Abstract

COMPASS is a new fixed target experiment presently in operation at CERN. It has the goal to investigate hadron structure and hadron spectroscopy by using either muon or hadron beams. From measurements of various hadron asymmetries in polarized muon - nucleon scattering for the first time it will be possible to determine the contribution of the gluons to the nucleon spin. Main objective of the hadron program is the search of exotic states, and glueballs in particular. This physics programme is carried out with a two-stage magnetic spectrometer, with particle identification and calorimetry in both stages, which has started collecting physics data in 2002, and will run at the CERN SPS at least until 2010.

1. Introduction

The COMPASS experiment [1] aims at a deeper understanding of nucleon structure and confinement. The main physics observables studied are the polarization of the constituents of a polarized nucleon, the mass and decay patterns of light hadronic systems with either exotic quantum numbers or strong gluonic excitations, and the leptonic decays of charmed hadrons.

A possible polarization of gluons \( \Delta G/G \) in a polarized nucleon is searched for by the study of hard processes in polarized polarized muon – polarized nucleon deep inelastic scattering, open charm production and high \( p_T \)-meson pair production. Using very large event samples COMPASS should determine for the first time \( \Delta G/G \) in the kinematical region of \( x_{\text{ gluon}} \) around 0.05 and 0.3. The flavour-separated spin structure functions of the nucleon in deep inelastic scattering will also be measured, both in longitudinal and transverse polarization mode. In the latter the still unmeasured transversity spin structure function \( h_1 \) will be investigated.

With a hadron beam, gluonic degrees of freedom shall be excited in hadrons using diffractive and double-diffractive scattering. High statistics measurements will allow to access the mass range above 2 GeV/c\(^2\). Leptonic and semileptonic decays of charmed hadrons will be studied using a specialized detector arrangement to identify such processes and discriminate background. In addition many soft processes can be studied testing low energy theorems of QCD.
2. The Muon Beam Physics Programme

In the initial phase of the experiment we have concentrated on the physics measurements which are accessible with the polarized muon beam. The main goal of this programme is a direct measurement of $\Delta G$ by measuring the open charm cross-section asymmetry $A_{\mu N}^{c\bar{c}}$ as originally suggested already fifteen years ago [2, 3] to solve the nucleon spin puzzle raised by the EMC result [4]. At COMPASS energies the production of charm goes predominantly via photon-gluon fusion (PGF), according to the diagram shown in Fig. 1, and the quantities $\sigma_{\mu N \rightarrow c\bar{c}X}$ and $\Delta \sigma_{\mu N \rightarrow c\bar{c}X}$ can be expressed as a convolution of the elementary photon-gluon cross-section with the gluon distributions $G$ and $\Delta G$ [1].

The open charm asymmetry expected from three possible shapes [5] of the gluon helicity distribution function $\Delta G$ are shown in Fig. 2. Also shown is the projected precision expected by COMPASS by measuring open charm only by detecting $D^0$ and $\bar{D}^0$, decaying into the two body $(K + \pi)$ channel. The sensitivity to $\Delta G$ by this method was estimated in the Proposal to be $\delta(\Delta G/G) \approx 0.11$.

The large acceptance of the COMPASS spectrometer and its capability of identifying the particles produced in the muon-nucleon scattering open up additional ways to access $\Delta G$.

The most promising additional way to measure $\Delta G$ in polarized DIS uses the asymmetry of oppositely charged hadron pairs at high $p_t$. Originally developed for the COMPASS experiment [6], the method has been recently applied also to the HERMES data [7]. The basic diagram is still the PGF, $\gamma g \rightarrow q\bar{q} \rightarrow h^+h^-X$, and the hardness of the process is guaranteed by the large $p_t$. The background from the leading order process $\gamma q \rightarrow q$, and the QCD-Compton process, $\gamma g \rightarrow \gamma q$, is in general dominating the PGF creation of a light $q\bar{q}$ pair, but suitable kinematic cuts can enhance considerably this process and allow for a statistically precise measurement. The accuracy with which $\Delta G/G$ can be determined by this method will be discussed in Section.
Apart from \( \Delta G \), the COMPASS spectrometer is measuring \( \Delta q \) and \( \Delta_T q \) from the relevant identified hadron asymmetries, in semi-inclusive polarized muon - polarized nucleon DIS, in the longitudinal and in the transversal mode respectively.

The measurement of \( \Delta q \) is performed in parallel to the measurement of \( \Delta G \), i.e. with longitudinal beam and target polarizations. The double spin asymmetry of a given hadron \( h \) is a linear combination of all quark helicity distributions:

\[
A^h(x, Q^2) = \frac{\sum_q e_q^2 \left[ \Delta q(x, Q^2) \cdot D^h_q(Q^2) + \Delta \bar{q}(x, Q^2) \cdot D^{\bar{q}}_h(Q^2) \right]}{\sum_q e_q^2 \left[ q(x, Q^2) \cdot D^h_q(Q^2) + \bar{q}(x, Q^2) \cdot D^{\bar{q}}_h(Q^2) \right]} \cdot [1 + R(x, Q^2)]
\]

where \( D^h_q(Q^2) = \int_{x_{\text{min}}}^{1} D^h_q(z, Q^2) \, dz \), and \( R \) is the ratio of longitudinal to transverse unpolarized virtual photon cross-section [8]. The quantities \( q(x, Q^2) \) are the unpolarized quark distributions, and the summations run over all quark flavours \( (u, d \) and \( s \) at our energies). Both the quark distributions and the fragmentation functions \( D^h_q(Q^2) \) are known, therefore measuring asymmetries for different hadrons one obtains a system of linear equations which can be solved for the \( \Delta q(x, Q^2) \)'s.

Particularly interesting is the physics case for transversity, which is relatively recent, but has gained a high momentum over the past few years. As originally shown by Jaffe and Ji [9], to completely specify the quark state at the twist-two level, to the momentum distribution \( q(x) \) and to the helicity distribution \( \Delta q(x) \) one has to add the transverse spin distributions \( \Delta_T q(x) \), which, summed up over the quark flavours and weighted by the squared charges, make up a new structure function \( h_1(x) \). The transversity distribution \( h_1 \) has never been measured, since it is a chirally-odd function and therefore absent in inclusive deep inelastic scattering. The density \( h_1 \) may instead be extracted from measurements of the spin asymmetries in cross-sections for semi-inclusive deep inelastic scattering between leptons and transversely polarized nucleons, in which a hadron is also detected in the final state. In such processes the measurable asymmetry is due to the combined effect of \( h_1 \) and another chirally-odd function, \( \Delta_T D^h_q \), that describes the hadronization of a transversely polarized quark \( q \) in a hadron \( h \).

In the case in which the observed final hadron is a pion or, in general, a scalar particle, this new fragmentation function is the so-called Collins function [10], as yet unmeasured, which in its own right merits serious study. In the case in which the observed final particle is for example a \( \Lambda^0 \), the chirally-odd function is a transverse fragmentation function, also unknown and interesting. Other channels for accessing \( h_1 \) require the detection of a vector particle or two pions in the final state. An important side-product of the study of the partonic density \( h_1 \) is, therefore, the determination of a certain number of fragmentation functions \( \Delta_T D^h_q \).

Measuring transversity requires setting the target polarization perpendicular to the incoming beam, therefore a sharing of the running time between longitudinal and transverse polarization running is required. In 2002 and 2003 the running time has been divided by COMPASS roughly in the ratio 4:1 for longitudinal:transverse.

3. The COMPASS spectrometer

The COMPASS spectrometer has been set up at the CERN SPS muon beam. It combines very high rate beams with a modern two stage fixed target magnetic spectrometer. The design of detector components, electronics and data acquisition system allows to handle
beam rates up to $10^8$ muons/s and about $5 \cdot 10^7$ hadrons/s with a maximal interaction rate of about $2 \cdot 10^6$/s. The triggering system and the tracking system of COMPASS have been designed to stand the associated rate of secondaries, and use state-of-the-art detectors. Also, fast front-end electronics, multi-buffering, and a large and fast storage of events are essential.

The experiment in so far has been run with the muon beam. The layout used in 2002, also called "initial layout" is shown in Fig. 3.

Figure 3: Top view of the initial layout of the spectrometer for the COMPASS experiment.

In the following I will mainly quote the detectors which were on the floor during the 2002 run.

The main problem COMPASS has had in this initial phase is the delay in the delivery of the new COMPASS Polarized Target Magnet (PTM). Presently a new superconducting coil is being wound, since we experienced problems with the previous one. The net result of this is that in the first years of data taking, 2002 and 2003 (and much likely 2004), the experiment has run with the SMC superconducting PTM, which has similar characteristics, but reduced acceptance (about a factor of three in angle).

This limitation affects only marginally the measurement of $\Delta G$. Most of the events are produced by quasi-real photons, $Q^2 \approx 0$, and the scattered muon is detected at fairly small angles. Moreover, the acceptance of the SMC magnet is sufficient (at least at 160 GeV/c incident muon momentum) to allow for the hadrons from the $D^0 \rightarrow K\pi$ decay to be detected in the Spectrometer. Still, the small acceptance of the presently used SMC superconducting PTM does not allow to carry on the measurement of the quark spin distribution functions $\Delta g(x)$ and $\Delta_T q(x)$ at large $x$.

The experiment has been run at a muon energy of 160 GeV. The beam is naturally polarized by the $\pi-$decay mechanism. The beam polarization was measured by the SMC Collaboration to be about 80% at 190 GeV [11]. The beam intensity is $2 \cdot 10^8$ muons per spill (4.5 s long).

We use the polarized target system of the SMC experiment, which allows for two
oppositely polarized target cells, 60 cm long each. The PT magnet can provide both a solenoidal field (2.5 T) and a dipole field (0.5 T), for adiabatic spin rotation and for the transversity measurements. Correspondingly, the target polarization can then be oriented either longitudinally or transversely to the beam direction. Use of two different target materials, NH3 as proton target and 6 LiD as deuteron target, is foreseen. Polarizations of 85 % and 50 % have been reached, respectively. In so far we have used 6 LiD: its favourable dilution factor of ~0.5 is of the utmost importance for the measurement of ΔG.

Particle tracking is performed using several stations of scintillating fibres, silicon detectors, micromegas chambers [12] and gas chambers using the GEM-technique [13]. Large area tracking devices are made from gaseous detectors (Saclay Drift Chambers, Straw tubes [14], MWPC's, and W4/5 Drift Chambers) placed around the two spectrometer magnets. Table 1 summarizes the spatial resolution and the timing properties of the tracking detectors, as derived from the 2002 data. Muons are identified in large-area

<table>
<thead>
<tr>
<th>Detector</th>
<th>number of coordinates</th>
<th>efficiency</th>
<th>resolution</th>
<th>timing</th>
</tr>
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<tr>
<td>Scintillating fibers</td>
<td>21</td>
<td>94 %</td>
<td>130 µm</td>
<td>0.45 ns</td>
</tr>
<tr>
<td>Micromegas</td>
<td>12</td>
<td>95 - 98 %</td>
<td>65 µm</td>
<td>8 ns</td>
</tr>
<tr>
<td>GEM</td>
<td>40</td>
<td>95 - 98 %</td>
<td>50 µm</td>
<td>12 ns</td>
</tr>
<tr>
<td>SDC</td>
<td>24</td>
<td>94 - 97 %</td>
<td>170 µm</td>
<td></td>
</tr>
<tr>
<td>Straw tubes</td>
<td>18</td>
<td>&gt; 90 %</td>
<td>270 µm</td>
<td></td>
</tr>
<tr>
<td>MWPC</td>
<td>32</td>
<td>97 - 99 %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W4/5</td>
<td>8</td>
<td>&gt; 80 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1: Trackers performances in the 2002 run.

Iarocci-like tubes and drift tubes downstream of muon absorbers. The charged particle identification relies on the RICH technology. Presently, RICH1 only exists [15]. The length of the radiator (C4F10 gas) vessel is 3 m. The entire downstream surface is covered by 116 aluminized mirrors with spherical geometry and a focal length of 3.3 m. As VUV photon detectors we use MWPC's with a CsI photocathode [16] (segmented in 8 x 8 mm² pads) which detect photons with wave length shorter than 200 nm, i.e. in the far UV domain. The active area of each of the two photon detectors is 2.8 m² and the total number of pads is about 70,000. The front-end electronics uses a modified version of the Gas-siplex chip, and the read-out cards constitute a major project, utilizing hundreds of DSP's. RICH1 has been designed to give a 3 standard deviation π/K separation up to momenta of ~60 GeV/c. Fig. 4 shows a "typical" event, as seen by the on-line monitor.

The trigger is formed by two hadron calorimeters and several hodoscope systems.
Electromagnetic calorimetry is being installed upstream of the hadronic calorimeters at the end of each spectrometer section. The readout mostly follows the pipeline principle and requires very fast signal conversion. The DAQ can handle about $10^5$ events/s which are sent into an on-line computing farm for data filtering. About $2 \times 10^4$ events/spill are being recorded centrally in the CERN computing centre requiring a steady data stream of 35–40 MB/s.

In 2002 we have taken for the first time a large amount of physics data, recording about 260 TB. A similar amount of data has been collected also in the run of 2003, which is going to terminate at the end of this week.

4. A first look at the data

Over the 80 days of the 2002 run, we have collected a total of about 6000 millions of events, which are currently being analyzed. Given the novelty of several detectors in the spectrometer, its intrinsic complexity, the difficulties in the event reconstruction, and in general the problems associated with the handling of very large amounts of data, the analysis is still at an early stage, and I will only mention some preliminary physics signals. In this sense, the projected statistical errors have to be regarded as lower limits, since the efficiency of events reconstruction is expected to improve by refining the present analysis tools.

In the following I will skip altogether two important subjects, $\Lambda$ and $\bar{\Lambda}$ polarization, and low-$Q^2$ vector meson $\rho^0$ and $\varphi$ production, which are covered by M. Sapozhnikov and by J. Marroncle respectively in two separate contributions to this workshop [17, 18].

4.1. Collins asymmetry and transversity

Semi-inclusive deep inelastic scattering provides the possibility to measure the transverse polarized parton distribution function $\Delta_T q(x)$ via the azimuthal dependence (Collins angle $\Phi_C$) of the leading hadron. This measurement has been performed on a our $^6$LiD target polarized in the transverse mode: about 3 weeks of 2002 run have been devoted to this measurement. Figure 5 shows the expected statistical error on the Collins asymmetry from the 2002 data when a positive or negative leading hadron is selected. Also shown are the Efremov [7] calculations of asymmetry $A_{UT}$, which include

Figure 5: Expected statistic error compared to Efremov calculation of asymmetry $A_{UT}$ in case of deuterium target. The statistic error is extrapolated to the whole statistics available from year 2002 run and to the combined (positive and negative charged hadrons) signal.

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the transversity structure function $\Delta_Tq(x)$ by the following linear combination over the quark flavours:

$$A_{UT}(x) = \sum e_q^2 \cdot \Delta_Tq(x) \cdot \Delta_TD_q^h \over \sum e_q^2 \cdot q(x) \cdot D_q^h$$

where $D_q^h$ and $\Delta_TD_q^h$ are the fragmentation function of quark $q$ (unpolarized or transversely polarized) into a hadron $h$.

4.2. $\Delta q$ from identified hadrons asymmetries

Following the procedure outlined in Section we have measured several hadron double-spin asymmetries. Particularly important is the case of kaon asymmetries, since they allow to access $\Delta s$, which otherwise cannot be extracted from unidentified hadrons asymmetries. From our measured yields of $K^+$, $K^-$ and $K_s$ we could predict the sensitivity of our measurement for $\Delta s$ based on the data of 2002. The projected errors on $\Delta s$ are plotted in Fig. 6, which also shows the most recent results from the HERMES experiment [20]. Needless to say, the issue of what the sign of $\Delta s$ is is very important, and once again the capability of measuring at low $x$ will be decisive.

4.3. $\Delta G/G$ from charm photo-production

As mentioned in Section, the gluon polarization will be obtained from the measured cross-section asymmetry of open charm events. Open-charm events are identified by reconstructing $D^0$, $\bar{D}^0$, and $D^{*\pm}$ mesons from they decay products, i.e. $D^0 \rightarrow K^-\pi^+$ and $D^{*+} \rightarrow D^0\pi^+ \rightarrow K^-\pi^+\pi^+$ and charge conjugate. In the first case, cuts on the $K$ direction in the $D^0$ rest frame ($|\cos(\theta_K^*)| < 0.5$) and on the $D^0$ energy fraction ($z_D = E_D/E_{\gamma^*} > 0.25$) are needed to reduce the background contamination. Preliminary signals of the D meson are shown on Fig. 7. Kaon-pion pairs are selected by asking $z_D > 0.2$, $|\cos(\theta_K^*)| < 0.85$, and $10 < p_K < 35$ GeV in order to be in the RICH $K$ identification region. A soft pion ($< 10$ GeV) is also required.

4.4. $\Delta G/G$ from high $p_T$ hadron pairs

For this analysis, candidate events are events with a primary vertex with a scattered muon and at least two high transverse momentum hadrons ($p_T > 1.1$ GeV/c). To enhance the PGF process in the data, a number of kinematical cuts have been tried, i.e.

$$0.4 < y < 0.9, \quad x_F > 0.1, \quad p_T^2 + p_T'^2 > 2.5 (GeV/c)^2.$$

With these requirements the extrapolated full 2002 statistics of DIS events with $Q^2 > 1$ GeV$^2$ is 18000, corresponding to an estimated error on $\Delta G/G$ of about 0.31.
Figure 7: $D^*$ produced by requiring the invariant mass of the $K\pi$ pair to be in the 60 MeV window around the $D^0$ peak, together with a detected soft pion. Using this $D^*$ cut, the $D^0$ peak in the invariant mass spectrum of $K\pi$ is very clear.

The $Q^2$ cut reduces the available statistics by almost an order of magnitude. If all $Q^2$ events are used for this analysis (as HERMES did), $\delta(\Delta G/G)$ becomes $\approx 0.1$, but the theoretical interpretation of the result becomes more difficult. In passing, the statistics of our 2002 data corresponds in this case to the HERMES integrated statistics from 1996 to 2000.

5. Conclusions

It has been a pleasure to present the COMPASS experiment at this Workshop, and I would like to thank the Organizers for the invitation.

The COMPASS experiment is an important effort to progress in the understanding of the material world in which we live. It was born in 1996, when times were really hard at CERN. It has taken a very large effort to build it, but now it is a running experiment.

The experiment has already collected data over two years, and is expected to run for several more years. I have described the variety of detectors we are using and given numbers for their characteristic responses. For several of these detectors, this is the first time they are used in an experiment, the necessary R&D work having been done for them by groups of COMPASS physicists. I have shown first physics signals from the data analysis, and underlined the very large effort which is presently ongoing to fully understand the spectrometer and the data. What I have not shown are the physics results on $\Delta G$ or on the other polarized parton distributions we are after: it will take some time in order to be able to have original results. From the statistics point of view, the entire data set from 2002, 2003 and 2004 will be needed to grasp upon $\Delta G$, therefore very likely we will have to wait until 2005 to give our contribution to the solution of the spin puzzle.
References


