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RECENT RESULTS FROM COMPASS SPIN PROGRAM

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COMPASS is a fixed target experiment at CERN's Super Proton Synchrotron. Part of its physics program is dedicated to the spin structure of the nucleon, which it studies with a polarized muon beam and polarized targets. An overview of its recent results along this line is given, in particular: the first results of our 2011 longitudinally polarized proton run, a report on our progress towards the extraction of the gluon polarization, ΔG, at NLO and an update on our measurements of transverse spin and k_T-dependent processes, from our 2010 transversely polarized proton data, and of hadron multiplicities.

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INTRODUCTION

COMPASS represents a continuation of experiments investigating the spin structure of the nucleon *via* DIS. Its advantage lies in its ability to achieve good precision over a wide x range, down to $\sim 10^{-3}$ for $Q^2 > 1$, and in the fact that it does so not only for inclusive DIS, but also for a variety of semi-inclusive measurements, both in DIS and photoproduction regimes. This is made possible thanks to the concurrence of a unique beamline (CERN SPS M2), that is able to deliver high-energy polarized muons, a thick (~ 1.2 m), large aperture polarized target and a forward spectrometer equipped, in particular, for particle identification.

The collaboration has taken spin structure data for a total of seven years since 2002, alternating longitudinal and transverse polarization on either deuteron or proton polarized targets. The latest results extracted from these data are reported here. They comprise the first results of our 2011 proton run at 200 GeV, as well as updates on ΔG, transverse spin and k_T-dependent processes and multiplicities.

In 2010, the COMPASS II proposal [1] was submitted to investigate further the nucleon structure towards a three-dimensional picture. For this, a series of a new measurements is planned, accessing GPDs and TMDs. Moreover, the studies of semi-inclusive DIS on unpolarized target will be continued. This aspect is the object of separate presentation at this Symposium [2].

1. EXPERIMENTAL ESSENTIALS

The COMPASS spectrometer is described in detail in [3]. Its experimental setup was designed to allow a precise determination of asymmetries. An important point, in this respect, is the control of fake asymmetries. We achieve it thanks to the simultaneous measurement of the two spin states in two oppositely polarized target cells ($1/2\uparrow$, $1/2\downarrow$) so that fluctuations in incident muon flux cancel out. In order to correct for the difference of acceptance seen by the two cells, the spin orientations are periodically reversed, *via* target field rotation when possible, *i.e.*, in the longitudinal case, and *via* repolarization, which allows a spin reversal in a constant field.

An even better control of the instrumental asymmetries is achieved starting with the 2006 run, where the target is divided in 3 ($1/4\uparrow$, $1/2\downarrow$, $1/4\uparrow$ and *vice versa*), so that both spin states have permanently the same average acceptance.

The cross-section asymmetry, $\mathcal{A}$, is related to the counting asymmetry, A, by factors describing the polarization of the incoming particles, P_μ for the beam, P_T and f for the target polarization and for the process-dependent dilution factor. It is best expressed as $\mathcal{A}/D$,

$$\frac{\mathcal{A}}{D} = \frac{A}{P_\mu \times P_T f \times D}, \tag{1}$$

where one takes also into account a kinematical factor, D, describing the polarization transfer from the muon to the photon. D is process-dependent and typically averages to $\sim$60%. Typical values for the LiD, polarized deuteron target are $P_T \simeq 50\%$ and $f \simeq 40\%$, yielding a figure of $\sim 10\%$ for the overall dilution factor relating the physics asymmetry of interest to the expermimental asymmetry. For the polarized proton target (NH_3), the corresponding numbers are $P_T \simeq 90\%$ and $f \simeq 14\%$, and $\sim 6\%$ for the overall factor.

The first four years of data taking have been spent on deuterons, to benefit for the larger figure of merit, mainly in the longitudinal mode. Since 2007, the proton target has been used, shared equally between longitudinal and transverse modes. An estimate of the overall integrated luminosity for the longitudinal mode is ~ 4 fb^{-1}.

Electromagnetic calorimetry has been progressively installed in both spectrometer stages next to the already existing hadronic one. It is not yet included in the muon data analysis.

2. 2011 PROTON RUN

An important aspect of our understanding of the polarized structure of the nucleon is the determination of the longitudinally polarized parton densities (pPDFs) in QCD and their first moments, which correspond to the spins carried by the quarks and gluons. DIS has played a crucial role in this determination, with

measurements being taken from SLAC, CERN, DESY and JLab experiments. In this context, COMPASS occupies a strategic position, in the small x range. It has been undertaken to provide a boost in precision for the inclusive and semi-inclusive g_1 data in this range. The 2011 run represents the last building block of this undertaking, bringing the precision on the proton close to that already achieved on the deuteron. This is illustrated in Fig. 1, for the case of inclusive g_1.

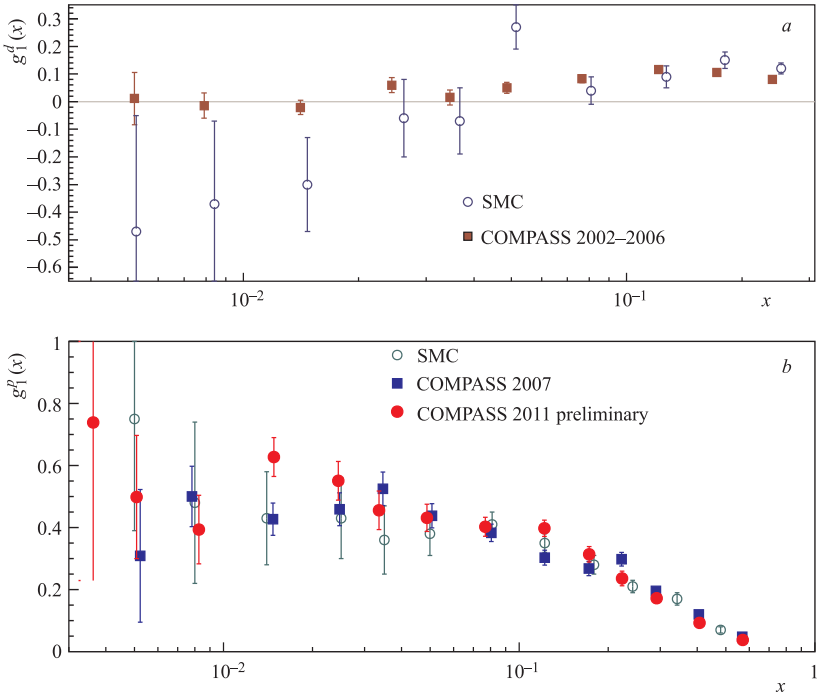

Fig. 1. g_1^d (*a*) and g_1^p (*b*): COMPASS, including preliminary results from the 2011 (200 GeV) [4] and earlier data (160 GeV), compared to SMC (190 GeV)

The analysis of the 2011 SIDIS data, *i.e.*, the semi-inclusive production of hadrons (π and K) in DIS, is under way. It is projected to shed light on the strange quark polarization puzzle, *i.e.*, the contradiction between the strange quark pPDF obtained from inclusive DIS data and that obtained from SIDIS, described in detail in [5].

3. ΔG

Among all pPDFs, the gluon, ΔG, is the least constrained by DIS or SIDIS. Firstly, it does not couple directly to the photon. Secondly, the available level arm in Q^2 is too small for it to inferred from the evolution of quark distributions, at least when considering DIS experiments alone, since these are at present

restricted to fixed target geometries. COMPASS overcomes the problem by considering direct approaches, *viz.* open charm and high-p_T hadron productions, where the contributions of gluons are enhanced, typically *via* the second-order process called photon–gluon fusion (PGF). This solution has the drawback that the momentum fraction x is not measured in the interaction. In order to access the pPDFs, one has then to devise a way to fold these soft distributions with the partonic level hard processes. Traditionally, COMPASS has relied on Monte-Carlo generators (LEPTO or PYTHIA) to achieve this goal, limiting itself to LO in pQCD. Recently, it has made progress towards NLO.

Firstly, it performed a new analysis of its open charm data [6], still relying on LEPTO but including NLO corrections to hard processes based on [7]. The obtained value is

$$\Delta G/G = -0.13 \pm 0.15(\text{stat.}) \pm 0.15(\text{syst.}), \quad x_G = 0.20^{+0.13}_{-0.08}, \quad \mu^2 \approx 13\ \text{GeV}^2.$$

Compared with LO extractions, it is still compatible with zero, with improved precision and at a higher average x. Which, combined with what is otherwise conjectured for the functional shape of the distribution as a function of x, reinforces the conclusion that ΔG is small.

Secondly, a new pQCD calculation became available for the unpolarized cross section of the hadron photoproduction at high p_T [8]. It updates a previous NLO calculation [9] by including higher-order corrections, and reproduces much more accurately our data [10]. It therefore gives confidence in our ability to extract valuable information on ΔG beyond LO from the $\sim$4 fb^{-1} of photoproduction data accumulated by COMPASS.

4. TRANSVERSE SPIN AND k_T-DEPENDENT PROCESSES

COMPASS 2010 run was entirely dedicated to data taking in the transverse polarization mode. Transverse spin effects arise in SIDIS from various k_T-dependent parton distributions (TMDs) [11, 12]. For example, the transversity distribution, $h1(x, k_T)$, couples to the Collins fragmentation $H_1^\perp(z, p_T)$ describing the azimuthal hadron distribution correlated with the quark transverse polarization. And the Sivers distribution, $f_{1T}^\perp(x, kT)$, describing the azimuthal distribution of quarks correlated with the nucleon transverse polarization couples with the usual unintegrated fragmentation function $D_1(z, p_T)$.

A first analysis of these two mechanisms in the 2010 data was already published [13]. One of its remarkable results concerns the Q^2 dependence of the effects: negligible for Collins and significant for Sivers. This is evidenced by comparing measurements by COMPASS and HERMES, but also within COMPASS data alone, and, thanks to their good statistical precision, by comparing low and high y data. The Sivers dependence turns out to be compatible with the TMD evolution calculations of [14].

Since then, the analysis has been refined and expanded, yielding many new interesting results. These are the object of dedicated presentations at this conference [15–17]. The main aspects are the following. The Collins and Sivers asymmetries have been determined for identified $\pi^{\pm}$ and $K^{\pm}$, cf. Fig. 2. The six

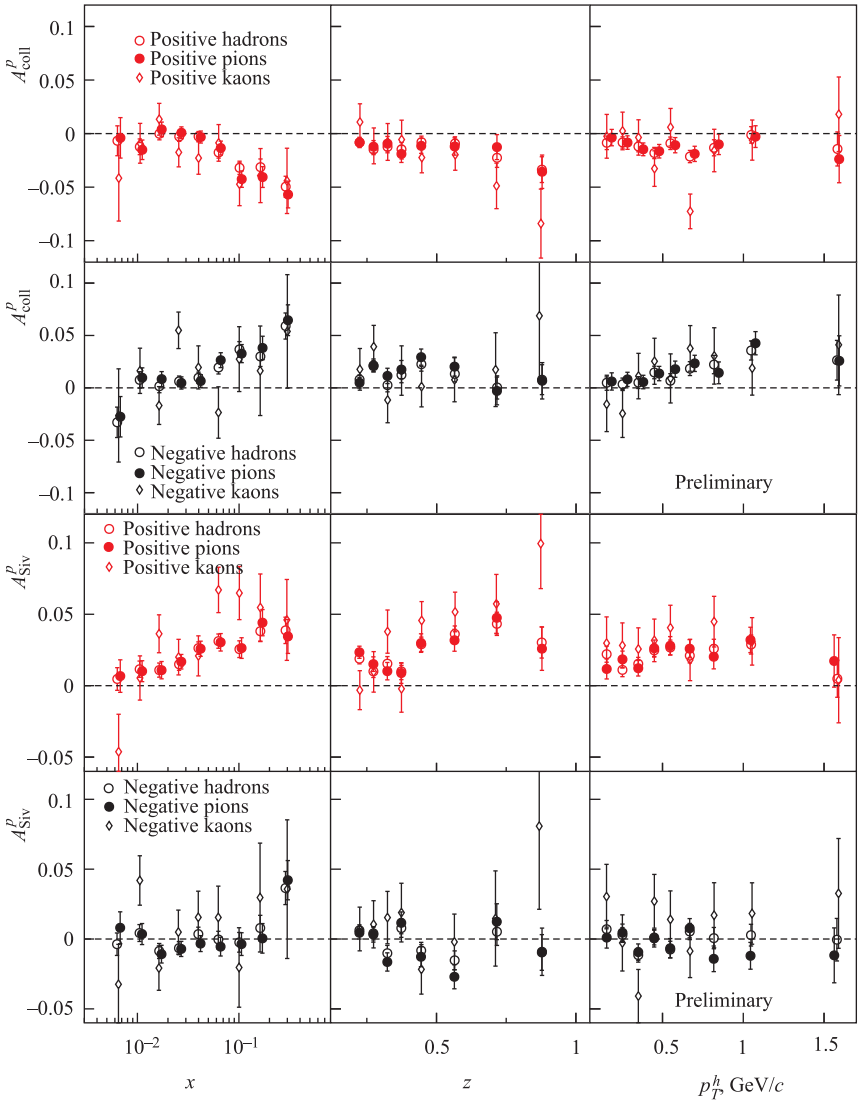

Fig. 2. Collins (top) and Sivers (bottom) asymmetries from COMPASS 2010 proton run: $\pi^{\pm}$ and $K^{\pm}$ compared to unidentified hadrons, as a function of x, z, and p_T

extra transverse spin asymmetries showing up in the azimuthal modulation of the SIDIS cross section have been released, demonstrating significant effects in two of the harmonics, cf. Fig. 3. The so-called two-hadron asymmetries, resulting from the coupling of the transversity distribution with the interference fragmentation $H_1^{\sphericalangle}$ have been extracted, cf. Fig. 4. All these results confirm the trends already observed by HERMES, with improved precision and over a wider kinematical domain.

In parallel, the analysis of unpolarized azimuthal modulations, related to combinations of Cahn effect and Boer–Mulders $h_1^{\perp}$ TMD, and measured on our

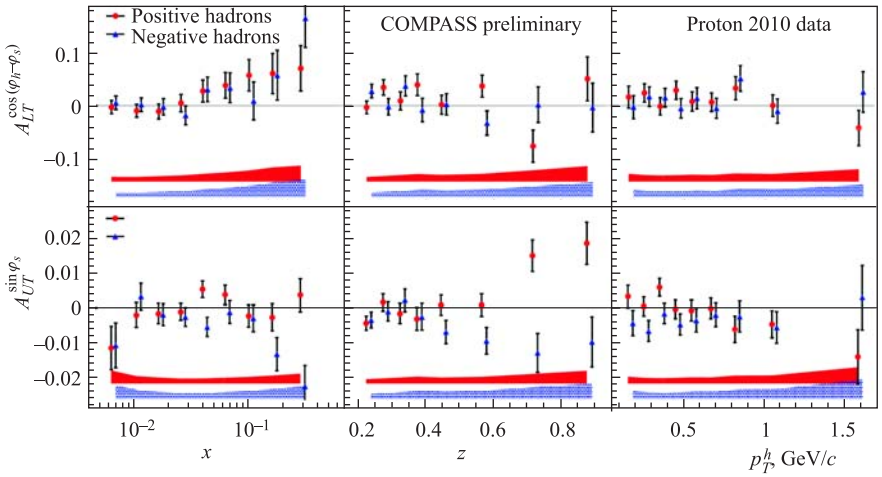

Fig. 3. Modulation of the transverse spin asymmetry on $\cos(\phi_h - \phi_S)$ (top) and $\sin\phi_S$ (bottom) in the 2010 proton run, with ϕ_h and ϕ_S — the azimuthal angles of the hadron and nucleon's spin in the $\gamma^* N$ system, respectively

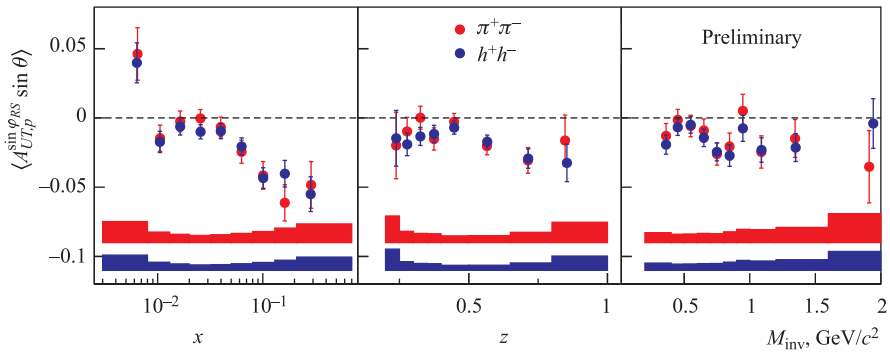

Fig. 4. Two-hadron asymmetries from the 2010 proton run: $\pi^+\pi^-$ *vs.* h^+h^-, as a function of x, and the momentum fraction and the invariant mass of the hadron system, z and $M_{\rm inv}$

isoscalar LiD target, has been continued, cf. dedicated presentation at this Symposium [18].

Finally, the Λ polarization, as a way to access transversity, and pPDFs, are also explored. A related study, concerning Λ production *via* the decay of heavy hyperons, is presented at this Symposium [19].

5. MULTIPLICITIES

In parallel with the study of spin asymmetries, COMPASS is undertaking a program of investigation of the fragmentation process. The latter obviously contributes to all the semi-inclusive channels described *supra*. In the framework of independent fragmentation, it is embodied in Fragmentation Functions (FFs). FFs have initially been extracted from, mostly high energy, e^+e^- collider data. Such extractions suffer from two limitations. They can only separate quarks from antiquarks based on model assumptions. Their evolution to the Q^2 accessible to fixed target SIDIS, relies heavily on the poorly constrained gluon distributions, D_g^h. More reliable and versatile FFs can be obtained from a global fit of data comprising, in addition to e^+e^-, pp and SIDIS data, such as the DSS fit [20].

Experimentally, we study the fragmentation process by determining multiplicity distributions for the detected hadrons, using the data from our polarized deuteron LiD target, which is an isoscalar target, with little expected nuclear effects. Preliminary results have been released, on single $\pi^\pm$ and $K^\pm$ multiplicities, *cf.* dedicated presentation at this Symposium [21]. Since these results display some significant deviations with respect to the DSS fit, we are presently investigating the systematics involved in the measurement, by comparing the results obtained with two of the different experimental setups that we have used in conjunction with the LiD target. We are also exploring the dihadron fragmentation function, *i.e.*, the unpolarized counterpart of $H_1^\sphericalangle$ (*cf.* [21]), as well as other aspects of the single-hadron case such as its p_T dependence or the fragmentation to K_S^0.

6. OUTLOOK

The 2011 polarized proton run closes the first phase of COMPASS. The COMPASS-II proposal [1] has been approved by the CERN Research Board. For what concerns its nucleon structure part, it focuses on GPDs and TMDs. Data taking is planned to start after CERN long shutdown. In the mean time, a GPD pilot run is taking place in 2012, acquiring DIS and DVCS data on a liquid H_2 target.

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