^2$

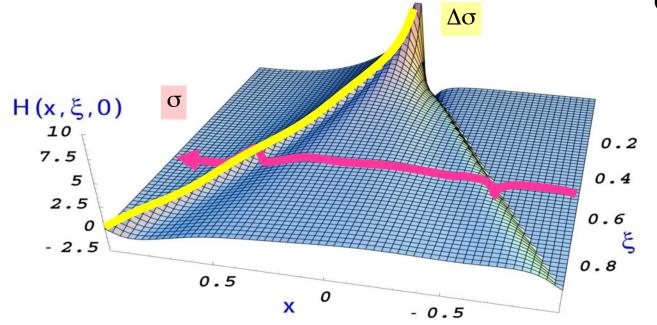
Compton Form Factors in DVCS

Experimentally accessible in DVCS cross-sections and spin asymmetries, eg:

$$A_{LU} = \frac{d\vec{\sigma} - d\vec{\sigma}}{d\vec{\sigma} + d\vec{\sigma}} = \frac{\Delta \sigma_{LU}}{d\vec{\sigma} + d\vec{\sigma}}$$

At leading twist, leading order:

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



Only ξ and t are accessible experimentally!

To get information on x need extensive measurements in Q^2 .

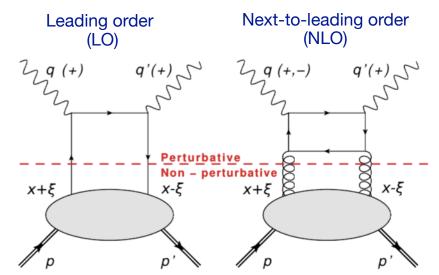
Need measurements off proton and neutron to get flavour separation of CFFs in DVCS.

Twist and orders in GPD extraction

*Twist: powers of $\frac{1}{\sqrt{Q^2}}$ in the DVCS amplitude. Leading-twist is twist-2.

- * Order: introduces powers of α_s
- *Leading-twist considers only transverse photon polarisation (helicity-conserved and helicity-flip CFFs):

$$\mathbb{H}_{++}, \widetilde{\mathbb{H}}_{++}, \mathbb{H}_{-+}, \widetilde{\mathbb{H}}_{-+}$$



*Longitudinal-to-transverse helicity flip of the virtual-to-real photon leads to twist-3, eg:

$$\mathbb{H}_{++},\,\widetilde{\mathbb{H}}_{++},\,\mathbb{H}_{0+},\,\widetilde{\mathbb{H}}_{0+}$$
 helicity of real produced photon helicity of virtual incoming photon

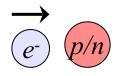
- *Traditionally, use Belinsky definition of light-cone axis, in plane of q and P:
 - A. Belitsky et al, **Nucl. Phys. B878** (2014), 214
- * New, Braun definition using q and q': V. Bruan et al, Phys. Rev. D89 (2014), 074022

Which DVCS experiment?

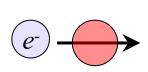
Real parts of CFFs accessible in cross-sections and double polarisation asymmetries,

imaginary parts of CFFs in single-spin asymmetries.

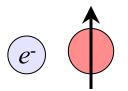
Beam, target polarisation



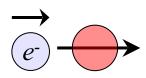
$$\Delta \sigma_{LU} \sim \sin \phi \Im(F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E) d\phi$$



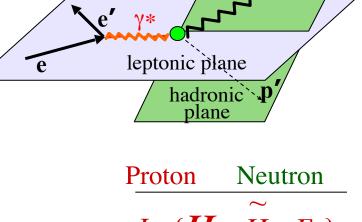
$$\Delta \sigma_{UL} \sim \sin \phi \Im(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E))$$
$$-\xi \frac{t}{4M^2} F_2 \tilde{E} + ...) d\phi$$



$$\Delta \sigma_{UT} \sim \cos \phi \Im(\frac{t}{4M^2} (F_2 H - F_1 E) + ...) d\phi$$



$$\Delta \sigma_{LL} \sim (A + B \cos \phi) \Re(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) + ...) d\phi$$



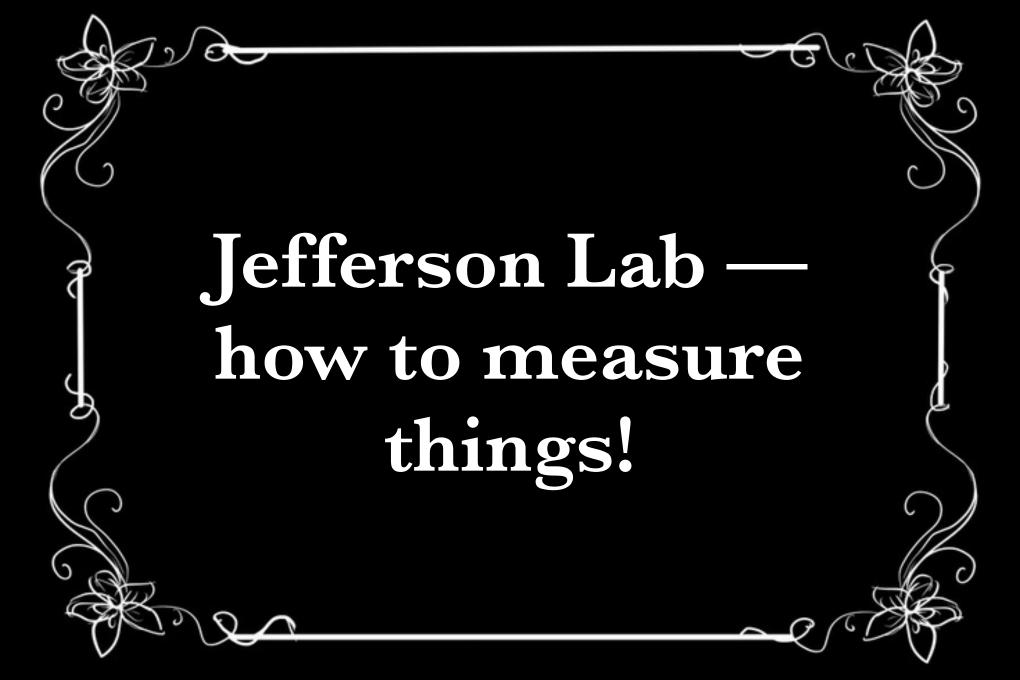
$$Im\{\boldsymbol{H_{p}}, \overset{\sim}{H_{p}}, E_{p}\}$$

$$Im\{H_{n}, H_{n}, \boldsymbol{E_{n}}\}$$

$$Im\{\boldsymbol{H_{p}},\boldsymbol{H_{p}}\}\ [Im\{\boldsymbol{H_{n}},E_{n},\widetilde{E_{n}}\}]$$

$$\frac{\mathit{Im}\{H_{p},E_{p}\}}{\mathit{Im}\{H_{n}\}}$$

$$Re\{H_{\mathbf{p}}, \widetilde{H}_{\mathbf{p}}\}\$$
 $Re\{H_{\mathbf{n}}, E_{\mathbf{n}}, \widetilde{E}_{\mathbf{n}}\}$

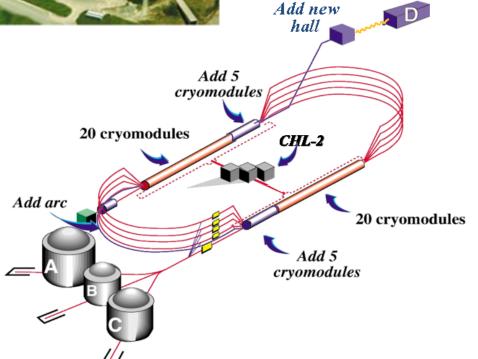




Jefferson Lab

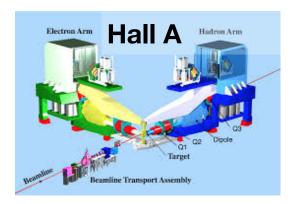
CEBAF: Continuous Electron Beam Accelerator Facility.

- * Energy up to 11 GeV (Halls A, B, C), 12 GeV Hall D
- ***** Energy spread $\delta E/E_e \sim 10^{-4}$
- * Electron polarisation up to ~80%, measured to 3%
- ♣ Beam size at target < 0.4 mm</p>

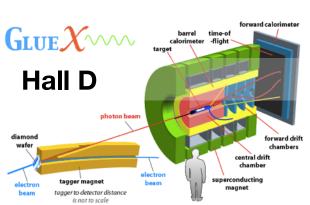




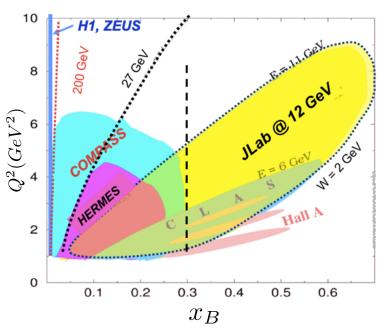
JLab @ 12 GeV



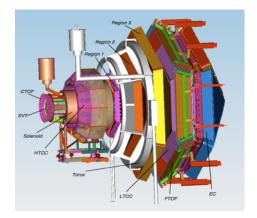
High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity, large installation experiments.



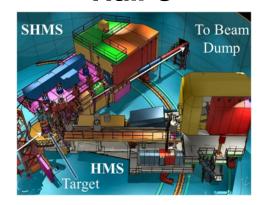
9 GeV tagged polarised photons, full acceptance



Hall B: CLAS12



Hall C



Two movable high momentum spectrometers, well-defined acceptance, very high luminosity.

Very large acceptance, high luminosity.

CLAS12

Design luminosity $L \sim 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

High luminosity & large acceptance:
Concurrent measurement of exclusive, semi-inclusive, and inclusive processes

Acceptance for photons and electrons:

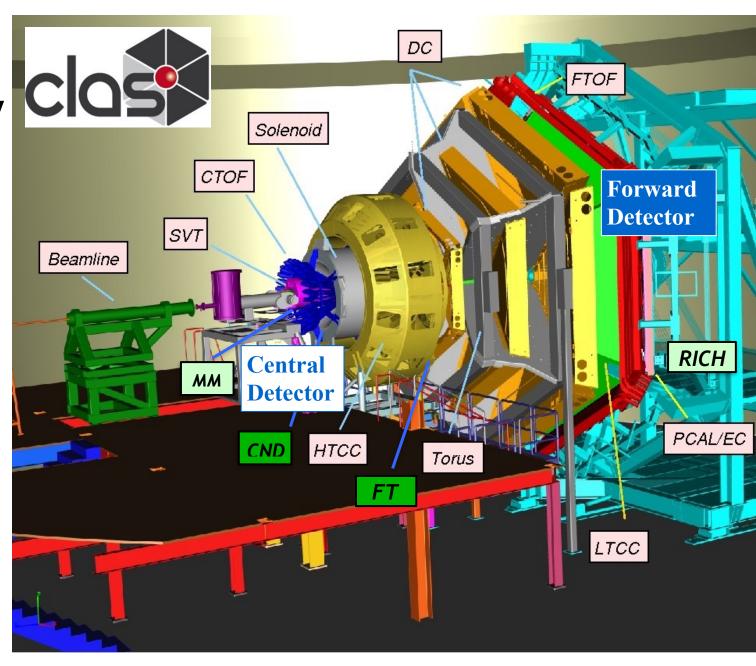
• $2.5^{\circ} < \theta < 125^{\circ}$

Acceptance for all charged particles:

• $5^{\circ} < \theta < 125^{\circ}$

Acceptance for neutrons:

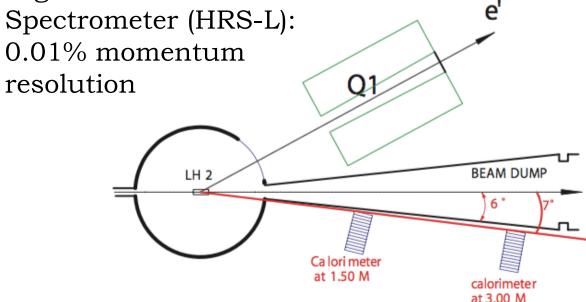
• $5^{\circ} < \theta < 120^{\circ}$



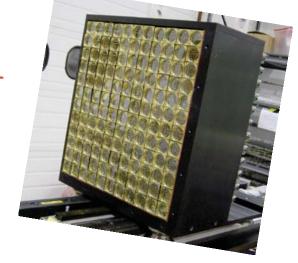
DVCS in Hall A @ 11 GeV

Detect electron in the Left

High Resolution



Detect photon in PbF₂ calorimeter: < 3% energy resolution



Reconstruct recoiling proton through missing mass.

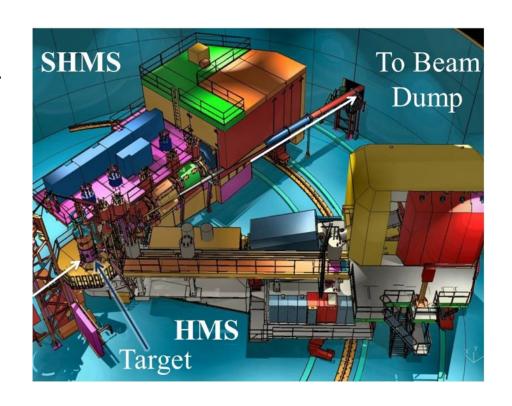
DVCS in Hall C @ 11 GeV

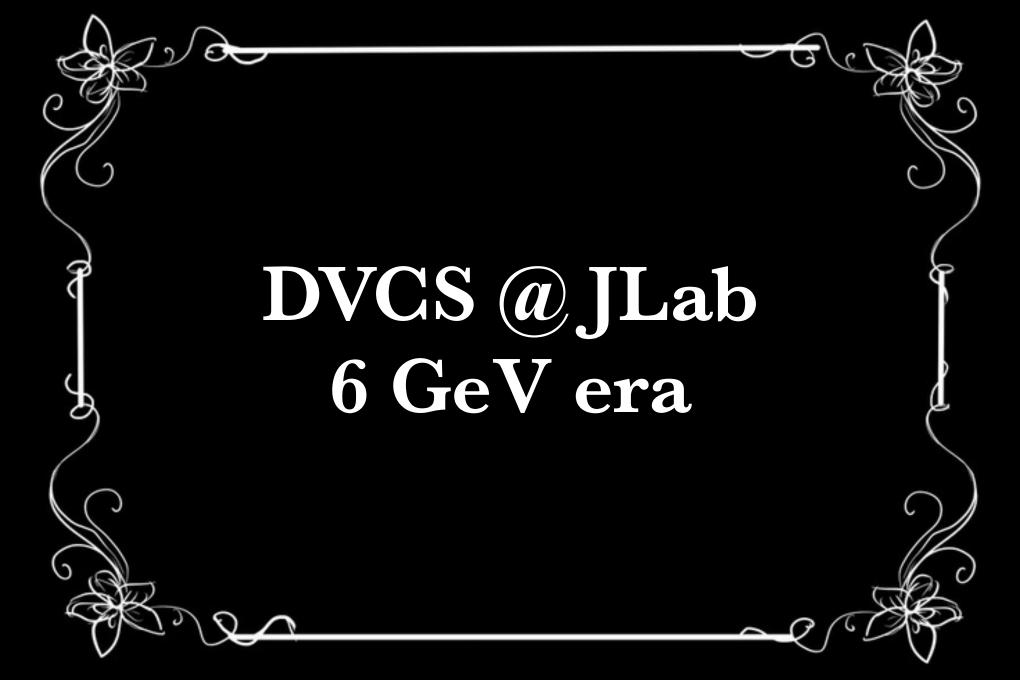
Detect electron with (Super) High Momentum Spectrometer, (S)HMS.

Detect photon in PbWO₄ calorimeter.

Sweeping magnet to reduce backgrounds in calorimeter.

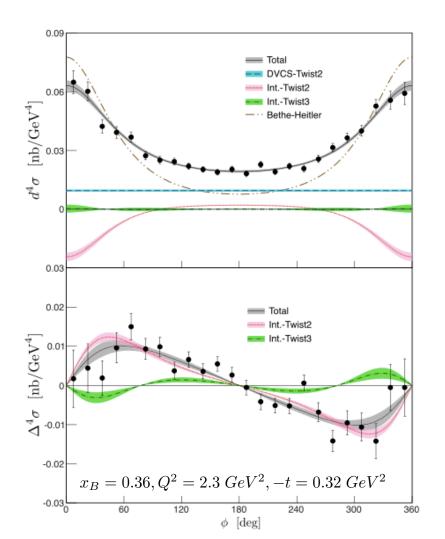
Reconstruct recoiling proton through missing mass.





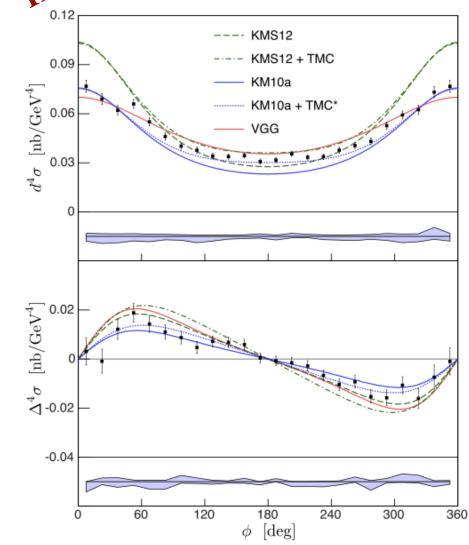
First DVCS cross-sections in valence region

* Hall A, ran in 2004, high precision, narrow kinematic range. Data recently re-analysed. Q^2 : 1.5 - 2.3 GeV², $x_B = 0.36$.



- * CFFs show scaling in DVCS: leading twist (twist-2) dominance at moderate Q² (1.5 2.3 GeV²).
- * GPDs can be extracted at JLab kinematics
- *Extraction of $|T_{DVCS}|^2$ amplitude as well as interference terms.
- *Strong deviation of DVCS cross-section from BH: new experiment to probe its energy dependence and isolate $|T_{DVCS}|^2$. E07-007, C. Muñoz *et al*.
- M. Defurne et al, PRC 92 (2015) 055202.





$$x_B = 0.36, Q^2 = 1.9 \ GeV^2, -t = 0.32 \ GeV^2$$

First DVCS crosssections in valence region

- *KMS parameters tuned on very low x_B meson-production data
- *Target-mass and finite-t corrections (TMC) improve agreement for KM10a model

VGG model: Vanderhaeghen, Guichon, Guidal

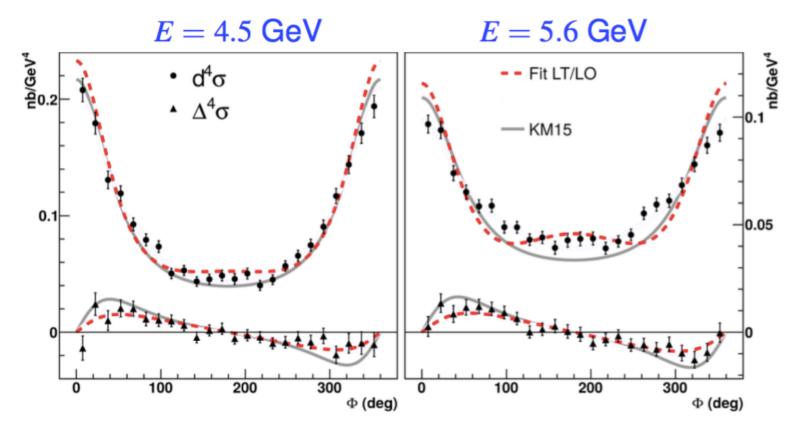
KMS model: Kroll, Moutarde, Sabatié

KM model: Kumericki, Mueller

M. Defurne et al, **PRC 92** (2015) 055202.

DVCS cross-sections at different beam energies

* E07-007: Hall A experiment to measure helicity-dependent and -independent cross-sections at two beam energies and constant x_B , Q^2 and t.

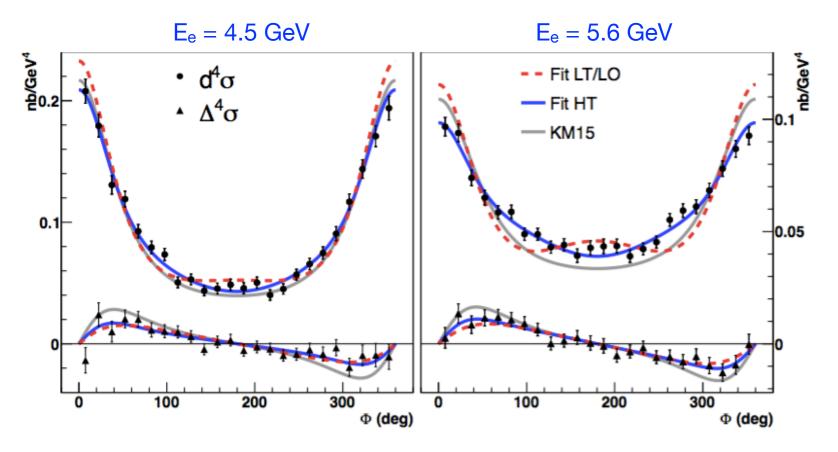


*Simultaneous fit to cross-sections at both energies using only leading twist and leading order (LT/LO) do not describe the cross-sections fully: higher twist/order effects! Using Braun's decomposition, \mathbb{H}_{-+} and \mathbb{H}_{0+} can't be neglected.

M. Defurne *et al*, arXiv:1703.09442

Hall A DVCS cross-sections at different beam energies

* Including either higher order or higher twist effects (HT) improves the match with data:

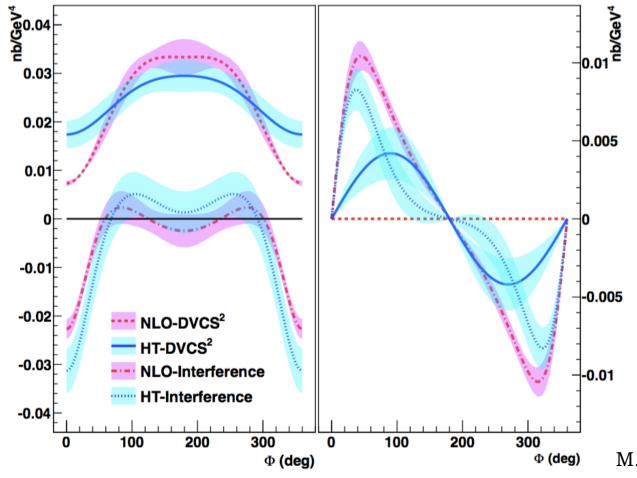


Higher-order and / or higher-twist terms are important!

Hall A

Rosenbluth separation of DVCS² and BH-DVCS terms

* Rosenbluth separation of the DVCS² and the BH-DVCS interference terms in the cross-section is possible, NLO and higher-twist required.

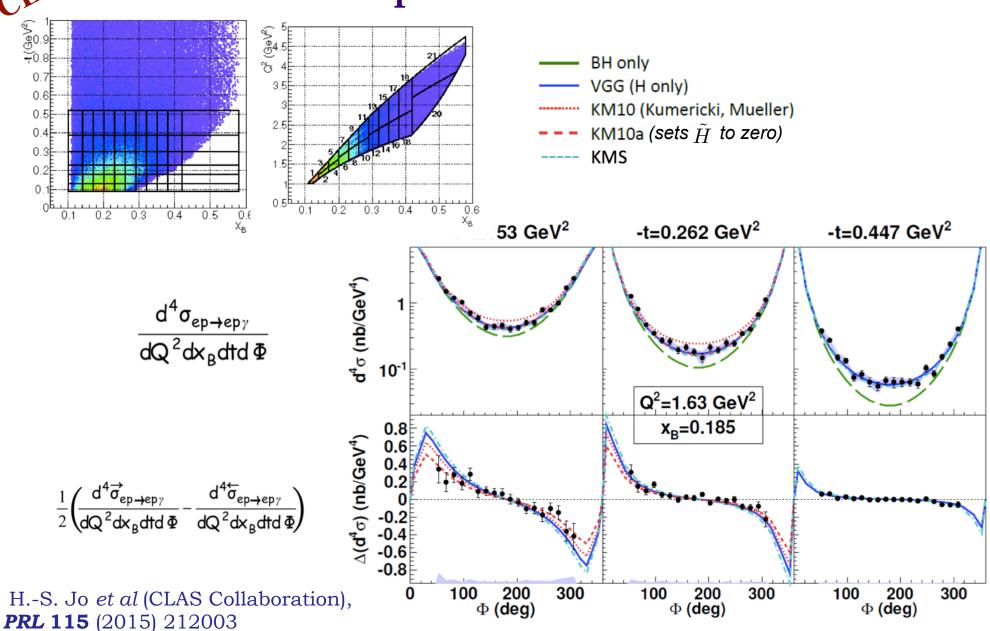


- *Significant differences between pure DVCS and interference contributions.
- * Helicity-dependent crosssection has a sizeable DVCS² contribution in the higher-twist scenario.
- * Separation of HT and NLO effects requires scans across wider ranges of Q² and beam energy: JLab12!

M. Defurne et al, arXiv:1703.09442

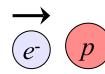
CLAS

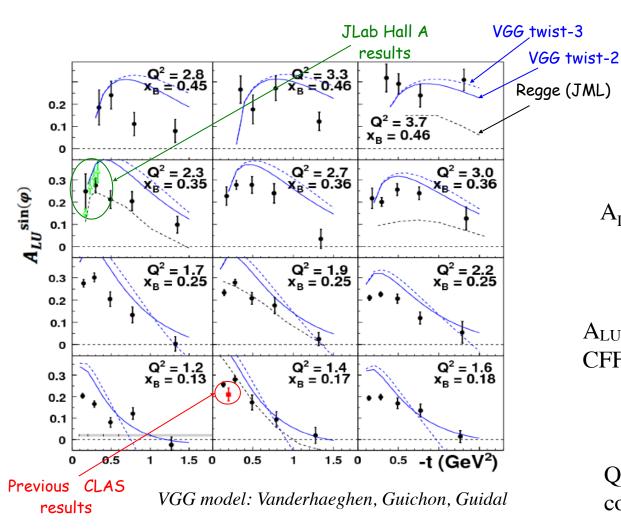
CLAS unpolarised cross-sections





Beam-spin Asymmetry (A_{LU})





Follows first CLAS measurement: S. Stepanyan *et al* (CLAS), *PRL* 87 (2001) 182002

A_{LU} from fit to asymmetry:

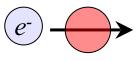
$$A_i = \frac{\alpha_i \sin \phi}{1 + \beta_i \cos \phi}$$

A_{LU} characterised by imaginary parts of CFFs via: $F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} E$

Qualitative agreement with models, constraints on fit parameters.

F.-X. Girod *et al* (CLAS Collaboration), *PRL* **100** (2008) 162002

Target-spin Asymmetry (A_{UL})



Follows first CLAS measurement:

S. Chen *et al* (CLAS Collaboration), *PRL* **97** (2006) 072002

A_{III.} from fit to asymmetry:

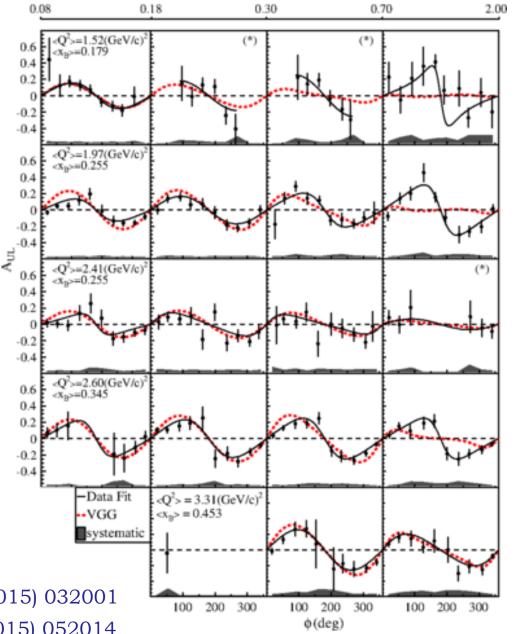
$$A_i = \frac{\alpha_i \sin \phi}{1 + \beta_i \cos \phi}$$

A_{UL} characterised by imaginary parts of CFFs via:

$$F_1 \tilde{\underline{H}} + \xi G_M (\underline{H} + \frac{x_B}{2} \underline{E}) - \frac{\xi t}{4M^2} F_2 \tilde{\underline{E}} + \dots$$

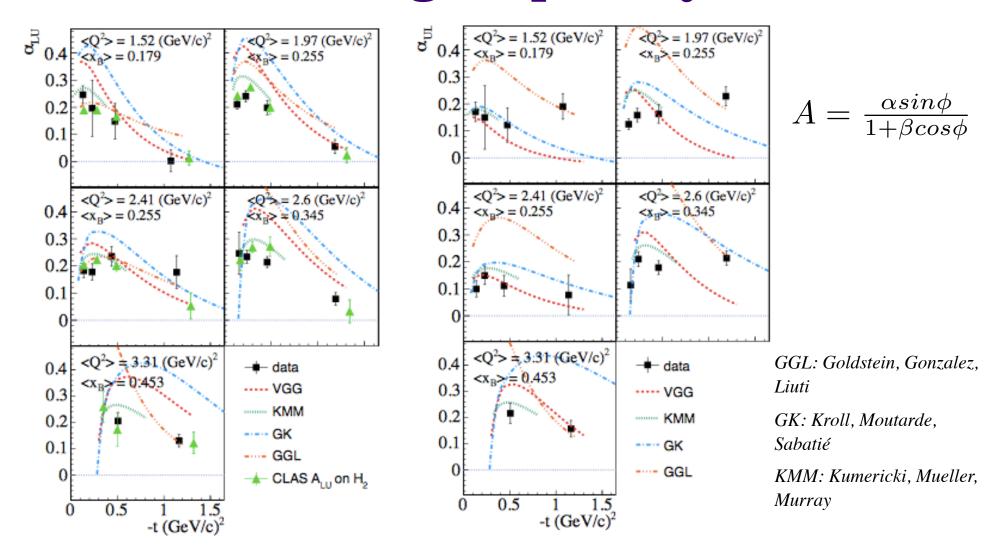
High statistics, large kinematic coverage, strong constraints on fits, simultaneous fit with BSA from the same dataset.

- E. Seder et al (CLAS Collaboration), **PRL** 114 (2015) 032001
- S. Pisano et al (CLAS Collaboration), PRD 91 (2015) 052014

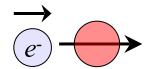


-t (GeV/c)2

Beam- and target-spin asymmetries

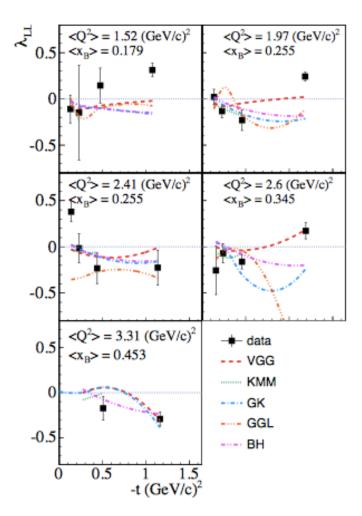


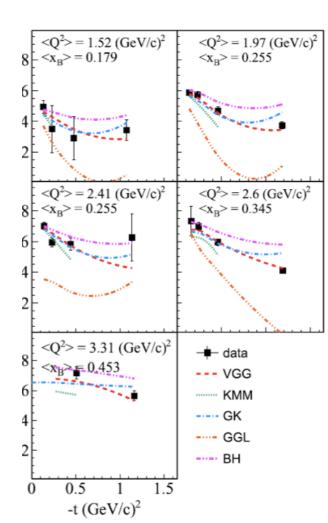
- S. Pisano et al (CLAS Collaboration), **PRD 91** (2015) 052014
- E. Seder et al (CLAS Collaboration), **PRL** 114 (2015) 032001



Double-spin Asymmetry (A_{LL})







- E. Seder et al (CLAS Collaboration), PRL 114 (2015) 032001
- S. Pisano et al (CLAS Collaboration), PRD 91 (2015) 052014

A_{LL} from fit to asymmetry:

$$\frac{\kappa_{\rm LL} + \lambda_{\rm LL}\cos\phi}{1 + \beta\cos\phi}$$

A_{LL} characterised by real parts of CFFs via:

$$F_1 \tilde{\boldsymbol{H}} + \xi G_M (\boldsymbol{H} + \frac{x_B}{2} \boldsymbol{E}) + \dots$$

- *Fit parameters extracted from a simultaneous fit to BSA, TSA and DSA.
- *CFF extraction from three spin asymmetries at common kinematics.



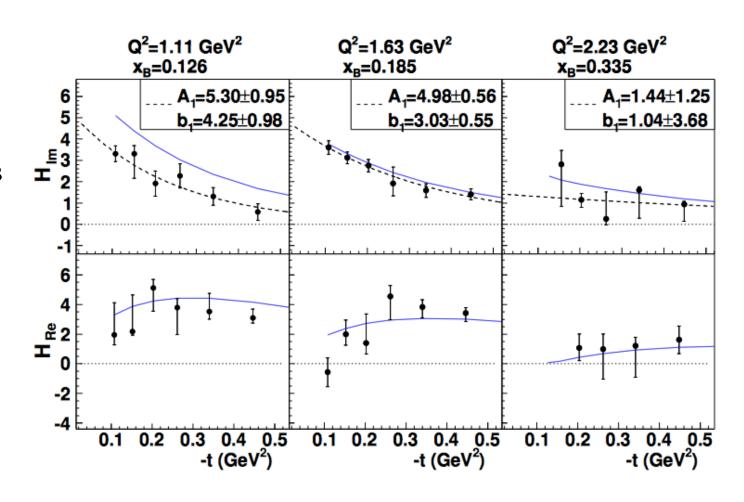
CFFs from the cross-sections

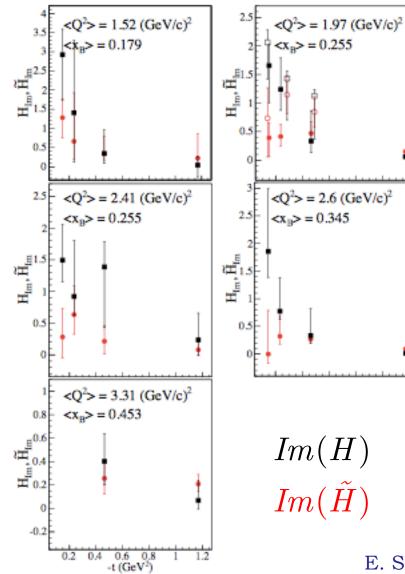


* Slope in t becomes flatter at higher x_B



* Valence quarks at centre, sea quarks at the periphery.





What can we learn from the asymmetries?

Answers hinge on a global analysis of all available data.

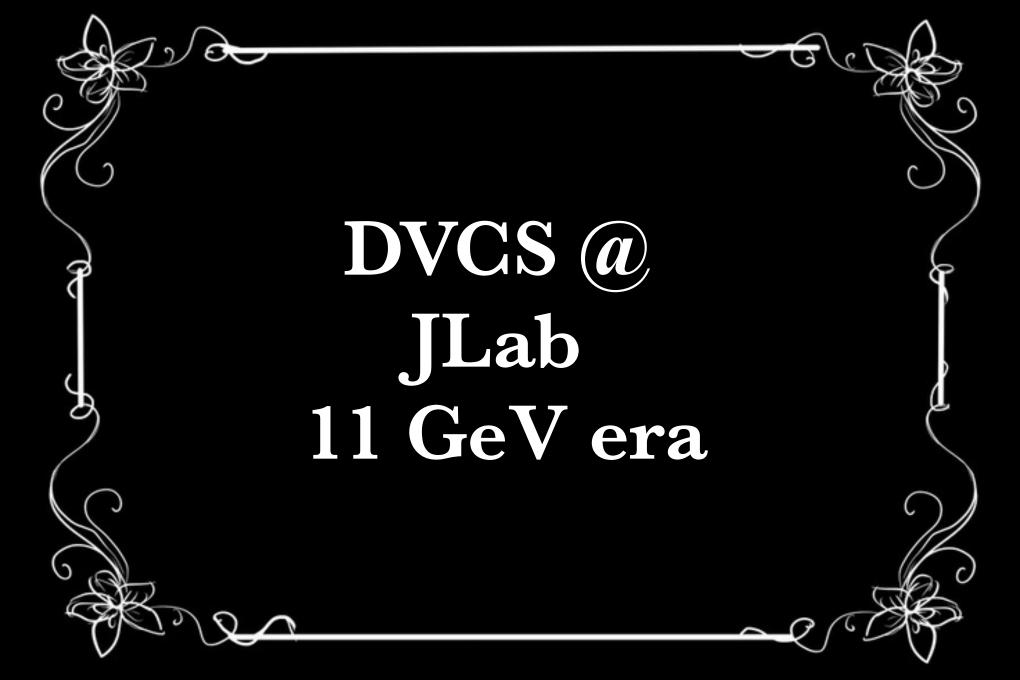
$$H^q(x,0,0) = f_1(x)$$

$$\tilde{H}^q(x,0,0) = g_1(x)$$

Information on relative distributions of quark momenta (PDFs) and quark helicity, $\Delta q(x)$.

Indications that axial charge is more concentrated than electromagnetic charge

- E. Seder et al (CLAS Collaboration), **PRL 114** (2015) 032001
- S. Pisano et al (CLAS Collaboration), PRD 91 (2015) 052014



Proton DVCS @ 11 GeV



Experiment E12-06-119

F. Sabatié et al.

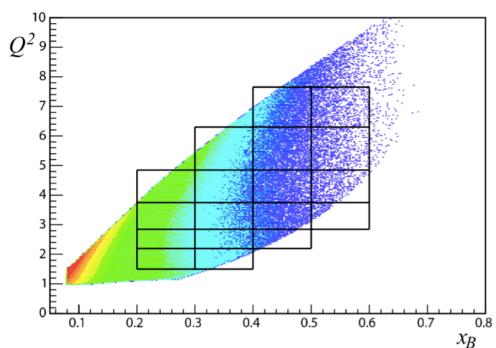
$$\begin{aligned} &P_{beam} = 85\% \\ &L = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \\ &1 < Q^2 < 10 \text{ GeV}^2 \\ &0.1 < x_B < 0.65 \\ &-t_{min} < -t < 2.5 \text{ GeV}^2 \end{aligned}$$

Kinematics similar for all proton DVCS (a) 11 GeV with CLAS12 experiments

Unpolarised liquid H₂ target:

- Statistical error: 1% 10% on $\sin \varphi$ moments
- Systematic uncertainties: ~ 6 8%

A_{LU} characterised by imaginary parts of CFFs via: $F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} E$



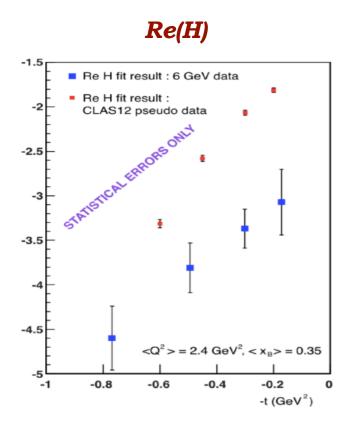
First experiment with CLAS12!

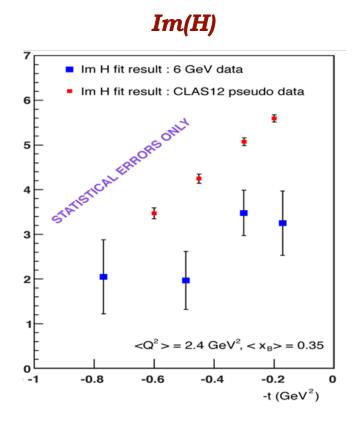
Due to start this autumn!

Proton DVCS @ 11 GeV



Impact of CLAS12 unpolarised target proton-DVCS data on the extraction of Re(H) and Im(H).





(CLAS 6 GeV extraction H. Moutarde)

Neutron DVCS @ 11 GeV

Experiment E12-11-003 S. Niccolai, D. Sokhan et al.

CLAS12

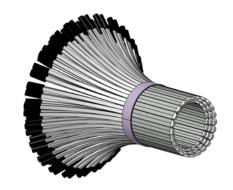
 $\Delta \sigma_{LU} \sim \sin \phi \operatorname{Im} \{F_1 H + \xi (F_1 + F_2) \widetilde{H} - k F_2 E\} d\phi$



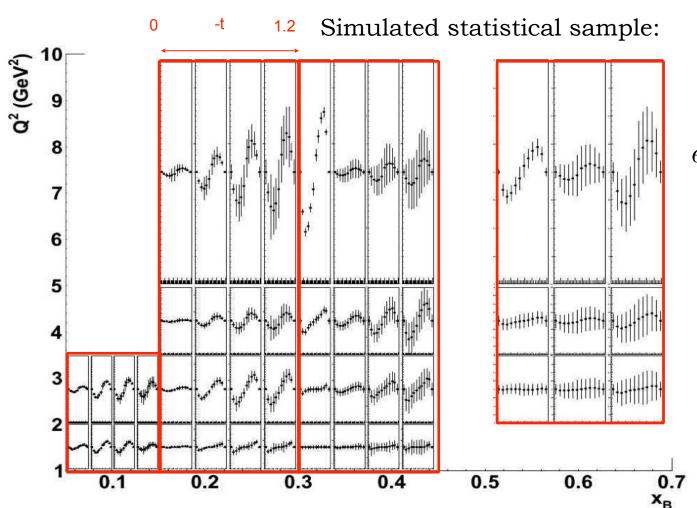
Im (E_n) dominates.

L =
$$10^{35}$$
 cm⁻²s⁻¹/nucleon $e+d \rightarrow e'+\gamma+n+(p_s)$

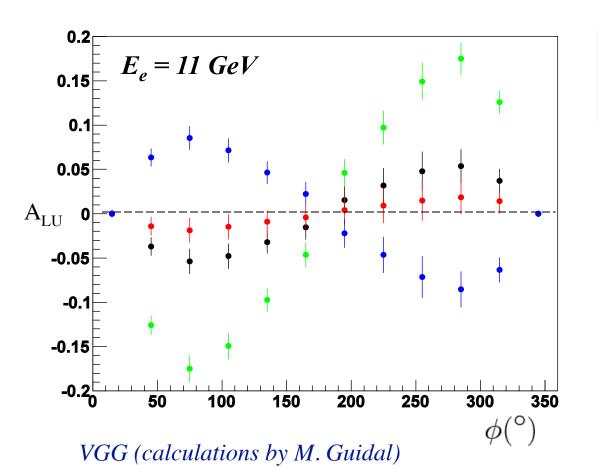
CLAS12 +
Forward Tagger +
Neutron Detector



Tentative schedule: 2019



Beam-spin asymmetry in neutron DVCS @ 11 GeV



$$J_u = 0.3, J_d = -0.1$$
 $J_u = 0.3, J_d = 0.1$
 $J_u = 0.1, J_d = 0.1$ $J_u = 0.3, J_d = 0.3$

- * At 11 GeV, beam spin asymmetry (A_{LU}) in neutron DVCS is very sensitive to J_u, J_d
- * Wide coverage needed!

Fixed kinematics: $x_B = 0.17$ $Q^2 = 2 \text{ GeV}^2$ $t = -0.4 \text{ GeV}^2$



Proton DVCS with a longitudinally polarised target

Experiment E12-06-119 *F. Sabatié et al.*

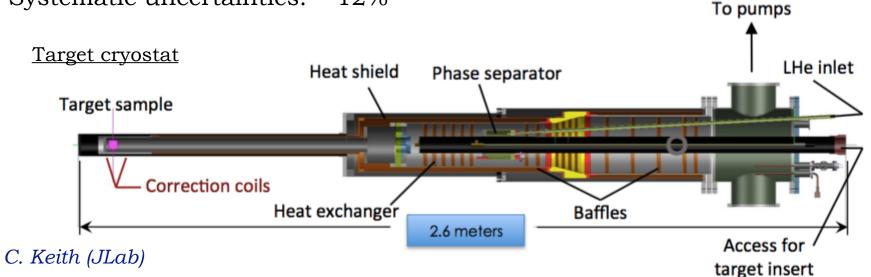
A_{UL} characterised by imaginary parts of CFFs via: $F_1\tilde{H} + \xi G_M(H + \frac{x_B}{2}E) - \frac{\xi t}{4M^2}F_2\tilde{E} + ...$

Longitudinally polarised NH₃ target:

- Dynamic Nuclear Polarisation (DNP) of target material, cooled to 1K in a *He* evaporation cryostat.
- P_{proton} > 80%
- Statistical error: 2% 15% on $\sin \varphi$ moments

• Systematic uncertainties: ~ 12%







Neutron DVCS with a longitudinally polarised target

Experiment E12-06-109A. S. Niccolai, D. Sokhan et al.

Longitudinally polarised ND₃ target:

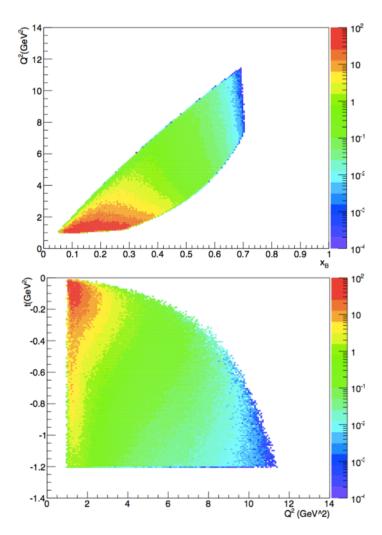
- Dynamic Nuclear Polarisation (DNP) of target material in a cryostat shared with the NH₃ target.
- P_{deuteron} up to 50%
- Systematic uncertainties: ~ 12%

A_{UL} characterised by imaginary parts of CFFs via:

$$F_1 \tilde{\boldsymbol{H}} + \xi G_M (\boldsymbol{H} + \frac{x_B}{2} \boldsymbol{E}) - \frac{\xi t}{4M^2} F_2 \tilde{\boldsymbol{E}} + \dots$$



In combination with pDVCS, will allow flavourseparation of the H_q CFFs.



Tentative schedule: 2020

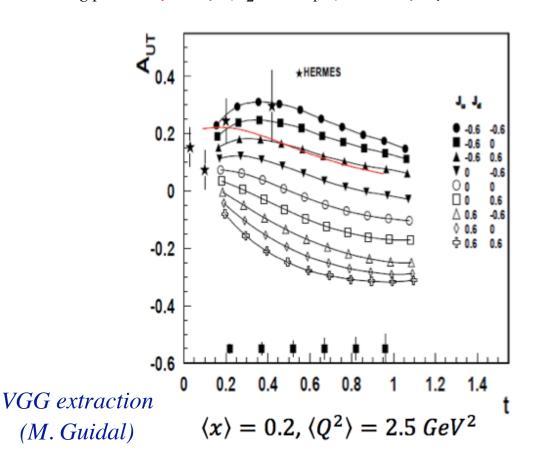


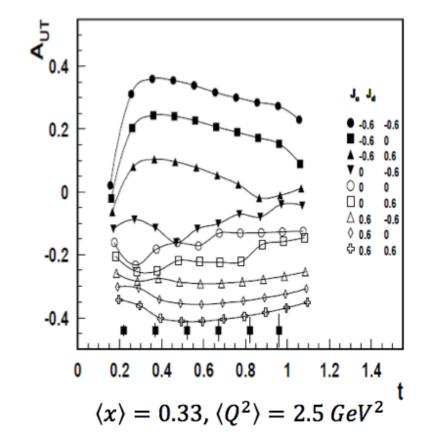
Proton DVCS with transversely polarised target at CLAS12

C12-12-010: with transversely polarised HD target (conditionally approved). *L. Elouardhiri et al.*

$$\Delta \sigma_{\text{UT}} \sim \cos \phi \text{ Im} \{k(F_2 H - F_1 E) + \dots\} d\phi$$

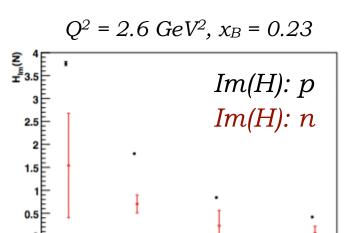
Sensitivity to *Im(E)* for the proton.





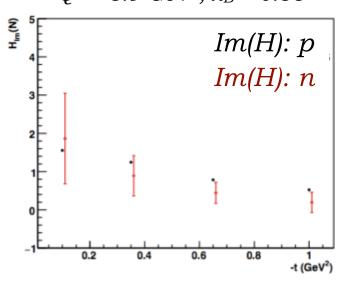
Projected sensitivities to Im(H) CFF



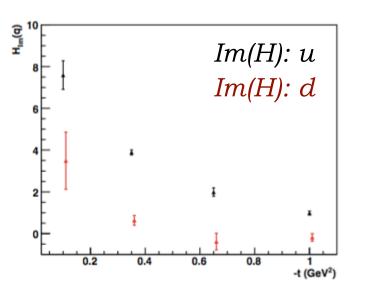


0.2



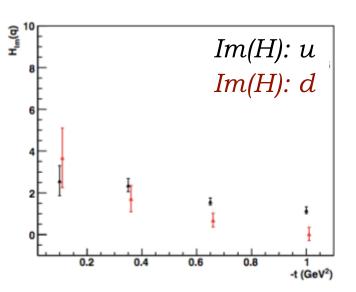


Projections for *Im(H)* neutron and proton and up and down CFFs extracted from approved CLAS12 experiments.



0.8

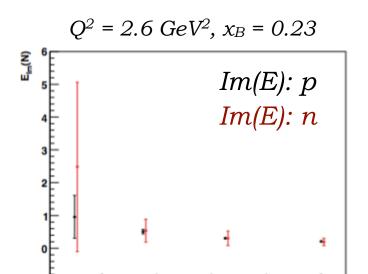
-t (GeV²)

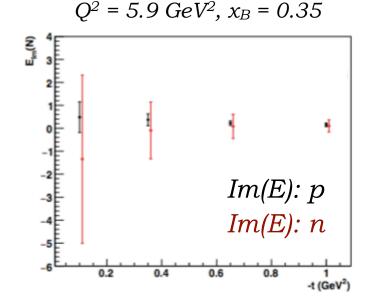


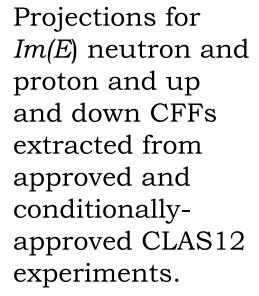
VGG fit (M. Guidal)

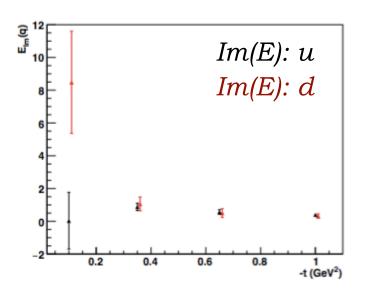
Projected sensitivities to Im(E) CFF



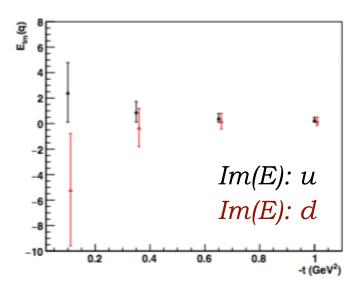








-t (GeV2)



VGG fit (M. Guidal)

DVCS Cross-sections: Halls A and C

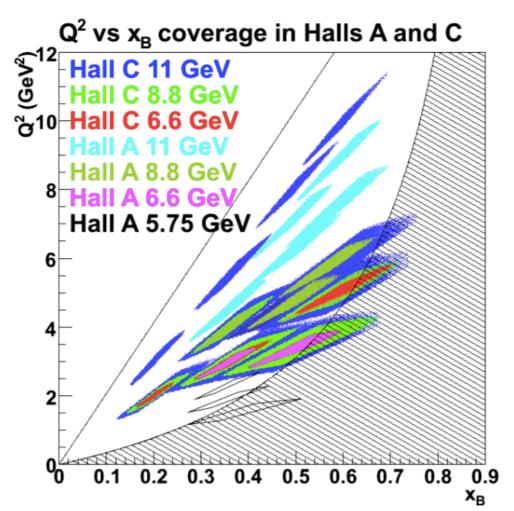
Experiments:

E12-06-114 (Hall A, 100 days), **E12-13-010** (Hall C, 53 days)

C. Muñoz Camacho et al., C. Hyde et al.

Unpolarised liquid H₂ target:

- Beam energies: 6.6, 8.8, 11 GeV
- Scans of Q^2 at fixed x_B .
- Hall A: aim for absolute crosssections with 4% relative precision.
 - * Azimuthal, energy and helicity dependencies of cross-section to separate $|T_{DVCS}|^2$ and interference contributions in a wide kinematic coverage.
 - * Separate *Re* and *Im* parts of the DVCS amplitude.



Hall A started taking data last spring!

DVCS at lower energies with CLAS12

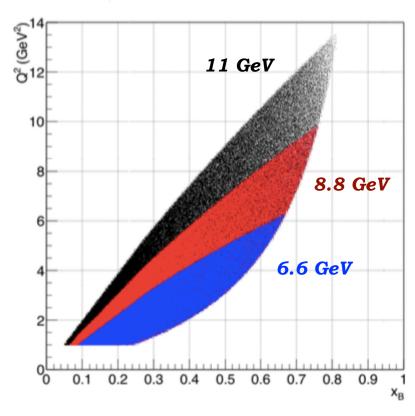


Experiment E12-16-010B *F.-X. Girod et al.*

Unpolarised liquid H₂ target:

- Beam energies: 6.6, 8.8 GeV
- Simultaneous fit to beam-spin and total cross-sections.
- * Rosenbluth separation of interference and $|T_{DVCS}|^2$ terms in the cross-section
- * Scaling tests of the extracted CFFs
- * Model-dependent determination of the D-term in the Dispersion Relation between *Re* and *Im* parts of CFFs.

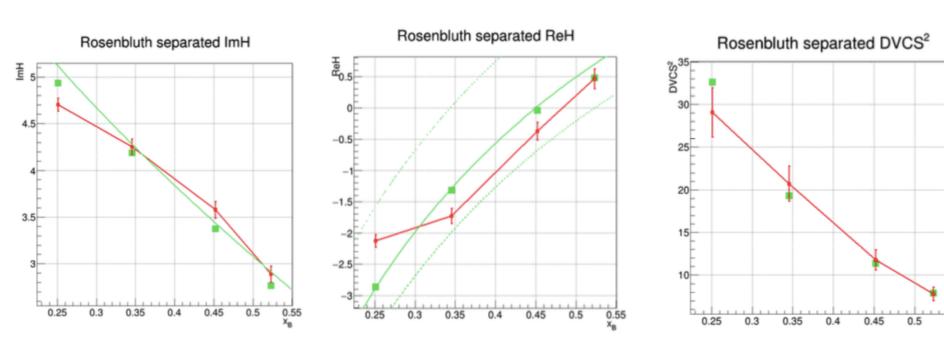
Deep Process Kinematics with 6.6, 8.8, and 11 GeV



Compare with measurements from Halls A and C: cross-check model and systematic uncertainties.

DVCS at lower energies with CLAS12

Projected extraction of CFFs (red) compared to generated values (green). Three curves on the *Re(H)* show three different scenarios for the D-term.



F.-X. Girod et al.

To conclude...

- * Success of the initial DVCS programme at **Jefferson Lab with 6 GeV beams**, which produced measurements of the cross-section, beam- target- and double-spin asymmetries in proton DVCS and a first measurement on neutron DVCS:
 - Indications that factorisation holds at the low Q² kinematics of JLab,
 - constraints on a number of CFFs,
 - tentative conclusions on relative quark distributions,
 - importance of higher order / higher twist in high-precision measurements.
- *Upgrade of **JLab to 12 GeV** max beam energy (11 GeV to halls A, B and C) opens a new region of phase space at higher kinematics in the valence region: high luminosity, high precision.
- * DVCS measurements are a flagship part of the the new experimental programme: first experiments in Hall A and with CLAS12.
- * Approved proposals aimed at greatly constraining CFF fits in a global analysis.
- *Extraction of *H* and *E* from proton and neutron DVCS, flavour separation of CFFs, separation of pure DVCS amplitude from the interference term, measurements at higher precision and statistics, sensitivity to higher-twist contributions.

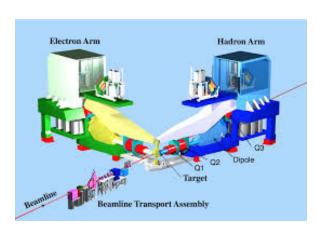


Jefferson Lab: 6 GeV era

CEBAF: Continuous Electron Beam Accelerator Facility.

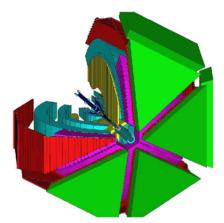
- **★** Energy up to ~6 GeV
- * Energy resolution $\delta E/E_e \sim 10^{-5}$
- * Longitudinal electron polarisation up to ~85%

Hall A:



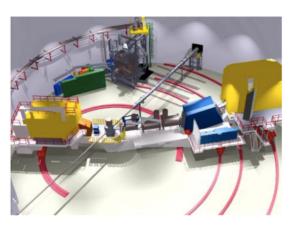
* High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity.

Hall B: CLAS



* Very large acceptance, detector array for multiparticle final states.

Hall C:



*Two movable spectrometer arms, well-defined acceptance, high luminosity