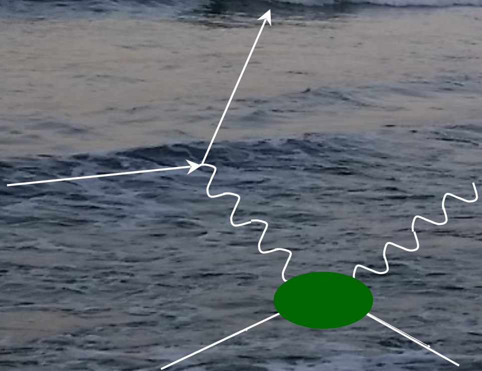
University of Glasgow

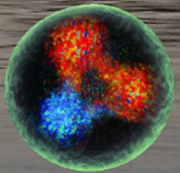
Jefferson Lab
EXPLORING THE NATURE OF MATTER

Nucleons under the electron microscope: Deeply Virtual Compton Scattering at JLab in the 6 GeV and 11 GeV eras.

Daria Sokhan

University of Glasgow,
Scotland

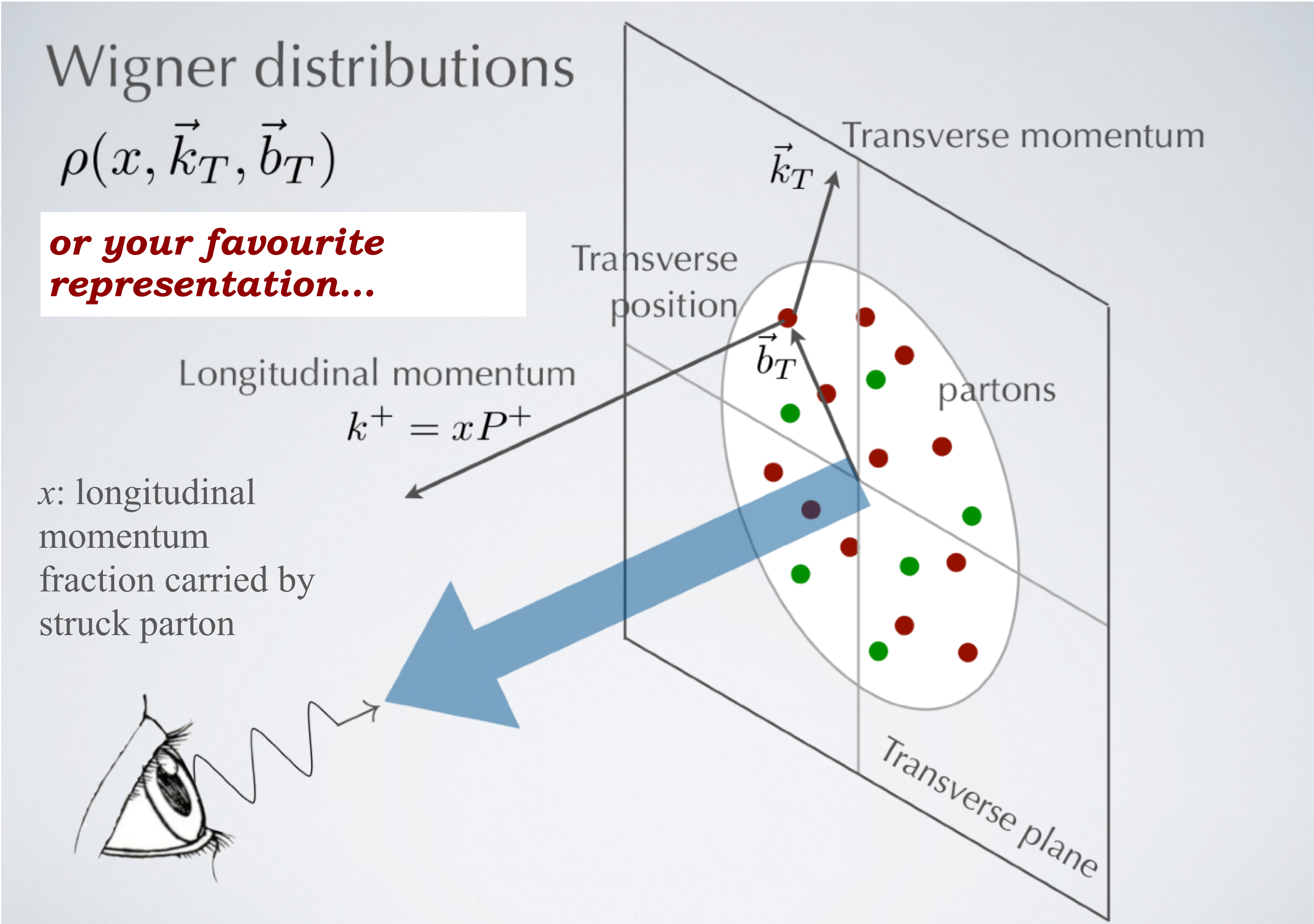




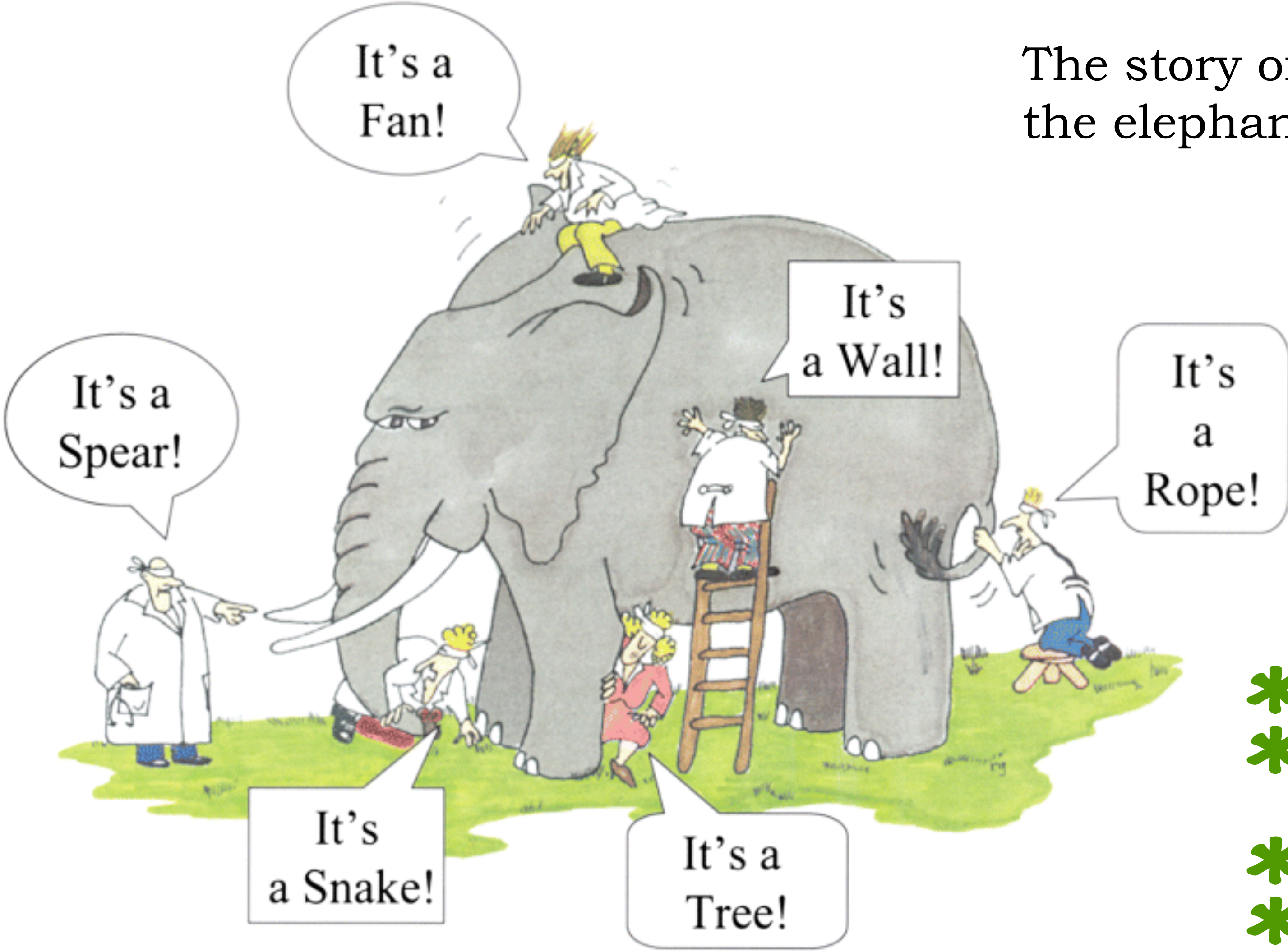
Many Manifestations of Non-Perturbative QCD
Camburi, Sao Paulo, Brazil— 3rd May 2018

Nucleon Tomography: Intro

A full knowledge of the nucleon…



… is hard to come by

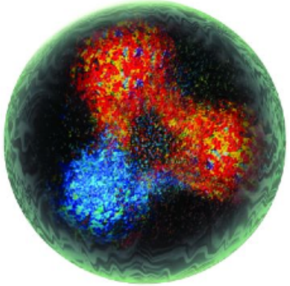


G. Renee Guzlas, artist.

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

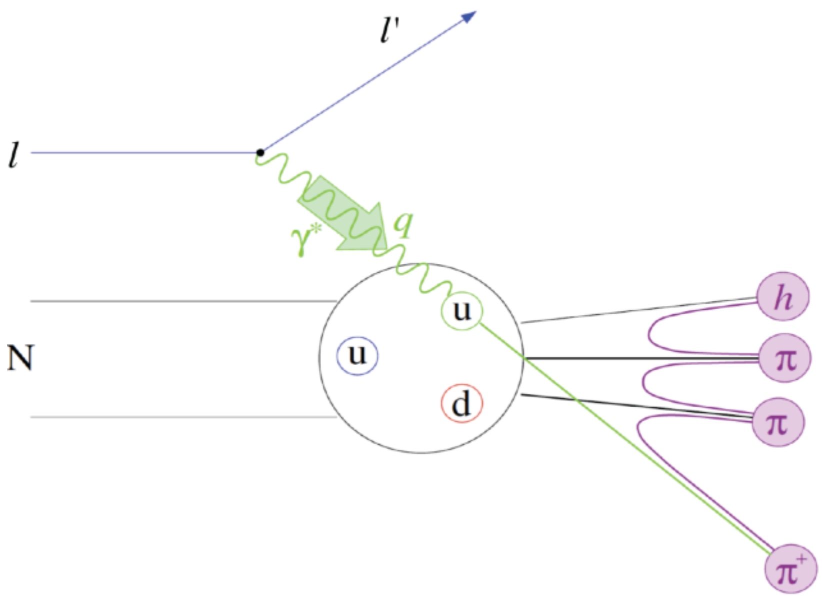


Wigner function:
full phase space parton
distribution of the nucleon

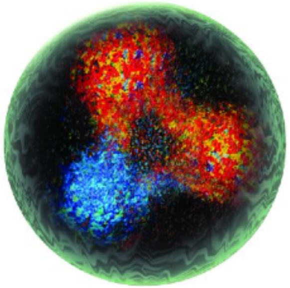
$$\int d^2 b_T$$

Transverse
Momentum
Distributions
(TMDs)

* Semi-inclusive DIS



Images of the nucleon



Wigner function:
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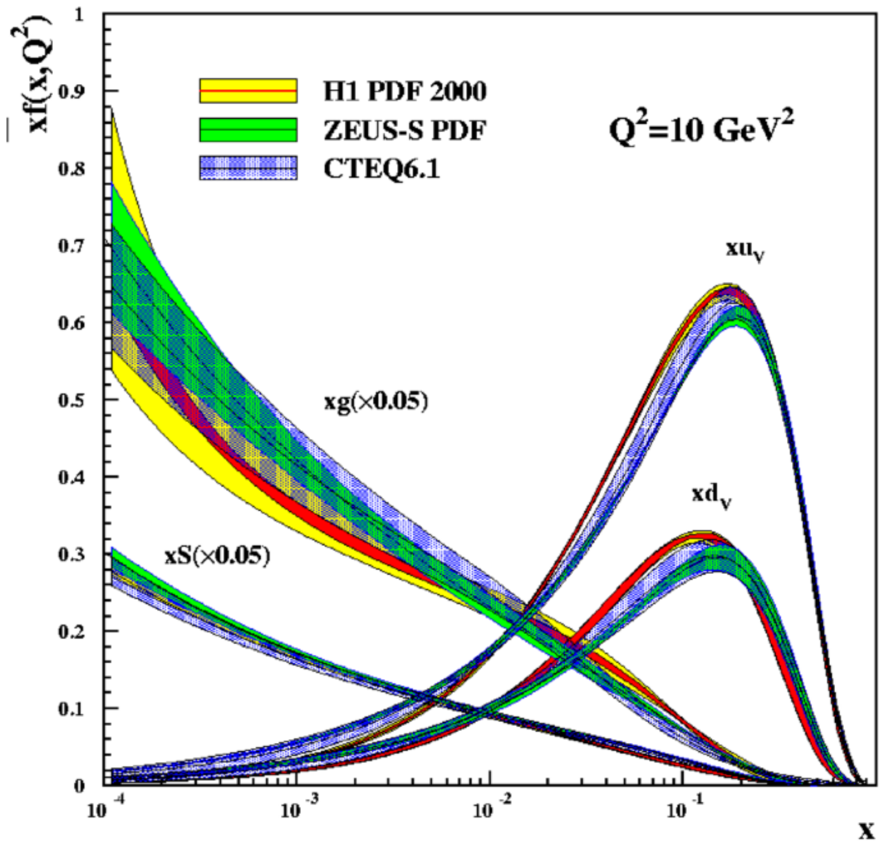
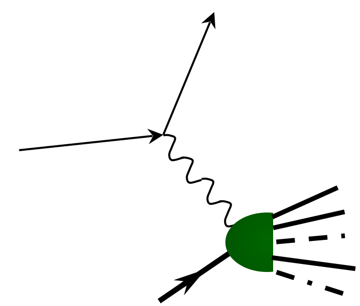
$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

$$\int d^2 k_T$$

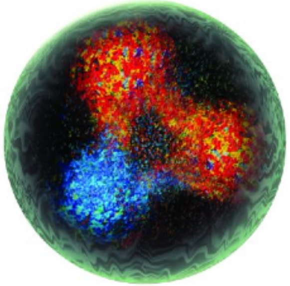


Parton Distribution Functions (PDFs)



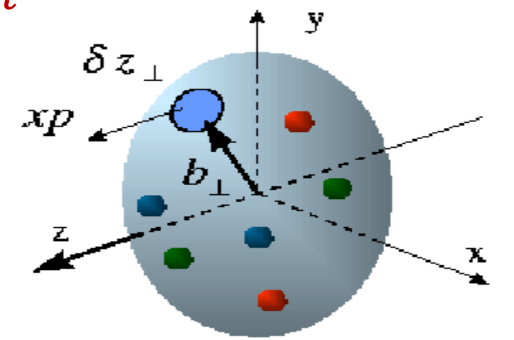
* Deep Inelastic Scattering

Images of the nucleon



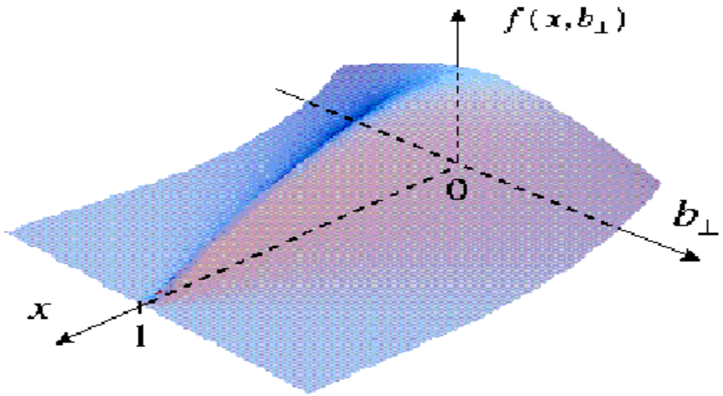
Wigner function: full phase space parton distribution of the nucleon

$$\int d^2k_T$$



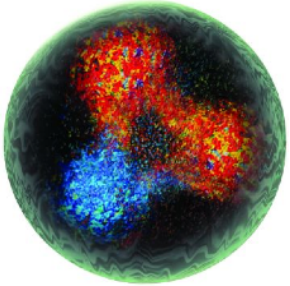
Generalised Parton Distributions (GPDs)

- 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, …

Images of the nucleon

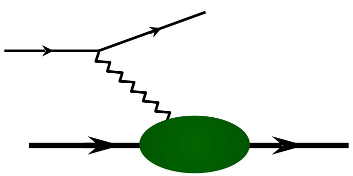


Wigner function:
full phase space parton
distribution of the nucleon

$$\int d^2 k_T$$

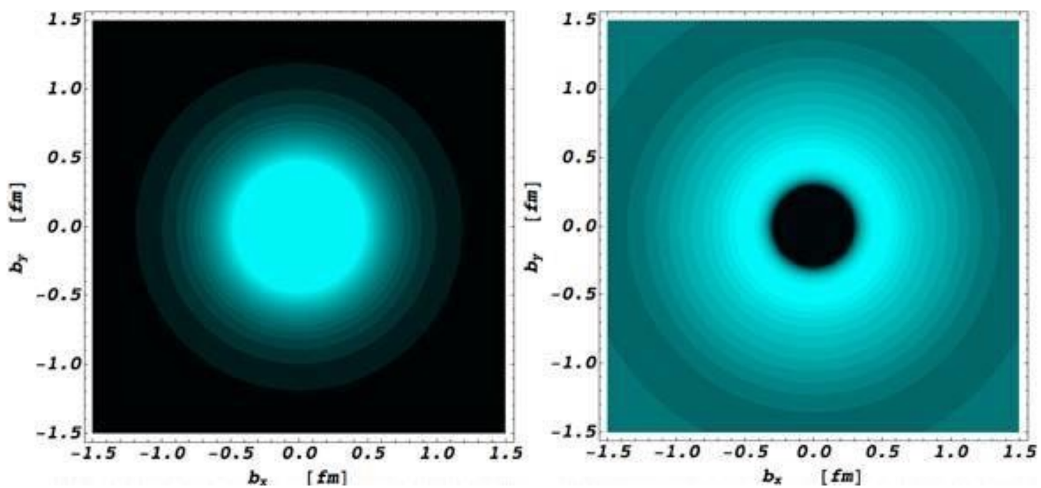
Generalised Parton Distributions (GPDs)

$$\int dx$$



Form Factors
eg: $G_{E,}\, G_M$

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

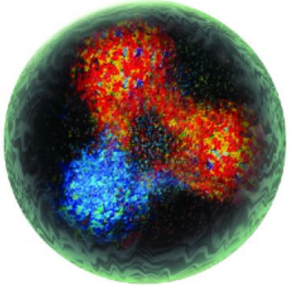


proton

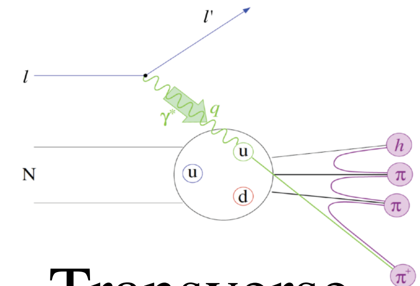
neutron

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

Images of the nucleon

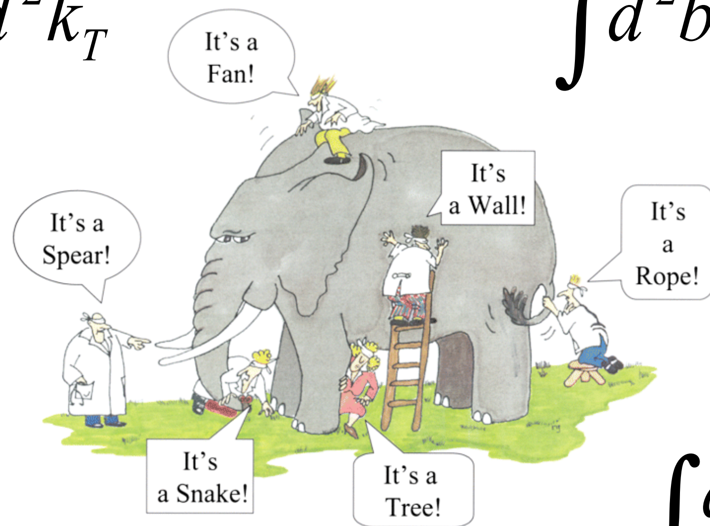


Wigner function:
full phase space parton distribution of the nucleon



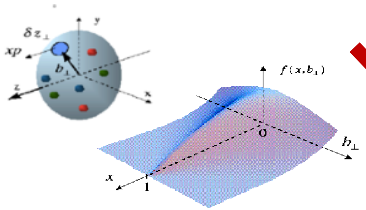
$\int d^2 k_T$

$\int d^2 b_T$



G. Renee Guzlas, artist.

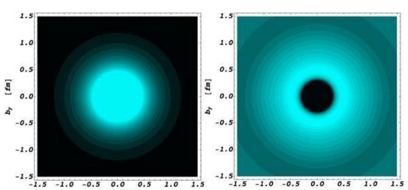
Generalised Parton Distributions (GPDs)



Transverse Momentum Distributions (TMDs)

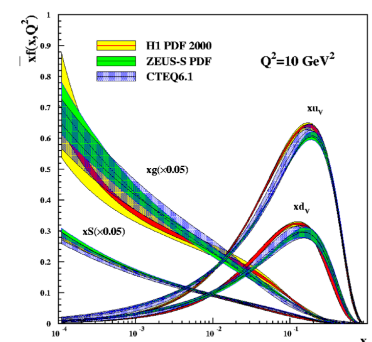
$\int dx$

$\int d^2 k_T$

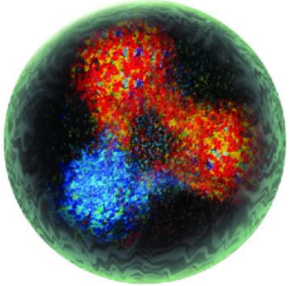


Form Factors
eg: G_{E}, G_{M}

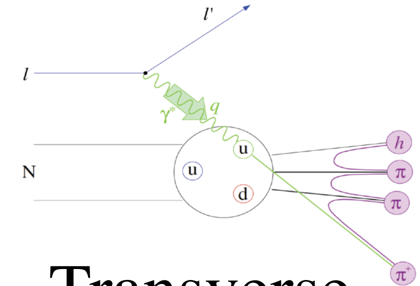
Parton Distribution Functions (PDFs)



Images of the nucleon



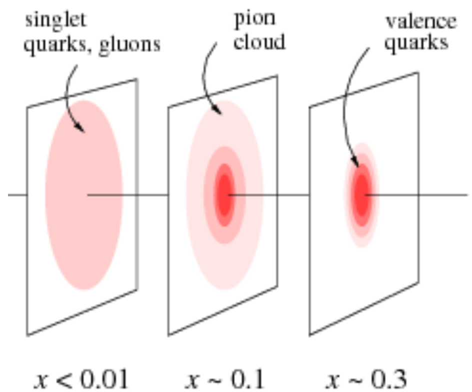
Wigner function: full phase space parton distribution of the nucleon



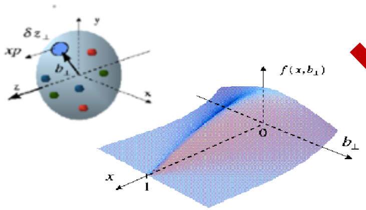
$\int d^2 k_T$

$\int d^2 b_T$

Generalised Parton Distributions (GPDs)

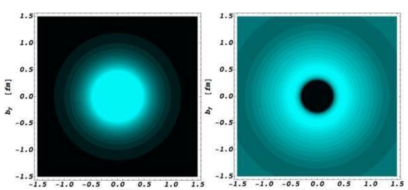


Transverse Momentum Distributions (TMDs)



$\int dx$

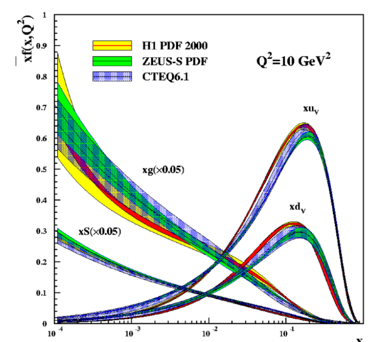
$\int d^2 k_T$



Form Factors

eg: G_{E}, G_{M}

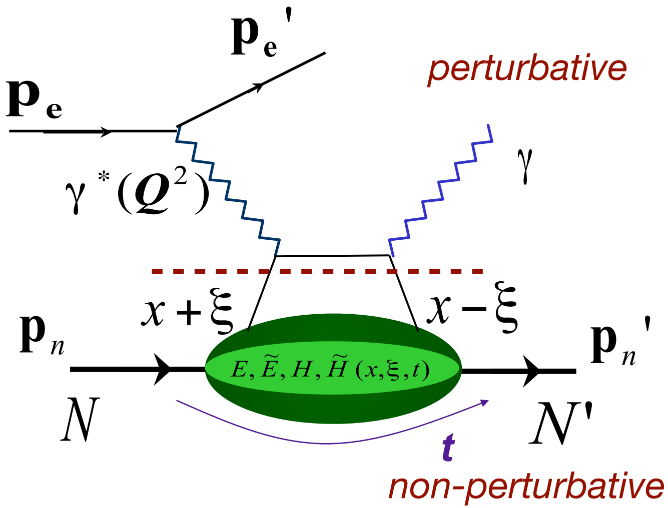
Parton Distribution Functions (PDFs)



DVCS — an experimental window on GPDs

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 chiral-even GPDs:

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

* Can be related to PDFs:

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

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.

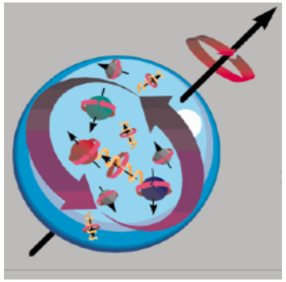
GPDs and nucleon spin

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

* 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:

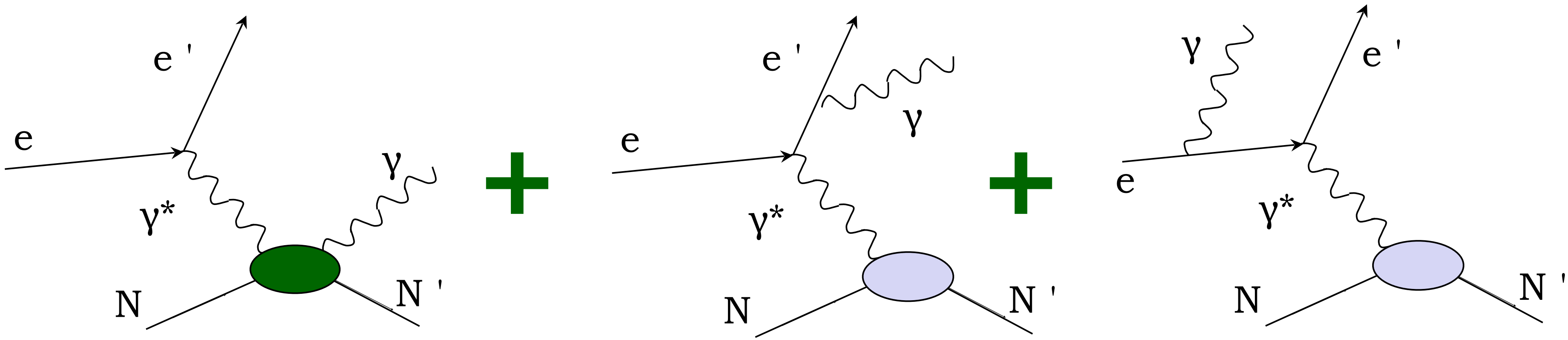
M. Mazouz et al, PRL 99 (2007) 242501



* 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

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

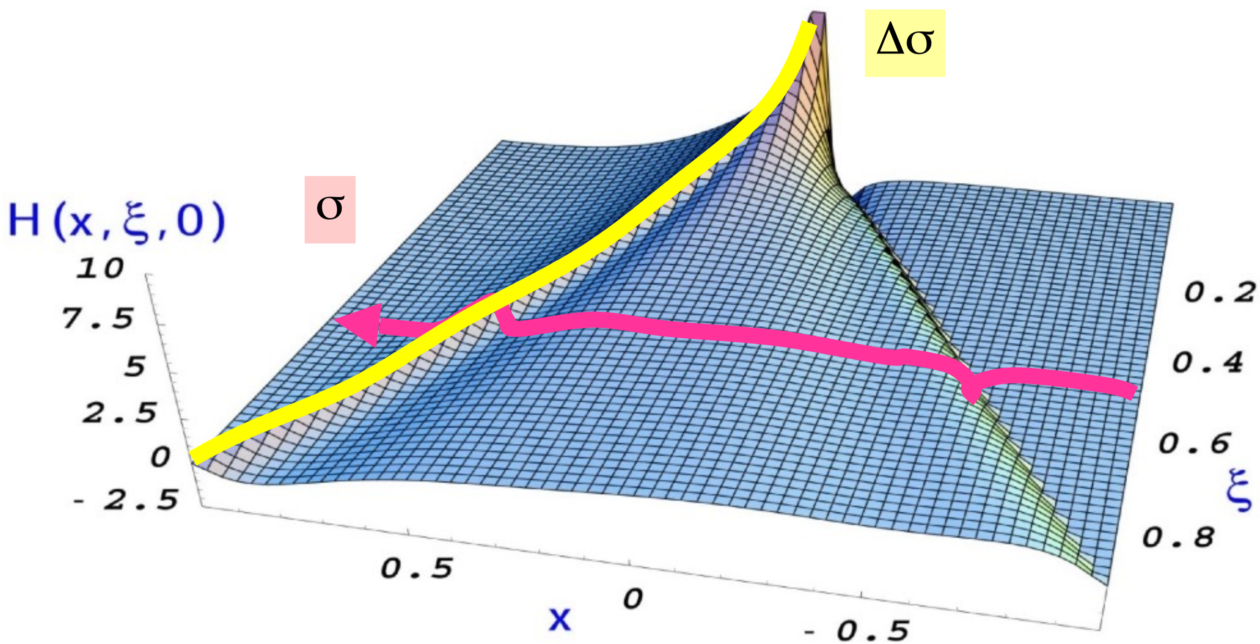
Compton Form Factors in DVCS

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

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

At leading twist, leading order:

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

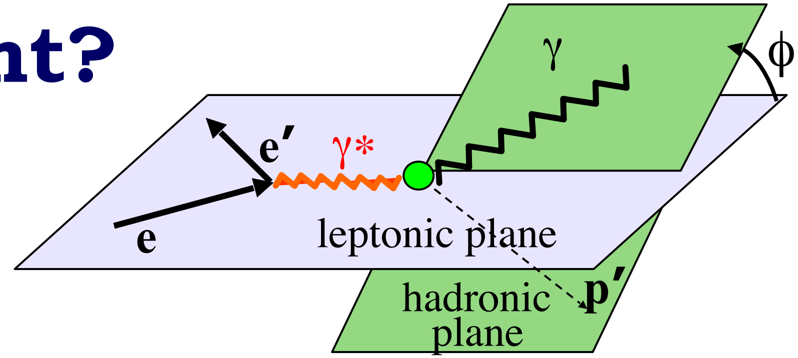


Only ξ and t are accessible experimentally!

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.

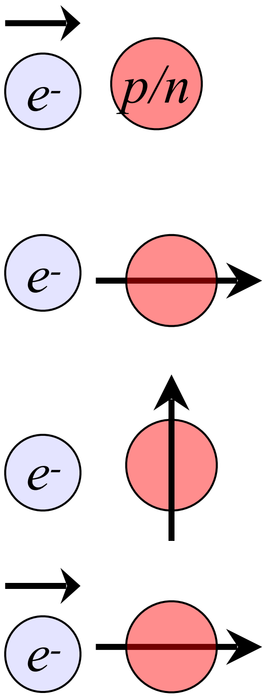
Which DVCS experiment?



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

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

$Im\{\mathbf{H_p}, \tilde{H}_p, E_p\}$
$Im\{H_n, \tilde{H}_n, \mathbf{E_n}\}$

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

$Im\{\mathbf{H_p}, \mathbf{\tilde{H}_p}\}$
$Im\{\mathbf{H_n}, E_n, \tilde{E}_n\}$

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

$Im\{\mathbf{H_p}, \mathbf{E_p}\}$
$Im\{\mathbf{H_n}\}$

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

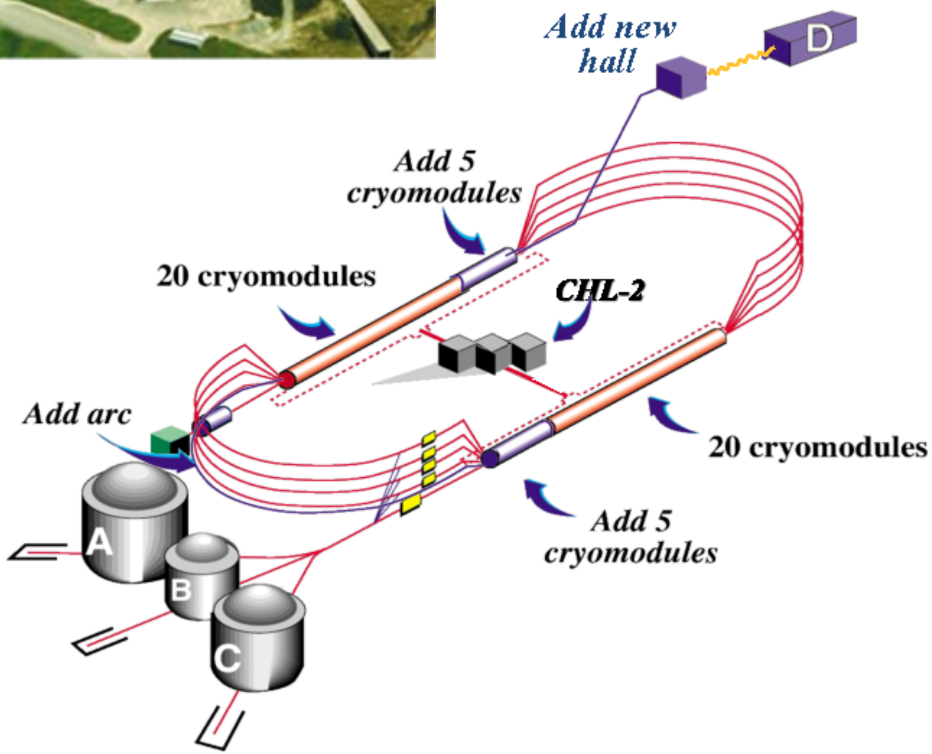
$Re\{\mathbf{H_p}, \mathbf{\tilde{H}_p}\}$
$Re\{\mathbf{H_n}, E_n, \tilde{E}_n\}$

Jefferson Lab

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

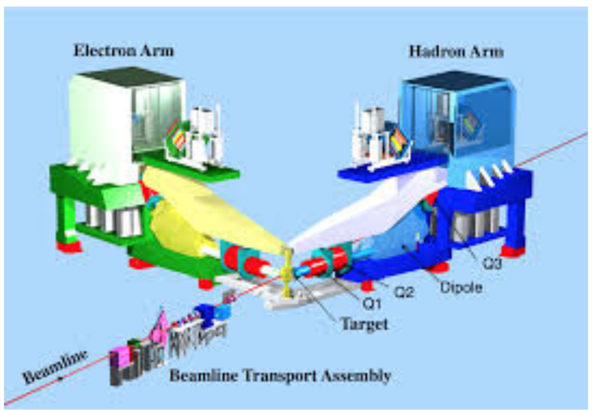


Jefferson Lab: 6 GeV era

CEBAF: Continuous Electron Beam Accelerator Facility.

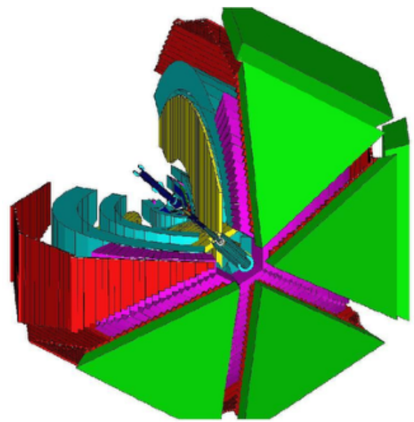
- Energy up to ~6 GeV
- Energy resolution $\delta E/E_e \sim 10^{-5}$
- Longitudinal electron polarisation up to ~85%

Hall A:



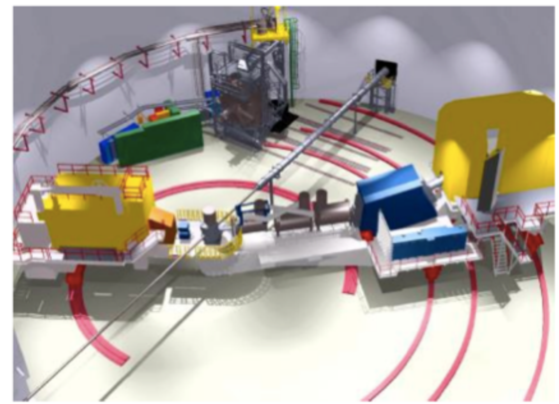
- High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity.

Hall B: CLAS



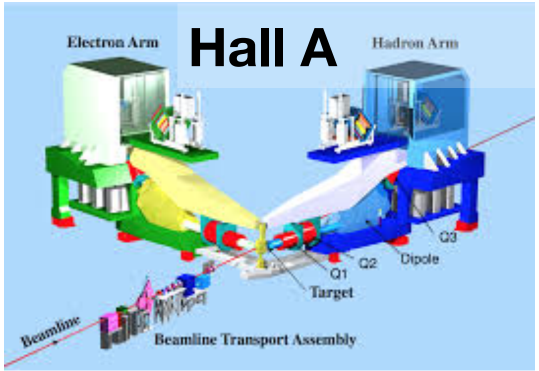
- Very large acceptance, detector array for multi-particle final states.

Hall C:

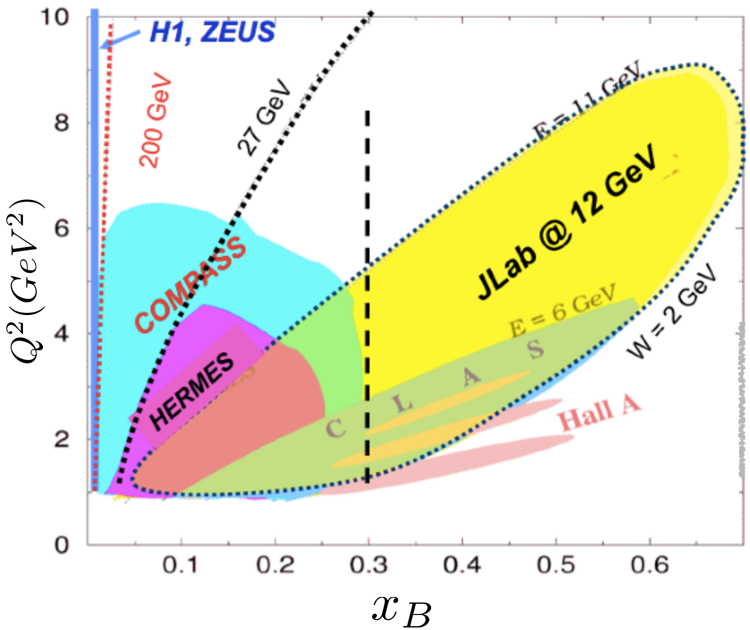


- Two movable spectrometer arms, well-defined acceptance, high luminosity

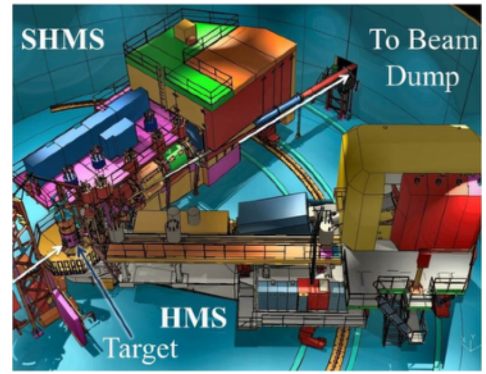
JLab @ 12 GeV



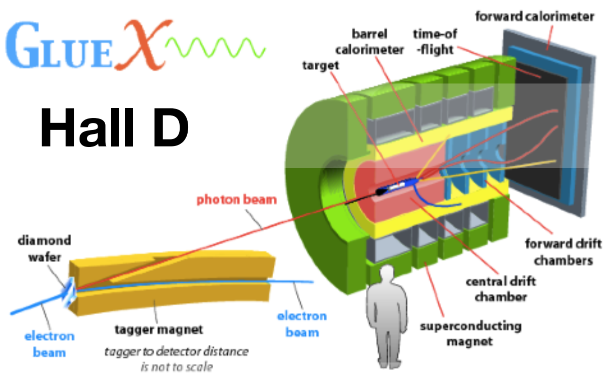
High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity, large installation experiments.



Hall C

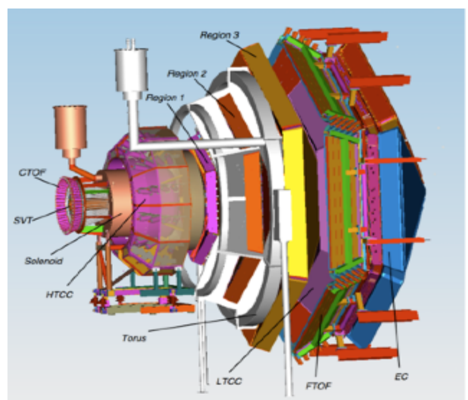


Two movable high momentum spectrometers, well-defined acceptance, very high luminosity.



9 GeV tagged polarised photons, full acceptance

Hall B: CLAS12



Very large acceptance, high luminosity.

CLAS12

Design luminosity

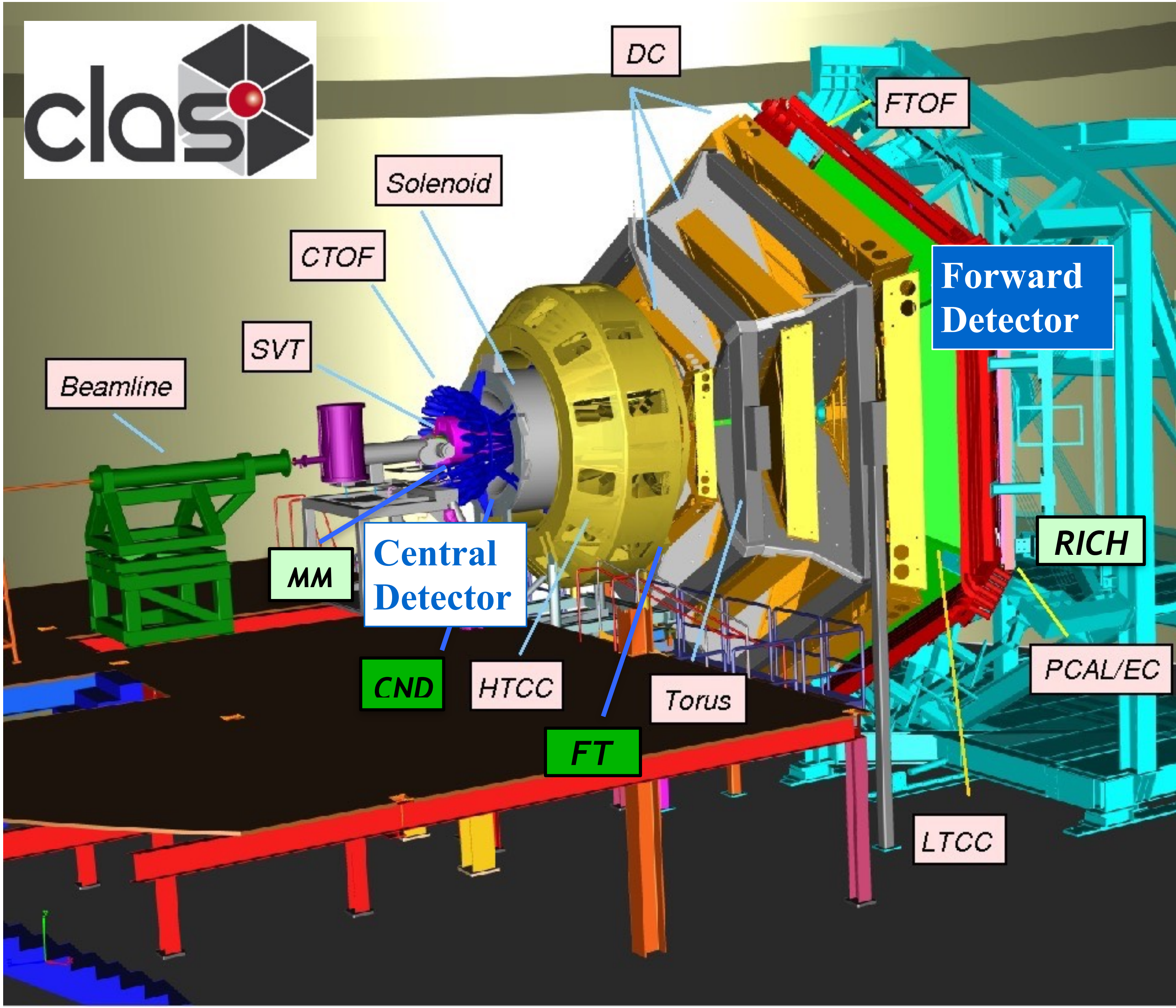
$L \sim 10^{35}\ cm^{-2}\ s^{-1}$

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

Acceptance for photons and electrons:
- $2.5^o < \theta < 125^o$

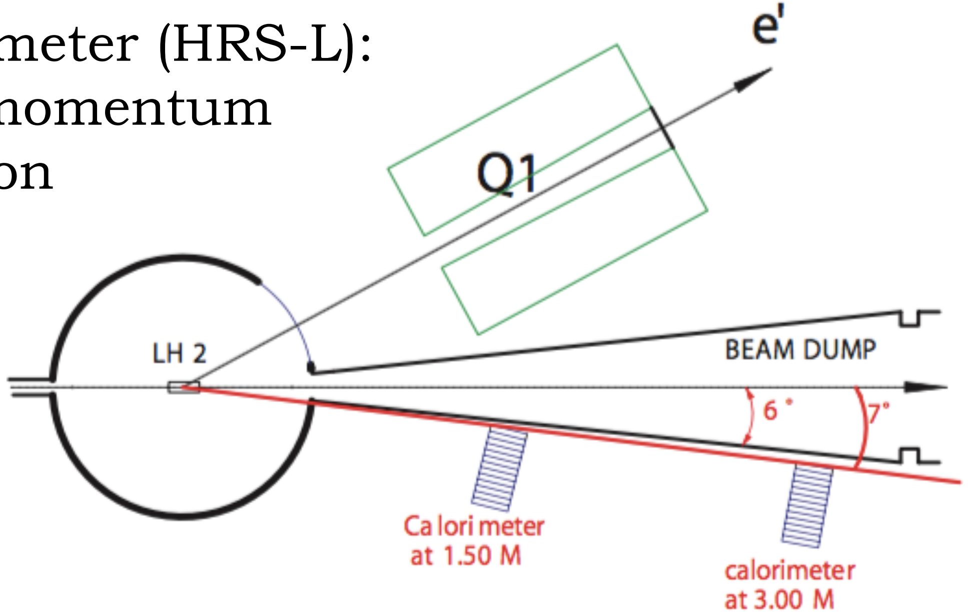
Acceptance for all charged particles:
- $5^o < \theta < 125^o$

Acceptance for neutrons:
- $5^o < \theta < 120^o$

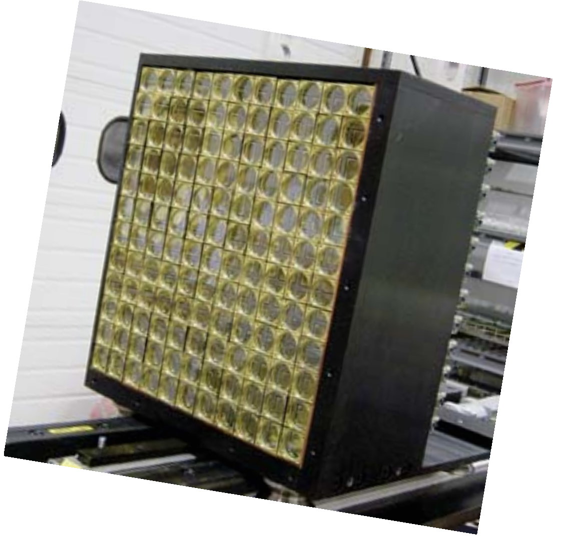


DVCS in Hall A @ 11 GeV

Detect electron in the Left High Resolution Spectrometer (HRS-L): 0.01% momentum resolution



Detect photon in PbF_2 calorimeter: < 3% energy resolution



Reconstruct recoiling proton through missing mass.

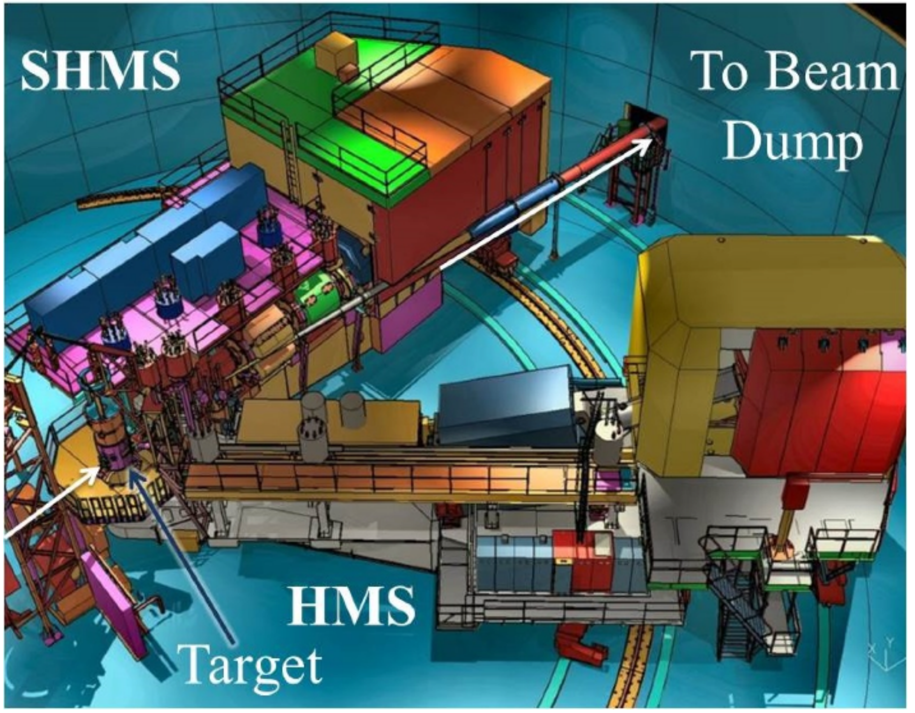
DVCS in Hall C @ 11 GeV

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

Detect photon in $PbWO_4$ calorimeter.

Sweeping magnet to reduce backgrounds in calorimeter.

Reconstruct recoiling proton through missing mass.

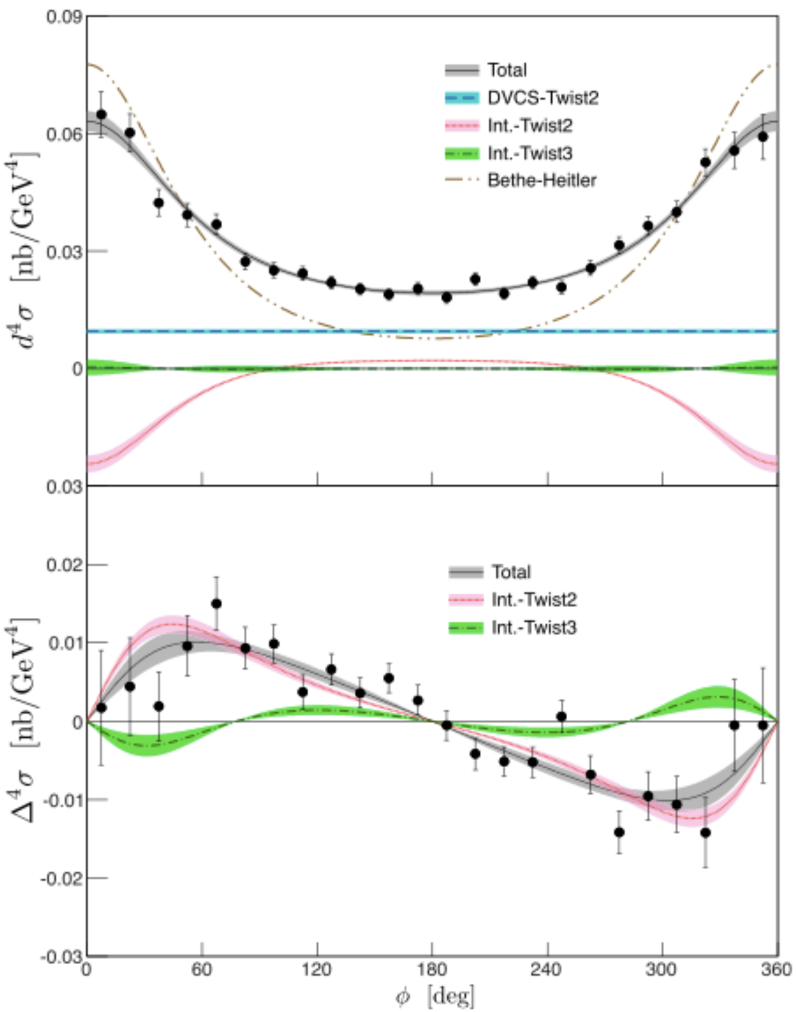


DVCS highlights from the 6 GeV era

First DVCS cross-sections in valence region

Hall A

- Hall A, ran in 2004, high precision, narrow kinematic range. Q^2: 1.5 - 2.3 GeV^2, $x_B = 0.36$.



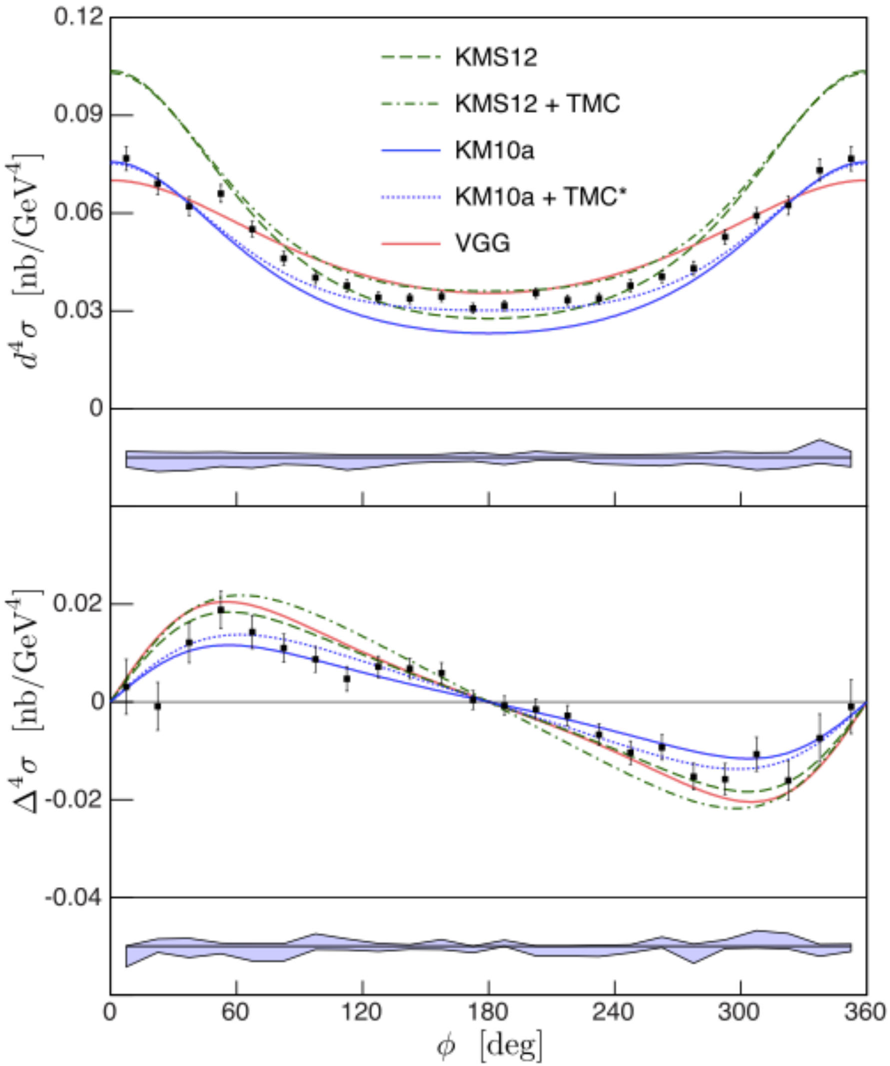
$x_B = 0.36, Q^2 = 2.3\ GeV^2, -t = 0.32\ GeV^2$

- CFFs show scaling in DVCS: leading twist (twist-2) dominance at this moderate Q^2.
- Strong deviation of DVCS cross-section from BH: extraction of $|T_{DVCS}|^2$ amplitude as well as interference terms.
- Separation of real part of the twist-2 interference term and the $|T_{DVCS}|^2$ amplitude is very sensitive to relative cross-sections at $\phi = 0°$ and $\phi = 180°$.

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

First DVCS cross-sections in valence region

Hall A



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

- High precision of the data: sensitivity to subtle differences in model predictions.

VGG model: Vanderhaeghen, Guichon, Guidal
KMS model: Kroll, Moutarde, Sabatié
KM model: Kumericki, Mueller

TMC: kinematic twist-4 target-mass and finite-t corrections, calculated for proton DVCS and estimated for KMS12.

- KMS parameters tuned on very low x_B meson-production data: not adapted to valence quarks.

→ TMC*: TMC extracted from the KMS12 model and applied to KM10a.

- TMC improve agreement for KM10a model, especially at $\phi = 180^\circ$. Higher-twist effects?

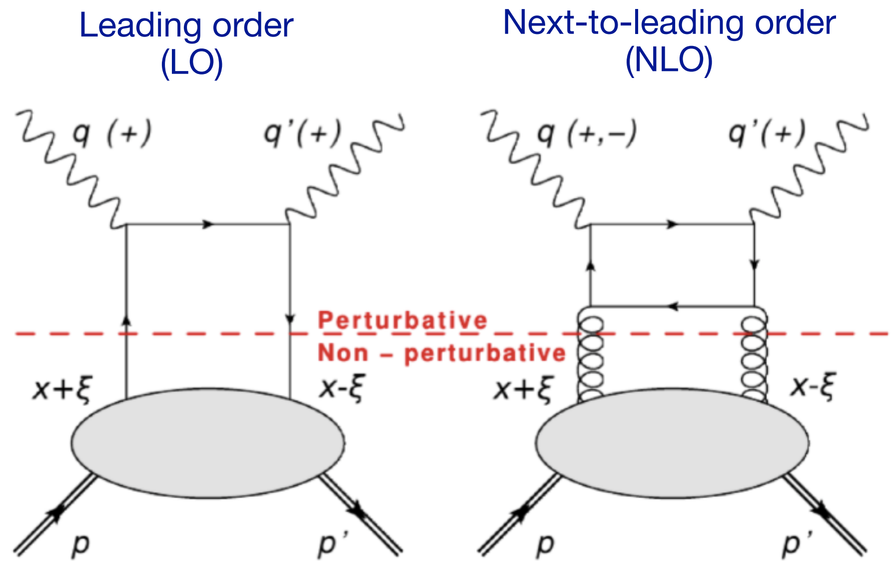
The devil is in the detail…

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

Here comes the twist...

- Twist: powers of $\frac{1}{\sqrt{Q^2}}$ in the DVCS amplitude. Leading-twist (LT) is twist-2.
- Order: introduces powers of α_s
- LO requires $Q^2 >> M^2$ (M: target mass)

  Bold assumption for JLab 6 GeV kinematics!



- CFFs can be classified according to real and virtual photon helicity:

$\mathcal{F}_{++}$

helicity of real produced photon

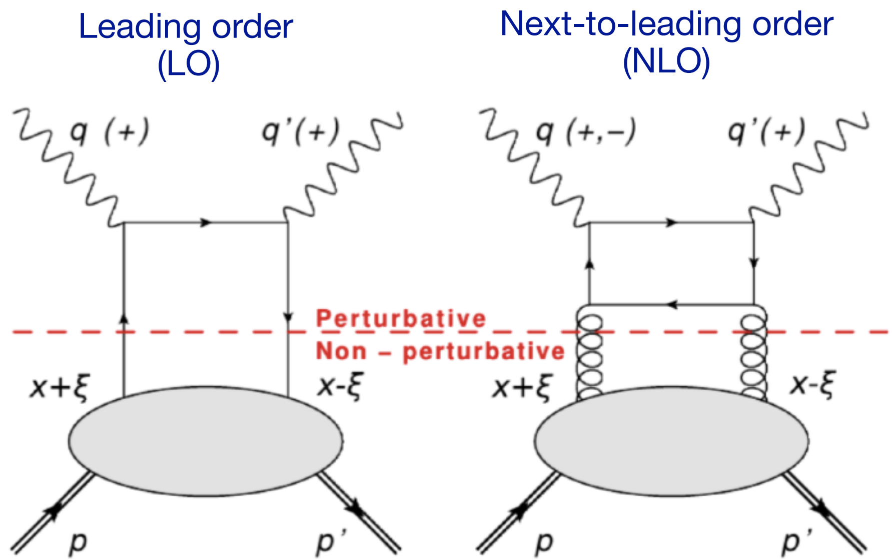
helicity of virtual incoming photon

  - Helicity-conserved CFFs — $\mathcal{F}_{++}$
  - Helicity-flip (transverse) — $\mathcal{F}_{-+}$
  - Longitudinal to transverse flip — $\mathcal{F}_{0+}$

- CFFs contributing to the scattering amplitude:
  - LT in LO: only $\mathcal{F}_{++}$
  - LT in NLO: both $\mathcal{F}_{++}$ and $\mathcal{F}_{-+}$
  - Twist-3: $\mathcal{F}_{0+}$

Here comes the twist…

- At finite Q^2 and non-zero t there's ambiguity in defining the light-cone axis:
  - Traditional GPD phenomenology uses the Belitsky convention, in plane of q and P:
    A. Belitsky *et al*, ***Nucl. Phys. B878*** (2014), 214
  - New, Braun definition using q and q': more natural.
    V. Braun *et al*, ***Phys. Rev. D89*** (2014), 074022



Reformulating CFFs in this frame absorbs most kinematic power corrections (TMC):

$$\mathcal{F}_{++} = \mathbb{F}_{++} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+}$$

$$\mathcal{F}_{-+} = \mathbb{F}_{-+} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+}$$

$$\mathcal{F}_{0+} = -(1+\chi)\mathbb{F}_{0+} + \chi_0\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right]$$

Belitsky CFFs

Braun CFFs

Assuming LO and LT in the Braun frame leaves higher-twist, higher-order contributions in the Belitsky frame, scaled by kinematic factors χ and χ_0.

Non-negligible at the Q^2 and x_B of the Hall A cross-section measurement!

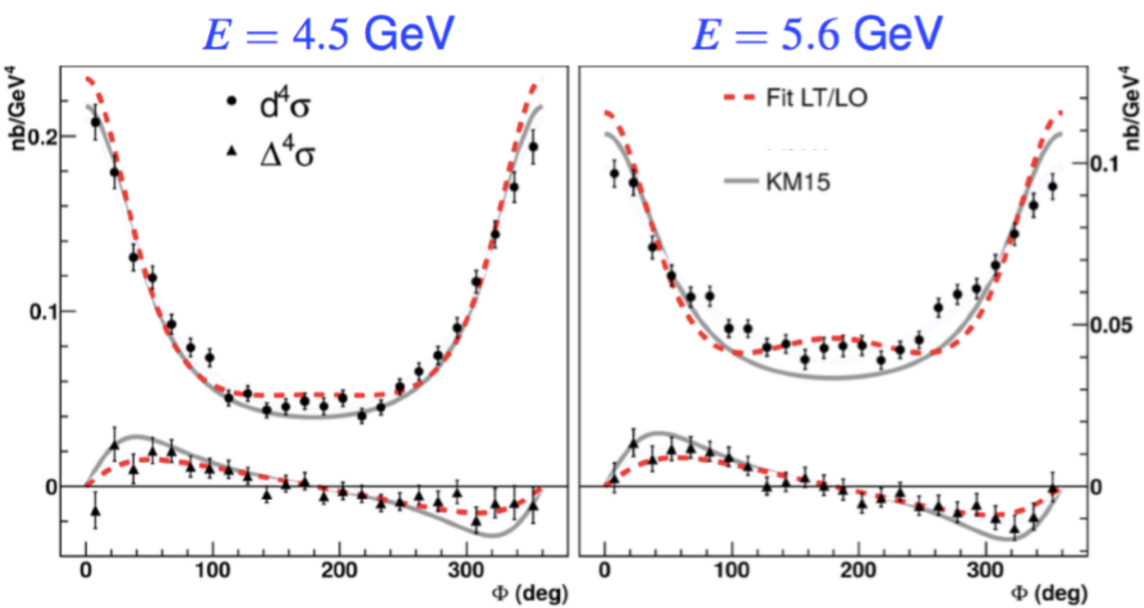
M. Defurne *et al*, ***Nature Communications 8*** (2017) 1408.

Hints of higher twist or higher orders

Hall A

- Strong deviation of the measured cross-section from Bethe-Heitler: a beam-energy scan can be used to identify pure DVCS and interference terms in a Rosenbluth-like separation, and to look for higher-twist effects.

→ E07-007: Hall A experiment to measure helicity-dependent and -independent cross-sections at two beam energies and constant x_B and t.



- Simultaneous fit to cross-sections at both energies and three values of Q^2 using only leading twist and leading order (LT/LO) do not describe the cross-sections fully: **higher twist/order effects?**

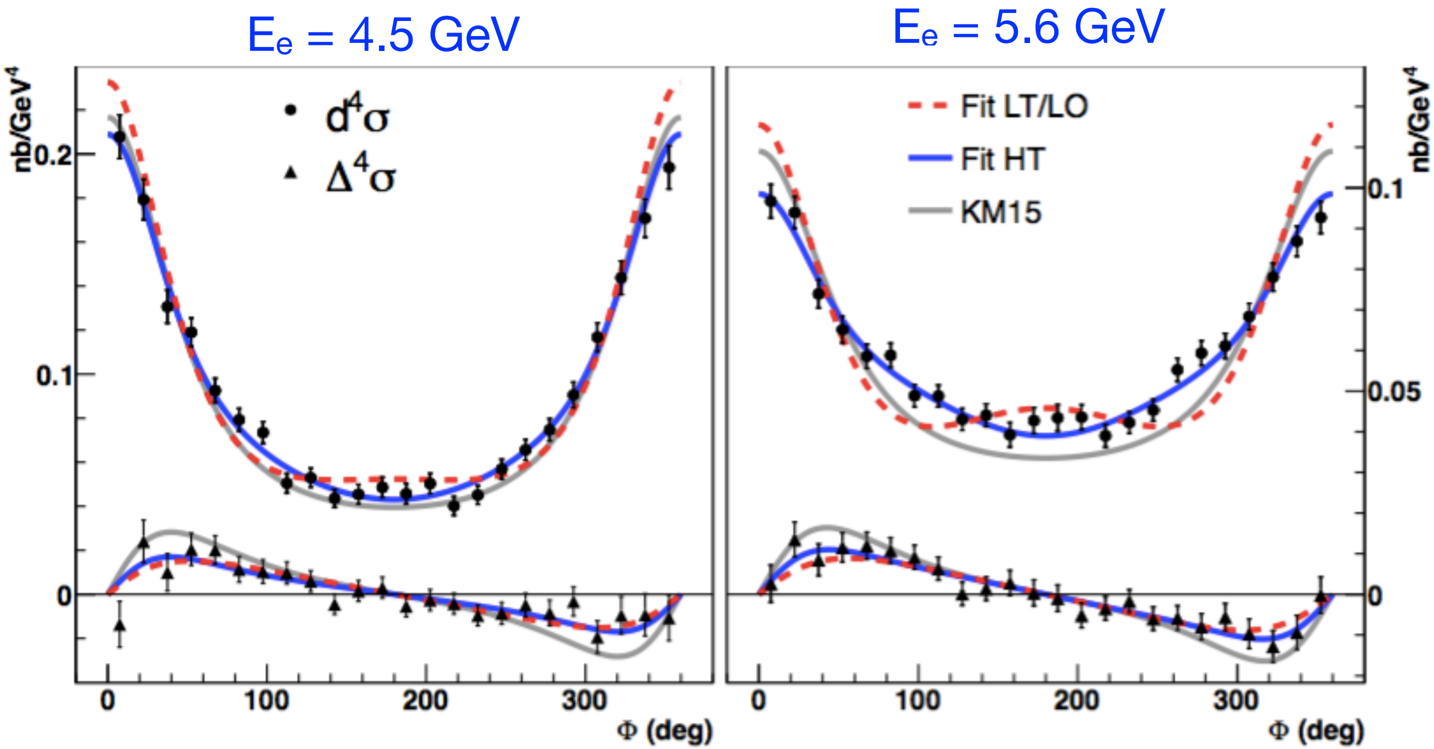
Using Braun's decomposition, $\mathbb{H}_{-+}$ and $\mathbb{H}_{0+}$ can't be neglected.

M. Defurne *et al*, ***Nature Communications* 8** (2017) 1408.

Hints of higher twist or higher orders

Hall A

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



Higher-order and / or higher-twist terms are important! A glimpse of gluons.

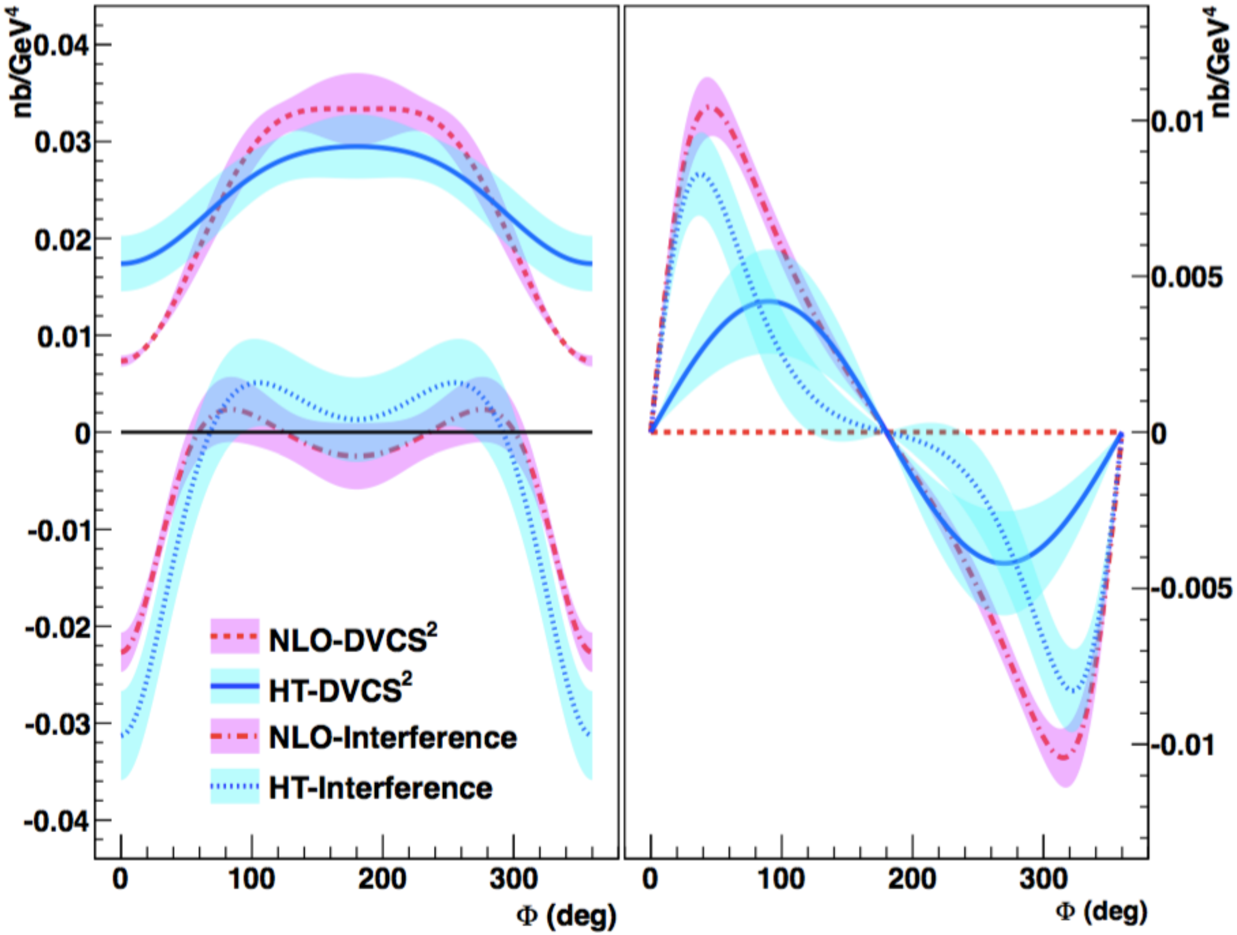
Wider range of beam energy needed to identify the dominant effect → **JLab at 11 GeV.**

M. Defurne *et al*, ***Nature Communications* 8** (2017) 1408.

Rosenbluth separation of $DVCS^2$ and BH-DVCS terms

Hall A

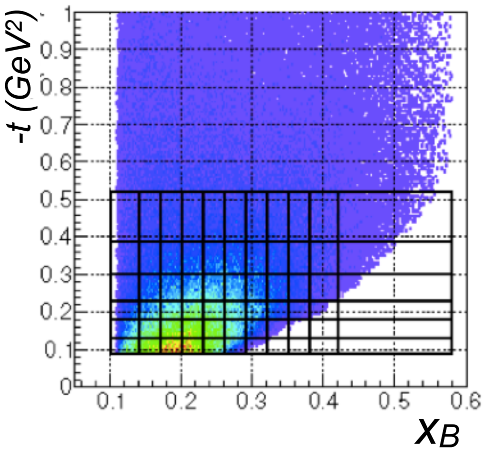
- Generalised Rosenbluth separation of the $DVCS^2$ and the BH-DVCS interference terms in the cross-section is possible but NLO and/or higher-twist required.

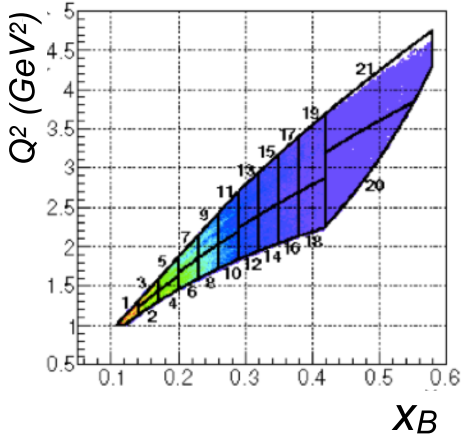


- Significant differences between pure DVCS and interference contributions.
- Helicity-dependent cross-section has a sizeable $DVCS^2$ contribution in the higher-twist scenario.
- Separation of HT and NLO effects requires scans across wider ranges of Q^2 and beam energy: JLab12!

M. Defurne *et al*, ***Nature Communications 8*** (2017) 1408.

CLAS unpolarised cross-sections



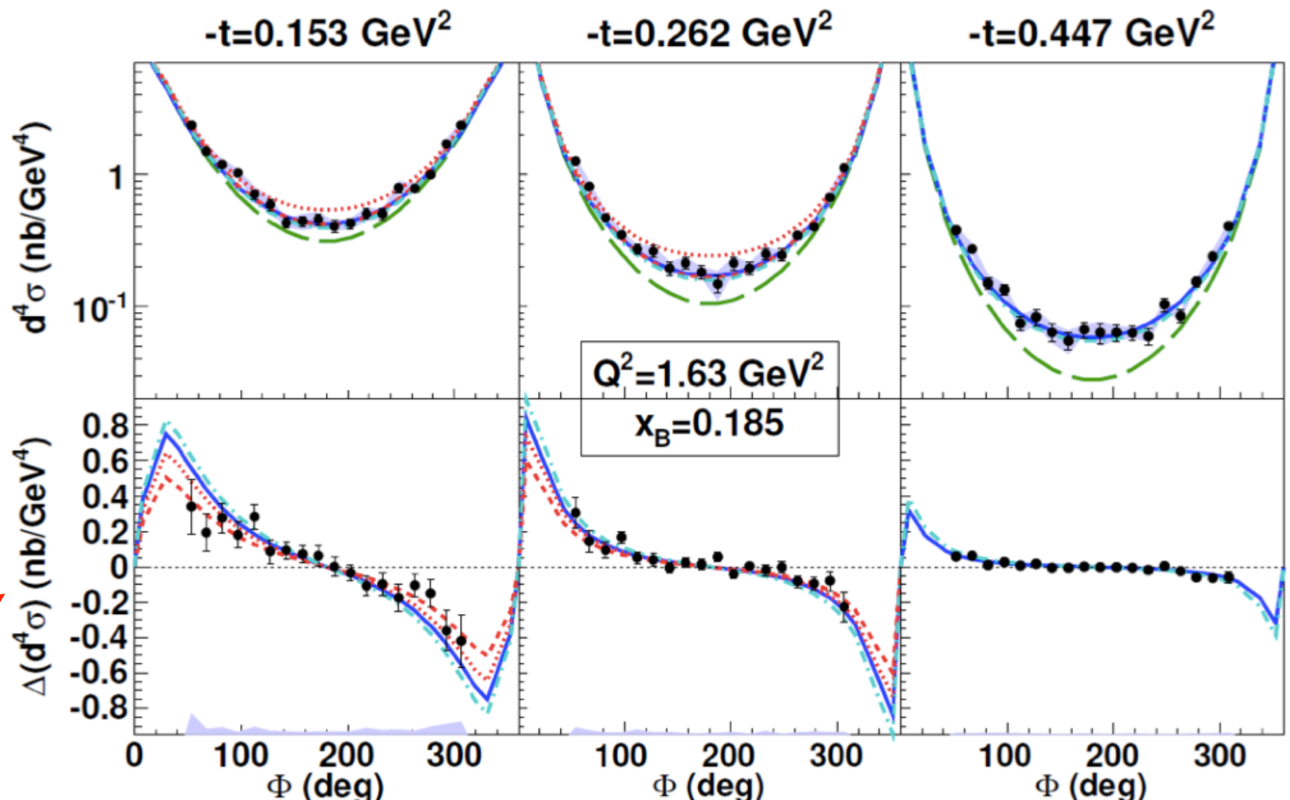


- BH only
- VGG (H only)
- KM10 (Kumericki, Mueller), *includes strong* $\tilde{H}$
- KM10a *(sets* $\tilde{H}$ *to zero)*
- KMS *(tuned on low* x_B *meson-production data)*

- Widest phase space coverage in valence quark region: CFF constraints.
- Dominance of GPD *H* in unpolarised cross-section.

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

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

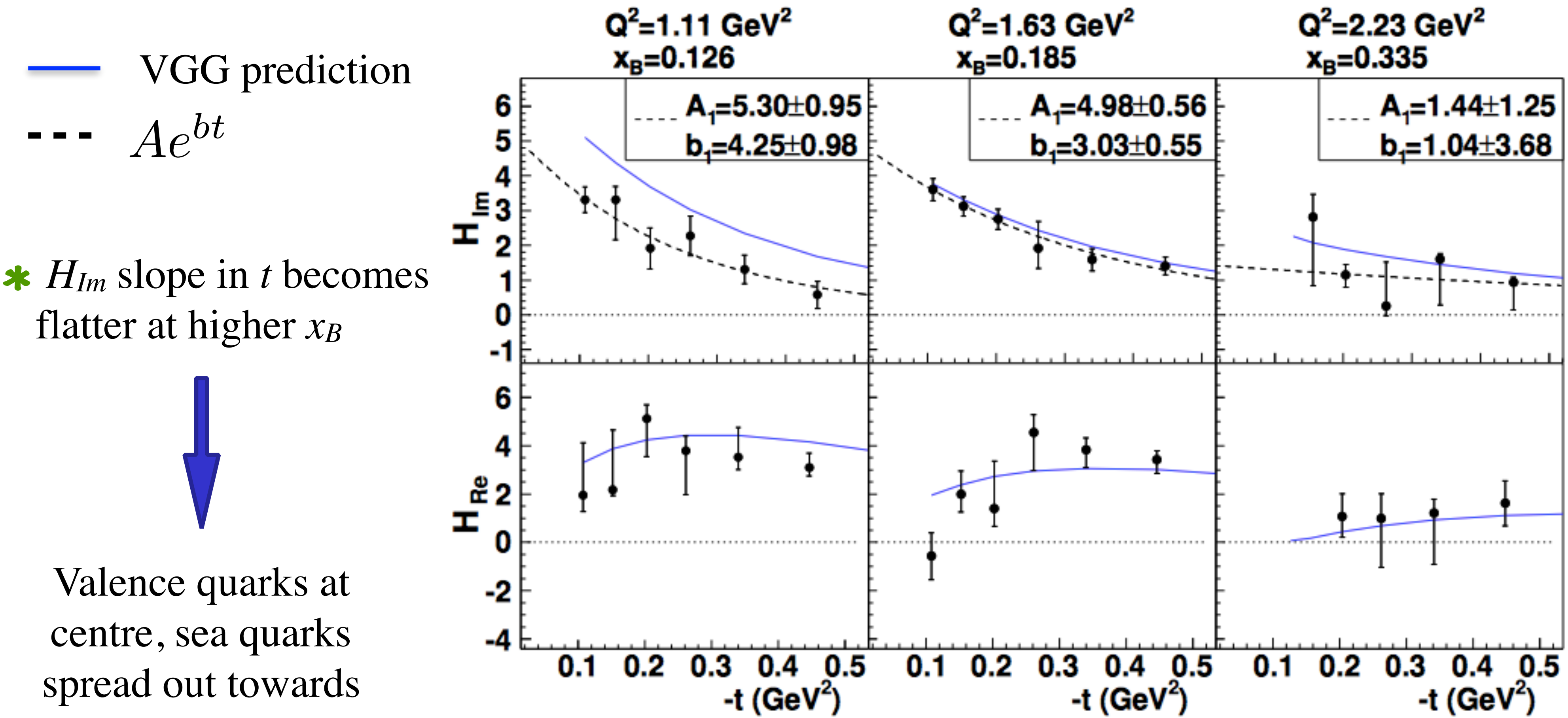


H.-S. Jo *et al* (CLAS), ***PRL* 115** (2015) 212003

Tomography of the proton

CLAS

- CFFs extracted in a VGG fit.
- Imaginary part of CFF: $F_{Im}(\xi, t) = F(\xi, \xi, t) \mp F(-\xi, \xi, t)$

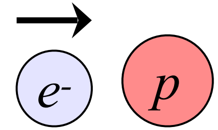


- H_{Im} slope in t becomes flatter at higher x_B

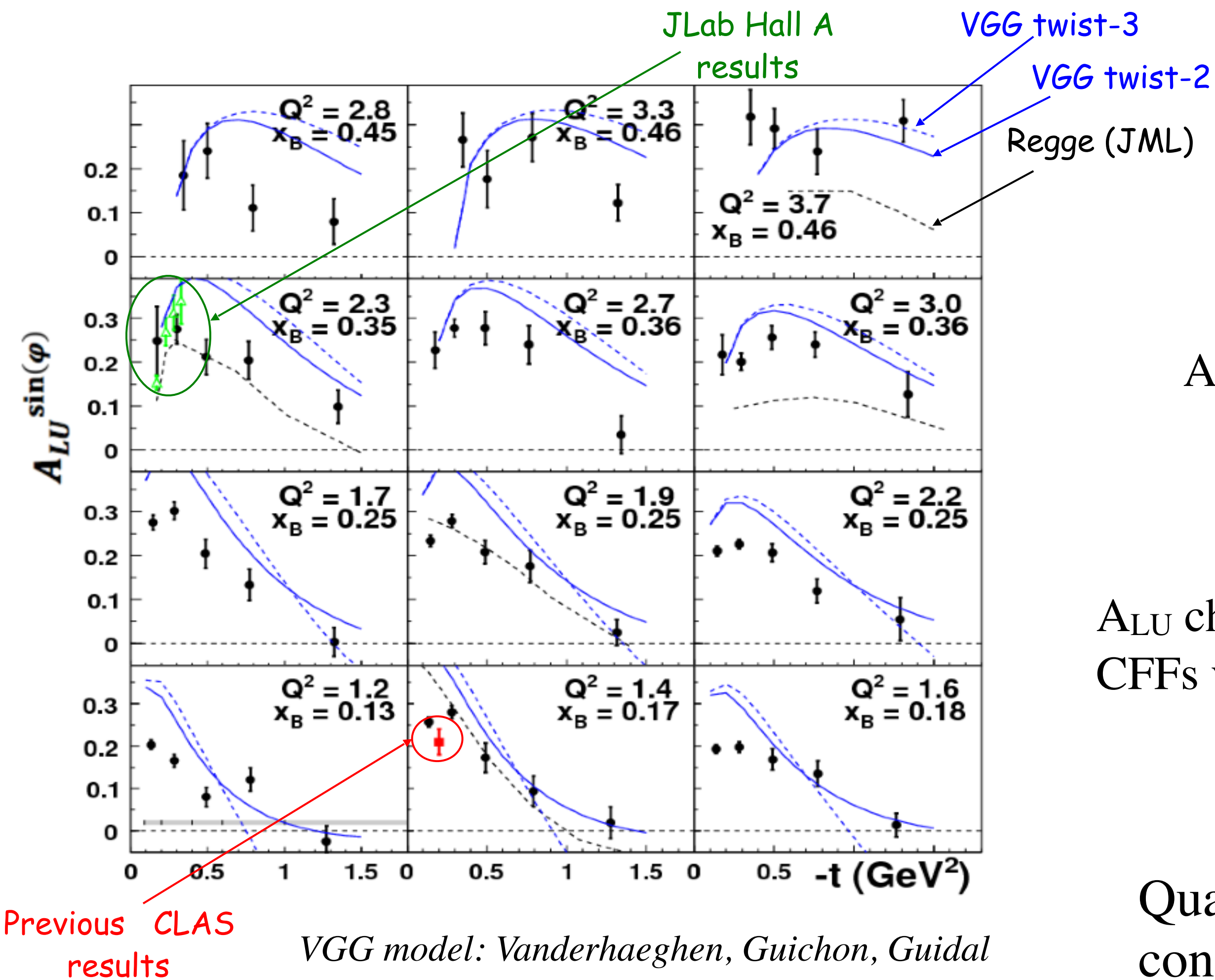
Valence quarks at centre, sea quarks spread out towards the periphery.

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

Beam-spin Asymmetry (A_{LU})



CLAS



VGG model: Vanderhaeghen, Guichon, Guidal

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

A_{LU} from fit to asymmetry:

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

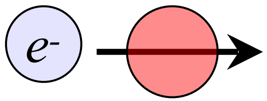
A_{LU} characterised by imaginary parts of CFFs via:

$$F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} E$$

Qualitative agreement with models, constraints on fit parameters.

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

Target-spin Asymmetry (A_{UL})



Follows first CLAS measurement:
S. Chen *et al* (CLAS),
***PRL* 97** (2006) 072002

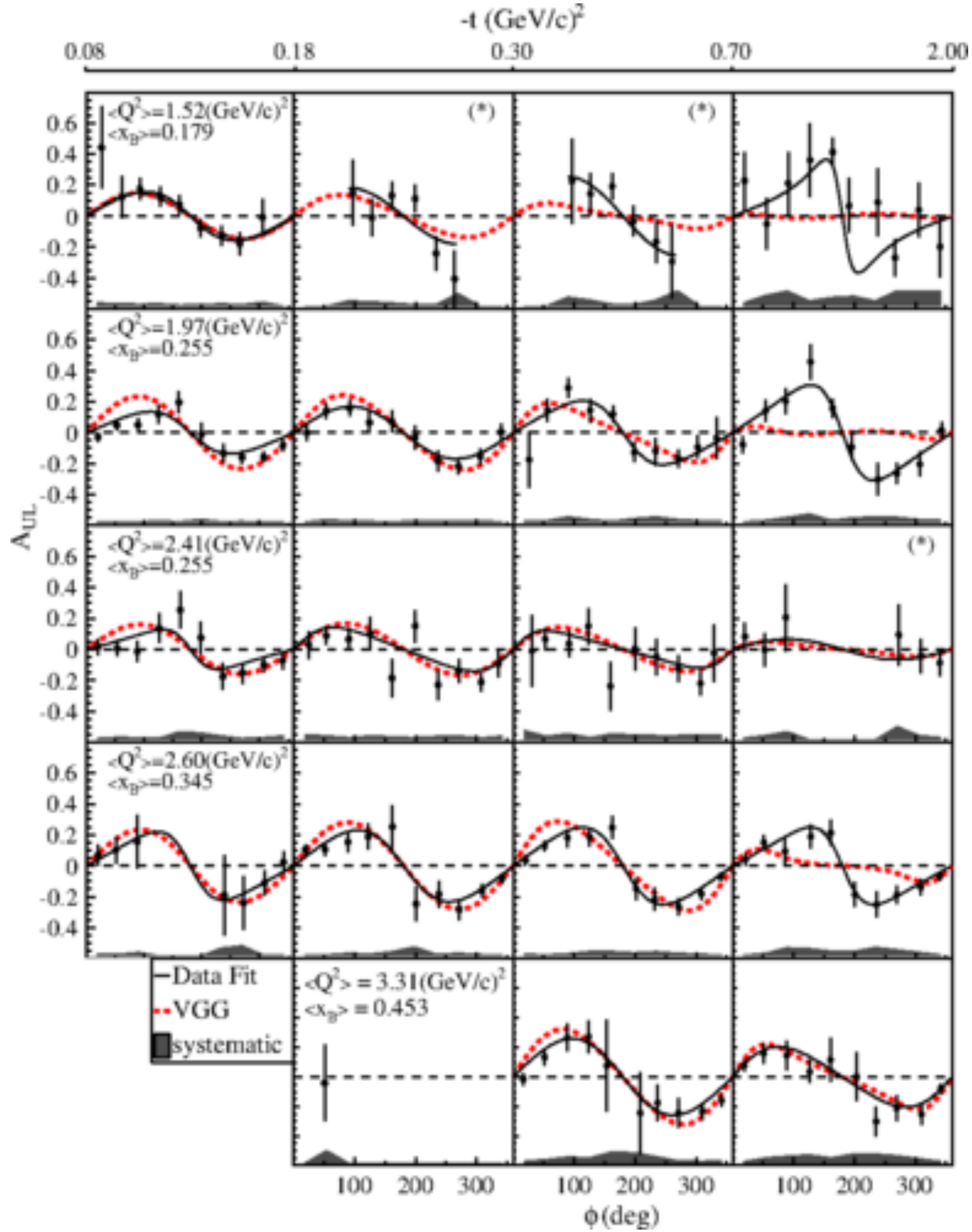
A_{UL} from fit to asymmetry:

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

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

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

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

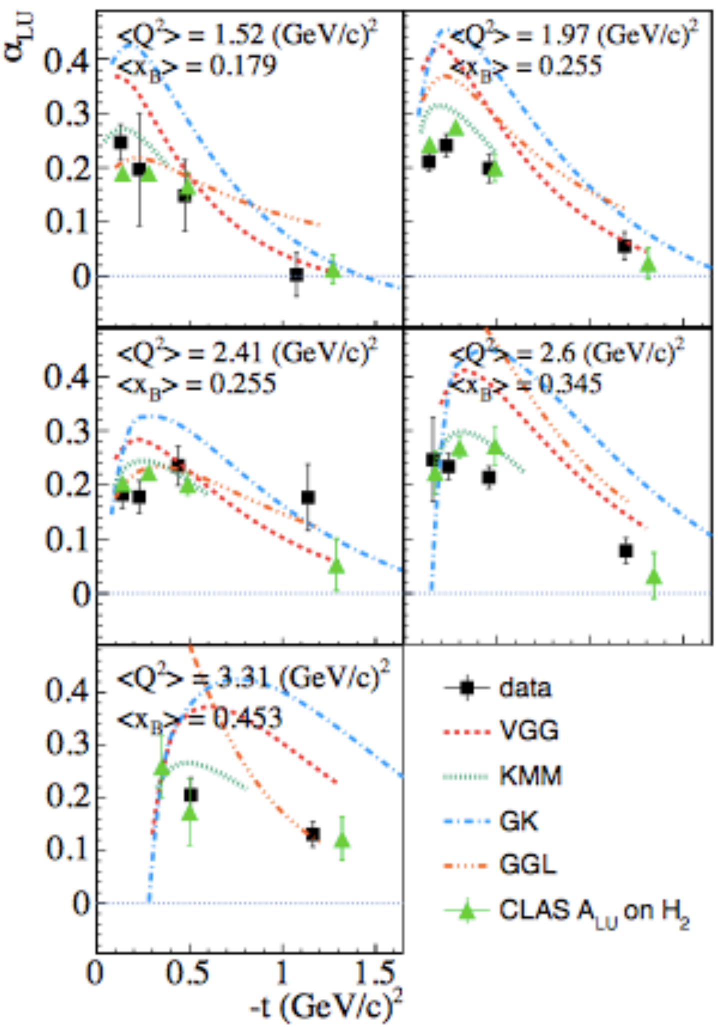


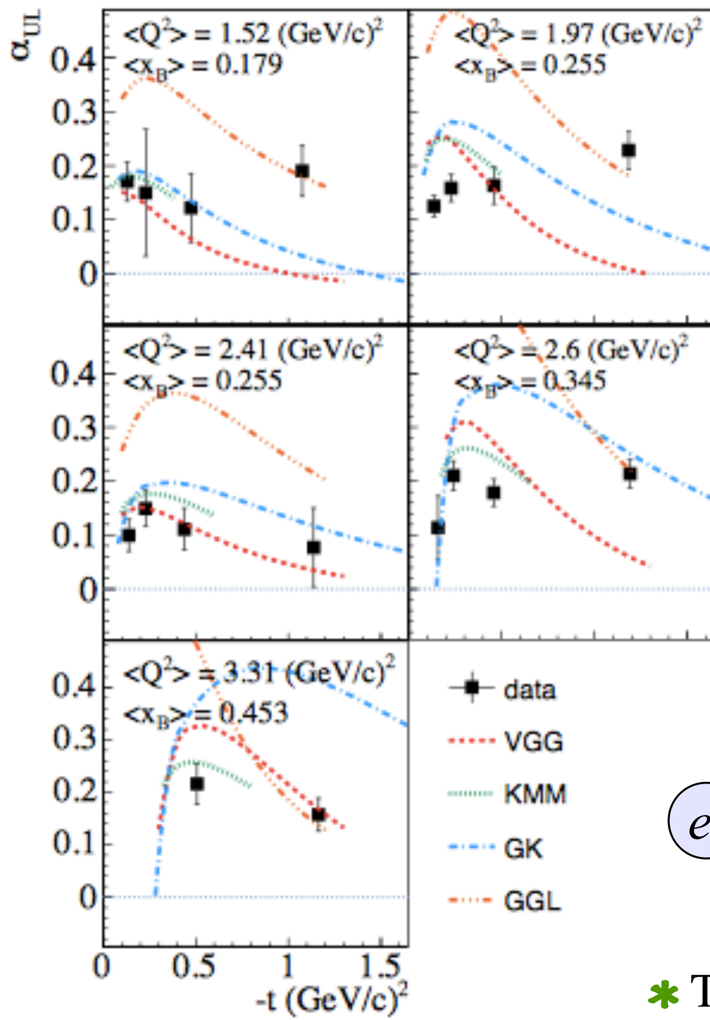
E. Seder *et al* (CLAS), ***PRL* 114** (2015) 032001

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

Beam- and target-spin asymmetries

CLAS



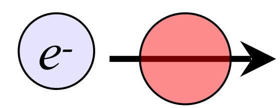


$$A = \frac{\alpha sin\phi}{1+\beta cos\phi}$$

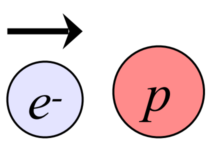
GGL: Goldstein, Gonzalez, Liuti

GK: Kroll, Moutarde, Sabatié

KMM: Kumericki, Mueller, Murray

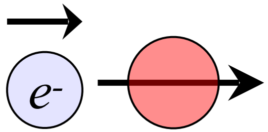


* TSA shows a flatter distribution in *t* than BSA.



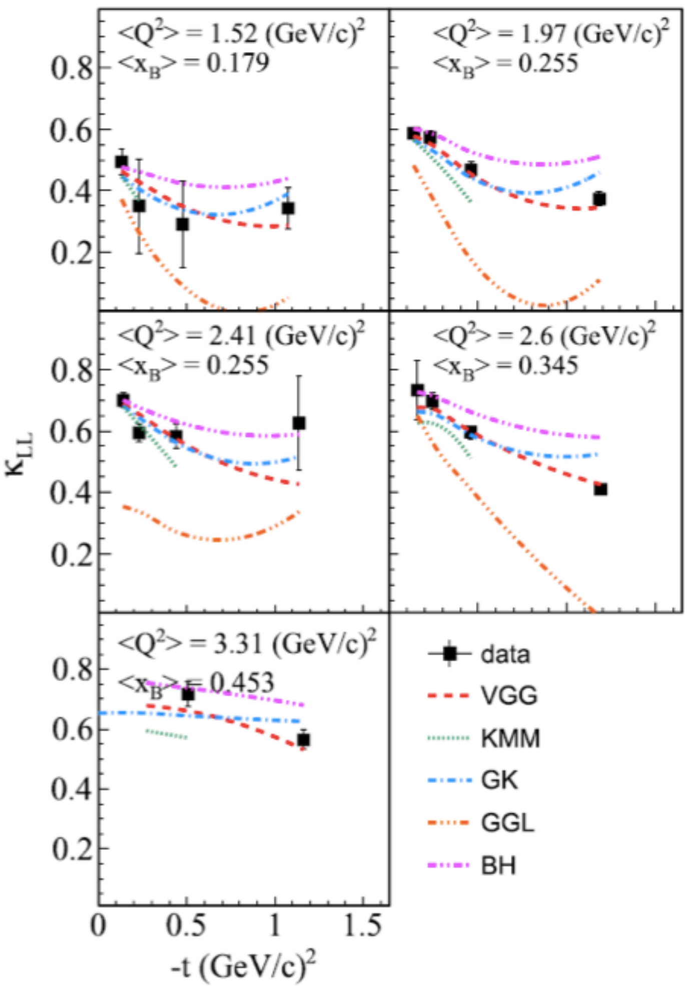
S. Pisano *et al* (CLAS), ***PRD* 91** (2015) 052014

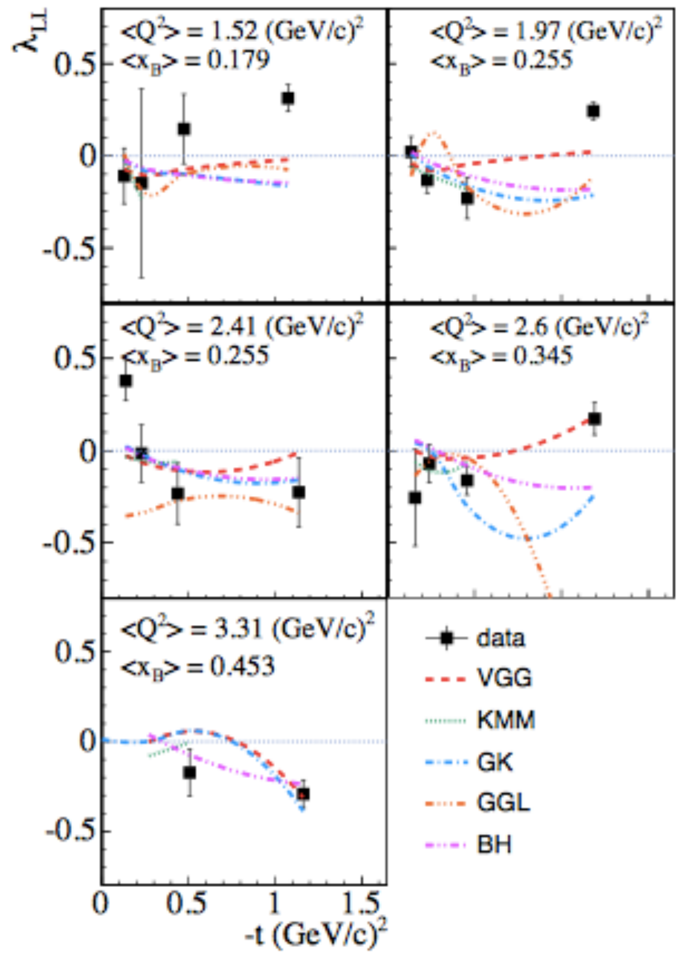
E. Seder *et al* (CLAS), ***PRL* 114** (2015) 032001



Double-spin Asymmetry (A_{LL})

CLAS





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:

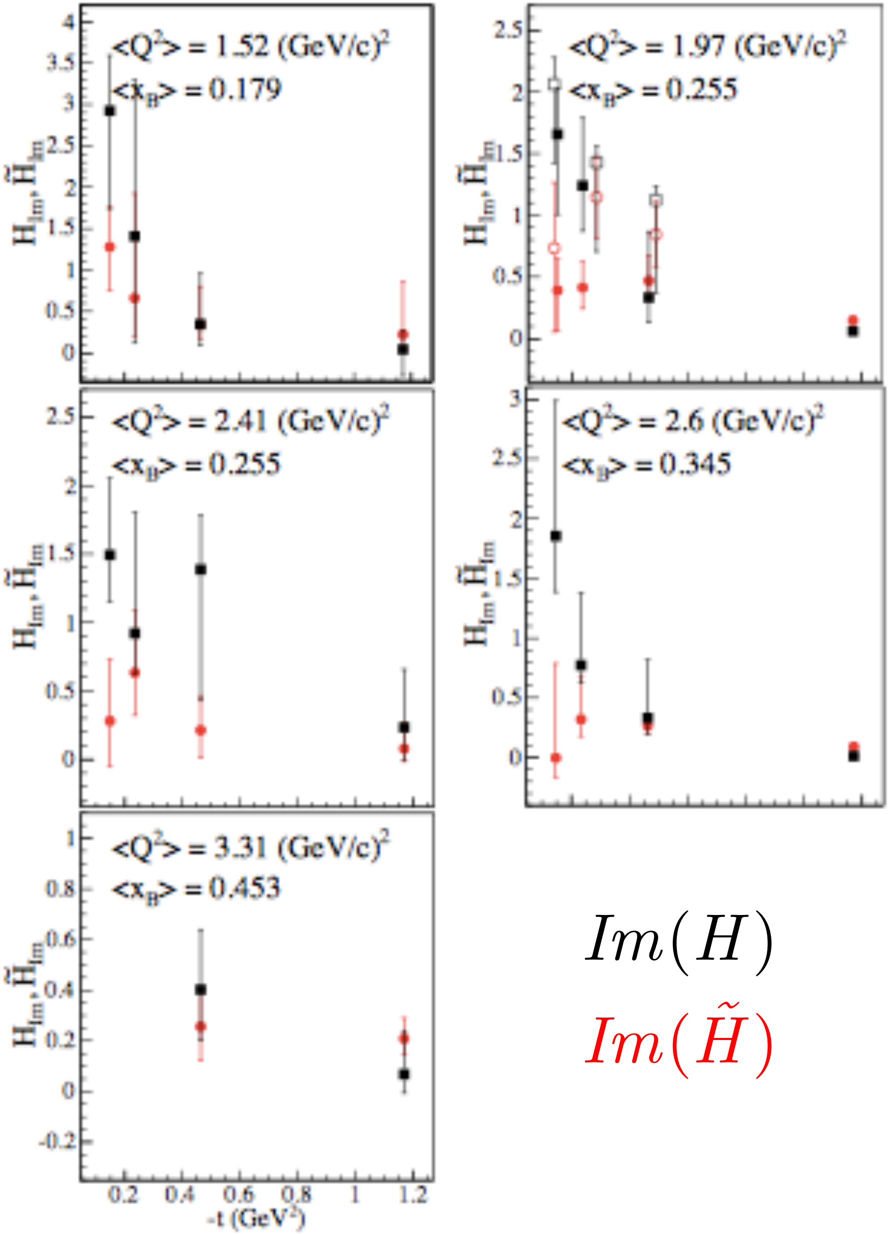
$$F_1 \tilde{H} + \xi G_M \left(H + \frac{x_B}{2} E\right) + \ldots$$

- Fit parameters extracted from a simultaneous fit to BSA, TSA and DSA.
- Constant term dominates and is almost entirely BH.

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

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

CFF extraction from three spin asymmetries at common kinematics.



$$Im(H)$$

$$Im(\tilde{H})$$

What can we learn from the asymmetries?

Answers hinge on a global analysis of all available data.

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

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

- Indications that axial charge is more concentrated than electromagnetic charge.

$$\int_{-1}^{+1} H dx = F_1$$

$$\int_{-1}^{+1} \tilde{H}\ dx = G_A$$

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

DVCS at JLab: 11 GeV era

Proton DVCS @ 11 GeV

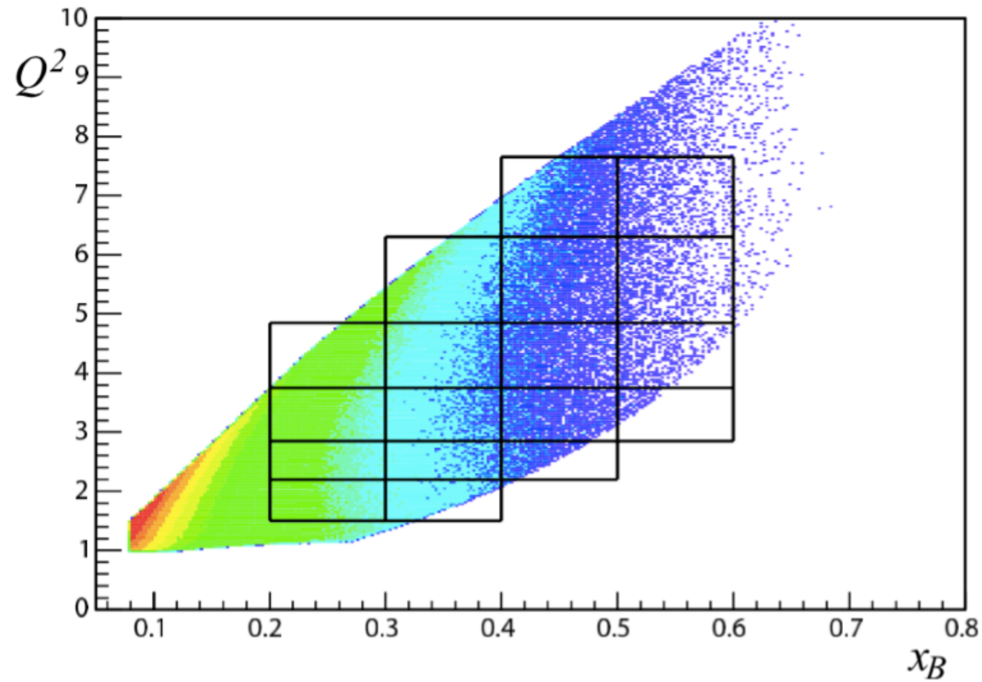
CLAS12

Experiment E12-06-119

F. Sabatié et al.

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

Kinematics similar for all proton DVCS @ 11 GeV with CLAS12 experiments



First experiment with CLAS12

Unpolarised liquid H_2 target:

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

Started this February!

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

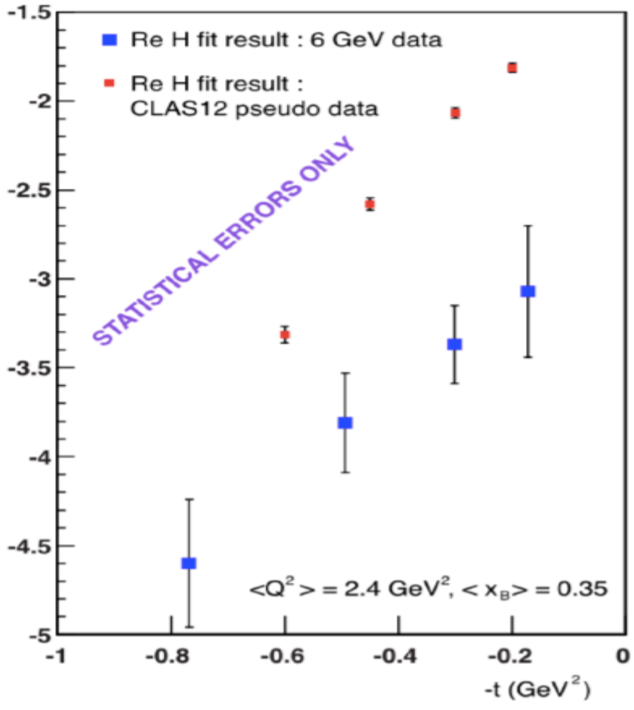
$$F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} E \longrightarrow Im(H_p)$$

Proton DVCS @ 11 GeV

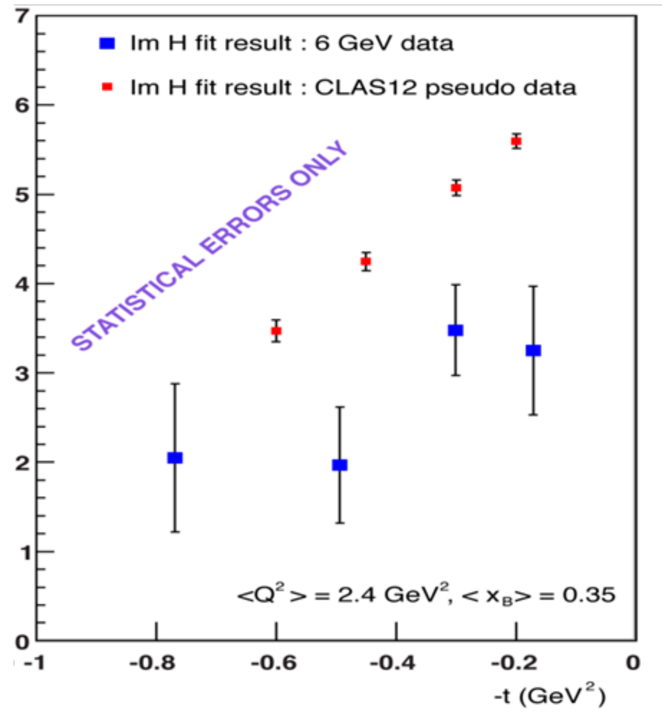
CLAS12

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

Re(H)



Im(H)



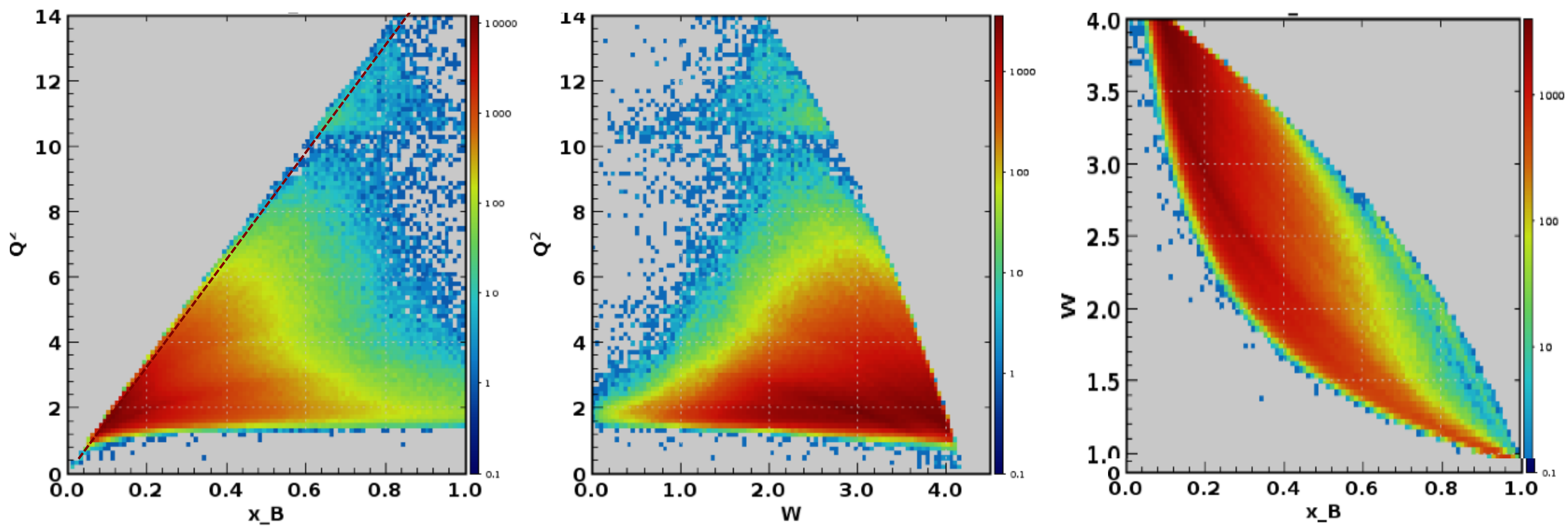
(CLAS 6 GeV extraction H. Moutarde)

CLAS12: first experiment (Run Group A)

It's started!

Target: 5cm long liquid H_2,
L = 10^{35} cm^{-2} s^{-1},
Beam energy: 10.6 GeV,
Electron polarisation: ~85% +/- 4%
Triggers: inclusive electron,
forward electron + charged particle (for quasi-real events),
muon pair (for J/Psi decay).

Operational specifications achieved.



Aim for first CLAS12 publication by end year…

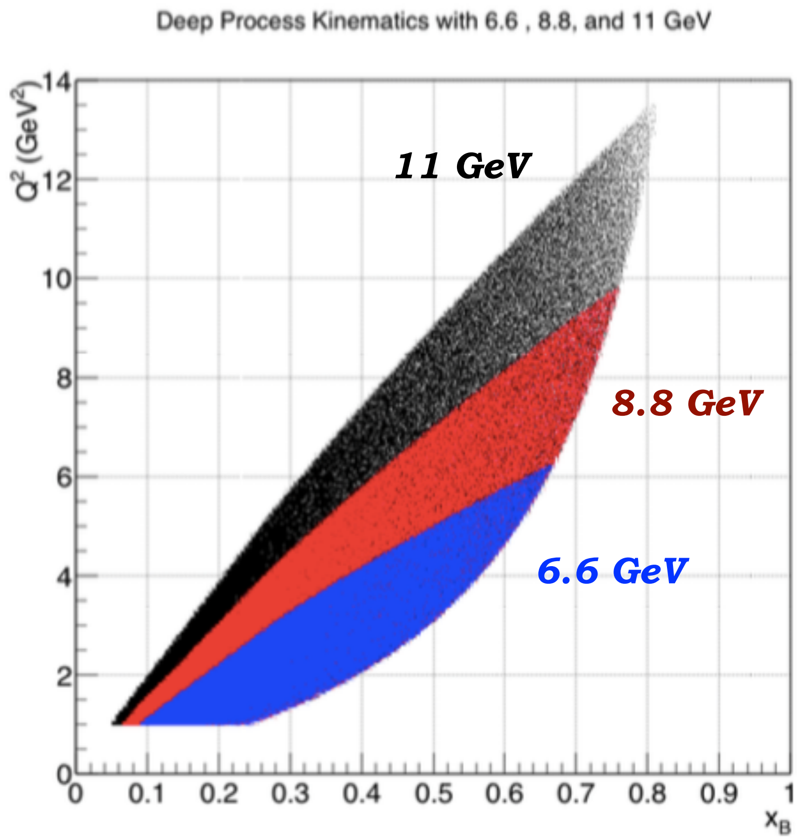
DVCS at lower energies with CLAS12

CLAS12

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

Unpolarised liquid H_2 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

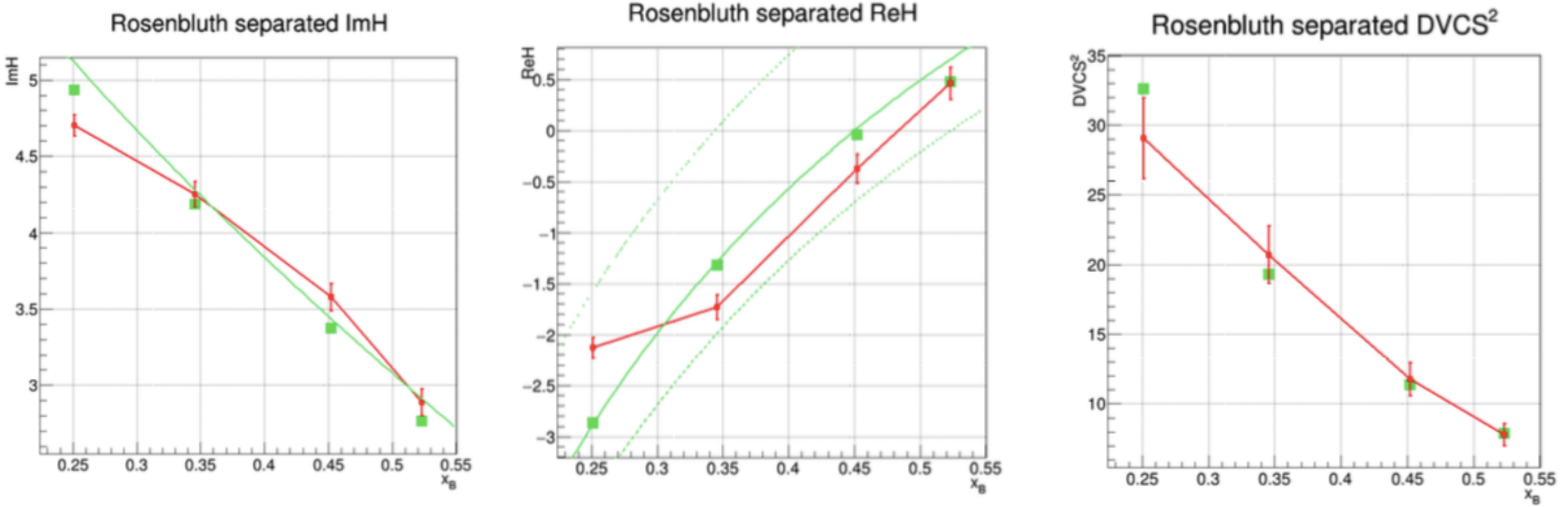
✱ Scaling tests of the extracted CFFs

✱ Model-dependent determination of the D-term in the Dispersion Relation between *Re* and *Im* parts of CFFs.

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.

Neutron DVCS @ 11 GeV

Experiment E12-11-003

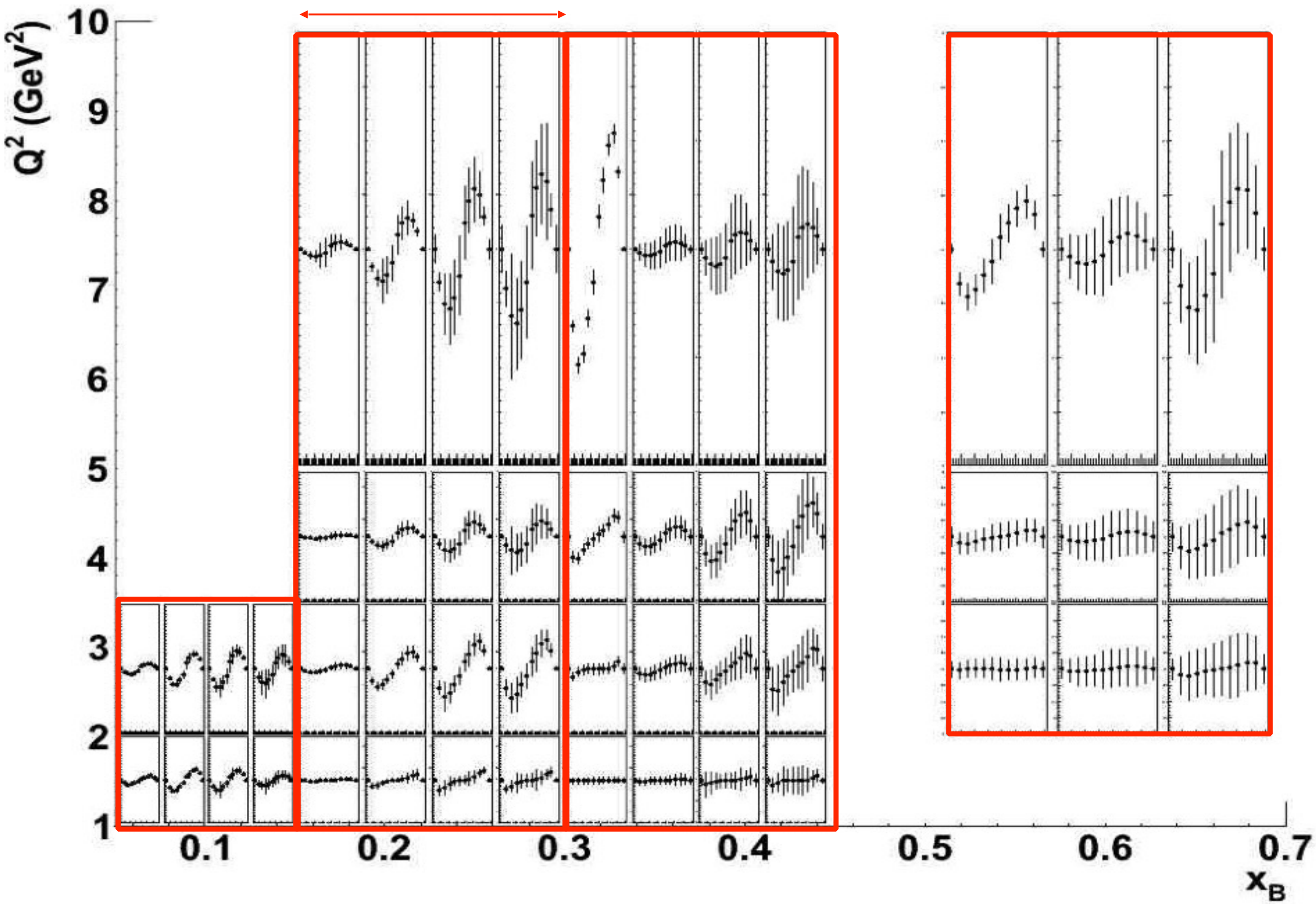
S. Niccolai, D. Sokhan et al.

$$\Delta\sigma_{LU} \sim \sin\phi \; \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} - kF_2 E\} d\phi$$

Im (E_n) dominates.

Simulated statistical sample:

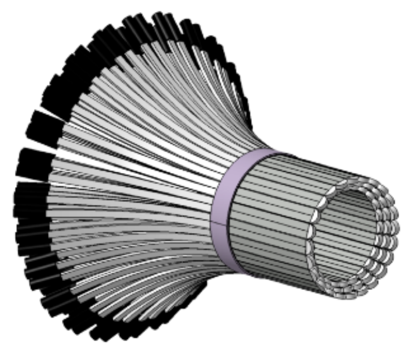
0 -t 1.2



L = 10^{35} cm^{-2}s^{-1}/nucleon

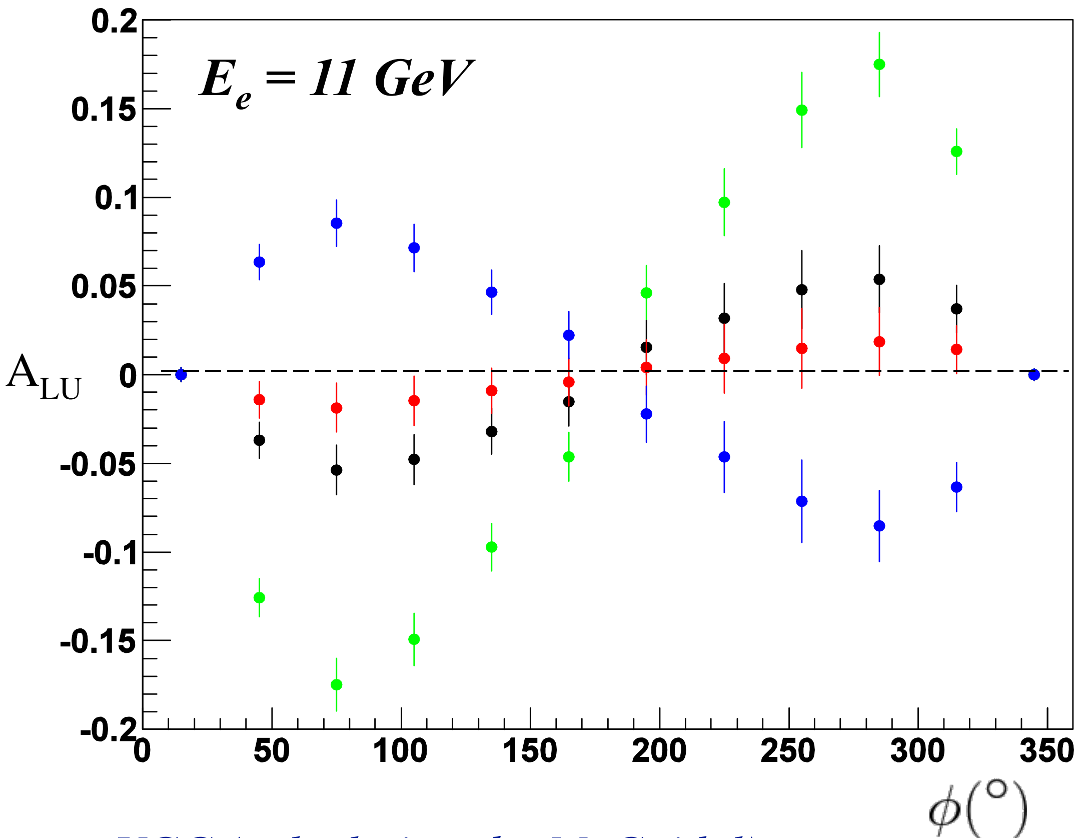
$$e + d \rightarrow e' + \gamma + n + (p_s)$$

CLAS12 +
Forward Tagger +
Neutron Detector



Tentative schedule: 2019

Beam-spin asymmetry in neutron DVCS @ 11 GeV



VGG (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
- Wide coverage needed!

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

Proton DVCS with a longitudinally polarised target

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

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

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

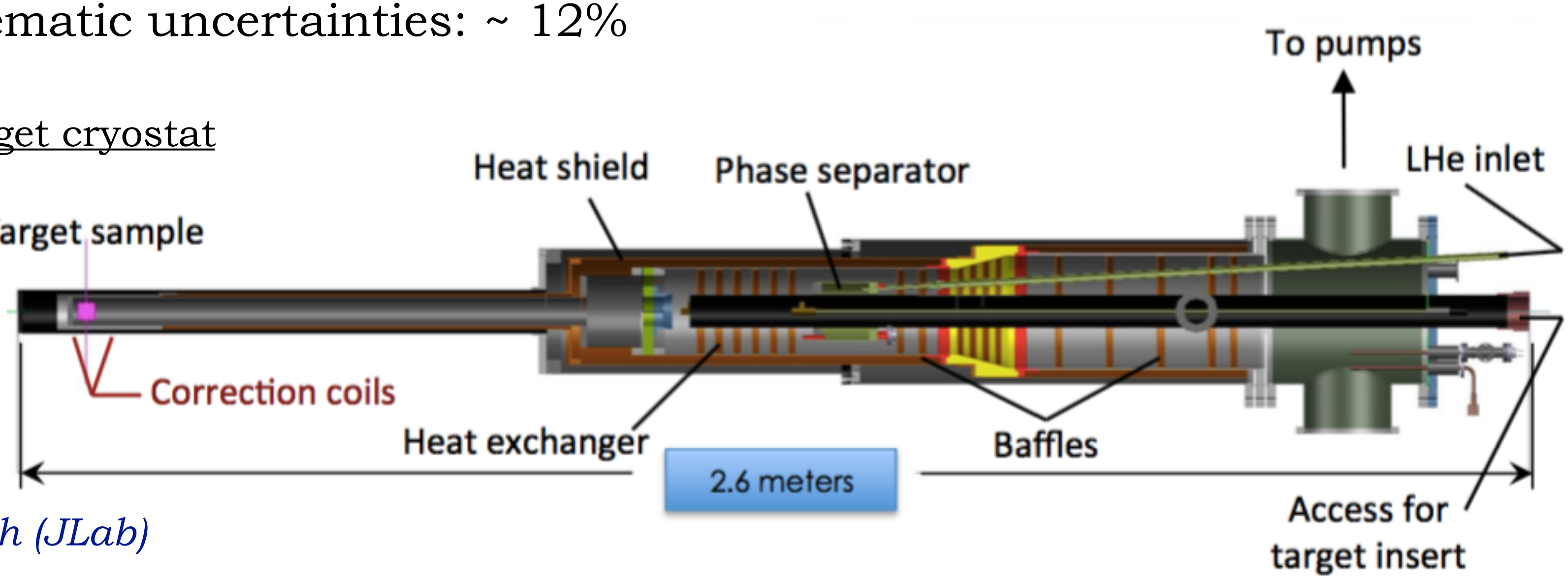
→ ***Im*($\widetilde{\mathrm{H}}_\mathrm{p}$)**

Longitudinally polarised NH_3 target:

- Dynamic Nuclear Polarisation (DNP) of target material, cooled to 1K in a *He* evaporation cryostat.
- $P_{proton} > 80\%$
- Statistical error: 2% - 15% on sinφ moments
- Systematic uncertainties: ~ 12%

Tentative schedule: 2020

Target cryostat



C. Keith (JLab)

CLAS12

Neutron DVCS with a longitudinally polarised target

Experiment E12-06-109A.

S. Niccolai, D. Sokhan et al.

Longitudinally polarised ND_3 target:

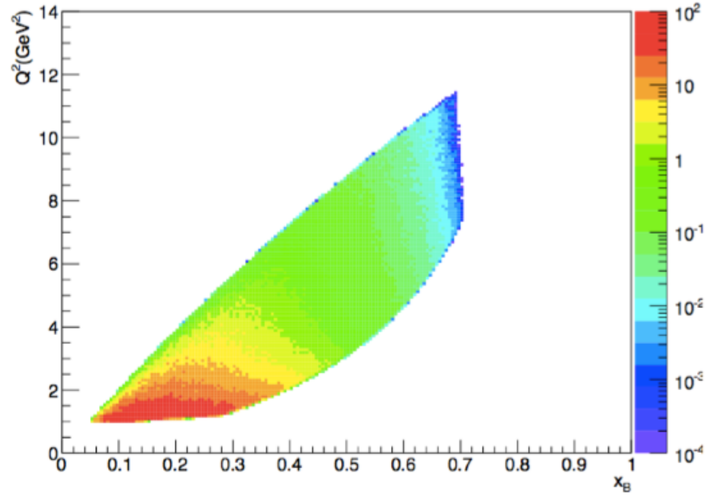
- Dynamic Nuclear Polarisation (DNP) of target material in a cryostat shared with the NH_3 target.
- $P_{deuteron}$ up to 50%
- Systematic uncertainties: ~ 12%

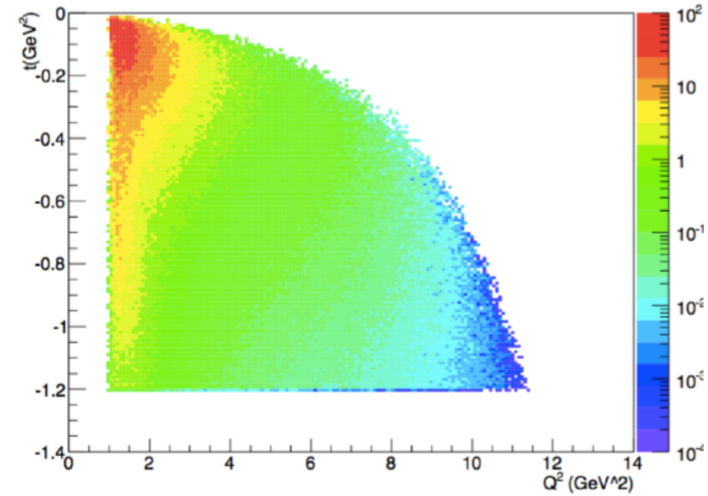
A_{UL} characterised by imaginary parts of CFFs via:

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

→ ***Im*(H$_n$)**

In combination with pDVCS, will allow flavour-separation of the H_q CFFs.





Tentative schedule: 2020

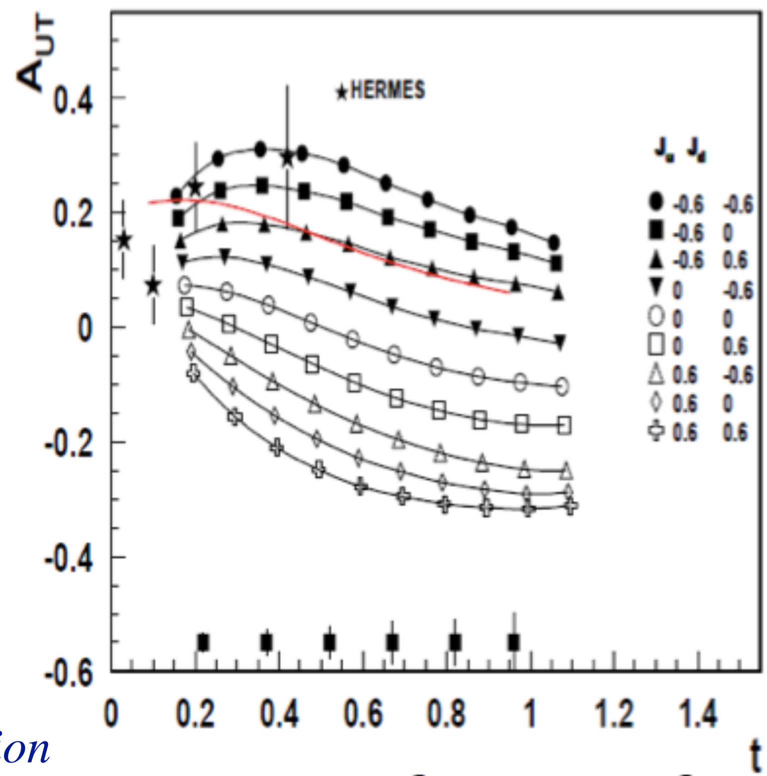
Proton DVCS with transversely polarised target at CLAS12

C12-12-010: with transversely polarised HD target (conditionally approved).

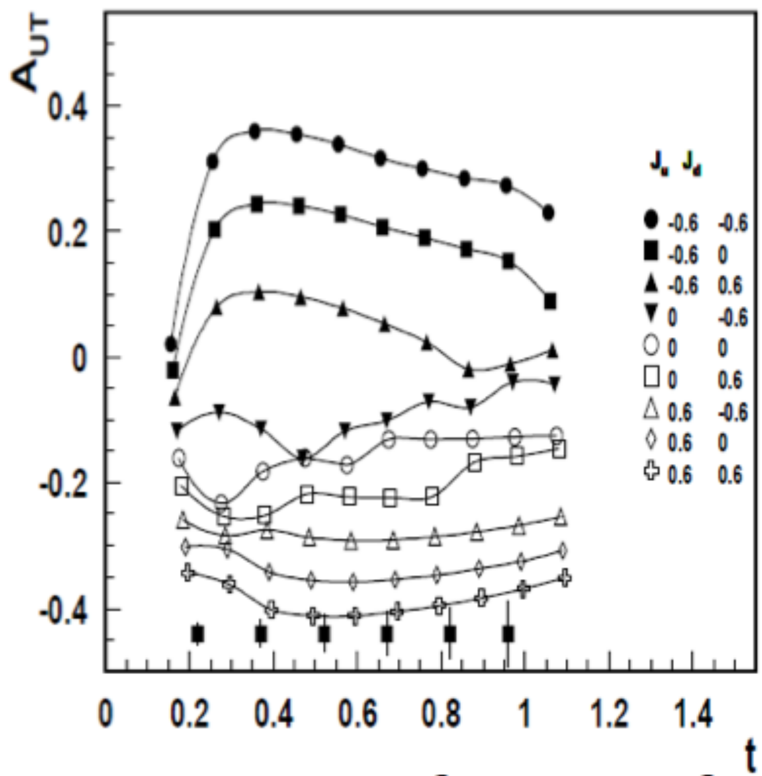
L. Elouardhiri et al.

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

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



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



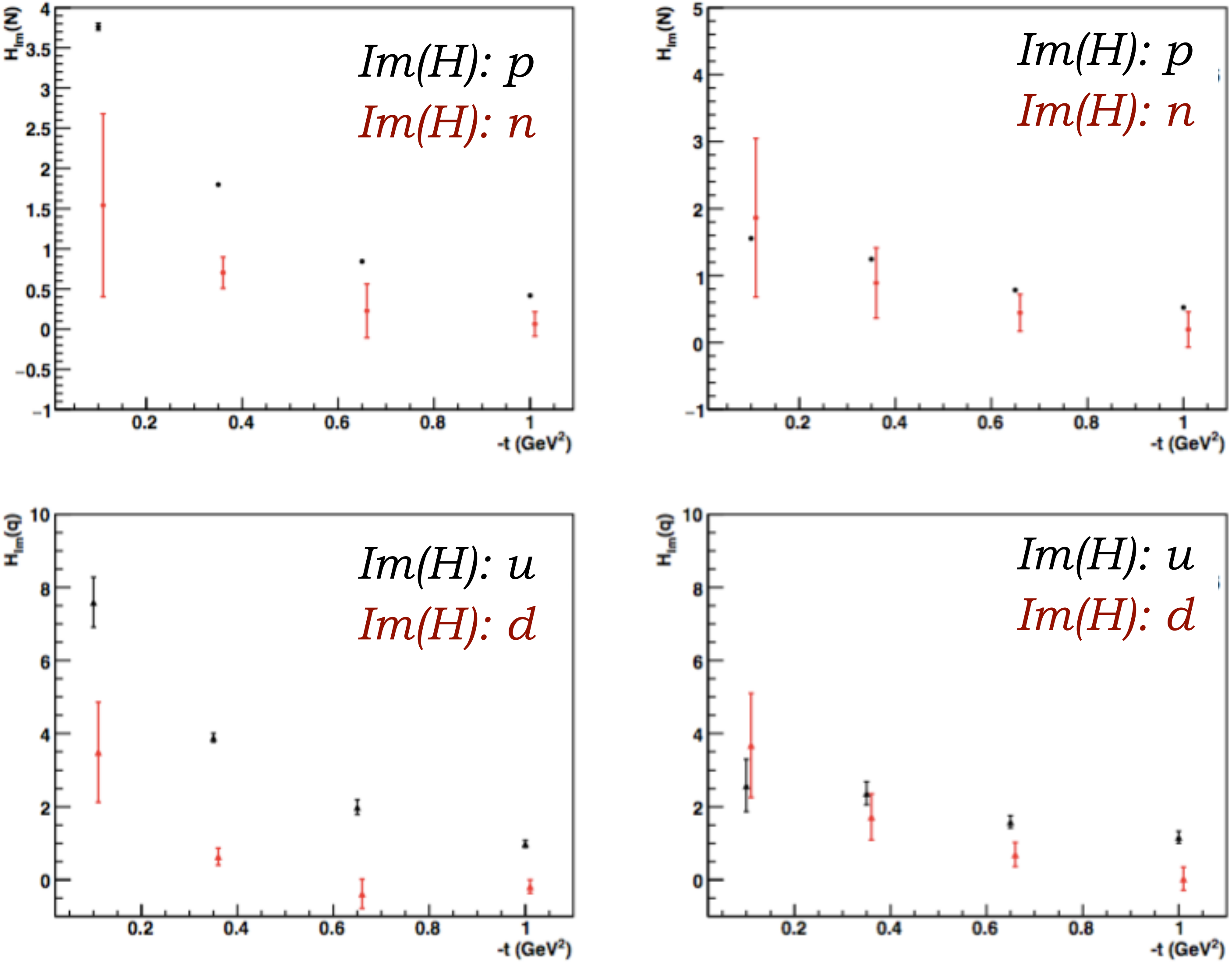
$\langle x \rangle = 0.33, \langle Q^2 \rangle = 2.5\ GeV^2$

VGG extraction (M. Guidal)

Projected sensitivities to *Im(H)* CFF

CLAS12

$Q^2 = 2.6\ GeV^2,\ x_B = 0.23$ | $Q^2 = 5.9\ GeV^2,\ x_B = 0.35$



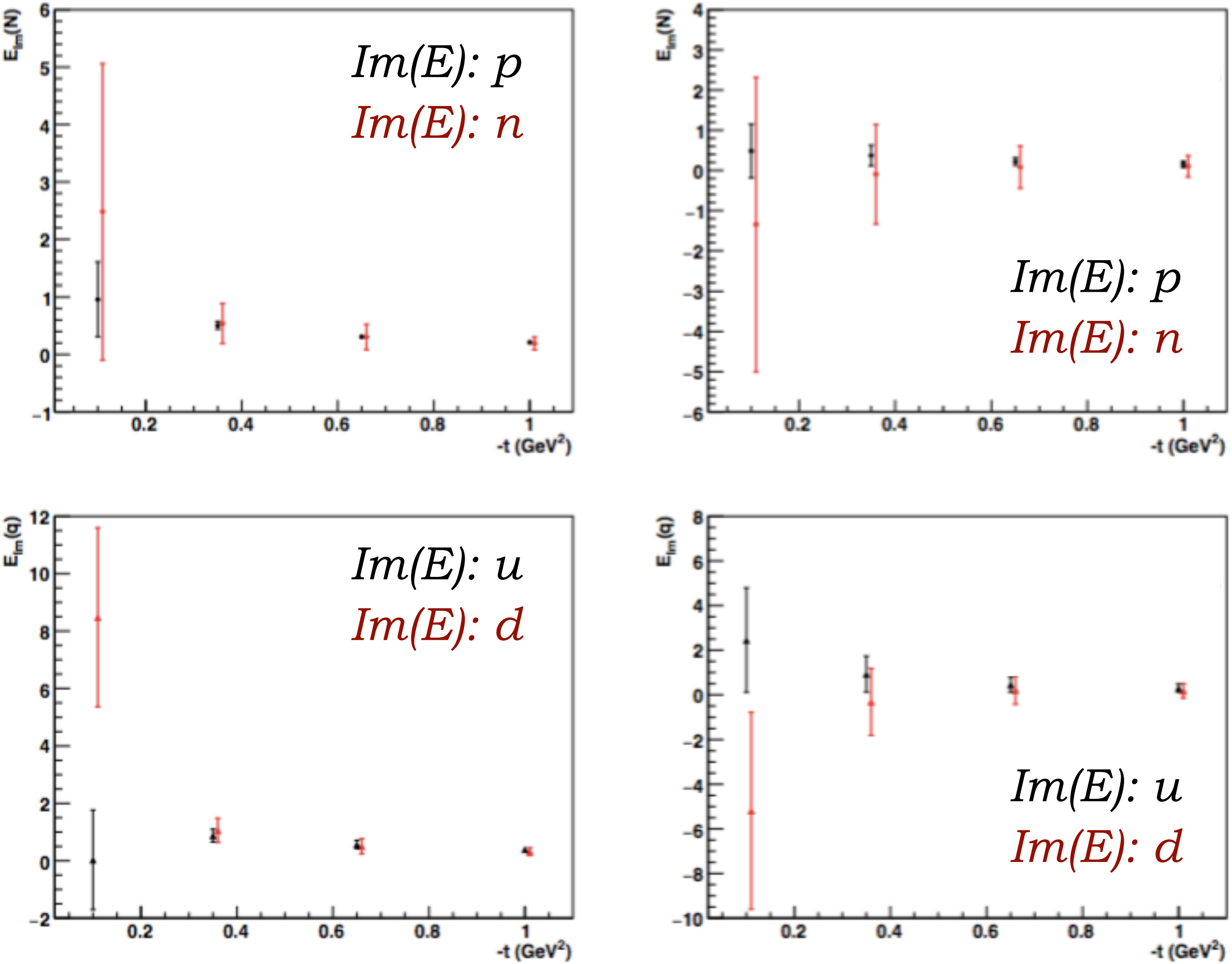
Projections for *Im(H*) neutron and proton and up and down CFFs extracted from approved CLAS12 experiments.

VGG fit (M. Guidal)

Projected sensitivities to *Im(E)* 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(E)* neutron and proton and up and down CFFs extracted from approved and conditionally-approved CLAS12 experiments.

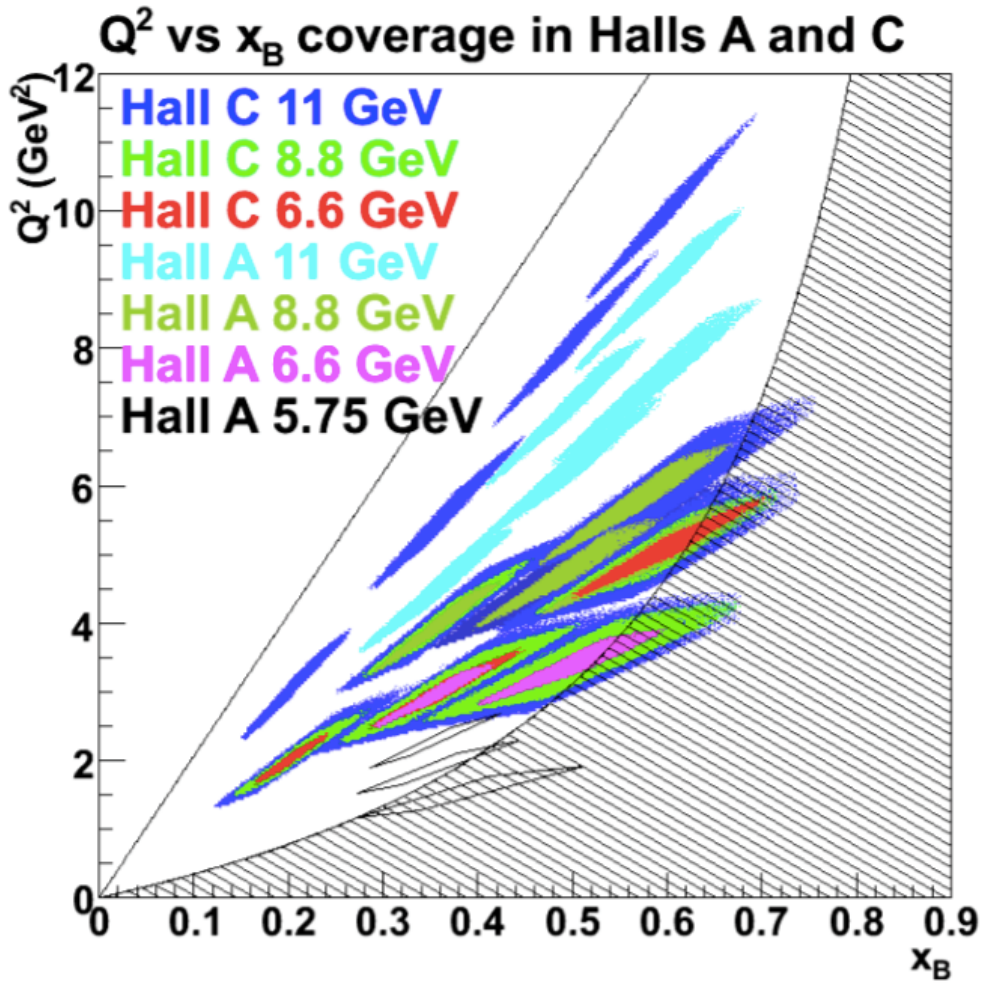
VGG fit (M. Guidal)

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 H_2 target:

- Beam energies: 6.6, 8.8, 11 GeV
- Scans of Q^2 at fixed x_B.
- Hall A: aim for absolute cross-sections with 4% relative precision.



Hall A started taking data last spring!

✱ 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.

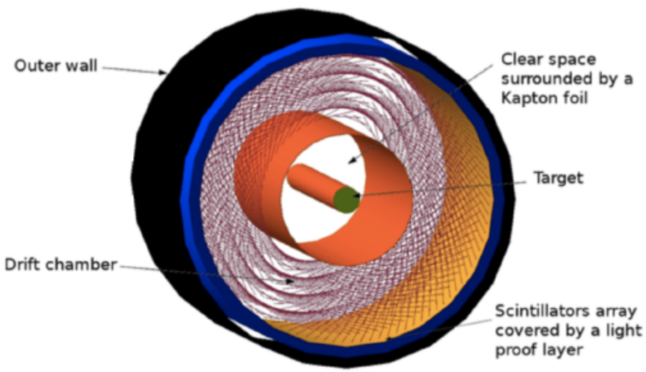
DVCS on ^{4}He: CLAS12 with ALERT

Experiment E12-17-012: Measurement of BSA in coherent DVCS from a *^{4}He* target: partonic structure of nuclei.

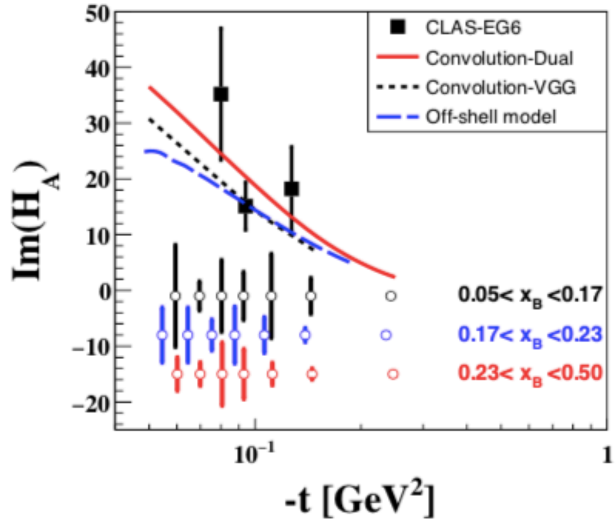
Z.-E. Meziani et al.

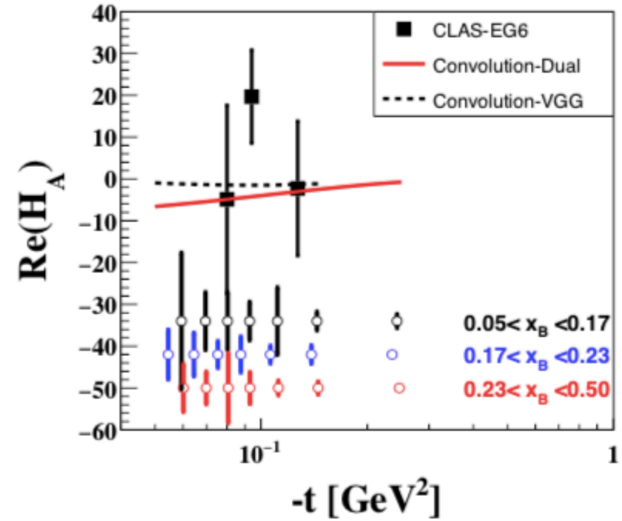
✱ Spin 0 target, so at leading twist only one chiral-even GPD: $\mathbf{H_A}$.

11 GeV beam, 80% polarised.
Gas target straw @ 3 atm
$L = 6 \times 10^{34}$ nucleon $cm^{-2}s^{-1}$ with 1000 nA beam.



CLAS12 + ALERT: central recoil detector





Experiment E12-17-012B
W. Armstrong et al.

Incoherent, spectator-tagged DVCS on *^{4}He* and *d*.

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 Q^2 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.


Thank you!