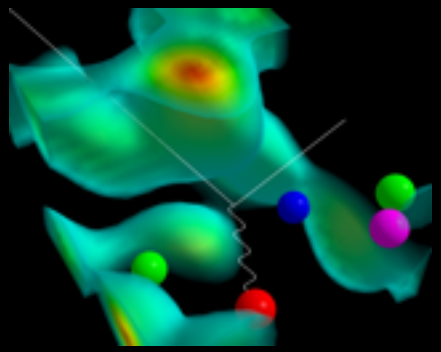
Towards Generalised Parton Distributions at the Electron Ion Collider



Derek Leinweber

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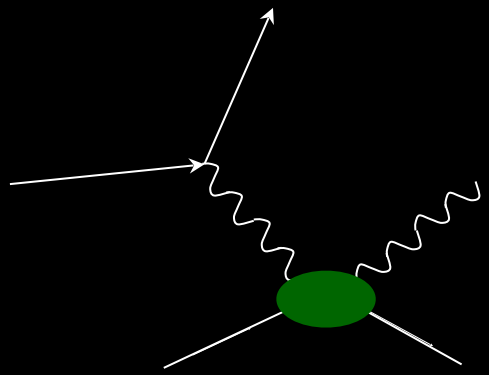
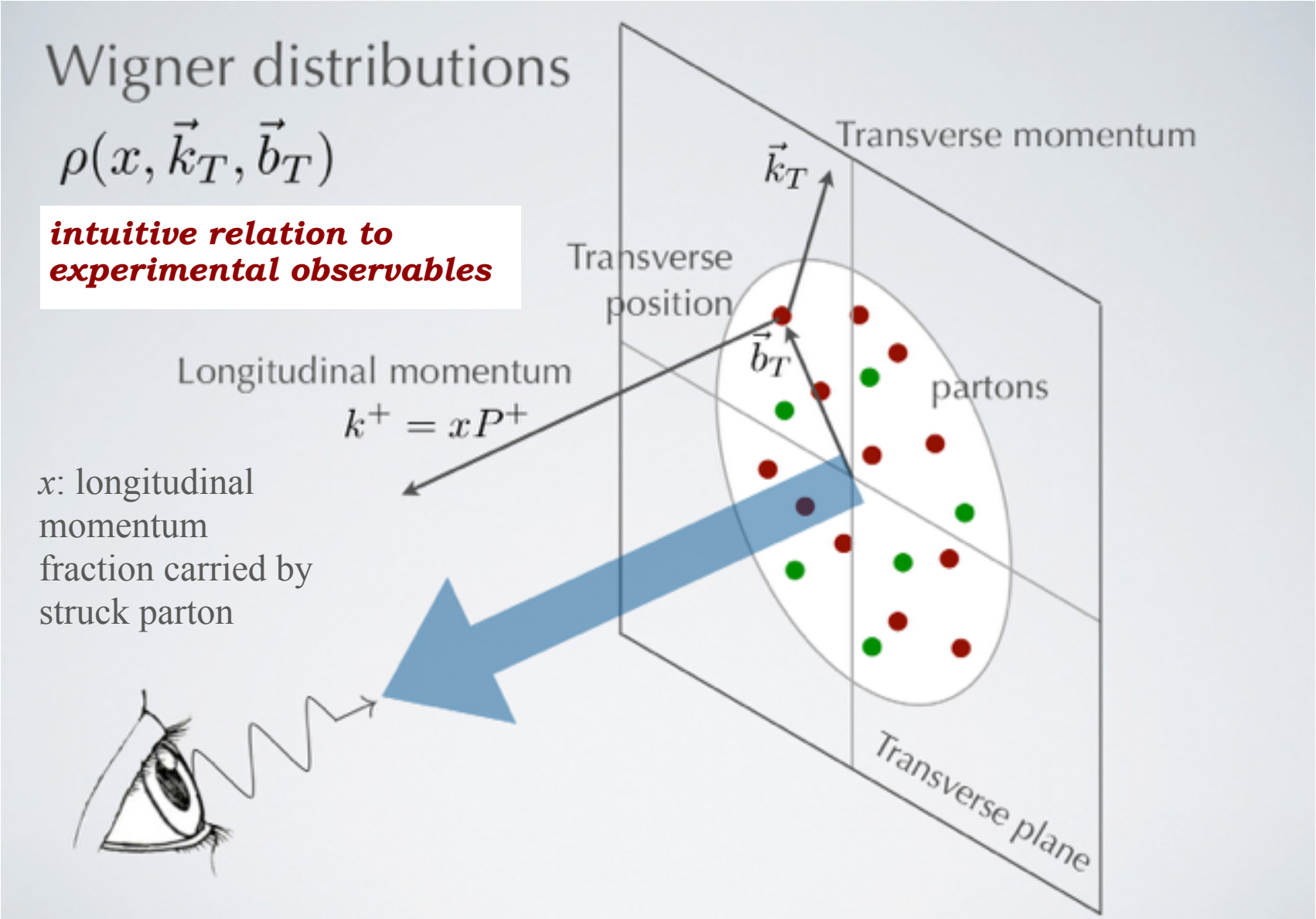


EIC User Group Meeting, Argonne National Lab, USA — 8 July 2016

Structure of the nucleon

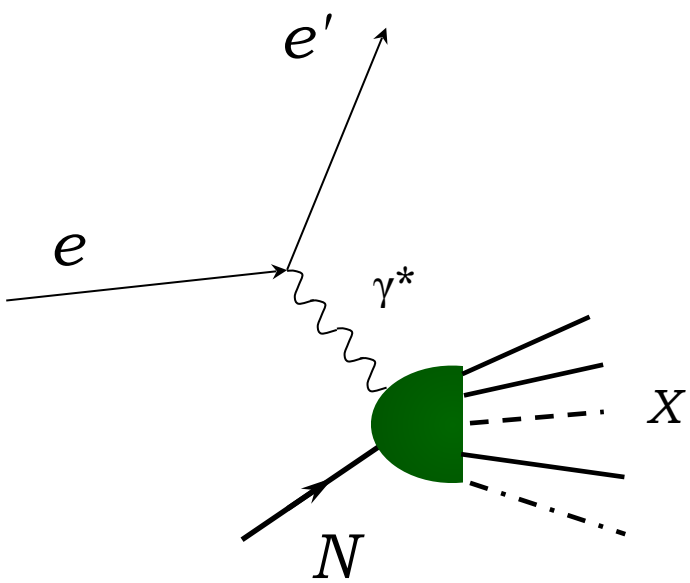
What we would like to know



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.

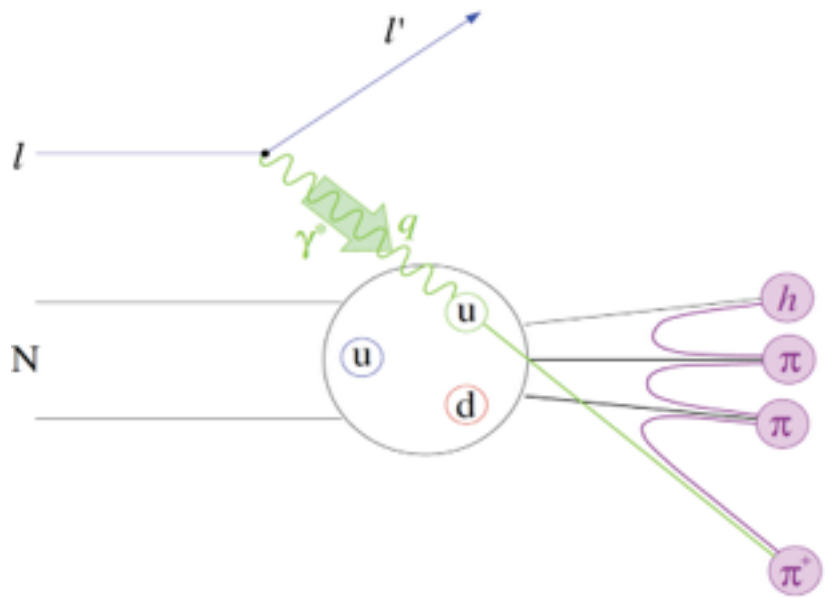
Nucleon from different views: I

Wigner function:
full phase space parton
distribution of the nucleon

$$\int d^2 b_T$$

Transverse Momentum Distributions (TMDs)

* Semi-inclusive DIS



Nucleon from different views: II

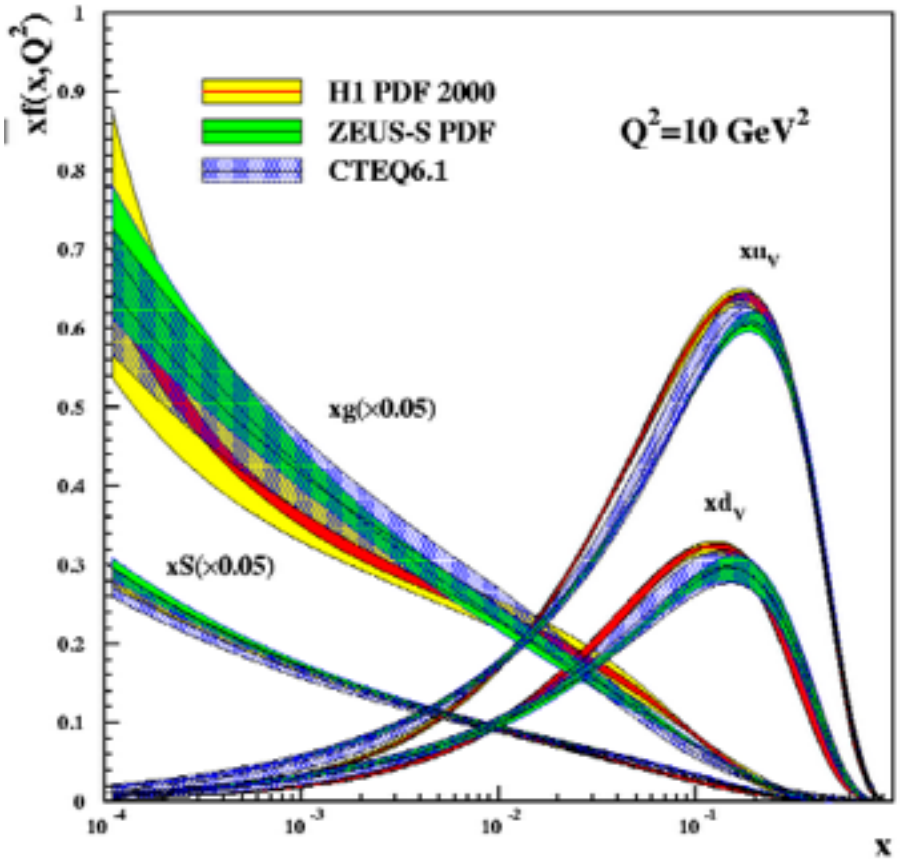
Wigner function: full phase space parton distribution of the nucleon

$\int d^2 b_T$

Transverse Momentum Distributions (TMDs)

$\int d^2 k_T$

Parton Distribution Functions (PDFs)



Nucleon from different views: II

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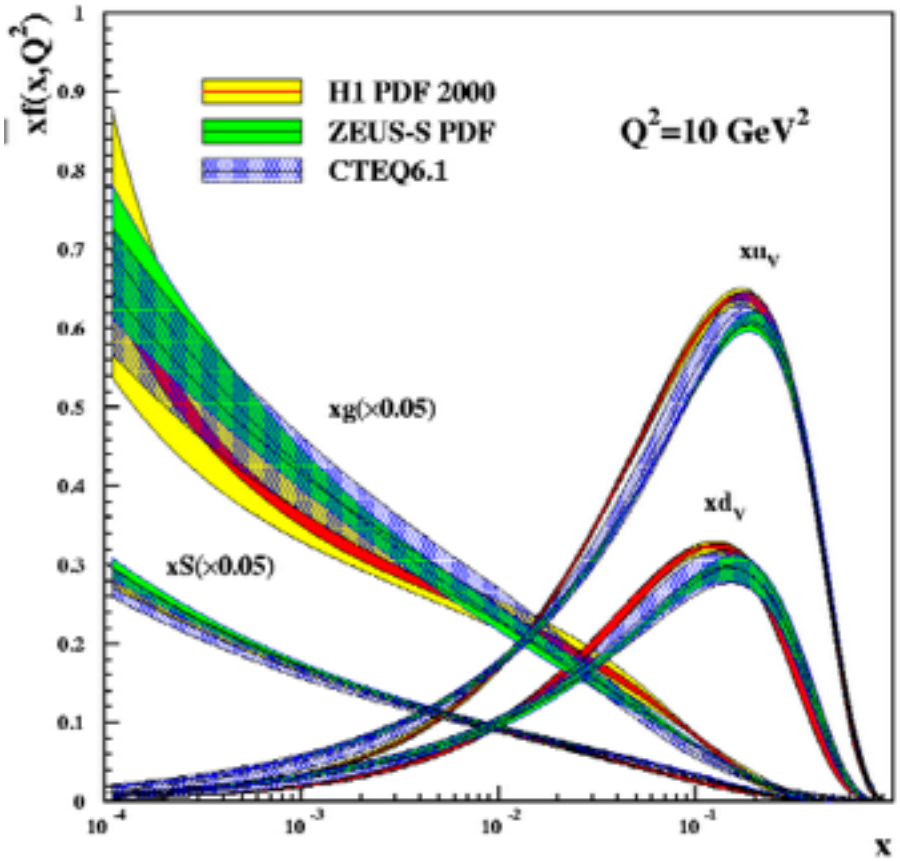
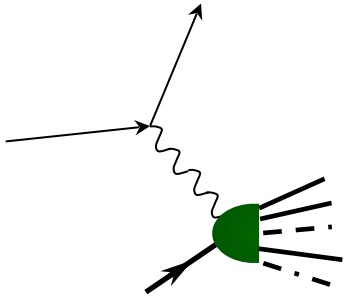


Parton Distribution Functions (PDFs)



* DIS

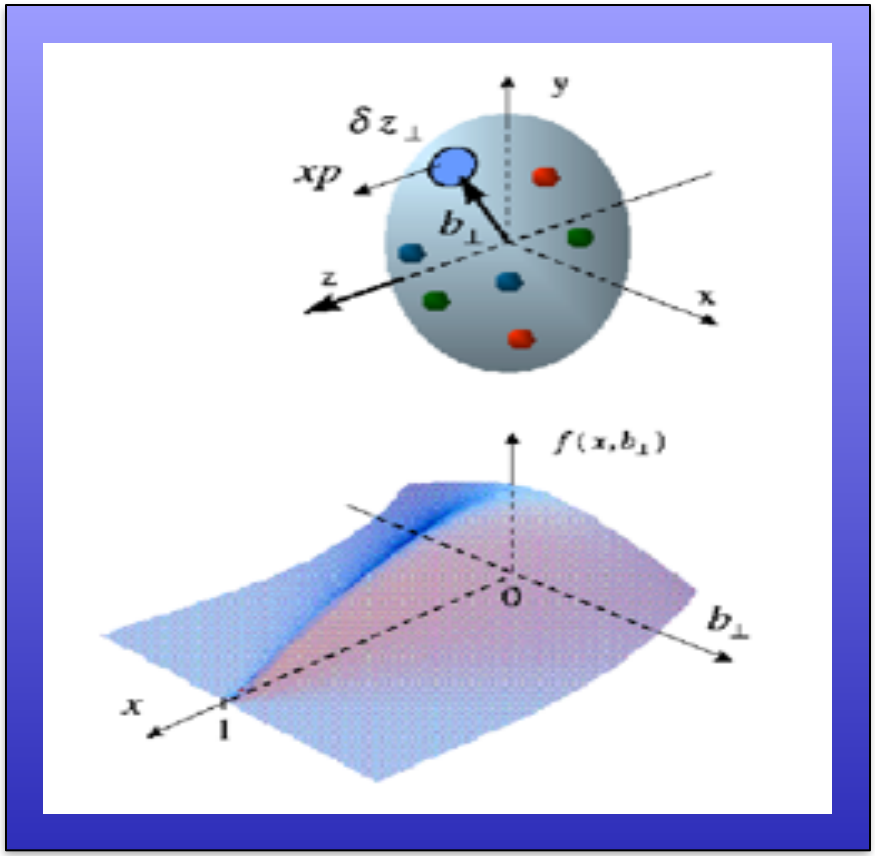
Nucleon from different views: III

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).



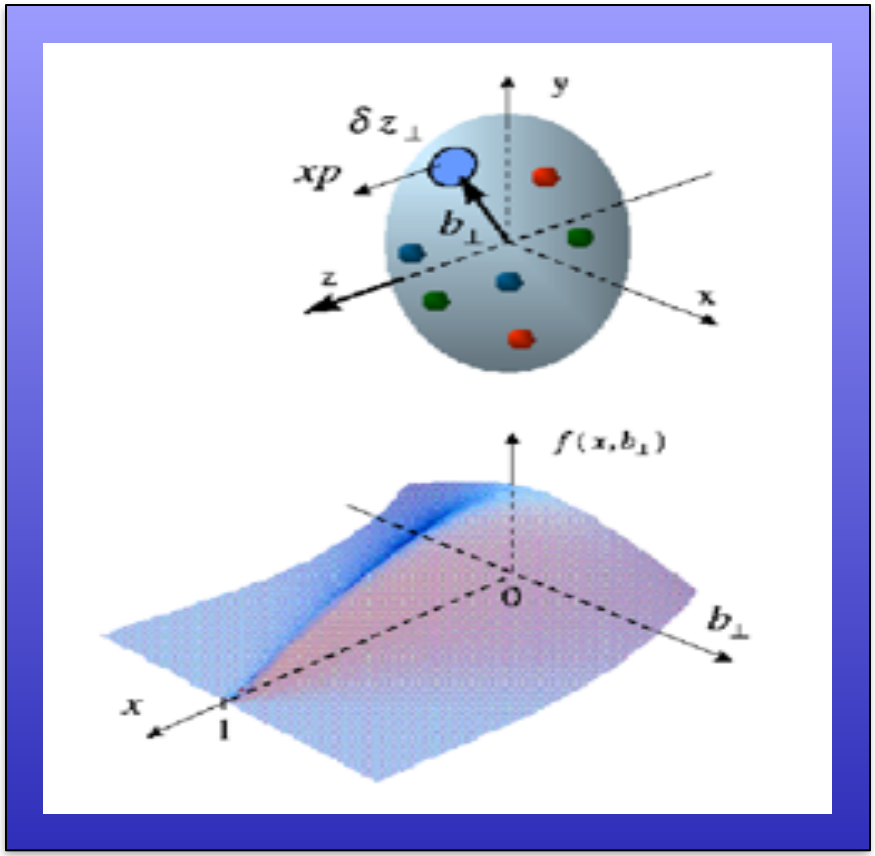
Nucleon from different views: III

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

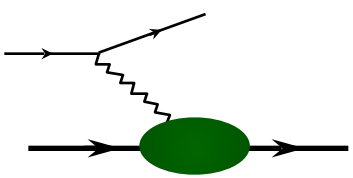
Nucleon from different views: IV

Wigner function:
full phase space parton
distribution of the nucleon

$$\int d^2 k_T$$

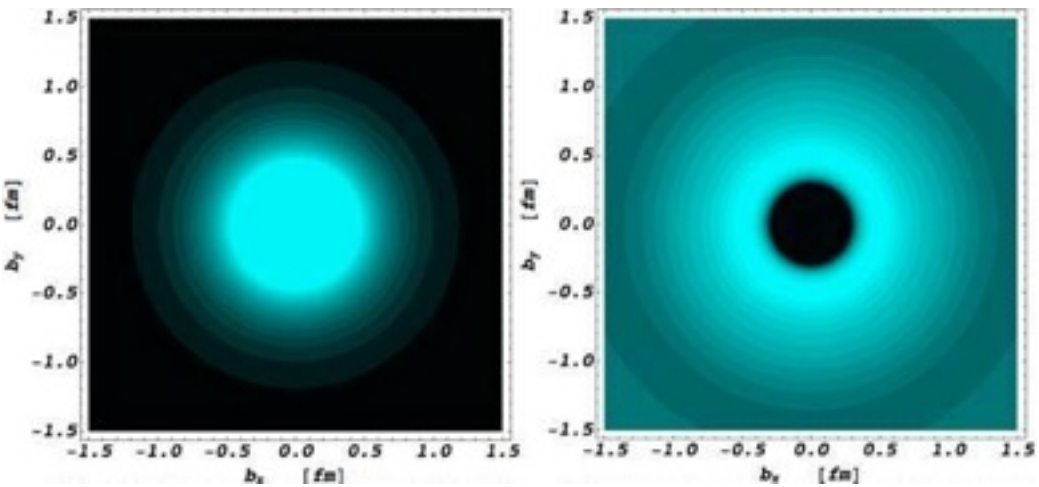
Generalised Parton Distributions (GPDs)

$$\int dx$$



Form Factors
eg: G_E, G_M

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



proton neutron

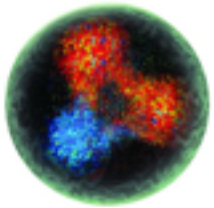
C. Carlson, M. Vanderhaeghen
PRL 100, 032004 (2008)

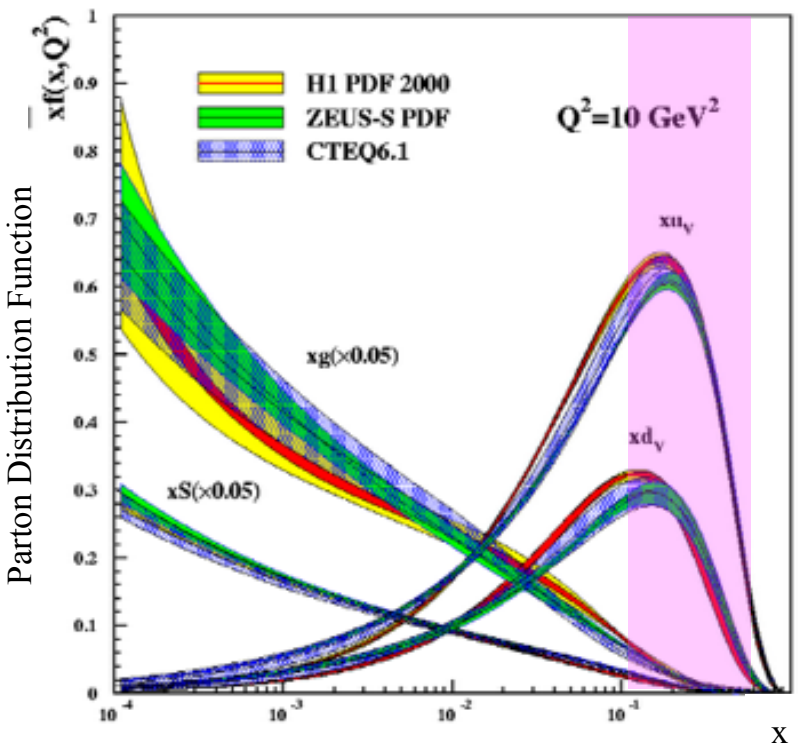
Nucleon at different scales

Valence quarks

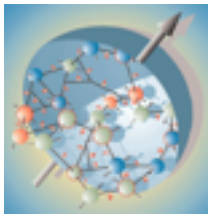
Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$





Nucleon at different scales



Valence quarks

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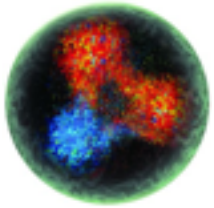
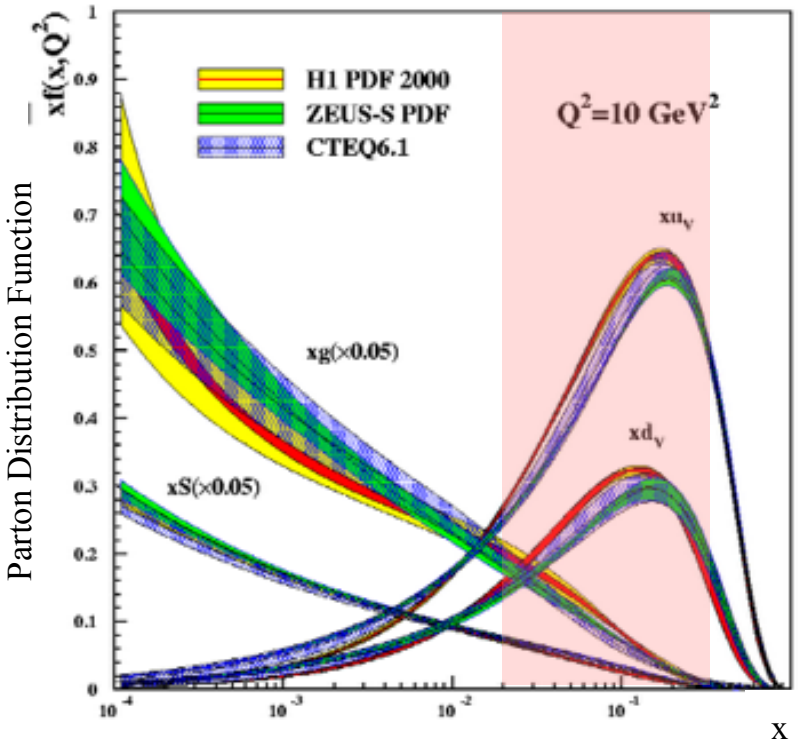


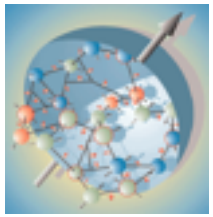
Sea quarks

HERMES: fixed gas-target electron/positron scattering

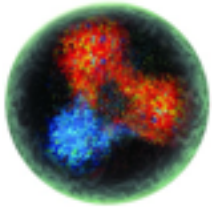
$0.02 < x_B < 0.3$



Nucleon at different scales

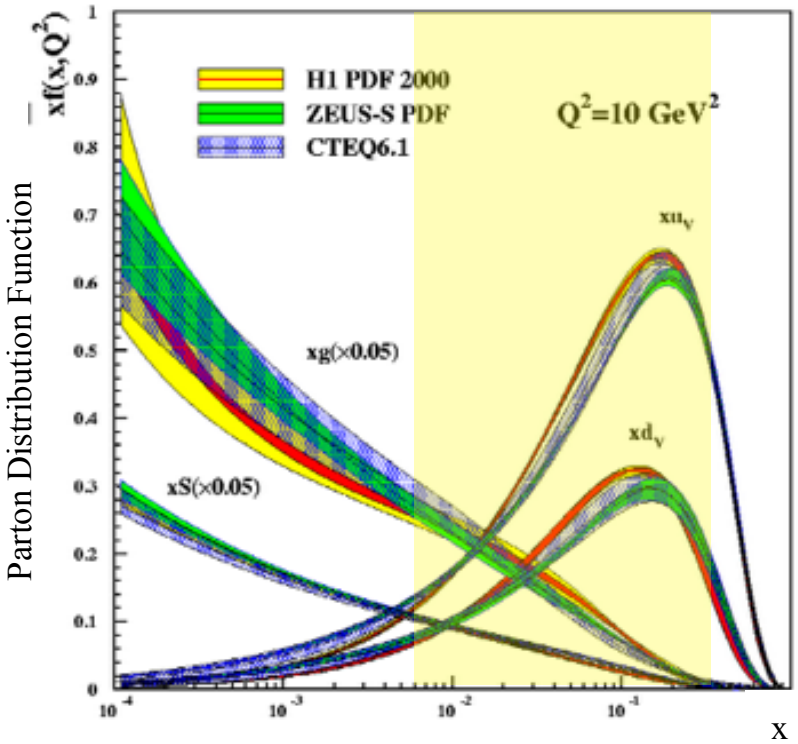


Valence quarks



Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$



Sea quarks

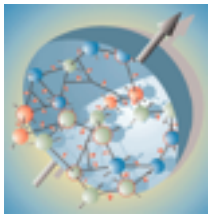
HERMES: fixed gas-target electron/positron scattering

$0.02 < x_B < 0.3$

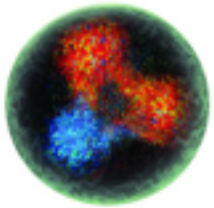
COMPASS: fixed-target muon scattering

$0.006 < x_B < 0.3$

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

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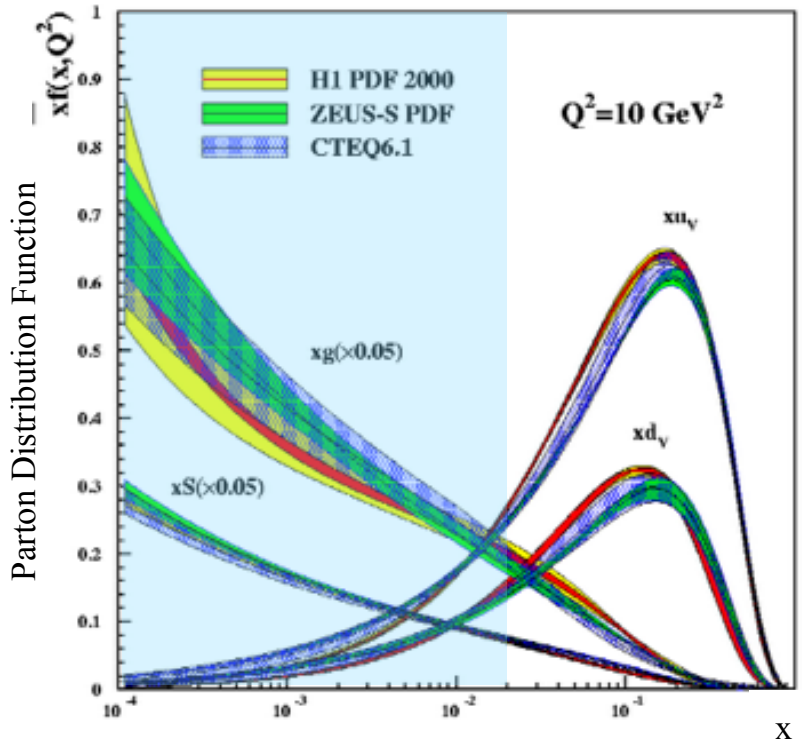
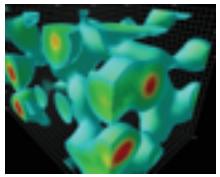


The glue

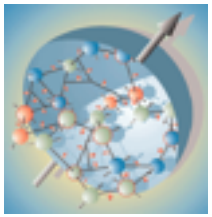


Derek Leinweber

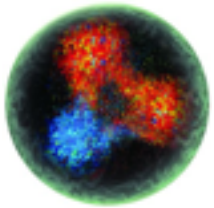
ZEUS/H1: electron/positron-proton collider

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

Nucleon at different scales

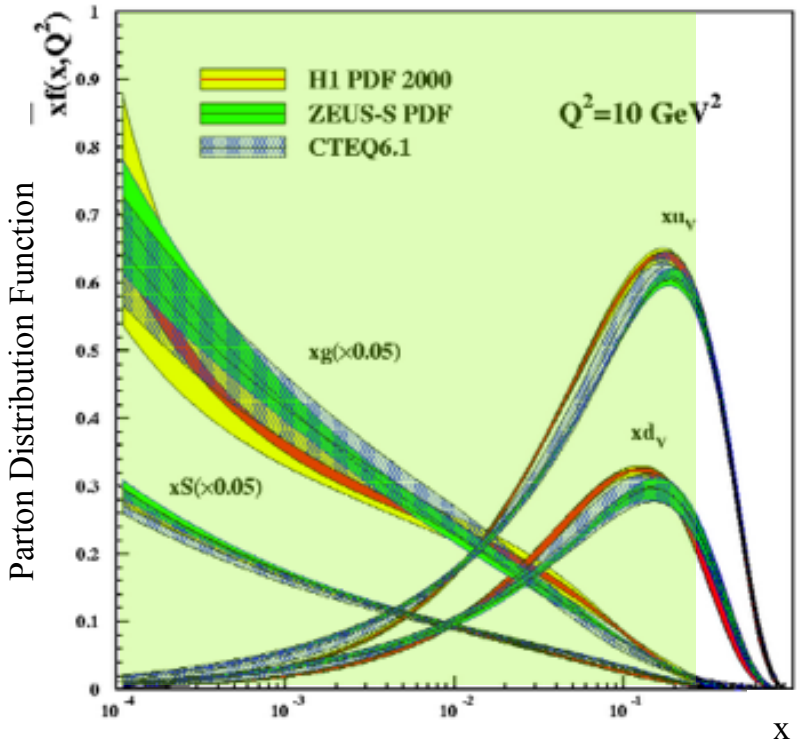


Valence quarks



Jefferson Lab: fixed-target electron scattering

$0.1 < x_B < 0.7$



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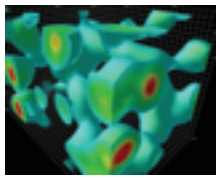


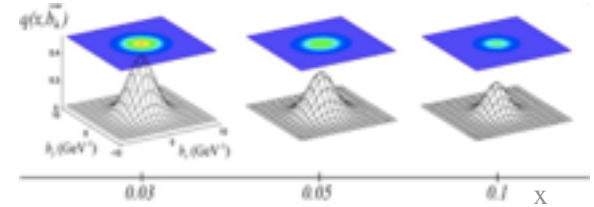
Derek Leinweber

ZEUS/H1: electron/positron-proton collider

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

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

What do GPDs tell us?

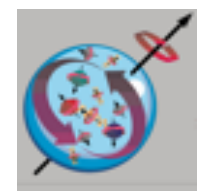


* **Tomography** of the nucleon: transverse spacial distributions of quarks and gluons in longitudinal momentum space.

* 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.

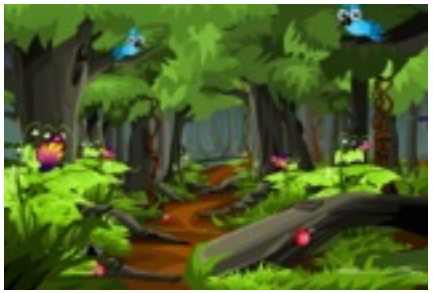
* Provide information on the orbital angular momentum contribution to nucleon spin: **the spin puzzle**.



* 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.

How to access GPDs

Experimental paths to GPDs

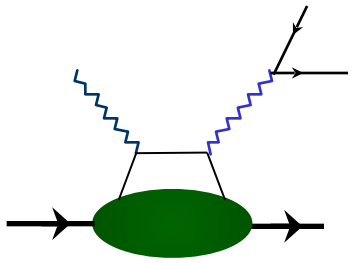


cliparts.co

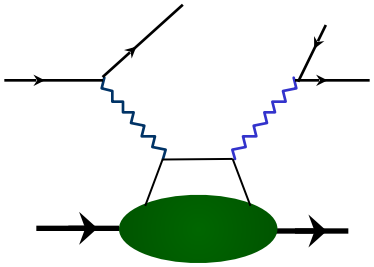
Accessible in *exclusive* reactions, where all final state particles are detected.

Trodden paths, or ones starting to be explored:

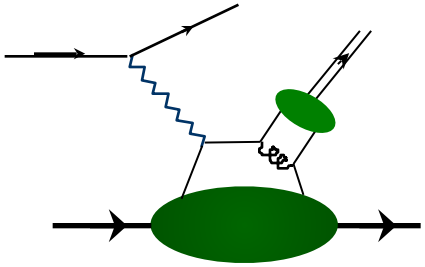
- Deeply Virtual Compton Scattering (DVCS)
- Deeply Virtual Meson Production (DVMP)
- Time-like Compton Scattering (TCS)
- Double DVCS



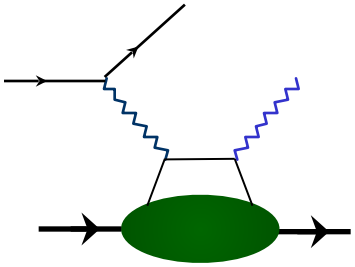
TCS



DDVCS



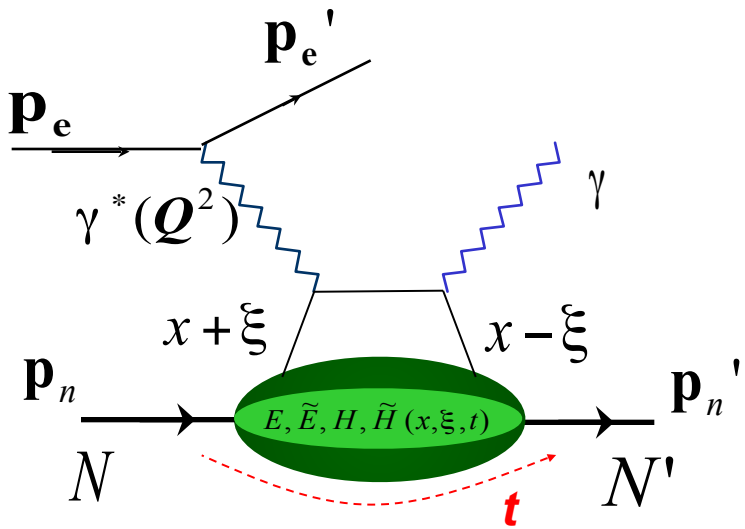
DVMP



DVCS

Deeply Virtual Compton Scattering

the "golden channel"



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

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

Can be related to PDFs:

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

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

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

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

and form factors:

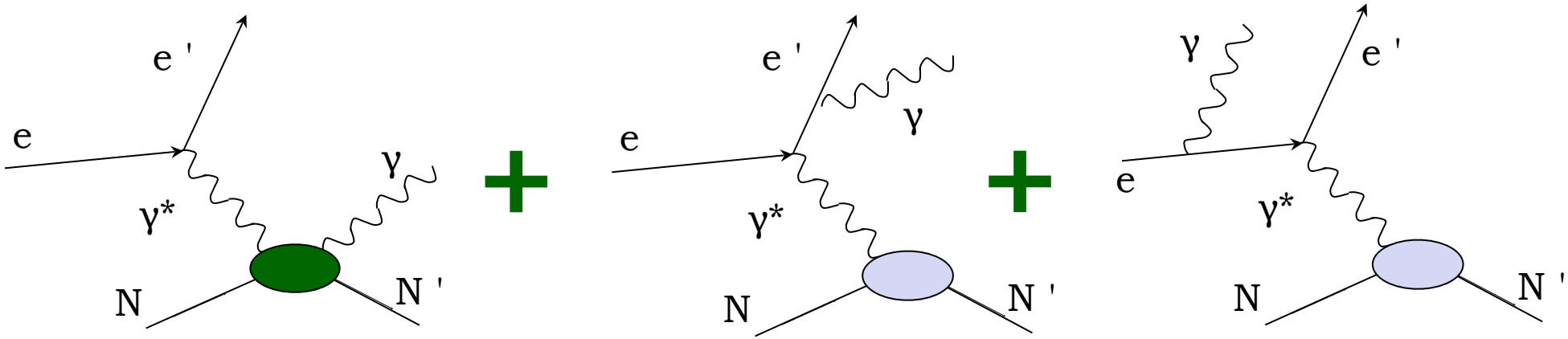
$$\int_{-1}^{+1} H\,dx = F_1 \qquad \int_{-1}^{+1} \tilde{H}\,dx = G_A$$

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

(Dirac and Pauli) $\qquad$ *(axial and pseudo-scalar)*

Measuring DVCS

✳ Process measured in experiment:



DVCS

Bethe - Heitler

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

Amplitude parameterised in terms of Compton Form Factors

Amplitude calculable from elastic Form Factors and QED

Interference term

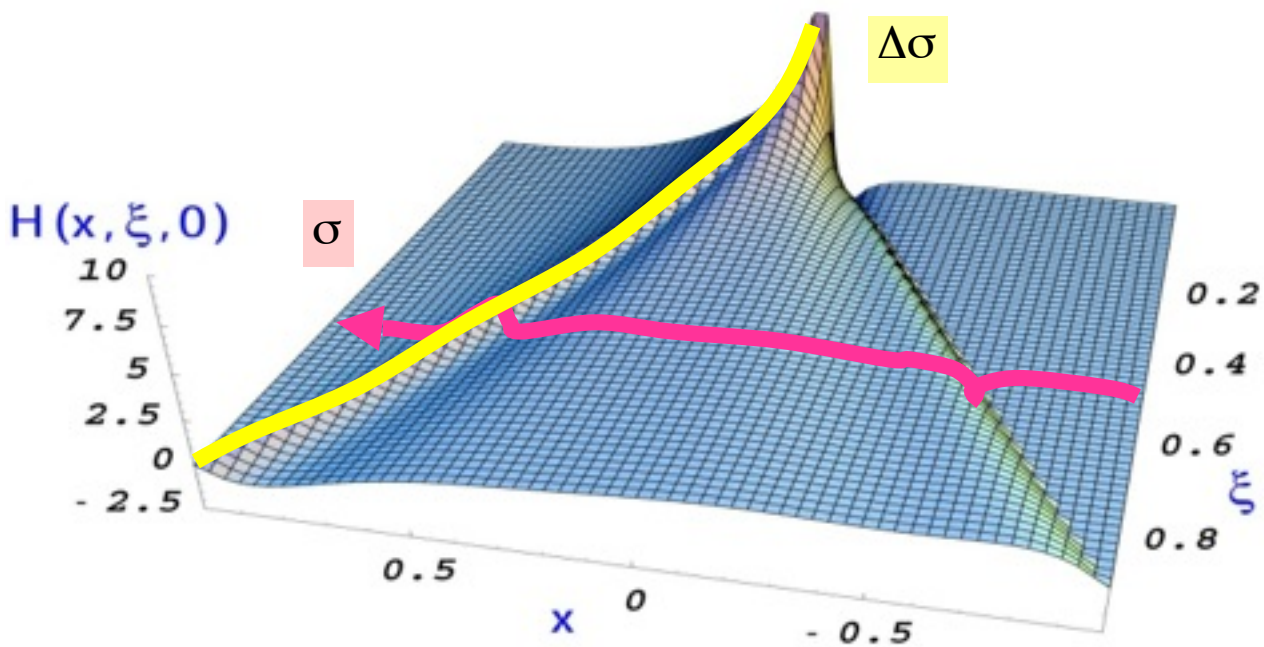
$$\left|T_{DVCS}\right|^2 << \left|T_{BH}\right|^2$$

Compton Form Factors in DVCS

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

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

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



Only ξ and *t* are accessible experimentally!

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

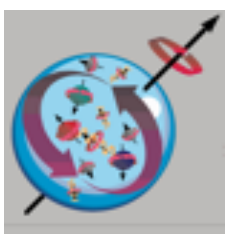
* Total angular momentum of a nucleon:

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

Only ~ 30% contribution

* Ji's relation:

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

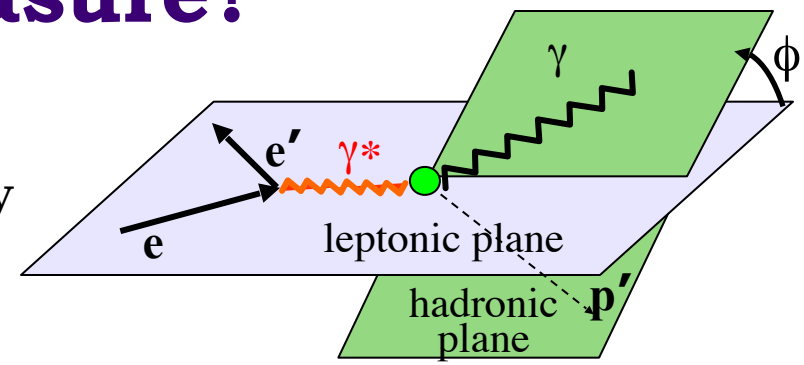


* Need measurements at low t, across wide Q^2, of a range of observables to extract both H and E.

* Need flavour separation of GPDs.

What should we measure?

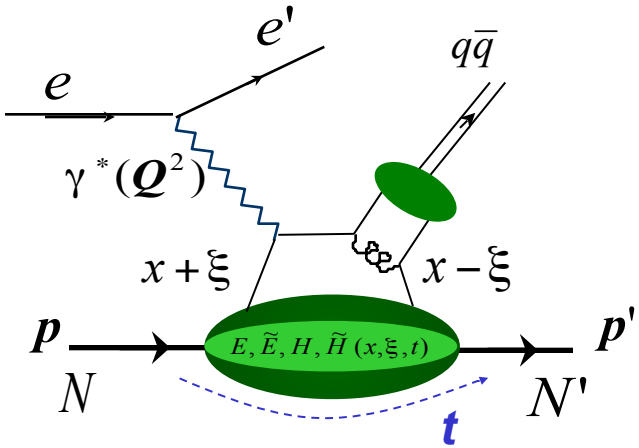
Real parts of CFFs accessible in cross-sections and double polarisation asymmetries, imaginary parts of CFFs in single-spin asymmetries.



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

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

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:

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

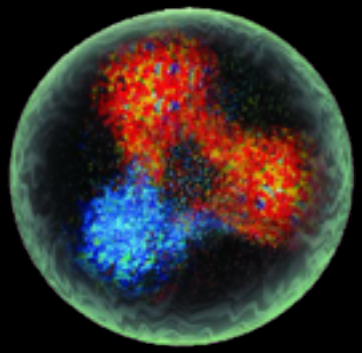
Transversity GPDs can be related to transverse anomalous magnetic moment:

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

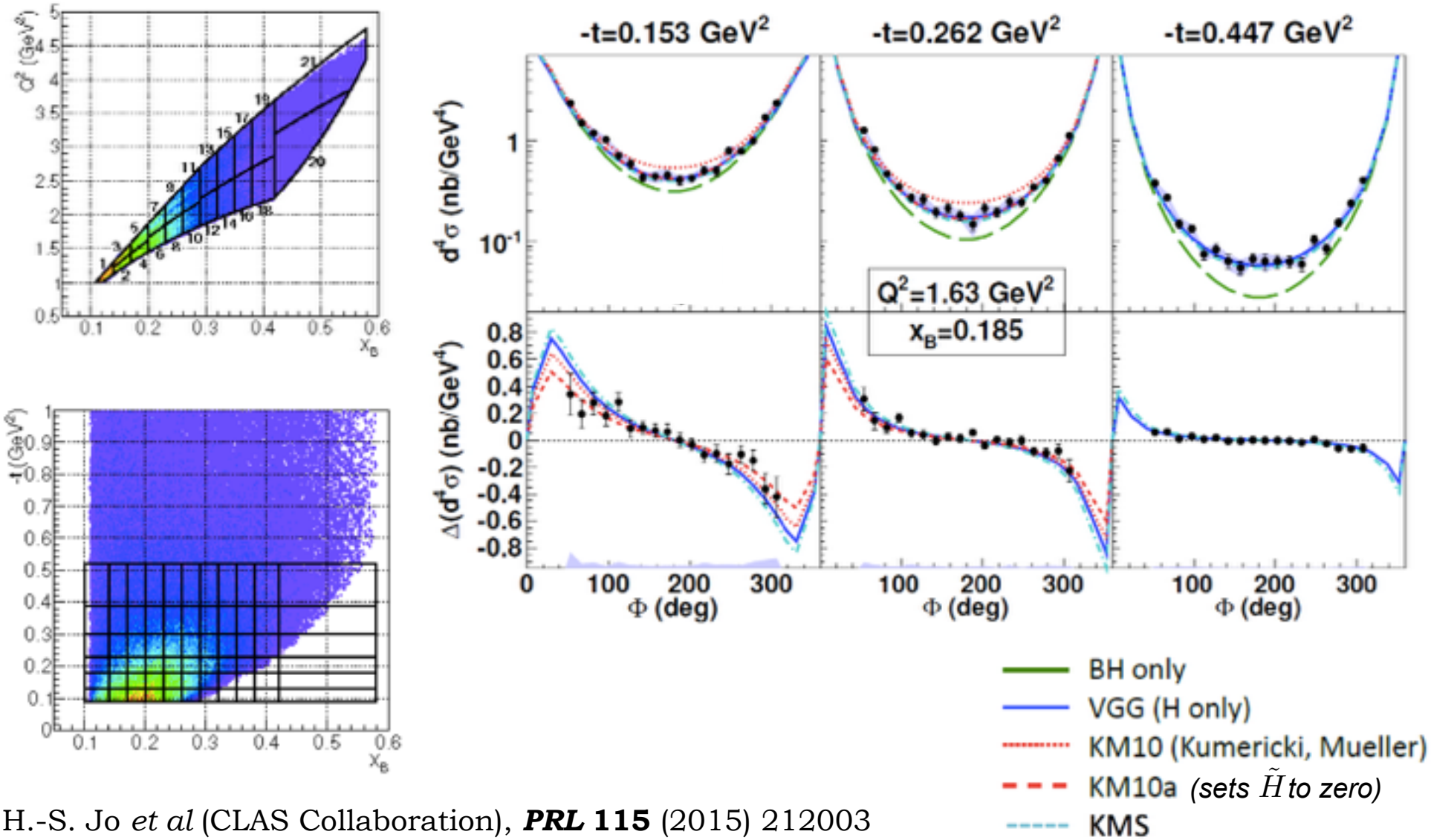
and transversity distribution: $H_T(x,0,0) = h_1(x)$

which describes distribution of transverse partons in a transverse nucleon.

GPDs from DVCS in the valence region



CLAS cross-sections (JLab)



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

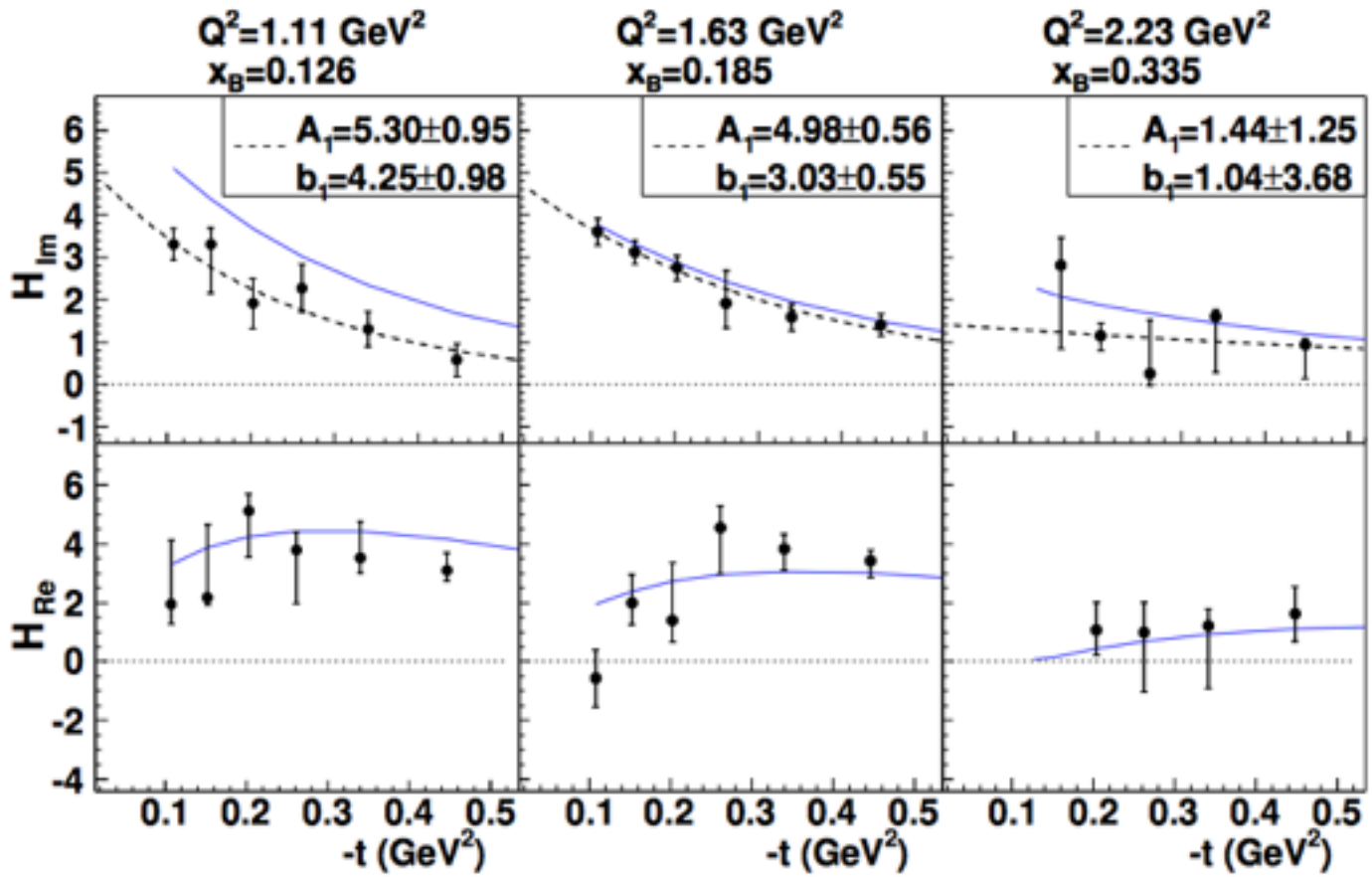
What do the CFFs from the cross-sections tell us?

VGG

Ae^{bt}

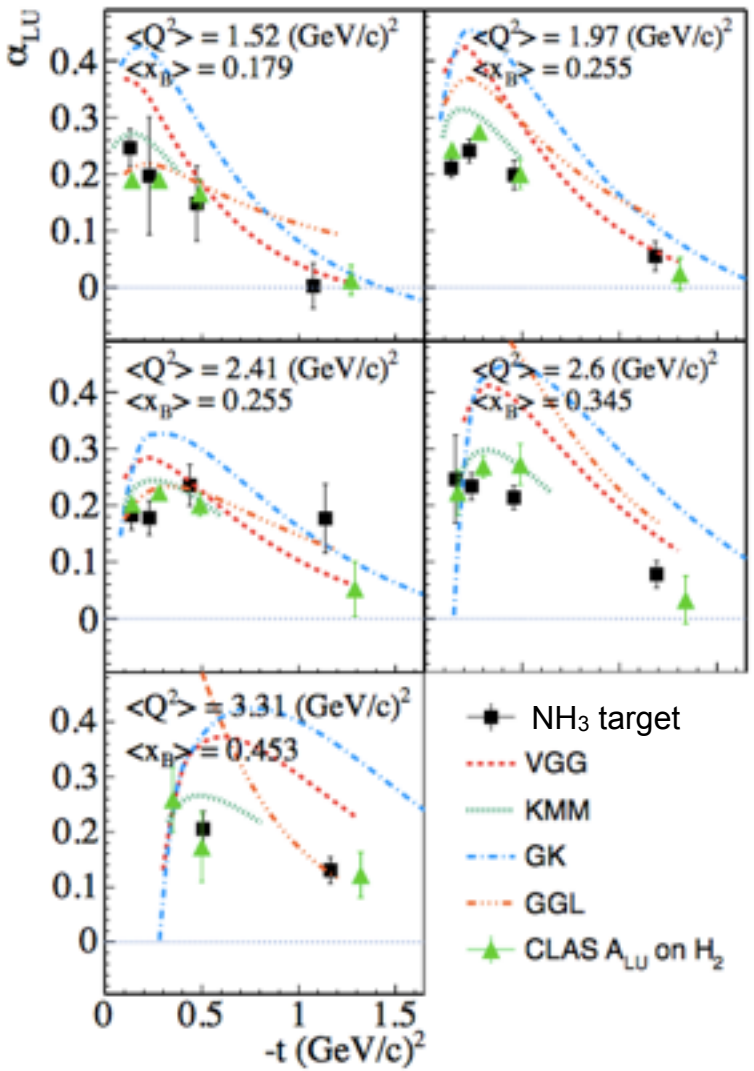
- Slope in t becomes flatter at higher x_B

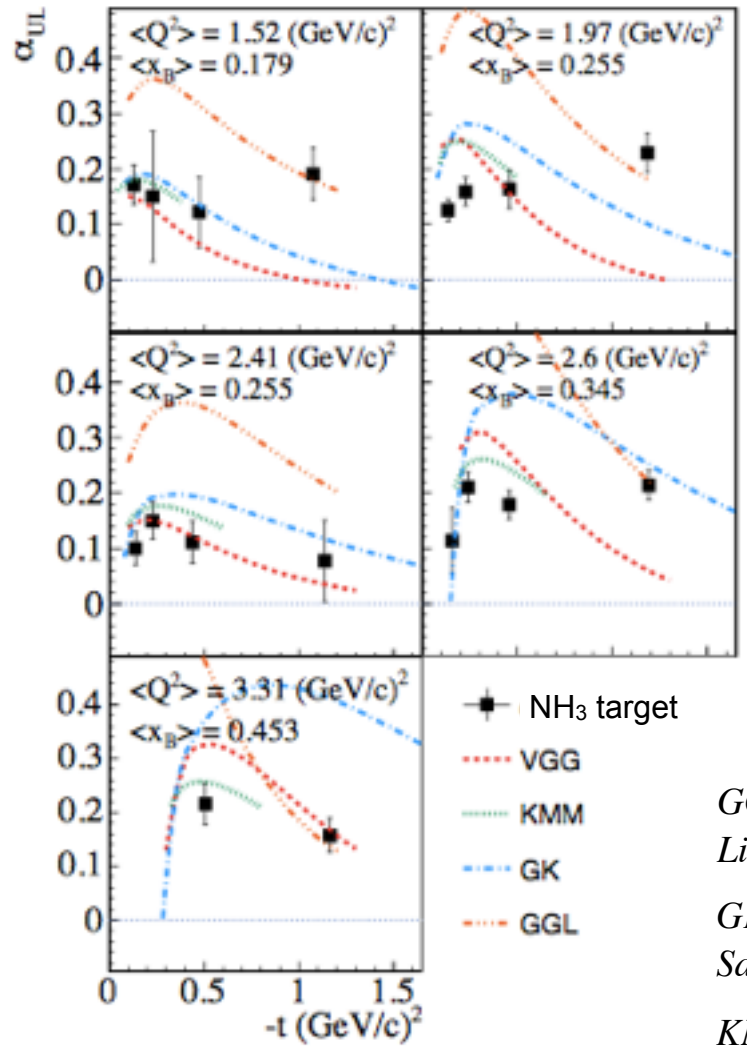
- Valence quarks at centre, sea quarks at the periphery.



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

Beam- and target-spin asymmetries from CLAS





Fit function:

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

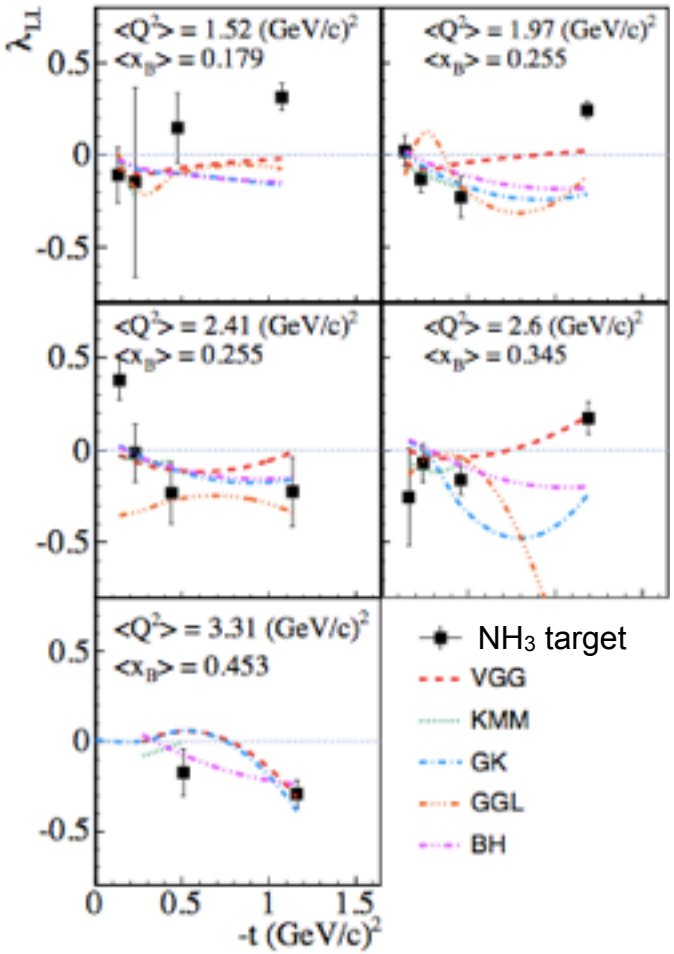
GGL: Goldstein, Gonzalez, Liuti

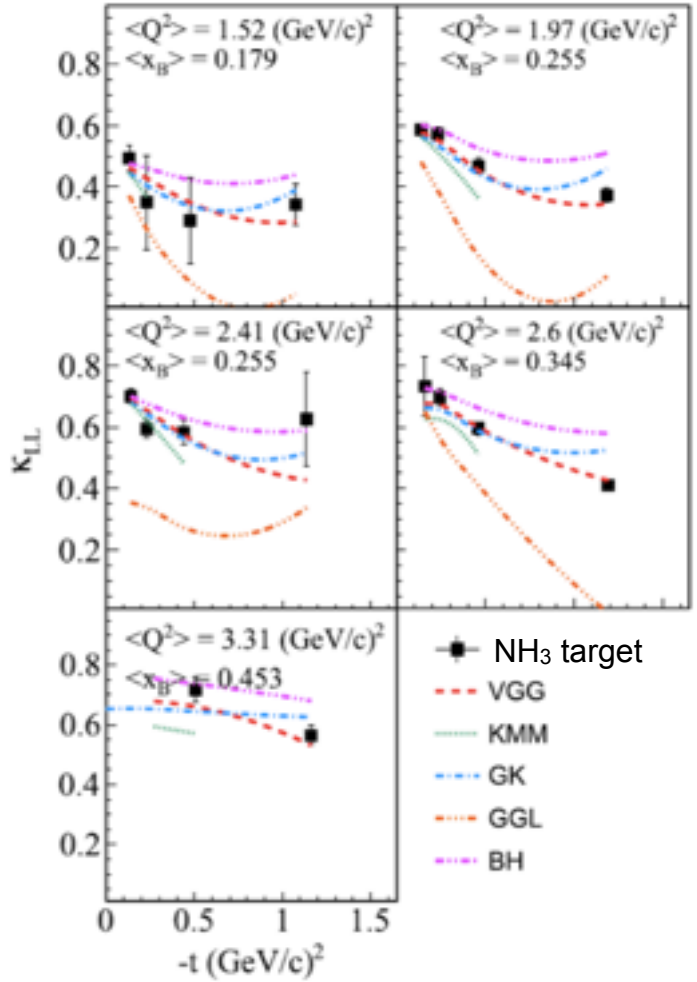
GK: Kroll, Moutarde, Sabatié

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}) from CLAS





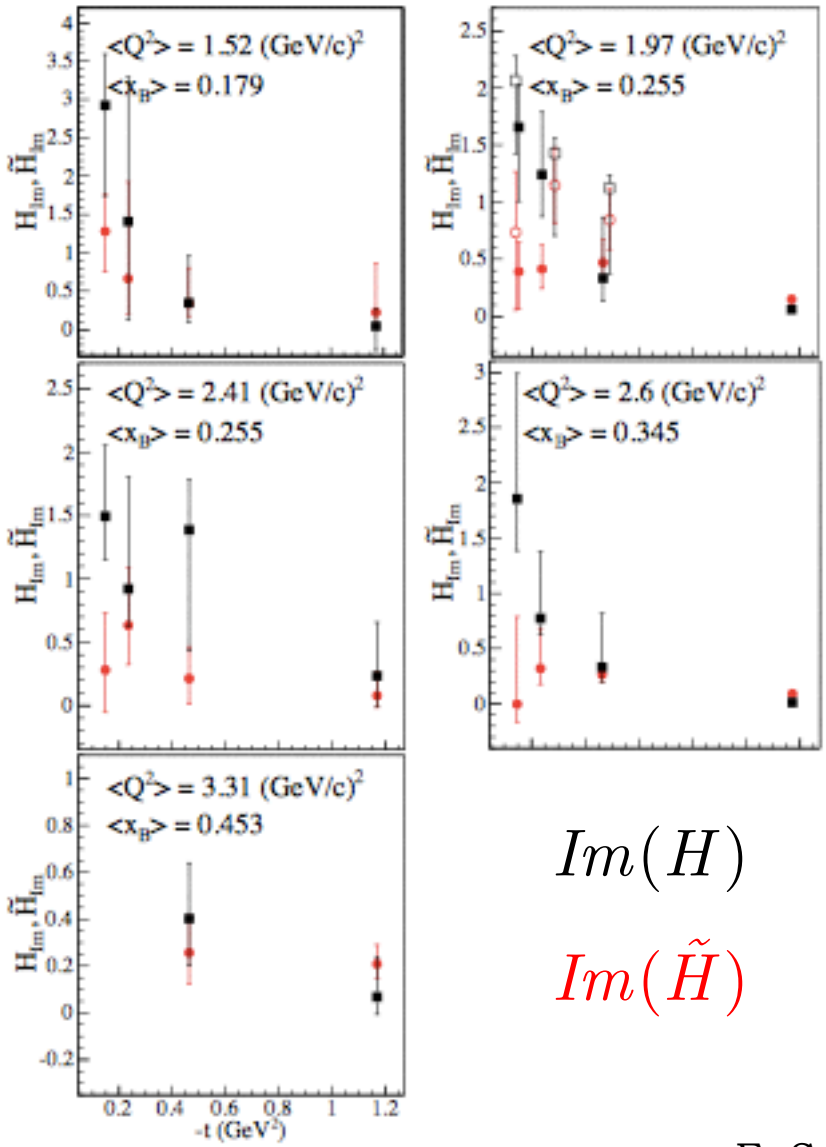
Fit function:

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

- Fit parameters extracted from a simultaneous fit to A_{LU}, A_{UL} and A_{LL}.
- CFF extraction from three spin asymmetries at common kinematics.

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

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?

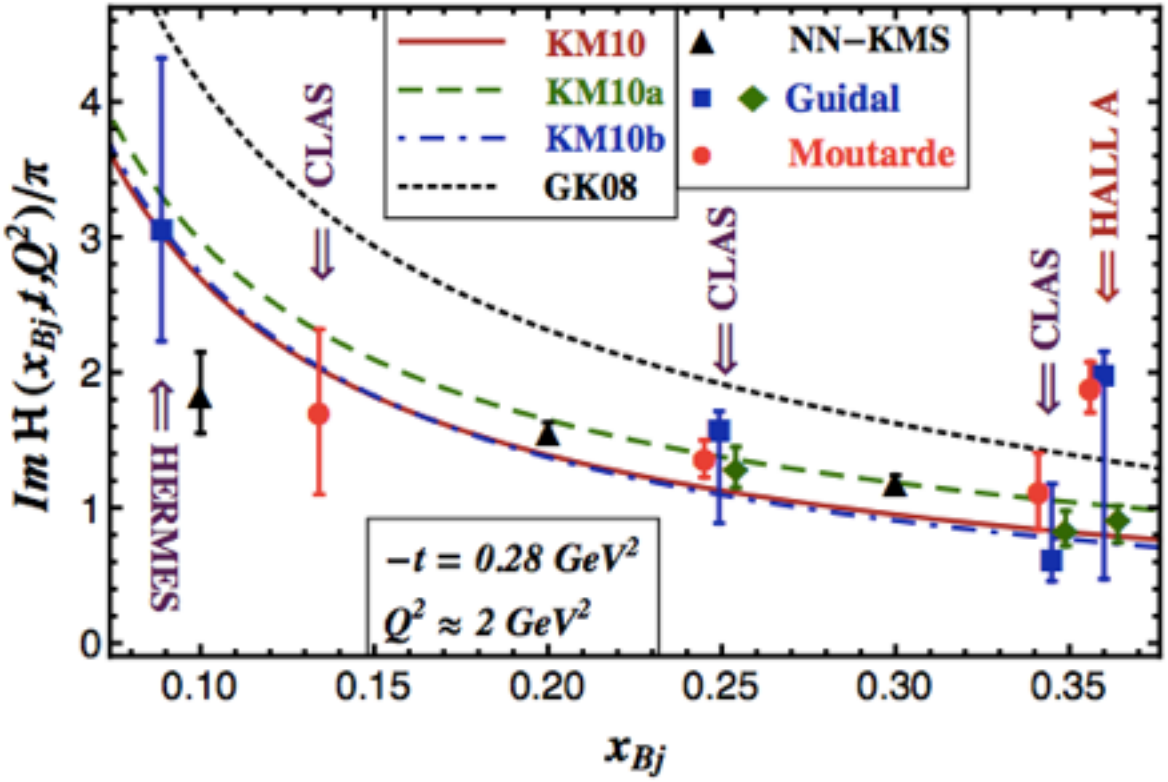
$$H^q(x,0,0) = f_1(x)$$

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

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

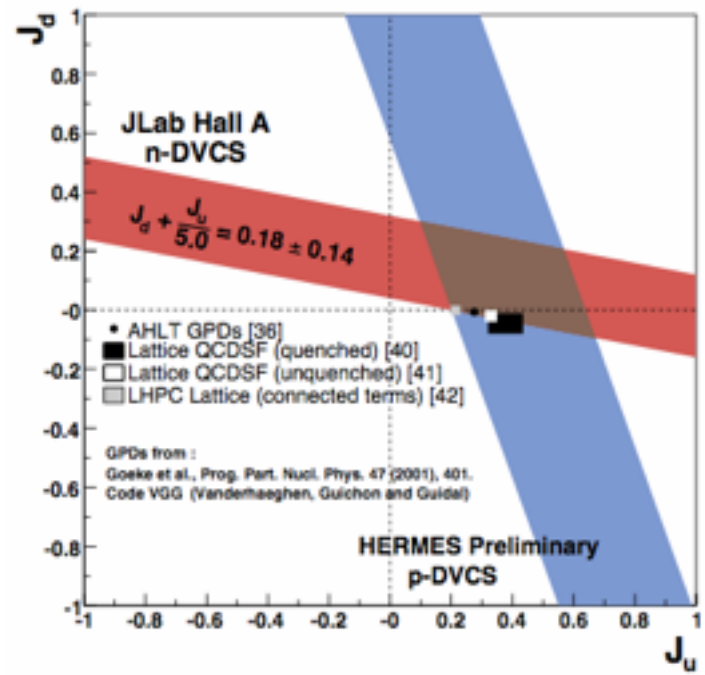
Combining data from different experiments

Proton measurements from JLab and HERMES:



E.C. Aschenauer *et al*, ***JHEP*** **1309** (2013) 093

Proton (HERMES) and neutron (Hall A, JLab) DVCS measurements:



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

What have we learned in the valence region?

- Factorisation and the handbag formalism can be used to describe DVCS at moderate Q^2 and small but finite t: a wide range of Q^2, smaller t desirable.

- Beam and target polarisation in experiment is crucial to extract different Compton Form Factors (we want polarised beams and targets!)

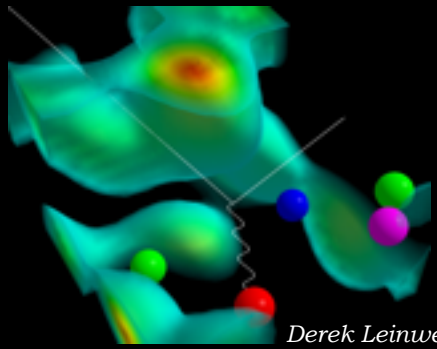
- Very high statistics are required to differentiate between models and extract CFFs with high accuracy (we want high luminosity and full acceptance!)

- Measurements on both proton and neutron are crucial to allow flavour separation of GPDs from DVCS.

- Meson production provides a handle on flavour-separation, combined with DVCS points to universality of GPDs.

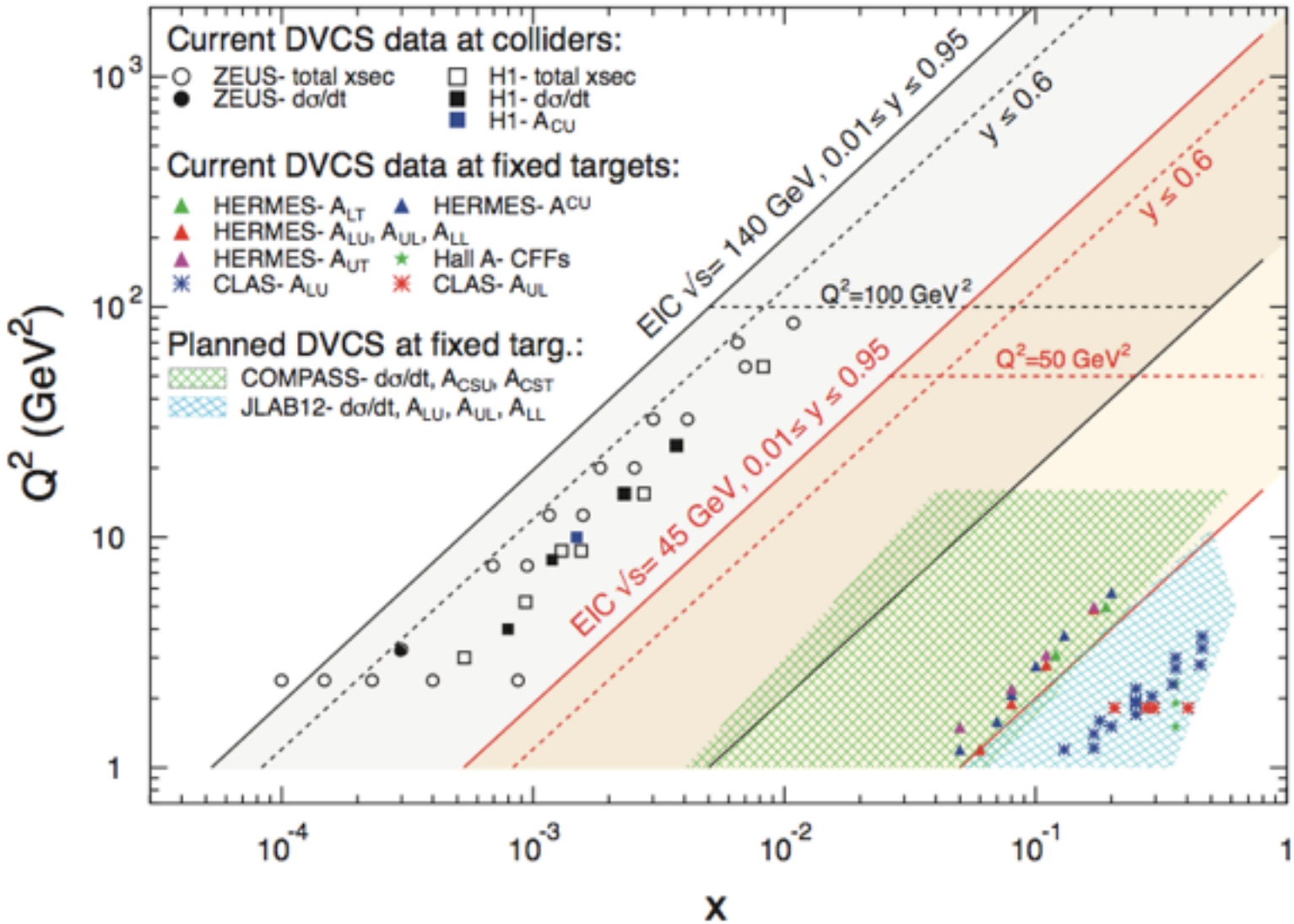
Tantalising views into nucleon structure… but we want to know more!

Measurements in the quark-gluon sea



Derek Leinweber

Phase-space of DVCS measurements



EIC White Paper, arXiv:1212.1701v3 [nucl-ex]

GPD opportunities at the EIC: I

DVCS

- Nucleon tomography at low x: sea quarks and gluons. Gluon distributions accessible via a log dependence of GPDs on Q^2.
- Access phase of the Compton amplitude through beam-charge asymmetry (using electron and positron beams) or Rosenbluth separation of cross-sections at different electron energies.

TCS

- Asymmetries carry similar information to beam-charge asymmetry in DVCS, without need for positron beams.

DVMP

- Flavour-separation of contributions from q and $\bar{q}$ and from gluons.
- J/Ψ production direct access to gluon GPDs.
- Vector meson production allows separation of cross-sections for longitudinal, σ_L, and transverse, σ_T, photon polarisation.
- $\pi^+\pi^-$ production is sensitive to differences in q and $\bar{q}$ distributions.

GPD opportunities at the EIC: II

DDVCS

- Direct access to x-dependence of GPDs.

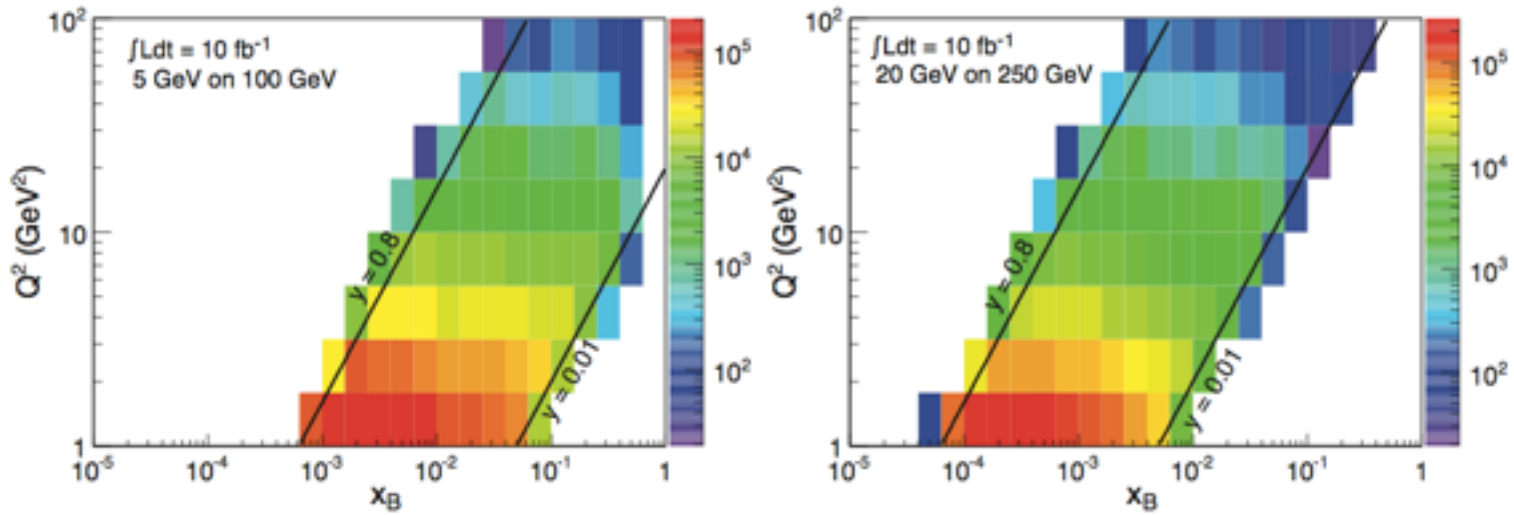
Measurements on other hadrons

- Could potentially measure DVCS/DVMP off the virtual pion.
- Light nuclei (He, deuteron) allow measurements off the neutron: flavour separation of GPDs.
- Nuclear DVCS /DVMP: tomography of the nucleus, parton saturation.
- Scattering and J/Ψ-production off nuclei with multi-nucleon knockout: short-range correlations, contribution of glue.

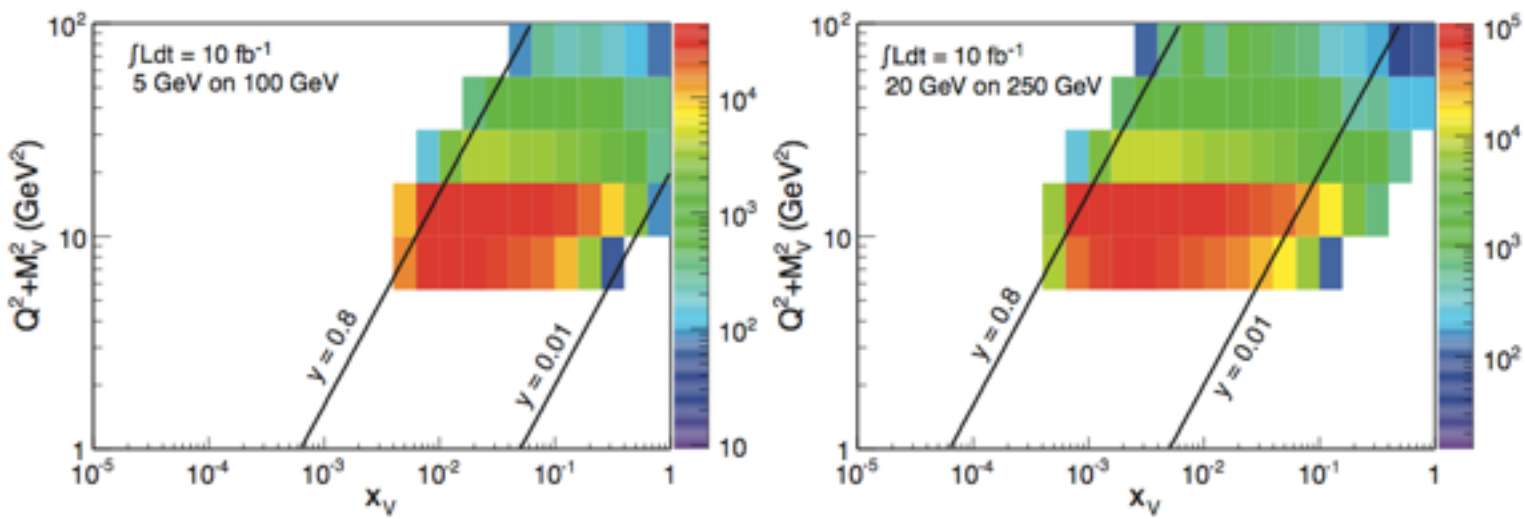
Wide range of Q^2 in the valence region will complement valence measurements: can observe scaling violations.

The estimated EIC reach

Simulations of expected distributions for DVCS



Simulations of expected distributions for J/Ψ production



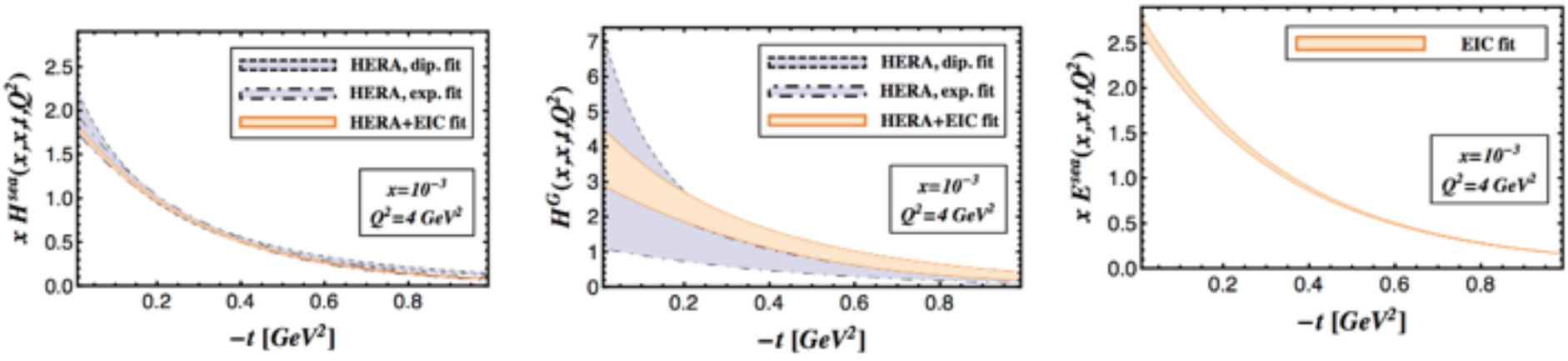
EIC White Paper, arXiv:1212.1701v3 [nucl-ex]

What can we expect from the EIC?

- Cross-sections and beam-charge asymmetries measured at H1 and ZEUS (HERA).

- Sensitivity expected from inclusion of EIC data with HERA measurements:

$E_e E_p$ = 20 x 250 GeV^2

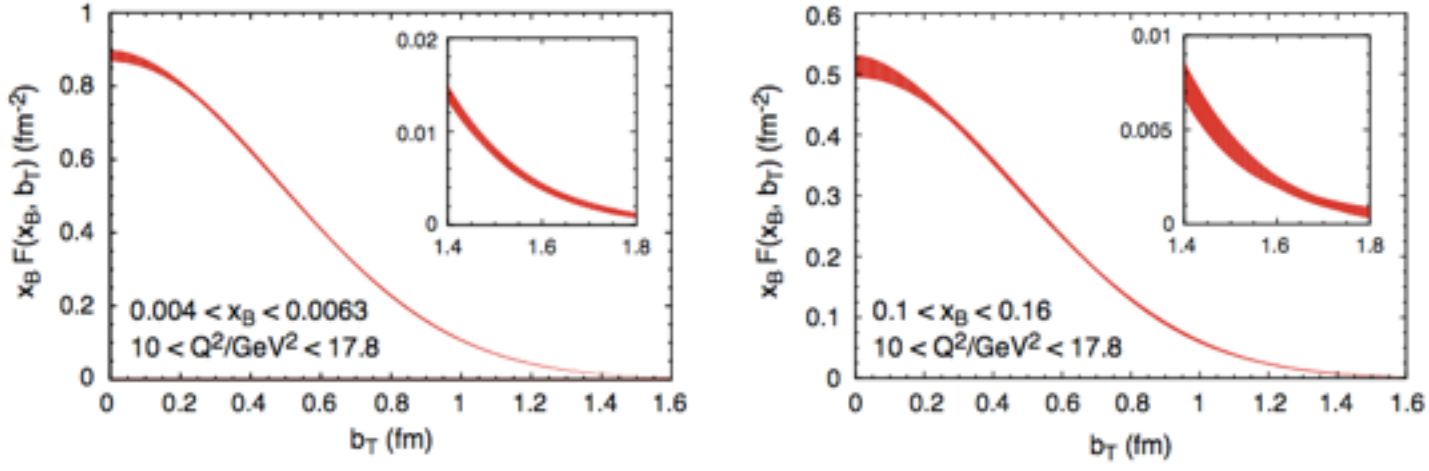


Least-squares fit with dipole and exponential ansatz from HERA collider data with and without EIC simulated pseudo-data (unpolarised cross-sections and transverse target spin asymmetry produced with AFKM12 model) fitted with the exponential ansatz.

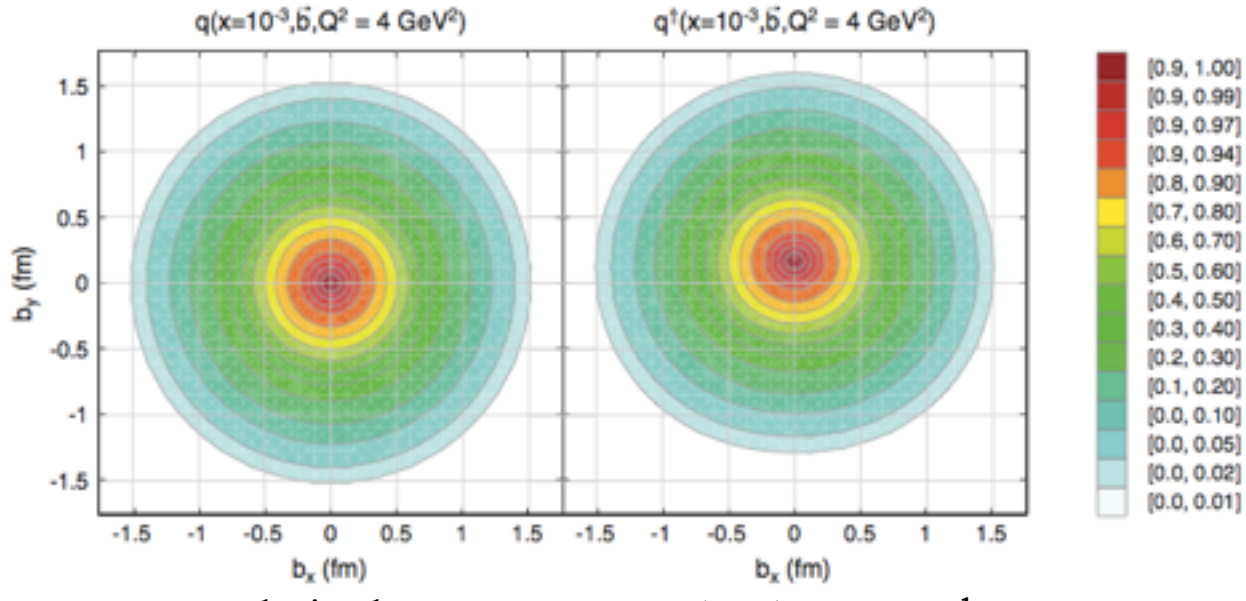
E.C. Aschenauer *et al*, ***JHEP* 1309** (2013) 093

Sea quarks at the EIC

Simulations of transverse spatial quark distributions from DVCS cross-sections.



Simulated density of sea quarks in transverse plane from DVCS cross-sections and spin-asymmetries.



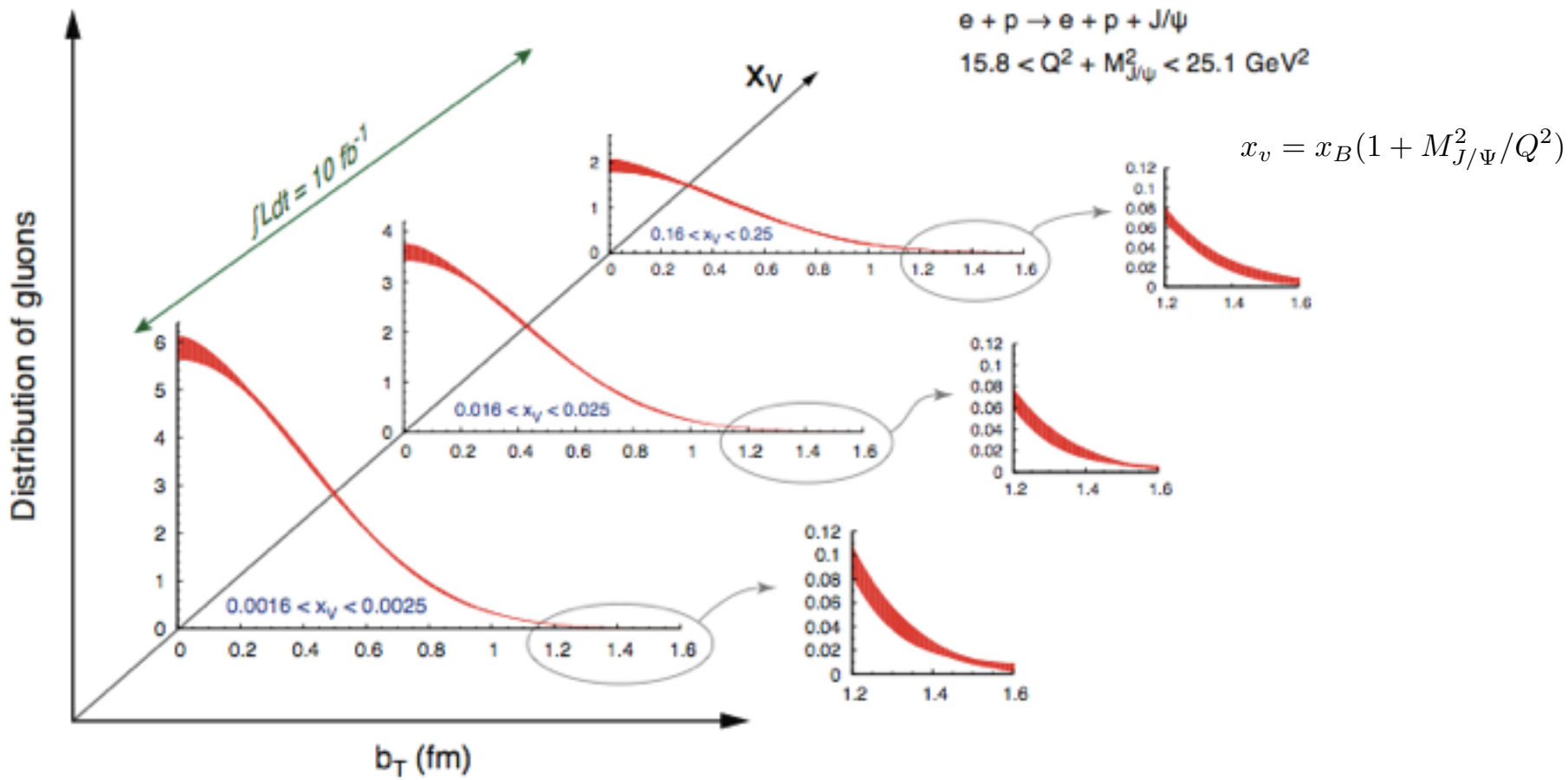
unpolarised proton

proton transversely polarised along x

EIC White Paper
arXiv:1212.1701v3 [nucl-ex]

Gluons at the EIC

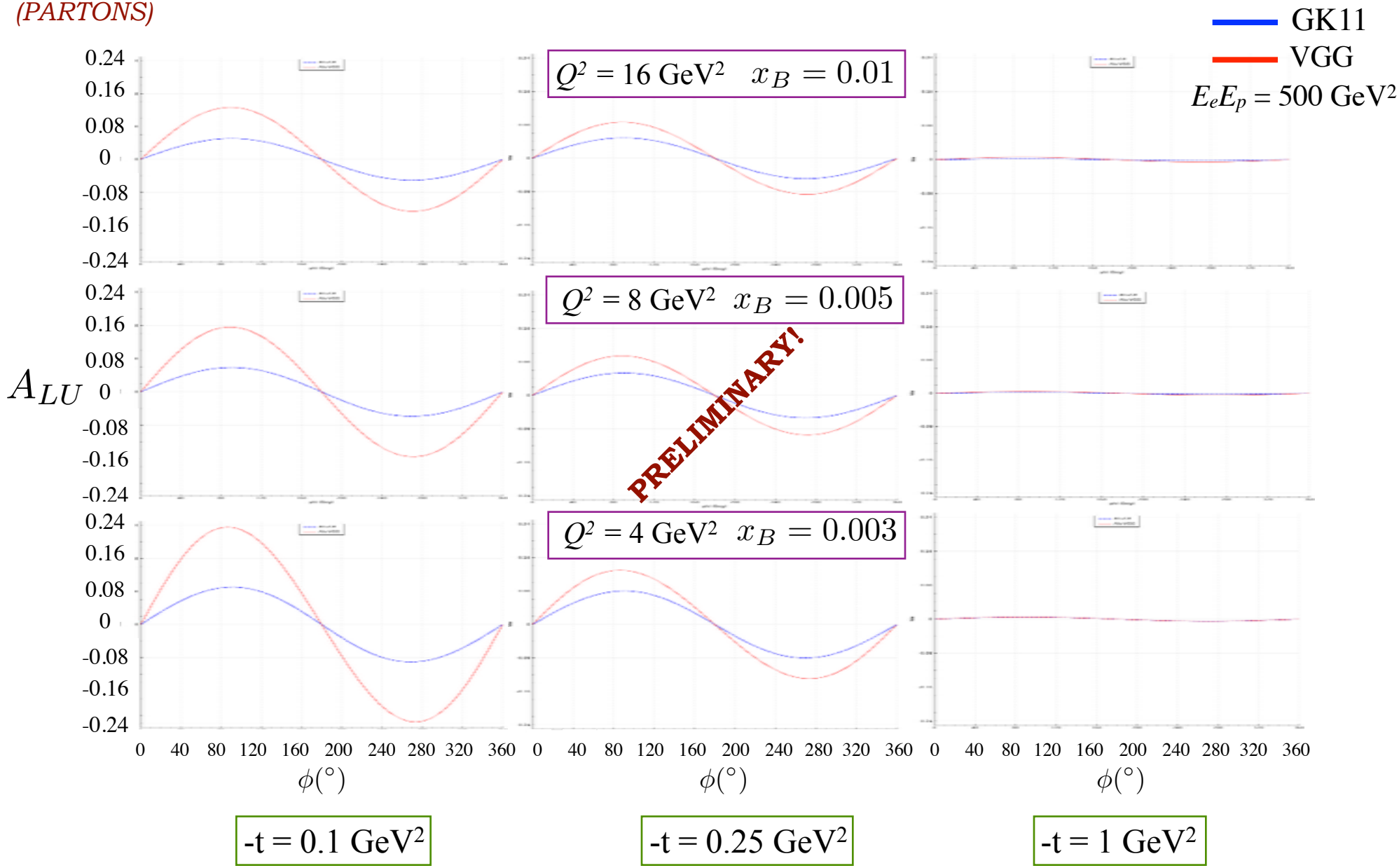
Simulations of transverse spatial gluon distributions from J/Ψ production at different gluon momenta x_v.



EIC White Paper, arXiv:1212.1701v3 [nucl-ex]

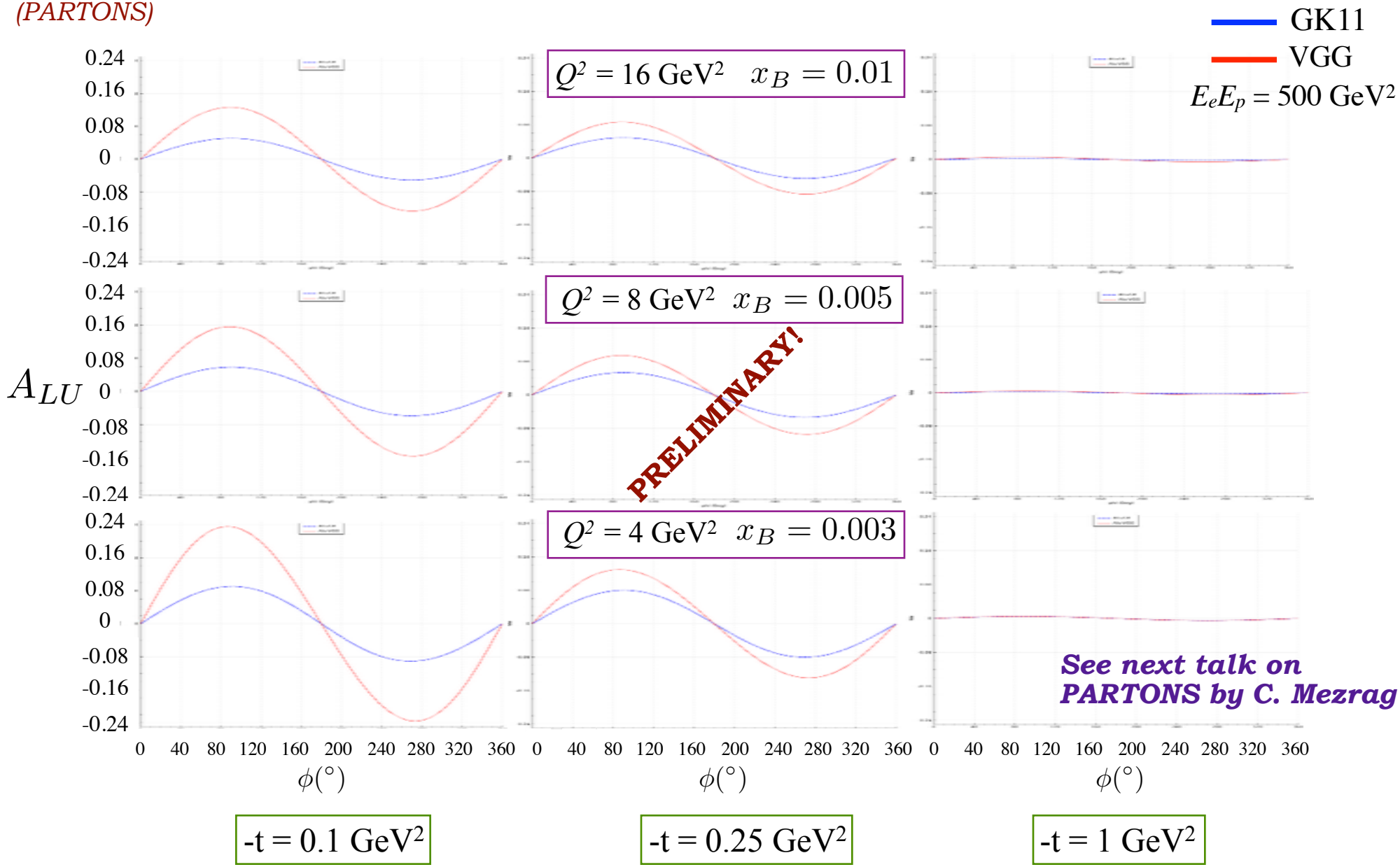
Luca Colaneri,
Nabil Chouika
(PARTONS)

DVCS beam-spin asymmetries at EIC



Luca Colaneri,
Nabil Chouika
(PARTONS)

DVCS beam-spin asymmetries at EIC



See next talk on PARTONS by C. Mezrag

To conclude...

* **GPDs** present a form of **tomography** of the nucleon, carry information on the composition of its **spin** and on the non-perturbative aspects of nucleon structure and confinement.

* Exclusive measurements from Jefferson Lab and HERMES provided validation of the GPD formalism and glimpses of nucleon structure in the **valence region**.

* EIC is crucial in exploring nucleon structure at the level of **sea quarks and gluons**; it needs to have *high luminosity, high polarisations, full acceptance detectors, a range of CM energies and nucleon and nuclear targets.*

* There is a strong theoretical and phenomenological effort in model development, data fitting and predictions across different kinematics — crucial to inform and guide EIC design: e.g.: the **PARTONS** framework.

* An exciting future for nucleon structure is opening with JLab @ 12 GeV and COMPASS II in the transition region and the EIC for the quark-gluon sea.

Thank you