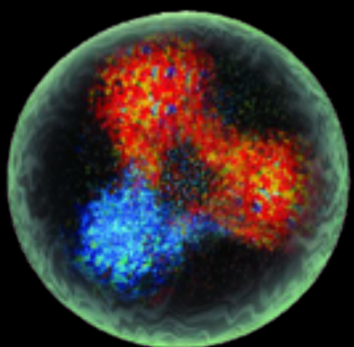
University of Glasgow

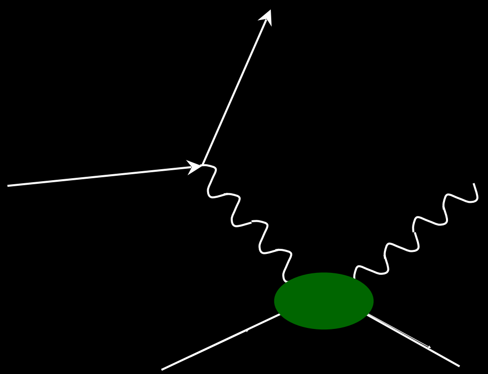
Jefferson Lab
EXPLORING THE NATURE OF MATTER

A view into the nucleon: electron scattering at Jefferson Lab



Daria Sokhan

University of Glasgow, UK

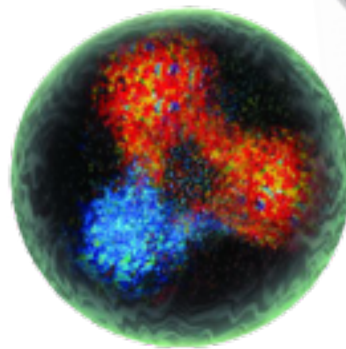


International School of Nuclear Physics: 38th Course
Erice, Sicily — 21st September 2016

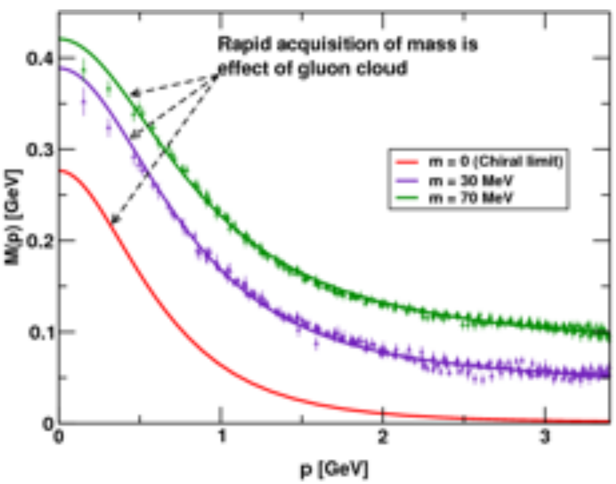
Prologue…

The nucleon through the electromagnetic lens

- Present day state (since ~1ms after the Big Bang).
- Cold: quarks in confinement.
- Abundant: almost all of the visible mass of the universe.



- Not well-understood: perturbative QCD cannot describe it. What makes up its spin? Why is its mass so large? …



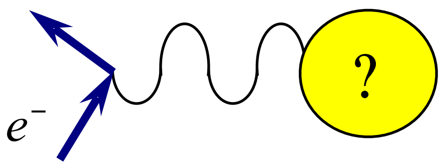
Power of a lepton probe: non-strongly interacting, “observes” the structure of the nucleon in a stop-motion picture.

→ **What your room-temperature nucleon looks like today**

Scales of resolution – an elephantine analogy

Lyuba, baby mamoth found in Siberia, imaged with visible light…

International Mammoth Committee



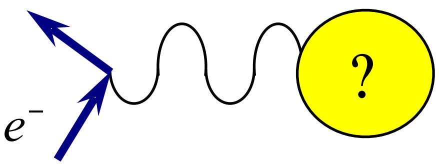
Q^2 ~ MeV^2

Scales of resolution – an elephantine analogy

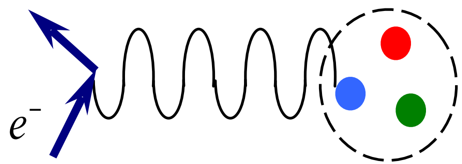
Lyuba, baby mamoth found in Siberia, imaged with visible light…

… and X-rays.

International Mammoth Committee



Q^2 ~ MeV^2



Q^2 >> GeV^2

Equivalent wavelength of the probe:

$$\lambda \approx \frac{1}{\sqrt{Q^2}}$$

Scales of resolution – an elephantine analogy

Lyuba, baby mamoth found in Siberia, imaged with visible light…

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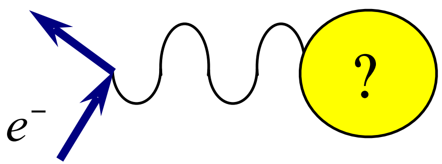
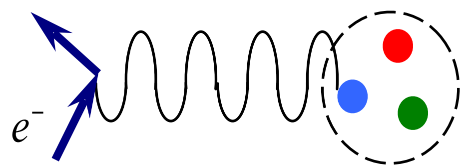


Q^2 ~ MeV^2



Q^2 >> GeV^2

Equivalent wavelength of the probe:

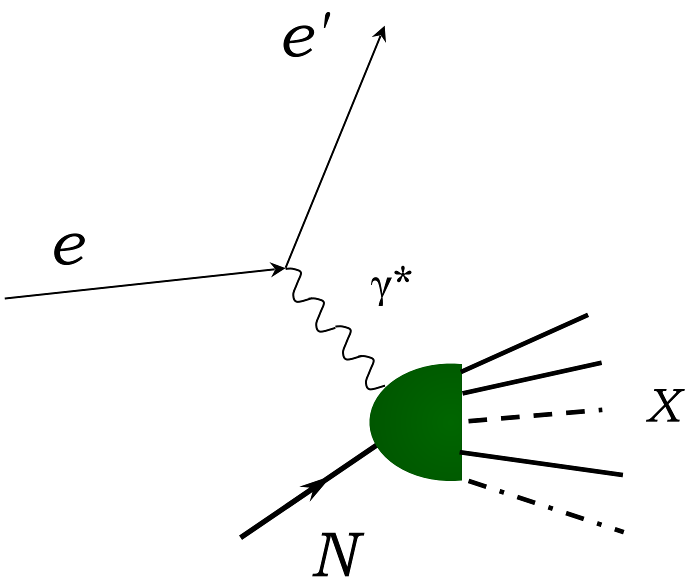
$$\lambda \approx \frac{1}{\sqrt{Q^2}}$$

What you see depends on what you use to look…

Electron scattering

Electromagnetic interaction: sensitive to distributions of charge and magnetisation — information on quark structure of the hadron at different energy scales.

Deep inelastic scattering (DIS):



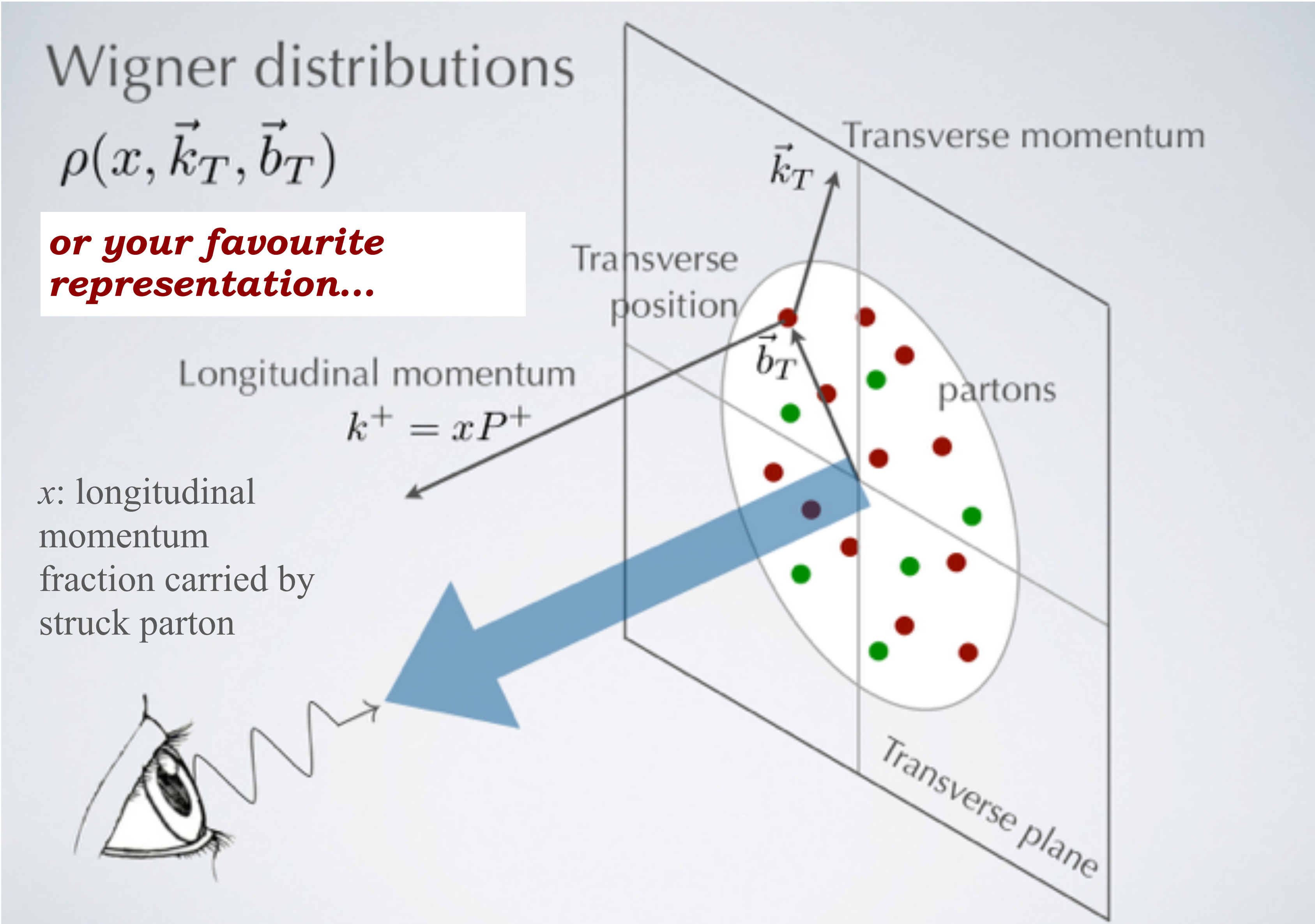
Measurements:

- ★ Inclusive — only the electron is detected.
- ★ Semi-inclusive — electron and typically one hadron detected.
- ★ Exclusive — all final state particles detected.
- ★ Polarised electrons / hadrons — sensitivity to helicity distributions.
- ★ Cross-sections, cross-section differences and asymmetries.

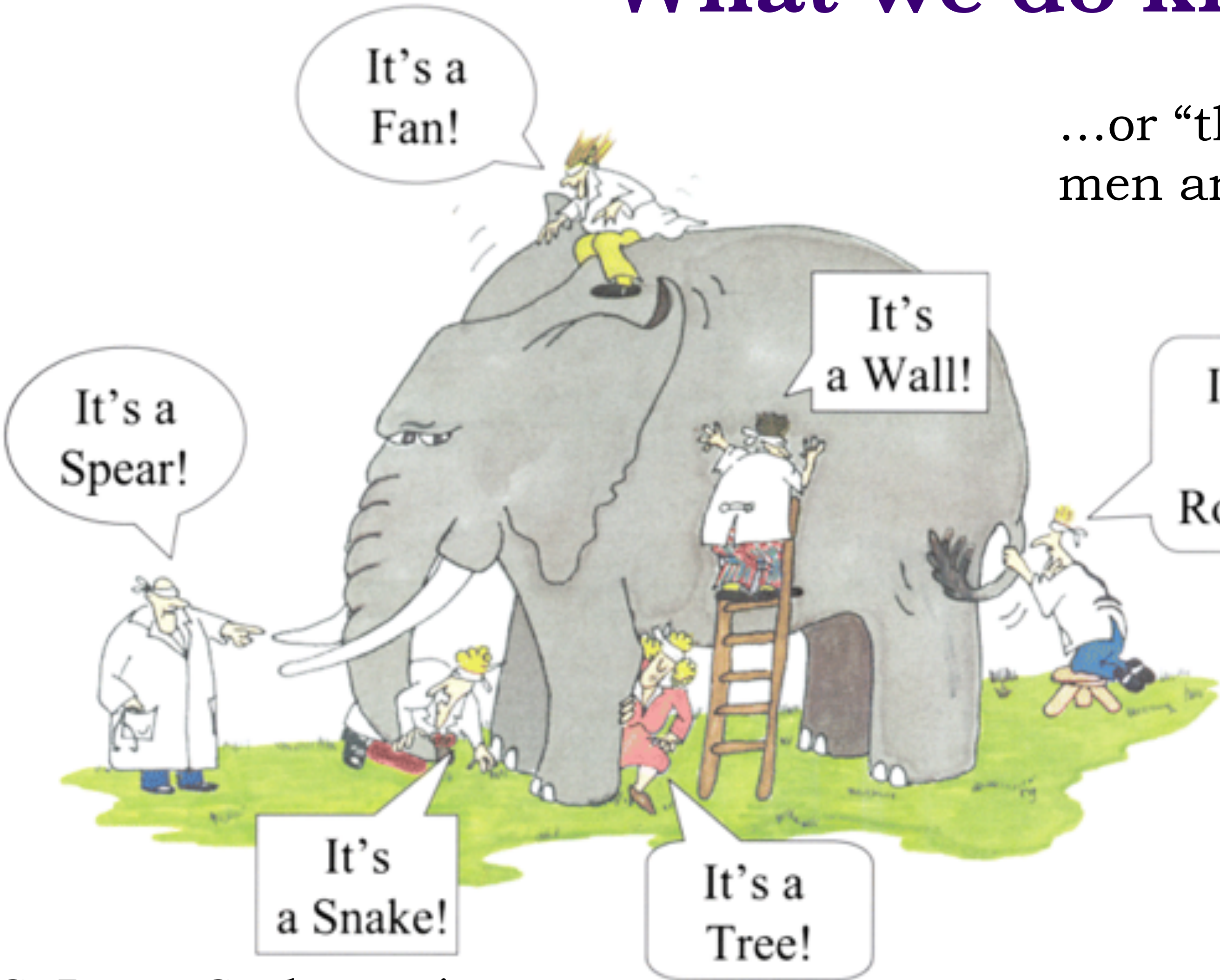
Complementary information on the nucleon's structure.

Structure of the nucleon

What we would really like to know…



What we do know…



G. Renee Guzlas, artist.

…or "the story of the blind men and the elephant"

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

What we do know…

G. Renee Guzlas, artist.

…or "the story of the blind men and the elephant"

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

What you see depends also on how you to look…

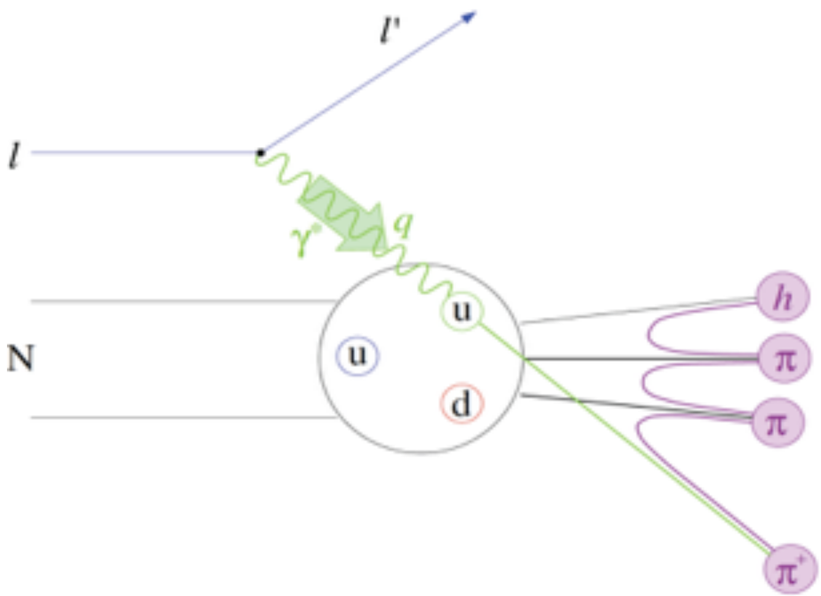
Different views of the nucleon: I

Wigner function:
full phase space parton
distribution of the nucleon

$\int d^2 b_T$

Transverse
Momentum
Distributions
(TMDs)

* Semi-inclusive DIS



Different views of the nucleon: II

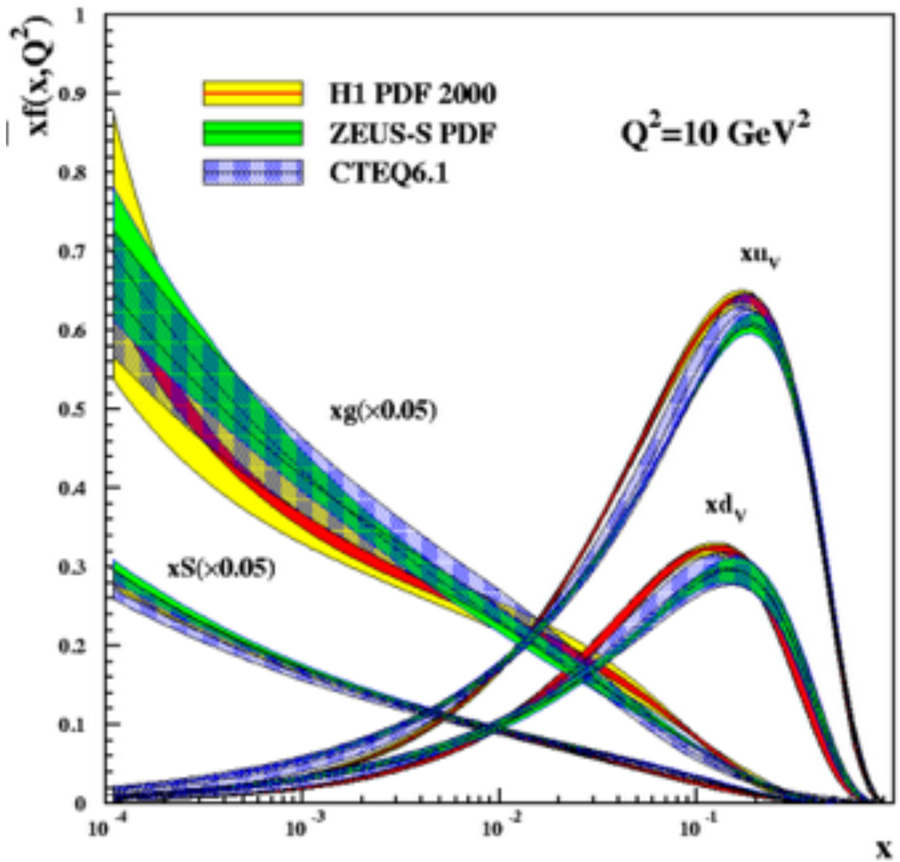
Wigner function:
full phase space parton distribution of the nucleon

$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

$$\int d^2 k_T$$

Parton Distribution Functions (PDFs)



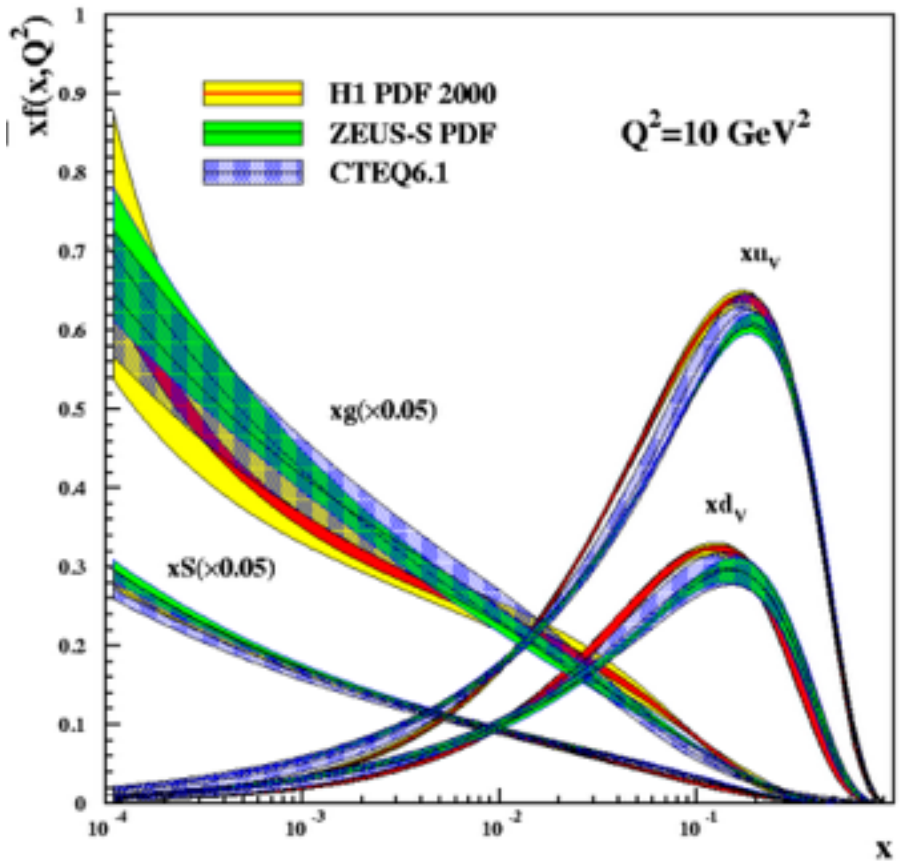
Different views of the nucleon: II

Wigner function: full phase space parton distribution of the nucleon

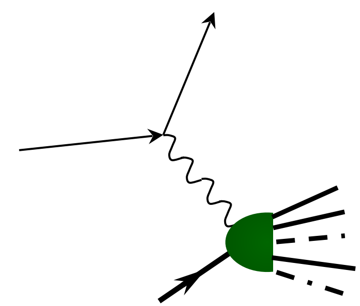
$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

$$\int d^2 k_T$$



Parton Distribution Functions (PDFs)



* Deep Inelastic Scattering

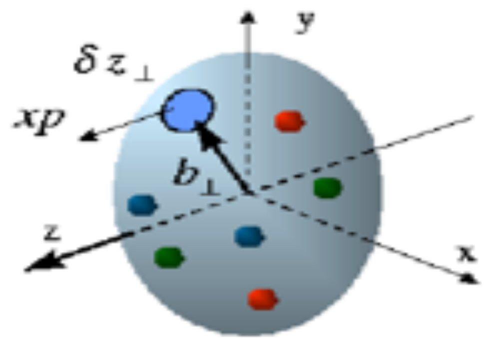
Different views of the nucleon: III

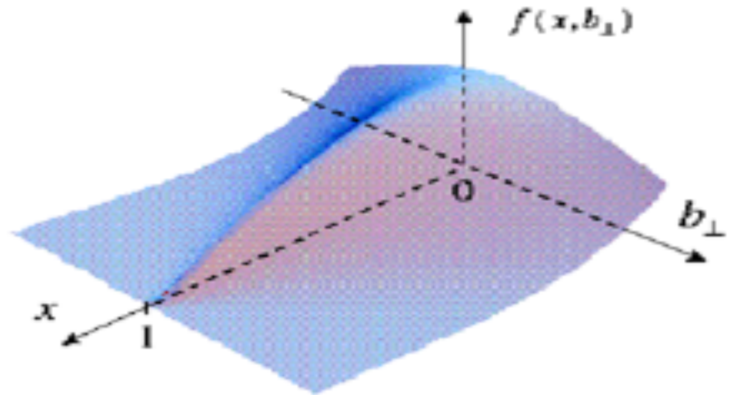
Wigner function:
full phase space parton distribution of the nucleon

$$\int d^2 k_T$$

Generalised Parton Distributions (GPDs)

- relate transverse position of partons ($b_\perp$) to longitudinal momentum (x).





✱ Deep exclusive reactions

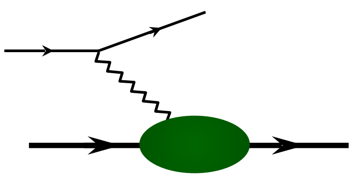
Different views of the nucleon: IV

Wigner function:
full phase space parton distribution of the nucleon

$$\int d^2 k_T$$

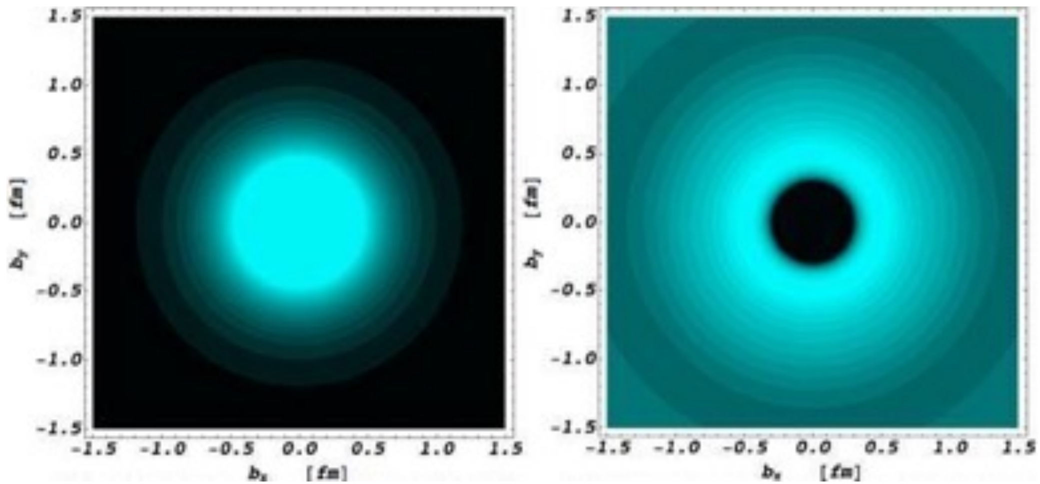
Generalised Parton Distributions (GPDs)

$$\int dx$$



Form Factors
eg: G_{E}, G_M

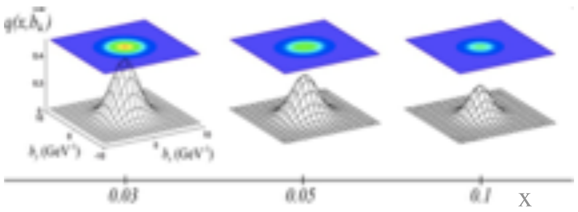
Fourier Transform of electric Form Factor: transverse charge density of a nucleon



proton   neutron

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

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.

Jefferson Lab

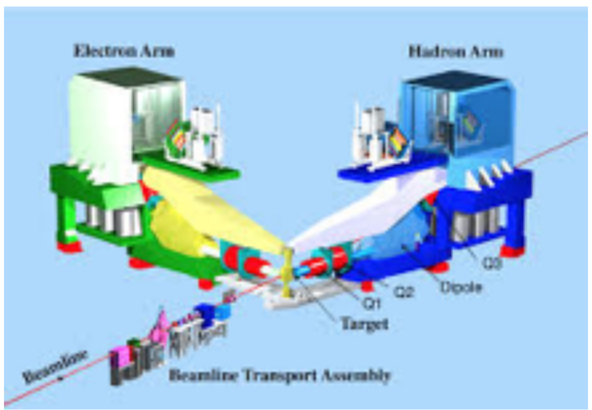
Jefferson Lab, Virginia, USA

Jefferson Lab: 6 GeV era

CEBAF: Continuous Electron Beam Accelerator Facility.

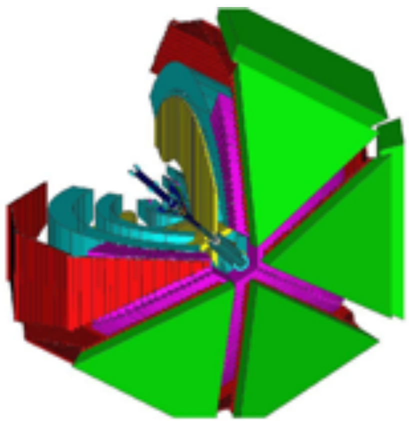
- Energy up to ~6 GeV
- Energy resolution $\delta E/E_e \sim 10^{-5}$
- Longitudinal electron polarisation up to ~85%
- Three experimental fixed-target halls

Hall A:



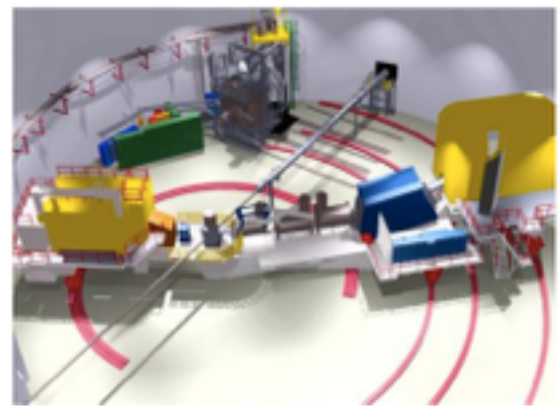
- High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity.

Hall B: CLAS



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

Hall C:

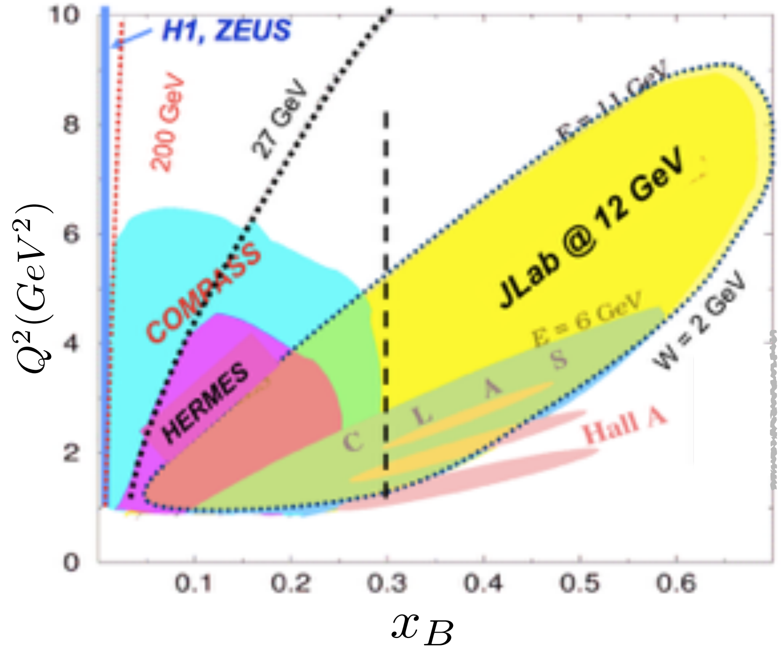


- Two movable spectrometer arms, well-defined acceptance, high luminosity

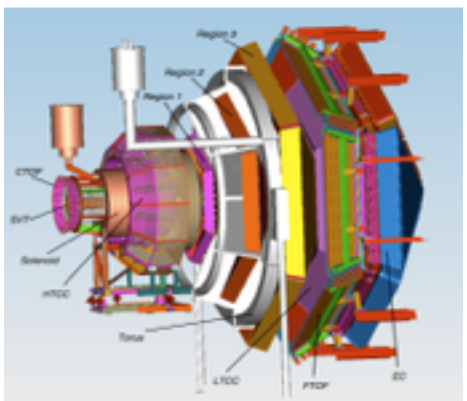
Jefferson Lab: 12 GeV era

- 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

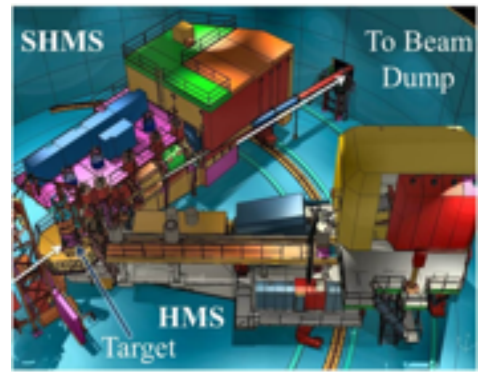


Hall B: CLAS12



Very large acceptance, high luminosity

Hall C:



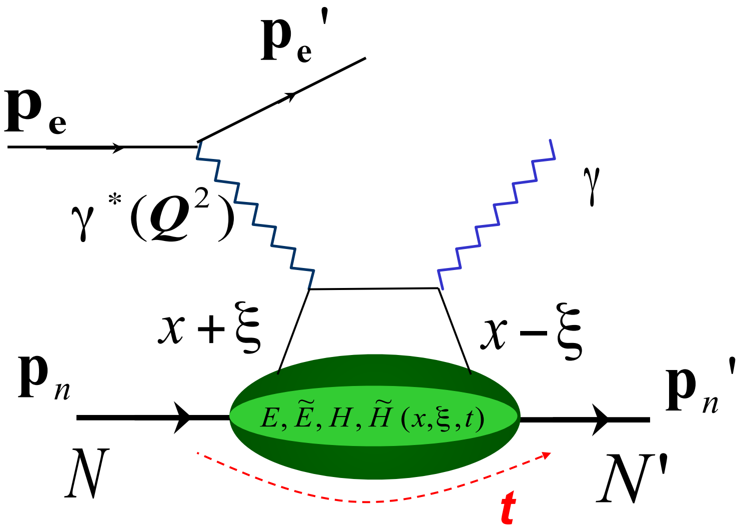
Super-high Momentum Spectrometer added, very high luminosity

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

Deeply Virtual Compton Scattering

Deeply Virtual Compton Scattering

the "golden channel" for GPD extraction



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:

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

and form factors:

$$\int_{-1}^{+1} H\,dx = F_1 \quad \int_{-1}^{+1} \tilde{H}\,dx = G_A$$

$$\int_{-1}^{+1} E\,dx = F_2 \quad \int_{-1}^{+1} \tilde{E}\,dx = G_P$$

(Dirac and Pauli) *(axial and pseudo-scalar)*

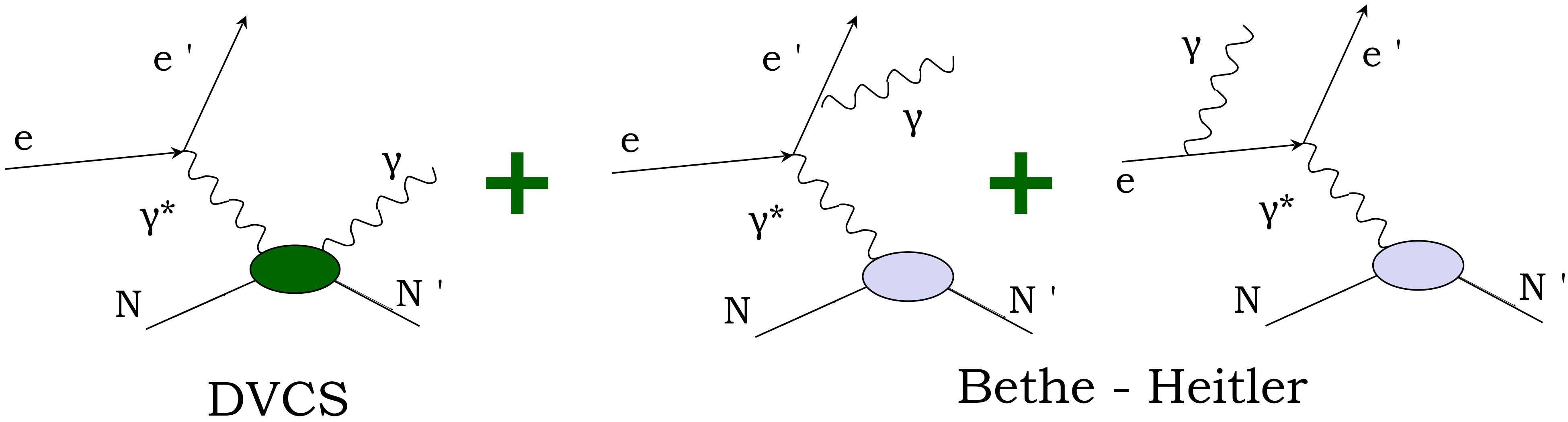
$Q^2 = -(\mathbf{p}_e - \mathbf{p}_e')^2 \qquad t = (\mathbf{p_n} - \mathbf{p_n}')^2$

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

$x \pm \xi$ *longitudinal momentum fractions of quarks* $\qquad \xi \cong \dfrac{x_B}{2 - x_B}$

Measuring DVCS

✳ Process measured in experiment:



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

Amplitude parameterised in terms of Compton Form Factors

Amplitude calculable from elastic Form Factors and QED

Interference term

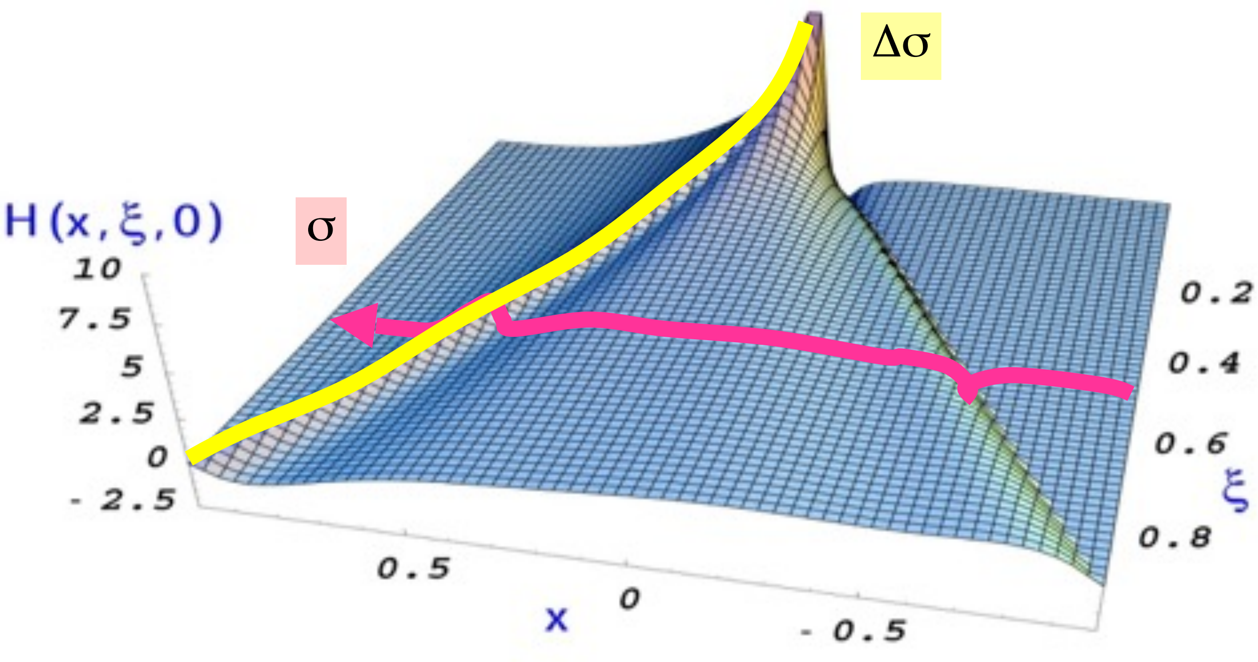
$$|T_{DVCS}|^2 << |T_{BH}|^2$$

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.

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:

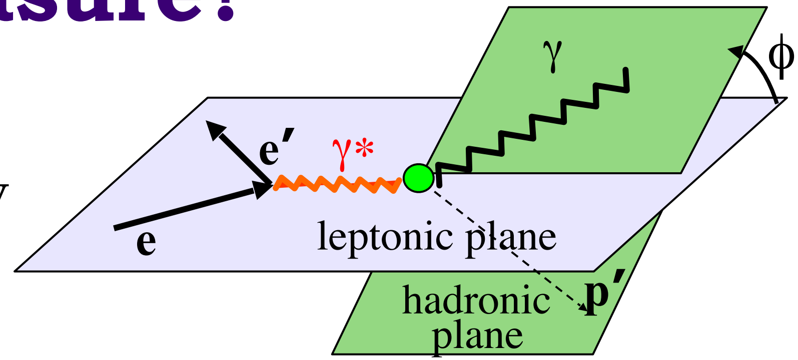
$$J^q = \frac{1}{2} - J^g = \frac{1}{2}\int_{-1}^{1} xdx \left\{ H^q(x,\xi,0) + E^q(x,\xi,0) \right\}$$

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

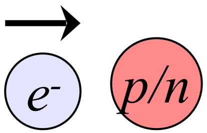
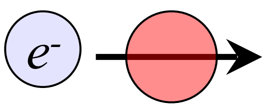
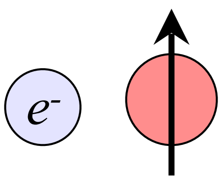
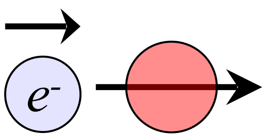
✳Need flavour separation of GPDs.

What should we measure?

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



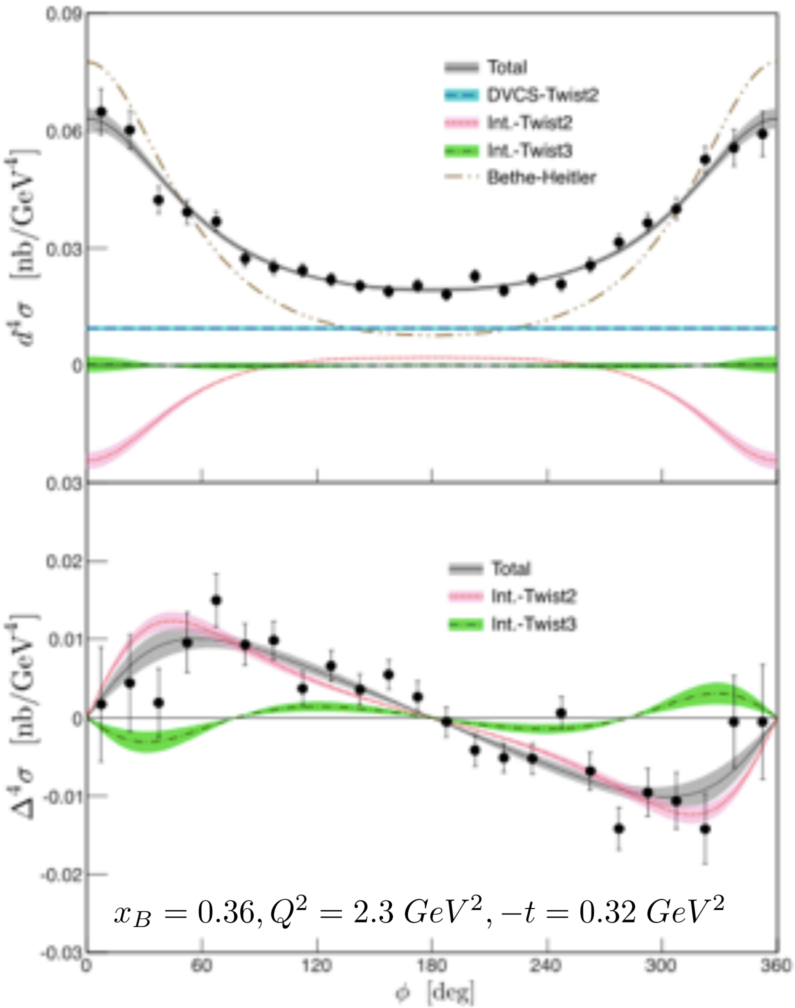
$\xi = x_B/(2-x_B) \quad k = t/4M^2$

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

Hall A

First DVCS cross-sections in valence region

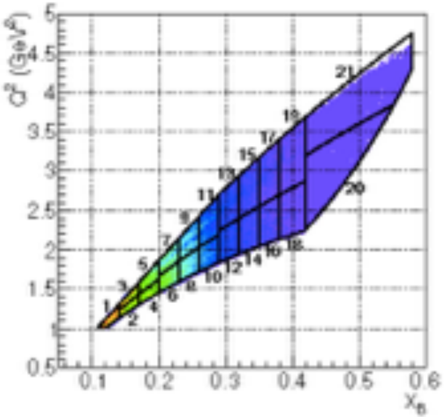
- Hall A, ran in 2004, high precision, narrow kinematic range. Data recently re-analysed. Q^2: 1.5 - 2.3 GeV^2, $x_B = 0.36$.



- 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.

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



VGG

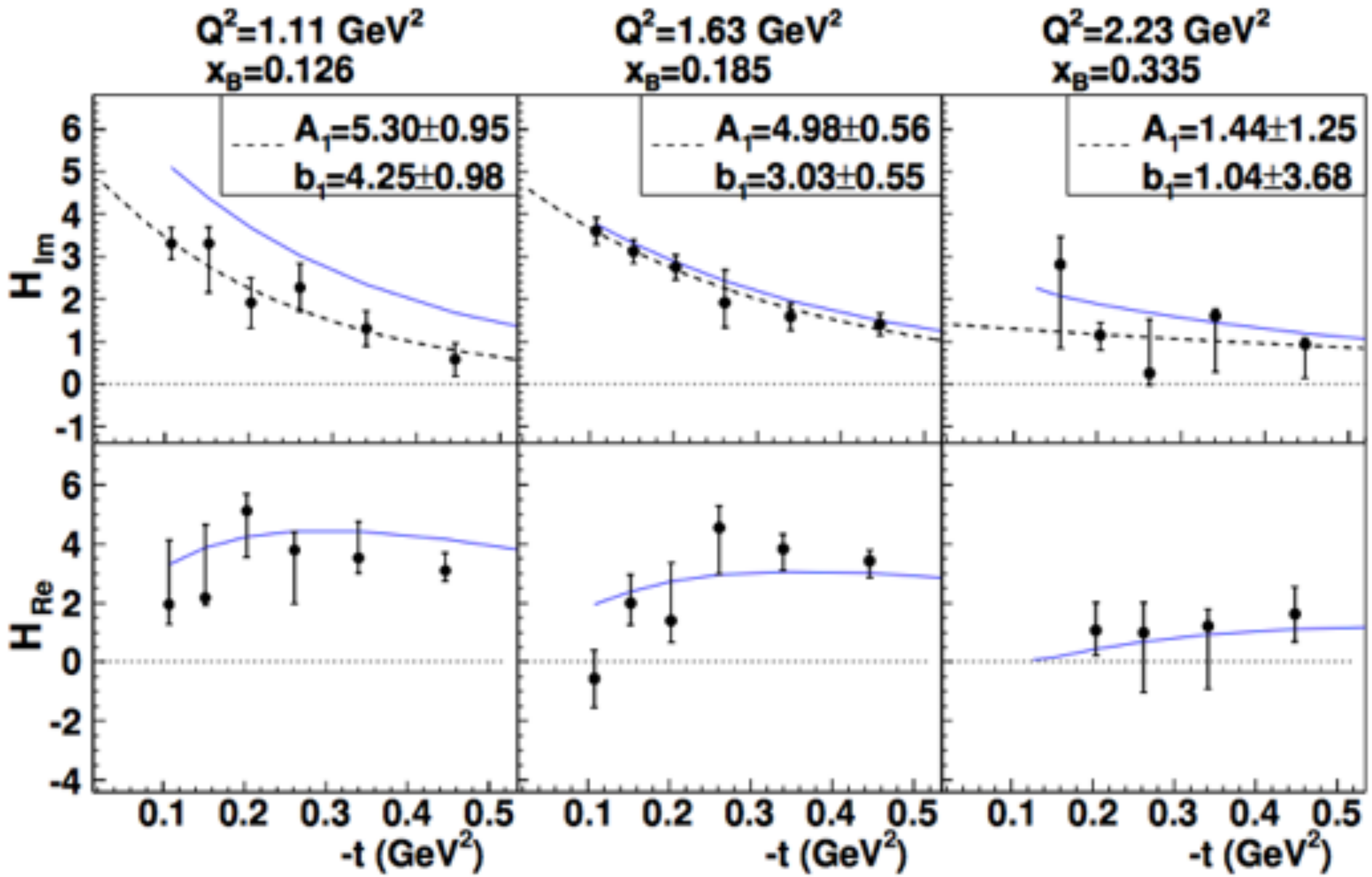
--- Ae^{bt}

✱ 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:

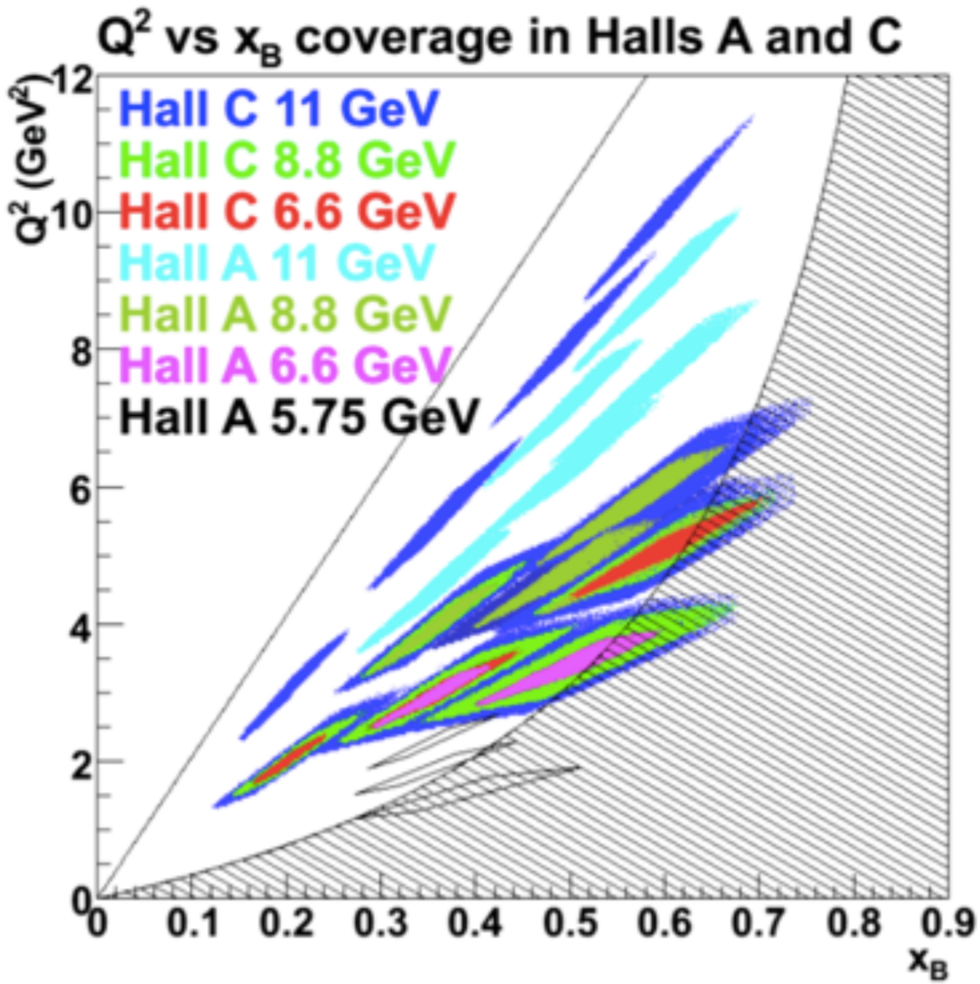
H.-S. Jo *et al* (CLAS Collaboration), ***PRL* 115** (2015) 212003



Halls A & C

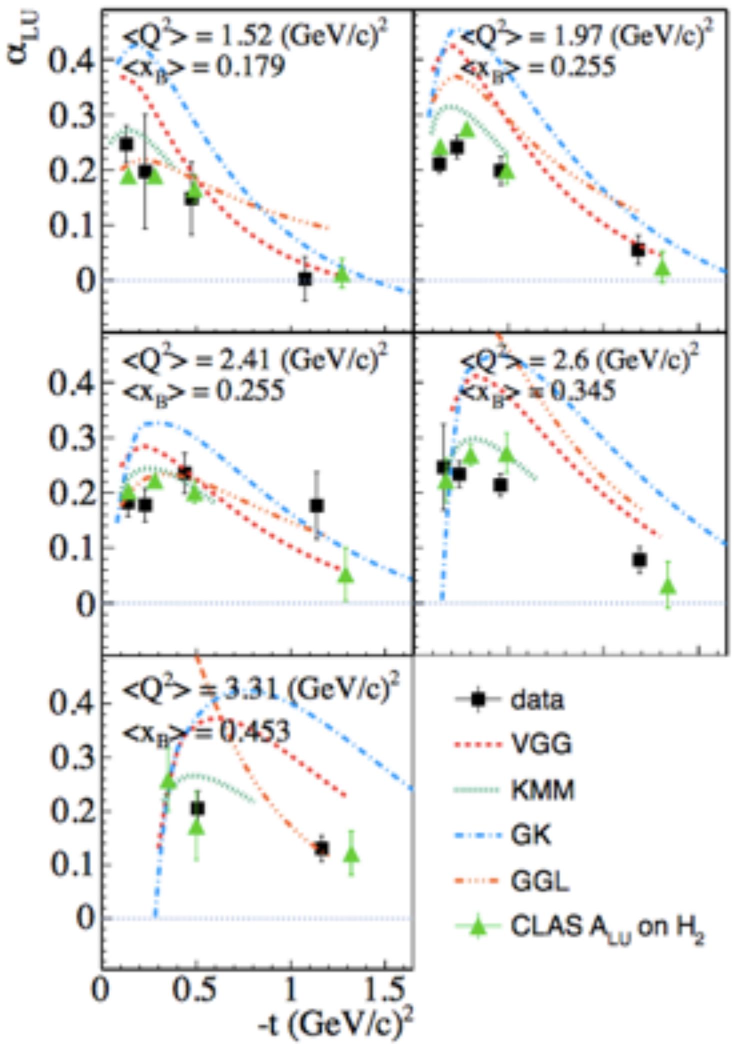
DVCS Cross-sections @ 11 GeV

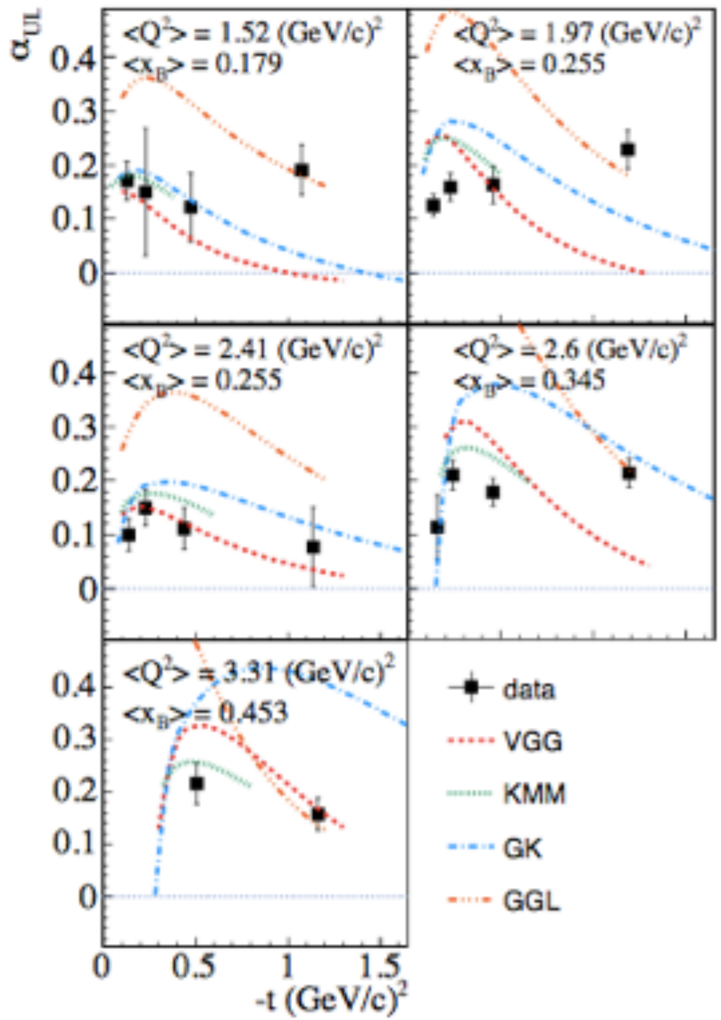
Experiments:
E12-06-114 (Hall A, 100 days),
E12-13-010 (Hall C, 65 days)
at a range of beam energies.



✱ Azimuthal, energy and helicity dependencies of cross-section to separate $|T_{DVCS}|^2$ and interference contributions in a wide kinematic coverage.

Beam and target-spin asymmetries





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

GGL: Goldstein, Gonzalez, Liuti

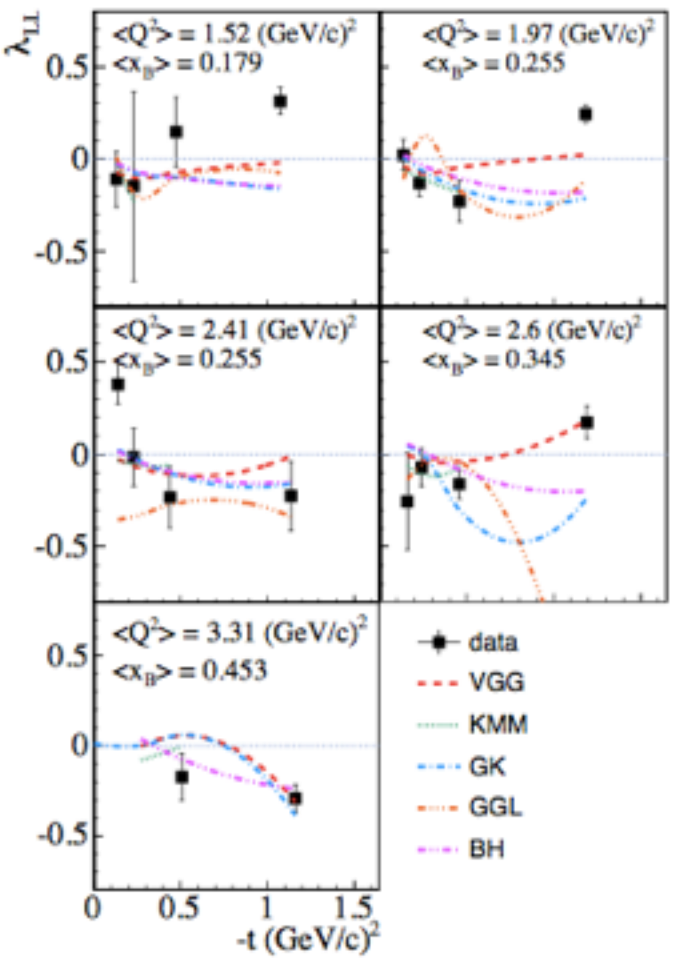
GK: Kroll, Moutarde, Sabatié

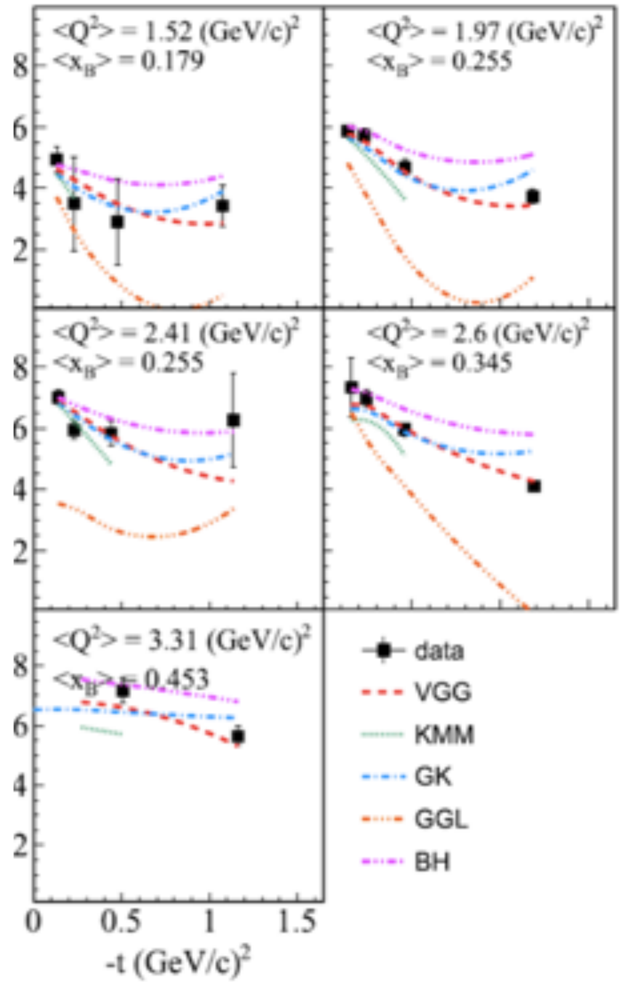
KMM: Kumericki, Mueller, Murray

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})





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

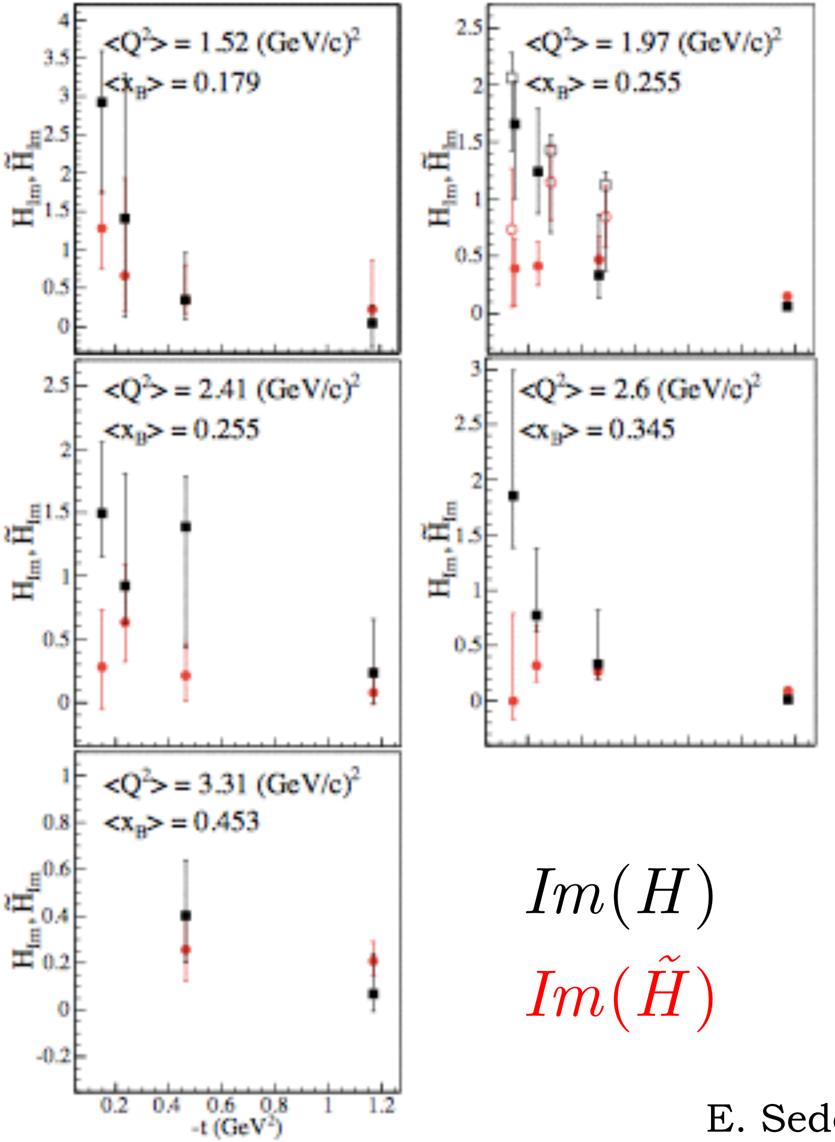
- Fit parameters extracted from a simultaneous fit to BSA, TSA and DSA.
- CFF extraction from three spin asymmetries at common kinematics.

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

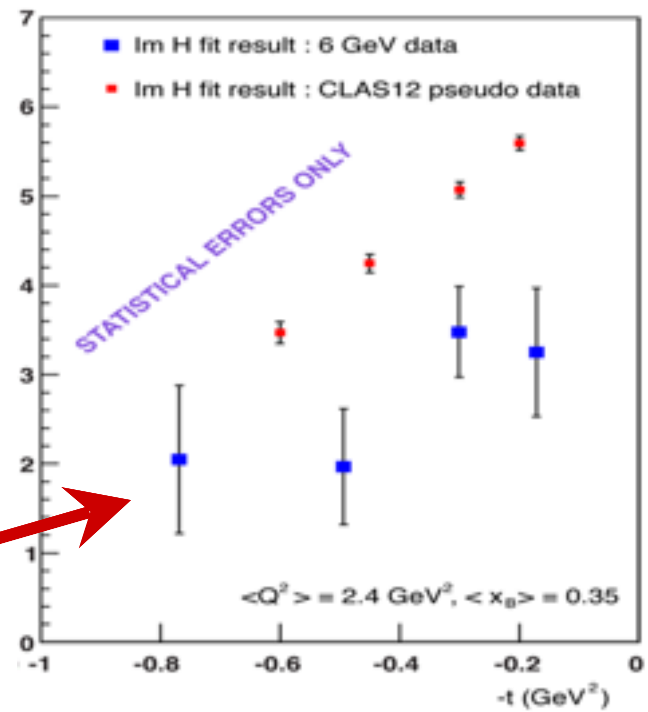
Asymmetries in Proton-DVCS with CLAS12

Approved experiment (E12-06-119):

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

120 days (polarised target)
$P_{target} = 80\%$
Statistical error: 2% - 15%
on sinφ moments
Systematic uncertainties: ~ 6 - 8%

85 days (unpolarised target):
Statistical error: 1% - 10%
on sinφ moments
Systematic uncertainties: ~ 6 - 8%



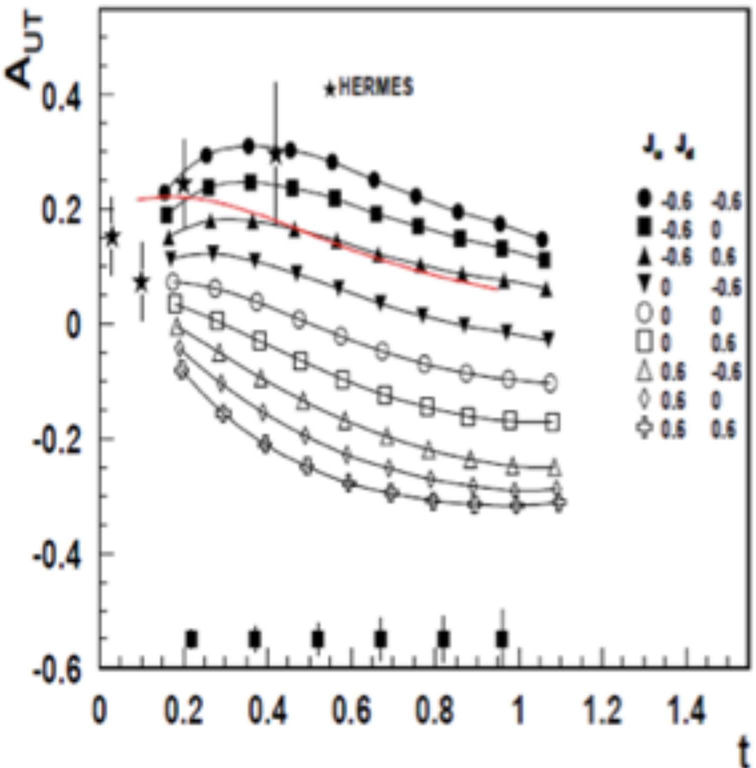
Impact of CLAS12 DVCS A_{LU} data on **model-independent fit to extract *Im*(H)**

DVCS with transversely polarised target at CLAS12

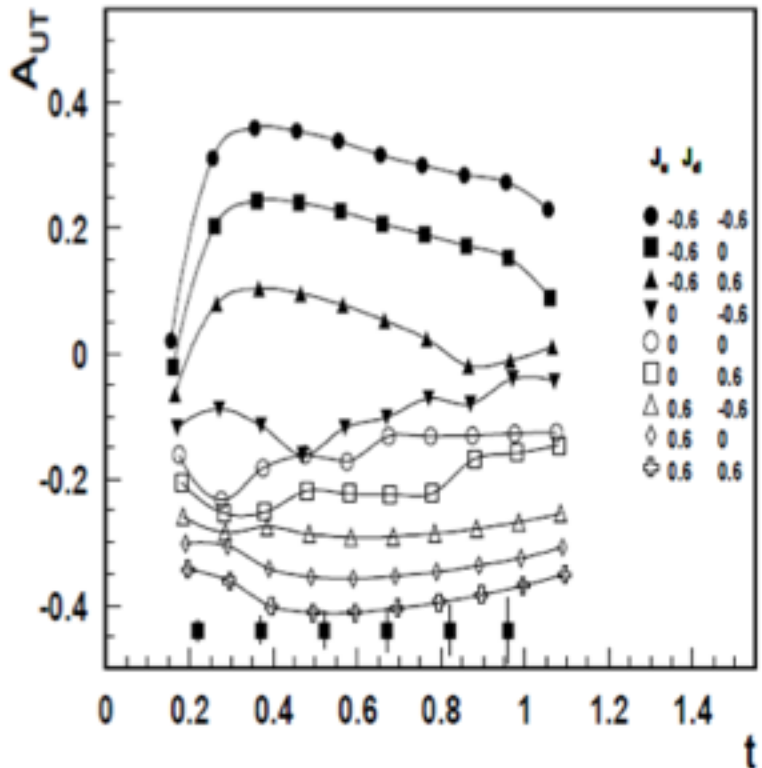
E12-12-010: transversely polarised HD target.

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

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

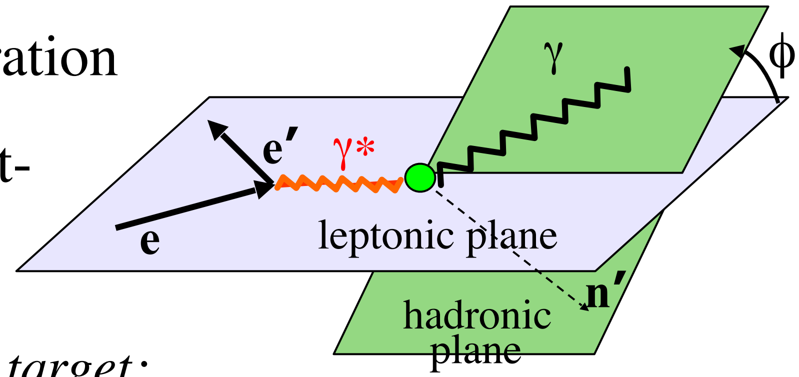


$\langle x \rangle = 0.2, \langle Q^2 \rangle = 2.5\ GeV^2$

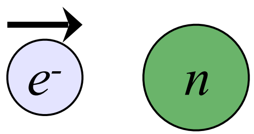


$\langle x \rangle = 0.33, \langle Q^2 \rangle = 2.5\ GeV^2$

Neutron DVCS



- GPDs from proton and neutron: flavour separation
- Neutron DVCS extremely sensitive to E, least-known and least-constrained GPD



Polarized beam, unpolarized neutron target:

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

- Ji's relation:

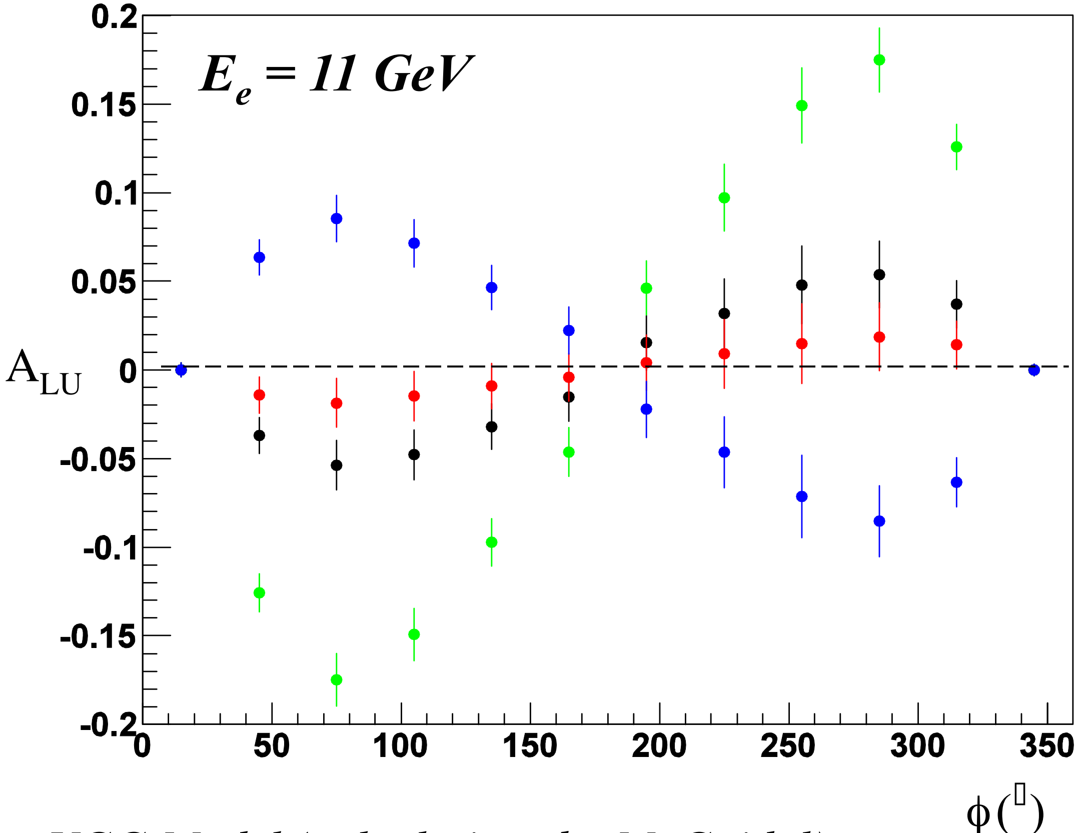
$$J^q = \frac{1}{2} - J^g = \frac{1}{2}\int_{-1}^{1} x dx \left\{H^q(x,\xi,0) + E^q(x,\xi,0)\right\}$$

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

Important missing link in the nucleon spin puzzle…

- First measurement in Hall A, consistent with zero: M. Mazouz et al, PRL **99** (2007) 242501
- Analysis on CLAS data in a different kinematic region ongoing…

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

- Wide coverage needed!

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

A_{LU} in Neutron DVCS with CLAS12

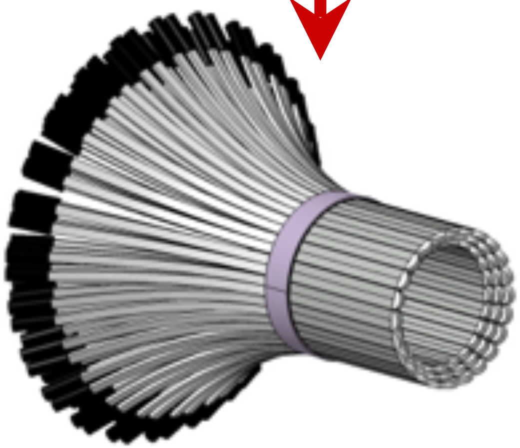
$$e + d \rightarrow e' + \gamma + n + (p_s)$$

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

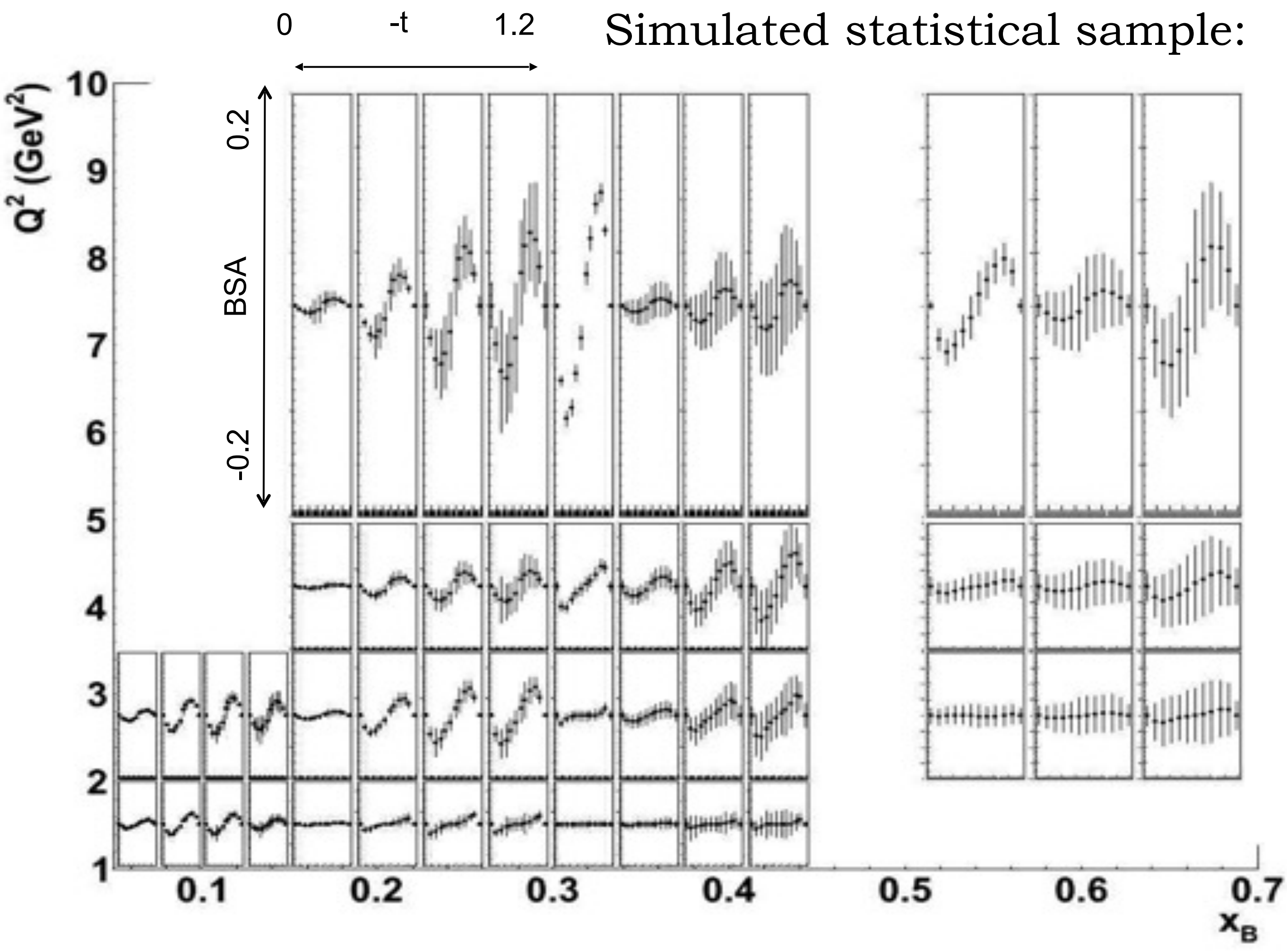
80 days of data taking

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

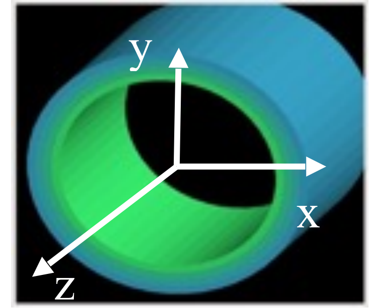
CLAS12 +
Forward Calorimeter
+
Neutron Detector



Simulated statistical sample:

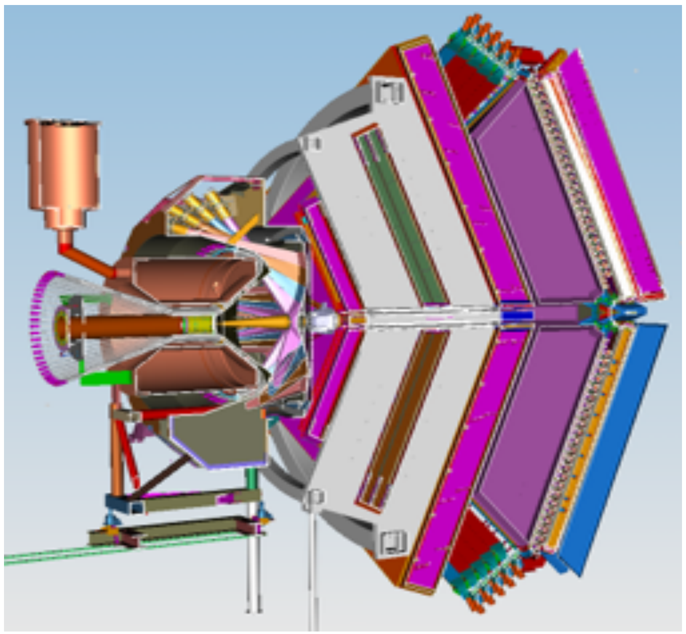


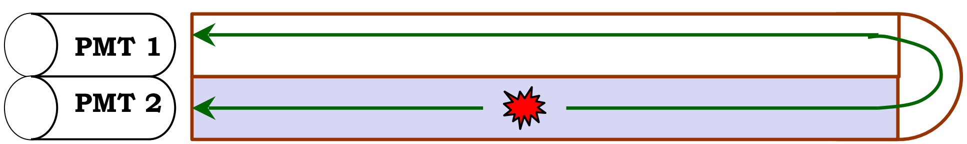
Neutron Detector for CLAS12

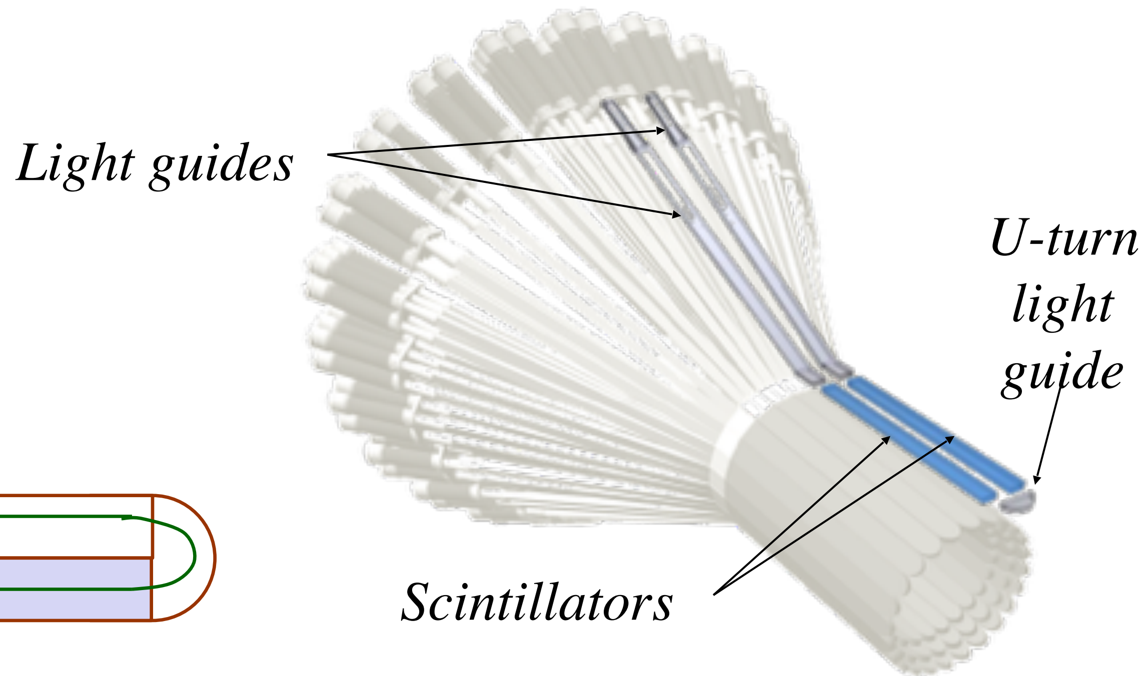


Available:
- ★ 10 cm of radial space
- ★ in a high magnetic field (~ 5T)

Detector design
- ★ Plastic scintillator barrel:
  3 layers, 48 paddles in each
- ★ Length ~ 70 cm, inner radius 28.5 cm
- ★ Long (~ 1.5 m) light-guides
- ★ PMT read-out upstream, out of high B field

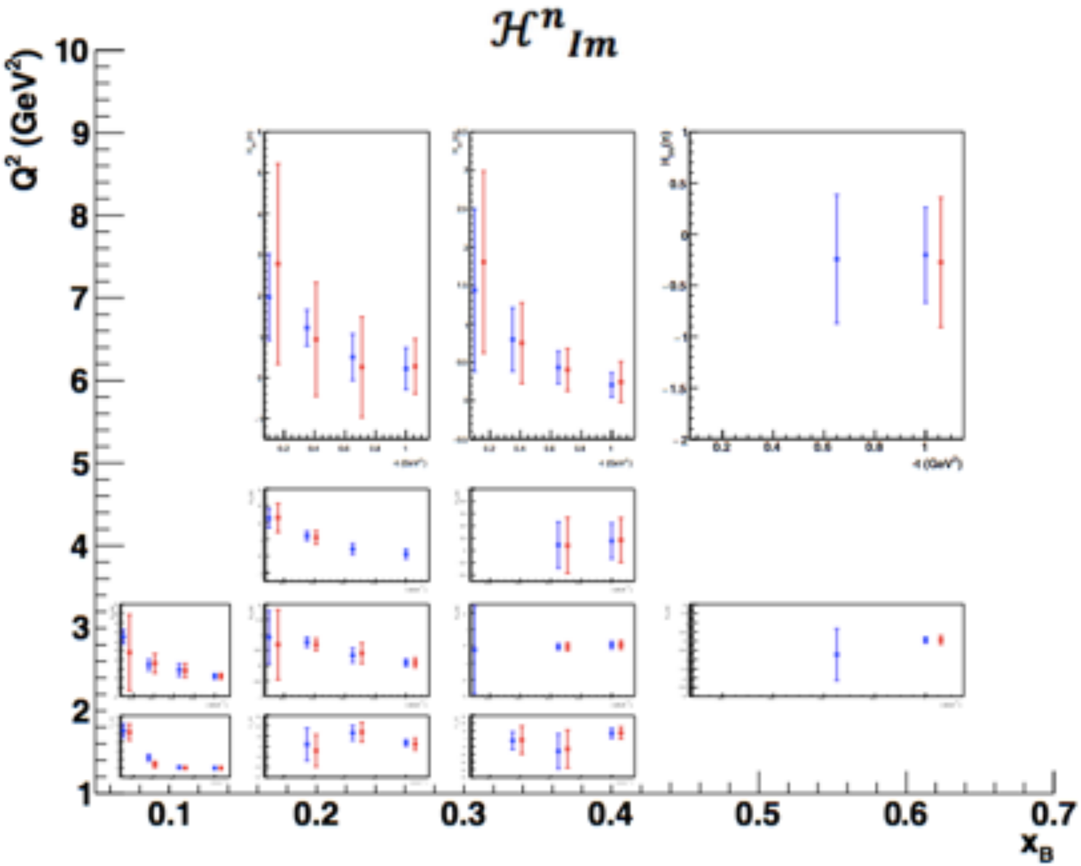


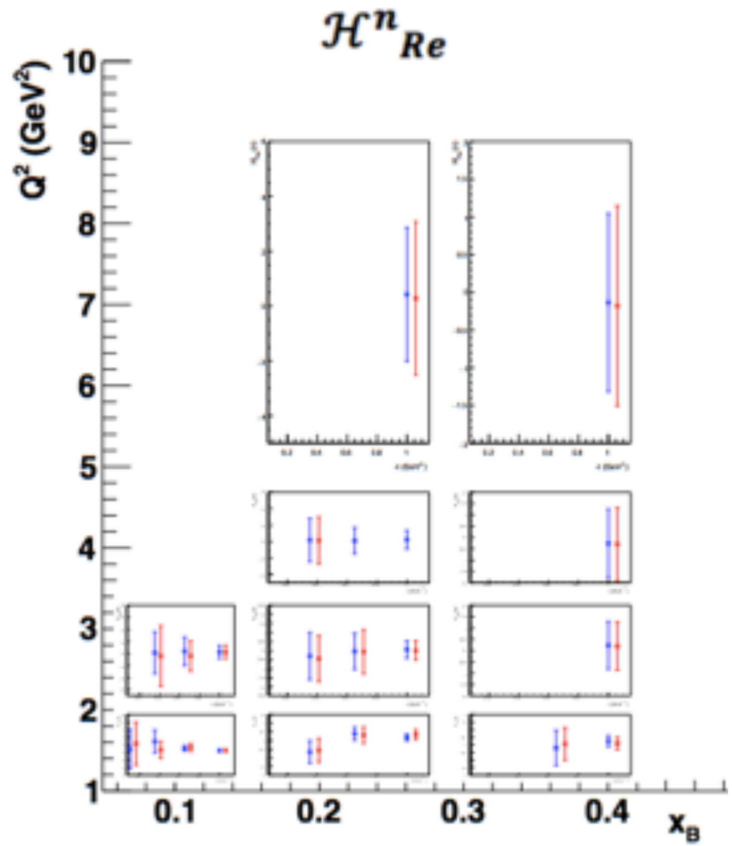




DVCS on the neutron with a longitudinally polarised deuterium target

In combination with pDVCS, allow flavour-separation of CFFs.
Expected sensitivities:





To conclude...

- Electron scattering is a clean and versatile probe into the **structure of the nucleon**.

- The past decade saw the start of **3D imaging** of the nucleon and the experimental programme at **Jefferson Lab** will study the **valence region** in detail.

- A wide programme planned for Halls A, B and C in the **11 GeV** era: higher luminosity, higher precision, wider reach of phase space, greater range of observables.

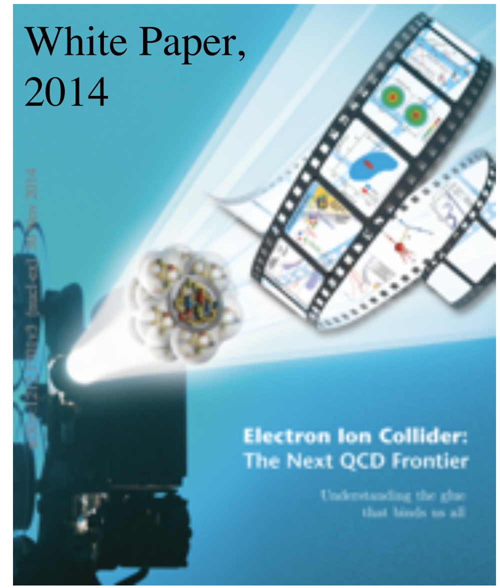
- A full understanding of the nucleon requires diverse measurements, for example **form factors** in elastic scattering, structure functions (for **PDFs**) in DIS, Compton form factors (for **GPDs**) in exclusive reactions and a variety of different functions in SIDIS (for **TMDs**). Data is required across a **wide range of Q^2** to image the nucleon at all depths.

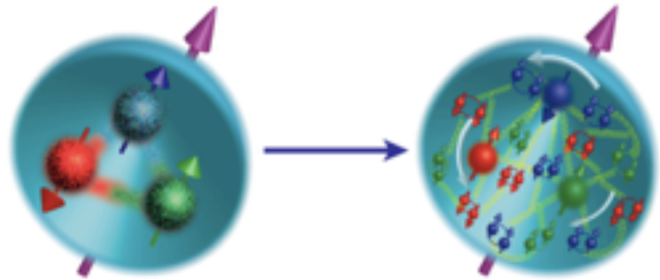
Thank you

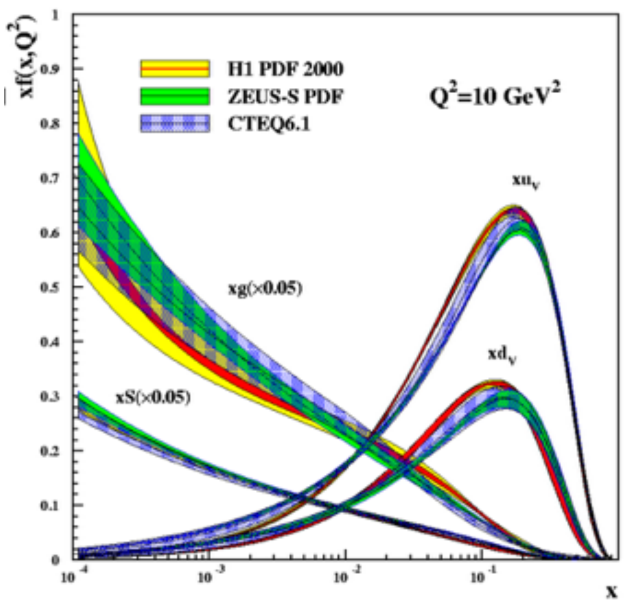
Looking to the future: Electron-Ion Collider

"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

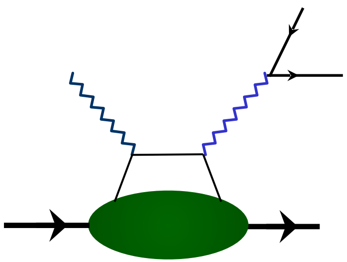
Experimental paths to GPDs

cliparts.co

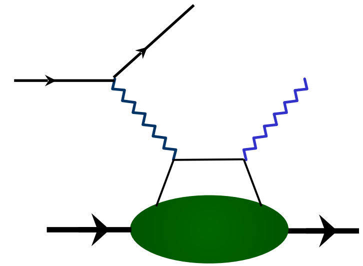
Accessible in *exclusive* reactions, where all final state particles are detected.

Trodden paths, or ones starting to be explored:

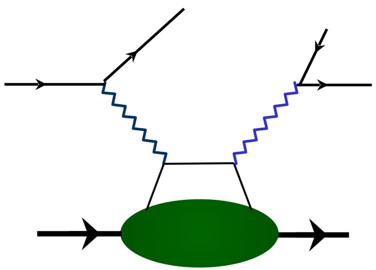
- Deeply Virtual Compton Scattering (DVCS)
- Deeply Virtual Meson Production (DVMP)
- Time-like Compton Scattering (TCS)
- Double DVCS



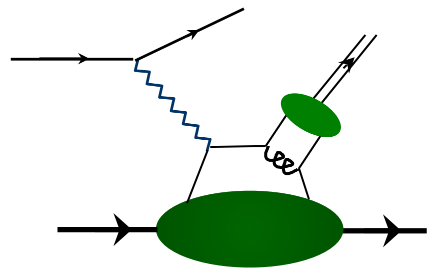
TCS



DVCS

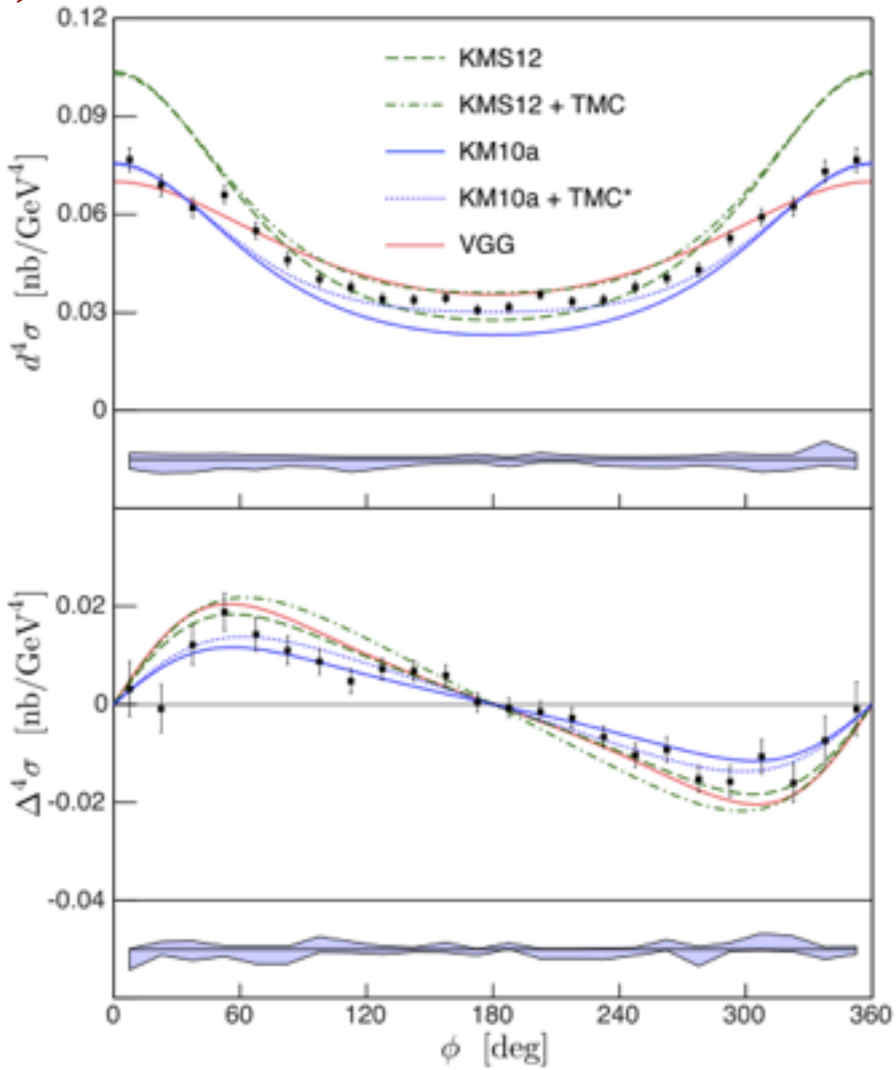


DDVCS



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

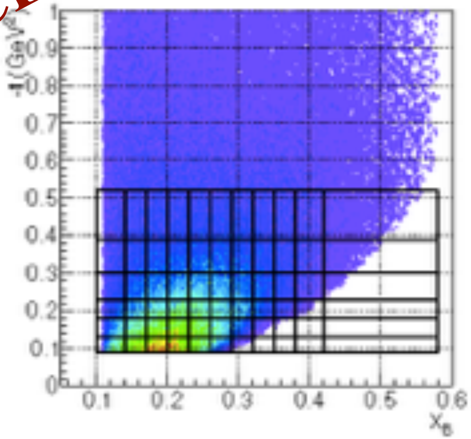
VGG model: Vanderhaeghen, Guichon, Guidal

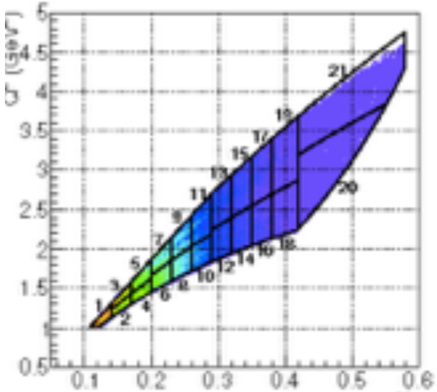
KMS model: Kroll, Moutarde, Sabatié

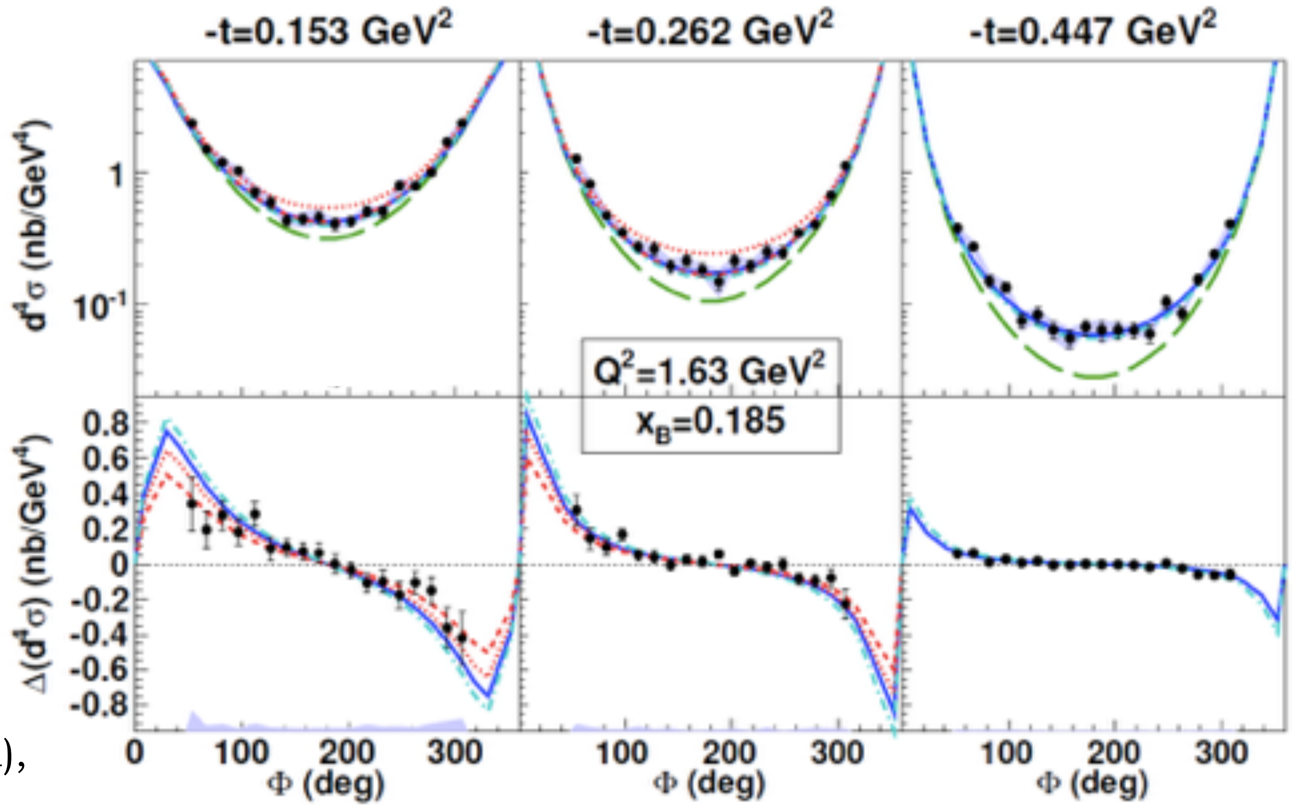
KM model: Kumericki, Mueller

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

CLAS unpolarised cross-sections





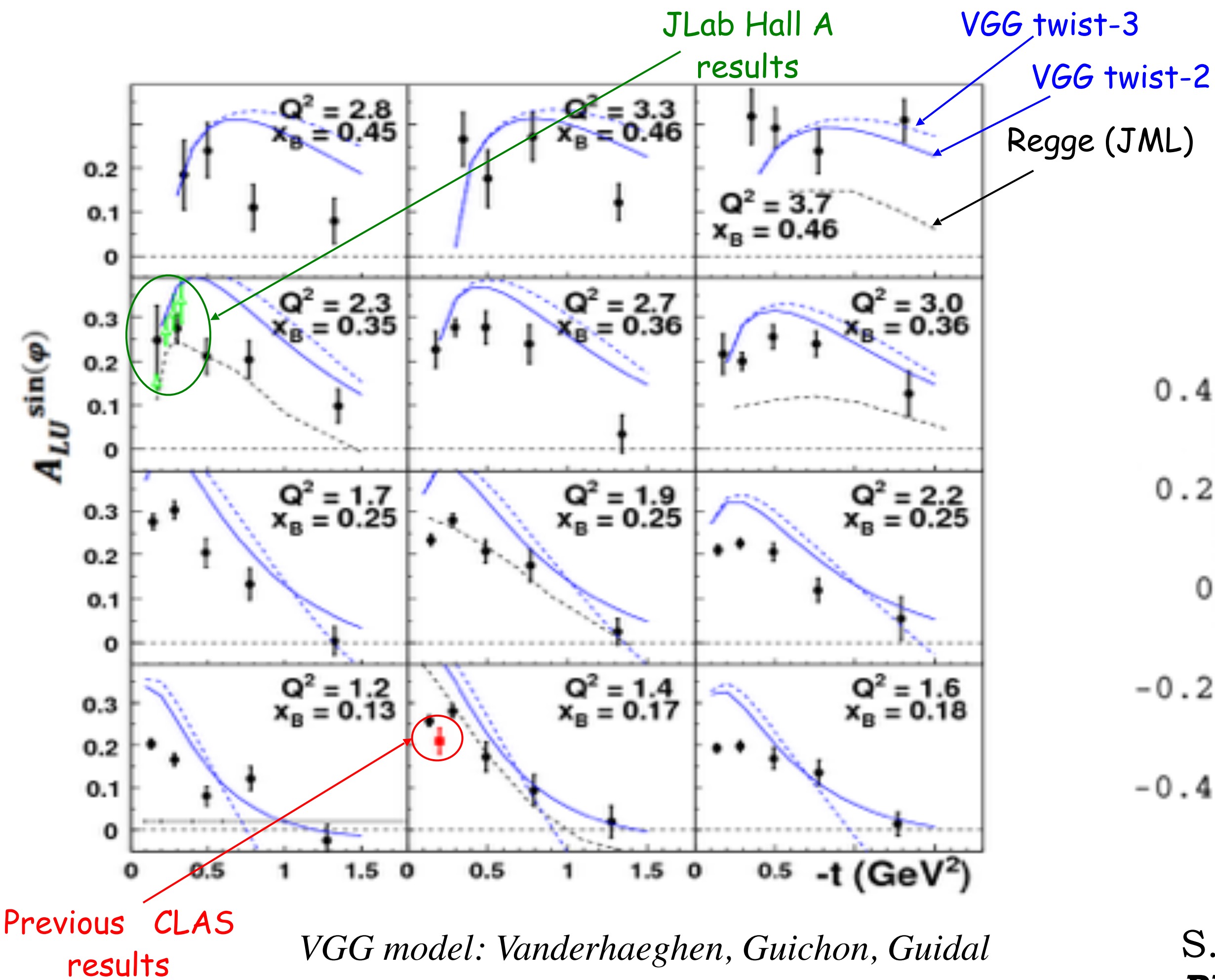


$$\frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}$$

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

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

Beam-spin Asymmetry (A_{LU})

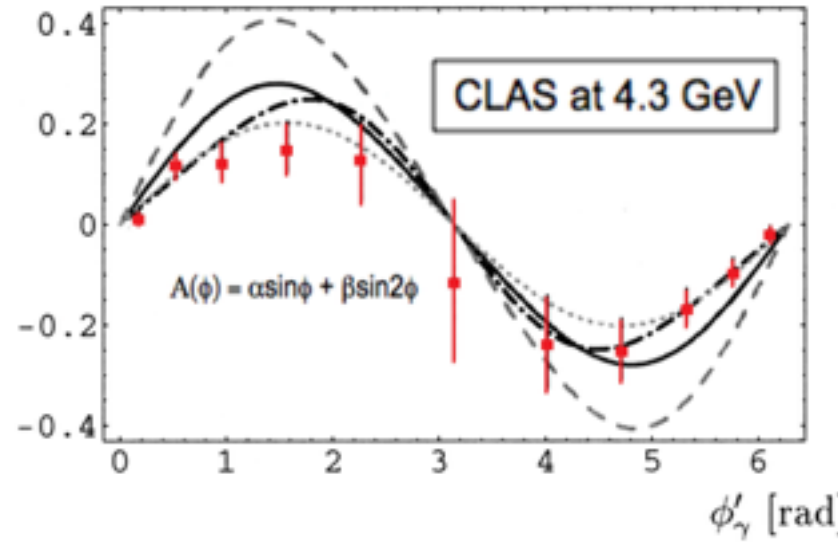


VGG model: Vanderhaeghen, Guichon, Guidal

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

A_{LU} from fit to asymmetry:

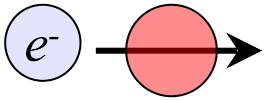
$$A_i = \frac{\alpha_i \sin\phi}{1 + \beta_i \cos\phi}$$



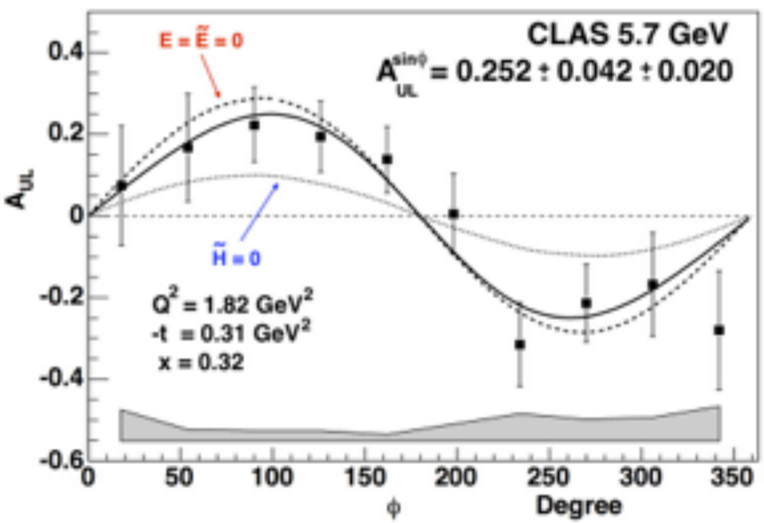
S. Stepanyan *et al* (CLAS Collaboration), ***PRL* 87** (2001) 182002

CLAS

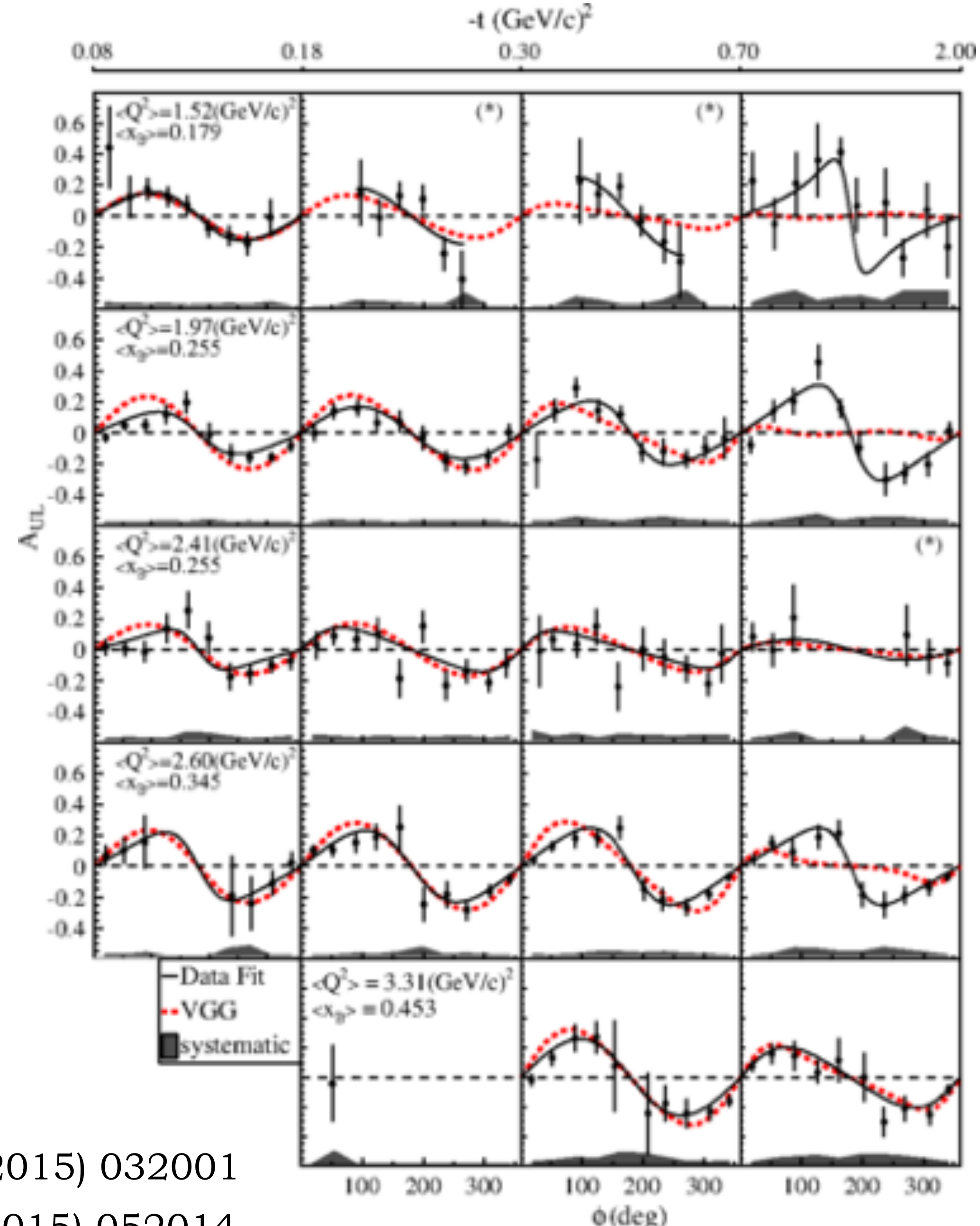
Target-spin Asymmetry (A_{UL})



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



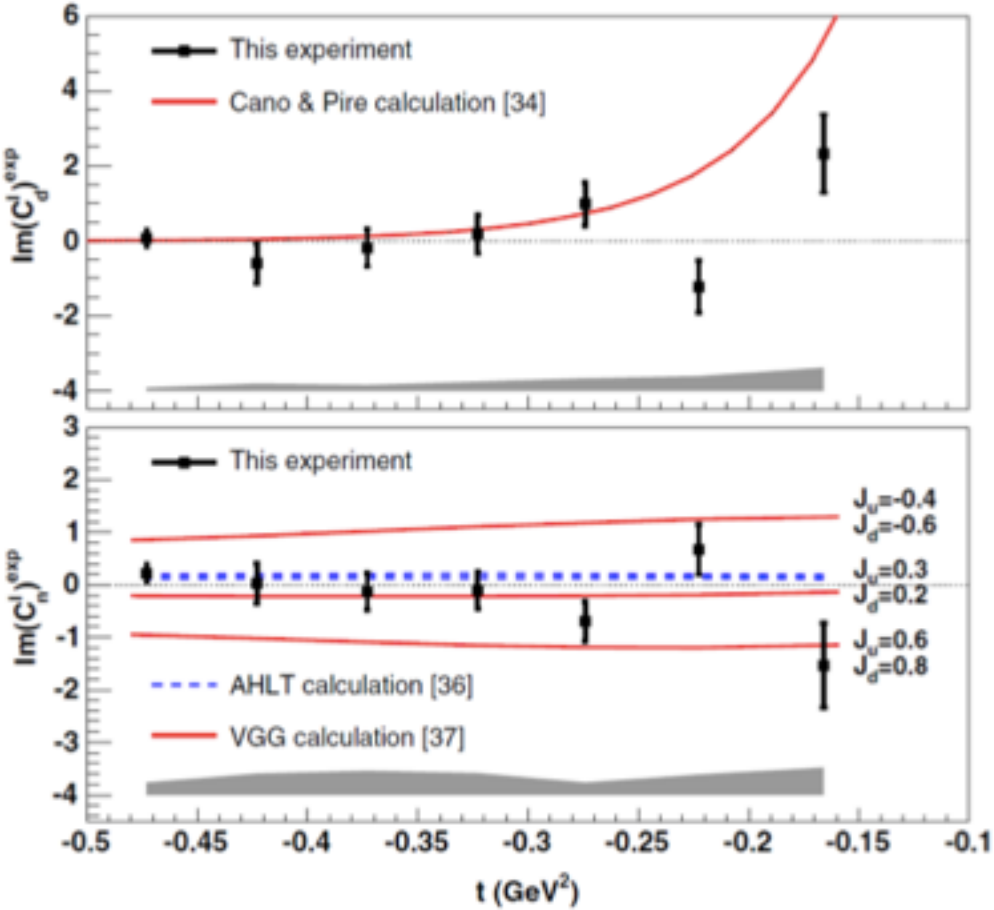
S. Chen *et al* (CLAS Collaboration), ***PRL* 97** (2006) 072002



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

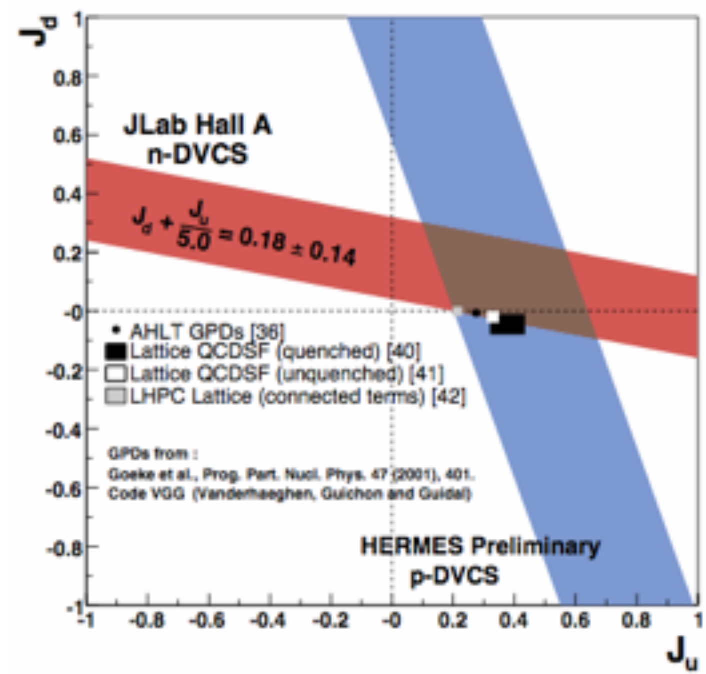
S. Pisano *et al* (CLAS Collaboration), ***PRD* 91** (2015) 052014

Beam-spin asymmetry in neutron DVCS



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

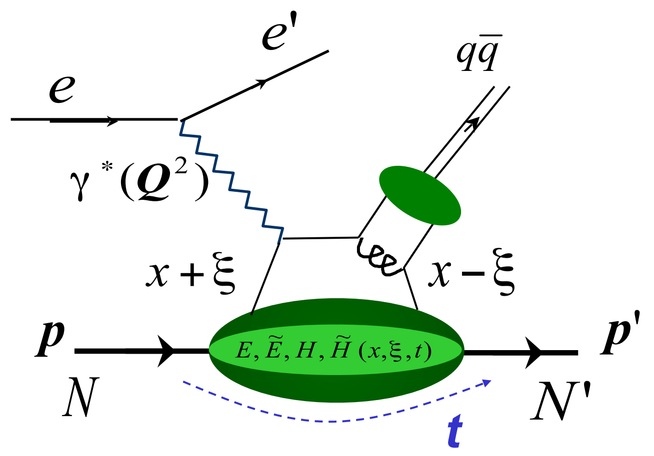
- First experimental constraint on E^q, through model interpretation gives constraints on orbital angular momentum of quarks.



- Analysis underway on CLAS data.

GPDs through other channels

Deeply Virtual Meson Production



Enables flavour decomposition.

At high exchanged Q², access to four chiral-even (parton helicity conserving) GPDs:

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

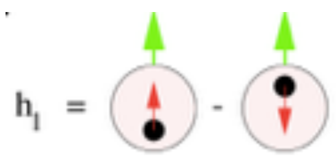
and four chiral-odd (parton helicity flipping) GPDs:

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

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

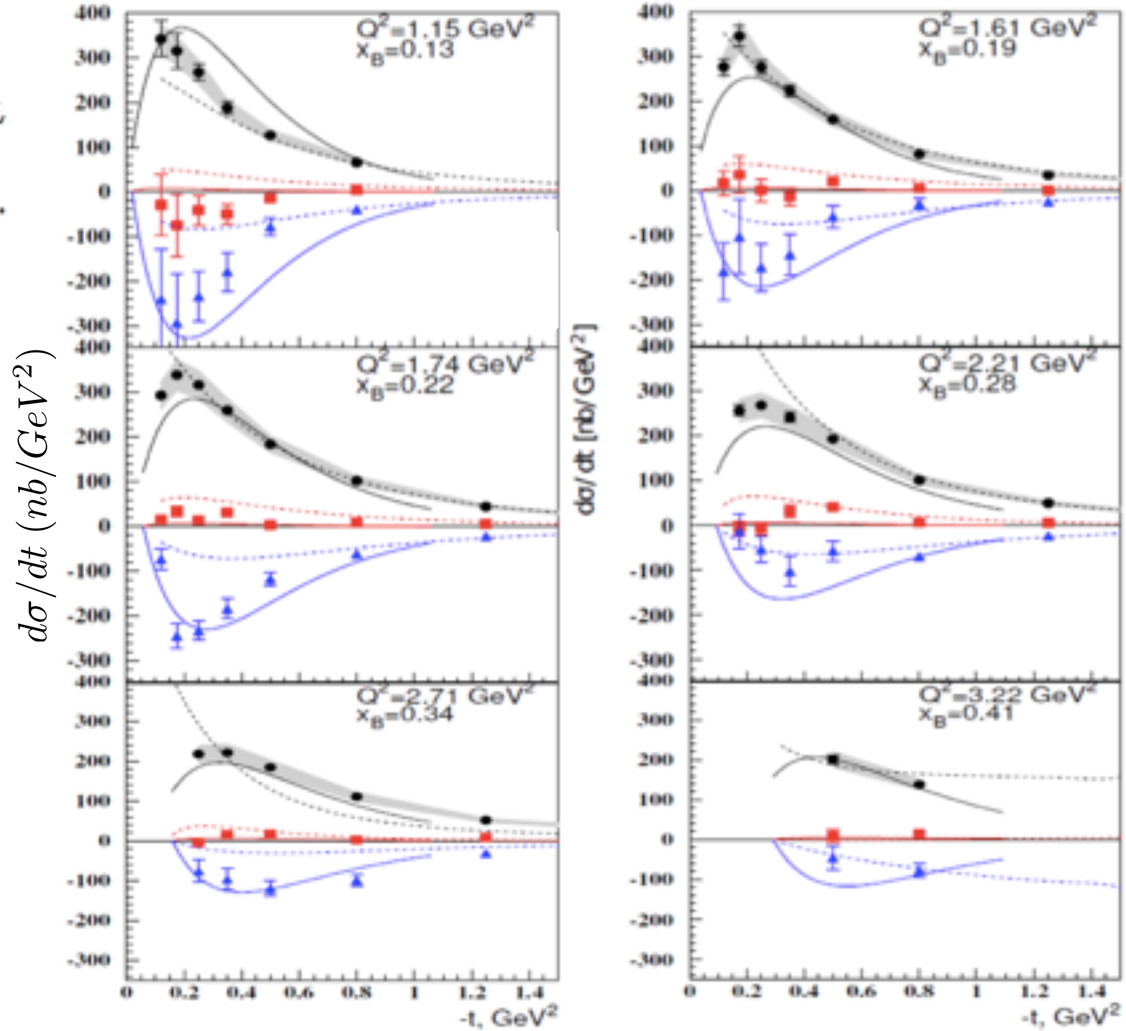
$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi_\pi} = \Gamma(Q^2, x_B, E)\frac{1}{2\pi}(\sigma_T + \epsilon\sigma_L + \epsilon\cos 2\phi_\pi \sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \sigma_{LT}).$$

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

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

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

Contribution of σ_T and σ_{TT} is large.

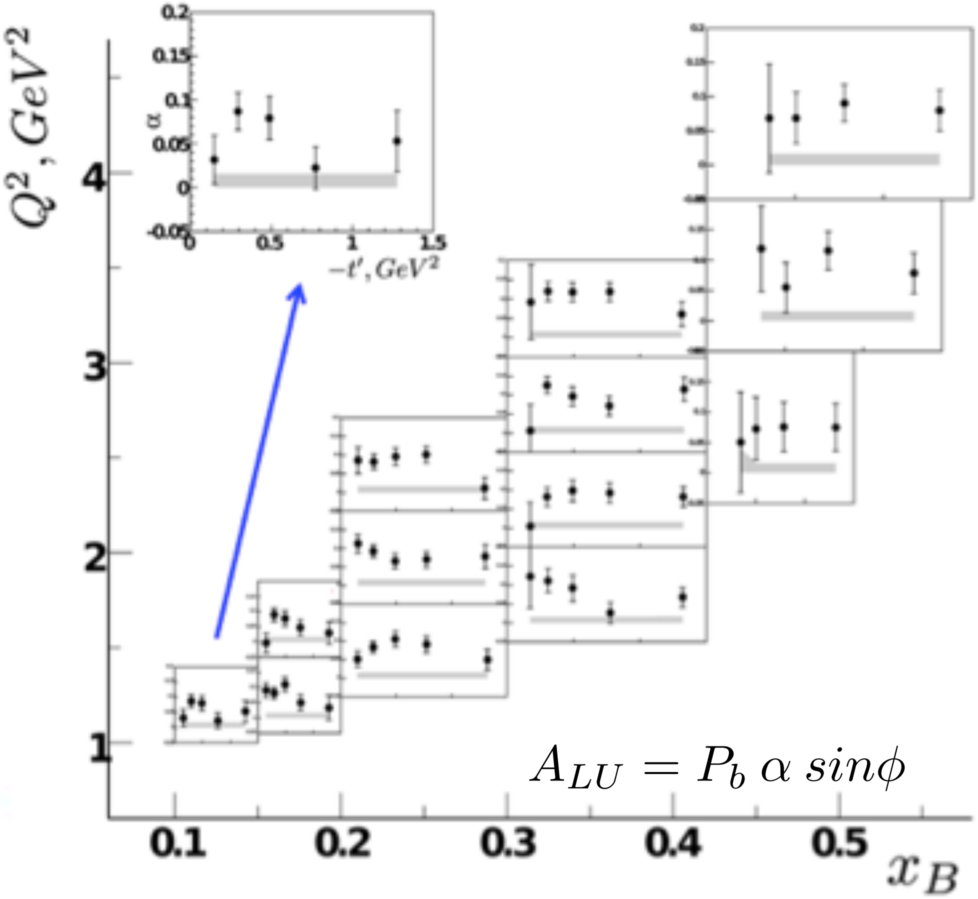


Solid: P. Kroll, S. Goloskokov
Dashed: G. Goldstei, J. Gonzalez, S. Liuti

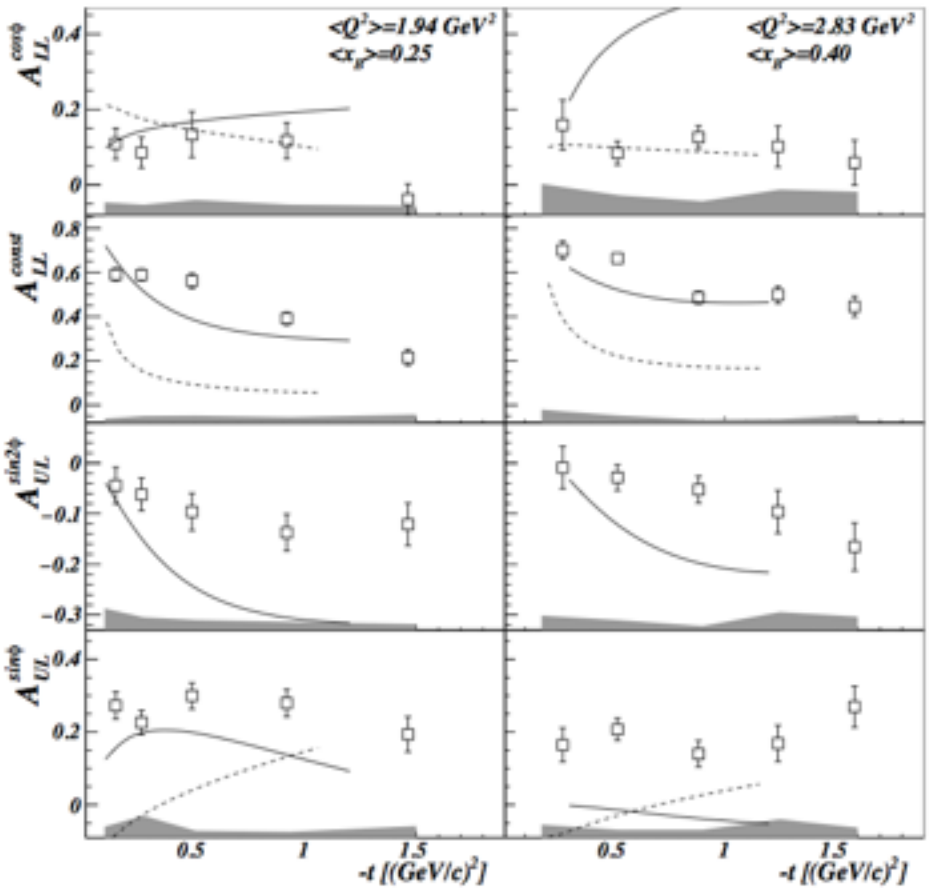
I. Bedlinskiy *et al* (CLAS Collaboration), ***PRL*** 109, (2012) 112001

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

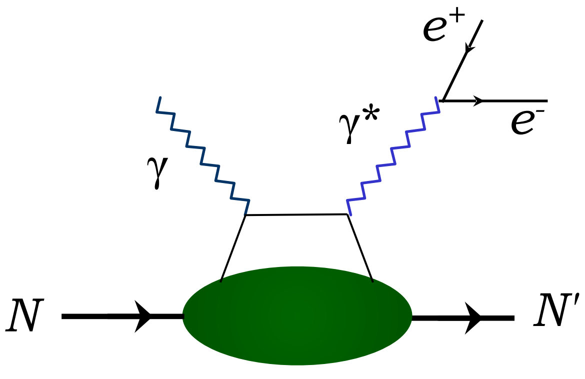
A. Kim *et al* (CLAS Collaboration), submitted to ***PRL***

Prospects at CLAS12

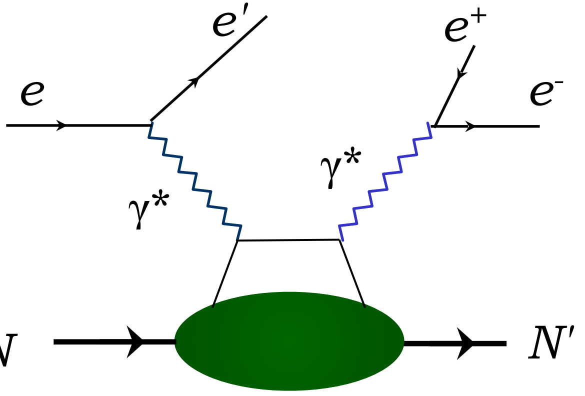
- Deeply Virtual Meson Production, e.g.: η and π^0 (E12-06-108), ϕ (E12-12-007).

- 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