JLab Results on Hadron Structure

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Outline

1. Theoretical context
2. Unpolarized hydrogen target
3. Longitudinally polarized target
4. Some projections for future measurements
5. Summary and outlook
Theoretical context
Unified view of hadron structure

Wigner Distributions

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

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

\[ \gamma^* p \rightarrow \gamma p', \rho p', \omega p', \phi p' \]

Bjorken regime:
\[ Q^2 \rightarrow \infty, x_B \text{ fixed} \]

\[ t \text{ fixed } \ll Q^2, \xi \rightarrow \frac{x_B}{2-x_B} \]

\[ \frac{P^+}{2\pi} \int d\gamma^- e^{ixP^+y^-} \langle p' | \bar{\psi} q(0) \gamma^+(1+\gamma^5)\psi(y) | p \rangle \]

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

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

<table>
<thead>
<tr>
<th>spin</th>
<th>N no flip</th>
<th>N flip</th>
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<tbody>
<tr>
<td>q no flip</td>
<td>( H )</td>
<td>( E )</td>
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<tr>
<td>q flip</td>
<td>( \tilde{H} )</td>
<td>( \tilde{E} )</td>
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GPDs and Transverse Imaging

\[(x_B, t)\) correlations

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

Target polarization

Lattice calculation

Flavor dipole

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Sep 16th 2015
GPDs and Energy Momentum Tensor

(x, ξ) correlations

Form Factors accessed via second x-moments:

\[ \langle p' | \hat{T}^{q}_{\mu\nu} | p \rangle = \bar{N}(p') \left[ M^q_2(t) \frac{P_\mu P_\nu}{M} + J^q(t) \frac{(P_\mu \sigma_{\nu\rho} + P_\nu \sigma_{\mu\rho}) \Delta^\rho}{2M} + d^q_1(t) \frac{\Delta^\mu \Delta^\nu - g_{\mu\nu} \Delta^2}{5M} \right] N(p) \]

Angular momentum distribution

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

Distribution of pressure

Mass and force/pressure distributions

\[ M^q_2(t) + \frac{4}{5} d^q_1(t) \xi^2 = \frac{1}{2} \int_{-1}^{1} dx x H^q(x, \xi, t) \]

\[ d^q_1(t) = 15M \int d^3r j_0(r \sqrt{-t}) \frac{p(r)}{2t} \]

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Sep 16th 2015 8/30
Deeply Virtual Compton Scattering
The cleanest GPD probe at low and medium energies

\[ \gamma^* \rightarrow \gamma e^- \]

GPDs

\[ \begin{align*}
\sigma (ep \rightarrow ep\gamma) & \propto \left[ \begin{array}{c}
(a) \\
(b) \\
(c)
\end{array} \right] 2 \\
\end{align*} \]

Diehl, Gousset, Pire, Ralston (1997)
Belitsky, Müller, Kirchner (2002, 2010)

\[ A_{LU} = \frac{d^4\sigma_{\gamma \rightarrow} - d^4\sigma_{\gamma \rightarrow}}{d^4\sigma_{\gamma \rightarrow} + d^4\sigma_{\gamma \rightarrow}} \approx \frac{\alpha \sin \phi}{1 + \beta \cos \phi} \]

\[ \alpha \propto \text{Im} \left( F_1 H + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 E \right) \]

\[ \mathcal{H}(\xi, t) = i\pi H(\xi, \xi, t) + \mathcal{P} \int_{-1}^{1} dx \frac{H(x, \xi, t)}{x - \xi} \]

\[ A_{UL} \propto \text{Im} \left( F_1 \tilde{H} + \xi G_M \mathcal{H} + G_M \frac{\xi}{1 + \xi} E + \cdots \right) \sin \phi \]
A global analysis is needed to fully disentangle GPDs
SIDIS and TMDs

The Nucleon is Moving Out of the Page

\[ f_1 = h_1 \]
\[ g_1 = g_{1T} \]
\[ h_1 = h_{1L} \]
\[ f_{1T} = h_{1T} \]

\( \begin{array}{|c|c|c|c|}
\hline
N & q & U & L & T & Higer Twist \\
\hline
U & f_1 & h_1 & f_1, g_1, h, e \\
L & g_1 & h_{1L} & f_1, g_{1L}, h_L, e_L \\
T & f_{1T} & g_{1T} & h_{1T}, h_1 & f_T, f_{1T}, g_T, g_{1T}, h^T, e_T, h_T, e_T \\
\hline
\end{array} \)

- Sivers
- Boer-Mulders
- Worm-Gear
- Kotzinian-Mulders
- Pretzelosity

\[ k_x (\text{GeV}) \]
\[ k_y (\text{GeV}) \]

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Unpolarized hydrogen target
Scaling tests of $\Delta\sigma_{DVCS}$

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

C. Muñoz et al., PRL 97 (2006) 262002
High precision in a narrow kinematical range
Separation of $I$ and DVCS\(^2\)

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

- Imaginary part scaling?
- High precision in a narrow kinematical range
$F_1 \mathcal{H} + \xi G_M \tilde{H} - \frac{t}{4M^2} F_2 \mathcal{E}$

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

\[ \frac{d^4\sigma_{ep\rightarrow ep\gamma}}{dQ^2 dx_B dt d\Phi} \text{ (nb/GeV}^4) \]

- BH
- VGG (H only)
- KM10
- KM10α

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

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Compton Form Factors

Hall-B

Im($\mathcal{H}_p$)

CFF fits (by M. Guidal) using:
the results of this work
Hall A $\sigma$ 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.
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 $\pi^0$ SIDISHall-B
Collins or Boer-Mulders?

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

$$F_{LU}^{\sin \phi_h} = \frac{2M}{Q} \int d^2p_T \, dk_T^2 \, \delta^{(2)}(p_T - \frac{P_T}{z} - k_T) \times \hat{P}_T \cdot \left\{ \left[ \frac{M_h h_1^\perp}{M} \, \tilde{E} \, \frac{1}{z} + x_B g_1^\perp D_1 \right] \frac{p_T}{M} - \left[ \frac{M_h f_1^\perp}{M} \, \tilde{G} \, \frac{1}{z} + x_B \epsilon H_1^\perp \right] \frac{k_T}{M_h} \right\}$$

$P_T$ detected hadron

$p_T$ active quark in Boer-Mulders DF $h_1^\perp$

$k_T$ 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 $\pi^0$. 
Without significant contribution from the Collins mechanism this would be evidence for spin-orbit correlations, or another dynamical origin.
Longitudinally polarized target
$A_{UL} \propto F_{1} \Im \tilde{H}$

$A_{LL} \propto F_{1} \Re \tilde{H}$
Model independent extraction
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 $h_{UL}^{1L}$ (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.
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

Model profile

Projected error band

Q^2 = 3.75 GeV^2

q(b^⊥x_B) = FT[H(x,ξ=x, t)]

Precision tomography in the valence region
N polarization

\[ \zeta = 0.06, \quad x_B = 0.12 \]

\[ \zeta = 0.10, \quad x_B = 0.19 \]

\[ \zeta = 0.17, \quad x_B = 0.29 \]
N polarization

$\xi = 0.06 \quad x_B = 0.12$

$\xi = 0.10 \quad x_B = 0.19$

$\xi = 0.17 \quad x_B = 0.29$

E contribution only
Gluons at large $x$

- Large glue density at $x > 0.1$
  
  PDF from global fits
  ($F_2$ evolution, $\nu_{\text{DIS}}$, 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 $\phi$
Extraction of gluonic profiles

Longitudinal cross-section

Corresponding sensitivity in transverse position space

\[ b = \frac{1}{\sqrt{-t}} \]

Error propagation study
Skewness \( \xi \neq 0 \) neglected
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.