The impact of final-state interaction on the $\pi\Sigma$ photoproduction in the $\Lambda(1405)$ region

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Abstract. It was recently demonstrated [1] that the meson-baryon rescattering in the final state has a major impact on the magnitude and structure of the $\pi\Sigma$ mass distributions observed in the $\gamma p \rightarrow K^{+}\pi\Sigma$ photoproduction. We discuss briefly several aspects of this work emphasizing the model dependence of the meson-baryon amplitudes, used to represent the final-state interaction, and the role of the adopted photoproduction mechanism.

1 Introduction

The modern theoretical approaches to meson-baryon (MB) interactions are based on effective chiral Lagrangians. When such theory is applied to the coupled channel $\pi\Sigma - \bar{K}N$ system the enigmatic $\Lambda(1405)$ resonance emerges as a two-pole state (on the complex energy plane), generated dynamically as a result of sufficiently strong inter-channel couplings. The theoretical predictions tend to agree on the position of the narrower pole located around 1425 MeV and often interpreted as a $\bar{K}N$ molecular state, while the position of the second pole is not determined so well, lying at significantly lower energies and much further from the real axis. Since the model parameters are typically fixed by fitting $K^{-}p$ reactions and threshold data, it is not so surprising that the theoretical predictions are quite varied at energies below the $\bar{K}N$ threshold. In this respect, the *two-meson photoproduction* reaction $\gamma p \rightarrow K^{+}\pi\Sigma$ enables a scan in the invariant mass of the MB system down to its production threshold and the calculated mass spectra also reveal a strong model dependence [1]. The determined line-shapes of the $\pi\Sigma$ mass distributions cover the energies relevant for the $\Lambda(1405)$ formation and put additional constraints on the parameters of the strangeness $S = -1$ meson-baryon system.

The corresponding experiment was performed by the CLAS collaboration several years ago, taking very precise, high-resolution data [2]. These data have already made a significant impact on the field, see e.g. Refs. [3–6] where various photoproduction models were tested and the model predictions compared with the data. In this contribution we follow the recent work [1] applying the photoproduction model presented in [7]. While doing so we demonstrate the sensitivity of the calculated $\pi\Sigma$ mass spectra to ambiguities inherent in extending the $\pi\Sigma - \bar{K}N$ coupled-channel models to energies below the $\bar{K}N$ threshold.

2 Formalism

The MB coupled channel models mentioned in the previous section provide us with partial wave scattering amplitudes $f^{c',c}_{\ell\pm}(M_{\pi\Sigma})$ that describe the transitions from channel c to channel

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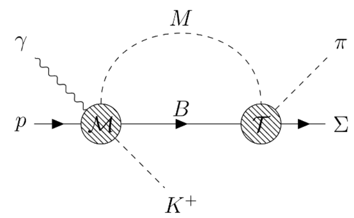

Figure 1. Illustration of the final-state interaction (FSI) of the meson-baryon pair. $\mathcal{M}$ represents the amplitude for the $\gamma p \to K^+MB$ without FSI, and $\mathcal{T}$ is the meson-baryon scattering amplitude, which can be decomposed into partial waves $f_{\ell\pm}$.

c' $(c, c' = \pi\Lambda,\ \pi\Sigma,\ \bar{K}N,\ \eta\Lambda,\ \eta\Sigma,\ K\Xi)$ at a given two-body c.m. energy (invariant MB mass) $M_{\pi\Sigma}$ and for total angular momentum $\ell \pm \frac{1}{2}$ and orbital angular momentum $\ell = 0, 1, 2, \ldots$. These amplitudes are designed to be consistent with ChPT up to a fixed order of the low-energy expansion and fulfill the requirement of coupled-channel unitarity above the lowest reaction threshold. Considering the photoproduction reaction $\gamma p \to K^+MB$ as illustrated in Fig. 1, the s-wave scattering amplitudes f_{0+} can be implemented to describe the final-state interaction of the produced MB pair. It was shown in Refs. [1, 7] that one can obtain four independent photoproduction amplitudes $\mathcal{A}_{0+}^{i(\mathrm{tree})}(s, M_{\pi\Sigma})$[1] that combine the structure functions contributing to the tree-level photoproduction amplitude $\mathcal{M}$ which is projected on the $\ell = 0$ state of the $\pi\Sigma$ pair. Since the outgoing K^+ can be treated effectively as a spectator particle in the unitarization procedure, the FSI is then restricted to the $S = -1$ meson-baryon subspace, the sector relevant for the formation of the $\Lambda(1405)$.

The unitarized photoproduction amplitudes for $\gamma p \to K^+MB$ are taken as the coupled-channel vector

$$[\mathcal{A}_{0+}^{i}(s, M_{\pi\Sigma})] = [\mathcal{A}_{0+}^{i(\mathrm{tree})}(s, M_{\pi\Sigma})] + [f_{0+}(M_{\pi\Sigma})]\,[8\pi M_{\pi\Sigma} G(M_{\pi\Sigma})]\,[\mathcal{A}_{0+}^{i(\mathrm{tree})}(s, M_{\pi\Sigma})]\,, \qquad (1)$$

where $G(M_{\pi\Sigma})$ is a diagonal matrix with entries given by suitably regularized MB loop integrals and the square brackets mark the vector or matrix character of the involved quantities in the MB channel-space. The $MB = \pi\Sigma$ entries of the vector $\mathcal{A}_{0+}^{i}$ can then be used to obtain the required s-wave cross sections. We note that the tree-level amplitudes $\mathcal{A}_{0+}^{i(\mathrm{tree})}$ are constructed from 16 $\mathcal{M}$-structures representing the Weinberg-Tomozawa, Born, and anomalous graphs adhering strictly to constraints arising from unitarity, gauge invariance and chiral perturbation theory, see Refs. [1, 7] for details. The whole formalism does not contain any free parameters and refrains from including additional graphs based e.g. on vector meson exchanges or on triangular singularities that were considered by other authors [5, 6].

We find it illustrative to compare our formalism with the early phenomenological approaches adopted in [3, 4]. There, the FSI was implemented in the photoproduction amplitudes as

$$[\mathcal{A}_{0+}(s, M_{\pi\Sigma})] = [f_{0+}(M_{\pi\Sigma})]\,[8\pi M_{\pi\Sigma} G(M_{\pi\Sigma})]\,[C(s)]\,, \qquad (2)$$

where the channel-space vector $C(s)$ was introduced to simulate the reaction mechanism. A direct comparison of the two equations shows that the phenomenological approach based on Eq. (2) corresponds to setting the tree graphs in the first term on the r.h.s. of Eq. (1) to zero and at the same time replaces them by energy-dependent constants in the second term. It is obvious that such an ad-hoc treatment cannot reflect fully the complexity of the photoproduction process and the resulting MB amplitudes may not be quite reliable. However, by fitting

[1] In fact, the $\mathcal{A}$ amplitudes depend also on t_K which we do not show explicitly to keep the notation concise.

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the constants $C^c(s)$ (at each energy $W = \sqrt{s}$ separately) the authors of [3, 4] were able to describe quite well the CLAS data [2] on the $\pi\Sigma$ mass spectra.

3 Results and discussion

The formalism described in the previous section and based on Eq. (1) was used in [1] to calculate the $\pi\Sigma$ mass distributions observed in the CLAS experiment [2]. In Fig. 2 we show the results obtained in [1] at two sample energies, $W = 2.0$ (left figures) and 2.4 GeV (right figures) considering four different $\pi\Sigma - \bar{K}N$ models that provide the final state rescattering amplitudes f_{0+}. The models include the recent version of the Prague amplitudes [8], tagged as P model, and three versions of the Bonn model amplitudes: B2, B4 [4], and BW [9]. First of all, we note that the P model seems to work reasonably well for the $\pi^0\Sigma^0$ and $\pi^+\Sigma^-$ cross sections at the c.m. energy $W = 2.0$ GeV. Unfortunately, one cannot say the same about the $\pi^-\Sigma^+$ mass spectrum at the same energy, but we should bear in mind that all theoretical predictions shown in Fig. 2 were made without any adjustment of the MB rescattering amplitudes, and without introducing any free parameter in the formalism. The varied predictions provided by the selected models reflect the ambiguities when extending their application below the $\bar{K}N$ threshold, to a completely different sector of experimental data and to energies much lower

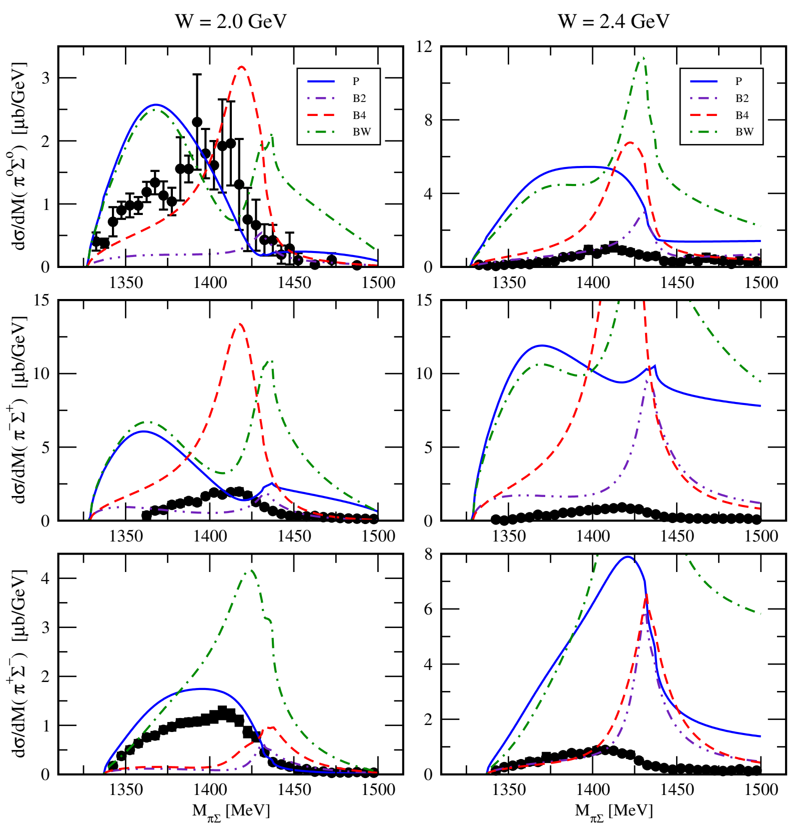

Figure 2. Comparison of $\pi\Sigma$ mass distributions calculated at two c.m. energies, $W = 2.0$ and 2.4 GeV, while employing MB amplitudes generated by four different coupled-channel models. The experimental data are taken from [2].

than those of the K^-p reaction data the f_{0+} model parameters were fitted to. The Fig. 2 also shows that the Bonn model amplitudes do not reproduce the CLAS data when employed in the current formalism based on Eq. (1), despite providing adequate description of the same data when the phenomenological $C(s)$ factors defining the formalism based on Eq. (2) were adjusted to fit the photoproduction data in Refs. [4, 9]. Apparently, the calculated $\pi\Sigma$ mass distributions depend strongly on both, the adopted photoproduction scheme as well as on the MB model used to describe the FSI, so both aspects are intertwined and should be considered in the same framework.

Taking aside the partial success of the P model at $W = 2.0$ GeV, all other calculated spectra provide much higher cross sections than those observed experimentally. It was demonstrated in [1] that this problem can be addressed by tuning down the mass-scales used to regularize the MB loop functions that connect the tree-level amplitudes $\mathcal{M}$ with the FSI amplitudes $\mathcal{T}$ in Fig. 1. In addition, since the formalism adopted to calculate the tree-level amplitudes $\mathcal{A}_{0+}^{i(\mathrm{tree})}(s, M_{\pi\Sigma})$ is based on LO ChPT, we anticipate that at $W = 2.4$ GeV the kaon momentum is probably too large for the LO ChPT photo-kernel making the theoretical predictions less reliable. It is also understood that the energy dependence can be augmented and a better agreement with experimental data reached by including contributions which go beyond the standard ChPT approach, see Refs. [5, 6] for examples of such model extensions.

4 Summary

We have reviewed the recent implementation [1] of the MB FSI into the two-meson photoproduction amplitude for the $\gamma p \to K^+\pi\Sigma$ reaction. Although all employed $\pi\Sigma - \bar{K}N$ coupled channel models provide practically equivalent description of the experimental data for K^-p reactions, the results differ significantly when the models are used to calculate the $\pi\Sigma$ mass spectra in the photoproduction process. This reflects the ambiguities in the MB scattering amplitudes when extended below the $\bar{K}N$ threshold [10], and also demonstrates the crucial role played by the FSI in the reaction. Although the calculated $\pi\Sigma$ mass distributions (in general) fail to reproduce the data reported by the CLAS experiment [2] it is understood that a better agreement can be reached when including the photoproduction data in future fits that would narrow the parameter space of the MB models.

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