COMPASS RESULTS ON GLUON POLARISATION FROM HIGH PT HADRON PAIRS

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Abstract

One of the goals of the COMPASS experiment is the determination of the gluon polarisation $\Delta G/G$, for a deep understanding of the spin structure of the nucleon. In DIS the gluon polarisation can be measured via the Photon-Gluon-Fusion (PGF) process, identified by open charm production or by selecting high $p_T$ hadron pairs in the final state. The data used for this work were collected by the COMPASS experiment during the years 2002-2004, using a 160 GeV naturally polarised positive muon beam scattering on a polarised nucleon target. A new preliminary result of the gluon polarisation $\Delta G/G$ from high $p_T$ hadron pairs in events with $Q^2 > 1 \text{ (GeV/c)}^2$ is presented. In order to extract $\Delta G/G$, this analysis takes into account the leading process $\gamma q$ contribution together with the PGF and QCD Compton processes. A new weighted method based on a neural network approach is used. A preliminary $\Delta G/G$ result for events from quasi-real photoproduction ($Q^2 < 1 \text{ (GeV/c)}^2$) is also presented.

1 Introduction

The COMPASS experiment is located in the Super Proton Synchrotron (SPS) accelerator at CERN. For a more complete description of the experimental apparatus the reader is addressed to [1]. In 2007, the COMPASS collaboration estimated the quark contribution to the nucleon spin with high precision [2], using a NLO QCD fit with all world data available. This contribution confirms that approximately 1/3 of the nucleon spin is carried by the quarks, as demonstrated by earlier experiments [3].

The nucleon spin can be written as:

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

(1)

$\Delta \Sigma$ and $\Delta G$ are, respectively, the quark and gluon contributions to the nucleon spin and $L$ is the orbital angular momentum contribution coming from the quarks and gluons.

The aim of this analysis is to estimate the gluon polarisation, $\Delta G/G$, using the high transverse momentum (high $p_T$) hadron pairs sample. The analysis is performed in two complementary kinematic regions: $Q^2 < 1 \text{ (GeV/c)}^2$ (low $Q^2$) and $Q^2 > 1 \text{ (GeV/c)}^2$ (high $Q^2$) regions. The present work is mainly focused on the analysis for high $Q^2$. However, the analysis for the low $Q^2$ region is summarised in sec. 6.

For completeness, the slides of the presentation can be found in [4].
2 Analysis Formalism

Spin-dependent effects can be measured experimentally using the helicity asymmetry

\[ A_{\text{LL}} = \frac{\Delta \sigma}{2\sigma} = \frac{\sigma^{\uparrow \downarrow} - \sigma^{\uparrow \uparrow}}{\sigma^{\uparrow \downarrow} + \sigma^{\uparrow \uparrow}} \]  

(2)
defined as the ratio of polarised (\(\Delta \sigma\)) and unpolarised (\(\sigma\)) cross sections. \(\uparrow \downarrow\) and \(\uparrow \uparrow\) refer to the parallel and anti-parallel spin helicity configuration of the beam lepton (\(\uparrow\)) with respect to the target nucleon (\(\uparrow\) or \(\downarrow\)).

According to the factorisation theorem, the (polarised) cross sections can be written as the convolution of the (polarised) parton distribution functions, \((\Delta)q_i\), the hard scattering partonic cross section, \((\Delta)\hat{\sigma}\), and the fragmentation function \(D_f\).

Figure 1: The contributing processes: a) DIS LO, b) QCD Compton and c) Photon-Gluon Fusion.

The gluon polarisation is measured directly via the Photon-Gluon Fusion process (PGF); which allows to probe the spin of the gluon inside the nucleon. To tag this process directly in DIS a high \(p_T\) hadron pairs data sample is used to calculate the helicity asymmetry. Two other processes compete with the PGF process in leading order QCD approximation, namely the virtual photo-absorption leading order (LO) process and the gluon radiation (QCD Compton) process. In Fig. 1 all contributing processes are depicted.

The helicity asymmetry for the high \(p_T\) hadron pairs data sample can thus be schematically written as:

\[ A_{\text{LL}}^{gh}(x_Bj) = R_{\text{PGF}} a_{\text{LL}}^{\text{PGF}} \frac{\Delta G}{G}(x_G) + R_{\text{LO}} D A_{1}^{\text{LO}}(x_{ Bj}) + R_{\text{QCDC}} a_{\text{LL}}^{\text{QCDC}} A_{1}^{\text{LO}}(x_{ C}) \]  

(3)

The \(R_i\) (the index \(i\) refers to the different processes) are the fractions of each process. \(a_{\text{LL}}^{i}\) represents the partonic cross section asymmetries, \(\Delta \hat{\sigma}^i/\hat{\sigma}^i\), (also known as analysing power). \(D\) is the depolarisation factor.\(^1\) The virtual photon asymmetry \(A_1^{\text{LO}}\) is defined as \(A_1^{\text{LO}} \equiv \sum_i c_i^2 \Delta \hat{\sigma}^i/\hat{\sigma}^i\).

To extract \(\Delta G/G\) from eq. (3) the contribution from the physical background processes LO and QCD Compton needs to be estimated. This is done using Monte Carlo (MC) simulation to calculate \(R_i\) fractions and \(a_{\text{LL}}^{i}\). The virtual photon asymmetry \(A_1^{\text{LO}}\) is estimated using a parametrisation based on the \(A_1\) asymmetry of the inclusive data.\(^5\) Therefore a similar equation to (3) can be written to express the inclusive asymmetry of a data sample, \(A_{1\text{LL}}^{\text{incl}}\).

Using eq. (3) for the high \(p_T\) hadron pairs sample and a similar eq. for the inclusive sample the following expression is obtained:

\(^1\)The depolarisation factor is the fraction of the muon beam polarisation transferred to the virtual photon.
\[ \frac{\Delta G}{G}(x_{av}^G) = \frac{A_{2h}^{2h}(x_{Bj}) + A^{corr}}{\beta} \]

\[ A^{corr} = -A_1(x_{Bj}) D R^{incl}_{LO} - A_1(x_C) \beta_1 + A_1(x'_C) \beta_2 \] (4)

\[ \beta_1 = \frac{1}{R^{incl}_{LO}} \left[ a_{QLC}^{QCDC} R^{incl}_{QCDC} - a_{LL}^{incl,QCDC} R^{incl}_{QCDC} a_{LL}^{QCDC} R^{incl}_{LO} R^{incl}_{LO} \right] \]

\[ \beta_2 = a_{LL}^{incl,QCDC} R^{incl}_{QCDC} a_{LL}^{QCDC} \]

\[ \alpha_1 = a_{LL}^{PGF} R^{incl}_{PGF} - a_{LL}^{incl,PGF} R^{incl}_{PGF} a_{LL}^{PGF} R^{incl}_{PGF} R^{incl}_{LO} R^{incl}_{LO} \] (5)

\[ \alpha_2 = a_{LL}^{incl,PGF} R^{incl}_{QCDC} a_{LL}^{QCDC} \]

\[ \beta = \alpha_1 - \alpha_2. \]

The term \( A^{corr} \) comprises the correction due to the other two processes, namely the LO and the QCD Compton processes. \( \alpha_1, \alpha_2, \beta_1, \beta_2, x_C, x'_C \) and \( x_{av}^G \) are estimated using high \( p_T \) and inclusive MC samples.

3 Data Selection

Data from 2002 to 2004 years is used. The selected events have an interaction vertex containing an incoming muon beam and a scattered muon. As mentioned in sec. 2 the data samples are divided into two data sets: the high \( p_T \) hadron pairs and the inclusive data samples.

Both data sets have the \( Q^2 > 1 \) (GeV/c)^2 kinematic cut applied. Another cut is applied on the fraction of energy taken by the virtual photon, \( y : 0.1 < y < 0.9 \). These cuts described previously are used to select the inclusive sample.

In the high \( p_T \) hadrons data sample, besides the inclusive selection, events with (at least) two outgoing high \( p_T \) hadrons are considered. These so-called hadron candidates must fulfill the following requirement: the two hadrons with the highest transverse momentum must have \( p_T > 0.7 \) GeV/c. This requirement constitutes the high \( p_T \) cut. All these cuts additionally correspond to the high \( p_T \) sample selection.

4 Monte Carlo simulation

Important information to be used in the \( \Delta G/G \) extraction is obtained from MC simulation. In this analysis it is fundamental that the simulation describes well the experimental data. Two MC samples were produced: one for the high \( p_T \) sample and another for the inclusive sample, to estimate the terms in the set of eq. (5).
The MC production comprises three steps: first the events are generated, then the particles pass through a simulated spectrometer using a program based on GEANT3 \[9\] and finally the events are reconstructed using the same procedure applied to real data.

For the first step the LEPTO 6.5 \[7\] event generator is used together with a leading order parametrisation of the unpolarised parton distributions. The MRST04LO set of parton distributions is used in a fixed-flavour scheme generation. This set of parton distributions has a good description of $F_2$ in the COMPASS kinematic region.

NLO corrections are simulated partially by including gluon radiation in the initial and final states (parton shower – PS).

The fragmentation is based on the Lund string model \[9\] implemented in JETSET \[10\]. In this model the probability that a fraction $z$ of the available energy will be carried by a newly created hadron is expressed by the Lund symmetric function $f(z) = z^{-1}(1-z)^a e^{-bm^2/z}$, with $m^2 = m^2 + p^2$, where $m$ is the hadron mass.

To improve the agreement between MC and data, the parameters $(a,b)$ in the fragmentation function are modified from their default values $(0.3,0.58)$ to $(0.6, 0.1)$.

The transverse momentum of the hadrons, $p_T$, at the fragmentation level is given by the sum of the $p_T$ of each hadron quarks. Then the $p_T$ of the newly created hadrons is described by three steering parameters JETSET parameters: PARJ(21), PARJ(23) and PARJ(24). The default values of these three parameters are $(0.36, 0.01, 2.0)$, and were

Figure 2: Comparison between data and MC simulations – The distributions and ratios of Data/MC for: inclusive variables: $x_{Bj}, Q^2, y$ (1st row). For hadrons $p_T$ (2nd raw). For hadron momenta (3rd row), and also the comparison of MC with LEPTO default tuning.
modified to (0.30, 0.02, 3.5).

The remarkable agreement of the MC simulation with the data is illustrated in Fig. 2; this figure shows the data–MC comparison of the kinematic variables: \(x_{Bj}\), \(y\) and \(Q^2\) (1st row), the hadronic variables, \(p_T\) for the leading and sub-leading hadrons, together with the sum of \(p_{T1}^2 + p_{T2}^2\) (2nd row), and the momentum \(p\) of those hadrons (3rd row), also two comparisons of the \(\sum p_{T}^2\) variable one using the COMPASS tuning and another using the default LEPTO tuning. In this example, it is evident that the COMPASS tuning describes better our data sample than the LEPTO default one.

5 The \(\Delta G/G\) extraction method

In the original idea of the high \(p_T\) analysis, the selection was based on a very tight set of cuts to suppress LO and QCD Compton. This situation results in a dramatic loss of statistics. A new approach was found, in which a loose set of cuts applied, combined with the use of a neural network [11] to assign a probability to each event to be originated from each of the three processes. The main goal of this method is to enhance the PGF process in the events sample, which accounts for the gluon contribution to the nucleon spin.

The neural network is trained using MC samples. In this way the neural network is able to learn about the three processes in order to be disentangled. A parametrisation of the variables \(R_i\), \(x^i\) and \(a_{iLL}^i\) for each process type are estimated by the neural network using as input the kinematic variables: \(x_{Bj}\) and \(Q^2\), and the hadronic variables: \(p_{T1}\), \(p_{T2}\), \(p_{L1}\), and \(p_{L2}\).

As the fractions of the three processes sum up to unity, we need two variables to parameterise them: \(o_1\) and \(o_2\). The relations between the two neural network outputs \(o_1\) and \(o_2\) and the fraction are:

\[
R_{\text{PGF}} = 1 - o_1 - 1/\sqrt{3} \cdot o_2,
R_{\text{QCDC}} = o_1 - 1/\sqrt{3} \cdot o_2,
R_{\text{LO}} = 2/\sqrt{3} \cdot o_2.
\]

A statistical weight is constructed for each event based on these probabilities. In this way we do not need to remove events that most likely do not came from PGF processes, because the weight will naturally reduce their contribution in the gluon polarisation, thus enhancing the sample of events that have a PGF likelihood.

The resulting neural network outputs for the fractions are presented in Fig. 3 in a 2-dimensional plot. The triangle limits the region where all fractions are positive. For the inclusive sample the average value of \(o_2\) is quite large, which means that the LO process is the dominant one. The situation is different for the high \(p_T\) sample, in which the average outputs are \(\langle o_1 \rangle \approx 0.5\) and \(\langle o_2 \rangle \approx 0.35\). Note also that the spread along \(o_2\) is larger than along \(o_1\).

This means that the neural network is able to select a region where the contribution of PGF and QCDC is significant compared to LO, although it can not easily distinguish
between the PGF and QCDC processes themselves.

6 High \( p_T \) hadron pair analysis for low \( Q^2 \) region

The reason for splitting the \( Q^2 \) range in two complementary regions is that for the low \( Q^2 \) region the resolved photon contributions are considerably higher (\( \approx 50 \% \)) than in the high \( Q^2 \) region, which contains practically only the three processes previously mentioned. This means that the QCD hard scale is also different for both \( Q^2 \) regions: for low \( Q^2 \) the scale is given by the high \( p_T \) hadrons, while for the high \( Q^2 \) is given by the \( Q^2 \) value itself.

A more complicated description of the physics than pure QCD in lowest order needs to be included in the MC simulation for this case. Therefore the event generator used in this analysis is PYTHIA 6.2 \([12]\) which covers the physical processes for quasi-real photoproduction.

In this analysis the selection is essentially the same as in high \( Q^2 \) region plus a slightly strict set of cuts: \( x_F > 0.1 \), \( z > 0.1 \), and \( \sum p_T^2 > 2.5 \) (GeV/c)\(^2\). The data sample in this region is 90 % of the whole data for all \( Q^2 \) range. The weighting method used in the high \( Q^2 \) analysis is not applied in this case.

The MC simulated and real data samples of high \( p_T \) events are compared in Fig. 4 for \( Q^2 \), \( y \) (1st row), and for the total and transverse momenta of the high \( p_T \) hadron (2nd row), showing a good agreement.

The gluon polarisation in the low \( Q^2 \) region is extracted using averaged values as shown by this expression:

\[
\left\langle \frac{A_{LL}}{D} \right\rangle = R_{\text{PGF}} \left\langle \frac{a_{\text{PGF}}^{\text{LL}}}{D} \right\rangle \left\langle \frac{\Delta G}{G} \right\rangle + R_{\text{QCDC}} \left\langle \frac{a_{\text{QCD}}^{\text{LL}}}{D} A_1 \right\rangle + \sum_{f,f'} R_{ff'} \left\langle \frac{a_{\text{LL}}^{f f'} \Delta f}{f \Delta f_{f'}} \right\rangle
\]

\( R_{ff'} \) is the fraction of events in the high \( p_T \) sample for which a parton \( f \) from the nucleon interacts with a parton \( f' \) from a resolved photon; \( A_1 \) is the virtual photon deuteron asymmetry measured in an inclusive sample; \( \Delta f/f (\Delta f_{f'}/f_{f'}) \) is the polarisation of quarks or gluons in the deuteron (photon).

This analysis was performed using a data sample from the years 2002 to 2004. For more details about this analysis the reader is invited to look into ref. \([13]\).
7 Results

The preliminary measurements of the gluon polarisation in low and high $Q^2$ regions, using data from the years 2002 to 2004, are:

\[
\begin{align*}
(\Delta G/G)_{\text{low } Q^2} &= 0.02 \pm 0.06_{\text{(stat.)}} \pm 0.06_{\text{(syst.)}} \quad \text{with } x_G = 0.09^{+0.07}_{-0.04} \\
(\Delta G/G)_{\text{high } Q^2} &= 0.08 \pm 0.10_{\text{(stat.)}} \pm 0.05_{\text{(syst.)}} \quad \text{with } x_G = 0.08^{+0.04}_{-0.03}
\end{align*}
\]

The average of the hard scale, $\mu^2$, for low and high $Q^2$ is about $3 \text{ (GeV/c)}^2$. $x_G$ is the momentum fraction carried by the probed gluons obtained from the MC parton kinematics. The result of the measurement for low $Q^2$ using data from 2002 and 2003 can be found in [13].

Fig. 5 shows these new values of $\Delta G/G$ together with the preliminary value from the open charm analysis. Also the figure shows the measurements from SMC collaboration, from the high $p_T$ analysis for the $Q^2 > 1 \text{ (GeV/c)}^2$ region [14] and also the measurements from HERMES collaboration, for single hadrons and high $p_T$ hadron pairs analyses [15]. The curves in the figure are the parameterisation of $\Delta G/G(x)$ using a NLO QCD analysis done by COMPASS [2] in the $\overline{MS}$ scheme with a renormalisation scale $\langle \mu^2 \rangle = 3 \text{ (GeV/c)}^2$. The dashed line curve is the QCD fit assuming that $\Delta G > 0$, the dotted line is the QCD fit assuming $\Delta G < 0$. It is seen that both results from high $p_T$ analyses, for high and low $Q^2$ regions, are compatible with each other and also, within their $x_G$ region, in agreement with the NLO QCD fits.

8 Conclusions

The preliminary values of the gluon polarisation for low and high $Q^2$ regions were presented. The gluons were probed at an average scale $\langle \mu^2 \rangle \approx 3 \text{ (GeV/c)}^2$. Both measurements show that the gluon contribution to the nucleon spin for $x_G \approx 0.1$ is compatible with zero. In that region of $x_G$ the presented measurements are in agreement with other well known results.

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