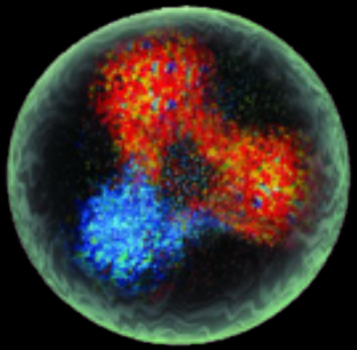
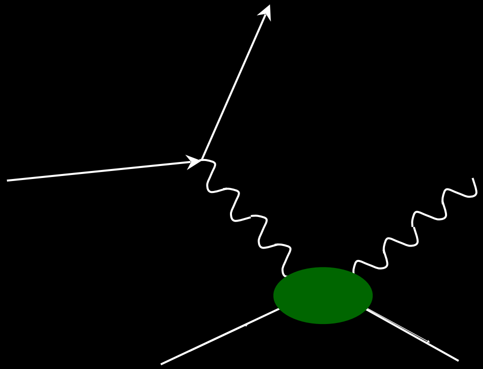
Tomography of the Nucleon: Quark Dynamics under the Microscope





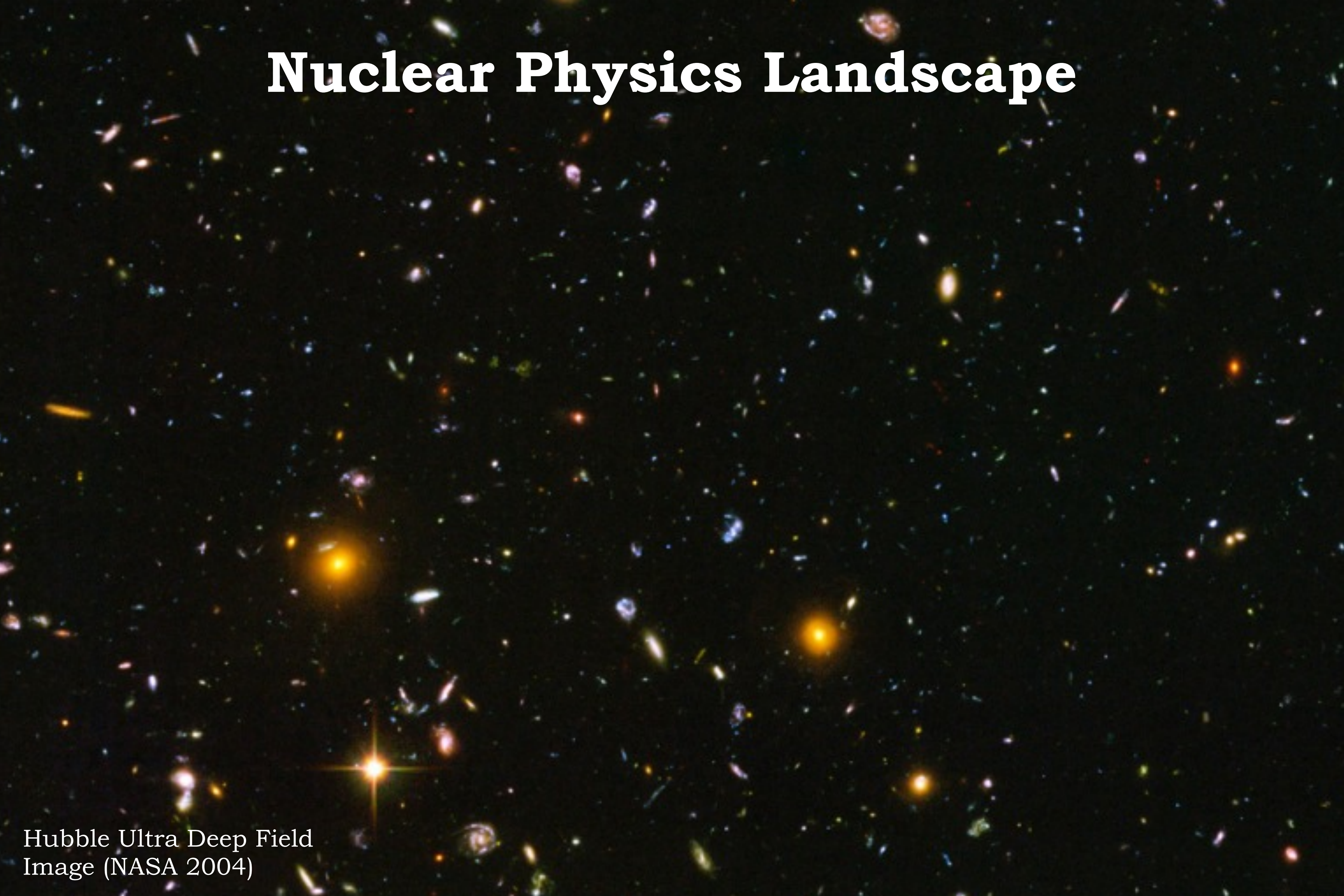
Daria Sokhan

University of Glasgow, UK

SPhN, Saclay, France — 24th June 2016

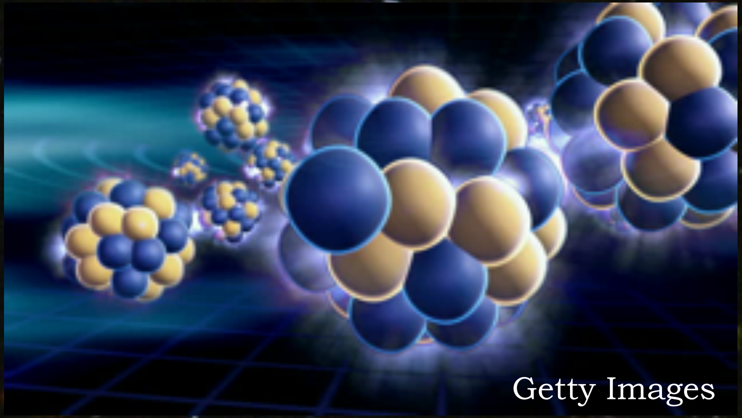
Prologue…

Nuclear Physics Landscape



Hubble Ultra Deep Field
Image (NASA 2004)

Nuclear Physics Landscape

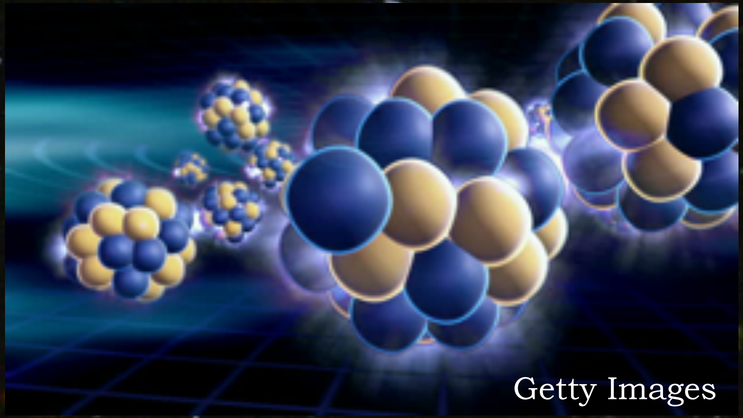


Getty Images

Nucleon-nucleon
interactions

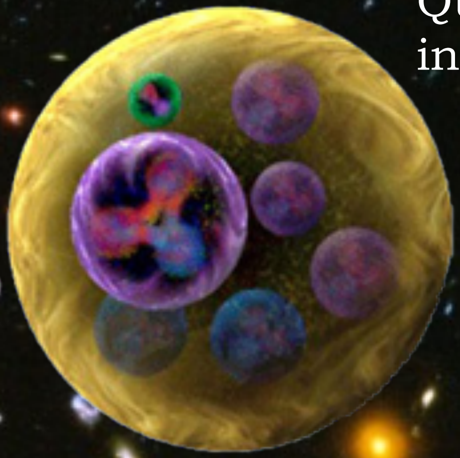
Hubble Ultra Deep Field
Image (NASA 2004)

Nuclear Physics Landscape


Getty Images

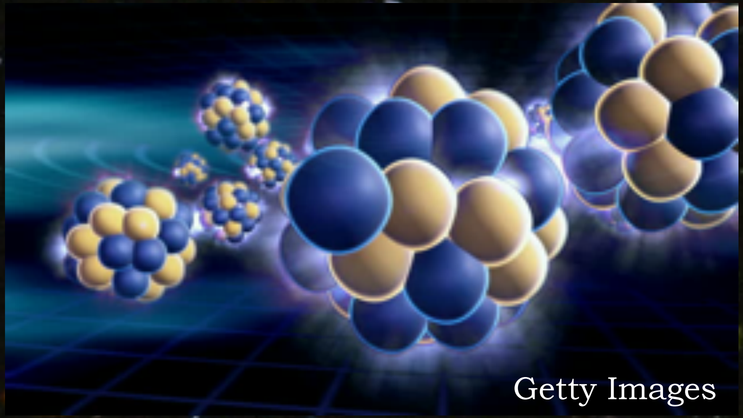
Nucleon-nucleon interactions

Quark-gluon interactions


J. Griffin (JLab)

Hubble Ultra Deep Field Image (NASA 2004)

Nuclear Physics Landscape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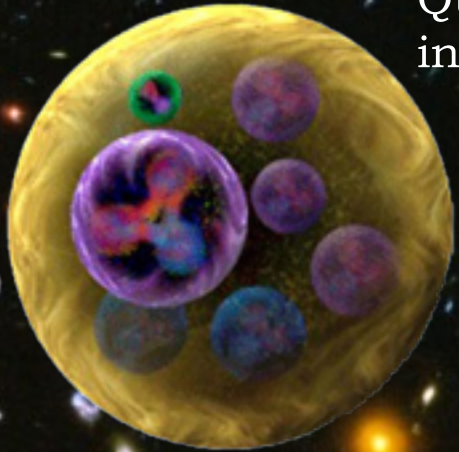
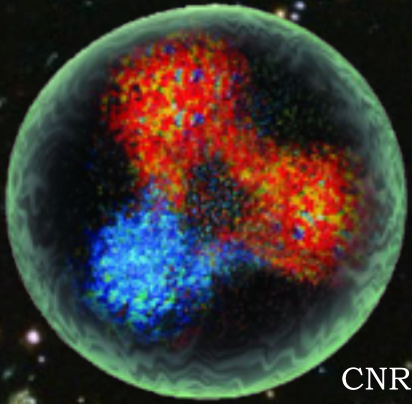

J. Griffin (JLab)

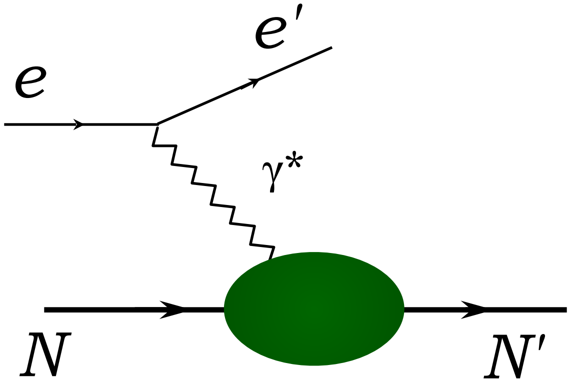
Quantum Chromodynamics


CNRS

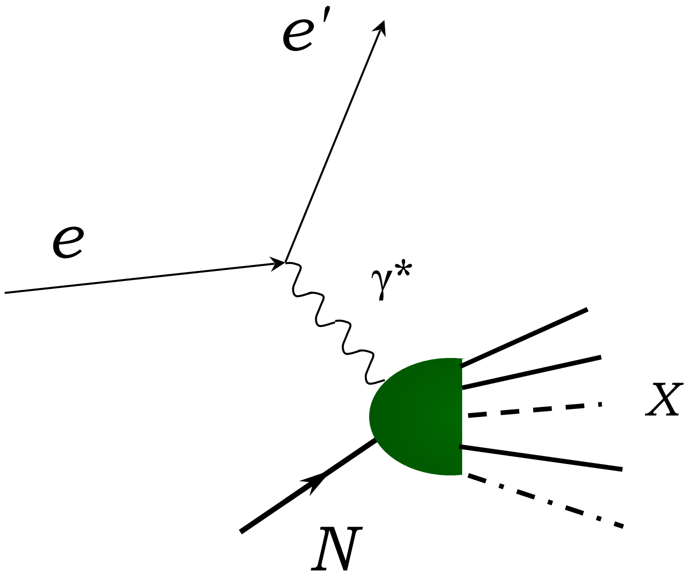
Hubble Ultra Deep Field Image (NASA 2004)

Electron scattering: the basics

Elastic scattering: initial and final state is the same, only momenta change.



Deep inelastic scattering (DIS): state of the nucleon changed, new particles created.



Measurements:

★ Inclusive — only the electron is detected
★ Semi-inclusive — electron and typically one hadron detected
★ Exclusive — all final state particles detected

→ Complementary information on the nucleon’s structure

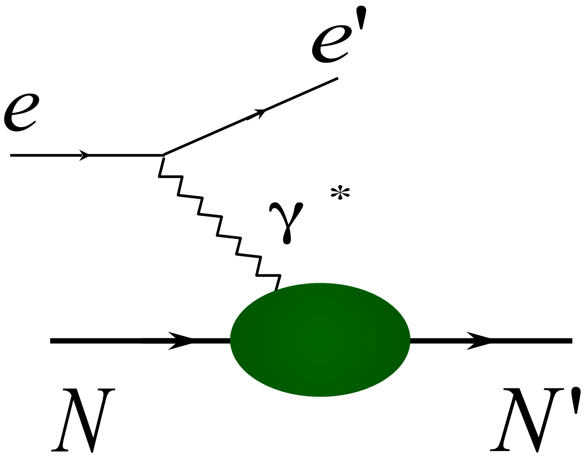
A (very abridged) history

<1956: the nucleon is point-like and fundamental…

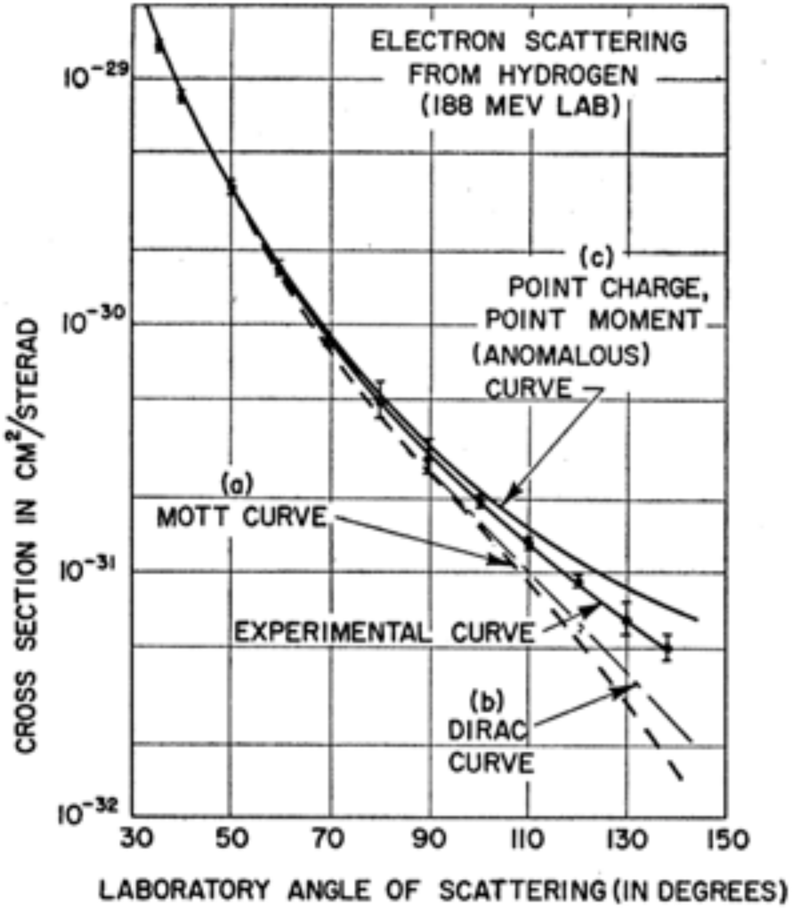
1956: *Elastic scattering* at SLAC.

The proton is not point-like and has internal structure! Our field is born…

Hofstadter: Nobel Prize 1961



Robert Hofstadter
1915 - 1990
(Wikipedia)

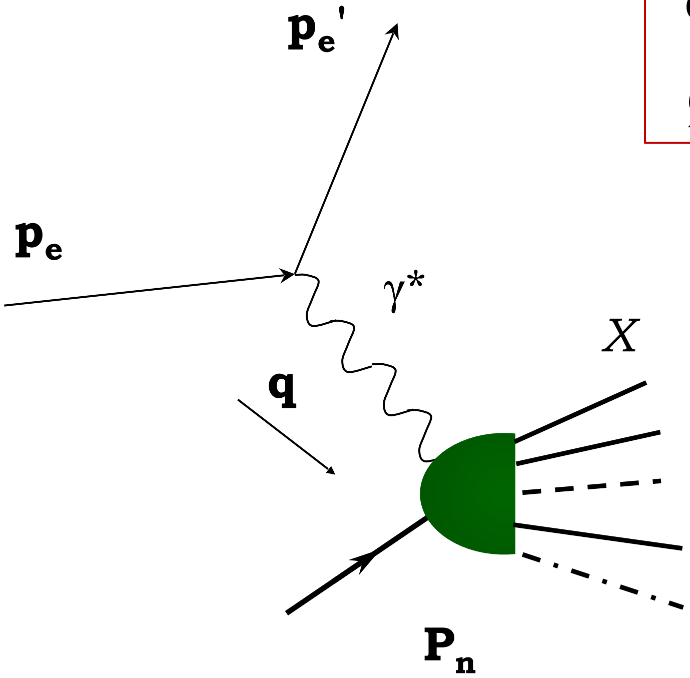


R. W. McAllister & R. Hofstadter, *Physical Review* 102, p.851 (1956)

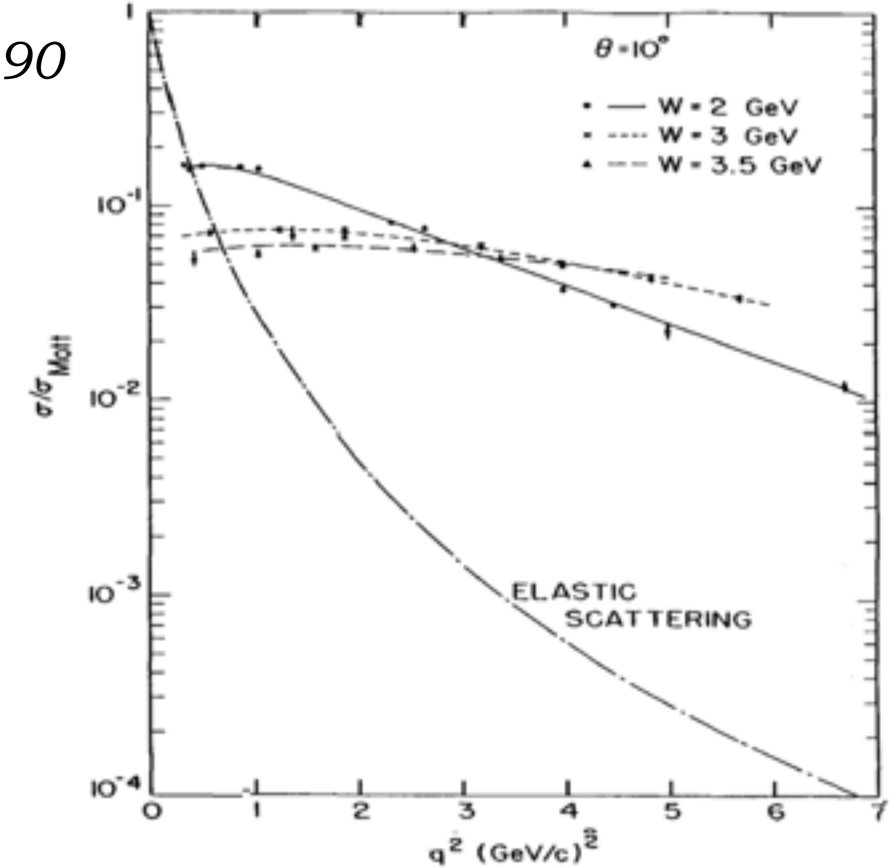
A (very abridged) history

1968: *Deep Inelastic scattering* at SLAC: scaling observed. The proton consists of point-like charges: quarks.

Friedman, Kendall, Taylor: Nobel Prize 1990



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



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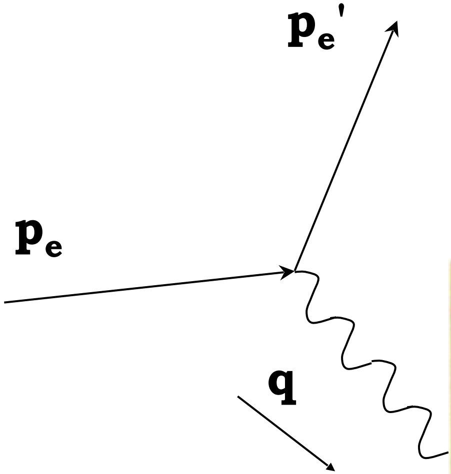
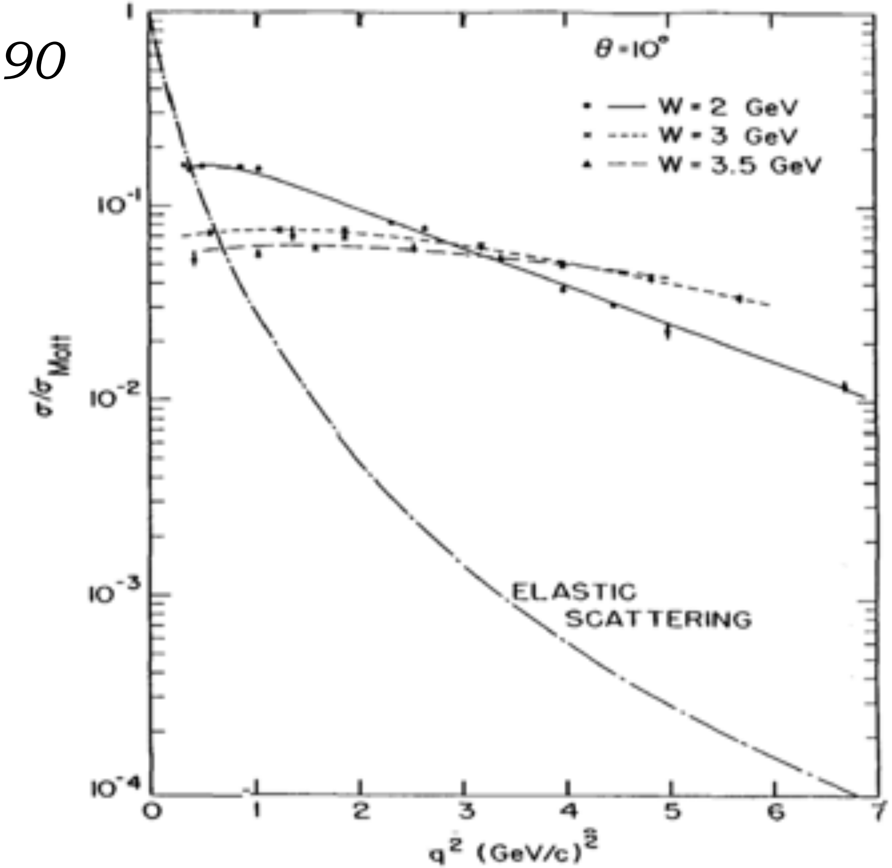


Here be dragons?

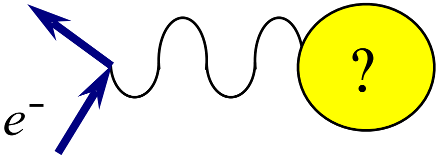
Fra Mauro world map, 1450s (Wikipedia)



Scales of resolution – an elephantine analogy

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

International Mammoth Committee



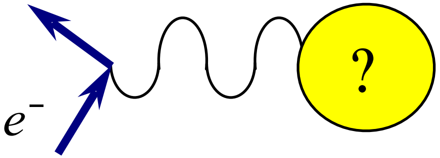
Q^2 ~ MeV^2

Scales of resolution – an elephantine analogy

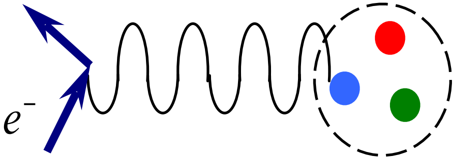
Lyuba, baby mamoth found in Siberia, imaged with visible light…

… and X-rays.

International Mammoth Committee



Q^2 ~ MeV^2

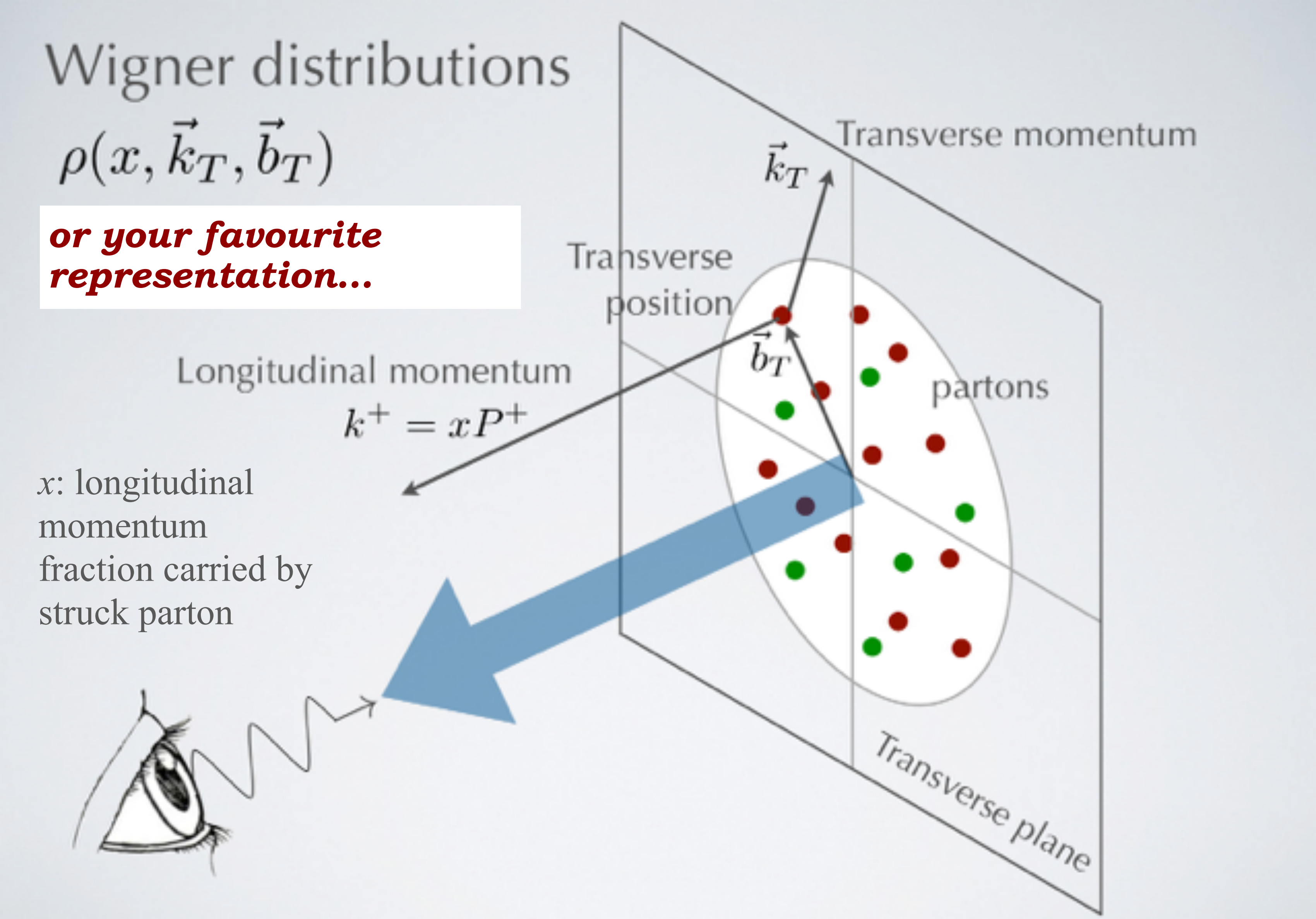


Q^2 >> GeV^2

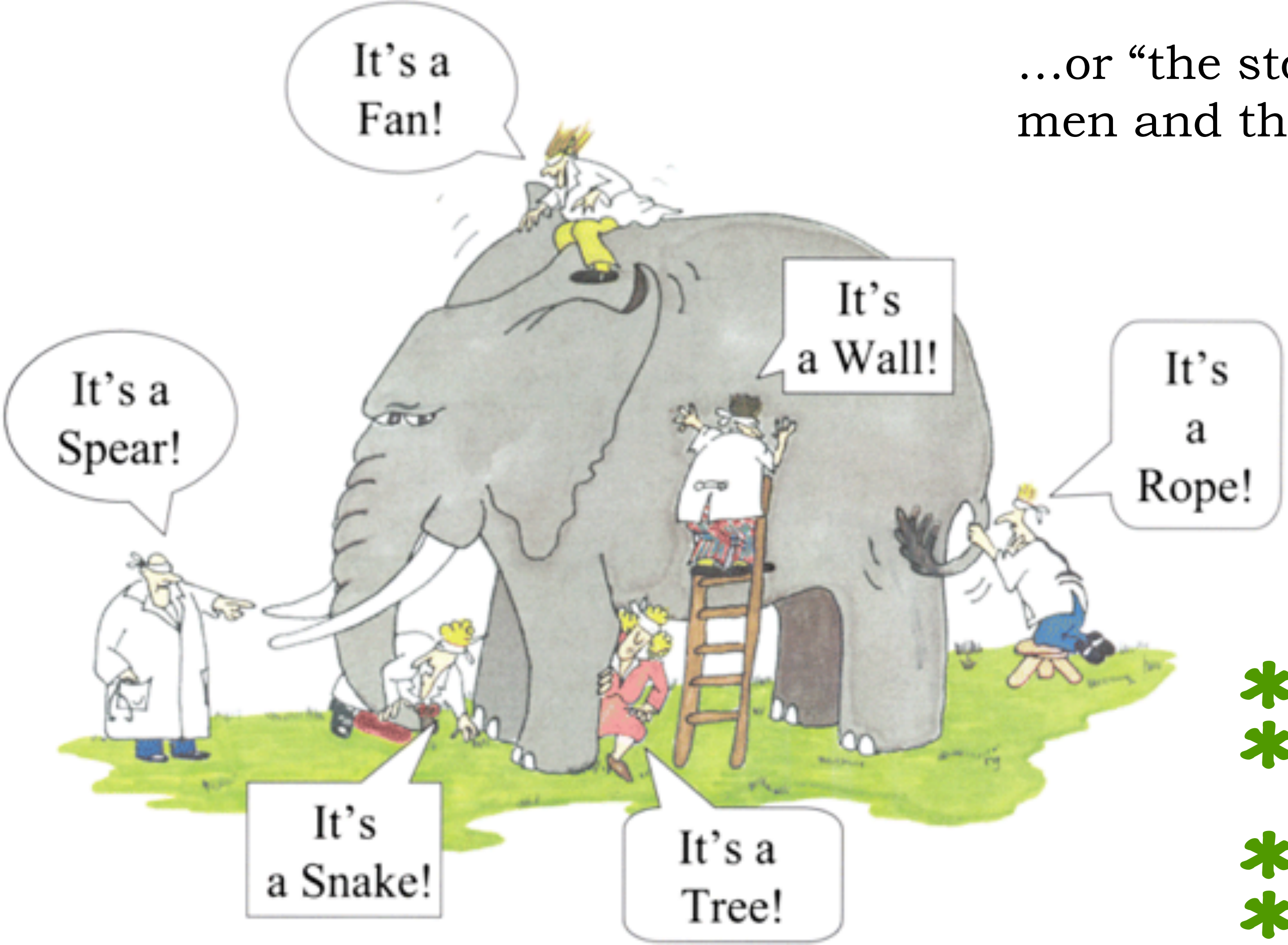
Equivalent wavelength of the probe:

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

What we would really like to know…



What we do know…

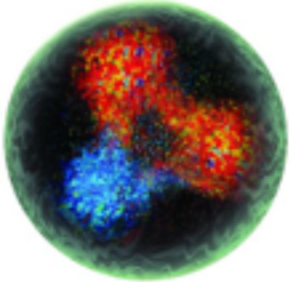


…or "the story of the blind men and the elephant"

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

G. Renee Guzlas, artist.

Different views of the nucleon: I

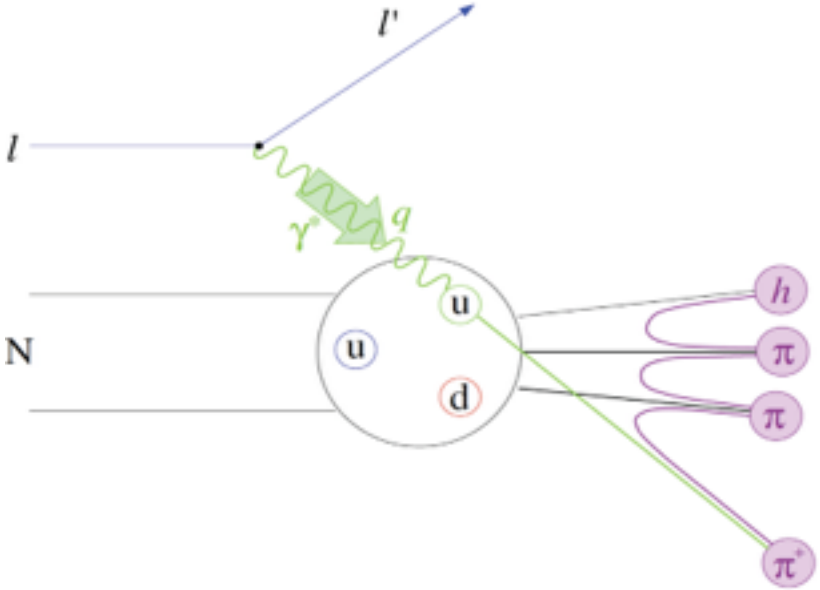


Wigner function:
full phase space parton
distribution of the nucleon

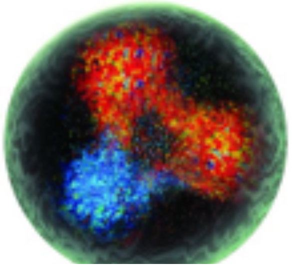
$$\int d^2 b_T$$

Transverse
Momentum
Distributions
(TMDs)

- Semi-inclusive DIS



Different views of the nucleon: II



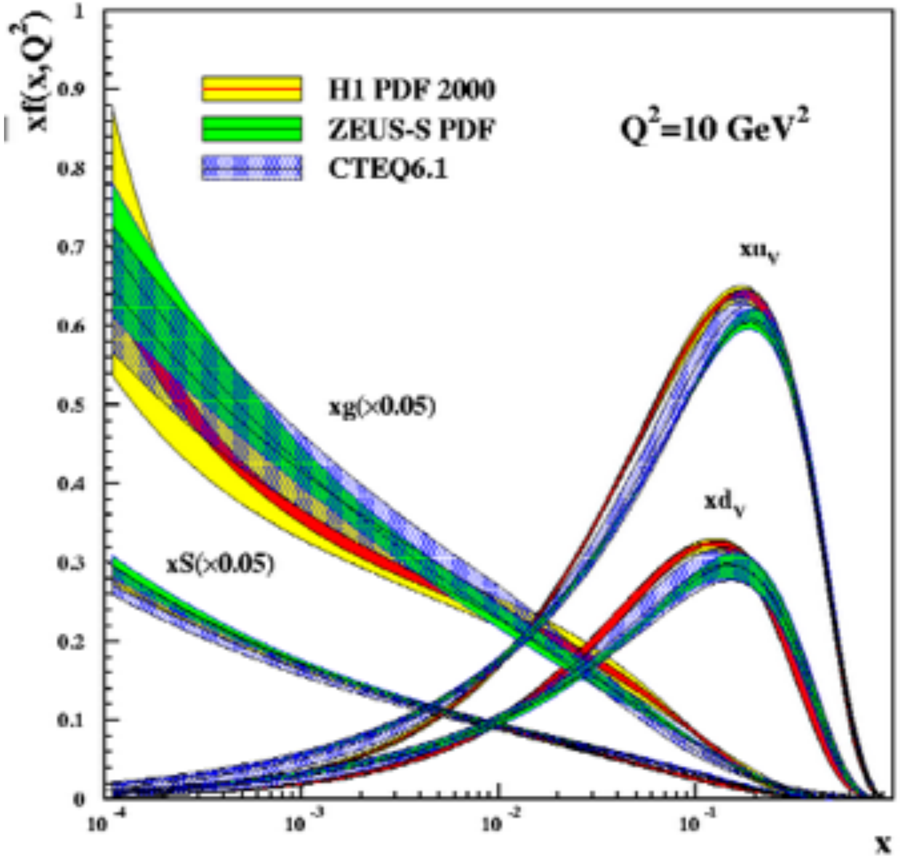
Wigner function: full phase space parton distribution of the nucleon

$$\int d^2 b_T$$

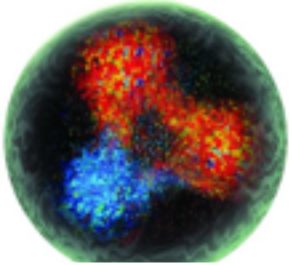
Transverse Momentum Distributions (TMDs)

$$\int d^2 k_T$$

Parton Distribution Functions (PDFs)



Different views of the nucleon: II



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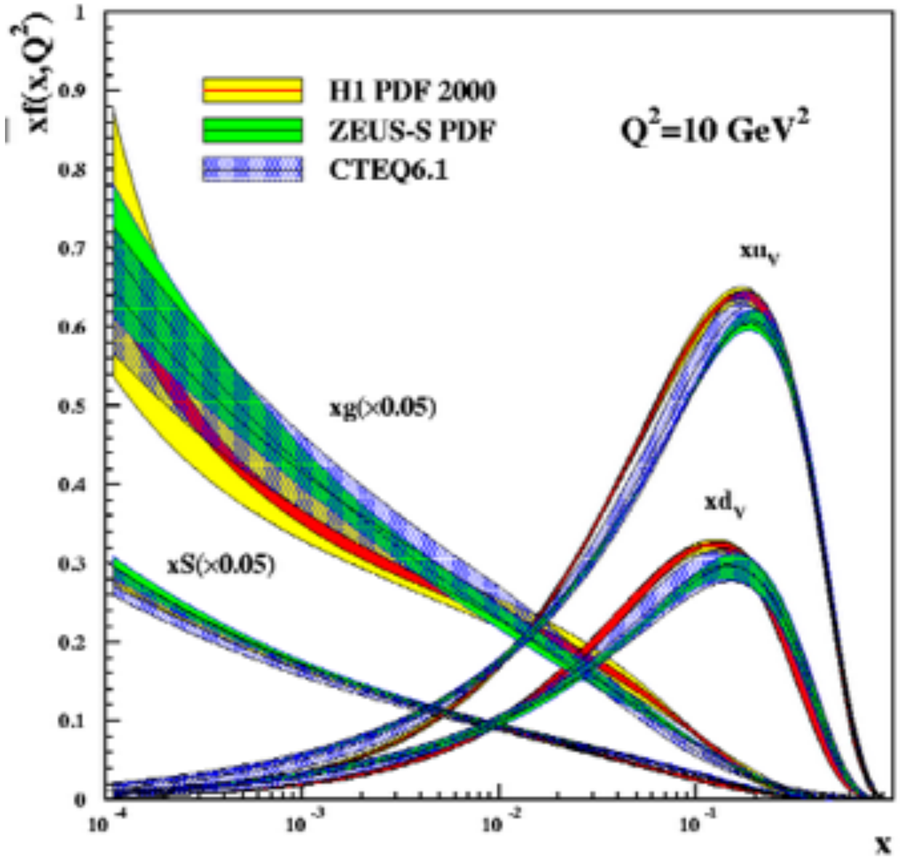
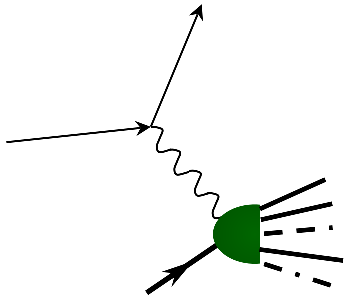
$$\int d^2 b_T$$

Transverse
Momentum
Distributions
(TMDs)

$$\int d^2 k_T$$

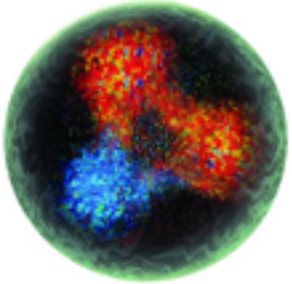


Parton Distribution
Functions (PDFs)



* Deep Inelastic
Scattering

Different views of the nucleon: III



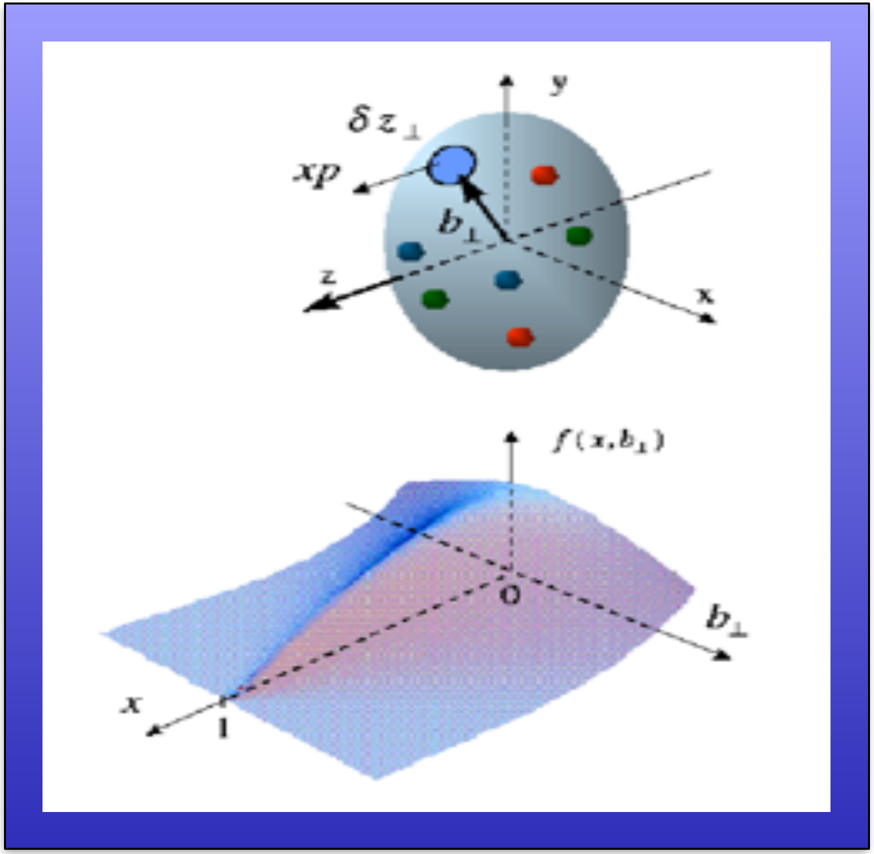
Wigner function:
full phase space parton
distribution of the nucleon

$\int d^2 k_T$

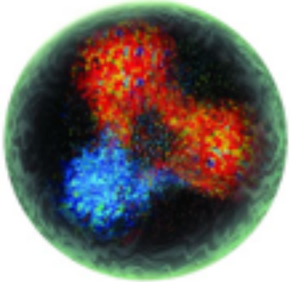
Generalised Parton Distributions (GPDs)

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

✱ Deep exclusive reactions



Different views of the nucleon: IV

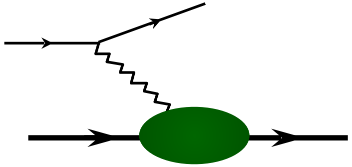


Wigner function:
full phase space parton
distribution of the nucleon

$\int d^2 k_T$

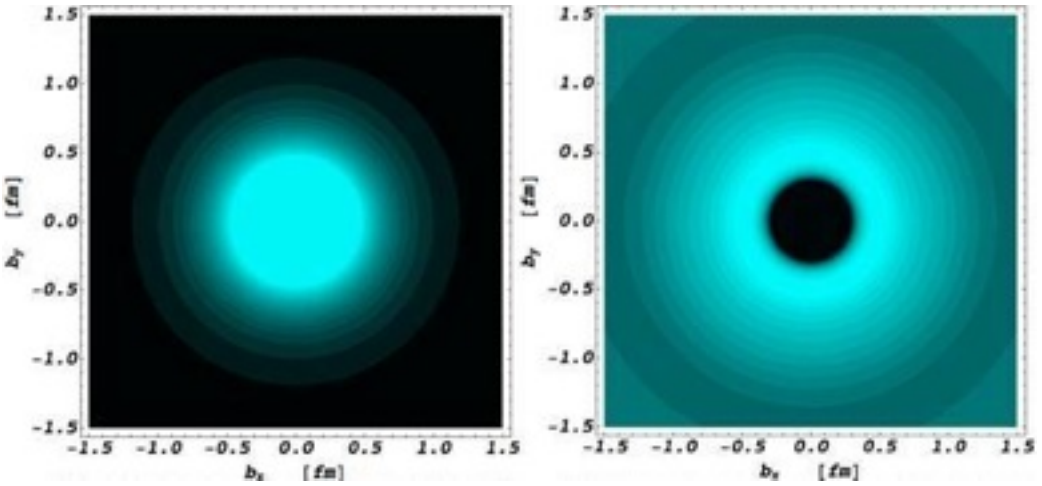
Generalised Parton
Distributions (GPDs)

$\int dx$



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)

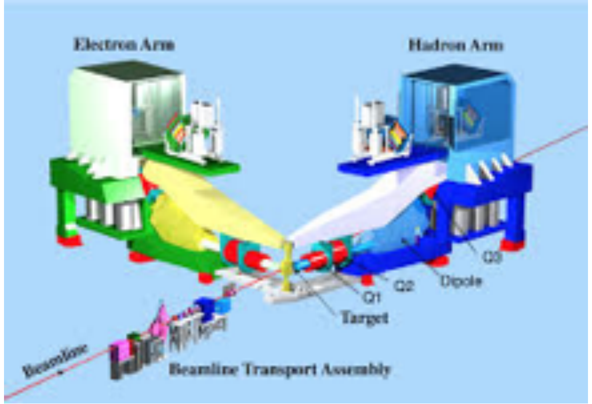
Jefferson Lab

Jefferson Lab: 6 GeV era

CEBAF: Continuous Electron Beam Accelerator Facility.

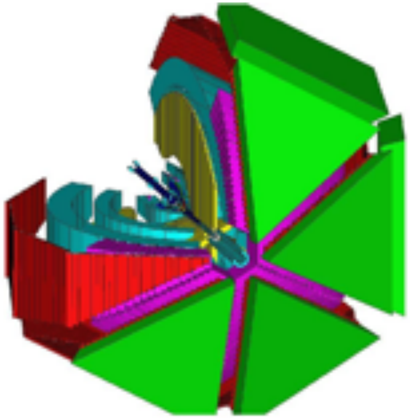
- Energy up to ~6 GeV
- Energy resolution $\delta E/E_e \sim 10^{-5}$
- Longitudinal electron polarisation up to ~85%

Hall A:



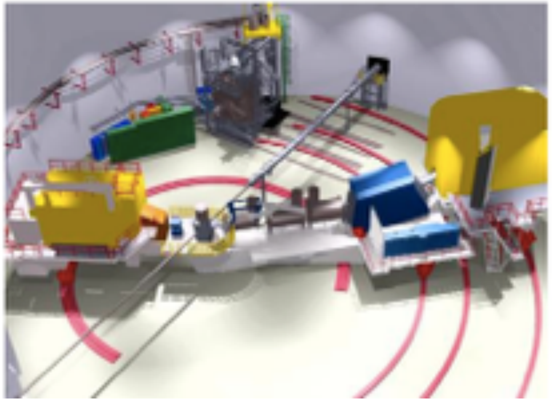
- High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity.

Hall B: CLAS



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

Hall C:



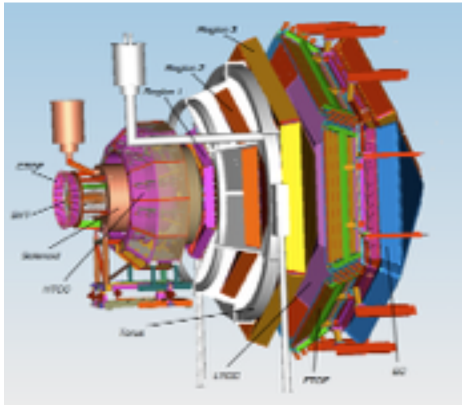
- Two movable spectrometer arms, well-defined acceptance, high luminosity

Jefferson Lab: 12 GeV era

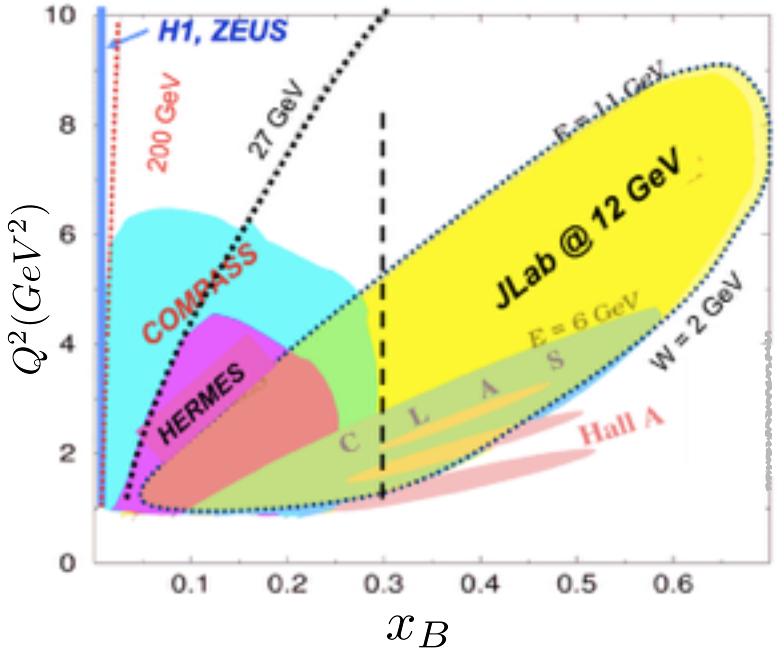
- Maximum electron energy: 12 GeV to new Hall D
- 11 GeV deliverable to Halls A, B and C

Hall A: High resolution spectrometers, large installation experiments

Hall B: CLAS12

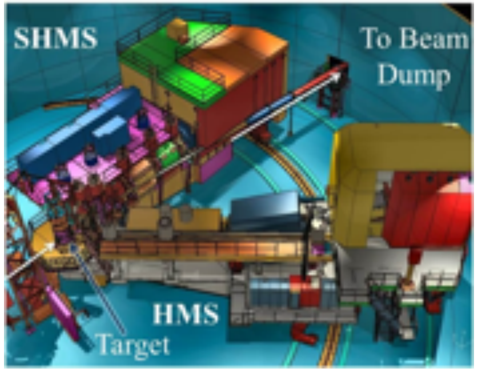


Very large acceptance, high luminosity



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

Hall C:



Super-high Momentum Spectrometer added, very high luminosity

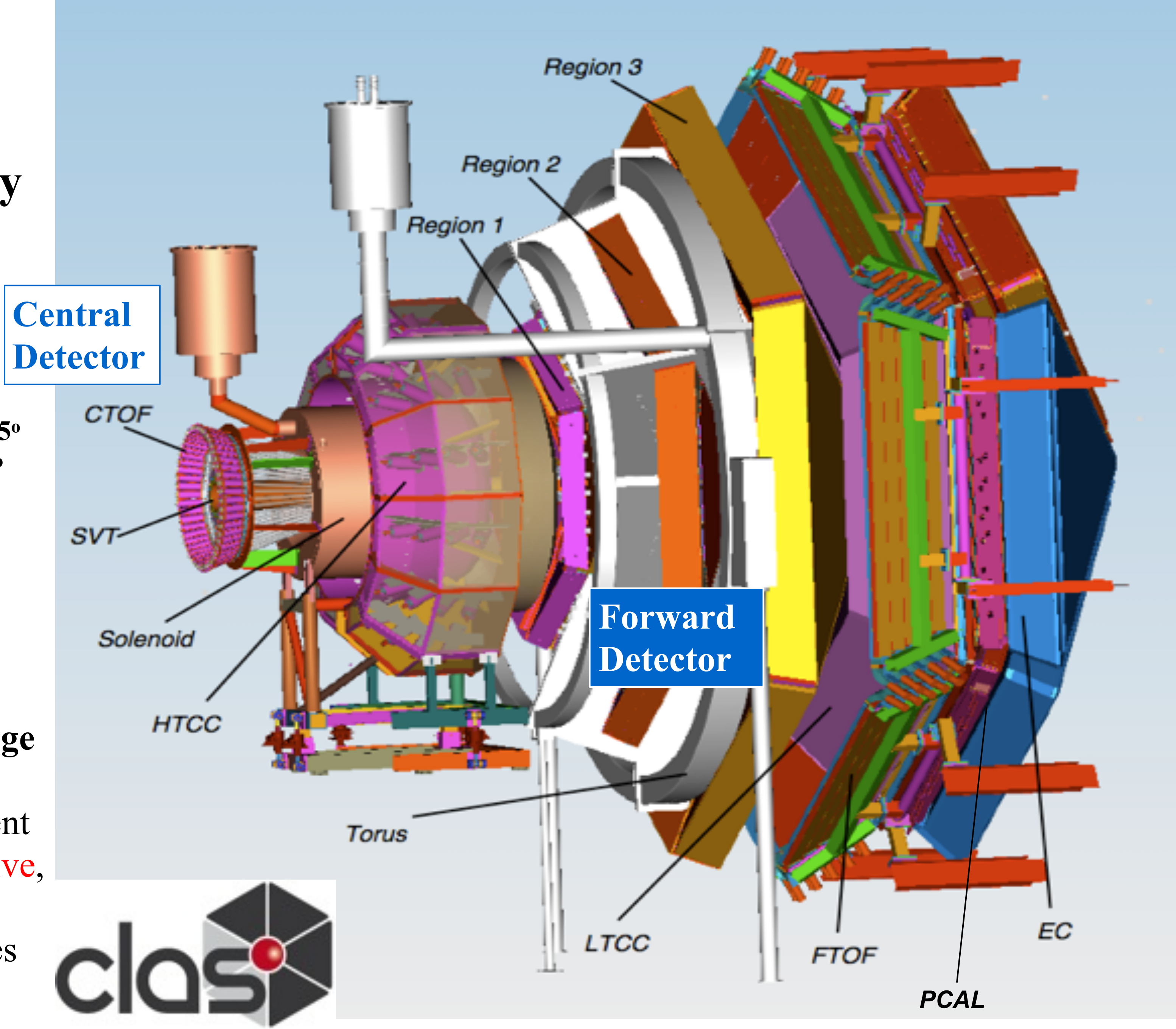
CLAS12

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

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

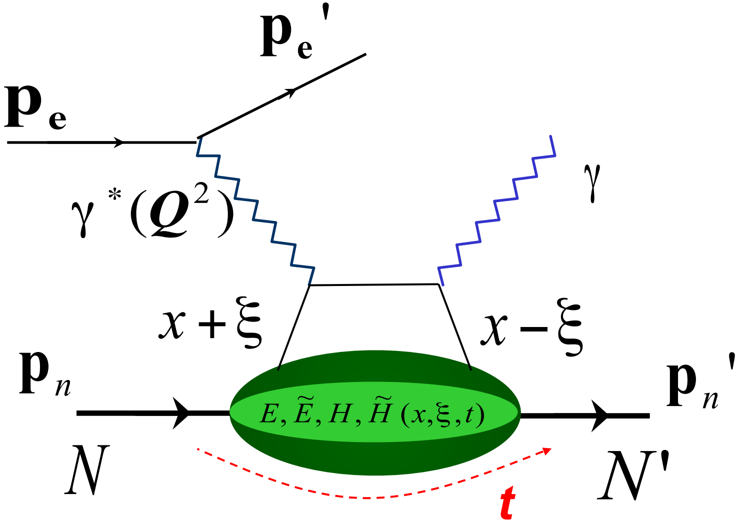
Acceptance for photons:
- **IC $2^o < \theta < 5^o$**
- **EC, $5^o < \theta < 40^o$**

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



Deeply Virtual Compton Scattering

Deeply Virtual Compton Scattering



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:

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

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

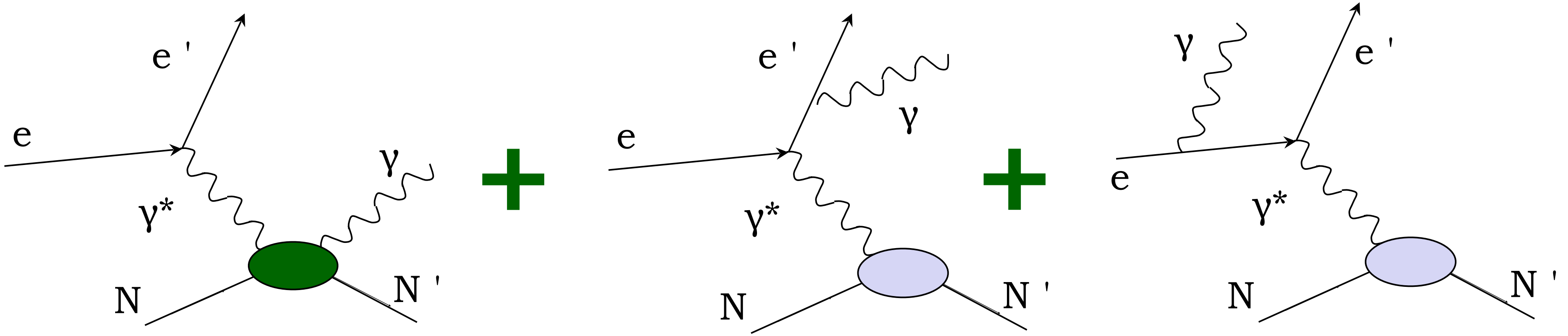
$Q^2 = -(\mathbf{p}_e - \mathbf{p}_e')^2$ $\qquad$ $t = (\mathbf{p_n} - \mathbf{p_n}')^2$

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:



DVCS

Bethe - Heitler

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

Amplitude parameterised in terms of Compton Form Factors

Amplitude calculable from elastic Form Factors and QED

Interference term

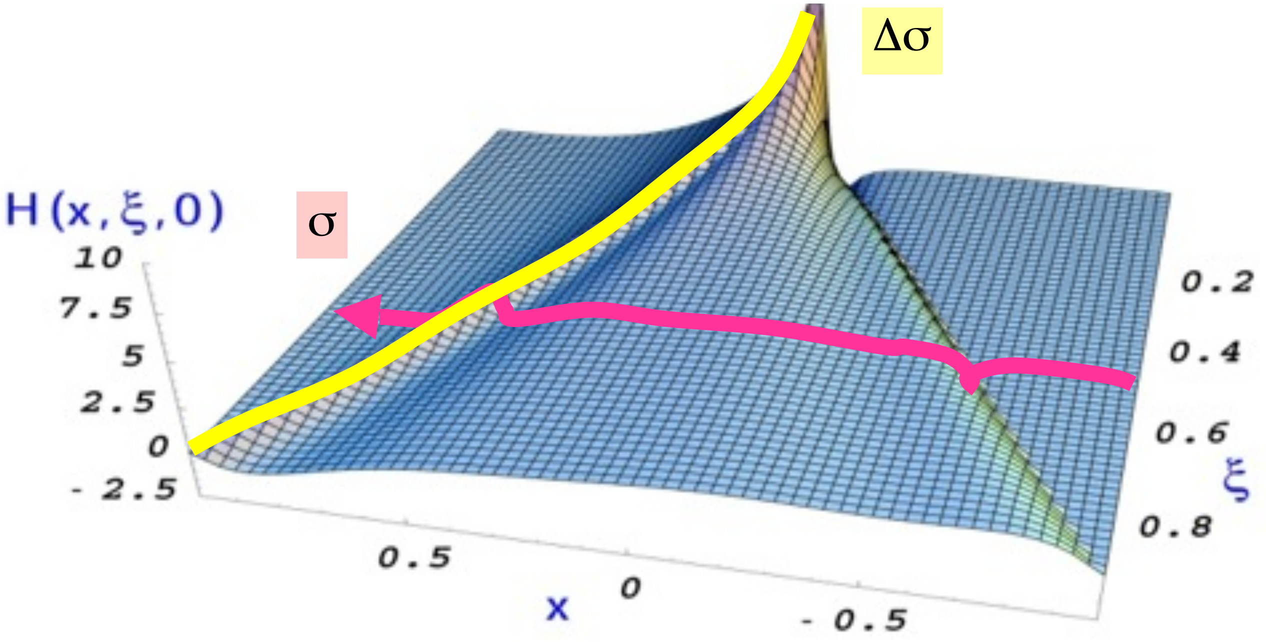
$$\left|T_{DVCS}\right|^2 << \left|T_{BH}\right|^2$$

Compton Form Factors in DVCS

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

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

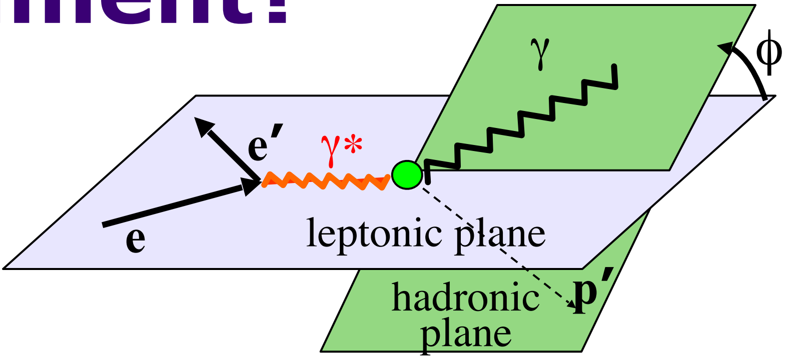
$$T^{DVCS} \sim \int_{-1}^{+1} \frac{GPDs\,(x,\xi,t)}{x \pm \xi + i\varepsilon}\,dx + \ldots \sim \quad P\int_{-1}^{+1} \boxed{\frac{GPDs\,(x,\xi,t)}{x \pm \xi}\,dx} \pm i\pi \boxed{GPDs\,(\pm\xi,\xi,t) +} \ldots$$



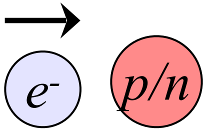
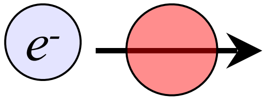
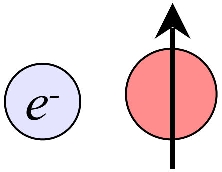
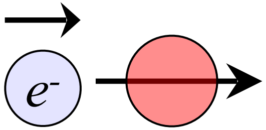
Only ξ and *t*
are accessible
experimentally!

Which DVCS experiment?

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



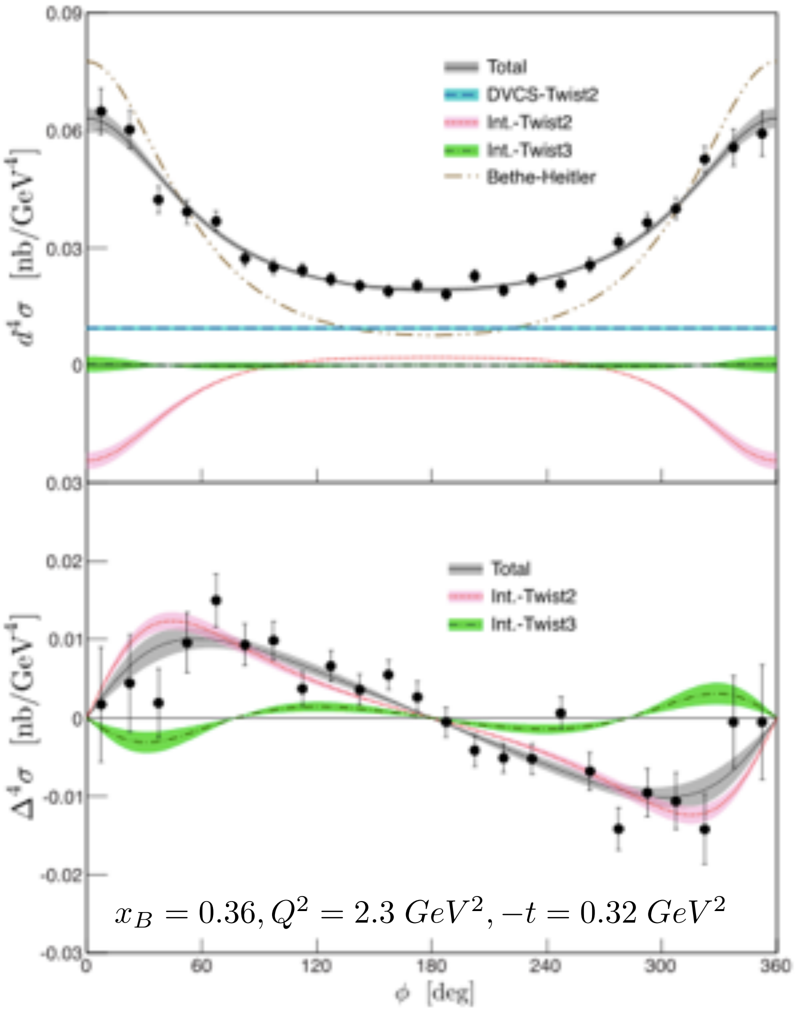
$\xi = x_B/(2-x_B) \quad k = t/4M^2$

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

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

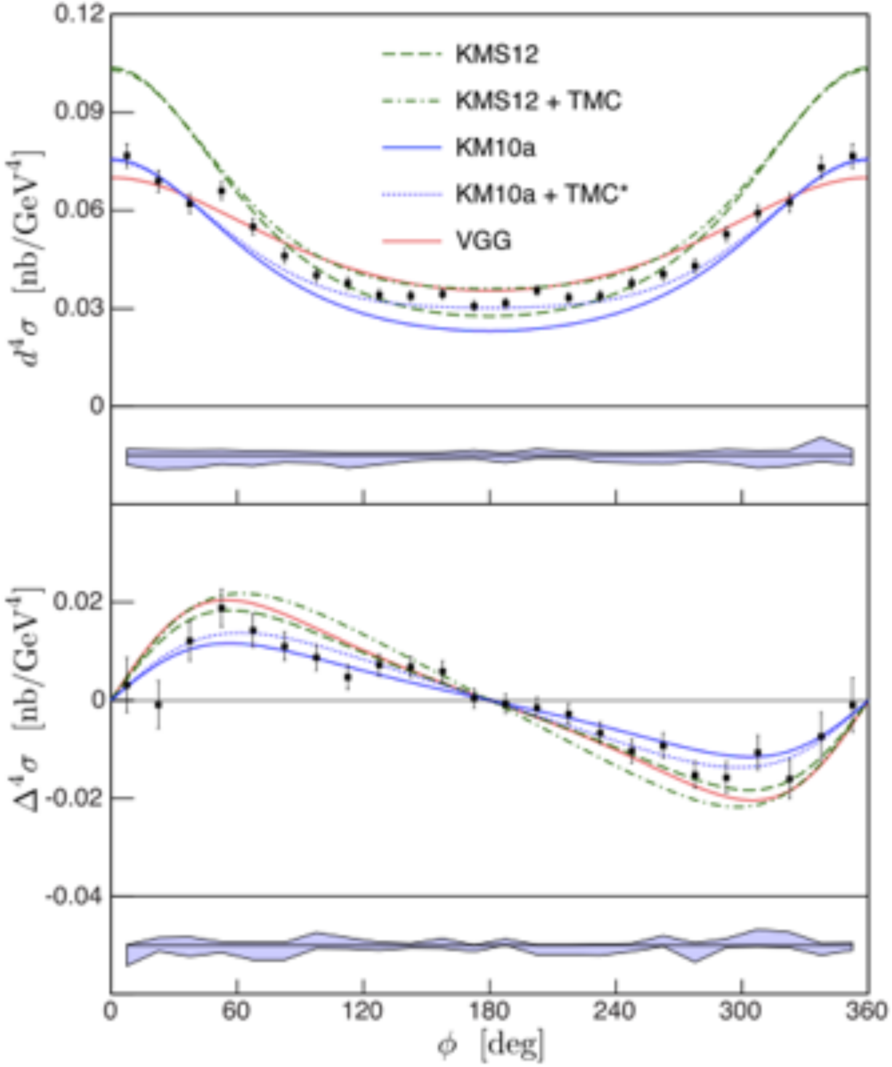
- Extraction of $\left|T_{DVCS}\right|^2$ amplitude as well as interference terms.

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

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

Hall A

First DVCS cross-sections in valence region



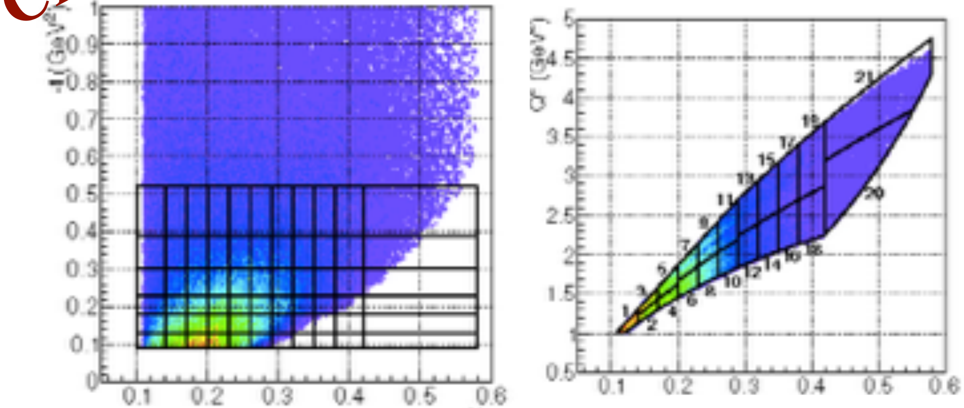
$x_B = 0.36, Q^2 = 1.9\ GeV^2, -t = 0.32\ GeV^2$

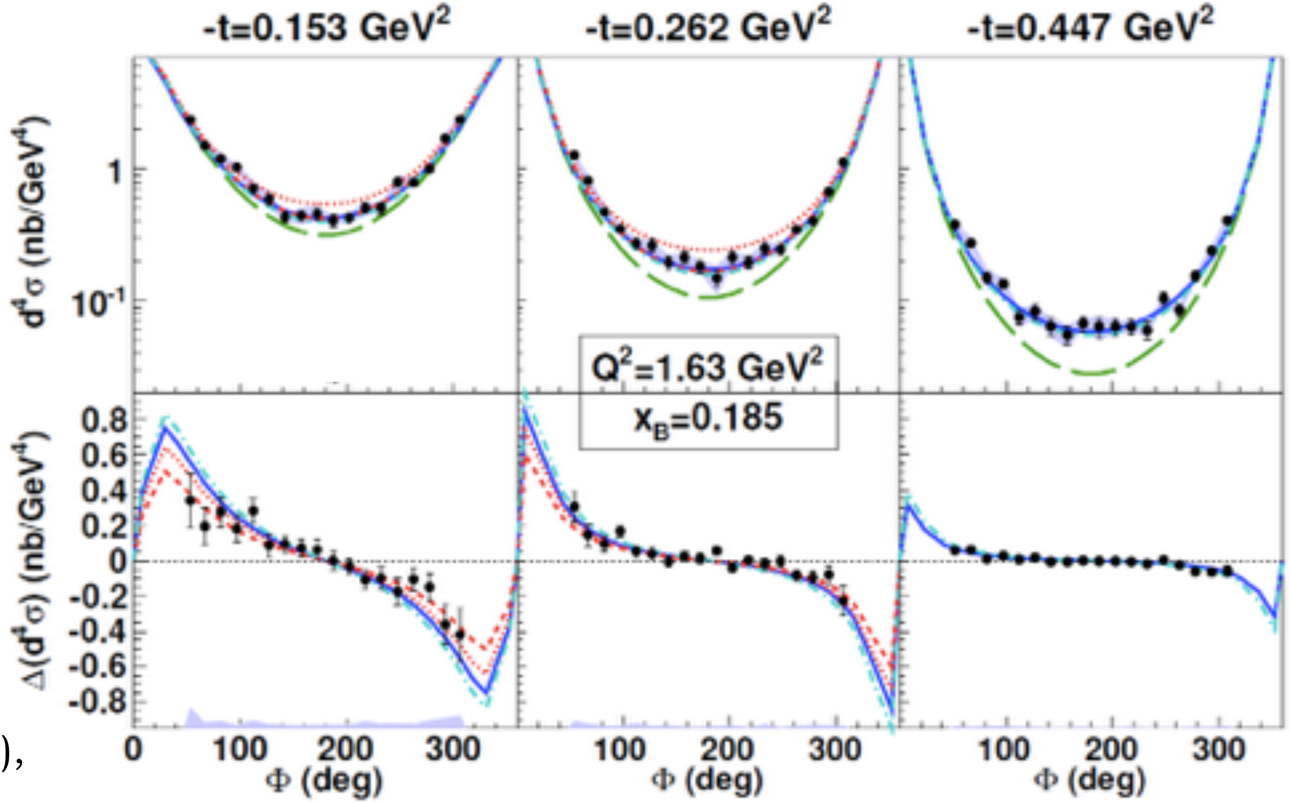
- KMS parameters tuned on very low x_B meson-production data
- Target-mass and finite-t corrections (TMC) improve agreement for KM10a model

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





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

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

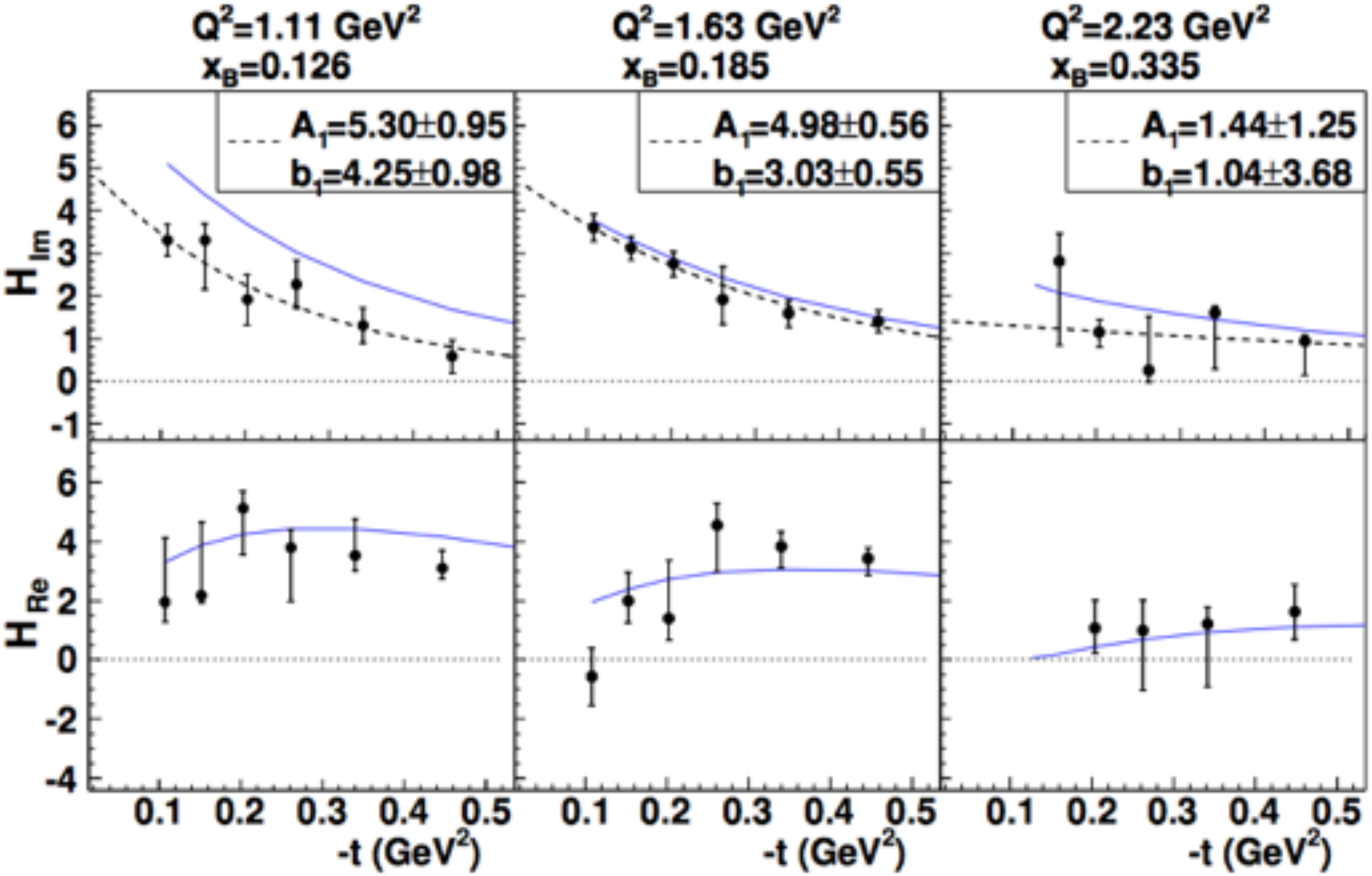
H.-S. Jo *et al* (CLAS Collaboration),
***PRL* 115** (2015) 212003

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.

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

CLAS

Beam-spin Asymmetry (A_{LU})

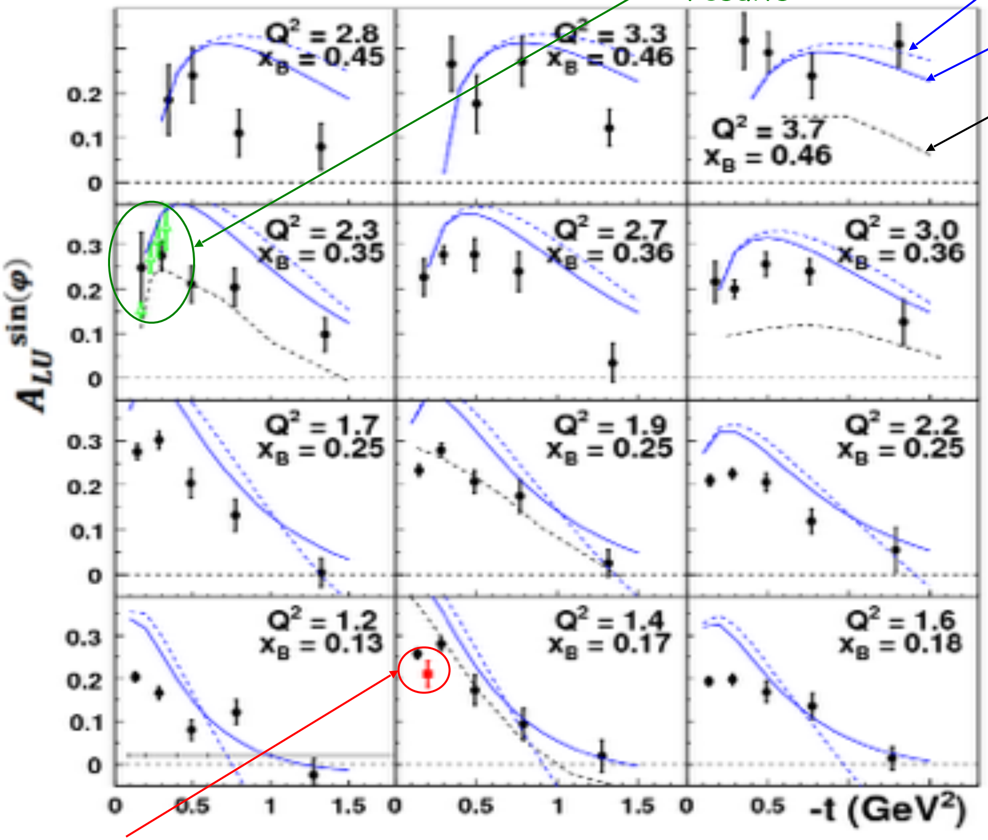
$\overrightarrow{e^-}$ p

JLab Hall A results

VGG twist-3

VGG twist-2

Regge (JML)



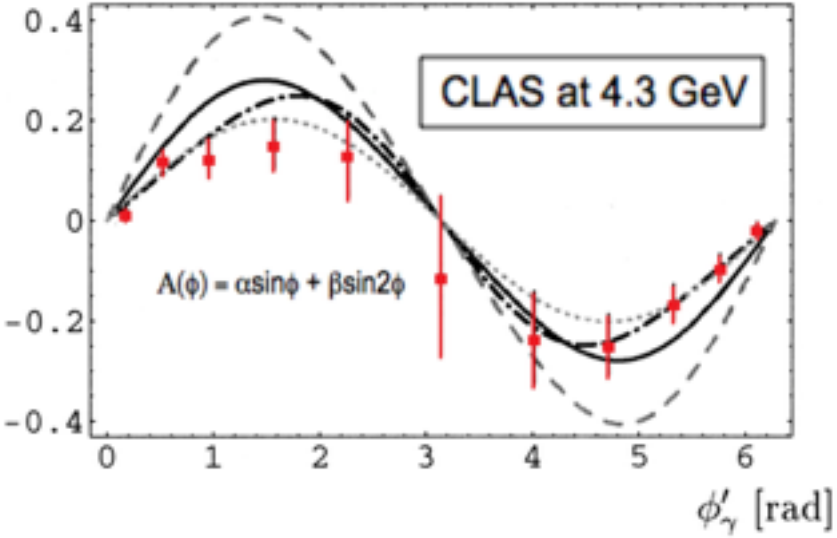
Previous CLAS results

VGG model: Vanderhaeghen, Guichon, Guidal

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

A_{LU} from fit to asymmetry:

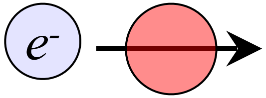
$$A_i = \frac{\alpha_i \sin\phi}{1 + \beta_i \cos\phi}$$



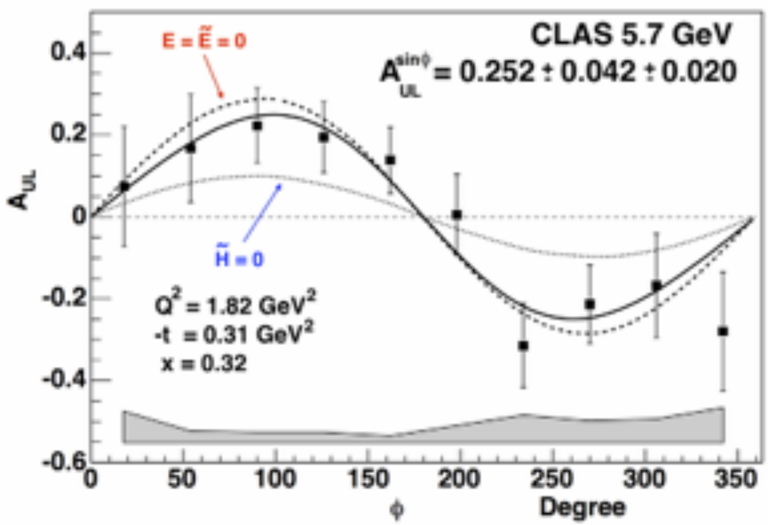
S. Stepanyan *et al* (CLAS Collaboration), ***PRL* 87** (2001) 182002

CLAS

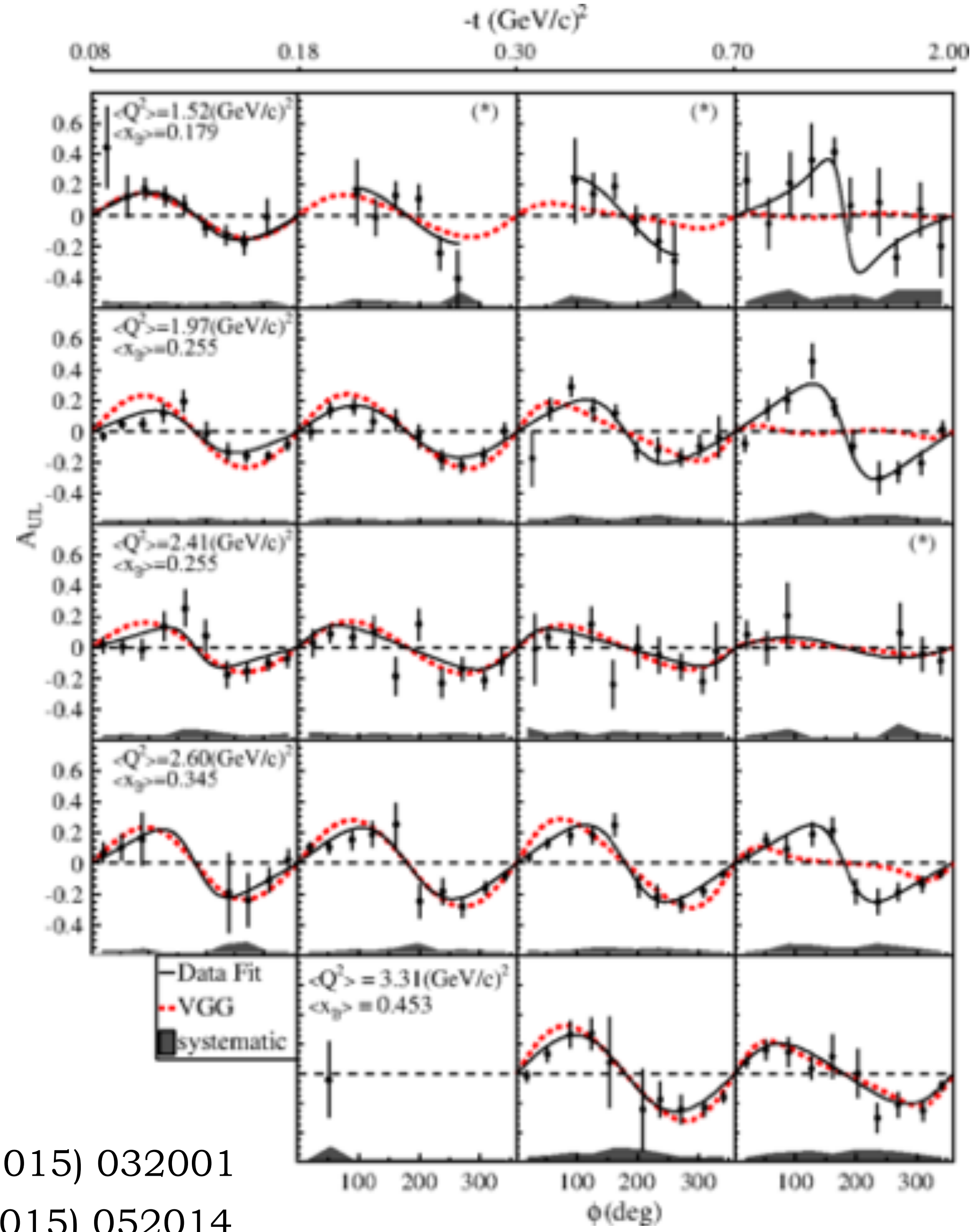
Target-spin Asymmetry (A_{UL})



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



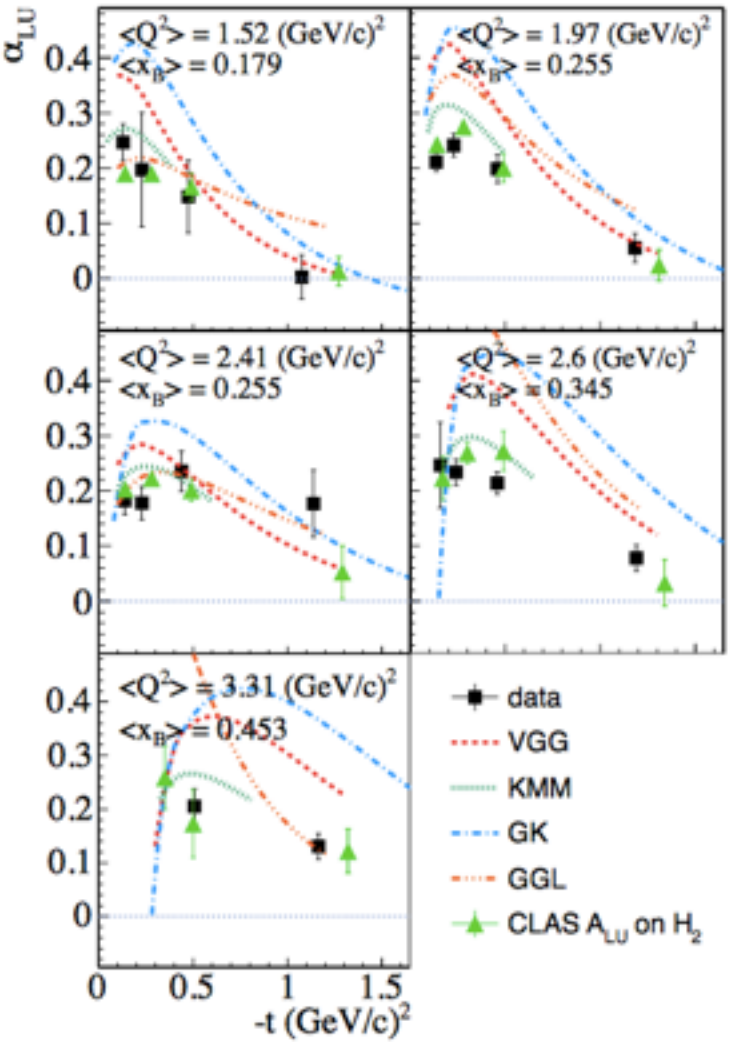
S. Chen *et al* (CLAS Collaboration), ***PRL* 97** (2006) 072002

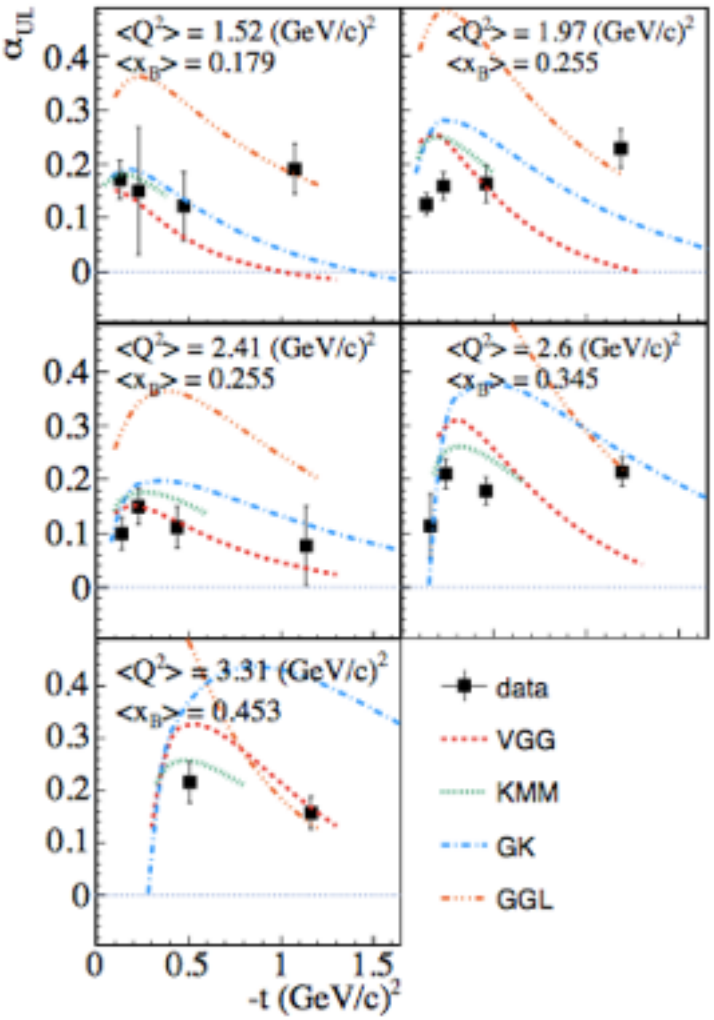


E. Seder *et al* (CLAS Collaboration), ***PRL* 114** (2015) 032001

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

Beam and target-spin asymmetries





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

GGL: Goldstein, Gonzalez, Liuti

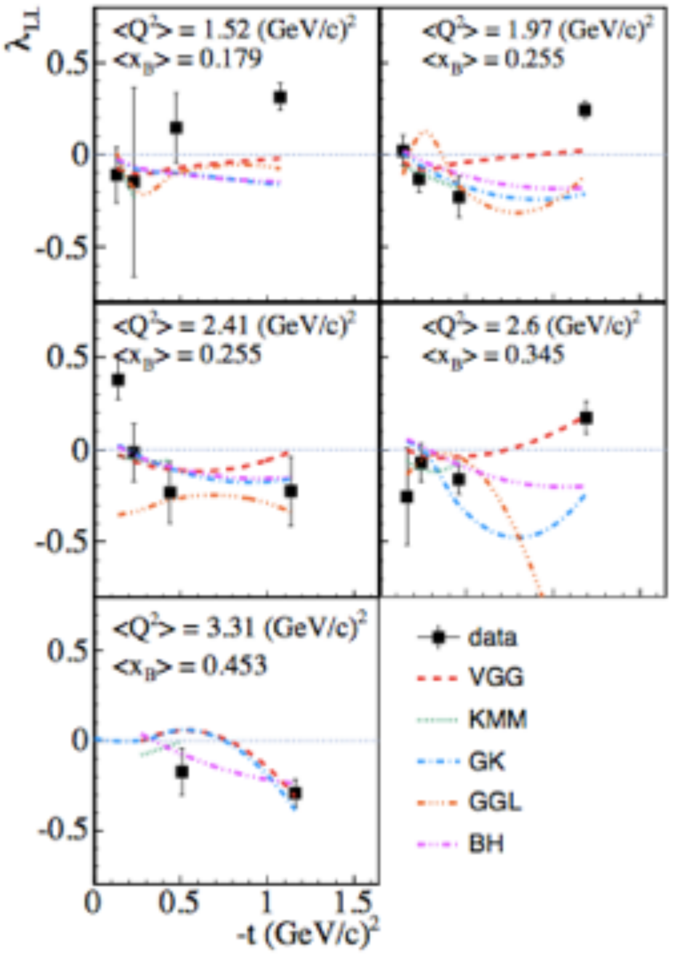
GK: Kroll, Moutarde, Sabatié

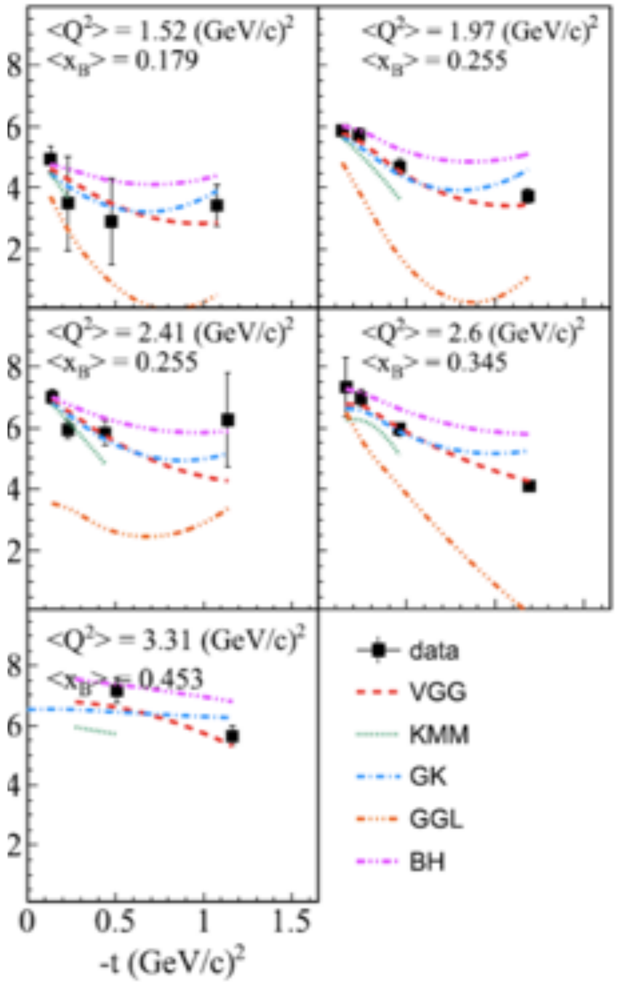
KMM: Kumericki, Mueller, Murray

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})





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

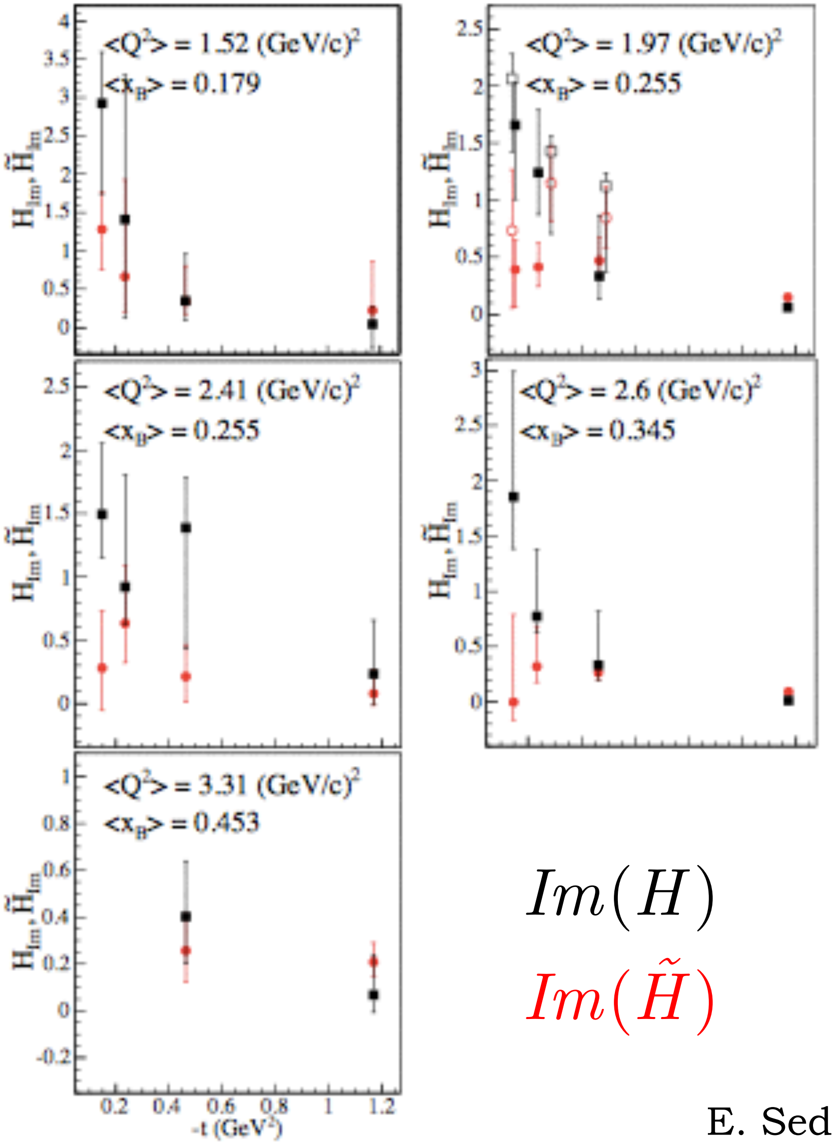
- Fit parameters extracted from a simultaneous fit to BSA, TSA and DSA.
- CFF extraction from three spin asymmetries at common kinematics.

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

Asymmetries in Proton-DVCS with CLAS12

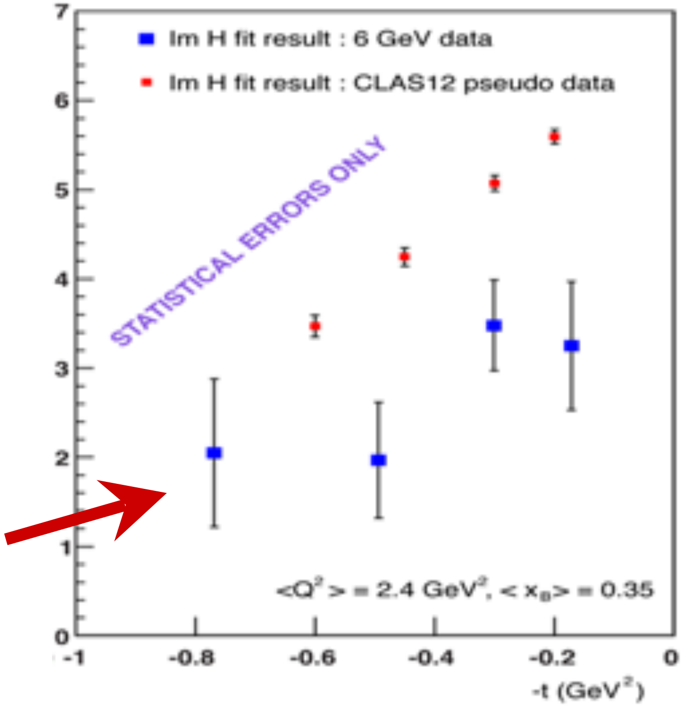
Approved experiment (E12-06-119):

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)**

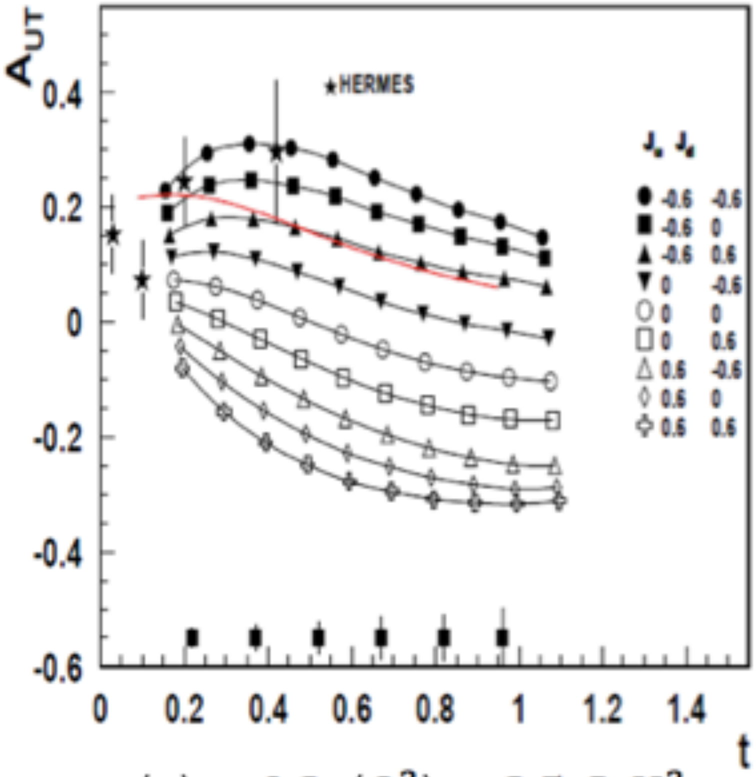


DVCS with transversely polarised target at CLAS12

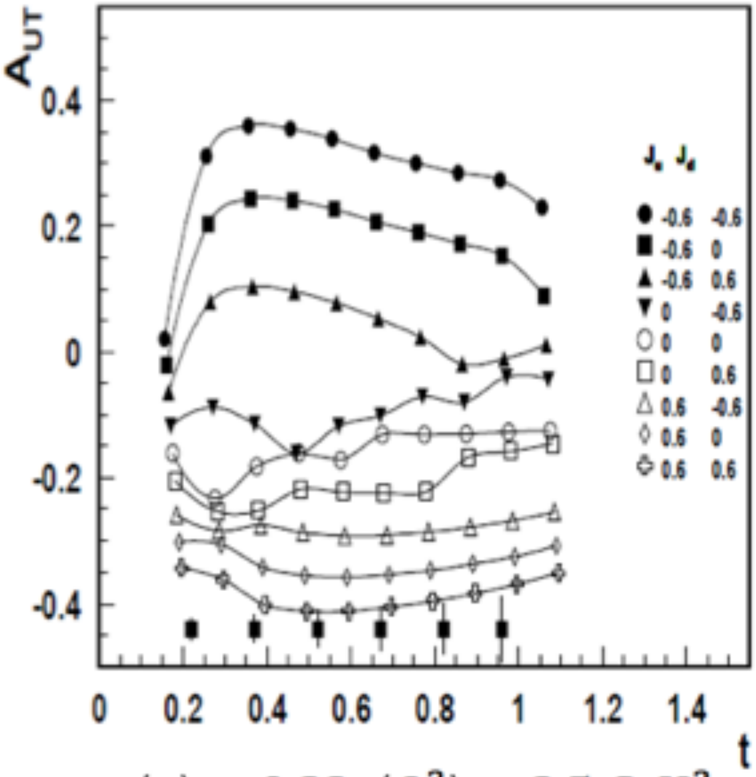
E12-12-010: transversely polarised HD target.

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

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



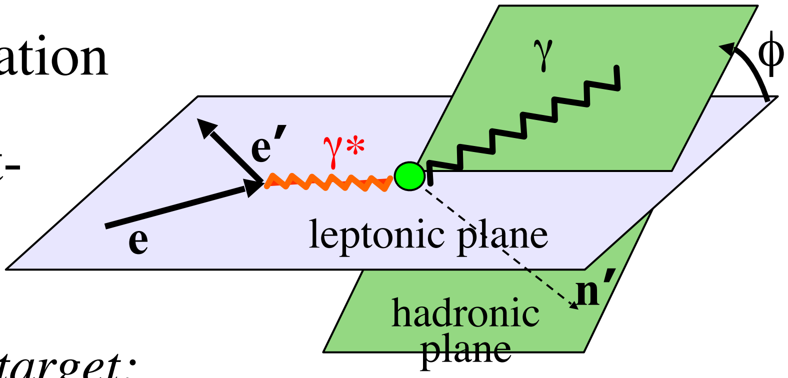
$\langle x\rangle = 0.2$, $\langle Q^2\rangle = 2.5\ GeV^2$

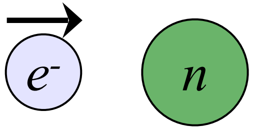


$\langle x\rangle = 0.33$, $\langle Q^2\rangle = 2.5\ GeV^2$

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:

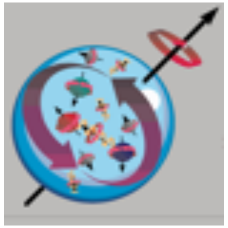
$$\Delta\sigma_{LU} \sim \sin\phi\ \mathbf{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} - kF_2 E\}d\phi \longrightarrow \mathbf{Im}\ \{E_n\}$$ dominates.

- Ji's relation:

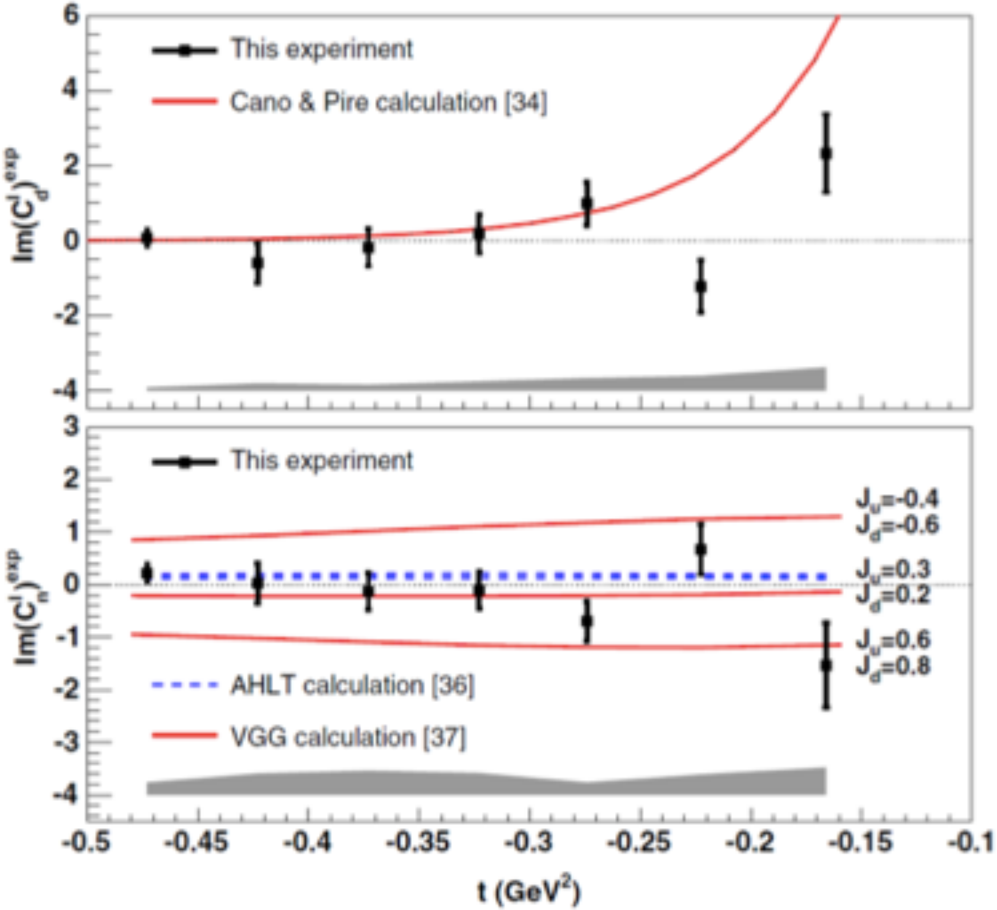
$$J^q = \frac{1}{2} - J^g = \frac{1}{2}\int_{-1}^{1} x dx \left\{H^q(x,\xi,0) + E^q(x,\xi,0)\right\}$$

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

Important missing link in the nucleon spin puzzle…

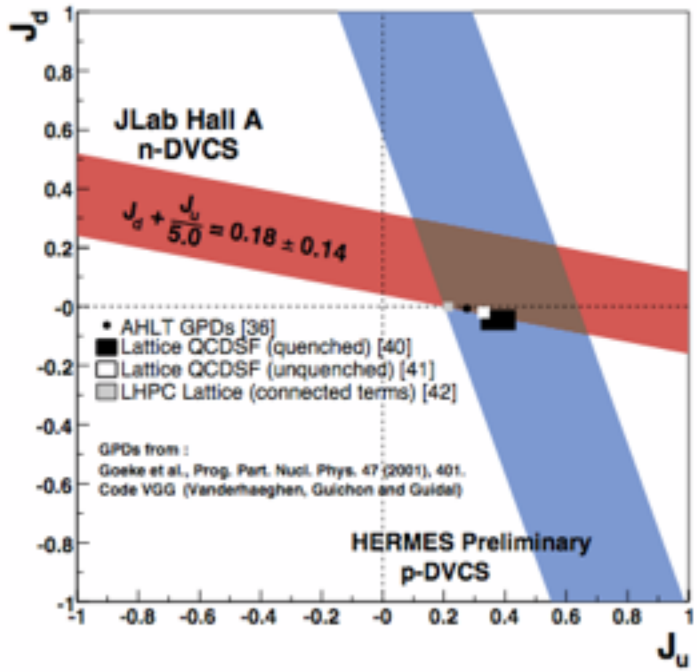


Beam-spin asymmetry in neutron DVCS



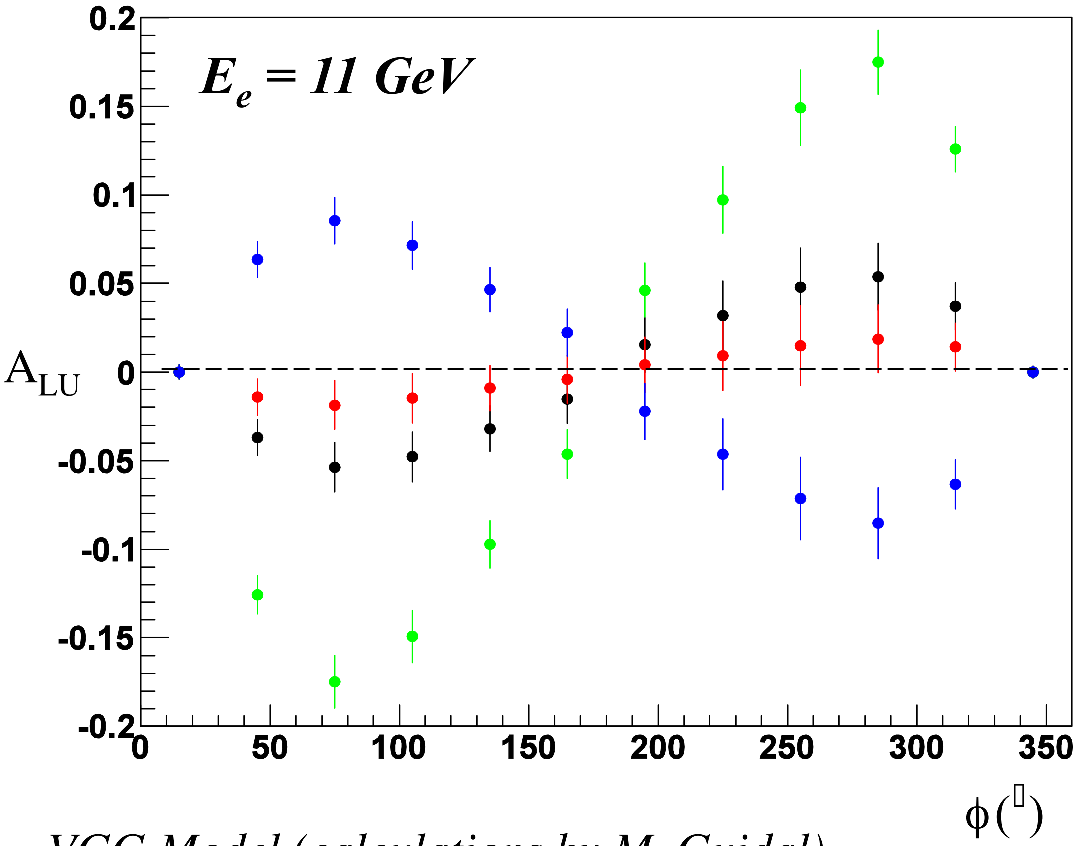
M. Mazouz et al, PRL **99** (2007) 242501

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



- Analysis underway on CLAS data.

A_{LU} in Neutron DVCS @ 11 GeV



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

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

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

VGG Model (calculations by M. Guidal)

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

A_{LU} in Neutron DVCS with CLAS12

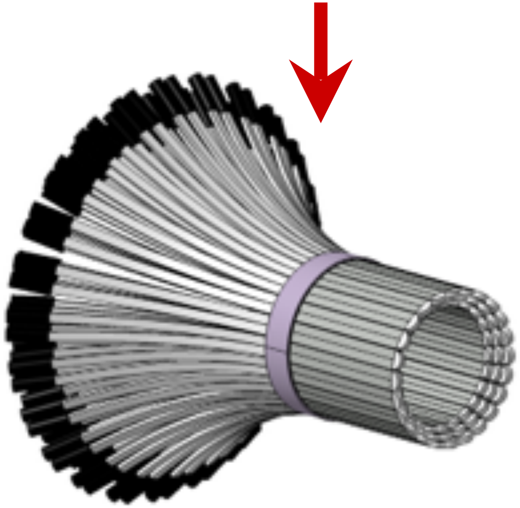
The **most sensitive** observable to the GPD **E_n**

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

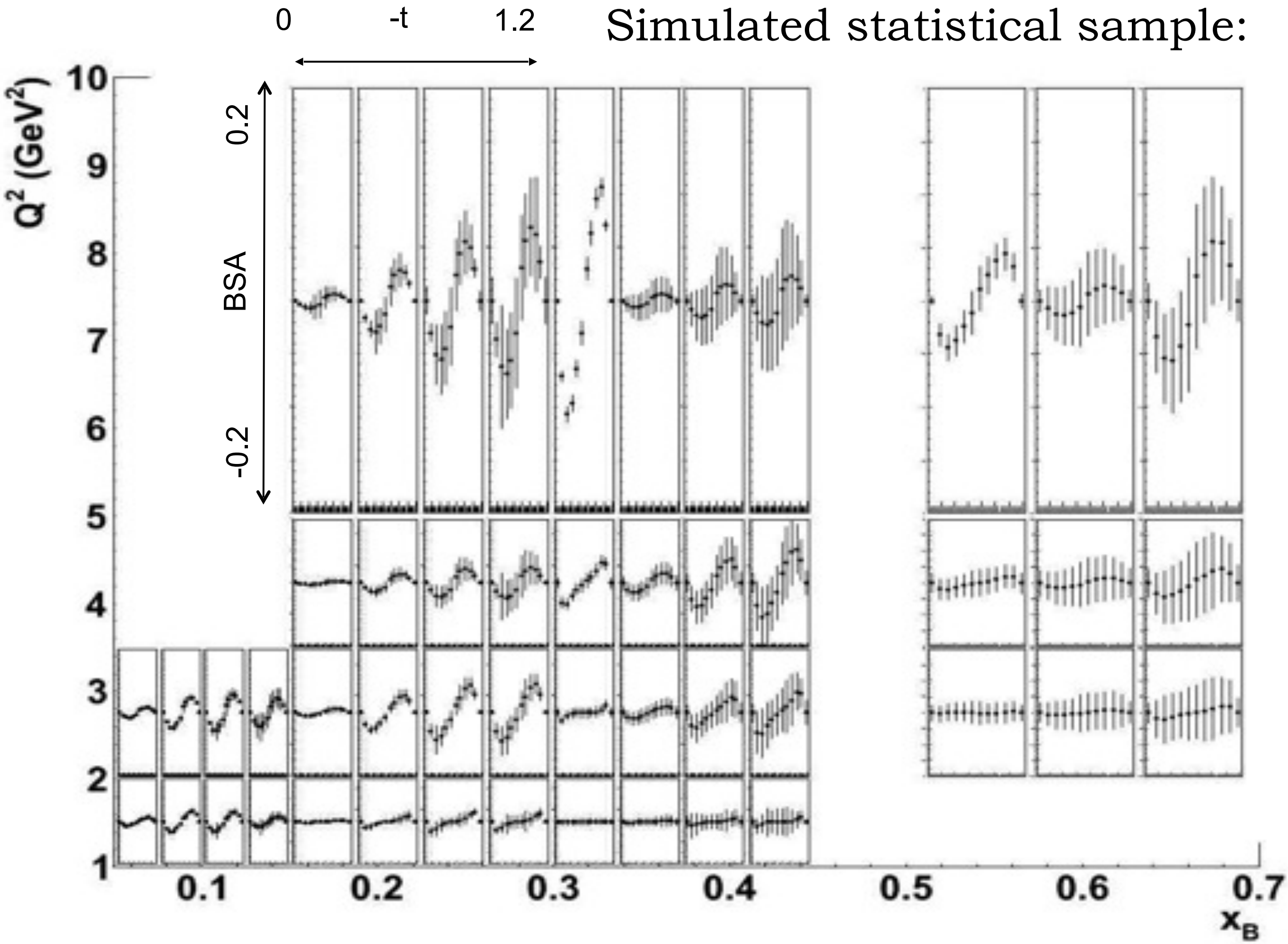
80 days of data taking

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

CLAS12 +
Forward Calorimeter
+
Neutron Detector



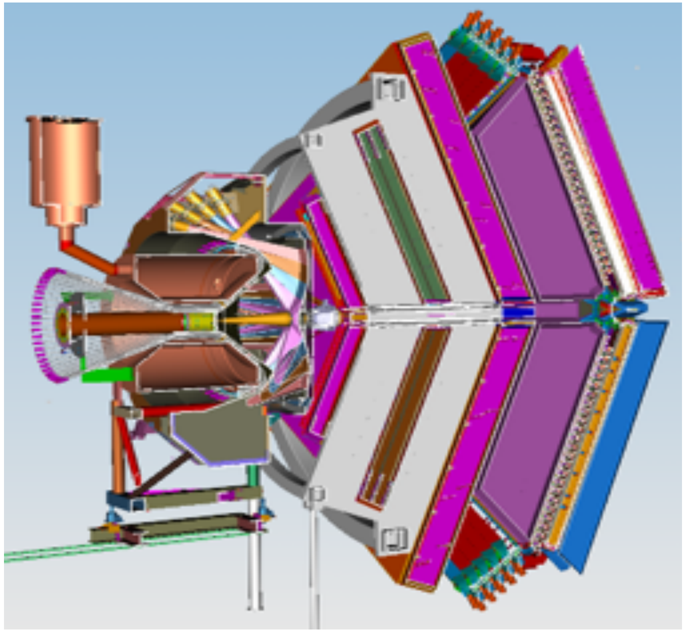
Simulated statistical sample:

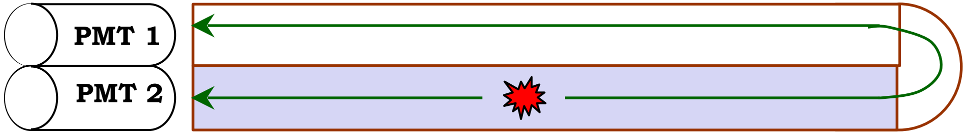


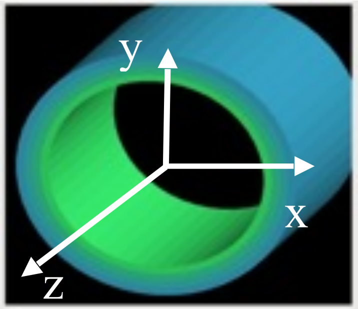
Neutron Detector for CLAS12

Available:

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



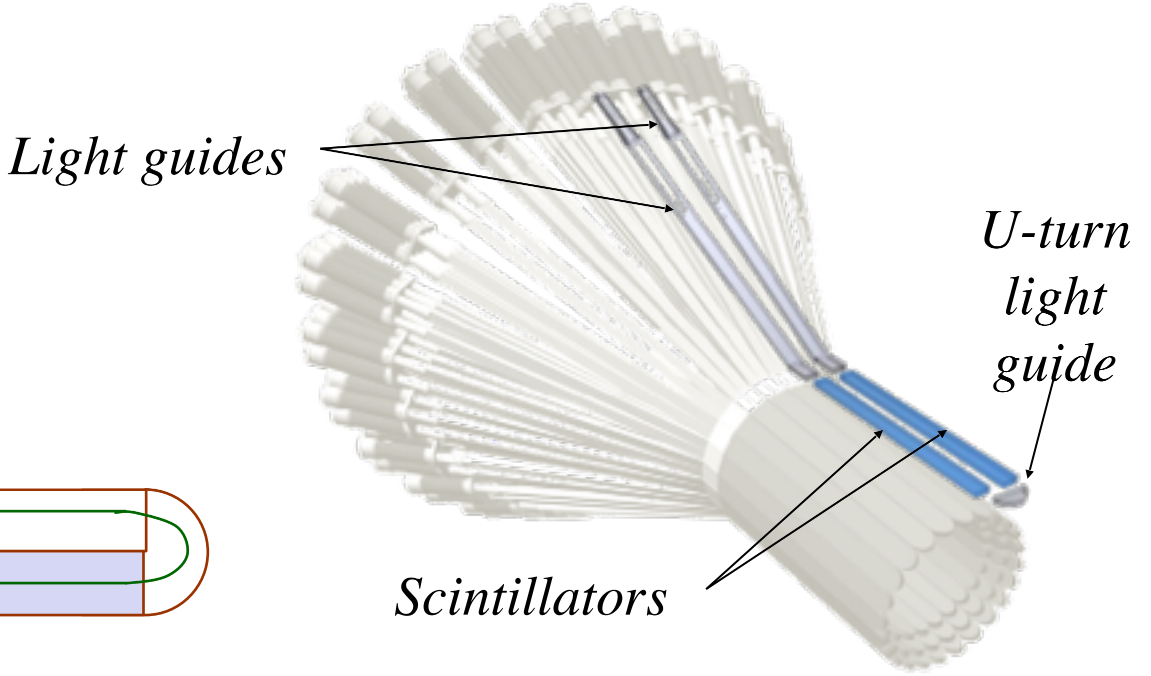




Detector design

- Plastic scintillator barrel:

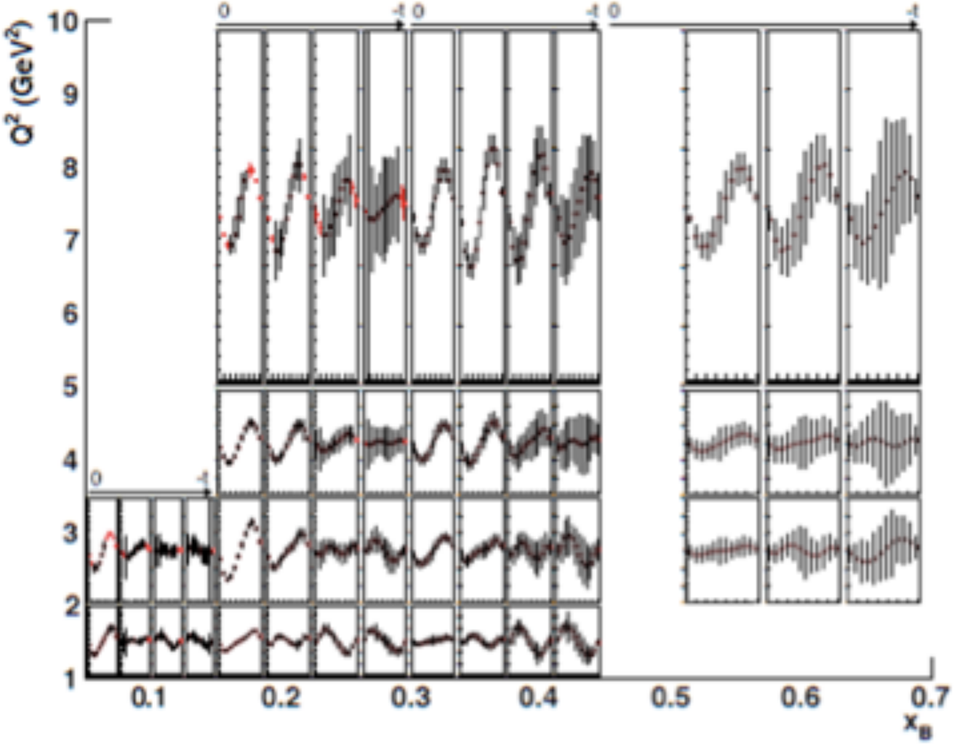
  3 layers, 48 paddles in each
- Length ~ 70 cm, inner radius 28.5 cm
- Long (~ 1.5 m) light-guides
- PMT read-out upstream, out of high B field



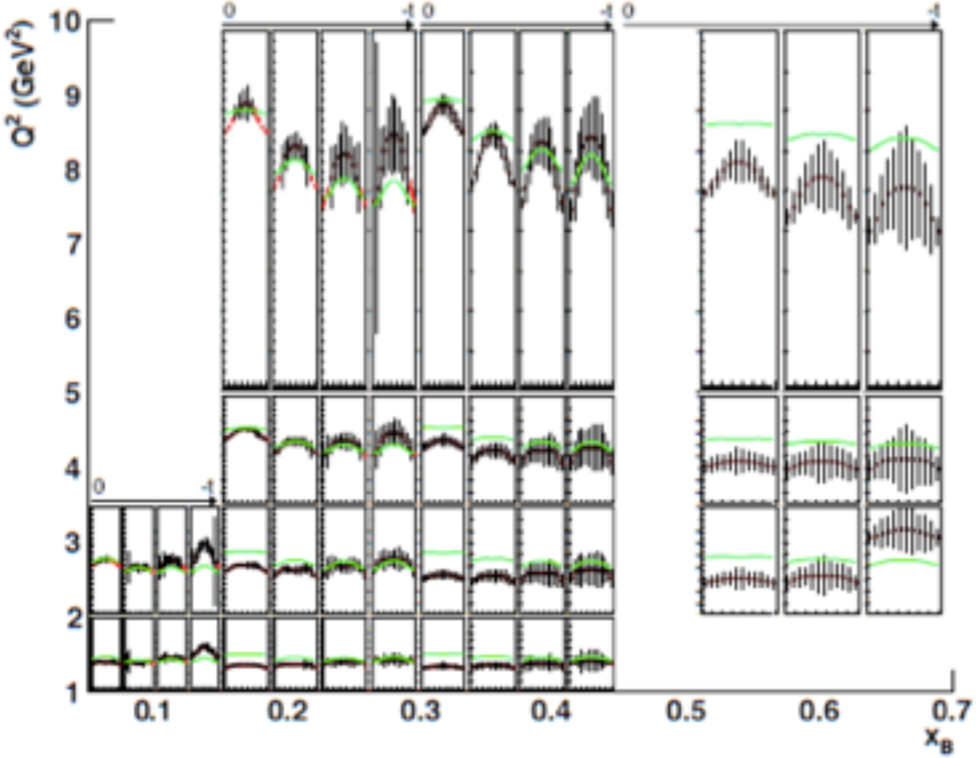
DVCS on the neutron with a longitudinally polarised deuterium target

Expected statistics for requested 100 days of beam-time:

$A_{UL}{}^{n}$

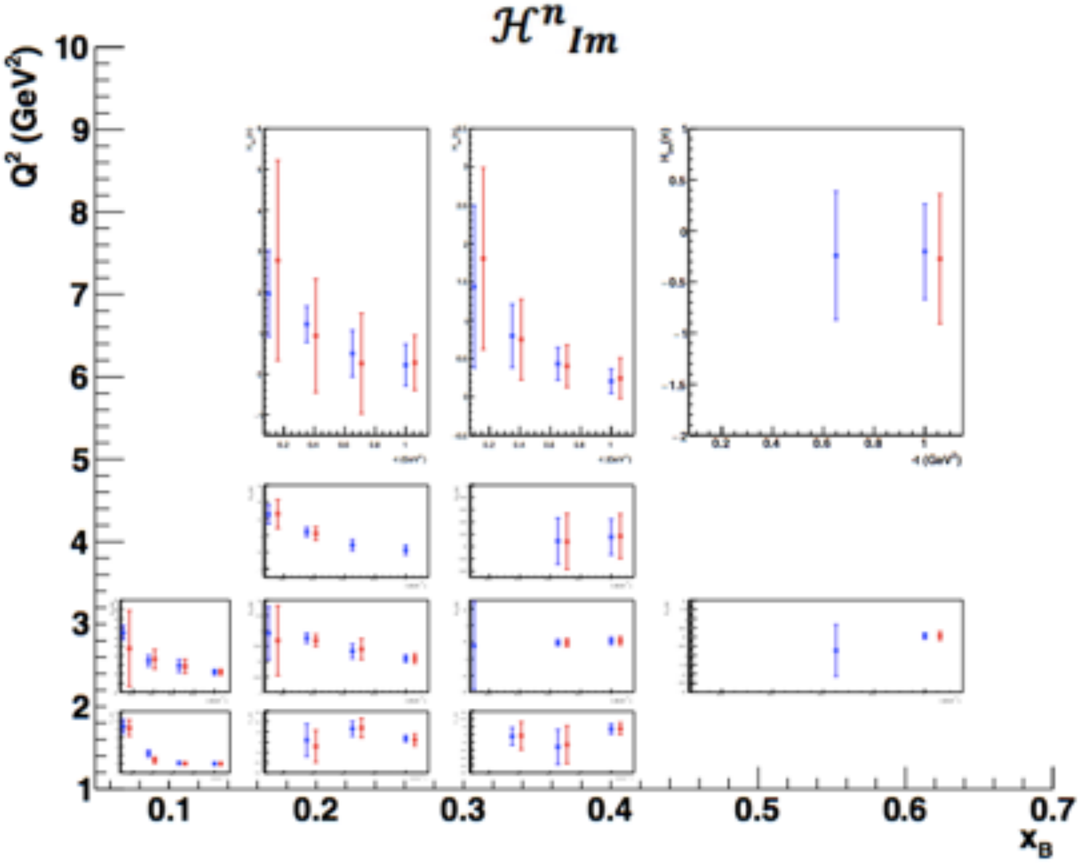


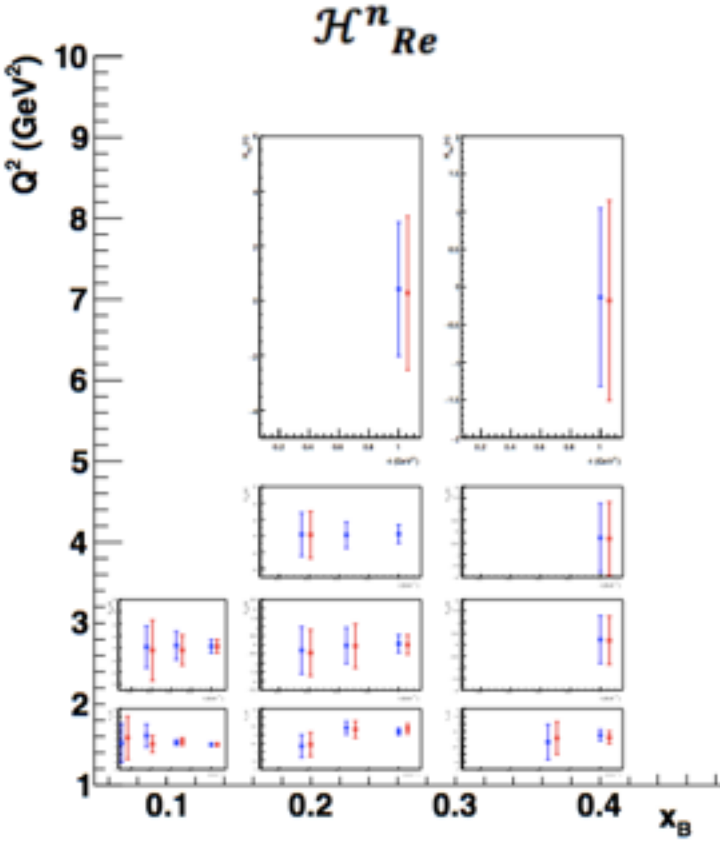
$A_{LL}{}^{n}$



DVCS on the neutron with a longitudinally polarised deuterium target

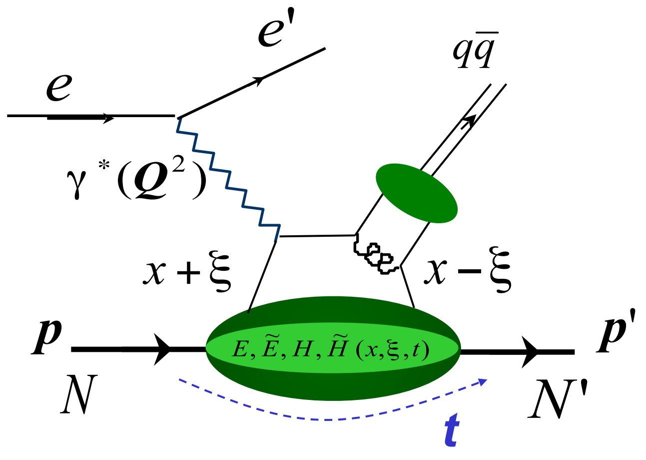
Expected sensitivities:





GPDs through other channels

Deeply Virtual Meson Production



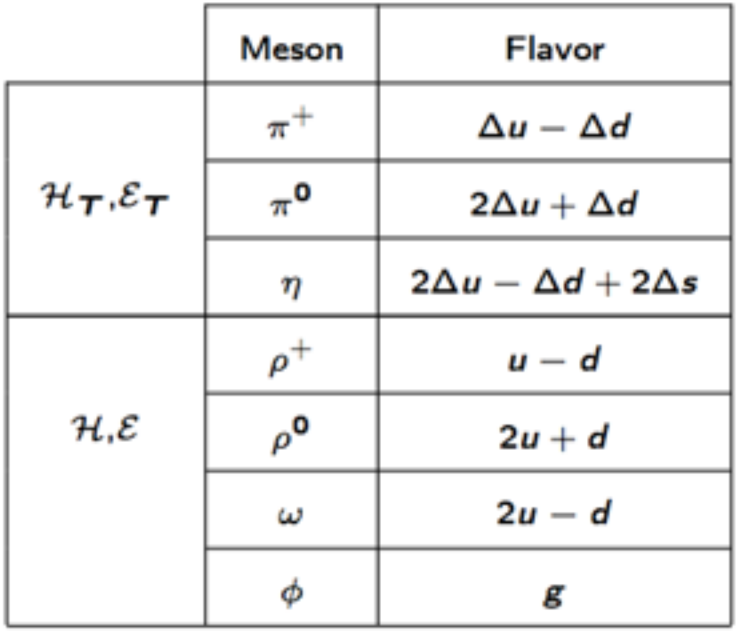
Enables flavour decomposition.

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:

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

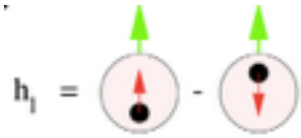


	Meson	Flavor
$\mathcal{H}_T, \mathcal{E}_T$	π^+	$\Delta u - \Delta d$
	π^0	$2\Delta u + \Delta d$
	η	$2\Delta u - \Delta d + 2\Delta s$
$\mathcal{H}, \mathcal{E}$	ρ^+	$u - d$
	ρ^0	$2u + d$
	ω	$2u - d$
	ϕ	g

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: $H_T(x,0,0) = h_1(x)$



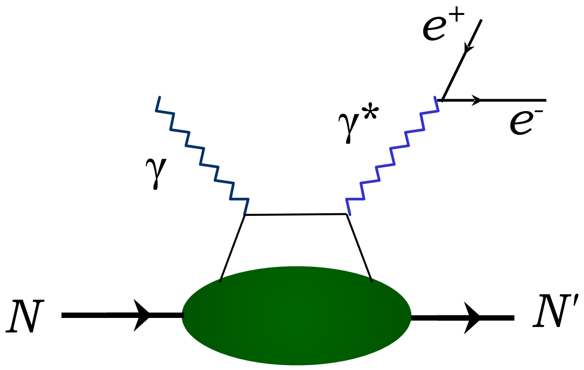
which describes distribution of transverse partons in a transverse nucleon.

Prospects at CLAS12:

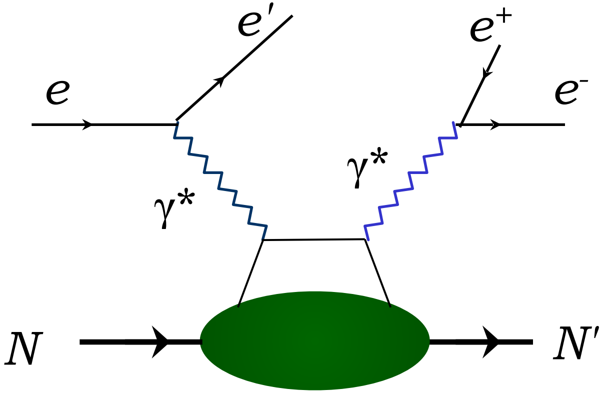
- Deeply Virtual Meson Production, e.g.: η and π^0 (E12-06-108), ϕ (E12-12-007).

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

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



TCS

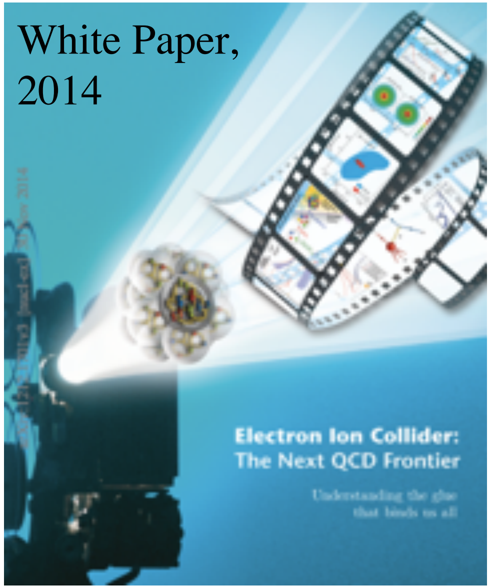


DDVCS

Looking to the future: Electron-Ion Collider

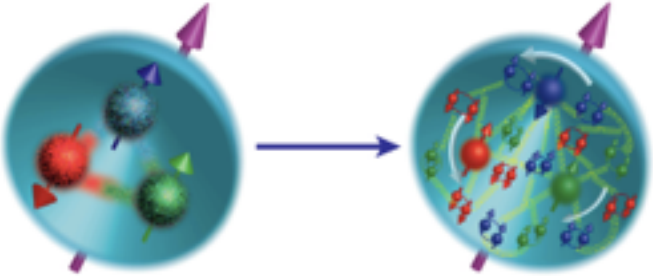
"Understanding the glue that binds us all"

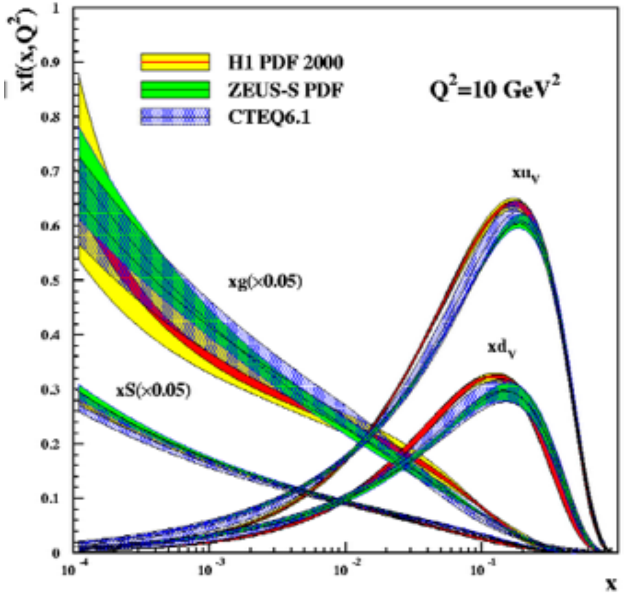
- Two sites considered: JLab and Brookhaven National Lab
- Polarised *e* and light nuclei, unpolarised heavy nuclei
- Centre of mass energy range: 20 - 140 GeV
- High luminosity (10^{33} - 10^{34} cm^{-2}s^{-1})
- High resolution detectors


White Paper, 2014

Electron Ion Collider: The Next QCD Frontier

Understanding the glue that binds us all





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

Summary

- 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 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.

- The Electron-Ion Collider will probe into the **quark-gluon sea.**

- The nucleon is still a little-understood beast. To make progress, close collaboration between theory and experiment is required.

Thank you