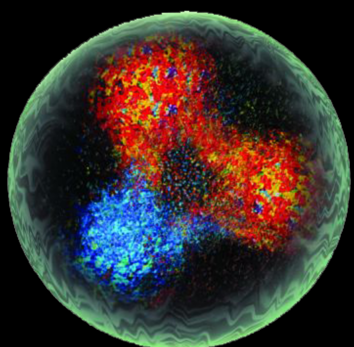
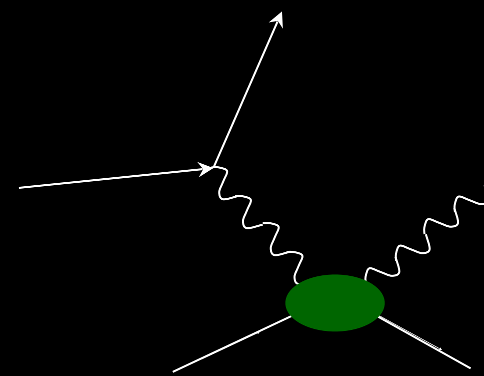
Status of DVCS experiments and open questions



Daria Sokhan

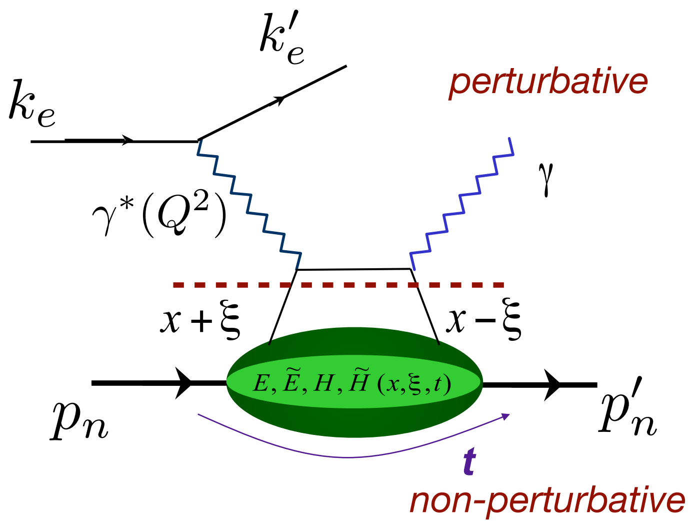
University of Glasgow, UK



Probing Nucleons and Nuclei in High Energy Collisions
Institute for Nuclear Theory, Seattle - 1st October 2018

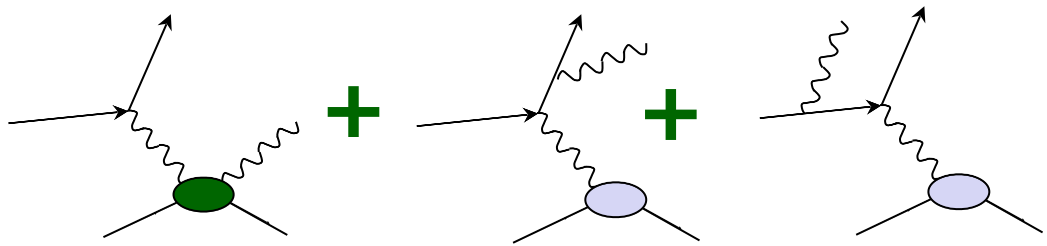
Deeply Virtual Compton scattering

DVCS: golden channel for the extraction of GPDs.



* At high exchanged Q^2 and low t access to four chiral-even GPDs:

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



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

interference term

$$Q^2 = -(\mathbf{k}-\mathbf{k}')^2 \qquad t = (\mathbf{p}'_\mathbf{n} - \mathbf{p}_\mathbf{n})^2$$

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

$x \pm \xi$ *longitudinal momentum fractions of the struck parton*

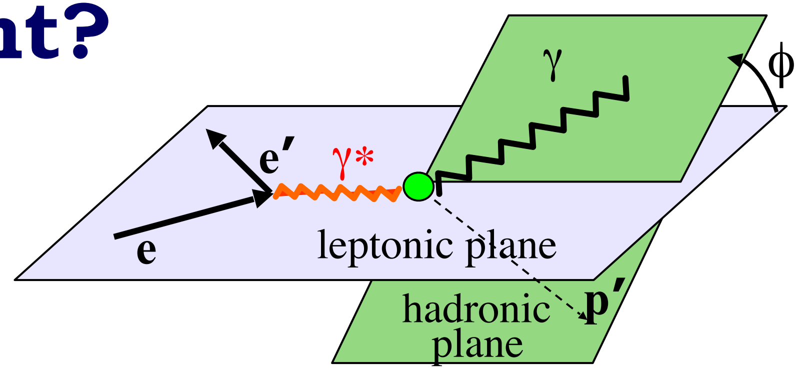
$$\xi \cong \frac{x_B}{2-x_B}$$

Experimentally accessible (at leading twist, leading order):

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

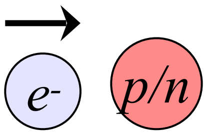
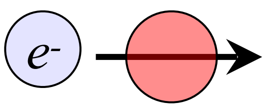
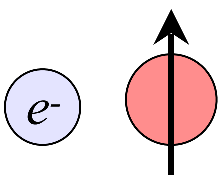
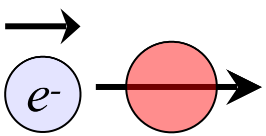
Compton Form Factors (CFF)

Which DVCS experiment?



Real parts of CFFs accessible in cross-sections, beam-charge and double polarisation asymmetries,

imaginary parts of CFFs in single-spin asymmetries.

Beam, target polarisation	*For example:*		Proton / Neutron
	$\Delta\sigma_{LU} \sim \sin\phi\, \Im(F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E)\, d\phi$	→	$Im\{\boldsymbol{H}_\mathbf{p}, \tilde{H}_\mathrm{p}, E_\mathrm{p}\}$ $Im\{H_\mathrm{n}, \tilde{H}_\mathrm{n}, \boldsymbol{E}_\mathbf{n}\}$
	$\Delta\sigma_{UL} \sim \sin\phi\, \Im(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) - \xi \frac{t}{4M^2} F_2 \tilde{E} + \ldots)\, d\phi$	→	$Im\{\boldsymbol{H}_\mathbf{p}, \boldsymbol{\tilde{H}}_\mathbf{p}\}$ $Im\{\boldsymbol{H}_\mathbf{n}, E_\mathrm{n}, \tilde{E}_\mathrm{n}\}$
	$\Delta\sigma_{UT} \sim \cos\phi\, \Im(\frac{t}{4M^2}(F_2 H - F_1 E) + \ldots) d\phi$	→	$Im\{\boldsymbol{H}_\mathbf{p}, \boldsymbol{E}_\mathbf{p}\}$ $Im\{\boldsymbol{H}_\mathbf{n}\}$
	$\Delta\sigma_{LL} \sim (A + B\cos\phi)\, \Re(F_1 \tilde{H} + \xi G_M (H + \frac{x_B}{2} E) + \ldots) d\phi$	→	$Re\{\boldsymbol{H}_\mathbf{p}, \boldsymbol{\tilde{H}}_\mathbf{p}\}$ $Re\{\boldsymbol{H}_\mathbf{n}, E_\mathrm{n}, \tilde{E}_\mathrm{n}\}$

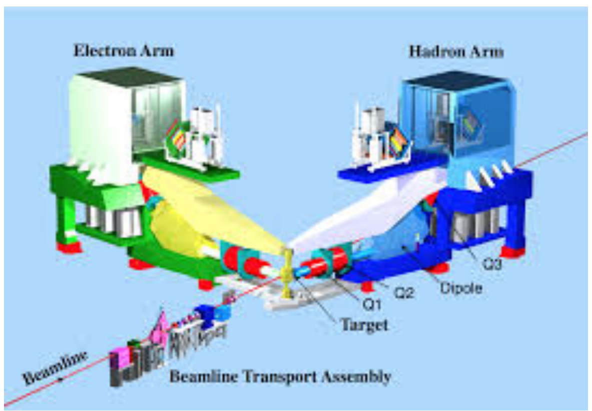
JLab: the experimental facility

Jefferson Lab: 6 GeV era

CEBAF: Continuous Electron Beam Accelerator Facility.

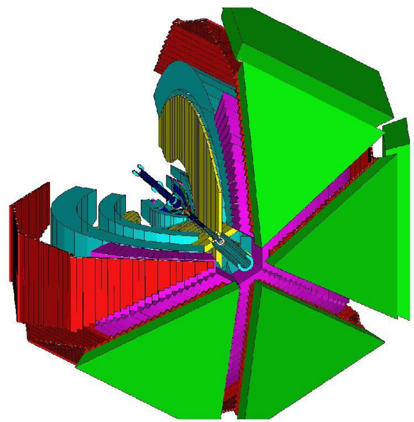
- Energy up to ~6 GeV
- Energy resolution $\delta E/E_e \sim 10^{-5}$
- Longitudinal electron polarisation up to ~85%

Hall A:



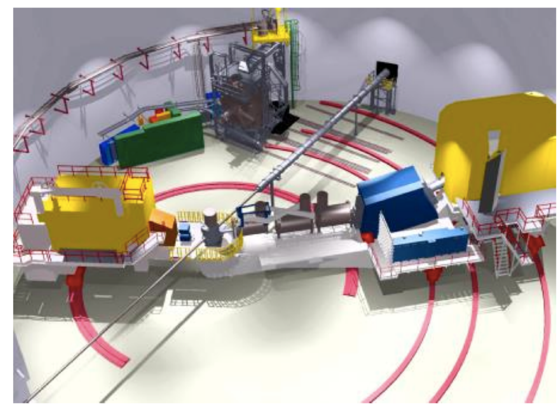
- High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity.

Hall B: CLAS



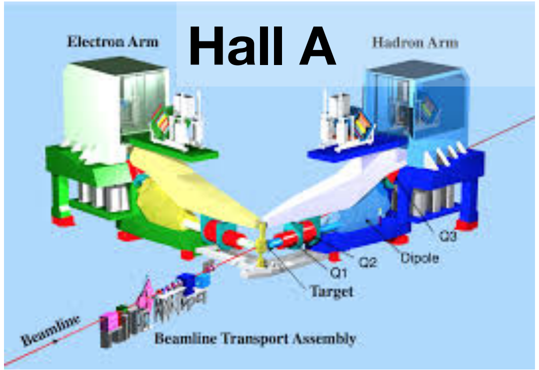
- Very large acceptance, detector array for multi-particle final states.

Hall C:

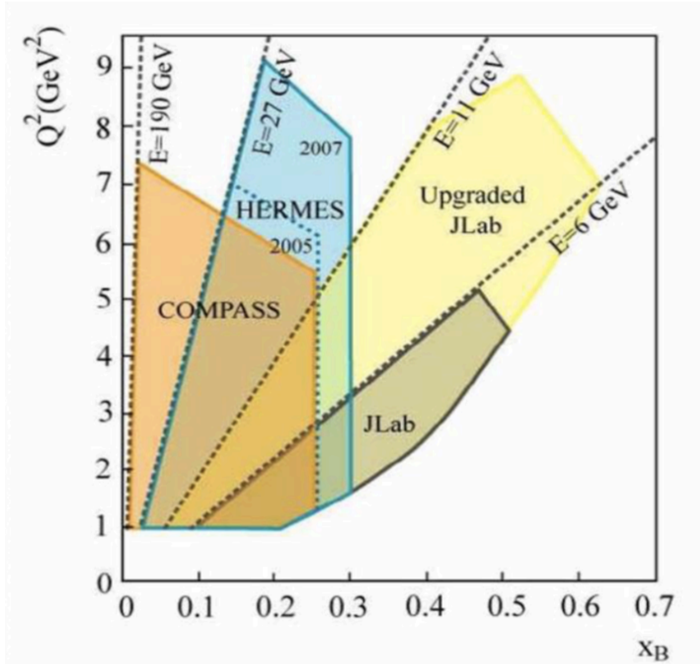


- Two movable spectrometer arms, well-defined acceptance, high luminosity

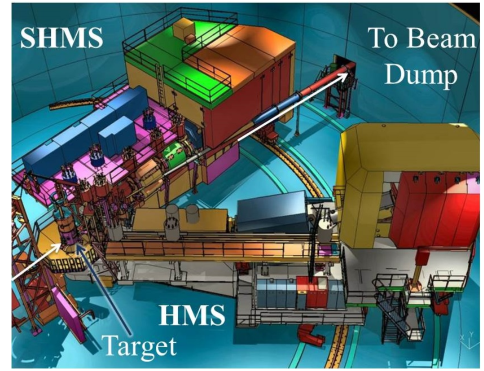
JLab @ 12 GeV



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

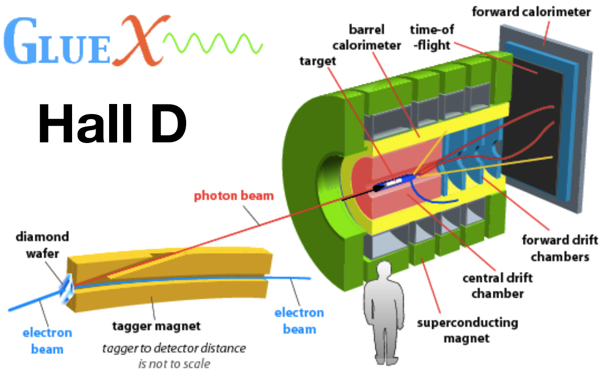


Hall C



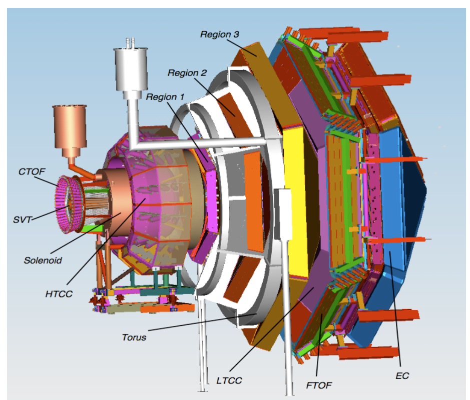
Two movable high momentum spectrometers, well-defined acceptance, very high luminosity.

Hall D



9 GeV tagged polarised photons, full acceptance

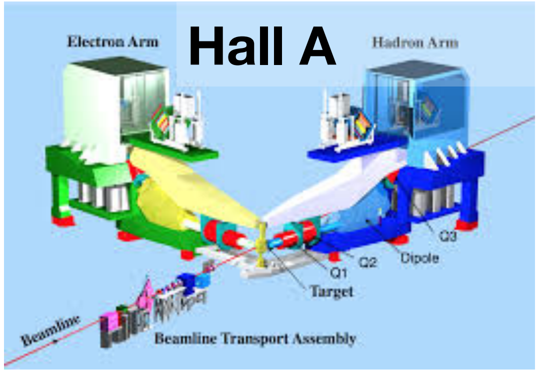
Hall B: CLAS12



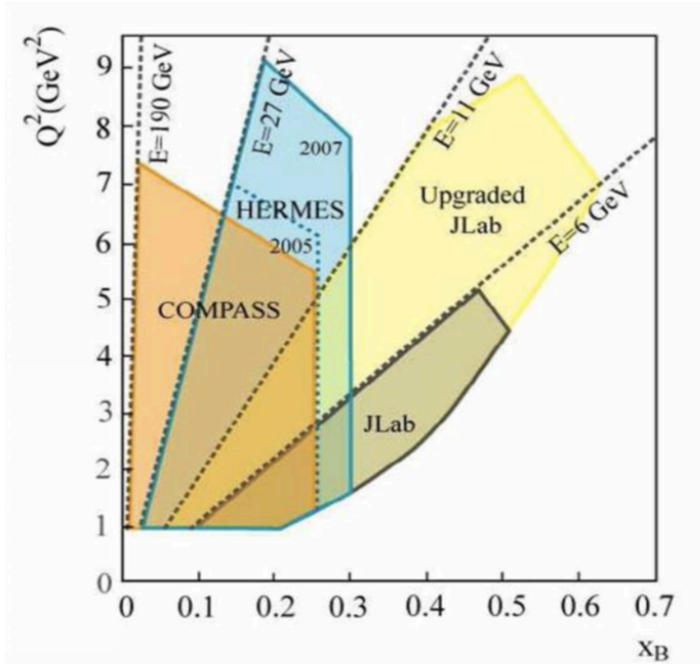
Very large acceptance, high luminosity.

JLab @ 12 GeV

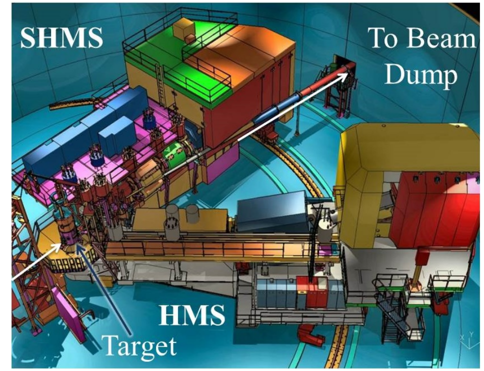
Hall A



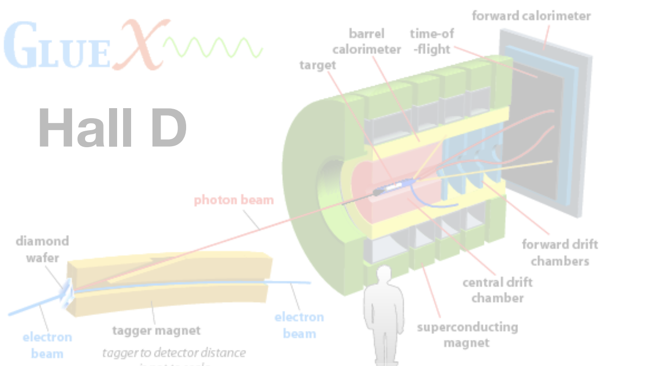
High resolution($\delta p/p = 10^{-4}$) spectrometers, very high luminosity, large installation experiments.



Hall C

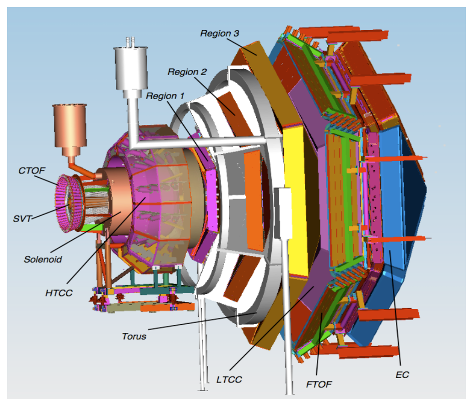


Two movable high momentum spectrometers, well-defined acceptance, very high luminosity.



9 GeV tagged polarised photons, full acceptance

Hall B: CLAS12



Very large acceptance, high luminosity.

CLAS12

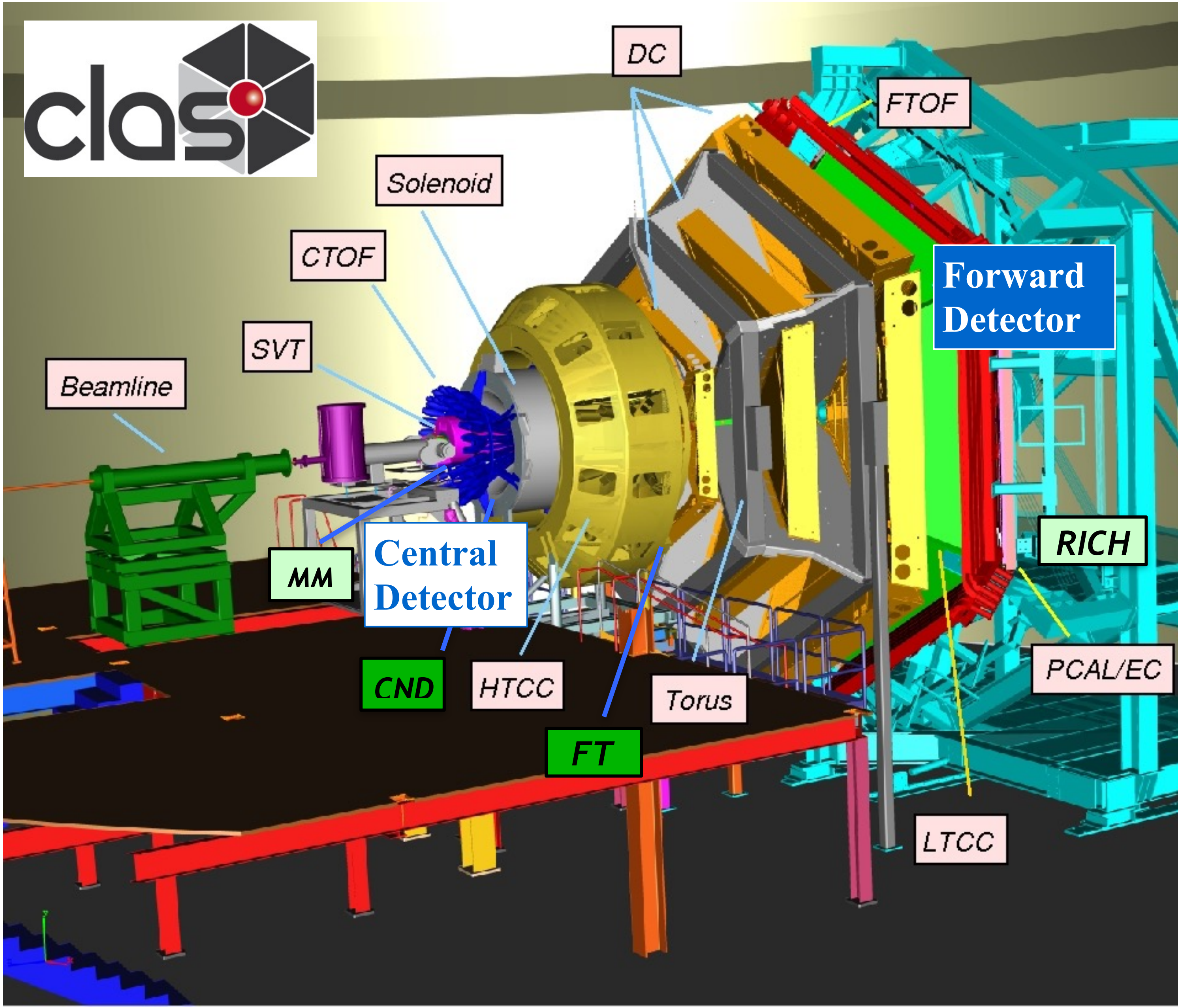
Design luminosity
$L \sim 10^{35}$ cm^{-2} s^{-1}

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

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

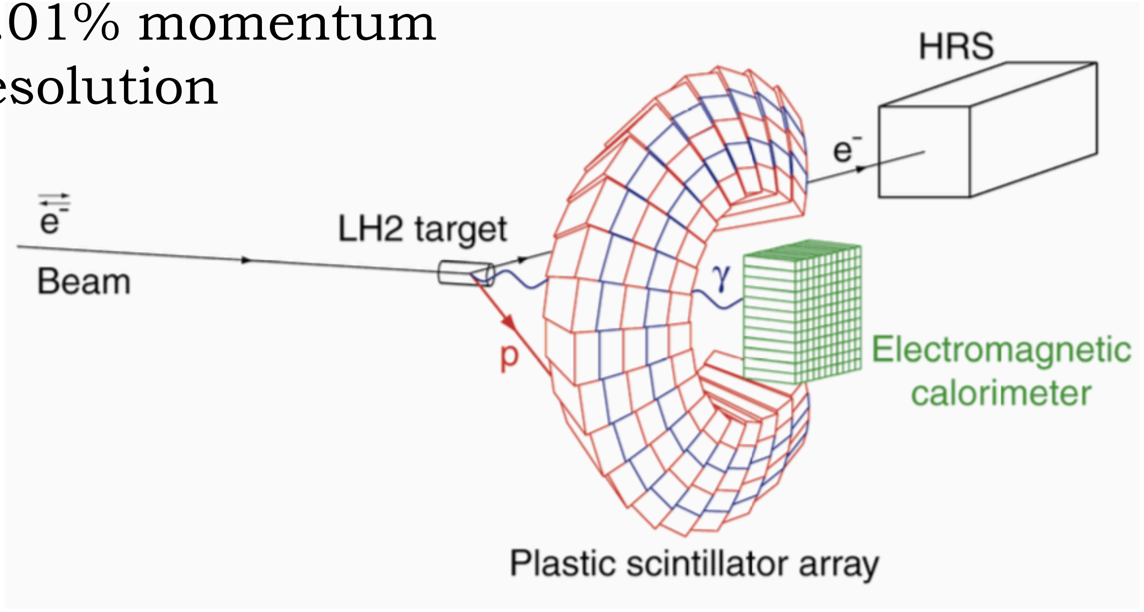
Acceptance for all charged particles:
- $5^o < \theta < 125^o$

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

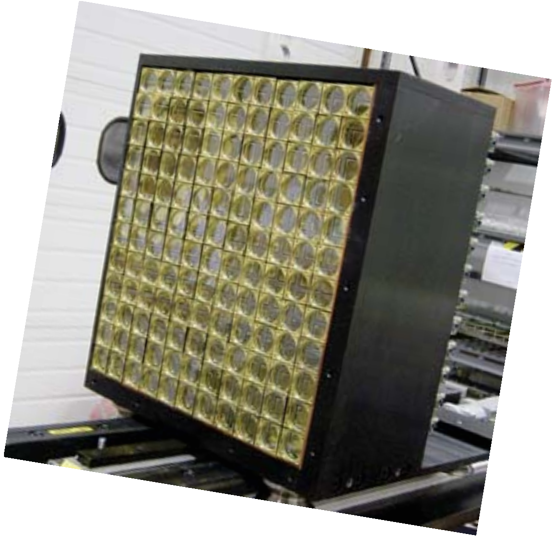


DVCS in Hall A

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



Detect photon in PbF_2 calorimeter: < 3% energy resolution



Detect recoil proton in plastic scintillator array.

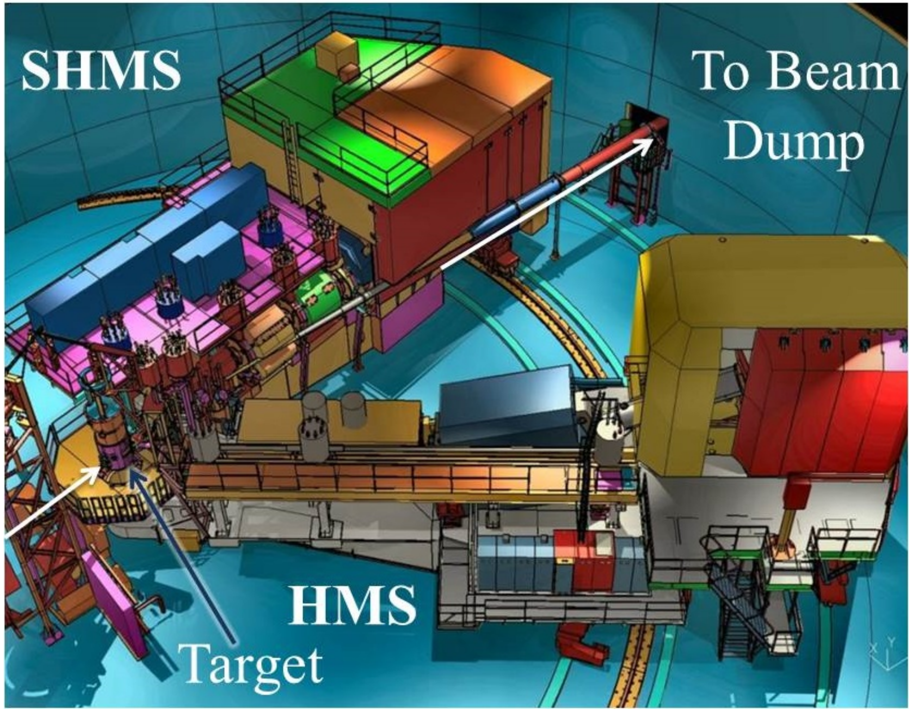
DVCS in Hall C

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

Detect photon in $PbWO_4$ calorimeter.

Sweeping magnet to reduce backgrounds in calorimeter.

Reconstruct recoiling proton through missing mass.

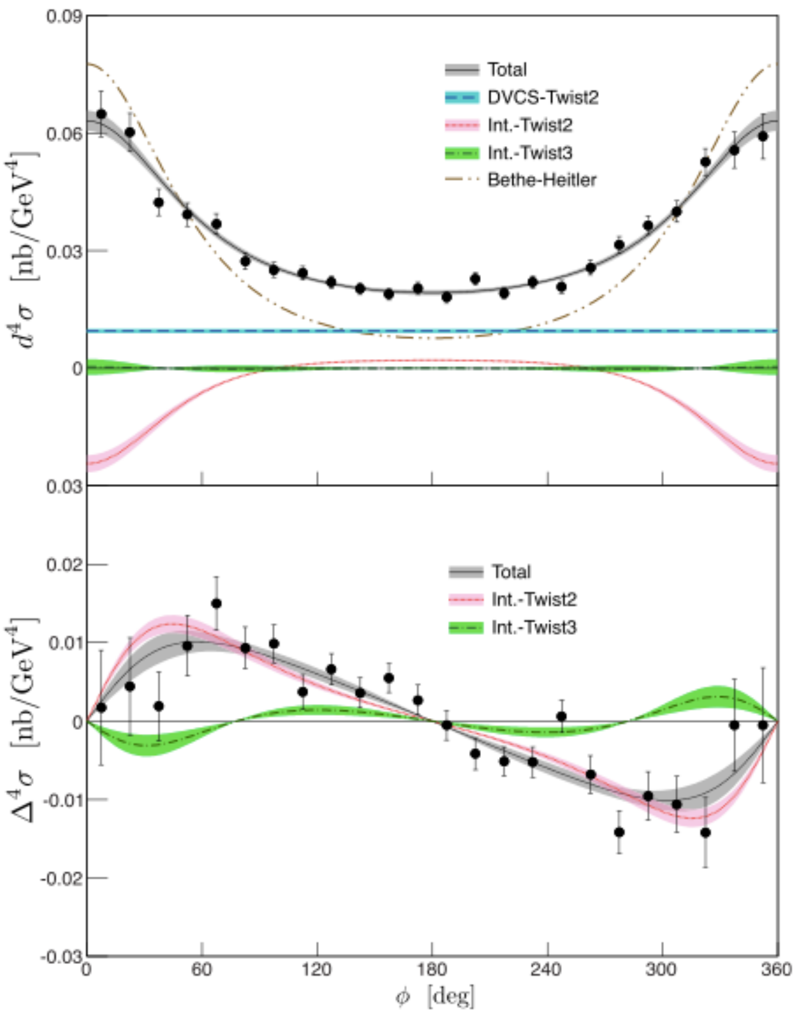


DVCS @ JLab:
6 GeV era

First DVCS cross-sections in valence region

Hall A

* E00-110: Hall A, ran in 2004, high precision, narrow kinematic range.



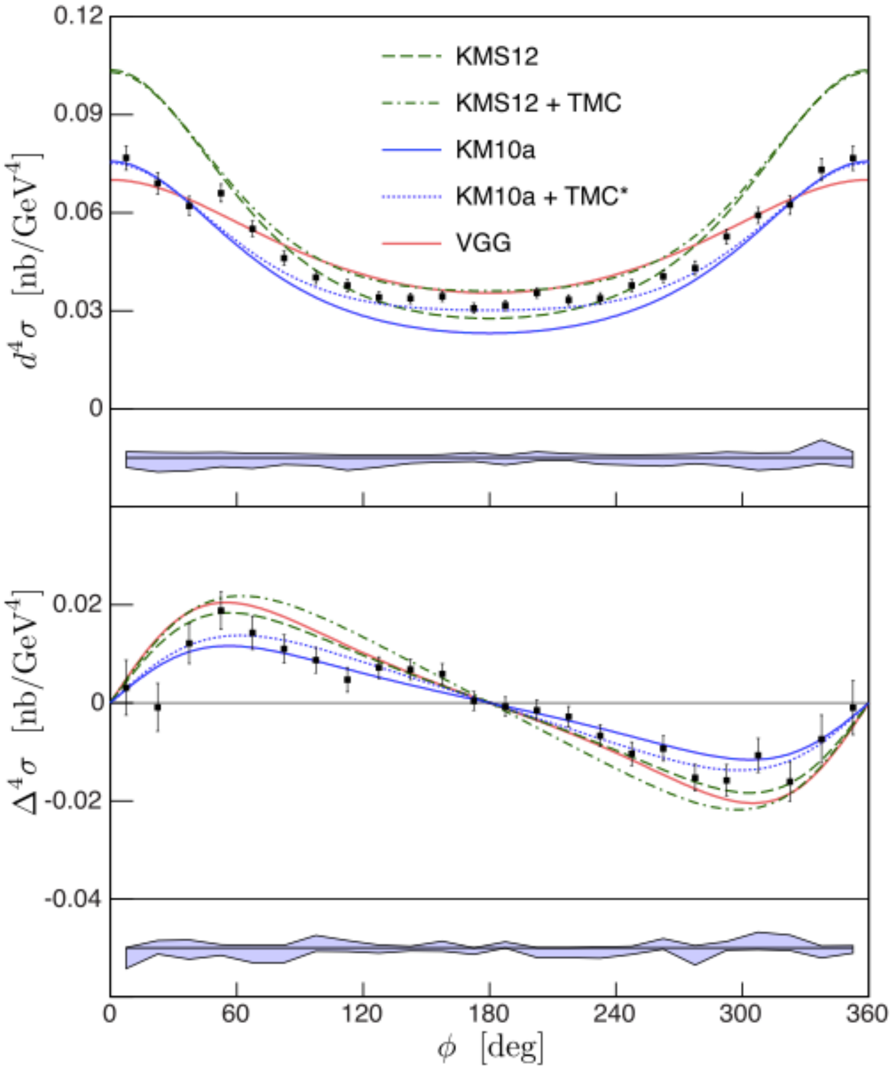
$x_B = 0.36, Q^2 = 2.3\ GeV^2, -t = 0.32\ GeV^2$

* Luminosity =10^{37} cm^{-2}s^{-1}.
* Measure Q^2-dependence (Q^2: 1.5, 1.9, 2.3 GeV^2) of DVCS-BH cross-sections at fixed x_B (0.36).
* Also x_B dependence at constant Q^2.
* CFFs show scaling in DVCS: leading twist (twist-2) dominance at this moderate Q^2.
* Strong deviation of unpolarised DVCS cross-section from BH: extraction of $\left|T_{DVCS}\right|^2$ amplitude as well as interference terms.
* Separation of real part of the twist-2 interference term and the $\left|T_{DVCS}\right|^2$ amplitude is very sensitive to relative cross-sections at $\phi = 0^\circ$ and $\phi = 180^\circ$.

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

First DVCS cross-sections in valence region

Hall A



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

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

VGG model: Vanderhaeghen, Guichon, Guidal

KMS model: Kroll, Moutarde, Sabatié

KM model: Kumericki, Mueller

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

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

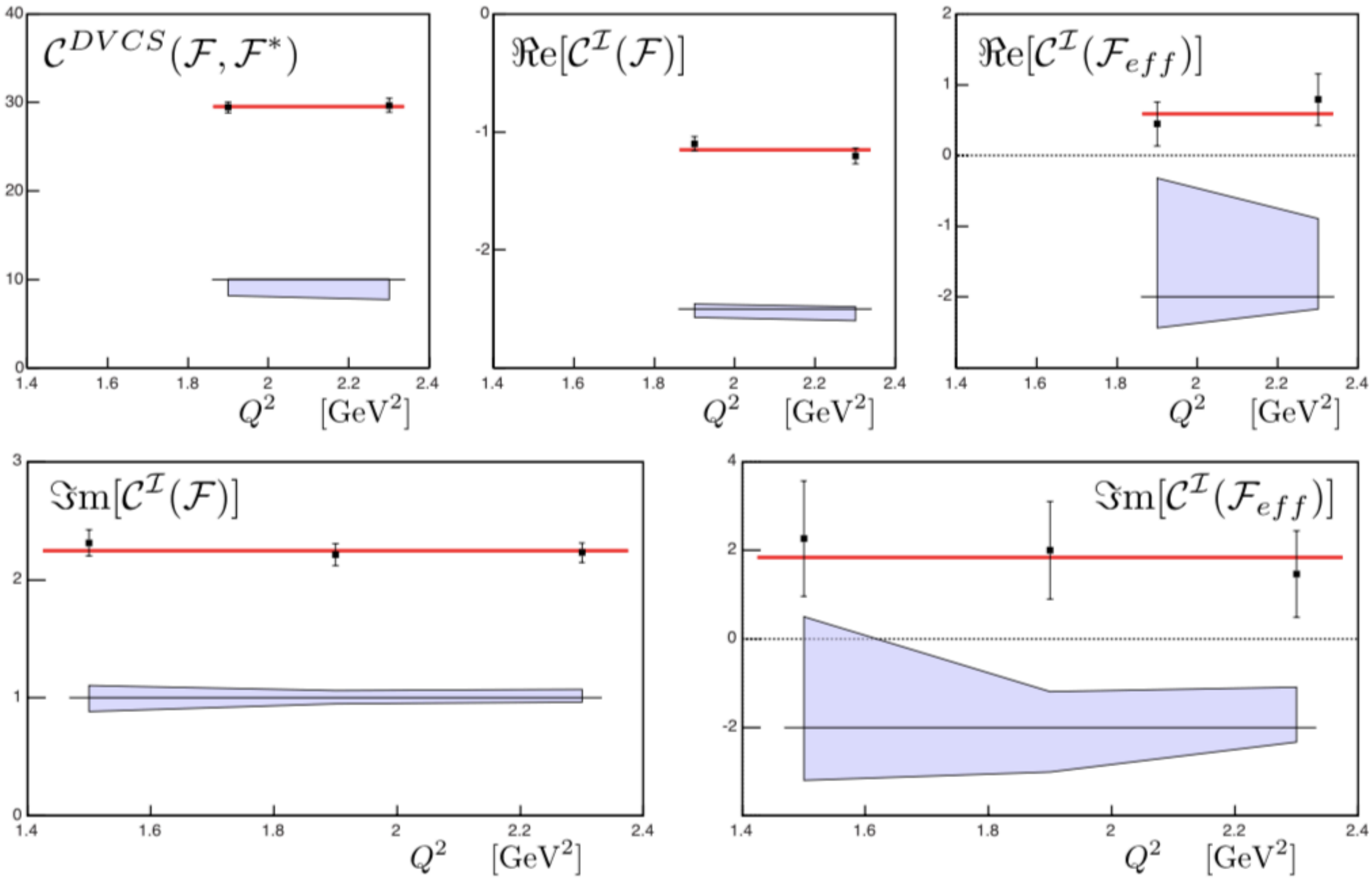
→ TMC*: TMC extracted from the KMS12 model and applied to KM10a.

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

The devil is in the detail…

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

CFFs from the Hall A cross-sections



No Q^2 dependence within this range: scaling.

F_{eff}: "Effective" twist-3 CFF

C terms are combinations of CFFs, eg:

$$\mathcal{C}^{\mathcal{I}}(\mathcal{F}) = F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

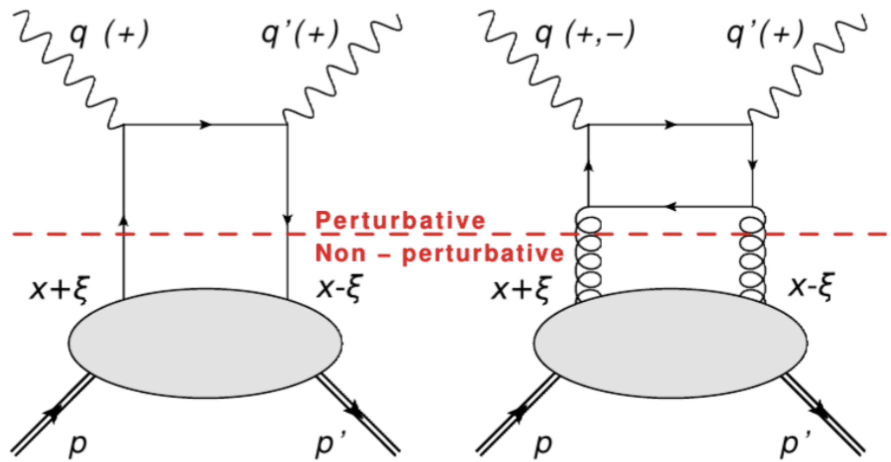
M. Defurne *et al*, ***PRC* 92** (2015) 055202.

Here comes the twist...

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

  Bold assumption for JLab 6 GeV kinematics!

Leading order (LO) | Next-to-leading order (NLO)



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

helicity of real produced photon

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

helicity of virtual incoming photon

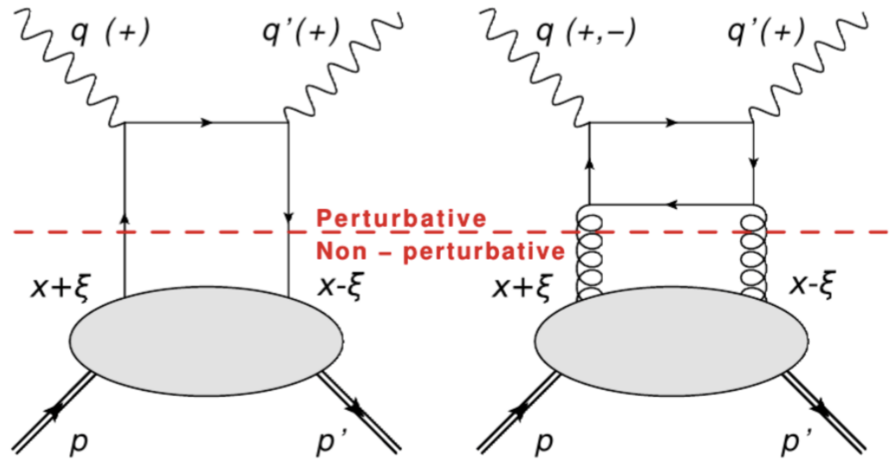
  - Helicity-conserved CFFs — $\mathcal{F}_{++}$
  - Helicity-flip (transverse) — $\mathcal{F}_{-+}$
  - Longitudinal to transverse flip — $\mathcal{F}_{0+}$

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

Here comes the twist...

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

Leading order (LO) | Next-to-leading order (NLO)



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

$$\mathcal{F}_{++} = \mathbb{F}_{++} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+}$$
$$\mathcal{F}_{-+} = \mathbb{F}_{-+} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+}$$
$$\mathcal{F}_{0+} = -(1+\chi)\mathbb{F}_{0+} + \chi_0\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right]$$

Belitsky CFFs

Braun CFFs

Assuming LO and LT in the Braun frame:

$$\begin{aligned} \mathcal{F}_{++} &= (1 + \tfrac{\chi}{2})\mathbb{F}_{++} \\ \mathcal{F}_{-+} &= \tfrac{\chi}{2}\mathbb{F}_{++} \\ \mathcal{F}_{0+} &= \chi_0 \mathbb{F}_{++} \end{aligned}$$

HT/HO contributions in the Belitsky frame, scaled by kinematic factors χ and χ_0.

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

$\chi_0 = 0.25,\ \chi = 0.06$ for $Q^2 = 2\ \mathrm{GeV}^2,\ x_B = 0.36,\ t = -0.24\ \mathrm{GeV}^2$

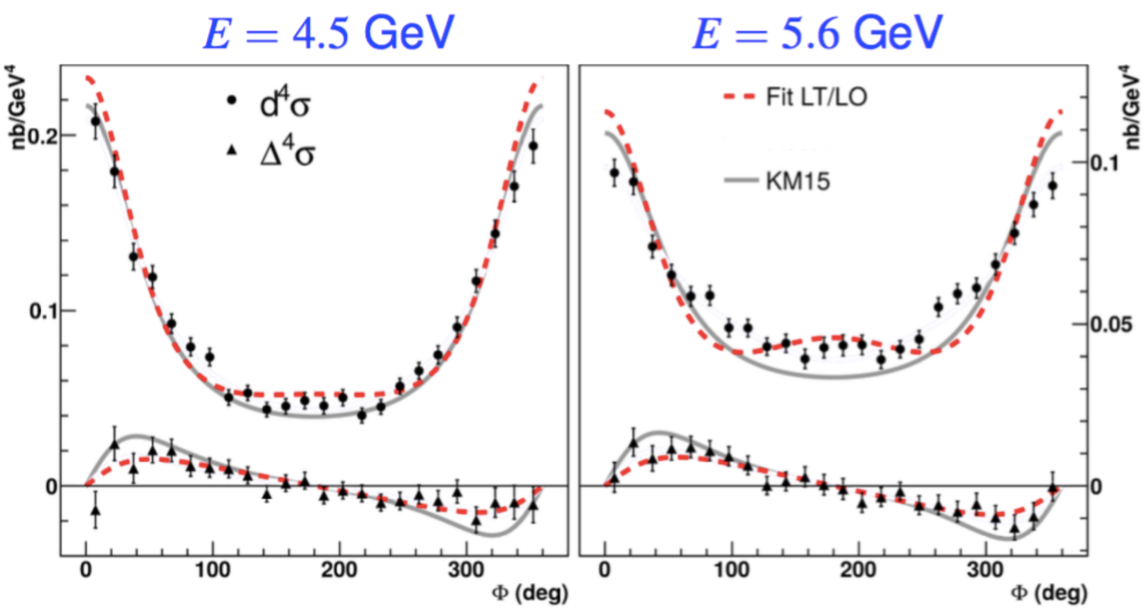
M. Defurne *et al*, ***Nature Communications 8*** (2017) 1408

Hints of higher twist or higher orders

Hall A

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

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



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

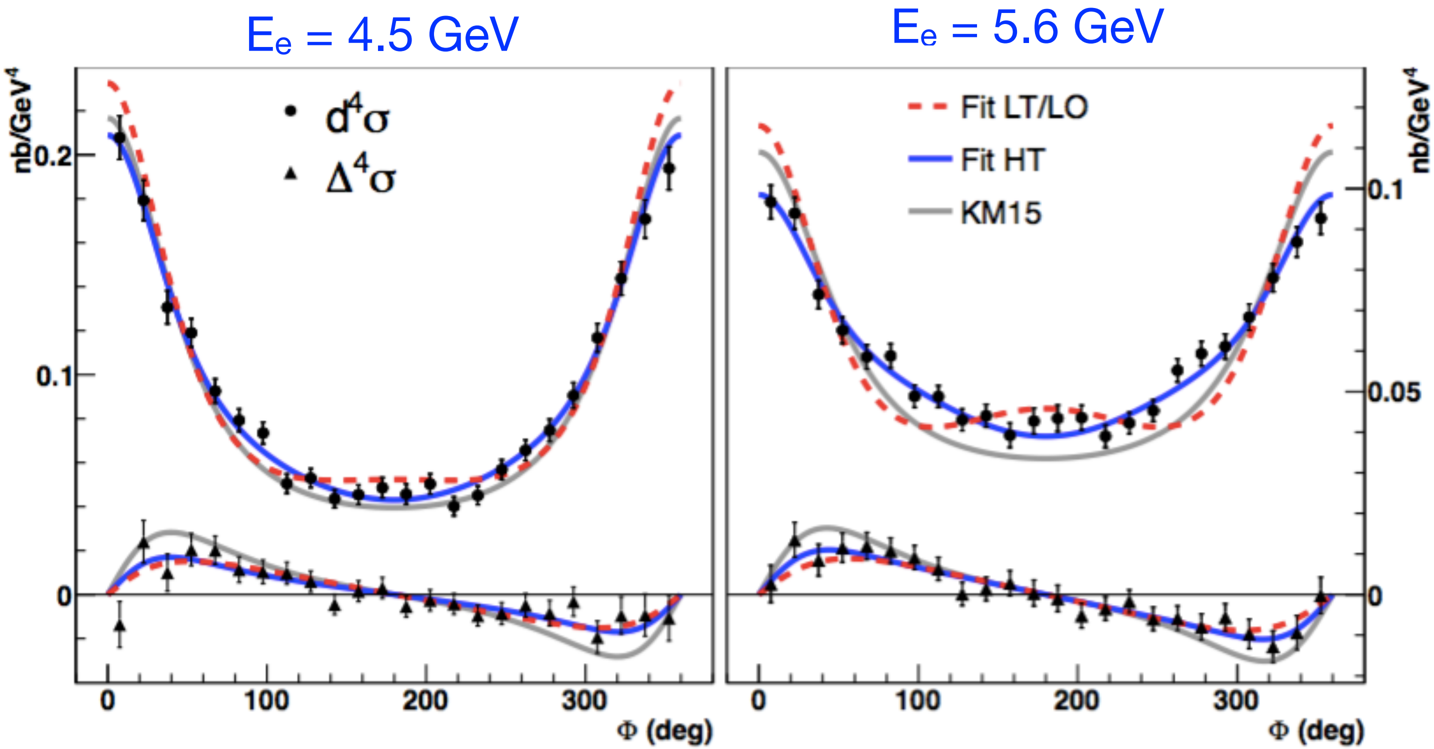
Using Braun's decomposition, $\mathbb{H}_{-+}$ and $\mathbb{H}_{0+}$ can't be neglected.

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

Hints of higher twist or higher orders

Hall A

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



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

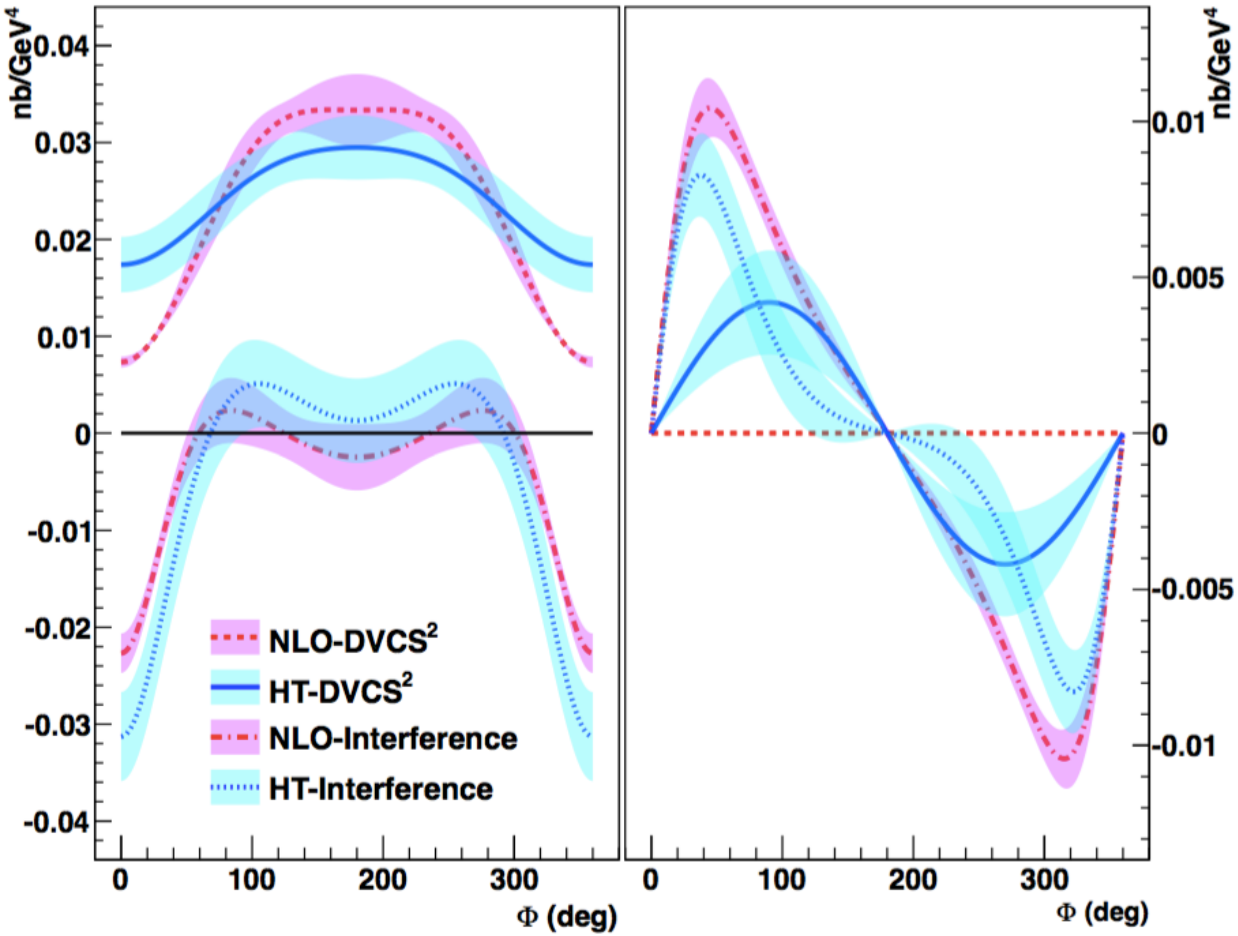
Wider range of beam energy needed to identify the dominant effect → **JLab at 11 GeV.**

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

Rosenbluth separation of DVCS² and BH-DVCS terms

Hall A

- Generalised Rosenbluth separation of the DVCS² (scales as E_e^2) and the BH-DVCS interference (scales as E_e^3) terms in the cross-section is possible but NLO and/or higher-twist required.

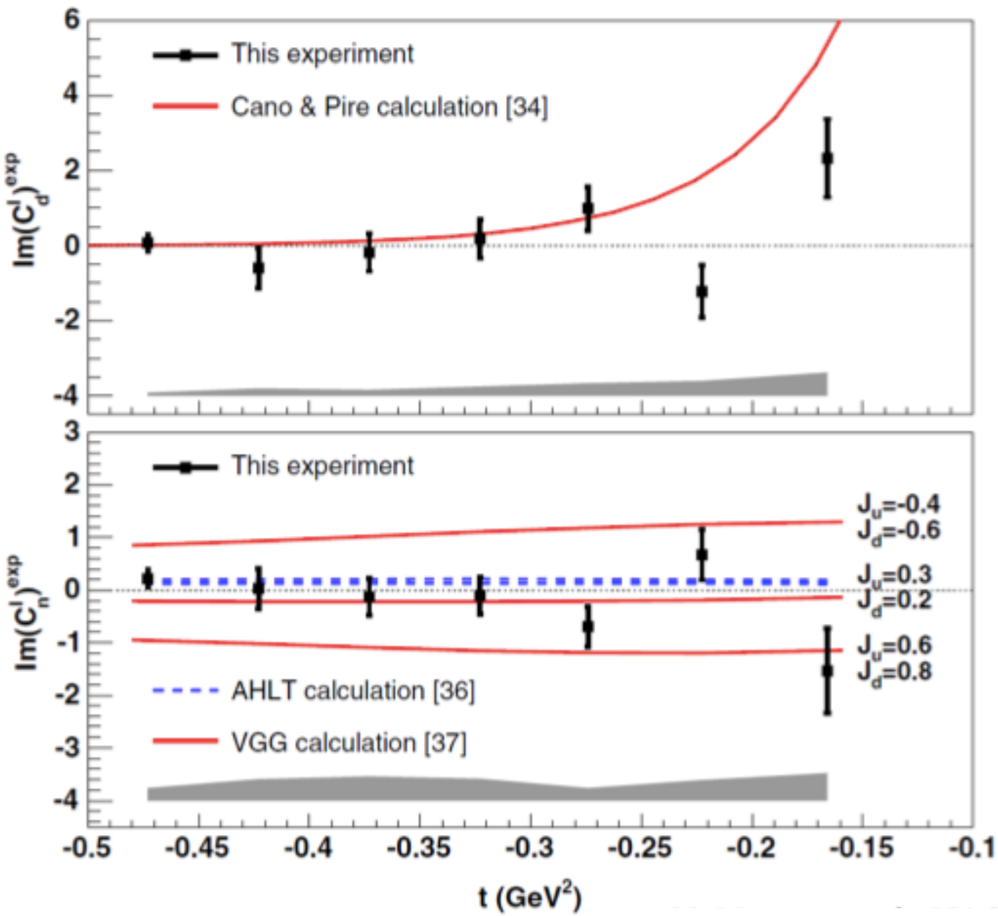


- Significant differences between pure DVCS and interference contributions.
- Helicity-dependent cross-section has a sizeable DVCS² contribution in the higher-twist scenario.
- Separation of HT and NLO effects requires scans across wider ranges of Q^2 and beam energy: JLab12!

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

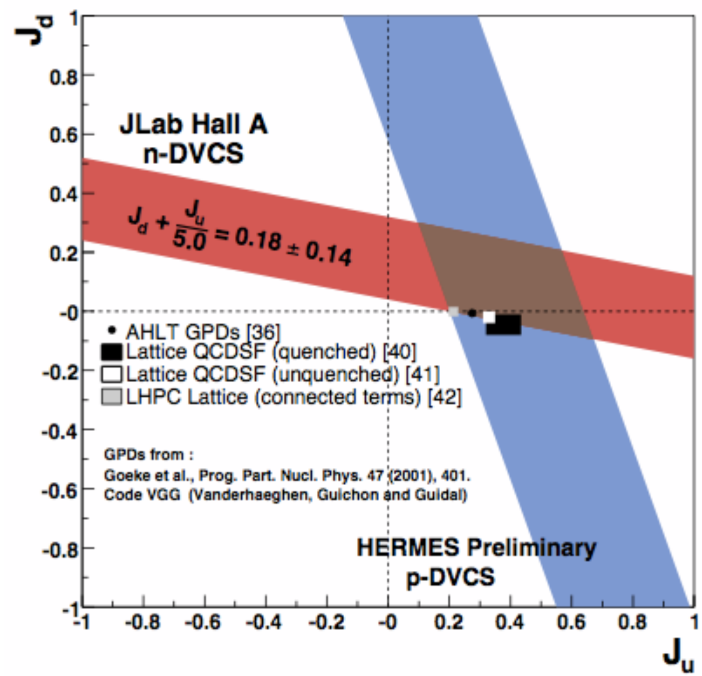
Beam-spin asymmetry in neutron DVCS

Hall A



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.



Experiment E03-106

DVCS on neutron @ different beam energies

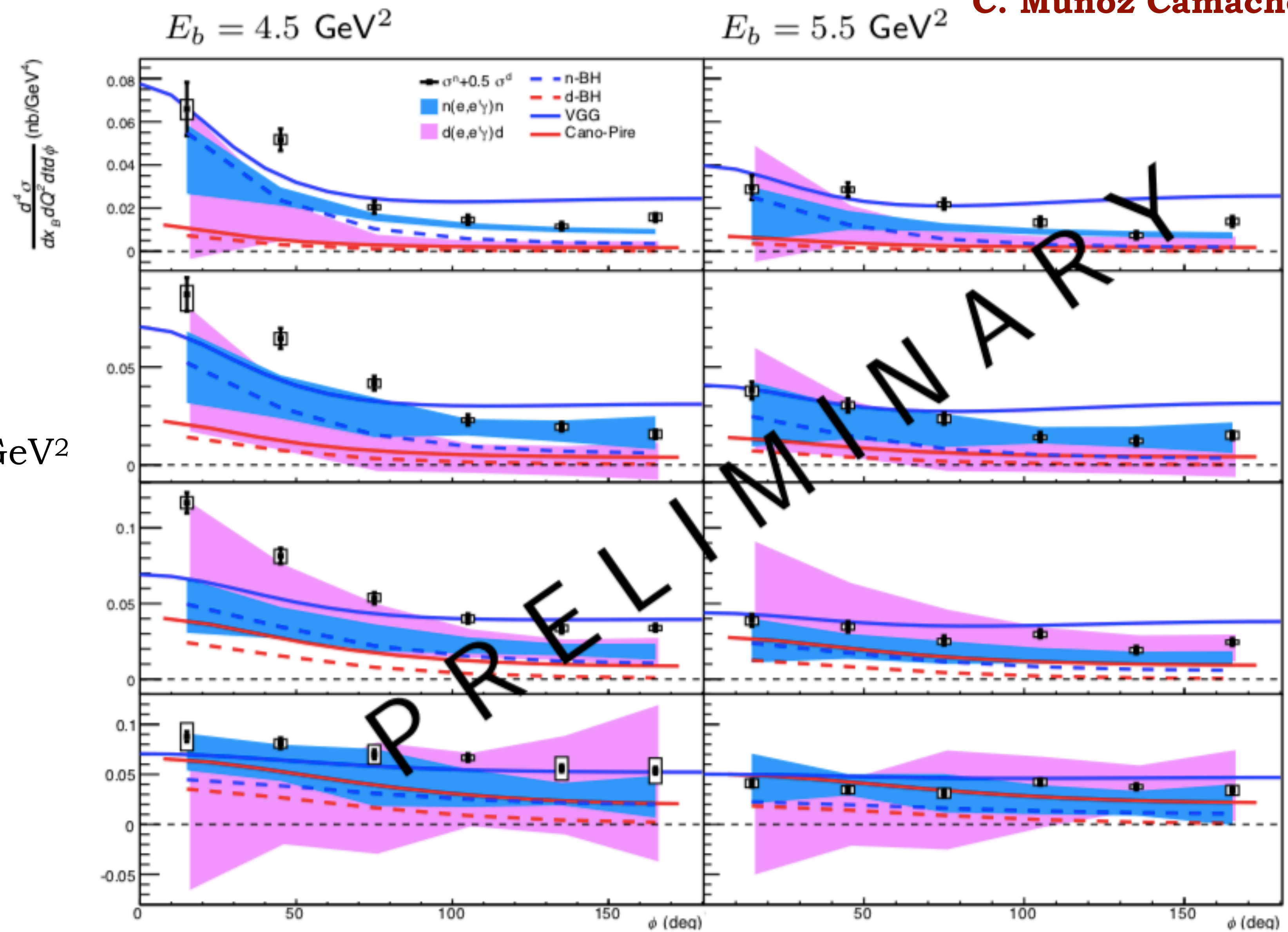
C. Muñoz Camacho

Experiment:
E08-025

LD_2 target

$<Q^2>$ = 1.75 GeV^2

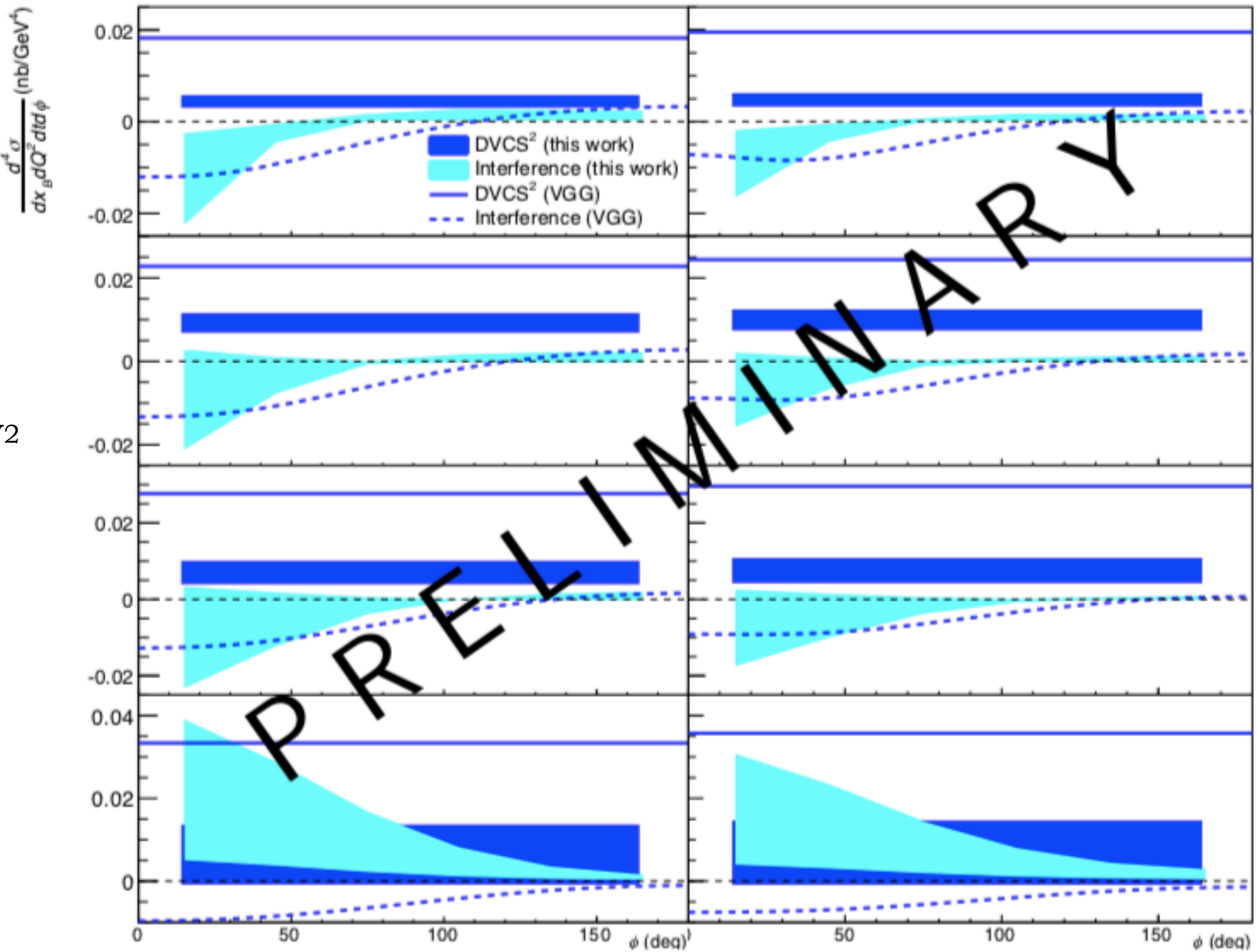
$<x_B>$ = 0.36



DVCS on neutron @ different beam energies

C. Muñoz Camacho

Experiment:
E08-025



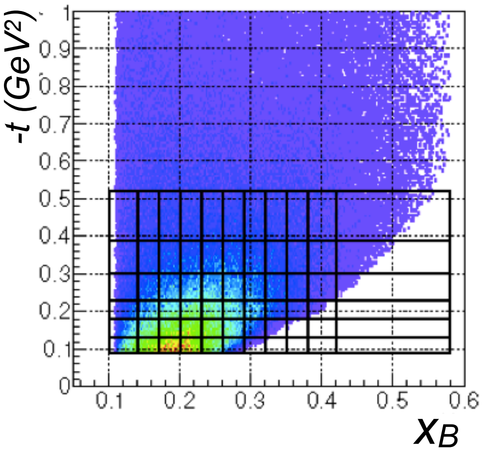
LD$_2$ target

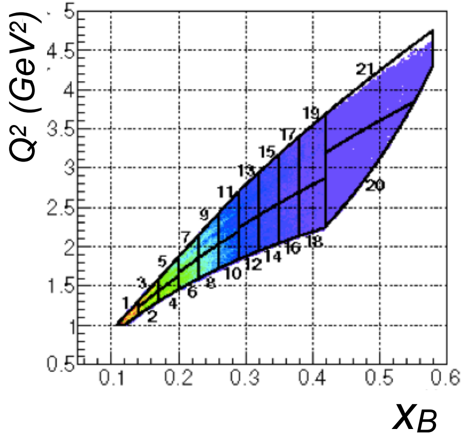
$<Q^2>$ = 1.75 GeV^2

$<x_B>$ = 0.36

Separation of Interference and DVCS terms

CLAS unpolarised cross-sections



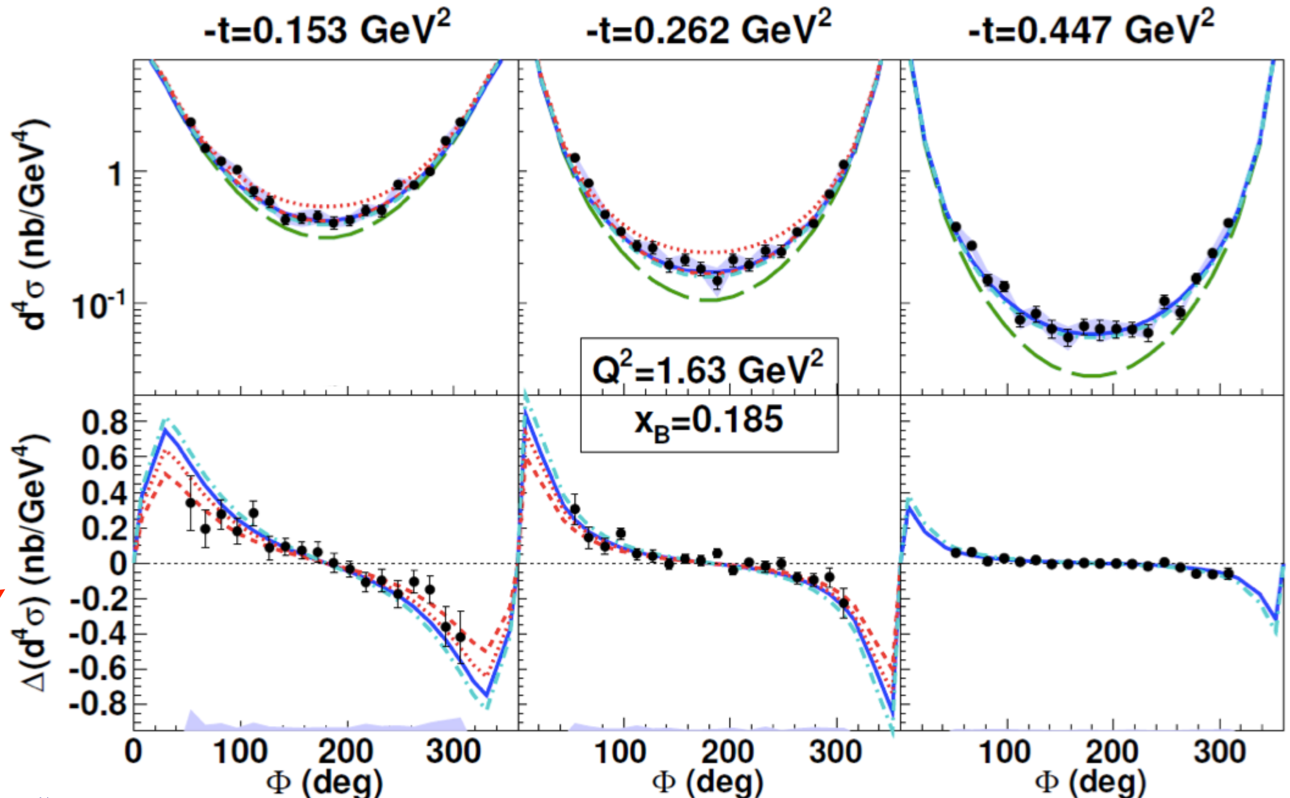


- BH only
- VGG *(Vanderhaeghen, Guichon, Guidal) - H only*
- KM10 (Kumericki, Mueller) *includes strong* $\tilde{H}$
- KM10a *(sets* $\tilde{H}$ *to zero)*
- KMS *(Kroll, Moutarde, Sabatié, tuned on low* x_B *meson-production data)*

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

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

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



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

Towards tomography of the proton

CLAS

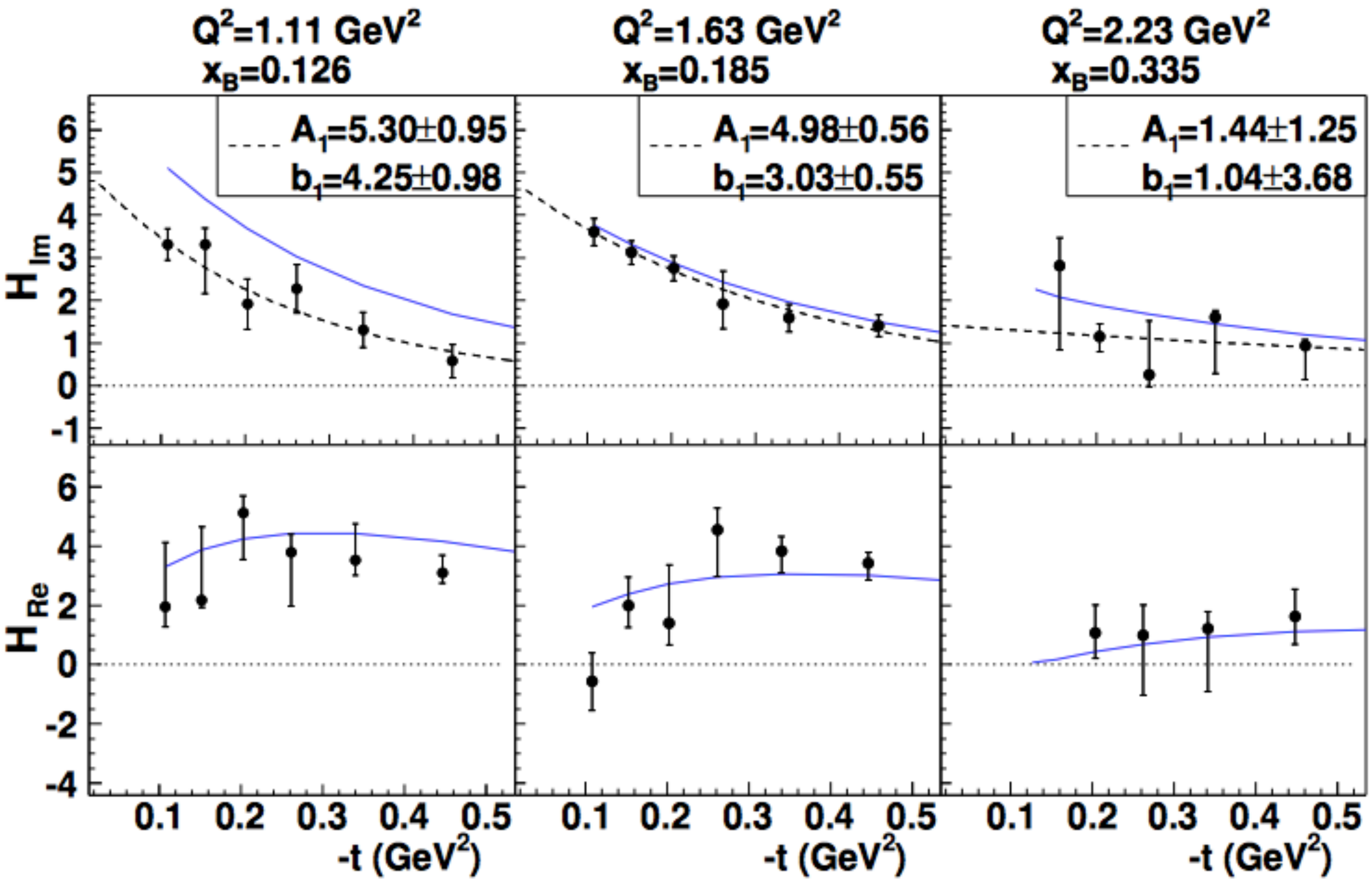
- CFFs extracted in a VGG fit (local fit: constraint 5 times the predicted value)
- Imaginary part of CFF: $F_{Im}(\xi, t) = F(\xi, \xi, t) \mp F(-\xi, \xi, t)$

VGG prediction

Ae^{bt}

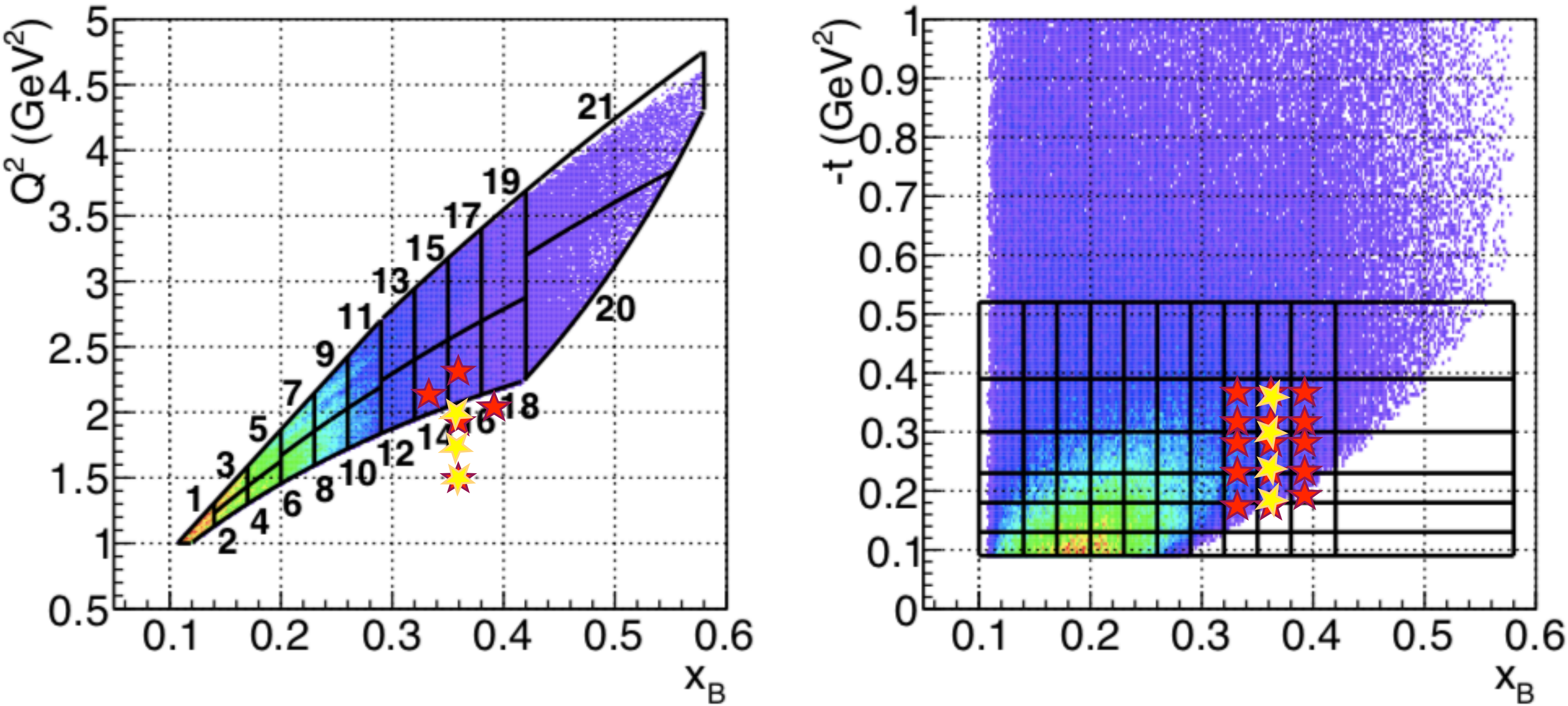
- H_{Im} slope in t becomes flatter at higher x_B

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



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

JLab 6 GeV era DVCS X-sections: kinematics

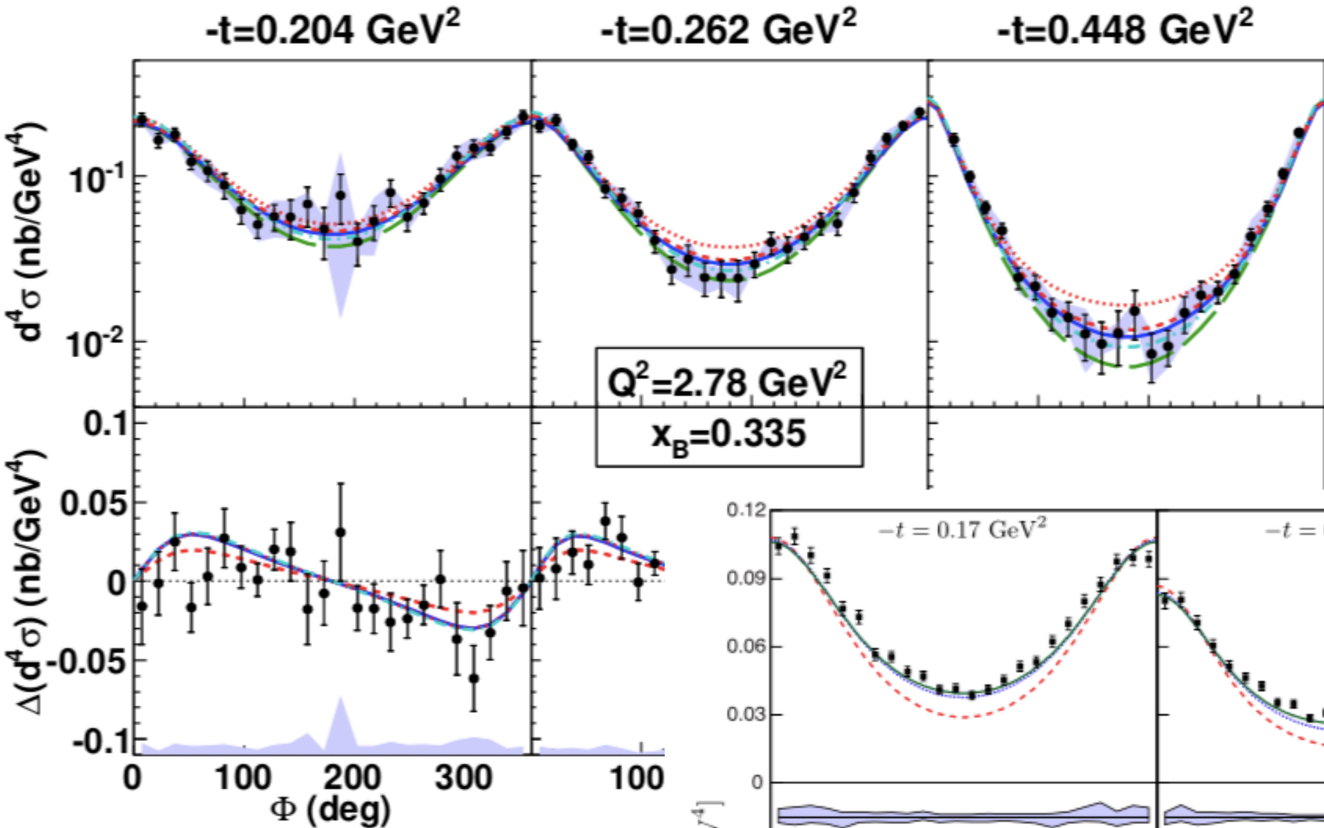


CLAS 2D distributions: H.-S. Jo *et al* (CLAS), ***PRL* 115** (2015) 212003

Hall A

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

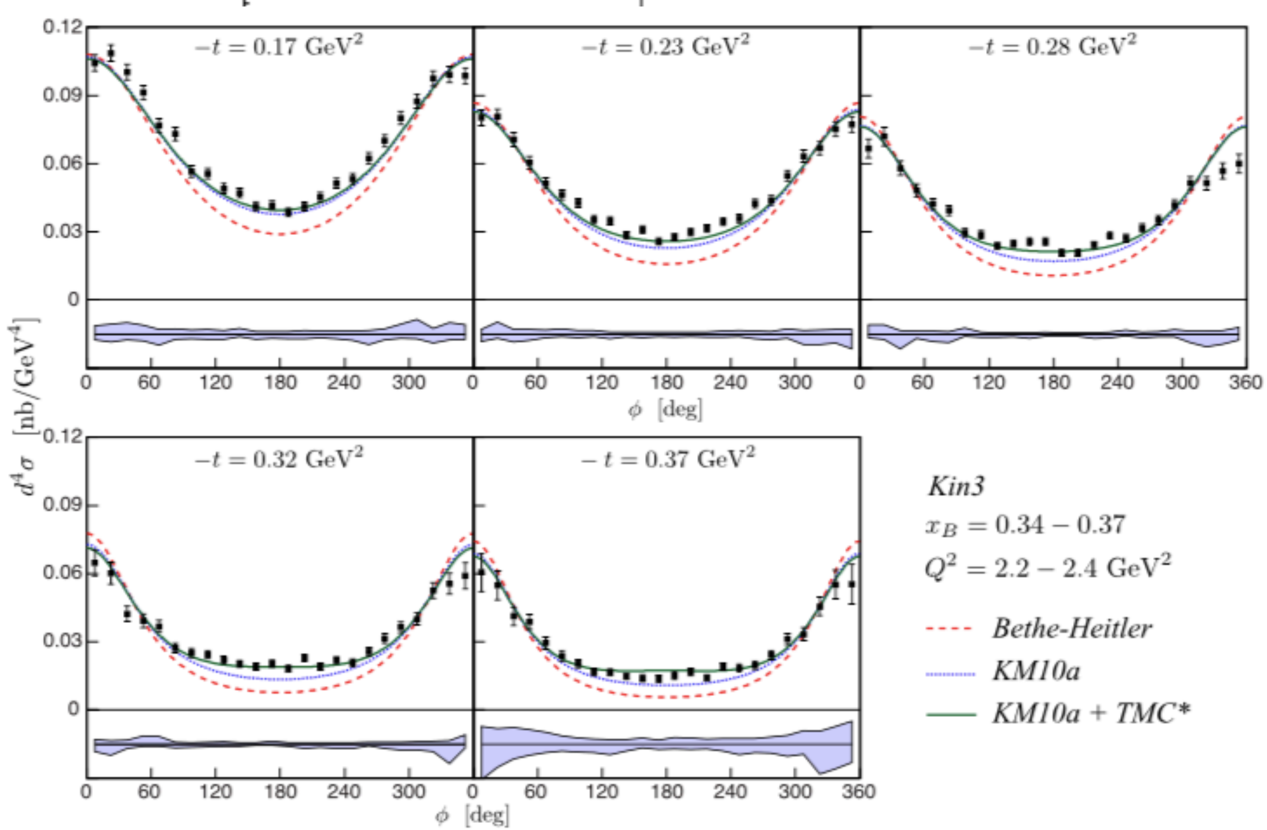
★ M. Defurne *et al*, ***Nature Communications 8*** (2017) 1408



-t=0.204 GeV^2
-t=0.262 GeV^2
-t=0.448 GeV^2
Q^2=2.78 GeV^2
x_B=0.335
$d^4\sigma$ (nb/GeV^4)
$\Delta(d^4\sigma)$ (nb/GeV^4)
Φ (deg)

CLAS

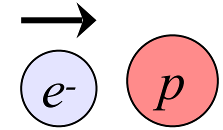
Hall A

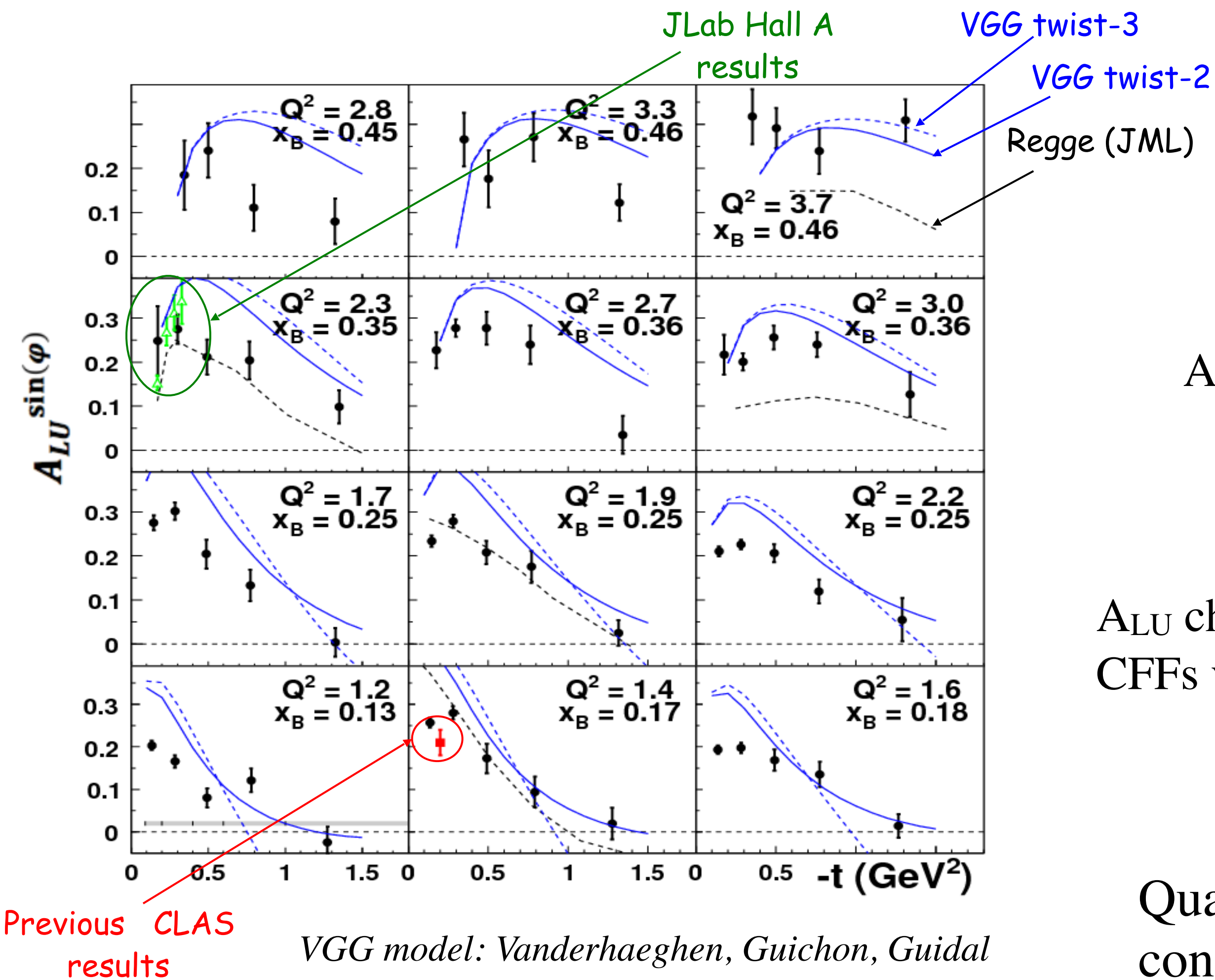


$-t = 0.17$ GeV^2
$-t = 0.23$ GeV^2
$-t = 0.28$ GeV^2
$-t = 0.32$ GeV^2
$-t = 0.37$ GeV^2
$d^4\sigma$ [nb/GeV^4]
ϕ [deg]
Kin3
$x_B = 0.34 - 0.37$
$Q^2 = 2.2 - 2.4$ GeV^2
Bethe-Heitler
KM10a
KM10a + TMC*

CLAS

Beam-spin Asymmetry (A_{LU})





VGG model: Vanderhaeghen, Guichon, Guidal

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

A_{LU} from fit to asymmetry:

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

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

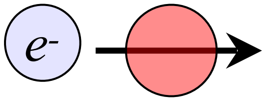
$$F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} E$$

Qualitative agreement with models, constraints on fit parameters.

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

CLAS

Target-spin Asymmetry (A_{UL})



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

A_{UL} from fit to asymmetry:

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

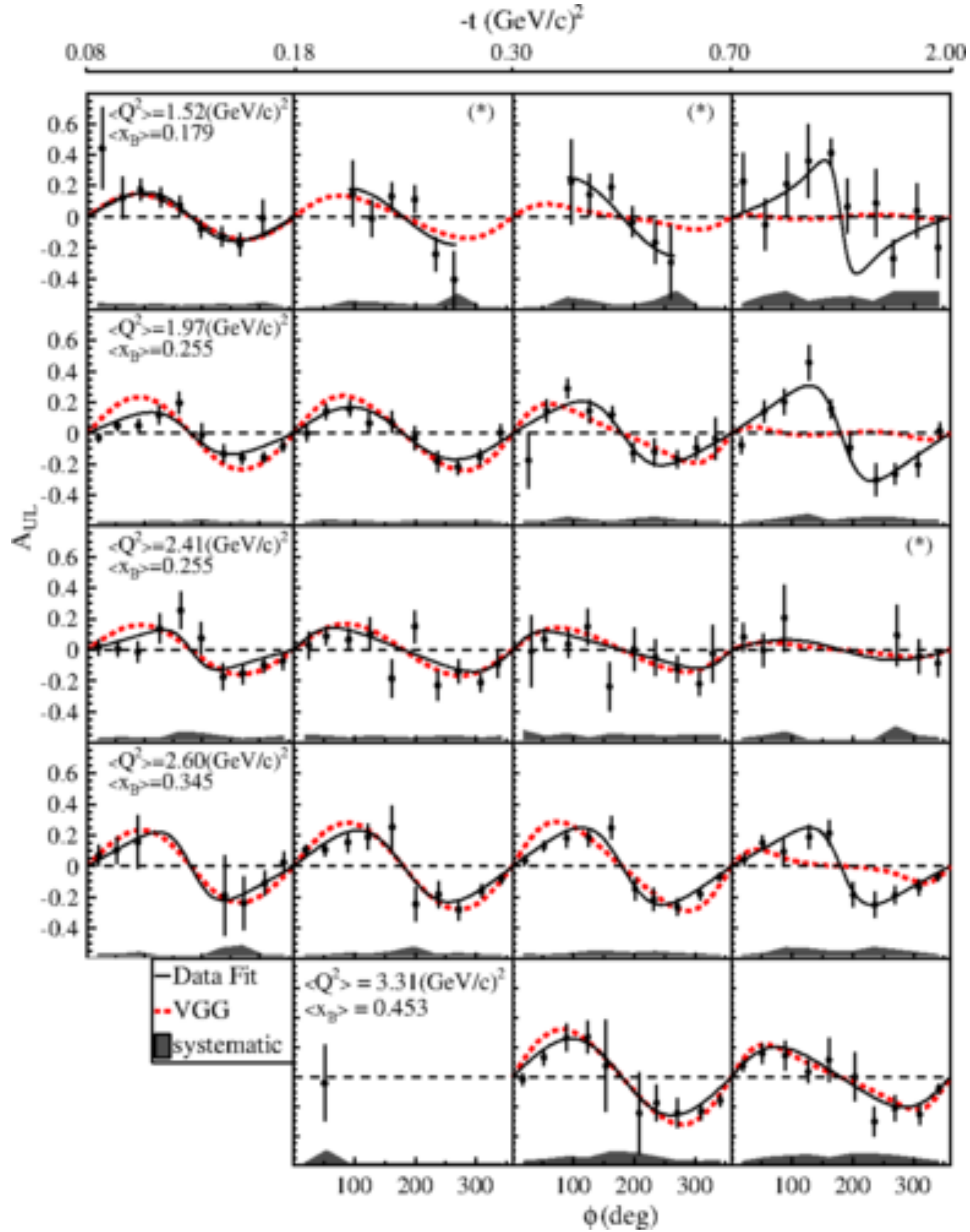
A_{UL} characterised by imaginary parts of CFFs via:

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

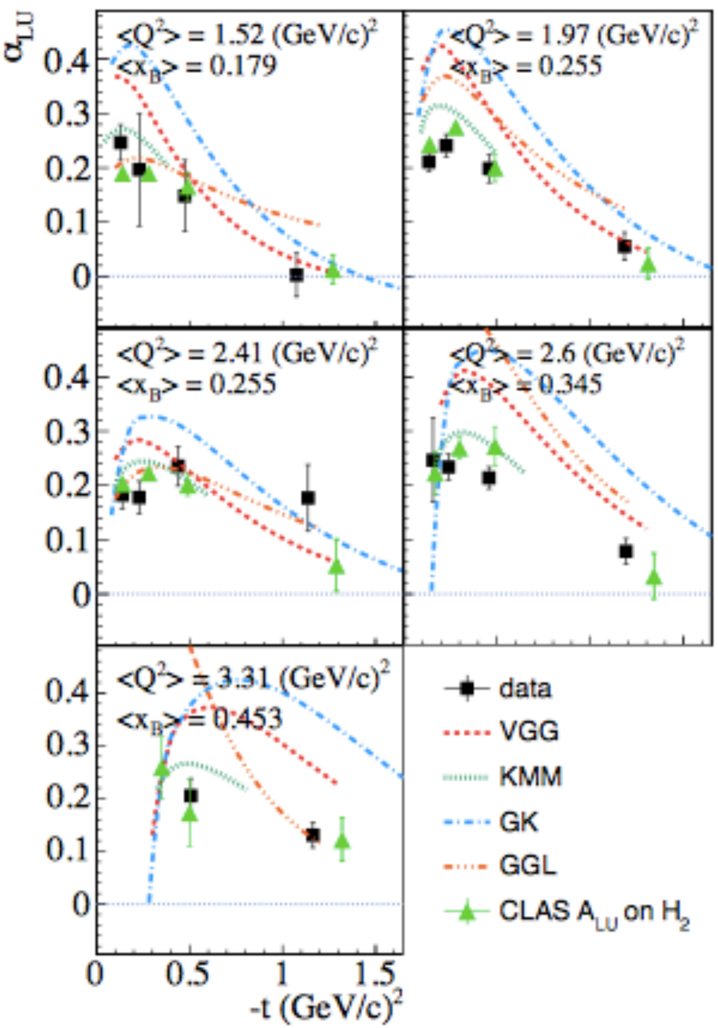
High statistics, large kinematic coverage, strong constraints on fits, simultaneous fit with BSA and DSA from the same dataset.

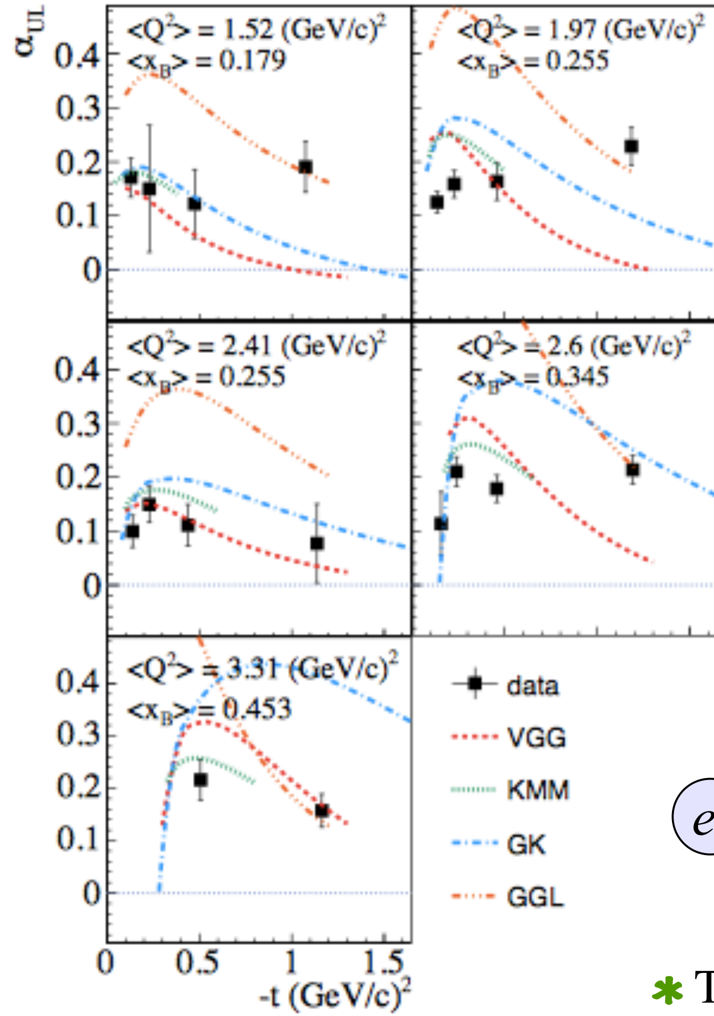
E. Seder *et al* (CLAS), ***PRL* 114** (2015) 032001

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



Beam- and target-spin asymmetries





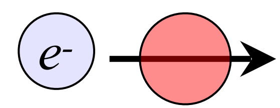
$$A = \frac{\alpha sin\phi}{1+\beta cos\phi}$$

GGL: Goldstein, Gonzalez, Liuti

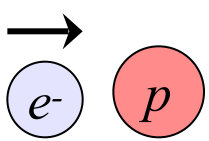
GK: Kroll, Moutarde, Sabatié

KMM: Kumericki, Mueller, Murray

VGG: Vanderhaeghen, Guichon, Guidal

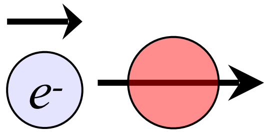


- TSA shows a flatter distribution in *t* than BSA.

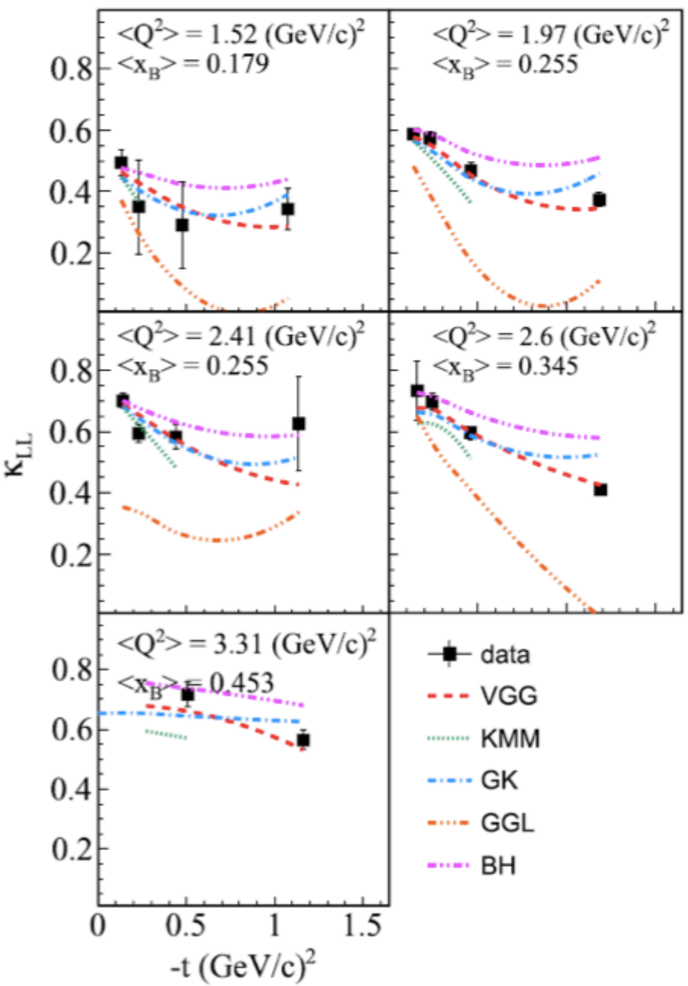


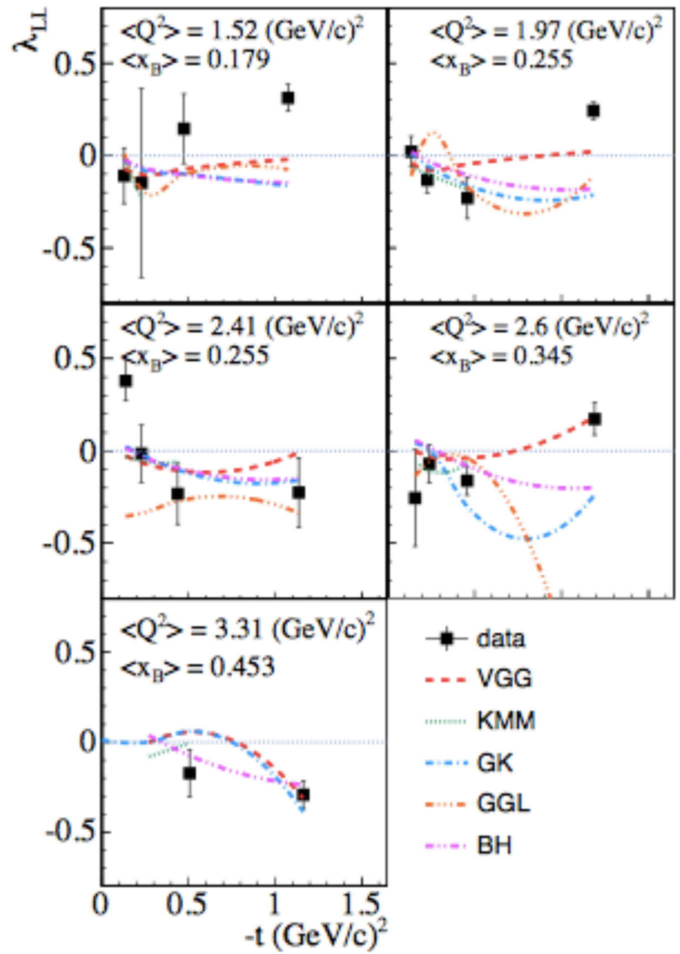
S. Pisano *et al* (CLAS), ***PRD* 91** (2015) 052014

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



Double-spin Asymmetry (A_{LL})





A_{LL} from fit to asymmetry:

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

A_{LL} characterised by real parts of CFFs via:

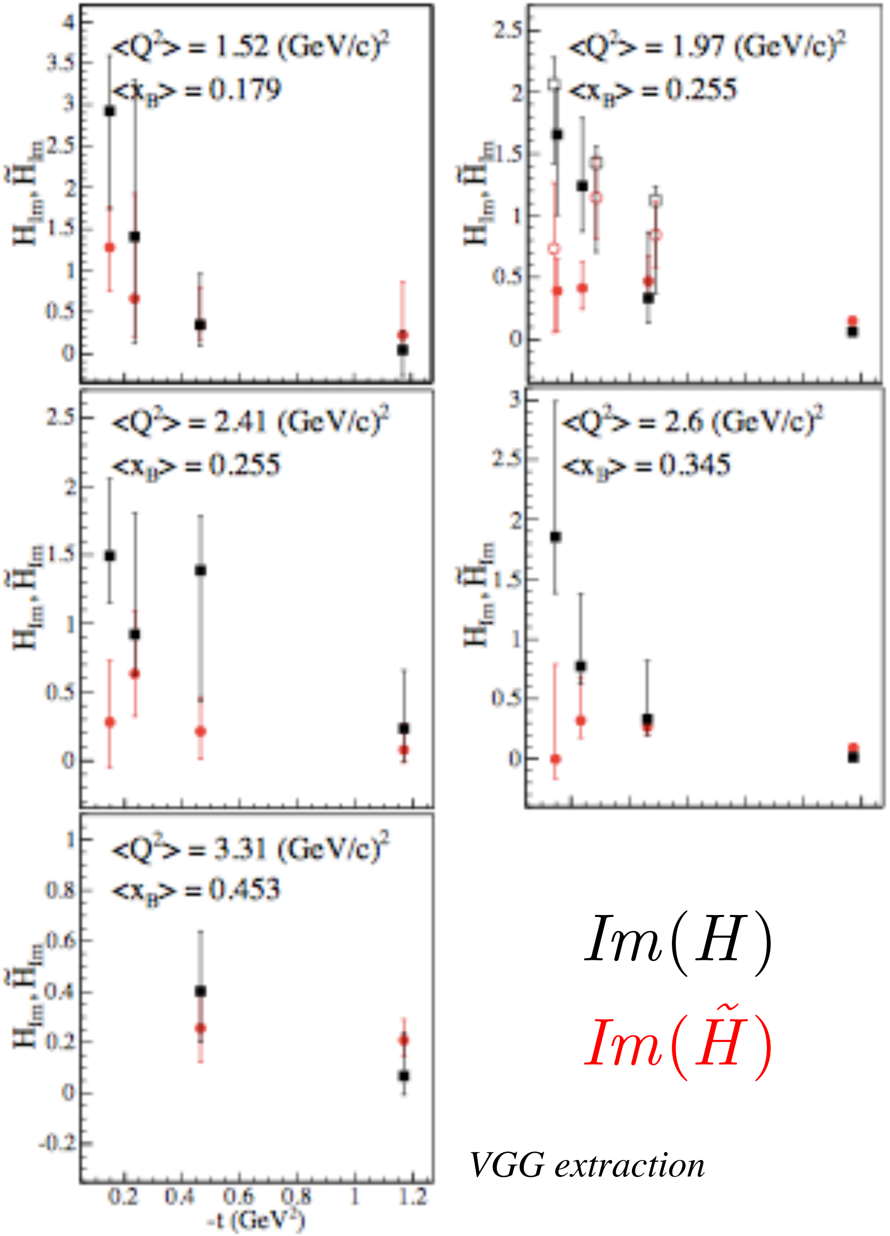
$$F_1 \tilde{H} + \xi G_M \left(H + \frac{x_B}{2} E\right) + \ldots$$

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

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

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

CFF extraction from three spin asymmetries at common kinematics.



$Im(H)$

$Im(\tilde{H})$

VGG extraction

What can we learn from the asymmetries?

Answers hinge on a global analysis of all available data.

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

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

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

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

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

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

Towards nucleon tomography

Quasi model-independent extraction of CFFs based on a local fit:

- Set 8 CFFs as free parameters to fit, at each (x_B, t) point, the available observables.
- Limits imposed within +/- 5 times the VGG model predictions (Vanderhaeghen-Guichon-Guidal).
- Leading-twist DVCS amplitude parametrisation based on Double Distributions.

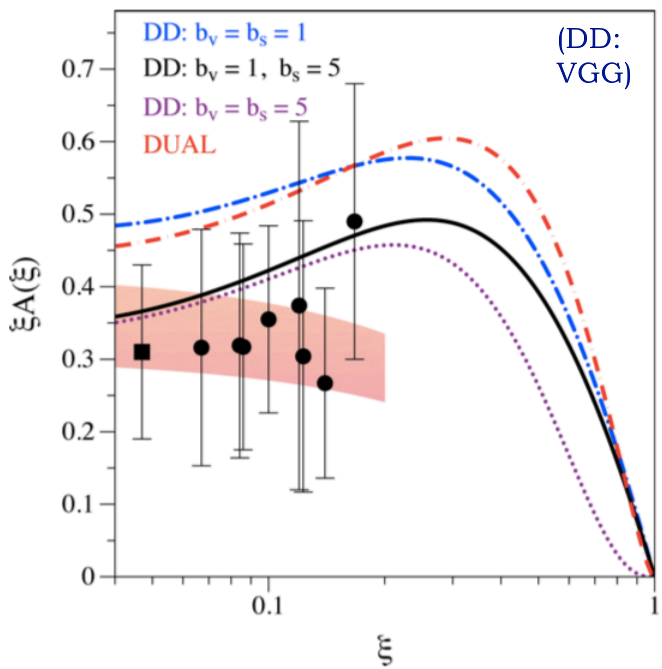
The best constraints in fits to CLAS data were obtained on H_{Im}.

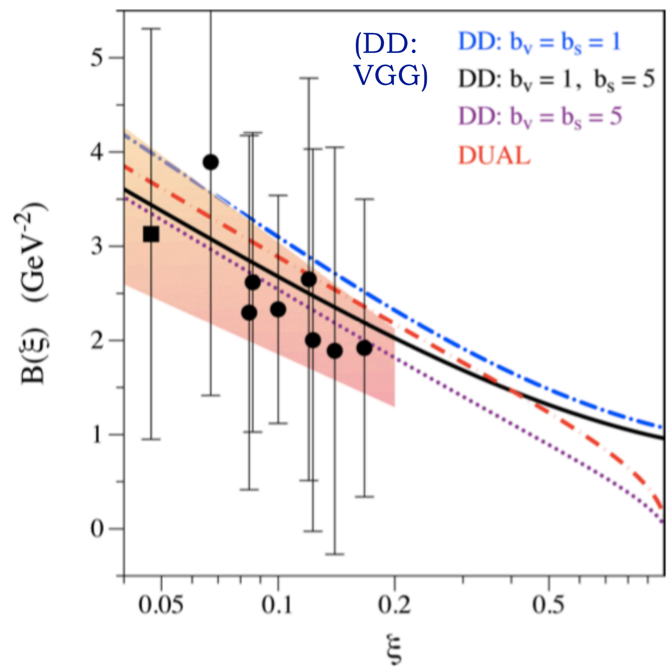
Parametrise its dependence on t:

$$H_{Im}(\xi, t) = A(\xi)e^{B(\xi)t}$$

Relates to quark density ($A(\xi)$)

Inverse relation to spatial distribution ($B(\xi)$)





R. Dupré *et al.*, Eur. Phys. J **A 53** (2017) 171

Towards nucleon tomography

Relating the impact parameter to helicity-averaged transverse distribution:

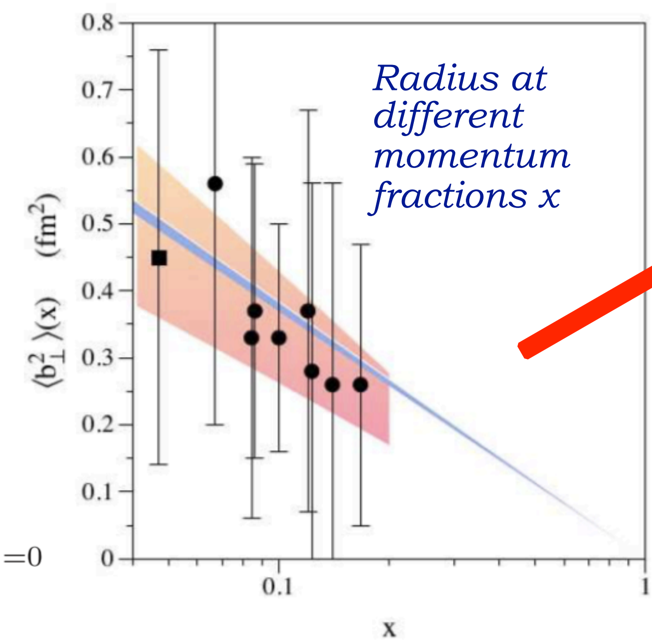
$$\rho^q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp} H^q_-(x, 0, -\mathbf{\Delta}_\perp{}^2)$$

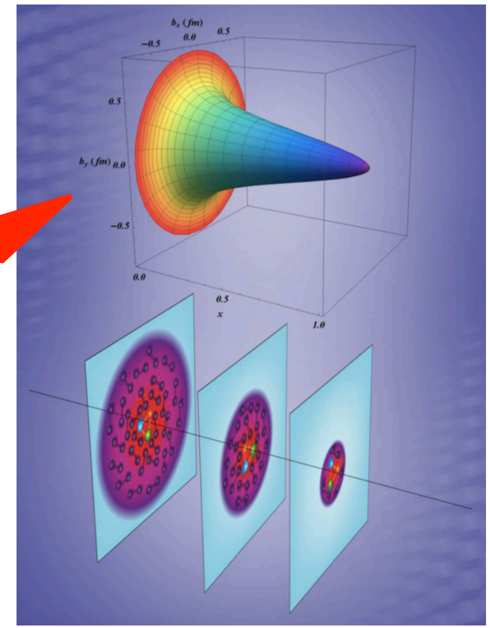
Transverse four-momentum transfer to nucleon

$$H^q_-(x, 0, t) \equiv H^q(x, 0, t) + H^q(-x, 0, t)$$

Assuming leading-twist and exponential dependence of GPD on t, using models to extrapolate to the zero skewness point $\xi = 0$ and assuming similar behaviour for u and d quarks there:

$$\langle b_\perp^2 \rangle^q(x) = -4 \frac{\partial}{\partial \mathbf{\Delta}_\perp^2} \ln H^q_-(x, 0, -\mathbf{\Delta}_\perp{}^2)\Big|_{\mathbf{\Delta}_\perp = 0}$$





Tentative hints of 3D distributions are emerging.

R. Dupré *et al.*, Eur. Phys. J **A 53,** (2017) 171

Imaging pressure within the nucleon

- GPDs provide indirect access to mechanical properties of the nucleon (encoded in the gravitational form factors, GFFs, of the energy-momentum tensor).

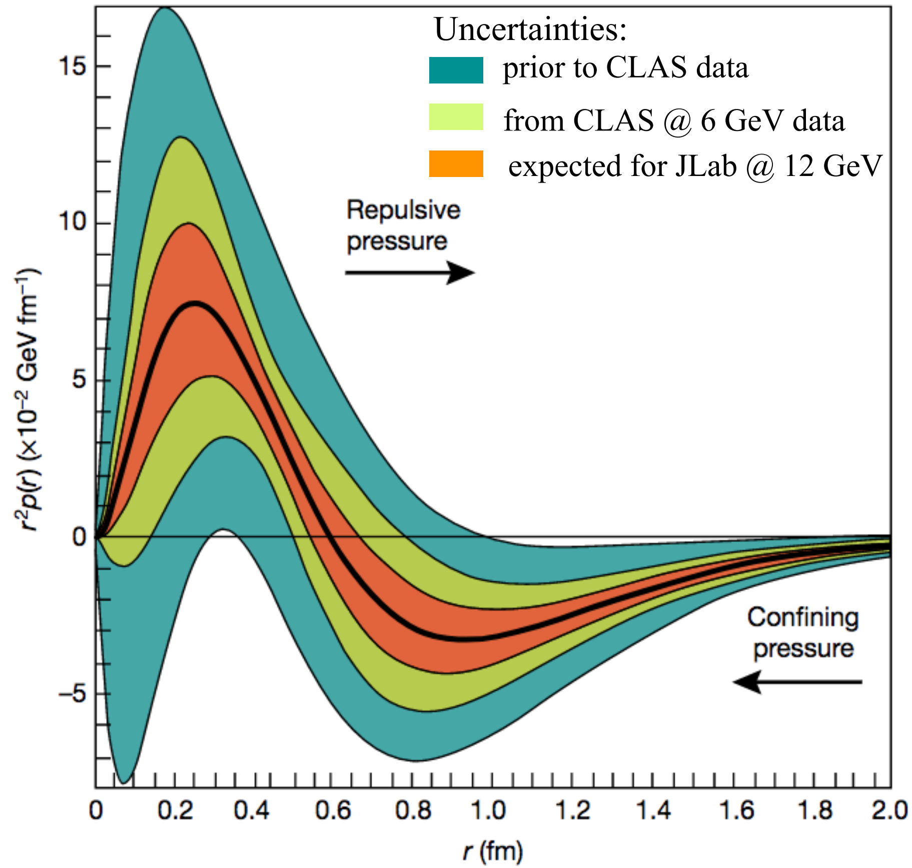
- Three scalar GFFs, functions of t: encode pressure and shear forces ($d_1(t)$), mass ($M_2(t)$) and angular momentum distributions ($J(t)$).

- Can be related to GPDs via sum rules:

$$\int x\,[H(x,\xi,t)+E(x,\xi,t)]\,\mathrm{d}x = 2J(t)$$

$$\int xH(x,\xi,t)\mathrm{d}x = M_2(t)+\frac{4}{5}\xi^2 d_1(t)$$

- Possibility of extracting pressure distributions! More data needed.



V. Burkert, L. Elouadrhiri, F.-X. Girod, Nature **557**, 396-399 (2018)

DVCS @ JLab in the 11 GeV era

DVCS Cross-sections: Halls A and C

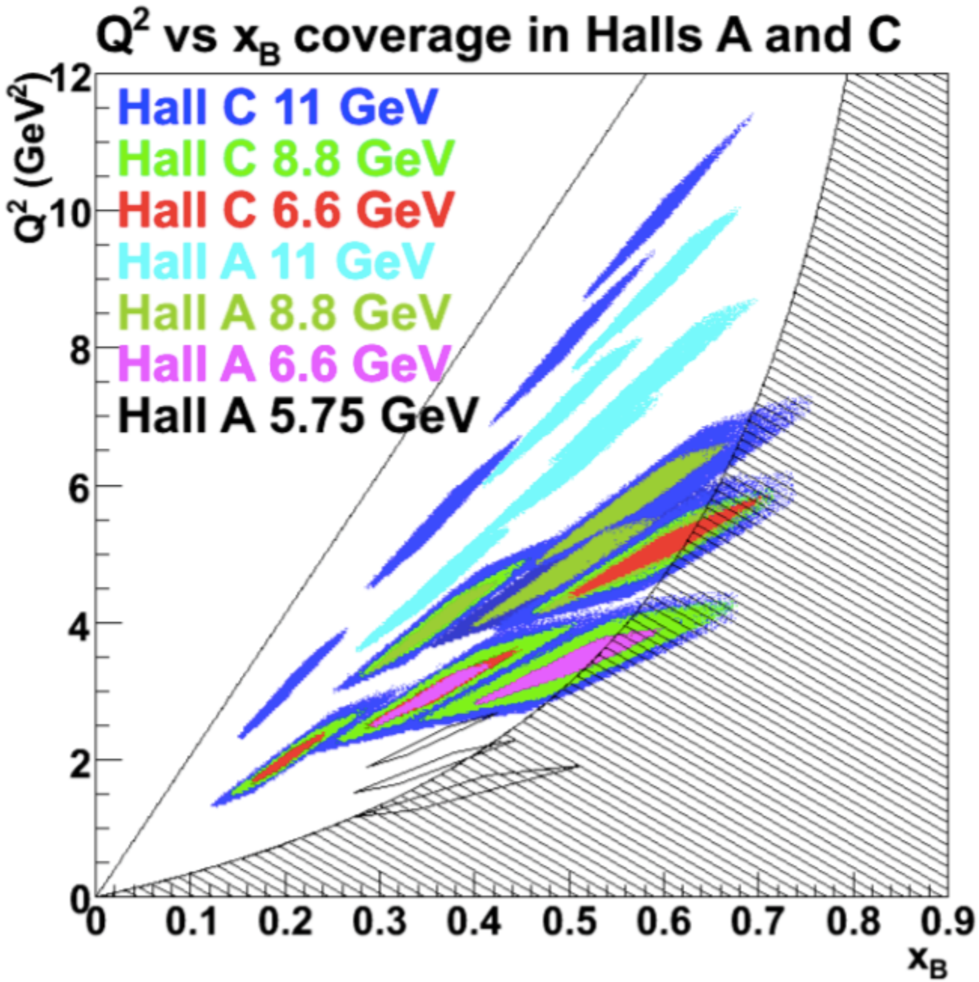
Experiments:
E12-06-114 (Hall A, 100 days),
E12-13-010 (Hall C, 53 days)
C. Muñoz Camacho et al.,
C. Hyde et al.

Unpolarised liquid H_2 target:

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

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

✱ Separate *Re* and *Im* parts of the DVCS amplitude.



Hall A started taking data last spring!

Proton DVCS @ 11 GeV

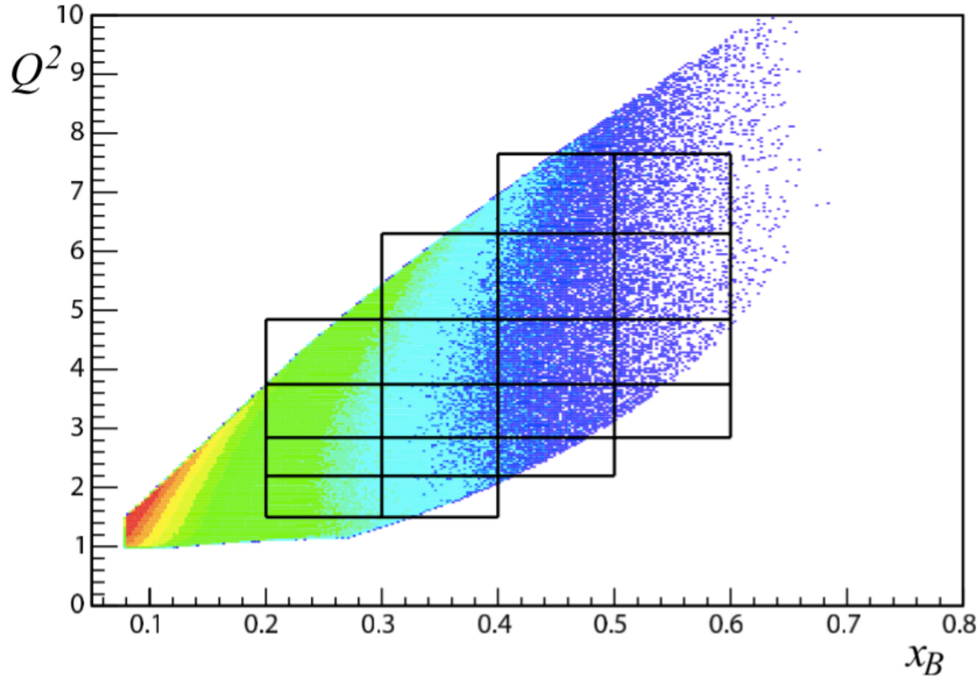
CLAS12

Experiment E12-06-119

F. Sabatié et al.

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

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



Unpolarised liquid H_2 target:

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

First experiment with CLAS12

Started this February!

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

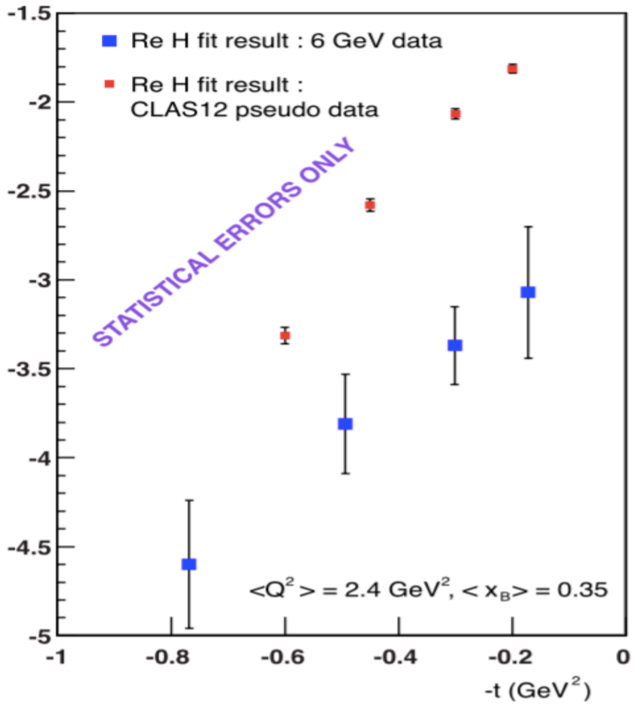
$$F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} E \longrightarrow \boldsymbol{Im(H_p)}$$

Proton DVCS @ 11 GeV

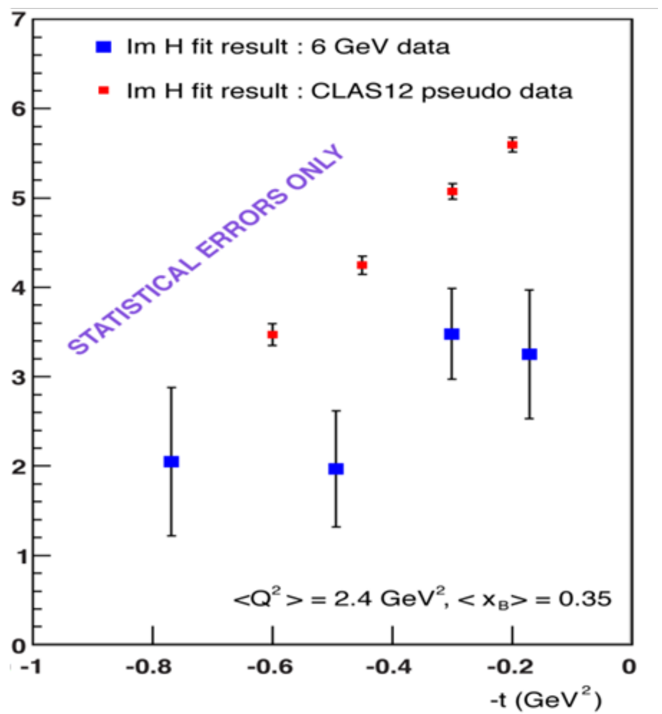
CLAS12

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

Re(H)



Im(H)



(CLAS 6 GeV extraction H. Moutarde)

DVCS at lower energies with CLAS12

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

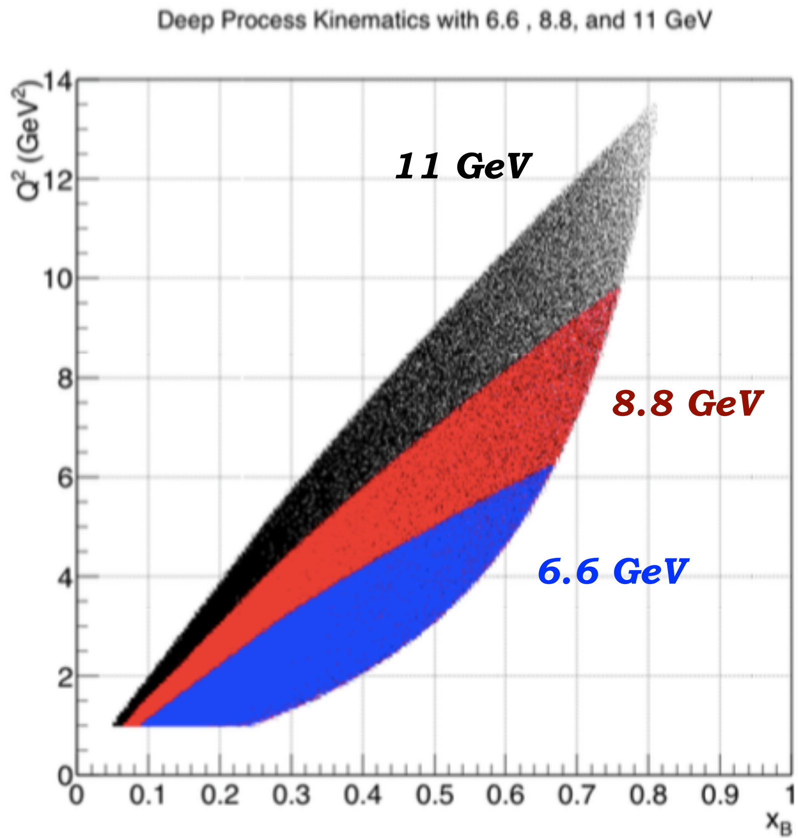
Unpolarised liquid H_2 target:

- Beam energies: 6.6, 8.8 GeV
- Simultaneous fit to beam-spin and total cross-sections.

✱ Rosenbluth separation of interference and $\left|T_{DVCS}\right|^2$ terms in the cross-section

✱ Scaling tests of the extracted CFFs

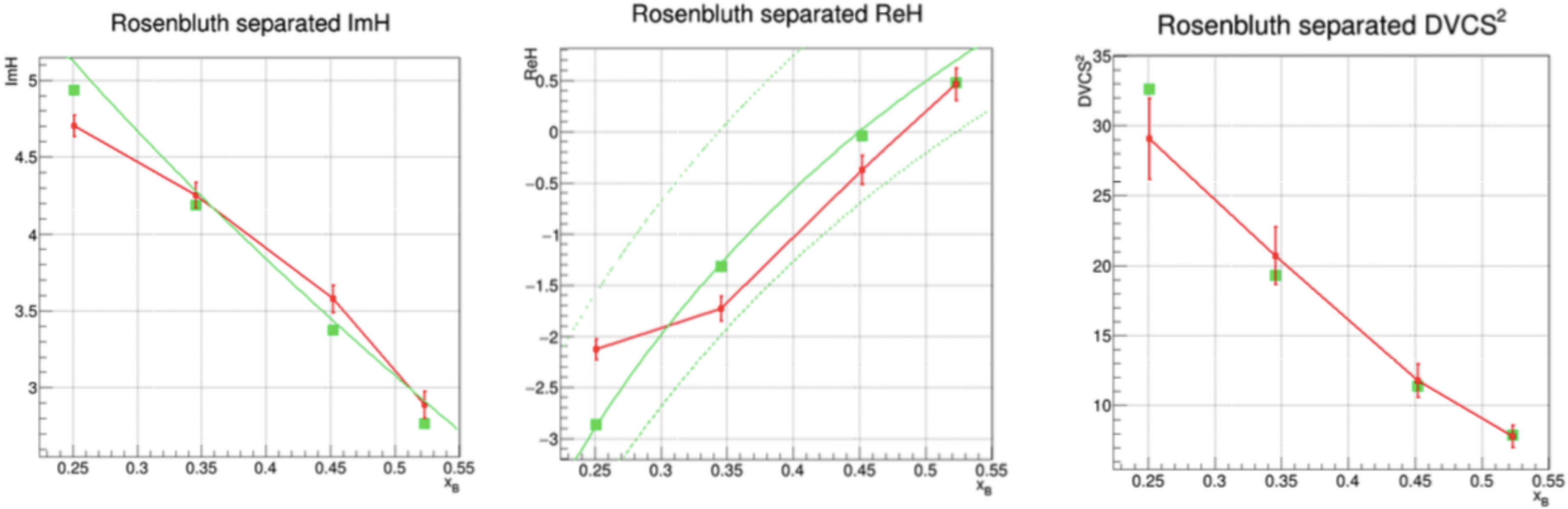
✱ Model-dependent determination of the D-term in the Dispersion Relation between *Re* and *Im* parts of CFFs: sensitivity to Gravitational Form Factors.



Compare with measurements from Halls A and C: cross-check model and systematic uncertainties.

DVCS at lower energies with CLAS12

Projected extraction of CFFs (red) compared to generated values (green). Three curves on the *Re(H)* show three different scenarios for the D-term.



F.-X. Girod et al.

CLAS12

Neutron DVCS @ 11 GeV

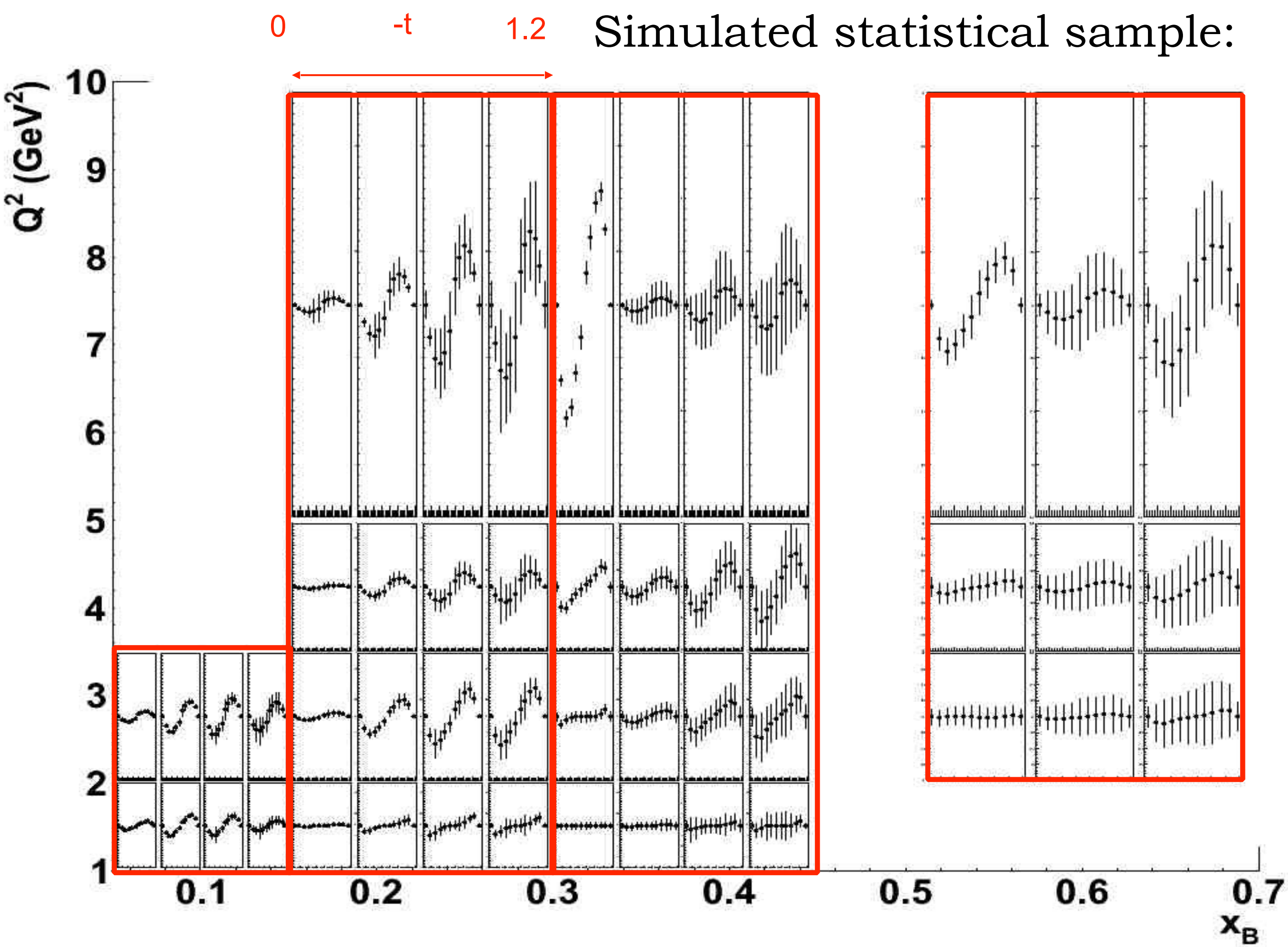
Experiment E12-11-003

S. Niccolai, D. Sokhan et al.

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

Im ***(E_n)*** dominates.

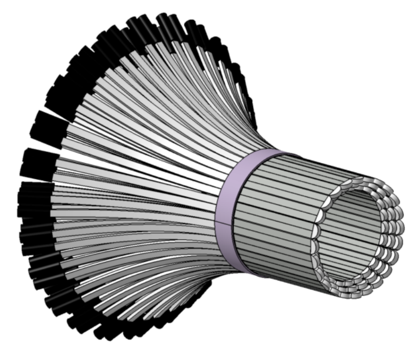
Simulated statistical sample:



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

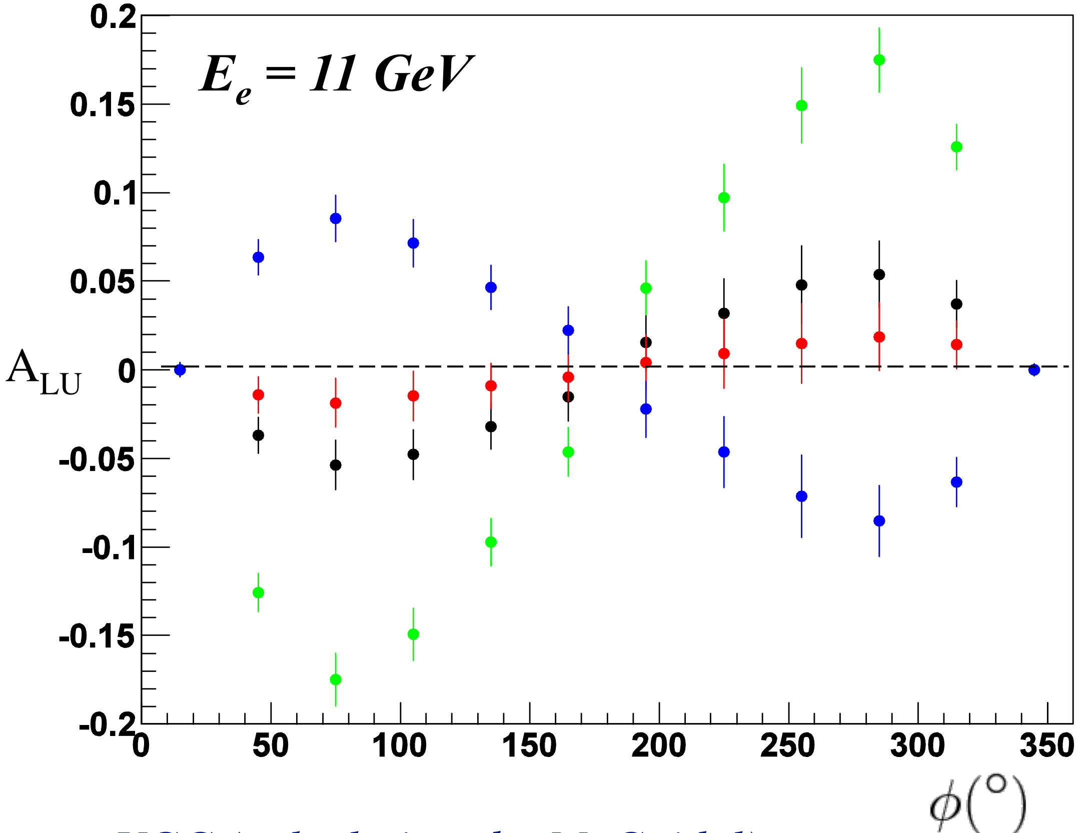
$$e + d \rightarrow e' + \gamma + n + (p_s)$$

CLAS12 +
Forward Tagger +
Neutron Detector



Scheduled: 2019

Beam-spin asymmetry in neutron DVCS @ 11 GeV



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

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

VGG (calculations by M. Guidal)

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

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

Proton DVCS with a longitudinally polarised target

CLAS12

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

A_{UL} characterised by imaginary parts of CFFs via: $$F_1\tilde{H} + \xi G_M(H + \frac{x_B}{2}E) - \frac{\xi t}{4M^2}F_2\tilde{E} + \ldots$$

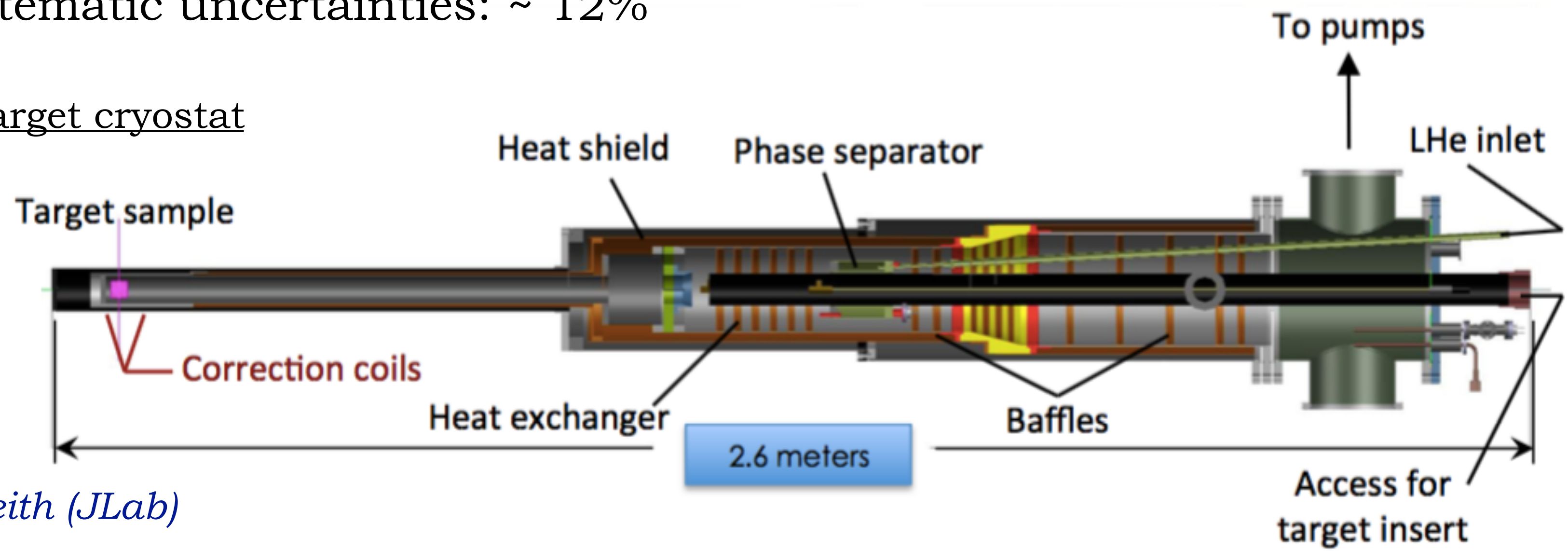
$\longrightarrow$ ***Im***$(\widetilde{\mathbf{H}}_\mathbf{p})$

Longitudinally polarised NH_3 target:

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

Tentative schedule: 2020

Target cryostat



C. Keith (JLab)

Neutron DVCS with a longitudinally polarised target

Experiment E12-06-109A.

S. Niccolai, D. Sokhan et al.

Longitudinally polarised ND_3 target:

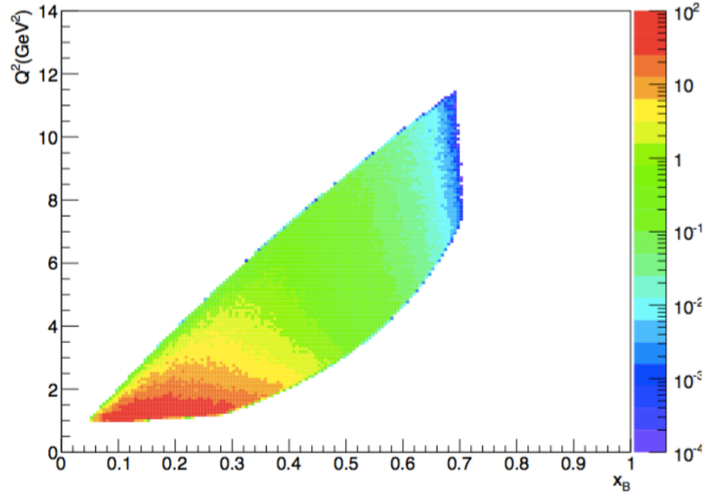
- Dynamic Nuclear Polarisation (DNP) of target material in a cryostat shared with the NH_3 target.
- $P_{deuteron}$ up to 50%
- Systematic uncertainties: ~ 12%

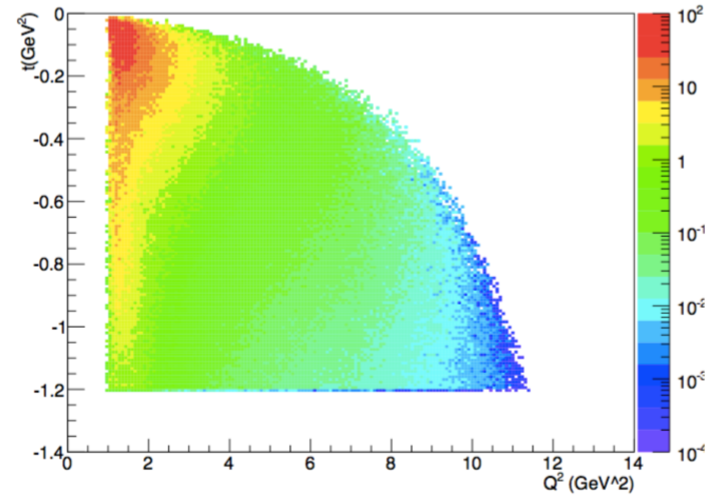
A_{UL} characterised by imaginary parts of CFFs via:

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

→ ***Im*(H$_n$)**

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





Tentative schedule: 2020

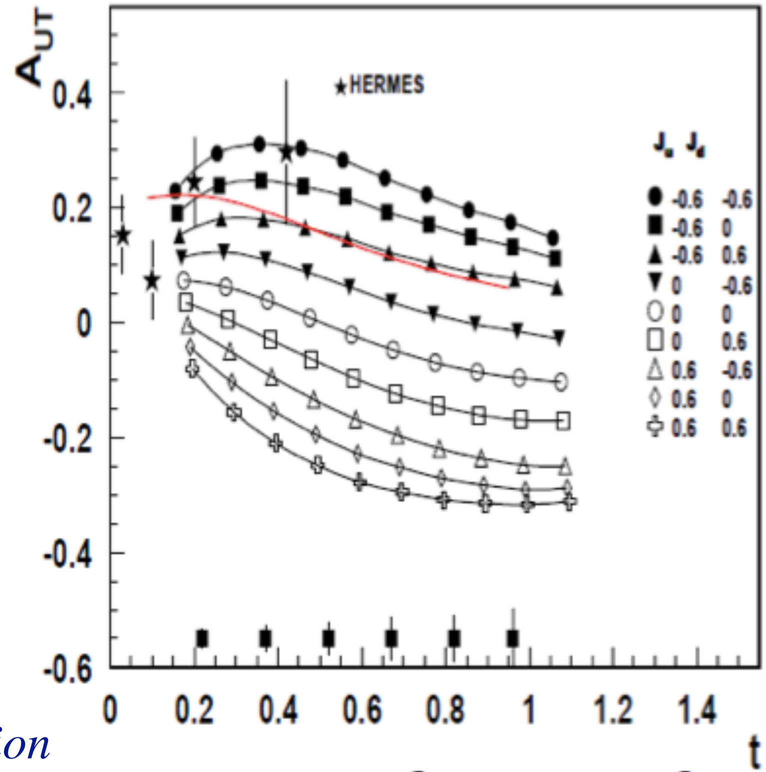
Proton DVCS with transversely polarised target at CLAS12

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

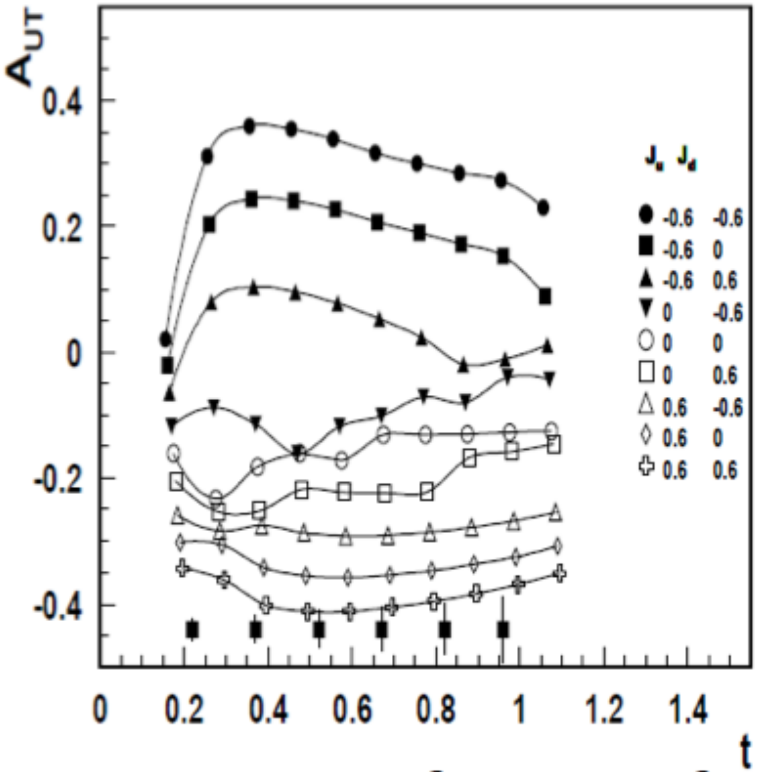
L. Elouardhiri et al.

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

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



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

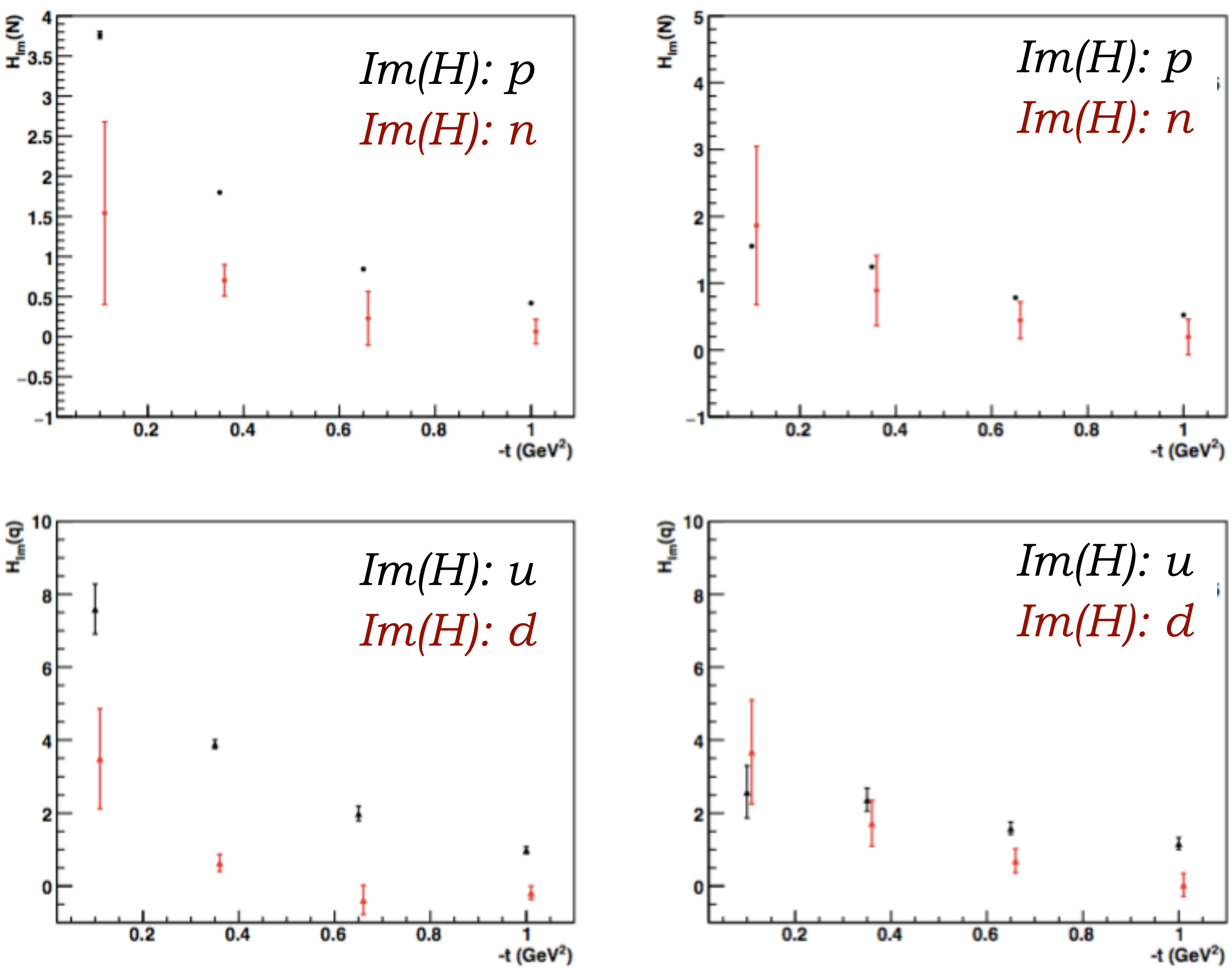


$\langle x \rangle = 0.33, \langle Q^2 \rangle = 2.5\ GeV^2$

VGG extraction (M. Guidal)

Projected sensitivities to *Im(H)* CFF

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



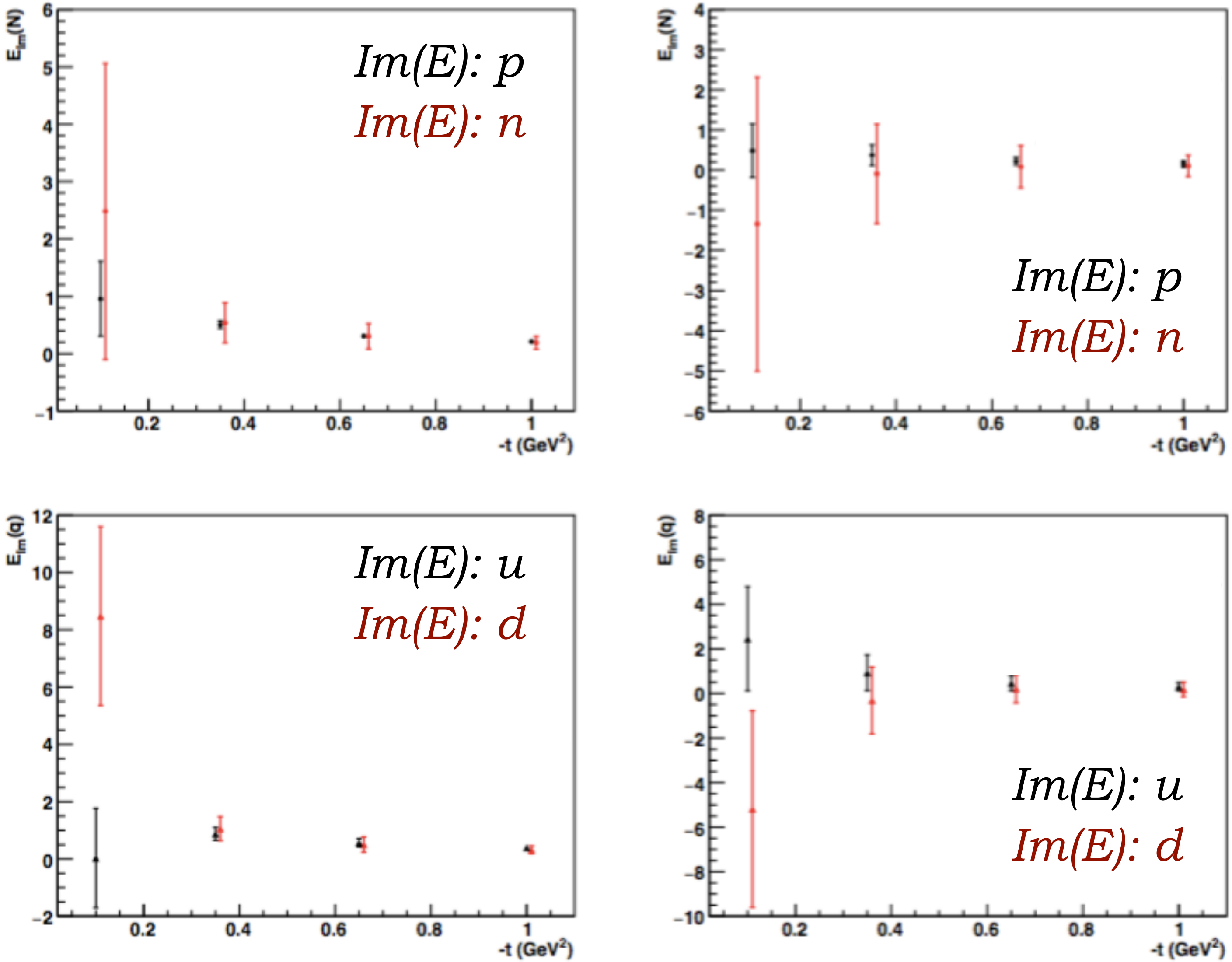
Projections for *Im(H)* neutron and proton and up and down CFFs extracted from approved CLAS12 experiments.

VGG fit (M. Guidal)

Projected sensitivities to *Im(E)* CFF

CLAS12

Q^2 = 2.6 GeV^2, x_B = 0.23 Q^2 = 5.9 GeV^2, x_B = 0.35



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

VGG fit (M. Guidal)

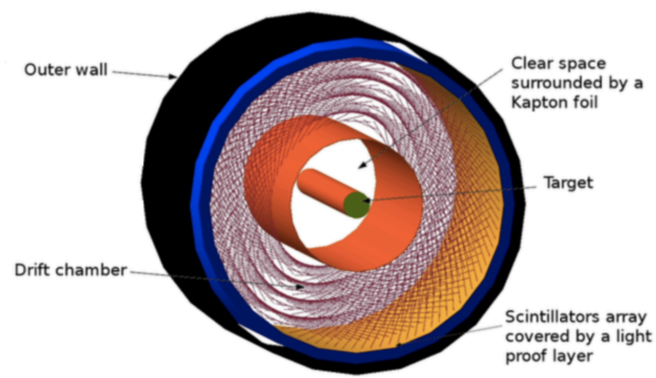
DVCS on ^{4}He: CLAS12 with ALERT

Experiment E12-17-012:
Z.-E. Meziani et al.

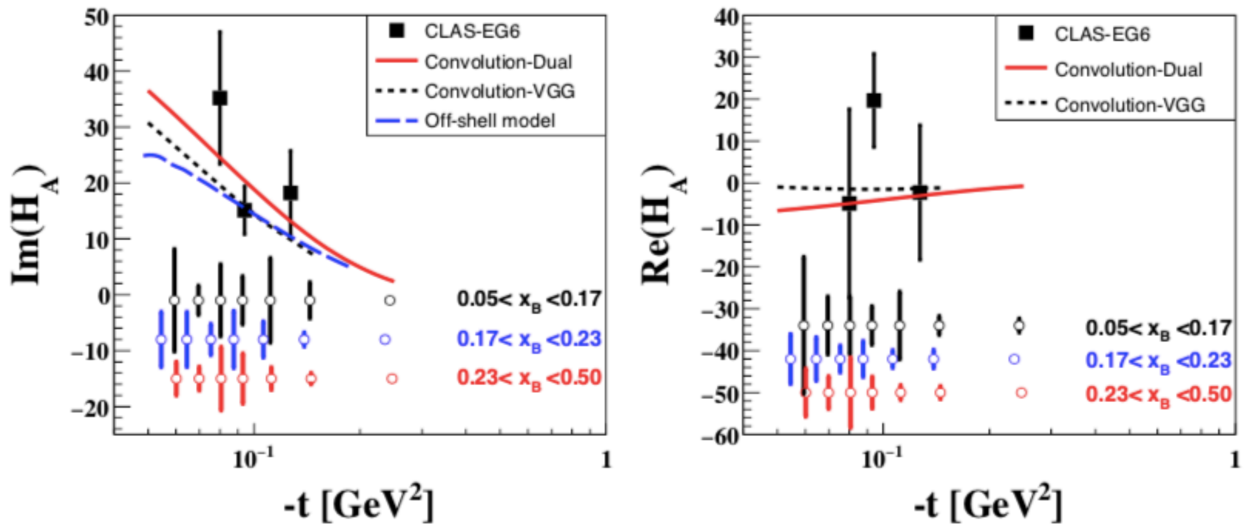
Measurement of BSA in coherent DVCS from a ^{4}*He* target: partonic structure of nuclei.

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

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



CLAS12 + ALERT: central recoil detector



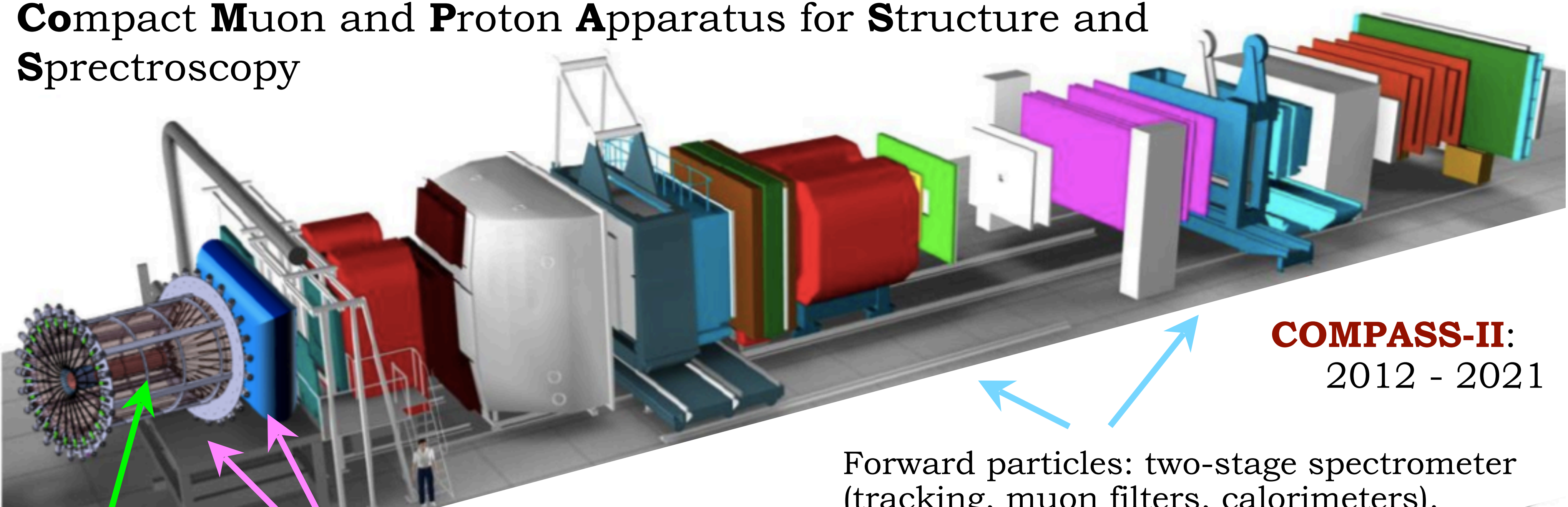
Experiment E12-17-012B
W. Armstrong et al.

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

DVCS at COMPASS: sea quarks

COMPASS @ Cern (SPS)

Compact **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



COMPASS-II: 2012 - 2021

Forward particles: two-stage spectrometer (tracking, muon filters, calorimeters).

2.5m liquid *H_2* target

Upgrades: new scintillator ToF for recoil proton detection & new EM calorimeter.

DVCS : $\mu\ p \rightarrow \mu'\ p\ \gamma$

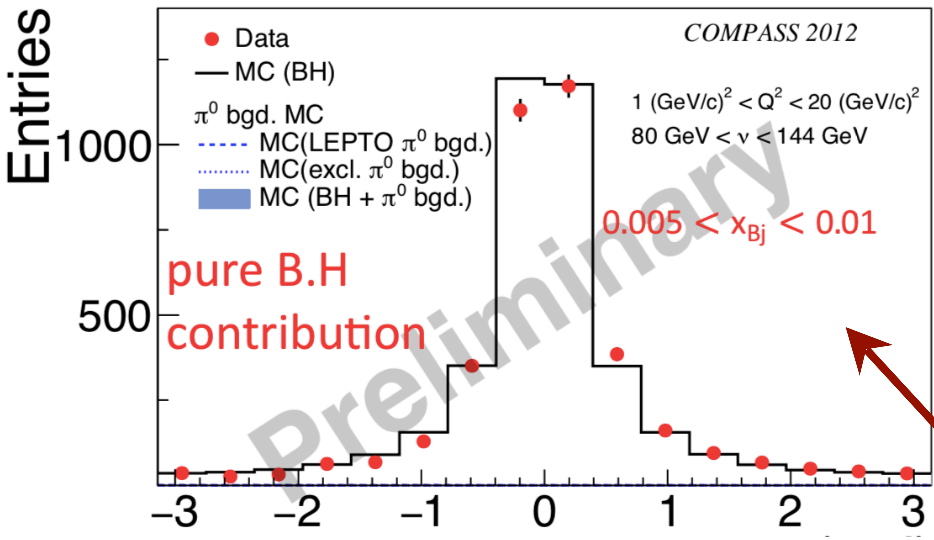
Full exclusive reconstruction

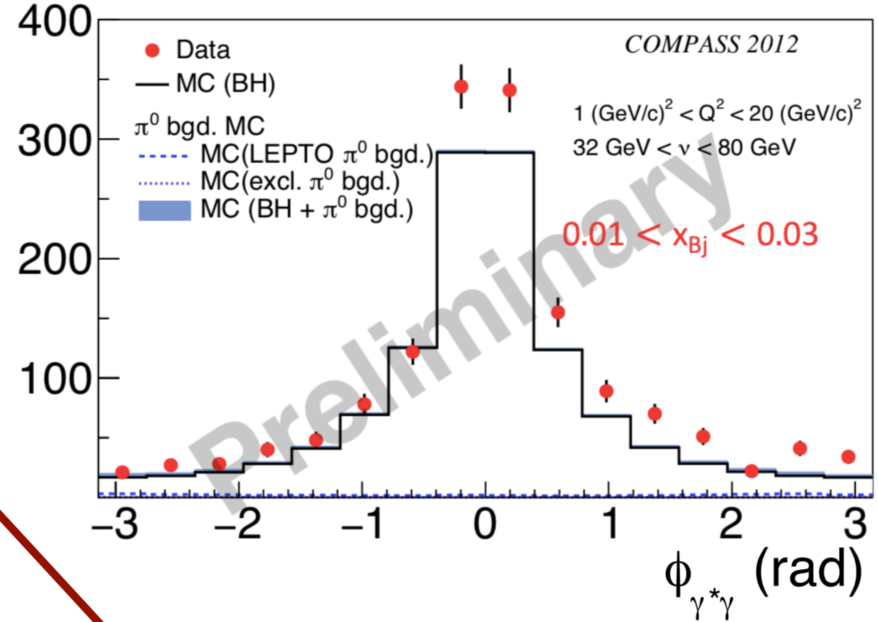
- 160 GeV 80% polarised μ^+/μ^-
- $\sim 4 \times 10^8 \mu/spill$, 9.6s/40s duty cycle

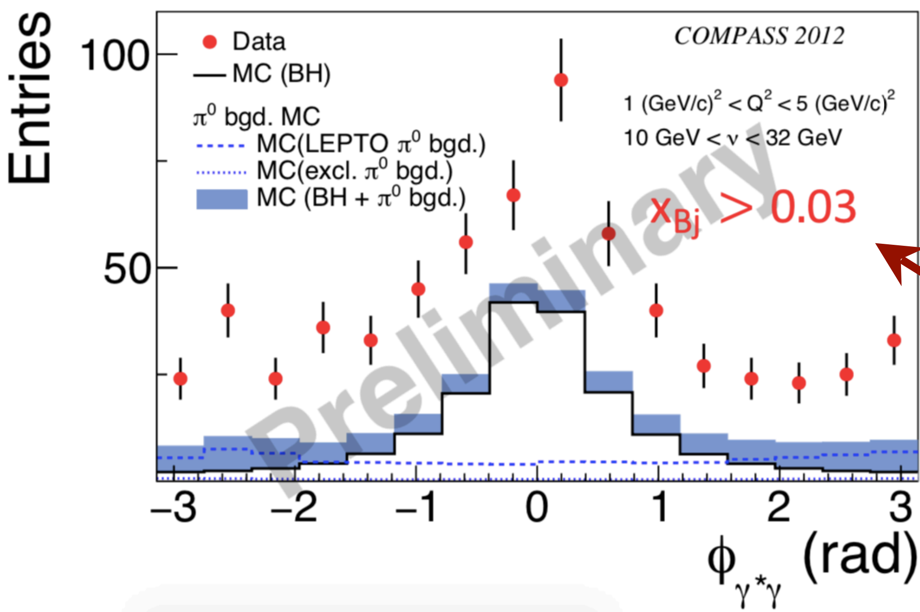
Data:

- 2008 & 2009: two v. short test runs, 40 cm LH_2 target.
- COMPASS-II: 1 month in 2012, 6 months in 2016 & 2017 each (GPD **H**).
- 2022+: transversely pol. NH_3 target (GPD **E**). LOI stage…

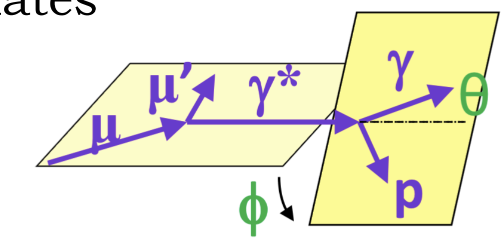
DVCS @ COMPASS (2012 run)







Bethe-Heitler dominates at very low x_B



DVCS dominates at these kinematics

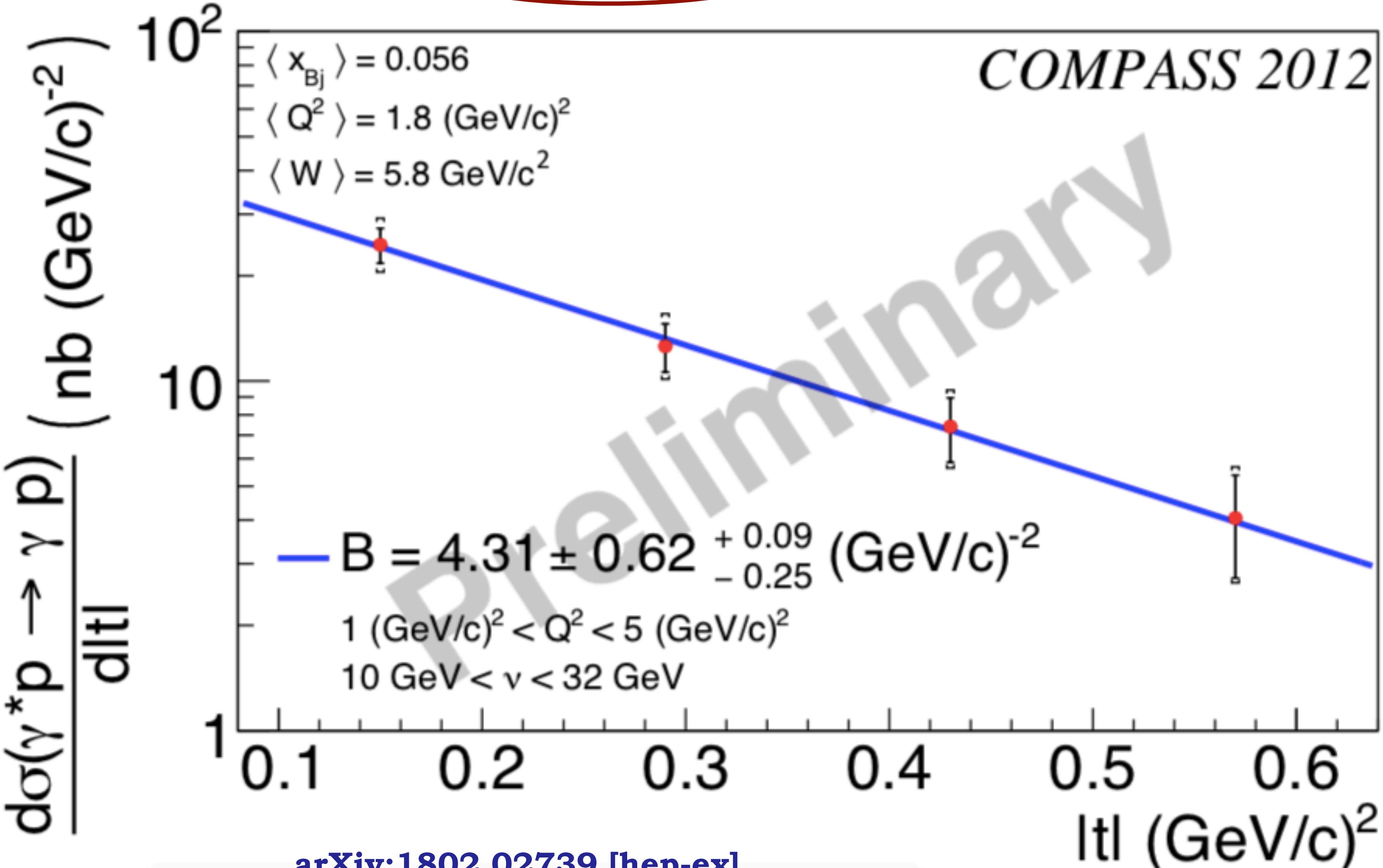
Slide mash-up from N. d'Hose and A. Ferrero

DVCS x-section and t-slope extraction

Kinematically constrained vertex fit applied

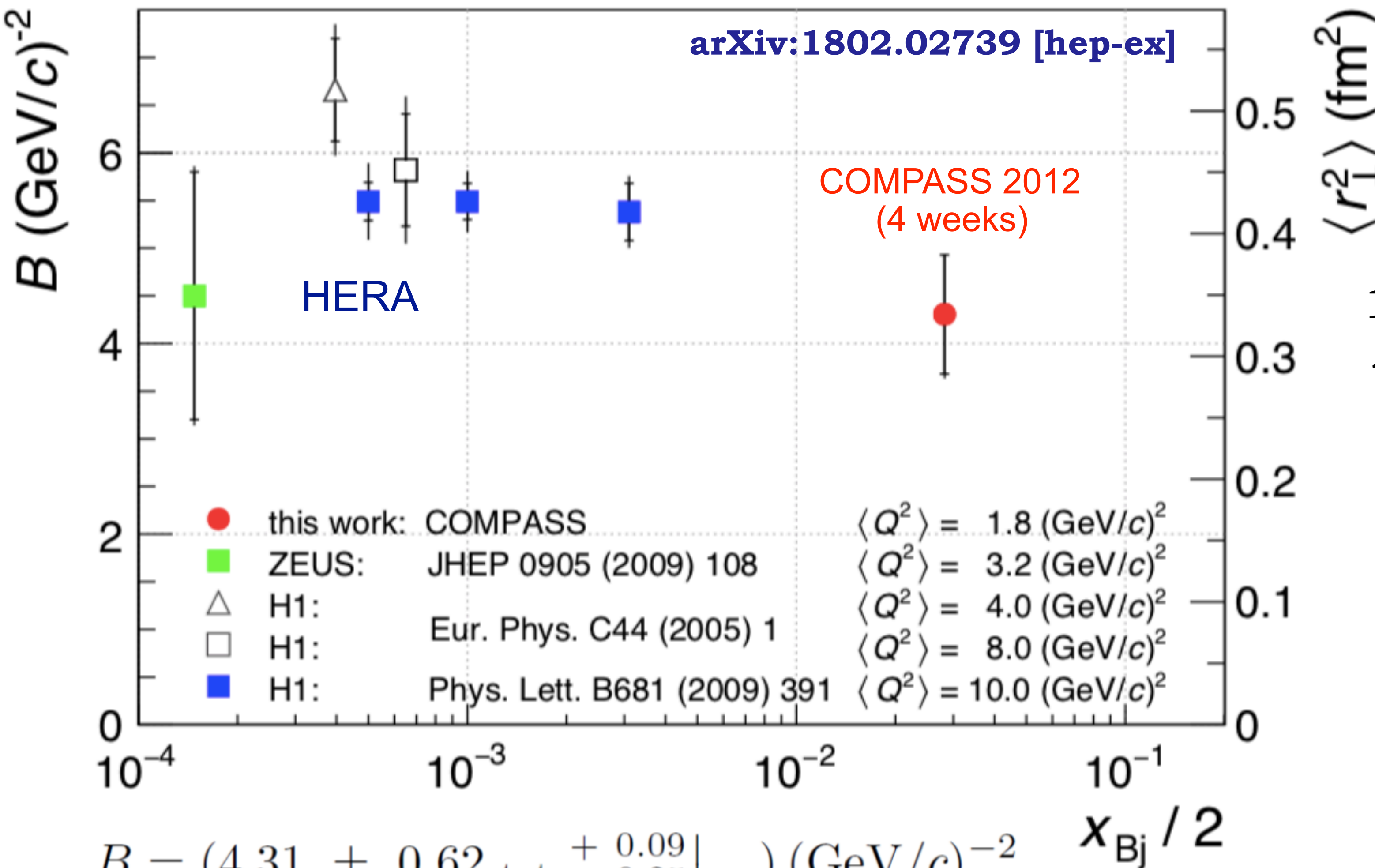
$$d\sigma^{DVCS}/dt = e^{-B|t|}$$

Slide from: A. Ferrero @ SPIN 2018



arXiv:1802.02739 [hep-ex]

Tomography of sea quarks



$1 < Q^2 < 5$ GeV^2

$\langle Q^2 \rangle = 1.8$ GeV^2

$\langle x_B \rangle = 0.056$

Integrated luminosity: 42.4 pb^{-1}

10 times more stats in 2016-17 runs

$$B = (4.31 \pm 0.62_{\text{stat}} \,{}^{+0.09}_{-0.25}\big|_{\text{sys}})\,(\text{GeV}/c)^{-2}$$

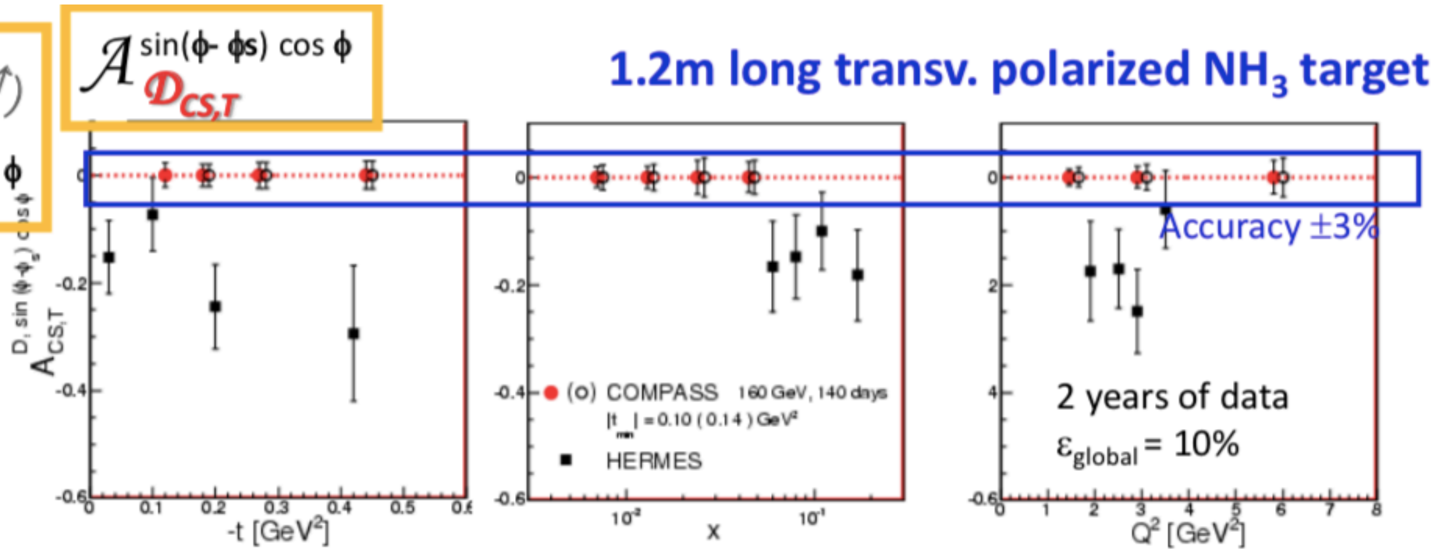
$$\sqrt{\langle r_\perp^2 \rangle} = (0.58 \pm 0.04_{\text{stat}} \,{}^{+0.01}_{-0.02}\big|_{\text{sys}})\text{ fm}$$

$$\langle r_\perp^2(x_B) \rangle \approx 2B(x_B)$$

DVCS with transversely polarised target @ COMPASS

$$\mathcal{D}_{CS,T} \equiv \Delta\sigma_T(\mu^{+\downarrow}) - \Delta\sigma_T(\mu^{-\uparrow})$$

$$\rightarrow Im(F_2\mathcal{H} - F_1\mathcal{E}) \sin(\phi\text{-}\ \phi s) \cos\phi$$



Indications of statistical accuracy.

Slide from: N. d'Hose @ Getting to Grips with QCD, Primosten 2018

Summary

JLab 6 GeV programme:

- Experimental support for factorisation & the handbag diagram, evidence of scaling
- Indications of higher-twist or higher-orders at play: hint of gluons?
- Constraints for GPD models
- Most information on *Re* and *Im* parts of $\mathbf{H_p}$ CFF, a little on $\mathbf{\tilde{H}_p}$, $\mathbf{E_n}$
- First attempt at tomography with the limited data

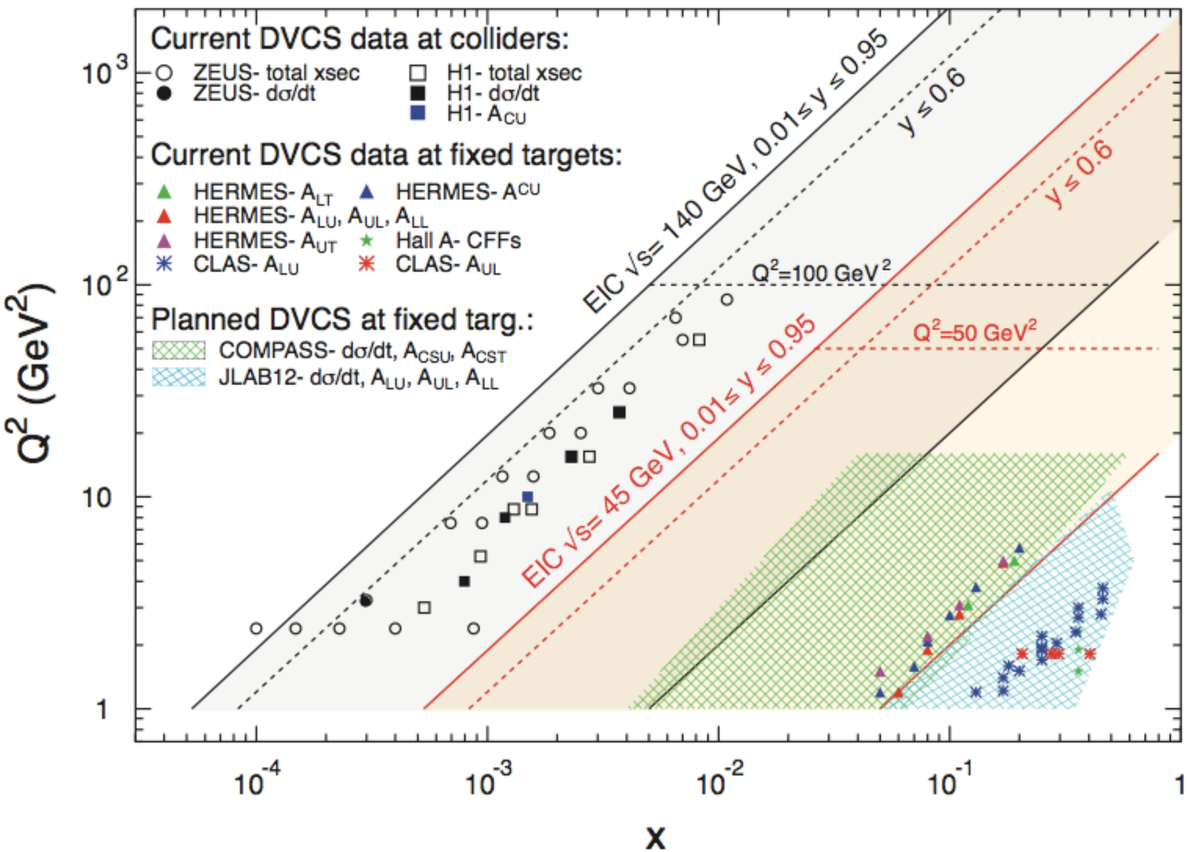
JLab 12 GeV programme:

- High precision — separation of DVCS and interference terms: sensitivity to higher twist and higher orders, gluons.
- Extensive mapping of a wider kinematic region — tomography.
- Extraction of *Re* and *Im* parts of **H** CFF, $\mathbf{\tilde{H}}$, **E**, flavour-separation: u/d.
- OAM contribution to spin, tomography within the valence region, constraints on GPD models.

COMPASS:

- **H** and **E** CFFs - tomography, OAM of the sea quarks, model constraints.

Some questions for the EIC…



EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

- Tomography of sea quarks: wide kinematic reach.
- Higher-twist / higher-order: what sensitivity to this will we have? Luminosity factor of 10^3-10^4 lower than Hall A, *but* can run more or less continuously.
- Access to gluons easier through DVMP…
- $H, \tilde{H}, E$ — what about $\tilde{E}$?
- Energy scans - separation of DVCS / Interference.
- Q^2 scans - scaling.
- Overlap of kinematics valuable: check of systematics by comparison to JLab, COMPASS results.
- … ?

Thank you!

Back-up and sundry

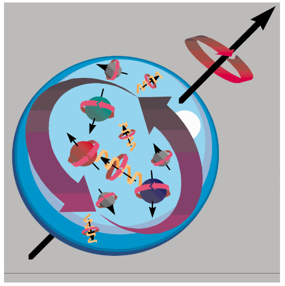
GPDs and nucleon spin

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

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

H accessible in DVCS off the proton, first experimental constraint on *E*, through neutron-DVCS:

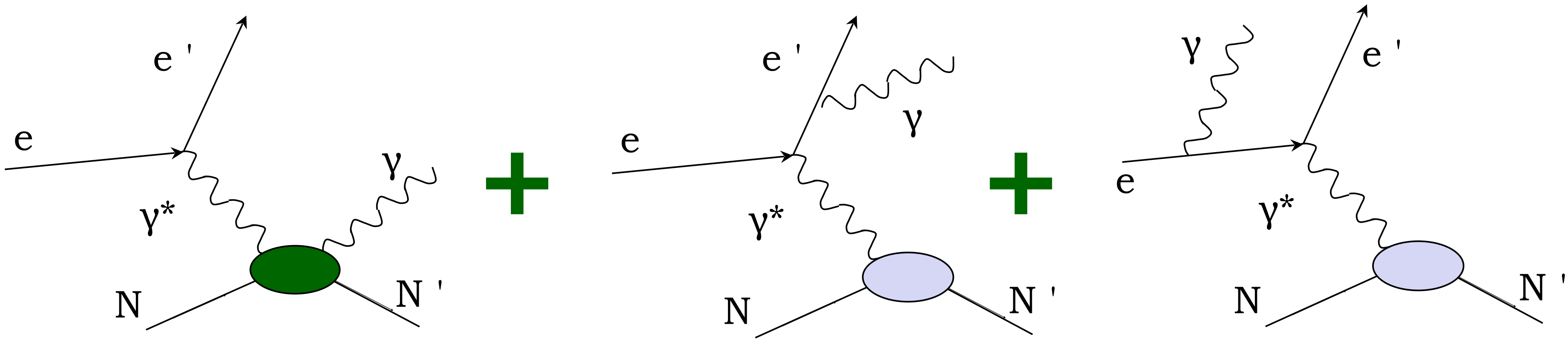
M. Mazouz et al, PRL 99 (2007) 242501



* GPDs can provide insight into the orbital angular momentum contribution to nucleon spin: **the spin puzzle**.

DVCS in experiment

- Process measured in experiment:



DVCS

Bethe - Heitler

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

Amplitude parameterised in terms of Compton Form Factors

Amplitude calculable from elastic Form Factors and QED

Interference term

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

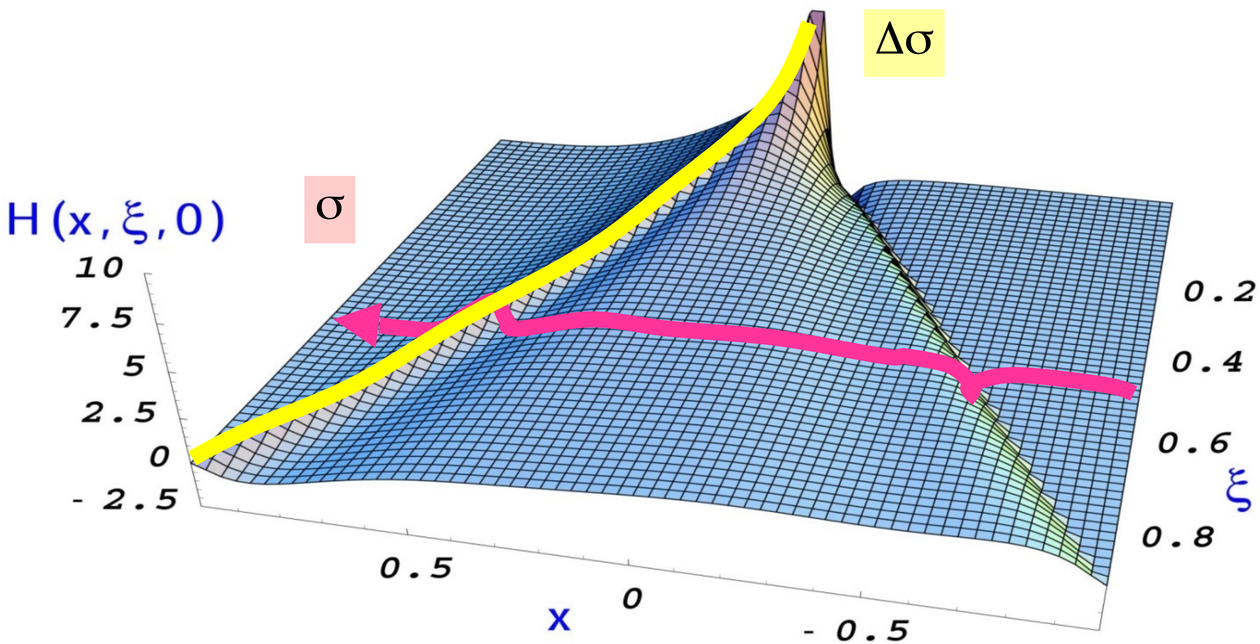
Compton Form Factors in DVCS

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

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

At leading twist, leading order:

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



Only ξ and t are accessible experimentally!

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

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

The DVCS/BH amplitude

$$\mathcal{T}^2 = |\mathcal{T}_{\rm BH}|^2 + |\mathcal{T}_{\rm DVCS}|^2 + \mathcal{I}$$

Interference term for DVCS/BH

$$|\mathcal{T}_{\rm BH}|^2 = \frac{e^6}{x_B^2 y^2 (1+\epsilon^2)^2 t\, \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} [c_0^{\rm BH} + \sum_{n=1}^{2} c_n^{\rm BH} \cos n\phi + s_1^{\rm BH} \sin\phi]$$

$$|\mathcal{T}_{\rm DVCS}|^2 = \frac{e^6}{y^2 \mathcal{Q}^2} \{c_0^{\rm DVCS} + \sum_{n=1}^{2} [c_n^{\rm DVCS} \cos n\phi + s_n^{\rm DVCS} \sin n\phi]\}$$

$$\mathcal{I} = \frac{e^6}{x_B y^3 t \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \{c_0^{\mathcal{I}} + \sum_{n=1}^{3} [c_n^{\mathcal{I}} \cos n\phi + s_n^{\mathcal{I}} \sin n\phi]\}$$

Intermediate lepton propagators

Coefficients depending on Compton Form Factors

From asymmetries to CFFs

At leading twist, beam-spin asymmetry (BSA) can be expressed as:

$$A_{\mathrm{LU}}(\phi) \sim \frac{s^{\mathcal{I}}_{1,\mathrm{unp}} \sin\phi}{c^{\mathrm{BH}}_{0,\mathrm{unp}} + (c^{\mathrm{BH}}_{1,\mathrm{unp}} + c^{\mathcal{I}}_{1,\mathrm{unp}} + \ldots)\cos\phi \ldots}$$

higher-twist terms…

The leading coefficient is related to the imaginary part of the Compton Form Factors:

$$s^{\mathcal{I}}_{1,\mathrm{unp}} \propto \Im\mathrm{m}[F_1\mathcal{H} + \xi(F_1+F_2)\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}]$$

At CLAS kinematics, this dominates

F_1, F_2: Dirac, Pauli form factors

Likewise, for the target-spin asymmetry (TSA):

$$A_{\mathrm{UL}}(\phi) \sim \frac{s^{\mathcal{I}}_{1,\mathrm{LP}} \sin\phi}{c^{\mathrm{BH}}_{0,\mathrm{unp}} + (c^{\mathrm{BH}}_{1,\mathrm{unp}} + c^{\mathcal{I}}_{1,\mathrm{unp}} + \ldots)\cos\phi + \ldots}$$

$$s_{1,\mathrm{LP}} \propto \Im\mathrm{m}[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E}) - \xi(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}]$$

At CLAS kinematics, these CFFs dominate

* Obtain coefficients from fitting the phi-dependence of the asymmetry:

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

Double-spin asymmetry

At leading twist, double-spin asymmetry (DSA) can be expressed as:

$$A_{\rm LL}(\phi) \sim \frac{c_{0,\rm LP}^{\rm BH} + c_{0,\rm LP}^{\mathcal{I}} + (c_{1,\rm LP}^{\rm BH} + c_{1,\rm LP}^{\mathcal{I}})\cos\phi}{c_{0,\rm unp}^{\rm BH} + (c_{1,\rm unp}^{\rm BH} + c_{1,\rm unp}^{\mathcal{I}} + \ldots)\cos\phi\ldots}$$

$$c_{0,\rm LP}^{\mathcal{I}}, c_{1,\rm LP}^{\mathcal{I}} \propto \Re\mathrm{e}[F_1\widetilde{\mathcal{H}} + \xi(F_1+F_2)(\mathcal{H} + \frac{x_B}{2}\mathcal{E}) - \xi(\frac{x_B}{2}F_1 + \frac{t}{4M^2}F_2)\widetilde{\mathcal{E}}]$$

At CLAS kinematics, leading-twist dominance of these CFFs

* Fit function for the phi-dependence of the asymmetry: $\dfrac{\kappa_{\rm LL} + \lambda_{\rm LL}\cos\phi}{1+\beta\cos\phi}$

Shares denominator with BSA and TSA!
If measurements at same kinematics, can do a simultaneous fit.

Transverse extension of partons in the proton

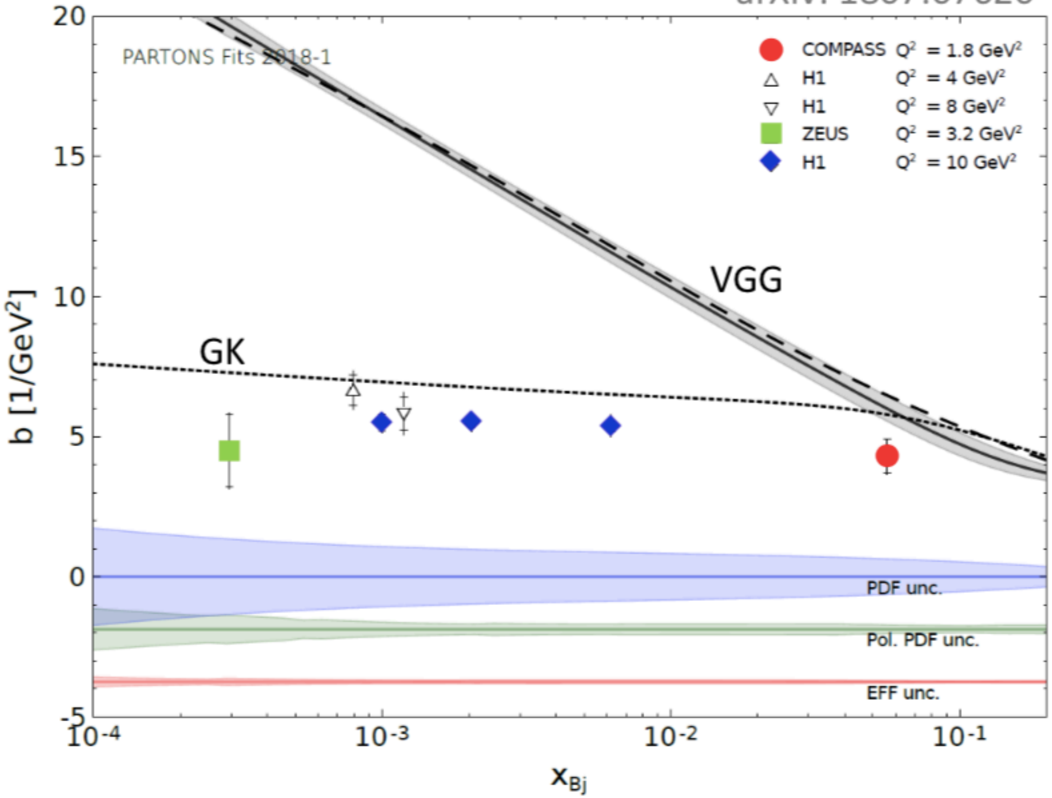
Comparison to GPD models

Figure from Moutarde, Sznajder, Wagner
arXiv: 1807.07620

The grey band is a global fit of CFF
in the PARTON framework
at LO and LT using a GPD parametrization
(only valence and sea quarks)

GK includes gluons (at next order in α_S)

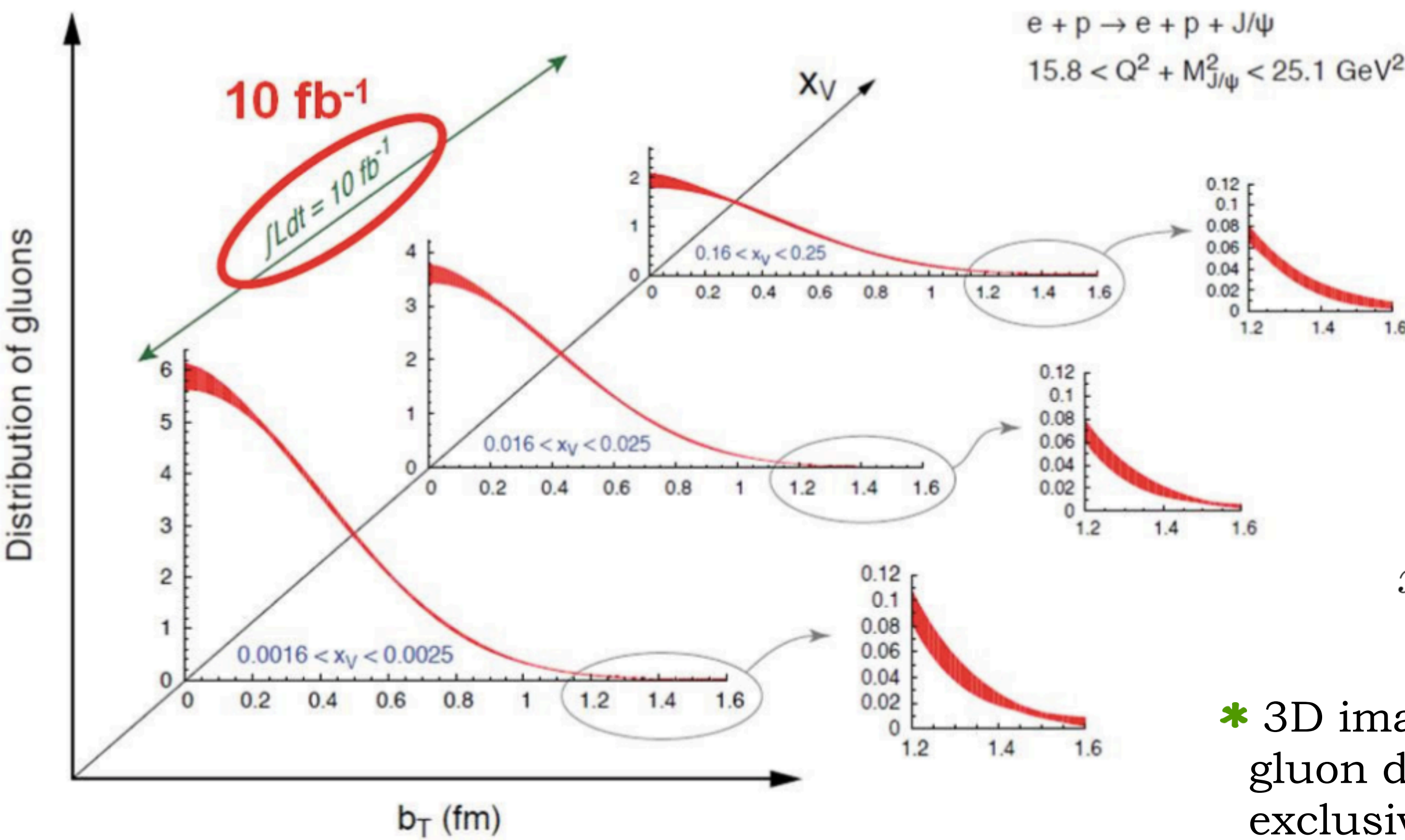
→ Manifestation of gluons or NLO

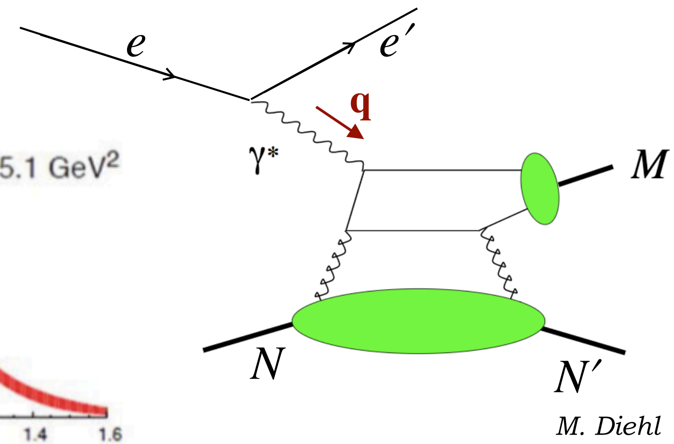


Slide from: N. d'Hose @ Getting to Grips with QCD, Primosten 2018

Nucleon tomography: imaging glue

- Gluon GPDs can be accessed through deeply virtual meson production (DVMP), eg: J/Ψ
- Access to spatial distributions of gluons at different longitudinal momentum fractions:





Gluon momentum fraction related to:

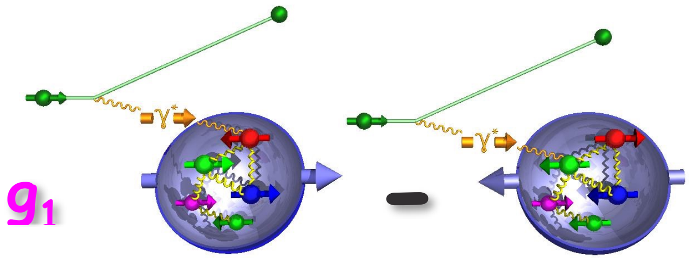
$$x_V = x_B(1 + M^2_{J/\Psi}/Q^2)$$

- 3D images of sea quark and gluon distributions from exclusive reactions: DVCS and DVMP.

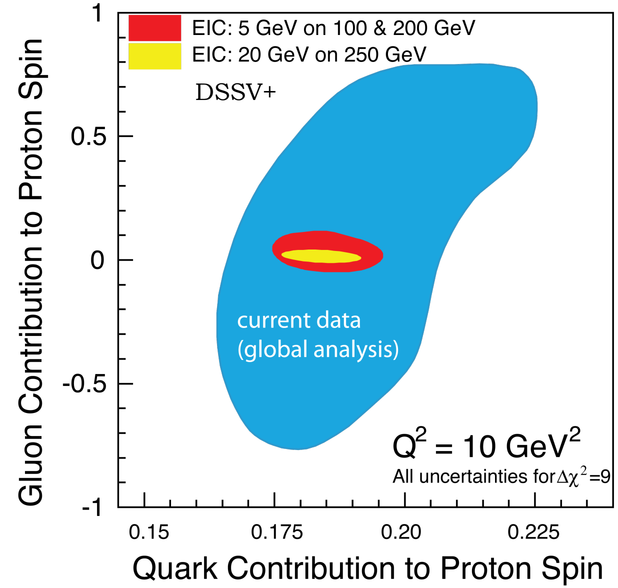
EIC White Paper, *Eur. Phy. J. A 52, 9 (2016)*

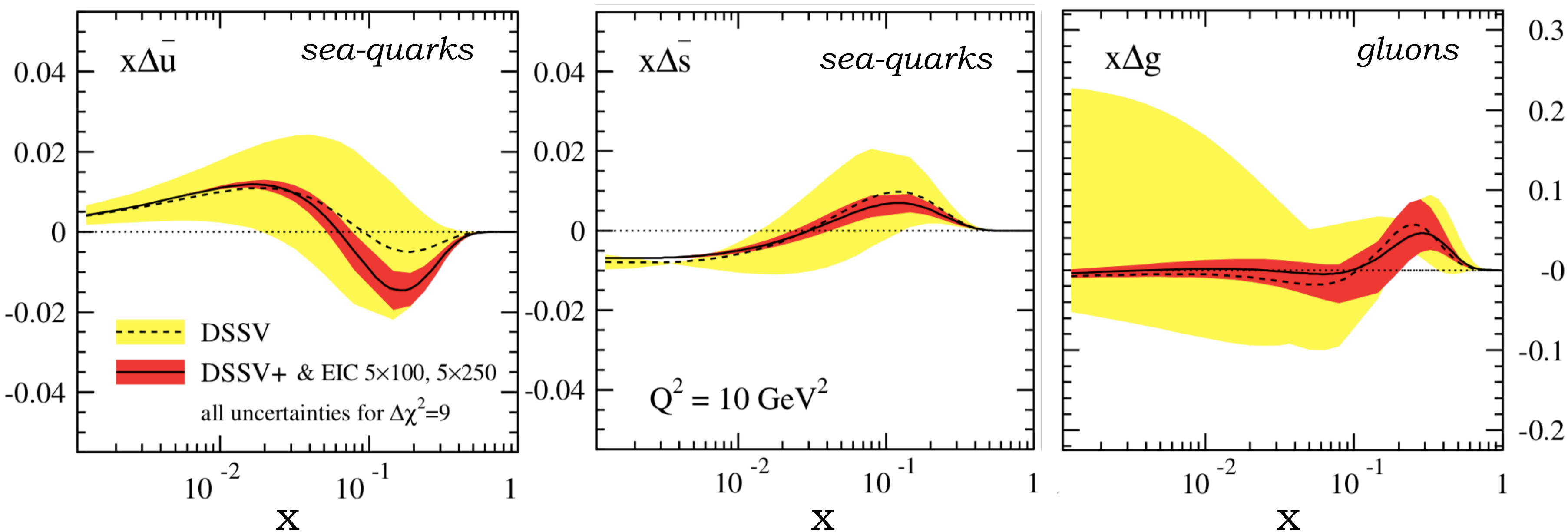
Gluon spin

- DIS and SIDIS will contribute extremely precise measurements of the helicity distributions of sea-quarks and gluons.



$$\Delta\Sigma(Q^2) = \int_0^1 g_1(x,Q^2)\,dx = \int_0^1 \Delta q_f(x,Q^2)\,dx$$





E. Aschenauer *et al.*,
Phys. Rev. D 86, 054020 (2012)

DSSV: D. de Florian, R. Sassot, M. Stratmann, W. Vogelsang, Phys. Rev. **D 80**, 034030 (2009).

DSSV+: arXiv:1112.0904 [hep-ph]