Gluon Polarisation Results from the COMPASS Experiment

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Outline:

• Motivation
• High $p_T$ Analysis
• Open Charm (LO and NLO) Analyses
• $\Delta G/G$ Results
• Summary and Conclusions
THE COMPASS EXPERIMENT
Common Muon and Proton Apparatus for Structure and Spectroscopy

~250 physicists
25 institutes
11 countries

Data taken: 2002 - 2012, ...

Fixed-target experiment at SPS
Muon & hadron beams ~ 200 GeV
Polarised p&d targets, LH target
Versatile spectrometer
Running since 2002
Nucleon structure & hadron spectroscopy
The Nucleon Spin

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

Quarks

Gluons

Well known!

In 1988 EMC measured
\[ \Delta \Sigma = 0.12 \pm 0.17 \] (Phys.Lett.B206,364)

A recent result, including COMPASS, gives:
\[ \Delta \Sigma = 0.30 \pm 0.01_{\text{(stat.)}} \pm 0.02_{\text{(evol.)}} \] Phys.Lett.B647,8

Not completely known

Exploratory and discovery stage. Some experiments and data might give hints.

COMPASS, HERMES, CLAS, STAR, PHENIX, EIC.

Partons Angular Orbital Momenta

Future! GPDs
Direct Measurement of $\Delta G/G$

Photon-gluon fusion (PGF) process

$$A_{PGF} = \frac{N_{PGF}^{\Rightarrow} - N_{PGF}^{\Leftarrow}}{N_{PGF}^{\Rightarrow} + N_{PGF}^{\Leftarrow}}$$

$$\Rightarrow \Delta G/G$$
Direct Measurement of $\Delta G/G$

To select this process there are two methods:

- **High transverse momentum hadrons** ($Q^2<1$ and $Q^2>1$ (GeV/c)$^2$)
  - 😊 Much more statistics.
  - 😞 Physical background: strongly model dependent requires a very good agreement between MC and Data.

- **Open-charm meson** (D mesons)
  - 😊 Provides the purest sample of PGF events, almost free from background contamination.
  - 😞 Small dependence on MC.
  - 😞 Low statistics.

Photon-gluon fusion (PGF) process

\[ \gamma^* g \rightarrow q \bar{q} \]
High \( p_T \) Analysis

\[ A_{2h}^{LL}(x) = \frac{\Delta G}{G}(x_g) a_{LL}^{PGF} \sigma^{PGF}_{Tot} + A_{1}^{LO}(x_C) a_{LL}^{C} \sigma^{C}_{Tot} + A_{1}^{LO}(x_{Bj}) D \sigma^{LO}_{Tot} \]

\( A_{1}^{LO} \): estimated by an inclusive sample

Final formula for the gluon polarisation

\[
\frac{\Delta G}{G}(x_g^{av}) = \frac{1}{\beta} \left[ A_{2h}^{LL}(x_{Bj}) + A_{corr} \right]
\]

\[
\beta = a_{LL}^{PGF} R_{PGF} - a_{LL}^{PGF, incl} R_{PGF}^{incl} \frac{R_{LO}}{R_{LO}^{incl}} - a_{LL}^{PGF, incl} R_{C} R_{PGF}^{incl} \frac{R_{LO}^{incl}}{D}
\]

\[
A_{corr} = - \left( A_{1}(x_{Bj}) D \frac{R_{LO}}{R_{LO}^{incl}} - A_{1}(x_{C}) \beta_{1} + A_{1}(x_{C}^{'}) \beta_{2} \right)
\]

\( R_{i} = \frac{\sigma^{i}_{TOT}}{\sigma^{TOT}_{Tot}} \)

- \( A_{2h}^{LL} \): measured from the two hadron sample.
- \( a_{LL}^{PGF, incl} \) and \( R_{i} \): estimated from MC and parametrised using a Neural Network.
MC Simulation and Neural Network

Data-MC comparison: $Q^2$, $p_T$ and hadron multiplicities.

- Full chain of MC has been used: Generator (LEPTO) + Apparatus Simulation (GEANT) + Reconstruction Program.
- PDF: MSTW2008LO.
- High $p_T$ sample:
  - MC with parton shower ON.
  - A new tuning was performed to improve the hadron description.
Results

\[ \frac{\Delta G}{G} = 0.125 \pm 0.060 \pm 0.063 \quad x_g = 0.09^{+0.08}_{-0.05} \quad \mu^2 = 3 \ (\text{GeV/c})^2 \]

- The whole statistics was divided, for the first time, in 3 independent samples, having each one its own \( x_g \) distribution.

<table>
<thead>
<tr>
<th></th>
<th>1(^{st}) point</th>
<th>2(^{nd}) point</th>
<th>3(^{rd}) point</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta G/G )</td>
<td>0.147 \pm 0.091 \pm 0.088</td>
<td>0.079 \pm 0.096 \pm 0.082</td>
<td>0.185 \pm 0.165 \pm 0.143</td>
</tr>
<tr>
<td>( &lt;x_g&gt; )</td>
<td>0.07 ( +0.05 ) ( -0.03 )</td>
<td>0.10 ( +0.07 ) ( -0.04 )</td>
<td>0.17 ( +0.10 ) ( -0.06 )</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \text{Within the errors the 3 points show no } x_g \text{ dependence} \]

*Physics Letters B 718 (2013) 922–930*
High $p_T$ Analysis, $Q^2 < 1 \text{ (GeV/c)}^2$

2002-2004 Preliminary:
$\Delta G/G = 0.016 \pm 0.058 \text{(stat)} \pm 0.055 \text{(syst)}$

2002-2003 Published:
$\Delta G/G = 0.024 \pm 0.089 \text{(stat)} \pm 0.057 \text{(syst)}$

New $\Delta G/G$ Result from High $p_T$ Analysis

$\Delta g/g$ vs $x_g$

- New COMPASS, high $p_T$, $Q^2 > 1 \text{(GeV/c)}^2$, 2002-2006
- COMPASS, high $p_T$, $Q^2 < 1 \text{(GeV/c)}^2$, 2002-2003
- COMPASS, open charm, 2002-2007
- SMC, high $p_T$, $Q^2 > 1 \text{(GeV/c)}^2$
- HERMES, high $p_T$, all $Q^2$

- DSSV fit, $\mu^2 = 3 \text{(GeV/c)}^2$
- LSS fit with $\Delta G > 0$, $\mu^2 = 2.5 \text{(GeV/c)}^2$
- LSS fit with $\Delta G$ changing sign, $\mu^2 = 2.5 \text{(GeV/c)}^2$

Open Charm

- The relation between the number of reconstructed $D^0$ (for each target cell configuration) and $\Delta G/G$ is given by:

\[
N_t = a \phi n (S + B) \left( 1 + f_{PT} P_\mu \left[ a_{LL} \frac{S}{S+B} \frac{\Delta G}{G} + D \frac{B}{S+B} A^{bg} \right] \right), \quad t = (u, d, u', d')
\]

acceptance, muon flux, number of target nucleons

- Each equation is weighted with a signal weight $w_S = f_P m a_{LL} S/(S+B)$ and also with a background weight $w_B = f_P m D B/(S+B)$:

8 equations with 7 unknowns: $\Delta G/G$, $A^{bg}$ + 5 independent $\alpha = (a \phi n)$ factors

The system is solved by a $\chi^2$ minimisation
**D^0 Invariant Mass Spectra: 2002-2007 Data**

**Number of D^0:**
- Total = 86250
- $^6$LiD = 57400
- NH$_3$ = 28850
Neural Network Parametrisation

- Two real data samples (with the same cuts applied) are compared by a Neural Network (using some kinematic variables as a learning vector):
  - **Signal model** $gcc = K^+\pi^-\pi_s^- + K^-\pi^+\pi_s^+$
    
    *(D^0 spectrum: signal + background)*
  
  - **Background model** $wcc = K^+\pi^-\pi_s^- + K^-\pi^+\pi_s^+$
    
    *(no D^0 is allowed)*

- If the background model is good enough, the Neural Network is able to distinguish the signal from the combinatorial background on a event by event basis (inside $gcc$).
NLO Corrections for Open Charm Analysis

NLO corrections to the analysing power $a_{LL}$
Open Charm $\Delta G/G$ Results: LO and NLO

\[ \frac{\Delta G}{G} = -0.06 \pm 0.21_{(\text{stat})} \pm 0.08_{(\text{syst})} \]

\[ \langle x_g \rangle = 0.11^{+0.11}_{-0.05}, \quad \langle \mu^2 \rangle = 13 \text{ (GeV/c)}^2 \]

\[ \Delta G/G = -0.13 \pm 0.15_{(\text{stat})} \pm 0.15_{(\text{syst})} \]

\[ \langle x_g \rangle = 0.20^{+0.13}_{-0.08}, \quad \langle \mu^2 \rangle = 13 \text{ (GeV/c)}^2 \]

\textbf{Physical Review D 87, 052018 (2013)}
Summary and Conclusions

Summary:
- The importance of the gluon polarisation measurement concerning the nucleon spin structure was emphasised.
- The direct measurement methods were explained.
- The gluon polarisations results are presented.

Conclusions:
- Around $X_g \sim 0.1$ all measurements of $\Delta G/G$ are compatible with zero.
- Still there is the contribution of $L_{\text{partons}}$ to be taken into account.
- The COMPASS-II program foresees to measure $L_{\text{partons}}$ via GPDs.
Spares
**High $p_T$ Asymmetries**

$5 p_T$ bins x $5 X_{bj}$ bins

$A_{LL}^{2h}/D$ asymmetries as a function of $x_{bj}$ and $\sum p_T^2$.

<table>
<thead>
<tr>
<th>$x_{bj}$</th>
<th>$p_{T1}^2 + p_{T2}^2$ (GeV/c)$^2$</th>
<th>$\langle x_{bj} \rangle$</th>
<th>$\langle Q^2 \rangle$ (GeV/c)$^2$</th>
<th>$\langle p_{T1}^2 + p_{T2}^2 \rangle$ (GeV/c)$^2$</th>
<th>$A_{LL}^{2h}/D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.004–0.01</td>
<td>0.65–1.0</td>
<td>0.007</td>
<td>1.4</td>
<td>0.86</td>
<td>0.002 ± 0.011</td>
</tr>
<tr>
<td>0.004–0.01</td>
<td>1.0–2.0</td>
<td>0.007</td>
<td>1.4</td>
<td>1.35</td>
<td>−0.002 ± 0.009</td>
</tr>
<tr>
<td>0.004–0.01</td>
<td>2.0–3.0</td>
<td>0.007</td>
<td>1.4</td>
<td>2.39</td>
<td>−0.019 ± 0.020</td>
</tr>
<tr>
<td>0.004–0.01</td>
<td>3.0–4.0</td>
<td>0.007</td>
<td>1.4</td>
<td>3.41</td>
<td>−0.075 ± 0.037</td>
</tr>
<tr>
<td>0.004–0.01</td>
<td>4.0–</td>
<td>0.007</td>
<td>1.5</td>
<td>5.45</td>
<td>0.001 ± 0.045</td>
</tr>
<tr>
<td>0.01–0.02</td>
<td>0.65–1.0</td>
<td>0.014</td>
<td>2.4</td>
<td>0.86</td>
<td>−0.009 ± 0.012</td>
</tr>
<tr>
<td>0.01–0.02</td>
<td>1.0–2.0</td>
<td>0.014</td>
<td>2.4</td>
<td>1.35</td>
<td>−0.016 ± 0.010</td>
</tr>
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<td>0.01–0.02</td>
<td>2.0–3.0</td>
<td>0.014</td>
<td>2.5</td>
<td>2.39</td>
<td>0.007 ± 0.024</td>
</tr>
<tr>
<td>0.01–0.02</td>
<td>3.0–4.0</td>
<td>0.014</td>
<td>2.6</td>
<td>3.41</td>
<td>0.054 ± 0.045</td>
</tr>
<tr>
<td>0.01–0.02</td>
<td>4.0–</td>
<td>0.014</td>
<td>2.7</td>
<td>5.48</td>
<td>−0.033 ± 0.056</td>
</tr>
<tr>
<td>0.02–0.05</td>
<td>0.65–1.0</td>
<td>0.030</td>
<td>4.8</td>
<td>0.85</td>
<td>0.015 ± 0.016</td>
</tr>
<tr>
<td>0.02–0.05</td>
<td>1.0–2.0</td>
<td>0.030</td>
<td>5.0</td>
<td>1.35</td>
<td>0.018 ± 0.013</td>
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<td>0.02–0.05</td>
<td>2.0–3.0</td>
<td>0.030</td>
<td>5.3</td>
<td>2.39</td>
<td>0.056 ± 0.031</td>
</tr>
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<td>0.02–0.05</td>
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<td>5.5</td>
<td>3.41</td>
<td>0.054 ± 0.057</td>
</tr>
<tr>
<td>0.02–0.05</td>
<td>4.0–</td>
<td>0.031</td>
<td>5.9</td>
<td>5.52</td>
<td>0.066 ± 0.068</td>
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<tr>
<td>0.05–0.10</td>
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<td>0.069</td>
<td>10.9</td>
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<td>0.074 ± 0.029</td>
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<tr>
<td>0.05–0.10</td>
<td>1.0–2.0</td>
<td>0.068</td>
<td>11.4</td>
<td>1.35</td>
<td>0.038 ± 0.025</td>
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<tr>
<td>0.05–0.10</td>
<td>2.0–3.0</td>
<td>0.069</td>
<td>12.2</td>
<td>2.39</td>
<td>0.051 ± 0.057</td>
</tr>
<tr>
<td>0.05–0.10</td>
<td>3.0–4.0</td>
<td>0.068</td>
<td>12.9</td>
<td>3.40</td>
<td>−0.079 ± 0.105</td>
</tr>
<tr>
<td>0.05–0.10</td>
<td>4.0–</td>
<td>0.069</td>
<td>13.6</td>
<td>5.67</td>
<td>−0.087 ± 0.123</td>
</tr>
<tr>
<td>0.10–1.00</td>
<td>0.65–1.0</td>
<td>0.170</td>
<td>28.2</td>
<td>0.85</td>
<td>0.100 ± 0.043</td>
</tr>
<tr>
<td>0.10–1.00</td>
<td>1.0–2.0</td>
<td>0.172</td>
<td>29.9</td>
<td>1.35</td>
<td>0.143 ± 0.036</td>
</tr>
<tr>
<td>0.10–1.00</td>
<td>2.0–3.0</td>
<td>0.172</td>
<td>31.7</td>
<td>2.39</td>
<td>−0.037 ± 0.083</td>
</tr>
<tr>
<td>0.10–1.00</td>
<td>3.0–4.0</td>
<td>0.158</td>
<td>29.0</td>
<td>3.41</td>
<td>−0.191 ± 0.156</td>
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<tr>
<td>0.10–1.00</td>
<td>4.0–</td>
<td>0.168</td>
<td>32.8</td>
<td>5.67</td>
<td>0.593 ± 0.180</td>
</tr>
</tbody>
</table>
The COMPASS Spectrometer

Common Muon and Proton Apparatus for Structure and Spectroscopy

Two staged spectrometer:
LAS and SAS
Polarised beam and target

- Trackers
- Magnets
- RICH
- Electromagnetic Calorimeters
- Hadronic Calorimeters
- Absorbers
- Target

Acceptance:
70 mrad (2002-04)
180 mrad (2006)

About 350 detector planes
Track reconstruction p > 0.5 GeV/c

NIM A577 (2007) 455

160 GeV μ⁺
The final formula for the gluon polarisation:

\[
\frac{\Delta G}{G} (x_g^{av}) = \frac{A_{LL}^{2h}(x_{Bj})}{\beta} - \frac{A_1(x_{Bj})}{\beta} D \frac{R_{LO}}{R_{LO}^{incl}} - \frac{A_1(x_C)}{\beta} \beta_1 + \frac{A_1(x_C')}{\beta} \beta_2
\]

\[
\beta = a_{LL}^{PGF} R_{PGF} - a_{LL}^{PGF, incl} R_{PGF}^{incl} \frac{R_{LO}}{R_{LO}^{incl}} - a_{LL}^{PGF, incl} \frac{R_C R_{PGF}^{incl}}{R_{LO}^{incl} D}
\]

\[
\beta_1 = \frac{1}{R_{LO}^{incl}} \left( a_{LL}^C R_C - a_{LL}^{incl} R_{C}^{incl} R_{LO} \right)
\]

\[
\beta_2 = a_{LL}^{C, incl} \frac{R_C R_{C}^{incl} a_{LL}^C}{(R_{LO}^{incl})^2 D}
\]

- \(A_{LL}^{2h}\) is the measured 2-h asymmetry.
- \(a_{LL}\) and \(R\) are estimated using MC.
- The \(A_1\) are taken using a parametrisation on inclusive data. (EPJ C52 (2007)255)
Monte Carlo Simulation

This analysis uses information from the MC, thus a strong effort and care to ensure that the MC simulation describes as good as possible the data was undertaken.

Two MC samples were used in the analysis: high $p_T$ and inclusive samples.

- Full chain of MC has been used: Generator (LEPTO) + Apparatus Simulation (GEANT) + Reconstruction Program.
- PDF: MSTW2008LO.
- High $p_T$ sample:
  - MC with parton shower ON has been used in the analysis.
  - A new tuning was performed to improve the hadron description.
MC Tuning

- The purpose of the **MC tuning** is to **correct** the shapes of the **hadron variables** (momenta) and **fragmentation** (multiplicity).

- In **LEPTO** this can be **achieved** by changing **JETSET** parameters:

  - These **parameters** can be **divided** into **two sets** regarding the component of the **trajectory** of the particles: **transverse** and **longitudinal** variable components.

  - The **sets** can be **tuned independently**.

    ⇒ The tuning improves substantially the Data-MC agreement.
Monte Carlo Simulation

\[ f(z) \propto \frac{1}{2} (1-z)^a \exp \left( -\frac{b m_T^2}{z} \right) \]

\begin{align*}
\sigma &= \text{PARJ}(21) \\
\text{ampl.} &= \text{PARJ}(23) \times A \\
\sigma &= \text{PARJ}(24) \times \text{PARJ}(21) \\
\text{ampl.} &= \text{PARJ}(23) \times A
\end{align*}

<table>
<thead>
<tr>
<th>\text{COMPASS new tuning}</th>
<th>\text{LEPTO default tuning}</th>
</tr>
</thead>
<tbody>
<tr>
<td>\text{PARJ(21)}</td>
<td>0.34</td>
</tr>
<tr>
<td>\text{PARJ(23)}</td>
<td>0.04</td>
</tr>
<tr>
<td>\text{PARJ(24)}</td>
<td>2.8</td>
</tr>
<tr>
<td>\text{PARJ(41)}</td>
<td>0.025</td>
</tr>
<tr>
<td>\text{PARJ(42)}</td>
<td>0.075</td>
</tr>
</tbody>
</table>

Transverse momentum of the hadron fragmentation

Fragmentation function
Data – Monte Carlo comparison
Data – Monte Carlo comparison

high-$p_T$ sample: hadron variables ($p_{T1}$, $p_{T2}$, $p_1$, $p_2$, and hadron multiplicity)
Weighted method

• A weight is applied on event-by-event basis:

\[ W = fDP_b \beta \]

, where \( \beta \) is a factor depending on \( a_{LL}^i \) and \( R^i \)

• Therefore for every event we have to know:

\[ R_{PGF}, R_C, R_{LO}, R_{PGF}^{incl}, R_C^{incl}, R_{LO}^{incl}, \]

\[ a_{LL}^{PGF}, a_{LL}^C, a_{LL}^{PGF, incl}, a_{LL}^{C, incl}, \]

\[ \chi_C, \chi_G, \]

\[ f, D, P_b \]

\( f, D, P_b \) are directly obtained from data.
The all the others variables have to be estimated/parametrised.
Results

\[ \frac{\Delta G}{G} = 0.125 \pm 0.060 \pm 0.063 \quad x_q = 0.09^{+0.08}_{-0.05} \quad \mu^2 = 3 \ (\text{GeV/c})^2 \]
# Systematic Uncertainties

<table>
<thead>
<tr>
<th>Sources of Systematic Uncertainties</th>
<th>δ(ΔG/G)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High pT</td>
</tr>
<tr>
<td>MC Simulation</td>
<td>0.045</td>
</tr>
<tr>
<td>Formula Simplification</td>
<td>0.035</td>
</tr>
<tr>
<td>False Asymmetries</td>
<td>0.019</td>
</tr>
<tr>
<td>A_1 Parametrisation</td>
<td>0.015</td>
</tr>
<tr>
<td>NN Parametrisation</td>
<td>0.010</td>
</tr>
<tr>
<td>P_B', P_T', f</td>
<td>0.004</td>
</tr>
<tr>
<td>a_LL</td>
<td></td>
</tr>
<tr>
<td>s/(s+b)</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.063</td>
</tr>
</tbody>
</table>
Neural Network qualification of events

- Two real data samples (with the same cuts applied) are compared by a Neural Network (using some kinematic variables as a learning vector):

  - **Signal model** → \( \text{gcc} = K^+\pi^-\pi_s^- + K^-\pi^+\pi_s^+ \) (\(D^0\) spectrum: signal + background)

  - **Background model** → \( \text{wcc} = K^+\pi^+\pi_s^- + K^-\pi^-\pi_s^+ \) (no \(D^0\) is allowed)

- If the background model is good enough: The Neural Network is able to distinguish the signal from the combinatorial background on a event by event basis (inside gcc)

  Example of a good learning variable

![Preliminary](image1.png)

**COMPASS 2006 D^0 (D^+ tagged): D^0 signal region**

**COMPASS 2006 D^0 (D^+ tagged): sidebands**
Analysing power (muon-gluon asymmetry $a_{LL}$)

- $a_{LL}$ is dependent on the full knowledge of the partonic kinematics:

$$a_{LL} = \frac{\Delta \sigma^{PGF}}{\sigma_{PGF}}(y, Q^2, x_g, z_C, \Phi)$$

Can't be experimentally obtained: only one charmed meson is reconstructed

- $a_{LL}$ is obtained from Monte-Carlo (in LO), to serve as input for a Neural Network parameterisation on some reconstructed kinematical variables: $y, x_{Bj}, Q^2, z_D$ and $p_T$

Parameterised $a_{LL}$ shows a strong correlation with the generated one (using AROMA)
Comparison of $a_{LL}$(LO) with $a_{LL}$(NLO)

- The AROMA generator is used to simulate the phase space for the NLO (PS on) / LO (PS off) calculations of $a_{LL}$. The resulting $D^0$ mesons are reconstructed in the COMPASS spectrometer like real events. The respective $a_{LL}$ distributions are: