Non-strange light-meson spectroscopy at COMPASS

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Summary. — Lattice-QCD predicts the exotic meson $\pi_1(1600)$ to dominantly decay to $b_1\pi$. The $b_1\pi$ decay channel is accessible via the $\omega\pi^-\pi^0$ final state. COMPASS recorded the so far largest data set of this final state. A partial-wave analysis allows to determine the resonant content in this final state including possible contributions from $\pi_1(1600)$. Decomposing the measured intensity into amplitudes of partial waves gives a first qualitative insight into contributing intermediate states. We observe signals in agreement with well-established states like the $\pi(1800)$ and $a_4(1970)$. Smaller resonance-like signals are visible in the J^{PC} sectors 3^{++} and 6^{++}, where possible states were claimed but none are established. For $J^{PC} = 1^{-+}$ a signal at $1.65\,\mathrm{GeV}/c^2$ in $b_1(1235)\pi$ partial waves is consistent with the expected $\pi_1(1600)$.

1. – Introduction

The constituent quark model describes mesons as $q\bar{q}$ bound states, systematically following a multiplet structure derived from basic symmetries. However, QCD allows further states beyond this $q\bar{q}$ configuration. Other possible states — so-called exotic mesons — are hybrids, glueballs, and multiquark-states. Mesons with J^{PC} quantum numbers forbidden for a conventional $q\bar{q}$ state, like $J^{PC} = 1^{-+}$, are called spin-exotic mesons. Lattice-QCD predicts the lightest hybrid state as a single pole with $J^{PC} = 1^{-+}$ [1]. Thanks to recent advances, lattice-QCD also predicts the partial decay widths of this pole from first principle [2], where $b_1\pi$ is the dominant decay channel. Other channels like $\rho\pi$, $f_1(1285)\pi$, $\eta^{(\prime)}\pi$, and $K^*\bar{K}$ should be suppressed by about an order of magnitude and the final state $\rho\omega$ is predicted to contribute less than 1% to the total decay width.

Experimentally, π_1 signals were observed in different decay modes at masses of $1.4\,\mathrm{GeV}/c^2$ and $1.6\,\mathrm{GeV}/c^2$. As a result, two π_1 states were claimed, namely $\pi_1(1400)$ and $\pi_1(1600)$. A coupled-channel analysis of $\eta\pi$ and $\eta'\pi$ using COMPASS data demonstrated

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that a single pole is sufficient to describe the partial waves in both decay channels [3]. COMPASS further observed the $\pi_1(1600)$ decaying to $\rho\pi$ and $f_2(1270)\pi$ [4].

Here, we present a new study of the $b_1\pi$ decay mode of $\pi_1(1600)$ at COMPASS which requires a partial-wave analysis of the $\omega\pi^-\pi^0$ final state. We present the recent status of this analysis.

2. – Analysis of the $\omega\pi\pi$ final state

At COMPASS excited mesons X^- are produced by diffractive scattering of an 190 GeV π^- beam off a liquid-hydrogen target. At such energies, Pomeron exchange is expected to be the dominant production mechanism. This process gives access to excited intermediate states $X = a_J, \pi_J$. As states in the light-meson sector overlap, a partial-wave analysis is necessary to disentangle the different contributing X^- mesons. It also allows to measure the quantum numbers of the states. We model the intermediate states — the partial waves — using the isobar model, where X^- decays to $\omega\pi\pi$ in successive two-body decays. To uniquely identify a particular partial wave, a set of quantum numbers

$$i = J^P M^\epsilon [\xi l] b L S$$

is necessary. Here, J is the total spin of X^-, P is the parity, and M^ϵ characterises the spin projection of X^- on the beam axis. L and S are the orbital angular momentum and intrinsic spin of the $X \to \xi b$ decay, respectively. ξ is the so-called isobar, an intermediate state in a two-body subsystem of $\omega\pi\pi$, which is modelled using known resonances. For $\omega\pi^-\pi^0$, the possible two-body subsystems are $\pi^-\pi^0$, $\omega\pi^-$, or $\omega\pi^0$. We consider the isobars $\rho(770)$, $\rho(1450)$, and $\rho_3(1690)$ for the $\pi^-\pi^0$ intermediate state and $b_1(1235)$, $\rho(1450)$, and $\rho_3(1690)$ for the $\omega\pi$ intermediate states. Further, l is the orbital angular momentum between the two daughters of the isobar. b is the bachelor particle, e.g. the remaining particle in $\omega\pi\pi$ outside of the isobar. Two partial waves that differ only in the charge of ξ and b, i.e. $\xi b = b_1(1235)^-\pi^0$ and $\xi b = b_1(1235)^0\pi^-$, are expected to have the same amplitude and are combined into one partial wave.

The description of the final state of X^- requires a set of 8 phase-space variables τ. The description of the decay $X^- \to \omega\pi^-\pi^0$ via an intermediate state ξ requires the mass m_ξ of the intermediate state and two two-particle decays, each described by two angles ϕ and θ. In addition the decay of $\omega \to \pi^-\pi^0\pi^+$ requires a mass m_ω of ω and two Dalitz-plot variables.

Following the method presented in ref. [4], we model our measured intensity $\mathcal{I}$ as

$$\mathcal{I}(m_X, t', \tau) = \left| \sum_i \mathcal{T}_i(m_X, t')\psi_i(m_X, \tau) \right|^2 . \quad (1)$$

The intensity depends on the invariant mass m_X of the excited X^- state, the squared four-momentum transfer t', and the phase-space variables τ. In eq. 1 we calculate the decay amplitude $\psi_i(m_X, \tau)$ using the isobar model. We model the mass line-shapes of isobars as Breit-Wigner resonances with dynamic width using the parameters from ref. [5]. The transition amplitude $\mathcal{T}_i$ contains all information about the production, the propagation, and the coupling of X^- to a partial-wave i. We obtain its complex value by fitting eq. 1 to the measured intensity distribution in a maximum-likelihood fit. We fit $\mathcal{T}_i$ as independent constants in cells of m_X and t'. With this approach, we approximate

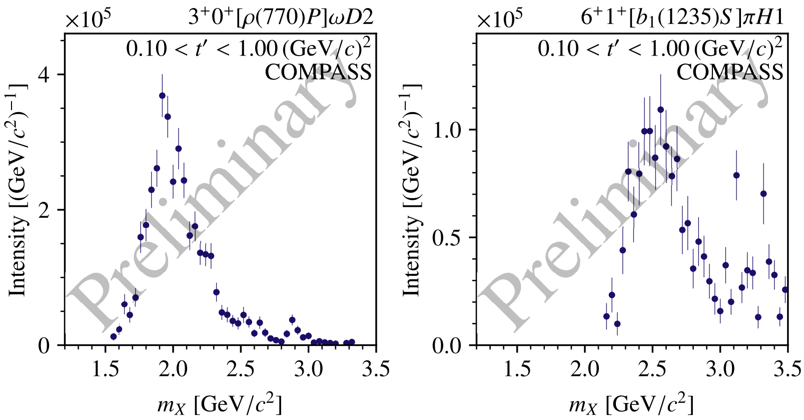

Fig. 1.: Intensities of the $3^+0^+[\rho(770)P]\omega D2$ (*left*) and $6^+0^+[b_1(1235)S]\pi H1$ (*right*) partial waves.

$\mathcal{T}_i(m_X, t')$ as step-wise constant function without prior knowledge about any resonant content of X^- in i.

To perform the fit, one must choose a finite subset of the infinite number of partial waves i used in eq. 1. Traditionally, this has been done by manually selecting waves based on the expected strength of $\mathcal{T}_i$. To reduce potential bias in this selection, we developed an alternative approach at COMPASS based on regularisation-based model-selection techniques. In this approach, a large wave pool is constructed based on loose systematic constraints. In our case, we consider all waves with $J \leq 8$, $M \leq 2$, $L \leq 8$, and $\epsilon = +1$ using all aforementioned isobars. This results in a total of 893 partial-waves. We fit all considered waves for each (m_X, t') cell using a regularised likelihood. Due to the regularisation most of the waves are close to zero. The remaining waves are used as the wave set that is unique for each cell in (m_X, t'). By refitting the data with the selected waves and no regularisation we decompose the measured intensity into the amplitudes $\mathcal{T}_i$ of all significant partial waves i.

2˙1. *Results.* – To discuss the results, we focus on the intensity $|\mathcal{T}_i|^2$ and the phase $\arg \mathcal{T}_i$ of a partial wave as a function of m_X. Since the total phases are not measurable, we consider the phase difference between two partial waves $\phi = \arg(\mathcal{T}_i - \mathcal{T}_j)$. For an isolated pole far from thresholds one expects a Breit-Wigner resonance characterised by a peak in the intensity and a phase motion of 180° around the resonances mass. We observe clear signals for the established states $\pi(1800)$ and $a_4(1970)$. In the 2^{++} and 2^{-+} sectors the picture is more complex as multiple established states overlap.

In the intensity of the $3^+0^+[\rho(770)P]\omega D2$ wave, a clear peak arises around $m_X = 2.0\,\text{GeV}/c^2$, shown in fig. 1 (*left*). Consistent signals are observed in the decays into $b_1\pi$ and $\rho_3(1690)\pi$. The PDG lists two unconfirmed states at nearby masses, the $a_3(1874)$ and $a_3(2030)$. This would be the first observation of an a_3 in these decay channels.

Another sector in which we observe a resonance-like signal is the 6^{++} sector. Figure 1 (*right*) shows the intensity of the $6^+1^+[b_1(1235)S]\pi H1$ wave. We observe a clear peak around $m_X = 2.5\,\text{GeV}/c^2$, consistent with the $a_6(2450)$ listed in the PDG. This state has only been seen in one experiment in $K_S K$ [6] and requires further confirmation. This would be the first observation in the $b_1(1235)\pi$ decay channel.

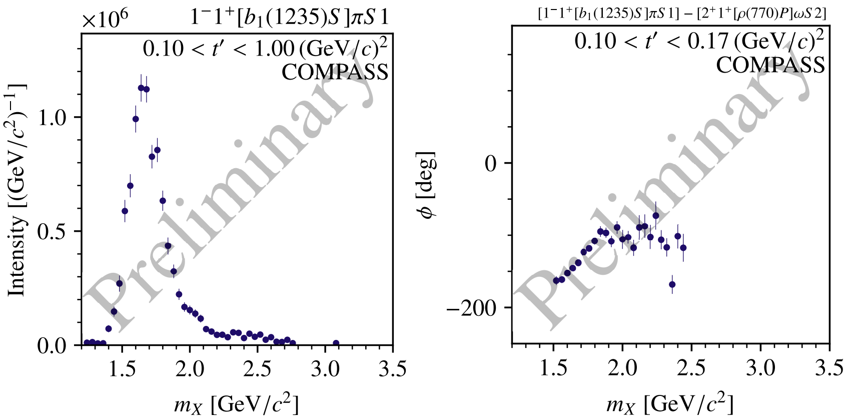

Fig. 2.: *Left:* Intensity of the $1^-1^+[b_1(1235)S]\pi S1$ partial wave. *Right:* phase of the same wave w.r.t. the $2^+1^+[\rho(770)P]\omega S2$ wave.

In the 1^{-+} sector, we expect to observe a strong contribution from the $\pi_1(1600)$ in $b_1\pi$ waves. Figure 2 shows the intensity and phase of the $1^-1^+[b_1(1235)S]\pi S1$ wave. A signal close to $m_X = 1.6\,\mathrm{GeV}/c^2$ suggests a contribution from the well-established spin-exotic meson. We observe a similar signal in the wave where $b_1(1235)$ decays not via S- but D-wave, as shown in fig. 3 (*left*). This signal is consistent with the $\pi_1(1600)$ observed at COMPASS in $\rho\pi$ and $\eta'\pi$ decays. We also observe a resonance-like signal in 1^{-+} $\rho\omega$-waves, which is shown in fig. 3 (*right*). The $1^-1^+[\rho(770)P]\omega P1$ wave exhibits a signal around $m_X = 1.8\,\mathrm{GeV}/c^2$. This signal could correspond to the $\pi_1(1600)$ with a shifted mass due to limited phase space. It would be the first observation of the $\pi_1(1600)$ in $\rho(770)\omega$ and would be inconsistent with the prediction of a small $\rho\omega$ partial decay width of $\pi_1(1600)$.

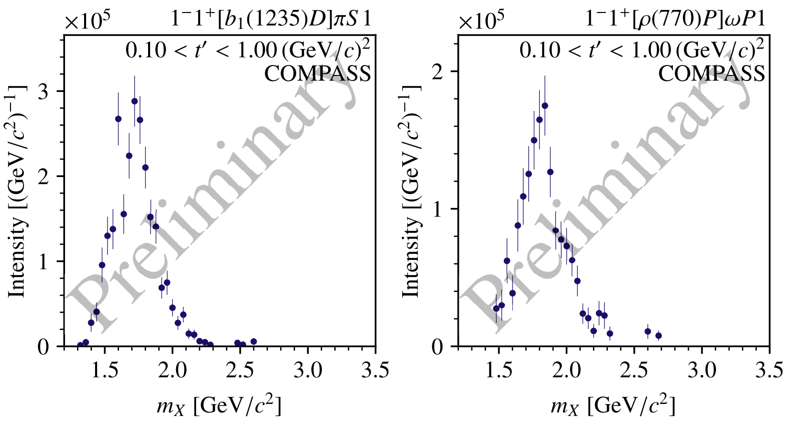

Fig. 3.: Intensities of the $1^-1^+[b_1(1235)D]\pi S1$ (*left*) and $1^-1^+[\rho(770)P]\omega P1$ (*right*) partial waves.

3. – Conclusion and outlook

We have decomposed the COMPASS data selecting the $\omega\pi^-\pi^0$ and observe clear signals in several partial waves. In addition to the expected resonances, such as the $a_4(1970)$ and $\pi(1800)$, we observe further signals in the $J^{PC} = 3^{++}$ and $J^{PC} = 6^{++}$ sectors, where some candidates are listed in the PDG, but no state is yet established. As predicted by lattice-QCD, we observe signals for $b_1(1235)\pi$ waves in the $J^{PC} = 1^{-+}$ sector consistent with the $\pi_1(1600)$. We also observe a signal in $\rho\omega$ in the $J^{PC} = 1^{-+}$ sector. To validate these promising signals and to quantify their parameters, the next step of this analysis is to model the mass dependence of the extracted partial-wave amplitudes.

In addition to the analysis of the $\omega\pi^-\pi^0$ final state, we investigate further channels. These include the K_SK^- channel, which is the only channel in which an a_6 state has been observed so far. The $K_SK_S\pi$ channel is a good candidate for investigating the nature of the $a_1(1420)$. It also gives access to the $K^*\bar{K}$ channel, predicted to have a significant partial decay width of the $\pi_1(1600)$. The $f_1(1285)\pi$ channel could give access to the $\pi_1(1600)$ as it is predicted to have the second largest partial decay width. Its decay to $\eta\pi\pi\pi$ is being studied. By including the latter two decay channels, we plan to study the $\pi_1(1600)$ in practically all of its decay channels at COMPASS and thus obtain a complete picture of this state. This is only possible because of the unique COMPASS data set.

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