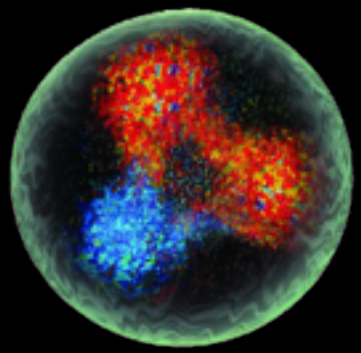
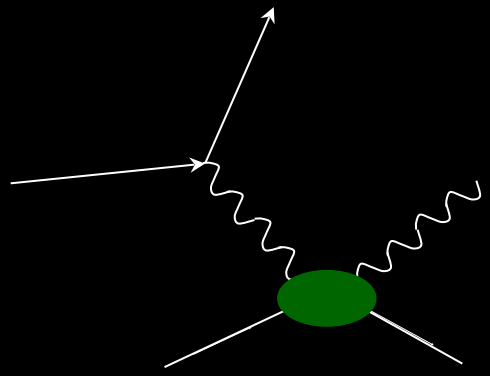
Nucleon Tomography through Deeply Virtual Compton Scattering @ CLAS and CLAS12



Daria Sokhan

University of Glasgow, UK

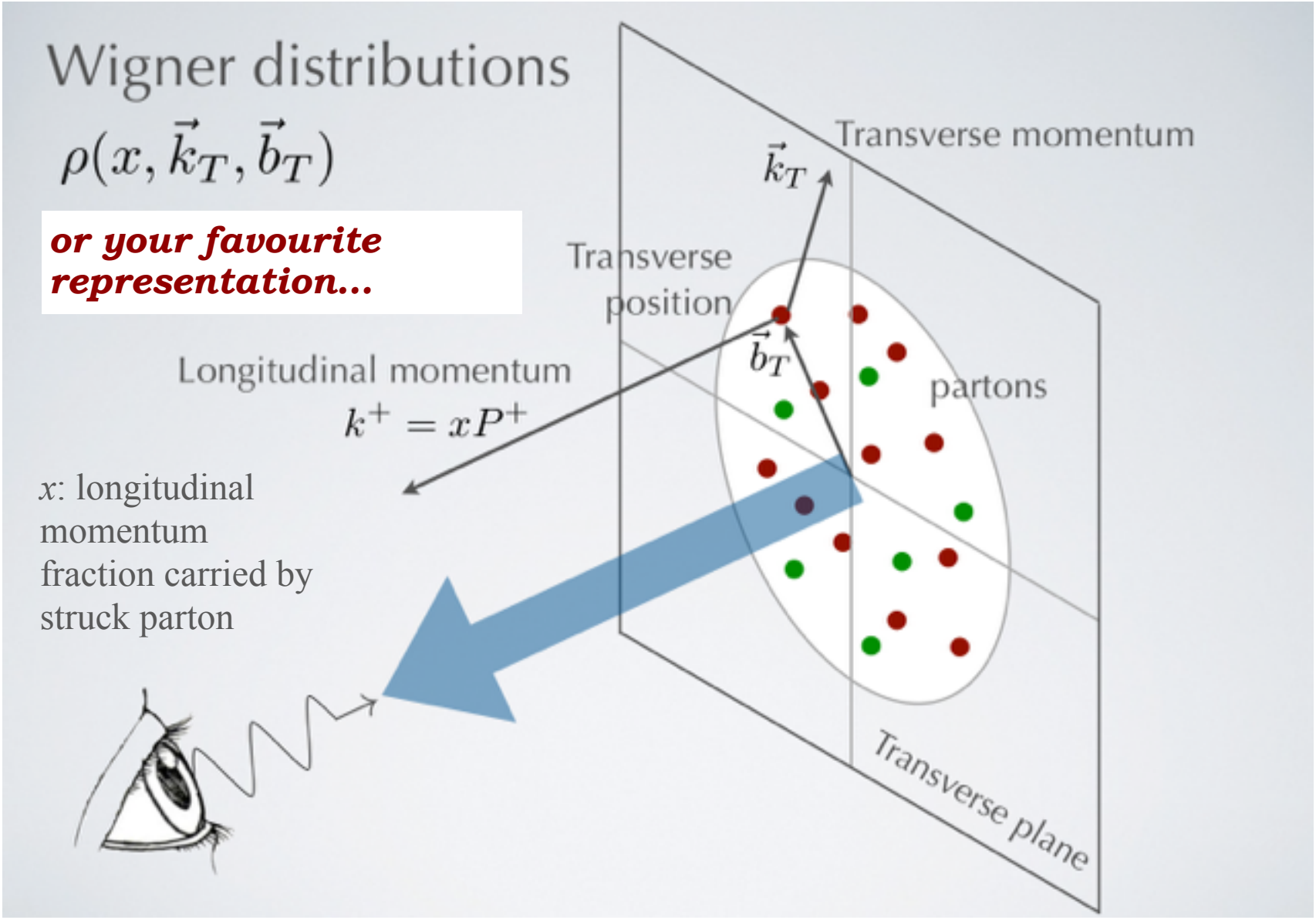


25th International Workshop on Deep Inelastic Scattering and Related Topics

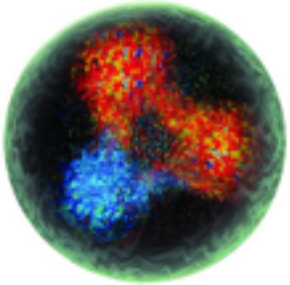
University of Birmingham, UK — 5th April 2017

Introduction

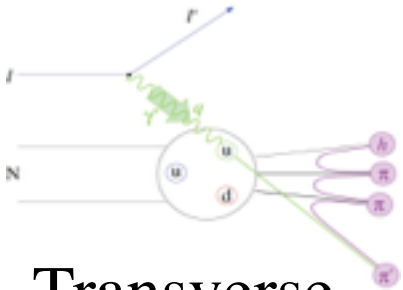
A full knowledge of the nucleon



Images of the nucleon



Wigner function:
full phase space parton distribution of the nucleon

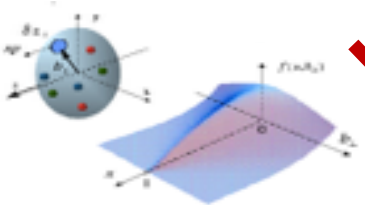


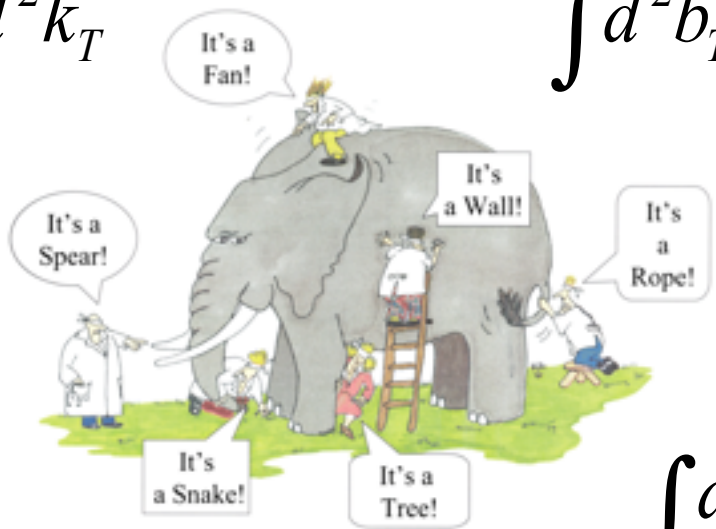
$\int d^2k_T$

$\int d^2b_T$

Transverse Momentum Distributions (TMDs)

Generalised Parton Distributions (GPDs)

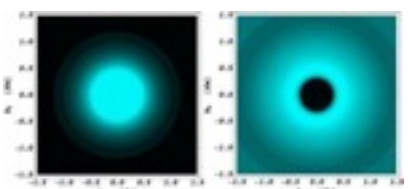




G. Renee Guzlas, artist.

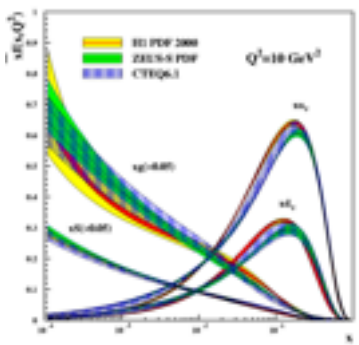
$\int dx$

$\int d^2k_T$

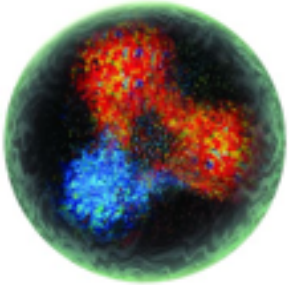


Form Factors
eg: G_E, G_M

Parton Distribution Functions (PDFs)



Images of the nucleon



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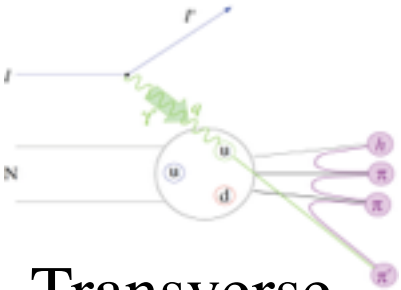
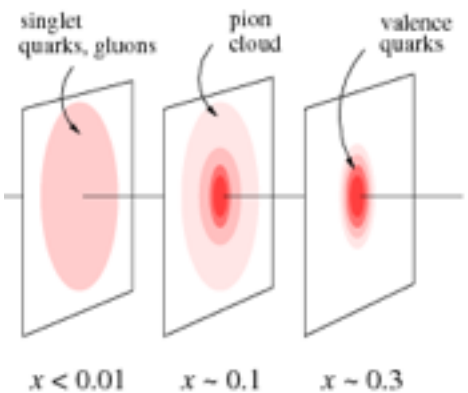


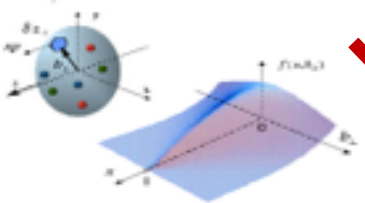
$\int d^2 k_T$

$\int d^2 b_T$

Transverse Momentum Distributions (TMDs)

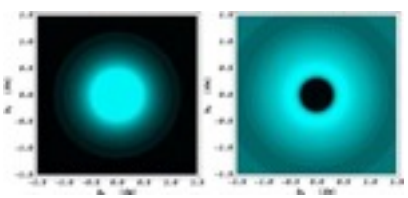
Generalised Parton Distributions (GPDs)





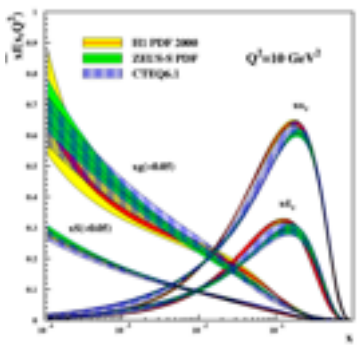
$\int dx$

$\int d^2 k_T$

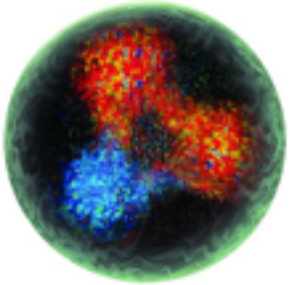


Form Factors
eg: G_E, G_M

Parton Distribution Functions (PDFs)

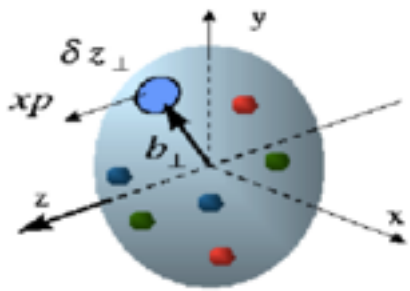


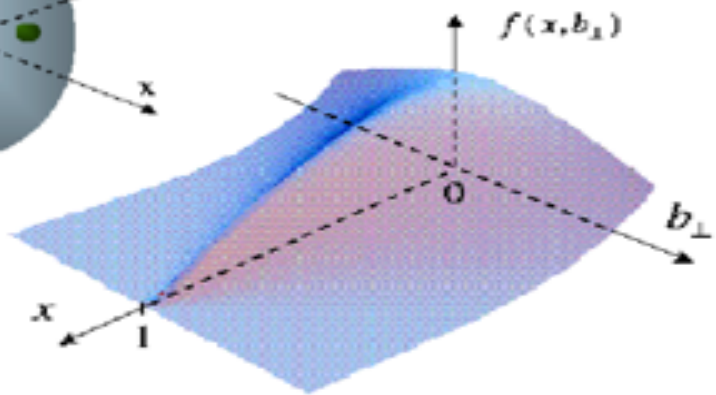
Generalised Parton Distributions



Wigner function:
full phase space parton distribution of the nucleon

$$\int d^2 k_T$$





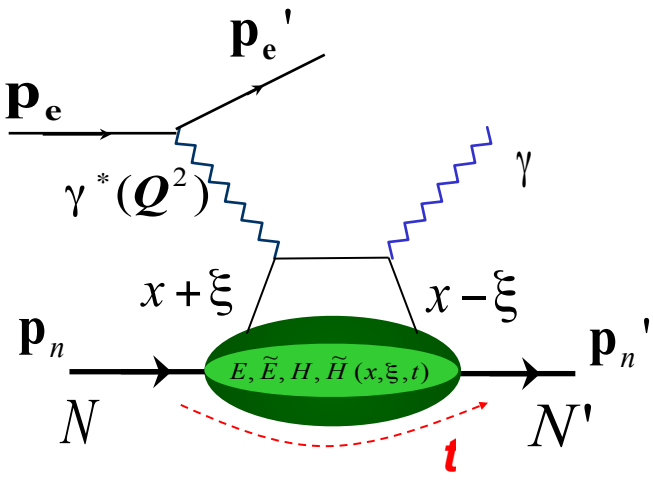
Generalised Parton Distributions (GPDs)

- relate, in the infinite momentum frame, transverse position of partons ($b_\perp$) to their longitudinal momentum (x): **tomography** of the nucleon.

✱ Deep exclusive reactions, e.g.: Deeply Virtual Compton Scattering (*talk by C. Munoz Camacho*), Deeply Virtual Meson Production (*talks: T. Horn, C. Van Hulse, F. Sabatié*), …

GPDs and DVCS

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



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

Bjorken variable: $x_B = \dfrac{Q^2}{2\mathbf{p}_n \cdot \mathbf{q}}$

$x \pm \xi$ *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 GPDs:

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

- Can be related to PDFs:

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

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**.

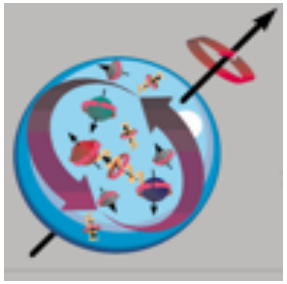
GPDs and nucleon spin

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

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

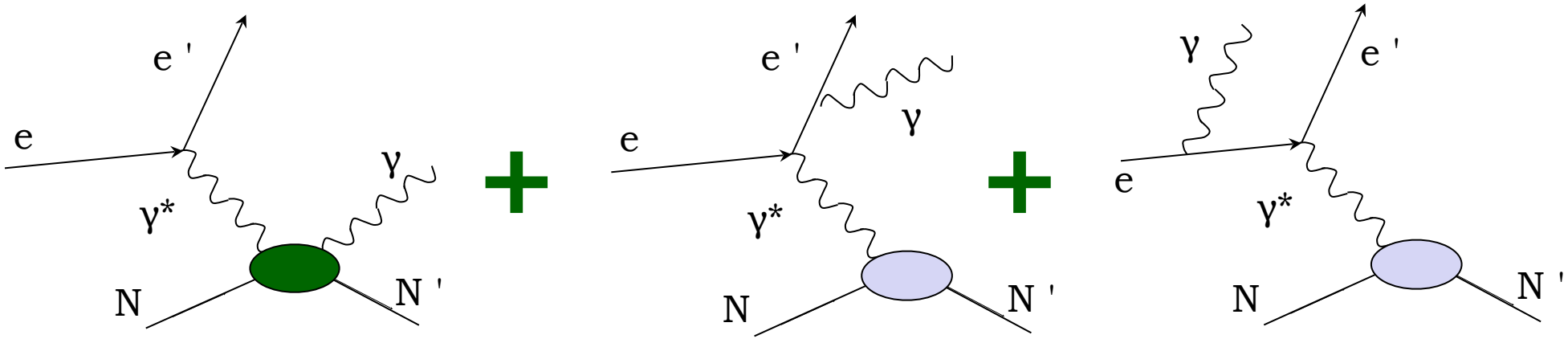
M. Mazouz et al, PRL 99 (2007) 242501



* GPDs can provide insight into the orbital angular momentum contribution to nucleon spin: **the spin puzzle**.

Measuring DVCS

✳ Process measured in experiment:



DVCS

Bethe - Heitler

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

Amplitude parameterised in terms of Compton Form Factors

Amplitude calculable from elastic Form Factors and QED

Interference term

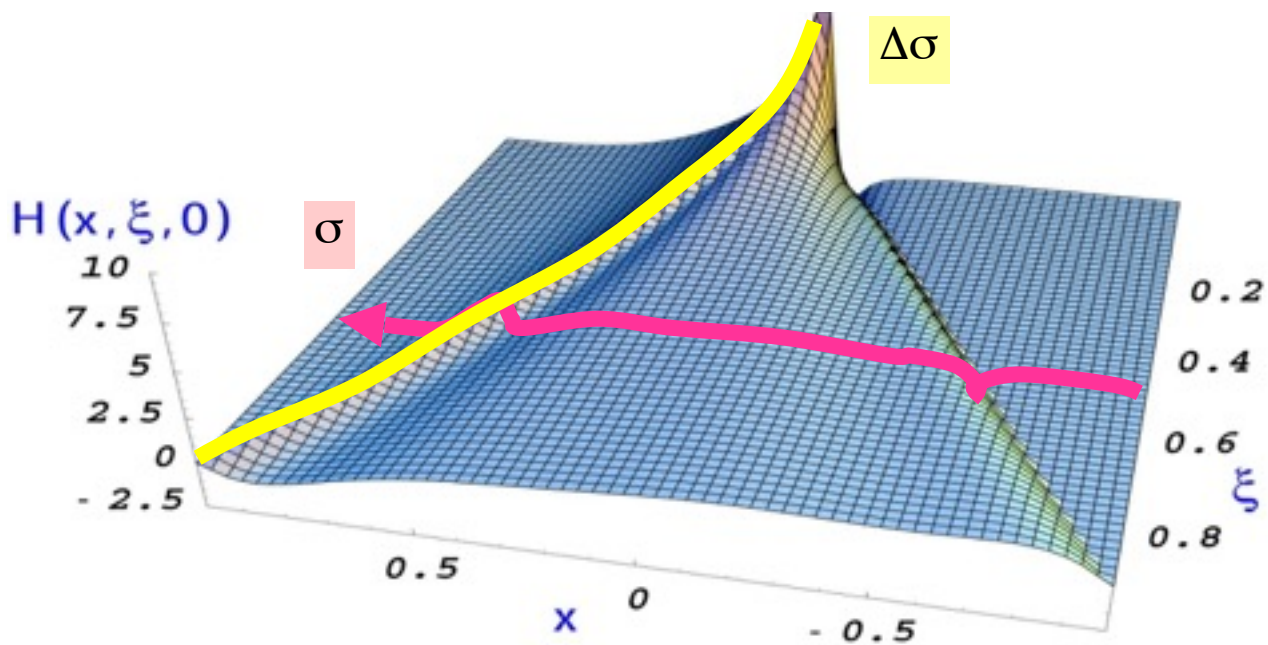
$$\left|T_{DVCS}\right|^2 << \left|T_{BH}\right|^2$$

Compton Form Factors in DVCS

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

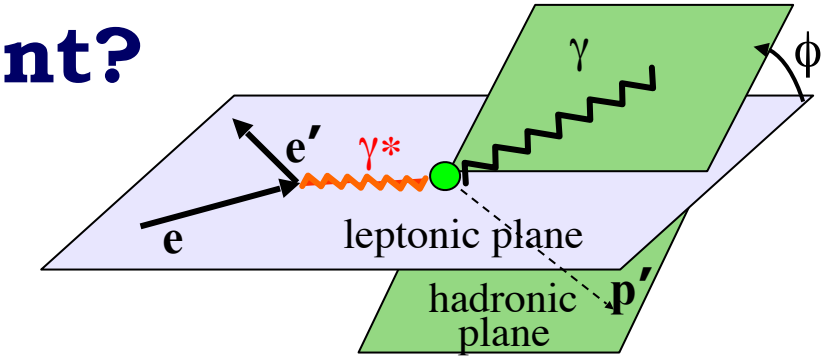
$$A_{LU} = \frac{d\vec{\sigma} - d\overleftarrow{\sigma}}{d\vec{\sigma} + d\overleftarrow{\sigma}} = \frac{\Delta\sigma_{LU}}{d\vec{\sigma} + d\overleftarrow{\sigma}}$$

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



Only ξ and t are accessible experimentally!

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		Proton	Neutron
$\vec{e}^-$ p/n	$\Delta\sigma_{LU} \sim \sin\phi\, \Im(F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E)\, d\phi$	$Im\{\mathbf{H_p}, \tilde{H}_p, E_p\}$	$Im\{H_n, \tilde{H}_n, \mathbf{E_n}\}$
e^- ⟶	$\Delta\sigma_{UL} \sim \sin\phi\, \Im(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) - \xi \frac{t}{4M^2} F_2 \tilde{E} + \ldots)\, d\phi$	$Im\{\mathbf{H_p}, \tilde{\mathbf{H}}_\mathbf{p}\}$	$Im\{\mathbf{H_n}, E_n, \tilde{E}_n\}$
e^- ↑	$\Delta\sigma_{UT} \sim \cos\phi\, \Im(\frac{t}{4M^2}(F_2 H - F_1 E) + \ldots) d\phi$	$Im\{\mathbf{H_p}, \mathbf{E_p}\}$	$Im\{\mathbf{H_n}\}$
$\vec{e}^-$ ⟶	$\Delta\sigma_{LL} \sim (A + B\cos\phi)\, \Re(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) + \ldots) d\phi$	$Re\{\mathbf{H_p}, \tilde{\mathbf{H}}_\mathbf{p}\}$	$Re\{\mathbf{H_n}, E_n, \tilde{E}_n\}$

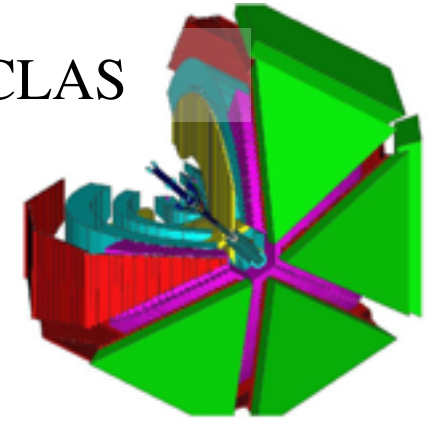
Jefferson Lab

JLab: 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%

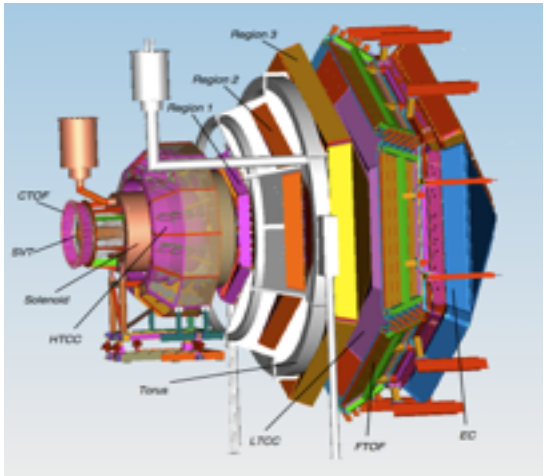
Hall B: CLAS

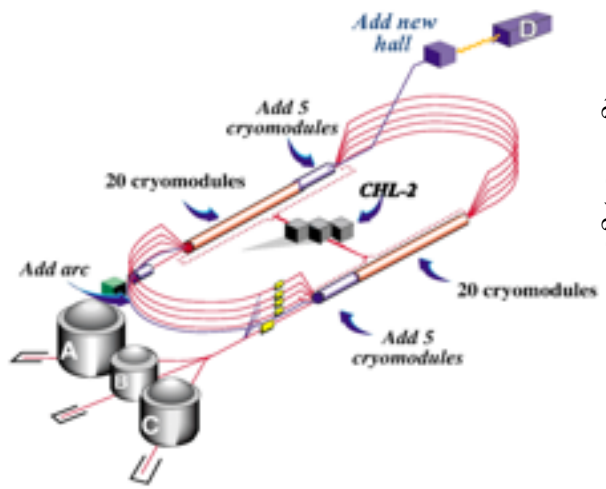


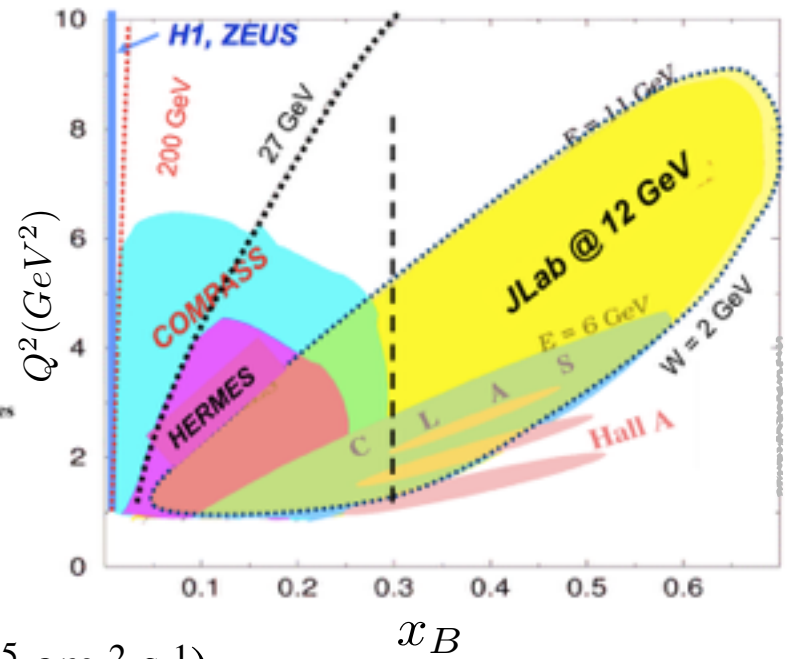
- Very large acceptance detector array for multi-particle final states.

12 GeV era

- Maximum electron energy: 12 GeV to new Hall D
- 11 GeV deliverable to Halls A, B and C



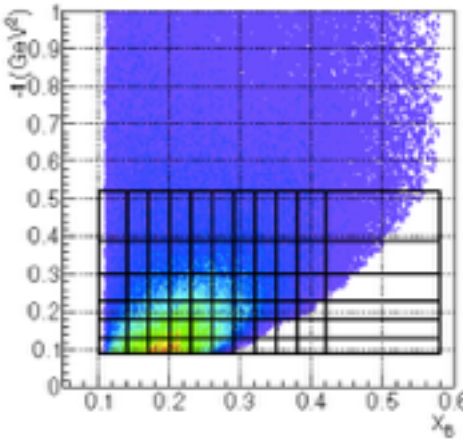


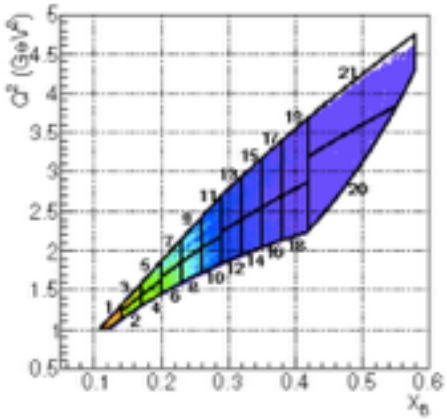


CLAS12: Very large acceptance, high luminosity (~10^{35} cm^{-2} s^{-1})

DVCS @ CLAS

CLAS unpolarised cross-sections

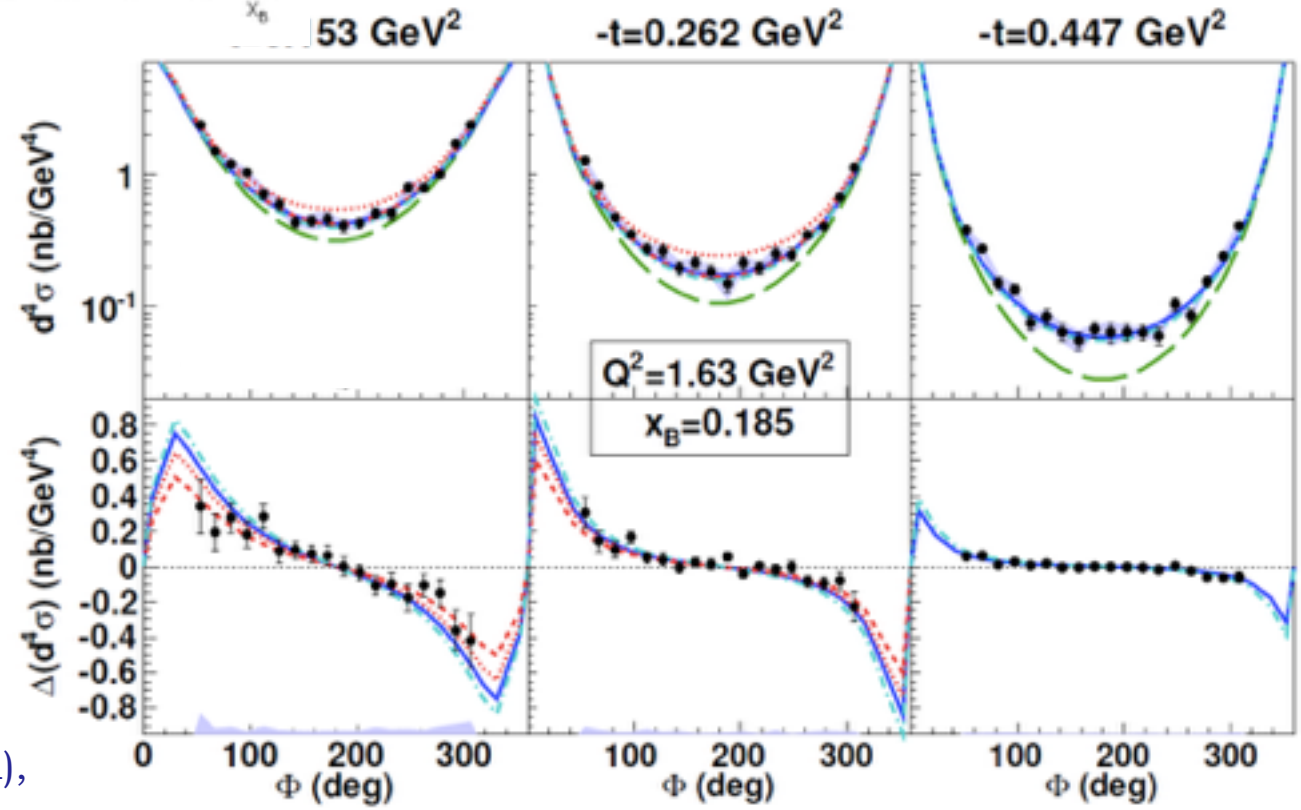




BH only
VGG (H only)
KM10 (Kumericki, Mueller)
KM10a *(sets $\tilde{H}$ to zero)*
KMS

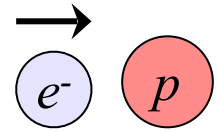
$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}$$

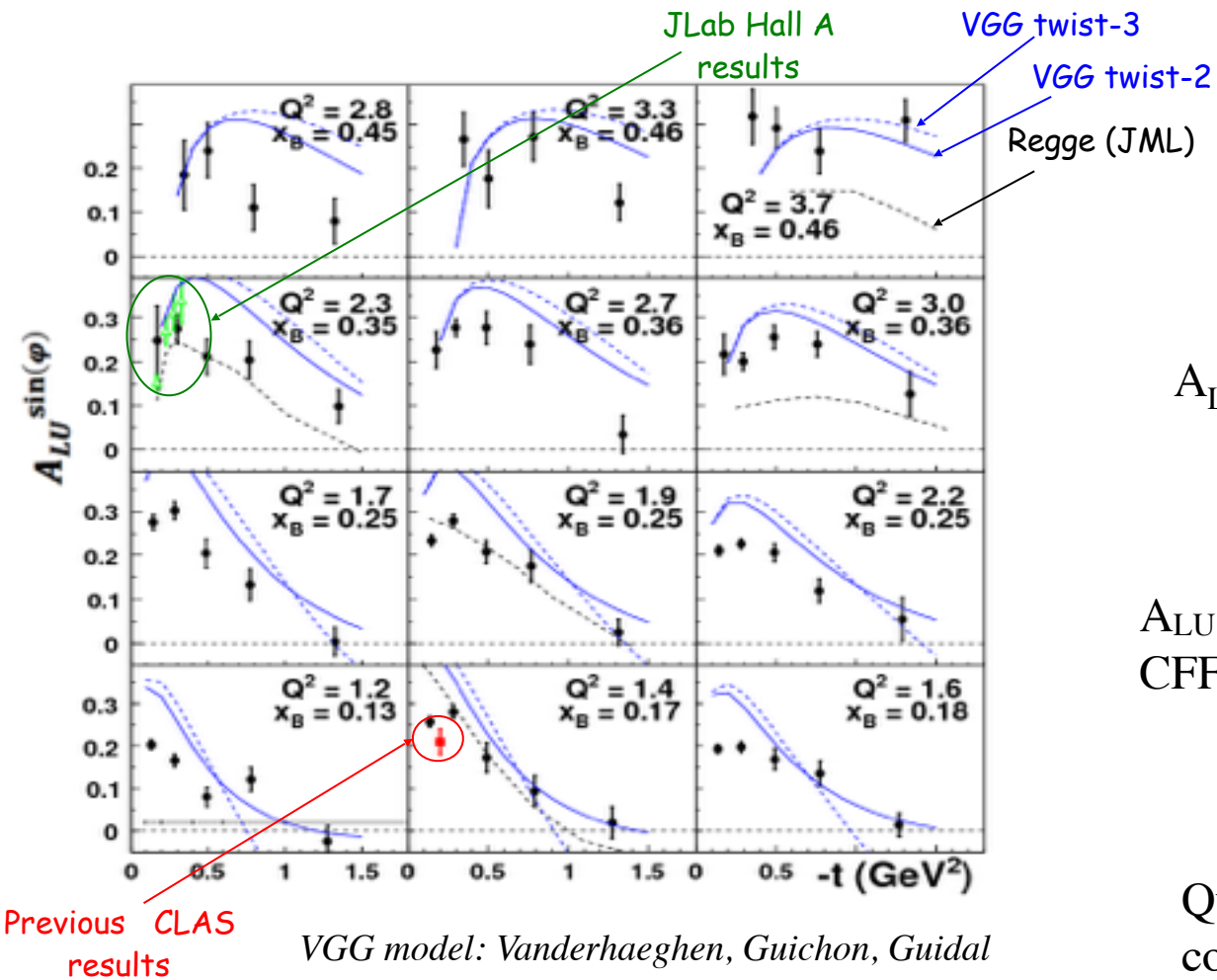
$$\frac{1}{2}\left(\frac{d^4\vec{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} - \frac{d^4\overleftarrow{\sigma}_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}\right)$$



H.-S. Jo *et al* (CLAS Collaboration), ***PRL* 115** (2015) 212003

Beam-spin Asymmetry (A_{LU})





VGG model: Vanderhaeghen, Guichon, Guidal

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

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

A_{LU} from fit to asymmetry:

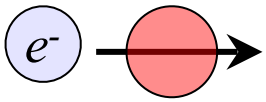
$$A_i = \frac{\alpha_i \sin\phi}{1 + \beta_i \cos\phi}$$

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.

Target-spin Asymmetry (A_{UL})



Follows first CLAS measurement:

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

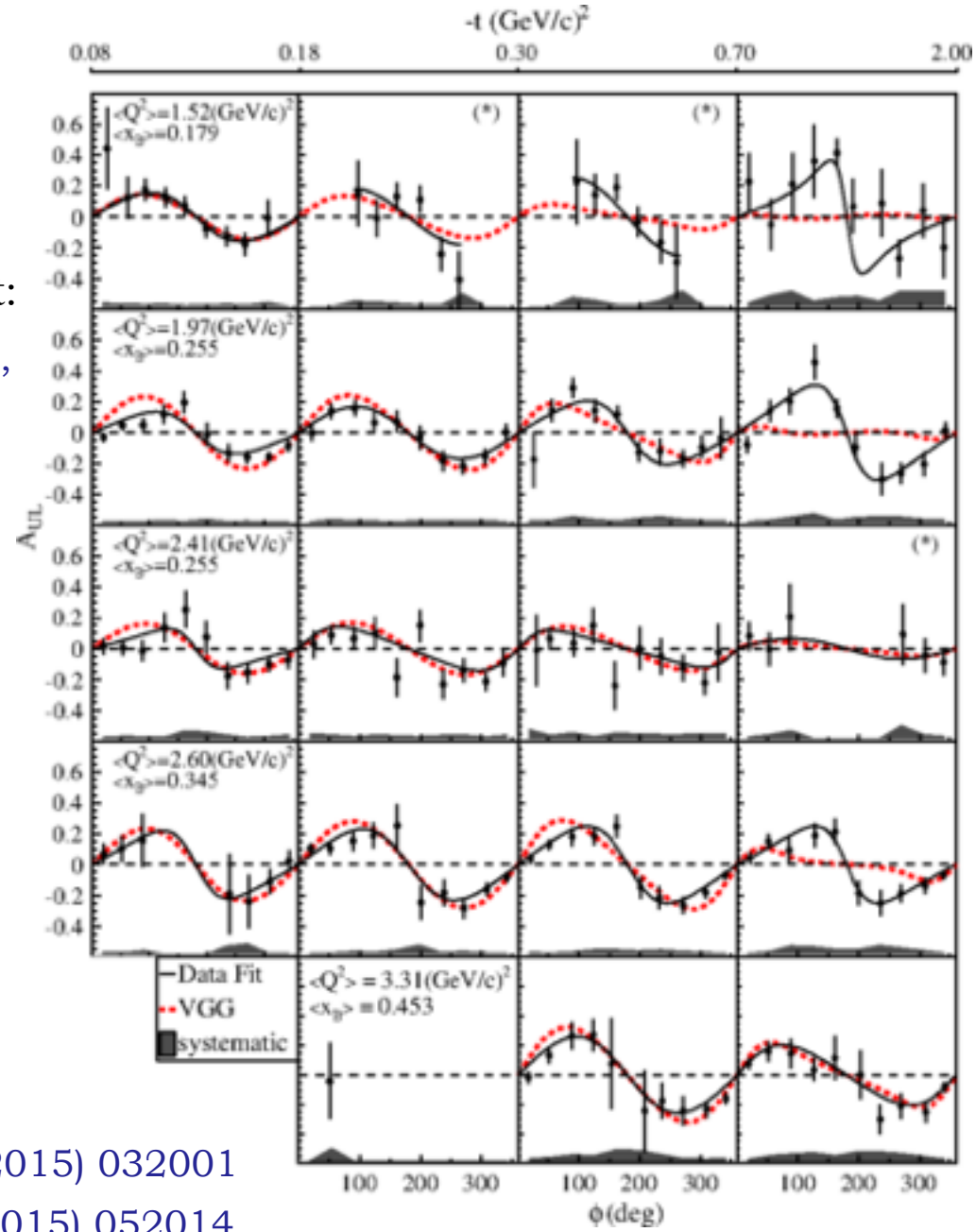
A_{UL} from fit to asymmetry:

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

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

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

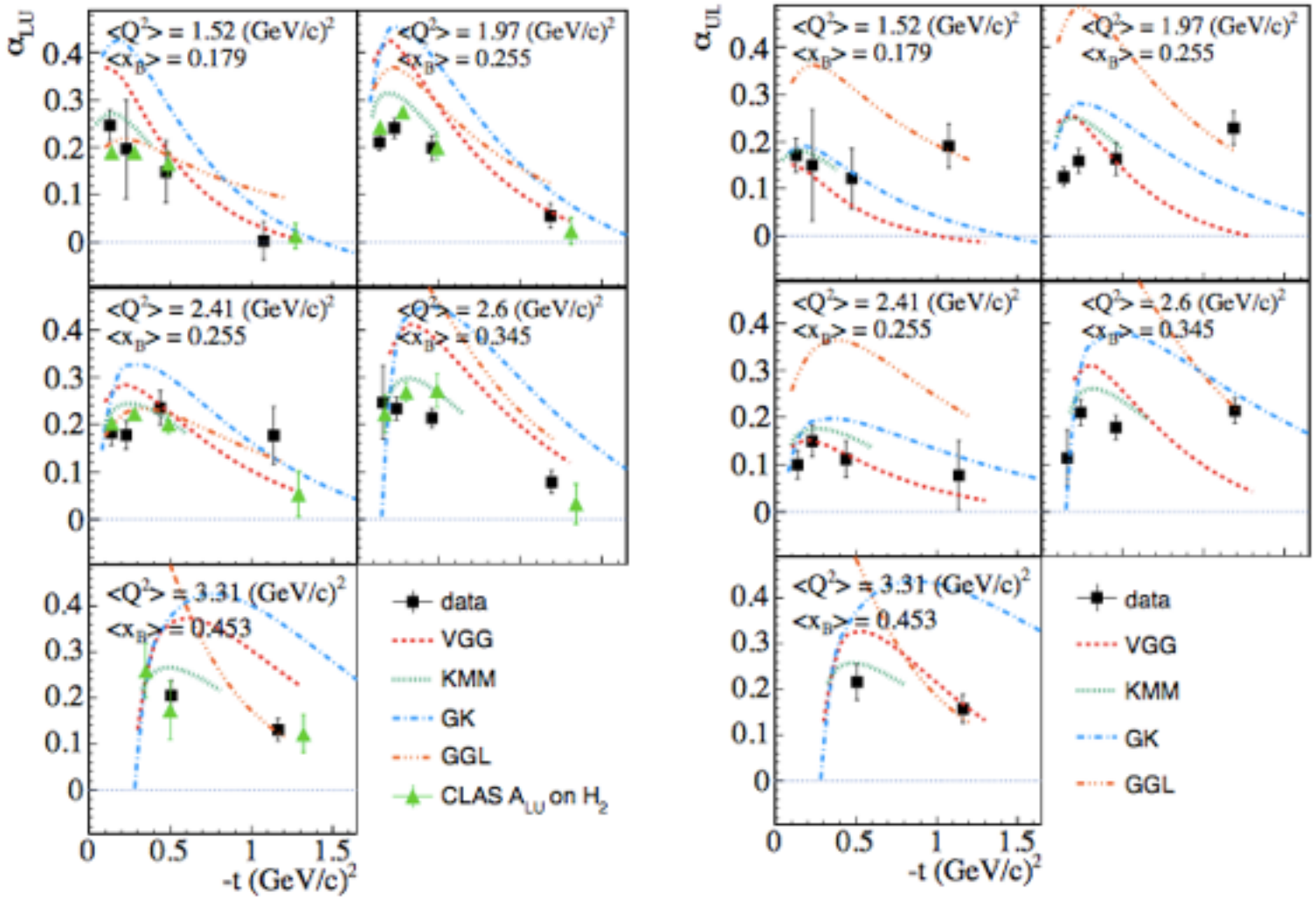
High statistics, large kinematic coverage, strong constraints on fits, simultaneous fit with BSA from the same dataset.



E. Seder *et al* (CLAS Collaboration), ***PRL* 114** (2015) 032001

S. Pisano *et al* (CLAS Collaboration), ***PRD* 91** (2015) 052014

Beam- and target-spin asymmetries



$$A = \frac{\alpha sin\phi}{1+\beta cos\phi}$$

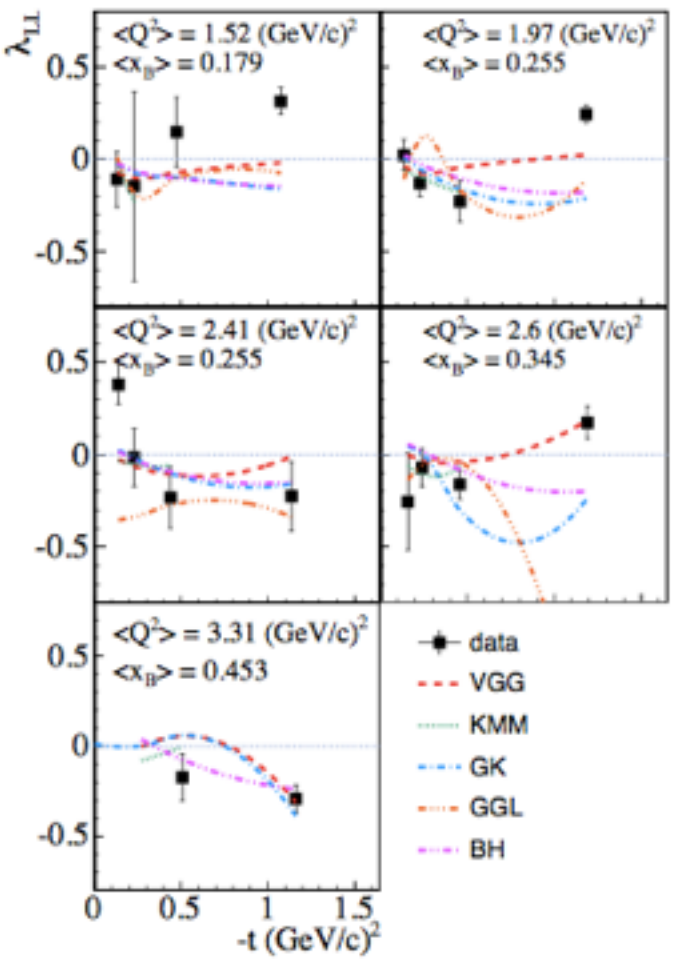
GGL: Goldstein, Gonzalez, Liuti

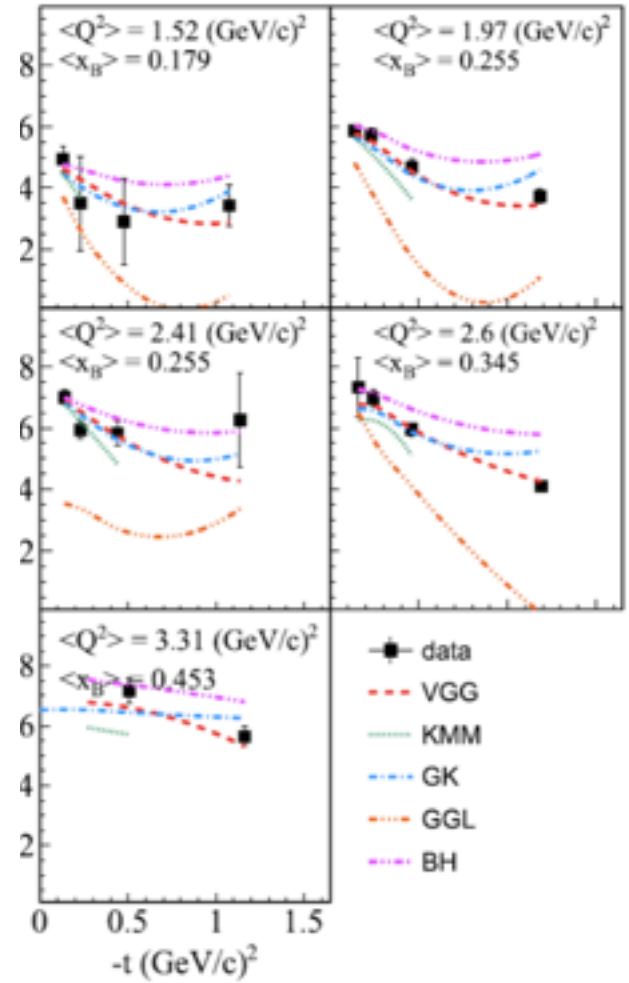
GK: Kroll, Moutarde, Sabatié

KMM: Kumericki, Mueller, Murray

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})





A_{LL} from fit to asymmetry:

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

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

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

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

E. Seder *et al* (CLAS Collaboration), ***PRL* 114** (2015) 032001

S. Pisano *et al* (CLAS Collaboration), ***PRD* 91** (2015) 052014

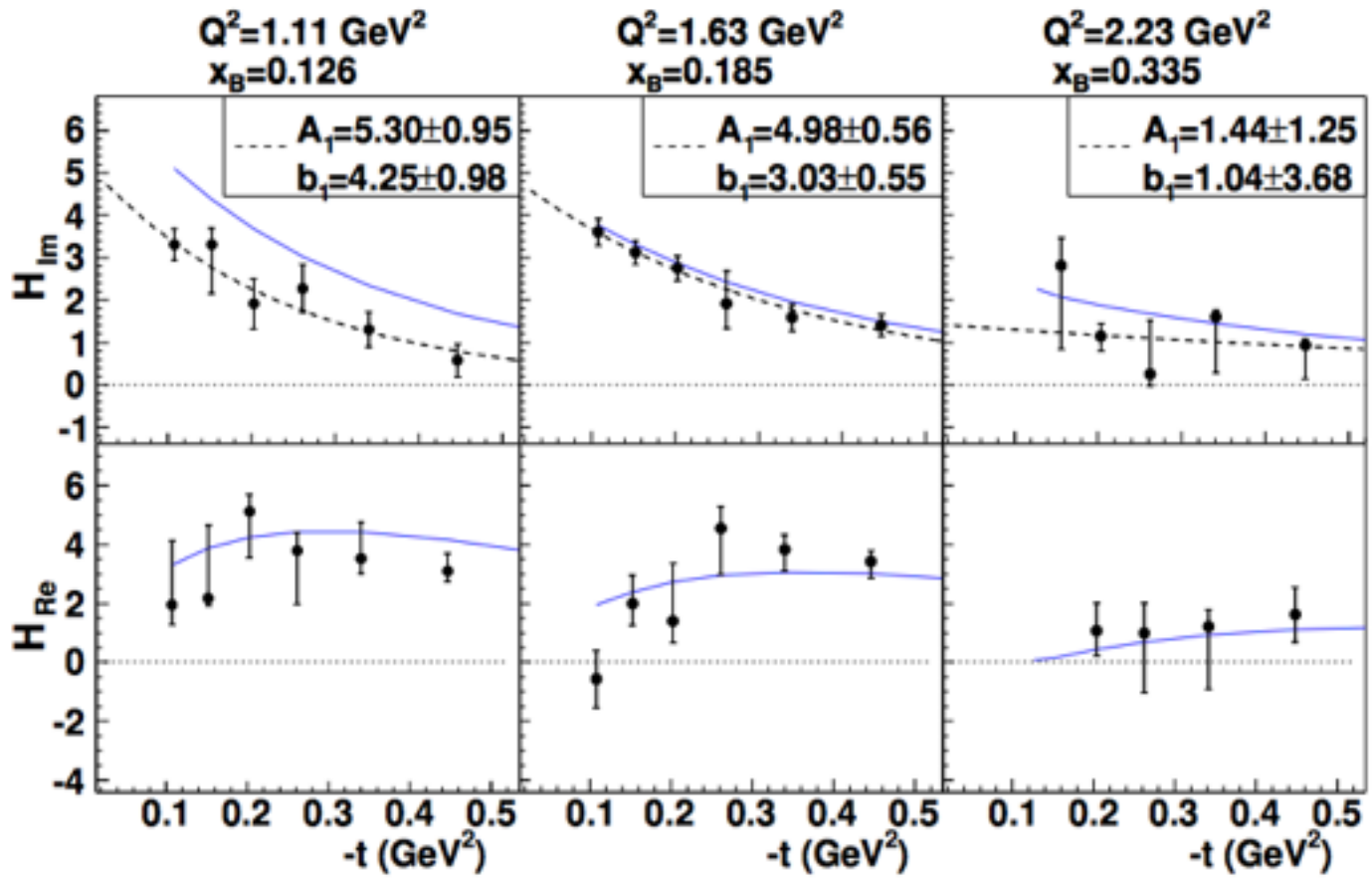
CFFs from the cross-sections

VGG

Ae^{bt}

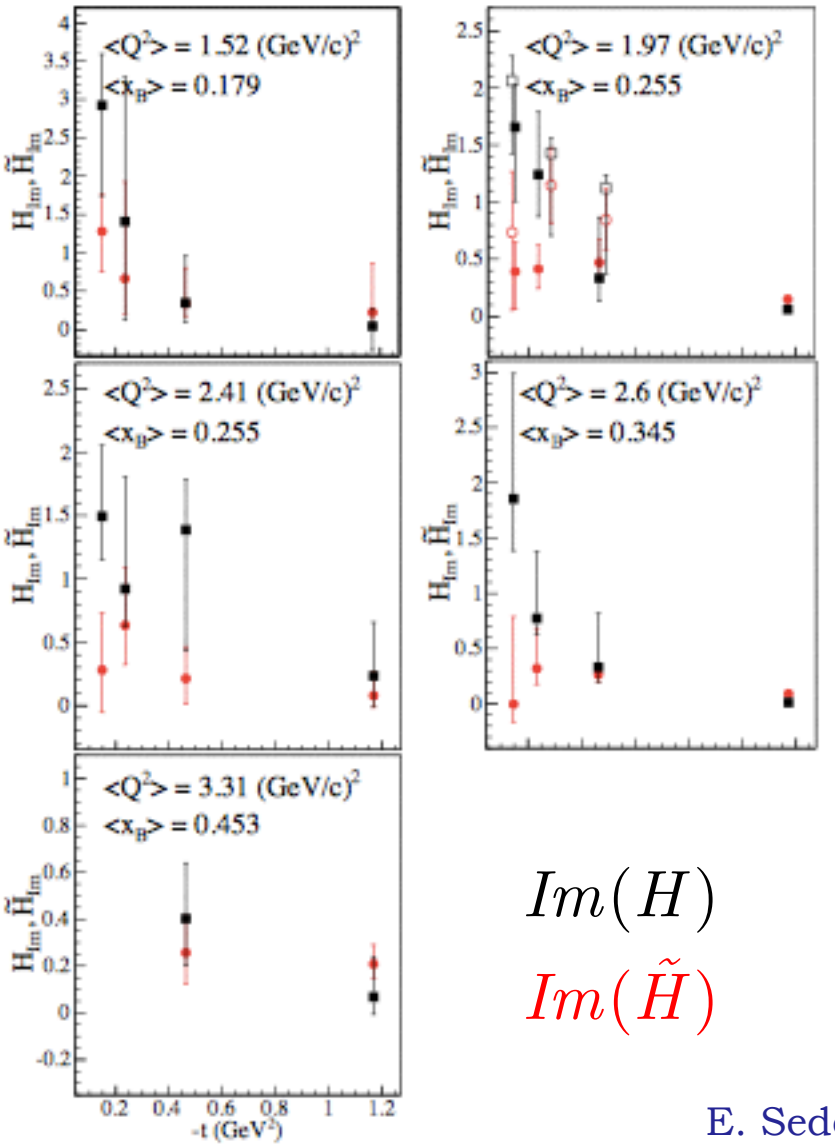
* Slope in t becomes flatter at higher x_B

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



H.-S. Jo *et al* (CLAS Collaboration), ***PRL* 115** (2015) 212003

What can we learn from the asymmetries?



$Im(H)$

$Im(\tilde{H})$

Answers hinge on a global analysis of all available data (*See talk by P. Sznajder on PARTONS*).

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

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

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

Future DVCS with CLAS12

DVCS with CLAS12

E12-06-119: Unpolarised liquid H_2 target

Beam-spin asymmetry → ***Im*(H$_p$)**

First experiment with CLAS12! Autumn '17

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

E12-16-010: Unpolarised liquid H_2 target

Beam energy: 6.6 GeV, 8.8 GeV ~2018/20

E12-11-003: Unpolarised liquid D_2 target

$$e + d \rightarrow e' + \gamma + n + (p_s)$$

Beam-spin asymmetry in neutron-DVCS → ***Im*(E$_n$)**

~2019

E12-12-010: Transversely polarised HD target.

Target-spin asymmetries → ***Im*(E$_p$)**

~2021/22

E12-06-109: Longitudinally polarised NH_3 and ND_3 targets

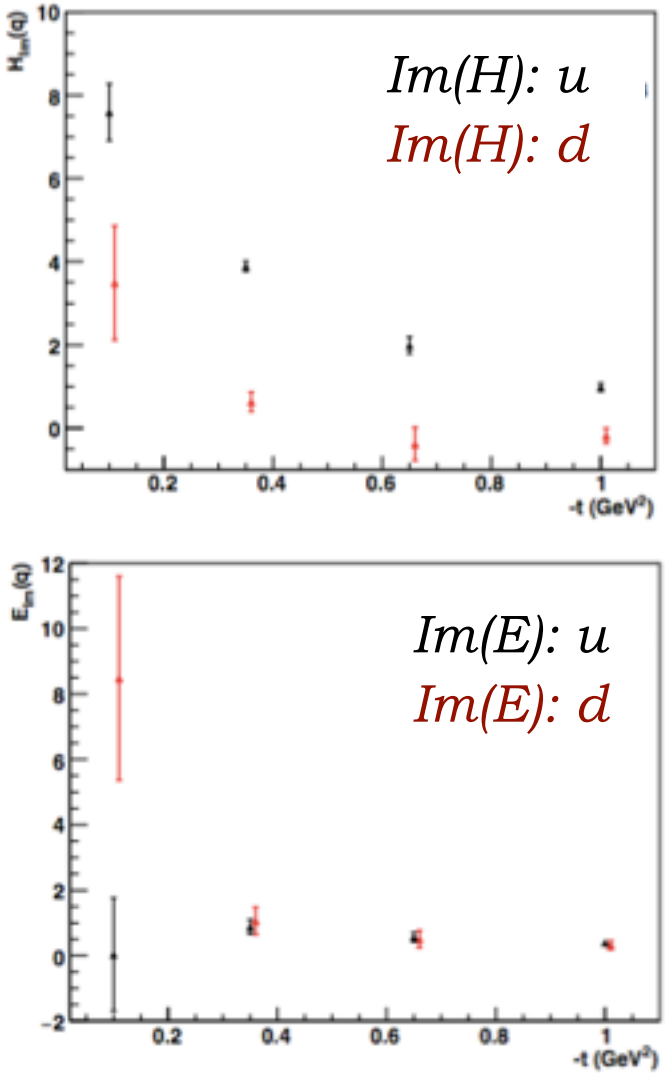
- Dynamic Nuclear Polarisation (DNP) of target material, cooled in a *He* evaporation cryostat.
- P_{proton} = 80%, $P_{deuteron}$ up to 50%

Target-spin asymmetry in proton- and neutron-DVCS → ***Im*($\widetilde{H}_p$), *Im*(H$_n$)**

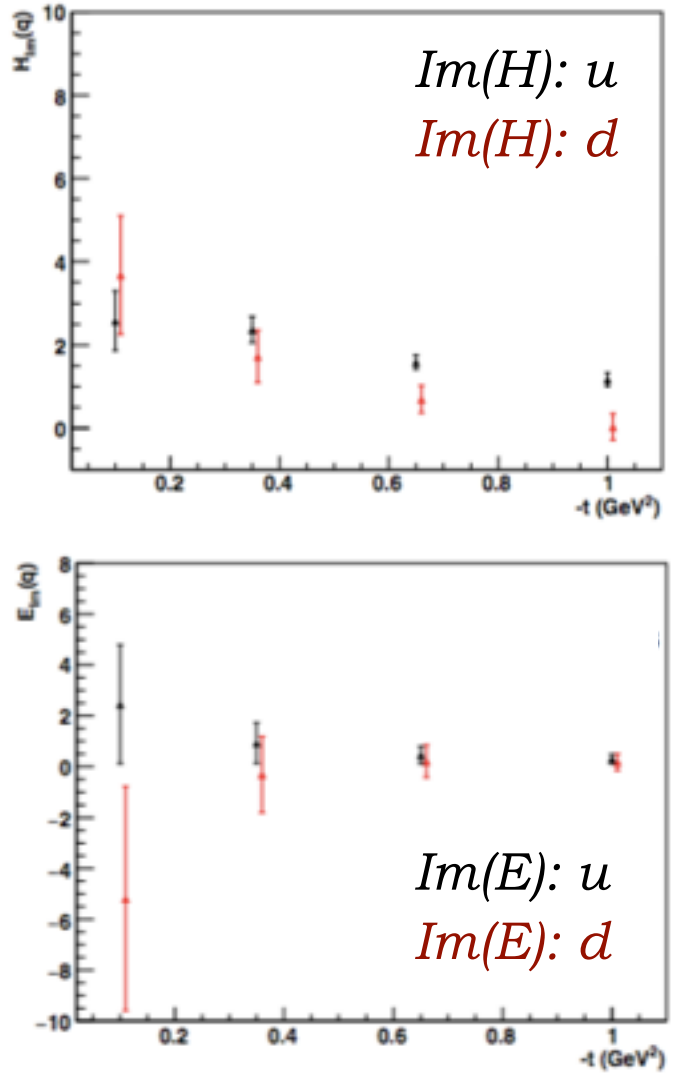
~ 2020

Projected sensitivities to CFF: CLAS12

$Q^2 = 2.6\ GeV^2$, $x_B = 0.23$



$Q^2 = 5.9\ GeV^2$, $x_B = 0.35$



Projections for *Im(H)* and *Im(E)* up and down CFFs to be extracted from approved CLAS12 experiments.

Using VGG fit (M. Guidal)

To conclude...

- Measurements of cross-sections and asymmetries in dedicated, high statistics DVCS experiments with 6 GeV and CLAS provide some of the first extractions of the Compton Form Factors in the valence quark region: tentative conclusions on relative quark distributions.

- A wide programme planned for CLAS12 in the 12 GeV era: higher luminosity, higher precision, wider reach of phase space, greater range of observables.

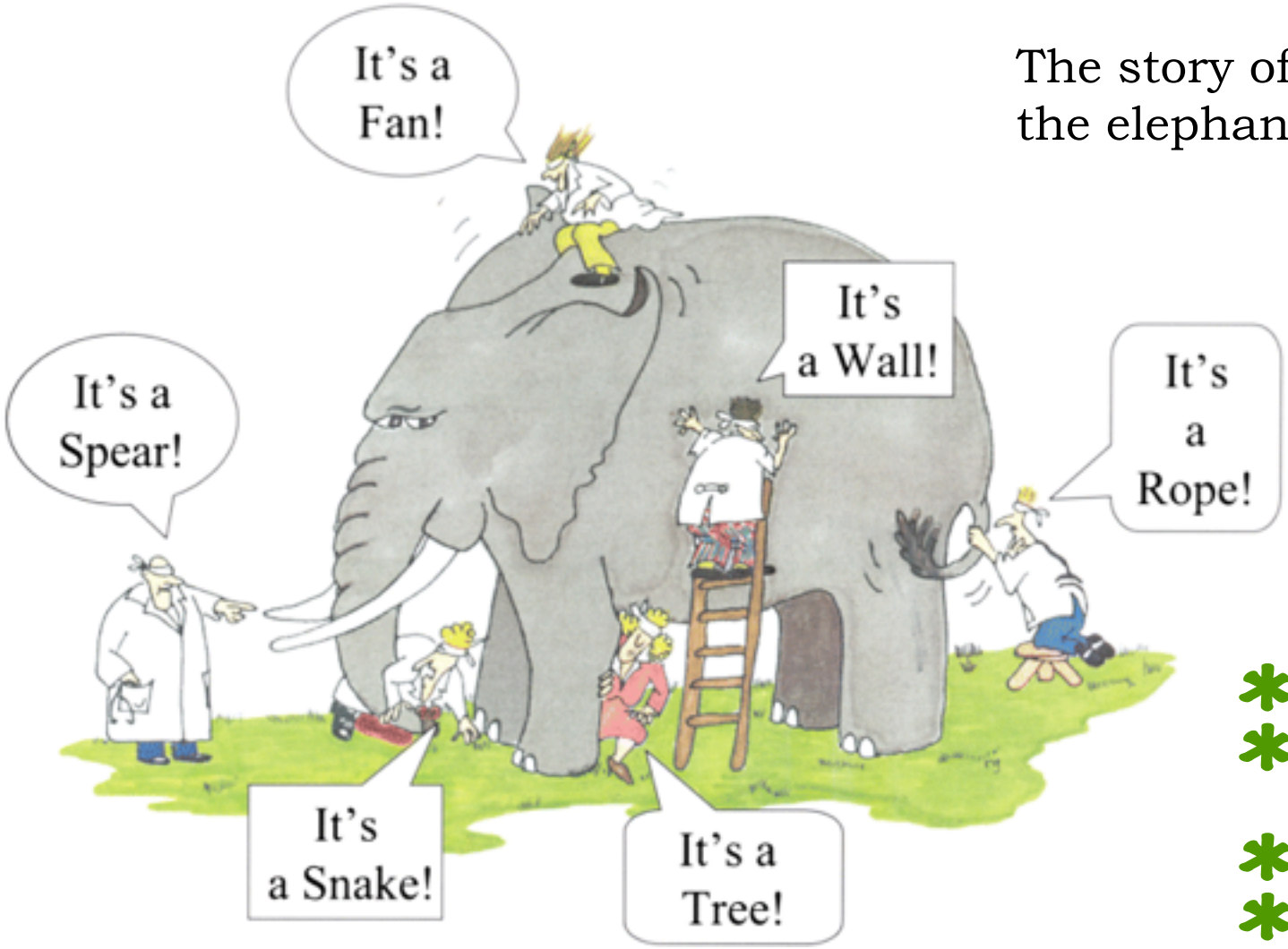
- Global analyses of all data a necessity for nucleon tomography.

- JLab @ 12 GeV: exciting opportunities for the study of nucleon structure.

- Watch this space!

Thank you

… is hard to come by

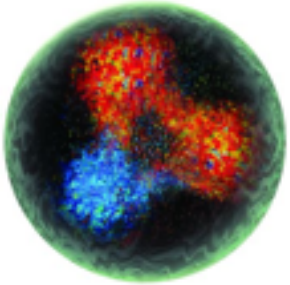


G. Renee Guzlas, artist.

The story of the blind men and the elephant.

- Elastic scattering
- Deep Inealstic Scattering (DIS)
- Semi-inclusive DIS
- Deep exclusive reactions

Images of the nucleon: I

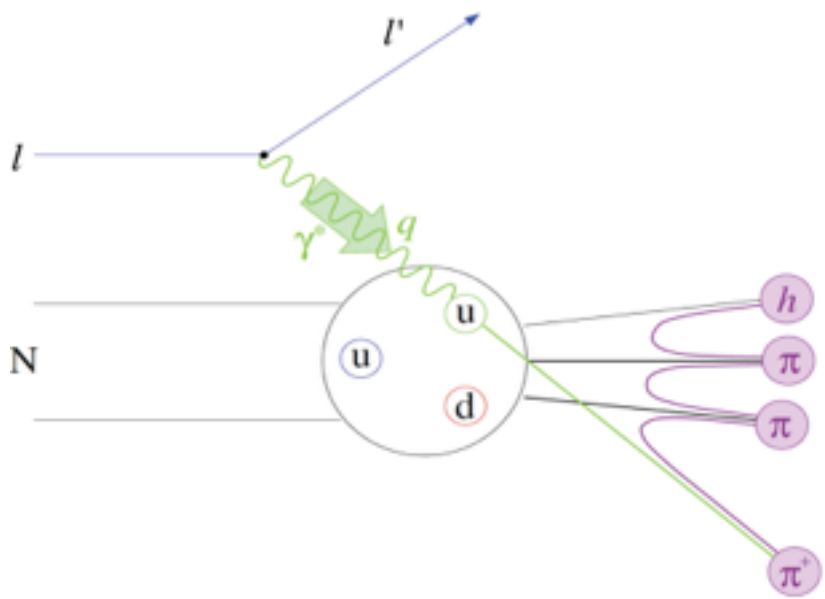


Wigner function:
full phase space parton
distribution of the nucleon

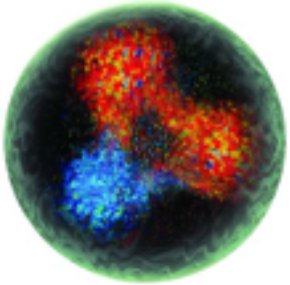
$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

* Semi-inclusive DIS



Images of the nucleon: II

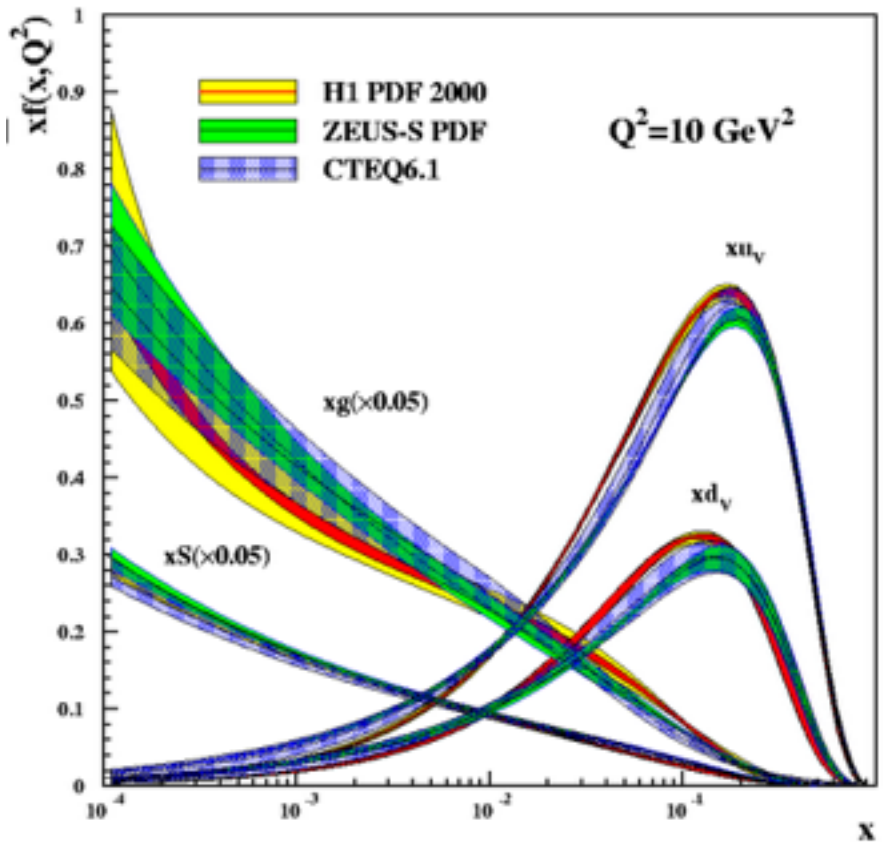


Wigner function:
full phase space parton distribution of the nucleon

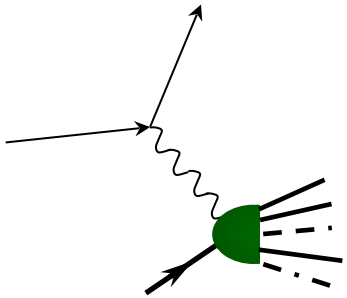
$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

$$\int d^2 k_T$$

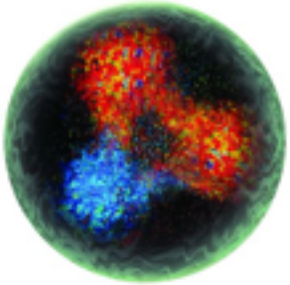


Parton Distribution Functions (PDFs)



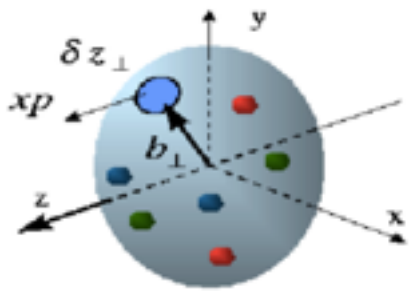
* Deep Inelastic Scattering

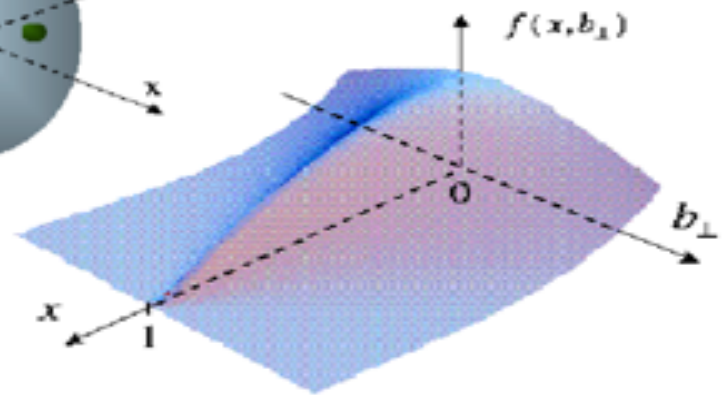
Images of the nucleon: III



Wigner function:
full phase space parton distribution of the nucleon

$$\int d^2 k_T$$



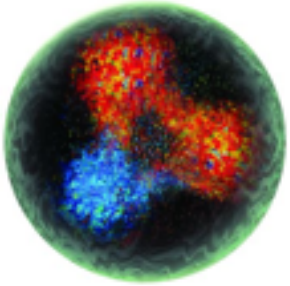


Generalised Parton Distributions (GPDs)

- relate, in the infinite momentum frame, transverse position of partons ($b_\perp$) to their longitudinal momentum (x): **tomography** of the nucleon.

✱ Deep exclusive reactions, e.g.: Deeply Virtual Compton Scattering, Deeply Virtual Meson Production, Time-like Compton Scattering, …

Images of the nucleon: IV

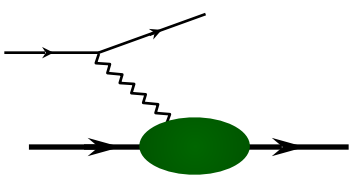


Wigner function:
full phase space parton distribution of the nucleon

$$\int d^2 k_T$$

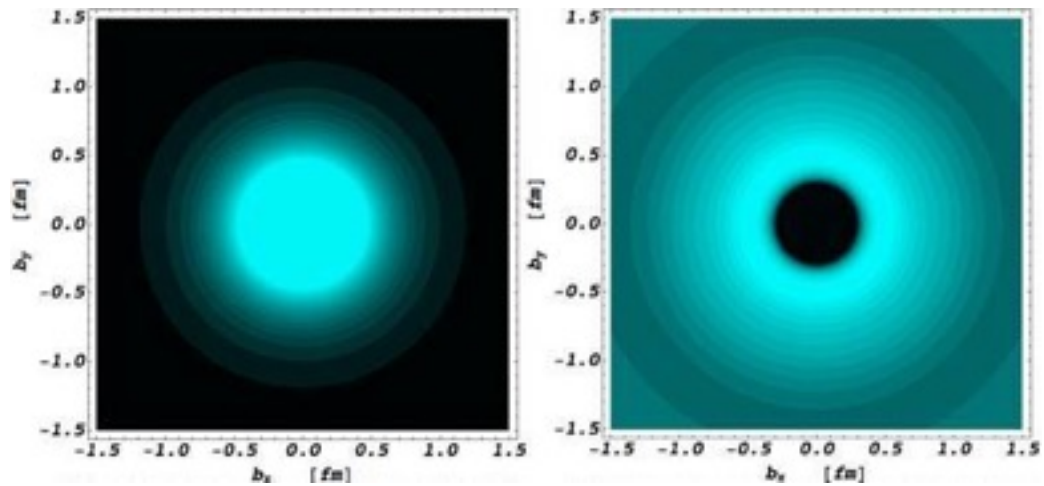
Generalised Parton Distributions (GPDs)

$$\int dx$$



Form Factors
eg: G_E, G_M

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



proton neutron

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

Beam-spin asymmetry: proton-DVCS

Experiment E12-06-119

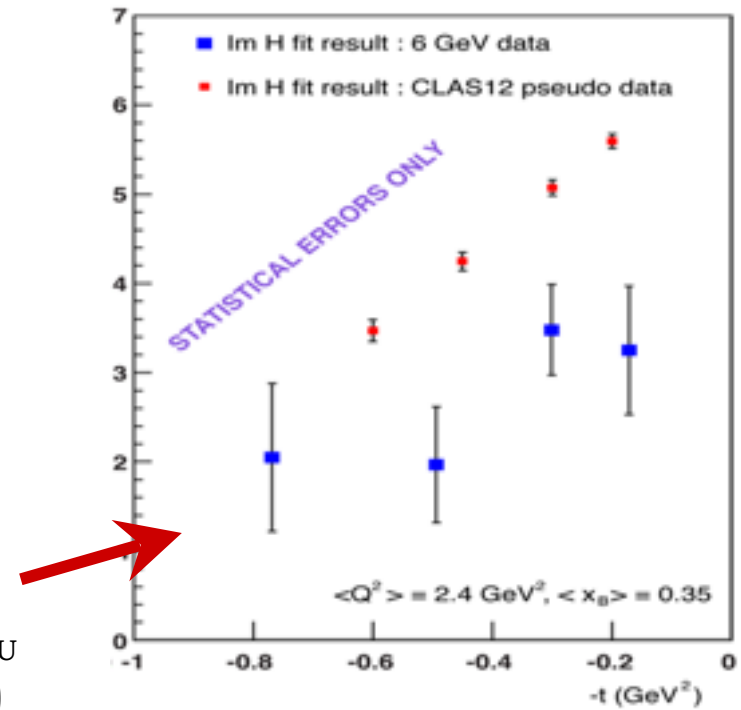
$P_{beam} = 85\%$
$L = 10^{35}\ cm^{-2}s^{-1}$
$1 < Q^2 < 10\ GeV^2$
$0.1 < x_B < 0.65$
$-t_{min} < -t < 2.5\ GeV^2$

Unpolarised liquid H_2 target:

- 80 days
- Statistical error: 1% - 10% on sinφ moments
- Systematic uncertainties: ~ 6 - 8%

First experiment with CLAS12!

Due to start this autumn



Impact of CLAS12 DVCS A_{LU} data on extraction of ***Im*(H)**

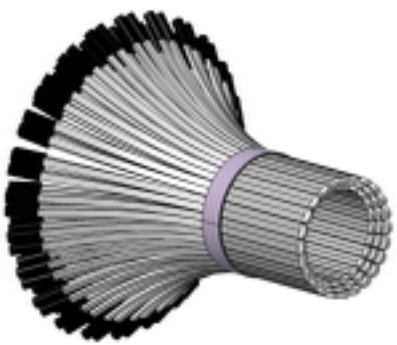
Beam-spin asymmetry: neutron-DVCS

Experiment E12-11-003

$$e + d \rightarrow e' + \gamma + n + (p_s)$$

80 days of data taking

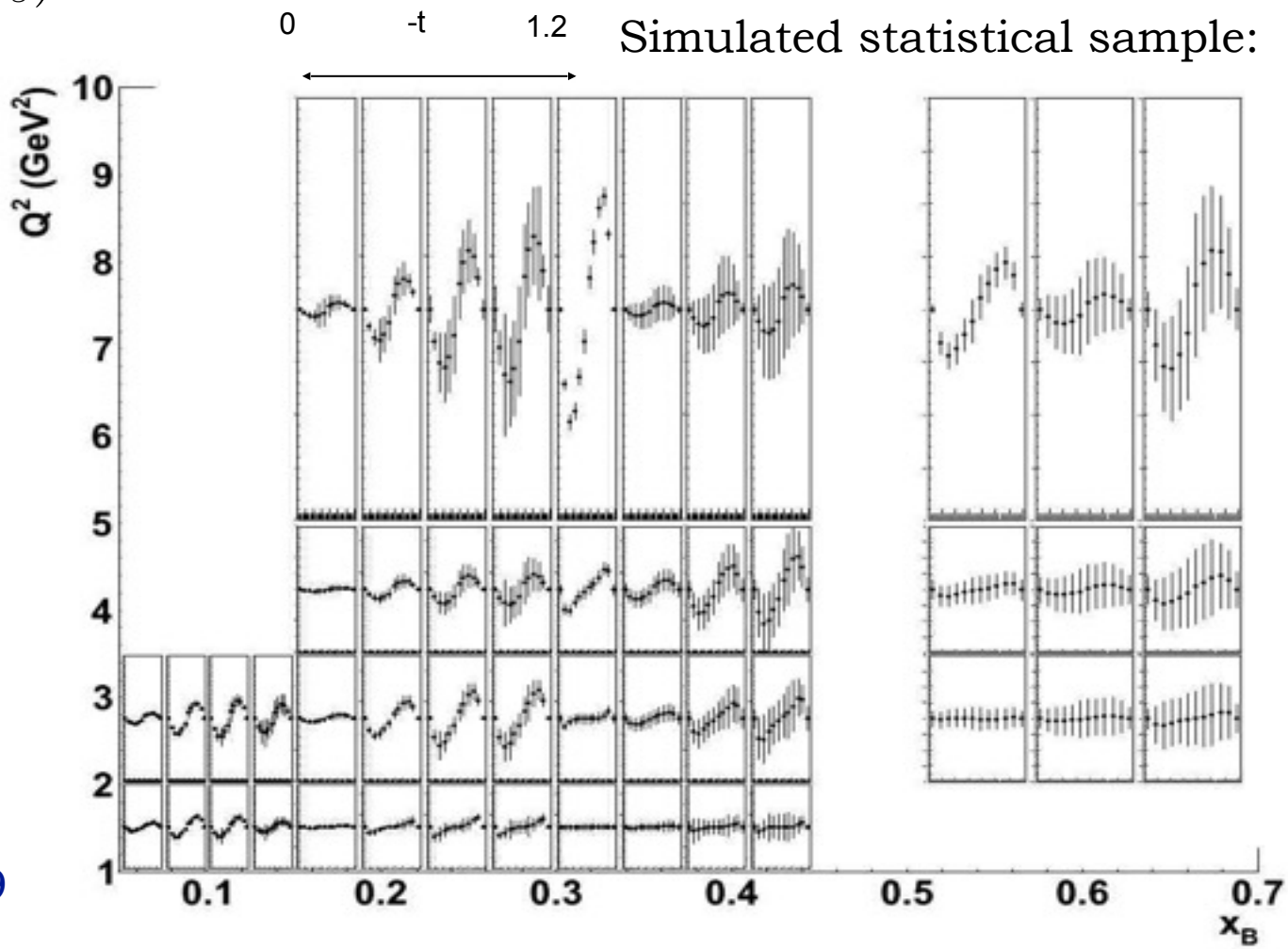
CLAS12 +
Forward Calorimeter
+
Neutron Detector



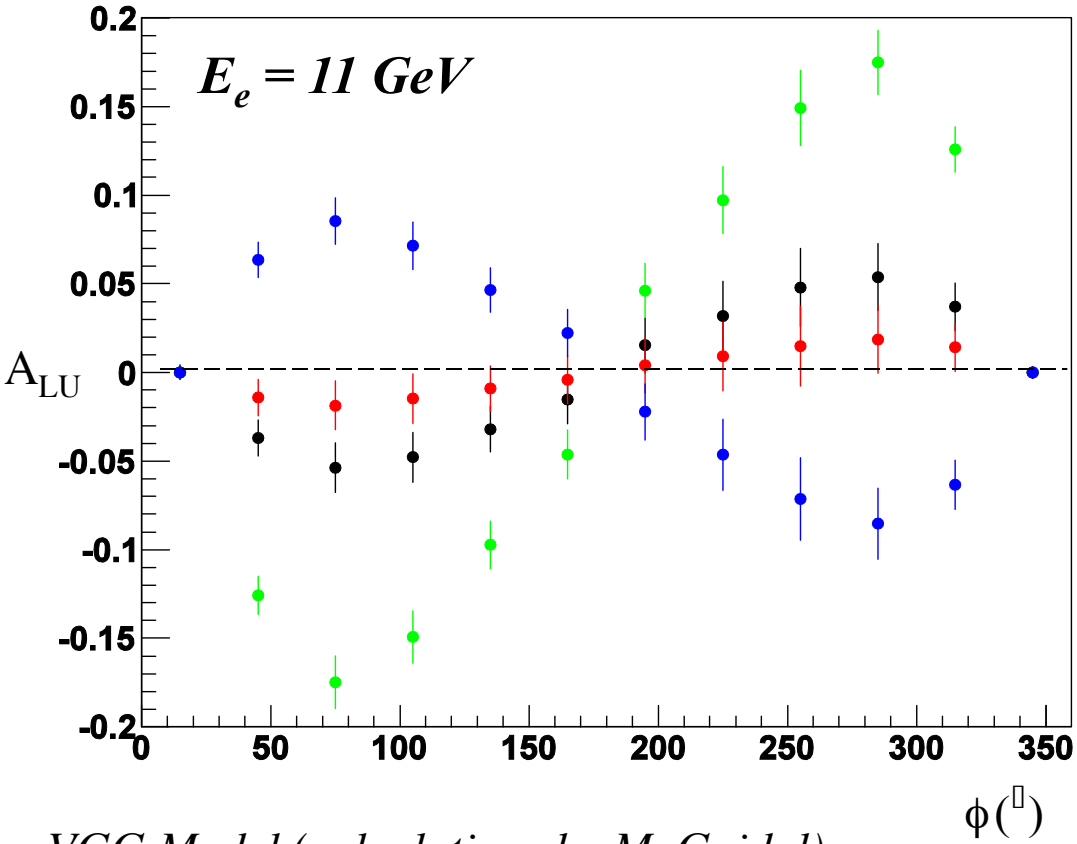
Tentative schedule: 2019

The **most sensitive** observable to the GPD $\mathbf{E_n}$

Simulated statistical sample:



A_{LU} in Neutron DVCS @ 11 GeV



VGG Model (calculations by M. Guidal)

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

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

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

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

Longitudinally polarised targets

Experiment E12-06-109

Longitudinally polarised NH_3 and ND_3 target:

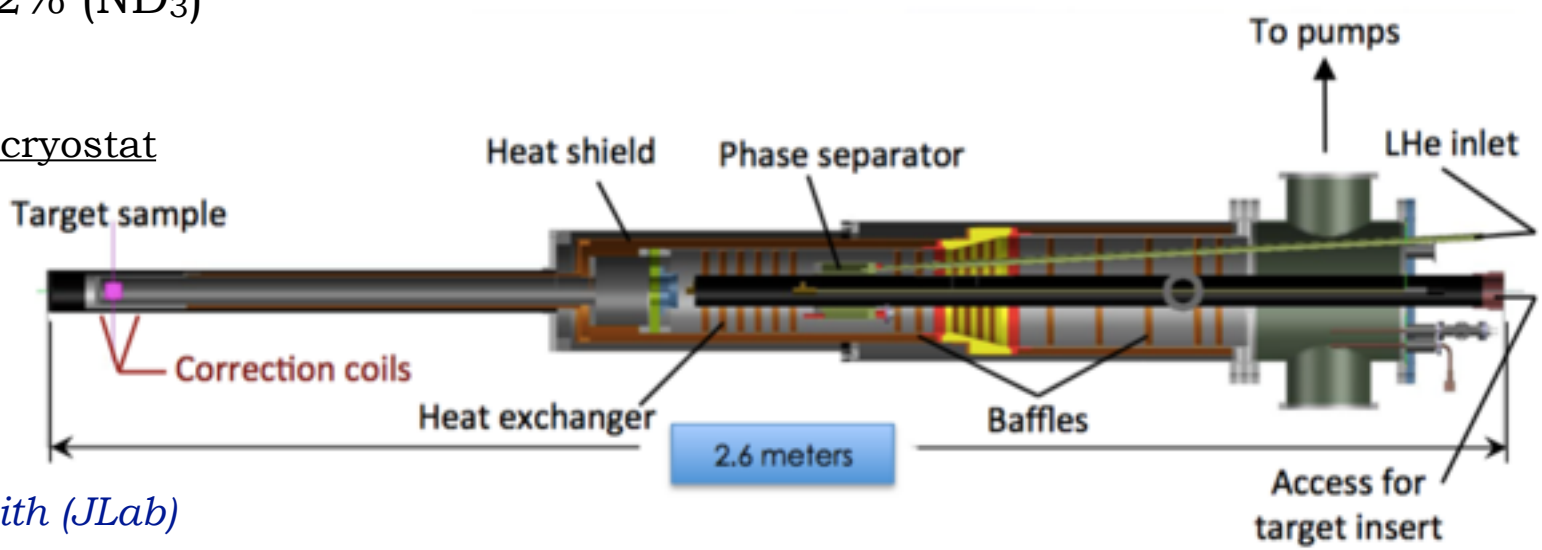
- 120 days (NH_3) 60 days (ND_3)
- Dynamic Nuclear Polarisation (DNP) of target material, cooled in a *He* evaporation cryostat.
- P_{proton} = 80%, $P_{deuteron}$ up to 50%
- Statistical error: 2% - 15% (NH_3)
- Systematic uncertainties: ~ 6 - 8% (NH_3), ~ 12% (ND_3)

Target-spin asymmetries in **proton- and neutron-DVCS:**

* Sensitivity to $\tilde{H}_p$ and H_n.

* In combination with A_{LU} in proton-DVCS, allows flavour separation of H_q.

Traget cryostat



C. Keith (JLab)

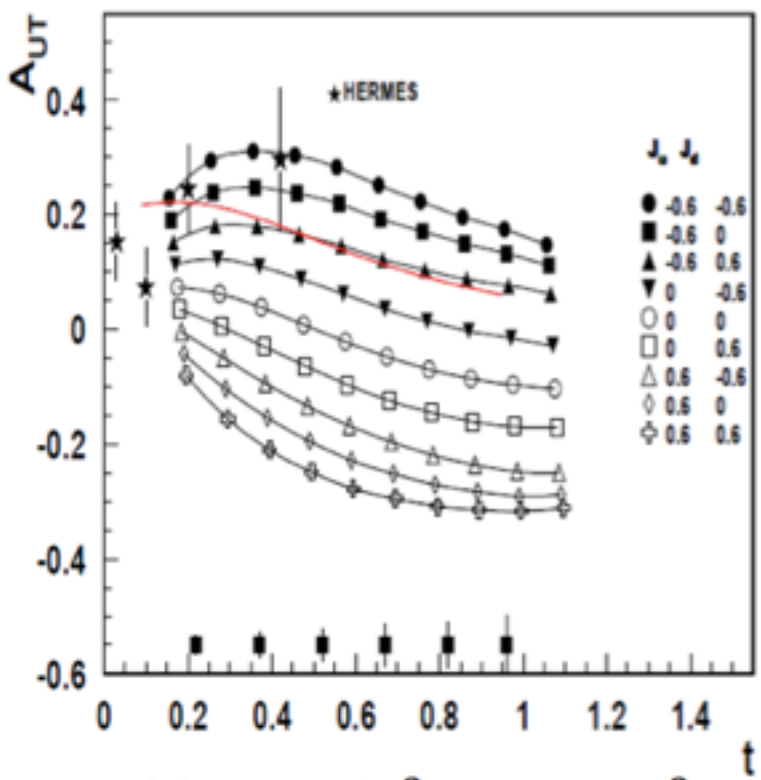
~ 2020

Transversely polarised target

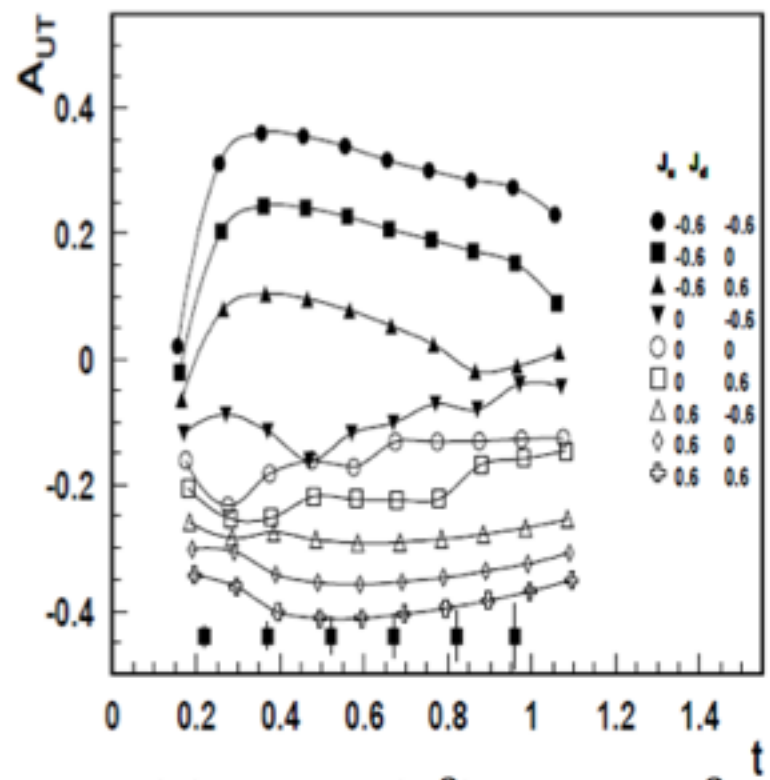
Experiment E12-12-010: transversely polarised HD target (conditional on target operation with electron beam).

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

Sensitivity to ***Im(E)***



$\langle x \rangle = 0.2, \langle Q^2 \rangle = 2.5\ GeV^2$



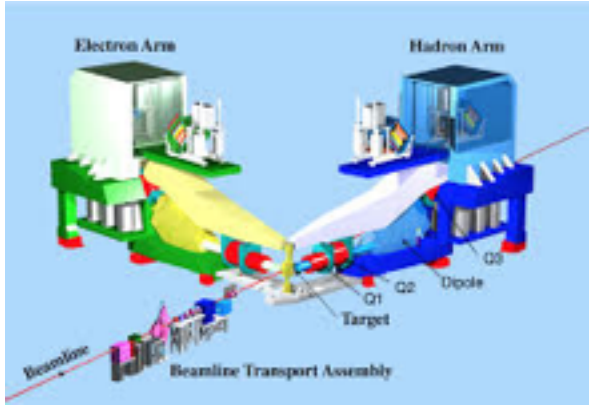
$\langle x \rangle = 0.33, \langle Q^2 \rangle = 2.5\ GeV^2$

Jefferson Lab: 6 GeV era

CEBAF: Continuous Electron Beam Accelerator Facility.

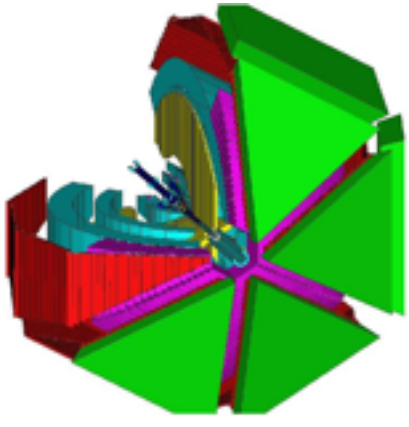
- Energy up to ~6 GeV
- Energy resolution $\delta E/E_e \sim 10^{-5}$
- Longitudinal electron polarisation up to ~85%

Hall A:



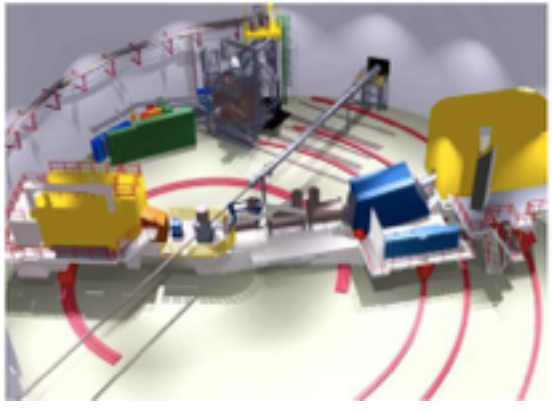
- High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity.

Hall B: CLAS



- Very large acceptance, detector array for multi-particle final states.

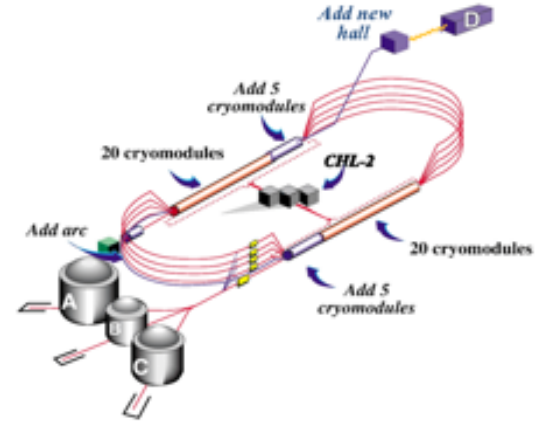
Hall C:



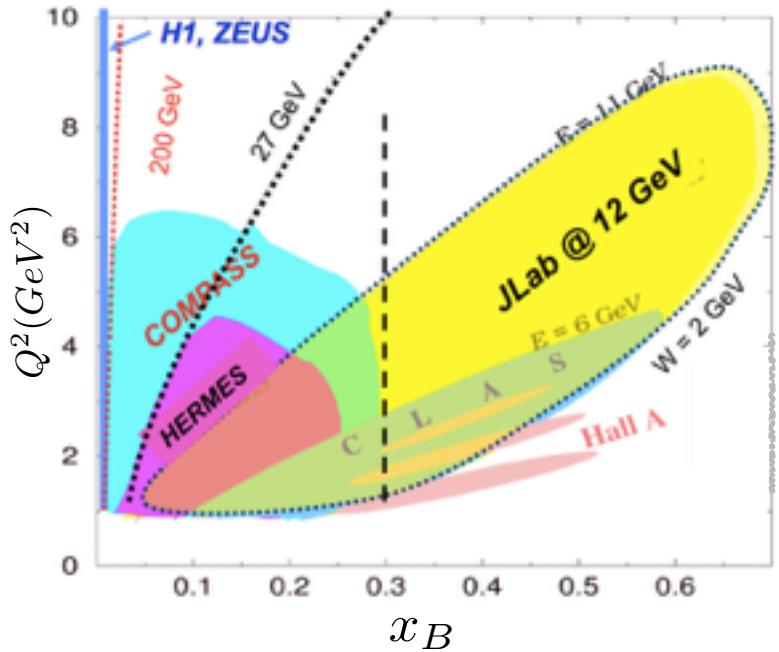
- Two movable spectrometer arms, well-defined acceptance, high luminosity

Jefferson Lab: 12 GeV era

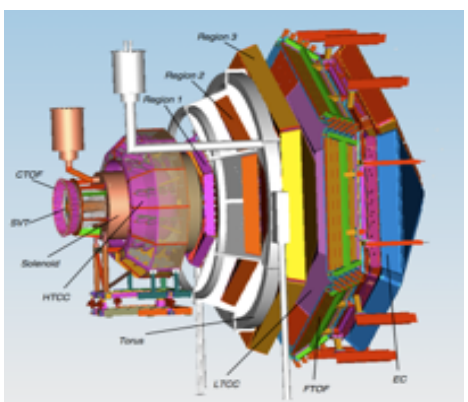
- Maximum electron energy: 12 GeV to new Hall D
- 11 GeV deliverable to Halls A, B and C



Hall A: High resolution spectrometers, large installation experiments



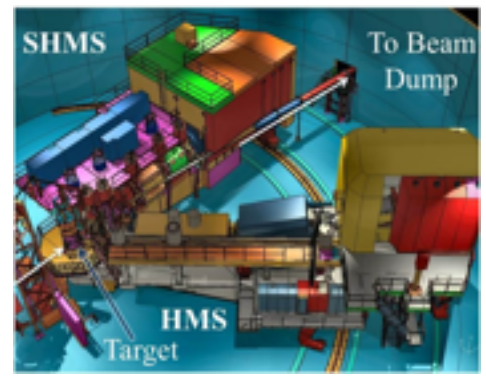
Hall B: CLAS12



Very large acceptance, high luminosity

Hall D: 9 GeV tagged polarised photons, full acceptance detector

Hall C:



Super-high Momentum Spectrometer added, very high luminosity