Gluon polarization measurements at COMPASS

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Abstract

One of the missing keys in the present understanding of the spin structure of the nucleon is the contribution from the gluons: the so-called gluon polarization. This quantity can be determined in deep inelastic scattering (DIS) through the photon–gluon fusion process, in which two analysis methods may be used: (i) identifying open charm events or (ii) selecting events with high-transverse-momentum (high-\(p_T\)) hadrons. The data used in the present work were collected in the COMPASS experiment, where a 160 GeV/c naturally polarized muon beam, impinging on a polarized nucleon fixed target, is used. Preliminary results for the gluon polarization from high-\(p_T\) and open charm analyses are presented. The gluon polarization result for high-\(p_T\) hadrons is divided, for the first time, into three statistically independent measurements at leading order (LO) in quantum chromodynamic (QCD). The result from open charm analysis is obtained at LO and next-to-leading order in QCD. In both analyses a new weighted method based on a neural network approach is used.

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(Some figures may appear in colour only in the online journal)

1. The nucleon spin

The nucleon spin sum rule can be written in a heuristic way as

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_{q,g}, \quad \text{where } \Delta \Sigma \text{ and } \Delta G \text{ are the quark and gluon contributions to the nucleon spin, respectively, and } L_{q,g} \text{ is the parton orbital angular momentum. In the late 1980s, it was announced and confirmed by several experiments that the contribution carried by the quarks is } \sim \frac{1}{3} \text{ of the nucleon spin} \ [1–5]. \text{ The purpose of this work is to estimate the gluon polarization } \Delta G/g, \text{ which is deeply related to the gluon contribution to the nucleon spin.}

2. Gluon polarization measurements

The spin-dependent effects are measured experimentally using the helicity asymmetry \(A_{LL}^{\exp}\) defined as \(\frac{\sigma_{\parallel} - \sigma_{\perp}}{\sigma_{\parallel} + \sigma_{\perp}}\), where (\(\parallel\)) and (\(\perp\)) refer to the parallel and anti-parallel spin helicity configurations of the beam lepton (\(\leftrightarrow\)) with respect to the target nucleon (\(\leftarrow\) or \(\rightarrow\)). The data for the present analyses were taken in the COMPASS experiment [6]. The gluon polarization can be measured via the photon–gluon fusion (PGF) process, depicted in figure 1(c), which allows us to probe the spin of the gluon inside the nucleon. The PGF process may be selected using two analysis methods: (i) selecting high-transverse-momentum (high-\(p_T\)) hadron events or (ii) selecting events containing open charm mesons.

2.1. High-\(p_T\) analysis

In the high-\(p_T\) analysis the spin helicity asymmetry is calculated by selecting events containing high-\(p_T\) hadron pairs above 0.7 and 0.4 GeV/c, respectively, for the highest and the second highest \(p_T\) hadron with respect to the virtual photon direction.

Two variables are used to define the deep inelastic scattering (DIS) phase space: \(Q^2 = -q^2\), the negative squared virtual photon four-momentum, \(q\) and \(y = (E - E')/E\), the fraction of energy loss of the incoming muon (\(E\) and \(E'\) are, respectively, the incoming and scattered muon energies). In order to select DIS events a cut on the two aforementioned variables is applied, namely \(Q^2 > 1\) (GeV/c)\(^2\) and 0.1 > \(y\) > 0.9. Besides the PGF process, two other processes are involved in the quantum chromodynamics.


(QCD) leading order (LO) approximation, namely the virtual photo-absorption leading order process (LP) and the gluon radiation (QCD Compton) process, illustrated in figure 1. The spin helicity asymmetry for the high-\(p_T\) hadron pair data sample can thus be schematically written as

\[
A_{LL}(x_{Bj}) = R_{PQF} \Delta G_{LL}(x_G) + R_{LP} D A_1(x_{Bj}) + R_{QCD} \Delta G_{QCD}(x_C).
\] (1)

The process fractions are represented by \(R_i\), \(i\) referring to the different processes. \(\Delta G_{LL}\) represents the partonic cross-sectional asymmetries, \(\Delta \hat{\sigma}^i/\hat{\sigma}^i\), also known as analysing power. The depolarization factor \(D\) is the fraction of the muon beam polarization transferred to the virtual photon. \(A_1\) represents the virtual photon–nucleon asymmetry. \(x_{Bj}\) is the Berken scaling variable which represents the fraction of momentum carried by the struck quark, and \(x_C\) and \(x_G\) are also the fraction of momentum carried, in this case by the struck quark and gluon, for QDC Compton and PGF processes, respectively. A similar equation as (1) can be written to express the inclusive asymmetry of a data sample, \(A_{LL}^{incl}\). Using (1) for the high-\(p_T\) hadron pair sample and the above-mentioned equation for the inclusive sample, the final expression to extract the gluon polarization is obtained:

\[
\Delta G_{LL}(x_G) = A_{LL}^{incl}(x_{Bj}) + A_{LL}^{corr} \lambda
\] (2)

This formula corresponds to the spin helicity asymmetry \(A_{LL}^{incl}\), measured directly from data, plus a correcting asymmetry \(A_{LL}^{corr}\) involving mainly the virtual photo-absorption and the gluon radiation processes. The \(\lambda\)-factor relates the partonic asymmetries and the fractions of the involved processes. During the data selection process, it is not possible to identify the process that originated each event, nor to access its partonic variables. Therefore, the partonic asymmetries and the process fractions need to be estimated using a dedicated and well-tuned Monte Carlo (MC) simulation. The quality of the simulation is illustrated by a comparison of the distributions for three variables, presented at the conference [7]. In the high-\(p_T\) analysis, a Bayesian neural network (NN) [8] approach was used. The purpose of such an approach is to assign an event probability for each process involved: LP, QCD Compton and PGF. These probabilities represent the process fractions in (1). Also the NN is used to provide

\[ N_t = \alpha(S + B) \left[ 1 + \beta \left( A_{LL}^{incl} \frac{\Delta G}{G} + \frac{B}{S+B} \Delta G^{bg} \right) \right]. \] (3)

The number of events with \(D^0\) particles in the final state is related to the helicity asymmetries as shown by this expression:

\(A_{LL}^{incl}\) is calculated directly from data, plus a correcting asymmetry \(A_{LL}^{corr}\) involving mainly the virtual photo-absorption and the gluon radiation processes. The \(\lambda\)-factor relates the partonic asymmetries and \(x_C\) and \(x_G\) variables. The gluon polarization is calculated on an event by event basis using an optimal weight which improves the figure of merit. Details of the high-\(p_T\) analysis, for \(Q^2 > 1\) (GeV/c)^2, can be found in [8]. A similar analysis was performed for the \(Q^2 < 1\) (GeV/c)^2 data, which contains \(\sim 90\%\) of the whole \(Q^2\) range. This separation is due to the physical processes contained in the two \(Q^2\) regimes. The \(Q^2 < 1\) (GeV/c)^2 regime represents the quasi-real photon; in such conditions the photon may exhibit some inner structure. Therefore, besides the already mentioned three intervening processes, inclusion of photon structure processes in the MC simulation needs to be accomplished. Details of this analysis can be found in [9].

2.2. Open charm analysis

For the open charm analysis the spin helicity asymmetries are calculated using data with \(D^0\) mesons in the final state. These events are selected from their decaying products, i.e. \(K\pi\) pairs. To achieve this selection a good particle identification is required. Applying a set of kinematic cuts, the combinatorial background originating from the process in which the virtual photon strikes a parton inside the nucleon is reduced. In addition, the background is suppressed by selecting the \(D^* \rightarrow D^0\) channel. In this way, three channels were included in the final analysis: \(D^0 \rightarrow K\pi\), \(D^0 \rightarrow K\pi\pi^0\) and \(D^0 \rightarrow K\pi\pi\). The data used in this analysis are deuterons data collected from 2002 to 2006 and proton data collected in 2007.

The number of events with \(D^0\) particles in the final state is related to the helicity asymmetries as shown by this expression:

\[ N_t = \alpha(S + B) \left[ 1 + \beta \left( A_{LL}^{incl} \frac{\Delta G}{G} + \frac{B}{S+B} \Delta G^{bg} \right) \right]. \] (3)

The subscript \(t\) in the number of events corresponds to the possible muon target spin configurations. The \(\alpha\)-factor contains the acceptance, the muon flux and the number of nucleons, and \(\beta\) the beam and target polarizations and the
dilution factor. $S$ and $B$ represent the number of signal and background events taken under the invariant mass spectrum peak. $S/(B+S)$ is the signal (background) significance. $A_{gB}$ is the asymmetry of the background. Taking into account all the possible muon target spin configurations and the unknown variables, a set of equations is derived from expression (3). This equation set is solved by $\chi^2$ minimization. As in high-$p_T$ analysis, the gluon polarization calculation is performed event by event with an appropriate weight. Still, to solve this equation system the partonic asymmetry $a_{LL}$ and the signal significance $\frac{S}{\sqrt{B}}$ must be estimated for every event. To compute the partonic asymmetry $a_{LL}$ a dedicated MC simulation is used. An NN approach is designed to parameterize the partonic asymmetry and the signal significance $\frac{S}{\sqrt{B}}$ as a function of the kinematics. The latter represents the event probability for having $D^0$ particles.

Details of this analysis can be found in [10]. A next-to-leading order (NLO) QCD analysis was also performed. Into the analysing power, NLO QCD virtual and gluon bremsstrahlung corrections were included in the PGF process, as well as background processes.

3. Results and conclusions

Preliminary results on gluon polarization using high-$p_T$ ($Q^2 < 1$ and $Q^2 > 1$ (GeV/c)^2, LO QCD order) and open charm (LO and NLO in QCD) analyses are now presented. The $\Delta g/g$ value obtained in high-$p_T$ analysis, for $Q^2 > 1$ (GeV/c)^2, averaged at $x_g = 0.09^{+0.08}_{-0.04}$ was found to be equal to $\Delta g/g = 0.125 \pm 0.060_{\text{stat}} \pm 0.063_{\text{sys}}$. This measurement is presented in three statistically independent points in $x_g$ in table 1. The same result for $Q^2 < 1$ (GeV/c)^2 is $\Delta g/g = 0.016 \pm 0.058_{\text{stat}} \pm 0.055_{\text{sys}}$.

The gluon polarization value for the open charm analysis was found to be $\Delta g/g = -0.08 \pm 0.21_{\text{stat}} \pm 0.08_{\text{sys}}$, averaged at $x_g = 0.11^{+0.16}_{-0.05}$ for QCD LO and $\Delta g/g_{\text{NLO}} = -0.20 \pm 0.21_{\text{stat}} \pm 0.08_{\text{sys}}$ averaged at $x_g = 0.28^{+0.19}_{-0.10}$ for QCD NLO. The gluon polarization values from high-$p_T$ hadrons are measured at a hard scale of $\langle \mu^2 \rangle = 3$ (GeV/c)^2, whereas the ones from open charm mesons were evaluated at a hard scale of $\langle \mu^2 \rangle = 13$ (GeV/c)^2. All the gluon polarization results of the COMPASS Collaboration are summarized in figure 2: the LO preliminary results of this work are presented together with the SMC [11] and HERMES [12] ones in figure 2(a); the NLO preliminary result from the open charm analysis is shown in figure 2(b); also theoretical curves of the gluon polarization obtained using NLO QCD global fit curves to the spin asymmetries in the inclusive and semi-inclusive DIS data from the LSS [13] and DSSV [14] groups are drawn together.

The gluon polarization preliminary results presented here show that, in the region of $x_g \approx 0.1$, these results are compatible with all the remaining ones from other analyses and also compatible with a small value for $\Delta g/g$. This result is also confirmed by the NLO QCD global fit curves in figure 2(b) that also predict a small value for the gluon contribution to the nucleon spin.

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Figure 2. Gluon polarization results: (a) LO QCD order results, (b) NLO QCD order results.