Recent highlights in Spin and 3D Nucleon Structure

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DIS2022
XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects
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Outline

Spin and 3D Nucleon Structure

Helicity structure:
- Polarized structure functions
- Structure function at large-x
- News from RHIC

3D Imaging of the nucleon:
- Generalized Parton Distributions
  - DVCS, TCS, HEMP
- Transverse Momentum Dependent Functions
  - Sivers and Collins asymmetries
  - Spin transfer of Lambda hyperons
  - Unpolarized TMDs
  - Twist-3 trigluon correlations

Future prospect and Summary

Disclaimer: The selection is not complete and based on personal biases. Apologies for missing out many important results. For details, please refer to the parallel session talks!
Spin and 3D Nucleon Structure

• What’s the origin of the proton spin? How the constituents of the proton contribute and make up for the proton spin?

• 3D structure of the nucleon How are quarks and gluons distributed in the polarized proton?

• Spin as a tool for fundamental tests of QCD Interplay between intrinsic properties and interactions of quarks and gluons
Origin of the Proton Spin

- Proton spin can be studied via spin decomposition

\[
\frac{\hbar}{2} = \frac{1}{2} \Delta \Sigma + L^\text{kin}_q + J_g
\]

- Sum Rules

  Ji sum rule
  \[
  \frac{\hbar}{2} = \frac{1}{2} \Delta \Sigma + L^\text{kin}_q + J_g
  \]

  Jaffe-Manohar sum rule
  \[
  \frac{\hbar}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L^\text{can}_q + L^\text{can}_g
  \]

  Frame-independent.
  Jq and Jg can be obtained from the moments of GPDs.

  All terms have partonic interpretations;
  Lq and Lg are twist-3 quantities, and can be extracted from twist-3 GPDs.

- Lattice QCD calculation of Jq and Jg

1+2D Structure of the Nucleon

2+3D

Wigner Distributions

Transverse Momentum Dependent Distributions (TMDs)

Generalized Parton Distributions (GPDs)

Parton Distribution Functions $f(x)$

Form Factors

$W(x, k_\perp, r_\perp)$

1+2D

$1D$

$dx$

$d^2k_\perp$

$d^2r_\perp$


Helicity PDFs
Decades of nucleon structure...

Decades of experimental and theoretical efforts

Complementary datasets

QCD factorization and Universality test

- Inclusive spin-dependent DIS: CERN, SLAC, DESY, Jlab
  \( \Delta q + \Delta \bar{q}, \Delta g \)

- Semi-inclusive DIS: SMC, COMPASS, HERMES, Jlab
  \( \Delta q + \Delta \bar{q}, \Delta g \)

- Polarized pp: RHIC: PHENIX & STAR, FNAL (pol Drell-Yan)
  \( \Delta q + \Delta \bar{q}, \Delta g \) (RHIC)
Deep Inelastic Scattering

- DIS experiments have been successful mapping out the momentum distributions of quarks and gluons.

- Polarized Structure Functions: $g_1(x, Q^2), g_2(x, Q^2)$

  In Quark parton model, $g_1(x, Q^2) \sim \sum_q e_q^2 \Delta q(x, Q^2)$

- Limited $(x, Q^2)$ level arm compared to the unpolarized case
  - EIC will improve it significantly

Polarized structure function $g_1(x, Q^2)$:
- Lepton, proton have same polarization direction
- Opposite polarization directions

Quark spin distribution

In the Quark parton model, quark spin distribution

- Limited $(x, Q^2)$ level arm compared to the unpolarized case
  - EIC will improve it significantly
Deep Inelastic Scattering

- DIS experiments have been successful mapping out the momentum distributions of quarks and gluons

- Polarized Structure Functions: $g_1(x, Q^2)$

  In Quark parton model, \( g_1(x, Q^2) \)

- Limited (\( x, Q^2 \)) level arm comparec
  - EIC will improve it significantly

  ![Graph showing polarized structure function $g_1(x, Q^2)$](image)

  \( g_1(x, Q^2) + \text{const}(x) \)

  - \( x = 5.2 \times 10^{-6} (+52) \)
  - \( EIC \times 100 \)
  - \( EIC \times 250 \)
  - \( EIC \times 200 \times 250 \)

  covered by present data

  - Talk by Barak Schmookler, WG6 Wednesday
  - Talk by Tyler Kutz, WG1+WG6 Thursday


Structure functions at large-x

- **JLab HallC A1n, d2n and g2n**
  - polarized 3He target
  - Took data in 2020

<table>
<thead>
<tr>
<th>Model</th>
<th>$F_n/F_p$</th>
<th>$d/u$</th>
<th>$\Delta u/u$</th>
<th>$\Delta d/d$</th>
<th>$A_1^n$</th>
<th>$A_1^p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SU(6) = SU3 flavor + SU2 spin</td>
<td>2/3</td>
<td>1/2</td>
<td>2/3</td>
<td>-1/3</td>
<td>0</td>
<td>5/9</td>
</tr>
<tr>
<td>Valence Quark + Hyperfine</td>
<td>1/4</td>
<td>0</td>
<td>1</td>
<td>-1/3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>pQCD + HHC</td>
<td>3/7</td>
<td>1/5</td>
<td>1</td>
<td>-0.33</td>
<td>0.17</td>
<td>0.59</td>
</tr>
<tr>
<td>DSE-1 (realistic)</td>
<td>0.49</td>
<td>0.28</td>
<td>0.65</td>
<td>-0.26</td>
<td>0.34</td>
<td>0.88</td>
</tr>
<tr>
<td>DSE-2 (contact)</td>
<td>0.41</td>
<td>0.18</td>
<td>0.88</td>
<td>-0.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Twist-3 matrix element, related to color polarizabilities. Calculable in lattice QCD

- **g2 structure function and moments**
  - No simple interpretation
  - Provides information on the quark-gluon correlations through higher twist effects
    \[
g_2(x, Q^2) = g_{2}^{WW}(x, Q^2) + \tilde{g}_2(x, Q^2)
\]

  - $x^2$ weighted moment, d2:
    \[
d_2(Q^2) = \int_0^1 x^2[g_2(x, Q^2) - g_{2}^{WW}(x, Q^2)]dx
\]

- **GDH sum rule and higher moments**: benchmark for theory, lattice calculation and chiral perturbative theory at low $Q^2$
  

Also expect new results on A1p from CLAS12

Talk by Mingyu Chen, WG5 Tuesday

Spin and 3D Nucleon Structure, S. Park
Gluon helicity distribution

- Accessed indirectly in pDIS
- Polarized p+p at RHIC

Positive gluon contribution to the proton spin $x > 0.05$

- New high precision jet data from STAR
  Further constraint gluon helicity
  Access parton kinematics via di-jet measurements

- First published direct photon $A_{LL}$

Talk by Scott Wissink, WG5 Tuesday
Talk by Y. Zhou, WG5 Tuesday
JAM helicity PDF analysis update

Spin and 3D Nucleon Structure, S. Park
Light sea quarks $\Delta\bar{u}, \Delta\bar{d}$

- **W single spin asymmetry**

  - $p + p \rightarrow W^- + X \rightarrow e^- + X$
    - $s = 510$ GeV
    - $25 < E_T < 50$ GeV

  - Polarized light sea quark asymmetry

  - Constraints to light sea quark helicity PDFs at intermediate $x$ region
    - [STAR, Phys. Rev. D 99, 051102(R) (2019)]

- Delta $u$ is now known to be positive
- Delta $d$ is now known to be negative
- The flavor asymmetry $\Delta # - \Delta \bar{#}$ is of similar size but opposite sign to the unpolarized flavor asymmetry $# - \bar{#}$

Impact of STAR 2013 results
- Constraints to light sea quark helicity PDFs at intermediate $x$ region
Light sea quarks $\Delta \bar{u}, \Delta \bar{d}$

- W single spin asymmetry

\[ \vec{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X \]
\[ E_T^X > 50 \text{ GeV} \]

Polarized light sea quark asymmetry

[JAM, arXiv:2202.03372]
Light sea quarks $\Delta \bar{u}, \Delta \bar{d}$

- **W single spin asymmetry**

  \[
  \vec{p} + p \rightarrow W^\pm + X \rightarrow e^\pm + X
  \]

  $s = 510$ GeV  \quad 25 < E_T < 50 GeV

  ![Graph showing $A_L$ vs. $\eta_\phi$](image)

- **Unpolarized antiquark sea asymmetry**

  ![Graph showing $x(\Delta \bar{u} - \Delta \bar{d})$ vs. $x$](image)

  - Included in the Global QCD analyses

    [STAR, Phys. Rev. D 103, 012001 (2020)]
    [SeaQuest, Nature 590, 561-565 (2021)]

  ![Graph showing $x(\bar{d} - \bar{u})$ vs. $x$](image)

  - Talk by Jae Nam, WG1 Wednesday
  - Talk by Chris Cocuzza, WG1 Wednesday
3D Nucleon Structure
Generalized Parton Distributions

- Nucleon Tomography

\[ J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx \, x \left[ H^q(x, \xi, t) + E^q(x, \xi, t) \right] \]
\[ J_q = \frac{1}{2} \Delta \Sigma + L_q \]

[X. Ji PRL 78, 610 (1997)]

- Quark OAM contribution to the proton spin

- Accessed via exclusive processes; cross section and asymmetries

Talk by S. Nabeebaccus, WG2 Wednesday

Leading-twist GPDs:
- 4 chiral-even GPDs \( H, \tilde{H}, E, \tilde{E} \)
  - DVCS, DVMP, Pseudoscalar mesons
- 4 chiral-odd GPDs \( H_T, \tilde{H}_T, E_T, \tilde{E}_T \)
  - \( \rho \) production, ..
Deeply Virtual Compton scattering

- Sensitive to H and E
- GPDs appear in the DVCS amplitude through CFFs

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

\[ \sigma(ep \to ep\gamma) = |DVCS|^2 + |BH|^2 + \text{Interference} \]

**COMPASS**

Talk by J. V. Giarra, WG5 Tuesday

[COMPASS, PLB 793 (2019) 188]

- t-slope of DVCS cross section related to distance between struck quark and spectator c.m. \( \langle r_{\text{perp}}^2 \rangle \)
DVCS at high-\(x\)

- **JLab HallA** arXiv:2201.03714 [hep-ph]
  - First experimental extraction of all four helicity-conserving CFFs

- **DVCS off neutron**
  - Flavor separation of CFFs (combined with proton data)
  - Sensitive to GPD \(E\)


  6 GeV data from HallA, NLO and HT analyses

- **New CLAS12 DVCS results with high statistics**

  Talk by M. Defurne, WG5 Wednesday

- **DVCS with positron beam at JLab**

  Talk by S. Niccolai Tuesday, WG6
Timelike Compton Scattering

- Time-reversal conjugate process of DVCS
- Both \( \text{Im}(H) \) and \( \text{Re}(H) \) can be accessed
- Comparison with DVCS: Universality test of GPDs
- Real part of the CFF and nucleon D-term:
  - pressure distribution in the nucleon  
    [Burkert et al., Nature 557, 396-399 (2018)]

- First measurement by CLAS12  
  [CLAS, Phys. Rev. Lett. 127, 262501 (2021)]

- TCS at EIC  
  Talk by Daria Sokhan, WG5 Wednesday
Hard Exclusive Meson Production

- **COMPASS** exclusive $\pi^0$ cross section
  - Input to Chiral-odd GPDs
    \[
    \frac{d^2\sigma_{\pi^0\pi^+}}{dtd\phi} = \frac{1}{2\pi} \left[ \frac{d\sigma_T}{dt} + \epsilon \frac{d\sigma_L}{dt} + \epsilon \cos(2\phi) \frac{d\sigma_{T\perp}}{dt} + \sqrt{2\epsilon (1+\epsilon) \cos\phi} \frac{d\sigma_{LT}}{dt} \mp \sqrt{2\epsilon (1-\epsilon) \sin\phi} \frac{d\sigma'_{LT}}{dt} \right]
    \]
    [COMPASS, PLB 805 (2020) 135454]

- Large negative contribution by $\sigma_{TT}$
  \[
  \langle \frac{d\sigma_{TT}}{dt} \rangle = (6.1 \pm 1.3_{\text{stat}}^{+0.7}_{-0.7})_{\text{sys}} \frac{\text{nb}}{(\text{GeV/c})^2}
  \]

- Significant role of transversely polarized photons in the process
- Evidence for the existence of chiral-odd GPD $\vec{E}_T$

- **CLAS12**
  - $\pi^0, \pi^+$ beam-spin asymmetry measurements
    [CLAS, Phys. Rev. Lett. 125, 182001 (2020)]
    - New result of $\pi^-$ beam-spin asymmetry
      Talk by S. Diehl, WG5 Wednesday

- **Spin Density Matrix Elements for exclusive $\omega$ meson production from COMPASS**
Transverse Momentum Dependent Functions

**Leading twist TMDs**

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Unpolarized (U)</th>
<th>Longitudinally Polarized (L)</th>
<th>Transversely Polarized (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>( f_U )</td>
<td>( g_L )</td>
<td>( h_{1L} )</td>
</tr>
<tr>
<td>L</td>
<td>( g_U )</td>
<td>( f_L )</td>
<td>( h_{1T} )</td>
</tr>
<tr>
<td>T</td>
<td>( f_{1T} )</td>
<td>( g_{1T} )</td>
<td>( h_{1L}^{\perp}, h_{1T}^{\perp} )</td>
</tr>
</tbody>
</table>

- Sensitive to confined motion of quarks and gluons inside the nucleon
- Connection to OAM: Off-diagonal part vanishes without parton’s transverse motion
  - Pretzelosity: Link to quark OAM (model-dependent)
- Accessed via various processes (SIDIS, DY, e+e-, p+p)
  - TMD factorization and universality test

**SIDIS**
- HERMES, COMPASS, JLab

**Drell-Yan and W, Z**
- COMPASS, STAR, SpinQuest

**e+e- annihilation**
- Belle, BaBar, BESIII

**pp collisions**
- STAR, PHENIX, BRAHMS

**and FFs:** \( D_1, G_1, H_1^{\perp} \)

Spin and 3D Nucleon Structure, S. Park
TMDs in SIDIS

- Semi-Inclusive process is ideal to study TMDs
  Naturally have two scales: $Q^2 \gg p_T^2, \Lambda_{QCD}^2$
- Access all 8 leading twist TMDs via spin (in)dependent azimuthal modulations

- HERMES “TMDs bible”
  [HERMES, J. High Energ. Phys. 2020, 10 (2020)]

  - TMD results with transversely polarized H target
  - Several new updates to the previous published results including 3D binning ($x, z, p_T$) analysis and proton asymmetries
  - Included in the new JAM fits

- COMPASS SIDIS
  - pT weighted Sivers asymmetries
  - First $\rho^0$ meson measurement
  - New data taking in 2022 with polarized proton and neutron targets
d-quark transversity and other TMDs

Talk by A. Bressan, WG5 Tuesday

Talk by B. Parsamyan, WG5 Tuesday
Sivers Sign Change

\[ f_{q/h^{\uparrow}}^{\text{SIDIS}}(x, k_T, Q^2) = -f_{q/h^{\uparrow}}^{\text{DY/W^+/Z}}(x, k_T, Q^2) \]

[Collins, PLB 536 (02)]

- Nonuniversality of Sivers function and sign change: fundamental prediction from the gauge invariance of QCD, direct verification of QCD factorization

- Measures SIDIS and DY with the same detector
- COMPASS DY results favor the sign change hypothesis

New results 2015+2018 data

Fully reconstructed W kinematics via its recoil compared to curves with sign-change scenario
Expect new results with higher precision to be published

Talk by B. Parsamyan, WG5 Wednesday
Transversity

- One of three standard PDFs, however least known
- Can be observed in combination with additional spin dependent final state effects (e.g. Collins FF or interference FF)

- Tensor charge
  - lowest moment of transversity
  - Fundamental quantity of nucleon. Can be compared with Lattice QCD calculation.

\[ \delta_{Tq} = \int_0^1 \left[ h_1^q(x) - h_1^q(x) \right] dx \]
Collins asymmetries

- **COMPASS**: SIDIS $\rho^0$
  - First SIDIS $\rho^0$ meson measurement
    Talk by A. Bressan, WG5 Tuesday

- **STAR**: Identified hardons within jets
  Talk by T. Lin, WG5 Thursday

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**Transversity via dihadron IFF:**
Talk by N. Ghimire, WG5 Tuesday
Transverse spin transfer $\Lambda$, $\bar{\Lambda}$

- **Longitudinal and transverse spin transfer of $\Lambda$, $\bar{\Lambda}$ hyperons**
  
  Shed light on the helicity and transversity distributions of the strange in the proton

- **Longitudinal spin transfer of $\Lambda$ and $\bar{\Lambda}$**
  
  Sensitive to strange helicity PDF

- **Transverse spin transfer of $\Lambda$ and $\bar{\Lambda}$**

  - **STAR (p+p)**
    
    Talk by T. Gao, WG5 Thursday

  - **e+e- Belle**
    
    Large transverse $\Lambda$ polarization observed
    Nonzero contribution from Polarizing Fragmentation Function

  - **COMPASS (SIDIS)**

    [Physics Letters B 824 (2022) 136834]

  - **Lambda polarization and spin transfer at EIC**
    
    Recent studies via SIDIS as well as back-to-back lepton-jet production and impact on the TMD PFF and transversely TMD FF.


Talk by Y. Yu, WG5 Thursday

Talk by Y. Song, WG5 Thursday,
Systematic study of Lambda polarization in SIDIS and e+e-
**Unpolarized TMDs: Boer-Mulder PDF**

- Unpolarized DY angular distribution
- Pion-induced DY from COMPASS

\[
\frac{d\sigma}{d\Omega} \propto \frac{3}{4\pi} \frac{1}{\lambda + 3} \left[ 1 + \lambda \cos^2\theta_{CS} + \mu \sin 2\theta_{CS} \cos \phi_{CS} + \frac{\nu}{2} \sin^2\theta_{CS} \cos 2\phi_{CS} \right]
\]

- Tend to deviate from pQCD calculation, indicating nonzero BM effect

**SIDIS measurements from COMPASS**
- Transverse momentum distributions and azimuthal symmetries
- Clear signal and kinematic dependence

\[
A_{UU}^{\cos 2\phi_h} = \frac{F_{UU}^{\cos 2\phi_h}}{F_{UU,T} + \epsilon F_{UU,L}}
\]

• First photon-induced DY results at SeaQuest

Talk by J. Matousek, WG5 Wednesday

Spin and 3D Nucleon Structure, S. Park

Talk by K. Nagai, WG5 Wednesday
TSSA and Twist-3 multiparton correlators

- Twist-3 trigluon correlation functions in collinear framework
  - Connected to TMDs

Talk by X. Liang, WG5 Thursday

**[STAR, PRD 103 (2021) 92009]**

Talk by Dillon Fitzgerald, WG5 Wednesday

**[PHENIX, Phys. Rev. Lett. 127, 162001 (2021)]**

**[PHENIX, arXiv:2204.12899]**


[Ji, Qui, Vogelsan, Yuan Phys. Rev. Lett. 97, 082002 (2006)]
Summary

• The study of nucleon spin has revealed the complicated and rich nature of the QCD

• New experimental data and theoretical developments are leading us into the precision era of 3D nucleon structure

• Future programs: Toward the understanding 3D structure of the nucleon