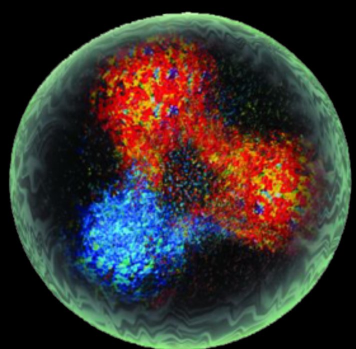
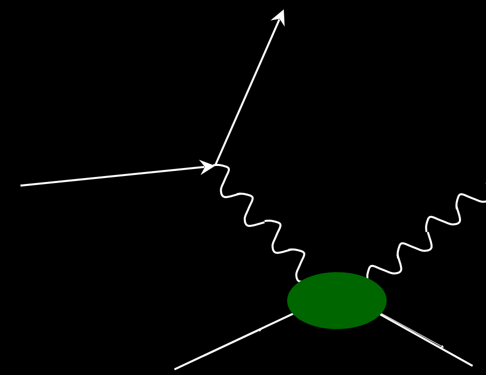
Deeply Virtual Compton Scattering at Jefferson Lab in the 11 GeV era



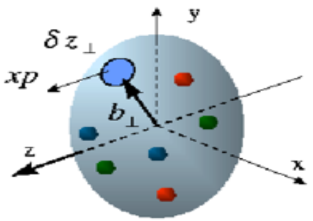
Daria Sokhan

University of Glasgow, UK

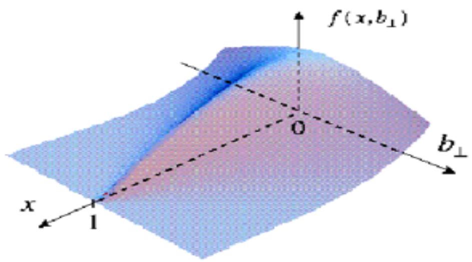


Réunion annuelle du GDR QCD
IPN Orsay, France— 10th November 2016

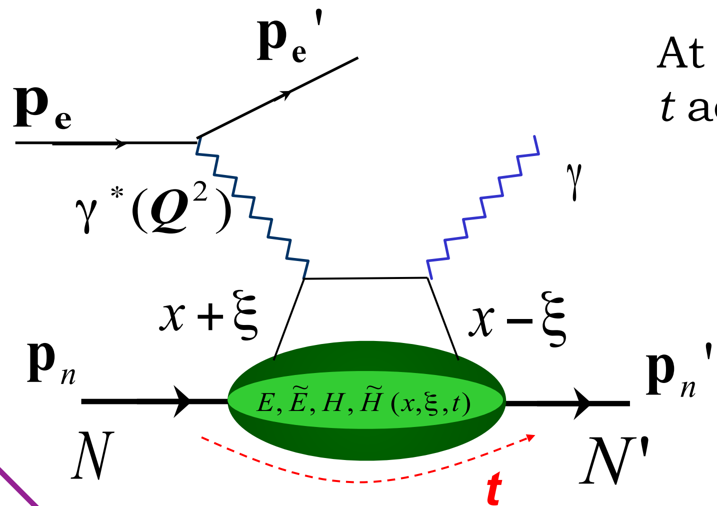
Generalised Parton Distributions and DVCS



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



* **Deeply Virtual Compton Scattering:** golden channel.



At high exchanged Q^2 and low t access to four GPDs:

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

* Provide information on the orbital angular momentum contribution to nucleon spin: **the spin puzzle**.

$$Q^2 = -(\mathbf{p}_e - \mathbf{p}_e')^2$$

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

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

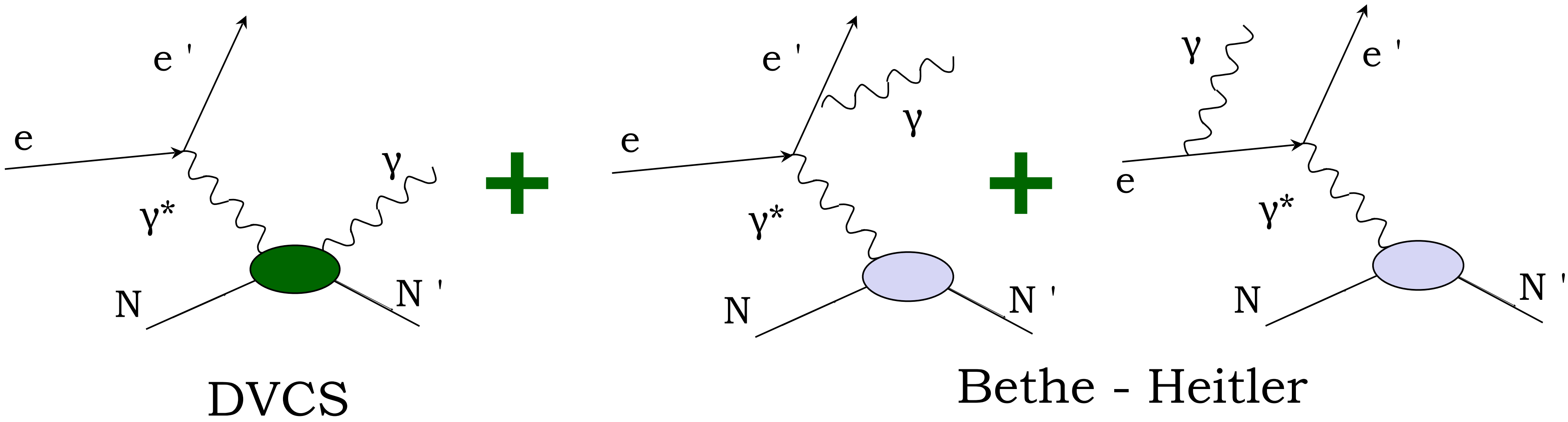
$x \pm \xi$ *longitudinal momentum fractions of quarks*

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

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

Measuring DVCS

✳ Process measured in experiment:



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

Amplitude parameterised in terms of Compton Form Factors

Amplitude calculable from elastic Form Factors and QED

Interference term

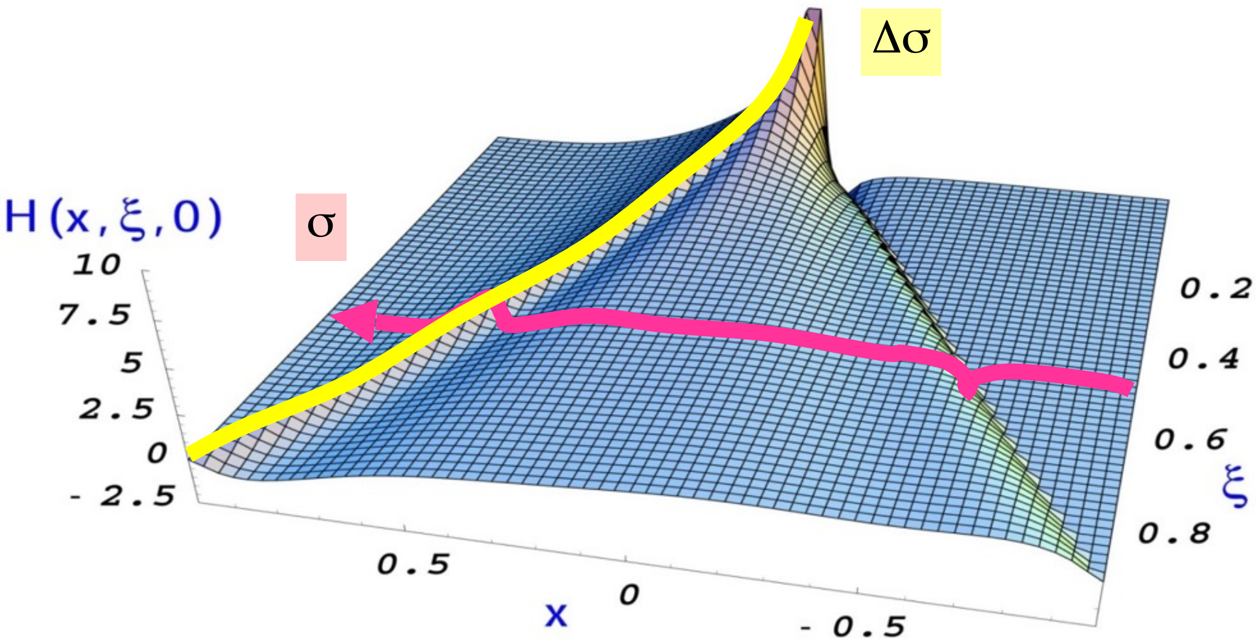
$$\left|T_{DVCS}\right|^2 << \left|T_{BH}\right|^2$$

Compton Form Factors in DVCS

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

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

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



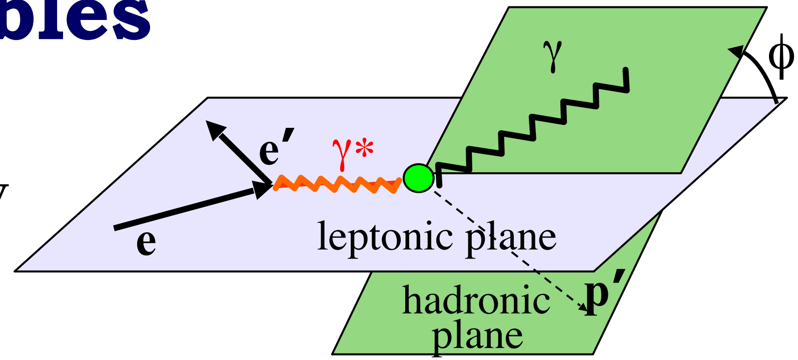
Only ξ and t are accessible experimentally!

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

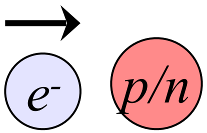
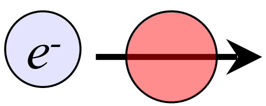
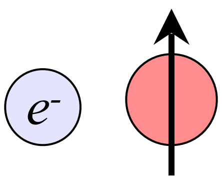
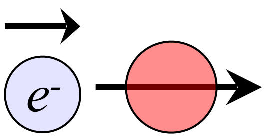
Need measurements off proton and neutron to get flavour separation of CFFs.

Experimental observables

Real parts of CFFs accessible in cross-sections and double polarisation asymmetries, imaginary parts of CFFs in single-spin asymmetries.



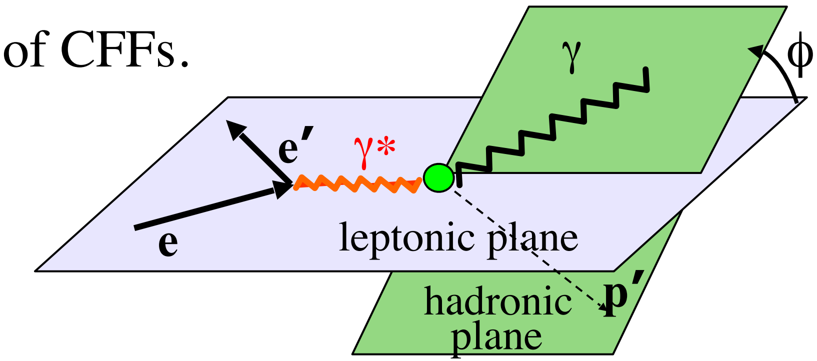
$\xi = x_B/(2-x_B) \quad k = t/4M^2$

Beam, target polarisation			Proton / Neutron
	$\Delta\sigma_{LU} \sim \sin\phi \; \mathrm{Im}\{F_1\mathcal{H} + \xi(F_1+F_2)\tilde{\mathcal{H}} - kF_2\mathcal{E}\}d\phi$	→	$Im\{\boldsymbol{H_p}, \tilde{H}_p, E_p\}$ $Im\{H_n, \tilde{H}_n, \boldsymbol{E_n}\}$
	$\Delta\sigma_{UL} \sim \sin\phi \; \mathrm{Im}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E}) - \xi k F_2 \tilde{\mathcal{E}} + \ldots\}d\phi$	→	$Im\{\boldsymbol{H_p}, \boldsymbol{\tilde{H}_p}\}$ $Im\{\boldsymbol{H_n}, E_n, \tilde{E}_n\}$
	$\Delta\sigma_{UT} \sim \cos\phi \; \mathrm{Im}\{k(F_2\mathcal{H} - F_1\mathcal{E}) + \ldots\}d\phi$	→	$Im\{\boldsymbol{H_p}, \boldsymbol{E_p}\}$ $Im\{\boldsymbol{H_n}\}$
	$\Delta\sigma_{LL} \sim (A+B\cos\phi) \; \mathrm{Re}\{F_1\tilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + x_B/2\,\mathcal{E})\ldots\}d\phi$	→	$Re\{\boldsymbol{H_p}, \boldsymbol{\tilde{H}_p}\}$ $Re\{\boldsymbol{H_n}, E_n, \tilde{E}_n\}$

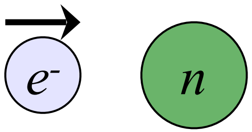
DVCS off the neutron

- For the fullest extraction of CFFs need measurements of a variety of experimental observables across a wide kinematic range and on different targets.

- DVCS on proton and neutron: flavour separation of CFFs.



- Neutron DVCS extremely sensitive to *E*, least-known and least-constrained GPD



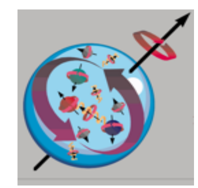
Polarized beam, unpolarized neutron target:

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

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

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

Important missing link in the nucleon spin puzzle…

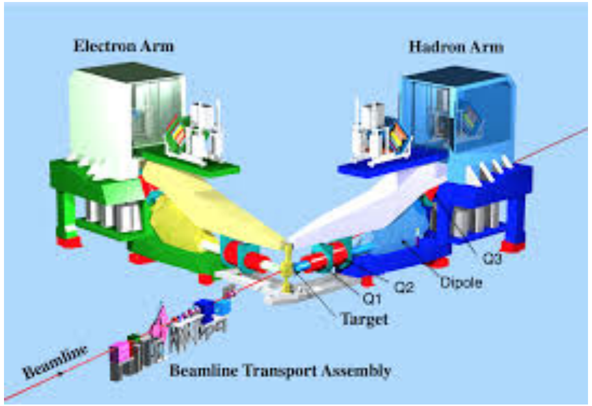


Jefferson Lab: 6 GeV era

CEBAF: Continuous Electron Beam Accelerator Facility.

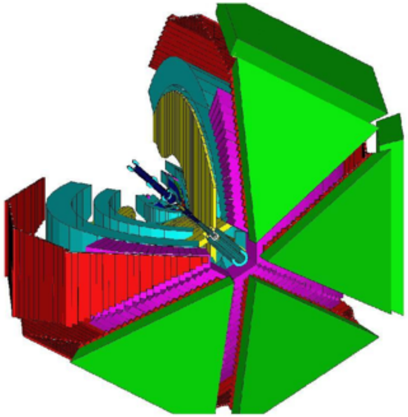
- Energy up to ~6 GeV
- Energy resolution $\delta E/E_e \sim 10^{-5}$
- Longitudinal electron polarisation up to ~85%
- Three experimental fixed-target halls

Hall A:



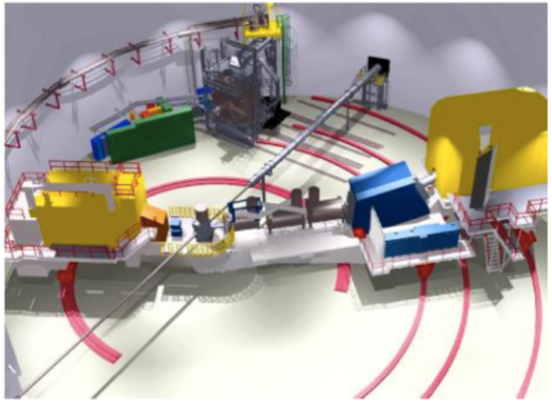
- High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity.

Hall B: CLAS



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

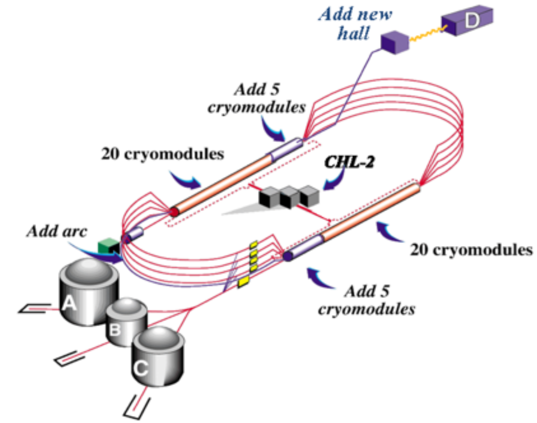
Hall C:



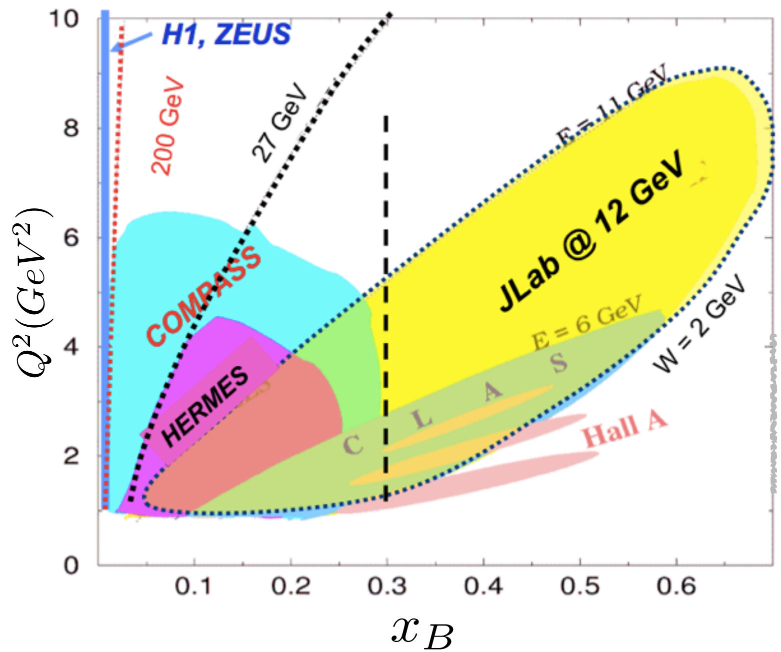
- Two movable high-momentum spectrometer arms, well-defined acceptance, high luminosity

Jefferson Lab: 12 GeV era

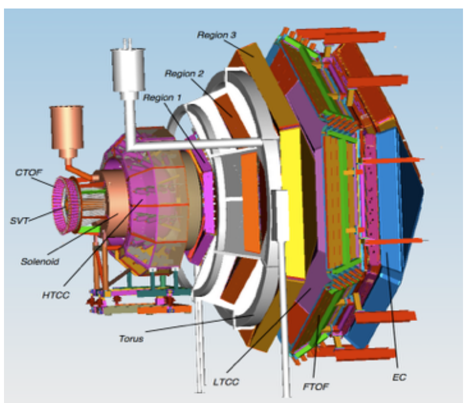
- Maximum electron energy: 12 GeV to new Hall D
- 11 GeV deliverable to Halls A, B and C



Hall A: High resolution spectrometers, large installation experiments



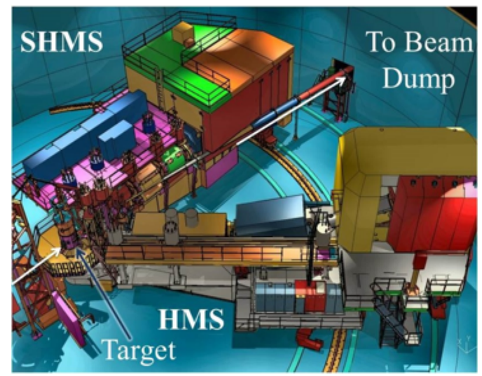
Hall B: CLAS12



Very large acceptance, high luminosity

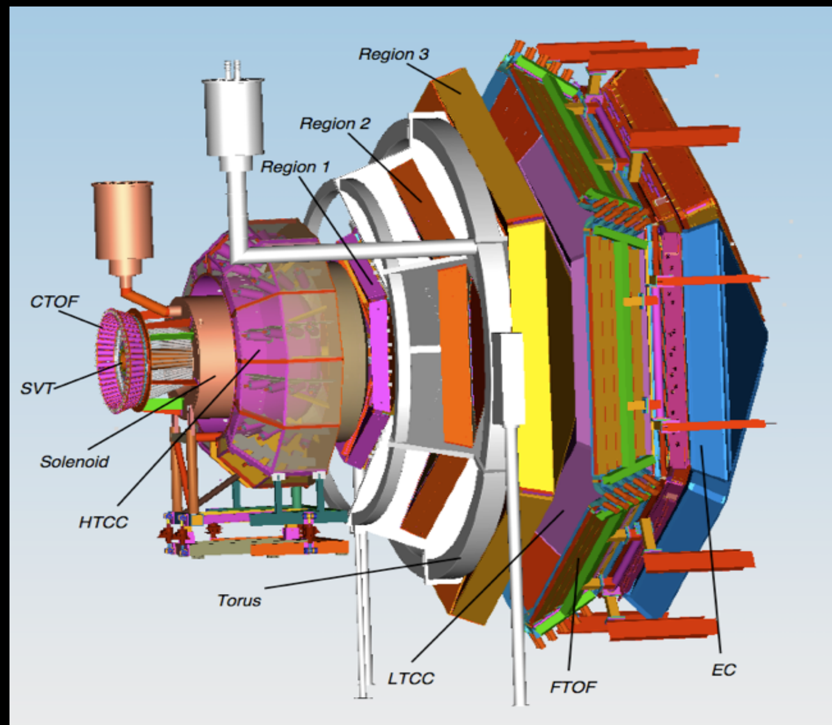
Hall D: 9 GeV tagged polarised photons, full acceptance detector

Hall C:



Super-high Momentum Spectrometer added, very high luminosity

CLAS12


Region 3
Region 2
Region 1
CTOF
SVT
Solenoid
HTCC
Torus
LTCC
FTOF
EC

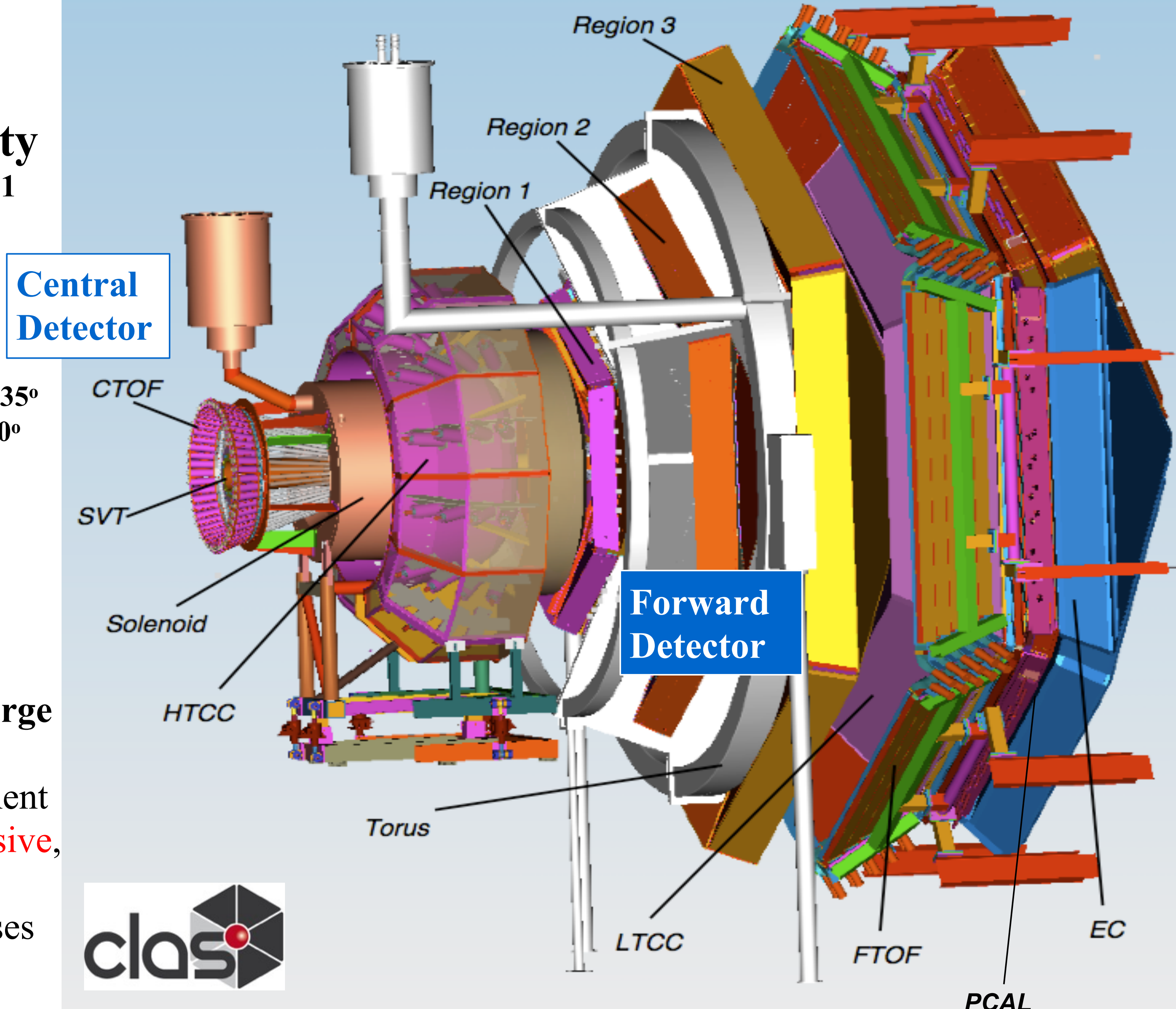
CLAS12

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

Acceptance for charged particles:
- **Central (CD), $40^o < \theta < 135^o$**
- **Forward (FD), $5^o < \theta < 40^o$**

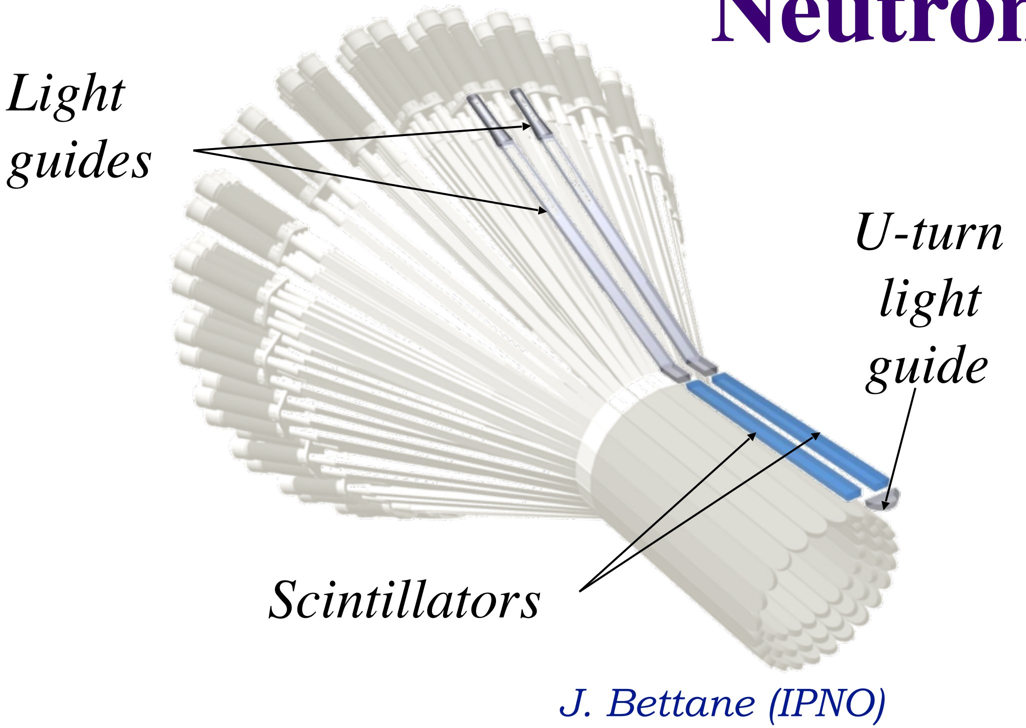
Acceptance for photons:
- **FT $2.5^o < \theta < 4.5^o$**
- **EC $5^o < \theta < 40^o$**

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

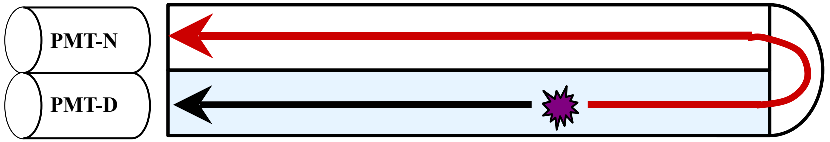


Neutron Detector for CLAS12

Constructed at IPN Orsay
S. Niccolai et al.



★ Neighbouring paddles coupled via u-turn light guide to provide read-out from both ends:



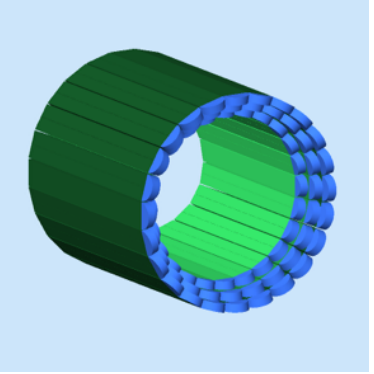
★ Plastic scintillator barrel: 3 layers, 48 paddles each

★ Within a 5T magnetic field of the solenoid

★ PMT read-out upstream, out of high B field

★ Efficiency ~ 10%

★ Momentum resolution ~ 5% - 12%



proton DVCS @ 11 GeV: CLAS12

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

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

Unpolarised liquid H_2 target:

- 80 days (Run Group A)
- Statistical error: 1% - 10% on sinφ moments
- Systematic uncertainties: ~ 6 - 8%

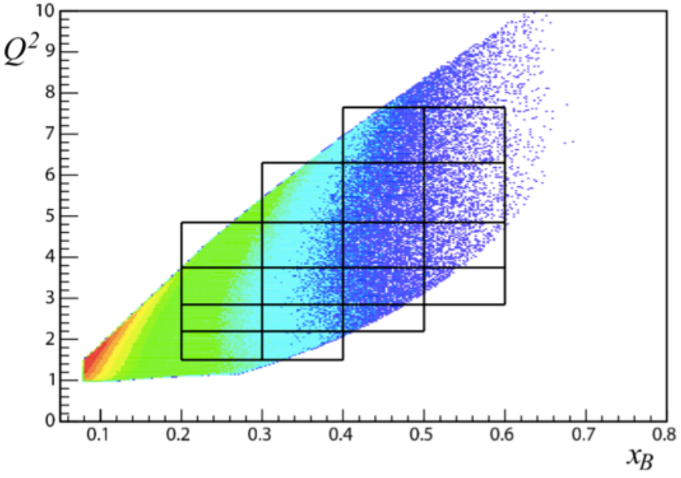
→ **First experiment with CLAS12!**

Tentative schedule: late 2017-18

Longitudinally polarised NH_3 target:

- 120 days (Run Group C)
- Dynamic Nuclear Polarisation (DNP) of target material, cooled in a *He* evaporation cryostat.
- P_{target} = 80%
- Statistical error: 2% - 15% on sinφ moments
- Systematic uncertainties: ~ 6 - 8%

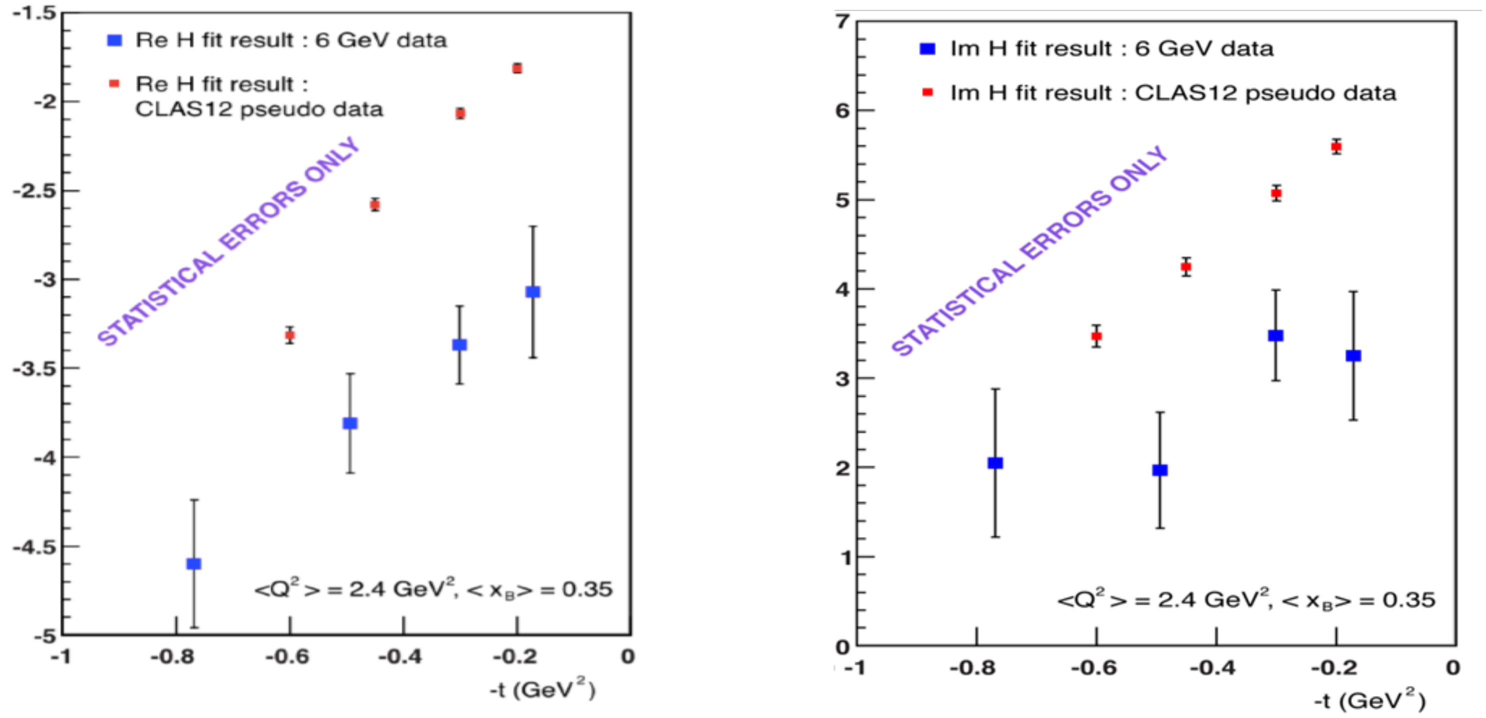
Tentative schedule: late 2019-20



proton DVCS @ 11 GeV: CLAS12

Impact of CLAS12 proton-DVCS beam-spin asymmetry data on the extraction of Re(H) and Im(H).

Re(H) **Im(H)**



(CLAS 6 GeV extraction H. Moutarde)

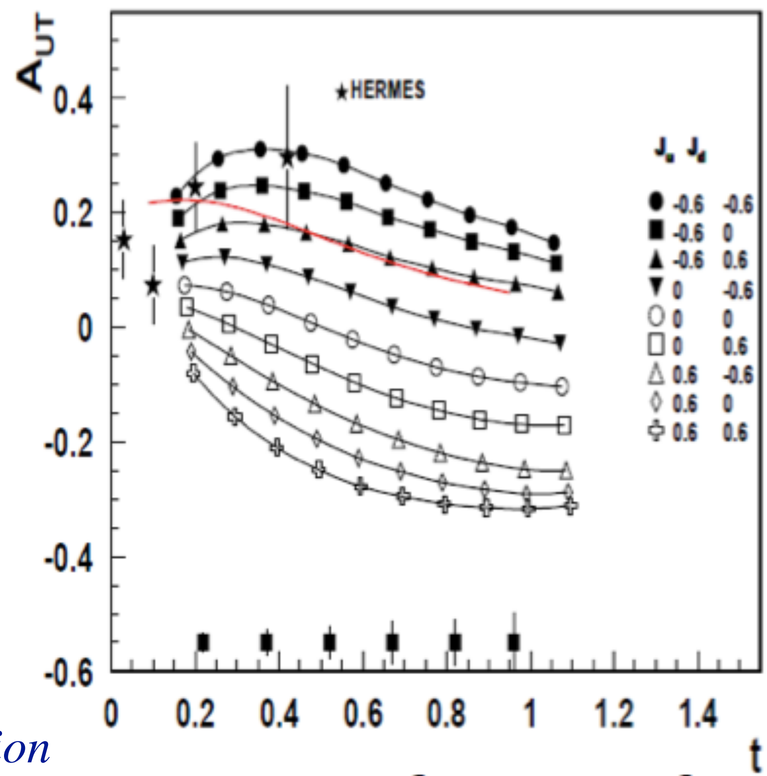
proton DVCS with transversely polarised target at CLAS12

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

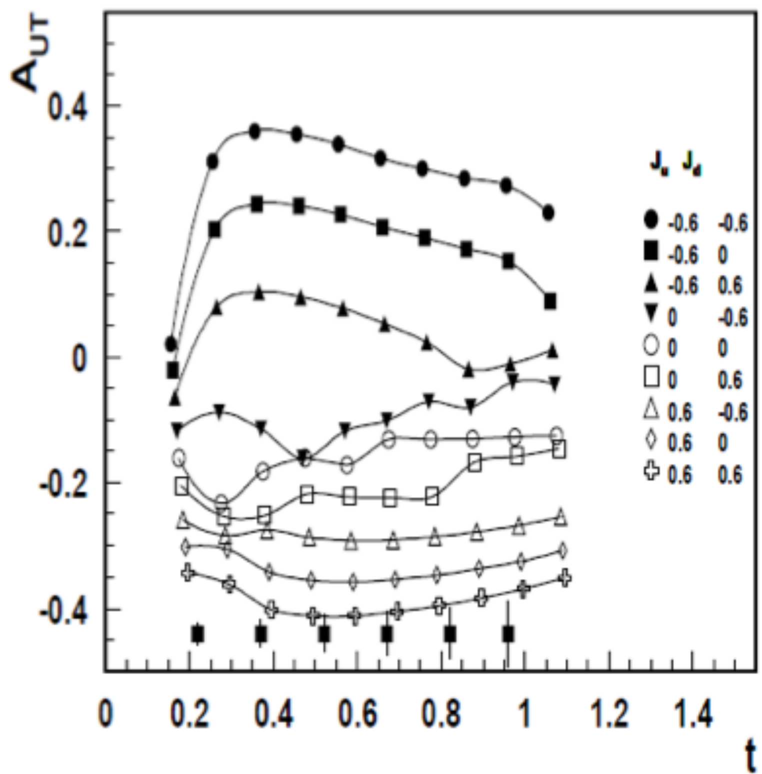
L. Elouardhiri et al.

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

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)

Beam-spin asymmetry in neutron DVCS: CLAS12

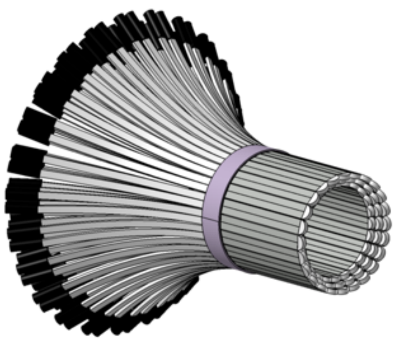
Experiment E12-11-003

S. Niccolai, D. Sokhan et al.

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

80 days of data taking
(Run group B)
L = 10^{35} cm^{-2}s^{-1}/nucleon

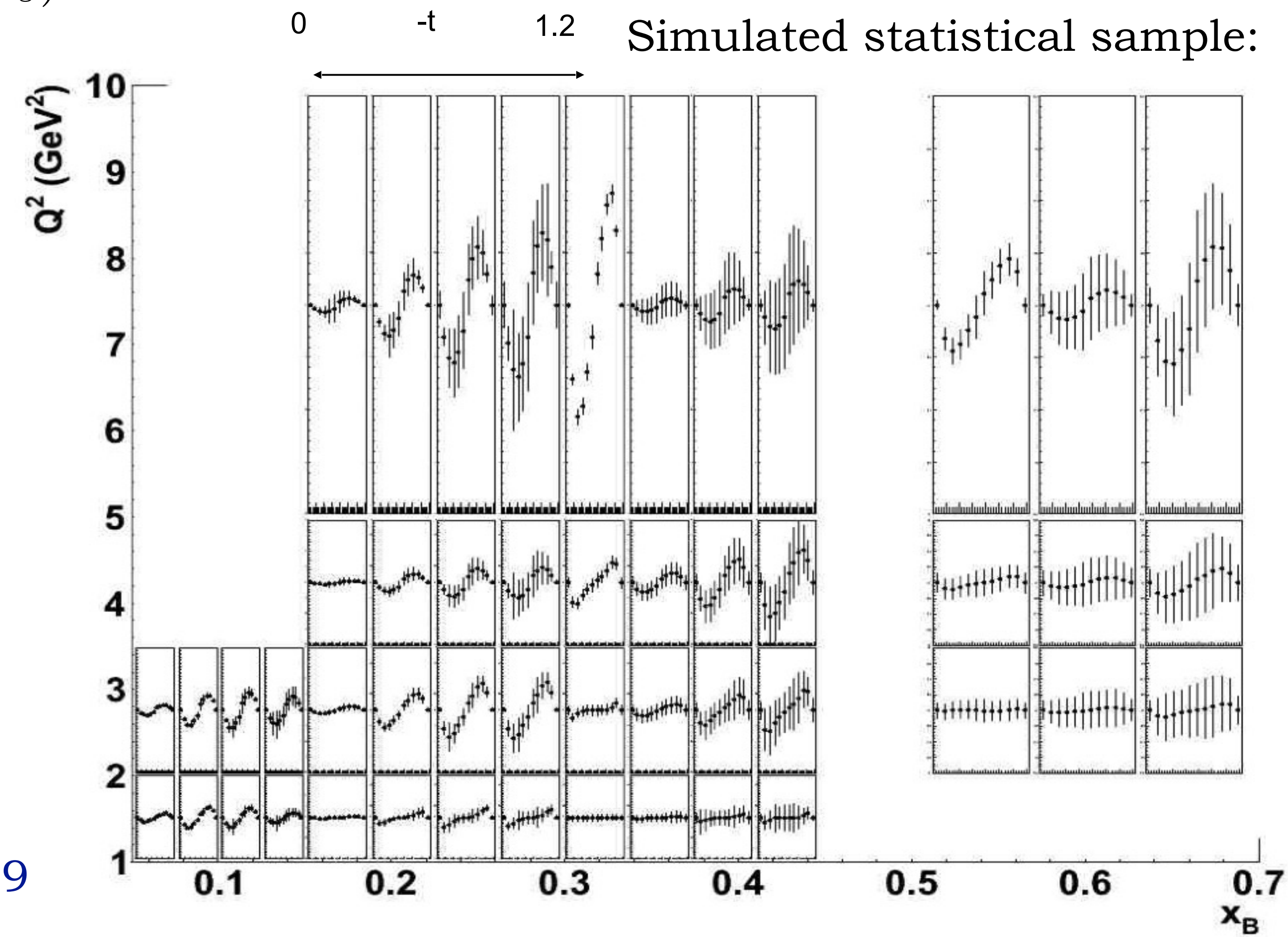
CLAS12 +
Forward Calorimeter
+
Neutron Detector



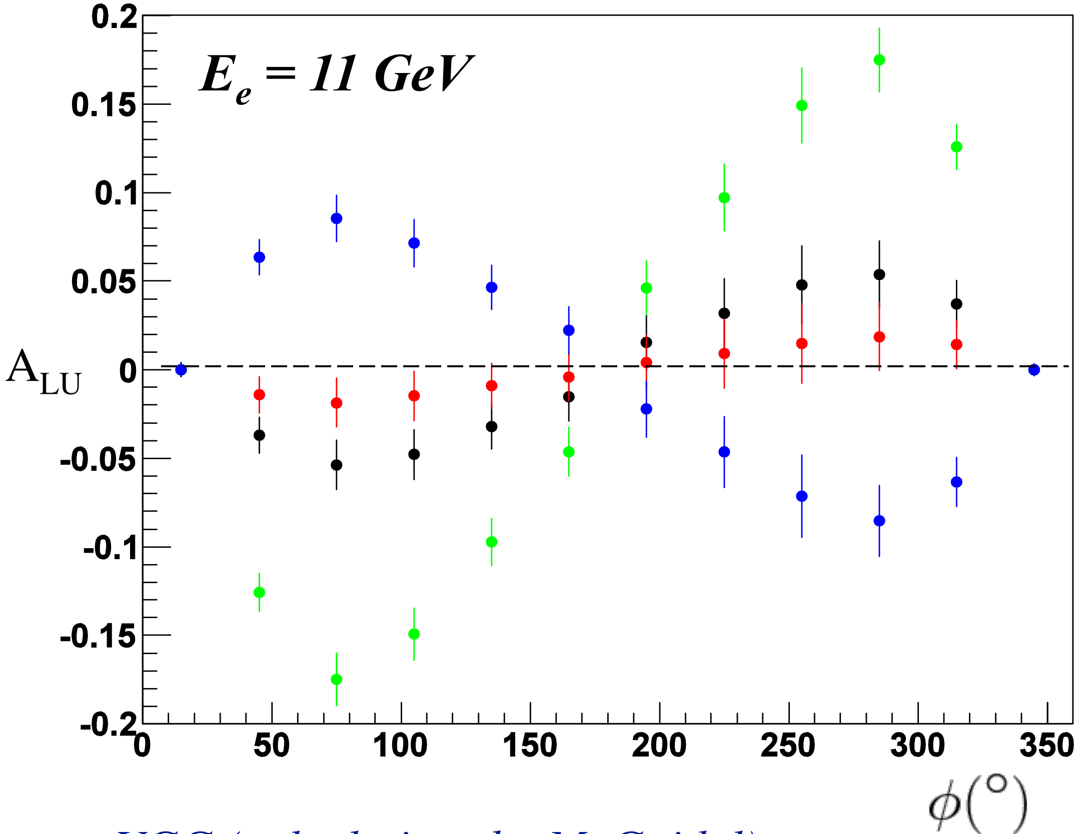
Tentative schedule: 2019

The **most sensitive** observable to the GPD **E_n**

Simulated statistical sample:



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

Neutron DVCS with a longitudinally polarised target: CLAS12

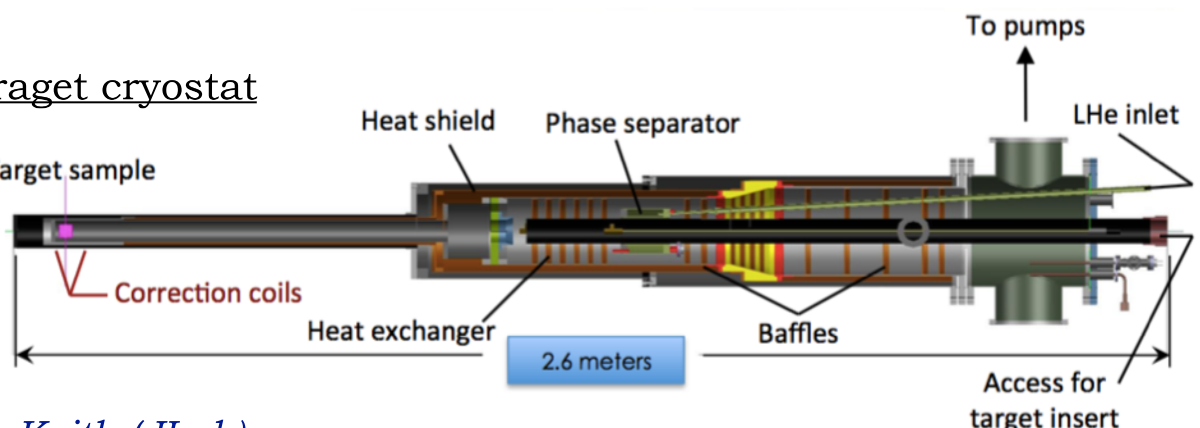
Experiment E12-06-109A.
S. Niccolai, D. Sokhan et al.

Longitudinally polarised ND_3 target:

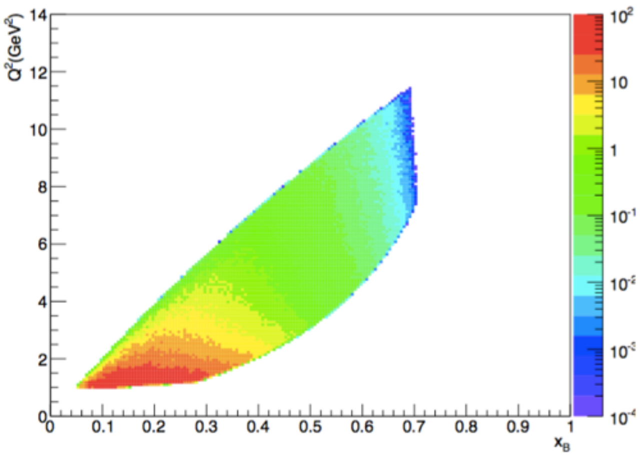
- 60 days (Run Group Cb)
- Dynamic Nuclear Polarisation (DNP) of target material, cooled in a *He* evaporation cryostat.
- $P_{deuteron}$ up to 50%
- Systematic uncertainties: ~ 12%

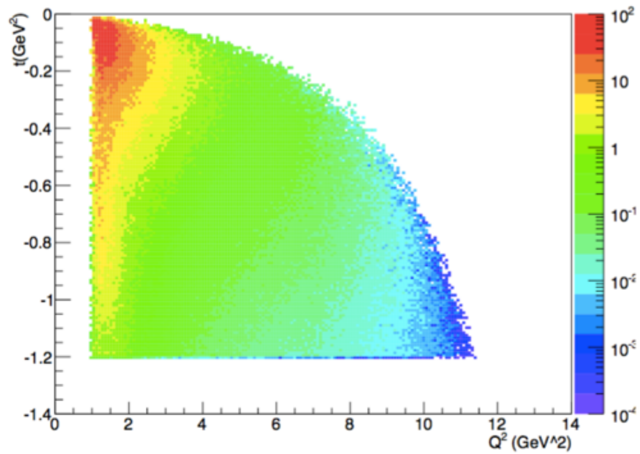
In combination with pDVCS, will allow flavour-separation of CFFs.

<u>Traget cryostat</u>



C. Keith (JLab)

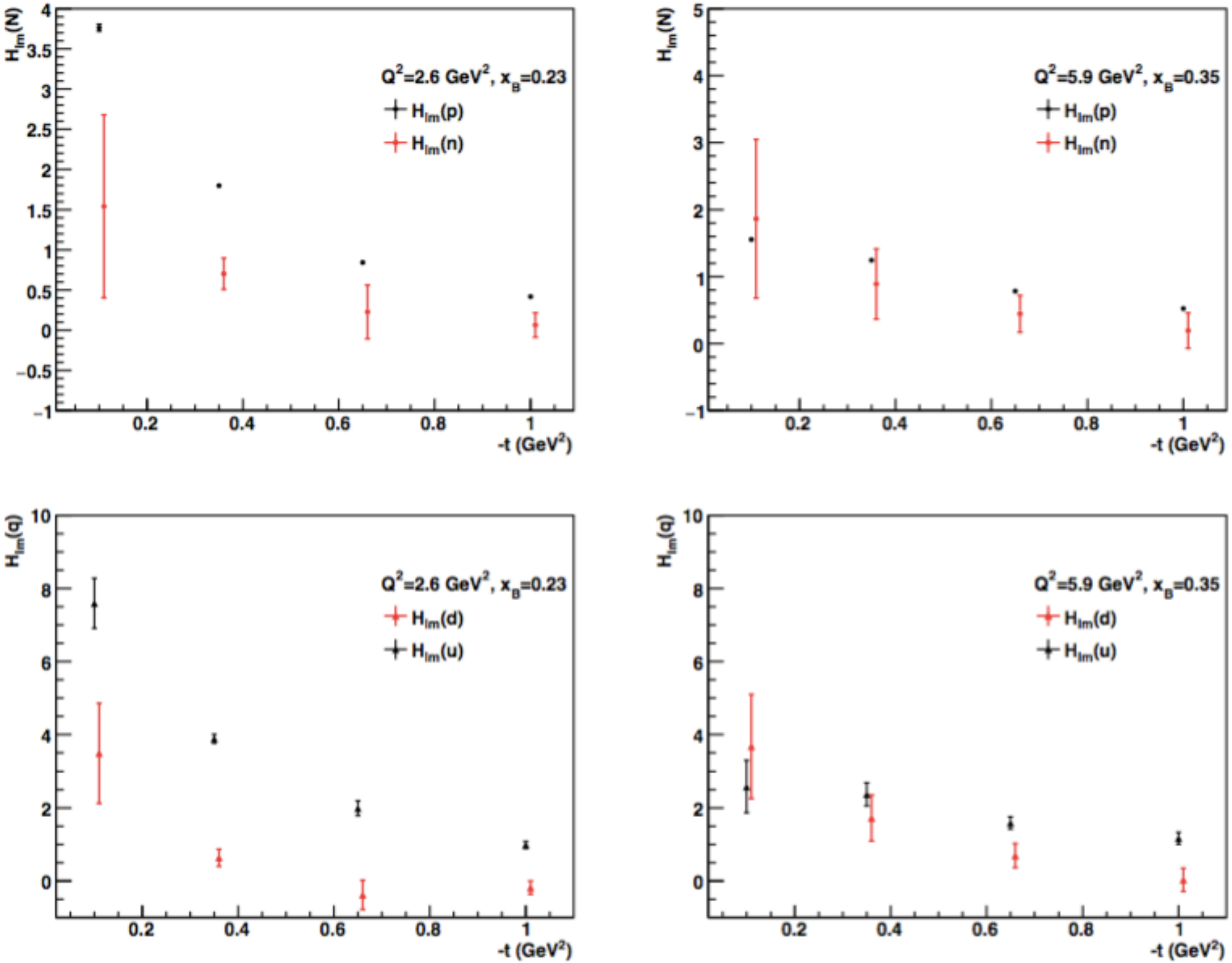




Tentative schedule: 2020

Projected sensitivities to CFF: CLAS12

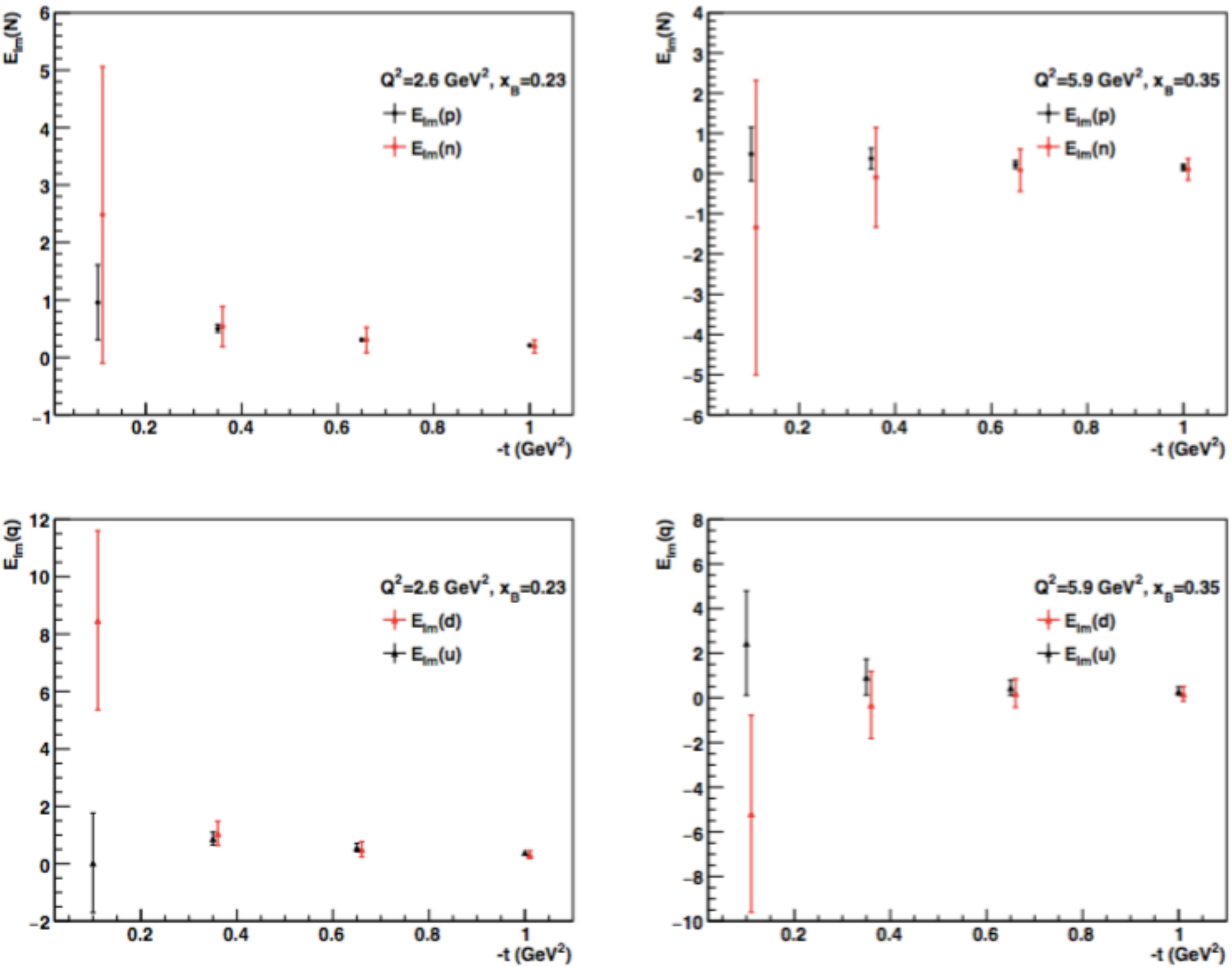
Im(H)



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

VGG fit (M. Guidal)

Projected sensitivities to CFF: CLAS12

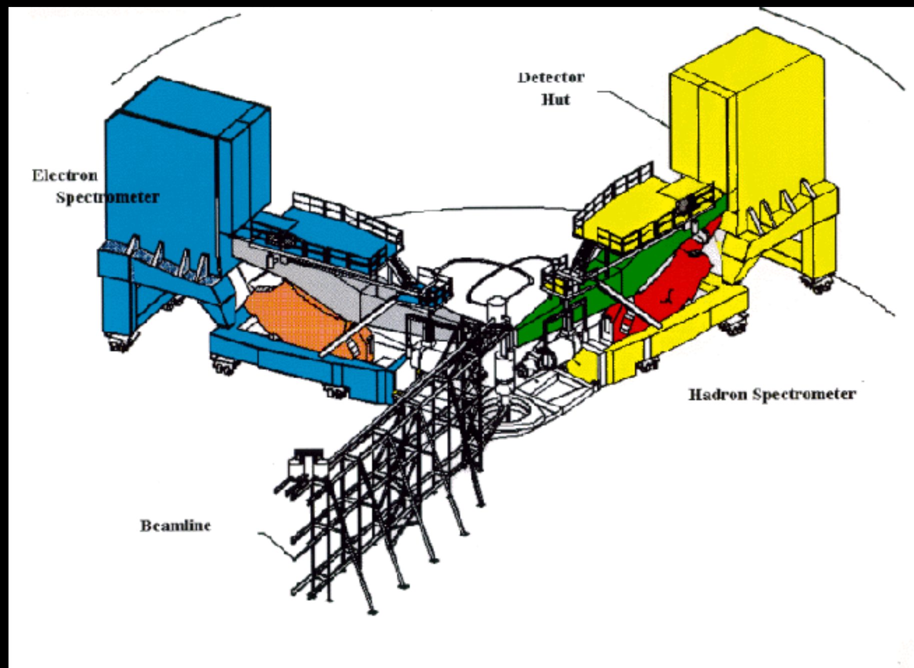


Im(E)

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

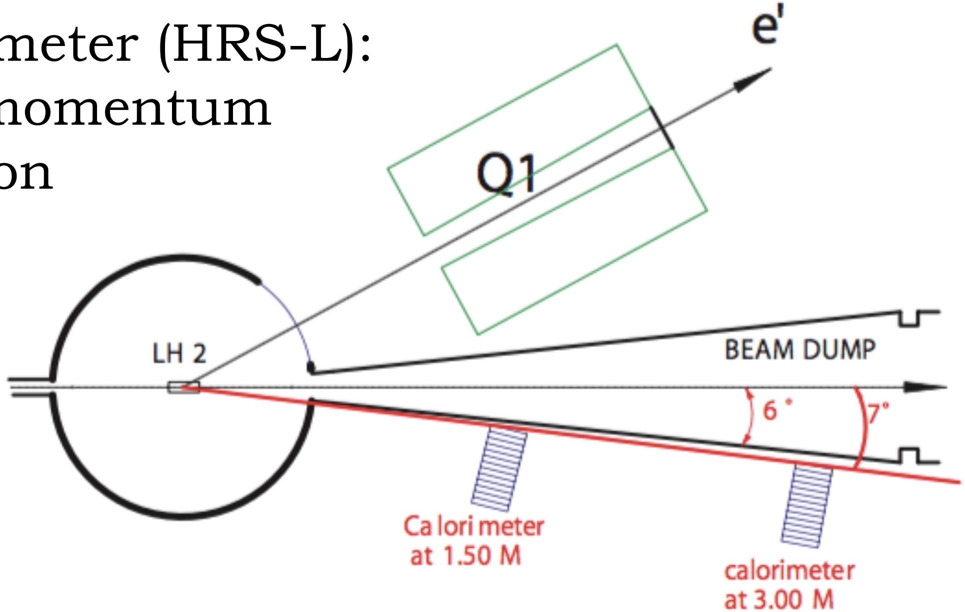
VGG fit (M. Guidal)

Hall A

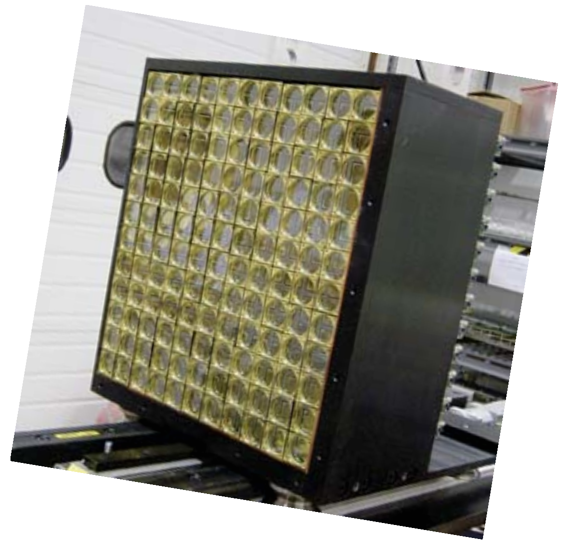

Detector
Hut
Electron
Spectrometer
Hadron Spectrometer
Beamline

DVCS in Hall A @ 11 GeV

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

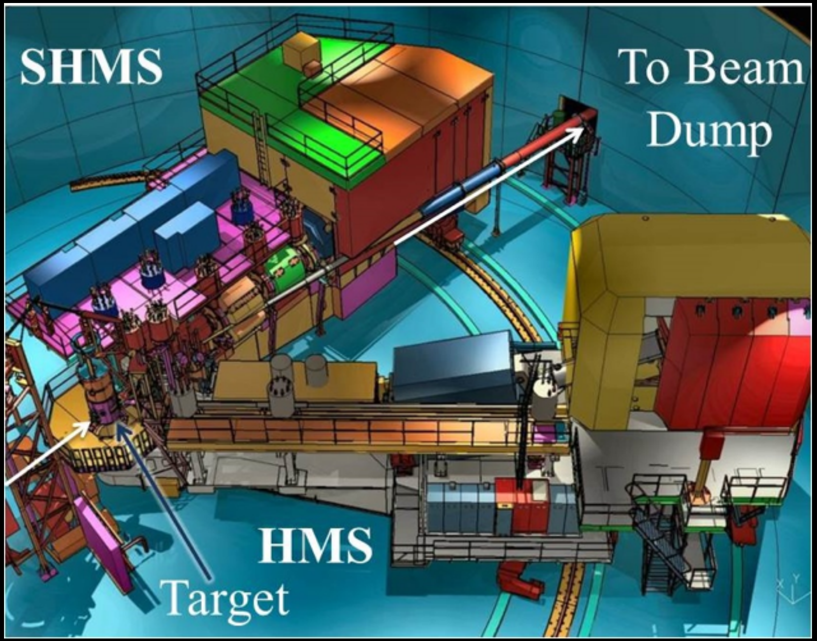


Detect photon in PbF_2 calorimeter: ~ 3% energy resolution



Reconstruct recoiling proton through missing mass.

Hall C



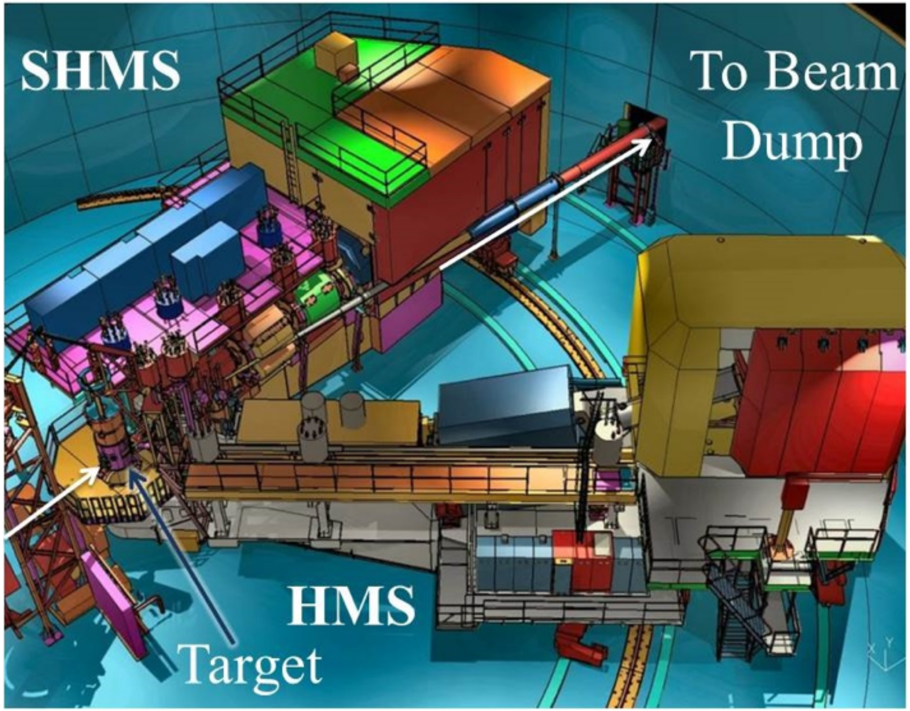
DVCS in Hall C @ 11 GeV

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 Cross-sections: Halls A and C

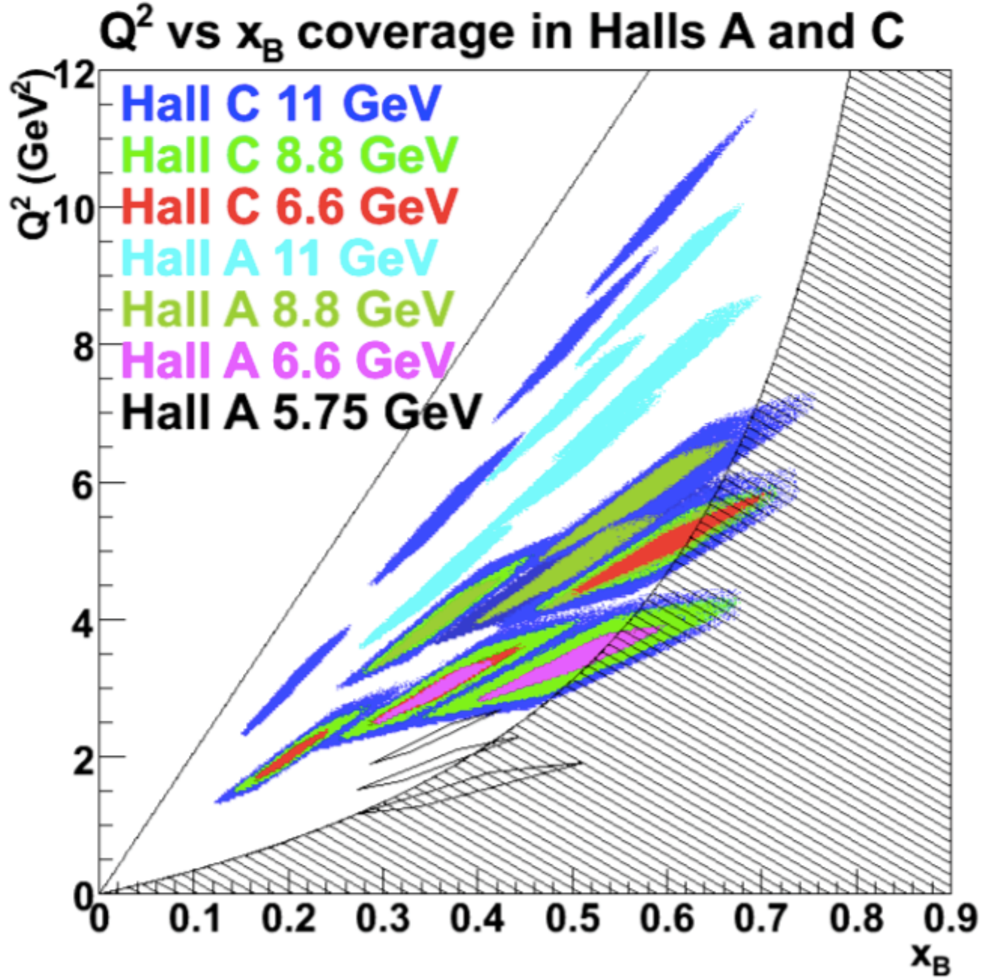
Experiments:
E12-06-114 (Hall A, 100 days),
E12-13-010 (Hall C, 53 days)
C. Muñoz Camacho et al.,
C. Hyde et al.

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.

✱ 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.



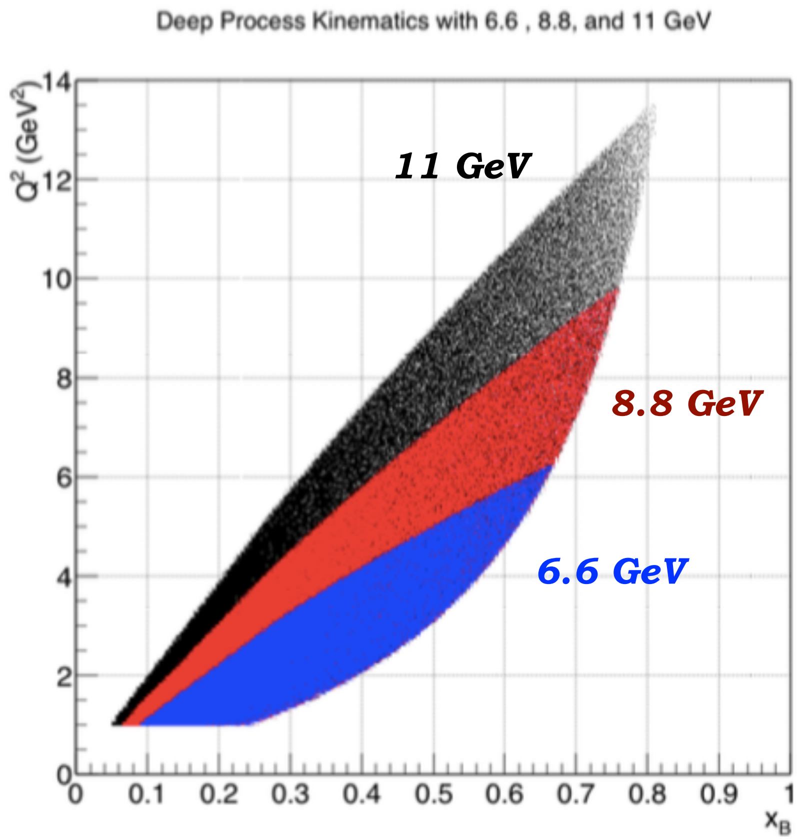
Hall A started taking data this spring, currently running!

DVCS at lower energies with CLAS12

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

Unpolarised liquid H_2 target:

- 100 days (Run group K)
- 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

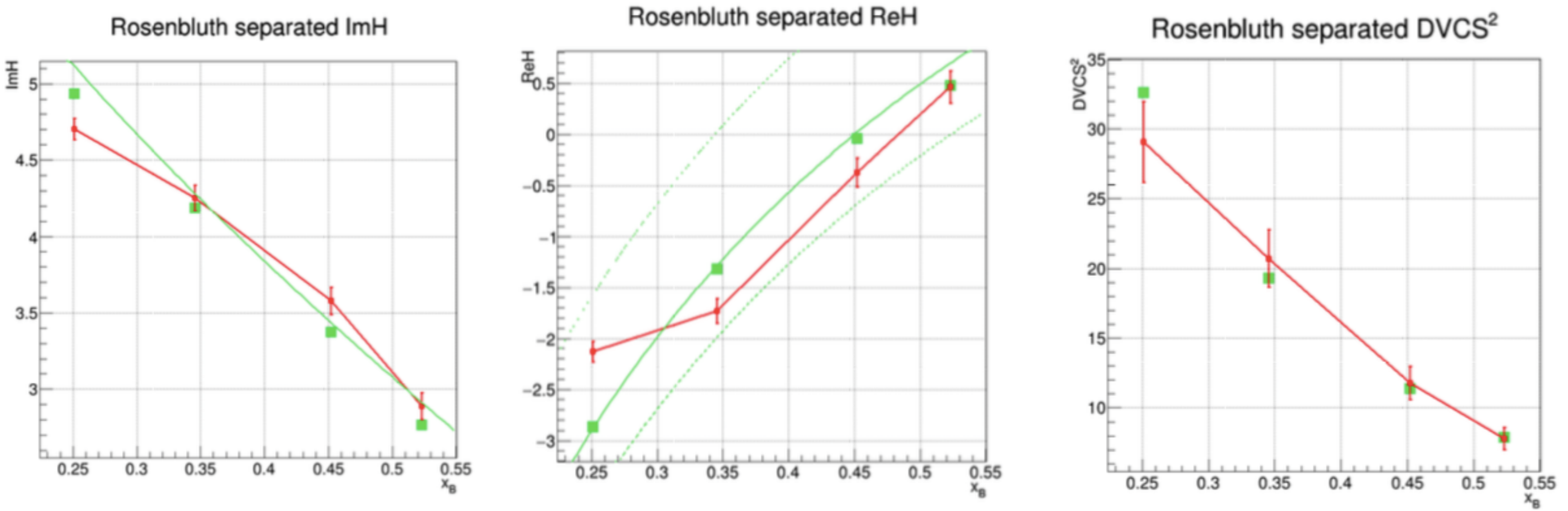
✱ Scaling tests of the extracted CFFs

✱ 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.

Summary

* Deeply Virtual Compton Scattering is the cleanest channel for the extraction of Generalised Parton Distributions.

* 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.

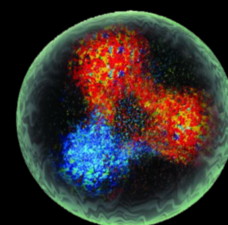
* Upgrade of JLab to 12 GeV max beam energy (11 GeV to halls A, B and C) opens a new region of phase space at higher kinematics in the valence region.

* 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.

* 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.

An exciting time to be exploring the valence region at JLab!

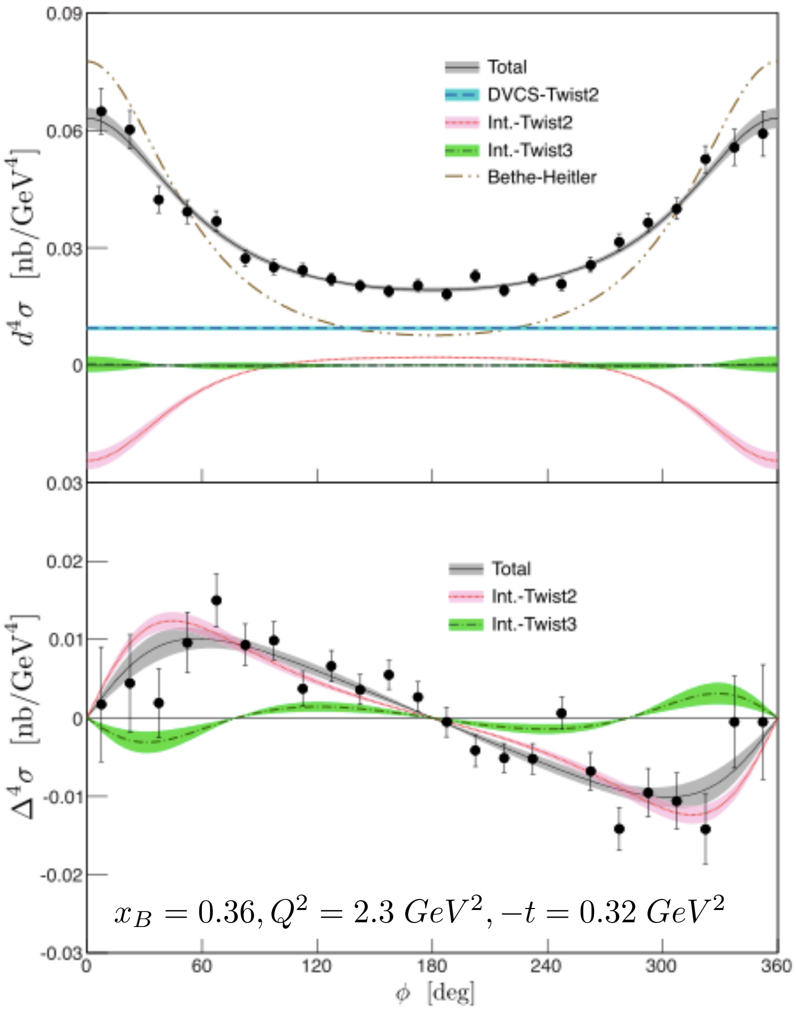


Thank you

Hall A

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 GeV^2, $x_B = 0.36$.



- CFFs show scaling in DVCS: leading twist (twist-2) dominance at moderate Q^2 (1.5 - 2.3 GeV^2).

- GPDs can be extracted at JLab kinematics

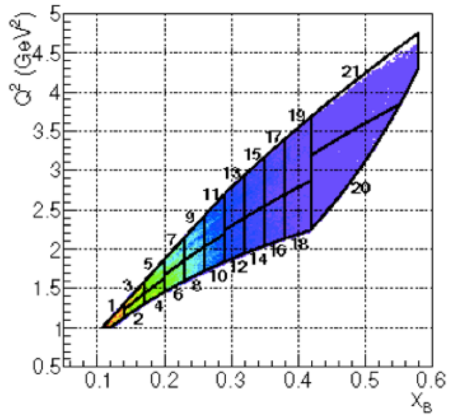
- Extraction of $|T_{DVCS}|^2$ amplitude as well as interference terms.

- Strong deviation of DVCS cross-section from BH: experiment probing its energy-dependence under analysis.

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

What do the CFFs from the cross-sections tell us?

CLAS



— VGG

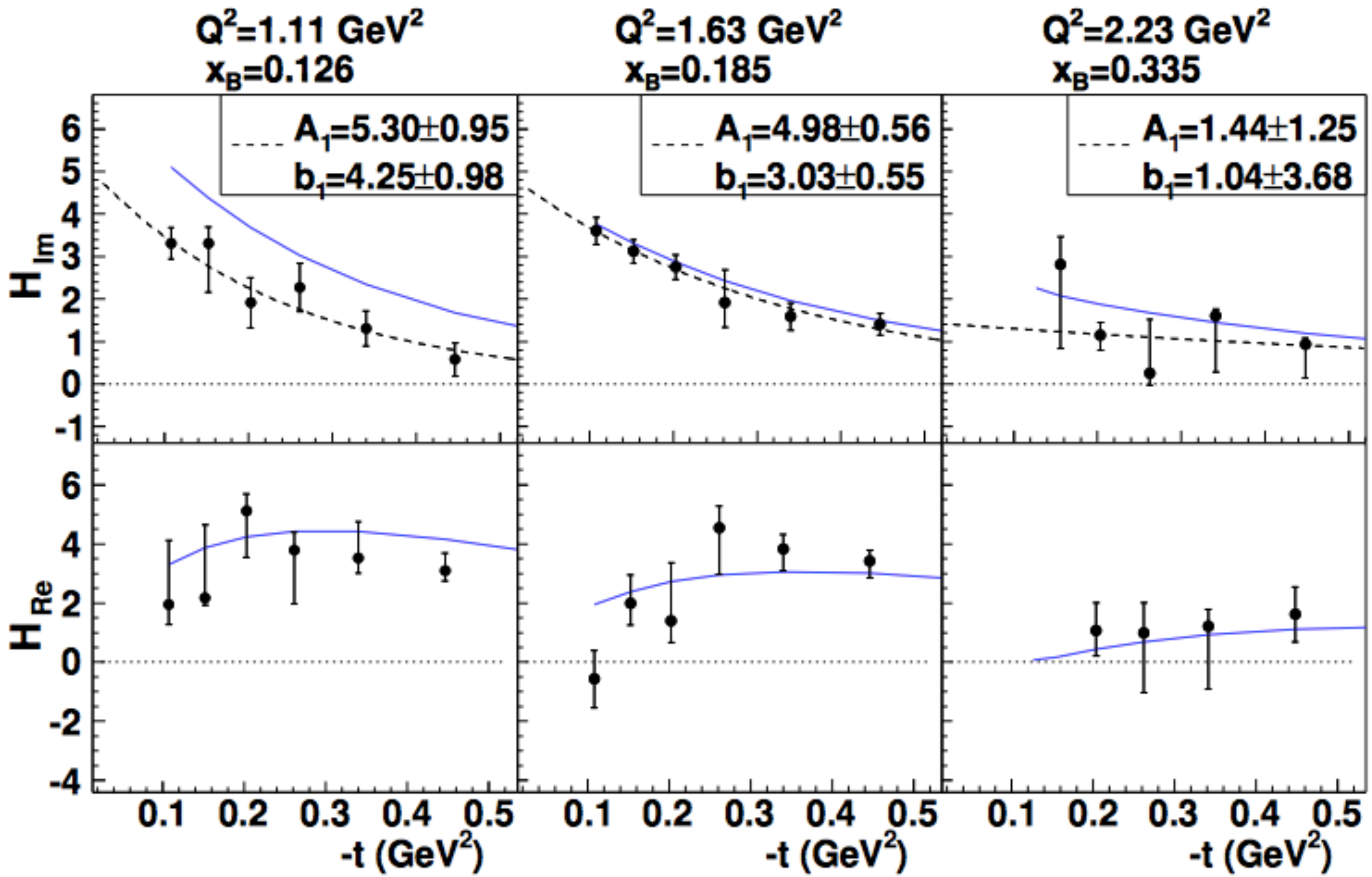
- - - Ae^{bt}

* Slope in t becomes flatter at higher x_B

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

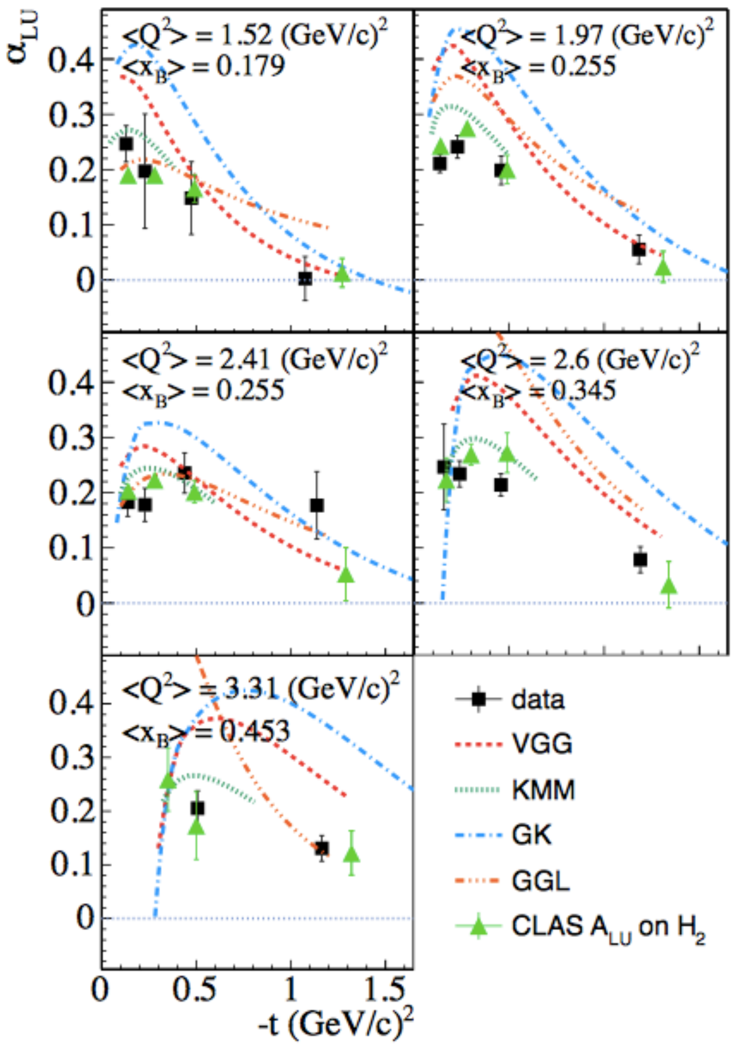
* High-statistics measurement across a wide kinematic range:

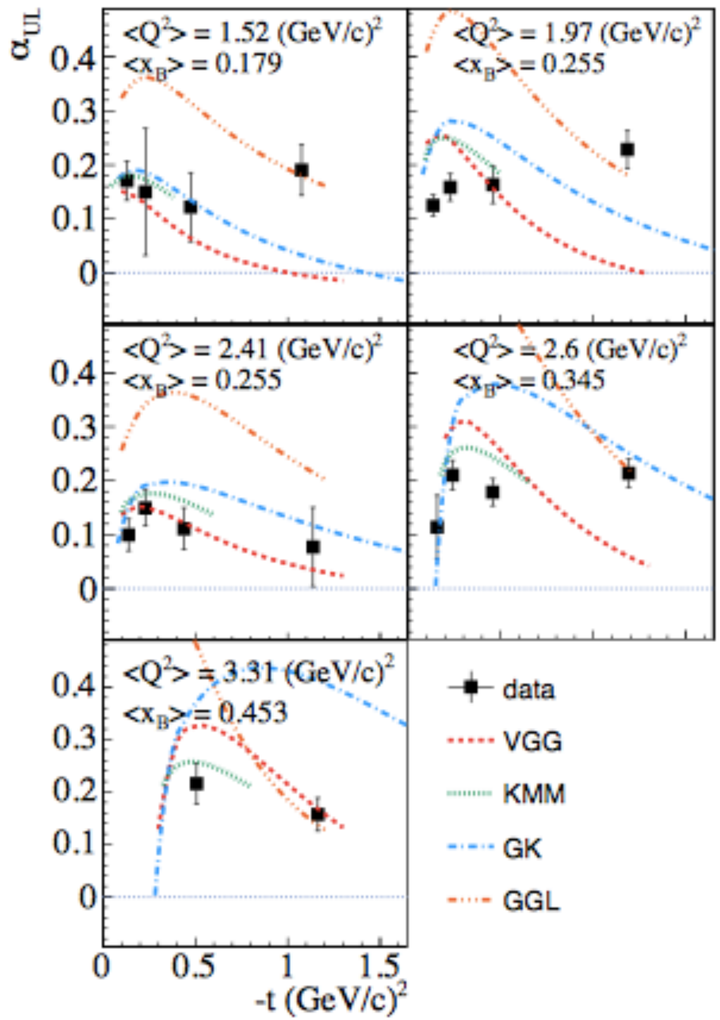
H.-S. Jo *et al* (CLAS Collaboration), ***PRL* 115** (2015) 212003



CLAS

Beam and target-spin asymmetries





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

GGL: Goldstein, Gonzalez, Liuti

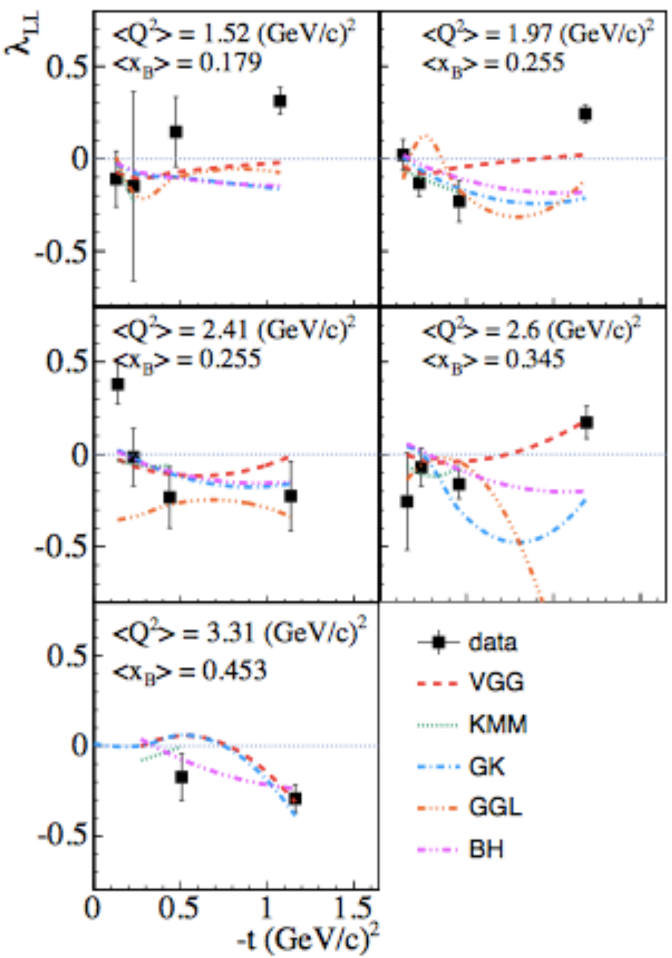
GK: Kroll, Moutarde, Sabatié

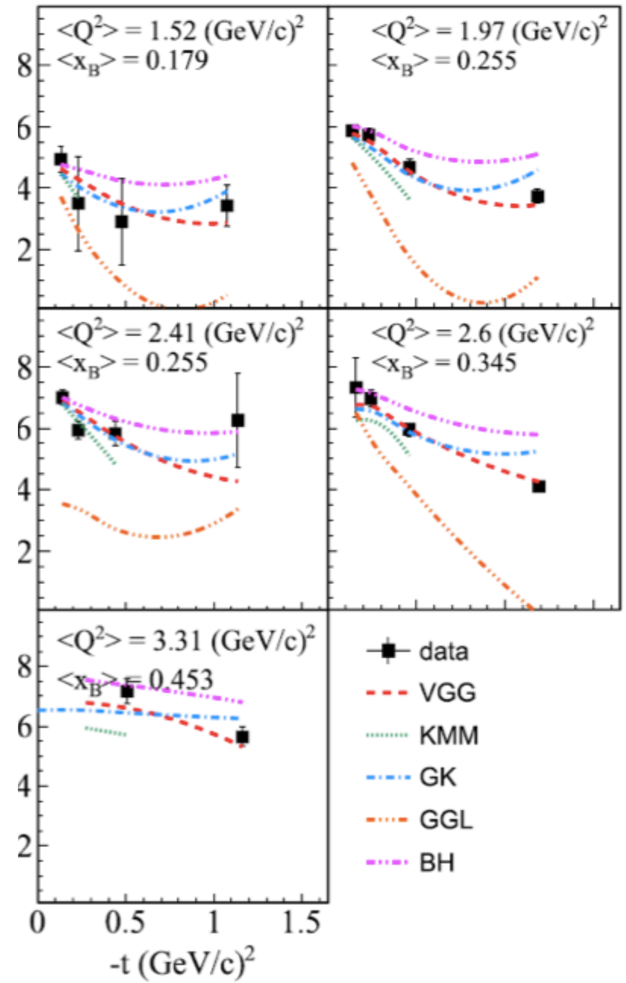
KMM: Kumericki, Mueller, Murray

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

CLAS

Double-spin Asymmetry (A_{LL})





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

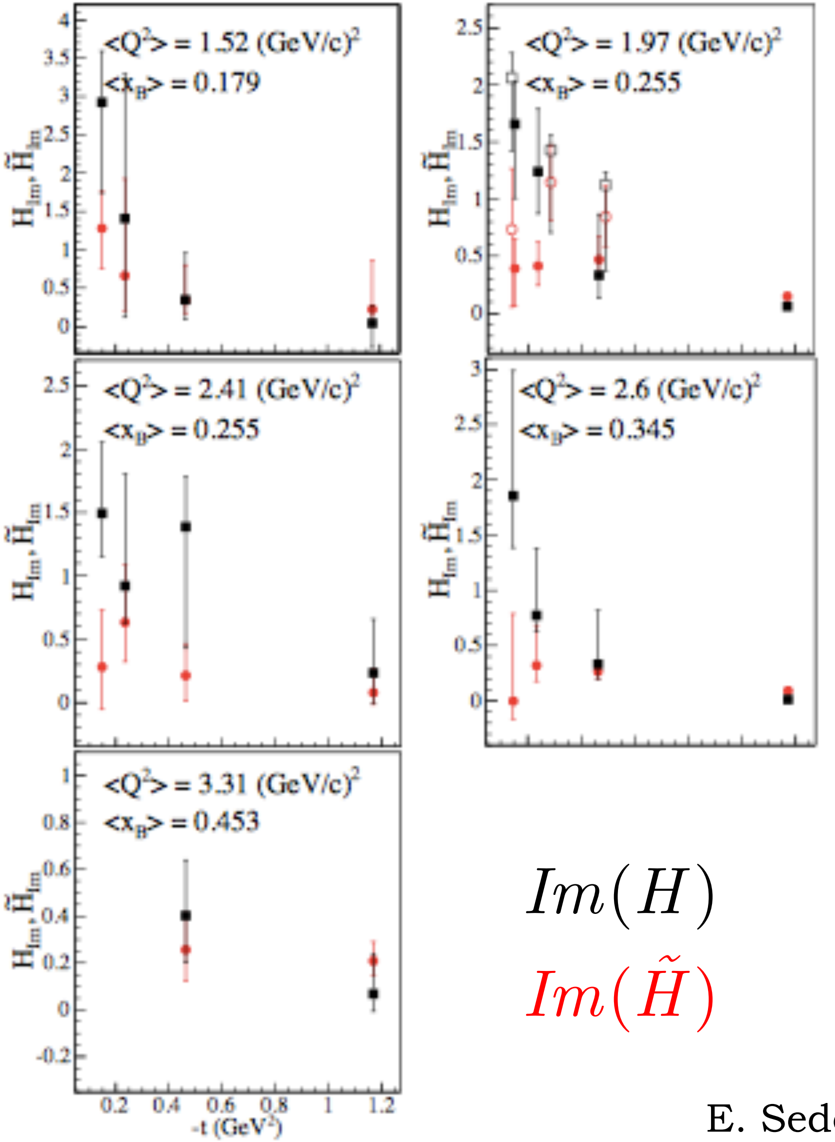
- Fit parameters extracted from a simultaneous fit to BSA, TSA and DSA.
- CFF extraction from three spin asymmetries at common kinematics.

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

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

CLAS

What can we learn from the asymmetries?



$Im(H)$

$Im(\tilde{H})$

Information about the relative spread of the axial and electric charges in the nucleon?

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

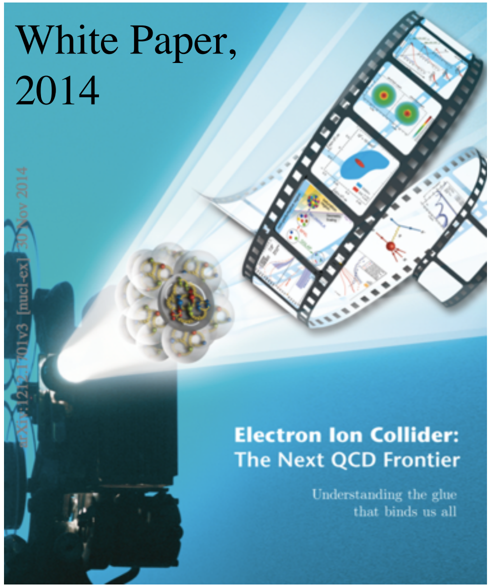
$$\tilde{H}^q(x,0,0) = g_1(x)$$

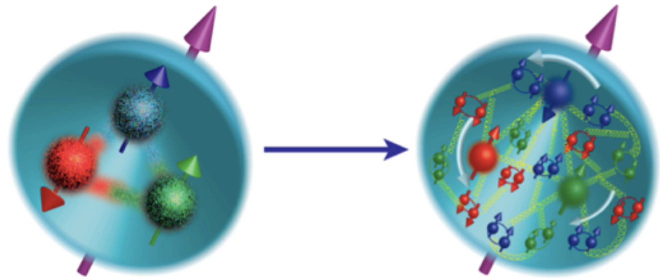
E. Seder *et al* (CLAS Collaboration), ***PRL* 114** (2015) 032001
S. Pisano *et al* (CLAS Collaboration), ***PRD* 91** (2015) 052014

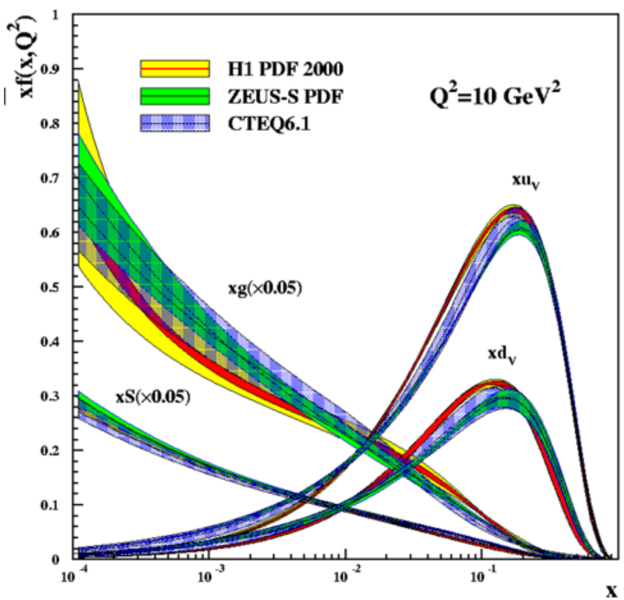
Looking to the future: Electron-Ion Collider

"Understanding the glue that binds us all"

- Two sites considered: JLab and Brookhaven National Lab
- Polarised *e* and light nuclei, unpolarised heavy nuclei
- Centre of mass energy range: 20 - 140 GeV
- High luminosity (10^{33} - 10^{34} $cm^{-2}s^{-1}$)
- High resolution detectors







- Gluon contribution to nucleon spin
- Tomography of the quark-gluon sea
- Saturation of gluon density
- Colour charge propagation in the nuclear medium

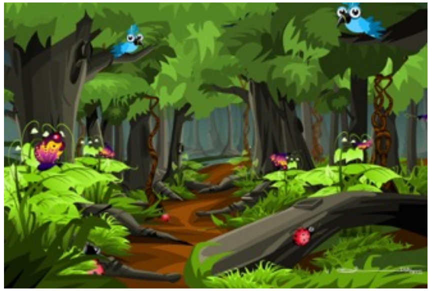
Workshop on Physics & Engineering Opportunities at the Electron-Ion Collider 2016

Home | Programme | Venue | Registration | Accommodation | Travel | Dinner | Entertainment

13 – 14 October 2016, Ross Priory on Loch Lomond, Scotland

https://ukeicworkshop2016.wordpress.com

Experimental paths to GPDs

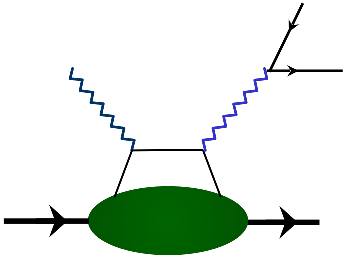


cliparts.co

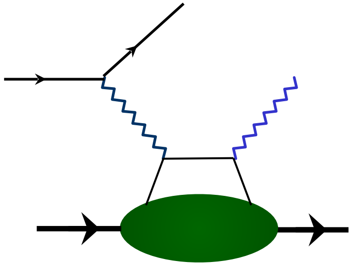
Accessible in *exclusive* reactions, where all final state particles are detected.

Trodden paths, or ones starting to be explored:

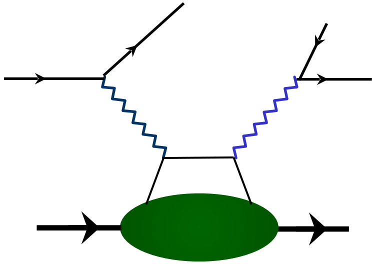
- Deeply Virtual Compton Scattering (DVCS)
- Deeply Virtual Meson Production (DVMP)
- Time-like Compton Scattering (TCS)
- Double DVCS



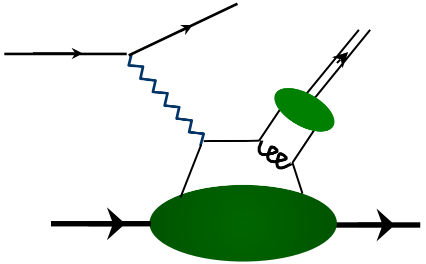
TCS



DVCS

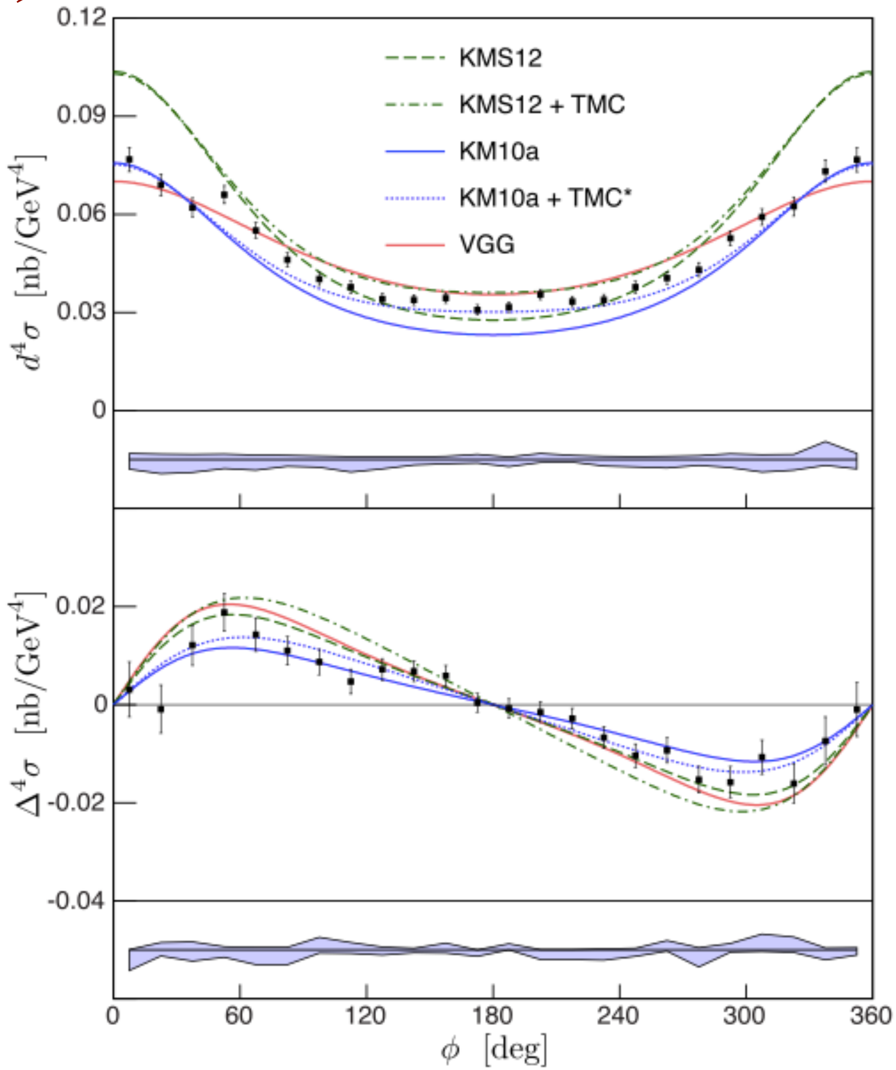


DDVCS



DVMP

Hall A



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

First DVCS cross-sections 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

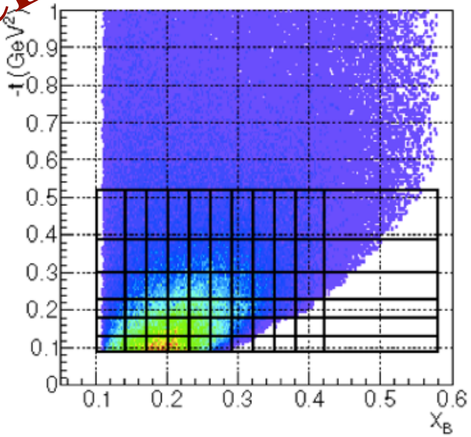
KMS model: Kroll, Moutarde, Sabatié

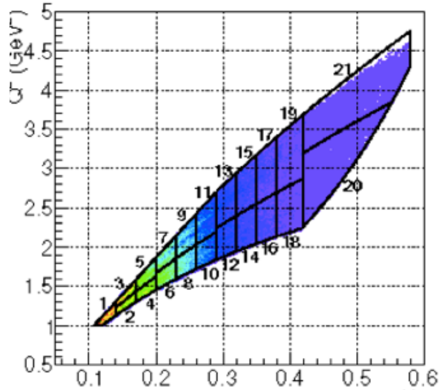
KM model: Kumericki, Mueller

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

CLAS

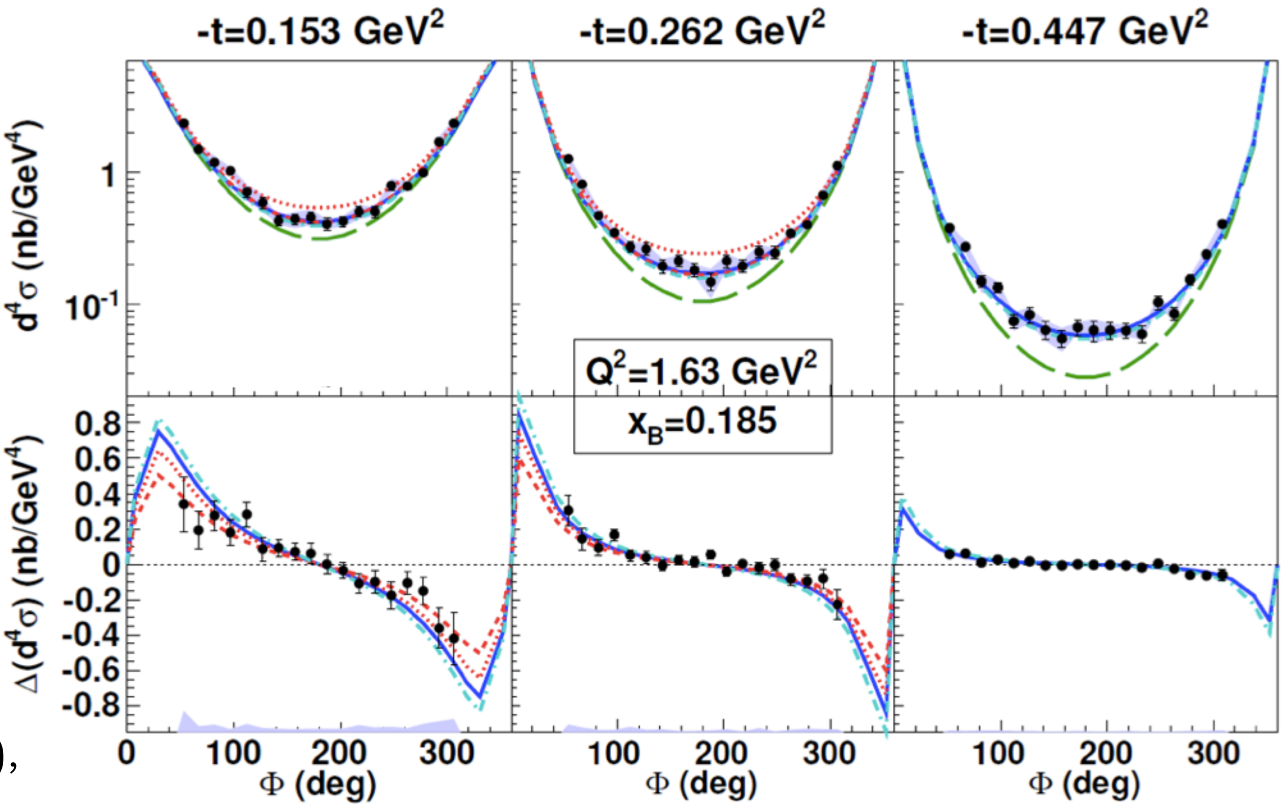
CLAS unpolarised cross-sections





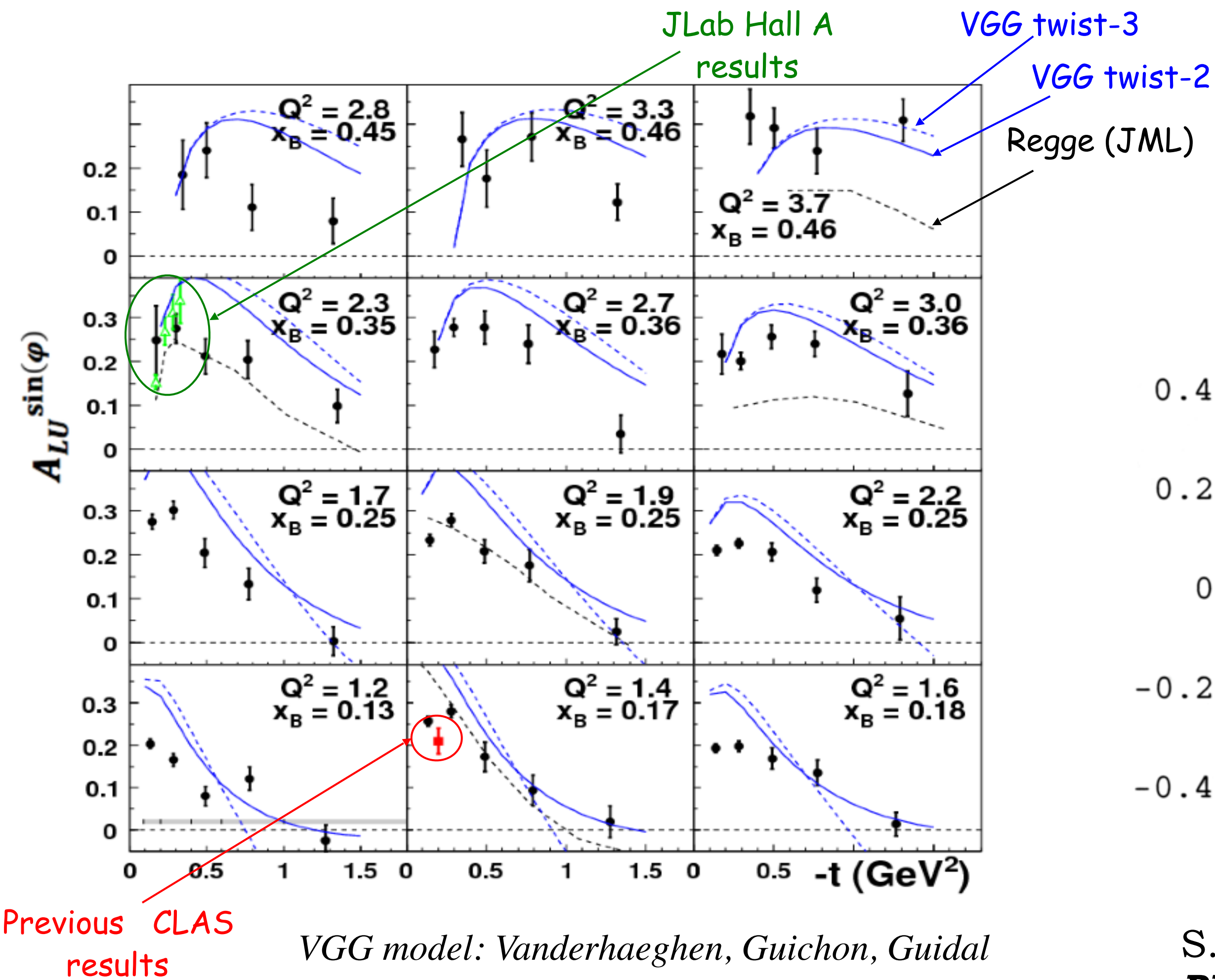
$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2dx_Bdtd\Phi}$$

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



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

Beam-spin Asymmetry (A_{LU})

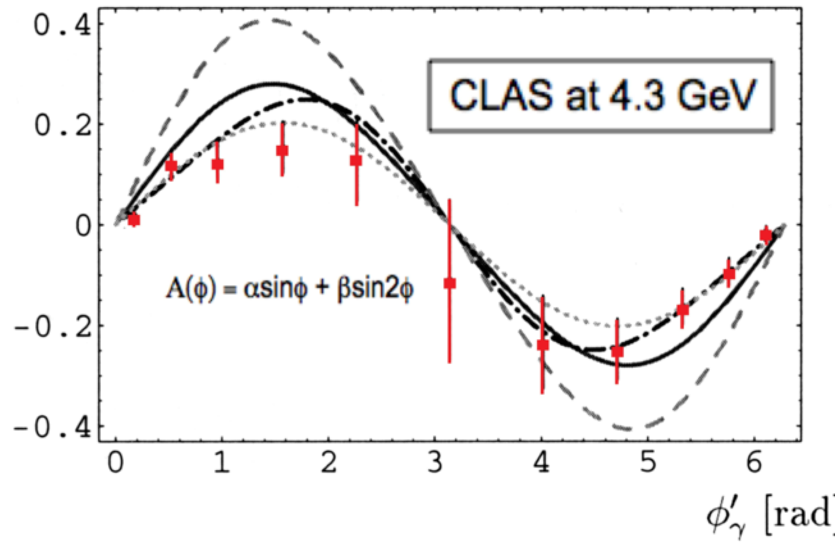


VGG model: Vanderhaeghen, Guichon, Guidal

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

A_{LU} from fit to asymmetry:

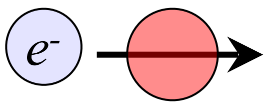
$$A_i = \frac{\alpha_i \sin\phi}{1 + \beta_i \cos\phi}$$



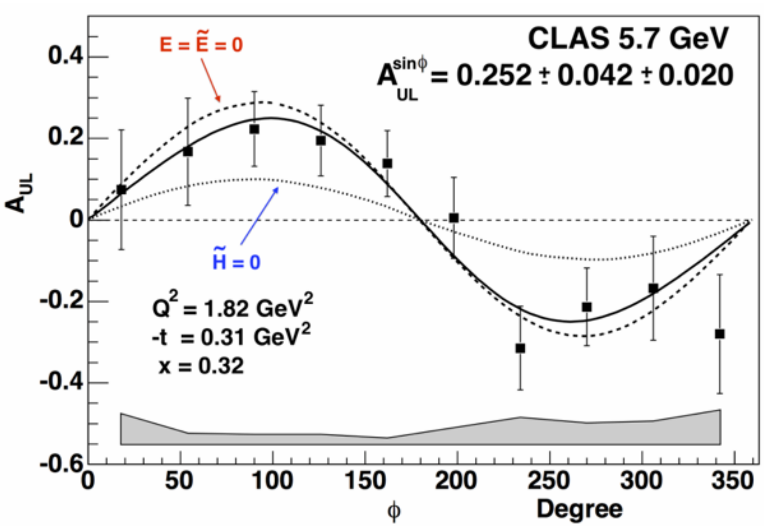
S. Stepanyan *et al* (CLAS Collaboration), ***PRL* 87** (2001) 182002

CLAS

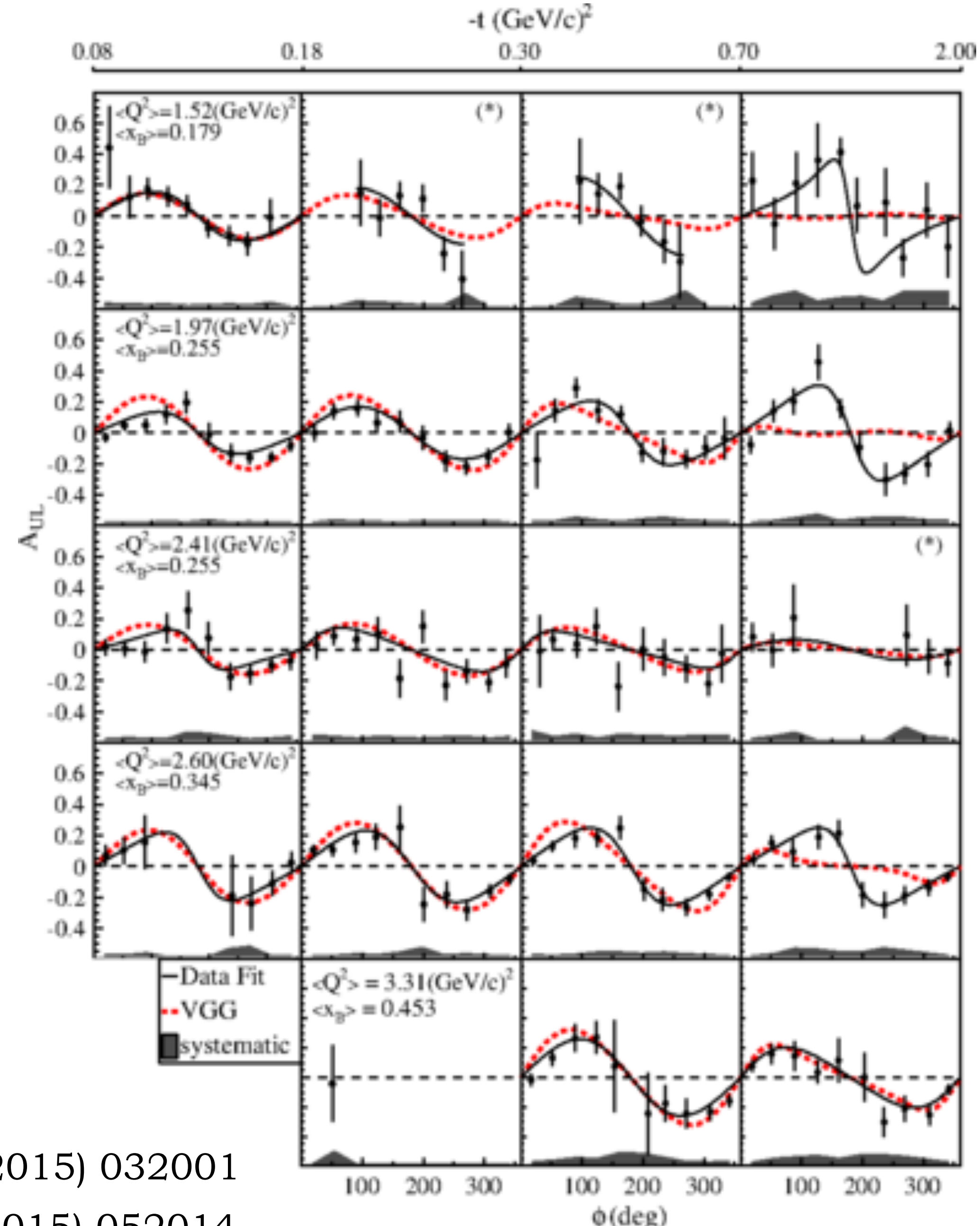
Target-spin Asymmetry (A_{UL})



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



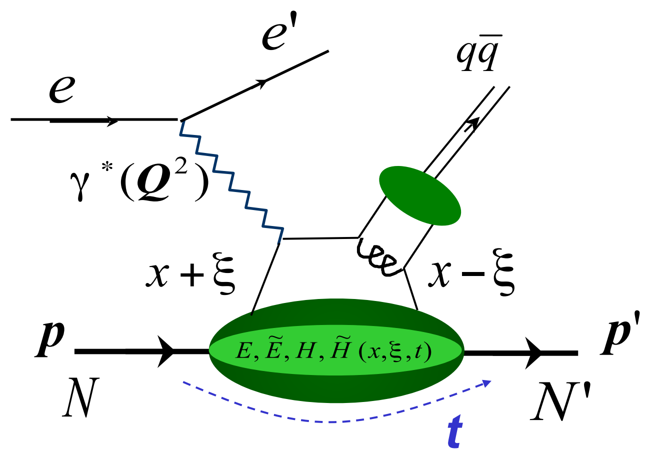
S. Chen *et al* (CLAS Collaboration), ***PRL* 97** (2006) 072002



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

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

Deeply Virtual Meson Production



Enables flavour decomposition.

At high exchanged Q^2, access to four chiral-even (parton helicity conserving) GPDs:

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

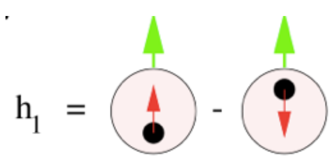
and four chiral-odd (parton helicity flipping) GPDs:

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

Transversity GPDs can be related to transverse anomalous magnetic moment:

$$\kappa_T = \int_{-1}^{+1} \tilde{E}_T(x, \xi, t = 0)\, dx$$

and transversity distribution: $H_T(x, 0, 0) = h_1(x)$



which describes distribution of transverse partons in a transverse nucleon.

DVMP Measurements at JLab

Vector mesons

K. Lukashin *et al.*, Phys. Rev. C 63, 065205, 2001 **(ϕ@4.2 GeV)**

C. Hadjidakis *et al.*, Phys. Lett. B 605, 256-264, 2005 **(ρ^0@4.2 GeV)**

L. Morand *et al.*, Eur. Phys. J. A 24, 445-458, 2005 **(ω@5.75GeV)**

J. Santoro *et al.*, Phys. Rev. C 78, 025210, 2008 **(ϕ@5.75 GeV)**

S. Morrow *et al.*, Eur. Phys. J. A 39, 5-31, 2009 **(ρ^0@5.75GeV)**

A. Fradi, Orsay Univ. PhD thesis **(ρ^+@5.75 GeV)**

Pseudo-scalar mesons

R. De Masi *et al.*, Phys. Rev. C 77, 042201(R), 2008 **(π^0@5.75GeV)**

E. Fuchey *et al.*, Phys. Rev. C 83, 025201, 2011 **(π^0@5.75GeV)**

K. Park *et al.*, Eur. Phys. J, A 49, 16, 2013. **(π^+@5.75 GeV)**

I. Bedlinskiy *et al.*, Phys. Rev. C 90, 039901, 2014 **(π^0@5.75GeV)**

A. Kim, submitted to PRL **(TSA, DSA π^0@5.75GeV)**

I. Bedlinskiy *et al.*,under analysis **(η@5.75GeV)**

DVMP Cross-section

unpolarised

$$\frac{2\pi}{\Gamma}\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_{meson}} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\phi$$

longitudinally polarised beam →

$$+P_b\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'}\sin\phi$$

longitudinally polarised target →

$$+P_{tg}\left(\sqrt{\epsilon(1+\epsilon)}\sigma_{UL}^{\sin\phi}\sin\phi + \epsilon\sigma_{UL}^{\sin 2\phi}\sin 2\phi\right)$$

Target and beam longitudinally polarised →

$$+P_b P_{tg}\left(\sqrt{1-\epsilon^2}\sigma_{LL} + \sqrt{\epsilon(1-\epsilon)}\sigma_{LL}^{\cos\phi}\cos\phi\right)$$

Sensitivity to longitudinal and transverse structure functions, which in turn are sensitive to transversity GPDs.

Unpolarised cross-sections: DV π^0 P

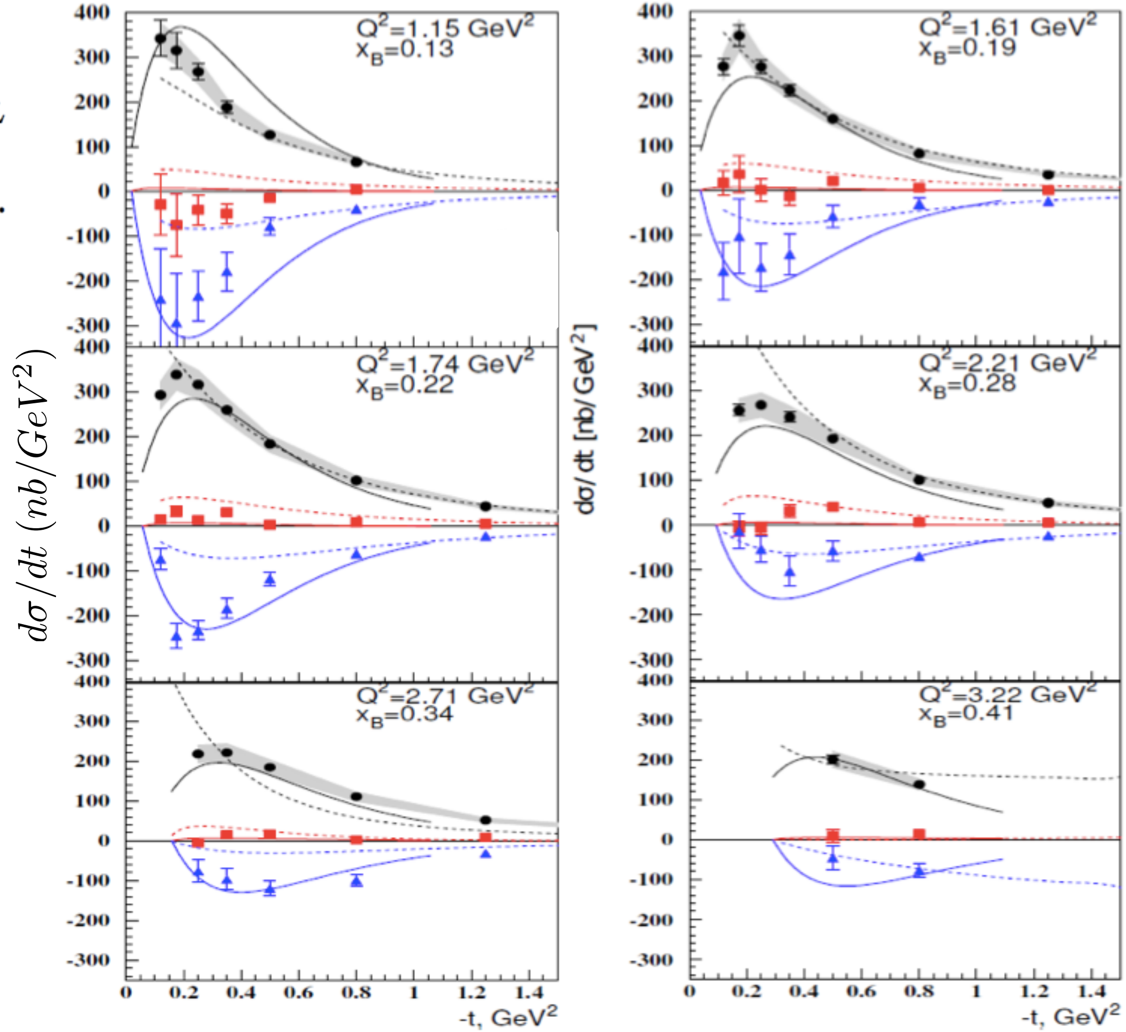
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT}).$$

$$\sigma_T \sim (1-\xi^2)|H_T|^2 - \frac{t'}{8m^2}|\bar{E}_T|^2$$

— $\sigma_0 = \sigma_T + \epsilon\sigma_L$
— σ_{TT}
— σ_{LT}

$$\sigma_{TT} \sim \frac{t'}{8m^2}|\bar{E}_T|^2$$

Contribution of σ_T and σ_{TT} is large.

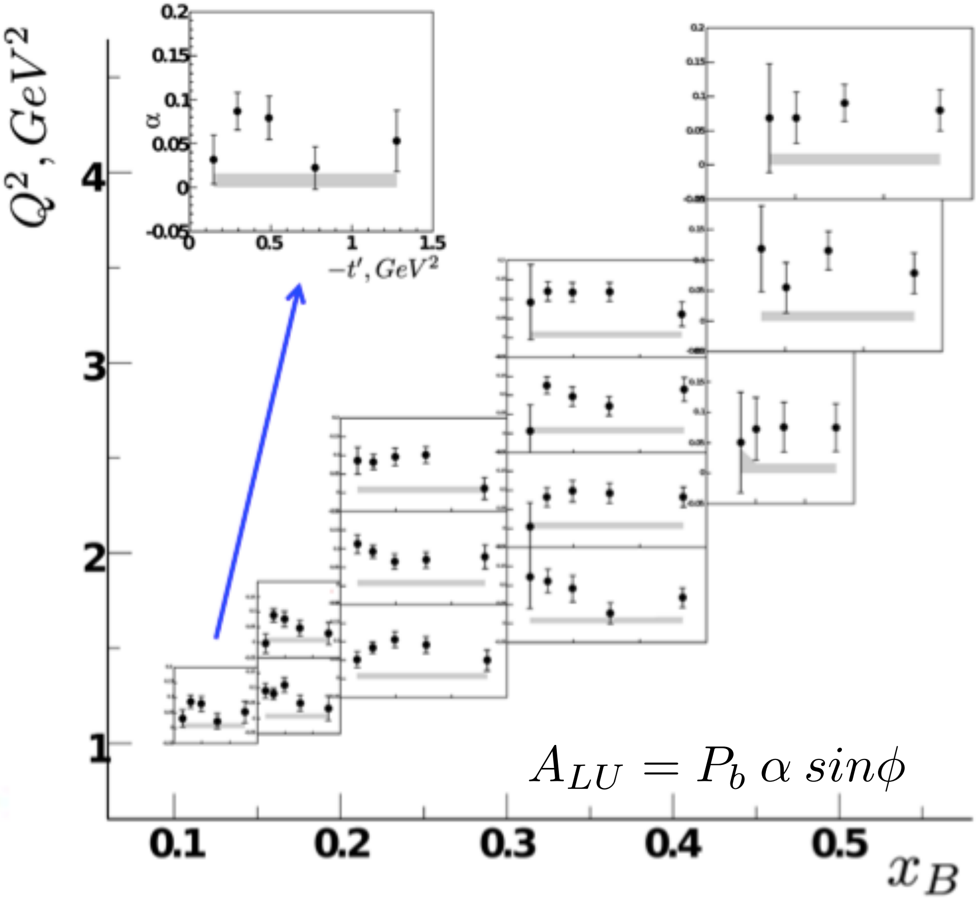


Solid: P. Kroll, S. Goloskokov
Dashed: G. Goldstei, J. Gonzalez, S. Liuti

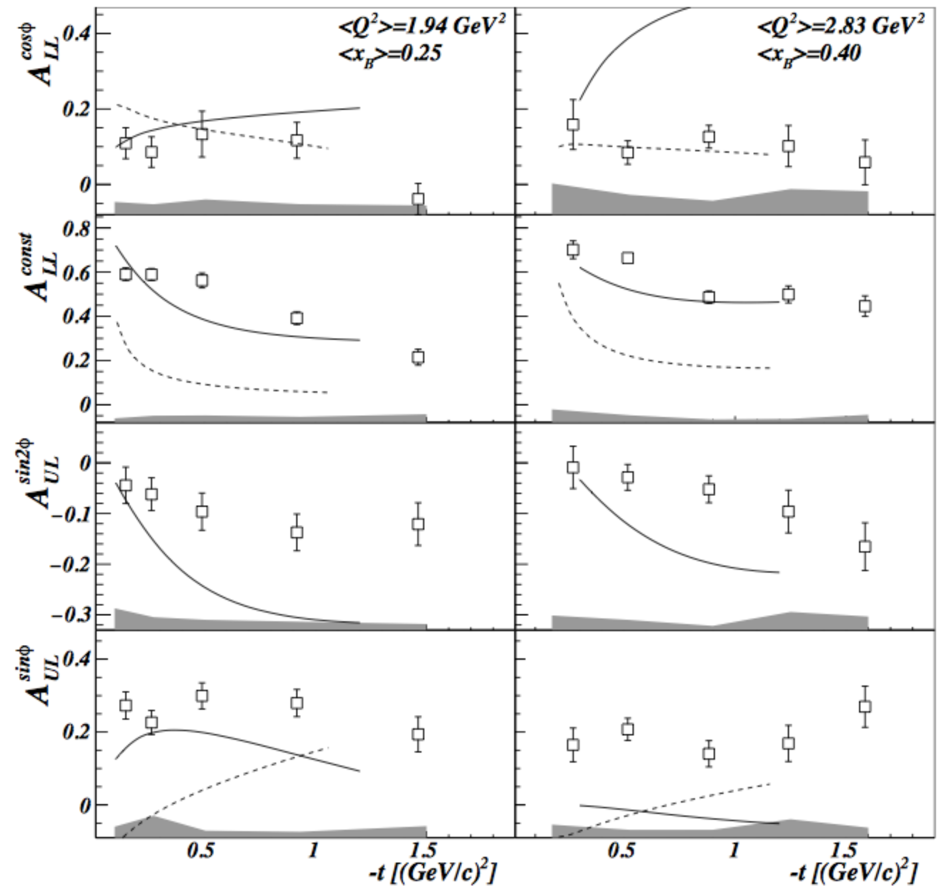
I. Bedlinskiy *et al* (CLAS Collaboration), ***PRL*** 109, (2012) 112001

Deeply Virtual Meson Production: π^0

Beam-spin asymmetry



Target-spin and Double-spin asymmetries



R. de Masi *et al* (CLAS Collaboration), ***PRC*** 77,(2008) 042201

- - - Goloskokov-Kroll
—— Goldstein-Gonzalez-Liuti

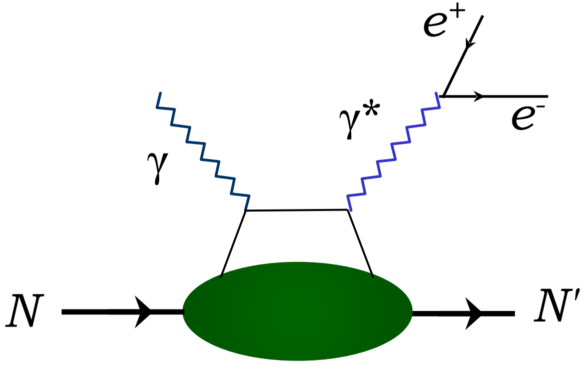
A. Kim *et al* (CLAS Collaboration), submitted to ***PRL***

Prospects at CLAS12

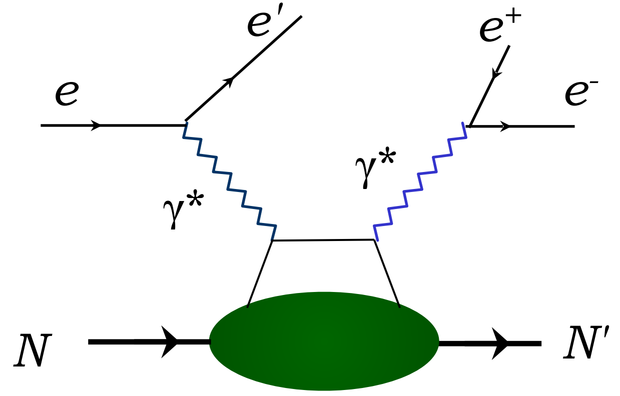
- Deeply Virtual Meson Production, e.g.: η and π^0 (E12-06-108), ϕ (E12-12-007).

- Time-like Compton Scattering (E12-12-001)

- Double Deeply Virtual Compton Scattering (Letter of Intent submitted).



TCS



DDVCS

Prospects in Halls A & C up to 11 GeV

Separation of the terms due to transverse and longitudinal virtual photon polarisation in the cross-sections of deeply virtual meson production:

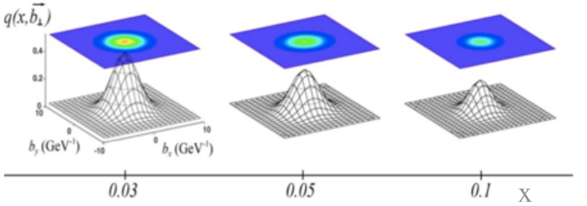
Hall C:

- E12-13-010: π^0
- E12-07-105: π^+
- E12-09-011: K^+

Hall A:

- E12-06-114: π^0

What do GPDs tell us?

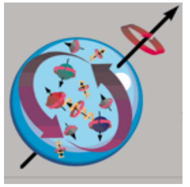


- **Tomography** of the nucleon: transverse spacial distributions of quarks and gluons in longitudinal momentum space.

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

- For additionally small *x* can image the pion cloud: chiral symmetry breaking.

- Provide information on the orbital angular momentum contribution to nucleon spin: **the spin puzzle**.



- Using transversely polarised targets can map transverse shift of partons due to the polarisation: combine with TMDs to access **spin-orbit correlations** of quarks and gluons, study non-perturbative interactions of partons.

GPDs and the spin puzzle

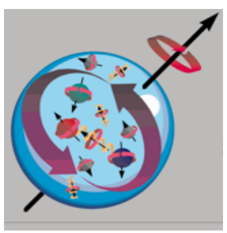
* Total angular momentum of a nucleon:

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

Only ~ 30% contribution

* Ji's relation:

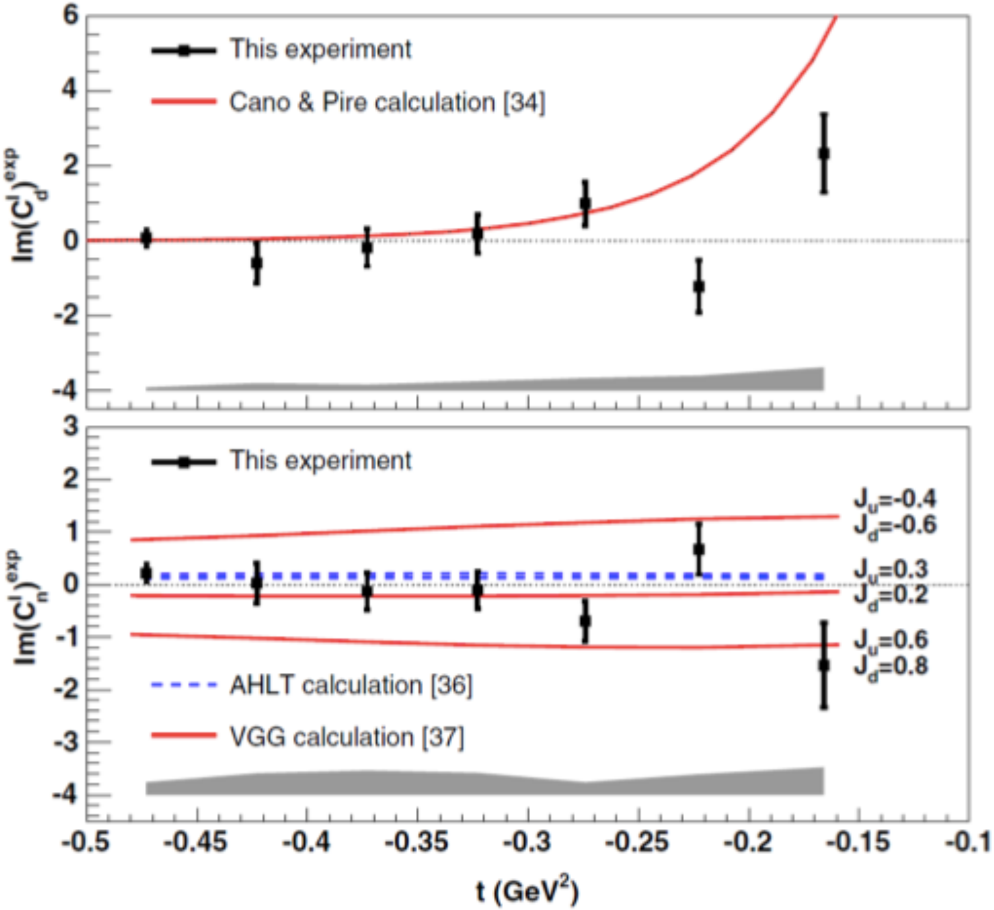
$$J^q = \frac{1}{2} - J^g = \frac{1}{2}\int_{-1}^{1} x dx \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\}$$



✳Need measurements at low t, across wide Q^2, of a range of observables to extract both H and E.

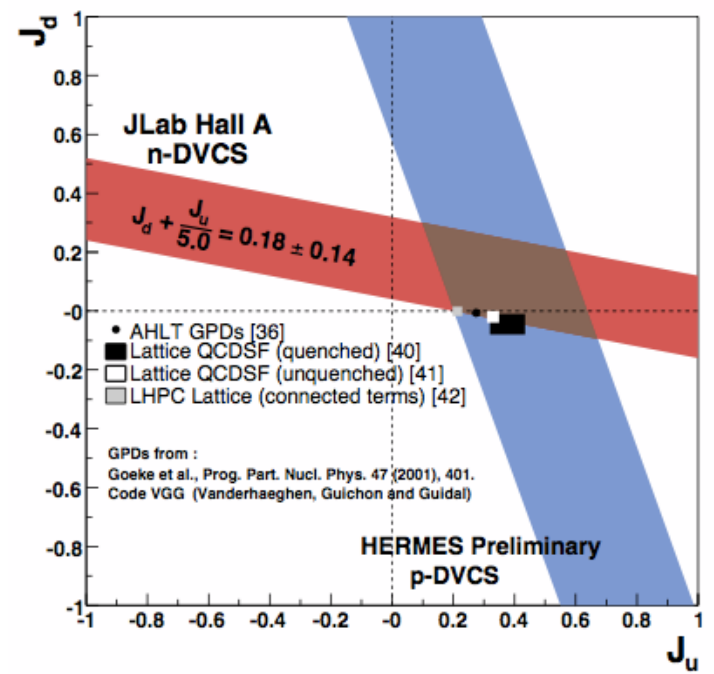
✳Need flavour separation of GPDs.

Beam-spin asymmetry in neutron DVCS



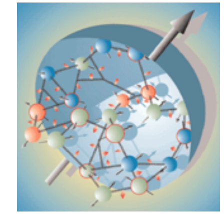
M. Mazouz et al, PRL **99** (2007) 242501

- First experimental constraint on E^q, through model interpretation gives constraints on orbital angular momentum of quarks.



- Analysis underway on CLAS data.

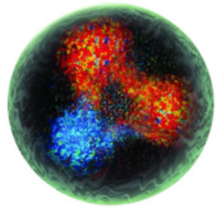
Nucleon at different scales

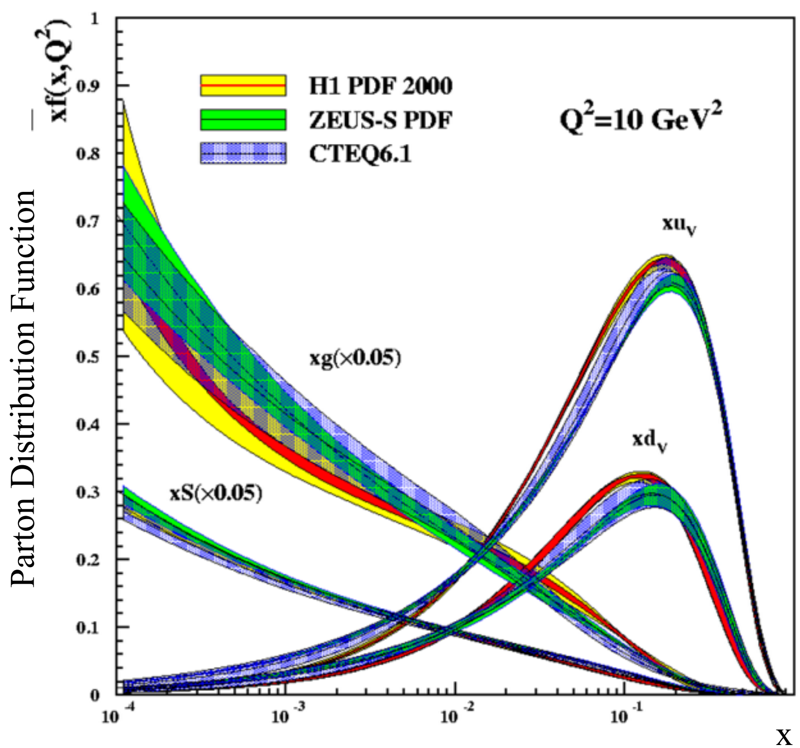


Valence quarks

Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$





Sea quarks

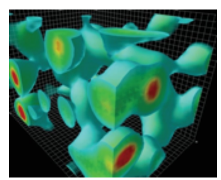
HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$

COMPASS: fixed-target muon scattering

$0.006 < x_B < 0.3$

The glue



Derek Leinweber

ZEUS/H1: electron/positron-proton collider

$10^{-4} < x_B < 0.02$

EIC: $10^{-4} < x_B < 0.3$

PID with CLAS12

$$e + N \rightarrow e' + N' + \gamma$$

Scattered electron / proton:

- *Vertexing*: silicon vertex tracker and Micromegas surrounding target.
- *Tracking and charge id*: Drift Chambers positioned within a toroidal magnetic filed.
- *Time of flight*: scintillator bars outside of the Drift Chambers.
- *Separation of electrons and pions*: energy deposit in Electromagnetic Calorimeter and signal in Čerenkov Counters.
- Very forward electrons also tracked through the forward Micromegas and detected in the Forward Tagger: energy deposit in the calorimeter and separation from photons in the hodoscope.
- Proton identified by its mass.

Photon:

- Energy deposited in the calorimeter of the Forward Tagger.