JLab Results on Hadron Structure

F.-X. Girod

Jefferson Laboratory

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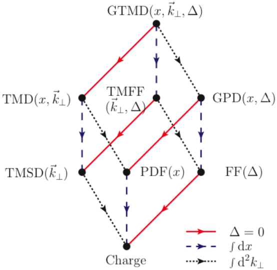
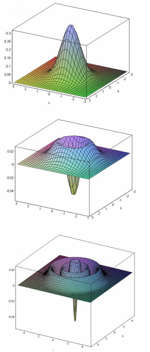
Outline

Theoretical context

FFs, PDFs, GPDs, TMDs, all related to the same Wigner distribution



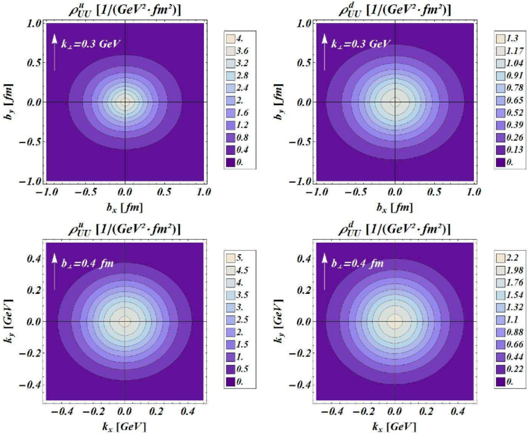
- Most general one-parton density matrix
- Not known how to measure
- Provides a unifying description
- Constraints for model building



Unified framework for GPDs and TMDs within a 3Q LC picture of the nucleon

C. Lorcé *et al*, JHEP 1105:041,2011

Unified view of hadron structure
Unpolarized quark in unpolarized nucleon

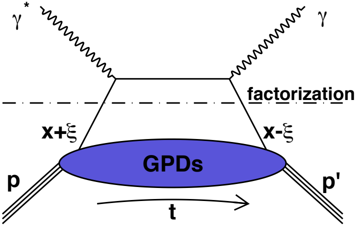


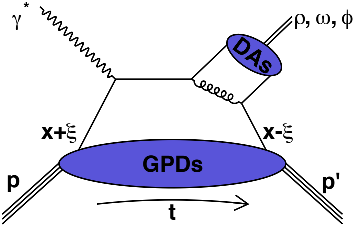
Quadrupole deformation of transverse position for quarks at large transverse momentum
Intuitive from a semi-classical picture of confinement

C. Lorcé *et al*, PRD 84 014015, 2011

Deep Exclusive Scattering

Generalized Parton Distributions





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

Bjorken regime :

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

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

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

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

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

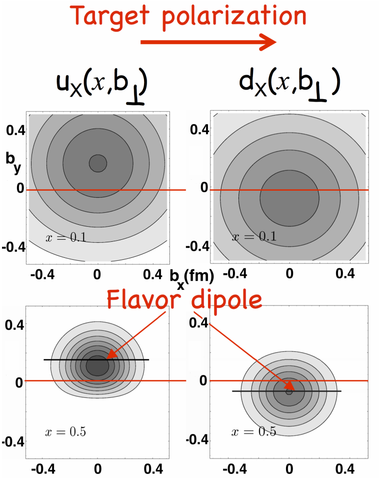
spin	N no flip	N flip
q no flip	H	E
q flip	$\tilde{H}$	$\tilde{E}$

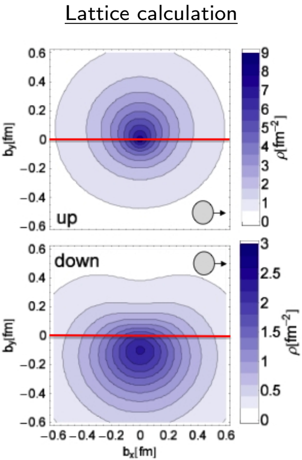
3-D Imaging conjointly in transverse impact parameter and longitudinal momentum

GPDs and Transverse Imaging

(x_B, t) correlations

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





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

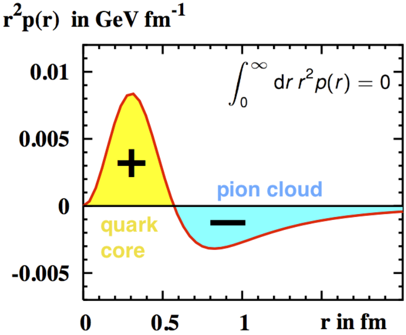
$$J^q(t) = \frac{1}{2}\int_{-1}^{1} \mathrm{d}x\, x\,[H^q(x,\xi,t) + E^q(x,\xi,t)]$$

Mass and force/pressure distributions

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

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

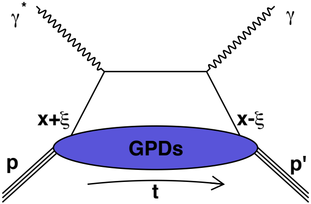
Distribution of pressure

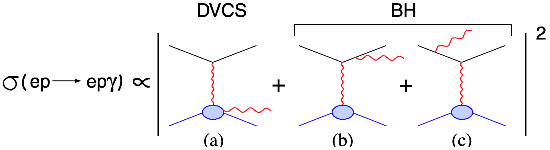


Deeply Virtual Compton Scattering

The cleanest GPD probe at low and medium energies

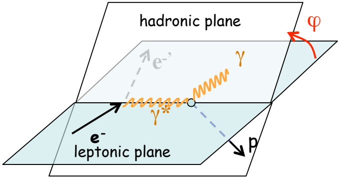
$$ep \longrightarrow ep\gamma$$





Diehl, Gousset, Pire, Ralston (1997)

Belitsky, Müller, Kirchner (2002, 2010)



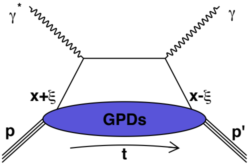
$$A_{\rm LU} = \frac{d^4\sigma^{\rightarrow} - d^4\sigma^{\leftarrow}}{d^4\sigma^{\rightarrow} + d^4\sigma^{\leftarrow}} \overset{\text{twist-2}}{\approx} \frac{\alpha \sin\phi}{1+\beta\cos\phi}$$

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

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

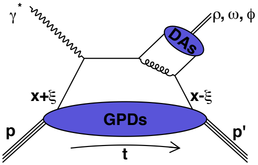
$$A_{\rm UL} \propto \mathcal{I}\mathrm{m}\left(F_1\tilde{\mathcal{H}} + \xi G_M\mathcal{H} + G_M\frac{\xi}{1+\xi}\mathcal{E} + \cdots\right)\sin\phi$$

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}	

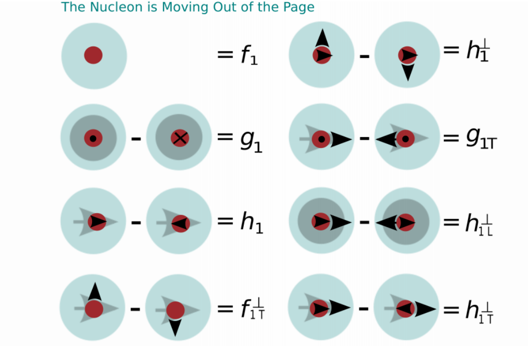


DVMP

	Meson	Flavor
$\mathcal{H}_T$,$\mathcal{E}_T$	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	g

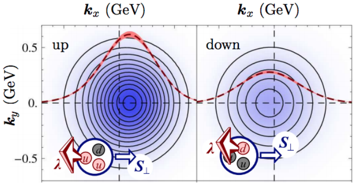
A global analysis is needed to fully disentangle GPDs

SIDIS and TMDs



N↓ q→	U	L	T	Higher Twist
U	f_1		$h_1^\perp$	$f^\perp$, $g^\perp$, h, e
L		g_1	$h_{1L}^\perp$	$f_L^\perp$, $g_L^\perp$, h_L, e_L
T	$f_{1T}^\perp$	g_{1T}	$h_{1T}^\perp$, h_1	f_T, $f_T^\perp$, g_T, $g_T^\perp$, $h^\perp$, e_T, $h_T^\perp$, $e_T^\perp$

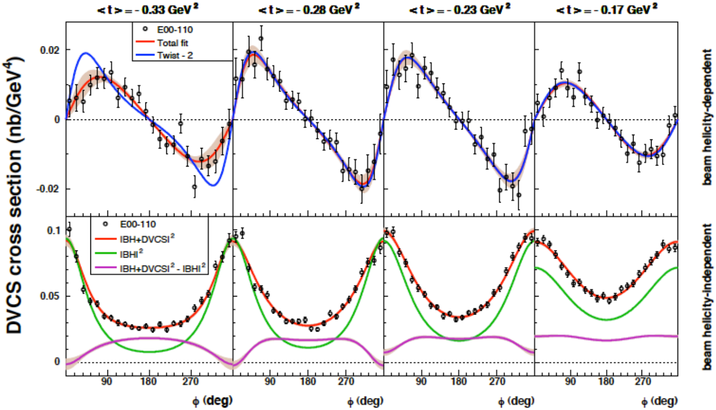
$f_{1T}^\perp$ Sivers
$h_1^\perp$ Boer-Mulders
g_{1T} Worm-Gear
$h_{1L}^\perp$ Kotzinian-Mulders
$h_{1T}^\perp$ Pretzelosity



Unpolarized hydrogen target

Scaling tests of $\Delta\sigma_{\rm DVCS}$ Hall-A

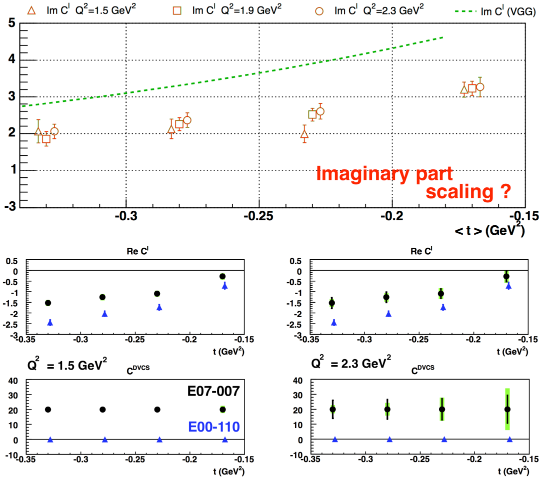
$$F_1\mathcal{H} + \xi G_M\tilde{\mathcal{H}} - F_2\frac{t}{4M^2}\mathcal{E} + \cdots$$



C. Muñoz *et al.*, PRL **97** (2006) 262002
High precision in a narrow kinematical range

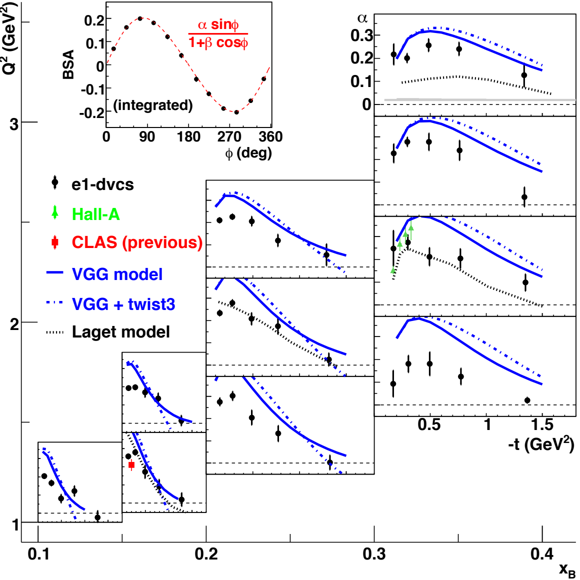
Separation of $\mathcal{I}$ and DVCS^2

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



High precision in a narrow kinematical range

DVCS Beam Spin Asymmetry Hall-B



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

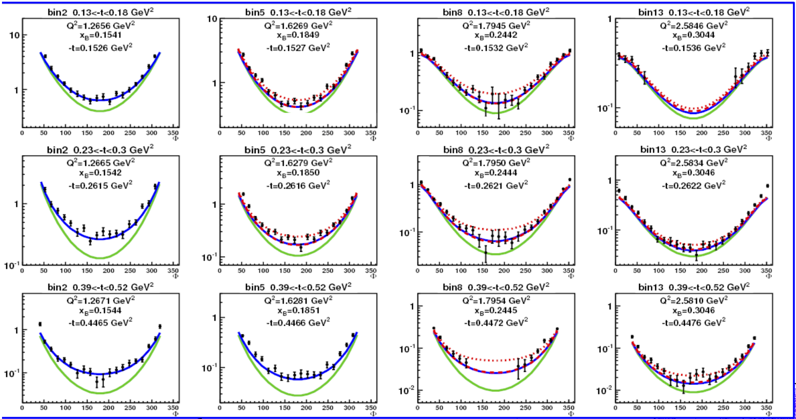
Precision in a large phase-space (x_B, Q^2, t)

Qualitative model agreement

quantitative constraints on parameters

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

DVCS Unpolarized Cross-Sections Hall-B

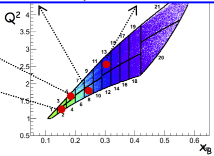


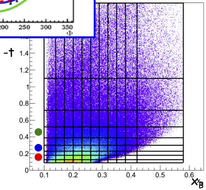
$\bullet \quad \frac{d^4\sigma_{ep\to ep\gamma}}{dQ^2 dx_B dt d\Phi}$ (nb/GeV^4)

BH — VGG (H only)

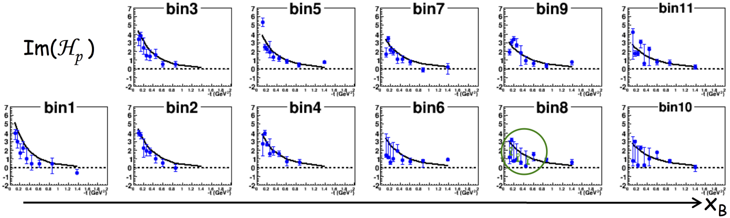
KM10 - - - KM10a

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



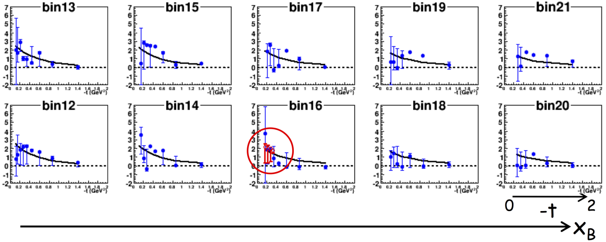


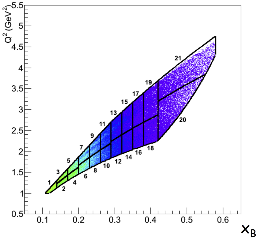
Compton Form Factors Hall-B



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

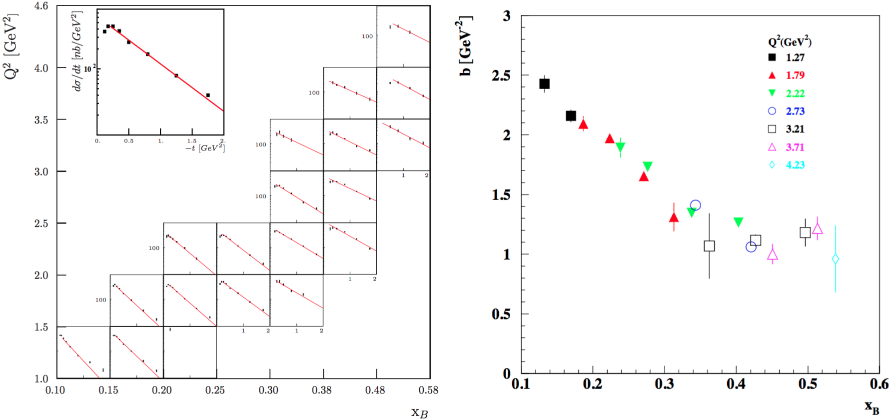
— VGG predictions





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

Exclusive π^0 production at $W > 2$ Hall-B



Sensitivity to the chiral-odd GPDs H_T and $2\tilde{H}_T + E_T$

The t-slope parameter is found independent of Q^2 and decreasing with x_B

Beam Spin Asymmetry in π^0 SIDIS Hall-B

Collins or Boer-Mulders ?

$$\frac{d\sigma_{LU}}{dx_B\, dy\, dz\, dP_T^2\, d\phi_h} = \frac{2\pi\alpha^2}{x_B y Q^2} \frac{y^2}{2(1-\epsilon)} \left(1 + \frac{\gamma^2}{2x_B}\right) \lambda_e \sqrt{2\epsilon(1+\epsilon)} \sin\phi_h F_{LU}^{\sin\phi_h}$$

$$F_{LU}^{\sin\phi_h} = \frac{2M}{Q} \int d^2\mathbf{p}_T d\mathbf{k}_T^2 \delta^{(2)}(\mathbf{p}_T - \frac{P_T}{z} - \mathbf{k}_T) \times \hat{P}_T \cdot \left\{ \left[\frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z} + x_B g^\perp D_1\right] \frac{\mathbf{p}_T}{M} - \left[\frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z} + x_B e H_1^\perp\right] \frac{\mathbf{k}_T}{M_h} \right\}$$

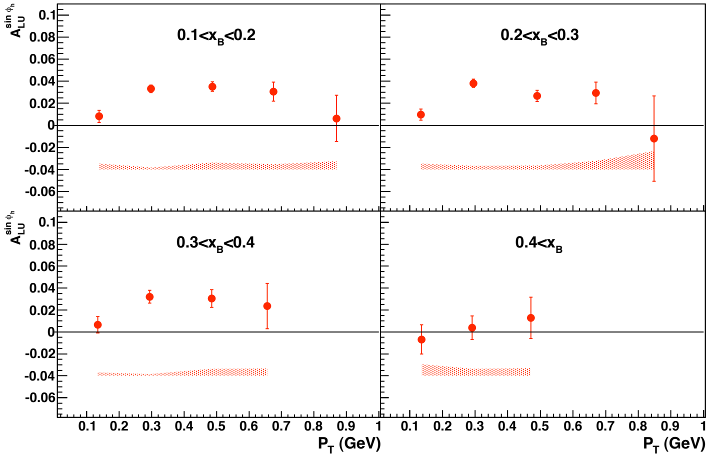
P_T	detected hadron
$\mathbf{p}_T$	active quark in Boer-Mulders DF $h_1^\perp$
$\mathbf{k}_T$	active quark in Collins FF $H_1^\perp$

The calculations based on Boer-Mulders $h_1^\perp$ predicted a sizable BSA

Those based on Collins $H_1^\perp$ mechanism predict a vanishing BSA for the π^0

Beam Spin Asymmetry in π^0 SIDIS Hall-B

Evidence for spin-orbit correlations

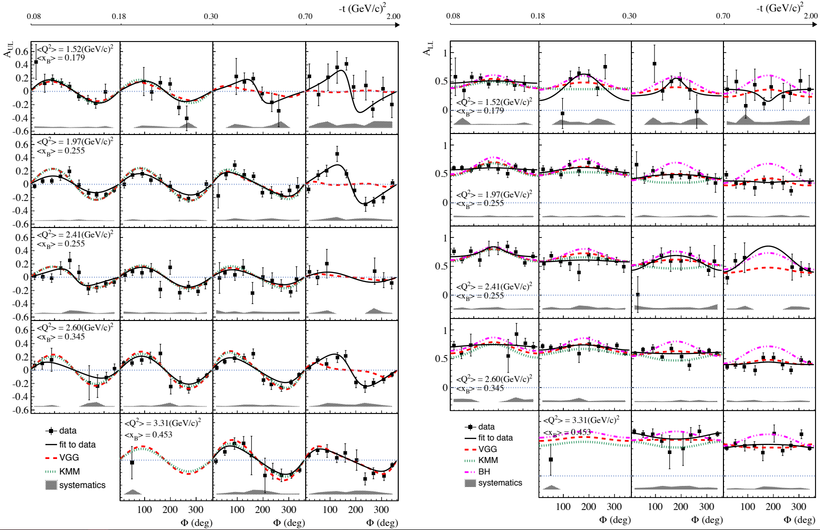


Without significant contribution from the Collins mechanism
this would be evidence for spin-orbit correlations, or another dynamical origin

Longitudinally polarized target

Target Longitudinal Spin DVCS Hall-B

$A_{UL} \propto F_1 \mathcal{I}m\, \tilde{\mathcal{H}}$ $\quad$ $A_{LL} \propto F_1 \mathcal{R}e\, \tilde{\mathcal{H}}$



Model independent extraction Hall-B

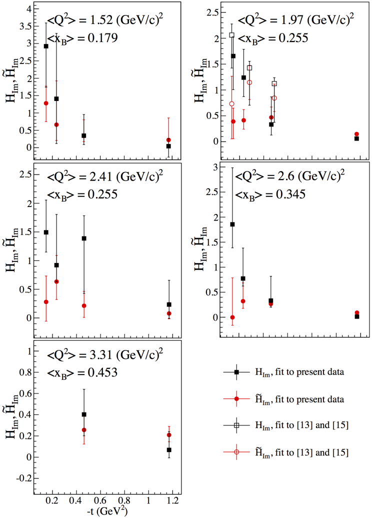
Using only A_{LU} and A_{UL}

GPD dependencies versus x_B mirror their respective ordinary PDFs

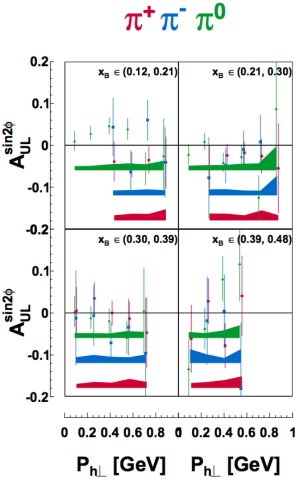
$\tilde{H}$ and $H \leftrightarrow \Delta q(x)$ and $q(x)$

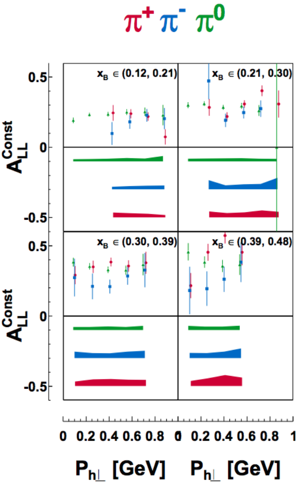
Change of $\Delta q(x)$ t-slope vs x_B less pronounced than $q(x)$

Axial charge more concentrated than EM charge



Target Spin Asymmetry in SIDIS Hall-B





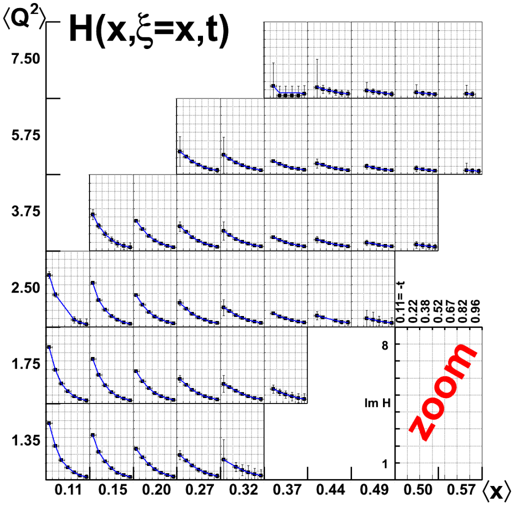
$A_{UL}^{\sin 2\phi}$ sensitive to $h_{1L}^{\perp}$ (Kotzinian-Mulders)
Changes sign at low x_B between positive and neutral pions

A_{LL}^{Const} related to g_1/F_1
no strong dependence on $P_{h\perp}$

Some projections for future measurements

Projected impact on GPD extraction

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



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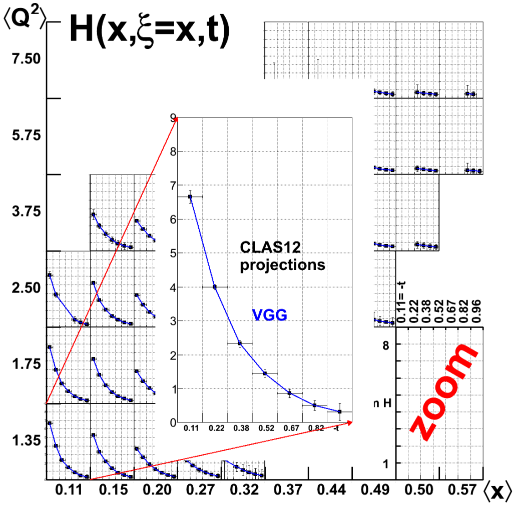

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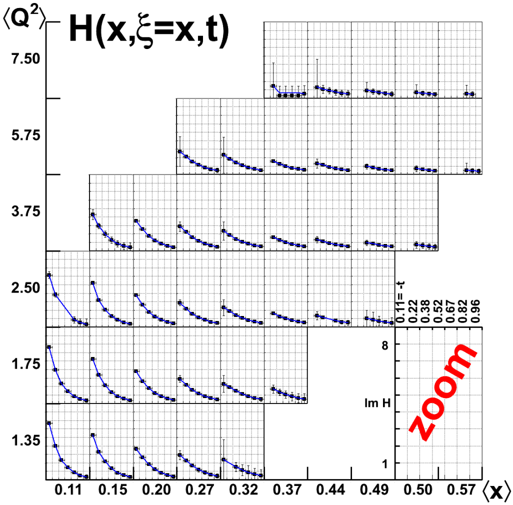

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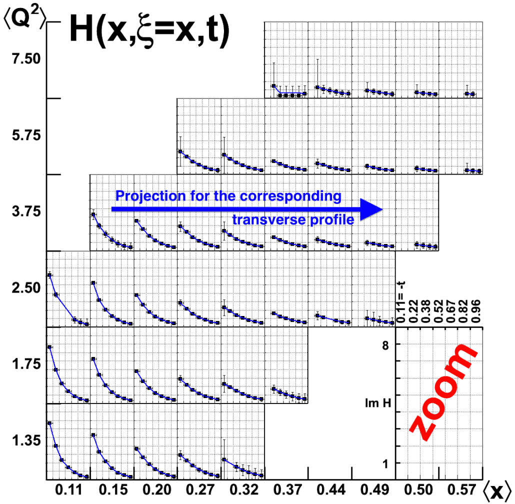
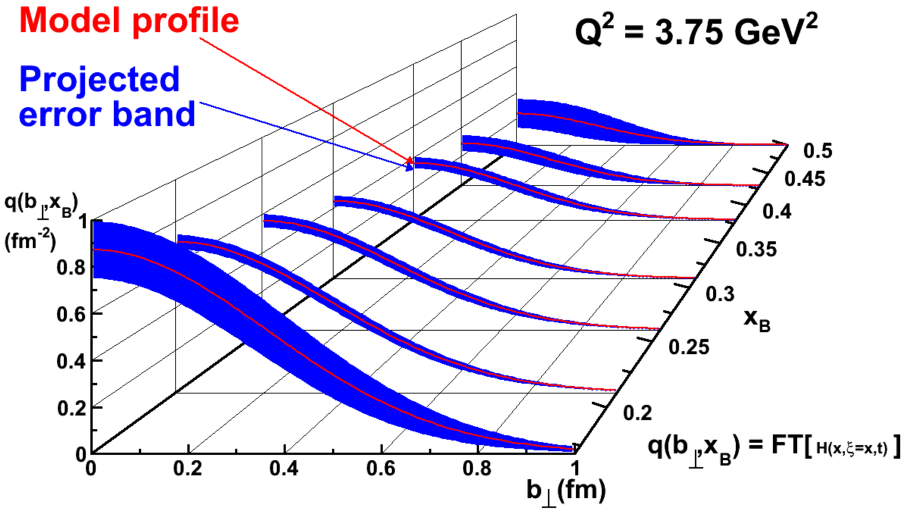
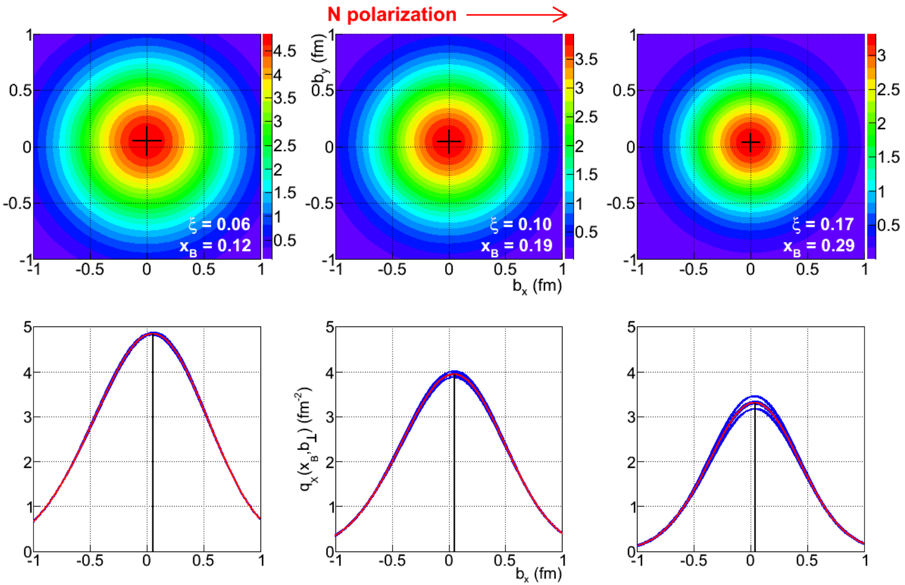


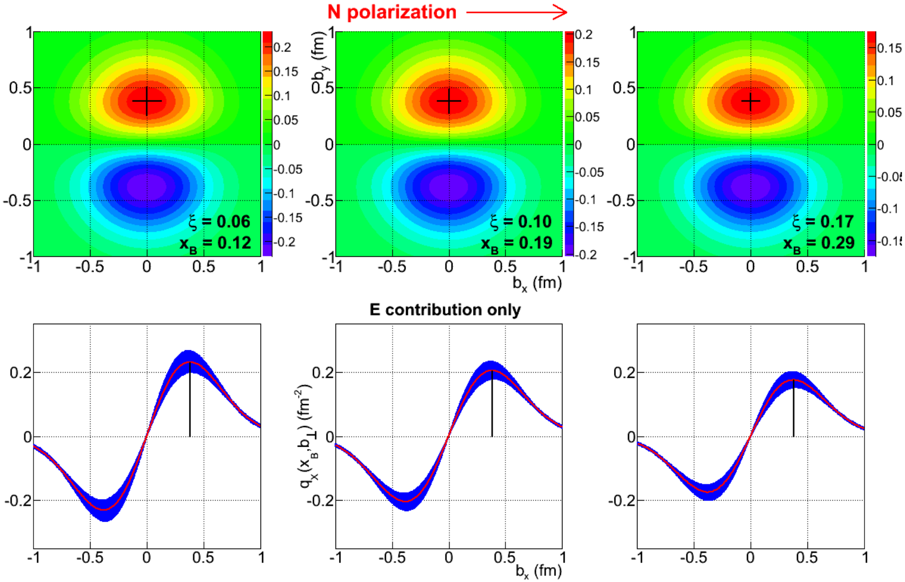
Projection for the Nucleon transverse profile



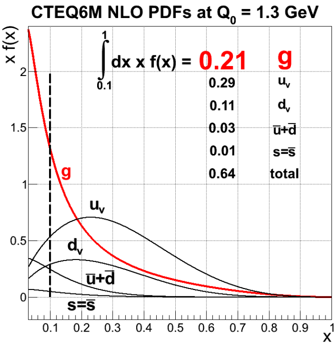
Precision tomography in the valence region

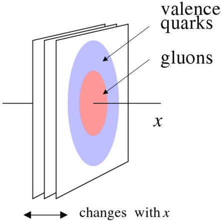


N polarization
ξ = 0.06
x_B = 0.12
ξ = 0.10
x_B = 0.19
ξ = 0.17
x_B = 0.29
b_y (fm)
b_x (fm)
$q_X(x_B, b_\perp)$ (fm^{-2})


N polarization
$\xi = 0.06$
$x_B = 0.12$
$\xi = 0.10$
$x_B = 0.19$
$\xi = 0.17$
$x_B = 0.29$
b_y (fm)
b_x (fm)
E contribution only
$q_X(x_B, b_\perp)$ (fm^{-2})
b_x (fm)

Gluons at large x





- Large glue density at $x > 0.1$

  PDF from global fits
  (F_2 evolution, $\nu_{\mathbf{DIS}}$, jets)

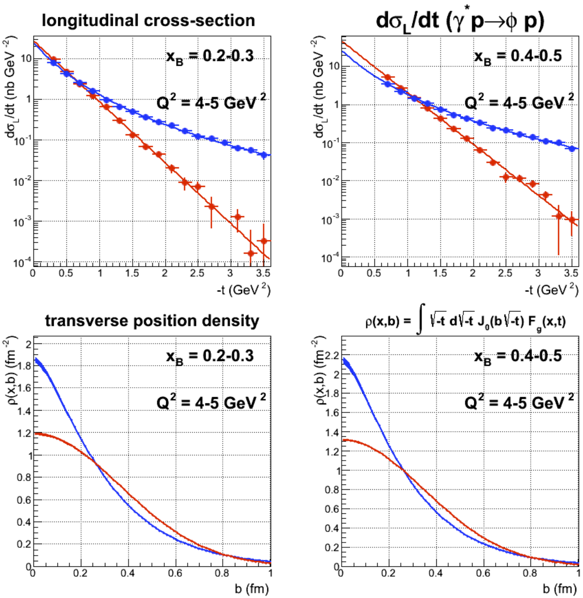
  Gluons carry more than 30% of the momentum for $0.1 < x$

- 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

Summary and outlook

- A unifying framework for nucleon tomography has been established
- 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
- A long range plan to extract GPDs and TMDs 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
- The EIC will expand the reach and probe the sea and gluons