The 3D structure of hadrons at Jefferson Lab

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Introduction

Outline

1. Experimental introduction to TMDs and GPDs (how they appear in exclusive and semi-inclusive experiments)

2. Jefferson Lab overview:
   - (Very!) short summary of 6 GeV achievements
   - Complementary of TMD/GPD programs in Hall A, B and C
   - Selected future measurements at 12 GeV

3. Summary and conclusion
Unified view of nucleon structure

Wigner distribution (1933): \[ W(p, r) = \int d^3 z e^{i p z} \psi^*(r + z/2) \psi(r - z/2) \]

- In quantum physics: \( \Delta p \Delta r \gtrsim \hbar/2 \) ("quasi-probability")
- In QCD: no known observable can access such a general function
From Wigner distribution to observables

Lorce, Pasquini, Vanderhaeghen, JHEP05 (2011)
Jefferson Lab: upgraded to 12 GeV

- 6-12 GeV longitudinally polarized (>85%) continuous electron beam
- High intensity (>100 μA): luminosities > $10^{38}$ s$^{-1}$ cm$^{-2}$
- 3 experimental Halls (A, B, C) w/ fixed target and dedicated detectors

Operations expected to start in Fall 2016, for 10–15 years...
Advantages & complementarities of Halls A/B/C for exclusive and semi-inclusive measurements

<table>
<thead>
<tr>
<th>Hall A</th>
<th>Hall B</th>
<th>Hall C</th>
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<tbody>
<tr>
<td>• Polarized neutron measurements ($\mathcal{L} &gt; 10^{37}$ Hz/cm$^2$)</td>
<td>• Very large acceptance ($\mathcal{L} \sim 10^{35}$ Hz/cm$^2$)</td>
<td>• L/T separations</td>
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<tr>
<td>• Large acceptance, open geometry spectrometers (SoLID)</td>
<td>• Many-dimensional phase space</td>
<td>• High luminosity ($\mathcal{L} &gt; 10^{38}$ Hz/cm$^2$)</td>
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<td>• Precision measurements with small acceptance spectrometers</td>
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Partial overlap
Excellent for cross-checks and understanding systematic effects
Semi-inclusive DIS cross section

\[ \ell(l) + p(P) \rightarrow \ell(l') + h(P_h) + X, \]

- Virtual photon:
  \[ q = l - l', \quad Q^2 = -q^2 \]
- Lepton fractional energy loss:
  \[ y = P \cdot q / P \cdot l \]
- Fraction of energy transfer carried by the struck quark:
  \[ z = P \cdot P_h / P \cdot q \]
Semi-inclusive DIS cross section

\[
\frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h \, F_{UU}^{\cos \phi_h} \\
+ \varepsilon \cos(2\phi_h) \, F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h \, F_{LU}^{\sin \phi_h} \\
+ S_\parallel \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h \, F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) \, F_{UL}^{\sin 2\phi_h} \right] \\
+ S_\parallel \lambda_e \left[ \sqrt{1-\varepsilon^2} \, F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h \, F_{LL}^{\cos \phi_h} \right] \\
+ |S_\perp| \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
+ \varepsilon \sin(\phi_h + \phi_S) \, F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) \, F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S \, F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) \, F_{UT}^{\sin(2\phi_h - \phi_S)} \right\},
\]

Bacchetta et al., JHEP 02, 093 (2007)
Accessing TMDs through experiment

For example, the unpolarized SIDIS cross section:

\[
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \varepsilon)} \left(1 + \frac{\gamma^2}{2x}\right) \times \\
\left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1 + \varepsilon)} \cos \phi_h \, F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) \, F_{UU}^{\cos 2\phi_h} \right\},
\]

\[
F_{UU,T} = x \sum_f e_f^2 \int d^2 p_T d^2 k_T \delta^{(2)}(zp_T + k_T - P_{h\perp}) f_1^f(x, p_T^2) D^f(z, k_T^2),
\]

\[
f_1^f(x, p_T^2) = \text{Unpolarized TMD}
\]
\[
D^f(z, k_T^2) = \text{Unpolarized fragmentation function}
\]
Twist-2 TMDs for spin 1/2 hadrons

The decomposition of this TMD correlator defines the different TMD functions. At twist-two level and for a spin-1/2 target, we have 8 TMDs defined as [6]:

\[
\Phi^{[\Gamma]}(\vec{k}_\perp, x, \vec{S}_\perp) = \frac{1}{2} \left\{ f_1(n) + \sum_{i,j} \varepsilon^{\perp}_{ij} T_{k_i \perp S_j \perp} + f_1(n) - \sum_{i,j} \varepsilon^{\perp}_{ij} T_{k_i \perp S_j \perp} + g_1(n) \gamma_5 + \sum_{i,j} \varepsilon^{\perp}_{ij} T_{k_i \perp S_j \perp} \right\}.
\]

(2.4)

The transverse momentum distribution functions depend on \(x\) and \(p_T^2\), the longitudinal and transverse momentum of the quarks, respectively. Each TMD represents a particular physical aspect of spin-orbit correlations at the parton level. Intuitively, TMDs describe the probability to find in a fast-moving nucleon a parton that has a specific momentum fraction of the nucleon’s longitudinal momentum and with a specific transverse momentum. They are a natural extension of the standard parton distribution functions (PDFs) from one to three dimensions in momentum space. Table 2.1 shows the different combinations of nucleon and parton polarization associated to each of the TMDs defined by (2.6).

<table>
<thead>
<tr>
<th>Nucleon polarization</th>
<th>Quark polarization</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>( f_1 )</td>
<td>Unpolarized</td>
<td></td>
<td>Boer-Mulder</td>
</tr>
<tr>
<td>L</td>
<td>( g_{1L} )</td>
<td>Helicity</td>
<td></td>
<td>Worm-gear</td>
</tr>
<tr>
<td>T</td>
<td>( f_{1T} )</td>
<td>Sivers</td>
<td></td>
<td>Transversity</td>
</tr>
<tr>
<td></td>
<td>( g_{1T} )</td>
<td></td>
<td></td>
<td>Pretzelosity</td>
</tr>
</tbody>
</table>

Table 2.1: Probabilistic interpretation of the twist-2 transverse-momentum-dependent distribution functions. The U, L, T correspond to unpolarized, longitudinally polarized and transversely polarized nucleons (rows), illustrated by the external arrows, and quarks (columns), shown by the internal arrows. The common names used to refer to each of these functions in the recent literature are also indicated.
Deeply Virtual Compton Scattering (DVCS): $\gamma^* p \rightarrow \gamma p$

Handbag diagram

**Bjorken limit:**

$$Q^2 = -q^2 \rightarrow \infty$$
$$\nu \rightarrow \infty$$

$$x_B = \frac{Q^2}{2M\nu} \text{ fixed}$$
Generalized Parton Distributions

- Correlate between different partonic states
- Correlate momentum and position of partons
- Access to new fundamental properties of the nucleon

Contribution of the \textit{angular momentum of quarks} to proton spin:

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g \quad \Rightarrow \quad J_q = \frac{1}{2} \int_{-1}^{1} dx \, x [H_q(x, \xi, 0) + E_q(x, \xi, 0)] \]

\textbf{DVCS cleanest process to access GPDs}
GPD experimentally: Compton Form Factors (CFFs)

Cross-section ($\sigma$) measurement and beam charge difference (Re$T$) integrate GPDs with $1/(x\pm\xi)$ weight

Beam or target spin $\Delta\sigma$ contain only Im$T$, therefore GPDs at $x = \xi$ and $-\xi$

Lattice Moments

$$= \int x^n H(x, \xi, t)dx$$
DVCS experimentally: interference with Bethe-Heitler (BH)

At leading twist:

\[
d^5 \sigma \rightarrow d^5 \sigma = \Im (T^{BH} \cdot T^{DVCS})
\]

\[
d^5 \sigma \leftarrow d^5 \sigma = |BH|^2 + \Re (T^{BH} \cdot T^{DVCS}) + |DVCS|^2
\]

\[
\mathcal{T}_{DVCS} = \int_{-1}^{+1} dx \frac{H(x, \xi, t)}{x - \xi + i\epsilon} + \cdots
\]

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

Access in helicity-independent cross section

\[
i\pi H(x = \xi, \xi, t) + \cdots
\]

Access in helicity-dependent cross-section
Accessing different GDPs

Polarized beam, unpolarized target (BSA)
\[d\sigma_{LU} = \sin \phi \cdot \Im \{F_1 \mathcal{H} + x_B (F_1 + F_2) \tilde{\mathcal{H}} - kF_2 \mathcal{E}\} d\phi\]

Unpolarized beam, longitudinal target (ITSA)
\[d\sigma_{UL} = \sin \phi \cdot \Im \{F_1 \tilde{\mathcal{H}} + x_B (F_1 + F_2) (\tilde{\mathcal{H}} + x_B/2 \mathcal{E}) - x_B kF_2 \tilde{\mathcal{E}} \ldots \} d\phi\]

Polarized beam, longitudinal target (BITSA)
\[d\sigma_{LL} = (A + B \cos \phi) \cdot \Re \{F_1 \tilde{\mathcal{H}} + x_B (F_1 + F_2) (\tilde{\mathcal{H}} + x_B/2 \mathcal{E}) \ldots \} d\phi\]

Unpolarized beam, transverse target (tTSA)
\[d\sigma_{UT} = \cos \phi \cdot \Im \{k(F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots \} d\phi\]
Kinematic coverage

Kinematic complementarity between different facilities:
Summary of JLab results at 6 GeV

- Different measurements of SIDIS asymmetries in polarized $p$ and $n$
- Initial tests of SIDIS reaction mechanism, compatible with LO approaches
- First indications of validity of GPD formalism at moderate $Q^2$
- DVCS primarily studied in detail (DVMP need higher $Q^2$)
- DVCS deviates significantly from Bethe-Heitler
  ($\rightarrow$ cross section measurements needed, not only asymmetries)
- Higher twist corrections likely necessary to fully describe the data
- Extremely accurate data to constrain models and global fits
Overview and selected highlights of SIDIS with JLab12

The JLab12 TMD/GPD program:

- High luminosity
- Large acceptance
- High-performance polarized targets
- Proton/Neutron for flavor separation
- Valence quark region
- Different Halls complementarity
Hall A: neutron transversity with BigBite + Super Bigbite

JLab E12-09-018 in Hall A: Approved for 64 beam-days, A rating by PAC38 (2011)

Electron Arm: BigBite Spectrometer @30 deg.

High-luminosity Polarized $^3$He Target
$(1.2 \times 10^{37} \text{ cm}^{-2} \text{ s}^{-1})$

Hadron Arm: Super BigBite Spectrometer @14 deg.
Polarized $^3He$ target

- $n$ lum. of $10^{36}/\text{cm}^2/\text{s}$ (14 atm $\times$ 40 cm)

- “Background” luminosity:
  - $p$ in $^3He$ + entrance/exit windows
  - $10^{37}/\text{cm}^2$ total luminosity

- Polarization: 50%
  - Nuclear physics dilution factor 0.86 (d-state)
  - -2.8% $p$ polarization
  - Long. & Trans.
$^3$He target upgrade

- Separate polarization and tgt volumes
  - Increase throughput by factor 10–100
  - Cool and/or compress $^3$He in target area by a factor of 10
    \[(10\text{K at } 10 \text{ atm} \times 20 \text{ cm})\]
  - Rapid cycling of $^3$He through target
    - Reduce depolarization effect of tgt density, beam current, tgt walls
    - Replace thick glass with thin metallic walls

- Neutron luminosity of $10^{37}$/cm$^2$/s
  - Proton luminosity $2 \cdot 10^{37}$/cm$^2$/s
  - Endcaps $\leq 10^{37}$/cm$^2$/s

- Target polarization: $0.5 \cdot (0.86n - 0.028p)$
E12-09-018: statistical FOM for the neutron $\sim 100$ better than HERMES proton data and $\sim 1000$ better than E06-010 neutron data

$K$ and $\pi^0$ data will help flavor separation and understanding the reaction mechanism
E12-06-114: JLab Hall A at 11 GeV

JLab12 with 3, 4, 5 pass beam

(6.6, 8.8, 11.0 GeV beam energy)

DVCS measurements in Hall A/JLab

- $Q^2$ (GeV$^2$)
- $x_B$ (GeV$^2$)

88 days
250k events/setting

1 year of operations in JLab/Hall A

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High precision \(Q^2\) dependence of GPD-related terms

- Very high precision \(Q^2\) dependence of each azimuthal term
- Check of applicability of QCD factorization at accessible values of \(Q^2\)
- High twist contributions will be quantified
CLAS12

- Non-based equipment for better tracking and PID:
  - RICH
  - MicroMegas tracker
  - Central Neutron Detector
  - Forward Tagger

- Large acceptance ($\sim 2\pi$), general purpose detector, $\mathcal{L} \sim 10^{35}$ Hz/cm$^2$
- Multi-dimensional survey of exclusive and semi-inclusive reactions

$Q^2$ and $x_B$ kinematic coverage of CLAS12
Run group A (139 days): unpolarized LH$_2$ target
- SIDIS unpolarized cross sections and $A_{LU}$
- DVCS and DVMP cross sections and BSA on the proton

Run group B (90 days): unpolarized LD$_2$ target
- SIDIS unpolarized cross sections and $A_{LU}$
- DVCS and DVMP BSA on the neutron

Run group C (170 days): longitudinally polarized proton (NH$_3$) and deuteron (ND$_3$) targets
- $A_{LL}$ and $A_{UL}$ for SIDIS
- $A_{LL}$ and $A_{UL}$ for DVCS and DVMP
CLAS12 multi-dimensional precision in SIDIS

4D analysis for $\pi^+$

4D analysis for $K^+$
E12-06-119: DVCS on the proton with CLAS12

High statistical precision in multi-dimensional BSAs
E12-06-119: DVCS on the proton with CLAS12

High statistical precision in multi-dimensional BSAs

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Hall C: high precision L/T separations

- High Momentum Spectrometer ($p < 7.3 GeV$): scattered electron
- PbWO$_4$ calorimeter: $\gamma/\pi^0$ detection
- Sweeping magnet

**DVCS experiment E12-13-010:**

$$\mathcal{I} \propto \frac{1}{y^3} = \left(\frac{k}{\nu}\right)^3$$

$$|\mathcal{T}^{DVCS}|^2 \propto \frac{1}{y^2} = \left(\frac{k}{\nu}\right)^2$$

$$\sigma(ep \to ep\gamma) = \underbrace{|BH|^2}_{\text{Known to } \sim 1\%} + \underbrace{\mathcal{I}(BH \cdot DVCS)}_{\text{Linear combination of GPDs}} + \underbrace{|DVCS|^2}_{\text{Bilinear combination of GPDs}}$$
E12-12-010: DVCS beam energy separation in Hall C

Recently approved by JLab PAC: to be run in ∼2019–2020
SoLID: Solenoidal Large Intensity Device

“Ultimate” precision 4D mapping of SIDIS pol. target $A_{UT}, A_{LT}, A_{UL}, A_{LL}$

Would combine large acceptance from Hall B with high luminosity of Hall A
SOLID $A_{UT}$ projections on the neutron (from $^3$He)
Summary

- JLab at 6 GeV has already made significant contributions to the TMD and GPD programs.
- The upcoming 12 GeV upgrade will enable a comprehensive multi-dimensional mapping of TMDs and GPDs in the valence region.
- Multi-hall attack will provide statistical precision and systematic control.
- JLab 12 GeV commissioning underway, first physics beam expected as soon as Fall 2016.