UNPRECEDENTED STUDIES OF THE LOW-ENERGY NEGATIVELY CHARGED KAONS INTERACTIONS IN NUCLEAR MATTER BY AMADEUS*

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The AMADEUS experiment deals with the investigation of the low-energy kaon-nuclei hadronic interaction at the DAΦNE collider at LNF-INFN, which is fundamental to solve longstanding open questions in the non-perturbative strangeness QCD sector. AMADEUS step 0 consisted in the analysis of 2004–2005 KLOE data, exploring the K^- absorptions

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in H, ^{4}He, ^{9}Be and ^{12}C in-flight and at-rest. With AMADEUS step 1, a dedicated pure carbon target was implemented in the central region of the KLOE detector, providing a high statistic sample of pure at-rest K^- nuclear interaction. For the future, a dedicated setup to perform detailed studies is under preparation. Our present analysis deals with the major open questions in hadron nuclear physics in the strangeness sector, namely how hadron masses and interactions change in nuclear environment, with a search ranging from kaonic nuclear clusters to strange baryon resonances and in-medium modification of the resonance parameters.

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1. The AMADEUS scientific case

The AMADEUS experiment [1, 2] is dealing with the study of the low-energy interactions of the negatively charged kaons with light nuclei. Such type of physics, extremely important for the understanding of the non-perturbative QCD in the strangeness sector, has important consequences, going from hadron and nuclear physics to astrophysics. In this context, our investigation proceeds along two lines of research, both intimately connected with the antikaon–nucleon potential: the strength of the K^- binding in nuclei and the in-medium modification of the Σ^* and Λ^* resonances properties.

On the one hand, the analysis of the Λp pairs correlations, produced in the absorption of K^- inside the volume of the KLOE [22] Drift Chamber (DC), is crucial for a clear characterization of the single *versus* multi-nucleon absorption processes and for the search of strongly bound kaon–nucleon(s) clusters. The possible existence of Deeply Bound Kaonic Nuclear States (DBKNS) was first predicted by Wycech [3]. In recent years, an intense debate is going on following the publication by Akaishi and Yamazaki [4], predicting that such states could be formed by K^- interactions in light nuclei, as a consequence of a strongly attractive K^-p interaction. As a result, DBKNS could have large binding energies and narrow widths. Various theoretical approaches describe the antikaon–nucleon potential using different treatments, thus leading to predictions for the strength of the K^- binding in nuclei. In the case of the K^-pp dibaryonic state, several predictions for the binding energy and widths are available, waiting to be confirmed or denied [4–7].

From the experimental point of view, two main approaches have been used in order to study the signal from a K^-pp cluster: pp and heavy ion collisions [8, 9], and in-flight or stopped K^- interactions in light nuclei. Among the second type of processes, results have been published by FINUDA [10] and KEK [11]. The interpretation of these results is far from being conclusive, and it requires an accurate description of the single and multi-nucleon absoption processes that a K^- would undergo when interacting with light nuclei. These processes are poorly known from the experimental point of view, with available data coming only from old bubble chamber experiments [12].

On the other hand, the unique quality of the 2004–2005 KLOE data, and of the AMADEUS step 1 data, offers the opportunity to explore Σ^* and Λ^* resonances properties and their behaviour in nuclear environment. Moreover, the non-resonant *versus* resonant formation transition amplitudes could be measured, for the first time, for different isospin states, for a broad range of light nuclei. Of particular interest is the case of the $\Lambda(1405)$ state, which we are investigating through its decay into $\Sigma^0\pi^0$ and $\Sigma^+\pi^-$. The $\Lambda(1405)$ is generally accepted to be a spin-1/2, isospin $I = 0$ and strangeness $S = -1$ negative parity baryon resonance ($J^{\rm P} = 1/2^-$) assigned to the lowest $L = 1$ supermultiplet of the three-quark system, together with its spin-orbit partner, the ($J^{\rm P} = 3/2^-$) $\Lambda(1520)$. Such state only decays into $(\Sigma\pi)^0$ ($I = 0$) through the strong interaction. Despite the fact that the $\Lambda(1405)$ has been observed in few experiments and is currently listed as a four-stars resonance in the table of the Particle Data Group (PDG) [13], its nature still remains an open issue. The three quark picture (uds) meets some difficulties to explain both the observed $\Lambda(1405)$ mass and the mass splitting with the $\Lambda(1520)$. The low mass of the $\Lambda(1405)$ can be explained in a five quark picture, which, however, predicts more unobserved excited baryons. In the meson–baryon picture, the $\Lambda(1405)$ is viewed as a $\overline{K}N$ quasi-bound $I = 0$ state, embedded in the $\Sigma\pi$ continuum, emerging in coupled-channel meson–baryon scattering models [14]. A complete review of the broad theoretical and experimental literature is not possible here (see, however, [15]). The $\Lambda(1405)$ production in $\overline{K}N$ reactions is of particular interest due to the prediction, in chiral unitary models [16–18], of two poles emerging in the scattering amplitude (with $S = -1$ and $I = 0$) in the neighborhood of the $\Lambda(1405)$ mass. One pole is located at higher energy with a narrow width, and is mainly coupled to the $\overline{K}N$ channel, while a second lower mass and broader pole is dominantly coupled to the $\Sigma\pi$ channel [19]. Both contribute to the final experimental invariant mass distribution [18, 20]. Since the resonance is always seen in the invariant mass spectrum of the $\Sigma\pi$ strong decay, the only chance to observe a higher mass component is to exploit the $\overline{K}N$ production mechanism. Moreover, the $\Sigma^0\pi^0$ channel, which is free from the $I = 1$ contribution and from the isospin interference term, turns to be the cleanest. Both objectives can be accomplished in the framework of AMADEUS.

2. The DAΦNE collider and the KLOE detector

DAΦNE [21] (Double Anular Φ-factory for Nice Experiments) is a double ring e^+e^- collider, designed to work at the center-of-mass energy of the ϕ particle $m_\phi = (1019.456 \pm 0.020)$ MeV$/c^2$. The ϕ meson decay produces charged kaons (with BR$(K^+K^-) = 48.9 \pm 0.5\%$) with low momentum ($\sim 127$ MeV$/c$) which is ideal either to stop them, or to explore the products of the low-energy nuclear absorptions of K^-s. The back-to-back topology, characterizing the kaons pair production, is extremely useful for the extrapolation of non-identified kaon tracks.

The KLOE detector [22] is centered around the interaction region of DAΦNE. KLOE is characterized by a $\sim 4\pi$ geometry and an acceptance of $\sim 98\%$; it consists of a large cylindrical Drift Chamber (DC) and a fine sampling lead-scintillating fibers calorimeter, all immersed in an axial magnetic field of 0.52 T, provided by a superconducting solenoid. The DC [23] has an inner radius of 0.25 m, an outer radius of 2 m and a length of 3.3 m. The DC entrance wall composition is 750 μm of carbon fibre and 150 μm of aluminium foil.

Dedicated Geant MC simulations of the KLOE apparatus were performed to estimate the percentages of K^- absorptions in the materials of the DC entrance wall (the K^- absorption physics were treated by the Geisha package). Out of the total fraction of captured kaons, about 81% results to be absorbed in the carbon fibre component and the residual 19% in the aluminium foil. The KLOE DC is filled with a mixture of helium and isobutane (90% in volume ^{4}He and 10% in volume C_4H_{10}).

The chamber is characterized by excellent position and momentum resolutions. Tracks are reconstructed with a resolution in the transverse R–ϕ plane of $\sigma_{R\phi} \sim 200\,\mu$m and a resolution along the z-axis of $\sigma_z \sim 2$ mm. The transverse momentum resolution for low-momentum tracks ($(50 < p < 300)$ MeV$/c$) is $\frac{\sigma_{p_\mathrm{T}}}{p_\mathrm{T}} \sim 0.4\%$. The KLOE calorimeter [24] is composed of a cylindrical barrel and two endcaps, providing a solid angle coverage of 98%. The volume ratio (lead/fibres/glue = 42:48:10) is optimized for a high light yield and a high efficiency for photons in the range of 20–300 MeV$/c$. The position of the cluster along the fibres can be obtained with a resolution $\sigma_\parallel \sim 1.4\,\mathrm{cm}/\sqrt{E[\mathrm{GeV}]}$. The resolution in the orthogonal direction is $\sigma_\perp \sim 1.3$ cm. The energy and time resolutions for photon clusters are given by $\frac{\sigma_E}{E_\gamma} = \frac{0.057}{\sqrt{E_\gamma[\mathrm{GeV}]}}$ and $\sigma_\mathrm{t} = \frac{57\,\mathrm{ps}}{\sqrt{E_\gamma[\mathrm{GeV}]}} \oplus 100$ ps.

As a step 0 of the presented work, we analysed the 2004–2005 KLOE collected data, for which the dE/dx information of the reconstructed tracks is available (dE/dx represents the truncated mean of the ADC collected counts due to the ionization in the DC gas). An important contribution of in-flight K^- nuclear captures, in different nuclear targets from the KLOE materials, was evidenced and characterized, enabling, for the first time, to perform invariant mass spectroscopy of in-flight K^- nuclear captures [25]. In order to increase the statistics and as an essential interpretation tool, AMADEUS step 1 consisted in the realization of a dedicated pure carbon target, implemented in the central region of the KLOE detector, providing a high statistics sample of pure at-rest K^- nuclear interaction, as described in the next section.

3. Data samples

Two different data samples are presently under study. A first sample was collected by KLOE in the period 2004–2005 (2.2 fb^{-1} total statistics, out of which 1.5 fb^{-1} were analysed). In this case the DAΦNE beam pipe, and the materials of the KLOE detector are used as active targets. The topology of these data is shown in figure 1, representing the radial position (ρ_Λ) of the $\Lambda(1116)$ decay vertex (see Section 4.1). Four components are distinguishable, from inside to outside we recognize K^- absorptions in the DAΦNE beryllium sphere ($\sim$ 5 cm), the DAΦNE aluminated beryllium pipe ($\sim$ 10 cm), the KLOE DC entrance wall (aluminated carbon fibre $\sim$ 25 cm) and the long tail originating from K^- interactions in the gas filling the KLOE DC (25–200 cm). Extremely rich experimental information is contained in this sample, with K^- hadronic interactions, both at-rest and in-flight, in a variety of light nuclear targets (H, ^{4}He, ^{9}Be and ^{12}C), which, of course, turned into a challenging analysis and interpretation effort.

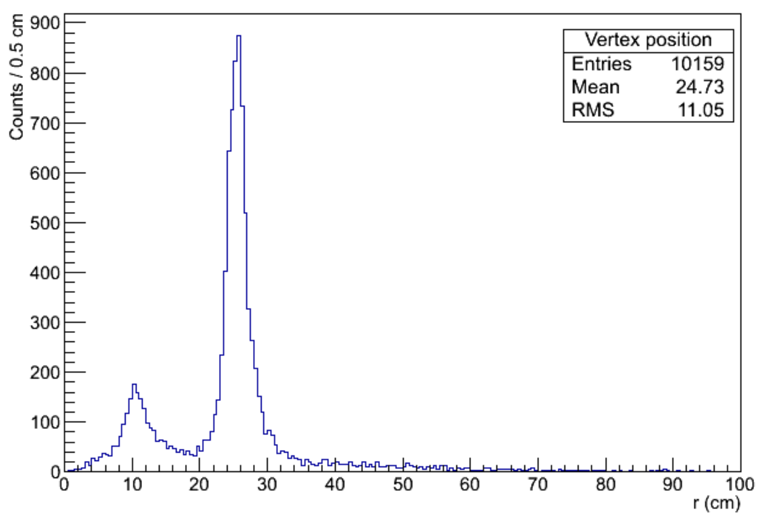

Fig. 1. Radial position distribution ρ_Λ, of the Λ decay vertex, for 2004–2005 KLOE collected data.

Motivated by the obtained results, a high purity carbon target (graphite) was realized in summer 2012 and installed inside the KLOE DC, between the beam pipe and the DC entrance wall. The target was realized with the aim to confirm the in-flight component hypothesis in the 2004–2005 data, and to collect a higher statistics for the study of the low-energy $K^{-}\,{}^{12}\mathrm{C}$ hadronic interaction.

The geometry of the target was optimized by means of a Geant3 MC simulation. The final configuration was a three-sector half-cylinder ($\rho = 0.95$ g/cm^3) supported by an aluminium frame, with a length of 600 mm and a mean radius of 24.7 mm. The thickness varied from 4 to 6 mm, in order to optimize the percentage of stopped kaons, taking into account the ϕ boost, derived by the limited crossing angle of the e^+e^- beams. The half-cylindrical configuration was chosen in order to take advantage of the K^+ tagging in the opposite direction. The final project of the realized target is shown in figure 2. We took data from 6 November to 14 December 2012, for a total integrated luminosity of $\sim$90 pb^{-1}. Up to now, we analysed a sample of 37 pb^{-1} reconstructed data. The topology of the reconstructed Λ decay vertices radial position is shown in figure 3, as expected, the majority of kaons are stopped in the target.

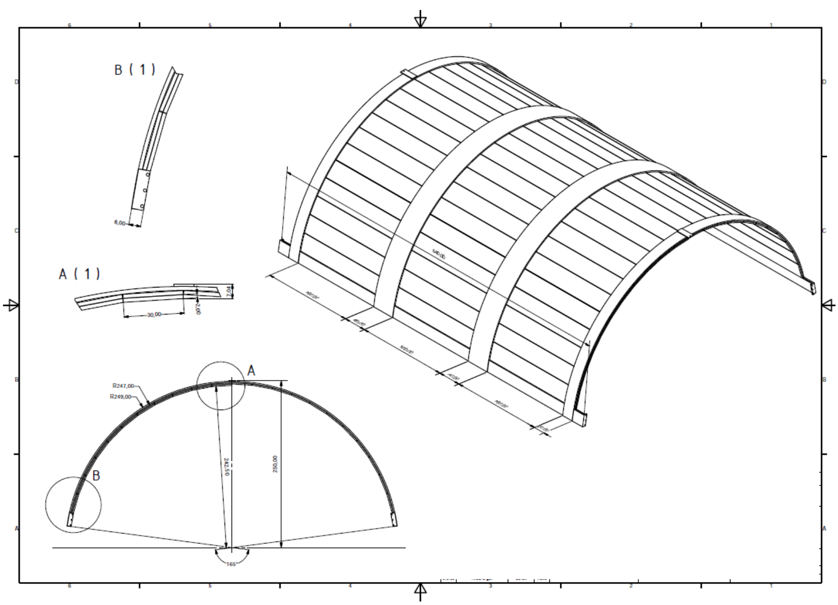

Fig. 2. Project of the graphite target inserted between the beam pipe and the KLOE DC entrance wall.

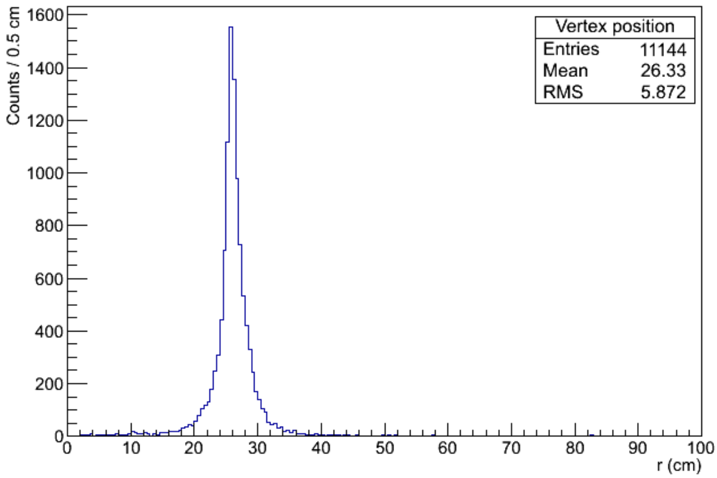

Fig. 3. Radial position distribution of ρ_Λ for carbon target events.

4. Preliminary results of the data analyses

As stated in Section 1, our purpose is a complete investigation of the low energy interactions of negatively charged kaons with light nuclei.

In order to do this, a first aim is the search for hyperon–pion and Λ–proton correlated pairs productions following the K^- absorptions in H, ^{4}He, ^{9}Be and ^{12}C. In particular, we are searching for $\Lambda\pi^-$ (isospin $I = 1$) production, both from direct formation process and from internal conversion of a primary produced Σ hyperon ($\Sigma N \to \Lambda N'$). Given the excellent resolution for the $\Lambda\pi^-$ invariant mass, we are aiming at distinguishing resonant (Σ^{*-}) from non-resonant formation, extracting, for the first time, the ratio between the transition amplitudes module for the two processes.

The search for the $\Lambda(1405)$ is performed through its decay in $\Sigma^0\pi^0$ (which is purely isospin 0) and $\Sigma^+\pi^-$ (the analysis of the $\Sigma^-\pi^+$ decay channel started recently with a characterization of neutron clusters in the KLOE calorimeter). The line shapes of the three combinations $(\Sigma\pi)^0$ were recently obtained, for the first time, in a single experiment by [26] and were found to be different. Of extreme interest will be a precise measurement of the $\frac{\Sigma^+\pi^-}{\Sigma^-\pi^+}$ production ratio in different targets, with strong consequences on the nature of the Λ^* state [27, 28].

To conclude, the search for correlated Λ-proton pairs production is intimately related with many, still poorly explored or not well understood physical processes, from multi-nucleon K^- absorption to the possible formation of strongly bound, kaonic nuclear clusters.

In what follows, we present details of the data analysis and of its quality.

4.1. The $\Lambda(1116)$ selection

The presence of a hyperon always represents the signature of K^- hadronic interaction inside the KLOE materials. For the analysis of Λ−proton and $\Sigma^0\pi^0$ channels first step consists in the identification of a $\Lambda(1116)$, through the reconstruction of the $\Lambda \to p + \pi^-$(BR $= 63.9 \pm 0.5\%$) decay vertex.

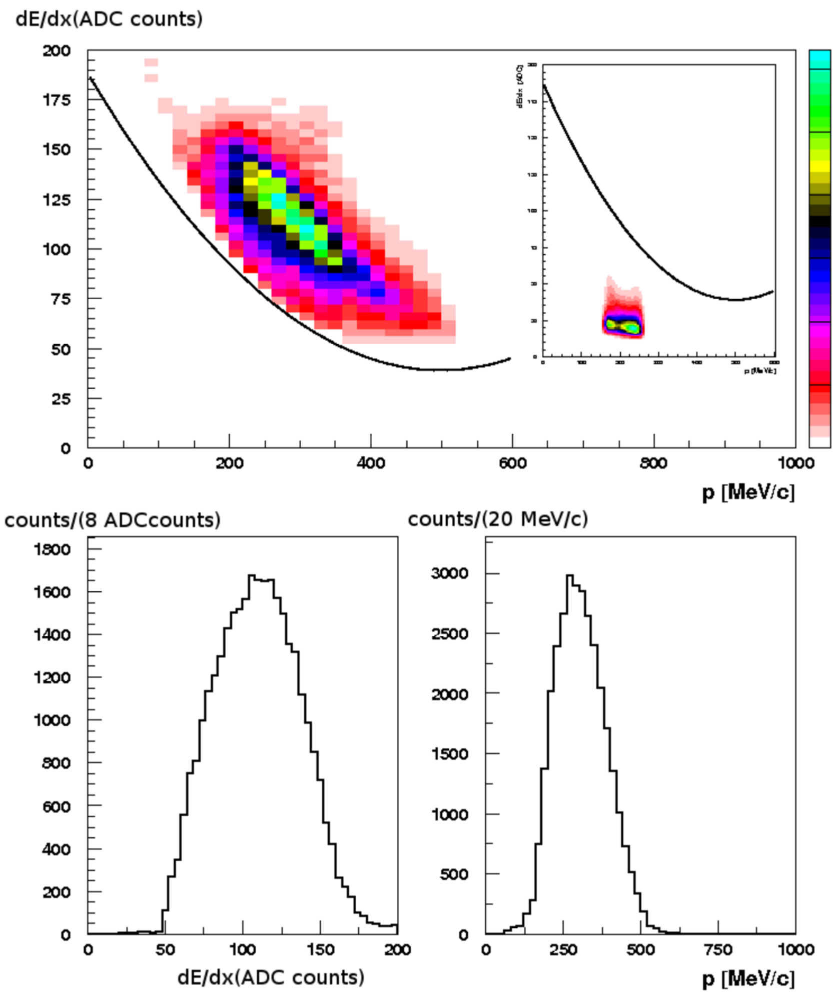

Fig. 4. Top: dE/dx *vs.* momentum of the protons for the final selection (protons with + protons without associated cluster) (in the top-right part, pions from two-body decays are shown for comparison). Bottom: the corresponding projections, left: dE/dx, right: momentum.

In order to reduce the copious background from the three-body $K^{\pm}$ decays ($K^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}$) we had to refine the search criteria for the proton. To this aim, a cut on dE/dx was optimized by characterizing proton tracks with an associated cluster in the calorimeter. The signature of a proton in the calorimeter is clean, since the corresponding signal is well-separated by the signal generated by the pions. We were tuning the cut on these protons and then applied it to all protons, *i.e.* including those which have the last DC measurement near the calorimeter (reaching it) but have no associated cluster. This last requirement enables to include in the selection low-momentum protons (lower than $p \sim 250$ MeV/c) not producing an observable signal in the calorimeter. The cut is shown in Fig. 4, in which the momentum and dE/dx of the finally selected protons are shown. The function in the bidi-

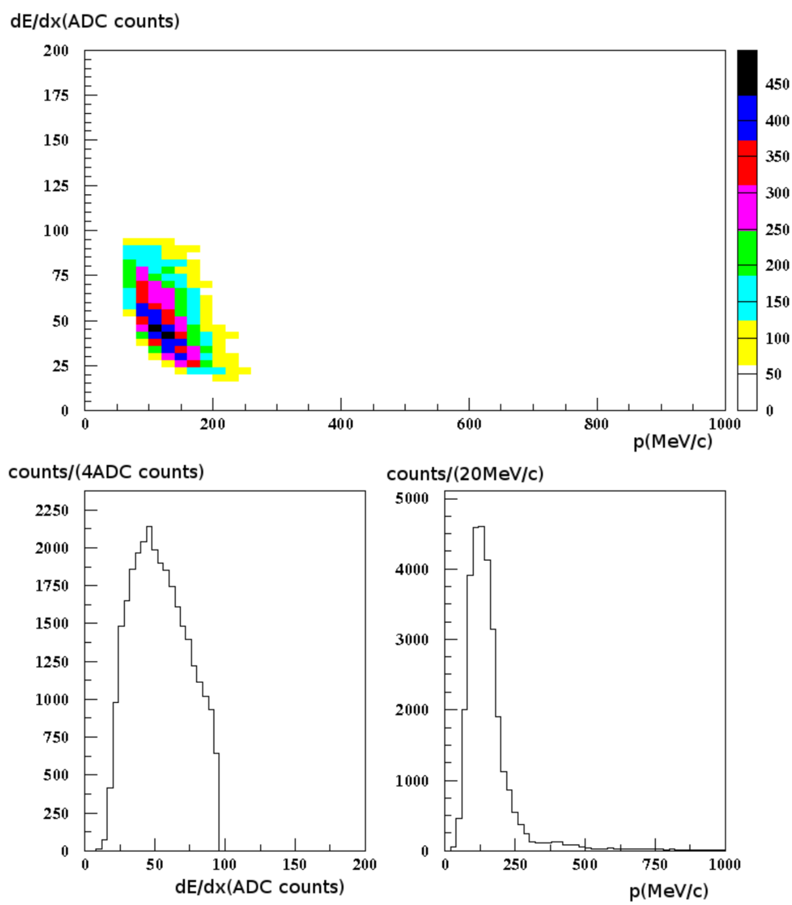

Fig. 5. Top: dE/dx *vs.* momentum of the pions for the final selection. Bottom: corresponding projections (left: dE/dx, right: momentum).

mensional plot shows the selection criterion. This cut was optimized in order to reject positive pions contamination, not loosing protons. Inserted in the top-right part of the upper picture we see the typical signature of pions in dE/dx and momentum. In this case, we plotted π^+s coming from the two-body $K^+ \to \pi^+\pi^0$ decay. This illustrates how the chosen cut is efficient for rejecting π^+ in a broad range of momenta.

In Fig. 5 the characteristics of the negative particle (pions) of the vertices included in the final selection are shown.

As a final step for the identification of Λ decays, the vertices are cross checked with quality cuts, using the minimum distance between the tracks and the chi-square of the vertex fit.

The invariant mass $m_{p\pi^-}$ is calculated under the p and π^- mass hypothesis and is shown in Fig. 6. A cut is then applied on the invariant mass $(1114 < m_{p\pi^-} < 1117)$ MeV/c^2.

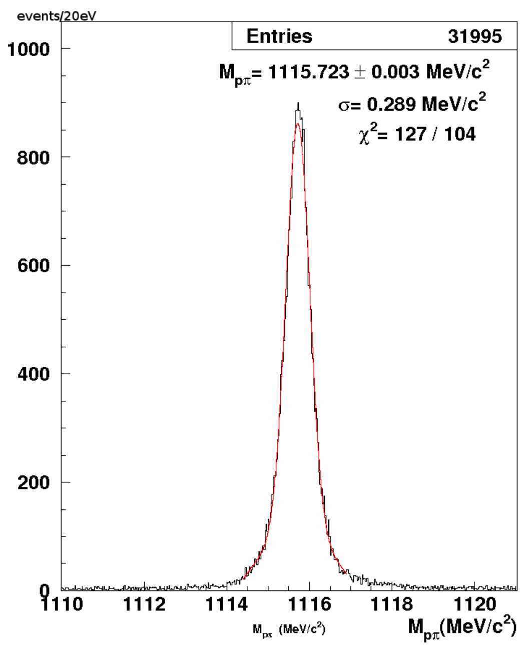

Fig. 6. $m_{p\pi^-}$ invariant mass spectrum for the Λ selection.

Cuts on the radial position (ρ_Λ) of the Λ decay vertex were optimized in order to separate two samples of K^- absorption events occurring in the DC wall and the DC gas: $\rho_\Lambda = 25 \pm 1.2$ cm and $\rho_\Lambda > 33$ cm, respectively. The ρ_Λ limits were set based on MC simulations and a study of the Λ decay path. In particular, the $\rho_\Lambda = 25 \pm 1.2$ cm cut guarantees, for the first sample, a *contamination* of K^- interactions in gas as low as $(5.5^{+1.3}_{-1.8}\%)$.

An excellent statistical error for the Λ invariant mass was obtained, $\sigma_m \sim 0.3$ MeV$/c^2$, confirming the unique performances of KLOE for charged particles (the systematics, depending on the momentum calibration of the KLOE setup, are presently under evaluation).

Besides charged channels, the KLOE calorimeter also gives the opportunity to measure neutral channels. The identification and selection procedure for $\Sigma^0\pi^0$ pairs, the golden decay channel of the $\Lambda(1405)$ state, is described in the next section.

4.2. The $\Sigma^0\pi^0$ identification

The selection of $\Sigma^0\pi^0$ events proceeds, after the $\Lambda(1116)$ identification, with the search for three additional in-time photon clusters. We will indicate as γ_3 the photon coming from the Σ^0 decay, γ_1 and γ_2 will then represent the photons from π^0 decay, according to the reaction

$$K^-p \to \Sigma^0\pi^0 \to (\Lambda\gamma_3)\ (\gamma_1\gamma_2) \to \left(p\pi^-\right)\gamma_1\gamma_2\gamma_3\,. \qquad (1)$$

A pseudo-chisquare minimization is performed, searching for three neutral clusters in the calorimeter ($E_{\rm cl} > 20$ MeV), in time from the decay vertex position of the $\Lambda(1116)$ ($\boldsymbol{r}_\Lambda$) ($\chi^2_t = (t_i - t_j)^2/\sigma^2_t$, where t_i is the $i^{\rm th}$ cluster time subtracted by the time of flight in the speed of light hypothesis). According to dedicated MC simulations, a cut was optimized on this variable $\chi^2_t \leq 20$.

Once the three candidate photon clusters are chosen, their assignment to the correct triplet of photons, $(\gamma_1, \gamma_2, \gamma_3)$, is based on a second pseudo-chisquare minimization ($\chi^2_{\pi\Sigma}$). $\chi^2_{\pi\Sigma}$ involves both the π^0 and Σ^0 masses. $\chi^2_{\pi\Sigma}$ is calculated for each possible combination and the minimizing triplet is selected. The $\chi^2_{\pi\Sigma} \leq 45$ cut was optimized based on MC simulations.

According to true MC information, the algorithm has an efficiency of $(98 \pm 1)\%$ in recognizing photon clusters and an efficiency of $(78 \pm 1)\%$ in distinguishing the correct $\gamma_1\gamma_2$ pair (π^0 decay) from γ_3.

A check is performed on the clusters energy and distance to avoid the selection of splitted clusters (single clusters in the calorimeter erroneously recognized as two clusters) for π^0s. Cluster splitting is found to not affect significantly the sample.

In Fig. 7 there is shown the obtained invariant mass $m_{\Lambda\gamma3}$ (for absorptions in the gas) together with a Gaussian fit. The resolution in the $m_{\Lambda\gamma3}$ invariant mass is $\sigma_{m_{\Lambda\gamma3}} \sim 15$ MeV$/c^2$. The resolutions on ρ_Λ for the final selected Λs are $\sigma_{\rho_\Lambda} \sim 0.20$ cm (DC wall) and $\sigma_{\rho_\Lambda} \sim 0.13$ cm (DC gas). The resolutions on the Λ momentum are $\sigma_{p_\Lambda} \sim 4.5$ MeV$/c$ (DC wall) and $\sigma_{p_\Lambda} \sim 1.9$ MeV$/c$ (DC gas). Each quoted mean resolution corresponds to

Gaussian fits to the distributions of the originally generated true-MC quantities subtracted by the reconstructed ones. The better resolution for the measured variables corresponding to K^- hadronic interactions in the gas filling the KLOE DC is a consequence of the charged particles energy loss, mainly in the material of the DC entrance wall, particularly important for protons.

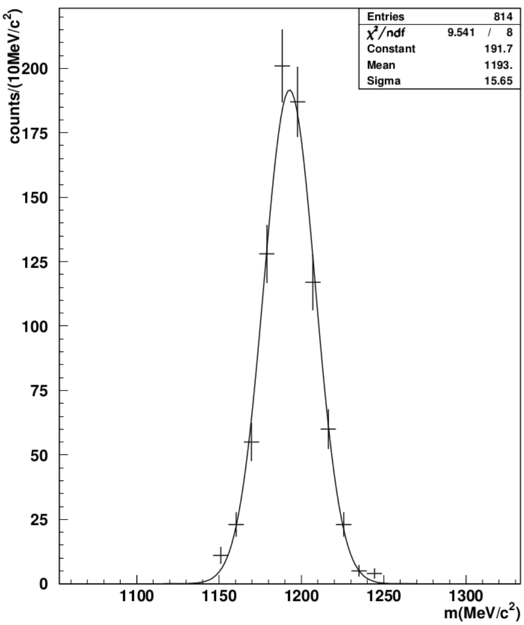

Fig. 7. $m_{\Lambda\gamma 3}$ invariant mass distribution, together with a Gaussian fit.

5. Conclusions and perspectives

The broad experimental program of AMADEUS, dealing with the non-perturbative QCD in the strangeness sector, is supported by the quest for high precision and statistics measurements, able to set more stringent constraints on the existing theoretical models. We demonstrated the capabilities of the KLOE detector to perform high quality physics (taking advantage of the unique features of the DAΦNE factory) in the open sector of strangeness nuclear physics. Our investigations, presently spread on a wide spectrum of physical processes, represent one of the most ambitious and systematic efforts in this field.

We are presently ongoing with the data analyses, both for the 2004–2005 KLOE data, and for the dedicated carbon-target data collected in 2012. In parallel, from the experimental point of view, we are considering the preparation of a dedicated setup, to explore more in detail and with an even higher precision, low-energy kaons interactions with targets going from hydrogen and helium, to lithium and beryllium.

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