Experimental study of Generalised Parton Distributions

J. Roche (Ohio University)

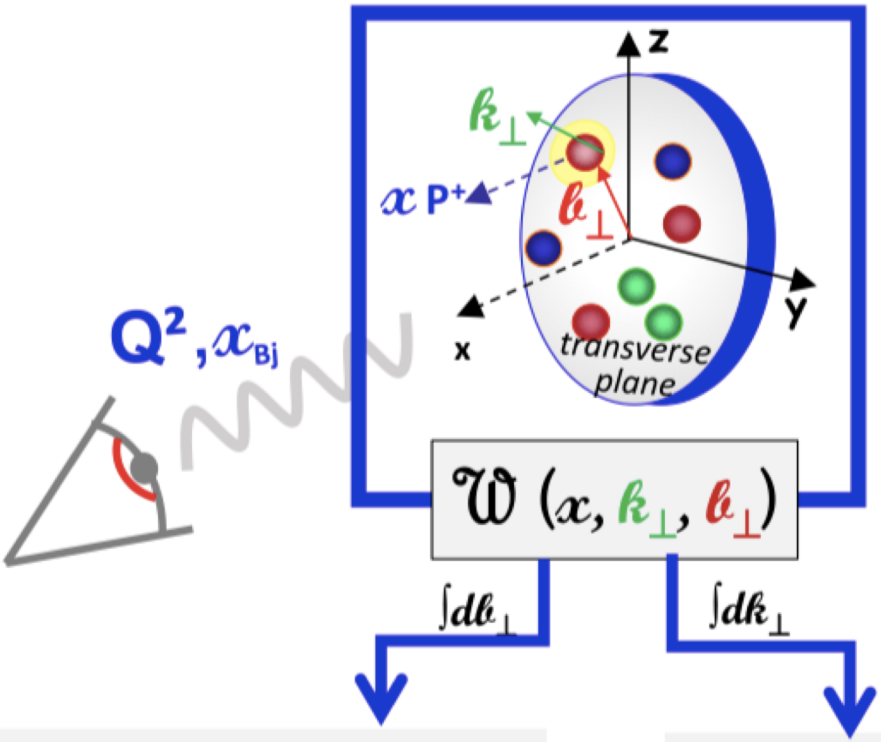
- Hard exclusive reactions allow the study of the 3D structure of nucleon through the measure of Generalized Parton Distributions that goes beyond what can be achieved with Elastic and Deep Inelastic Scattering.

- Dedicated experiments are conducted world-wide. In the valence region, the growing set of existing results is helping refine our approach to extracting the GPDs from the data.

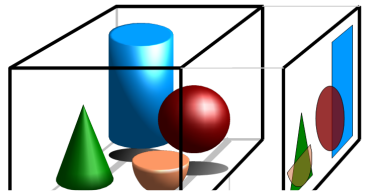
- The 12 GeV Hall A DVCS experiment is in the process of publishing its results.

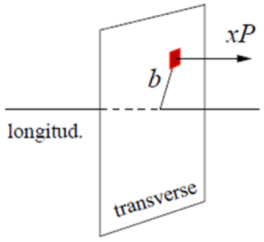
Award #1913170

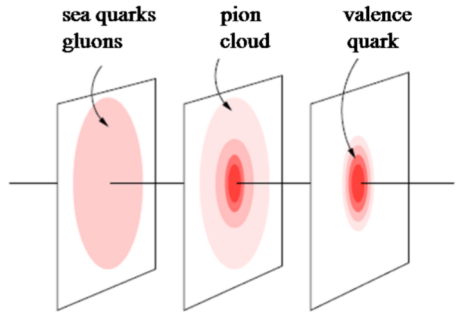
Toward a more complete description of the nucleon



Quantum tomography of the nucleon







Transverse momentum

$f(x, k_\perp)$
8 TMDs

accessible in SIDIS *and* Drell-Yan

$\int dk_\perp$

Transverse position

$q(x, b_\perp)$
8 GPDs

$\int dx$ → **Form Factors**

$\int db_\perp$

accessible in **exclusive reactions**

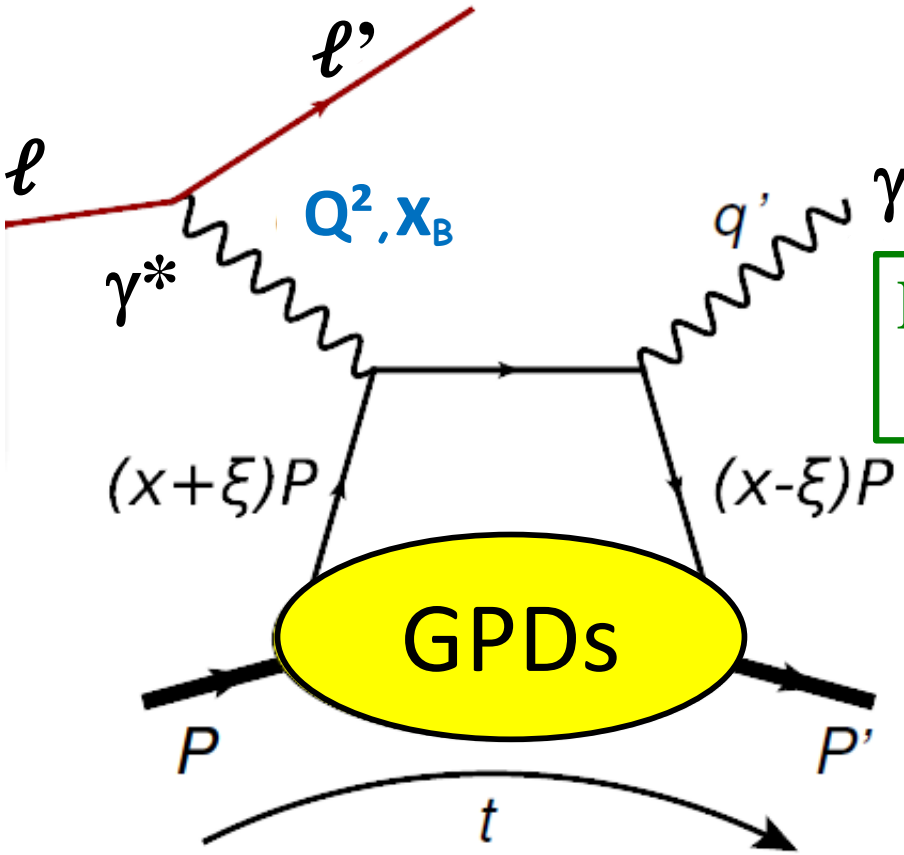
DVCS: Deeply Virtual Compton Scattering

DVMP: Deeply Virtual Meson Production

PDFs (x)

Slide from N. d'Hose, APS-April meeting 2019.

Exclusive reactions: handbag diagram



γ or $\pi, \rho, \phi, J/\psi, \ldots$

DVCS: $\ell p \rightarrow \ell' p' \gamma$ (golden channel)
DVMP: $\ell p \rightarrow \ell' p' \pi$ or ρ or ϕ or $J/\psi, \ldots$

Definition of variables:

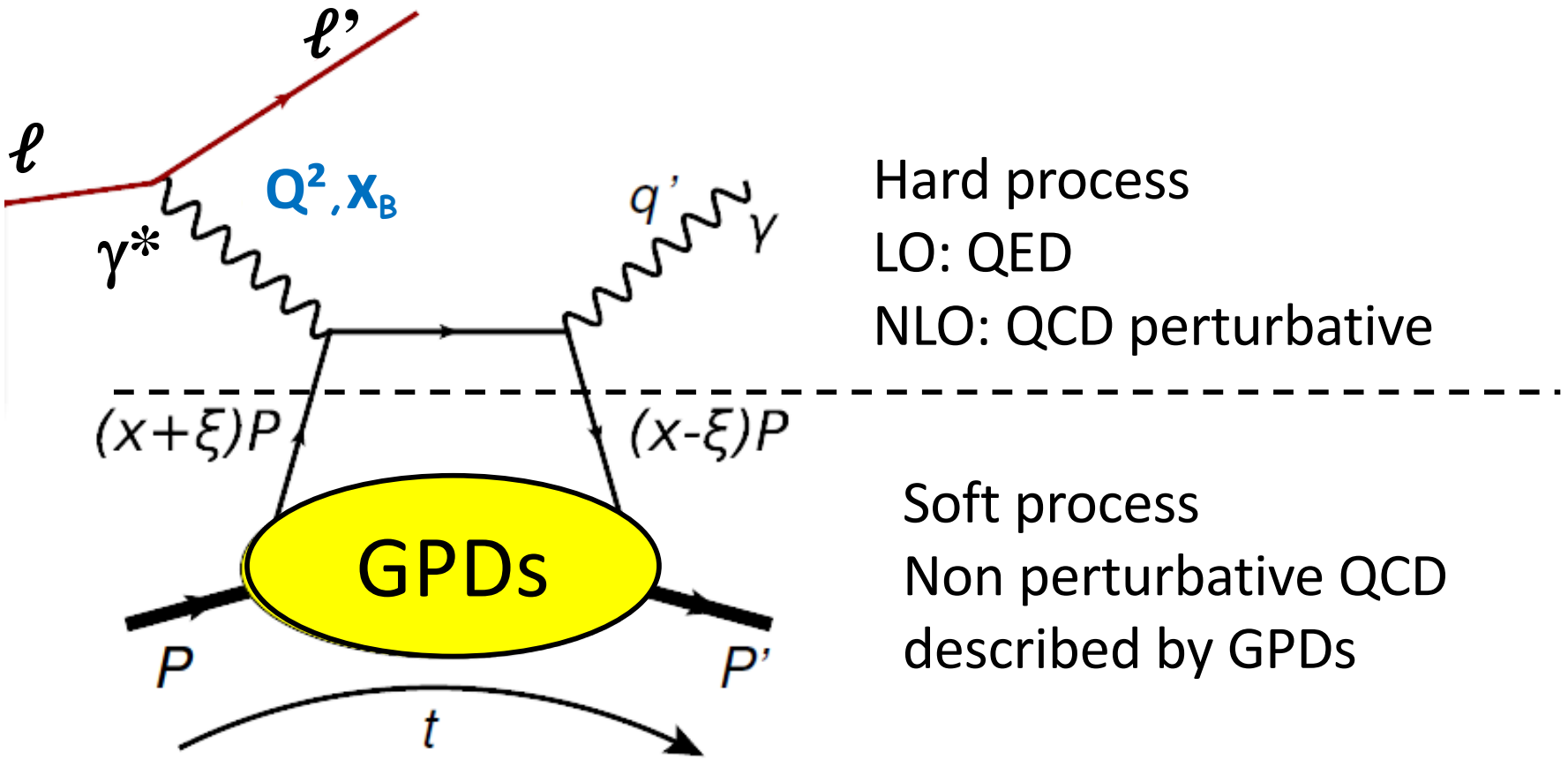
- x: average long. momentum - NOT ACCESSIBLE
- ξ: long. mom. difference $\simeq x_B/(2 - x_B)$
- t: four-momentum transfer related to $b_\perp$ via Fourier transform

Slide from N d'Hose, Tranversity 2014

GPDs and factorization

D. Mueller *et al*, Fortsch. Phys. 42 (1994)
X.D. Ji, PRL 78 (1997), PRD 55 (1997)
A. V. Radyushkin, PLB 385 (1996), PRD 56 (1997)

In the Bjorken limit: $\left.\begin{array}{rcl} Q^2 = -q^2 & \to & \infty \\ \nu & \to & \infty \end{array}\right\}$ $x_B = \frac{Q^2}{2M\nu}$ fixed

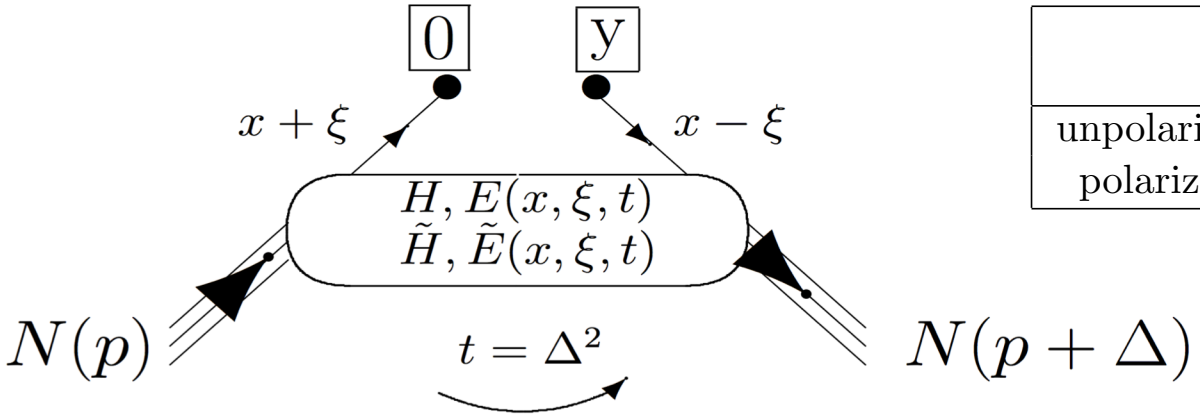


Hard process
LO: QED
NLO: QCD perturbative

Soft process
Non perturbative QCD
described by GPDs

The minimal Q^2 at which the factorization holds **must be tested** and established by **experiments**

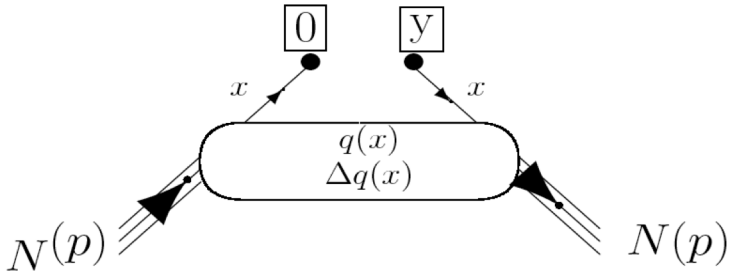
Generalized Parton Distributions



	Nucleon Helicity	
	conserving	non-conserving
unpolarized GPD	H	E
polarized GPD	$\tilde{H}$	$\tilde{E}$

$$\lim_{t\to 0}(GPD) \to PDF$$

DIS



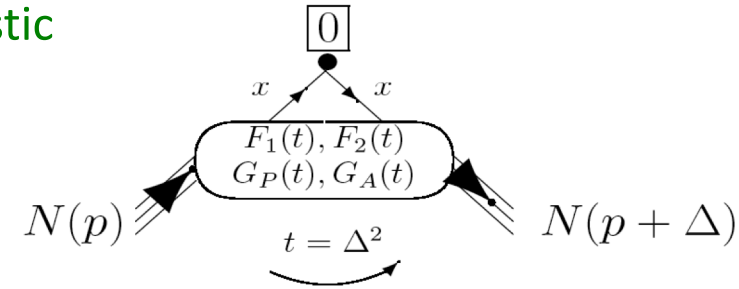
$$H^q(x,0,0) = q(x), -\bar{q}(-x)$$

$$\tilde{H}^q(x,0,0) = \Delta q(x), \Delta\bar{q}(-x)$$

No relation for the GPD E and $\tilde{E}$

GPD first moments → Form Factors

Elastic



$$\int_{-1}^{+1} dx H^q(x,\xi,t) = F_1^q(t) \quad \int_{-1}^{+1} dx \tilde{H}^q(x,\xi,t) = g_A^q(t)$$

$$\int_{-1}^{+1} dx E^q(x,\xi,t) = F_2^q(t) \quad \int_{-1}^{+1} dx \tilde{E}^q(x,\xi,t) = h_A^q(t)$$

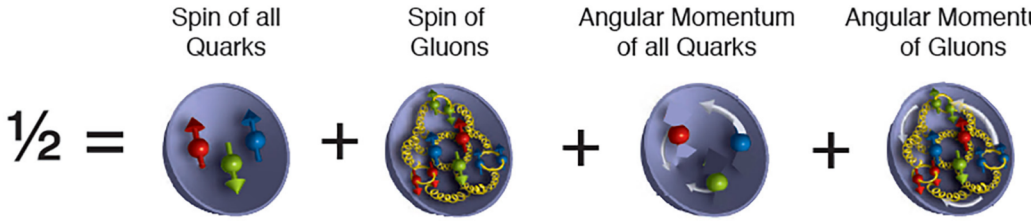
RPP 76(2013) 066202

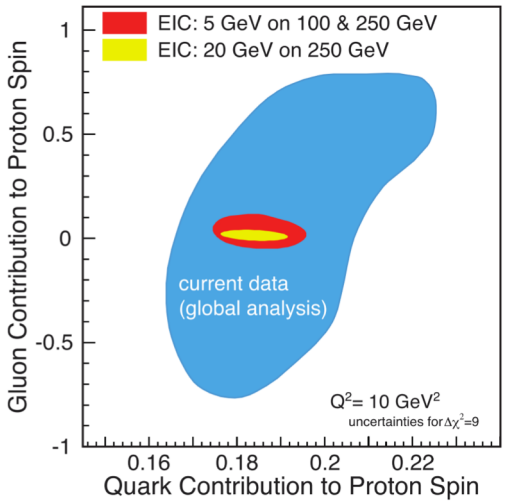
GPDs and hadronic physics issues

Contribution of the **angular momentum of quarks** to proton spin:

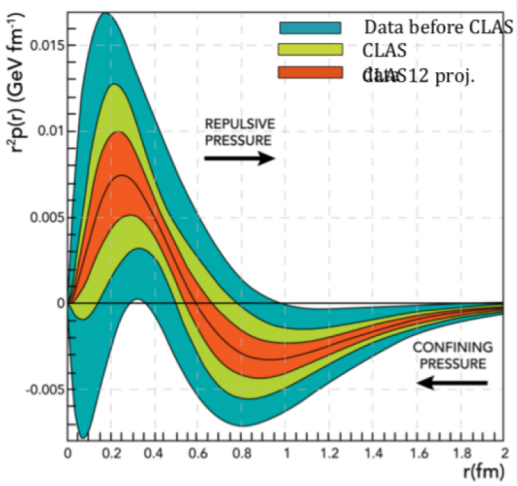
$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma + L_q}_{J_q} + J_g \quad \Rightarrow \quad J_q = \frac{1}{2}\int_{-1}^{1} dx\, x[H^q(x,\xi,0) + E^q(x,\xi,0)]$$

Ji's sum rule





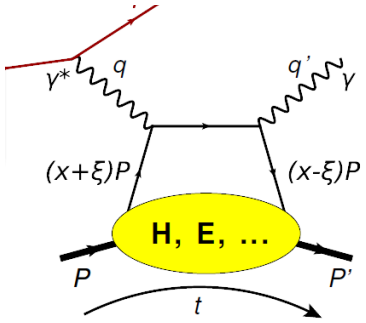
RHIC spin physics results (LRP 2015)



V. Burkert, L. Elouadrhiri, FX Girod
Nature 557 (2018, 7705, 396-399)

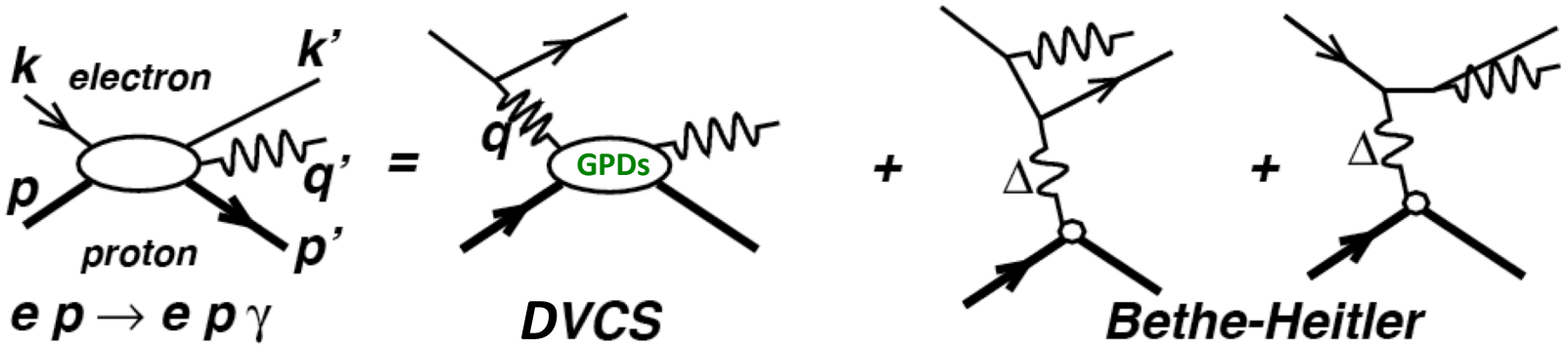
Access to the **mechanical properties** of the proton

$$\mathcal{H} = \int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi+i\varepsilon} = \underbrace{\mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}}_{} \underbrace{- i\,\pi\, H(x=\xi,\xi,t)}_{}$$



$$\mathbf{D(t) = \quad -Re(\mathcal{H}) \quad + \quad \int dx \frac{Im\mathcal{H}}{x+\xi}}$$

Measuring DVCS to access GPDs information

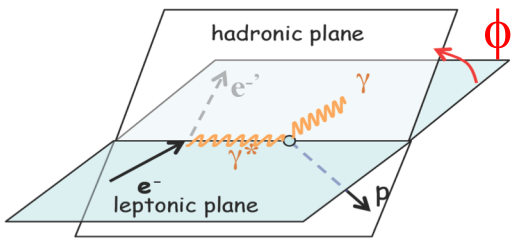


$$\frac{d^4\sigma(lp \to lp\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_l \; d\sigma^{DVCS}_{pol} + e_l \left(Re(I) + P_l Im(I)\right)$$

Known if Nucleon FFs are known

Bilinear combinations of GPDs

Linear combinations of GPDs and FFs



P_l : polarization target or beam

e_l : charge of the lepton beam

How to parametrize the measured cross-sections?

$$\frac{d^4\sigma(lp \to lp\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_l \; d\sigma^{DVCS}_{pol} + e_l \left(Re(I) + P_l Im(I)\right)$$

$$\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma^{DVCS}_{unpol} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
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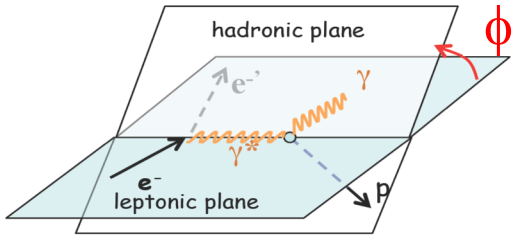
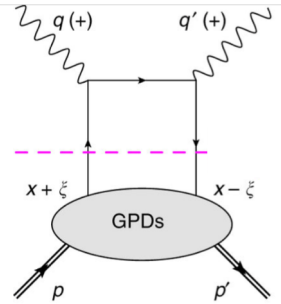
Re\, I &\propto c_0^{I} + c_1^{I}\cos\phi + c_2^{I}\cos 2\phi + c_3^{I}\cos 3\phi \\
Im\, I &\propto s_1^{I}\sin\phi + s_2^{I}\sin 2\phi
\end{aligned}$$

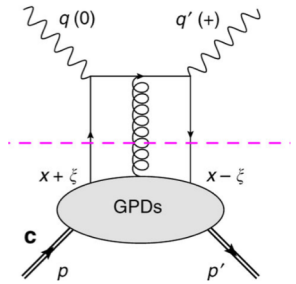
$$s_1^I = F_1\mathcal{H} + \xi(F_1 + F_2)\tilde{\mathcal{H}} + kF_2\mathcal{E}$$



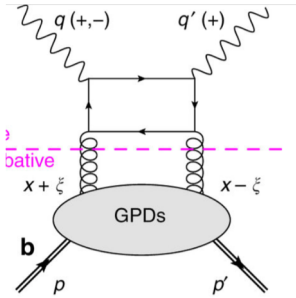
LT/LO



HT



NLO



Cross-sections analysis include more or less terms:
both in terms of harmonics (c's and s's) and
In term of GPD/CFFs.

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Award #1913170

The DVCS program worldwide

Experimental timeline

- Pioneering results from non-dedicated experiments (Hall B and Hermes): ~2001
- First round of dedicated experiments (Hall A/B, Hermes, H1&ZEUS): ~ 2005
- Second round of dedicated experiments (Halls A/B): ~2010
- Compelling DVCS program at JLab-12 GeV and Compass: 2015 and later
- EIC program…

The ideal experiment

High beam energy

ensure hard regime and large kinematic domain

polarized beam

availability of positive and negative leptons

variable energy (Rosenbluth type separations)

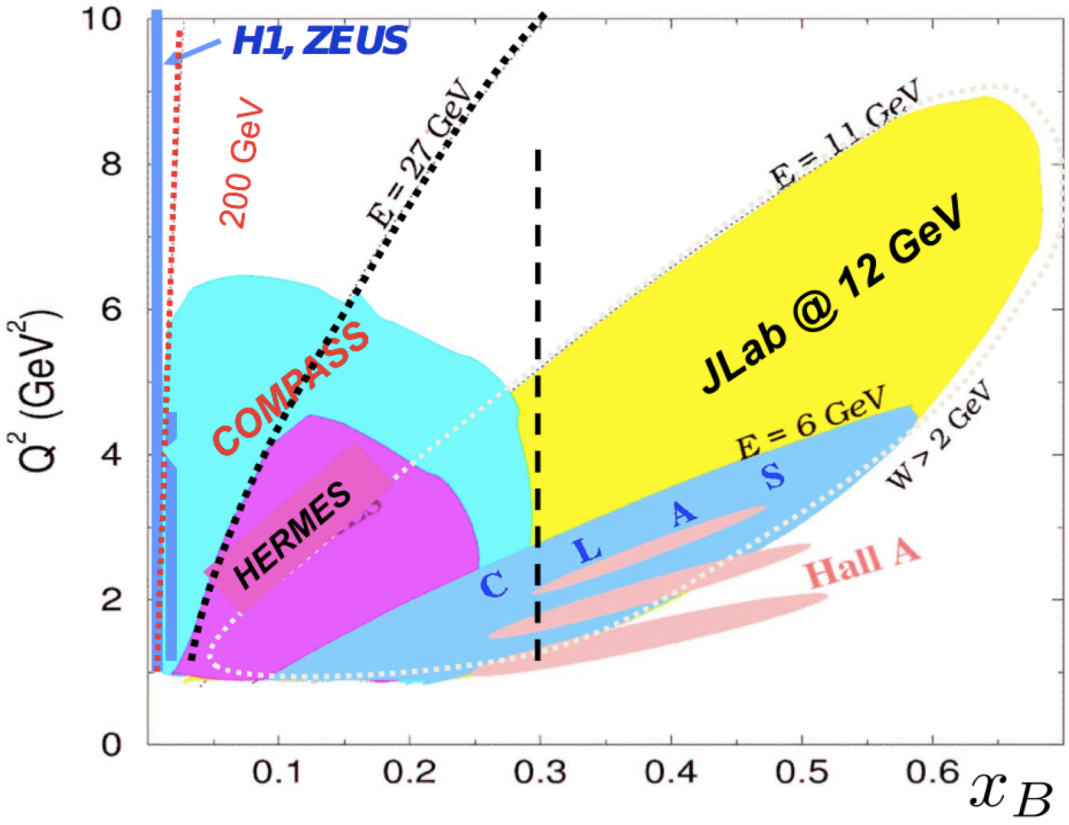
H_2, D_2, Longitudinaly and Transversely Polarized Target

High luminosity

small cross section

fully differential analysis (x_B, Q^2, t, ϕ)

Hermetic detectors (ensure exclusivity)



The past and future experiments

Collider mode e-p forward fast proton

ZEUS H1

Polarised 27 GeV e-/e+
Unpolarised 920 GeV p
~ Full event reconstruction

Fixed target mode slow recoil proton

hermes

Polarised 27 GeV e-/e+
Long, Trans polarised p, d target
Missing mass technique
2006-07 with recoil detector

HallA CLAS

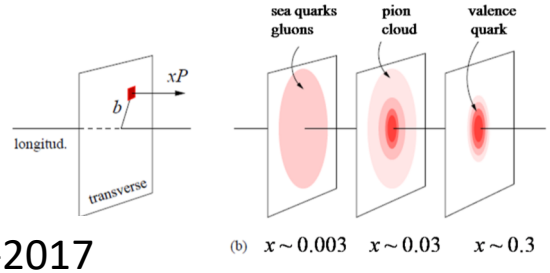
High lumi, highly polar. 6 & **12 GeV e-**
Long, (Trans) polarised p, d target
Missing mass technique

COMPASS

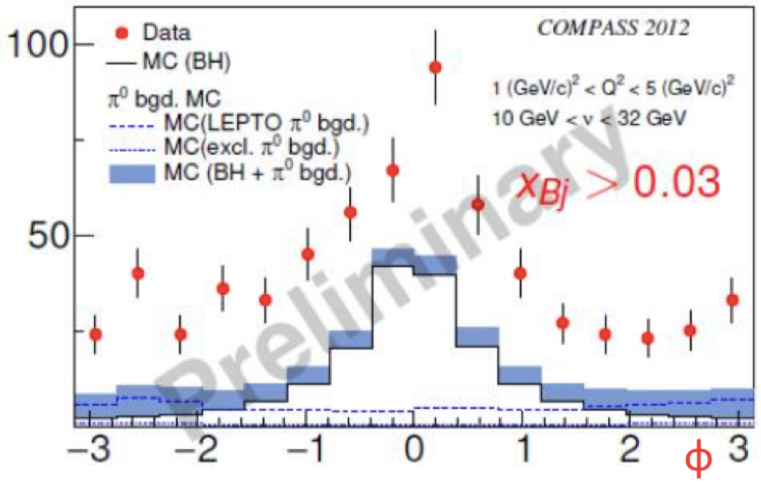
Highly polarised **160 GeV μ+/μ-**
p target, (Trans) polarised target
with recoil detection

Slide from N d'Hose, Tranversity 2014

Tomography in the sea quark domain



COMPASS 2012 results (hep-ex/1802.02739) 10 times more statistic in 2016-2017



$$
\begin{aligned}
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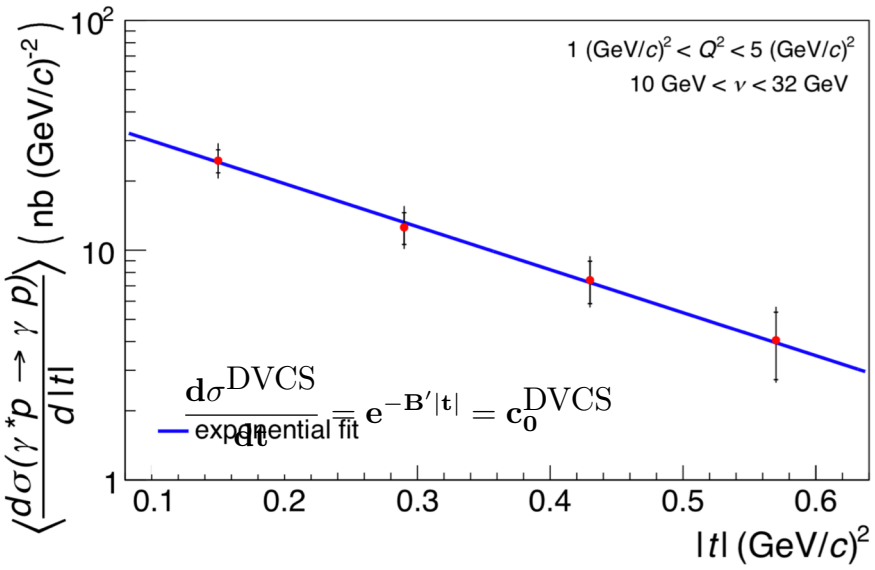
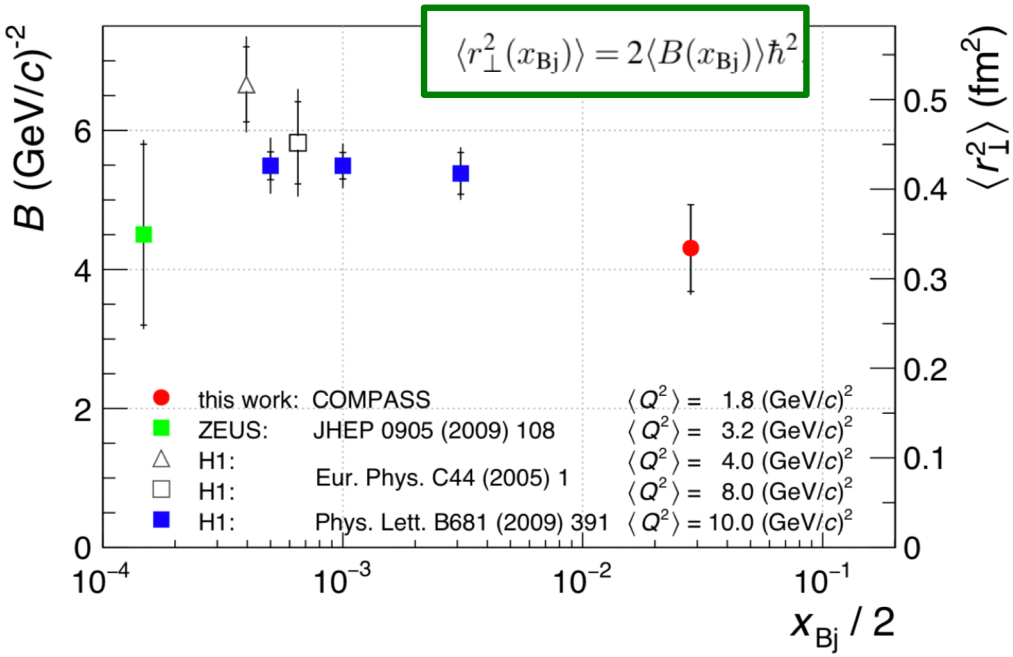
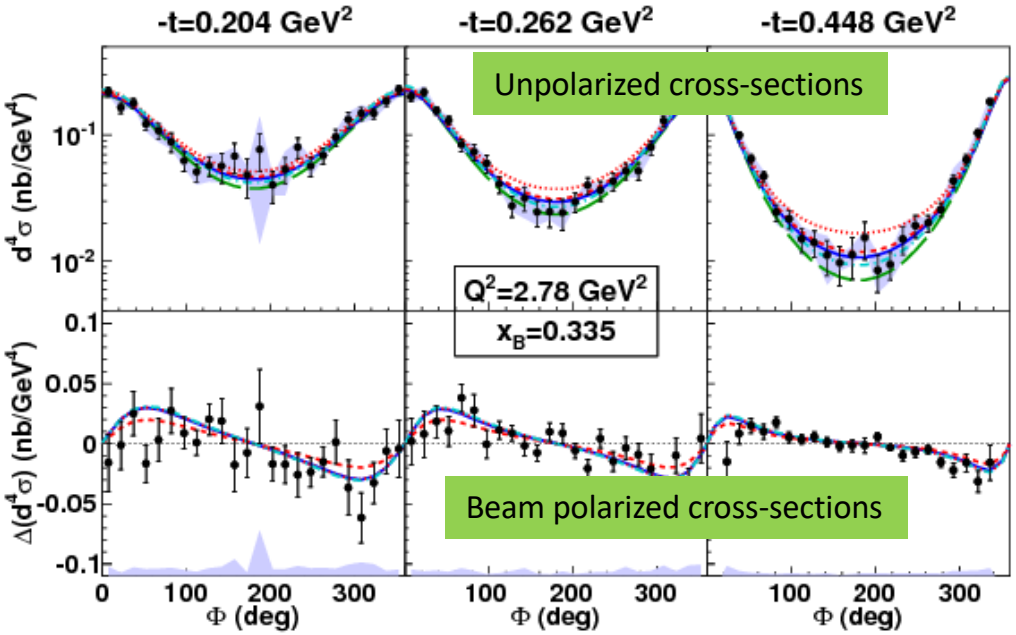
\end{aligned}
$$

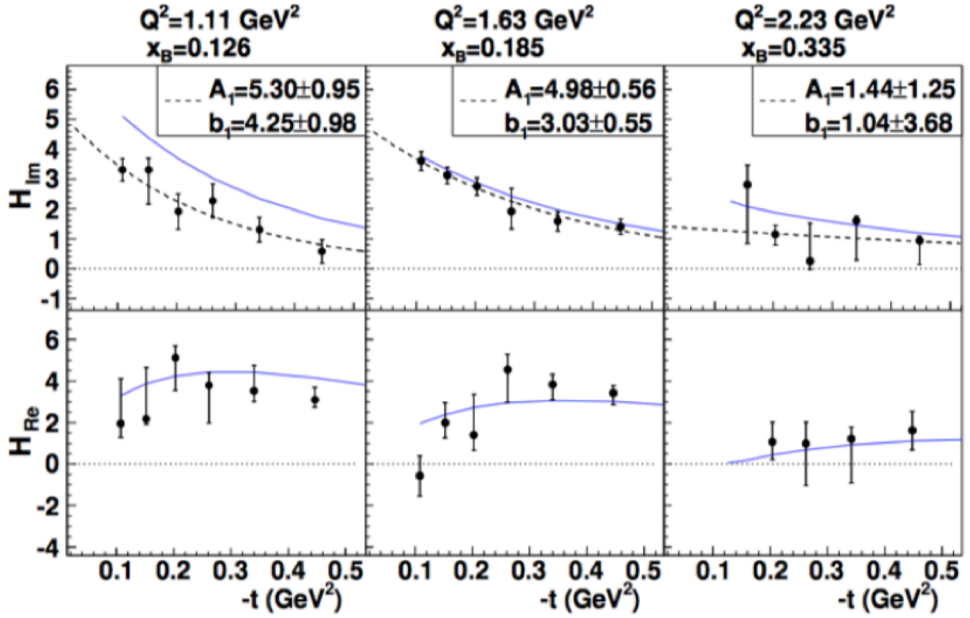




Tomography in the valence quark domain

CLAS 2005 data: 110 bins (xB, Q2, t) on LH2 target: Girod *et al*. PRL100('08) 162002 and Jo *et al.* PRL115, 212003 ('15)





---BH

…. KM10

--- KM10a

-.-. KMS12 using GK

--- VGG

Use LO and LT decomposition (red terms only)

$$
\begin{aligned}
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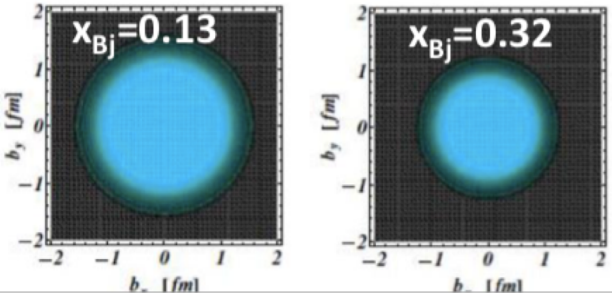
\mathrm{Im}\ I &\propto s_1^{I}\sin\phi + s_2^{I}\sin 2\phi
\end{aligned}
$$

Fit with 8 GPDs but only gets well defined results only for $\mathrm{Im}(\mathcal{H}), \mathrm{Re}(\mathcal{H})$

Guidal, Moutarde, Vanderhaeghen, PNPP 76 (2013)



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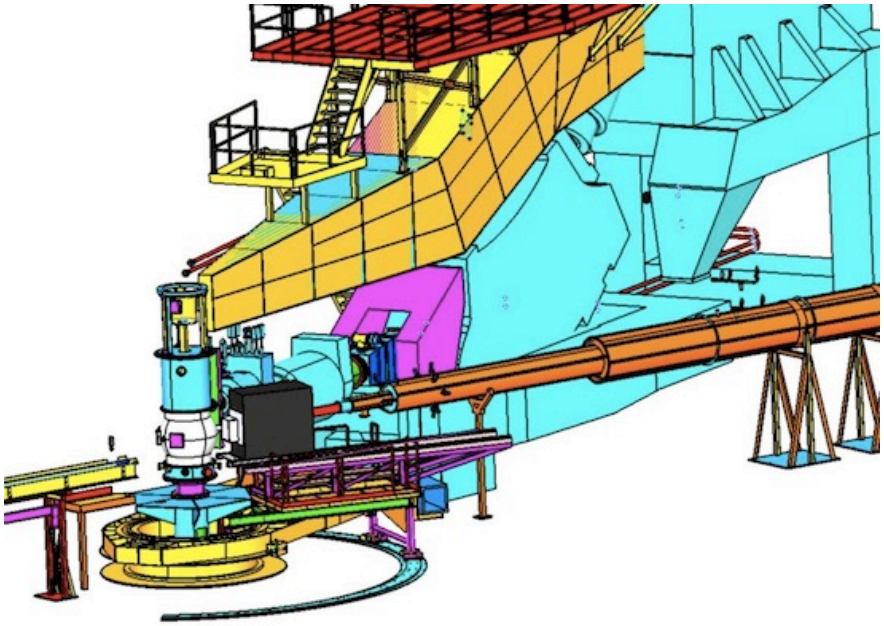
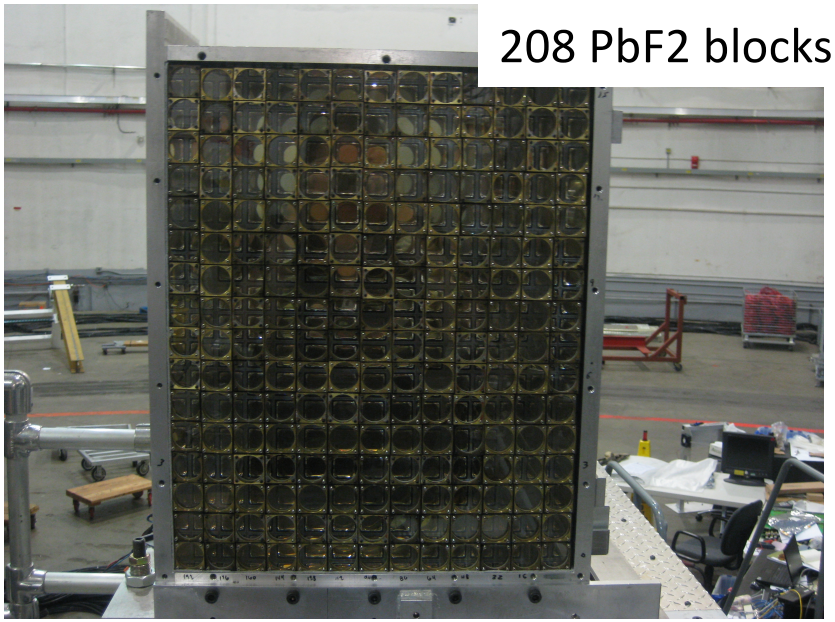
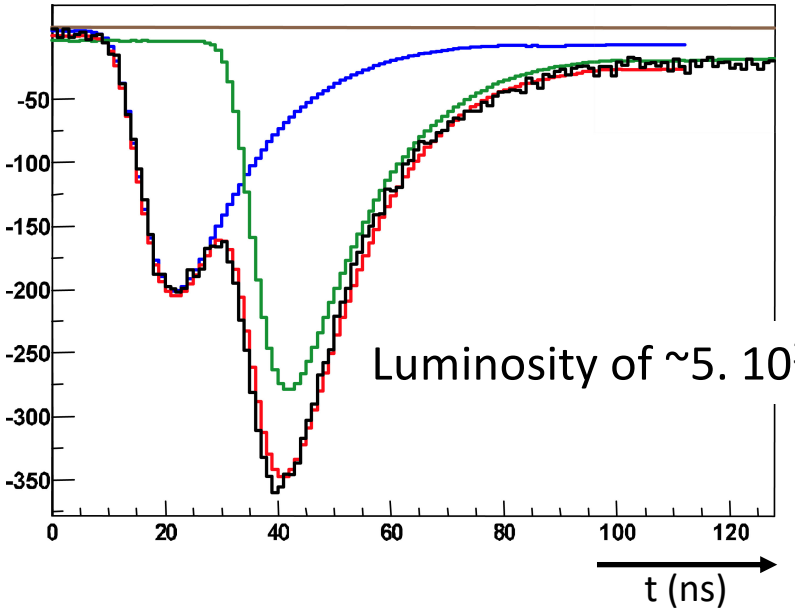
Award #1913170

Dedicated apparatus eg the Hall A scheme

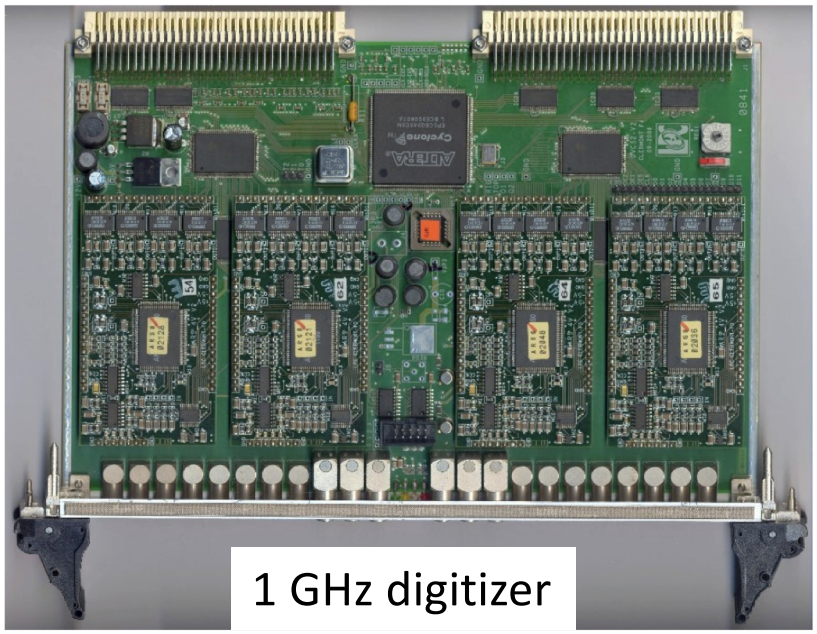




208 PbF2 blocks



Luminosity of ~5. 10^{37} Hz/cm^2



1 GHz digitizer

Exclusivity for the Hall A@DVCS scheme

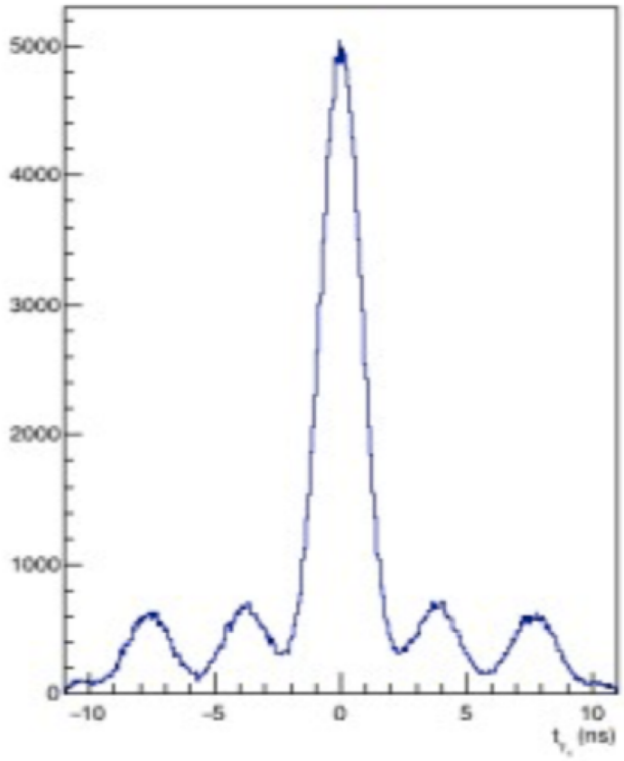
H(e,e'γ)X

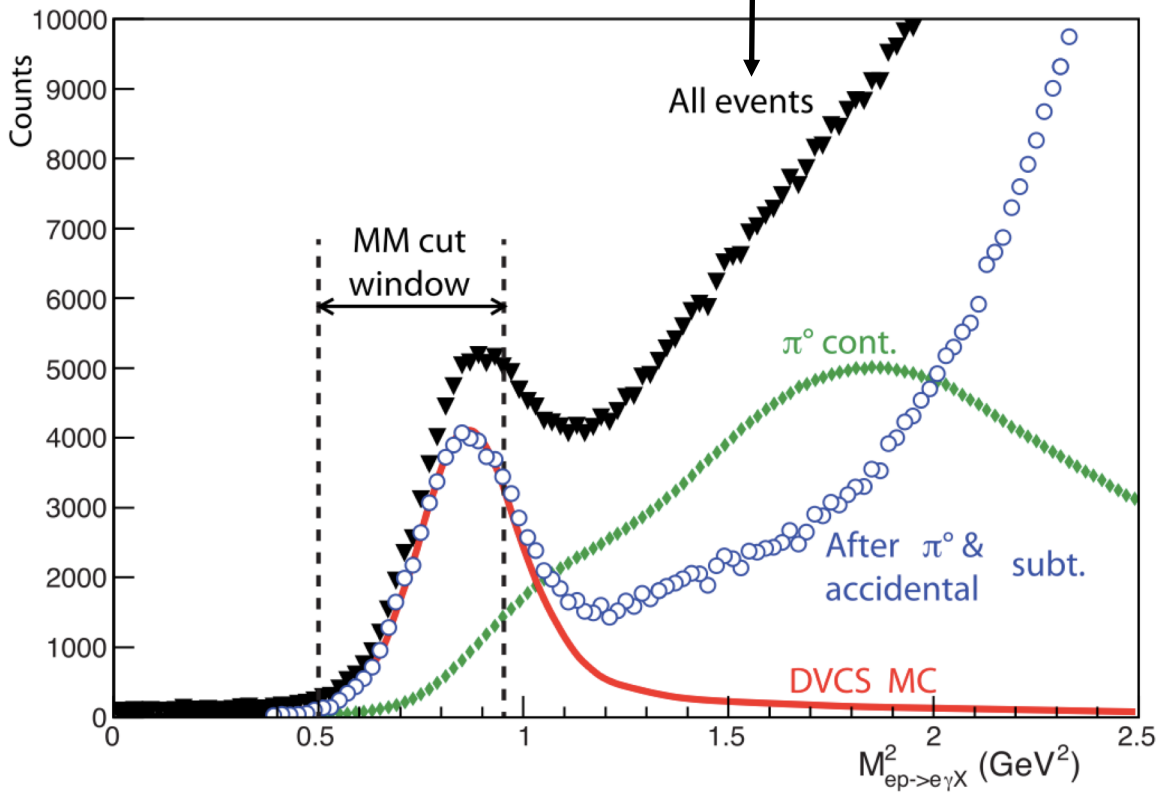
X can be

- p : ep -> epγ
- γp : ep -> epπ^0, π^0->γγ
- Nπ: ep -> eNγπ

...

Coincidence time (e-γ)





DVCS in Hall A@Jlab program

1st Generation (2004)

Q^2 dependence study (of red terms)

CM Camacho et al. PRL97, 2006

2nd Generation (2010)

Beam energy dependence study

a la Rosenbluth study:

Separate C_0^{DVCS} from C_0^I

Separate HT and NLO coeffcients *

M Defurne et al. PRL117, 2015

3rd Generation (2014-2016)

CEBAF12 allow the exploration

of high x_B and high Q^2

Paper under preparation

$$
\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma_{unpol}^{DVCS} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
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\mathrm{Re}\, I &\propto c_0^{I} + c_1^{I}\cos\phi + c_2^{I}\cos 2\phi + c_3^{I}\cos 3\phi \\
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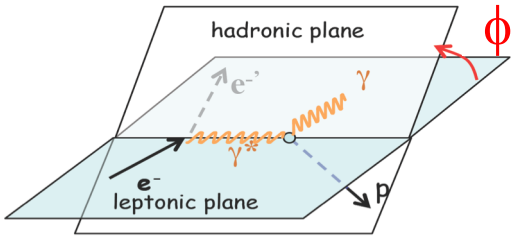
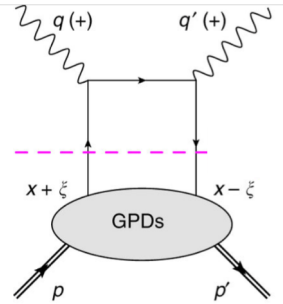
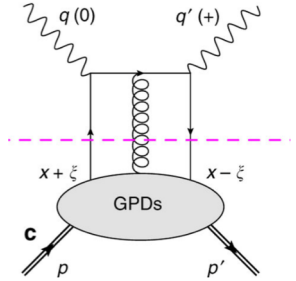
\end{aligned}
$$



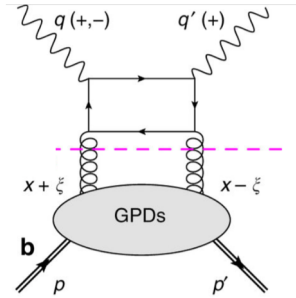
LT/LO



HT



NLO



Other results: off the neutron, π^0 electro-production*

*** More details in M. Defurne's talk**

DVCS Hall A@Jlab 1rst generation

$x_B = 0.37, \quad Q^2 = 2.36\ \mathrm{GeV}^2, \quad -t = 0.32\ \mathrm{GeV}^2$

Final paper PRC C92, Nov '15

$$d\sigma^{BH} \propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi$$

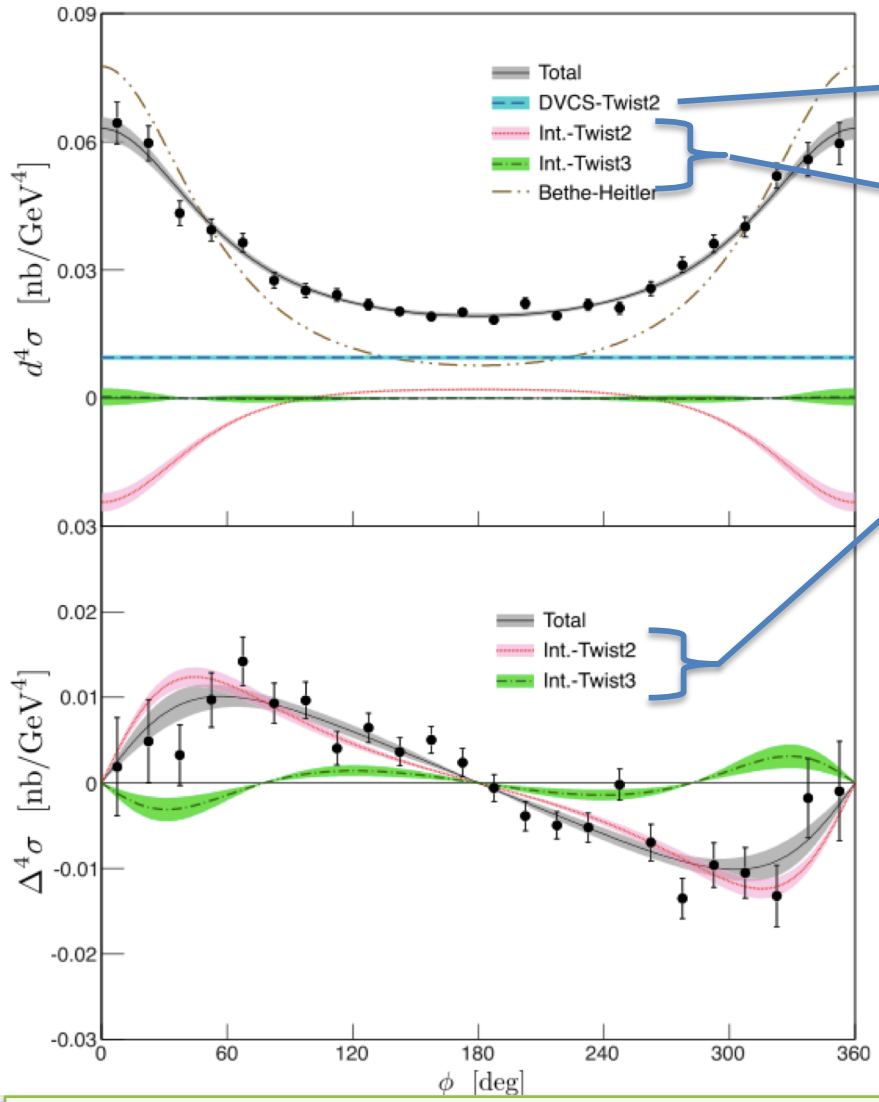
$$d\sigma_{unpol}^{DVCS} \propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi$$

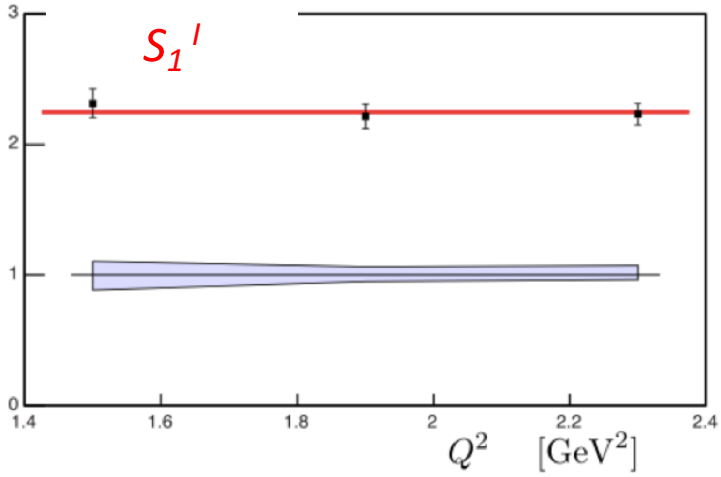
$$d\sigma_{pol}^{DVCS} \propto s_1^{DVCS}\sin\phi$$

$$\mathrm{Re}\ I \propto c_0^{I} + c_1^{I}\cos\phi + c_2^{I}\cos 2\phi + c_3^{I}\cos 3\phi$$

$$\mathrm{Im}\ I \propto s_1^{I}\sin\phi + s_2^{I}\sin 2\phi$$

LT/LO HT NLO





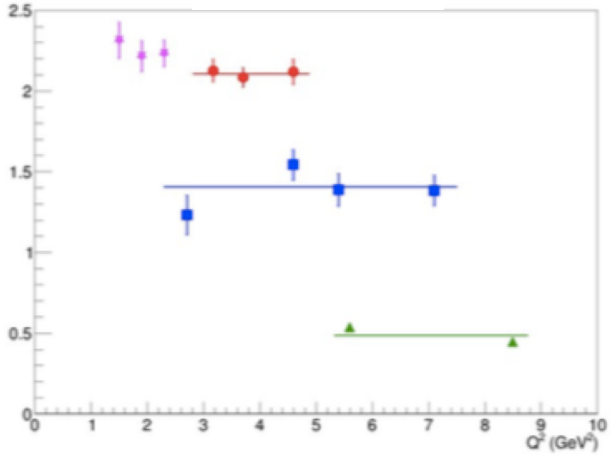
No Q^2 dependence within this limited range => leading twist dominance
Need to be checked over a larger Q^2 bite

DVCS Hall A@Jlab 3rd generation (12 GeV data)

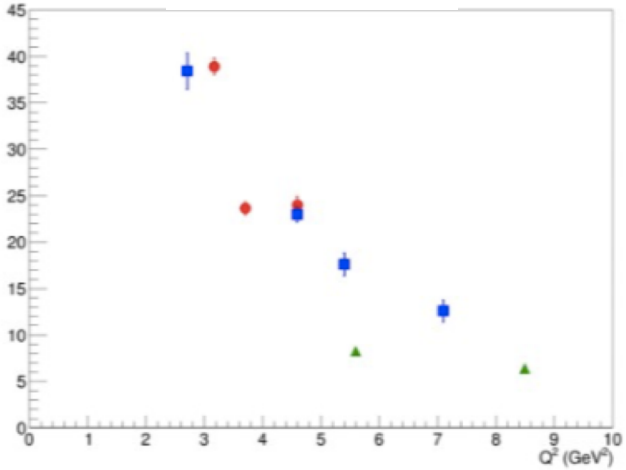
Analysis by F. Georges, INP Orsay

$$
\begin{aligned}
d\sigma^{BH} &\propto c_0^{BH} + c_1^{BH}\cos\phi + c_2^{BH}\cos 2\phi \\
d\sigma_{unpol}^{DVCS} &\propto c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi \\
d\sigma_{pol}^{DVCS} &\propto s_1^{DVCS}\sin\phi \\
\mathrm{Re}\, I &\propto c_0^{I} + c_1^{I}\cos\phi + c_2^{I}\cos 2\phi + c_3^{I}\cos 3\phi \\
\mathrm{Im}\, I &\propto s_1^{I}\sin\phi + s_2^{I}\sin 2\phi
\end{aligned}
$$

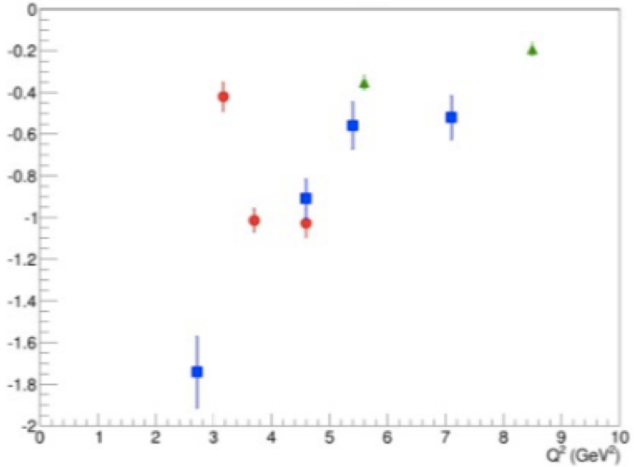
S_1^I



C_0^{DVCS}



C_1^I

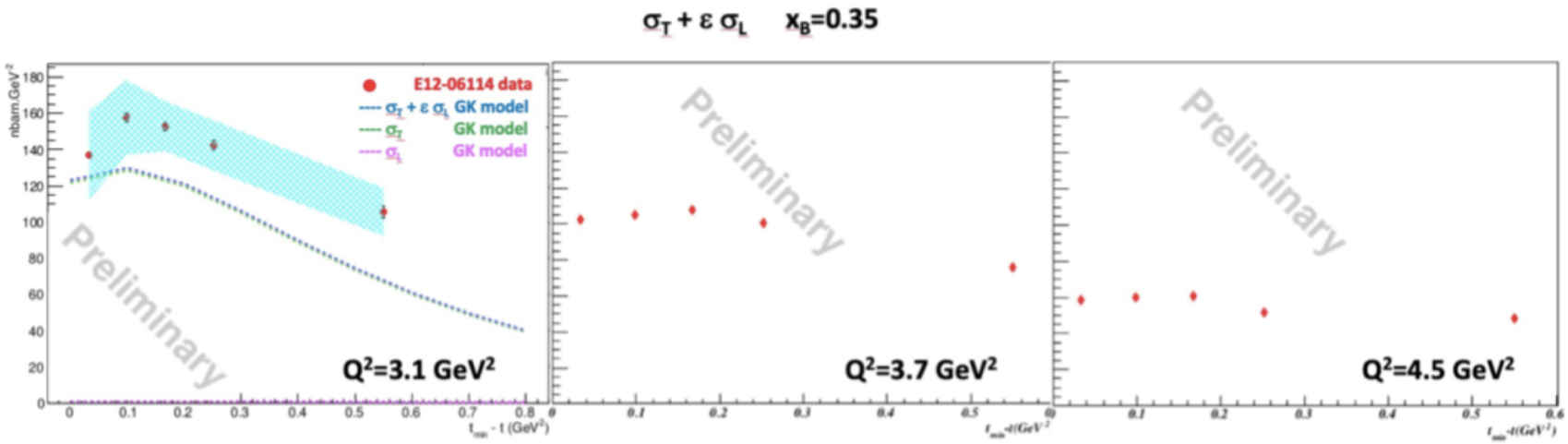


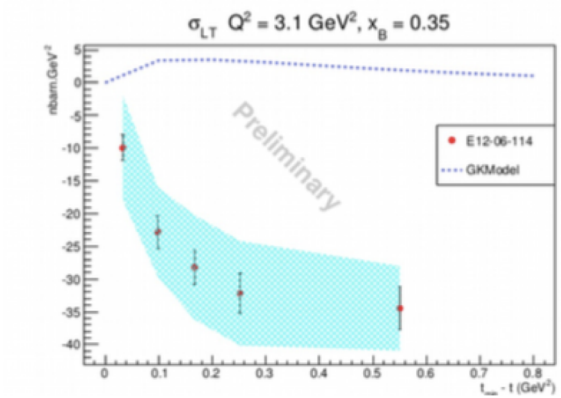
X_B = 0.36, <t> = -0.35
X_B = 0.48, <t> = -0.47
X_B = 0.60, <t> = -1.06
X_B = 0.36, <t> = -0.27

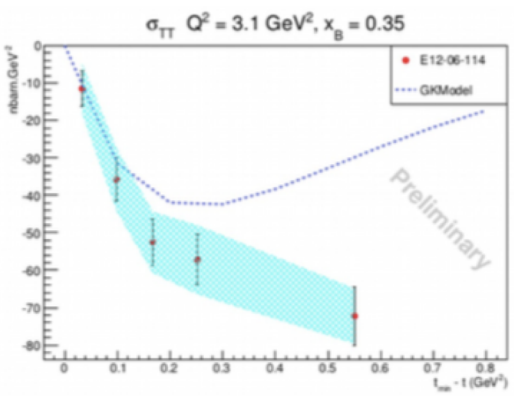
In depth study of trigger efficiency delayed the publication:
Could not resolve a 5% systematic inefficiency.

DVMP Hall A@Jlab 3rd generation (12 GeV data)

$$\frac{d^4\sigma}{dtd\phi dQ^2 dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\right]$$





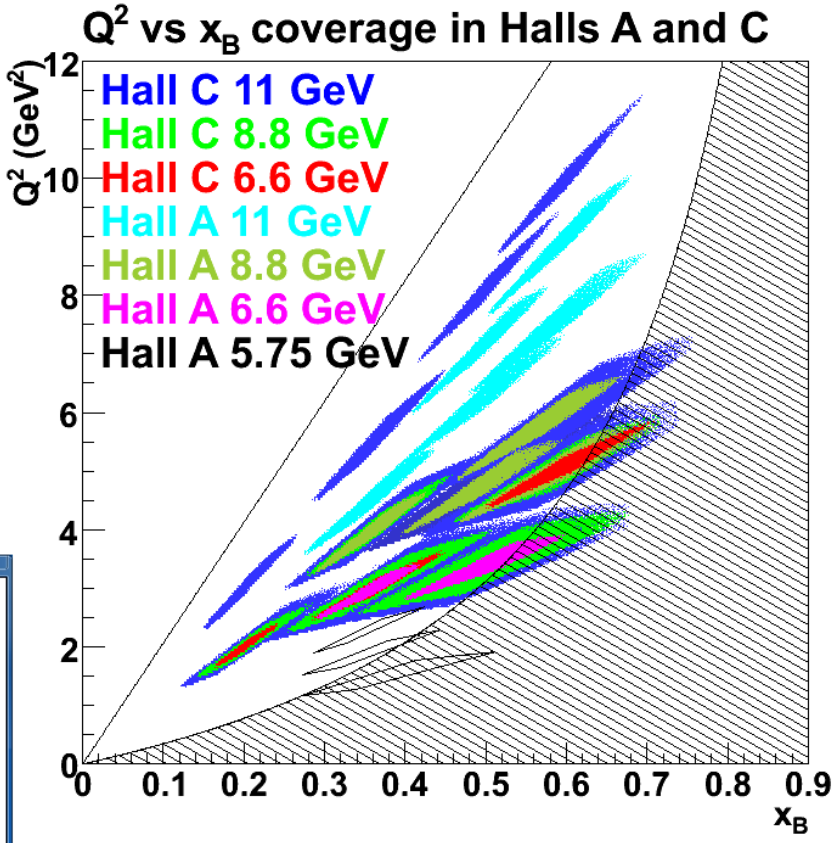


- $\sigma_T + \varepsilon\sigma_L$ decreases with Q^2 as expected
- $\boldsymbol{\sigma_{LT}}$ **:** opposite in sign, larger value
- σ_T is dominant

Analysis by M. Dlamini, Ohio U.

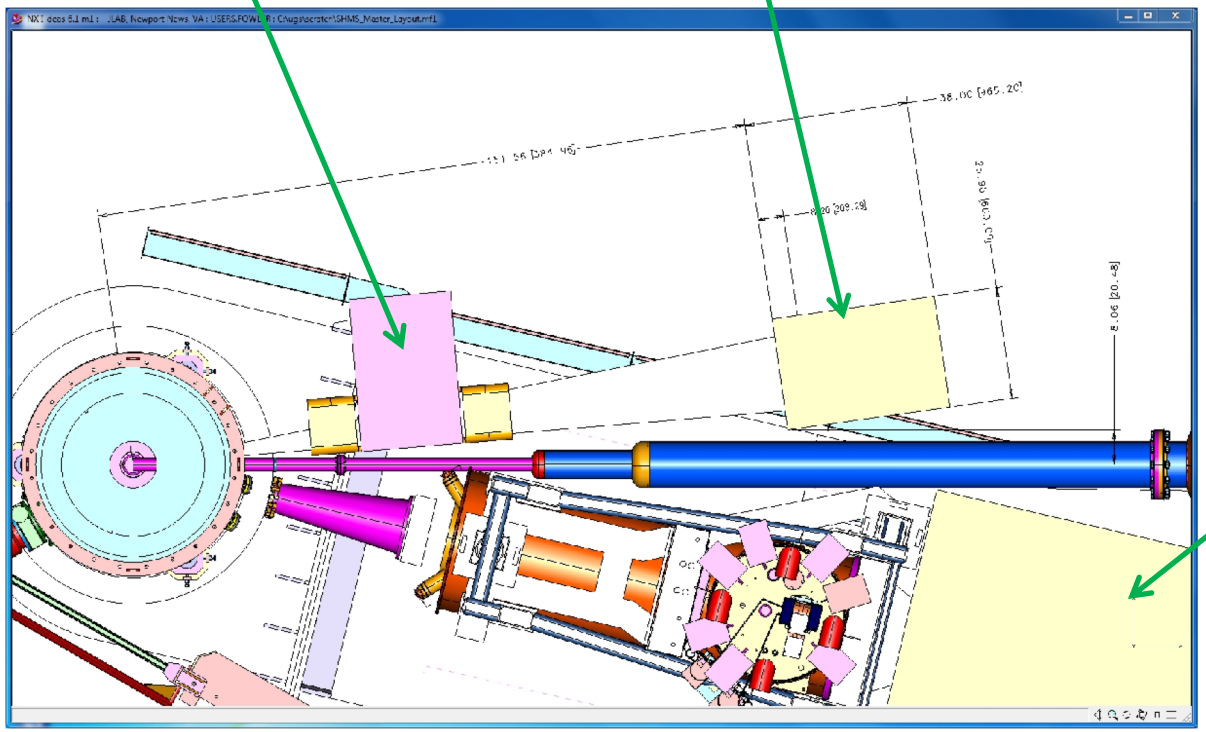
E12-13-010: DVCS at 11 GeV in Hall C

- Energy separation of the DVCS cross section
- Higher Q^2: measurement of higher twist contributions
- Low x_B extension (thanks to sweeping magnet)



Sweeping magnet

1116-block $PbWO_4$ calorimeter



Hall C HMS

Calorimeter under constructrion

Experimental study of Generalised Parton Distributions

- Hard exclusive reactions allow the study of the 3D structure of nucleon through the measure of Generalized Parton Distributions that goes beyond what can be achieved with Elastic and Deep Inelastic Scattering.

- Dedicated experiments are conducted world-wide. In the valence region, the growing set of existing results is helping refine our approach to extracting the GPDs from the data. In the interest of time I did not discuss DVCS off neutron or nucleus targets, nor DVMP.

- The 12 GeV Hall A DVCS experiment is in the process of publishing its results. In the interest of time I did not discuss other future results (eg CLAS12).

Award #1913170