COMPASS results on gluon polarisation

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On behalf of the COMPASS Collaboration

Outline:

• Brief Motivation
• High $p_T$ and Open Charm analyses
• $\Delta G/G$ results
• Summary and Conclusion
THE COMPASS EXPERIMENT

Beam: $2 \cdot 10^8 \mu^+$/spill
Luminosity: $\sim 5 \cdot 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$
Beam polarisation: 80%
Beam momentum: 160 GeV/c

Data taken: 2002 - 2011, ...

~250 physicists
25 institutes
11 countries
The COMPASS Spectrometer
Common Muon and Proton Apparatus for Structure and Spectroscopy

Two staged spectrometer:
LAS and SAS
Polarised beam and 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 $\mu^+$

Trackers
Magnets
RICH
Electromagnetic Calorimeters
Hadronic Calorimeters
Absorbers
Target
The Nucleon Spin

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

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

Partons
Orbital Angular Momenta

Quarks
Gluons

Well known!

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

COMPASS, HERMES, CLAS, STAR, PHOENIX

Future!
GPDs
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)$^2$)
  - Smiley face: High statistics.
  - Sad face: Physical background: strongly model dependent, requires a very good agreement between MC and Data.

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

Photon-gluon fusion process (PGF)
Direct measurement of $\Delta G/G$

Photon-gluon fusion process (PGF)

$$\gamma^* g \rightarrow q \bar{q}$$

Experiments with polarised beam and target are sensitive to gluon helicity

$$A_{PGF} = \frac{N_{PGF}^{\rightarrow} - N_{PGF}^{\leftarrow}}{N_{PGF}^{\rightarrow} + N_{PGF}^{\leftarrow}}$$

$$\Rightarrow \Delta G/G$$

Experiments with polarised beam and target are sensitive to gluon helicity
High $p_T$ Analysis

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

$A_{1}^{LO}$ : estimated by an inclusive sample

Final formula for the gluon polarisation

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

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

$$A_{corr} = - \left( A_{1}(x_{Bj}) D R_{LO}^{incl} - A_{1}(x_C) \beta_1 + A_{1}(x_C') \beta_2 \right)$$

- $A_{LL}^{2h}$ : measured from the two hadron sample.
- $a_{LL}^{i}$ and $R_{i}$ : estimated from MC and parametrised using a Neural Network.

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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.

Data

Training and Parametrisation

Event By Event

MC

NN

Extraction

$\Delta G/G$
High $p_T$ Results, $Q^2 > 1 \, (GeV/c)^2$

$\Delta g/g$

COMPASS, high $p_T$, $Q^2>1 \, (GeV/c)^2$, prel., 02-06

Preliminary
High $p_T$ Results, $Q^2 > 1 \text{ (GeV/c)}^2$

The whole statistics was divided, for the first time, resulting in 3 independent measurements, for $Q^2 > 1 \text{ GeV/c}$. 
High \( p_T \) Analysis, \( Q^2 < 1 \) (GeV/c)^2

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

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

\[ \text{Phys. Lett. B 633,25} \]
Open Charm

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

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

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
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**
    \[ g_{cc} = K^+\pi^-\pi^- + K^-\pi^+\pi^+ \]
    \((D^0 \text{ spectrum: signal + background})\)
  - **Background model**
    \[ w_{cc} = K^+\pi^-\pi^- + K^-\pi^-\pi^+ \]
    \((no \ D^0 \text{ is allowed})\)

- 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 \( g_{cc} \))

\[ \delta \left( \frac{\Delta G}{G} \right) \propto \frac{1}{\text{FOM}} \]
ΔG/G Results (LO)

- COMPASS, high $p_T$, $Q^2 > 1$ (GeV/c)$^2$, prel., 02-06
- COMPASS, high $p_T$, $Q^2 < 1$ (GeV/c)$^2$, prel., 02-04
- COMPASS, open charm, prel., 02-07
- SMC, high $p_T$, $Q^2 > 1$ (GeV/c)$^2$
- HERMES, high $p_T$, all $Q^2$

Preliminary
\[ \frac{\Delta G}{G} = -0.08 \pm 0.21_{\text{stat}} \pm 0.08_{\text{syst}} \quad \langle x_g \rangle = 0.11^{+0.11}_{-0.05}, \quad \langle \mu^2 \rangle = 13 \text{ (GeV/c)}^2 \]
NLO corrections for Open Charm analysis

NLO corrections to the analysing power $a_{LL}$

LO: PGF

NLO: bg

virtual corrections

NLO: PGF

gluon bremsstrahlung corrections

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$\Delta G/G = -0.20 \pm 0.21 \pm 0.08$ (syst) \hspace{1cm} \langle x_g \rangle = 0.28^{+0.19}_{-0.10}, \hspace{1cm} \langle \mu^2 \rangle = 13 \text{ (GeV/c)}^2$

Preliminary: theoretical uncertainties still under study ($a_{LL}$)
Summary and Conclusion

Summary:
- The direct measurement methods used in COMPASS experiment were explained.
- Several gluon polarisations results presented are in full agreement among themselves.

Conclusion:
- All measurements of $\Delta G/G$ are compatible with zero, around $X_g \sim 0.1$
- The $\Delta G$ seems to be a small contribution.
- The missing contribution could be in $L_g$ partons.
- COMPASS-II program foresees to measure $L_g$ partons via GPDs.
Spares
**D⁰ invariant mass spectra:** 2002-2007 data

- **D⁰ → K⁺π⁻**
  - Events / 10 MeV·c²
  - N(D⁰) = 62000

- **D* → D⁰π⁺ → K⁺π⁻π⁻**
  - Events / 10 MeV·c²
  - RICH sub-threshold Kaons
  - N(D⁰) = 3050

- **D* → D⁰π⁺ → K⁺π⁻π⁻π⁻**
  - Events / 10 MeV·c²
  - N(D⁰) = 4050

- **D⁰ → K⁺π⁰**
  - Events / 10 MeV·c²
  - N(D⁰) = 8500

**Number of D⁰:**

- **Total** = 90600
- **⁶LiD** = 65600
- **NH₃** = 25000
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:

<table>
<thead>
<tr>
<th>PARJ(21)</th>
<th>PARJ(23)</th>
<th>PARJ(24)</th>
<th>PARJ(41)</th>
<th>PARJ(42)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transverse momentum of the hadron fragmentation</td>
<td></td>
<td></td>
<td></td>
<td>Fragmentation function</td>
</tr>
</tbody>
</table>

• 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

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

\[ a = \text{PARJ}(41) \]
\[ b = \text{PARJ}(42) \]

<table>
<thead>
<tr>
<th>PARJ(21)</th>
<th>PARJ(23)</th>
<th>PARJ(24)</th>
<th>PARJ(41)</th>
<th>PARJ(42)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.34</td>
<td>0.04</td>
<td>2.8</td>
<td>0.025</td>
<td>0.075</td>
</tr>
<tr>
<td>0.36</td>
<td>0.01</td>
<td>2.0</td>
<td>0.3</td>
<td>0.58</td>
</tr>
</tbody>
</table>

COMPASS new tuning
LEPTO default tuning

Transverse momentum of the hadron fragmentation

Fragmentation function
Data – Monte Carlo comparison

- COMAPSS High $p_T$
- $Q^2 > 1$ (GeV/c)^2

Preliminary

- COMPASS High $p_T$
- $Q^2 > (GeV/c)^2$

Preliminary

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Data – Monte Carlo comparison

high-\(p_T\) sample: hadron variables (\(p_{T1}\), \(p_{T2}\) and \(\sum p_T^2\))
Data – Monte Carlo comparison

high-$p_T$ sample: hadron variables ($p_1$, $p_2$ and multiplicity)
Weighted method

A Neural Network is used to assign to each event a probability to be originated from one of the three processes (LO, PGF or Compton).

- A **MC** sample is used to train the Neural Network (NN).
- A parametrisation is constructed for all variables involved in the weight.
- A **Data** sample is weighted on an event-by-event basis.

Optimal usage of the data sample statistics
Weighted method

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

\[ W = f D P_b \beta \]

where \( \beta \) is a factor depending on \( a^i_{LL} \) 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.
Example: Stability plots for NN

We parametrise the $R^i$ fractions as probabilities.
Results

\[ \frac{\Delta G}{G} = 0.125 \pm 0.060 \pm 0.063 \quad x_c = 0.09^{+0.08}_{-0.04} \quad \langle \mu^2 \rangle = 3.4 \text{ (GeV/c)}^2 \]
Systematic Uncertainties

<table>
<thead>
<tr>
<th>Sources of Systematic Uncertainties</th>
<th>$\delta(\Delta G/G)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High pT</td>
</tr>
<tr>
<td>MC Simulation</td>
<td>0.05</td>
</tr>
<tr>
<td>Formula Simplification</td>
<td>0.04</td>
</tr>
<tr>
<td>False Asymmetries</td>
<td>0.02 0.08</td>
</tr>
<tr>
<td>$A_1$ Parametrisation</td>
<td>0.02</td>
</tr>
<tr>
<td>NN Parametrisation</td>
<td>0.01</td>
</tr>
<tr>
<td>$P_B$, $P_T$, f</td>
<td>0.004 0.01</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><strong>0.06 0.08</strong></td>
</tr>
</tbody>
</table>
**S/(S+B):** Obtaining final probabilities for a $D^0$ candidate

- Events with small $S/(S+B)_{\text{NN}}$
  - Mostly combinatorial background is selected

$S/(S+B)$ is obtained from a fit inside this bins (correcting with the NN parameterisation)

- Events with large $S/(S+B)_{\text{NN}}$
  - Mostly Open Charm are selected

$$\delta \left( \frac{\Delta G}{G} \right) \propto \frac{1}{\text{FOM}}$$
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** $\rightarrow$ $\text{gcc} = K^+\pi^-\pi^- + K^-\pi^+\pi^+$ (*$D^0$ spectrum: signal + background*)
  - **Background model** $\rightarrow$ $\text{wcc} = K^+\pi^+\pi^- + K^-\pi^-\pi^+$ (*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 $\text{gcc}$)

**Example of a good learning variable**
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 $a_{\text{LL}}$(LO) with $a_{\text{LL}}$(NLO)

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

![Analysing power distributions](image)

- NLO
- LO