Studies of light Mesons at COMPASS

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The COMPASS experiment has taken a large data set with a negative pion beam impinging on a liquid-hydrogen target to study the spectrum of light mesons in diffractive dissociation reactions. The properties of known resonances are studied, and new, possibly spin-exotic states are searched in three-pion final states. A new state at about $1.4\,\mathrm{GeV}/c^2$ with a_1 quantum numbers is observed in the decay to $f_0\,(980)\,\pi$. The spin-exotic 1^{-+} wave is investigated in order to search for the controversial $\pi_1\,(1600)$.

1 Introduction

The **Co**mmon **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy (COMPASS) is a fixed-target experiment located at CERN's Super Proton Synchrotron (SPS). It is aimed to study the structure and dynamics of hadrons. The spectrum of light mesons is investigated using reactions of a negative hadron beam, consisting mostly of pions, with a liquid-hydrogen target. Isovector states are diffractively produced and dissociate into multi-particle final states. The decay products are detected in a two-stage magnetic spectrometer equipped with an electromagnetic and hadronic calorimeter in each spectrometer stage [1]. The apparatus provides full coverage for charged and neutral particles, resulting in a homogenous acceptance over a rather wide kinematic range.

The diffractive dissociation of a beam pion into a three-pion final state is the dominant reaction in the data COMPASS collected by impinging a $190\,\mathrm{GeV}/c$ pion beam on a liquid-hydrogen target. A recoil-proton detector in the trigger selected events with a reduced four-momentum transfer squared t' from the beam to the target between 0.1 and $1.0\,\mathrm{GeV}^2/c^2$. In COMPASS the three-pion final state can be detected simultaneously in two different channels, $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$. About 50 million exclusive $\pi^- p \to \pi^-\pi^-\pi^+ p$ and 3.5 million exclusive $\pi^- p \to \pi^-\pi^0\pi^0 p$ have been recorded.

The process is sketched in Fig. 1. The beam pion is excited to an intermediate state X^-, which subsequently decays into three pions. In order to study the intermediate state a partial-wave analysis using the isobar model is employed, decomposing the three-pion spectrum into its spin-parity components. In the isobar model the decay of the state X^- happens via successive two-body decays. In the case of the three-pion final state, X^- first decays to a bachelor pion and an isobar $R_{\pi\pi}$, which then decays to two pions. The $\rho\,(770)$, $f_0\,(980)$, $f_2\,(1270)$, $f_0\,(1500)$, $\rho_3\,(1690)$, and a broad $(\pi\pi)_S$ component are used as isobars in the present analysis. The fit model considers partial waves with the spin J of X^- up to 6. Also the relative orbital angular momentum L between the isobar $R_{\pi\pi}$ and the bachelor pion can go up to 6. Of the possible combinations, 87 waves with non-negligible intensity are kept for the final analysis:

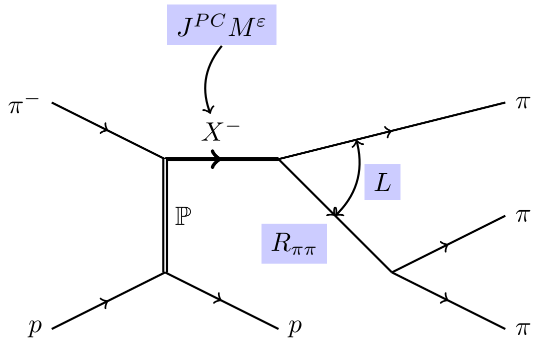

Figure 1: Sketch of the diffractive dissociation process under study.

80 with a positive reflectivity $\varepsilon = +1$ and 7 with $\varepsilon = -1$. In addition one incoherent wave with an isotropic angular distribution is included. The wave names $J^{PC}M^{\varepsilon}R_{\pi\pi}\pi L$ encode the quantum numbers of the intermediate state X^- and the information on the decay channel. The three-pion mass range between 500 and 2500 MeV/c^2 is divided into bins of 20 MeV/c^2 for the $\pi^-\pi^-\pi^+$ channel, and 40 MeV/c^2 for the $\pi^-\pi^0\pi^0$ channel. In addition the data are also divided into eleven bins of t' for $\pi^-\pi^-\pi^+$ and eight bins for $\pi^-\pi^0\pi^0$, such that all bins contain approximately the same number of events. The general features of this partial-wave analysis fit have been described before [2, 3].

2 The spin-exotic $J^{PC} = 1^{-+}$ wave

The existence of the $\pi_1(1600)$ is disputed. Previous experiments have claimed its observation [4], but could not reproduce this result on a larger sample with an extended set of waves in a limited range of t' [5]. COMPASS has also observed this state scattering a pion beam off a lead disk [6].

The partial-wave intensity of the spin-exotic $1^{-+}1^{+}\rho(770)\,\pi P$ wave found in the liquid-hydrogen data used for the present analysis is depicted in Fig. 2 (blue points) for the $\pi^-\pi^-\pi^+$ channel. A strong dependence of the intensity on the squared four-momentum transfer t' is observed. At lower values of t' only a broad structure is found, whereas when going towards higher t' a bump above 1600 MeV/c^2 is becoming more evident. This behavior is also observed in the $\pi^-\pi^0\pi^0$ channel.

Such a behavior could be caused by the interference of a genuine resonance with a large non-resonant contribution, for which the Deck effect [7] is a possible explanation. In order to study this Monte Carlo events were generated using the model from [8]. The same partial-wave decomposition was performed as for real data. The contribution to the exotic wave is displayed in Fig. 2 (green points). The intensity of the Deck model has been rescaled such that the total intensities in this wave over all mass and t' bins match. At lower values of t' a large part of the intensity can be described as coming from the Deck effect by this ansatz, at higher t' it is almost negligible.

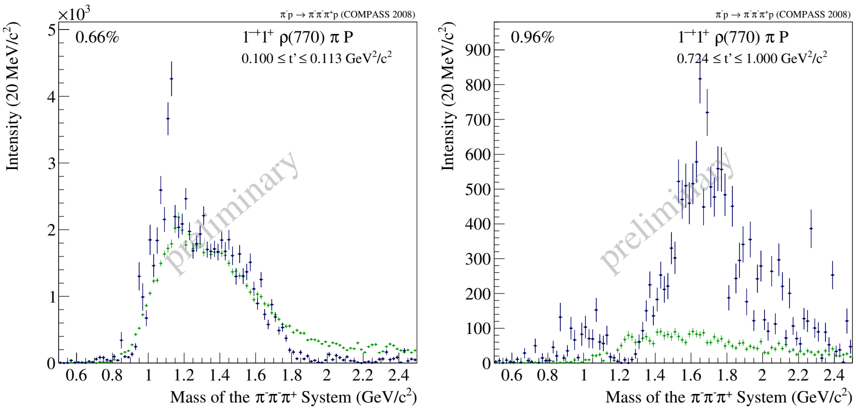

Figure 2: Partial-wave intensity of the spin-exotic $1^{-+}1^{+}\rho\,(770)\,\pi P$ wave (blue points) overlaid with a projection of a simulated Deck-effect into this wave (green points) for the lowest (left) and the highest (right) t' bin.

3 A new axial-vector state $a_1\,(1420)$

Compared to the previous COMPASS analysis [6] the number of partial-waves has almost been doubled. This is owed to the huge number of events allowing us to search also for smaller signals. One particularly interesting signal was found in the $1^{++}0^{+}f_0\,(980)\,\pi P$ wave. Fig. 3 shows the intensity of this wave for the two channels $\pi^-\pi^-\pi^+$ and $\pi^-\pi^0\pi^0$. A narrow structure around $1400\,\mathrm{MeV}/c^2$ is observed in both channels. In addition to the peak in the intensity spectrum, also rapid phase-motions with respect to the other waves are observed. This previously unobserved signal would correspond to a new state $a_1\,(1420)$. Different parameterizations for the isobar, in particular for the $f_0\,(980)$ and the broad $(\pi\pi)_S$ component have been tested in order to exclude a possible artifact from the used model.

Resonance parameters for this state and some well-known resonances are extracted from a fit of Breit-Wigner amplitudes to a subset of the spin-density matrix for the $\pi^-\pi^-\pi^+$ channel. This fit does not only describe the intensities of the individual waves, but also takes into account the interference between them. In the current analysis six waves are used, at least one resonant contribution is put into each wave: the $a_1\,(1260)$ and an a_1' in the $1^{++}0^{+}\rho\,(770)\,\pi S$ wave, the $a_2\,(1320)$ and an a_2' in the $2^{++}1^{+}\rho\,(770)\,\pi D$, the $\pi_2\,(1670)$ and $\pi_2\,(1880)$ in the $2^{-+}0^{+}f_2\,(1270)\,\pi S$, the $\pi\,(1800)$ in the $0^{-+}0^{+}f_0\,(980)\,\pi S$, the $a_4\,(2040)$ in the $4^{++}1^{+}\rho\,(770)\,\pi G$, and finally the new $a_1\,(1420)$ in the $1^{++}0^{+}f_0\,(980)\,\pi P$ wave. In addition there is one non-resonant contribution in each wave. The Breit-Wigner parameters are obtained from a simultaneous χ^2 fit to the spin-density submatrix of the six waves in all t' bins.

The extracted parameters of the major resonances are in agreement with previous measurements by COMPASS and other experiments [6]. Fig. 3 shows the result from this fit for the new $a_1\,(1420)$. A well determined mass of $M = 1412 - 1422\,\mathrm{MeV}/c^2$ and a narrow width of $\Gamma = 130 - 150\,\mathrm{MeV}/c^2$ is obtained. This is in contrast to other signals of similar magnitude like the a_1', the a_2' or the $\pi_2\,(1880)$ for which a larger uncertainty in mass and width is retrieved from the same fit.

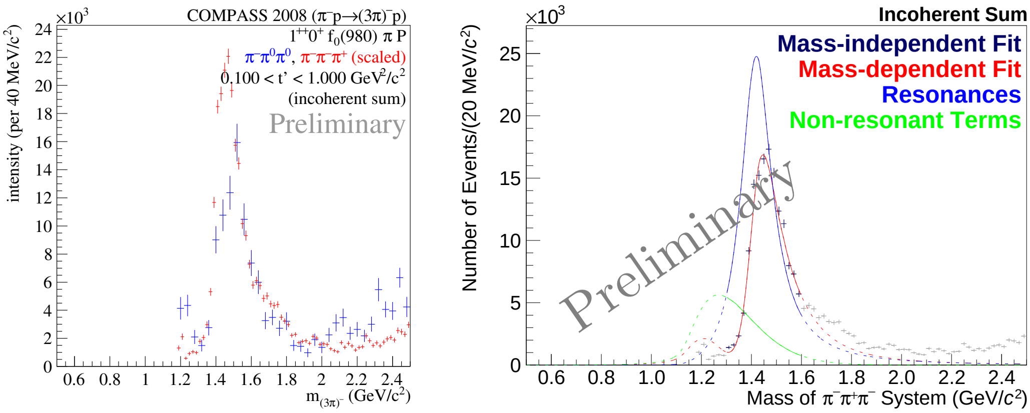

Figure 3: Left: Partial-wave intensity of the $1^{++}0^{+} f_0\,(980)\,\pi P$ wave for the $\pi^-\pi^0\pi^0$ (blue) and the $\pi^-\pi^-\pi^+$ (red) channel. Right: Mass-dependent fit for the $\pi^-\pi^-\pi^+$ channel.

4 Conclusions

COMPASS has collected a huge data set of three-pion events to study the spectrum of light mesons. A possible new resonance with a_1 quantum numbers with a mass around $1420\,\mathrm{MeV}/c^2$ and a width below $150\,\mathrm{MeV}/c^2$ is found in the $f_0\,(980)\,\pi P$ decay mode. Compared to other small resonances the parameters are well constrained. The corresponding wave shows a rapid phase-motion with respect to the reference waves. The t'-resolved analysis provides valuable insight into the spin-exotic candidate $\pi_1\,(1600)$. Large parts of the intensity found in the corresponding wave at lower t' can be described with the Deck effect, which vanishes at higher t'. Work is ongoing to make a statement on the resonant nature of this state.

Acknowledgments

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References

[1] COMPASS collaboration, P. Abbon *et al.*, Nucl. Instrum. Meth. A **577**, 455 (2007), arXiv:hep-ex/0703049; COMPASS collaboration, P. Abbon *et al.*, submitted to Nucl. Instrum. Meth. A, arXiv:1410.1797.

[2] S. Paul on behalf of the COMPASS Collaboration, proceedings of the MENU 2013, arXiv:1312.3678.

[3] S. Uhl on behalf of the COMPASS Collaboration, PoS(Hadron 2013)087, arXiv:1401.4943.

[4] S.U. Chung *et al.*, Phys. Rev. D **65**, 072001 (2002).

[5] A.R. Dzierba *et al.*, Phys. Rev. D **73**, 072001 (2006).

[6] COMPASS collaboration, M.G. Alekseev *et al.*, Phys. Rev. Lett. **104**, 241803 (2010).

[7] R.T. Deck, Phys. Rev. Lett. **13**, 169 (1964).

[8] C. Daum *et al.*, Nucl. Phys. B **182**, 269 (1981).