Extraction of the $\pi^+\pi^-$ Subsystem in Diffractively Produced $\pi^-\pi^+\pi^-$ at Compass

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The Compass experiment at CERN has collected a large data sample of 50 million diffractively produced $\pi^-\pi^+\pi^-$ events using a 190 GeV/c negatively charged hadron beam. The partial-wave analysis (PWA) of these high-precision data reveals previously unseen details. The PWA, which is currently limited by systematic uncertainties, is based on an isobar model, where multi-particle decays are described as subsequent two-body decays and where a prior-knowledge parametrization for the intermediate two-pion resonances has to be assumed – usually a Breit-Wigner amplitude – thus increasing systematic uncertainties, due to the concrete choice of the parametrization. We present a novel method, which allows to extract isobar amplitudes directly from the data in a less biased way. The focus lies on the scalar $\pi^+\pi^-$ subsystem, where a previous analysis found a signal for a new axial-vector state $a_1(1420)$ decaying into $f_0(980)\pi$.

\textbf{KEYWORDS:} Compass, Partial-Wave Analysis, Isobar Model, $a_1(1420)$

1. Introduction

Compass is a two-stage multi-purpose spectrometer, located at CERN’s Prévessin site, which employs secondary hadron or tertiary muon beams from the Super Proton Synchrotron. Its large acceptance over a wide kinematic range allows Compass to study a broad physics program including, amongst others, light-meson spectroscopy, which is the focus here.

The particular channel of interest is $\pi^- p \rightarrow X^- p \rightarrow \pi^- \pi^+ \pi^- p$, for which Compass collected a data set consisting of approximately 50 million events.

2. Analysis method

2.1 The Isobar Model

To analyze the process $\pi^- p \rightarrow X^- p \rightarrow \pi^- \pi^+ \pi^- p$ we use the isobar model, which assumes that the appearing intermediate $3\pi$ state $X^-$ does not decay directly into $\pi^- \pi^+ \pi^-$, but undergoes subsequent two-particle decays until it ends up in the final state: $X^- \rightarrow \xi^0 \pi^- \rightarrow \pi^- \pi^+ \pi^-$. The intermediate two-pion state $\xi^0$ is called the isobar.

2.2 Conventional PWA

The conventional PWA expands the complex decay amplitude, which describes the measured intensity distribution $\mathcal{I}$, into partial waves [1]:

$$\mathcal{I}(\vec{r}, m_{3\pi}, t') = \sum_{\text{waves}} |\mathcal{T}_{\text{wave}}(m_{3\pi}, t')\Psi_{\text{wave}}(\vec{r}, m_{3\pi})|^2.$$ (1)
The production amplitudes $T_{\text{wave}}$ depend on the invariant mass $m_{3\pi}$ of the $\pi^+\pi^-\pi^-$ system and on the reduced squared four-momentum transfer $t'$. They are fitted to the data in bins of their kinematic variables using an extended maximum likelihood fit.

For constant $m_{3\pi}$ and $t'$, the decay amplitudes $\Psi_{\text{wave}}$ depend on 5 kinematic variables, that define the $3\pi$ kinematics and are represented by $\vec{\tau}$, while the angular part alone is given by $\vec{\Theta}$. The decay amplitudes are known functions, which have to be put into the analysis model beforehand. They consist of a mass-dependent part $\Delta_\xi(m_{\pi^+\pi^-}; m_{3\pi})$ which depends on the mass of the $\pi^+\pi^-$ subsystem, and an angular part $K(\vec{\Theta})$:

$$\Psi_{\text{wave}}(\vec{\tau}; m_{3\pi}) = \Delta_\xi(m_{\pi^+\pi^-}; m_{3\pi}) K(\vec{\Theta}) + (\text{Bose symm.}).$$  \hspace{2cm} (2)

The angular-momentum quantum numbers appearing in a partial wave completely determine the function $K(\vec{\Theta})$.

The complex function $\Delta_\xi(m_{\pi^+\pi^-}; m_{3\pi})$ describes the complex amplitude of the corresponding isobar $\xi$ and usually has to be known without any free parameters. In the simplest cases, single Breit-Wigner amplitudes are used. Since no unique parametrizations for these amplitudes are given by theory and different models are available, the choice of a particular parametrization introduces a model bias.

A conventional PWA of this type, which was performed on the data-set collected by the Compass spectrometer, uses a set of 88 waves [1].

2.3 Freed-isobar PWA

In order to circumvent this problem we introduce a novel method, which was inspired by Ref. [2]. This method allows us to extract isobar amplitudes in bins of $m_{\pi^+\pi^-}$ directly from the data. To this end, the fixed parametrizations are replaced by sets of piece-wise constant functions:

$$\Pi_{\text{bin}}(m_{\pi^+\pi^-}) = \begin{cases} 1 & \text{if } m_{\pi^+\pi^-} \text{ lies in the corresponding mass bin,} \\ 0 & \text{otherwise.} \end{cases}$$ \hspace{2cm} (3)

These binned functions replace the fixed isobar amplitudes:

$$\Delta_\xi(m_{\pi^+\pi^-}) \rightarrow \sum_{\text{bins}} \Pi_{\text{bin}}(m_{\pi^+\pi^-}).$$ \hspace{2cm} (4)

The set of bins covers the whole kinematically allowed $m_{\pi^+\pi^-}$ mass range. With this replacement, equation (1) reads:

$$I(m_{\pi^+\pi^-}, \vec{\Theta}; m_{3\pi}, t') = \left| \sum_{\text{waves}} \sum_{\text{bins}} T_{\text{wave}}(m_{\pi^+\pi^-}, m_{3\pi}, t') \left[ \Pi_{\text{bin}}(m_{\pi^+\pi^-}) K_{\text{wave}}(\vec{\Theta}) \right] + (\text{Bose symm.}) \right|^2.$$ \hspace{2cm} (5)

The piece-wise constant isobar amplitudes effectively behave like independent partial waves and their corresponding production amplitudes now also encode information about the $m_{\pi^+\pi^-}$ dependence of the isobar amplitudes. Therefore, the same fit procedure as in the conventional approach can be used. We call this new approach \textit{freed-isobar} PWA.

A freed-isobar wave is named after the following scheme:

$$J_{\xi}^{PC} M^\varepsilon \pi\pi L,$$ \hspace{2cm} (6)

where $J_{\xi}^{PC}$ are the spin and eigenvalues and parity and generalized charge conjugation of the $3\pi$ system, while $M^\varepsilon$ are its spin projection and reflectivity. The term $[\pi\pi]$ denotes a freed-isobar wave with spin and eigenvalues and parity and charge conjugation of $J_{\xi}^{PC}$. Finally, $L$ is the orbital angular momentum between the isobar and the bachelor $\pi$. 
3. First Application

The analysis presented in the following employs 3 freed-isobar waves: \(0^{-+0^+} [\pi\pi]_{0\to\pi S}, 1^{++0^+} [\pi\pi]_{0\to\pi P}\) and \(2^{-+0^+} [\pi\pi]_{0\to\pi D}\). Due to quantum numbers of the \(\pi^+\pi^-\) subsystem, these waves describe seven waves in the conventional scheme. Therefore, the final model consists of 81 fixed and 3 freed-isobar waves.

3.1 0^{-+0^+}[\pi\pi]_{0\to\pi S} Wave

The \(0^{-+0^+}[\pi\pi]_{0\to\pi S}\) wave is able to describe all three isobars that are used in the conventional PWA: the \(f_0(500), f_0(980),\) and \(f_0(1500).\) Fig. 1 shows the two-dimensional intensity distribution \(|T_{\text{wave}}(m_{3\pi}, m_{\pi^+\pi^-})|^2\) for this wave for two bins in \(t'.\)

The most striking feature is a peak corresponding to the decay \(\pi(1800) \to f_0(980)\pi.\) A smaller peak corresponding to \(\pi(1800) \to f_0(1500)\pi^-\) is also visible. Broad structures appear at low \(2\pi\) and 3\(\pi\) masses and low \(t',\) which are probably of mostly non-resonant origin.

Fig. 2 and Fig. 3 show the intensity distributions and Argand diagrams as a function of \(m_{\pi^+\pi^-}\) in narrow \(m_{3\pi}\) bins around the \(\pi(1800)\) resonance. Peaks and phase motions corresponding to the \(f_0(980)\) and the \(f_0(1500)\) are visible. They are modulated by the intensity distribution and phase motion of the decay of \(\pi(1800)\).

\[\begin{align*}
\text{Fig. 1.} & \quad \text{Intensity distribution of the } 0^{-+0^+}[\pi\pi]_{0\to\pi S} \text{ wave as a function of } m_{3\pi} \text{ and } m_{\pi^+\pi^-} \text{ for two regions of } t'.
\end{align*}\]

3.2 1^{++0^+}[\pi\pi]_{0\to\pi P} Wave

The freed \(1^{++0^+}[\pi\pi]_{0\to\pi P}\) wave is able to describe two waves of the conventional PWA, since the \(1^{++0^+} f_0(1500)\pi P\) wave was not included in the conventional analysis. The two-dimensional intensity distribution is shown in Fig. 4 for two \(t'\) bins. It features a dominant broad structure at low \(2\pi\) and 3\(\pi\) masses, which moves with \(t',\) indicating a predominantly non-resonant origin. In addition, a narrow peak at \(m_{3\pi} \approx 1.4 \text{ GeV}/c^2\) and a \(m_{\pi^+\pi^-} \approx 0.98 \text{ GeV}/c^2\) is visible. It corresponds to the recently discovered \(a_1(1420)\) \[3\]. The observation of this peak in the freed-isobar analysis proves that the \(a_1(1420)\) signal is not an artifact of the parametrization of the scalar isobars in the conventional analysis \[3\].

Fig. 5 shows the \(2\pi\) intensity distributions below, on, and above the \(a_1(1420),\) which exhibits a strong correlation with the \(f_0(980)\) peak. A comparison of the \(f_0(980)\) mass region from the freed-isobar fit is in good agreement with the intensity of the \(1^{++0^+} f_0(980)\pi P\) wave from the conventional PWA (See Fig. 6).
Fig. 2. $0^+0^+[\pi\pi]_{0^-}^+\pi S$ intensity distributions for three bins of $m_{3\pi}$, below, on, and above the \(\pi(1800)\) resonance [1].

Fig. 3. Argand diagrams of the $0^+0^+[\pi\pi]_{0^-}^+\pi S$ amplitude for three bins of $m_{3\pi}$ below, on, and above the \(\pi(1800)\) resonance. The $m_{\pi\pi\pi}$ regions corresponding to the $f_0(980)$ and the $f_0(1500)$ are highlighted in blue [1].

4. Conclusions

We have introduced a novel PWA method for the process $\pi^- p \to \pi^- \pi^+ \pi^- p$ using binned amplitudes to describe the $\pi^+\pi^-$ subsystems. This not only removes the model bias introduced by formerly fixed amplitudes used for the appearing isobars in the conventional PWA, but also allows us to study the $2\pi$ subsystems and their dependence on the $3\pi$ source system.

The large data set collected by the COMPASS spectrometer enables us to apply this novel method. In a first analysis, we free the $0^{++}$ isobar prametrizations for three waves with different $J^{PC}$ of the $3\pi$ parent system, namely $0^+, 1^{++}$, and $2^-$. The analysis reproduces most of the expected structures, in particular a peak for the decay $a_1(1420) \to f_0(980)\pi$, which confirms the new signal observed with the conventional analysis not to be an artifact of the $f_0(980)$ parametrization.

In addition to resonances, broad structures are observed, that typically change their shape with $t'$. They probably originate from non-resonant processes or from cross-talk with waves, that still employ fixed isobar amplitudes.

We are currently studying the latter effect by increasing the number of freed isobars. At the moment, we aim for a set of 11 freed waves that would describe 75% of the total intensity. In these fits, we encounter several ambiguities in the fit and are currently working on techniques to resolve
Fig. 4. Intensity distribution of the $1^{+0^+}[^{\pi\pi}]_{0^+} \rightarrow \pi P$ wave as a function of $m_{3\pi}$ and $m_{\pi\pi}$ for two regions of $t'$ [1].

Fig. 5. $1^{+0^+}[^{\pi\pi}]_{0^+} \rightarrow \pi P$ intensity distributions for three bins of $m_{3\pi}$ around the $a_1(1420)$ resonance [1].

References

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Fig. 6. $1^{++}0^{+}f_{0}(980)\pi P$ intensity from the conventional PWA (left) and intensity sum over the $m_{\pi^{+}\pi^{-}}$ bins in the $f_{0}(980)$ region of the $1^{++}0^{+}[\pi\pi]_{0^{+}}\pi P$ wave from the freed-isobar analysis (right) [1].