EPJ Web of Conferences will be set by the publisher
DOI: will be set by the publisher

Light-Meson Spectroscopy at COMPASS

Fabian Krinner[1,a] and for the COMPASS collaboration

[1] *Technische Universität München - Physik-Department - E18*

Abstract. The goal of the COMPASS experiment at CERN is to study the structure and dynamics of hadrons. The two-stage spectrometer used by the experiment has good acceptance and covers a wide kinematic range for charged as well as neutral particles allowing to access a wide range of reactions. Light mesons are studied with negative (mostly π^-) and positive (p, π^+) hadron beams with a momentum of 190 GeV/c.
The light-meson spectrum is measured in different final states produced in diffractive dissociation reactions with squared four-momentum transfer t to the target between 0.1 and 1.0 (GeV/c)^2. The flagship channel is the $\pi^-\pi^+\pi^-$ final state, for which COMPASS has recorded the currently world's largest data sample. These data not only allow to measure the properties of known resonances with high precision, but also to search for new states. Among these is a new axial-vector signal, the $a_1(1420)$, with unusual properties. The findings are confirmed by the analysis of the $\pi^-\pi^0\pi^0$ final state.

1 The COMPASS experiment

The COMPASS experiment is located at CERN's Prevessin area and consists of a fixed-target two-stage spectrometer. Due to its full kinematic coverage it is capable of measuring a wide range of different physics programs, employing various beam conditions, such as secondary hadron or tertiary muon beams, impinging on a broad variety of different targets. Amog these programs are the study of hadron structure as well as light meson spectroscopy, which will be the focus here.

For the analysis presented here, data taken in 2008 is used, where a 190 GeV/c was shot onto a liquid hydrogen target. This beam consisted to 97% of π^- with some admixtures of K^- and antiprotons. The particular process under study is the diffractive production of three charged pions:

$$\pi^-_{\text{beam}} p_{\text{target}} \to \pi^-\pi^+\pi^- p_{\text{recoil}}, \tag{1}$$

for which COMPASS has collected a total of $46 \cdot 10^6$ exclusive events, resulting in the world's largest data set for this process so far.

2 Partial-Wave Decomposition

The main interest of the analysis is the extraction of light meson resonances from the data, following the assumption, that the production of the three final-state pions happens via intermediate resonances X^-:

$$\pi^-_{\text{beam}} p_{\text{target}} \to X^- p_{\text{recoil}} \to \pi^-\pi^+\pi^- p_{\text{recoil}}. \tag{2}$$

[a] e-mail: fabian-krinner@mytum.de

Name	J^{PC}
$f_0(500)$	0^{++}
$f_0(980)$	0^{++}
$f_0(1500)$	0^{++}
$\rho(770$	1^{--}
$f_2(1270)$	2^{++}
$\rho_3(1690)$	3^{--}

Table 1. Isobars used in the Partial-Wave Decomposition and their quantum numbers J^{PC}.

2.1 The Isobar Model

One further assumption, that has to be made, is the isobar model, which states that the resonances of interest do not decay directly into three pions, but undergo two subsequent two-particle decays with another intermediate state ξ^0 appearing, the so-called isobar. In contrast to the three-pion resonances X^-, the isobar states have to be well known beforehand and a fixed mass-shape, e.g. a Breit-Wigner parametrization, has to be put into the analysis. In the analysis presented here, we used the set of isobars given in table 1.

With these assumptions, the decay of an intermediate state X^- with quantum-numbers J^{PC}, spin-projection and reflectivity M^ε, decaying into an isobar ξ and a pion that have an orbital angular momentum L with respect to each other, completely determines the functional dependence $\psi_{\text{wave}}(\tau)$ on the five kinematic variables τ of the process. Specific combinations of quantum numbers and decay mode are called "partial waves" from hereon and are named by the following scheme:

$$J^{PC} M^\varepsilon \xi \pi L. \tag{3}$$

With these waves, we model the intensity $\mathcal{I}(m_{3\pi}, t', \tau)$ of the process in the following way, where the appearing sum runs in our case over a set of 88 waves [1]:

$$\mathcal{I}(m_{3\pi}, t', \tau) = \left| \sum_{i \in \text{waves}} T_i(m_{3\pi}, t') \psi_i(\tau) \right|^2 . \tag{4}$$

In above formula, the parameters T_i are complex transition amplitudes, that determine the strength and phase with which the single partial waves are produced. We extract them form the data using independent extended maximum likelihood fits in bins of the invariant mass of the three-pion system $m_{3\pi}$ and the squared four-momentum transfer t'. With 100 bins of 20 MeV width in $m_{3\pi}$, from 0.5 to 2.5 GeV, and 11 non-equidistant bins in t', this gives a total of 1100 independent fits to the data.

2.2 Results

The results of the Partial-Wave Decompositions are the complex production amplitudes T_i for every wave and bin in $m_{3\pi}$ and t'. In the following they will be discussed in terms of intensity and relative phases. The intensities are calculated by $|T_i|^2$ and given in number of events. Since in every bin, a global phase factor is free, only relative phases between two waves carry physical meaning, they are given by:

$$\phi_{ij} = -\phi_{ji} = \arg(T_i T_j^*). \tag{5}$$

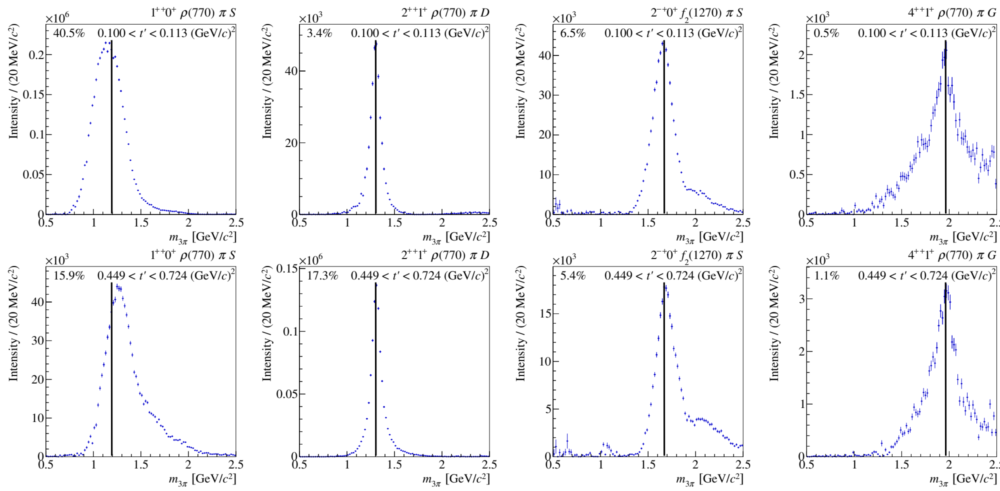

Figure 1. Result for the Partial-Wave Decomposition for 4 of the 88 waves in the model in 2 of 11 bins in t'. It can be seen, that peak positions shift with t', which should not happen for a resonant process.

3 Resonance-Model Fit

3.1 Model and Method

Since the result of the Partial-Wave Decomposition only gives binned amplitudes of the single waves, but no information on resonances and their masses and widths, these have to be extracted in a second step, the Resonance-Model Fit. To this end, we construct the Spin Density Matrix:

$$\rho_{ij}(m_{3\pi}, t') = T_i(m_{3\pi}, t') T_j^*(m_{3\pi}, t'), \tag{6}$$

where the indices i and j denote single waves. In this formulation, the global phase, which is free in every $m_{3\pi}$ and t' bin, drops out. The diagonal elements of the SDM give the intensities of the single waves, while the off-diagonal elements give their respective interferences. Since ρ_{ij} is hermitian it suffices to give intensities and relative phases, defined in equation (5), of the waves to encode the full information. Therefore, Spin Density Matrices will be shown as upper triangular matrices in the following.

For this second step, we parametrize the $m_{3\pi}$ dependence of the SDM elements, by modeling the amplitudes as:

$$\mathcal{A}_i(m_{3\pi}, t') = \sum_{r \in \text{resonances}} C_{\text{r}}(t') \text{BW}_r(m_{3\pi}) + C_{\text{non-resonant}}(t') \text{NR}_i(m_{3\pi}, t'), \tag{7}$$

where the sum runs over the respective resonance content for every wave. The functions $\text{BW}_r(m_{3\pi})$ are the Breit-Wigner amplitudes for the single resonances and the functions $\text{NR}_i(m_{3\pi}, t')$ are pure real phenomenological parametrizations of non-resonant contributions for every wave. All these functions are added with a complex coefficient C_i, that may vary with t'.

The fact, that the complex couplings, as well as the non-resonant terms may vary with t', while the Breit-Wigner amplitudes may not, allows to better disentangle both contributions.

For the fit presented here, we selected a subset of 14 wave out of the 88 waves in the model of the Partial-Wave Decomposition to be used in the Resonance-Model Fit. To parametrize these, we use a total of 11 resonances with six different sets of quantum numbers.

With this model, we end up with 722 free parameters in the fit. Most of them, however, are coupling coefficients and as such of minor physical interest. Only 51 parameters are shape-parameters, e.g. masses and width of the resonances, and will therefore be discussed here.

In this analysis, all 14 waves are fitted simultaneously in all 11 bins of t'. All results presented in the following are part of this one single fit.

3.2 Results

In the following we will discuss the fit-results for the six different combinations of quantum numbers included in the fit.

3.2.1 $J^{PC} = 0^{-+}$ sector

For the sector with $J^{PC} = 0^{-+}$, only the $0^{-+}0^{+} f_0(980)\pi S$ wave was included. In this wave a clear peak and phase motion corresponding to the well known $\pi(1800)$ resonance can be seen in figure 4. Its resonance parameters can be extracted with low uncertainties, as shown in table 2.

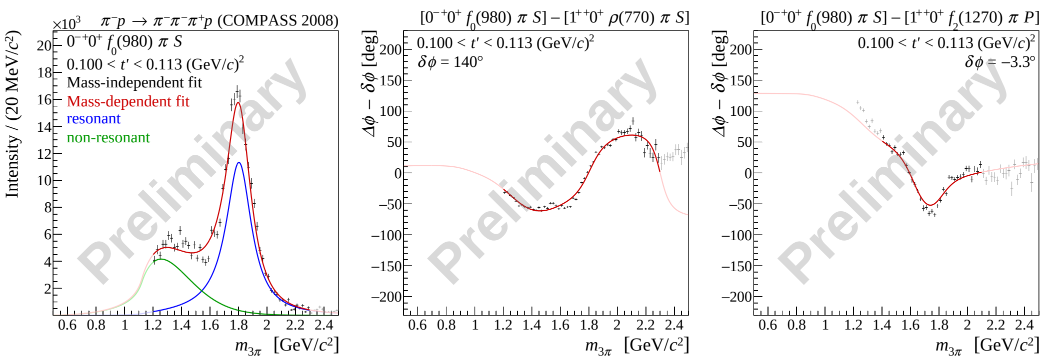

Figure 2. Intensity and and phase-motion for the $0^{-+}0^{+} f_0(980)\pi S$ wave in one bin of t'.

3.2.2 $J^{PC} = 1^{++}$ sector

Three waves with quantum numbers $J^{PC} = 1^{++}$ are included in the fit. Two of them, $1^{++}0^{+}\rho(770)\pi S$ and $1^{++}0^{+} f_2(1270)\pi P$ are parametrized by the more or less well known axial-vector resonances $a_1(1260)$ and $a_1(1640)$. These could be extracted with moderate systematic uncertainties from the fit (Table 2). For the extraction of these resonances, the t' resolved analysis turned out to be very valuable, since the movement of the peak position with t' (Fig. 1) could be explained by an interplay of non-resonant and resonant contributions, where the latter is not allowed to change with t'.

The third wave in this sector is $1^{++}0^{+} f_0(960)\pi P$, which is consistently described by a previously unknown resonance, the $a_1(1420)$. Even though there are several explanations for this signal, e.g. [3, 4], we can state, that it is compatible with a Breit-Wigner amplitude with very small systematic uncertainties (Table 2).

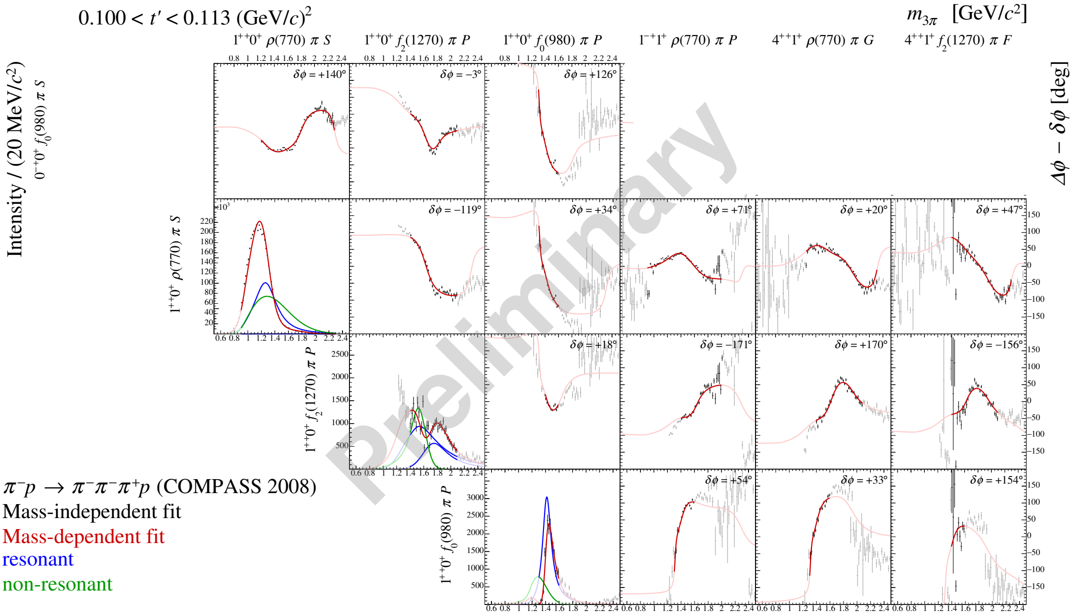

Figure 3. Section of the Spin Desity Matrix corresponding to waves with $J^{PC} = 1^{++}$.

3.2.3 $J^{PC} = 1^{-+}$ sector

Only one wave with $J^{PC} = 1^{-+}$ wave included in the fit. Since this is a spin-exotic combination of quantum numbers, a resonance in this wave could not be explained as a $q\bar{q}$ state, but by more sophisticated models. The signal extracted in our analysis is consistent with a Breit-Wigner resonance that dominates at high t', while the low t' regions are mostly described by the non-resonant part. However, the systematic uncertainties on the resonance parameters are rather large, thus we cannot draw a final conclusion on the existence of a resonance in this particular wave.

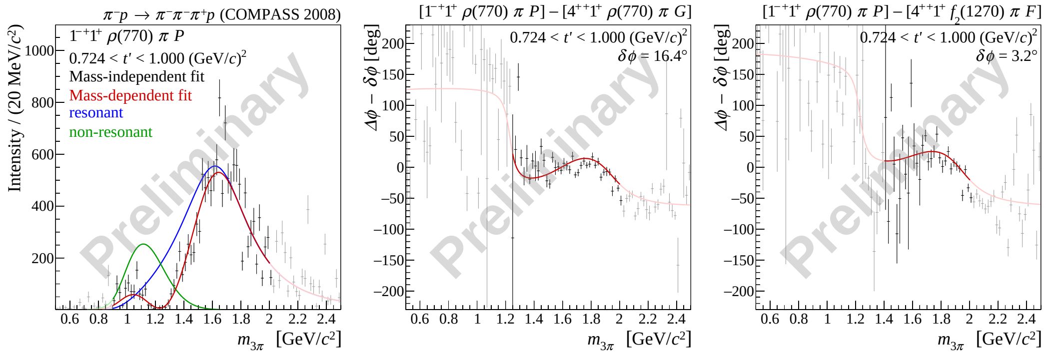

Figure 4. Intensity and and phase-motion for the $1^{-+}1^{+}\rho(770)\pi P$ wave in one bin of t'.

3.2.4 $J^{PC} = 2^{++}$ sector

In the sector with $J^{PC} = 2^{++}$, three waves were included in the Resonance Model Fit, described by two resonances, the $a_2(1320)$ and the $a_2(1700)$ The result for this sector is shown in Fig. 5. The $a_2(1320)$ is the resonance best determined by the analysis. The peak in the $2^{++}1^{+}\rho(770)\pi D$ wave is also the clearest resonance signal, meaning the wave with the least non-resonant contributions. The excited state, the $a_2(1700)$, could also be determined with reasonable systematic uncertainties.

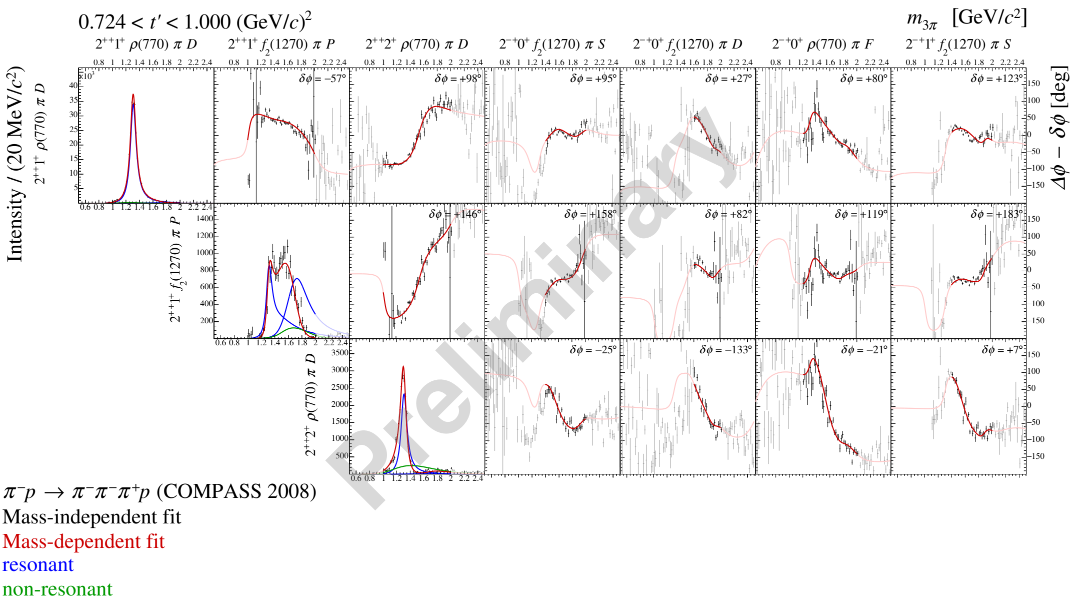

Figure 5. Section of the Spin Desity Matrix corresponding to waves with $J^{PC} = 2^{++}$.

3.2.5 $J^{PC} = 2^{-+}$ sector

Four waves were included in the $J^{PC} = 2^{-+}$ sector, which could be described using three resonances, two well known ones, $\pi_2(1670)$ and $\pi_2(1880)$, and one additional resonance, the $\pi_2(2005)$ which has only been observed once before [5]. As can be seen in figure 6, the $\pi_2(1670)$ is dominant in S-wave decays, while the $\pi_2(1880)$ dominates D-wave decays. A small amount of the $\pi_2(2005)$ is also present in every wave.

3.2.6 $J^{PC} = 4^{++}$ sector

The last sector included in the analysis is the $J^{PC} = 4^{++}$ sector, for which two waves were used. These could be described by the $a_4(2040)$ resonance, whose mass and width could be determined up to small systematic uncertainties.

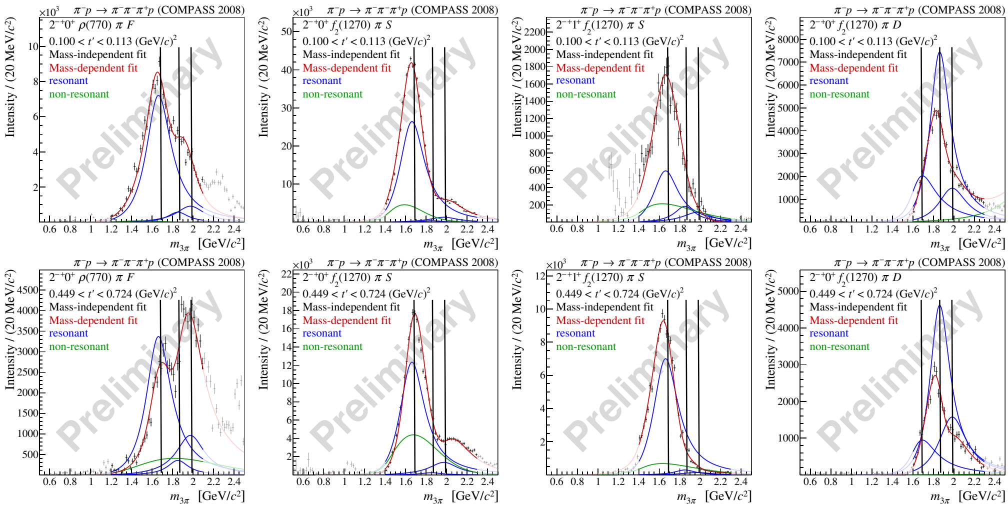

Figure 6. Intensities of the four $J^{PC} = 2^{-+}$ waves in the fit, in two bins of t'.

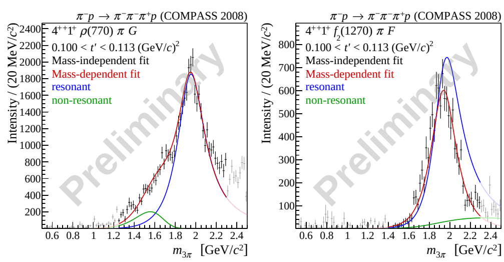

Figure 7. Intensities of the two $J^{PC} = 4^{++}$ waves in the fit, in one bin of t'.

3.3 Systematic Studies

All the results presented up to now were obtained by one complex fit to the data. To obtain this, 1000 fit attempts with random start values for the parameters and varying release orders of the single parameters were made using a total of 30000 CpuH.

To get a handle on the systematic uncertainties of the extracted resonance parameters, more than 200 systematic studies with 200 fit attempts each were performed in addition. These studies include the variation of:

- the set of fitted waves,
- the resonance content used to describe the single waves,
- the parametrizations of the non-resonant parts,
- cuts in $m_{3\pi}$, t' and event selection,
- the definition of the χ^2 function.

With these studies, we are confident to have a reasonable estimate of the systematic uncertainties on the extracted resonance parameters summarized in table 2.

Name	m_0[MeV]	Γ_0[MeV]
$a_1(1260)$	1298^{+13}_{-22}	403^{+0}_{-100}
$a_1(1420)$	$1411.8^{+1.0}_{-4.4}$	158^{+8}_{-8}
$a_1(1640)$	1688^{+40}_{-70}	534^{+124}_{-20}
$a_2(1320)$	$1314.2^{+1.0}_{-3.1}$	$106.7^{+3.5}_{-2.4}$
$a_2(1700)$	1674^{+143}_{-32}	435^{+52}_{-15}
$a_4(2040)$	1933^{+13}_{-14}	334^{+22}_{-19}
$\pi(1800)$	$1802.6^{+8}_{-3.5}$	218^{+11}_{-6}
$\pi_1(1600)$	1604^{+100}_{-50}	608^{+70}_{-240}
$\pi_2(1670)$	$1644.2^{+11.5}_{-3.4}$	306^{+14}_{-19}
$\pi_2(1880)$	1847^{+14}_{-6}	247^{+41}_{-18}
$\pi_2(2005)$	1968^{+21}_{-21}	337^{+50}_{-80}

Table 2. Breit-Wigner parameters extracted from the Resonance Model Fit with their systematic uncertainties. Statistical uncertainties are negligible due to the large size of the data-set.

4 Conclusion and Outlook

The large data-set for the process $\pi^-_{\text{beam}} p_{\text{target}} \rightarrow \pi^-\pi^+\pi^- p_{\text{recoil}}$ collected with the COMPASS spectrometer allows to preform a Partial-Wave Decomposition and a subsequent Resonance-Model Fit with unprecedented accuracy.

In the performed analysis, we were able to extract a new resonance, the $a_1(1420)$, which has been observed the first time [2]. In addition, a signal for a wave with the spin exotic quantum numbers $J^{PC} = 1^{-+}$ was observed, which is consistent with a Breit-Wigner resonance description. In addition to these two, we extracted nine resonances in a single big fit and were able to reproduce these previously known resonances.

Since the statistical uncertainties on our analysis are negligible small, due to the size of the data-set, good knowledge of the systematic uncertainties is essential to the analysis. To this extent we performed a large number of systematic studies that give a good handle on their size.

The analysis of the data is not completed, since several questions still stay unanswered. The first concerns the validity of the isobar model, which may not be fully given. To this extent, we explore a new analysis method, that does not rely on previously known parametrizations of the isobars [6], as well as the role of possible non-resonant production mechanisms like the Deck effect.

The second question concerns the selection of the wave-set for the Partial-Wave Decomposition, which was done by hand up to now and thus might have introduced a certain bias to the analysis. To study this, we are currently working on a automated model-selection procedure [7].

The last question concerns the resonance paramterizations used in the Resonance-Model Fit. At the moment simple Breit-Wigner amplitudes are used, but we are making efforts to use more advanced parametrizations that fulfill the requirement of analyticity. As a first application, we extracted resonance pole-positions in the $J^{PC} = 2^{-+}$ sector [8].

References

[1] C. Adolph *et al.*, arXiv:1509.00992 [hep-ex].

[2] C. Adolph *et al.* [COMPASS Collaboration], Phys. Rev. Lett. **115** (2015) no.8, 082001 doi:10.1103/PhysRevLett.115.082001.

[3] M. Mikhasenko, B. Ketzer and A. Sarantsev, Phys. Rev. D **91** (2015) no.9, 094015 doi:10.1103/PhysRevD.91.094015

[4] J. L. Basdevant and E. L. Berger, arXiv:1501.04643 [hep-ph].

[5] A. V. Anisovich, C. A. Baker, C. J. Batty, D. V. Bugg, V. A. Nikonov, A. V. Sarantsev, V. V. Sarantsev and B. S. Zou, Phys. Lett. B **517** (2001) 261 doi:10.1016/S0370-2693(01)01017-6

[6] F. Krinner [COMPASS Collaboration], arXiv:1609.08514 [hep-ex].

[7] K. A. Bicker (2016), "Model Selection for and Partial-Wave Analysis of a Five-Pion Final State at the COMPASS Experiment at CERN" (Doctoral Dissertation).

[8] M. Mikhasenko [COMPASS Collaboration], "EPJ Web of Conferences", these proceedings.