The COMPASS experiment at CERN

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Abstract

COMPASS (**CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy) is a fixed target experiment at CERN dedicated to studies of the spin structure of the nucleon and of the spectroscopy of hadrons. During the years 2002-2004, 2006-2007 and 2010-2011 the COMPASS collaboration has collected a large amount of data by scattering polarized 160(200) GeV/c muons on polarized ^{6}LiD and NH_3 targets. The COMPASS results on quark and gluon helicities are discussed, as well as results on transverse spin and transverse momentum effects in semi-inclusive deeply inelastic scattering. During 2008 and 2009, the world leading data sets diffractive and centrally produced events were collected with 190 GeV/c hadron beams which are currently being analyzed using Partial Wave Analysis (PWA) technique.

1 The COMPASS set-up

The COMPASS experiment at CERN investigates how nucleons and other hadrons are built up from quarks and gluons. The main physics observables studied by the Collaboration are the polarization of the constituents of a polarized nucleon, the mass and decay patterns of the light hadronic system with either exotic quantum numbers or strong gluonic excitation.

The COMPASS set-up was designed for beams of 100 to 200 GeV/c and was built around two large dipole magnets, defining two consecutive spectrometers, covering large and small scattering angles separately. Particle identification is performed using a RICH counter and both electromagnetic and hadron calorimeters. Until 2006, the polarized target was filled with a ^{6}LiD target material (mainly deuterium), for which polarization better than 50% were routinely achieved. In 2007 we began using ammonia (NH_3, mainly proton), reaching a polarization of 90% and higher. A full description of the spectrometer can be found in [1].

1.1 Longitudinal spin structure of the nucleon

1.1.1 The gluon polarization measurement

Worldwide experimental efforts in the last few decades have led to numerous results extending our knowledge of the nucleon spin structure. But major challenges like the "spin crisis" still remain since 1988, when the EMC experiment found that only a small fraction of the nucleon spin is carried by the quarks: $\Delta\Sigma = 12 \pm 9 \pm 14\%$ [2]. The EMC result has been confirmed by a series of deep inelastic scattering experiments giving, on average, a contribution from the quarks $\Delta\Sigma$ to the nucleon spin of $\sim 30\%$.

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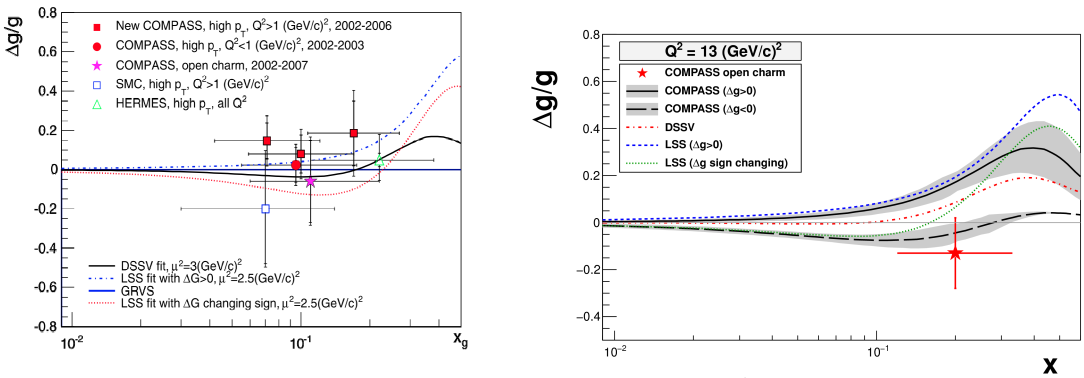

Figure 1: Left: Summary of the world efforts for the direct $\langle\frac{\Delta g}{g}\rangle$ measurement at LO in QCD. Right: NLO QCD result of COMPASS.

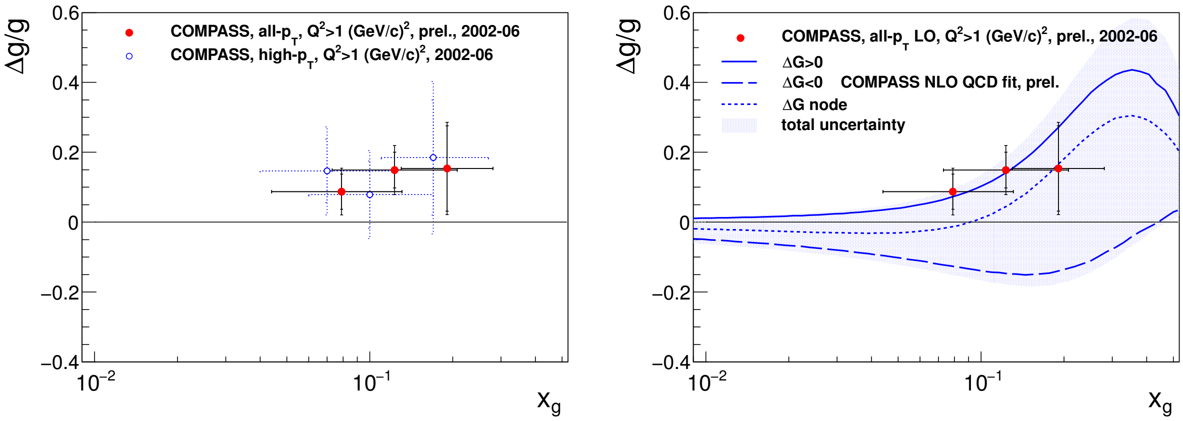

Figure 2: Left: Comparison of old and new results of $\langle\frac{\Delta g}{g}\rangle$ in three x_g bins. Right: Comparison of the new results with the newest COMPASS NLO QCD fit.

The spin 1/2 of the nucleon can be decomposed as $1/2 = 1/2\Delta\Sigma + \Delta G + L_{q+g}$ and one can conclude that the missing contribution to the nucleon spin must come from the gluons ΔG, and/or from the orbital angular momenta L_{q+g}. The gluon polarization can be directly measured via the spin asymmetry of the Photon-Gluon Fusion (PGF) process . The fragmenting $q\bar{q}$ pairs are then detected with two different, but complementary methods. In the first method ("open charm"), the events where the charmed quark hadronized into a D^0 or a D^* meson are selected. In the second method ("high-p_T pairs"), the PGF events are identified by requiring that two oppositely charged high-transverse momentum hadrons are detected in coincidence.

All gluon polarization measurements performed at COMPASS are summarized in Fig.1(left) together with the SMC [3] and HERMES [4] results. The world results for direct measurements of $\langle\frac{\Delta g}{g}\rangle$ are dominated by COMPASS and indicate a small value of ΔG, the first moment Δg. This was confirmed by the COMPASS "open charm" result at NLO [5], which also predicts a small value for the gluon spin contribution to the nucleon Fig.1(right).

It should be noted that a new LO extraction of the gluon polarization from COMPASS DIS data was done recently [6]. An evaluation of the gluon polarization $\langle\frac{\Delta g}{g}\rangle$ was done using the all-p_T method and $Q^2 > 1(GeV/c)^2$ events. This new method is based on a combination of neural network approach with a simultaneous extraction of A_1^{LO} and the gluon polarization. The resulting value, from 2002-2006 data, is $\langle\frac{\Delta g}{g}\rangle = 0.113 \pm 0.038 \pm 0.035$, at $\langle x_g\rangle = 0.10$. Results of $\langle\frac{\Delta g}{g}\rangle$ in three x_g intervals were also calculated Fig.2(left). A reduction of both systematic and statistical uncertainties by more than 50% was achieved comparing to the already published value using the same data [7]: $\langle \frac{\Delta g}{g} \rangle = 0.125 \pm 0.060 \pm 0.063$, at $\langle x_g \rangle = 0.09$. The comparison of the new results with the newest COMPASS NLO QCD fit is shown in Fig.2(right).

1.1.2 Global NLO QCD fits to world data on g_1

A new global NLO QCD fit of world data on g_1^p, g_1^d, g_1^n including the latest g_1^p COMPASS data which extend the kinematic domain to a lower value of x and higher values of Q^2 was done [8]. These g_1^p measurements were obtained from the 2011 data with an incident muon beam energy of 200 GeV/c on a polarized NH_3 target. The NLO pQCD fit including the world data on g_1 is used to extract a parametrization of the spin singlet, non-singlet and gluon distribution functions as functions of x and Q^2. Different scenarios of polarized parton distributions were investigated. A detailed study of systematic effects was done. The largest uncertainty arises from the choice of the functional forms. At the end, 3 scenarios cover all possible results with $\Delta G < 0$, $\Delta G \sim 0$ and $\Delta G > 0$ respectively. They lead to values of $\Delta\Sigma$ between 0.256 and 0.336 at $Q^2 = 3$ $(GeV/c)^2$. All fits in Fig.3 are performed in $\overline{MS}$ renormalization and factorization scheme.

In addition, the 2011 g_1^p data allow an update of the test of the Bjorken sum rule connecting the ratio of the weak coupling constants to the first moment of the non-singlet spin structure function g_1^{NS}. A value of $1.219 \pm 0.052 \pm 0.095$ is found for g_A/g_V in NLO, which is in excellent agreement with the results obtained from neutron β decay measurements.

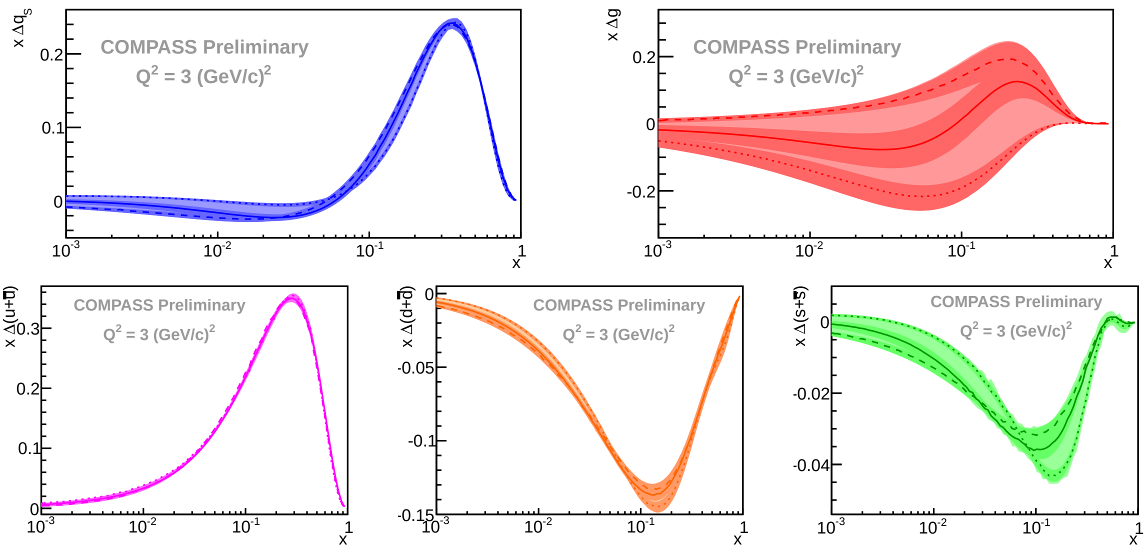

Figure 3: Results from the QCD fits of g_1 world data at Q^2=3 $(GeV/c)^2$. Top left: Quark spin distribution $x\Delta\Sigma$. Top right : Gluon spin distribution $x\Delta g(x)$. Bottom: $x(\Delta q + \Delta\bar{q})$ for u, d and s flavour going from left to right. For each distribution, the three solutions corresponding to the three different hypotheses of functional forms are shown

1.2 Transverse spin and momentum structure of the nucleon

The description of the partonic structure of the nucleon is one of the central problems of hadronic physics. In the present theoretical framework, eight transverse momentum dependent parton distribution functions (TMD PDFs) are required at leading twist for each quark flavour. They describe all possible correlations between the transverse momentum and spin of the quarks and the spin of the nucleon. When integrating over the quark transverse momentum five of these functions vanish, while three of them give the well known number, helicity and transversity distribution functions. Among these last three functions, the transversity distribution, which is the analogon of the helicity PDFs in the case of transversely polarized nucleons, was thoroughly studied only in the 90s and experimentally it is the least known one. On the experimental side, semi-inclusive deeply inelastic lepton scattering (SIDIS) is today the major source of information to access the TMD PDFs. The clear non-zero spin asymmetries recently measured in SIDIS off transversely polarized targets by both HERMES at DESY and COMPASS at CERN at different beam energies, can be described quite well with the present formalism, and thus give much confidence in the overall picture [9].

1.2.1 Collins and Sivers asymmetries

The results on azimuthal asymmetries in the reaction $\mu N \to \mu' h^{\pm} X$ r were extracted from data collected in semi-inclusive deep inelastic scattering using a 160 GeV/c positive muon beam and a transversely polarized NH_3 target. The Collins and Sivers asymmetries of the proton were extracted in the Bjorken x range $0.003 < x < 0.7$. These asymmetries were extracted as a function of Bjorken x, the relative hadron energy z and the hadron transverse momentum p_T^h .

The Collins asymmetries (Fig.4) for negative and positive hadrons are similar in magnitude and opposite in sign. They are compatible with model calculations in which the u-quark transversity is opposite in sign and somewhat larger than the d-quark transversity distribution function. These studies confirm the leading-twist nature of the Collins asymmetry. The correlations between the Collins asymmetries measured along x, z and p_T^h respectively, and the correlations between the Collins and Sivers asymmetries have been investigated and found to be small.

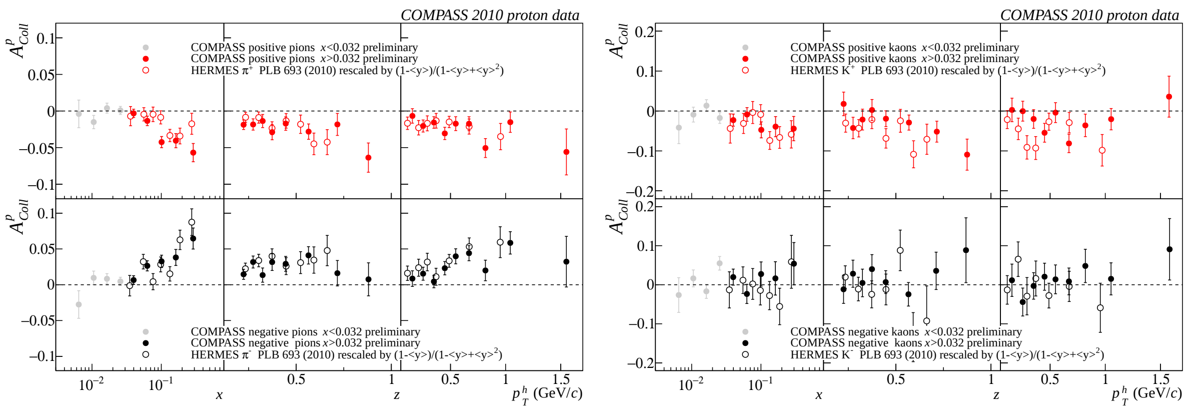

Figure 4: Comparison of the Collins asymmetries for charged pions and kaons as a function of x, z and p_T^h as measured by COMPASS (closed points) and HERMES [10] (open points). A cut on $x > 0.032$ has been applied to COMPASS data.

The Sivers asymmetries (Fig.5) was found to be compatible with zero for negative hadrons and positive for positive hadrons, a clear indication of a spin-orbit coupling of quarks in a transversely polarized proton. As compared to measurements at lower energy, a smaller Sivers asymmetry for positive hadrons is found in the region $x > 0.03$. The asymmetry is different from zero and positive also in the low x region, where sea-quarks dominate. The kinematic dependence of the asymmetry has also been investigated and results are given for various intervals of hadron and virtual photon fractional energy. In contrast to the case of the Collins asymmetry, the results on the Sivers asymmetry suggest a strong dependence on the four-momentum transfer to the nucleon, in agreement with the most recent calculations. In the light of the most recent theoretical advances refined combined analyzes to evaluate the Sivers function and its dependence on the SIDIS variables are required in order to understand the role of the Sivers function in the various transverse spin phenomena observed in hadron-hadron collisions and in future Drell-Yan measurements

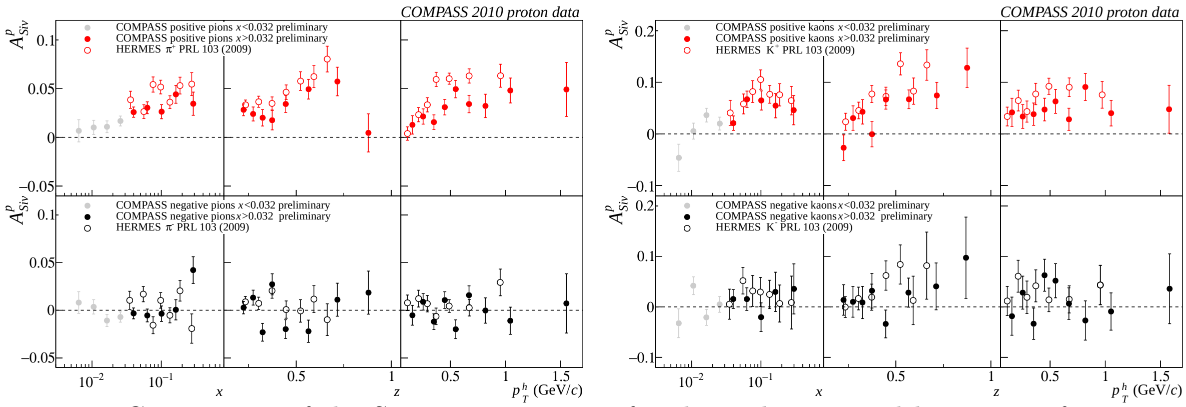

Figure 5: Comparison of the Sivers asymmetries for charged pions and kaons as a function of x,z and p_T^h as measured by COMPASS (closed points) and HERMES [11] (open points). A cut on $x > 0.032$ has been applied to COMPASS data.

1.2.2 Dihadron asymmetry and transversity PDF

An alternative to the Collins asymmetry approach to access the transversity PDF in SIDIS utilizes the transverse spin asymmetry in the production of pairs of oppositely charged hadrons, in the process $\mu N \to \mu' h^+ h^- X$ [12]. In this reaction a new chiral-odd fragmentation function appears, the dihadron Fragmentation Function (DiFF), which describes the spin-dependent part of the fragmentation of a transversely polarized quark into a pair of unpolarized hadrons describing a correlation of quark transverse spin with the normal pseudo-vector to the dihadron momenta plane.

The obtained asymmetry[13] is shown in Fig.6 as a function of x, z and $M_{\rm inv}^{\pi^+\pi^-}$. Large negative asymmetry amplitudes are observed in the high x region, which implies that both, the transversity distributions and the spin-dependent dihadron fragmentation functions do not vanish. Over the measured range of the invariant mass $M_{\rm inv}^{\pi^+\pi^-}$ and z, the asymmetry is negative and shows no strong dependence on these variables.

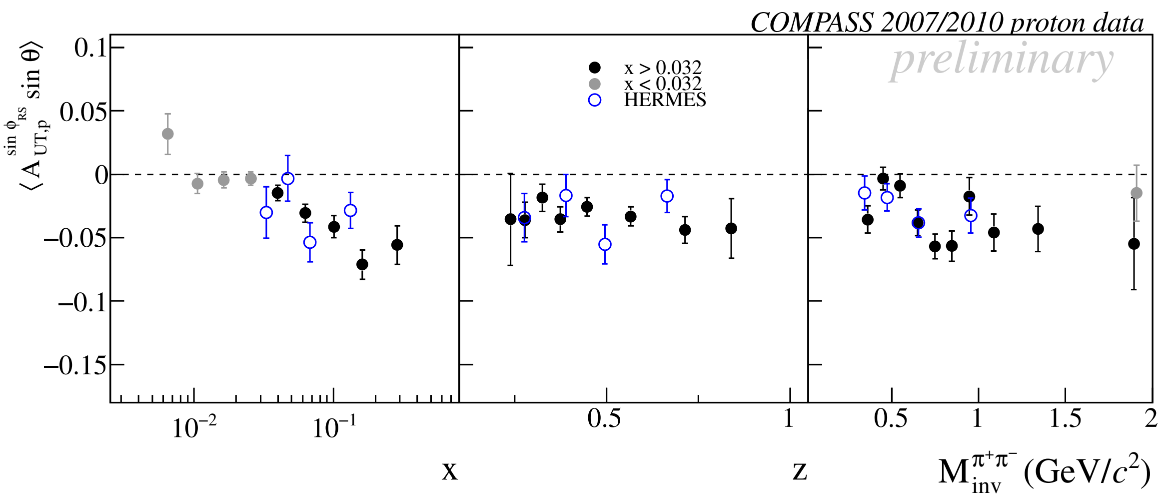

Figure 6: The $\pi^+\pi^-$ pair asymmetries of combined 2007/2010 proton COMPASS data in comparison with results from the HERMES experiment [14] scaled with $\frac{1}{D_{nn}}$ and sign changed.

The extracted transversity PDF are shown in Fig.7 demonstrate very good agreement for the u-quark transversity with the global fit and fair agreement for the d-quark. An approximate equality of the Collins asymmetry and the dihadron asymmetry is observed, suggesting a

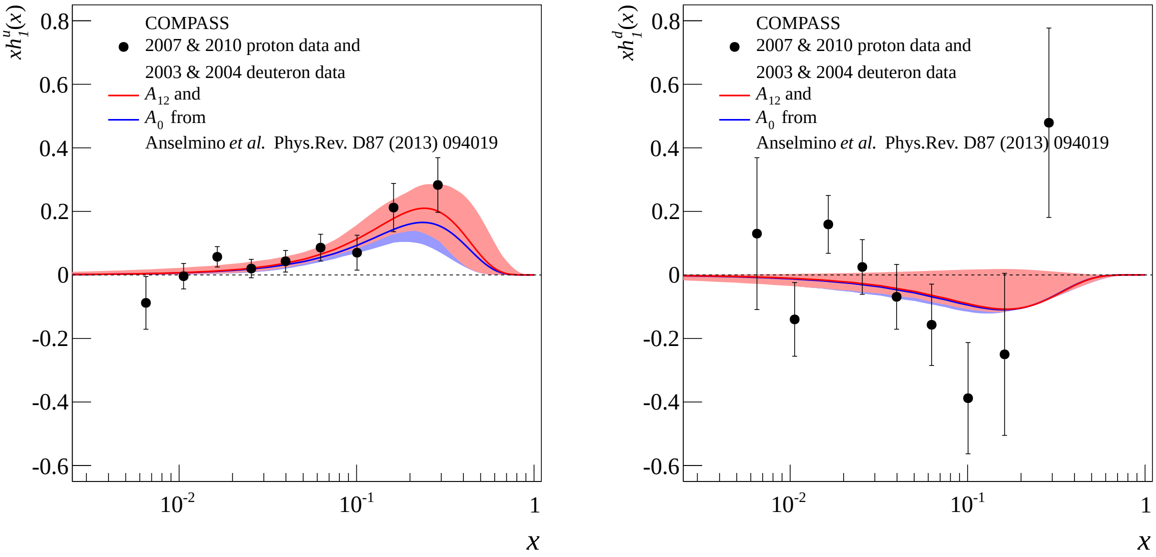

Figure 7: Comparison the results for u and d valence quarks transversity extracted from the 2003/2004 deuteron and the 2007/2010 proton pion-pair asymmetries with the single hadron Collins asymmetry global fit by [15]

common physical mechanism in the underlying fragmentation.

1.3 Hadron program

Forty years after the recognition that quark and gluons are the building blocks of matter, hadronic physics is at a turning point. The quark models of hadrons do not supply a realistic picture of the confinement of quarks and gluons in hadrons. A field theoretical based understanding is needed, in the framework of QCD. New theoretical tools have been developed and some experimental data have opened the way, but we are still lacking precise information on two central subjects: *the spectroscopy of so-called exotic states, and the spatial structure of the nucleon.*

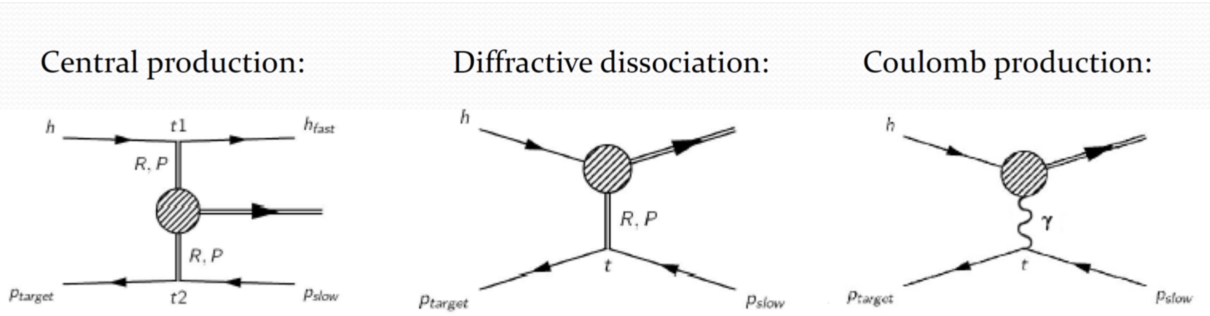

Figure 8: At COMPASS three production mechanisms are accessible. **Left**: Diffractive dissociation of a beam hadron via Reggeon exchange: forward kinematics; large cross-section ($\sim$ mb); need to separate particles at very small angles; study of J^{PC}-exotic mesons. **Middle**: Central production via double Reggeon fusion: large rapidity gap between scattered beam and produced particles; beam particle loses $\sim$ 10% of its energy; particles at large angles; possible source of glueballs. **Right**: Coulomb production: the pion and kaon polarizabilities measurements.

This is the context where, after several years of running with a muon beam to study nucleon spin structure, the COMPASS collaboration in 2008-2009 searched for the *exotic states, glueballs* *or hybrids*, through light hadron spectroscopy in high energy pion-proton reactions, using both centrally produced and diffractive events (Fig.8). QCD and derived models predict in particular the existence of $q\bar{q}g$ hybrids, which are difficult to identify experimentally due to mixing with ordinary $q\bar{q}$ mesons. However, some of them might have quantum numbers forbidden for $q\bar{q}$ systems, e. g. $J^{PC} = 0^{--}$, 0^{+-}, 1^{-+}. Their observation would therefore provide a fundamental confirmation of QCD. Lattice calculations predict a spin-exotic hybrid with mass within (1 - 2) GeV/c^2 [16]. Some promising candidates have been found for example the $\pi_1(1600)$ reported by BNL and VES [17].

1.3.1 The COMPASS hadron set-up

For the run with a hadron beam, several major modifications of the COMPASS setup were made [18]. The polarized target was substituted by a liquid hydrogen target with a cell of 40 cm length and 3.5 cm diameter, surrounded by a Recoil Proton Detector (RPD) to detect the slow recoil proton produced at large angle in central production and diffractive dissociation. A big effort has been dedicated to minimize the amount of material along the beam path and in the region close to it, thus reducing the background from secondary interactions. New GEM detectors, with a pixels readout in the central region, have been developed and used for a replacement of several of the scintillating fibre detectors tracking the particles at very small angles. A position resolution of 90 μm and timing resolution of 8 ns were reached.

The negative hadron beam consisted of 96.8% π^-, 2.4% K^- and 0.8% $\bar{p}$ whereas the positive beam consisted of 74.6% p, 24.0% π^+ and 1.4% K^+, all with momenta of 190 GeV/c. The beam particles were identified by CErenkov Differential counters with Achromatic Ring focus (CEDAR) detectors located upstream of the target.

1.3.2 Observation of $\pi_1(1600)$ spin-exotic state

First physics result from the COMPASS hadron program [19] were obtained from the pilot run in 2004 using a 190 GeV/c π^- beam impinging on a lead target: π^- Pb $\rightarrow \pi^-\pi^-\pi^+$. The

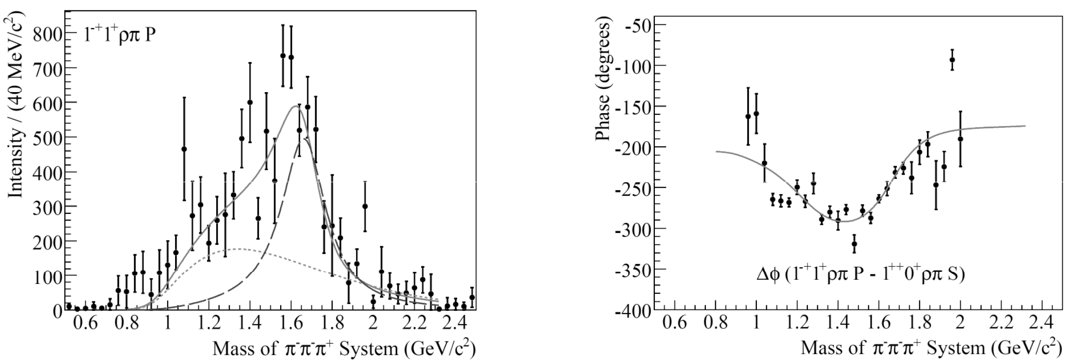

Figure 9: Pb target, charged final state, 2004 data. **Left:** Intensity of spin-exotic $1^{-+}1^+[\rho\pi]P$ wave as a function of 3π invariant mass for 4-momentum transfer $0.1 < t' < 1.0$ $(GeV/c)^2$). A background and a BW function have been used in the mass dependent fit to describe this partial wave. **Right:** Phase difference between the $1^{-+}1^+[\rho\pi]P$ and the $1^{++}0^+[\rho\pi]S$ waves.

Fig. 9 shows the spin-exotic $1^{-+}1^+[\rho\pi]P$ signal. The mass-dependent fit gives the values of the mass and width of $1660 \pm 10^{+0}_{-64}$ and $269 \pm 21^{+42}_{-64}$ MeV/c^2 respectively which is consistent with the hybrid candidate $\pi_1(1600)$ [20]

1.3.3 Search for the $\pi_1(1600)$ state in 2008-2009 data

A much bigger data set was taken by COMPASS with a liquid hydrogen target, surpassing the existing world statistics by a factor of more than 20. In addition to the $\pi^-\pi^+\pi^-$ final state with approximately 100M events, the dataset containing neutral pions, $\pi^0\pi^0\pi^-$, with more than 2.4M events has been analyzed. A preliminary mass independent PWA of the available data confirms the enhancement in the intensity around $M_X = 1.6$-$1.7\ GeV/c^2$ [21]. The phase motion with respect to the $1^{++}0^+[\rho\pi]S$ wave (Fig. 10) is also consistent with the 2004 data. Figure 10, which showing the $1^{-+}1^+[\rho\pi]P$ wave, a large bump is observed at around 1.1 GeV/c^2 for which the interpretation is under investigation. A mass-dependent fit, leakage studies and background studies of e.g. the Deck [22] effect are ongoing for more definite conclusions. It was found also that for hydrogen, the M = 1 states, including the spin-exotic $1^{-+}1^+[\rho\pi]P$, are suppressed with respect to lead data, whereas M = 0 are more populated in hydrogen, giving a sum of the M substates which remains unchanged. PWA, where the $\pi^-\pi^+\pi^-$ and the $\pi^0\pi^0\pi^-$ final states

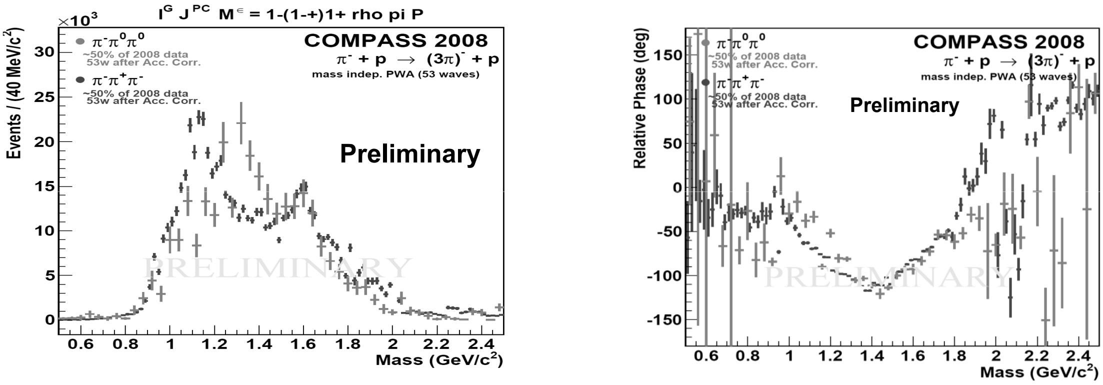

Figure 10: H target, charged and neutral final states, 2008 data. **Left:** Intensity of spin-exotic $1^{-+}1^+[\rho\pi]P$ wave as a function of 3π invariant mass for 4-momentum transfer $0.1 < t' < 1.0\ (GeV/c)^2)$). **Right:** Phase difference between the $1^{-+}1^+[\rho\pi]P$ and the$1^{++}0^+[\rho\pi]S$ waves.

are compared, show good agreement between the observed wave intensities and the predictions using isospin and Bose symmetry [21].

1.3.4 Observation of a new iso-vector resonance $a_1(1420)$

Recently COMPASS has reported [23] the results of a novel partial-wave analysis based on 50×10^6 events from the reaction $\pi^- + p \rightarrow \pi^-\pi^-\pi^+ + p_{recoil}$ at 190 GeV/c incoming beam momentum. A separated analysis in bins of $m_{3\pi}$ and four-momentum transfer t' reveals the interference of resonant and non-resonant particle production and allows their spectral separation. Besides well known resonances a new iso-vector meson $a_1(1420)$ at a mass of 1420 MeV/c^2 in the $f_0(980)\pi$ final state only was observed, the origin of which is still unclear.

1.4 Conclusion

The COMPASS experiment is one of the major players in the study of the nucleon spin structure.

Direct measurements of the gluon polarization $\langle\frac{\Delta g}{g}\rangle$ indicate a small value of the first moment ΔG. These results are the probable signature for a predominant role of the angular orbital momentum of quarks and gluons in the nucleon spin decomposition. Latest results of COMPASS NLO pQCD fit of g_1 world data are in fair agreement with other global fits and with Lattice QCD.

COMPASS has investigated transverse spin and TMD effects using deuterium and proton targets. A full set of results on the Collins and Sivers asymmetries, on pions and kaons is provided. An approximate equality of the Collins asymmetry and the dihadron asymmetry is observed, suggesting a common physical mechanism in the underlying fragmentation.

COMPASS has excellent potential to contribute for searching QCD allowed states like multiquarks, glueballs and hybrids because it has access to diffractive dissociation and central production reactions. A large amount of data, 10-100 times the world statistics, were collected with a hadron beam in 2008-2009. Interesting results - $\pi_1(1600)$ spin-exotic state and a new iso-vector resonance $a_1(1420)$ - have started to emerge.

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