Generalized Parton Distributions and Deeply Virtual Compton Scattering

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Outline

Presentation

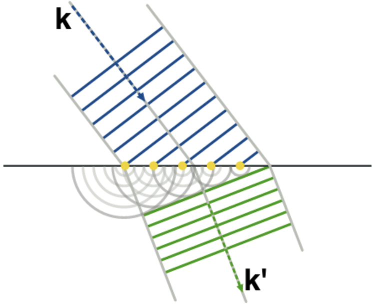
François-Xavier Girod

- 12/2006 PhD (Saclay)
  Deeply Virtual Compton Scattering Beam Spin Asymetries at CLAS for a study of Generalized Parton Distributions
- Feb. 2007 - Oct. 2011 : Post-doc in Hall-B at JLab
- Continued program support on DVCS, DVMP, and SIDIS studies
- Completed :
  - second part of e1dvcs (unpolarized H)
  - eg1dvcs (longitudinally polarized H and D)
  - eg6 (DVCS on He)
- 2011 Staff scientist in Hall-B
- Responsible for the CLAS12 beamline
- also member of the Heavy Photon Search

Introduction

Diffraction and Imaging

Huygens-Kirchhoff-Fresnel principle

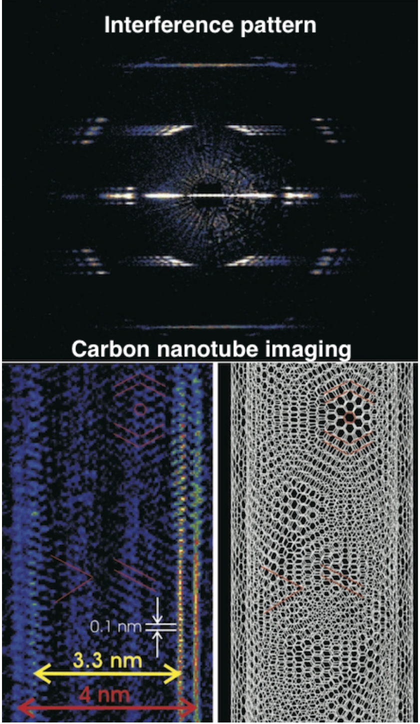


$\vec{q} = \vec{k} - \vec{k'}$

The interference pattern is given by the superposition of spherical wavelets

$$f(\Omega_{\vec{q}}) = \int \frac{d^3\vec{r}}{(2\pi)^3} F(\vec{r}) e^{i\vec{q}\cdot\vec{r}}$$

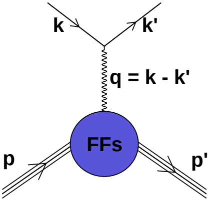
Fourier imaging



Elastic scattering

Form Factors

Probing deeper using virtual photons



$$J^{\mu}_{\rm EM} = {\color{red}F_1}\gamma^{\mu} + \frac{\kappa}{2M}{\color{red}F_2}i\sigma^{\mu\nu}q_{\nu}$$

$$\frac{d\sigma}{d\Omega} = \frac{\sigma_{\rm Mott}}{\epsilon(1+\tau)}\left[\tau G_M^2 + \epsilon G_E^2\right]$$

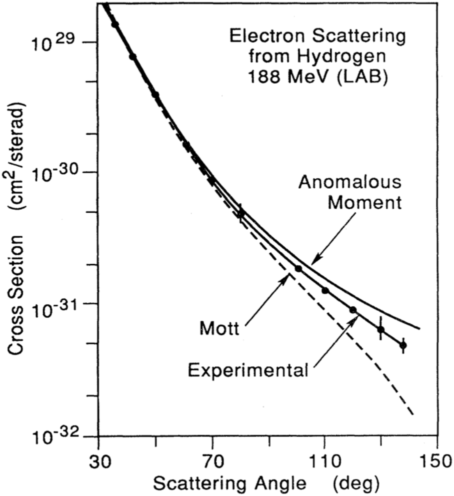
$$\tau = \frac{Q^2}{4M^2}$$

$$Q^2 = -\left(k-k'\right)^2 = -m^2_{\gamma^*}$$

$$\frac{1}{\epsilon} = 1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}$$

$$G_E = F_1 - \tau F_2$$

$$G_M = F_1 + F_2$$



Hofstadter Nobel prize 1961

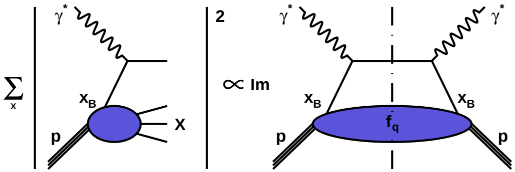
"The best fit in this figure indicates
an rms radius close to $0.74 \pm 0.24 \times 10^{-13}$ cm."

Imaging in transverse impact parameter space

Deeply Inelastic Scattering

Parton Distributions

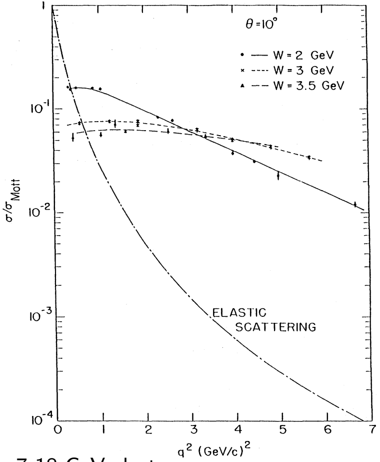
Optical theorem



The total cross section is given by
the imaginary part of the forward amplitude

$$\nu = E_{\gamma^*} \quad , \quad x_B = \frac{Q^2}{2M\nu}$$

$\sigma_{\rm DIS}(x_B, \not{Q^2}) \rightarrow$ scaling, point-like constituents



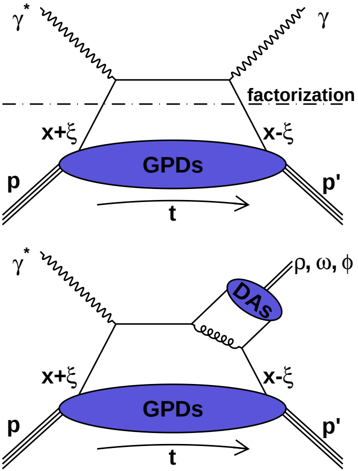
Discovery of quarks, SLAC-MIT group, 7-18 GeV electron
Friedman, Kendall, Taylor, Nobel prize 1990

$$\lim_{Q^2\to\infty} \sigma_{\rm DIS}(x_B) = \int_{x_B}^{1} \frac{d\xi}{\xi} \sum_a f_a(\xi,\mu)\hat{\sigma}^a\left(\frac{x_B}{\xi}, \frac{Q}{\mu}\right)$$

1-D distribution in longitudinal momentum space

Deep Exclusive Scattering

Generalized Parton Distributions



$$\gamma^* p \to \gamma p', \; \gamma^* p \to \begin{cases} \rho p' \\ \omega p' \\ \phi p' \end{cases}$$

Bjorken regime :

$Q^2 \to \infty$, x_B fixed

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

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

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

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

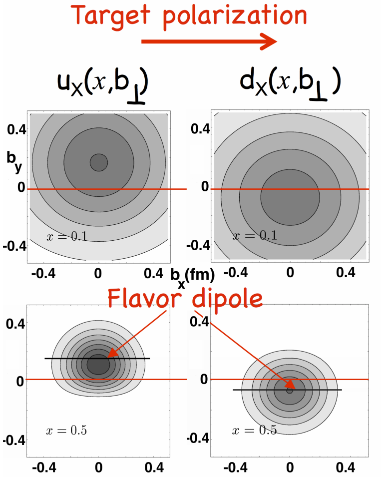
spin	N no flip	N flip
q no flip	H	E
q flip	$\tilde{H}$	$\tilde{E}$

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

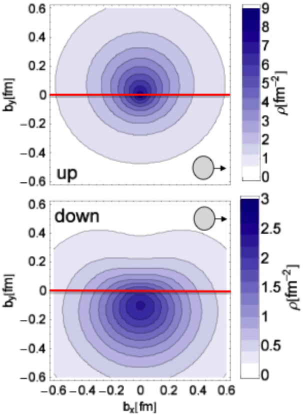
GPDs and Transverse Imaging

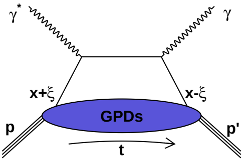
(x_B, t) correlations

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



Lattice calculation



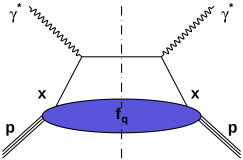


Generalized Parton Distributions

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

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

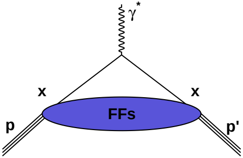
$$\left. + \tilde{H}^q(x,\xi,t)\gamma^+\gamma^5 + \tilde{E}^q(x,\xi,t)\gamma^5\frac{\Delta^+}{2M}\right]N(p)$$



Parton longitudinal momentum fraction distributions

$$\frac{1}{4\pi}\int dy^-\, e^{ixp^+y^-}\langle p|\bar{\psi}_q(0)\gamma^+\psi(y)|p\rangle = f_q(x)$$

$$H^q(x,\xi=0,t=0) = f_q(x)$$



Form Factors - Fourier transform of transverse spatial distributions

$$\langle p'|\bar{\psi}_q(0)\gamma^+\psi(0)|p\rangle = \bar{N}(p')\left[F_1^q(t)\gamma^+ + F_2^q(t)i\sigma^{+\nu}\frac{\Delta_\nu}{2M}\right]N(p)$$

$$\int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1^q(t) \qquad \text{First x-moment}$$

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

GPDs and Energy Momentum Tensor

(x, ξ) correlations

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

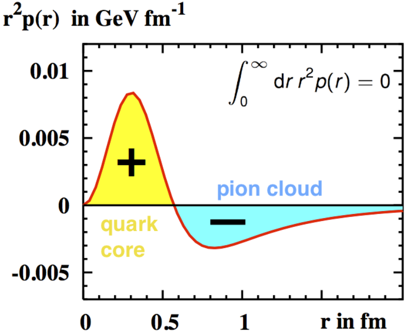
$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

Mass and force/pressure distributions

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

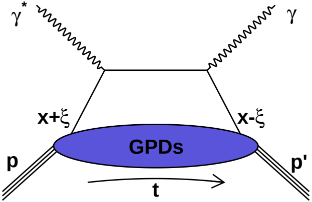
$$d_1(t) = 15M\int \mathrm{d}^3\vec{r}\,\frac{j_0(r\sqrt{-t})}{2t}\,p(r)$$

Distribution of pressure

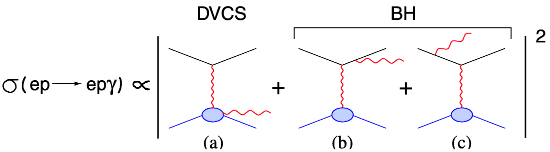


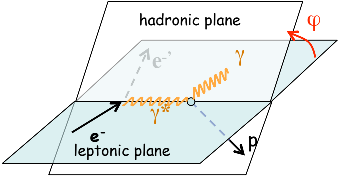
Deeply Virtual Compton Scattering

The cleanest GPD probe at low and medium energies



$$ep \to ep\gamma$$





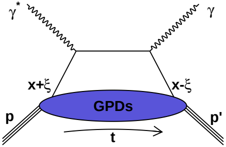
$$A_{\mathrm{LU}} = \frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}} \overset{\text{twist-2}}{\approx} \frac{\alpha \sin\phi}{1 + \beta\cos\phi}$$

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

$$\mathcal{H}(\xi, t) = i\pi H(\xi, \xi, t) + \mathcal{P}\int_{-1}^{1} \mathrm{d}x \, \frac{H(x, \xi, t)}{x - \xi}$$

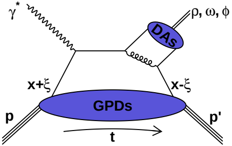
$$A_{\mathrm{UL}} \propto \mathcal{I}\mathrm{m}\left(F_1 \tilde{\mathcal{H}} + \xi G_M \mathcal{H} + G_M \frac{\xi}{1+\xi}\mathcal{E} + \cdots\right) \sin\phi$$

Observables sensitivities to GPD



DVCS

	$\mathcal{I}$m	$\mathcal{R}$e
$\mathcal{H}$	A_{LU}	σ
$\tilde{\mathcal{H}}$	A_{UL}	A_{LL}, A_{LT}
$\mathcal{E}$	A_{UT}	



DVMP

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

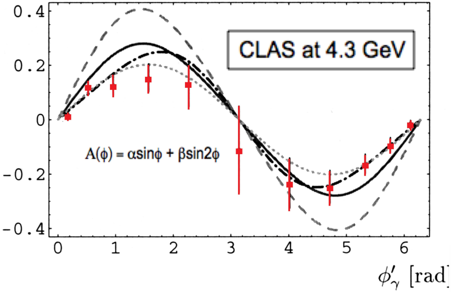
A global analysis is needed to fully disentangle GPDs

6 GeV era measurements

Pioneering observations

First DVCS BSA and TSA observations

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

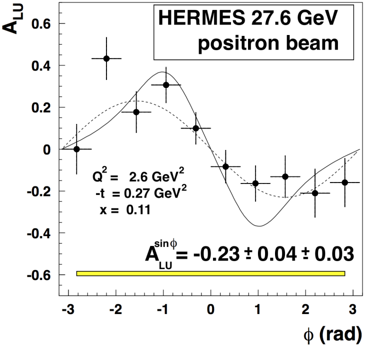


$Q^2 = 1.3$ GeV^2, $x_B = 0.2$, $-t = 0.2$ GeV^2

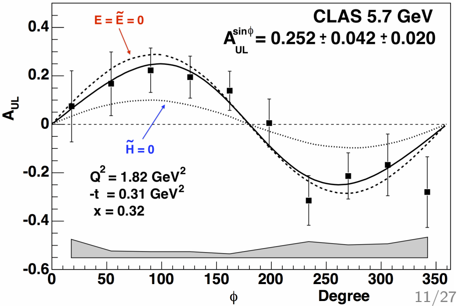
$$A(\phi) = \alpha \sin\phi + \beta\cos(2\phi)$$
$$\alpha = 0.202 \pm 0.028^{stat} \pm 0.013^{syst}$$
$$\beta = -0.024 \pm 0.021^{stat} \pm 0.009^{syst}$$

S. Stepanyan *at al.*, PRL **87** (2001) 182002

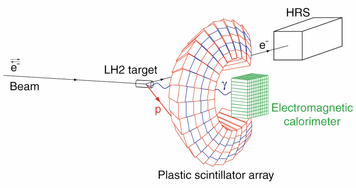
250+ citations

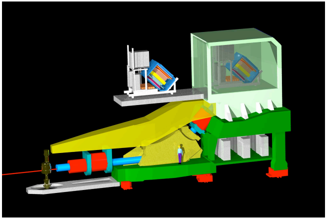


$A_{UL} \propto F_1\tilde{\mathcal{H}} + \xi G_M\left(\mathcal{H} + \frac{\xi}{1+\xi}\mathcal{E}\right) - \cdots$

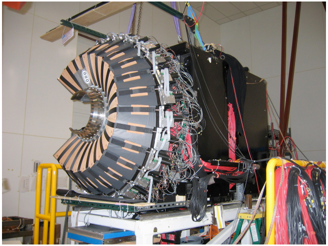


Scaling tests of $\Delta\sigma_{\mathrm{DVCS}}$ **E00-110**

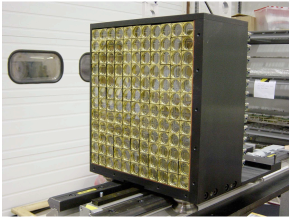




100-channel scintillator array



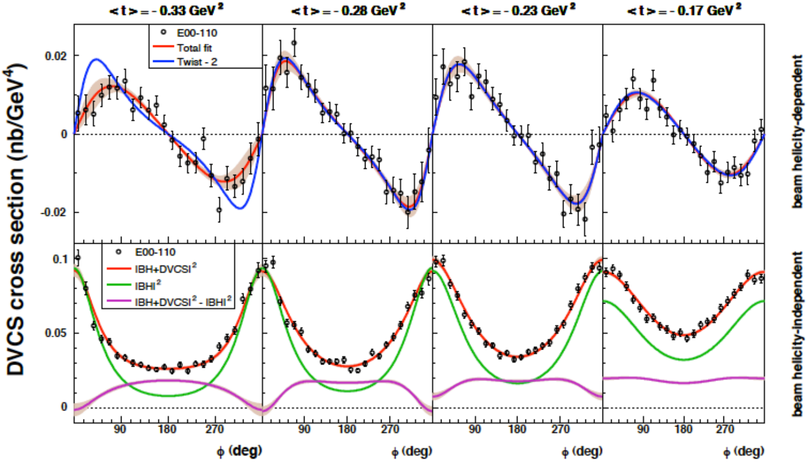
132-block PbF_2 electromagnetic calorimeter



Scaling tests of $\Delta\sigma_{\mathrm{DVCS}}$

E00-110

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

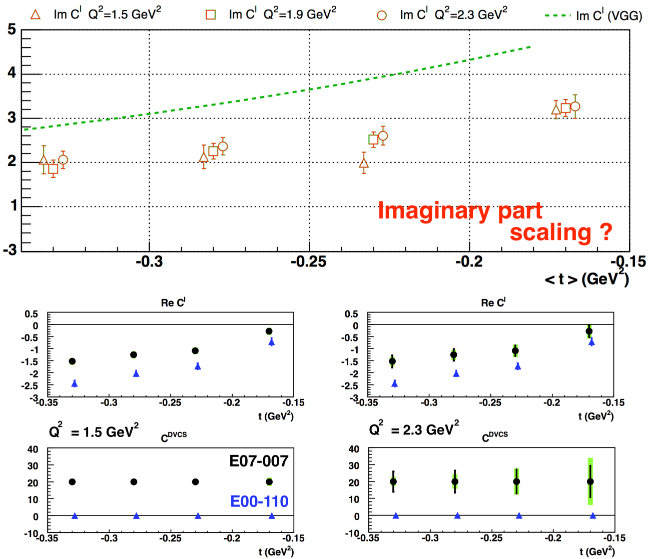


C. Muñoz *et al.*, PRL **97** (2006) 262002

High precision in a narrow kinematical range

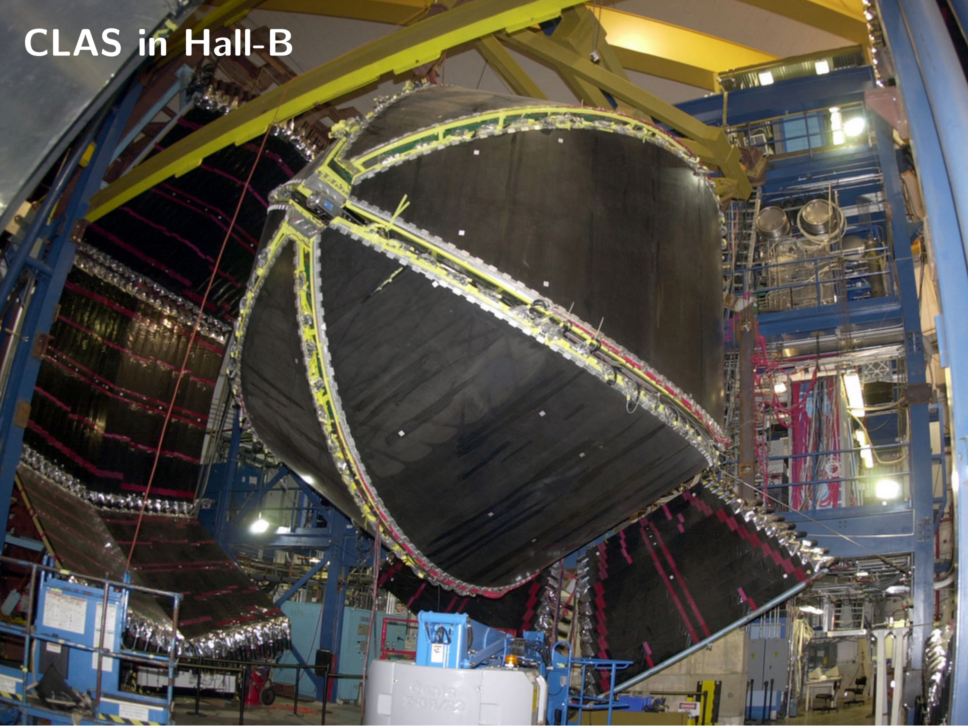
Separation of $\mathcal{I}$ and DVCS^2 E00-110/E07-007

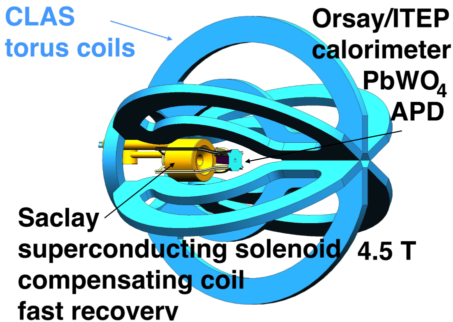
$$F_1\mathcal{H} + \xi G_M \tilde{\mathcal{H}} - F_2 \frac{t}{4M^2}\mathcal{E} + \cdots$$

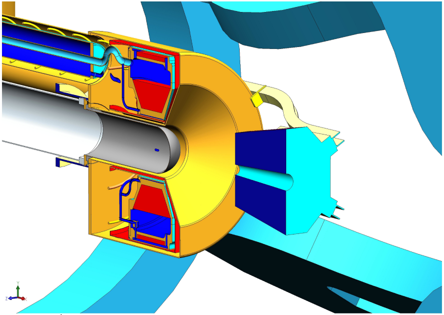


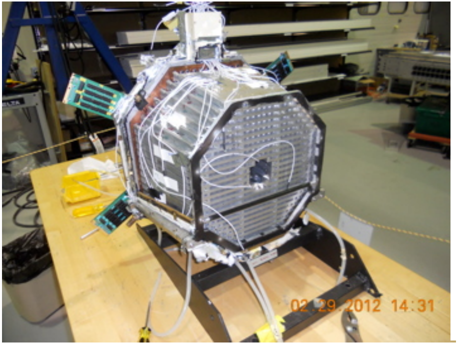
High precision in a narrow kinematical range

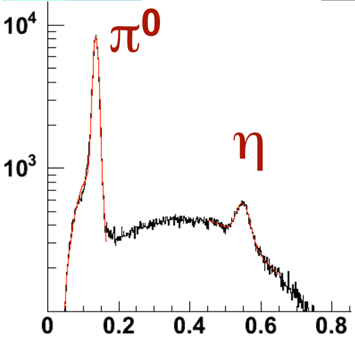
CLAS in Hall-B







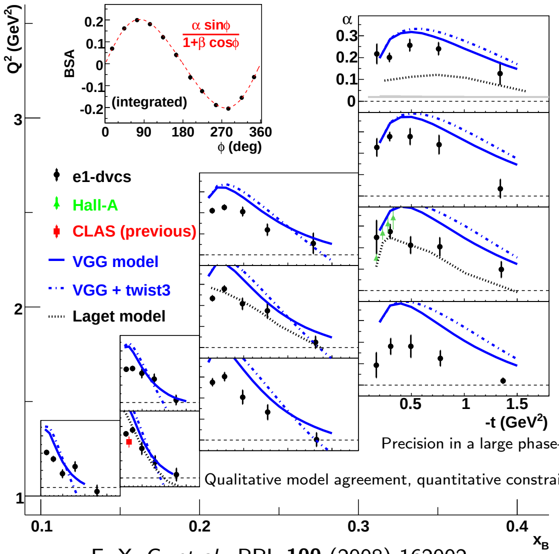




$$M_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}\left(1-\cos\theta_{\gamma\gamma}\right)}$$

CLAS proton Beam Spin Asymmetry   E01-113

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



Precision in a large phase-space (x_B, Q^2, t)

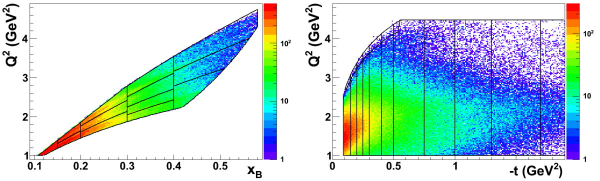
Qualitative model agreement, quantitative constraints on parameters

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

CLAS proton cross-section

E01-113

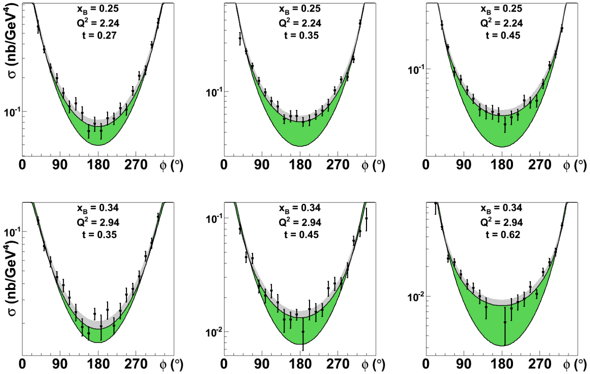
$$F_1\mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$$



More than 3k bins

Dispersion relation :

$$\mathcal{R}\text{e } \mathcal{H} = \left[\int \mathcal{I}\text{m } \mathcal{H}\right] + \mathcal{D}$$



green band shows difference with BH

→ sensitivity to d_1

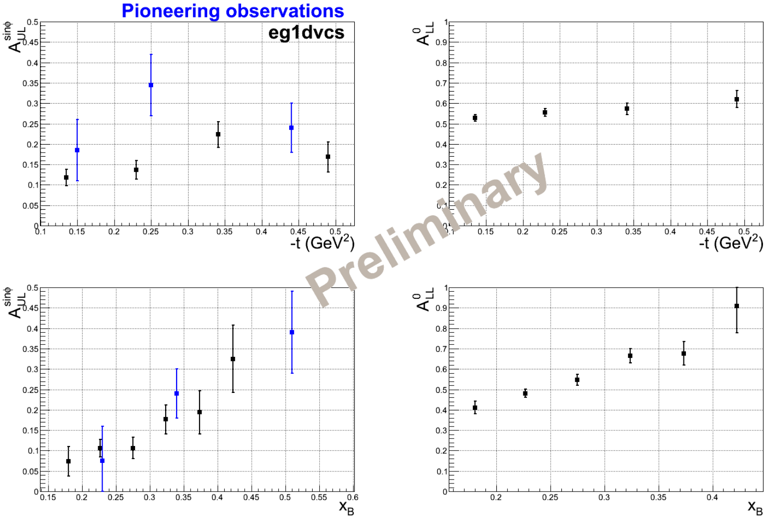
CLAS proton Target Spin Asymmetry E05-114

Ten fold improvement in statistics

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

$A_{UL} \propto F_1\, \mathcal{I}\text{m}\, \tilde{\mathcal{H}}$

$A_{LL} \propto F_1\, \mathcal{R}\text{e}\, \tilde{\mathcal{H}}$

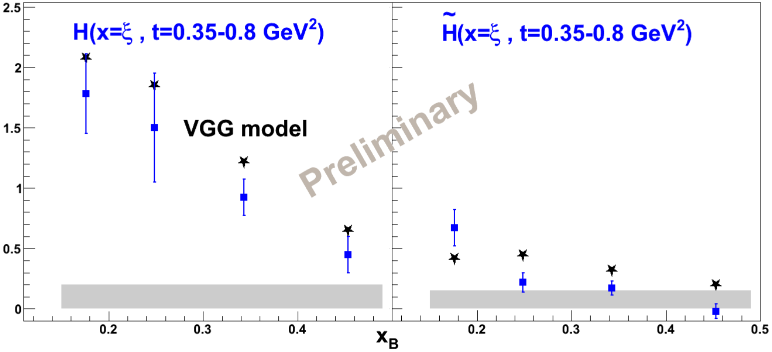


Model independent extraction

Using only A_{LU} and A_{UL}

Extraction with :

- Preliminary results from eg1dvcs A_{UL}
- Polarized cross-section from e1dvcs $\Delta\sigma$



GPD dependencies versus x_B mirror their respective ordinary PDFs

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

Drop of $\Delta q(x)$ at low x_B will be seen at 12 GeV

6 GeV era: lessons learned

- The feasibility of high luminosity exclusive measurements in complementary high precision (Hall-A) and large acceptance (CLAS) spectrometers has been demonstrated.
- The first dedicated generation of experiments suggests precocious scaling in Deeply Virtual Compton Scattering
- The experimental results have triggered theoretical developments for the consistent description of higher twist corrections
- Several approaches investigate Generalized Parton Distribution extraction methods from data
- Unified descriptions with Semi-Inclusive DIS in terms of Wigner distributions have recently been implemented into concrete predictions

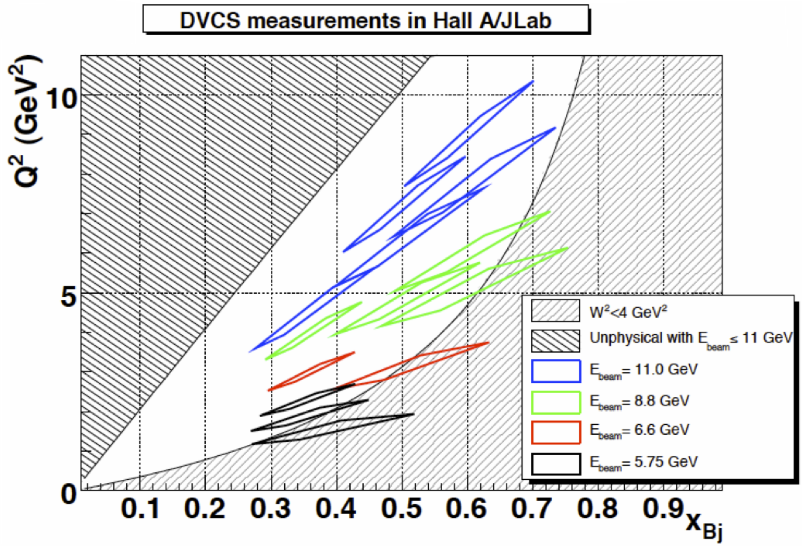
12 GeV era projections

GPDs in DVCS program at JLab12

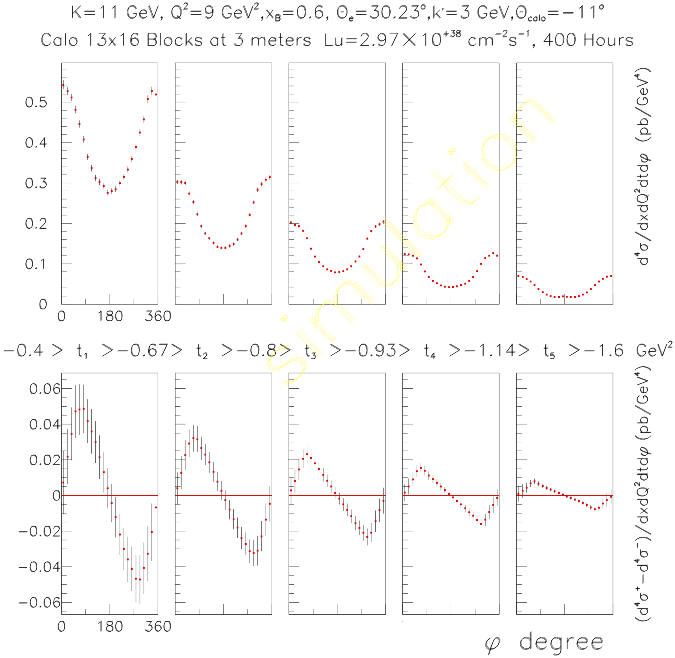
Nucleon polarization	Sensitivity to GPDs	Experiments
UP	H, $\tilde{H}$, E	E12-06-114 : γ, π^0 (A) proton E12-06-119 : γ, π^0 (B) proton E12-11-003: γ, π^0 (B) neutron
LP	$\tilde{H}$, H, E	E12-06-119 : γ, π^0 (NH_3) (B) proton
TP	E, H	LOI12-11-105 : γ, π^0 (HD) (B) proton

The JLab DVCS program will be carried out in two experimental Halls: **A & B (CLAS12)**

Hall-A DVCS at 12 GeV E12-06-114



Hall-A DVCS at 12 GeV E12-06-114



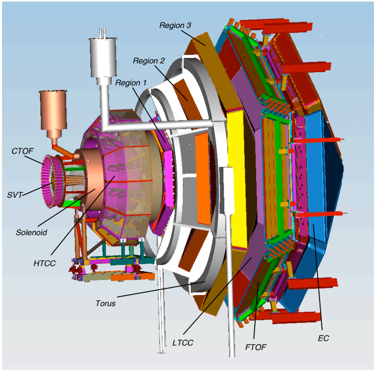
Only highest Q^2 shown
Long lever arm

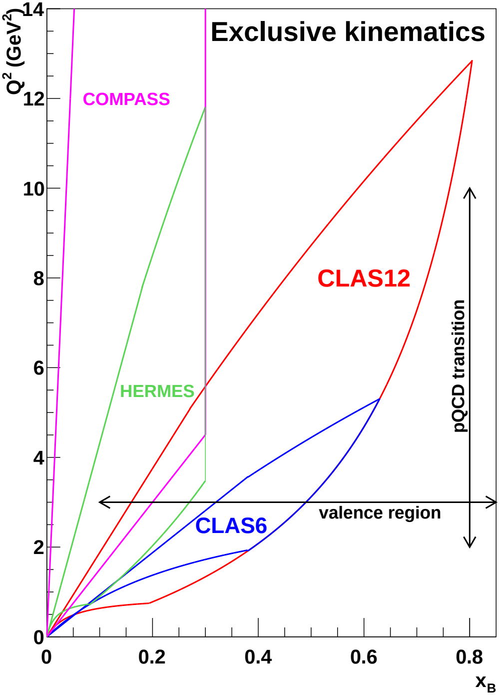
Rosenbluth separation of $\mathcal{I}$ and DVCS^2

High-precision scaling test on both $\mathcal{R}$e and $\mathcal{I}$m

CLAS12

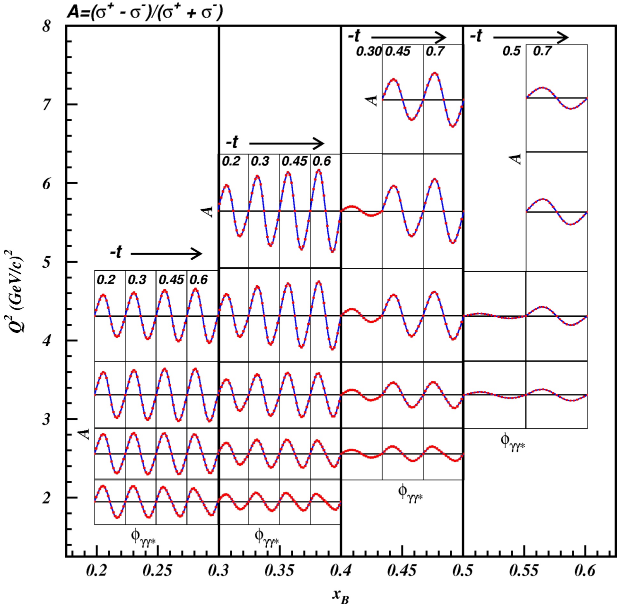
Higher energy
Higher luminosity
Better hermeticity





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

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



Projections for CLAS12

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

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

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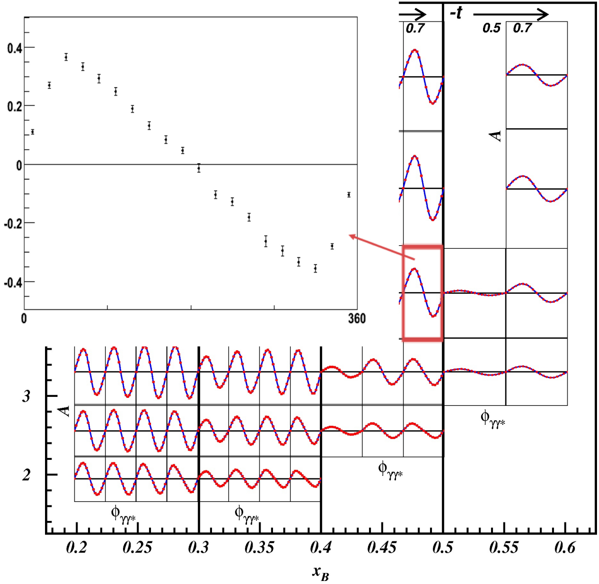

Projections for CLAS12

Statistical uncertainties :
from 1 % (low Q^2)
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Unprecedented statistics
over the full ϕ range
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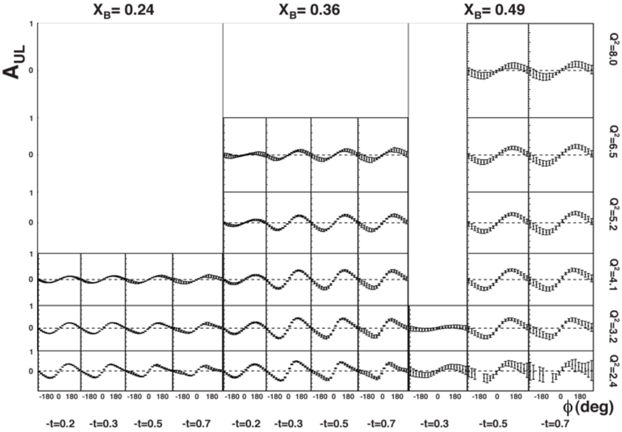
Proton DVCS TSA A_{UL}

E12-06-009

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

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



Projections for CLAS12

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

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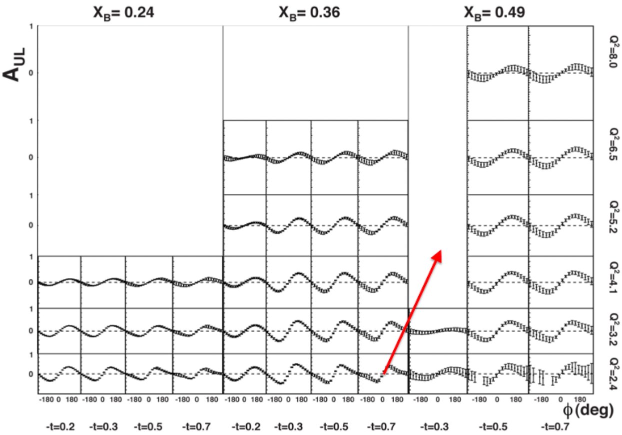

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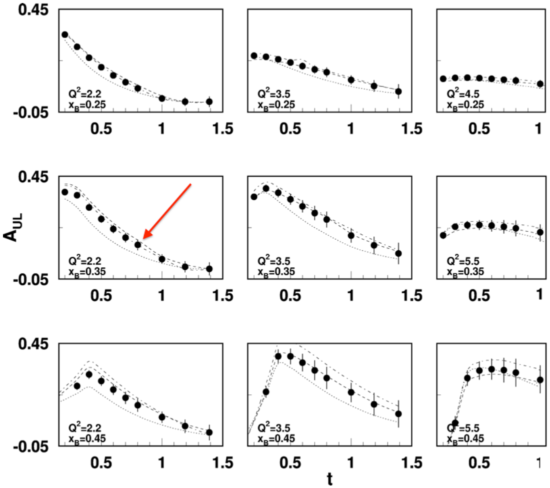


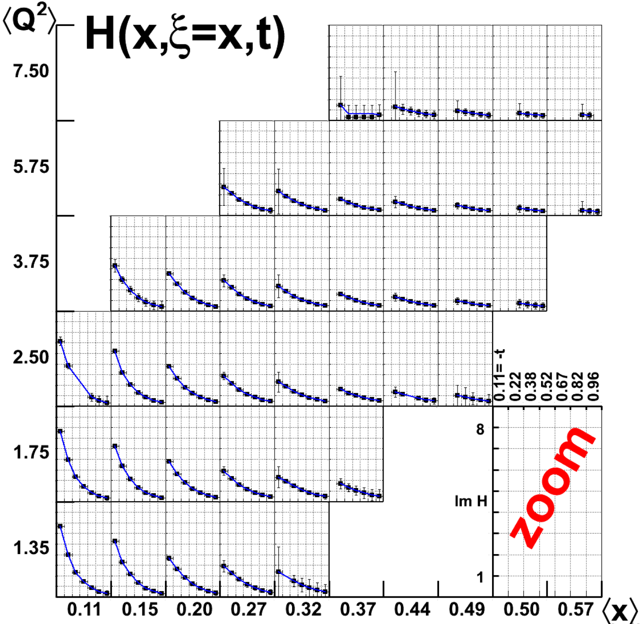
Projections for CLAS12

Sample kinematics
for target asymmetry

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

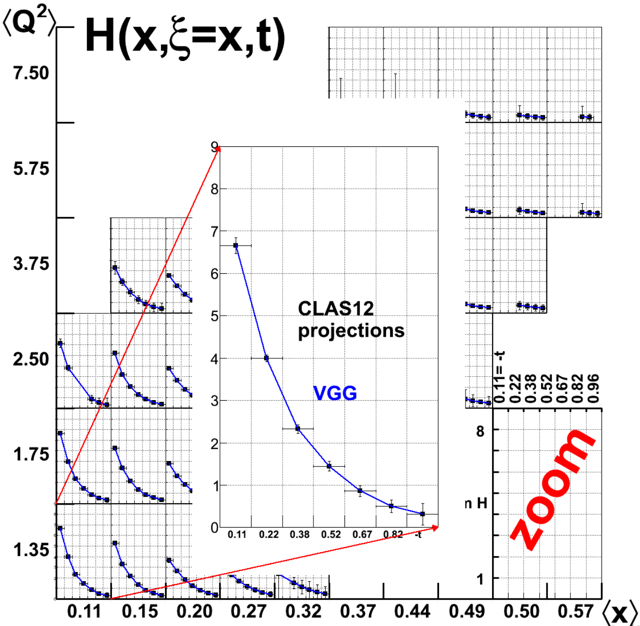
Projected impact on GPD extraction methods

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



Projected impact on GPD extraction methods

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



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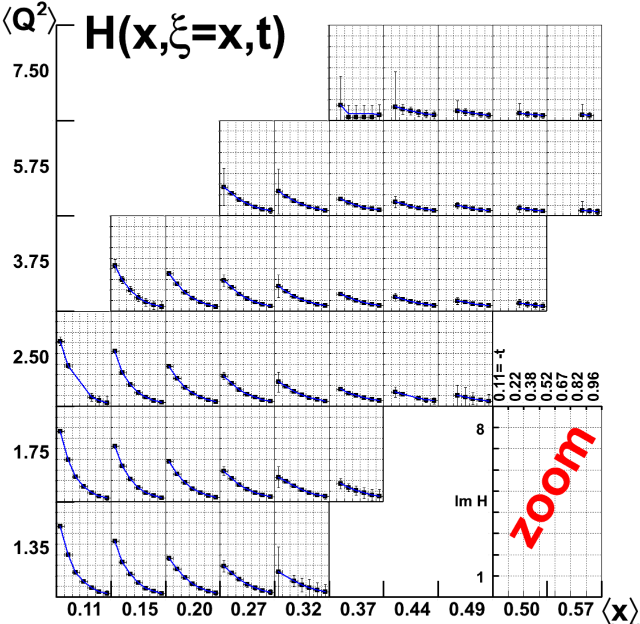

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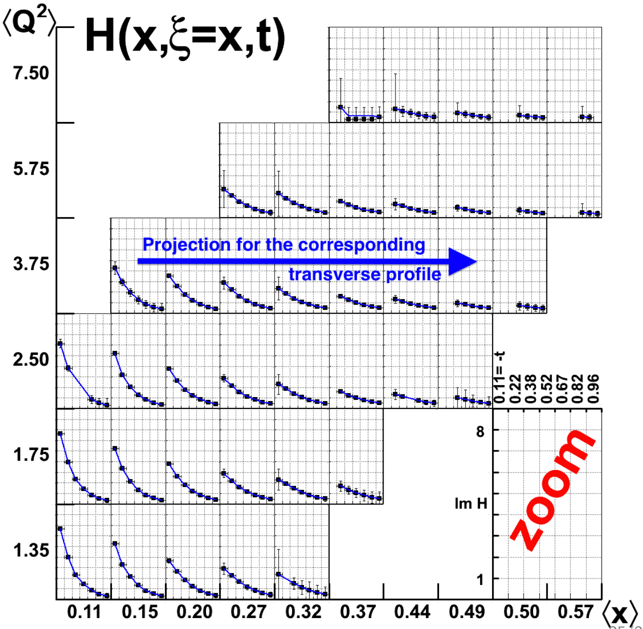
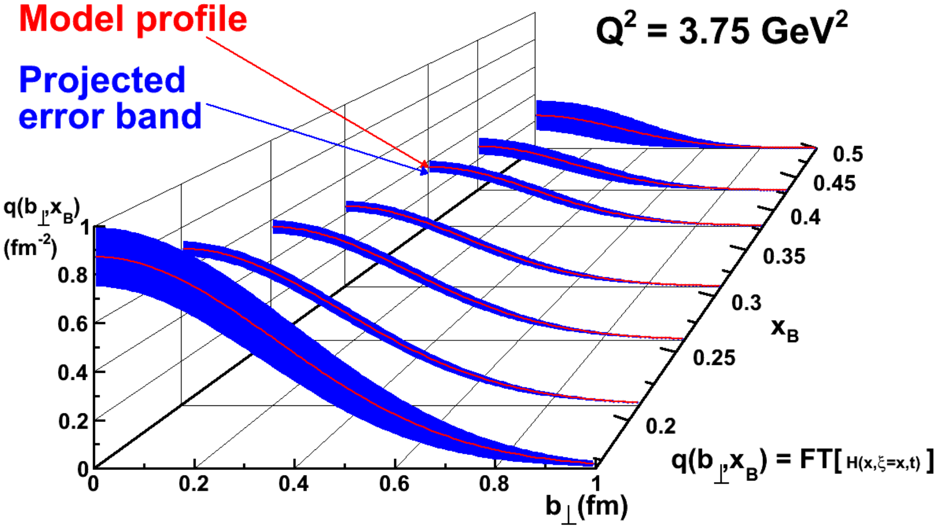


Projection for the Nucleon transverse profile



Precision tomography in the valence region

Summary

- A unified framework for nucleon tomography has been established
- The first dedicated results on Compton Scattering suggest precocious handbag dominance
- Accurate information on Generalized Parton Distributions in the valence region and at moderate momentum transfer was gathered
- The long range plan to extract GPDs has begun
- Interplay between spin and flavor decompositions requires also other reactions
- JLab 12 GeV will precisely test scaling and carry out the tomography of valence quarks
- Future measurements are planned at CERN/Compass and DESY/Panda
- The EIC will expand the reach and probe the sea and gluons
- Essential for QCD backgrounds at LHC and beyond