Nucleon Longitudinal Spin Structure
Experimental overview

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• Gluon helicity
• Quark helicities
• Outlook

Measurements at RHIC, COMPASS, HERMES, JLab
Nucleon spin

How is the nucleon spin distributed among its constituents?

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L \]

- quark
- gluon
- orbital momentum

\[ \Delta \Sigma : \text{sum over } u, d, s, \bar{u}, \bar{d}, \bar{s} \]

\[ \Delta q = \vec{q} - \vec{q} \]

Parton spin parallel or anti parallel to nucleon spin

Past:
- Theory: QPM estimations, with relativistic effects
  \[ \Delta \Sigma \sim 0.6 \]
- Experiment: “Spin crisis” in 1988, when EMC measured
  \[ a_0 = \Delta \Sigma = 0.12 \pm 0.17 \] MS scheme

Today:
- Precise world data on polarized DIS
  \[ g_1 + SU_f(3) \]
  \[ a_0 = \Delta \Sigma \sim 0.3 \]
- First results from Lattice QCD on \[ \Delta \Sigma_{u,d} \] and \[ L_{u,d} \]

Large experimental effort on \[ \Delta G \] measurement
also because
\[ a_0 = \Delta \Sigma - n_f (\alpha_s/2 \pi) \Delta G \] (AB scheme)
Three ways to study gluon contribution \( \Delta G \)

1. **Lepton Nucleon**
   - Photon Gluon Fusion
   - \( \Delta G/G(x) \)
   - SMC, HERMES, COMPASS

2. **Proton Proton collisions**
   - Gluon-Quark + Gluon-Gluon + …
   - \( \frac{\Delta G}{G} \times \frac{\Delta q}{q} + \frac{\Delta G}{G} \times \frac{\Delta G}{G} + … \)
   - \( A_{LL}(p_T) \)
   - RHIC : PHENIX & STAR

3. **QCD \( Q^2 \) evolution of spin structure function \( g_1(x,Q^2) \):**
   - Indirect determination assuming a functional form \( \Delta G(x) \).
   - Global fits include polarized DIS, SIDIS and pp data
HERMES at DESY

1995 to 2007

Spectrometer:
$\Delta p/p \sim 2\%$, $\Delta \Theta < 1$ mrad
Excellent separation of $\pi$, $K$, $p$

HERA $e^+ \& e^-$ 27 GeV
longitudinally polarized ~ 54%

Gaseous internal target
Longit. Polar. 85% H, D, He
Transv. Polar H
Unpol H, D, Ne, Kr
COMPASS at CERN

Fixed target
Secondary beams from SPS

Nucleon spin structure

Polarized muon beam:
160-200 GeV $\mu$, $P_B=80\%$

Solid polarized target:
$^6\text{LiD}$ $P_T=50\%$ 2002 to 2006
$\text{NH}_3$ $P_T=80\%$ 2007, 2010, 2011

Meson spectroscopy

Hadron beam:
190 GeV $\pi/p$
LH$_2$ 2008-2009

DIS events
$0.003 < x < 0.5$
$1 < Q^2 < 10$ (GeV/c)$^2$

COMPASS at CERN

Fixed target
Secondary beams from SPS

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NIMA 577 (2007) 455
1. $\Delta G/G$ from $\vec{\text{lepton}} \vec{\ell} \bar{N}$ scattering

**Photon Gluon Fusion (PGF) process**

Asymmetry of cross sections for longitudinal polarizations of beam and target, parallel and antiparallel

$$A_{LL} = R_{PGF} <a_{LL}> <\Delta G/G> + A_{\text{background}}$$

Fraction of process  Analyzing power

**Two signatures for PGF:**

1/ $q=c$ open charm $c \to D^0 \to K \pi$
   - Clean signature of PGF
   - pQCD scale $\mu^2 = 4 (m_c^2 + p_T^2)$
   - Combinatorial background & limited statistics
   - $\to$ Difficult experiment; 5 decay channels added

2/ $q=u,d,s$ high $p_T$ hadron pair $q \overline{q} \to h h$
   - High statistics
   - pQCD scale $Q^2$ or $\Sigma p_T^2$
   - Physical background, better described for high $Q^2$
**High $p_T$ hadrons:** $Q^2 \sim 3$

with model for physical background

**Open charm:** $Q^2 = 13$

- All measurements compatible with $0$
- Constraint on $\langle \Delta G \rangle$ for $0.05 < x < 0.3$
- Results disfavour value of the integral $> \sim \pm 0.3$
  - i.e. $\pm 60\%$ of the $\frac{1}{2}$ nucleon spin
- Contribution to $\langle \Delta G \rangle$ outside measured $x$ range not excluded

Note that these data are NOT included in global fits

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**Figure:**

Graph showing $\Delta g/g$ vs $x_g$ with data points and curves for different experiments:

- COMPASS, high $p_T$, $Q^2>1$ (GeV/c)$^2$, 02-06
- COMPASS, high $p_T$, $Q^2<1$ (GeV/c)$^2$, 02-04
- COMPASS, Open Charm, all $Q^2$, 02-07 (LO)
- SMC, high $p_T$, $Q^2>1$ (GeV/c)$^2$
- HERMES, high $p_T$, all $Q^2$

**Legend:**

- LSS10, $\Delta G \sim +0.32$ at $Q^2 = 4$
- LSS10, $\Delta G \sim -0.33$
- DSSV, $\Delta G = 0.02$

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**References:**

- i r f u
- CIPANP 2012, St Pertersburg, Florida, May 2012 – 7
COMPASS high $p_T$ hadron: Cross section

$\mu^+d \rightarrow \mu^+h^\pm X$

Quasi real photo production of hadron

Compared to predictions at NLO

Data agree with NLO pQCD over 5 orders of magnitude (within theory uncertainty)

Settles the theory framework for $\Delta G$ high $p_T$

Next step: produce spin asymmetries $A_{LL}(p_T)$ for same events
2. \( pp \) collisions at RHIC

\[ \sqrt{s} = 62, 200, 500 \, \text{GeV} \]

- Longitudinal spin asymmetries
  - hadron production for \(<\Delta G>\),
  - \( W \) production for \(<\Delta q>\)
- Transverse spin
RHIC luminosity increase vs time

- $\sqrt{s} = 200$ GeV
  - run 5, 6, 9, 12
- $\sqrt{s} = 500$ GeV
  - run 9, 11
2. \( p p \) collisions at RHIC, channels for \( \Delta G \)

- More abundant channels
  - \( p p \rightarrow \pi^0 \times \) PHENIX
  - \( p p \rightarrow \text{jet} \times \) STAR
  - 3 processes contribute
    \[
    \Delta G (x_1) \cdot \Delta G (x_2)
    \]

- Other channels
  - \( p p \rightarrow \text{jet jet} \) proj. STAR 500 GeV, low \( x \)
    \[
    \Delta G (x_1) \cdot \Delta q (x_2)
    \]
    \[
    \Delta q (x_1) \cdot \Delta q (x_2)
    \]

- Other channels
  - \( p p \rightarrow \gamma \text{ jet} \)
    - 1 process \( \rightarrow \) cleaner
    - Full kinematics reconstructed
    - Low statistics

- Other channels: \( \pi^+, \pi^-, \eta, \ldots \)

High potential for \( \Delta G \) from various channels, various kinematics
pp collisions at RHIC: cross-sections

Two examples

Inclusive jets at STAR

• Good agreement between data and pQCD calculations
• Exist also for other channels: π⁺, π⁻, dijet, direct γ, γ +jet, η, etc.
• Establishes validity of pQCD frame → validates method for ΔG extraction
**pp collisions at RHIC: inclusive jet at STAR**

\[ p + p \rightarrow \text{jet} + X \]

Measure double spin asymmetry \( A_{LL} (p_T) \)

Compare data to global fits with various \( \Delta G(x) \) parameterizations

High stat. run 9

→ New fit

\[ \int_{0.05}^{0.2} dx \Delta g \approx 0.1 \]

(See: STAR at DIS12, Stratmann at DIS12, Vogelsang at IWHSS12)

**Inclusive jet provides strong constraint on \( \Delta G \) in measured range giving \( \Delta G \) positive ~ 0.1 for 0.05<x<0.2**
pp collisions at RHIC: \( \pi^0 \) production at PHENIX

\[ p p \rightarrow \pi^0 X \]

Measure double spin asymmetry \( A_{LL}(p_T) \)

Compare data to global fits with various \( \Delta G(x) \) parameterizations

![Graph showing double spin asymmetry](image)

New fit

\( DSSV = -0.08 \)

Run9 vs Run 6: FoM increased by more than 2

Strong constraint on \( \langle \Delta G \rangle \) in x range probed 0.05 < x < 0.3
pp collisions at RHIC: other channels

charged pions: different FF for favored or unfavored

different $qg$ contributions for $\pi^0, +, - \rightarrow$ access sign of $\Delta G$

$$A_{LL}^{\pi^+} > A_{LL}^{\pi^0} > A_{LL}^{\pi^-} \Rightarrow \Delta G > 0$$

$$A_{LL}^{\pi^+} < A_{LL}^{\pi^0} < A_{LL}^{\pi^-} \Rightarrow \Delta G < 0$$

Promising channels when more statistics available
3. $\Delta G$ from global fits

Spin structure functions $g_1$

$$A_1^{DIS} \propto g_1(x) \propto \frac{1}{2} \sum_{q} e_q^2 (\Delta q(x) + \Delta \overline{q}(x))$$

$$\frac{d g_1}{d \log(Q^2)} \propto -\Delta g(x, Q^2)$$

$g_1$ as input to global QCD fits for extraction of $\Delta q_f(x)$ and $\Delta G(x)$

However $x$ and $Q^2$ coverage not yet sufficient for $\Delta G$

Use also constraint from pp data (DSSV)

Note: 200 GeV proton data to come from COMPASS 2011 run
Jlab experimental halls

6 GeV polarized CW electron beam
Pol=85%, 200µA

Will be upgraded to 12 GeV by ~2014

Hall A: two HRS’
Hall B: CLAS
Hall C: HMS+SOS

NH₃ & ND₃ targets

H. He target
Jlab CLAS - $g_1(x, Q^2)$ for the proton

Jlab/ CLAS - EG1
5.7 GeV e-
Polarized NH$_3$
(and ND$_3$) targets

Data included in LSS fit
3. $\Delta G(x)$ from global QCD fits of polarized data

**LSS ’10**
Only DIS & SIDIS data
*Leader, Sidorov, Stamenov,*
$\Delta G = 0.25 \pm 0.19$
$\Delta G = -0.40 \pm 0.43$
at $Q^2 = 2.5 \text{GeV}/c^2$

**DSSV-2009 (old)**
DIS, SIDIS & pp
*De Florian, Sassot, Stratmann, Vogelsang*
*PRL101 (2008)072001*
$\Delta G = -0.08 \pm ?$
at $Q^2 = 10 \text{GeV}/c^2$

- Data favored fits with $\Delta G$ close to 0, excluding $\Delta G$ std (DSSV-2009, LSS10)
- Strong constraint on $<\Delta G>$, now $> 0$ (DSSV+) in $x$ range probed
- No constraint outside $0.05 < x < 0.2$
<table>
<thead>
<tr>
<th>Source</th>
<th>( \Delta \Sigma )</th>
<th>Notes</th>
</tr>
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</table>
| COMPASS       | \( 0.30 \pm 0.01 \) \( \pm 0.02 \) (stat) \( \pm 0.01 \) (evol) | fit to \( g_1^{p,n,d} \) world data, MS scheme, \( Q^2=3 \) (GeV/c)^2 PLB 647 (2007) 8  \\
|               | \( \Delta s + \Delta \bar{s} = -0.08 \pm 0.01 \) (stat) \( \pm 0.02 \) (evol) | COMPASS data only                                                      |
| HERMES        | \( 0.33 \pm 0.01\) \( \pm 0.02 \) (theo) \( \pm 0.028 \) (evol) | HERMES \( g_1^d \) data, MS scheme, \( Q^2=5 \) (GeV/c)^2, neglecting \( x \) \(< 0.02\) contrib., PRD75 (2007)012007  \\
|               | \( \Delta s + \Delta \bar{s} = -0.085 \pm 0.013 \) (th) \( \pm 0.008 \) (exp) \( \pm 0.009 \) (evol) |                                                                 |
| DSSV          | \( 0.24 \)                          | \( Q^2=10 \) (GeV/c)^2 arXiv:0804.0422                              |
| LSS '10       | \( \Delta \Sigma = 0.25 \pm 0.04 \) | \( \Delta G \) with node \( Q^2=10 \) (GeV/c)^2, \( \Delta G >0 \) |
|               | \( \Delta \Sigma = 0.21 \pm 0.03 \) |                                                                      |
Bjorken sum rule

A fundamental result of QCD on the non-singlet combination $g_1^{NS}(x) = g_1^p(x) - g_1^n(x)$ derived from current algebra:

$$\int_0^1 g_1^{NS}(x) dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C^{NS}$$

Measuring the first moments provides a test of the Bjorken sum rule,

Fit to COMPASS data: $g_A/g_V = 1.28 \pm 0.07 \text{(stat)} \pm 0.10 \text{(syst)}$

PDG value:
$1.268 \pm 0.003$
Quark helicities from Semi-Inclusive DIS

- COMPASS
  - PLB693(2010)227, using DSS FF
- HERMES
  - PRD71(2005)012003
- DSSV

- Full flavour separation → $x \sim 0.004$
- Sea quark distributions ~ zero
- Good agreement with global fits

**HERMES** $\Delta s + \bar{\Delta s} = 0.037 \pm 0.019$ (stat) ± 0.027 (syst), *PLB666(2008)466*

**COMPASS** $\Delta s = -0.01 \pm 0.01$ (stat) ± 0.01 (syst), $0.003 < x < 0.3$

$\Delta s - \bar{\Delta s}$ compatible with 0

Extraction at LO

$$\frac{A_1^{h(p/d)}(x)}{\sum_q e_q^2 D_q^h q(x)} = \sum_q e_q^2 D_q^h \Delta q(x)$$
Light sea quark polarized distributions

\[ x(\Delta \bar{u} - \Delta \bar{d}) \]

\[ \int_{0.004}^{0.3} (\Delta \bar{u} - \Delta \bar{d}) \, dx = 0.052 \pm 0.035 \text{(stat.)} \pm 0.013 \text{(syst.)} \]

Slightly positive, compatible with zero.

Recall value for unpolarized case: \[ \int (\bar{d} - \bar{u}) \, dx = 0.118 \pm 0.012 \]
\[ \Delta s \] puzzle

- **DIS data**: the integral of \( \Delta s \) can be extracted from the integral of \( g_1 \) using two other inputs (\( n \) and hyperon decay) & SU(3)
  \[ \int \Delta s + \overline{\Delta s} = - 0.08 \pm 0.01 \pm 0.02 \]

- **SIDIS data**: the integral of \( \Delta s \) can be computed from \( \Delta s(x) \) measured from kaon spin asymmetries, using quark Fragmentation Functions
  \[ \Delta s(x) \approx 0 \]

**Several possible explanations to the discrepancy**:

- Uncertainty on quark fragmentation functions (\( s \to K \))
  - would need value twice bigger than DSS

- Global fits (DSSV, LSS) suggest negative \( \Delta s \) at low \( x \)
  - reconciles the two approaches

- Assume SU(3) violation \( a_8 \) from 0.58 to 0.42
  \[ \Delta s = -0.02 \]

\[ \text{Bass &Thomas, PLB 684(2010)216} \]

**Need more data on quark fragmentation functions**
**Need more data on \( \Delta s \) at low \( x \)**

**COMPASS** run 2011 at 200 GeV
**Certainly a physics case for EIC**
Δs puzzle cont’d. New fit DSSV+

From Stratmann at DIS-2012, Including COMPASS SIDIS results π, K at low x:

“Tendency toward negative low-x also from SIDIS? Heavily relies on Fragmentation Functions.”
Quark helicities from W production in $pp$

RHIC short exploratory run: first collisions at 500 GeV

Parity violating, single spin asymmetry

No fragmentation function uncertainty

$u + \bar{d} \rightarrow W^+ \rightarrow e^+ + \nu$

$\bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}$

PHENIX

STAR

J. Haggerty ICHÉP2010


- Signs as expected from polarized PDFs
- Promising channel
Jlab – CLAS $A_{1}^p, A_{1}^d$

$W > 2; Q^2 > 1$

Proton

Deuteron
Jlab – $A_1^n$ $A_1^p$

$W > 2; Q^2 > 1$

Neutron

Proton

$A_1^n$ at $x \rightarrow 1$, SU(6) symmetry breaking?

Polarized Quark Distributions - Valence sector

From $A_1^n$ and $A_1^p$ results
u quark spin as expected

d quark spin stays negative

• Disagree with pQCD model calculations assuming HHC (hadron helicity conservation)
• Quark orbital angular momentum

Consistent with valence quark models and pQCD PDF fits without HHC constraint

Chen, Seattle OAM Workshop, Feb2011
pQCD with Quark Orbital Angular Momentum


Inclusive Hall A and B and Semi-Inclusive Hermes

\[
\frac{\Delta u}{u}, \quad \frac{\Delta d}{d}
\]

\[
q^+(x) \propto (1 - x)^3 \quad q^-(x) \propto (1 - x)^5 \quad x \rightarrow 1
\]

Chen, Seattle OAM Workshop, Feb2011
Lattice: quark spin and angular momentum

- Impressive results from lattice QCD
- Agreement with measurements for quark spin
- Predictions for angular momentum

Ph. Haegler, MENU 2010

MS at 4 GeV² vs. $m_π^2$ [GeV²]
Conclusions

Gluon contribution to nucleon spin
All measurements point to zero or small contribution. Strong constraint on fits from RHIC. Only $0.05 < x < 0.2$ probed. Need low $x$ measurement.

Quark contribution to nucleon spin
Extraction for all flavours from SIDIS
Towards agreement with Lattice QCD calculation for $\Delta \Sigma$
$\Delta s(x) \sim 0$ from SIDIS in measured region, and $\int \Delta s < 0$ from DIS:
need more precision and Fragmentation Function knowledge.

Angular momentum
DVCS, DVMP:
data from HERMES & Jlab + projects at Jlab-12GeV & COMPASSII
Good prospects for Lattice QCD

Exciting future programs in preparation at RHIC, COMPASS-II, Jlab-12GeV, and... EIC/ENC