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Meson production from diffractive pion dissociation at COMPASS*

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Abstract. This paper presents results of $\pi^- N \to \pi^-\pi^-\pi^+ N'$ diffractive dissociation events at COMPASS, with 190 GeV/c π^- beam impinging on lead target during a short pilot run in 2004. A partial wave analysis was performed for the 3π final states with four-momentum transfer $0.1\,\mathrm{GeV}^2/c^2 \leq t' \leq 1.0\,\mathrm{GeV}^2/c^2$, showing well-known resonances and also a state with spin-exotic quantum numbers $J^{PC} = 1^{-+}$. Additionally first results of 5π final states from 2004 and 3π final states from 2008, obtained from a liquid hydrogen target, are presented.

1 Introduction

In the naive constituent quark model, mesons are simply color-neutral quark-antiquark ($q\bar{q}$) systems. They are described by their quantum numbers isospin I, G-parity, total angular momentum J, parity P and charge conjugation C. These are related by

$$P = (-1)^{L+1} \qquad C = (-1)^{L+S} \qquad G = (-1)^{I+L+S} \tag{1}$$

with L the relative orbital angular momentum of quark and antiquark, and S their total intrinsic spin. Quantum numbers violating the rules (1), e.g. $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, ...$, are thus forbidden for $q\bar{q}$ systems.

Quantum Chromodynamics (QCD) allows additional color-neutral objects. Possible states are tetraquarks ($q\bar{q}q\bar{q}$), hybrids ($q\bar{q}g$) and glueballs (gg), with quantum numbers not constrained to (1). They are difficult to find in experimental data when they mix with ordinary $q\bar{q}$ states of the same quantum numbers. The experimental observation of so-called *spin-exotic* states with forbidden quantum numbers would provide a clear evidence of physics beyond the naive quark model and a fundamental confirmation of QCD.

The lightest glueballs are predicted by Lattice QCD [1] at 1.7 GeV/c^2 ($J^{PC} = 0^{++}$) and 2.4 GeV/c^2 ($J^{PC} = 2^{++}$). As promising experimental candidate for the ground state scalar glueball, the $f_0(1500)$ was found by Crystal Barrel [2] and WA102 [3]. But this state features $J^{PC} = 0^{++}$, so that its interpretation is difficult due to mixing with isoscalar mesons.

The lowest-lying hybrid is with $J^{PC} = 1^{-+}$, not mixing with ordinary mesons. Lattice QCD simulations [4] and flux-tube model calculations [5] predict a mass between 1.7 and 2.2 GeV/c^2, and a preferred decay into $b_1\pi$ and $f_1\pi$. Two candidates, the $\pi_1(1400)$ and the $\pi_1(1600)$ have been reported by several experiments, but their resoncance nature is still heavily disputed. $\pi_1(1400)$ was mostly seen in $\eta\pi$ decays, e.g. by E852 [6], VES [7] and Crystal Barrel [8]. $\pi(1600)$ was found in $\rho\pi$ [9][10], $\eta'\pi$ [11][7], $f_1\pi$ [12][13] and $\omega\pi\pi$ [14][13] by E852 and VES.

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2 Hadron Spectroscopy at COMPASS

COMPASS (**CO**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy) [15] is a fixed-target experiment at CERN SPS. Its two-stage magnetic spectrometer can detect outgoing particles within a large kinematical range. Particle identification is done with a Ring Imaging Cherenkov (RICH) counter as well as electromagnetic and hadronic calorimeters.
In the first phase, from 2002 to 2007, the spin structure of the nucleon was measured by deep-inelastic scattering of 160 GeV/c muons off polarized LiD and NH_3 targets. The second phase in 2008 and 2009 is mostly dedicated to light-meson spectroscopy, with hadron beams (p, π and K) of 190 GeV/c impinging on a 40 cm long liquid hydrogen target or thin disks of nuclear targets.
Hadron spectroscopy in the light quark sector requires high statistics of data that covers the phase space as completely as possible, as provided by the large acceptance of the COMPASS spectrometer. Many decay modes can be accessed, including neutral and kaonic final states. Thereby two physical processes are exploited: Central production, which features a rapidity gap between the fast beam particle and the centrally produced system and is well suited for the search for glueballs [16], and diffractive dissociation with more forward kinematics that is used to study spin-exotic mesons as described in this paper.

3 Diffractive Dissociation

A diffractive dissociation process of high-energetic beam on a fixed target can be written as

$$a + b \to c + d \quad \text{with} \quad c \to 1 + 2 + \ldots + n \tag{2}$$

with a the beam particle that just grazes the target particle b. b recoils at small momentum transfer as d. a is excited to the intermediate resonance c, that subsequently decays into n particles. The reaction is a strong interaction and proceeds through a t-channel Reggeon exchange. It can be described by two kinematic variables, the squared center-of-mass energy $s = (p_a + p_b)^2$ and the square of the four-momentum transfer $t' = |t| - |t_{\text{min}}|$ with $t = (p_a - p_c)^2$ and $|t_{\text{min}}|$ the minimum momentum transfer that is needed to excite a to c.

4 Partial Wave Analysis Formalism

The goal of a partial wave analysis (PWA) is to determine all resonances present in the data and their properties. The PWA program used in this paper was originally developed at Illinois [22] and later modified at Protvino and Munich. The two basic assumptions are the factorization of the total cross-section into a resonance and a recoil vertex, and the *isobar model*: The diffractively produced resonance X with mass m_c decays sequentially via two-body decays into intermediate resonances, the isobars, that decay further into the particles observed in the experiment.
For a 3π final state emerging from a pion beam, a partial wave is usually written as $J^{PC}M^{\epsilon}[isobar\ \pi]L$, giving the quantum numbers of the resonance J^{PC}, spin projection M, reflectivity ϵ, the isobar and the angular momentum L between the di-pion resonance and the unpaired pion (bachelor). Assuming Reggeon exchange, I and G of the resonance are fixed to $I^G = 1^-$.
The PWA is performed in two steps. In the first step, the *mass-independent PWA*, the data is divided into bins of the invariant mass m_c, and angular distributions in phase space τ are fitted independently in each mass bin, assuming the production strenght for a given wave in this bin to be constant. The cross-section is written as

$$\sigma_{\text{indep}}(\tau, m) = \sum_{\epsilon=\pm 1} \sum_{r=1}^{N_r} \left| \sum_i T_{ir}^{\epsilon} \psi_i^{\epsilon}(\tau, m) \Big/ \sqrt{\int |\psi_i^{\epsilon}(\tau', m)|^2 \mathrm{d}\tau'} \right|^2 . \tag{3}$$

Here ψ_i^ϵ denotes the decay amplitude of a particular partial wave i, depending only on τ. The fitting parameters T_{ir}^ϵ contain the information about the strength of the waves and their interferences (*production amplitudes*). The complex numbers T_{ir}^ϵ are obtained using an extended-likelihood method, respecting the experimental acceptance obtained from a Monte Carlo simulation. The *rank* N_r of the spin-density matrix is chosen according to the (in)coherence of the process, related to the different final states of the (unobserved) recoiling particle. The t' dependence of the cross-section is taken into account by multiplying different functions of t', obtained from the data, to the decay amplitudes ψ_i^ϵ.
In the second step, the results of the mass-independent PWA are fitted using a *mass-dependent* χ^2 *fit*. The mass dependence of the partial waves and their interferences with each other are described by relativistic Breit-Wigner (BW) and eventually coherent background functions.

5 The COMPASS 2004 Pilot Hadron Run

In order to study the possible impact of COMPASS on light meson spectroscopy, and in addition to the measurement of Primakoff reactions, a short pilot run took place in 2004. A 190 GeV/c π^- beam was used with simple lead disk targets of 1-2 mm thickness. The target region was equipped with additional silicon detectors for improved vertexing. A recoil detector was not available yet. Particle identification was limited, as the RICH was not active on purpose, and identification of beam particles (admixture of 2.4 % K^- and 0.8 % p^- in the π^- beam) was not possible.
The trigger system consisted of a trigger on high energy deposit in ECAL2 and a dedicated diffractive trigger for interactions with at least two outgoing charged particles. In addition, an online data-filtering process enhanced the fraction of diffractive events by requiring at least five hits in four particular planes of the silicon tracking detectors just downstream of the target.
The results presented in this section are based on about two days of data taking. As especially the $\pi_1(1600)$ resonance seen in $\rho\pi$ results from $\pi^-\pi^-\pi^+$ final states has been controversially discussed [19][20], the diffractive 3π data was of primary great interest and has been thoroughly analyzed. In the offline analysis, a primary vertex inside the target with the beam and 3 outgoing particles with charges $(-,-,+)$ is required. The beam energy E_a is calculated from the energy of the 3 outgoing particles E_c (assuming they are all pions) and the scattering angle θ_0, assuming the target particle to remain intact during the scattering process. Then an exclusivity cut of $|E_a - 189\,\text{GeV}| < 4\,\text{GeV}$ is applied. More than 4 000 000 exclusive events have been obtained in the t' range between 0 and $10\,\text{GeV}^2/c^2$. Fig. 1 (left) shows the invariant mass spectrum for all events, and in addition for 5 different t' ranges. The invariant mass spectrum for the t' range $0.1 < t' < 1.0\,\text{GeV}^2/c^2$, where the candidates for the spin-exotic state have been reported before, is shown separately in Fig. 1 (right). The resonances $a_1(1260)$, $a_2(1320)$ and $\pi_2(1670)$ are clearly visible. On these data, containing about 420 000 events, the PWA (see section 4)

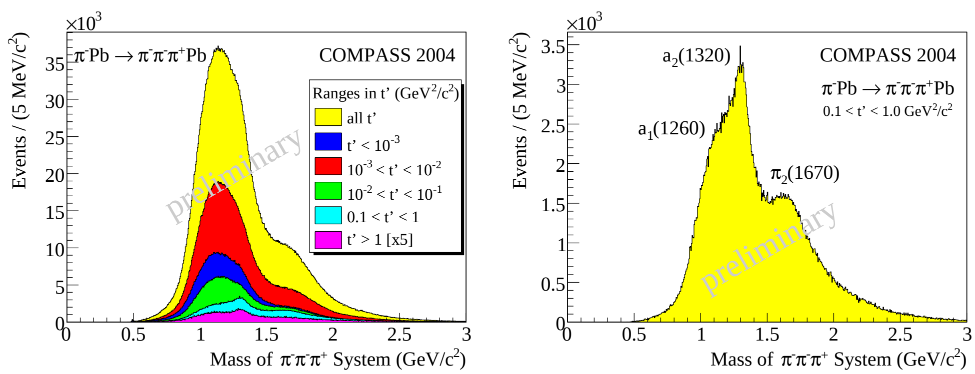

Fig. 1. Invariant mass of the 3π system for different t' bins (left) and $0.1 < t' < 1.0\,\text{GeV}^2/c^2$ (right).

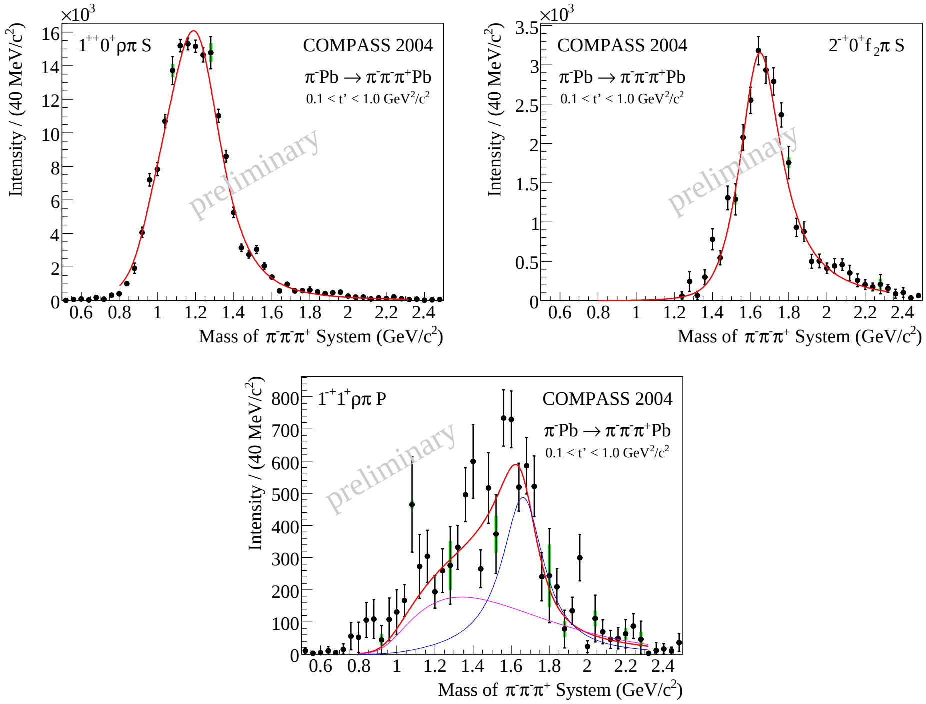

Fig. 2. Partial wave intensities (black points) and result of mass-dependent fit (red curve).

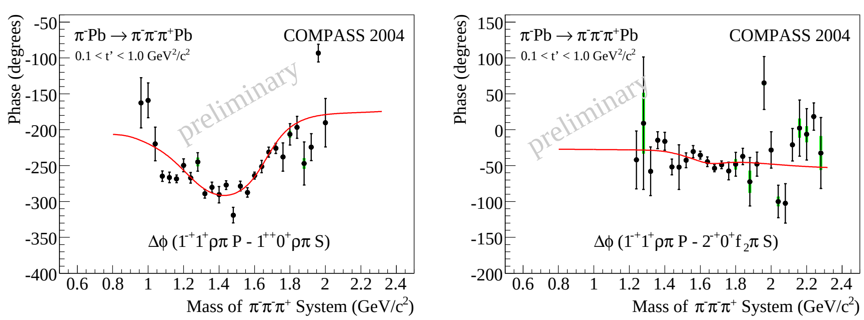

Fig. 3. Phase of the $1^{-+}1^{+}[\rho\pi]P$ wave w.r.t. the $1^{++}0^{+}[\rho\pi]S$ and the $2^{-+}0^{+}[f_2\pi]S$ wave.

has been carried out [21].
Assuming scattering at a single nucleon in the analyzed t' range, the rank $N_r = 2$ is to be chosen. A total of 42 partial waves is used in the mass-independent PWA, covering the isobars $\rho(770)$, $f_2(1270)$, $\rho_3(1690)$, $(\pi\pi)_s$ (broad $\sigma(600)$ and $f_0(1370)$) and $f_0(980)$. Mostly $\epsilon = +1$ amplitudes are needed to describe the data. This *wave set* also contains a background wave, which is flat in the relevant angles in Gottfried-Jackson frame and added incoherently. The results for the best fit are presented as black data points with statistical error bars. If two or more solutions are obtained, the statistical error for that mass bin is increased as indicated by a thick green bar (cf. Fig. 2). For the mass-dependent fit, six waves out of the initial 42 waves have been selected, namely $0^{-+}0^{+}[f_0(980)\pi]S$, $1^{++}0^{+}[\rho\pi]S$, $2^{-+}0^{+}[f_2\pi]S$, $2^{-+}0^{+}[f_2\pi]D$, $2^{++}1^{+}[\rho\pi]D$ and $4^{++}1^{+}[\rho\pi]G$ containing clear resonances, and the spin-exotic $1^{-+}1^{+}[\rho\pi]P$ wave. Fig. 2 shows the $1^{++}0^{+}[\rho\pi]S$, $2^{-+}0^{+}[f_2\pi]S$ (top left and right) and $1^{-+}1^{+}[\rho\pi]P$ (bottom) intensities. The first two correspond to the well-known $a_1(1260)$ and $\pi_2(1670)$ mesons. The third shows a broad bump around $1.6\,\mathrm{GeV}/c^2$ in the spin-exotic wave, as the disputed hybrid candidate

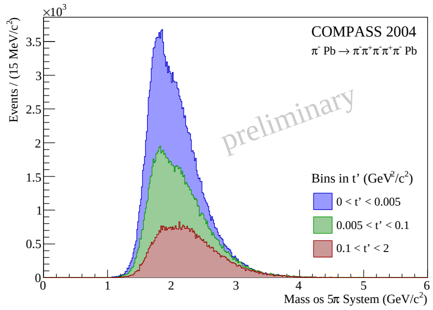

Fig. 4. Invariant mass spectrum of the 5π system for different t' ranges

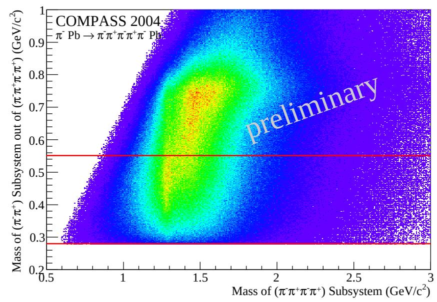

Fig. 5. 5π system: Neutral 4π subsystem vs. neutral 2π subsystem

$\pi_1(1600)$. Its phase motion w.r.t. the $1^{++}0^+[\rho\pi]S$ demonstrates the resonance nature of the 1^{-+} signal (Fig. 3). The phase motion w.r.t. the $2^{-+}0^+[f_2\pi]S$ is flat, as expected for two resonances with similar mass and width. A dedicated Monte-Carlo study with events covering the 16 dominant waves, but excluding the 1^{-+}, showed that the leakage to the spin-exotic wave is less than 5 %, i.e. negligible. In addition to the BW resonance (blue line in Fig. 2, bottom), a non-resonant background is observed. The parameters deduced for the $\pi_1(1600)$ resonance are $M = 1.660 \pm 0.010\ ^{+0.000}_{-0.064}\,\mathrm{GeV}/c^2$ and $\Gamma = 0.269 \pm 0.021\ ^{+0.042}_{-0.064}\,\mathrm{GeV}/c^2$, where first the statistical and second the systematic uncertainty is given.
The predicted $b_1\pi$ and $f_1\pi$ decay modes of a hybrid with $J^{PC} = 1^{-+}$ are accessible in final states with 5 charged pions, that also provide access to masses larger than $2\,\mathrm{GeV}/c^2$, making this channel highly interesting as well. The basic event selection for $\pi^-\pi^-\pi^-\pi^+\pi^+$ final states is analogous to the 3π analysis. 380 000 exclusive 5π (i.e. $|E_a - 189\,\mathrm{GeV}| < 6\,\mathrm{GeV}$) events have been obtained in total. The invariant mass distributions for three different t' ranges are shown in Fig. 4. One can clearly see a bump at $1.8\,\mathrm{GeV}/c^2$, where several resonances are expected, more prominently at small t'. As a preparation for the selection of isobars for the PWA, the invariant mass of the neutral 4π subsystem is plotted against its neutral 2π subsystems in Fig. 5. In the range between the two red lines, a clear $f_1(1285)$ signal can be seen around $1.2\,\mathrm{GeV}/c^2$, as predicted by the flux-tube model.

6 The COMPASS Hadron Run 2008

For the hadron beam time in 2008 the COMPASS spectrometer was upgraded significantly, also based on the experiences from 2004. A 40 cm long liquid hydrogen target was installed. It is surrounded by a recoil proton detector (RPD [16]), that consists of two scintillator rings to measure the recoil particle. In addition, the RPD forms the main part of the diffractive trigger. In the spectrometer, CEDAR detectors (using the Cherenkov effect [17]) were installed in the beam line, so that differentiation between e.g. π and K in the beam is possible. Very close to the target, even inside the RPD, there were additional silicon detectors installed in a specially shaped conical cryostat. The silicon detectors are cooled to 200 K to reduce the effect of radiation damage. Downstream of the RPD, an additional veto detector was installed, to veto on particles not going into the acceptance of the spectrometer [18]. Pixelized GEM detectors are used for tracking in the beam or near-beam region. Also both electromagnetic calorimeters were upgraded with new electronics and new blocks of scintillating lead glass.
The analysis of the $\pi^-\pi^-\pi^+$ final states is carried out analogous as in section 5. The invariant mass spectrum of the 3π mass in the t' range $0.1 < t' < 1.0\,\mathrm{GeV}^2/c^2$ is presented in Fig. 6. It contains about 20 000 000 events, what corresponds to only 21 % of the whole data taken in 2008. The well-known resonances $a_1(1260)$, $a_2(1320)$ and $\pi_2(1670)$ are clearly depicted. In Fig. 7, the Dalitz plot for the $\pi_2(1670)$ is shown, visualizing the $\rho\pi$ and the $f_2\pi$ decay modes.

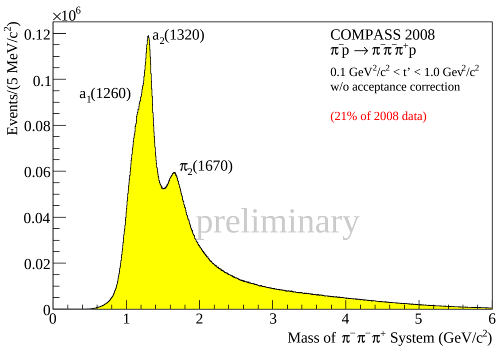

Fig. 6. Invariant mass of 3π system (2008).

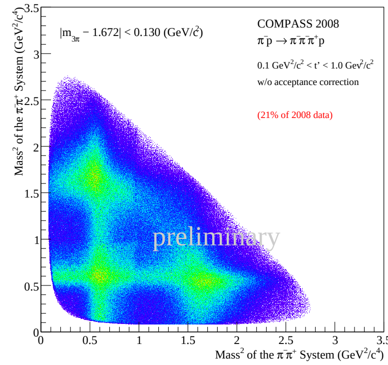

Fig. 7. Dalitz plot for $\pi_2(1670)$ (2008).

7 Conclusion and Outlook

Diffractive dissociation processes can be studied at COMPASS with high resolution, high statistics and high and uniform acceptance, providing excellent access to meson resonances in the light quark sector. Yet a short pilot run in 2004, using 190 GeV π^- beam on lead targets, allowed for a partial wave analysis on 420 000 $\pi^-\pi^-\pi^+$ events with momentum transfer $t' \in [0.1, 1.0]\mathrm{GeV}^2/c^2$. Apart from several established mesons, a resonance with the spin-exotic quantum numbers $J^{PC} = 1^{-+}$ is observed in $\rho\pi$ decay, that is consistent with the $\pi_1(1600)$ resonance. Furthermore the analysis of the $\pi^-\pi^-\pi^-\pi^+\pi^+$ final states is in progress.
In 2008 and 2009 the largest parts of the data taking periods were dedicated to meson spectroscopy. With a significantly upgraded spectrometer and a liquid hydrogen target, about two orders of magnitude more statistics with $t' \in [0.1, 1.0]\mathrm{GeV}^2/c^2$, also providing access to higher masses, have been collected in 2008 and are currently being analyzed. In addition, the data features central production with charged [16] and neutral final states, diffractive dissociation with neutral and kaonic [18] final states, and diffractive dissociation of kaons [17].

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