COMPASS results

CObmmon Muon and Proton Apparatus for Structure and Spectroscopy

D. Peshekhonov
on behalf of the COMPASS Collaboration
“...We understand the proton spin structure via the quark parton model and measuring the spin structure functions would not be fruitful...”

<table>
<thead>
<tr>
<th>Baryon</th>
<th>Wave Function</th>
<th>Quark Model Mag. Moment</th>
<th>Experiment (μN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ω⁻</td>
<td>↑s ↑s ↑s ↑s</td>
<td>( \mu_\Omega = 3\mu_s = -2.0\mu_N )</td>
<td>-2.02±0.05</td>
</tr>
<tr>
<td>Λ⁰</td>
<td>↑s ↑u ↑d ↓d</td>
<td>( \mu_\Lambda = \mu_s = -0.7\mu_N )</td>
<td>-0.63±0.05</td>
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<tr>
<td>Σ⁻</td>
<td>↑s↑s↑u↑, ↑s↑s↑u↑, ( \text{known weights} )</td>
<td>( \mu_{\Sigma^{-}} = 4\mu_s - \mu_d = -1.6\mu_N )</td>
<td>-1.25±0.14</td>
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<tr>
<td>Σ⁺</td>
<td>↑s↑u↑u↑</td>
<td>( \mu_{\Sigma^{+}} = 4\mu_u - \mu_s = +2.9\mu_N + 2.458 )</td>
<td>±0.10</td>
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<tr>
<td>Σ⁻</td>
<td>↑s↑d↑d↑</td>
<td>( \mu_{\Sigma^{-}} = 4\mu_d - \mu_s = -1.1\mu_N - 1.96 )</td>
<td>±0.025</td>
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<tr>
<td>p</td>
<td>↑u↑u↑d↑</td>
<td>( \mu_p = 4\mu_u - \mu_d = 3.0\mu_N )</td>
<td>2.793</td>
</tr>
<tr>
<td>n</td>
<td>↑d↑d↑u↑</td>
<td>( \mu_n = 4\mu_d - \mu_u = -2.0\mu_N )</td>
<td>-1.913</td>
</tr>
</tbody>
</table>
\[ \int_0^1 g_1^p \, dx = \frac{1}{12} G_A f(\alpha_s) + a_8 \frac{f(\alpha_s)}{36} + \Delta \frac{h(\alpha_s)}{9} \]
\[ \int_0^1 g_1^n \, dx = -\frac{1}{12} G_A f(\alpha_s) + a_8 \frac{f(\alpha_s)}{36} + \Delta \frac{h(\alpha_s)}{9} \]

\( f(\alpha_s); \ h(\alpha_s) \) - QCD Radiative correction factors \( \sim 1 \)

**SU3:**
\[
a_8 = \frac{1}{\sqrt{3}} (3F-D); \quad G_A = F + D = 1.26 \quad (a_8 \text{ } G_A \text{ from } \pi^0 \text{ from p, D, F, D Symmetric, antisymmetric SU(3) couplings from hyperon decay, } \ F = 0.48 \pm 0.01, \ D = 0.76 \pm 0.01) \]

**In QPM**

\[ \Delta \Sigma = \Delta u + \Delta u + \Delta d + \Delta d + \Delta s + \Delta s \]

= Total fraction of proton spin carried by quarks

\[ a_8 = \frac{1}{\sqrt{3}} \{ \Delta u + \Delta u + \Delta d + \Delta d - 2(\Delta s + \Delta s) \} \]

\[ G_A = \Delta u + \Delta u - \Delta d - \Delta d \]

- use \( \Gamma_f^p, \Gamma_f^n \) to obtain \( \Delta \Sigma \); then \( G_A \) and \( a_8 \) to solve for \( \Delta u, \Delta d, \Delta s \).
- previously Ellis-Jaffe sum rule obtained by assuming \( \Delta s = 0 \) to get predictions for \( \Gamma_f^p, \Gamma_f^n \)
- the modern data shows that the Ellis-Jaffe sum rule is violated, so the strange sea is polarised.

**EMC Measured**

\[ \int_0^1 g_1^p \, dx = 0.126 \pm 0.010 \pm 0.015 \]

ie \[ \Delta \Sigma = 0.12 \pm 0.09 \pm 0.14 \]

i.e. \( \sim 12\% \) of spin of proton carried by quark
Laboratories &

SLAC

49 GeV e^-

DESY

27 GeV e^+ e^-

HERA

CERN

160/280 GeV μ^+

COMPASS

JLab

6 GeV e^-

250+250 GeV pp

RHIC
### & Experiments

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<td>E142/3</td>
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<td>CLAS/HALL-A</td>
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<td>RHIC</td>
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<td>Phenix/Star</td>
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**A worldwide effort since decades**
Tools to study the nucleon structure

DIS

SIDIS

PDF

PDF $\otimes$ FF

PDF $\otimes$ PDF
Deep inelastic scattering

\[ Q^2 = -(k - k')^2 \]
\[ P \cdot q_{\text{lab}} = M \nu \]
\[ P \cdot k_{\text{lab}} = M E \]
\[ x_{\text{lab}} = \frac{Q^2}{2M \nu} = \frac{-q^2}{2P \cdot q} \]
\[ y_{\text{lab}} = \frac{\nu}{E} = \frac{P \cdot q}{P \cdot k} \]

\[ 0 \leq x, y \leq 1 \]

**Bjorken-\(x\):** fraction of longitudinal momentum carried by the struck quark in infinite-momentum frame (Breit)
Structure: Parton Distribution Functions

\[ q(x) \quad f_1^q(x) \]

**unpolarised PDF**
quark/gluon with momentum \( xP \) in a nucleon

*well known – unpolarized DIS*

\[ \Delta q(x) \quad g_1^q(x) \]

**helicity PDF**
quark/gluon with spin parallel to the nucleon spin in a longitudinally polarised nucleon

*known – polarized DIS*

\[ \Delta_T q(x) \quad h_1^q(x) \]

**transversity PDF**
quark with spin parallel to the nucleon spin in a transversely polarised nucleon

*chiral odd, fairly known*
• Measure cross-section asymmetry
\[
\frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}
\]
• Need polarised beam & target
  (for longitudinal spin structure)
\[ \frac{A_{\text{exp}}}{f \cdot P_\mu \cdot P_T \cdot D} \sim A_1 \]

- **Inclusive scattering**

\[ A_1 = \frac{\sum_q e_q^2 g_1^q(x, Q^2)}{\sum_q e_q^2 f_1^q(x, Q^2)} \]

- **Semi-inclusive scattering**

\[ A_1^h = \frac{\sum_q e_q^2 g_1^q(x, Q^2) D_1^h(z, Q^2)}{\sum_q e_q^2 f_1^q(x, Q^2) D_1^h(z, Q^2)} \]

\[ z = \frac{E_h}{\nu} \]
Questions:

- What is helicity contribution of quarks to nucleon spin $\Delta \Sigma$?
- How do contributions of different flavours $\Delta q(x)$, $q=u,d,s$ and antiquarks look like?
- Is gluon helicity distribution $\Delta G = \int \Delta g(x) dx$ small or not?
- How does $\Delta g(x)$ look like?
After almost 40 years

\[ \Delta \Sigma = \Delta u + \Delta d = 1 \]

**SQM:** valence quarks carry the nucleon spin!

**EMC:** Quarks spins contribute little (1987/88)
\[ \Delta \Sigma = 0.12 \pm 0.09 \pm 0.14 \]

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

- quarks: small ~0.25
- gluons: Still poorly known
- orbital: unknown
COMPASS experiment
• nucleon spin-structure ($\mu$)
  • helicity distributions of gluons and quarks
  • transverse spin structure
  • 3D structure of the nucleon
• hadron spectroscopy ($p$, $\pi$, $K$)
  • light mesons, glue-balls
  • exotic mesons
  • polarisability of pion and kaon
• members:
  • 220 physicists, 23 institutes, 12 countries
COMPASS spectrometer

h^+ beam: 190 GeV, p/π/K 75/24/1%
h^- beam: 190 GeV, π/K/p 97/2/1%
μ^+ beam: 160/200 GeV, 2×10^7/s

60m long
COMPASS Beams

Muon beam
- Energy: 160 GeV
- Intensity: $2 \times 10^8$/spill
- Polarization: 80%

Hadron beams
- Pions(97%), kaons(2.6%), anti-p(0.6%)
- Energy: 190 GeV
- Intensity: up to $10^8$/spill

Electron beam
- 40 GeV, few $10^3$/spill,
  used for calibration
Polarized target system

3He – 4He dilution refrigerator (T~50mK)

6LiD/NH₃ (d/p)
50/90% pol.
40/16% dil. factor

Reconstructed interaction vertices
Helicity structure of the nucleon
Structure function $g_1(x, Q^2)$

- very precise data
- only COMPASS for $x < 0.01$ ($Q^2 > 1$)
- deuteron data:
  \[ \Delta \Sigma = 0.33 \pm 0.03 \pm 0.05 \]
  \[ \Delta s + \bar{\Delta s} = -0.08 \pm 0.01 \pm 0.02 \]
Sum rules

- first moment $\Gamma_1$ of $g_1$ with
  \[ \Delta q = \int_0^1 \Delta q(x) \, dx \]
  \[ \Gamma_1 = \int_0^1 g_1(x) \, dx \quad \text{proton} \quad = \frac{1}{2} \left\{ \frac{4}{9} \Delta u + \frac{1}{9} \Delta d + \frac{1}{9} \Delta s \right\} \]

- Neutron decay
  \[ \Gamma_1^p = \frac{1}{12} (\Delta u - \Delta d) \quad + \quad \frac{1}{36} (\Delta u + \Delta d - 2\Delta s) \quad + \quad \frac{1}{9} (\Delta u + \Delta d + \Delta s) \]
  \[ a_3 \] Neutron decay $a_3 = |g_a/g_v|$  \[ a_8 \] (3F-D)/3

- Hyperon decay
  \[ \Delta \Sigma \]

- Bjorken sum rule:
  \[ \Gamma_1^p - \Gamma_1^n = \frac{1}{6} (\Delta u - \Delta d) \]
\[ \Gamma_1^{NS}(Q^2) = \frac{1}{6} \left| \frac{g_A}{g_V} \right| C_1^{NS}(Q^2) \]

\[ g_1^{NS}(x, Q^2) = g_1^p(x, Q^2) - g_1^n(x, Q^2) \]

\[ |g_A/g_V| = 1.28 \pm 0.07 \text{(stat.)} \pm 0.10 \text{(syst.)} \]

from neutron $\beta$ decay \[ |g_A/g_V| = 1.269 \]
DIS & SIDIS asymmetries - deuteron

\[ A_{1,d}^{\pi^+}, \quad A_{1,d}^{K^+}, \quad A_{1,d}^{\pi^-}, \quad A_{1,d}^{K^-} \]

- COMPASS
- HERMES

\[ x \]
► Leading Order (LO) fit of the 10 asymmetries (2x5)
► Determine 6 flavor separated PDFs: $\Delta u, \Delta d, \Delta \bar{u}, \Delta \bar{d}, \Delta s, \Delta s$
Helicity distributions

$\Delta s$: Truncated first moment: 
(with DSS FF )

$$\int_{0.004}^{0.3} \Delta s(x)dx = -0.01 \pm 0.01 \pm 0.01$$
Double spin asymmetries for production of charged pions and kaons in semi inclusive deep inelastic muon scattering off longitudinally polarized protons have been measured.

A leading order evaluation of the helicity distributions for the three lightest quarks and anti-quark flavors, derived from these asymmetries and from previous deuteron data, are performed.

The resulting values for $u$ and $d$ quarks have opposite signs. The sea quark distributions are small and do not show sizable dependence on $x$ in the range of the measurements. No significant difference is observed between the strange and anti-strange helicity distributions, both compatible with zero. The integrated value of the flavor asymmetry of the helicity distribution of the light quark sea, $\Delta\bar{u}-\Delta\bar{d}$, is found to be slightly positive, about 1.5 standard deviations away from zero.
Gluon polarization measurements

- **open charm**: single $D$ meson cleanest process wrt physics background

- high-$p_T$ hadron pairs with $Q^2 > 1$ GeV$^2$
- high-$p_T$ hadron pairs with $Q^2 < 1$ GeV$^2$
- single hadron production $Q^2 < 0.1$ GeV$^2$
The gluon polarization, $\Delta g/g$, in the nucleon is measured by several methods. One of them is based on the longitudinal double spin asymmetry of SIDIS events with a pair of large transverse momentum hadrons in the final state. The gluon polarization is evaluated at leading order OCD by a Neural Network approach for three intervals of the gluon momentum fraction $x_g$ covering the range $0.04 < x_g < 0.27$. The values obtained do not show significant dependence on $x_g$.

The average is: $\Delta g/g = 0.125 \pm 0.060$ (stat.) $\pm 0.063$ (syst.) at $x_g = 0.09$ and at a scale of $\mu^2 = 3$ (GeV/c)$^2$. ($\Delta g/g$ evaluations in NLO QCD are in preparation for publication)
The main goal is to improve the extraction by removing few sources of systematic effects.

However, also a considerable reduction of the statistical error of $\Delta g/g$ was achieved.

Three processes contribute to the cross-section

$$A_{LL}^h(x) = R_{LO} D A_1^{LO}(x) + R_{PQCD} a_{LL}^{QCD} A_1^{LO}(x_C) + R_{PGF} a_{LL}^{PGF} \frac{\Delta g}{g}(x_g)$$

Simultaneous extraction of $\Delta g/g$, and $A_1^{LO}$

Extraction based on effective Monte Carlo description of all processes giving the relative weights ($R_i$) and analyzing powers ($a_{LL}^i$)

Process weights depends on $p_T$ (at small $p_T$ LO contribution is $> 0.95$)
$\Delta g/g$ using “all $p_T$” events: correlations
\( \Delta g / g \) using “all \( p_T \)” events: results

\[ \Delta g / g \bigg|_{x_g=0.10} = 0.113 \pm 0.038 \pm 0.035 \]

| \( \langle x_g \rangle \) | \( x_g \) range | \( \Delta g / g \) |
|------------------------|-------------|-----------------
| \( x_g = 0.08 \)      | 0.04 – 0.13 | 0.087 \( \pm \) 0.050 |
| \( x_g = 0.12 \)      | 0.07 – 0.21 | 0.149 \( \pm \) 0.051 |
| \( x_g = 0.19 \)      | 0.13 – 0.28 | 0.154 \( \pm \) 0.122 |
Global NLO QCD fits to world data on $g_1$

- 138 out of 679 points are from COMPASS

\[ g_1 = \frac{1}{2} \langle e^2 \rangle (C^S(\alpha_s) \otimes \Delta q_S + C^{NS}(\alpha_s) \otimes \Delta q_{NS} + C^g(\alpha_s) \otimes \Delta g) \]

\[ \Delta q_S = \Delta u + \Delta d + \Delta s; \ \Delta q_{NS} \text{ is a combination of } \Delta q_3 = \Delta u - \Delta d \text{ and } \Delta q_8 = \Delta u + \Delta d - 2\Delta s \]

Evolving as

\[ \frac{d}{d \ln Q^2} \Delta q_{NS} = \frac{\alpha_s(Q^2)}{2\pi} \Delta P_{qq} \otimes \Delta q_{NS} \]

\[ \frac{d}{d \ln Q^2} (\Delta q_S) = \frac{\alpha_s(Q^2)}{2\pi} \left( \Delta P_{qq} \otimes \Delta P_{gg} \right) \otimes (\Delta q_S) \]

First moments of $\Delta q_3$ and $\Delta q_8$ fixed by baryon decay constants $(F + D)$ and $(3F - D)$ assuming $SU(2)_f$ and $SU(3)_f$ symmetries.

\[ \Delta f_k(x) = \Delta q_k \frac{x^{\alpha_k}(1 - x)^{\beta_k}(1 + \gamma_k x + \rho \sqrt{x})}{\int_0^1 x^{\alpha_k}(1 - x)^{\beta_k}(1 + \gamma_k x + \rho \sqrt{x})} \]
Results

3 initial $\Delta g$ shapes; positive, negative with node.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>First moment at $Q^2 = 3 \text{ (GeV/c)}^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \Sigma$</td>
<td>[0.25, 0.34]</td>
</tr>
<tr>
<td>$\Delta u + \Delta \bar{u}$</td>
<td>[0.82, 0.85]</td>
</tr>
<tr>
<td>$\Delta d + \Delta \bar{d}$</td>
<td>[-0.45, -0.42]</td>
</tr>
<tr>
<td>$\Delta s + \Delta \bar{s}$</td>
<td>[-0.11, -0.08]</td>
</tr>
</tbody>
</table>

Range in $\Delta \Sigma$ driven by uncertainty on initial $\Delta g$ shape
Many results on the helicity distributions $\Delta q$ and $\Delta g$

Full flavor decomposition $\Delta u$, $\Delta d$, $\Delta s$ and antiquarks

- $\Delta u$ and $\Delta d$ are rather well-known
- open questions: $\Delta u = \Delta d$ and $\Delta s = \Delta s$ ?

$\Delta \Sigma = 0.25 \pm 0.05$; $\Delta G \approx 0 \pm 0.5$

Nucleon spin puzzle is still not solved
Transverse spin structure
### TMD parton distributions

- 8 intrinsic-transverse-momentum dependent PDFs at leading twist
- Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, $\Phi_h$ and $\Phi_s$
- Vanish upon integration over $k_T$ except $f_1$, $g_1$, and $h_1$

### Quark Polarization

<table>
<thead>
<tr>
<th>nucleon polarization</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
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<tbody>
<tr>
<td>U</td>
<td>$f_1$</td>
<td>$f_{1T}$</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>$g_1$</td>
<td>$g_{1T}$</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$h_{1}^\parallel$, $h_{1L}^\parallel$</td>
<td>$h_1^\perp$, $h_{1T}^\perp$</td>
<td></td>
</tr>
</tbody>
</table>

- **Boer–Mulders**
- **Transversity**
- **Sivers**
- **Chiral odd**

aka $\Delta_0 T q$

\[ \Delta_T q \]
The Sivers asymmetry is found to be compatible with zero for negative hadrons and positive for positive hadrons, a clear indication of a spin-orbit coupling of quarks in a transversely polarised proton.
Physics with hadron beams

- Proton, pion (and kaon) beams
- Hydrogen, nickel and lead targets

Not discussed today
The COMPASS-II measurements have started in 2012 with a pion/kaon polarisability via Primakoff reactions and with GPD feasibility test using partially upgraded COMPASS-II spectrometer.

The further measurements will start in 2014 after the accelerator shutdown. They will be focused on studies of transverse momentum dependent (TMD) distributions of partons in nucleons via Drell-Yan lepton pair production and measurements of generalized parton distributions (GPDs) via hard exclusive meson production and DVCS.

In parallel with the GPD program, high statistic data for unpolarized SIDIS will be taken.
Exploring the 3-dimensional phase-space structure of the nucleon

- GPD: Generalised Parton Distribution (position in the transverse plane)

- TMD: Transverse Momentum Distribution (momentum in the transv. plane)
2012 Primakoff scattering: Polarizabilities of p and K
DVCS pilot run: $t$-slope, transverse size
2013 Accelerator shutdown
2014/15 Drell-Yan: Universality of TMDs
2016/17 DVCS and DVMP: Study GPDs,
Unpolarized SIDIS: “nucleon tomography”
FF, strangeness PDF, TMDs
• COMPASS has a rich programme on QCD and hadron physics

• Nucleon spin
  – Essential contributions to clarify the spin structure of the nucleon both longitudinal and transverse
  – Gluon polarisation
  – Flavour separation (SIDIS)

• Huge data set on hadron spectroscopy
  – tests of chiral perturbation theory
  – new meson discovered, exotic mesons being studied
  – many more channels, e.g. $\pi^0, \eta, \eta', pp \rightarrow p_{\text{fast}} \pi^+ \pi^- p_{\text{slow}}$
  – just the beginning...

• Future experiments
  – Starting future program on GPDs and TMD PDFs
  – Maybe come back to spectroscopy
Thank you!
Backup
Sum Rules

Bjorken sum rule

\[ \Gamma_p^1 - \Gamma_n^1 = \frac{1}{6} g_a \]

PR 148 (1966) 1467

if wrong \(\Rightarrow\) QCD wrong, "worthless equation", needs neutron measurement

Ellis-Jaffe sum rule

\[ \Gamma_p^1 = \frac{1}{12} g_a + \frac{5}{36} \sqrt{3} a_8 + \frac{1}{3} \Delta s \]

\[ \Delta \Sigma \approx 0.6 \]

PR D9 (1974) 1444

formulated for \(\Delta s=0\), unpolarised strange quarks

Consequences of violation:

\[ \Delta s = -0.19 \pm 0.06 \]
\[ \Delta \Sigma = 0.12 \pm 0.17 \]

EMC 1987
Collins Asymmetries

- large asymmetry for proton $\sim 10\%$
- zero deuteron result important $\Rightarrow$ opposite sign of u and d

PLB717 (2012) 326
Proton Sivers Asymmetry

- compatible with zero for the deuteron
- non-zero asymmetry for pos. hadrons

![Graph showing COMPASS 2010 proton data with positive and negative hadrons](image)
The strange quark polarization puzzle

• **DIS (only) data:**
  - Sensitive to the integral value of $\Delta s(x)$; assuming that SU(3) is valid and using hyperon decay data:
    \[
    \int_0^1 s(x) + \bar{s}(x) \, dx = 0.08 \pm 0.01 \pm 0.01
    \]

• **SIDIS data:**
  - Measures the $\Delta s(x)$ directly; assuming that the fragmentation functions, specifically $D_s^K$, is known:
    \[
    s(x) \approx 0
    \]

• **Possible explanations:**
  1. Changing sign of $\Delta s(x)$
     DSSV and LSS global QCD fits
  2. Assume strong SU(3) violation
  3. Large uncertainty on the $D_s^K$ fragmentation function
     2013: data from Hermes and Compass