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Strange baryonic resonances and kaonic bound states

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Recent results of the HADES collaboration on the low-mass $\Lambda(1405)$ observed in proton-proton collisions at 3.5 GeV in the charged decay mode are discussed together with the status of the searches for the kaonic bound state ppK^- in the reaction $pp \to pK^+\Lambda$.

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1. Introduction

The low-energy antikaon-nucleon interaction is strongly affected by the presence of the strange baryonic resonances $\Sigma(1385)$ and $\Lambda(1405)$. The latter is of particular importance, since it is located just below the $\bar{K}N$ threshold. In modern theoretical analyses, the $\Lambda(1405)$ emerges as a dynamically generated state that couples to two poles [1, 2]. The first narrow pole is mainly associated with the $\bar{K}N$ bound state and located at energies of around 1420 MeV, whereas the second broad pole appears as a $\Sigma\pi$ resonance situated at lower energies (1390 MeV). A renewed interest in the $\Lambda(1405)$ rose due to a hypothesis that it might act as a doorway for the formation of a 3-particle cluster that is formed by two nucleons bound by an antikaon — a so-called ppK^- state [3, 4, 5].

In this context, the HADES collaboration addressed the low-energy $\bar{K}$N interaction in the following analyses of data collected in proton-proton collisions at beam energy of 3.5 GeV: 1) analysis of the $\Sigma(1385)^+$ as a benchmark measurement [6], 2) extraction of the $\Sigma(1385)^0$ contribution as an important background channel for the $\Lambda(1405)$ analysis [7], 3) reconstruction of the $\Lambda(1405)$ line shape in the charged decay mode $\Lambda(1405) \to \Sigma^{\pm}\pi^{\mp}$ [8, 9], 4) search for the antikaonic-bound state ppK^- with the help of a Partial Wave Analysis. In this contribution we concentrate on the two last items.

2. The HADES detector

Data for the analysis were collected with the **H**igh-**A**cceptance **D**i-**E**lectron **S**pectrometer (HADES). This is a versatile charged-particle detector currently operating at the SIS18 synchrotron (GSI Helmholtzzentrum, Darmstadt) in the region of beam kinetic energies of 1–2 GeV/nucleon for nucleus-nucleus collisions, up to 3.5 GeV in proton-induced reactions. The detector covers polar angles from 18° to 85° degrees and a large portion of the azimuthal angle; the momentum resolution of the spectrometer is $\Delta p/p \approx 3\%$. A detailed description of the detector ensemble can be found in [13]. In 2007 a measurement of proton-proton collisions at a kinetic beam energy of 3.5 GeV was performed: a beam with an average intensity $\sim 1\times10^7$ particles/s was incident on a liquid hydrogen target with a density of 0.35 $\mathrm{g/cm^2}$ and a total interaction probability of $\sim 0.7\%$. In total, 1.2×10^9 events were collected. The first-level trigger required at least three hits in the Time-of-Flight wall.

3. Reconstruction of the $\Lambda(1405)$ line shape

The reaction $p+p \to p+\Lambda(1405)+K^+$ was analysed [8, 9] and the resulting missing mass spectrum $MM(p,K^+)$, showing a signal of the $\Lambda(1405)$, is presented on Fig. 1. The most interesting finding is the location of the $\Lambda(1405)$ mass peak — at low mass of around 1385 MeV/c^2. This is the first reconstruction of the $\Lambda(1405)$ in proton-proton collisions in the charged decay mode and these data impose new constraints for models describing the production of $\Lambda(1405)$ in proton-proton collisions.

A possible interpretation of the observed low-mass $\Lambda(1405)$ peak has been proposed in [10] as an effect of the interference of the $\Lambda(1405)$ with the non-resonant $\Sigma^{\pm}\pi^{\mp}$ background. Here, the $\Lambda(1405)$ was modelled as a coherent sum of two Breit-Wigner functions, corresponding to

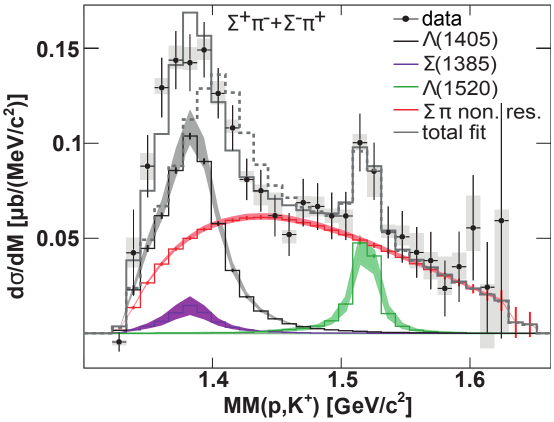

Figure 1: Sum of missing mass $MM(p,K^+)$ distributions reconstructed with the $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ pairs [9]. The gray band shows the contribution of the $\Lambda(1405)$.

the two poles, positions of which were constrained by the recent calculations done in [11]. The non-resonant $\Sigma^\pm\pi^\mp$ background was modelled as a 4th order polynomial. These two contributions ($\Lambda(1405)$ + background) were added up coherently with a complex mass-independent relative phase (a "maximum interference" scenario), which was set free as a fit parameter. Additional contributions of the $\Sigma(1385)^0$ and $\Lambda(1520)$ were added up incoherently. The result of the successful fit is shown in Fig. 2. Although a number of strong assumptions has been made in this simplified consideration, it shows that the observed low mass of the $\Lambda(1405)$ peak *might* be caused by an interference of the initial $\Lambda(1405)$ amplitude that exhibits a maximum at 1400 MeV$/c^2$ with the non-resonant background. Other scenarios are also considered in [10], including the possibility that the spectral shape of the $\Lambda(1405)$ in p+p reactions gets more influenced by the presence of the broad $\Sigma\pi$ peak.

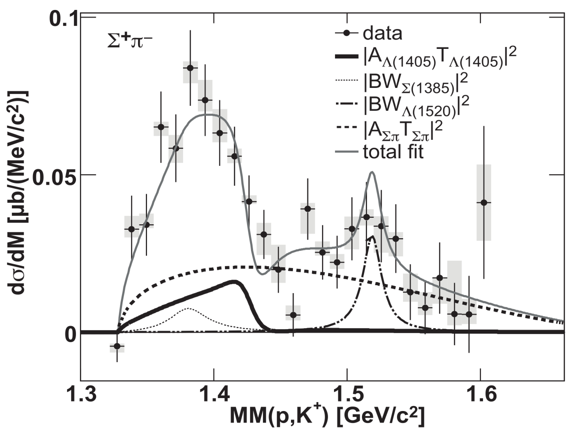

Figure 2: Missing mass spectrum to proton and K^+. The black data points are the measurements of [9], for the $\Lambda(1405)$ in the $\Sigma^+\pi^-$ decay channel. The thin solid curve corresponds to the result of the fit within the scenario of a maximum interference of the $\Lambda(1405)$ amplitude (thick solid curve) and the non-resonant $\Sigma^\pm\pi^\mp$ background (dashed curve).

4. Search for the ppK^- state

In case the antikaon-nucleon attraction is strong enough, a system of two nucleons bound by an antikaon, a so-called ppK^- state might exist, as has been proposed in [3, 4, 5]. Most contemporary theoretical works (cf. [12] and references therein) predict that such a system is indeed bound. The ranges of predicted binding energies and widths are, however, very broad: $B \in [16, 80]$ MeV/c^2 and $\Gamma \in [35, 110]$ MeV/c^2.

The expected decay channel $ppK^- \to p + \Lambda$ motivates the search for this state in the reaction $p + p \to p + K^+ + \Lambda$. A dedicated analysis allowed to reconstruct $\sim 20 \times 10^3$ exclusive $pK^+\Lambda$ reactions with — owing to a good momentum resolution of the detector — a high purity.

In order to search for the ppK^- signal as a peak in the invariant mass distribution of the proton-Λ pairs a good understanding of the background sources is mandatory. A complication due to the role of N^* resonances ($N^*(1650)$, $N^*(1720)$, ...) arises here. Indeed, the decay mode $N^* \to \Lambda K$, is a major source of open strangeness production in the considered energy range. Contributing N^* resonances will not only appear as broad structures in the invariant mass spectrum of decay products (i. e. Λ-K pairs), but also, as kinematic reflections, in the proton-Λ invariant mass spectrum, hampering the extraction of the ppK^- signal, or, potentially, producing a fake signal. Therefore, a firm control over the background shaped by decays of N^* resonances is a key issue in this search.

In order to take into account the contribution of the N^* resonances (including interference effects) a Partial Wave analysis (PWA) of the reaction $p + p \to p + K^+ + \Lambda$ has been performed using the Bonn-Gatchina PWA framework [14]. A set of resonances plus non-resonant waves was included in the solution. In fact, it was found that no unique solution can be obtained. Instead, a set of best solutions that differ in their resonance content has been chosen. First, a null-hypothesis has been considered and no contribution from the ppK^- state has been taken into account, but only conventional sources.

The resulting description of the p-Λ invariant mass spectrum is shown in Fig. 3. The experimental data are compared to the four best solutions (represented by the gray band) extracted from the PWA. Apparently, a good description of the data within the null-hypothesis is achieved, leaving little room for the ppK^- signal. A corresponding upper limit for the kaonic cluster formation is currently under evaluation.

5. Summary

The HADES collaboration reconstructed for the first time the contribution of the $\Lambda(1405)$ in the spectrum of $\Sigma^\pm\pi^\mp$ pairs produced in proton-proton collisions. The observed $\Lambda(1405)$ mass peak is located around 1385 MeV/c^2. The interference with the non-resonant background might play an important role in the generation of the observed line shape and must be considered by theoretical calculations.

The study of the sub-threshold $\bar{K}N$ interaction is continued with a Partial Wave analysis of the reaction $p + p \to p + K^+ + \Lambda$ with the aim to find a footprint of the kaonic bound state formation. No clear structure associated with the ppK^- has been observed and an upper limit for the ppK^- production will be reported in a dedicated publication.

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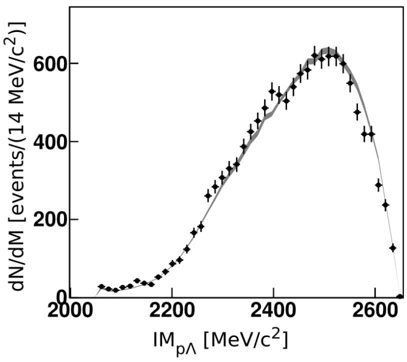

Figure 3: Invariant mass distribution of proton-Λ pairs in the reaction $p+p \to p+K^{+}+\Lambda$. Symbols show experimental data. The gray band corresponds to a set of four PWA solutions obtained *without* inclusion of the hypothetical ppK^{-} state.

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