New Results on Nucleon Spin and 3D Structure Measurements

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Haiyan Gao
Duke University and Duke Kunshan University
QCD: still unsolved in non-perturbative region

- 2004 Nobel prize for ``asymptotic freedom''
- non-perturbative regime QCD ??????
- One of the top 10 challenges for physics!
- QCD: Important for discovering new physics beyond SM
- Nucleon structure is one of the most active areas: spin puzzle, ...

Gauge bosons: gluons (8)
Spin structure of the nucleon

1980s: “Proton spin crisis” (original EMC result from CERN)

Where does the proton’s spin come from?

- $p$ is made of 2 $u$ and 1 $d$ quark (Constituent Quark Model)
- $S = \frac{1}{2} = \sum S_q$
- Explains magnetic moment of baryon octet

QCD dynamics: Sea quarks and gluons

$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g$

Check via electron scattering and find quarks carry only $\sim 1/3$ of the proton’s spin!

Jets, pions, $A_{LL}$
Impressive experimental progress in QCD spin physics in the last 30 years

- **Inclusive spin-dependent DIS**
  - CERN: EMC, SMC, COMPASS
  - SLAC: E80, E142, E143, E154, E155
  - DESY: HERMES
  - JLab: Hall A, B and C

- **Semi-inclusive DIS**
  - SMC, COMPASS
  - HERMES, JLab

- **Polarized pp collisions**
  - BNL: PHENIX & STAR
  - FNAL: POL. DY

- **Polarized e+e- collisions**
  - KEK: Belle
Global Analysis: Polarized PDF

Global analysis of spin-dependent parton distribution functions


\[ \Delta \Sigma = 0.36(9) \]
\[ \Delta s^+ = -0.03(10) \]

\( (\mu^2 = 1 \text{ GeV}^2) \)
Measurement of the gluon polarization $\Delta g$ at RHIC

D. de Florian et al, PRL 113 (2014) 012001

E. Nocera et al, NPB 887 (2014) 276

Surrow et al on sea quark spin from $W$ production at RHIC

$$\int \! dx \Delta g(x, Q^2 = 10 \text{GeV}^2) = 0.20^{+0.06}_{-0.07} \quad \text{DSSV++}$$

$$\int \! dx \Delta g(x, Q^2 = 10 \text{GeV}^2) = 0.17^{+0.06}_{-0.06} \quad \text{NNPDFpol1.1}$$

$$\int \! dx \Delta g(x, Q^2 = 1 \text{GeV}^2) = 0.5^{+0.1}_{-0.4} \quad \text{JAM15}$$
Longitudinal DSA for Dijet in pp Collisions

First measurement of $A_{LL}$ for midrapidity dijet in polarized pp collisions

Support analyses that find $\Delta g \sim 0.2$ for the region of $x>0.05$

Gluon Spin From Lattice QCD

First lattice QCD calculation of the gluon spin in the nucleon

\[ \Delta G \approx S_g (|p| \to \infty) : \quad 0.251(47)(16) \quad \text{for} \quad (\mu^2 = 10 \text{ GeV}^2) \]

50(9)(3)% of the total proton spin

Proton Spin Structure Function at Small-x

Spin effects are found at such small-x (down to $4 \times 10^{-5}$) for the first time

M. Aghasyan et al. (COMPASS Collaboration), arXiv:1710.01014 [hep-ex].
Deuteron Spin Structure Function

Final COMPASS results:

Longitudinal spin asymmetry

Spin-dependent structure function

Flavor singlet axial charge (COMPASS deuteron data alone)

\[ a_0(Q^2 = 3 \, (GeV/c)^2) = 0.32 \pm 0.02_{\text{stat}} \pm 0.04_{\text{syst}} \pm 0.05_{\text{evol}} \] (NLO)

**GDH Sum Rule**

- **GDH sum rule**

\[
I_N^{GDH} = \int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu} \left( \sigma_{\frac{3}{2}}(\nu) - \sigma_{\frac{1}{2}}(\nu) \right) = 2\pi^2 \alpha \frac{\kappa^2}{M^2}
\]

\[
I^{GDH} = \int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu} (\sigma_P(\nu) - \sigma_A(\nu)) = 4\pi^2 \alpha \frac{\kappa^2}{M^2} S
\]

- **Generalized GDH sum rule**

\[
I_{TT}(Q^2) = \frac{M^2}{4\pi^2 \alpha} \int_{\nu_{th}}^{\infty} \frac{K(\nu, Q^2) \sigma_{TT}(\nu, Q^2)}{\nu^2} d\nu
\]

\[
= \frac{2M^2}{Q^2} \int_{0}^{x_{th}} \left[ g_1(x, Q^2) - \frac{4M^2}{Q^2} x^2 g_2(x, Q^2) \right] dx
\]
Generalized GDH Sum Rule for Nucleons

Proton:


Neutron:

Provided by V. Sulkosky (Preliminary result of E97110)
Deuteron Spin Structure Function at Low-$Q^2$

Deuteron generalized GDH sum, the moment $\Gamma_1$, and the spin polarizability $\gamma_0$ are determined down to $Q^2 \sim 0.02 \text{ GeV}^2$ for the first time

$$\Gamma_1(Q^2) = \int_0^{x_0} g_1(x, Q^2) dx = \frac{Q^2}{2M^2} I_1(Q^2)$$

$$\gamma_0(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \left( g_1 - \frac{4M^2}{Q^2} x^2 g_2 \right) dx$$

$$I^{GDH} = \int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu} \left( \sigma_P(\nu) - \sigma_A(\nu) \right) = 4\pi^2 \alpha \frac{\kappa^2}{M^2} S$$

The incomplete nucleon: spin puzzle

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + (L_q + L_g) \]

Proton Spin

\[ \frac{1}{2} \int dx (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}) \approx 30\% \]

Quark helicity
Best known

Gluon helicity
Start to know

\[ \Delta G = \int dx \Delta g(x) \approx 20\% \text{(STAR Data)} \]

Orbital Angular Momentum
of quarks and gluons
Little known

Maybe even more from Lattice

Net effect of partons’ transverse motion?
Orbital motion - Nucleon Structure from 1D to 3D

Generalized parton distribution (GPD)
Transverse momentum dependent parton distribution (TMD)

[Bacchetta’s talk (2016)]
Unified View of Nucleon Structure

\[ W_p^u(x,kT,r_T) \] Wigner distributions

\[ d^2r_T \]

TMD PDFs
\[ f_1^u(x,k_T), \ldots \]
\[ h_1^u(x,k_T) \]

\[ d^2k_T \]

GPDs/IPDs

\[ d^2r_T \]

3D imaging

\[ dx \& \] Fourier Transformation

\[ d^2k_T \]

PDFs
\[ f_1^u(x), \ldots \]
\[ h_1^u(x) \]

1D

Form Factors
\[ G_E(Q^2), \]
\[ G_M(Q^2) \]
## Leading Twist TMDs

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark polarization</th>
<th>Transversely Polarized</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Un-Polarized</td>
<td>Longitudinally Polarized</td>
</tr>
<tr>
<td>U</td>
<td>$f_1$</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>$g_1$</td>
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</tr>
<tr>
<td>T</td>
<td>$f_{1T\perp}$</td>
<td>$g_{1T\perp}$</td>
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</tbody>
</table>

- **Boer-Mulder**
- **Helicity**
- **Sivers**
- **Transversity**
- **Pretzelosity**

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Access TMDs through Hard Processes

**SIDIS**
- Proton
- Electron
- Positron
- Lepton
- Pion

**Drell-Yan**
- Proton
- Antilepton
- Lepton

- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

\[ f_{1T}^{+q} (\text{SIDIS}) = - f_{1T}^{+q} (\text{DY}) \]
\[ h_1^{\perp} (\text{SIDIS}) = - h_1^{\perp} (\text{DY}) \]

**Drell-Yan Programs**

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Global Analysis: Unpolarized TMD

Global analysis of semi-inclusive DIS, Drell-Yan and Z production data with TMD evolution

**SIDIS multiplicity (example)**

- $Q^2 = 1.5 \text{ GeV}^2$
  - $x = 0.061$
- $Q^2 = 1.8 \text{ GeV}^2$
  - $x = 0.096$
- $Q^2 = 2.9 \text{ GeV}^2$
  - $x = 0.15$
- $Q^2 = 5.2 \text{ GeV}^2$
  - $x = 0.24$
- $Q^2 = 9.2 \text{ GeV}^2$
  - $x = 0.41$

**Z production**

- CDF $\sqrt{s} = 1.8 \text{ TeV}$
- D0 $\sqrt{s} = 1.8 \text{ TeV}$
- CDF $\sqrt{s} = 1.96 \text{ TeV}$
- D0 $\sqrt{s} = 1.96 \text{ TeV}$

**Drell-Yan cross section**

- E288, $\sqrt{s} = 19.4 \text{ GeV}$
- $\eta = 0.4$
- $\eta = 0.21$
- $\eta = 0.03$
- $x_t = 0.1$

**Transverse momentum distribution**

Global Analysis: Transversity


Global Analysis: Polarized TMDs

Sivers

Anselmino et al, EPJA39, 89 (2009)

Transversity

Anselmino et al, PRD92, 114023 (2015)

Collins fragmentation

Anselmino et al, PRD92, 114023 (2015)


Pretzelosity

Anselmino et al, PRD93, 034025 (2016)
Transverse Spin Asymmetry in Drell-Yan

First measurement of transverse spin dependent azimuthal asymmetry in DY

190 GeV/c $\pi^-$ beam, transversely polarized NH$_3$ target

Sign change test

$$f_{1T,\text{DY}} = -f_{1T,\text{SIDIS}}$$

with sign change

Sivers Asymmetry for Gluon

First measurement of the Sivers asymmetry for gluon in SIDIS

\[ A_{PGF}^{Siv,d} = -0.14 \pm 0.15(\text{stat.}) \pm 0.10(\text{syst.}) \]
\[ \langle x_g \rangle = 0.13 \]

\[ A_{PGF}^{Siv,p} = -0.26 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.}) \]
\[ \langle x_g \rangle = 0.15 \]

Collins Asymmetry in pp Collisions

First measurement of the Collins-like asymmetry, sensitive to linearly polarized gluon, from pp collisions

Collins asymmetry

Collins-like asymmetry

**Access GPDs through Hard Processes**

Deeply Virtual Compton Scattering (DVCS)

Interference with Bethe-Heitler (BH) process gives access to real and imaginary part of DVCS amplitude

\[ d\sigma \propto |T|^2 = |T_{BH}|^2 + |T_{DVCS}|^2 + \mathcal{I} \]

\[ \mathcal{I} \propto -\frac{e_\ell}{\mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} [c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi)] \right\} \]

E.g.:

\[ c_{1,\text{unpol.}}^{\mathcal{I}} \propto \left[ F_1 \Re \mathcal{H} - \frac{t}{4M_p^2} F_2 \Re \mathcal{E} + \frac{x_B}{2 - x_B} (F_1 + F_2) \Re \tilde{\mathcal{H}} \right] \]

Access different GPDs

\[ d\sigma_{LU} = \sin\phi \cdot \Im\{F_1 \mathcal{H} + x_B (F_1 + F_2) \tilde{\mathcal{H}} - k F_2 \mathcal{E}\} d\phi \]

\[ d\sigma_{UL} = \sin\phi \cdot \Im\{F_1 \tilde{\mathcal{H}} + x_B (F_1 + F_2) (\tilde{\mathcal{H}} + x_B / 2 \mathcal{E}) - x_B k F_2 \tilde{\mathcal{E}} \ldots \} d\phi \]

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

\[ d\sigma_{UT} = \cos\phi \cdot \Im\{k (F_2 \mathcal{H} - F_1 \mathcal{E}) + \ldots \} d\phi \]

Alternative processes: deeply virtual meson production (DVMP), double DVCS, timelike Compton scattering (TCS)…

H. Gao
Global Analysis of GPDs

Kumerički and Müller NP B841, 1(2010)


Goldstein et al., PR D84, 034007(2011)
Global Fits of GPDs

12 GeV Upgrade Project

Upgraded is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.

**Scope of the project included:**

- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan. **Completed**
12 GeV Upgrade Physics Instrumentation

**GLUEx (Hall D):** exploring origin of confinement by studying hybrid mesons

**CLAS12 (Hall B):** understanding nucleon structure via generalized parton distributions

**SHMS (Hall C):** precision determination of valence quark properties in nucleons and nuclei

**Hall A:** nucleon form factors, & future new experiments like Moller & SOLID
Extensive DVCS experiments at 12-GeV JLab: E12-06-114 (unpolarized proton @ Hall A), E12-06-119 (unpolarized proton; long. Pol. proton @ Hall B), E12-11-003 (unpolarized neutron @ Hall B), E12-12-010 (trans. polarized proton @ Hall B), E12-13-010 (unpolarized proton @ Hall C)
Hall C E12-13-010 Experiment

Inaccessible with $E_p < 11$ GeV

Resonance region $W < 2$ GeV

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Ji’s sum rule: 

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

Access to quark orbital angular momentum with GPDs

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Solenoidal Large Intensity Device (SoLID) Physics

SoLID provides unique capability:

- high luminosity \(10^{37-39}\)
- large acceptance with full \(\phi\) coverage

→ multi-purpose program to maximize the 12-GeV science potential

1) Precision in 3D momentum space imaging of the nucleon

- \(x f_{\perp T}(x, k_{\perp})\)

\(Q^2 = 2.4 \text{ GeV}^2\)

2) Precise determination of the electroweak couplings

\(2g^{\text{ew}} - g^{\text{ed}}\)

A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.

3) \(J/\psi\) production cross section

→ Constrain the QCD trace anomaly, Proton mass, LHCb charmed pentaquark
**SoLID-Spin: SIDIS on $^3$He/Proton @ 11 GeV**

**Key of SoLID-Spin program:**
Large Acceptance + High Luminosity
→ 4-D mapping of asymmetries
→ Tensor charge, TMDs …
→ Lattice QCD, QCD Dynamics, Models.

**E12-10-006:** Single Spin Asymmetry on Transverse $^3$He @ 90 days, **rating A**

**E12-11-007:** Single and Double Spin Asymmetry on $^3$He @ 35 days, **rating A**

**E12-11-108:** Single and Double Spin Asymmetries on Transverse Proton @120 days, **rating A**

Three run group experiments approved: TMDs, GPDs, and much more
SoLID Impact on Transversity and Tensor Charges

World vs. SoLID including systematics

\[ xh_1(x) \]

\[ Q^2 = 2.4 \text{ GeV}^2 \]

\[ g_T^{(f)} = g_T^u - g_T^d \]

Z. Ye et al., PLB 767, 91 (2017)
Summary

• Spin remains important and puzzling for nucleon
• Three-dimensional imaging of nucleon will help solve this remaining puzzle, and uncover the rich dynamics of QCD
• Major progresses have been made in spin and three-dimensional structure of the nucleon worldwide
• Awaiting new results on nucleon spin, TMDs and GPDs, especially those planned at 12-GeV JLab


(Apology - not all results are included due to the time limit)