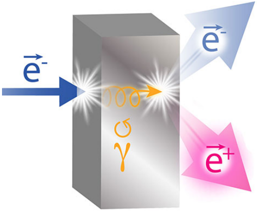
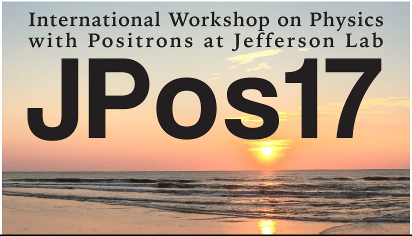
Deeply Virtual Compton Scattering with a Positron Beam

F.-X. Girod

Jefferson Laboratory

Sep 12th 2017

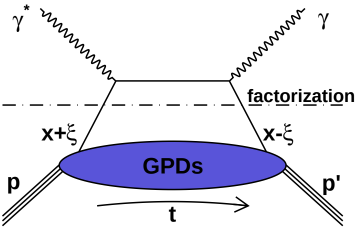


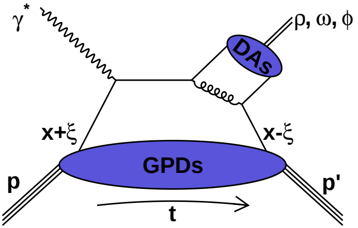


Outline

Generalized Parton Distributions

Deep Exclusive Scattering





$$\gamma^* p \to \gamma p', \rho p', \omega p', \phi p'$$

Bjorken regime :

$$Q^2 \to \infty,\ x_B \text{ fixed}$$

$$t \text{ fixed } \ll Q^2,\ \xi \to \frac{x_B}{2-x_B}$$

$$\frac{P^+}{2\pi}\int dy^- e^{ixP^+y^-}\langle p'|\bar{\psi}_q(0)\gamma^+(1+\gamma^5)\psi(y)|p\rangle$$

$$= \bar{N}(p')\left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t)i\sigma^{+\nu}\frac{\Delta_\nu}{2M}\right.$$

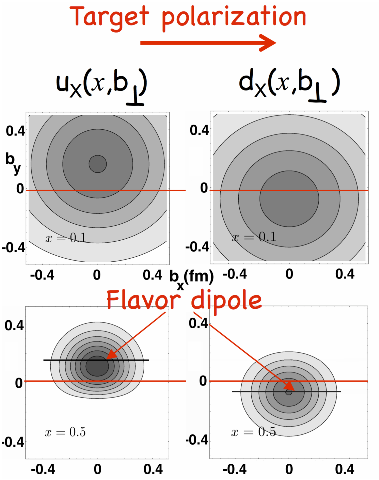
$$\left. + \tilde{H}^q(x,\xi,t)\gamma^+\gamma^5 + \tilde{E}^q(x,\xi,t)\gamma^5\frac{\Delta^+}{2M}\right]N(p)$$

spin	N no flip	N flip
q no flip	H	E
q flip	$\tilde{H}$	$\tilde{E}$

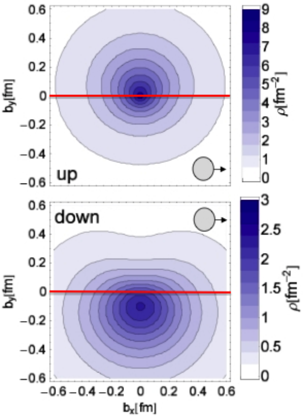
3-D Imaging conjointly in transverse impact parameter and longitudinal momentum

GPDs and Transverse Imaging (x_B, t)

$$q_X(x, \vec{b}_\perp) = \int \frac{d^2\vec{\Delta}_\perp}{(2\pi)^2} \left[H^q(x,0,t) - \frac{E^q(x,0,t)}{2M} \frac{\partial}{\partial b_y} \right] e^{-i\vec{\Delta}_\perp \cdot \vec{b}_\perp}$$



Lattice calculation



Energy Momentum Tensor (x,ξ)

Form Factors accessed *via* second x-moments :

$$\langle p'|\hat{T}^q_{\mu\nu}|p\rangle = \bar{N}(p')\left[\ M_2^q(t)\,\frac{P_\mu P_\nu}{M} + J^q(t)\,\frac{\imath(P_\mu\sigma_{\nu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + d_1^q(t)\,\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\ \right]N(p)$$

Angular momentum distribution

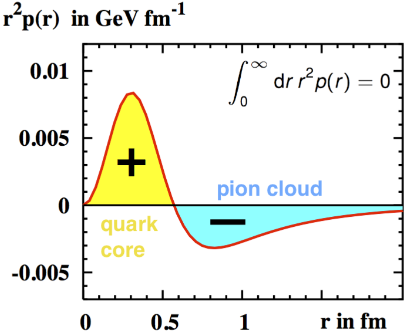
$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

Mass and force/pressure distributions

$$M_2^q(t) + \frac{4}{5}d_1^q(t)\xi^2 = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, xH^q(x,\xi,t)$$

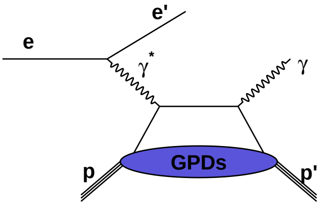
$$d_1^q(t) = 15M\int \mathrm{d}^3\vec{r}\,\frac{j_0(r\sqrt{-t})}{2t}\,p(r)$$

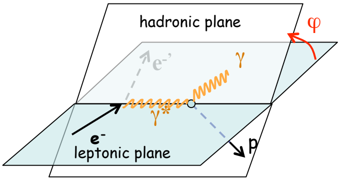
Distribution of pressure



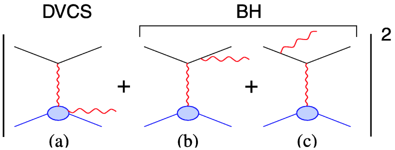
Deeply Virtual Compton Scattering

The cleanest GPD probe at low and medium energies





$\sigma(ep \longrightarrow ep\gamma) \propto$



$$\frac{d\sigma}{dx_B\, dQ^2\, dt\, d\phi} \propto |A_{BH} + A_{DVCS}|^2 = |A_{BH}|^2 + |A_{DVCS}|^2 - e_l \mathcal{I}$$

$$A_{LU} = \frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}} \overset{\text{twist-2}}{\approx} \frac{\alpha \sin\phi}{\beta \cos\phi + \gamma}$$

$$\mathcal{H}(\xi, t) = i\pi H(\xi, \xi, t) + \mathcal{PV}\int_{-1}^{1} dx\, \frac{H(x, \xi, t)}{x - \xi} \quad \text{Compton Amplitude}$$

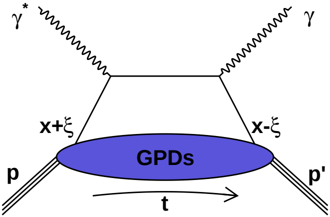
$$\alpha \propto \mathcal{I}m\left(F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}\right) \rightarrow A_{LU}$$

$$\beta \propto \mathcal{R}e\left(F_1 \mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}\right) \rightarrow A_C$$

$$\gamma \propto 4\,(1 - x_B)\left(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*\right) + \cdots \rightarrow \sigma_U$$

$$A_{UL} \propto \mathcal{I}m\left(F_1 \tilde{\mathcal{H}} + \xi G_M \mathcal{H} + G_M \frac{\xi}{1+\xi}\mathcal{E} + \cdots\right) \sin\phi$$

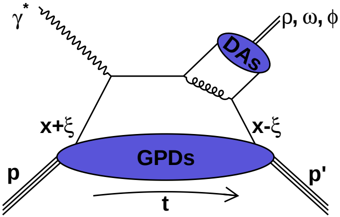
Observables sensitivities to GPD



DVCS

	$\mathcal{I}$mCFF	$\mathcal{R}$eCFF	|CFF| |CFF*|
$\mathcal{H}$	A_{LU}	A_C , $\sigma^I(y,\phi)$	$\sigma^{DVCS^2}(y,\phi)$
$\tilde{\mathcal{H}}$	A_{UL}	A_{LL}, A_{LT}	$A_{UT}(\phi-\phi_s)$
$\mathcal{E}$	A_{UT}		

$\rightarrow d_1(t)$



DVMP

	Meson	Flavor
$\mathcal{H}$,$\mathcal{E}$	ρ^+	$u-d$
	ρ^0	$2u+d$
	ω	$2u-d$

A global analysis is needed to fully disentangle GPDs
A_C gives access to $d_1(t)$ through a direct separation of $\mathcal{R}e\mathcal{H}$

Dispersion and the DVCS Amplitude

Analyticity and Unitarity applied to the Compton Amplitude

$$A(\xi,t) = \int \mathrm{d}x \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) H(x,\xi,t)$$

give the once subtracted fixed-t dispersion relation

$$\mathrm{Re}\mathcal{H}(\xi,t) = D(\xi,t) + \mathcal{PV} \int \mathrm{d}x \left(\frac{1}{\xi - x} - \frac{1}{\xi + x} \right) \mathrm{Im}\mathcal{H}(\xi,t)$$

Where $\mathrm{Im}\mathcal{H}(\xi,t) = \pi H(\xi,\xi,t)$ and $\mathrm{Re}\mathcal{H}(\xi,t) = \mathcal{PV} \int_{-1}^{1} dx \frac{H(x,\xi,t)}{x-\xi}$

The subtraction constant is called the D-term and its Gegenbauer expansion is linked to the Energy Momentum Tensor:

$$D(\xi,t) = (1-\xi^2) \left[d_1(t) C_1^{3/2}(\xi) + d_3(t) C_3^{3/2}(\xi) + d_5(t) C_5^{3/2}(\xi) + \cdots \right]$$

Calculations in the Chiral Quark Soliton Model indicate that :

$d_1 \approx -4.0$, $d_3 \approx -1.2$, $d_5 \approx -0.4$
with various uncertainties, including the scale

A measurement of the beam charge asymetry A_C gives direct access to the D-term

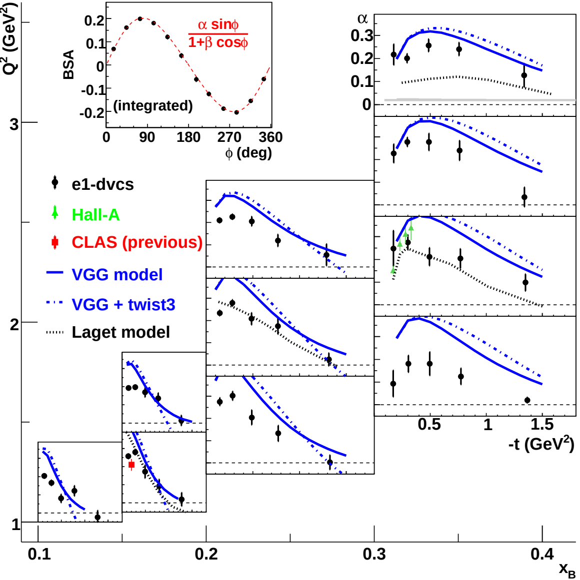
Beam requirements in Hall B

Hall B Beamline Design Parameters

Parameter	Design Value (?)
Energy	Up to 11 GeV
Energy spread	Better than 0.1%
Beam current	Up to 800 nA
Current measurement	Better than 1%
Helicity correlated charge asymmetry	Less than 0.1%
Beam polarization measurement	Better than 2.5% (relative)
Beam spot size	Smaller than 400 μm
Spot/Tail ratio	Better than 10^4
Beam position	Measured and stable better than 100 μm
Emittance	$\epsilon <$ 10 nm-rad

Hall B Published Data

DVCS Beam Spin Asymmetry 6 GeV

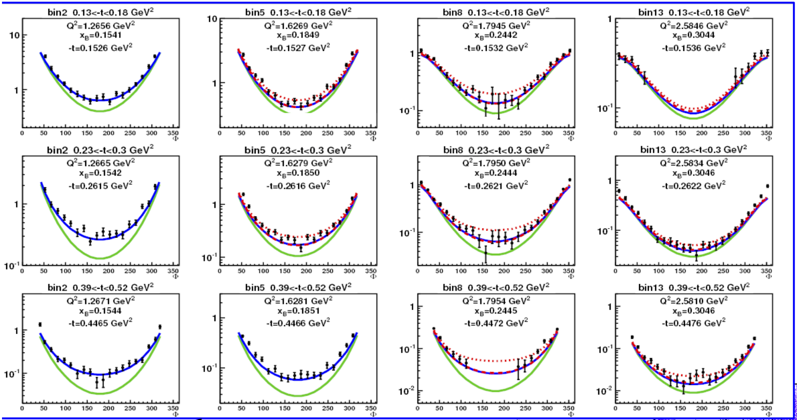


$$F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$

Precision in a large phase-space (x_B, Q^2, t)
Qualitative model agreement
quantitative constraints on parameters

Change of t-slopes across x_B
Nucleon size change

DVCS Unpolarized Cross-Sections 6 GeV

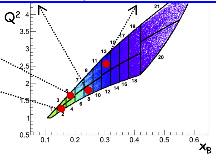


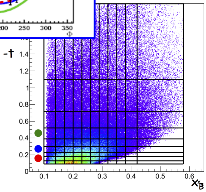
• $\dfrac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}$ (nb/GeV^4)

BH — VGG (H only)

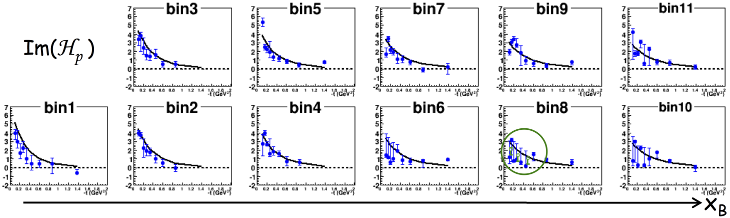
KM10 - - - KM10a

VGG : Vanderhaeghen, Guichon, Guidal   *KM : Kumericki, Mueller*



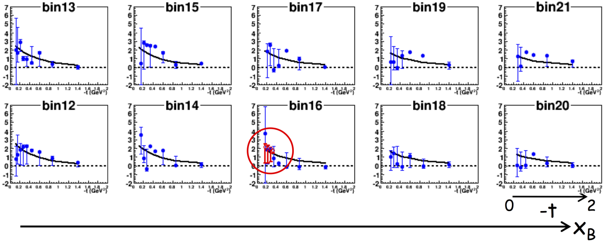


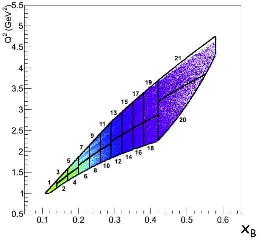
Compton Form Factors 6 GeV



CFF fits (by M. Guidal) using:
the results of this work
Hall A σ and Δσ
CLAS A_{LU} and A_{UL} (published results)

— VGG predictions

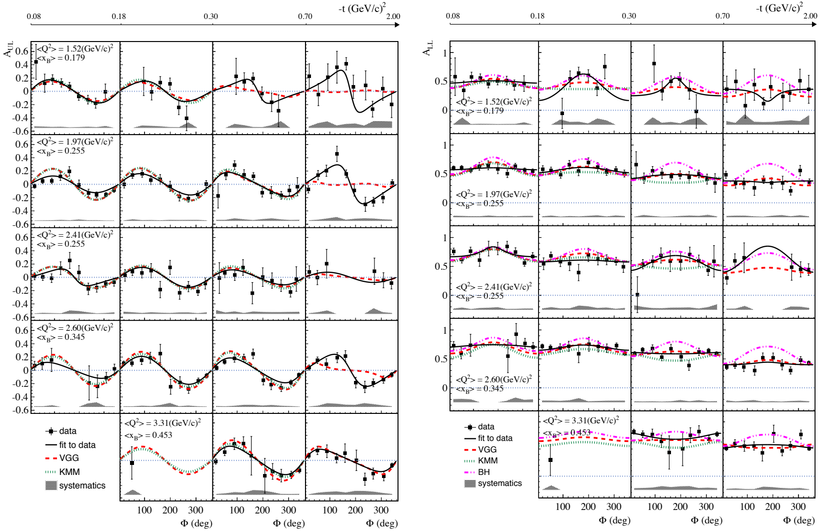




The t-slope becomes flatter with increasing x_B:
valence quarks (higher x_B) at the center of the nucleon and sea quarks (small x_B) at its periphery

Target Longitudinal Spin DVCS 6 GeV

$$F_1 \tilde{\mathcal{H}} + \xi G_M \left(\mathcal{H} + \frac{\xi}{1+\xi} \mathcal{E} \right)$$



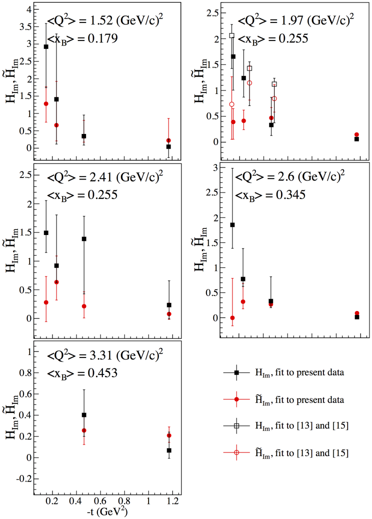
Model independent extraction 6 GeV

GPD dependencies versus x_B mirror their respective ordinary PDFs

$\tilde{H}$ and $H \leftrightarrow \Delta q(x)$ and $q(x)$

Change of t-slope vs x_B
less for $\Delta q(x)$ than for $q(x)$

Different spatial distributions of
Axial charge vs EM charge

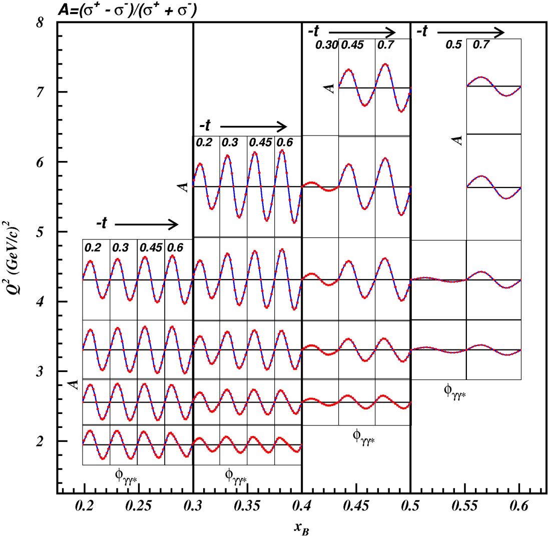


Hall B Future Measurements

CLAS12 GPD program

Number	Title	Contact	Days	Energy	Target
E12-06-108	Hard Exclusive Electroproduction of π^0 and η	Kubarovski	80	11	lH_2
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	80	11	lH_2
E12-12-001	Timelike Compton Scat. & J/Ψ prod. in e^+e^-	Nadel-Turonski	120	11	lH_2
E12-12-007	Exclusive ϕ meson electroproduction	FXG	60	11	lH_2
E12-11-003	DVCS on Neutron Target	Niccolai	90	11	lD_2
E12-06-119	Deeply Virtual Compton Scattering	Sabatie	120	11	NH_3
C12-12-010	DVCS with a transverse target	Elouadrhiri	110	11	HD-ice
E12-16-010	DVCS with CLAS12 at 6.6 GeV and 8.8 GeV	Elouadrhiri	50+50	6.6 & 8.8	lH_2

80 days @ $\mathcal{L} = 10^{35}$ $cm^{-2}s^{-1}$ with 85% polarized beam $\quad A_{LU} \propto F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$



Beam Spin Asymmetries
ϕ dependence

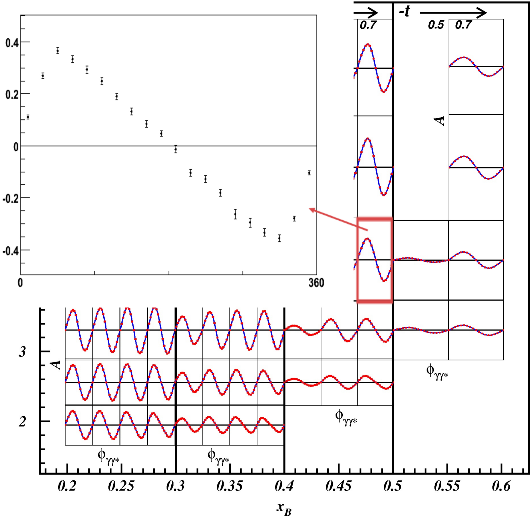
Statistical uncertainties :
from 1 % (low Q^2)
to 10 % (high Q^2)

Unprecedented statistics
over the full ϕ range
up to high $x = 0.6$

Proton BSA DVCS A_{LU} E12-06-009

80 days @ $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1} with 85% polarized beam

$$A_{LU} \propto F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - \frac{t}{4M^2}F_2\mathcal{E}$$



Beam Spin Asymmetries
ϕ dependence

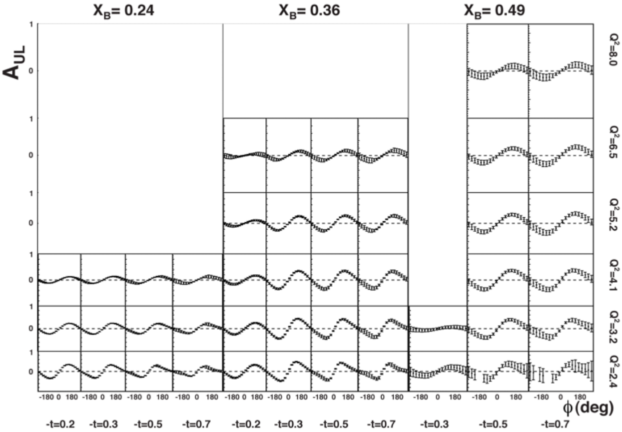
Statistical uncertainties :
from 1 % (low Q^2)
to 10 % (high Q^2)

Unprecedented statistics
over the full ϕ range
up to high $x = 0.6$

Proton DVCS TSA A_{UL} E12-06-009

120 days @ $\mathcal{L} = 2 \times 10^{35}$ cm^{-2}s^{-1} with 80% polarized NH_3

$$A_{UL} \propto F_1 \tilde{\mathcal{H}} + \xi G_M \left(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}\right) - \cdots$$



Target Spin Asymmetries
ϕ dependence

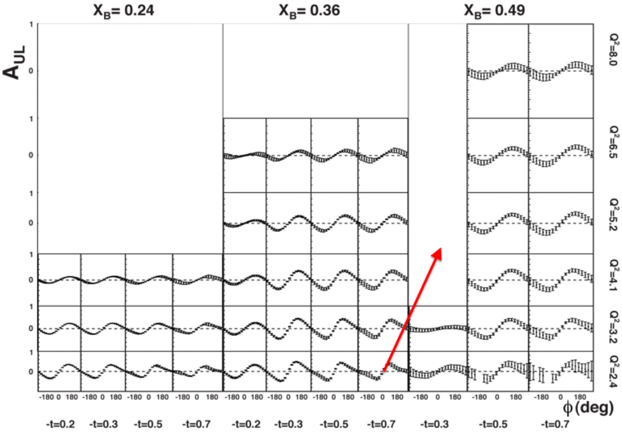
Statistical uncertainties :
from 2 % (low Q^2)
to 30 % (high Q^2)

Unprecedented statistics
over the full ϕ range
up to high $x = 0.6$

Proton DVCS TSA A_{UL} E12-06-009

120 days @ $\mathcal{L} = 2 \times 10^{35}$ cm^{-2}s^{-1} with 80% polarized NH_3

$$A_{UL} \propto F_1\tilde{\mathcal{H}} + \xi G_M \left(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}\right) - \cdots$$



Target Spin Asymmetries
ϕ dependence

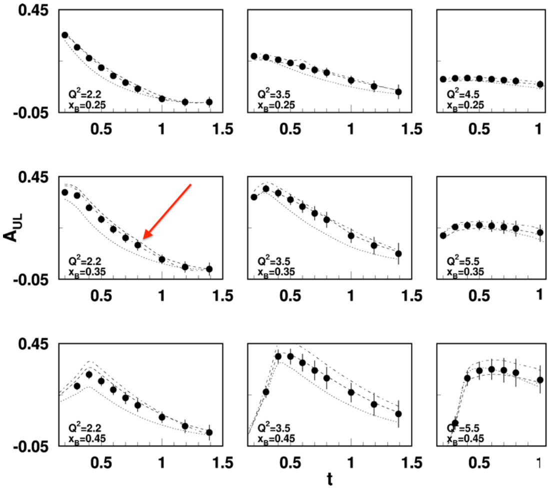
Statistical uncertainties :
from 2 % (low Q^2)
to 30 % (high Q^2)

Unprecedented statistics
over the full ϕ range
up to high $x = 0.6$

Proton DVCS TSA A_{UL} — E12-06-009

120 days @ $\mathcal{L} = 2 \times 10^{35}$ cm^{-2}s^{-1} with 80% polarized NH_3

$$A_{UL} \propto F_1 \tilde{\mathcal{H}} + \xi G_M \left(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}\right) - \cdots$$

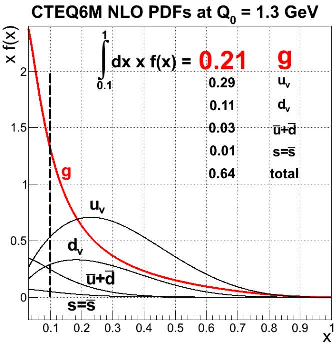


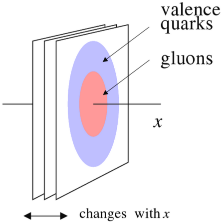
TSA t-slopes

Sample kinematics for target asymmetry

Change of t-slope with x_B $\leftrightarrow$ imaging $\Delta q(x_B, b_\perp)$

Gluons at large x E12-12-007





- Large glue density at $x > 0.1$

  PDF from global fits
  (F_2 evolution, ν_{DIS}, jets)

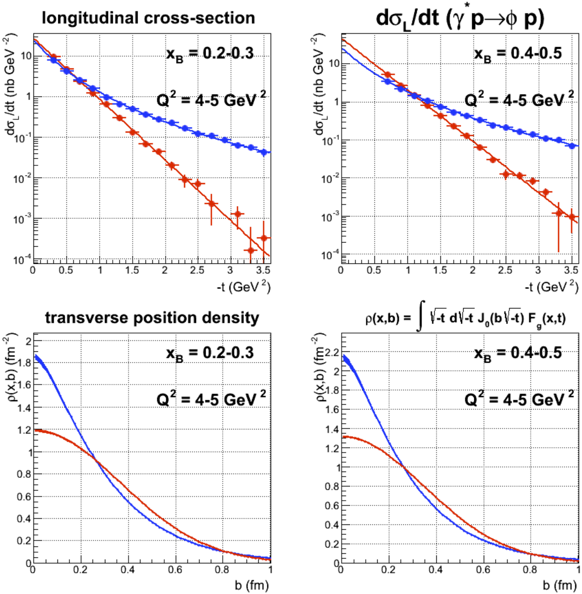
  Gluons carry more than 30% of the momentum for $0.1 < x$

- 3D imaging of the nucleon

  spatial distribution of valence quarks : elastic scattering, DVCS, . . .

  Nucleon gluonic radius ?
  exclusive ϕ

Extraction of gluonic profiles



Longitudinal cross-section

Corresponding sensitivity in transverse position space

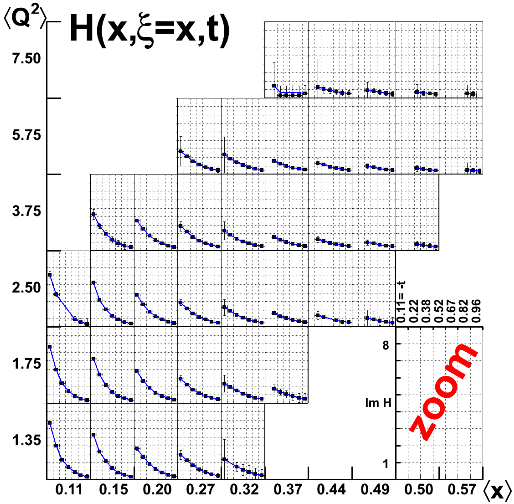
$$b = 1/\sqrt{-t}$$

Error propagation study
Skewness $\xi \neq 0$ neglected

Projected Impact on GPD Extractions

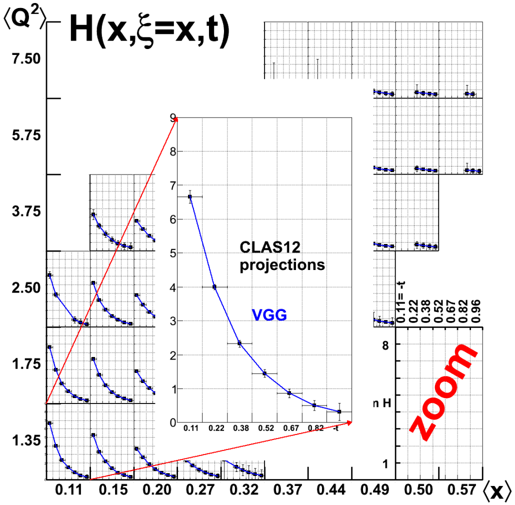
Projected Impact on GPD Extraction

Using simulated data based on VGG model. Input GPD H extracted with good accuracy



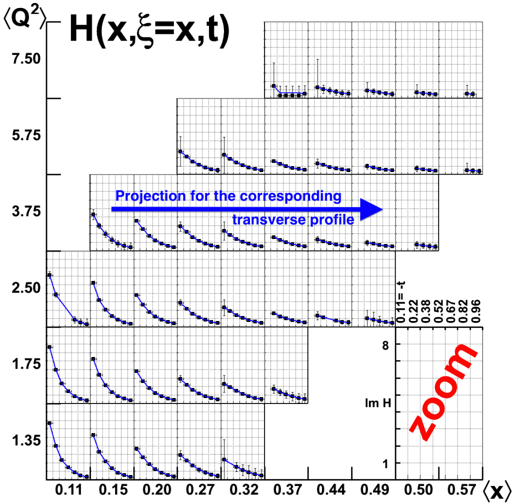
Projected Impact on GPD Extraction

Using simulated data based on VGG model. Input GPD H extracted with good accuracy

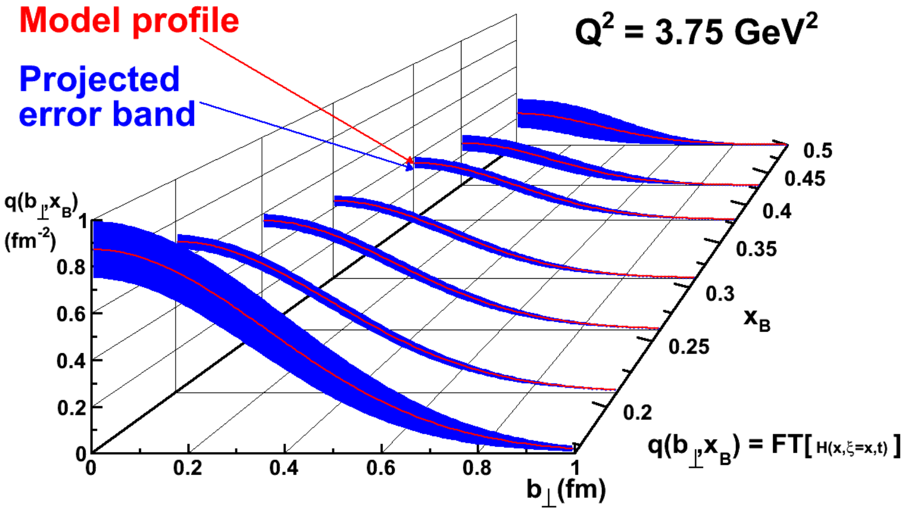


Projected Impact on GPD Extraction

Using simulated data based on VGG model. Input GPD H extracted with good accuracy

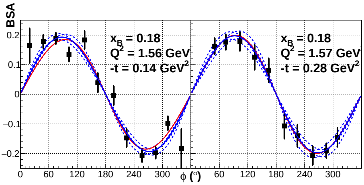


Projection for the Nucleon transverse profile



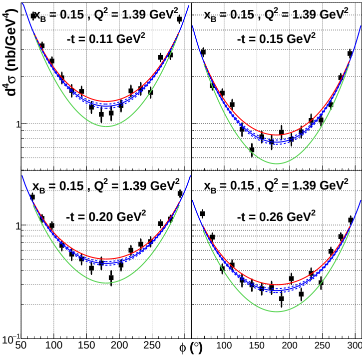
Precision tomography in the valence region

Global Fits to extract the D-term



Beam Spin Asymmetries

$$\mathrm{Im}\mathcal{H}(\xi,t) = \frac{r}{1+x}\left(\frac{2\xi}{1+\xi}\right)^{-\alpha(t)}\left(\frac{1-\xi}{1+\xi}\right)^{b}\left(\frac{1-\xi}{1+\xi}\frac{t}{M^2}\right)^{-1}$$

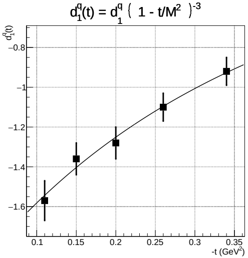


Unpolarized cross-sections
Use dispersion relation:

$$\mathrm{Re}\mathcal{H}(\xi,t) = D + \mathcal{P}\int dx\left(\frac{1}{\xi-x} - \frac{1}{\xi+x}\right)\mathrm{Im}\mathcal{H}(\xi,t)$$

pure Bethe-Heitler
local fit + uncertainty range
resulting global fit

D-term and Pressure distribution



$$D^q\left(\frac{x}{\xi}, t\right) = \left(1 - \frac{x^2}{\xi^2}\right)\left[d_1^q(t) C_1^{3/2}\left(\frac{x}{\xi}\right) + d_3^q(t) C_3^{3/2}\left(\frac{x}{\xi}\right) + \cdots\right]$$

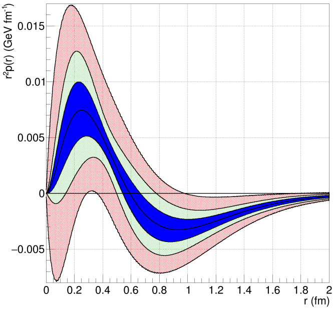
t-dependence of the D-term :

Dipole gives singular pressure at $r = 0$

Quadrupole implied by counting rules?

Exponential?

...



Resulting pressure distribution

Stability condition : $\int_0^\infty dt\, r^2 p(r) = 0$

World data fit

CLAS 6 GeV data

Projected CLAS12 data

DVCS with positrons

- Partonic Transverse Imaging and Energy Momentum Tensor
- First Generation of Experiments succesful
- 12 GeV era already underway
- Extraction frameworks established
- Challenges ahead for precision measurements
- A positron beam allows a straightforward clean separation of the BH/DVCS interference
- Invaluable handle on systematics on a novel approach to confinement