

Hadron Spectroscopy with COMPASS at CERN

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Abstract. The aim of the COMPASS hadron programme is to study the light-quark hadron spectrum, and in particular, to search for evidence of hybrids and glueballs. COMPASS is a fixed-target experiment at the CERN SPS that features a two-stage spectrometer with high momentum resolution and wide acceptance. It also provides particle identification and calorimetry. A short pilot run in 2004 resulted in the observation of a spin-exotic state with $J^{PC} = 1^{-+}$ consistent with the debated $\pi_1(1600)$ resonance. In addition, Coulomb production data at low momentum transfer provide a test of Chiral Perturbation Theory. During 2008 and 2009, a world leading data set was collected with hadron beam which is currently being analysed. The unprecedentedly large number of events allows for a thorough decomposition of the data into spin states. The COMPASS hadron data span over a broad range of channels and shed light on several different aspects of QCD.

1. Introduction

The aim of hadron physics is a fundamental understanding of all bound and resonant systems which interact *via* the strong force. At short distances, perturbation theory can be applied and its predictions have been rigorously and successfully tested [1]. At longer distances, the self-coupling of the gluons makes perturbation theory inapplicable and effective field theories such as Chiral Perturbation Theory (χ PT) [3], or advanced computational tools like Lattice QCD [2], have to be used instead. It is generally believed that the key to understand QCD at low and intermediate momentum transfers lies in the hadron spectrum. Apart from the conventional quark-antiquark ($q\bar{q}$) and quark triplet (qqq) states within the simple constituent quark model, QCD also allows for hadronic matter with excited gluonic degrees of freedom, provided they are colour neutral. A *glueball* is a state described entirely in terms of gluonic fields with no constituent quarks, whereas a *hybrid* is a meson with a constituent gluonic excitation. The excited glue in a hybrid contributes to its quantum numbers, which enables formation of states with J^{PC} quantum numbers forbidden for simple $q\bar{q}$ pairs. Such states are called *spin-exotics*. Lattice calculations predict a spin-exotic hybrid with mass within $1 - 2 \text{ GeV}/c^2$ [4]. Some promising candidates have been found in experiments: the $\pi_1(1400)$ seen by BNL, VES and Chrystal Barrel [5], the $\pi_1(1600)$ reported by BNL and VES [6] and the $\pi_1(2000)$ observed by BNL [7]. Nevertheless, the resonance character of these states is disputed to this day. One goal of the COMPASS hadron programme is to bring clarity into this issue.

2. The COMPASS hadron setup

The COMPASS (COmmom Muon and Proton Apparatus for Structure and Spectroscopy) spectrometer is located at the M2 beam line at the SPS accelerator at CERN. The physics

studied by the muon programme is presented elsewhere in these proceedings [8]. The basic features of the spectrometer are described in Ref. [9] and the specifics of the hadron programme will be outlined in a forthcoming paper [10]. The layout of the COMPASS spectrometer is shown in Fig. 1.

The data for the hadron programme were collected during 2008/09. 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 [11]. The major part of the hadron data were collected with a 40 cm long liquid hydrogen target, but there were also runs with various thin nuclear target discs such as lead, nickel and tungsten. The target was surrounded by a Recoil Proton Detector (RPD) which detected the recoil target proton. The forward going final-state particles were detected in the two-stage magnetic spectrometer providing large acceptance and precise tracking. The RICH detector provides separation between protons, pions and kaons (see Fig. 2 left) and thus enables studies of final states with *e.g.* kaons. Two electromagnetic calorimeters measure the energies of photons and electrons which opens up the possibility to study final states involving neutrals like π^0 , η and η' . As an example, the $\gamma\gamma$ invariant mass in an exclusive $p\pi^+\pi^-\gamma\gamma$ final state sample, with clear π^0 and η signals, is shown to the right in Fig. 2.

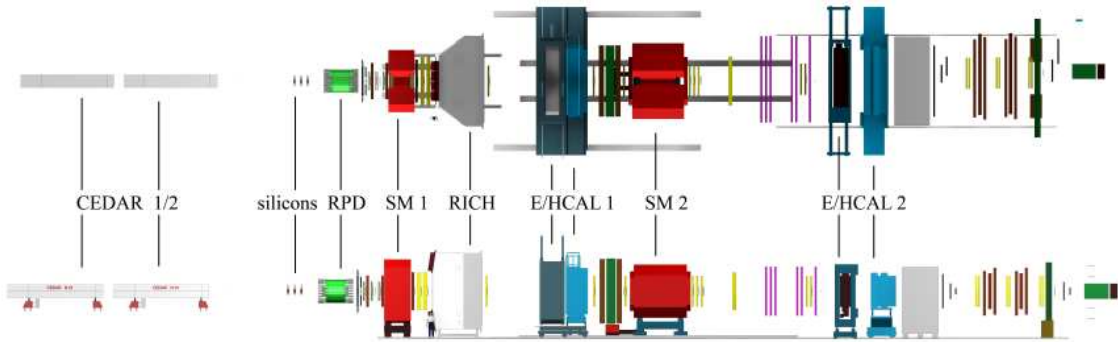


Figure 1. Top- and sideview of the COMPASS hadron setup.

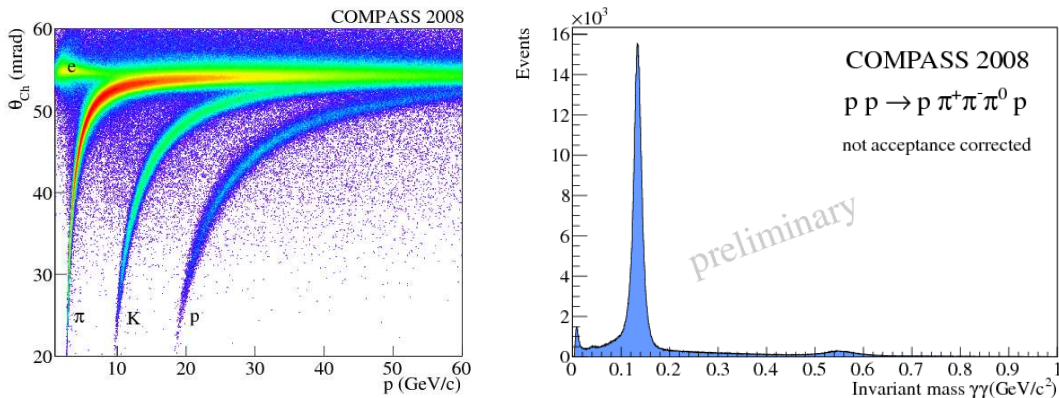


Figure 2. Left: The Cherenkov angle *vs.* the momentum of charged particles. Right: The $\gamma\gamma$ invariant mass for an exclusive $pp \rightarrow p\pi^+\pi^-\gamma\gamma p_{recoil}$ sample.

At the COMPASS beam momentum of 190 GeV/c, three production mechanisms are accessible, illustrated in Fig. 3. In *diffractive dissociation* (left), Reggeon exchange between the

target and the beam hadron excites the beam to an intermediate state X , which then decays. This is a likely production mechanism for spin exotic hybrids, provided they exist. In *central production* (middle), double Reggeon exchange forms a state X . Double Pomeron exchange is a special case of this process and provides a glue-rich environment which should be suitable for glueball production. In *Coulomb production* (right), the target radiates a photon which excites the beam hadron. This process is important at low momentum transfer and is a testing ground for χ PT.

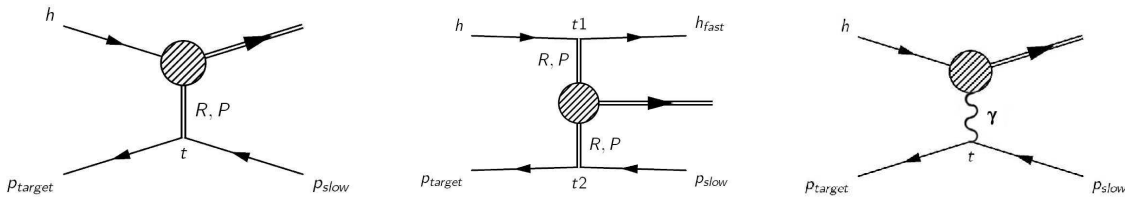


Figure 3. Left: Diffractive dissociation of a beam hadron *via* Reggeon exchange. Middle: Central production *via* double Reggeon fusion. Right: Coulomb production.

3. Recent results and ongoing analysis

Interesting physics results from the COMPASS hadron programme were obtained already from the three-day pilot run in 2004, using a 190 GeV/c π^- beam impinging on a lead target. In the analysis, presented in Ref. [12], 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. The *isobar model* was applied, in which X^- decays into a pion and an isobar, which in turn decays into two pions. This is illustrated in the upper left picture of Fig. 4. The selected momentum transfer range was $0.1 < t' < 1.0$ (GeV/c)², where $t' \equiv |t| - |t|_{\min}$ and $t = (p_{\text{beam}} - p_X)^2$. In this region, the nucleons in the lead nucleus act as quasi-free particles. 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 Partial-Wave Analysis (PWA). The PWA is performed in the *reflectivity basis* [13] in which the reflectivity ϵ describes the symmetry under a reflection through the production plane. COMPASS uses two independent PWA programs, one developed at Illinois, JINR Dubna and IHEP Protvino [14], and one at Brookhaven [15]. They have both been adapted for COMPASS [16]. The analysis was performed in two steps: fit in bins of the three-pion invariant mass m_X , followed by a mass-dependent fit (for details, see [12]). A spin-exotic $J^{PC} = 1^{-+}$ wave was observed, consistent with the disputed $\pi_1(1600)$ [6]. A preliminary mass-independent PWA of $\approx 25\%$ of the available data from 2008/09 data, collected using a hydrogen target and comprising 23 million $\pi^-\pi^+\pi^-$ events, confirms the enhancement in the intensity around $M_X = 1.7$ GeV/c² [17]. The phase motion with respect to the 1^{++} wave is also consistent with the 2004 data. The 1^{++} , the exotic 1^{-+} wave and the phase motion are presented in Fig. 4. In the lower left plot, showing the 1^{-+} wave, a large bump is observed at around 1.1 GeV/c² 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. Another striking observation is that the intensity of not only the exotic $1^{-+}1^+\rho\pi P$ wave but also other $M = 1$ waves are suppressed in the hydrogen data with respect to the lead data. On the other hand, states with $M = 0$ are more populated in hydrogen, giving a sum of the M substates which remains unchanged [17]. This dependence of the intensity with a given spin projection on the target material still lacks a theoretical explanation.

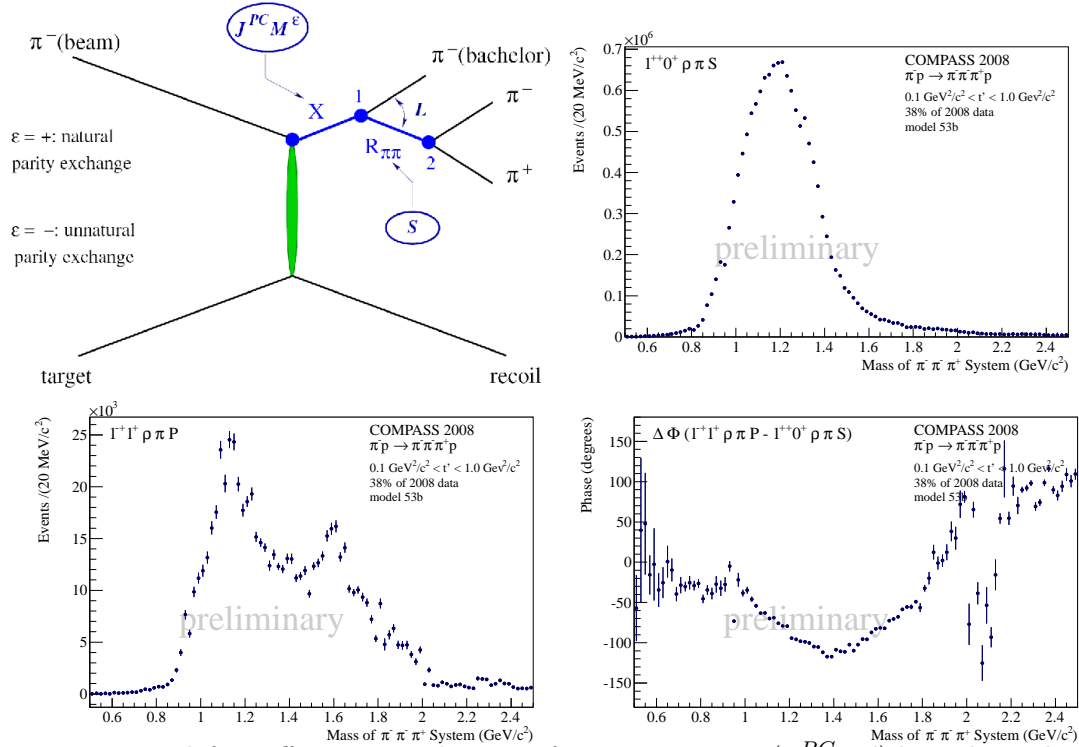


Figure 4. Upper left: Diffractive production of a resonance X^- ($J^{PC}M^\epsilon$) by t -channel Reggeon exchange and its subsequent decay *via* isobars into the $\pi^-\pi^+\pi^-$ final state. Upper right: The intensity of the $J^{PC}M^\epsilon$ [isobar] $L=1^{++}0^+\rho\pi S$ wave. Lower left: The intensity of the $1^{-+}1^+\rho\pi P$ wave. Lower right: The phase difference between the two waves. The fit results come from Ref. [17].

The two electromagnetic calorimeters allow for studies of neutral final states. One example is the $\pi^0\pi^0\pi^-$ final state, which provides an important consistency check of the results in the $\pi^-\pi^+\pi^-$ channel. Preliminary PWA's, where the $\pi^-\pi^+\pi^-$ and the $\pi^0\pi^0\pi^-$ final states are compared, show good agreement between the observed wave intensities and the predictions using isospin- and Bose symmetry [18]. Another channel with neutral particles in the final state is the $\eta'\pi^-$ with η' decaying into $\eta\pi^+\pi^-$. The first PWA of these data show a strong 1^{-+} wave, shown in Fig. 5 where also the intensity of the 2^{++} wave and their phase difference are given. However, further studies are needed in order to draw conclusions about the resonance interpretation of the 1^{-+} [19]. COMPASS can also confirm the decay of $a_4(2040)$ into $\eta'\pi^-$ observed by BNL [26].

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 [20]. The invariant mass of the $K^-\pi^+\pi^-$ final state is shown to the left in Fig. 6. Recent results from the ongoing PWA (see Ref. [20]) show a spectrum of states which is mostly in agreement with previous results from the ACCMOR collaboration [27]. 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 [23]. One example from this study is shown in the middle of Fig. 6, where the $K_s K^\pm \pi^\mp$ invariant mass is shown for the full sample (points) and for the special case when the $K_s K^\pm$ form an $a_0(980)$ resonance (filled yellow histogram). In the latter case, $f_1(1285)$ and $f_1(1420)$ are almost background free, in contrast to the BNL data [23]. This opens up possibilities to study *e.g.* the $f_1(1420)\pi^-$ system

for the first time.

The cross section of pion production in $\gamma\pi^- \rightarrow \pi^-\pi^+\pi^-$, a subprocess of $\pi^-Pb \rightarrow \pi^-\pi^+\pi^-Pb$, at low momentum transfer $t' < 0.001 (\text{GeV}/c)^2$ and a $\pi^-\pi^+\pi^-$ invariant mass below the ρ threshold, has been measured using data from 2004 [22]. The preliminary results, shown to the right in Fig. 6, are in agreement with Leading Order χ PT predictions [28].

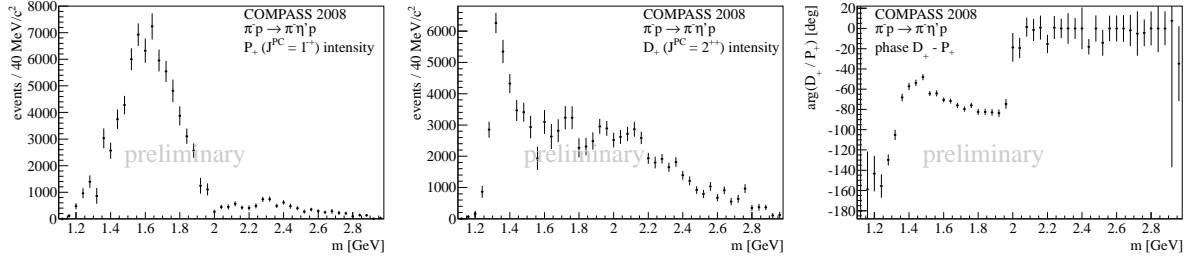


Figure 5. From left: [19]: The intensity of the 1^{-+} , the intensity of the 2^{++} wave, and the phase difference between 2^{++} and 1^{-+} in the $\eta'\pi^-$ channel. All figures are from Ref. [19]

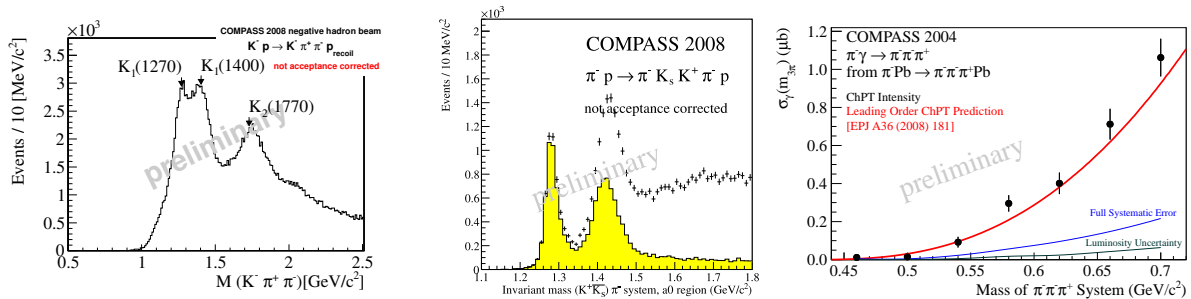


Figure 6. Left: The invariant mass of the $K^-\pi^+\pi^-$ final state from diffractive dissociation of beam kaons [20]. Middle: The invariant mass of the $K\bar{K}\pi$ system for $\pi^-p \rightarrow (K_s K^\pm \pi^\mp \pi^-)p_{recoil}$ channel [21]. The data points with error bars correspond to the full sample, whereas the yellow filled histogram represents the special case when the $K_s K^\pm$ form an $a_0(980)$ resonance. Right: The $\gamma\pi^- \rightarrow \pi^-\pi^+\pi^-$ cross section [22]. The points are COMPASS 2004 data, the red curve represent the χ PT predictions [28], the blue curve the full systematic uncertainty and the back curve the uncertainty from luminosity.

Data collected with the proton beam have been used to measure the ratio between the cross sections of $pp \rightarrow pp\phi$ and $pp \rightarrow pp\omega$. This provides a test of the Okubo-Iizuka-Zweig (OZI) rule [29] at high energy, and the first results are presented elsewhere in these proceedings [24]. The proton beam data are also being used for baryon spectroscopy [25]. 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^- . In the $p\pi^+\pi^-$, $p\pi^-$ and $p\pi^+$ invariant mass spectra, presented in Fig. 7, structures are seen which are compatible with known N^* and Δ resonances. The ongoing PWA can give deeper insight into the light baryon spectrum. The proton beam data also contain a substantial amount of centrally produced events [30] which are currently being analysed.

4. Summary

The COMPASS hadron programme provides excellent opportunities to study different aspects of QCD. A rich variety of channels are being studied, we can provide more than ten times the world statistics and interesting results have started to emerge.

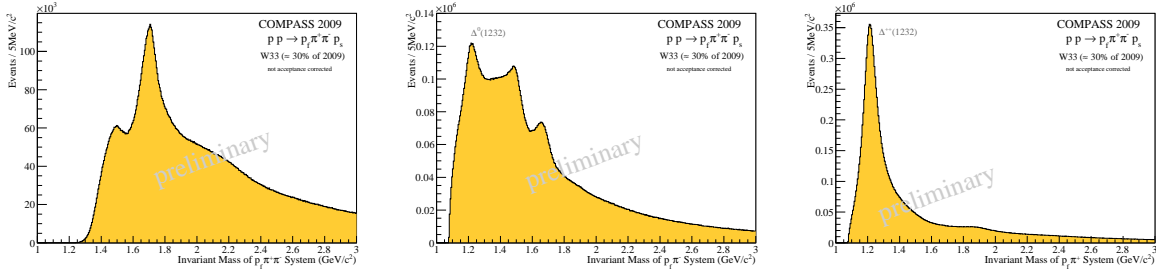


Figure 7. Baryon spectra from the reaction $pp \rightarrow p\pi^+\pi^-p_{recoil}$. Left: The invariant mass of the $p\pi^+\pi^-$ system. Middle: The $p\pi^-$ invariant mass. Right: The $p\pi^+$ invariant mass.

5. References

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