Unraveling confinement forces with DVCS

Francois-Xavier Girod (JLab)

NSTAR 2017

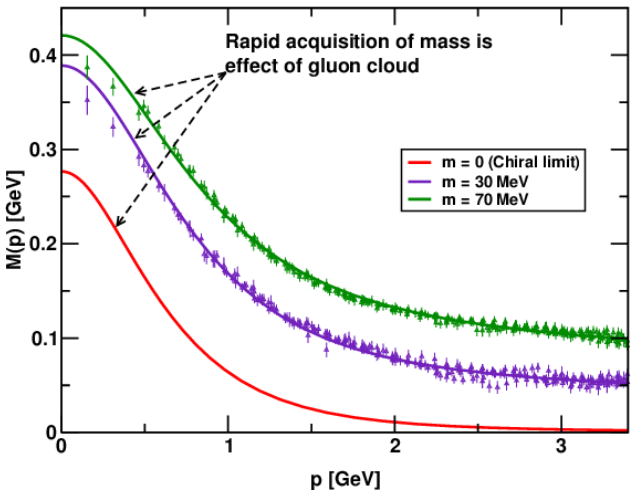
USC Columbia

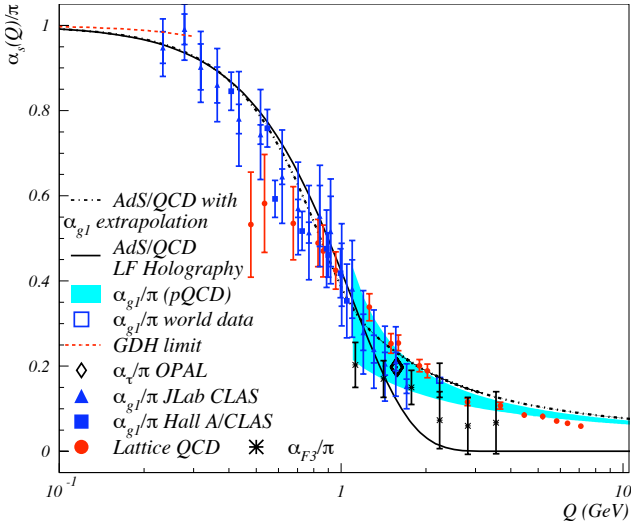
Outline

Theoretical Context

Confinement Mechanism(s?)

Hadrons are singlets under $SU(3)_{color}$: No net color charge in asymptotic particle states





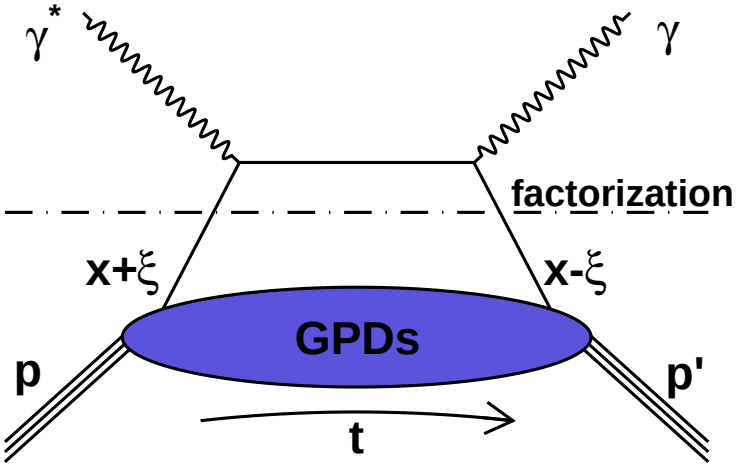
- **Linear growth of the static quark-antiquark pair**
  Area-law falloff for the Wilson loop
- **Gribov Confinement for light quarks**
  Analytical properties of the propagators in the infrared
  Instability of the vacuum above a supercritical charge

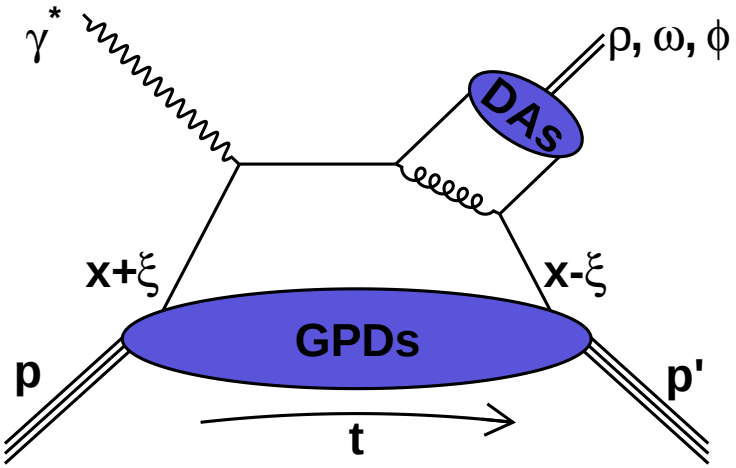
$$\alpha_{QED}^{crit} = 137 \text{ for a point-like nucleus}$$
$$\approx 180 \text{ for a finite size nucleus}$$
$$\frac{\alpha_{QCD}^{crit}}{\pi} = C_F^{-1}\left[1-\sqrt{\frac{2}{3}}\right] \approx 0.137$$

- **Light-Front AdS/QCD**
  quark and gluon chiral condensates confined!
  →condensates contribution to the cosmological constant already included in hadron mass
- Mass-Gap Millenium problem and Yang-Mills existence
  $1M from the Clay Mathematical Institute

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 fixed

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

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

$$= \bar{N}(p') \left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t) i\sigma^{+\nu}\frac{\Delta_\nu}{2M} + \tilde{H}^q(x,\xi,t)\gamma^+\gamma^5 + \tilde{E}^q(x,\xi,t)\gamma^5\frac{\Delta^+}{2M}\right] N(p)$$

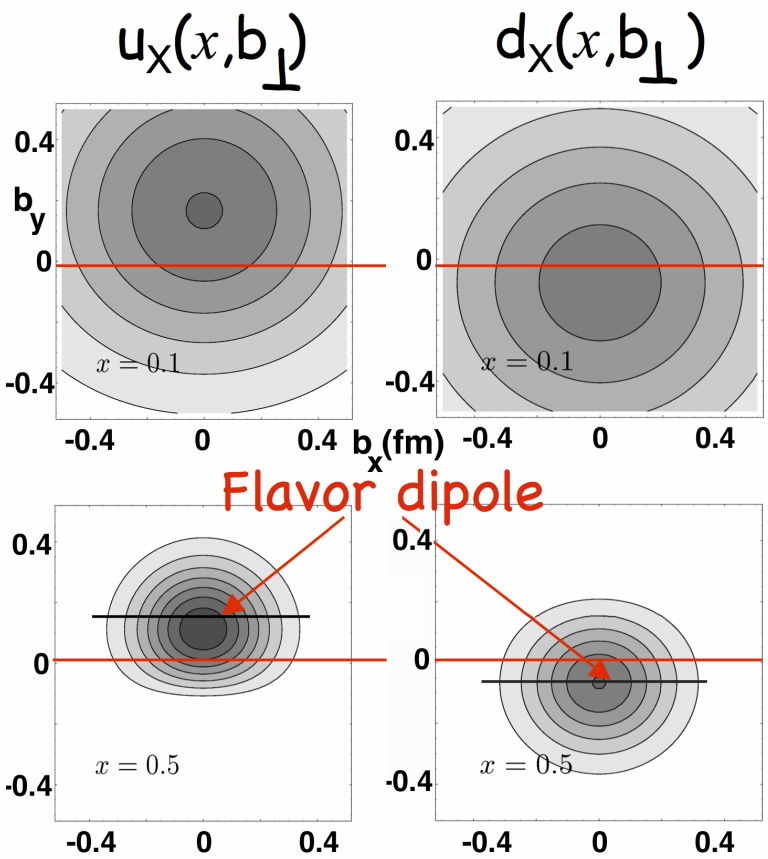
spin	N no flip	N flip
q no flip	H	E
q flip	$\tilde{H}$	$\tilde{E}$

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

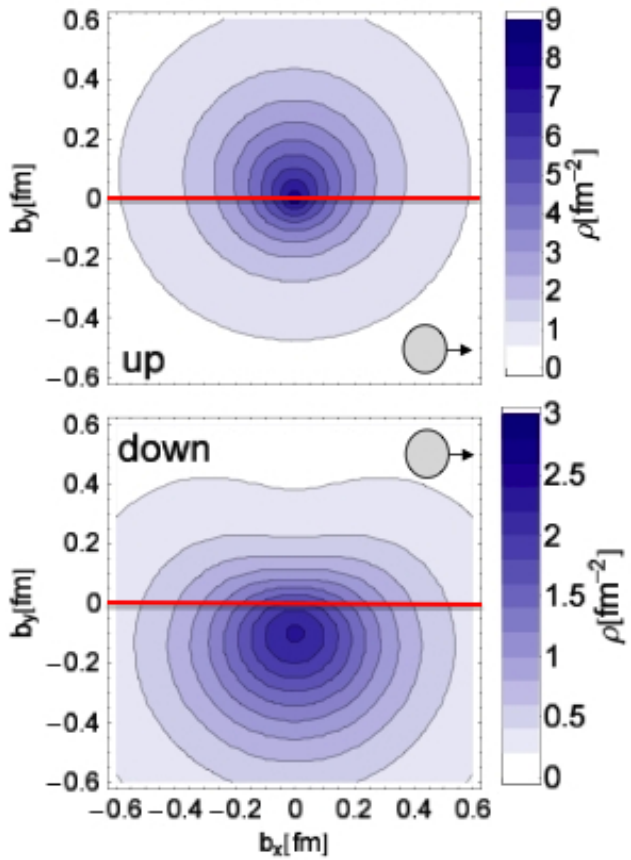
GPDs and Transverse Imaging (x_B, t)

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

Target polarization



Lattice calculation



Energy Momentum Tensor (x, ξ)

Form Factors accessed *via* second x-moments :

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

Angular momentum distribution

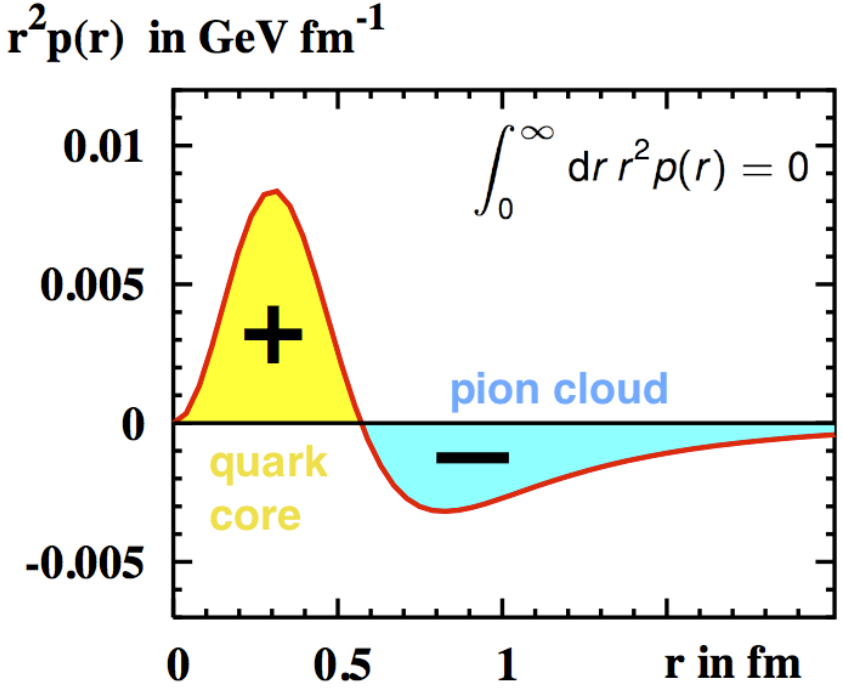
$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

Mass and force/pressure distributions

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

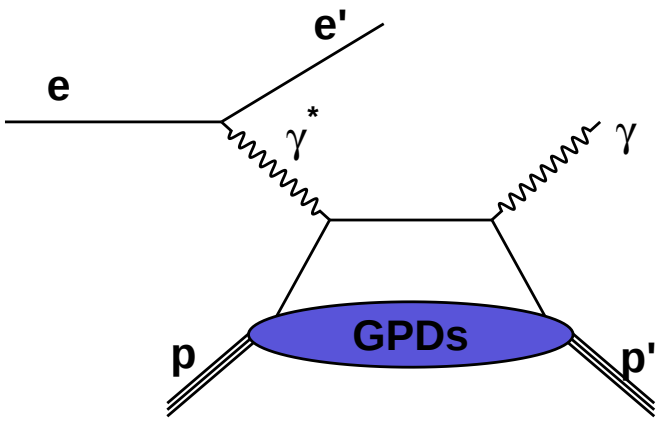
$$d_1(t) = 15M\int \mathrm{d}^3\vec{r}\,\frac{j_0(r\sqrt{-t})}{2t}\,p(r)$$

Distribution of pressure

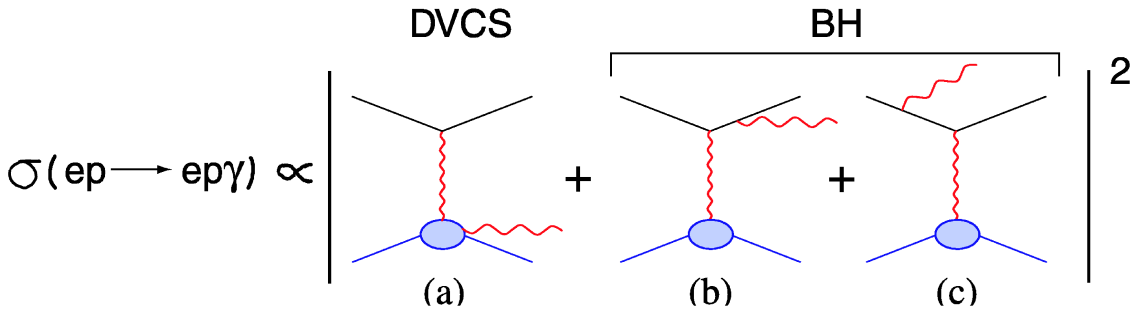


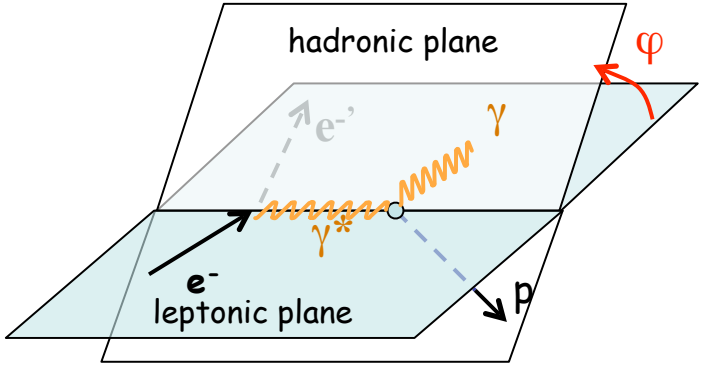
Deeply Virtual Compton Scattering

The cleanest GPD probe at low and medium energies



$$ep \to ep\gamma$$





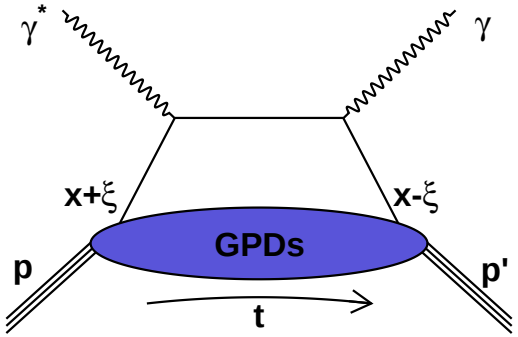
$$A_{LU} = \frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}} \overset{\text{twist-2}}{\approx} \frac{\alpha \sin\phi}{1 + \beta\cos\phi}$$

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

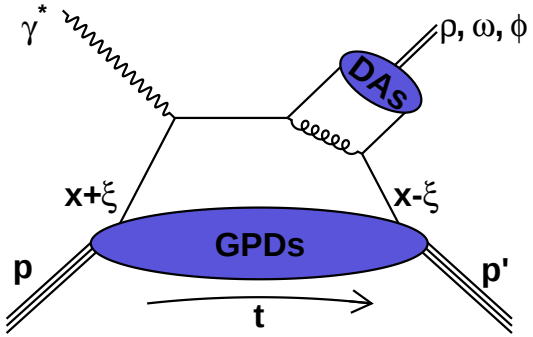
$$\mathcal{H}(\xi,t) = i\pi H(\xi,\xi,t) + \mathcal{P}\int_{-1}^{1} \mathrm{d}x\, \frac{H(x,\xi,t)}{x-\xi}$$

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

Observables sensitivities to GPD



DVCS



DVMP

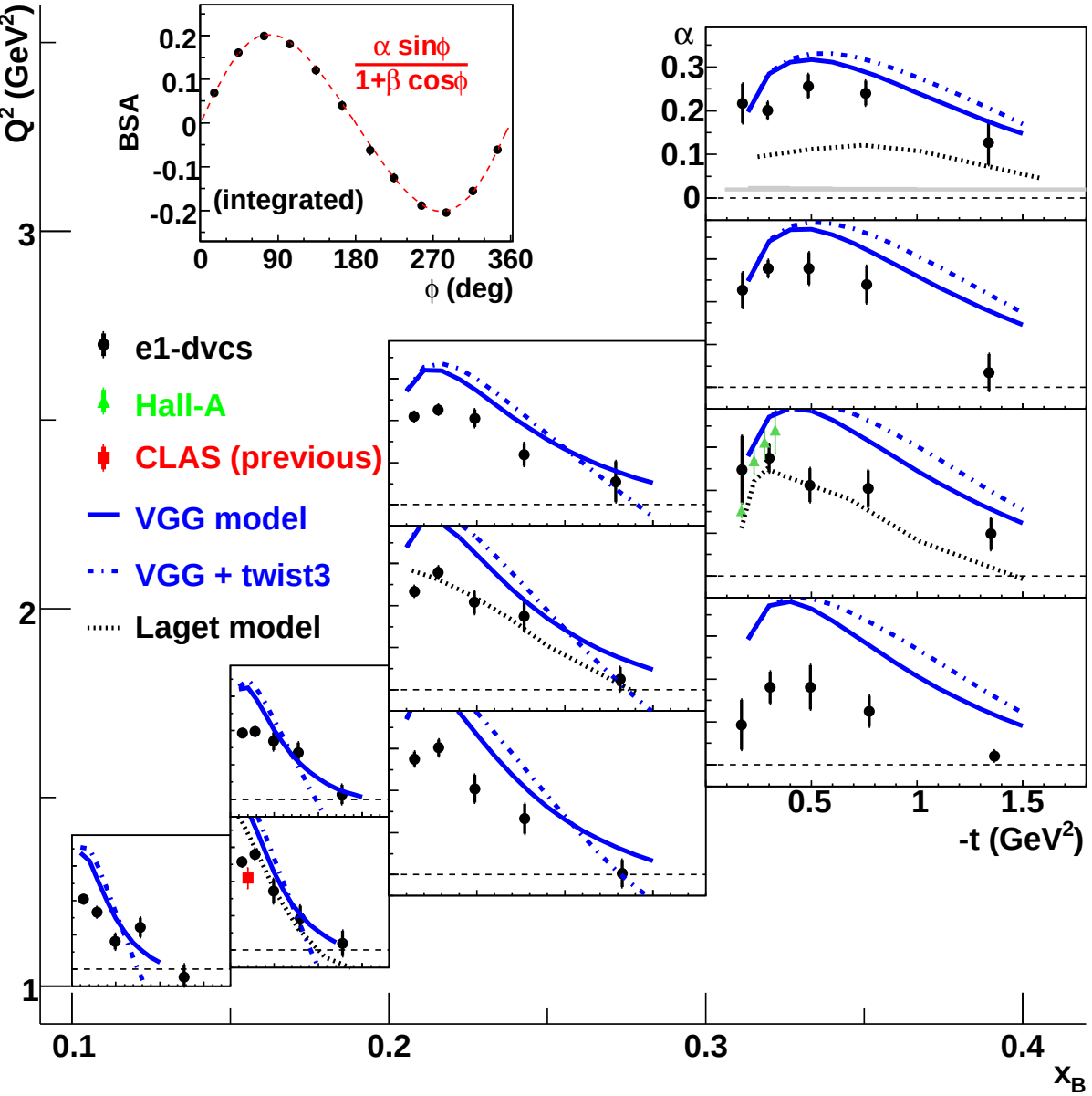
	$\mathcal{I}$m	$\mathcal{R}$e
$\mathcal{H}$	A_{LU}	σ
$\tilde{\mathcal{H}}$	A_{UL}	A_{LL}, A_{LT}
$\mathcal{E}$	A_{UT}	

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

A global analysis is needed to fully disentangle GPDs
All channels can also be measured in transition GPDs to excited Nucleon states

Published Data

DVCS Beam Spin Asymmetry 6 GeV



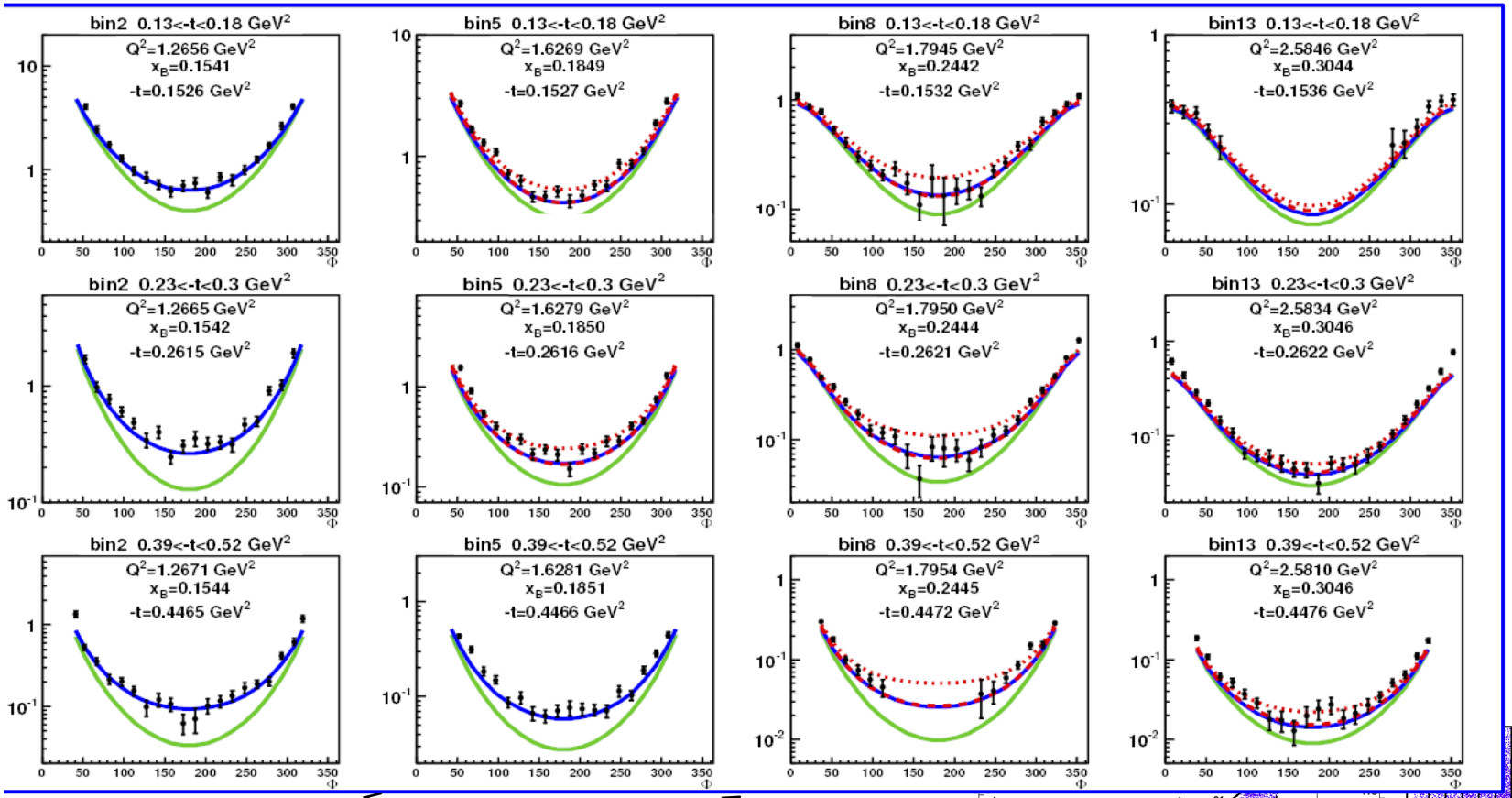
$$F_1\mathcal{H} + \xi G_M \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}$$

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

Qualitative model agreement

quantitative constraints on parameters

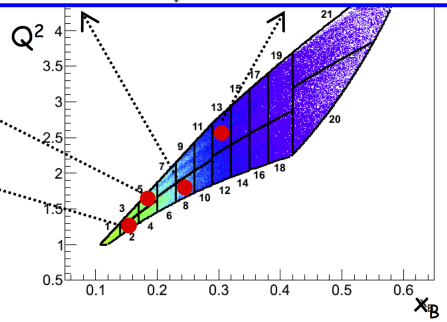
DVCS Unpolarized Cross-Sections 6 GeV

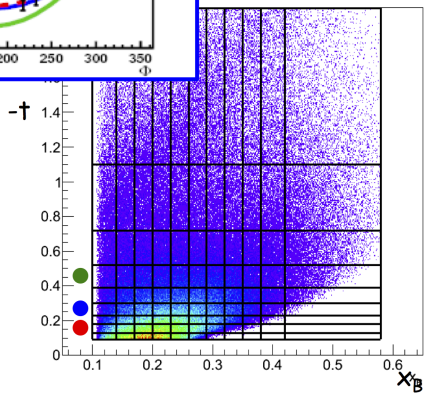


$$\bullet \quad \frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi} (nb/GeV^4)$$

BH — VGG (H only)

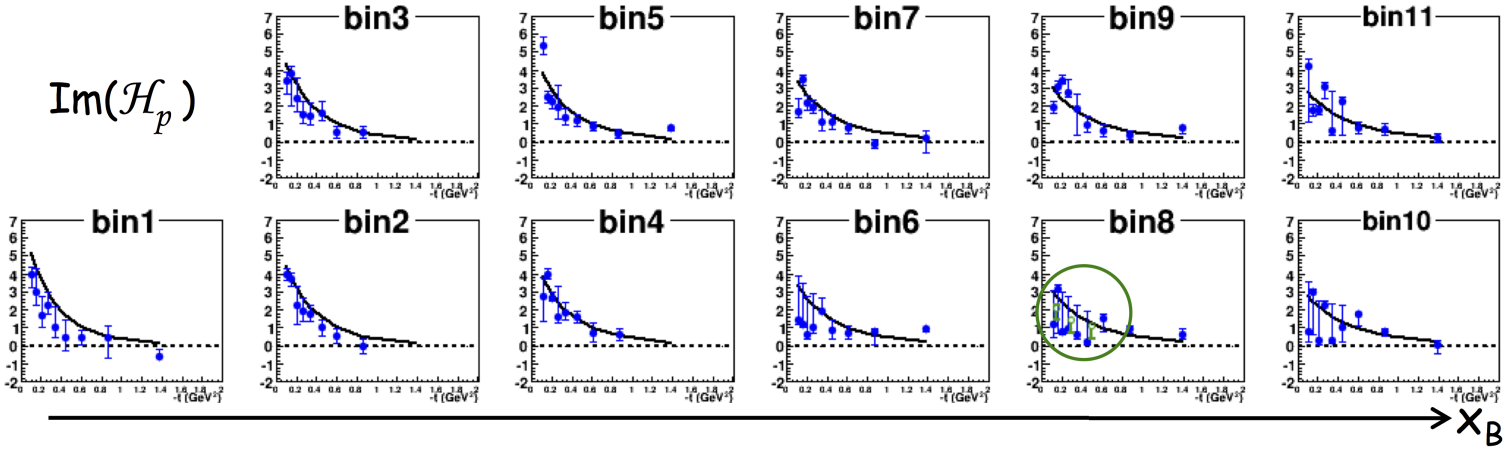
KM10 - - - KM10a



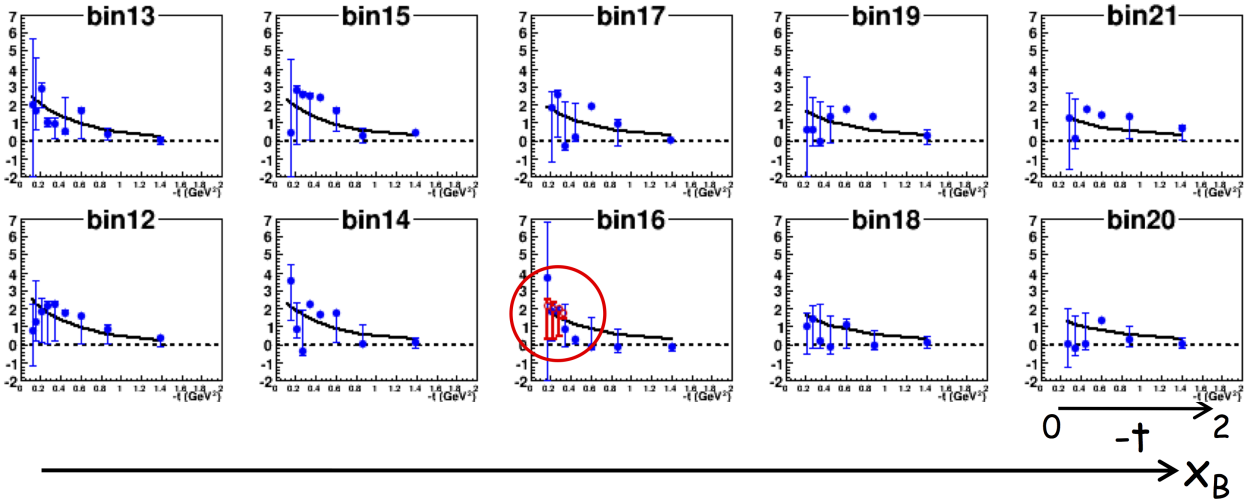


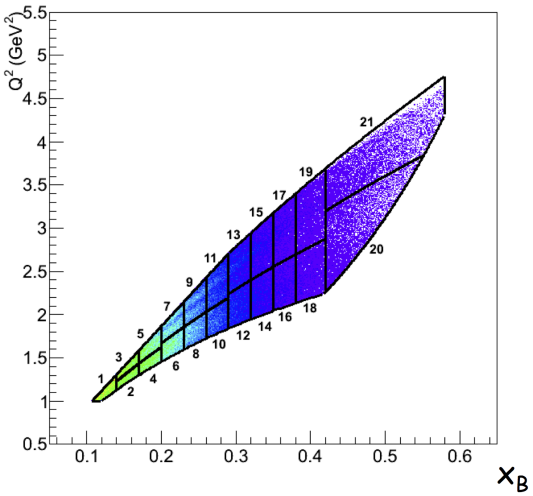
VGG : Vanderhaeghen, Guichon, Guidal *KM : Kumericki, Mueller*

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

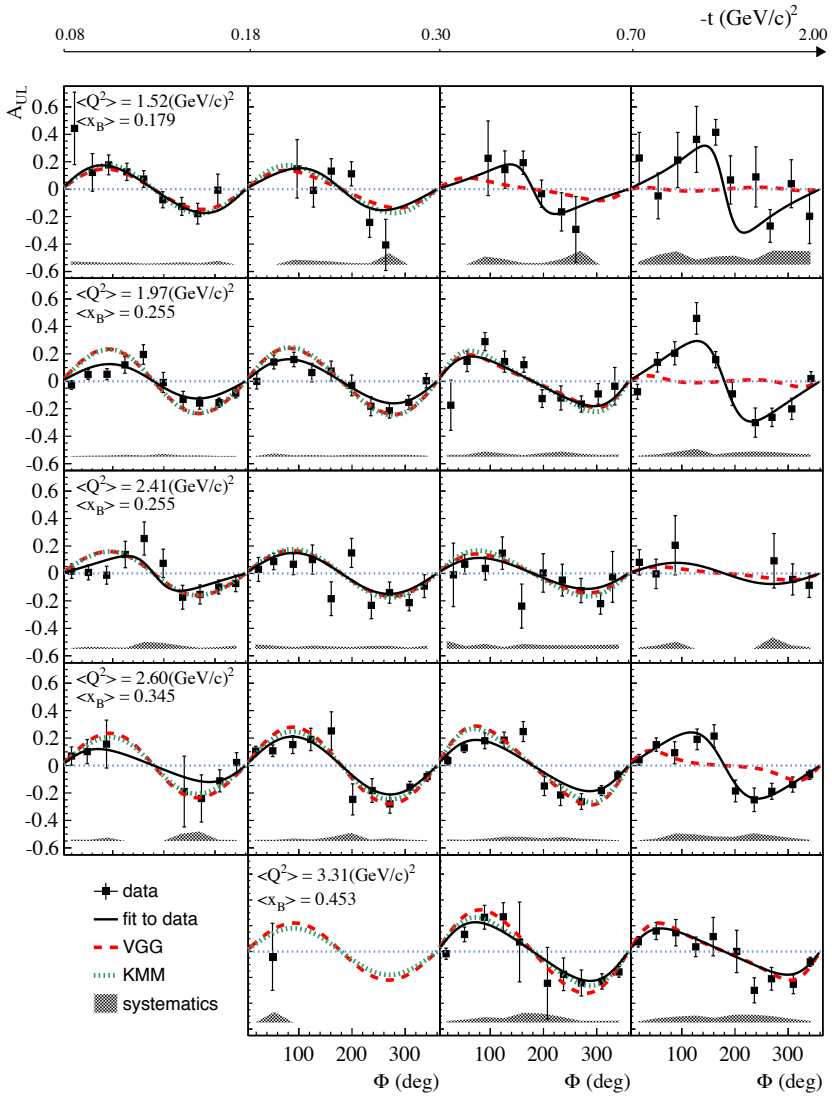


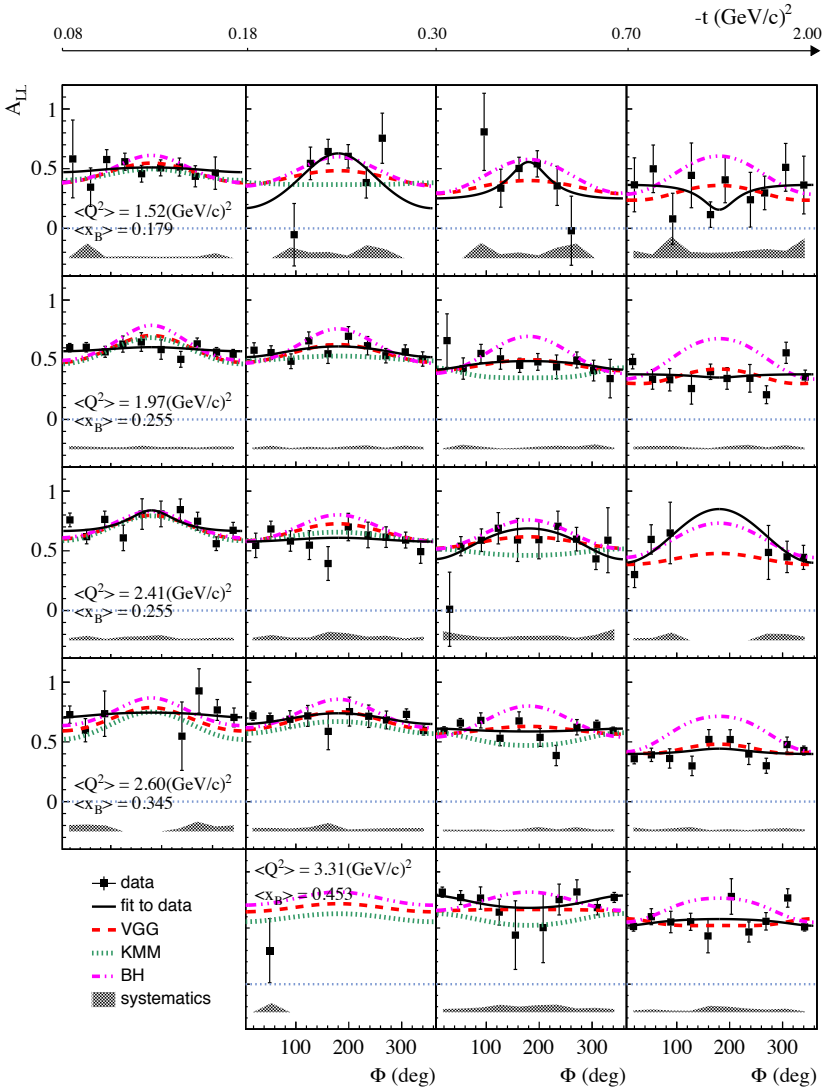


The t-slope becomes flatter with increasing x_B:
valence quarks (higher x_B) at the center of the nucleon and sea quarks (small x_B) at its periphery

Target Longitudinal Spin DVCS 6 GeV

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





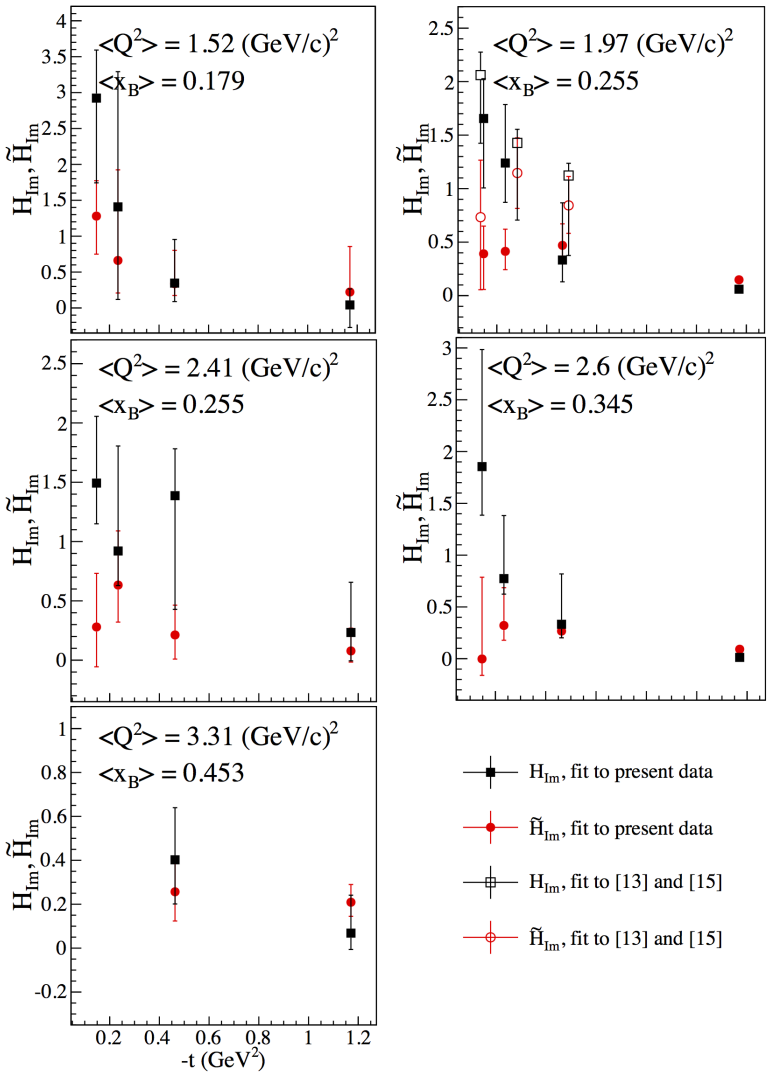
Model independent extraction 6 GeV

GPD dependencies versus x_B mirror their respective ordinary PDFs

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

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

Axial charge more concentrated than EM charge



Future Measurements

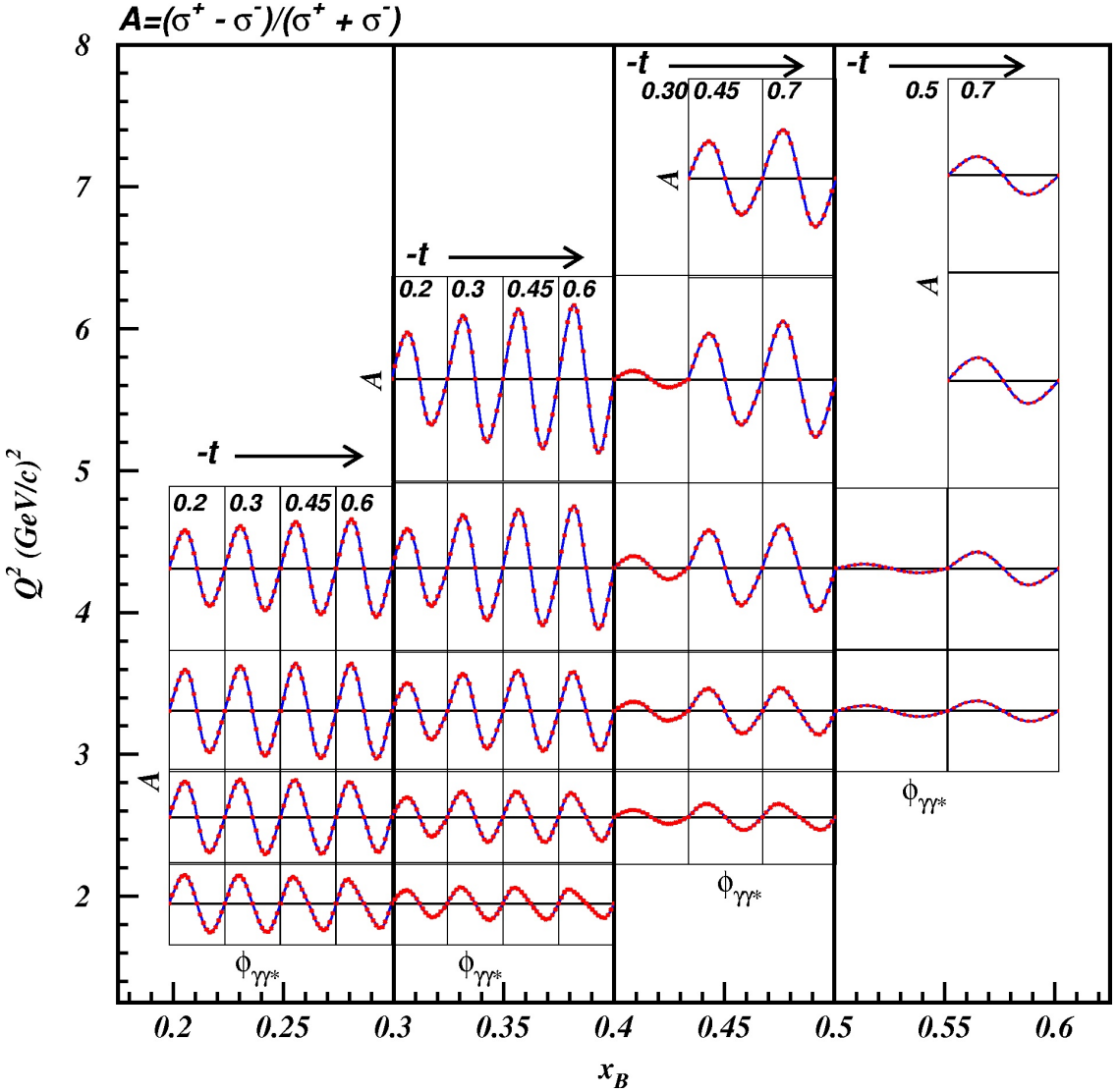
CLAS12 GPD program

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

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 $x = 0.6$

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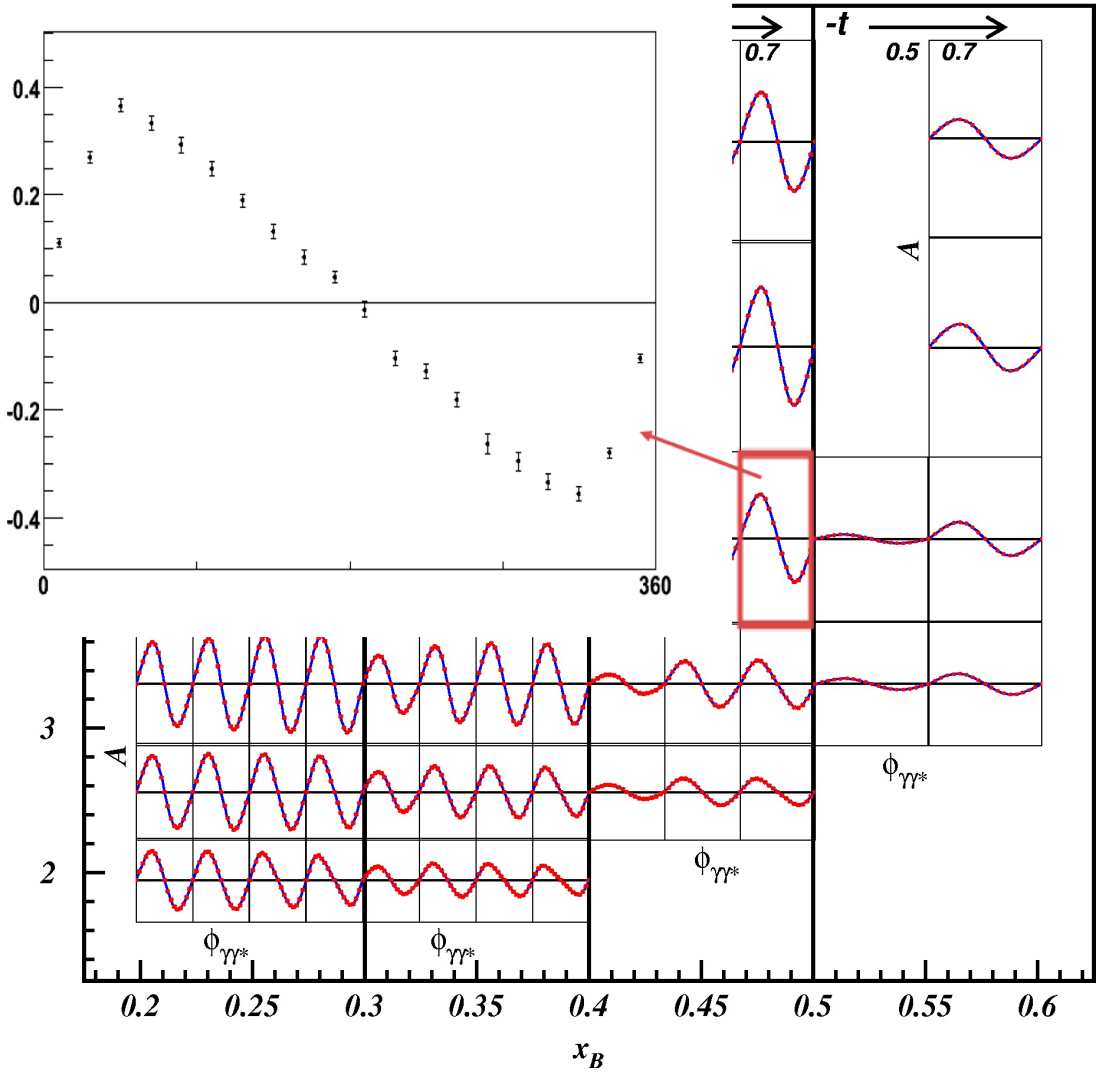

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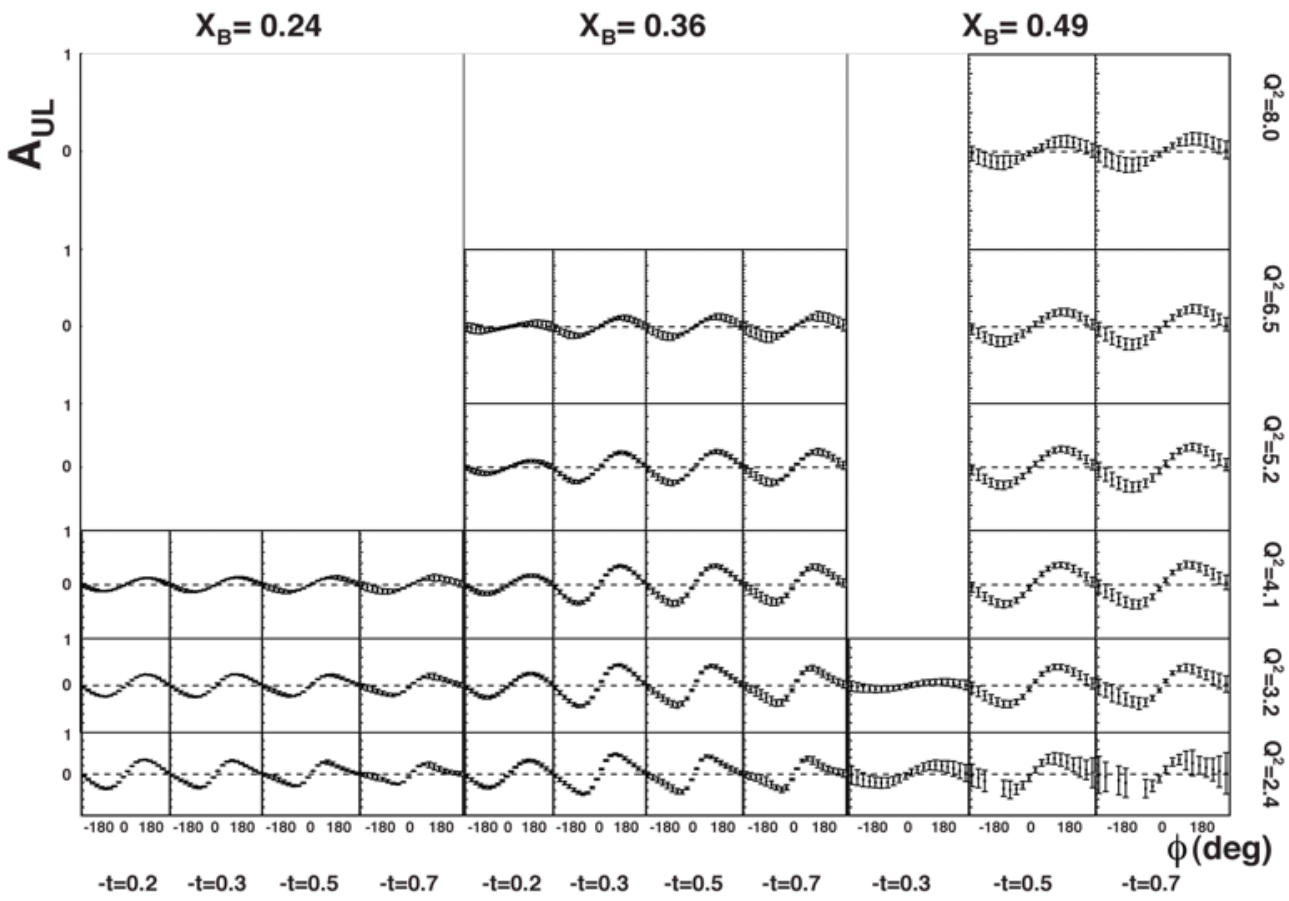
Proton DVCS TSA A_{UL} E12-06-009

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

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



Target Spin Asymmetries
ϕ dependence

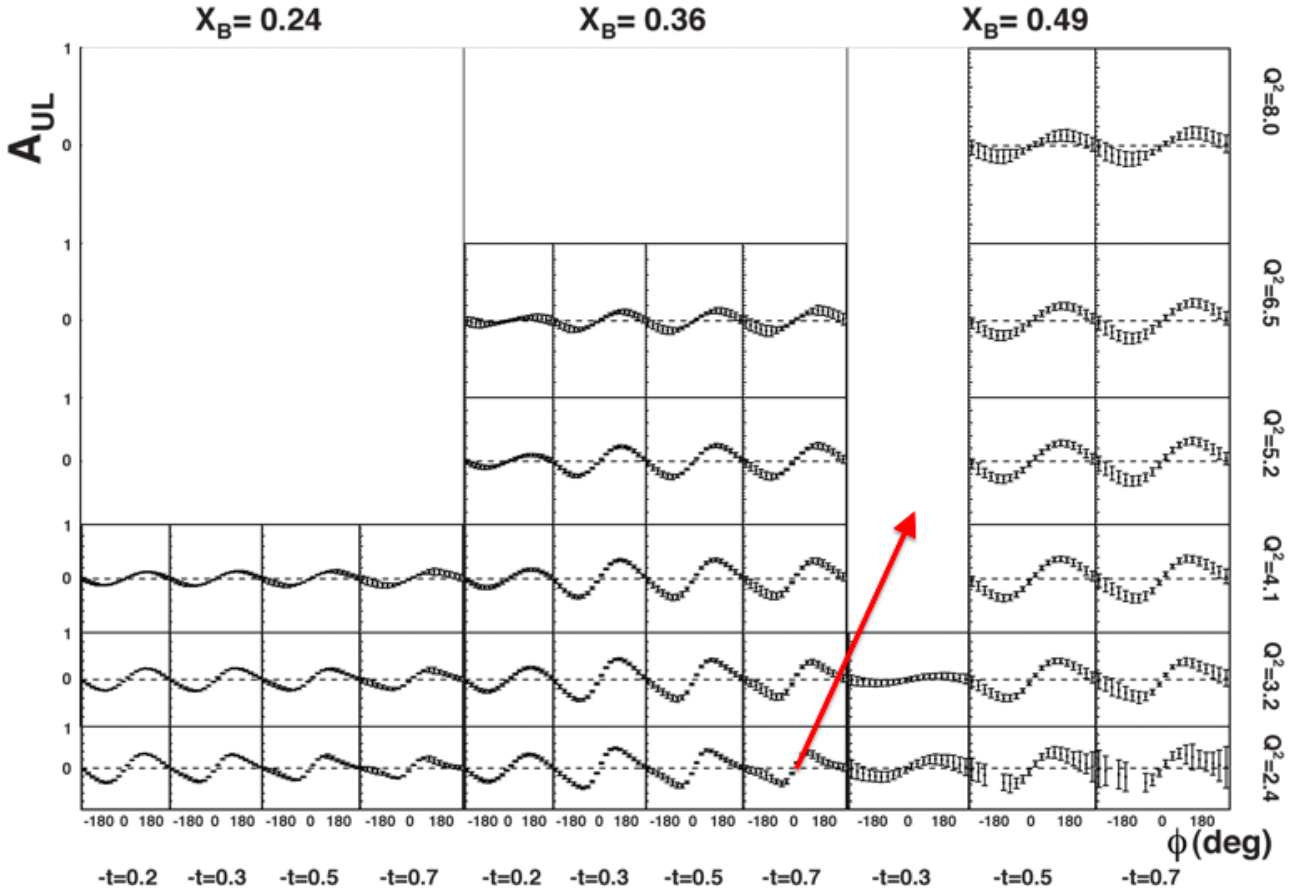
Statistical uncertainties :
from 2 % (low Q^2)
to 30 % (high Q^2)

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

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



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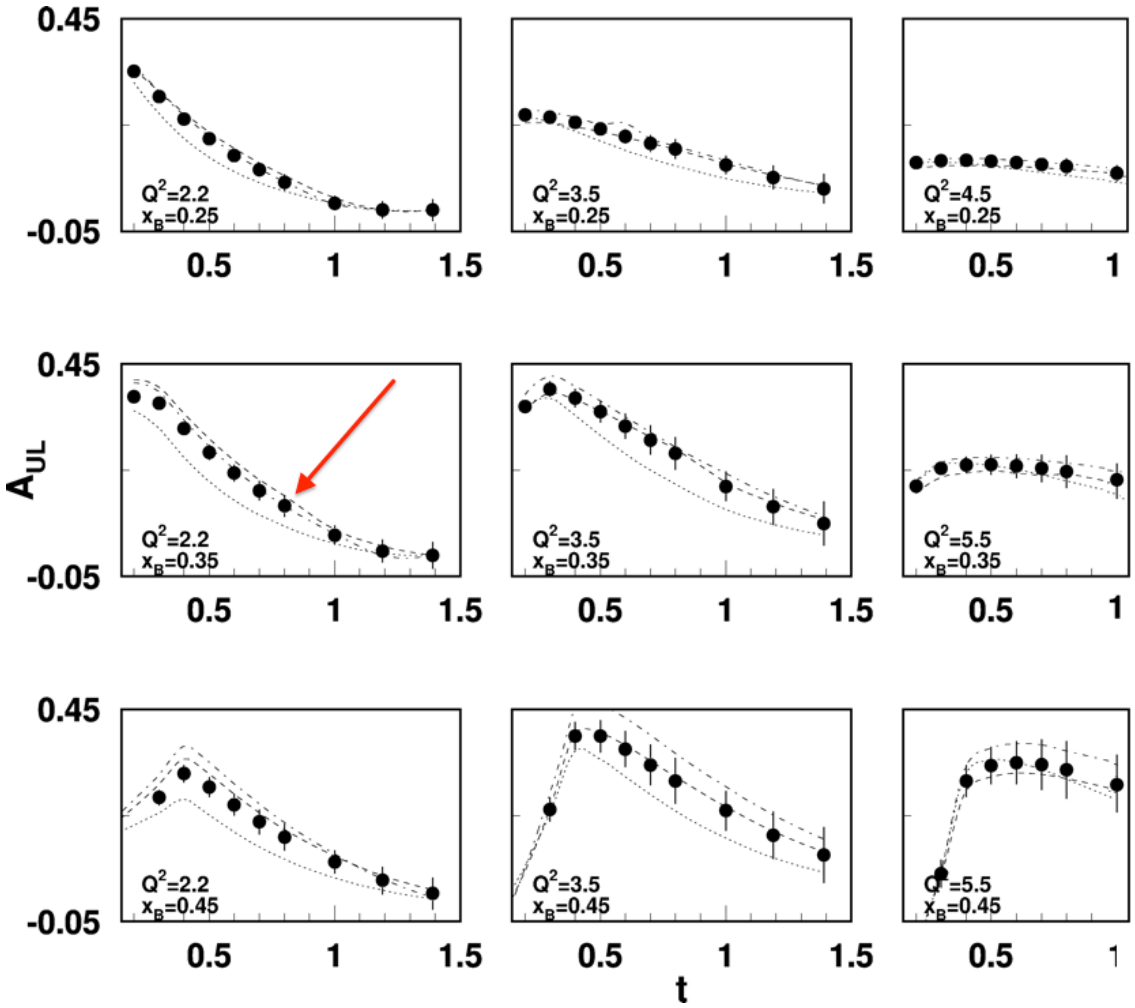


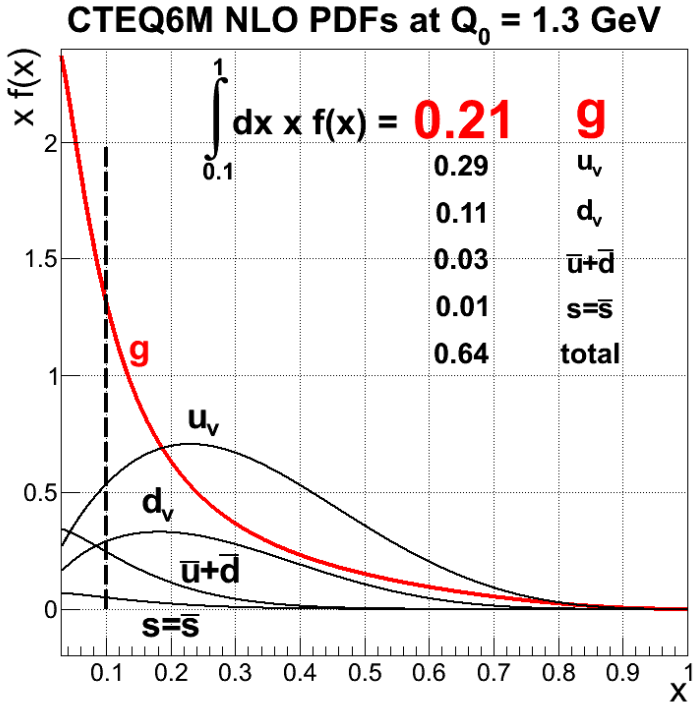
TSA t-slopes

Sample kinematics
for target asymmetry

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

Gluons at large x

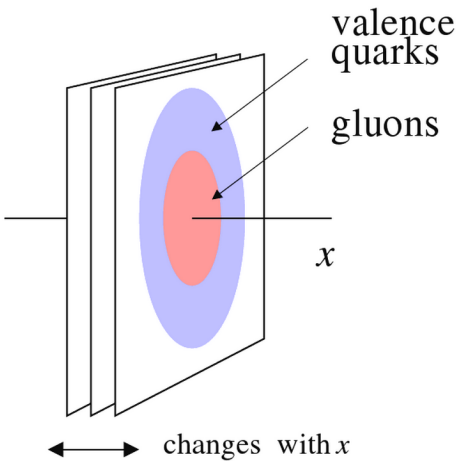
E12-12-007



- 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 $0.1 < x$

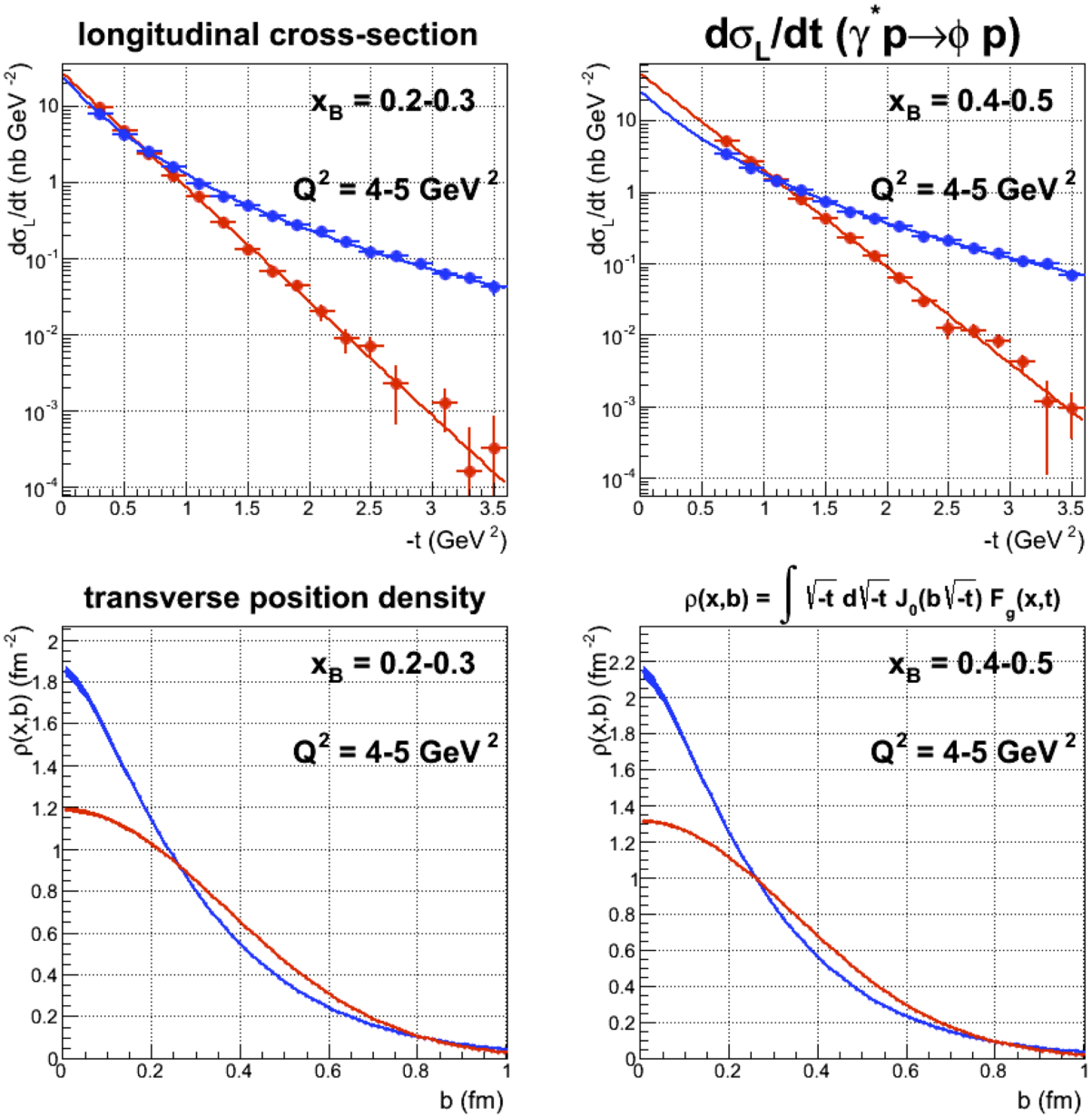


- 3D imaging of the nucleon

  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

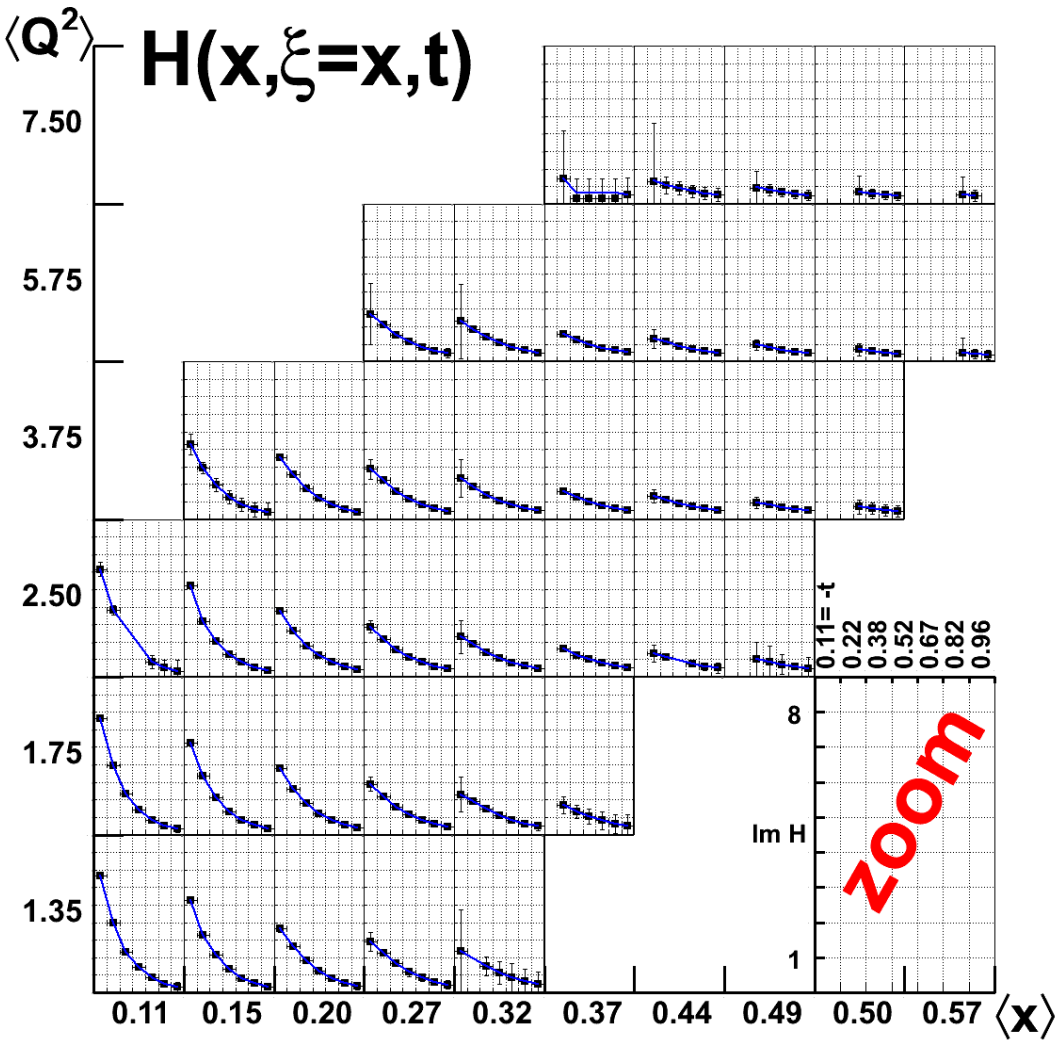
$$b = 1/\sqrt{-t}$$

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



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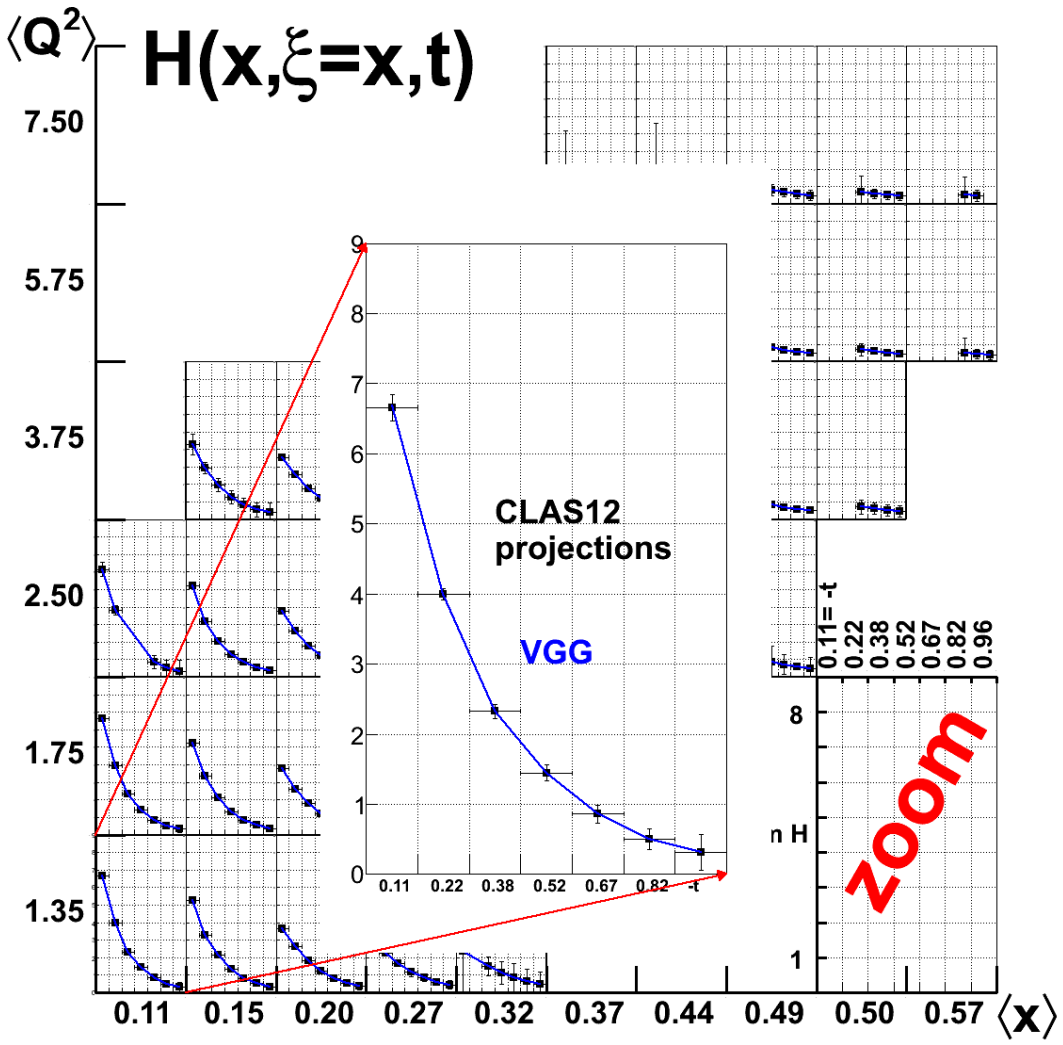

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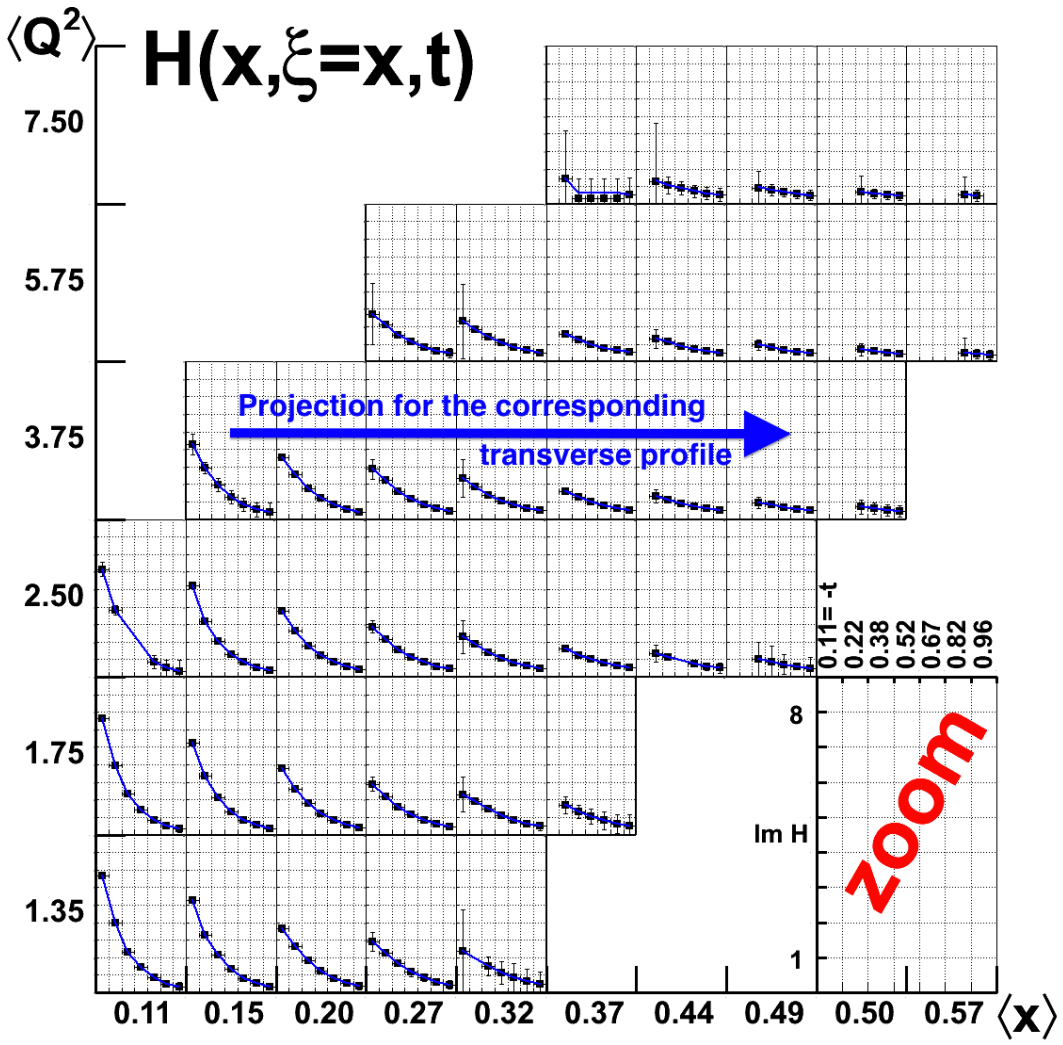
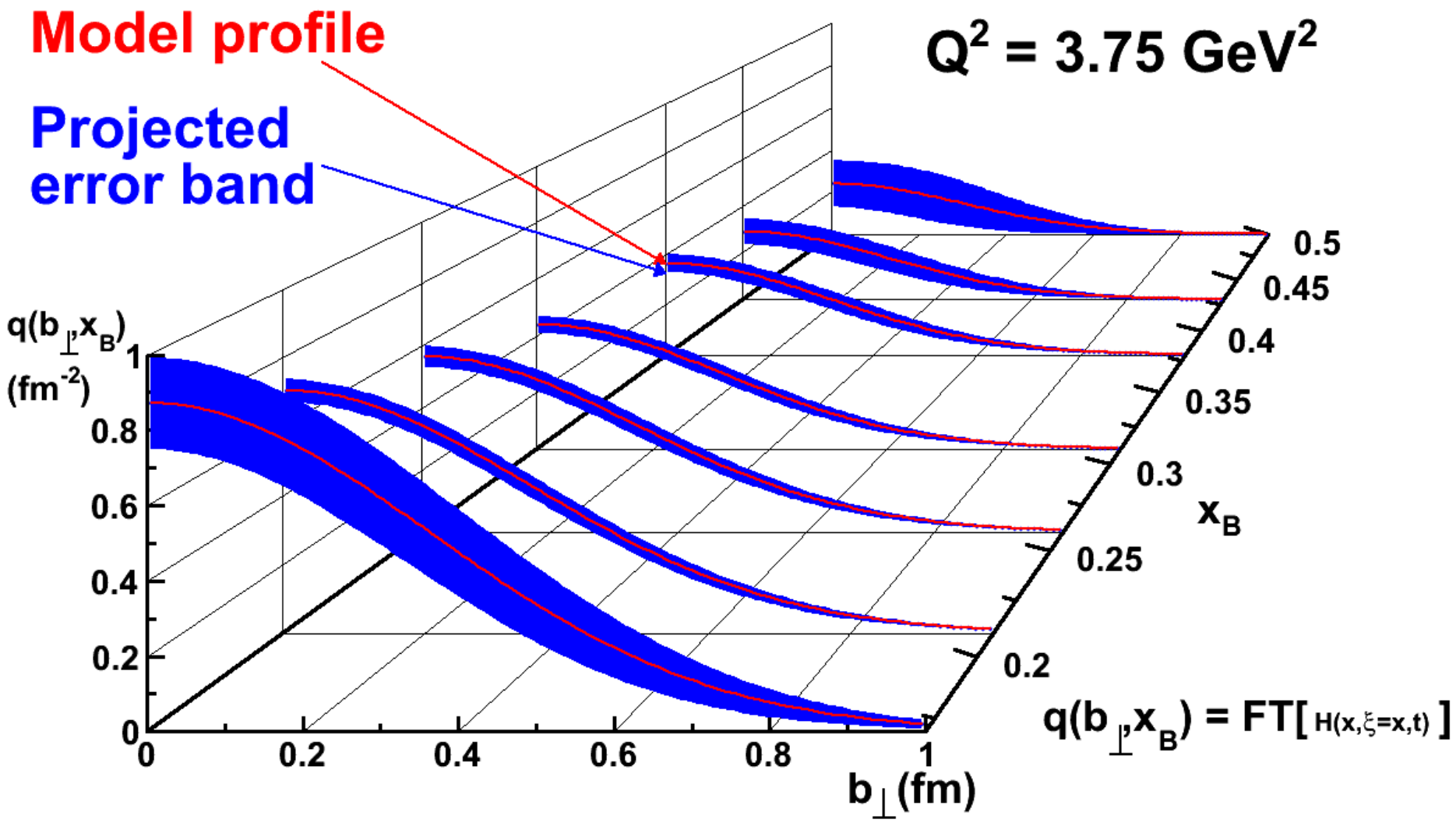
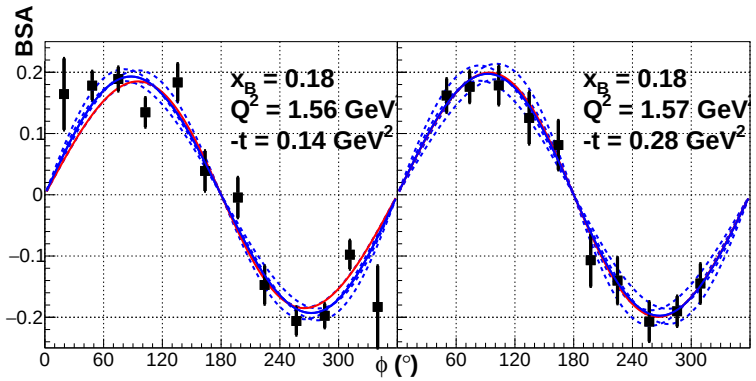


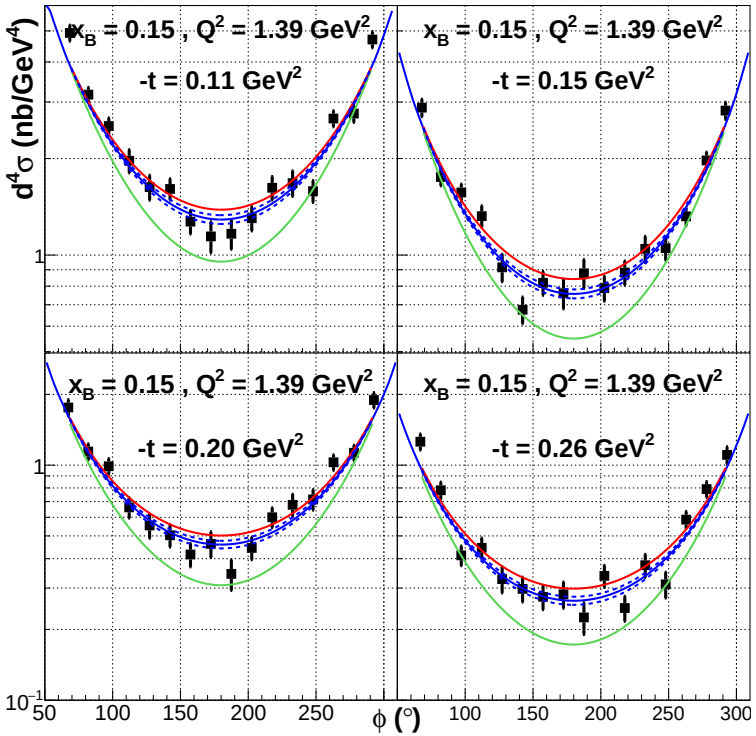
Projection for the Nucleon transverse profile



Precision tomography in the valence region

Global Fits to extract the D-term





Beam Spin Asymmetries

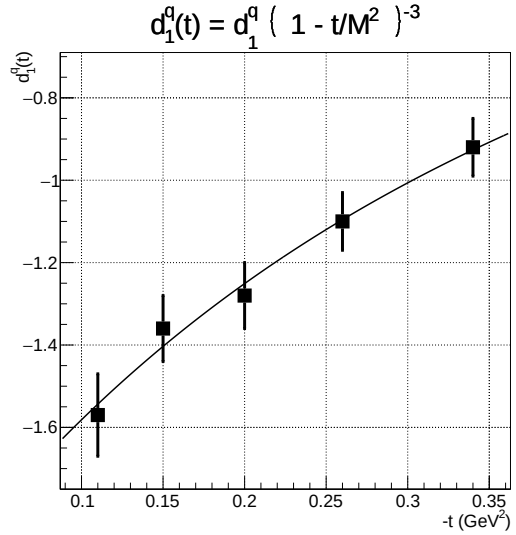
$$\mathrm{Im}\mathcal{H}(\xi,t) = \frac{r}{1+x}\left(\frac{2\xi}{1+\xi}\right)^{-\alpha(t)}\left(\frac{1-\xi}{1+\xi}\right)^{b}\left(\frac{1-\xi}{1+\xi}\,\frac{t}{M^2}\right)^{-1}$$

Unpolarized cross-sections
Use dispersion relation:

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

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

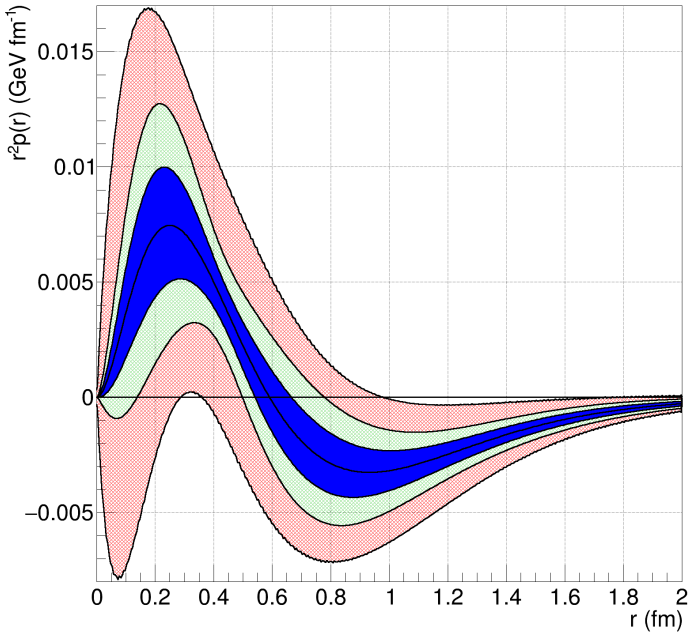
D-term and Pressure distribution



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

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

Summary and Outlook

- Exclusive reactions offer a partonic approach to the problem of confinement
- Transverse Imaging, Energy Momentum Tensor
- First Generation Experiments succesful
- Extraction frameworks already producing publications
- Formalism also applies to Nucleon Resonances
- Exciting times at the beginning of the 12 GeV high precision era!