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Nuclear Physics B Proceedings Supplement 00 (2012) 1–6

Nuclear Physics B Proceedings Supplement

COMPASS experiment at CERN: hadron spectroscopy and open charm results

O.Kouznetsov

Joint Institute of Nuclear Research, Joliot Curie 6, 141980 Dubna, Russia
on behalf of the COMPASS collaboration

Abstract

COmmon Muon and Proton Apparatus for Structure and Spectroscopy (COMPASS) 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 and 2006-2007 the COMPASS collaboration has collected a large amount of data by scattering polarized 160 GeV/c muons on polarized ^{6}LiD and NH_3 targets. These data were used to evaluate the gluon contribution to the nucleon spin. The gluon polarization $\frac{\Delta g}{g}$ was directly measured from the cross-section helicity asymmetry of D^0 mesons production in the photon-gluon fusion reaction.

During 2008 and 2009, the world leading data sets were collected with hadron beams which are currently being analyzed using Partial Wave Analysis (PWA) technique. COMPASS is performing a search for J^{PC}-exotic mesons, glueballs and hybrids, through light hadron spectroscopy in high energy 190 GeV/c hadron-proton reactions using both centrally produced and diffractive events. Preliminary results from these searches are discussed.

Keywords: deep inelastic scattering, polarized target, gluon polarization, central production, diffractive dissociation, spin-exotics

1. THE COMPASS EXPERIMENT

Understanding the nucleon structure and nature of quarks and gluons confinement inside the nucleons is a major goal of nuclear physics. In domain of nuclear structure very few experiments - COMPASS at CERN, STAR at RHIC and CLAS at JLAB - are active now and suppose will take the data during coming years.

The COMPASS experiment at CERN scrutinize 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. At hard scales Quantum Chromodynamics (QCD) is well established but in the non-perturbative regime, despite the numerous experimental data, a fundamental understanding of hadronic structure is still missing.

COMPASS takes advantage of a variety of high intensity beams (muons and hadrons) being located at the M2 beam line of CERN's Super Proton Synchrotron (SPS). The COMPASS set-up was designed for the beams of 100 to 200 GeV/c and was built around two large dipole magnets, defining two consecutive spectrometers, covering a large and small scattering angles separately. To match the expected particle flux in the various locations along the spectrometer, COMPASS uses wide variety of very different tracking detectors: silicon detectors and scintillating fibers, Micromegas and GEM micromesh detectors, large proportional and drift chambers. Particle identification is performed using a RICH counter and both electromagnetic and hadron calorimeters.

The polarized target (actually the largest polarized target in the world), consists of two oppositely polarized cells, 60 *cm* long each, surrounded by a large solenoid superconducting magnet. Until 2006, the two cells were filled with a ^{6}LiD target material (mainly deuterium), for which polarizations better than 50% are routinely achieved. In 2007 we are using ammonia

(NH_3, mainly proton), reaching polarizations of 90% and higher. Since 2006 a new target magnet has been used, increasing the acceptance from ±70 mrad to ±180 mrad. Also, the target material has been distributed in three cells, of 30, 60 and 30 cm length. A full description of the spectrometer can be found in [1].

During the years 2002-2004, 2006-2007 and 2010-2011 the COMPASS collaboration has studied the spin structure of the nucleon via deep inelastic polarized muon-nucleon scattering. The 160 GeV/c polarised muon beam[1] from SPS, with an intensity of 2×10^8 muons per 4.8 s spill and a polarization of $\simeq$ 76% is scattered off a polarized target.

The data for the hadron program were collected[2] during the years 2008-2009. For the run with a hadron beam, several major modifications of the COMPASS setup were made (see [2] for details). The polarized target was substituted by a liquid hydrogen target with a cell of 40 cm length and 3.5 cm diameter. The slow recoil proton produced at large angle in central production and diffractive projectile excitation is detected by the Recoil Proton Detector (RPD) which surrounds the liquid hydrogen target. The RPD is made of an inner ring and an outer ring of scintillator counters equipped with PMs fixed to a cylindrical support structure. The Monte Carlo momentum distribution of detected recoil protons produced in the diffractive pion-proton scattering shows that The momentum cutoff is at about 290 MeV/c, corresponding to a squared four momentum transfer $t' >$ 0.06 (GeV/c)^2.

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 differential Cerenkov detectors (CEDARs) located upstream of the target. The major part of the hadron data were collected using a 40 cm long liquid hydrogen target, but there were also runs with various thin nuclear target discs such as lead, nickel and tungsten.

2. A "SPIN-CRISIS" AND THE GLUON POLARIZATION MEASUREMENTS

Spin plays a central role in the theory of the strong interactions. Understanding the spin phenomena in Quantum Chromodynamics will help to understand the QCD itself. Worldwide experimental efforts in the last few decades have lead to numerous results extending our knowledge of the nucleon spin structure. But major challenges like "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: $\Delta\Sigma = 12 \pm 9 \pm 14\%$ [3]. The discrepancy between this measurement and an expectation following from the relativistic quark models, which predict that 60% of the nucleon spin should come from the spin of quark and anti-quark constituents[4], was named "spin-crises". The EMC result has been confirmed by series of deep inelastic scattering experiments at CERN, SLAC and DESY, giving, on average, a contribution from the quarks $\Delta\Sigma$ to the nucleon spin is $\sim$ 30%.

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 measurement of the gluon polarization is important for two reasons. First, as a component of the sum rule of the total angular momentum of the nucleon. Second, as a possible solution of the "spin-crisis" and violation of the Ellis-Jaffe sum rule [4] if ΔG is sufficiently big (of order of 3). Here ΔG is the first moment of the gluon helicity distribution $\Delta g(x_g)$. Experimentally, the polarization $\frac{\Delta g(x_g)}{g(x_g)}$[3] of gluons carrying a fraction x_g of nucleon momentum is measured. The gluon polarization can be directly measured via the spin asymmetry of the Photon-Gluon Fusion (PGF) process, shown in Fig. 1. The fragmenting $q\bar{q}$ pairs are then detected with two different, but complementary methods.

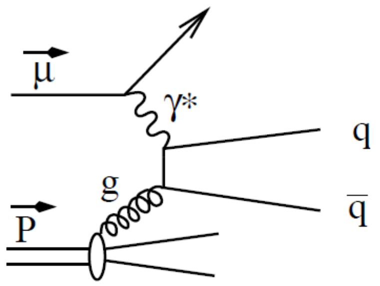

Figure 1: The photon gluon fusion process, used for direct measurements of the gluon polarization. Fragmentation of the created $q\bar{q}$ pairs into charmed D mesons gives a sample of events with minimal background for a $\frac{\Delta g}{g}$ measurement.

In the first method ("open charm"[5]) the events where the charmed quark hadronized into a D^0 or a D^*

[1] In year 2011 the energy of muon beam was 200 GeV/c .

[2] In year 2004 a short hadron pilot run were performed using 190 GeV/c π^- beam.

[3] Further instead of $\frac{\Delta g(x_g)}{g(x_g)}$ a simplified notation as $\frac{\Delta g}{g}$ will be used for gluon polarization non averaged on x_g interval and $\langle\frac{\Delta g}{g}\rangle$ for the averaged one.

meson are selected. In the second one (low [6] and high Q^2 [7] "high-p_T pairs"), the PGF events are identified by requiring that two opposite-charge high-transverse momentum hadrons are detected in coincidence. In the "high-p_T pairs" analysis the spin helicity asymmetry is calculated by selecting events containing hadrons with p_T above 0.7 and 0.4 GeV/c, for the first and for the second hadron with respect the virtual photon direction. Since this method selects light quarks as well, its counting rate is high; and competing background processes play an important role introducing model dependence of its description. On the contrary the "open charm" leptoproduction method is clean, free from physics background but statistically limited.

Here we report results of the "open charm" analysis which includes the data collected in 2002-2004 and 2006-2007.

2.1. The $\langle\frac{\Delta g}{g}\rangle$ from "open charm" method

The cleanest way to tag the PGF reaction is the $\gamma^* g \to c\bar{c}$ process because the presence of c quarks inside the nucleon is negligibly small. The created $c\bar{c}$ pairs predominantly fragment into vector and pseudoscalar charmed-non-strange mesons. All neutral and 68% of the charged vector mesons decay into the pseudoscalar D^0 meson and the $\pi^\pm$, π^0 mesons or γ: $D^*(2007)^0 \to D^0\pi^0, D^0\gamma$; $D^*(2010)^\pm \to D^0\pi^\pm$. Therefore, taking into account the D^0 direct production and the cascade decays of vector mesons, the D^0 mesons are produced more copiously than other weakly decaying D species.

The separation of the primary and secondary D^0 meson decay vertices is impossible due to multiple scattering in the thick polarized target. The constraint on mass difference $\Delta M = M_{D^*} - M_{D^0}$ (so-called "D* tag") was used for the effective combinatorial background suppression. In total 86250 D^0 mesons were reconstructed [5] in the following decay $D^0 \to K\pi$, $D^0 \to K\pi\pi^0$ and $D^0 \to K\pi\pi\pi$ modes.

The gluon polarization $\frac{\Delta g}{g}$ is extracted from the measured double spin asymmetry A_{exp} of the D^0 cross-section,

$$A_{exp} = P_B P_T f a_{LL} \frac{S}{S+B} \langle\frac{\Delta g}{g}\rangle \qquad (1)$$

using the analyzing power[4] a_{LL}, target polarization P_T, beam polarization P_B , dilution factor f and, finally, the signal purity $\frac{S}{S+B}$. As the"open charm" method is a statistically limited, a weighted method was developed to minimize the statistical error. In order to take into account the individual sensitivity of the selected events to $\frac{\Delta g}{g}$ they were weighted as $w = P_B f a_{LL} \frac{S}{S+B}$ [5]. The analyzing power a_{LL} has to be determined from a Monte Carlo simulation, as the kinematics of the PGF event is not fully known because only one of the two charmed mesons is reconstructed. A parametrization of a_{LL} was produced, using a neural network trained on a Monte Carlo sample generated by the AROMA generator and reconstructed as for the real data. A correlation of 82% is obtained between the parametrised and generated a_{LL}.

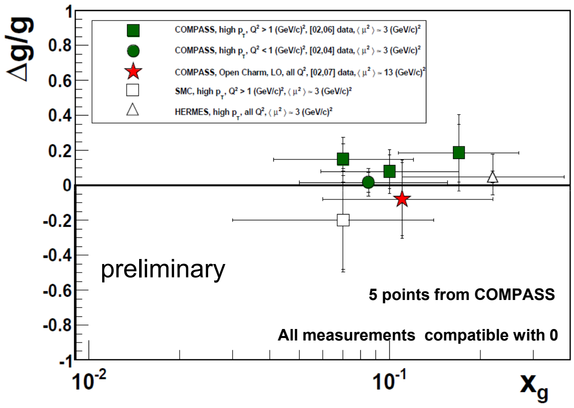

Figure 2: Summary of the world efforts for the direct $\langle\frac{\Delta g}{g}\rangle$ measurement at LO in QCD.

The signal purity $\frac{S}{S+B}$ parametrization was built with Real Data taking into account the kinematics of the event, the RICH response and the invariant mass of D^0 candidates. The statistical precision of the gluon polarization measurement depends from the signal purity as follows $\delta(\frac{\Delta g}{g}) \propto \frac{1}{\sqrt{\frac{S}{S+B}} \times S}$. Combining all 2002-2007 data a preliminary value of

$$\langle\frac{\Delta g}{g}\rangle = -0.081 \pm 0.213(stat) \pm 0.094(syst.) \qquad (2)$$

corresponding to $x_g = 0.11^{+0.11}_{-0.05}$ and a scale of $\mu^2 \simeq 13$ (GeV/c)^2 is obtained [5].

2.2. Summary of the direct $\langle\frac{\Delta g}{g}\rangle$ measurements

All the gluon polarization measurements of the COMPASS are summarized in Fig.2 together with the SMC [8] and HERMES [9] results. The world results for direct measurements of the $\langle\frac{\Delta g}{g}\rangle$ are dominated by COMPASS and indicate a small value of ΔG. Similarly, the global QCD analysis [10] of g_1 data also indicates a small value of the first moment of Δg: $|\Delta G|$ = 0.2-0.3. These results are the probable signature for a predominant role of the angular orbital momentum of quarks and gluons in nucleon spin decomposition.

[4]The analyzing power is defined as the ratio of spin-dependent and spin-independent photon-gluon cross-sections.

3. HADRON PROGRAM

3.1. Introduction

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. This is the context where, after several years of running with a muon beam to study nucleon spin structure, the COMPASS collaboration searched for new exotic states, glueballs or hybrids, through light hadron spectroscopy in high energy hadron-proton reactions, using both centrally produced and diffractive events (Fig. 3). 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.

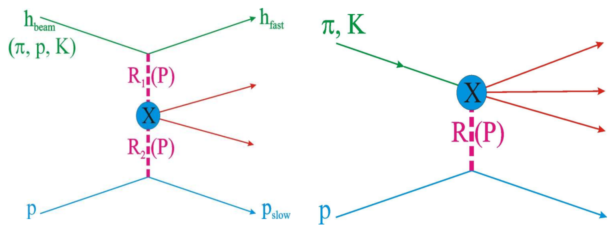

Figure 3: (*left*) Central production: large rapidity gap between scattered beam and produced particles; beam particle looses ~ 10% of its energy; particles at large angles; possible source of glueballs. (*right*) Diffractive scattering: forward kinematics; large cross-section (~ *mb*); need to separate particles at very small angles; study of J^{PC}-exotic mesons.

3.2. PWA and observation of $\pi_1(1600)$ spin-exotic state

First physics result from the COMPASS hadron program were obtained already from the three-day pilot run in 2004. In the analysis, presented in [11], the beam pion was assumed to dissociate diffractively into an intermediate state X^-. Exchange of a t-channel Pomeron is assumed, for which X^- gets the same isospin I, G-parity G and C-parity C as the incoming pion. π^- Pb $\to \pi^-\pi^-\pi^+$ in COMPASS using a 190 GeV/c π^- beam provide clean access to meson resonances with masses below 2.5 GeV/c^2. The data sample comprised 420 000 events. The quantum numbers of X^-, i.e. the spin J, parity P and the spin projection M, were disentangled by PWA. The PWA is based on the isobar model and the Zemach formalism. One partial wave is characterized by a set of quantum numbers $J^{PC}M^{\varepsilon}[isobar]$L, where J^{PC} represents the spin, parity and C-parity of the resonance X, respectively. M and ε (reflectivity) describe the spin projection. X is assumed to decay into a di-pion [*isobar*] and a bachelor π^-, which have a relative orbital angular momentum L. The *isobar* further decays into a $\pi^+\pi^-$ pair. The PWA is divided into two steps, namely a mass-independent and a mass-dependent fit.

For the subsequent mass-dependent fit a subset of seven waves has been selected: $0^{-+}0^+[f_0(980)\pi]S$, $1^{-+}1^+[\rho\pi]P$ (spin-exotic), $1^{++}0^+[\rho\pi]S$, $2^{-+}0^+[f_2\pi]S$, $2^{-+}0^+[f_2\pi]D$, $2^{++}1^+[\rho\pi]D$ and $4^{++}1^+[\rho\pi]G$. The intensities and interferences of these waves are parametrized with relativistic Breit-Wigner (BW) and eventually background functions. From this fit, which is shown as red curve overlayed to the mass independent fit results, resonance masses and widths have been obtained.

The Fig.4 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 $\pi_1(1600)$ [12]

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 also the one 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 [13]. The phase motion with respect to the $1^{++}0^+[\rho\pi]S$ wave (Fig.5) is also consistent with the 2004 data. In the plot of the Fig.5, 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. Mass-dependent fit, leakage studies and background studies of e.g. the Deck 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 [14].

PWA, where the $\pi^-\pi^+\pi^-$ and the $\pi^0\pi^0\pi^-$ final states are compared, show good agreement between the ob-

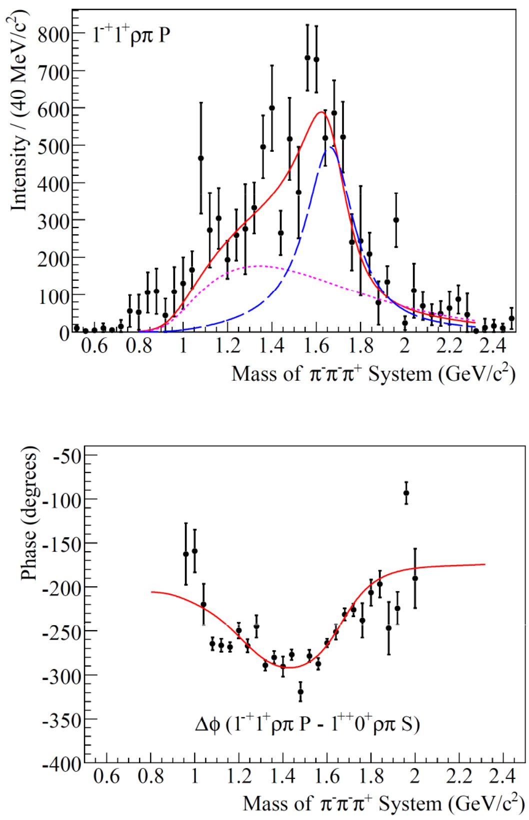

Figure 4: Pb target, charged final state, 2004 data. **Top:** Intensity of spin-exotic $1^{-+}1^{+}[\rho\pi]P$ wave as a function of 3π invariant mass for 4-momentum transfer $0.1 < t' < 1.0$ $(GeV/c)^2$). A background (*purple*) and a BW function (*blue*) have been used in the mass dependent fit to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

served wave intensities and the predictions using isospin and Bose symmetry [13].

3.4. Channels with $\eta\pi$ and $\eta'\pi$

COMPASS has also analyzed data for h $\eta\pi$ and $\eta'\pi$ (η' decaying into $\eta\pi^+\pi^-$) final states from diffractive scattering of 190 GeV/c π^- off a H target. In total, about 116k events were collected for the first final state, and about 39k events for the second one, exceeding the statistics of previous experiments by more than a factor of 5. The first PWA of these data show a strong 1^{-+} P wave, shown in Fig.6 where also the intensity of the 2^{++} D wave and their phase difference are given. The spin-exotic contribution to the total intensity is found to be much larger for the $\eta'\pi$ final state than for the $\eta\pi$ one, as expected for a hybrid candidate. However, further studies are needed in order to draw conclusions about the

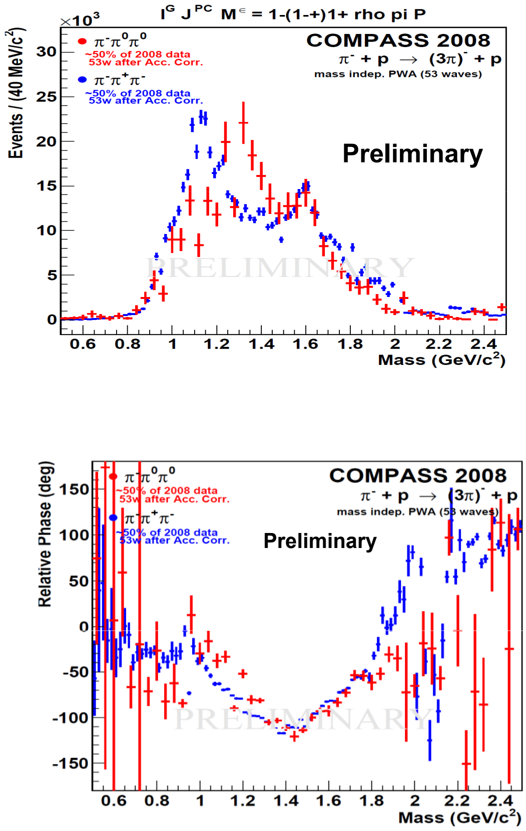

Figure 5: H target, charged (*blue*) and neutral (*red*) final states, 2008 data. **Top:** Intensity of spin-exotic $1^{-+}1^{+}[\rho\pi]P$ wave as a function of 3π invariant mass for 4-momentum transfer $0.1 < t' < 1.0$ $(GeV/c)^2$)). **Bottom:** Phase difference between the $1^{-+}1^{+}[\rho\pi]P$ and the$1^{++}0^{+}[\rho\pi]S$ waves.

resonance interpretation of the 1^{-+} P wave [15]. COMPASS can also confirm the decay of $a_4(2040)$ into $\eta'\pi^-$ observed by BNL [16].

3.5. Physics with Kaon and Proton beams

The possibility to tag beam kaons with the CEDARs in combination with the RICH identification of final state kaons makes COMPASS an excellent tool for studying kaon diffraction. In a recent study, the reaction $K^-p \rightarrow K^-\pi^+\pi^-p_{recoil}$ is investigated [17]. Recent results from the ongoing PWA show a spectrum of states which is mostly in agreement with previous results from the ACCMOR collaboration [18]. Channels with kaons in the final state are also of interest, in particular $\pi^-p \rightarrow (K\bar{K}\pi)\pi^-p_{recoil}$, where COMPASS can provide about an order of magnitude more events than a previous measurement by BNL [19].

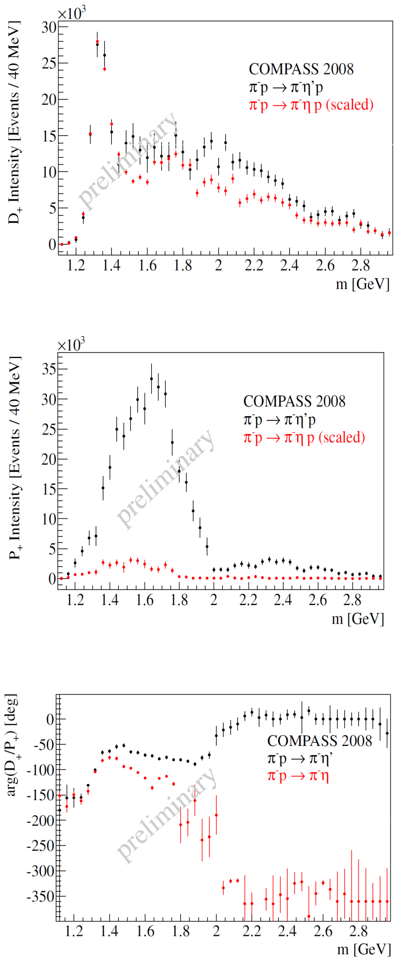

Figure 6: Comparison of waves for $\eta\pi$ (red data points) and $\eta'\pi$ (black data points) final states. **Top:** The intensity of the $J^{PC} = 2^{++}$ D wave. **Middle** the intensity of the spin-exotic $J^{PC} = 1^{-+}$ P wave. **Bottom:** the phase difference between D and P waves.

Data collected with the proton beam have been used to measure the ratio between the cross sections of $pp \to pp\phi$ and $pp \to pp\omega$. This provides a test [13] of the Okubo-Iizuka-Zweig (OZI) rule at high energy. The proton beam data are also being used for baryon spectroscopy [20]. Events are selected where the beam proton dissociates diffractively into a baryonic state X^+ which then decays subsequently, via mesonic or baryonic isobars, into the final states $p\pi^+\pi^-$ and pK^+K^-.

4. Conclusion and outlook

COMPASS 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. The global QCD analysis of g_1 also shows small values $|\Delta G| \approx 0.2 - 0.3$. These results are the probable signature for a predominant role of the angular orbital momentum of quarks and gluons in the nucleon spin decomposition.

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 world statistics, were collected with hadron beam in 2008-2009. Interesting results have started to emerge. A candidate for $\pi_1(1600)$ spin-exotic state ($\rho\pi$ channel) in the 2004 short pilot run was already observed. Preliminary analysis of the $\pi^-\pi^+\pi^-$ and the $\pi^0\pi^0\pi^-$ final states reconstructed in 2008-2009 data non contradict to this observation but needs further work for better understanding of background. The COMPASS experiment has provided clear evidence for the presence of a spin-exotic wave with quantum numbers $J^{PC} = 1^{-+}$ P in $\eta'\pi$ final state, consistent also with the $\pi_1(1600)$.

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