SPIN PHYSICS AT COMPASS

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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 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. Preliminary results from the 2002 run with a 160 GeV muon beam are presented for several physics channels under investigation.

1 Introduction

Five years ago I had the pleasure to illustrate to the participants to the 21-st course of the International School of Nuclear Physics the concept and the physics goals of the COMPASS experiment. In 1996 an international collaboration comprising some 200 physicists from 30 Institutes proposed COMPASS [1], a COmmon Muon and Proton Apparatus for Structure and Spectroscopy, a new state-of-the-art two-stage fixed target magnetic spectrometer to run at CERN and carry on an ambitious research programme aiming at a deeper understanding of nucleon structure and confinement. The experiment was approved in 1997, and the bulk of the apparatus constructed over the following 4-5 years.

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 muon – polarized nucleon deep inelastic scattering (DIS), 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_{gluon} between 0.05 and 0.3. The flavour-separated spin distribution functions of the nucleon in deep inelastic scattering are also being measured, both in longitudinal and transverse polarization mode. In the latter the still unmeasured transversity distribution $\Delta_T q$ 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 semi-leptonic 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.

What I had anticipated five years ago is now a reality. After a long and hard technical run in 2001, the experiment started taking data with the muon beam in 2002. Data taking was continued in 2003 and in 2004, again with the muon beam, and the 2004 run is presently still ongoing. To pave the way to the hadron beam measurements, a 3-week pilot run with a hadron beam is planned at the end of the 2004 run.

After the technical stop of all the accelerators at CERN in 2005, the experiment will resume data taking and is expected to be in operation until at least 2010.

2 The COMPASS spectrometer

The COMPASS spectrometer has been set up at the CERN SPS muon beam, in Hall 888 of the Prevessin site. It combines high rate beams with a modern two stage fixed target magnetic spectrometer. Both stages foresee charged particle identification with fast RICH detectors, electromagnetic calorimetry, hadronic calorimetry, and muon identification via filtering through thick absorbers. 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 layout of the spectrometer which was on the floor in 2002 is shown in Fig. 1.

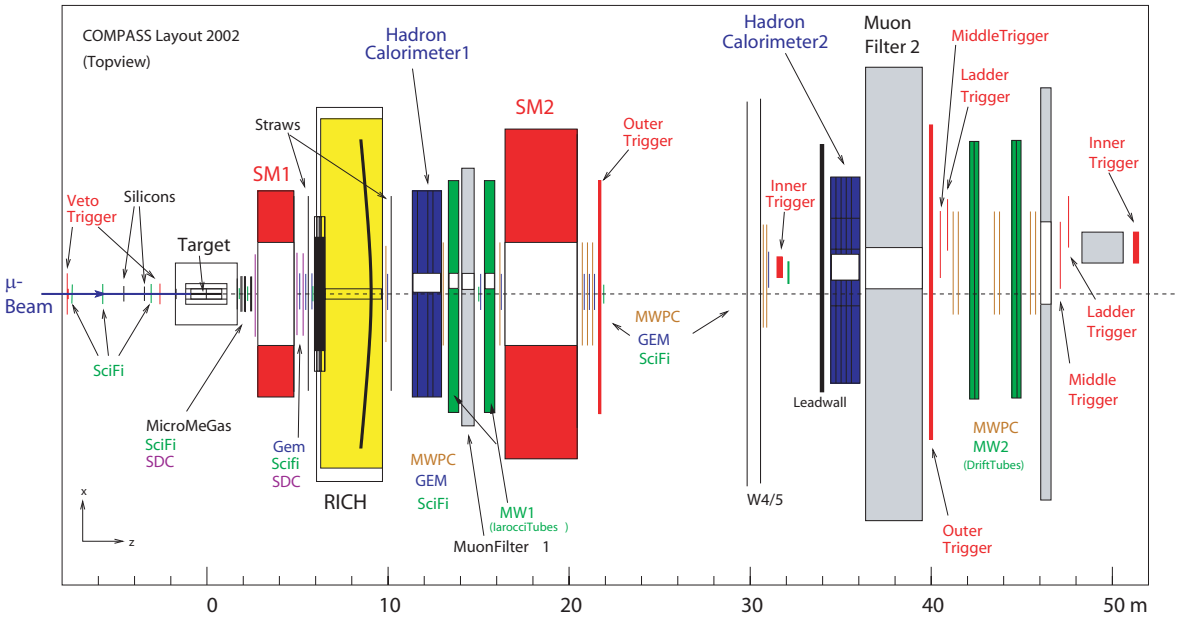

Figure 1: Top view of the lay-out of the spectrometer for the COMPASS experiment in 2002. The labels and the arrows refer to the major components of the tracking, trigger, and PID systems.

The experiment has been run at a muon energy of 160 GeV. The beam is naturally polarized by the $\pi-$decay mechanism, and the beam polarization is estimated to be 76%. 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, NH_3 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 $\sim$0.5 is of the utmost importance for the measurement of ΔG.

To match the expected particle flux in the various locations along the spectrometer, COMPASS uses very different tracking detectors. The small area trackers consist of several stations of scintillating fibres, silicon detectors, micromegas chambers [2] and gas chambers using the GEM-technique [3]. Large area tracking devices are made from gaseous detectors (Saclay Drift Chambers, Straw tubes [4], 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 Iarocci-like tubes and drift tubes downstream of muon absorbers.

Detector	number of coordinates	efficiency	resolution	timing
Scintillating fibers	21	94 %	130 μm	0.45 ns
Micromegas	12	95 - 98 %	65 μm	8 ns
GEM	40	95 - 98 %	50 μm	12 ns
SDC	24	94 - 97 %	170 μm	
Straw tubes	18	$>$ 90 %	270 μm	
MWPC	32	97 - 99 %		
W4/5	8	$>$ 80 %		

Table 1: Trackers performances in the 2002 run.

The charged particle identification relies on the RICH technology. Presently, only RICH1 (the RICH in the first magnetic spectrometer) exists [5]. The length of the radiator (C_4F_{10} 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 [6] (segmented in 8×8 mm^2 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 m^2 and the total number of pads is about 70,000. The front-end electronics uses a modified version of the Gassiplex chip, and the read-out cards constitute a major project, utilizing hundreds of DSP's.

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 system [7] uses a modern concept, involving highly specialized integrated circuits. The readout chips are placed close to the detectors and the data are concentrated at a very early stage via high speed serial links. At the next level high bandwidth optical links transport the data to a system of readout buffers. The event building system is based on PCs and Gigabit or Fast Ethernet switches and is highly scalable. This high performance network is also used to transfer the assembled data to the computer center for database formatting, reconstruction, analysis and mass storage. The data are sent via an optical link from the Hall 888 directly to the Computer building for Central Data Recording (CDR).

To handle the huge amount of data (the collected raw data size is $\sim$300 TB/year) we used Objectivity/DB until the end of 2002 [8], and Oracle since. The power needed to process COMPASS data is about 100 kSI2k. In the off-line farm, the data servers handle the network traffic from the CDR,

distribute the raw data to the CPU clients (where they are put in the data base), receive them back from the PCs, and finally send them to a hierarchical storage manager (HSM) system. In parallel, the data servers receive the data to be processed from the HSM, send them to the PCs for processing, collect the output (DST or mDST), and send it to the HSM. Data processing is performed on the farm at CERN while DST data analysis is done on satellite farms in the major home institutes.

A major effort was devoted to write from scratch the off-line programs (CORAL, the new COmpass Reconstruction and AnaLysis program) using object-oriented technology and C++ language.

3 First physics results

Over the 80 days of the 2002 run, a total of about 6000 millions of events have been collected, corresponding to a data size of 260 TB. Similar numbers have been taken in the 2003 run and are presently being collected in the 2004 run. Many different physics topics are presently being investigated,
- ΔG from open charm and high p_T hadron pair,
- A_{LL} to extract A_1^d, the virtual photon asymmetry, and g_1,
- vector meson (ρ, ϕ, J/Ψ) production to test s-channel helicity conservation,
- Λ physics,
- transversity (single hadron, hadron pairs, Λ),
- Cahn asymmetries,
- search of exotics (Θ^+, Ξ^{--}, ...).

A flavour of the physics results obtained from the 2002 data is given below.

3.1 $\Delta G/G$ from charm photo-production

The main goal of COMPASS is a direct measurement of ΔG by measuring the cross-section asymmetry of open charm in DIS $A_{\mu N}^{c\bar{c}}$

$$A_{\mu N}^{c\bar{c}} = \frac{\Delta\sigma^{\mu N \to c\bar{c}X}}{\sigma^{\mu N \to c\bar{c}X}}.$$

The possibility to measure directly ΔG by measuring $A_{\mu N}^{c\bar{c}}$ was put forward already sixteen years ago [9, 10] to solve the nucleon spin puzzle raised by the EMC result [11]. At COMPASS energies the production of charm goes predominantly via photon-gluon fusion (PGF), according to the diagram shown in Fig. 2, and the quantities $\sigma^{\mu N \to c\bar{c}X}$ and $\Delta\sigma^{\mu N \to c\bar{c}X}$ can be expressed as a convolution of the elementary photon-gluon cross-section with the gluon distributions G and ΔG.

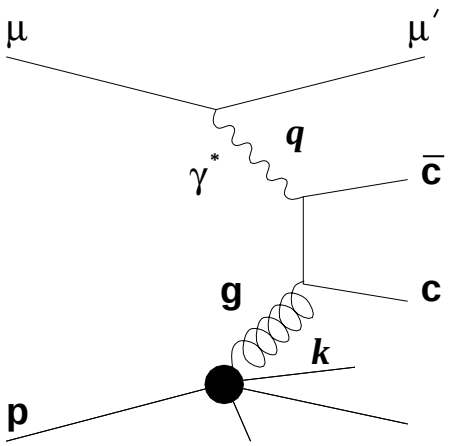

Figure 2: The photon-gluon fusion diagram, dominant mechanism for charm production at COMPASS energies.

Open-charm events are identified by reconstructing D°, $\bar{D}^\circ$, and $D^{*\pm}$ mesons from their decay products, i.e. $D^\circ \to K^-\pi^+$ and $D^{*+} \to D^\circ\pi^+ \to K^-\pi^+\pi^+$ and charge conjugate. In the first case, cuts on the K direction in the D° rest frame ($|cos(\theta^*_K)| < 0.5$) and on the D° energy fraction ($z_D = E_D/E_{\gamma^*} > 0.25$) are needed to reduce the background contamination. Preliminary signals of the D mesons are shown in fig. 3. Kaon-pion pairs are selected by asking: $z_D > 0.2$; $|cos(\theta^*_K)| < 0.85$; $10 < p_K < 35$ GeV in order to be in the RICH K identification region. A soft pion (< 10 GeV) is also required. This measurement is statistically limited. The D° signal in our data is at the level of 10^{-7}, and other decay channels are also being investigated presently. From the present analysis and this channel only the projected error on $\Delta G/G$ using the data from 2002, 2003 and 2004 should be about 0.24.

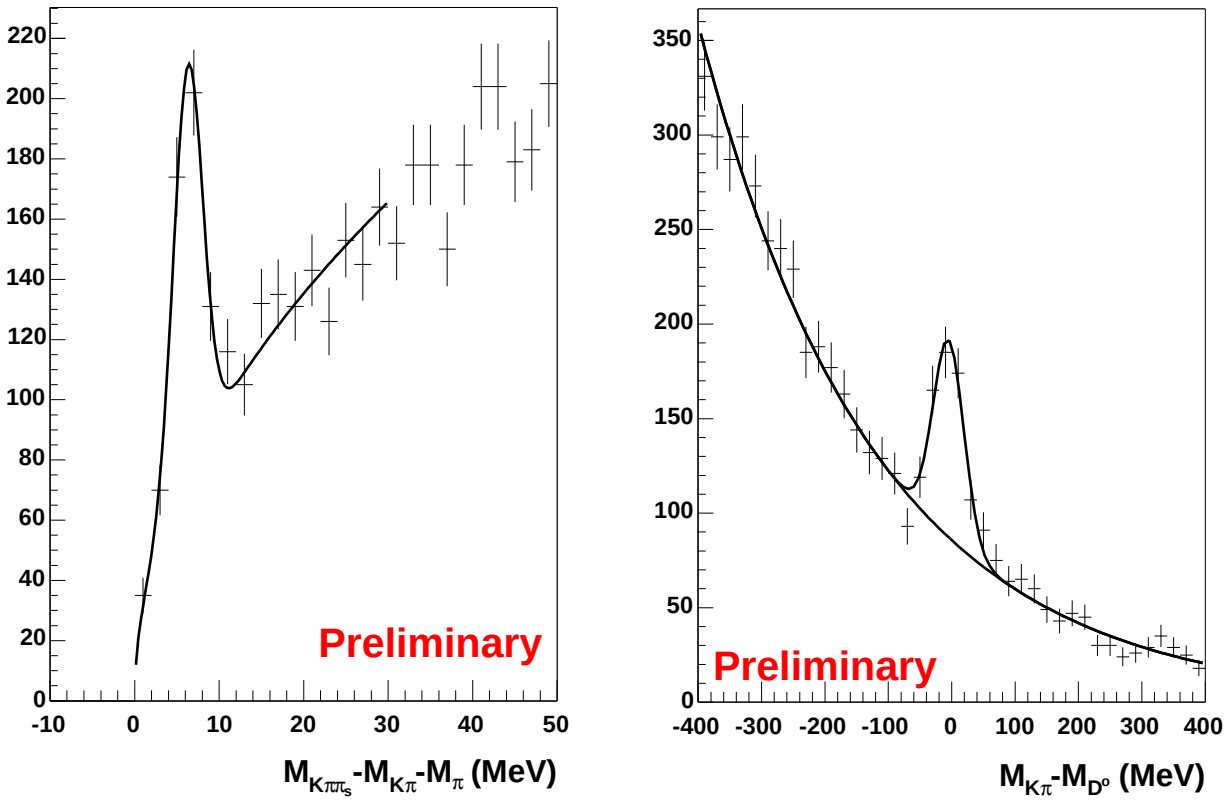

Figure 3: Left: D^* produced by requiring the invariant mass of the $K\pi$ pair to be in a 60 MeV window around the D^0 peak and a soft pion being detected. Selecting the events around the D^* mass, the D^0 peak in the invariant mass spectrum of $K\pi$ is very clear (figure at the right).

3.2 $\Delta G/G$ from high p_T hadron pairs

The most promising additional way to measure ΔG in COMPASS uses the asymmetry of charged hadron pairs at high p_T [12]. Originally developed for the COMPASS experiment, the method has been recently applied also to the HERMES data [13]. The basic diagram is still the PGF, $\gamma g \to q\bar{q} \to h^+h^-X$, and the hardness of the process is guaranteed by the large p_T. The background from the leading order process $\gamma q \to q$, and the QCD-Compton process, $\gamma q \to \gamma q$, 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 a statistically precise measurement.

The virtual photon-deuteron asymmetry $A^{\gamma * d}$ for high p_T pair production evaluated from the 2002 data for all Q^2, is found to be $A^{\gamma * d} = -0.065 \pm 0.036(stat) \pm 0.010(syst.)$, a hint that $\Delta G/G$ could be

small and positive. The systematic error is estimated only from measurements of the so-called "false asymmetries", i.e. asymmetries which should be zero for an apparatus with uniform acceptance. Prior to calculation of $\Delta G/G$ from $A^{\gamma * d}$, one needs to subtract the asymmetries from the physics background. Physics background contaminations can be reduced by selecting events with $Q^2 > 1$ GeV^2, but this cut substantially reduces statistics. Assuming that the contribution of PGF processes to the measured asymmetry is about 1/4 of the total and using all statistics expected at COMPASS by the end of 2004 run, one can determine $\Delta G/G$ with an accuracy $\sigma(\Delta G/G) \simeq 0.05$ for all Q^2 and $\simeq 0.17$ for events with $Q^2 > 1$ GeV^2.

3.3 Virtual photon-deuteron asymmetry $A_1^d(x)$

This asymmetry is related to the polarized structure function and has been measured before by SMC [14], SLAC [15] and HERMES [16] collaborations. Potential opportunities of COMPASS, especially in the region of small x, are seen from the preliminary COMPASS data on $A_1^d(x)$ obtained in 2002 (Fig. 4). This sample includes about $6.5{\cdot}10^6$ events within usual DIS cuts ($Q^2 > 1$ GeV^2). Also shown in figure 4

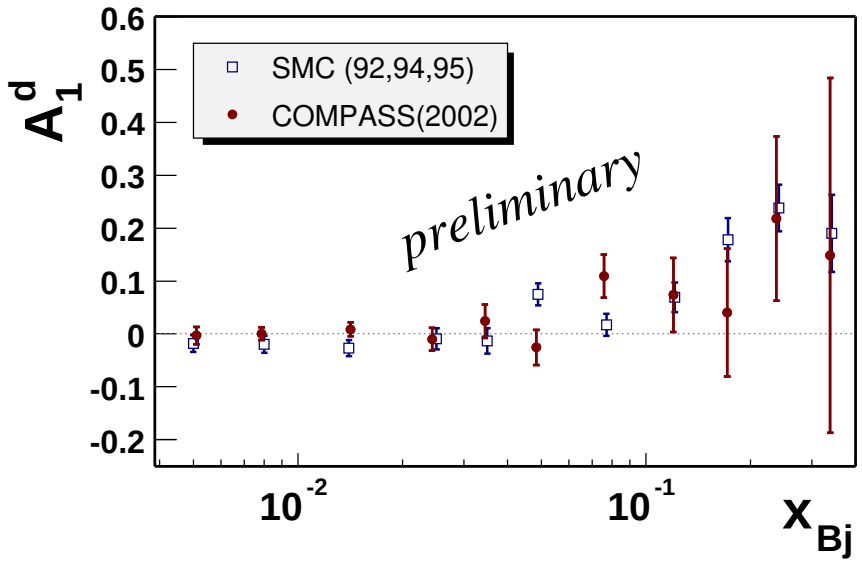

Figure 4: Virtual Photon-Deuteron asymmetry as a function of x-Bjorken compared to the SMC published data.

are the SMC data which are the only ones to also cover the low-x region. The two sets of data agree rather well although the new COMPASS data do not hint at the slightly negative values of A_1^d which were suggested by the SMC data. The statistical errors of the COMPASS data in the low-x region ($x < 3 \cdot 10^{-2}$) are already now smaller than the SMC ones, and will decrease by a factor of two when the data from 2003 and 2004 will be added to the analyzed sample. The final accuracy we will obtain in the low x region will allow to improve the measurement of the first moment of g_1, and thus $\Delta\Sigma$.

The addition of a new large-Q^2 trigger system in 2003 has already resulted in data points at large x with an accuracy comparable to that of the SMC experiment, therefore by 2004 even the large-x data of COMPASS will be more precise than the SMC data.

3.4 Collins asymmetry and transversity

As originally shown by Jaffe and Ji [17], to completely specify the quark state at the twist-two level one has to add the transverse spin distributions $\Delta_T q(x)$ to the momentum distribution $q(x)$ and to the helicity distribution $\Delta q(x)$. Measurement of $\Delta_T q(x)$ gives access to new information related to

relativistic effects for bound quark states, the study of new evolution in QCD, the knowledge of the tensor charge of the nucleon, and predictions for other processes involving transversity.

The transversity distributions $\Delta_T q(x)$ have never been measured, since they are chirally-odd functions and do not contribute to inclusive deep inelastic scattering. They may instead be extracted from measurements of the spin asymmetries in cross-sections for semi-inclusive deep inelastic scattering (SIDIS) 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 $\Delta_T q(x)$ and another chirally-odd function, which contributes to the fragmentation of the transversely polarized quark. 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 $\Delta_T D_q^h$ which describes the hadronization of a transversely polarized quark q in a hadron h [18], as yet unmeasured, which in its own right merits serious study. In the case in which the observed final particle is for example a Λ°, the chirally-odd function is a transverse fragmentation function, also unknown and interesting. Other channels for accessing $\Delta_T q$ require the detection of a vector particle or two pions in the final state.

To measure transversity, COMPASS has taken SIDIS data with the ^{6}LiD polarized along the vertical direction, i.e. orthogonally to the incoming μ momentum. About 20% of the COMPASS running time has been devoted to this measurement. Figure 5 shows preliminary values of the first ever measured single hadron Collins asymmetry on a deuteron target, separately for positive and negative leading hadrons. The data are compared with a model calculation [19] of the asymmetry A_{UT}, which includes

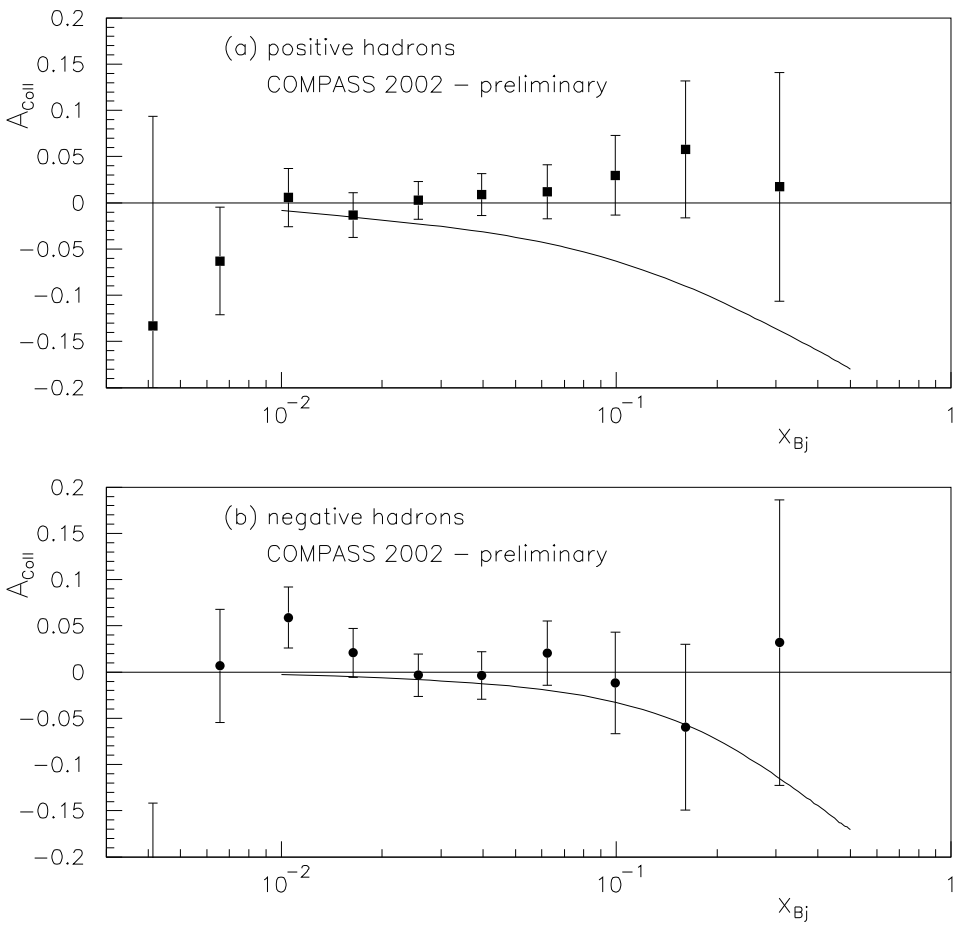

Figure 5: Preliminary results for the asymmetry A_{UT} for positive (a) and negative (b) leading hadrons produced by 160 GeV μ^+ on a transversely polarized deuterium target. The data refer to the year 2002 COMPASS run, while the curves are from Ref. [19].

the transversity distribution function $\Delta_T q(x)$ through the following linear combination of quark flavours:

$$A_{UT}(x) = \frac{\Sigma e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T D_q^h}{\Sigma e_q^2 \cdot q(x) \cdot D_q^h}.$$

The small values of the measured asymmetries at all x might imply either a cancellation between the proton and the neutron asymmetries, or a small Collins effect in the fragmentation.

Parallel work on the Collins asymmetry of hadron pairs, and on the transverse polarization of Λ's produced in the transversity runs, is ongoing.

3.5 Exclusive ρ^0 production

The large amount of data taken by COMPASS over a large kinematical domain make the investigation of several dynamical processes possible. A good example is provided by the study we have performed of the exclusive production of the ρ^0 vector meson on the nucleon $\mu + N \rightarrow \mu' + N' + \rho^0$. It is known from previous experimental data that the helicity of the photon in the $\gamma * N$ center-of-mass system is approximately retained by the vector meson, a phenomenon known as s-channel helicity conservation (SCHC). An accurate measurement of the violation of the SCHC will give further insight into the interaction. Using our longitudinally polarized muon beam we could measure the full set of ρ^0 spin density matrix elements [20] and determine their Q^2 dependence. From the 2002 run the total sample of good accepted events, with $Q^2 > 0.01$ GeV^2 is about 700000.

From the decay angular distribution of the two pions in the ρ^0 center-of-mass system we could determine the element r_{00}^{04}. Our result for this element, which can be interpreted as the fraction of longitudinal (helicity 0) ρ^0 in the sample, are given in fig. 6, where they are also compared with the results of other experiments [21, 22, 23]. This result indicates that at small Q^2 the production by transverse photons almost completely dominates.

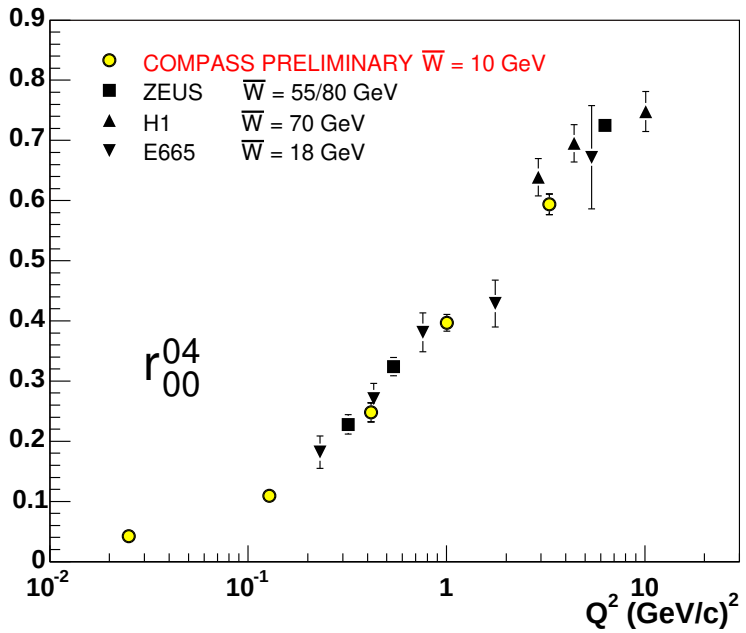

Figure 6: Preliminary results for the Q^2 dependence of the ρ^0 spin density matrix element r_{00}^{04} of the ρ^0 exclusive production in μN scattering. The COMPASS data are compared with existing measurements.

From the distribution of the angle between the ρ^0 production plane and the ρ^0 decay plane we could determine the two matrix elements r_{1-1}^{04} and $Im\, r_{1-1}^{3}$. It has to be stressed that the latter one

can only be determined using a polarized lepton beam. As shown in fig. 7 our measurements exhibit small negative values of r^{04}_{1-1} ($\approx$ -0.03), approximately independent of Q^2, whereas $Im\, r^3_{1-1}$ is consistent with zero. The non-zero value of r^{04}_{1-1} indicates a small contribution of amplitudes with helicity-flip, i.e. a small SCHC violation. Again our data are compared in the figure with the data from other experiments [21, 22, 23].

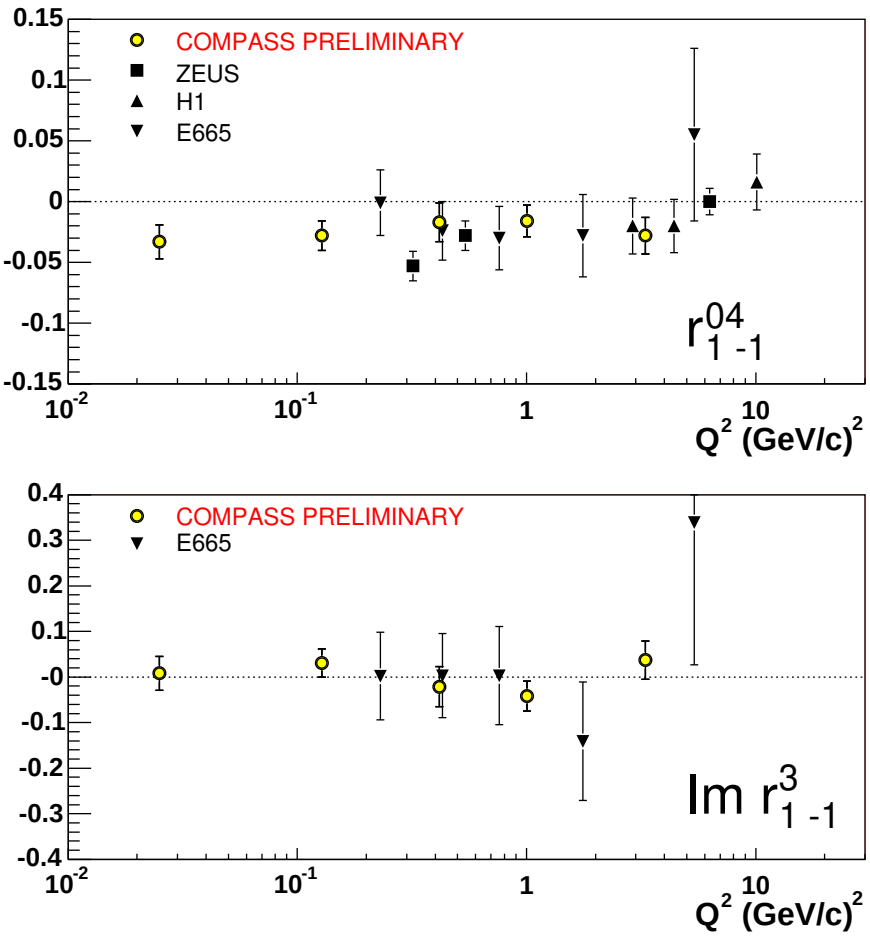

Figure 7: Preliminary results for the Q^2 dependence of the ρ^0 spin density matrix elements r^{04}_{1-1} and $Im\, r^3_{1-1}$ in ρ^0 exclusive production in μN scattering. The COMPASS data are compared with existing measurements.

4 Conclusions

It has been a pleasure to come to Erice and to present the COMPASS experiment at this most interesting School, and I am grateful to Amand for all the work and enthusiasm he puts in this initiative.

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 is presently half-way in its third year of data taking, 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 results from the data analysis, and underlined the very large effort which is

presently ongoing to fully understand the spectrometer and the data. From these first results it should be clear that COMPASS is fulfilling its promises and is already showing its huge physics potential. As an example I have mentioned the status and the preliminary results of a few analysis, A_{LL}, ΔG, exclusive ρ^0 production, and transversity, from the 2002 data set. Many more results based on 2002 and 2003 data will be presented at SPIN2004 [24].

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