Measurement of the Gluon Polarisation in the Nucleon at COMPASS

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Outline:
• COMPASS experiment
• Three methods of $\Delta G/G$ measurement:
  • Open charm
  • High $p_T$ pairs ($Q^2 > 1$ GeV$^2$)
  • High $p_T$ pairs ($Q^2 < 1$ GeV$^2$)
• Outlook and conclusions
Common Muon and Proton Apparatus for Structure and Spectroscopy

The experiment:
- ~250 physicists
- 28 institutes
- programs with muon and hadron beams
- data taking started in 2002
- continued in 2003/4
- break in 2005
- resumed in 2006

Beam parameters:
- momentum: 160 GeV
- luminosity: $\sim 5 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$
- intensity: $2 \cdot 10^8 \mu^+/spill$
- spills: 4.8/16.8 s
- longitudinally polarised
- polarisation: ~76% (~81%)
The production of the beam

- $\pi \rightarrow \mu \nu$ is a parity violating decay
- $\mu$ are 100% polarised in a decaying pion rest frame

In the LAB frame:

$$P_\mu = \frac{m_\pi^2 + \left(1 - 2 \frac{E_\pi}{E_\mu}\right)m_\mu^2}{m_\pi^2 - m_\mu^2}$$

The average polarisation is: -0.76 in 2002-3
- 0.81 in 2004

The polarisation: MC and SMC measurements
The target

Target:
- two cells – 60 cm long each
- high luminosity
- material: $^6\text{LiD}$
- opposite polarisation: ~50%
- exposed to the same beam flux
- dilution factor: 0.4
- polarisation reversal every 8 hours
- cooling system: 50 mK
- acceptance: ±70 mrad
- in 2006 acceptance: ±180 mrad
The spectrometer layout

Two-stage forward-spectrometer:
LAS – 1 Tm magnet (±180 mrad)
SAS – 4.5 Tm magnet (±30 mrad)

PID:
RICH, ECAL, HCAL, muon filters

Track reconstruction for momenta >0.4 GeV
Physics Motivation

Nucleon spin decomposition:

$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_{q,g}$

- contribution from quarks and anti-quarks
- contribution from gluons
- orbital momenta of quarks and gluons

- Only a small fraction of nucleon spin is carried by quarks ~0.3
- Where does the rest of the nucleon spin comes from?
- Gluons helped to solve the missing momentum problem. Will they also be a remedy for the missing spin?

SPIN CRISIS
How to measure $\Delta G$?

In DIS – through the interaction that probes directly gluons inside the nucleon.

Photon Gluon Fussion (PGF): $\gamma^* g \rightarrow \bar{q}q$
What is measured in the experiment

In the experiment we have:

Asymmetry for the interactions measured in the experiment:

\[ A_{\text{exp}} = \frac{N_u - N_d}{N_u + N_d} \]

Asymmetry of the cross sections for PGF process:

\[ A = \frac{\sigma^{\leftrightarrow} - \sigma^{\leftrightarrow}}{\sigma^{\leftrightarrow} + \sigma^{\leftrightarrow}} \]

The physics and experimental asymmetries:

\[ A_{\text{exp}} = P_T P_B f A \]

- \( P_T \) – target polarization (≈50%), ±5%
- \( P_B \) – beam polarization (≈76%, 81%), ±5%
- \( f \) – dilution factor (≈40%), ±5%
Methods of the PGF measurement

Photon Gluon Fussion:

Method I – open charm production (“golden channel”)
- $c\bar{c}$ production
- 1.2 $D^0$ per $c\bar{c}$-event
- $D^0 \rightarrow K\pi$ (BR $\sim$4%)
- hard scale set by $4m_c^2$
- no background asymmetry
- only weakly MC dependent
- limited statistics

Method II – 2 high $p_T$ hadrons ($Q^2$>1 GeV$^2$)
- hard scale set by $Q^2$
- larger statistics
- resolved photon negligible
- large dilution of other processes
- dependence on MC

Method III – 2 high $p_T$ hadrons ($Q^2$<1 GeV$^2$)
- hard scale set by $p_T^2$
- very large statistics
- resolved photon not negligible
- large dilution of other processes
- strong dependence on MC
Open charm production and decay

\[ D^0 \rightarrow K\pi \quad (BR \sim 4\%) \]

- Each of the cells 60 cm long
- Enclosed in the solenoid and cooling system
- No vertex detector
- Very high combinatorial background
- RICH identification of kaons essential

- Kaons identification for momenta > 9 GeV
- \( \pi \) is not identified as K

- Cuts on kinematics:
  - \( z(D^0) > 0.25 \) where \( z(D^0) = E_{D^0}/\nu \)
  - \( |\cos\theta_K^*| < 0.5 \)
Open charm signal

\[ S_{eff} = \frac{S}{1 + B/S} \]

\[ S_{eff} = 1051 \pm 18 \]

\[ N(D^0) = 14577 \pm 604 \]

Mass: \[ 2.9 \pm 1.1 \text{ MeV/c}^2 \]

Sigma: \[ 26.6 \pm 1.2 \text{ MeV/c}^2 \]

COMPASS preliminary

Still high combinatorial background...
Open charm tagged with D* 

~30% D⁰ come from D* decays:

\[ D^* \rightarrow D^0 \pi_S \rightarrow K \pi \pi_S \]
Open charm production and decay

\[ D^0 \rightarrow K\pi \quad (BR \sim 4\%) \]

\[ \sim 30\% \ D^0 \ \text{come from} \ D^* \ \text{decays:} \]

\[ D^* \rightarrow D^0 \pi_S \rightarrow K\pi\pi_S \]

From asymmetry to \( \Delta G/G \):

\[ A^{YN} = \frac{S}{S+B}a_{LL} \frac{\Delta G}{G} \]

Where \( a_{LL} \) – partonic asymmetry for the \( \gamma^*g \) reaction

(PGF analyzing power)
NN parametrisation

- $a_{LL}$ for each event cannot be calculated directly – only one charmed meson measured per event
- Parametrisation based on the Aroma Monte Carlo is used
- Parametrisation prepared with Neural Networks
- $z_{D^0}$, $p_{T_{D^0}}$, $(x_{bj}, y, Q^2)$ variables used for parametrisation

Correlation factor 82%
Preliminary results from open charm channel from 2002/3/4 data

$$\Delta G/G = -0.57 \pm 0.41 \text{ (stat.)}$$

$$x_g \approx 0.15 \text{ (RMS 0.08)}$$

scale $\approx 13 \text{ GeV}^2 \approx 4m_c^2$
Systematic error

A number of potential systematic effects studied:

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>δ(ΔG/G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background asymmetry</td>
<td>0.07</td>
</tr>
<tr>
<td>Binning procedure</td>
<td>0.04</td>
</tr>
<tr>
<td>False asymmetries (pulls method)</td>
<td>0.10</td>
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<tr>
<td>Fitting</td>
<td>0.09</td>
</tr>
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<td>Parameters of Aroma</td>
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<td>Target polarisation</td>
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</tr>
<tr>
<td>Beam polarisation</td>
<td>0.03</td>
</tr>
<tr>
<td>Dilution factor</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Combined systematic error is: 0.17

\[ \Delta G/G = -0.57 \pm 0.41 \text{ (stat.)} \pm 0.17 \text{ (syst.)} \]
2 hadrons with high $p_T$ ($Q^2 > 1$ GeV$^2$)

Signal

Background

\[ A = R_{PGF} a_{LL}^{PGF} \frac{\Delta G}{G} + (R_{QCDC} a_{LL}^{QCDC} + R_{LO} a_{LL}^{LO}) \frac{\Delta q}{q} \]

where $R_{PGF}$, $R_{QCDC}$, $R_{LO}$ are the fractions of processes

- $Q^2 > 1$ GeV$^2$ sample – 10% of the whole statistics
- MC needed for $R_{PGF}$ fraction and $a_{LL}^{PGF}$
- LEPTO 6.5.1 generator is used + GEANT
- $x < 0.05 \rightarrow A_1^d$ - small, LO and QCDC negligible
2 hadrons with high $p_T$ ($Q^2 < 1 \text{ GeV}^2$)

\[ A = R_{\text{PGF}} a_{LL}^{\text{PGF}} \frac{\Delta G}{G} \]
\[ + R_{\text{QCDC}} a_{LL}^{\text{QCDC}} \frac{\Delta q}{q} \]
\[ + R_{qq} a_{LL}^{qq} \frac{\Delta q}{q} \left( \frac{\Delta q}{q} \right)_{\gamma} \]
\[ + R_{qq} a_{LL}^{gq} \frac{\Delta G}{G} \left( \frac{\Delta G}{G} \right)_{\gamma} \]
\[ + R_{gg} a_{LL}^{gg} \frac{\Delta G}{G} \left( \frac{\Delta G}{G} \right)_{\gamma} \]

Fractions of each process obtained from PYTHIA 6.2 Monte Carlo.
Preliminary results from 2 hadrons with high $p_T$ ($Q^2>1$ GeV$^2$) channel for 2002/3 data

- $p_{T1}, p_{T2} > 0.7$ GeV
- $p_{T1}^2 + p_{T2}^2 > 2.5$ GeV$^2$

For $Q^2>1$ GeV$^2$

$$\Delta G/G = 0.06 \pm 0.31 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$$

$$R_{\text{PGF}} = 0.34 \pm 0.07$$

$$x_g = 0.13 \text{ (RMS 0.08)}$$

scale: 3 GeV$^2$

For $Q^2<1$ GeV$^2$

$$\Delta G/G = 0.016 \pm 0.058 \text{ (stat.)} \pm 0.055 \text{ (syst.)}$$

$$R_{\text{PGF}} = 0.30$$

$$x_g = 0.095^{+0.08}_{-0.04}$$

scale: 3 GeV$^2$
Results from COMPASS

Lines obtained from NLO QCD fits including a new COMPASS deuteron results on $g_1^d$ (hep-ex/0701014 and PLB 647 (2007)). Two equally good solutions for $\Delta G/G$ were found. For both $|\Delta G| = 0.2 - 0.3$. 
Summary

- Results of $\Delta G/G$ measurements were presented.
- 3 channels were studied:
  - Open charm (2002-4): $\Delta G/G = -0.57 \pm 0.41 \text{ (stat.)} \pm 0.17 \text{ (syst.)}$
  - High $p_T$ ($Q^2>1$) (2002-3): $\Delta G/G = 0.06 \pm 0.31 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$
  - High $p_T$ ($Q^2<1$) (2002-4): $\Delta G/G = 0.016 \pm 0.058 \text{ (stat.)} \pm 0.055 \text{ (syst.)}$

- Small $\Delta G$ are preferred.
- But still scenarios with large $\Delta G (>0.4)$ not excluded.
- The question of $L_{q,g}$ importance still open.
Prospects

• Results from 2002-4 high $p_T$ ($Q^2>1$) analysis available soon
• 2002-4 open charm analysis still ongoing
• For high $p_T$ analysis binning in $x_g$ considered, NN approach under investigation

• Improvements of COMPASS in 2006:
  • New target solenoid – improvement in hadron acceptance (+30%)
  • Improvements in RICH efficiency
  • New tracking detectors
Spares
• ~350 detector planes
• Track reconstruction for momenta > 0.4 GeV
• Very small angles: SciFi, Silicon Microstrips
• Small angles: Micromega, GEM
• Large angles: Drift Chamber, Straw Tubes, MWPC
The Dynamic Nuclear Polarisation (DNP)

- The target material is kept at a low temperature (0.4 K) + strong magnetic field – very high electron polarisation is achieved.
- Microwave radiation of energy needed for the simultaneous flip of the proton and electron spins.
- This energy depends on the value of the total spin of the electron-proton system.
- After rotation electron relaxates to the lower energy state.
- While proton does not change the spin orientation.
- Separate microwave system for each of the cells.
- In the gap there is a microwave stopper.
- Polarisation is measured by NMR coils
Particles Identification

- >80 m³ filled with C₄F₁₀
- 116 VUV mirrors
- active area: 5.3 m² photodetectors
  82 944 pixels
- >80k channels
- π/K/p identification up to 50 GeV
  from 2.5/9/17 GeV

80% of K from D⁰

For muons identification additionally muon filters and calorimeters are used

HCAL calorimeters

iron – scintillator sandwich
What is measured in the experiment

Taking into account also asymmetry after pol. rotation:

\[ A_{\text{exp}} = \frac{1}{2} \left( \frac{N_u - N_d}{N_u + N_d} + \frac{N_d' - N_u'}{N_d' + N_u'} \right) \]

The physical and experimental asymmetries:

\[ A_{\text{exp}} = P_T P_B f A \]

- \( P_T \) – target polarization (~50%), ± 5%
- \( P_B \) – beam polarization (~76%, 81%), ± 5%
- \( f \) – dilution factor (~40%), ± 5%
2 hadrons with high $p_T$ ($Q^2>1$ GeV$^2$)

- Cuts used:
  - hadrons detected in the hadronic calorimeters
  - & discarded if detected behind the hadron absorbers
  - current fragmentation region ($x_F>0.1$ & $z>0.1$)
  - $0.1<y<0.9$ (assure that there is no big influence of radiative corrections),
  - $x<0.05 \rightarrow A^d_1$ - small, LO and QCDC negligible
  - $p_{T1}, p_{T2} > 0.7$ GeV
  - $p_{T1}^2 + p_{T2}^2 > 2.5$ GeV$^2$
  - invariant mass $m_{h_1h_2} > 1.5$ GeV (avoid the resonance region)

as in SMC
2 hadrons with high $p_T$ ($Q^2<1$ GeV$^2$)

The fractions of each process obtained from PYTHIA 6.2 Monte Carlo.

+ GEANT for the detector description

The agreement between Real Data (blue points) and Monte Carlo:
2 hadrons with high $p_T$ ($Q^2<1\text{ GeV}^2$)

- The systematical error can be decomposed:
  - False asymmetries (experimental systematics): 0.014
  - Resolved photon contribution: 0.013
  - Monte Carlo tuning: 0.052
    - The MC parameters were changed in a range where the resonable agreement between the data and MC remains
    - 30% difference in $R_{_{PGF}}$ found
Results from COMPASS

\[ \int \Delta G \, dx = 2.5 \]
\[ \int \Delta G \, dx = 0.62 \]
\[ \int \Delta G \, dx = 0.16 \]
Figure 7: Gluon distribution $x\Delta G(x)$ corresponding to the fits with $\Delta G > 0$ (left) and $\Delta G < 0$ (right) obtained with the program of Ref. [27]. The dashed, solid and dotted lines correspond to $Q^2 = 1.5$, 3 and 10 $(\text{GeV}/c)^2$, respectively. The unpolarised distributions $\pm x G(x)$ which were used in the fit as constrains for the polarised ones are shown for $Q^2 = 1.5$ and 3 $(\text{GeV}/c)^2$. 
Values used for extraction of $\Delta G/G$
$A_1^d$ WORLD DATA

- COMPASS 2002-03, $Q^2 \geq 1$ GeV$^2$
- COMPASS 2002-03, $Q^2 < 1$ GeV$^2$ (PRELIMINARY)
- E143, $Q^2 \geq 1$ GeV$^2$
- E155, $Q^2 \geq 1$ GeV$^2$
- HERMES, $Q^2 > 1$ GeV$^2$
- SMC, all $Q^2$

![Graph showing $A_1^d$ as a function of $x$ with error bars for different experiments.](image-url)
**Figure 2.11:** The gluon momentum distribution extracted from a QCD analysis compared to the result obtained with an open charm tagging approach. The line ("H1 prel") shows $xG(x)$ as extracted via a QCD fit on NMC and H1 data, error bands taking into account theoretical and experimental uncertainties are indicated. The points are obtained from a $D^*$ meson cross-section measurement by the H1 collaboration. For the DIS measurement $Q^2 > 2 \text{(GeV/c)}^2$ was required, whereas for the photoproduction ($\gamma p$) $Q^2 < 0.01 \text{(GeV/c)}^2$ was used [50].