Preliminary results of the FINUDA experiment at DAΦNE

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FINUDA (FIsica NUcleare at DAΦNE) is an experiment of hypernuclear physics, which is carried out at the DAΦNE e^+e^- collider by means of a large-acceptance and high-resolution magnetic spectrometer. The aim of FINUDA is the study of formation and decay of hypernuclei, which are produced by negative kaons at rest (K^-_{stop}) in a nucleus (^AZ) through the reaction:

$$K^-_{stop} + \ ^AZ \rightarrow \ ^A_\Lambda Z + \pi^- \tag{1}$$

where the elementary process of strangeness exchange transforms a neutron into a Λ hyperon with a negative pion (π^-) emission. The FINUDA spectrometer is designed to perform a high-resolution spectroscopy with a resolution below 1 MeV, to trace the particles from hypernuclear decay and to measure the lifetime of hypernuclei.

The first e^+e^- collisions occurred in October 2003, and, after a short commissioning of FINUDA data taking started in November 2003. Data will be collected until the end of March 2004 for a total integrated luminosity of about 250 pb^{-1}. The present paper presents preliminary results. They concern with in-beam detector calibration, spectrometer performances, hypernuclear formation and decay spectra.

1. THE FINUDA EXPERIMENT AT DAΦNE

The basic idea [1–3] is to use the low energy K^-'s (∼16 MeV) following the decay of the ϕ's, bringing them to rest into thin targets, and study the dynamics of formation and decay of hypernuclei produced by the reaction (1). This technique presents several advantages when compared to the traditional ones based on K^- extracted beams. First-of-all, the low-energy and monochromatic K^- source offers the possibility of using thin nuclear targets (0.2 g cm^{-2}), instead of the thick targets needed with extracted K^- beams at hadron machines. Consequently, the intrinsic momentum resolution of the magnetic spectrometer can be fully exploited, which by design is $850\,KeV/c$ ($\Delta E = 750\,KeV$) for a pion of $275\,MeV/c$.

The cylindrical symmetry of the interaction region called for the construction of a cylindrical, high-acceptance ($> 2\pi$ sr) detector. Such a large acceptance along with the excellent performances of the machine, permits the observation of about 80 hypernuclei/hour (at $\mathcal{L}$=10^{32}cm^{-2}s^{-1}). Finally, the use of thin targets and the low-mass of the tracking system, allows for low-energy charged particles (π^-, p, d) to be detected.

1.1. The FINUDA apparatus

FINUDA is a non-focusing magnetic spectrometer, which detects K^+K^- pairs with an acceptance of about 90%. Its arrangement reflects the geometry of the kaons source. The apparatus is shown in Fig. 1.

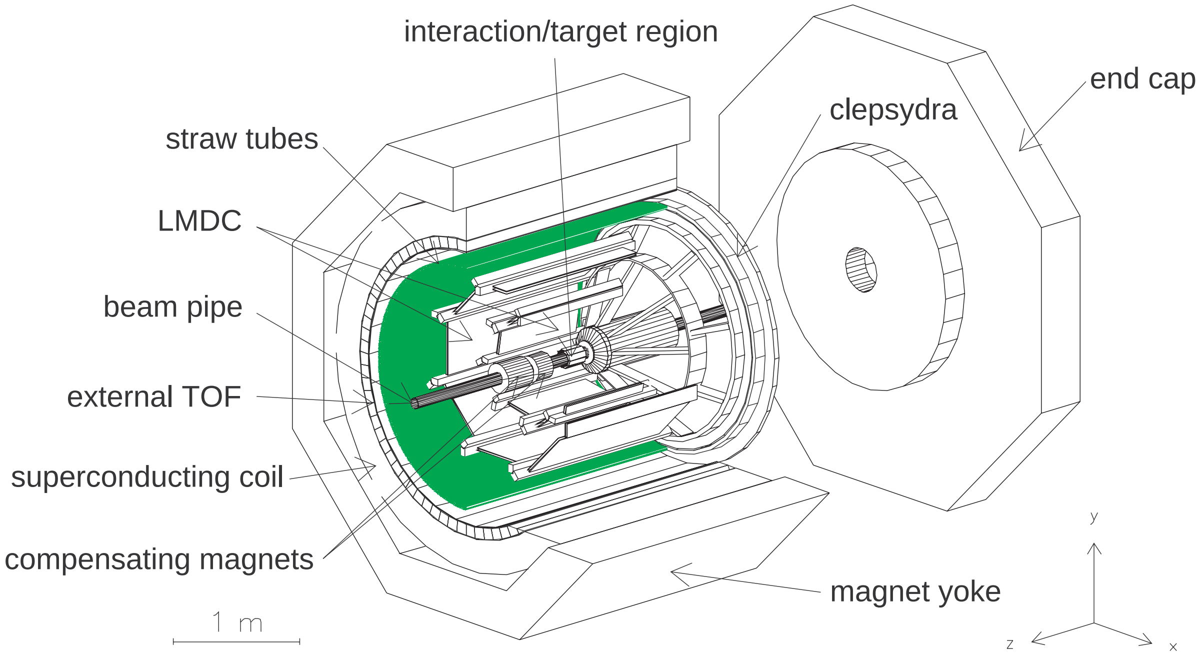

Figure 1. Schematic view of the FINUDA spectrometer.

FINUDA was designed to:

1. achieve a momentum resolution $\Delta p/p \leq 0.3\%$ FWHM;
2. have a versatile fast trigger, to select events with multiplicity ≥ 1;
3. trace and discriminate the charge particles involved in hypernuclear reactions;
4. detect neutrons (from non-mesonic decays).

In order to obtain $\Delta p/p \leq 0.3\%$ FWHM, the magnetic field is set at $B_z = 1.0\,T$ (B_x, B_y are less than $10^{-3}\,T$) and the B_z uniformity in the tracking volume is better than 0.1 % along z (1 % along x and y).

The inner element of the vertex region is the beam pipe, which is a cylinder of beryllium 500 μm thick. The beam pipe is surrounded by TOFINO, an array of 12 plastic scintillator slabs arranged like the staves of a barrel, with a diameter of 112 mm. Each slab is 2.3 mm thick and 20 cm long. It is viewed at both ends by a couple of hybrid photodiodes (HPD), which are capable of working in a magnetic field.

Moving outward, there is a first array of double-sided silicon microstrip detectors (ISIM), mounted according to the faces of an octagonal prism. ISIM measures the particle trajectories with a resolution better than 30 μm, which contributes to determine the K^- stop position with a precision of 600 μm, due to the multiple Coulomb scattering of the

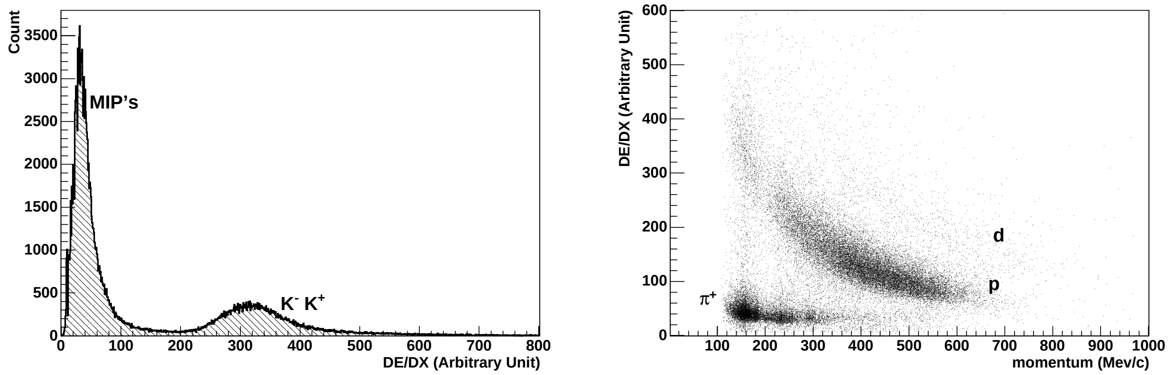

Figure 2. Figure on the left: kaons are identified in FINUDA by the energy deposited in ISIM. Figure on the right: pions, protons and deuterons are identified by the energy deposited in OSIM versus the particle momenta.

slowing down negative kaon. In addition, ISIM measures the energy deposited by a crossing particle ($\Delta E/\Delta x$), which is then used for particle identification PID [4] (see Fig. 2). Targets are arranged in a ladder, their average distance from ISIM is about $2\,mm$. In the present data taking FINUDA was equipped with the following targets: $2\times^6 Li$, $1\times^7 Li$, $3\times^{12} C$, $1\times^{27} Al$, $1\times^{51} V$. The target thickness ranges between 200 and $300\,mg/cm^2$.

A second set of 10 modules of double-sided silicon microstrip detectors (OSIM) surrounds the octogonal target ladder, which is the first element of the tracking system. Two layers of low-mass high-precision planar drift chambers (LMDC) follow OSIM. Both are arranged along the sides of an octagonal prism. To minimize the multiple Coulomb scattering, the LMCD gas mixture is an Helium based mixture (He-C4H10 70/30). The precision of the localization is $100\,\mu m$ (σ) across a drift cell, and $1\,cm$ (σ) along the wire. The last array of the tracking system is a stereo-organized layer of aluminized mylar straw tubes (ST), each ST is $2.5\,m$ long and $15\,mm$ in diameter. The layer consists of six sublayers arranged in three groups of two layers each one. The first group is placed along the beam axial direction and the other two are $\pm 12^o$ tilted. The spatial resolution is $100\,\mu m$ (σ) in the x-y plane and the information from the stereo ST gives a resolution along the z direction of $220\,\mu m$ (σ).

The outer detector (TOFONE) consists of large-volume plastic scintillator ($\sim 10\,cm\times 10\,cm\times 255\,cm$). TOFONE provides signals for the first level trigger, allows for the measurement of the time-of-flight of charged particles and neutrons from hypernucleus decay.

Finally, the tracking system of FINUDA is immersed in a helium atmosphere to minimize the particle multiple scattering.

1.2. The initial FINUDA physics program

The physics program of FINUDA relies on the simultaneous study of both hypernuclear formation and decay of the following targets [5]:

- *Two targets of* ^6Li (isotopically enriched to 90%): The hypernucleus $^6_\Lambda Li$ is unstable for proton emission and decays to $^5_\Lambda He + p$ or to the hyperfragments $^4_\Lambda He + p + n$ and $^4_\Lambda H + p + p$. Due to the momentum resolution of the apparatus, it will be possible to identify the $^5_\Lambda He$ production by simply selecting the end-part of the momentum spectrum of the π^-. FINUDA will also recognize the formation of the $^4_\Lambda He$ hyperfragment by detecting the decay channels: $^4_\Lambda He \rightarrow d + d$ and $^4_\Lambda He \rightarrow p + ^3H$, never seen before and with an estimated branching ratio of about 10^{-3}. Finally, an interesting reaction may occur on ^6Li: $K^-_{stop}+ \; ^6Li \rightarrow \, ^6_\Lambda H + \pi^+$, which may open a window on the unexplored field of neutron-rich hypernuclei.

- *One target of* ^7Li. The low-lying excited spectrum of $^7_\Lambda Li$ has largely been studied via high-resolution γ spectroscopy [6]. The energy resolution of FINUDA will identify the ground state doublet and Γ_{nn}, Γ_{np} will be measured in coincidence for the first time.

- *Three targets of* ^{12}C. $^{12}_\Lambda C$ has been the hypernucleus most extensively studied, BNL and KEK [7]. For this reason, the data obtained with FINUDA will mainly be used for comparison; however, the precision obtained for the measured observables will be improved.

- *One target of* ^{27}Al. Apart from an old measurement with K^- in flight [8], no further data have been published. Therefore, it would be very interesting to measure not only the excitation spectrum, but also its ground state capture rate, which will establish whether the measurement of Γ_{nn} and Γ_{np} in coincidence is achievable for medium/high A hypernuclei.

- *One target of* ^{51}V. The excitation spectrum of $^{51}_\Lambda V$ has been measured at KEK with a resolution of 1.65 MeV [7], and the peaks corresponding to the p and d single-particle orbits show possible splittings, which are tentatively attributed to a non-zero value of the Λ spin-orbit potential. The energy resolution of FINUDA, and the high statistics expected would shed light on this important issue.

2. FIRST PHYSICS RESULTS

The first type of events triggered by FINUDA were Bhabha events; i.e., $e^+ + e^- \rightarrow e^+ + e^-$ and $e^+ + e^- \rightarrow e^+ + e^- + \gamma$. The aim was to exploit these well known processes to perform an in-beam calibration of the apparatus, the measurement of the (e^+, e^-) collision topology, the e^+-e^- beam energy, the e^+-e^- beams crossing angle, and the evaluation of the luminosity delivered by DAΦNE to the experiment. By using Bhabha events [9], an average luminosity of $\mathcal{L} = 3.5 \cdot 10^{31}\text{cm}^{-2}\text{s}^{-1}$ was measured, corresponding to an integrated luminosity of ~ 3 pb^{-1} per day.

The Bhabha trigger consists of two back-to-back slabs of TOFINO, in coincidence with TOFONE. With such a trigger, events corresponding to the formation of ϕ followed by the decay into $K_S K_L$ and $K_S \rightarrow \pi^+\pi^-$ were also recorded. In Fig. 3 the reconstruction of such an event is shown. Fig. 4 depicts the invariant mass of the $\pi^+\pi^-$ system corresponding to Bhabha triggers. The narrow peak at 498 MeV/c^2 is K_S. The position and width of this peak yield direct information on the absolute calibration and the mass resolution of the

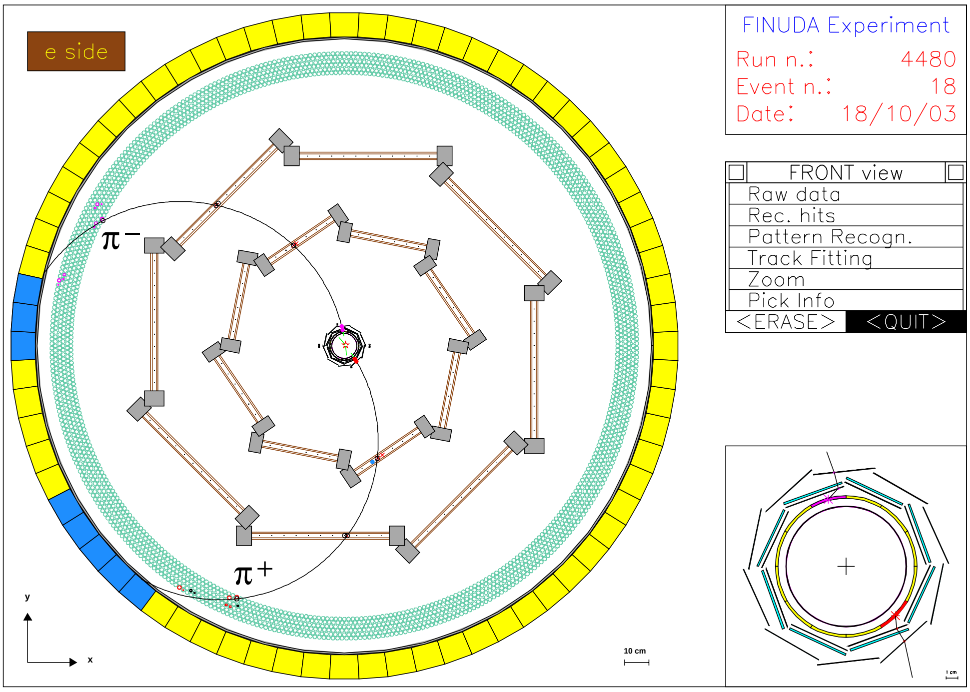

Figure 3. Reconstruction of a $\phi(1020)$-decay event: $\phi \to K_S K_L$ and $K_S \to \pi^+\pi^-$. In the picture, positive tracks turn clockwise. The inset shows the tracks crossing the vertex detector.

spectrometer. The bump on the right of the K_S peak corresponds to $\rho^0(770)(\to \pi^+\pi^-)$, which is due to the $\phi \to \rho^0\pi^0$ decay.

The trigger of hypernucleus formation [3] requires two back-to-back slabs of TOFINO firing in coincidence with TOFONE barrel. With such an approach, (K^+,K^-) pairs are detected in fast-coincidence with events traversing the whole apparatus (π^-).

Fig. 5 reports the reconstruction of a hypernuclear event: two tracks exit the interaction region and traverse the spectrometer. The positive-polarity track (turning clockwise) is the μ^+ from the K^+ decay, the negative-polarity track is the π^-, which follows the interaction of K^- with ^6Li. The inset shows the vertex region with the reconstructed K^+ and K^- trajectories.

Fig. 6 reports the momentum distribution of positive events coming from the K^+_{stop} decays: the two peaks at 236 MeV/c and 205 MeV/c correspond to the two body decays $K^+ \to \mu^+\nu_\mu$ and $K^+ \to \pi^+\pi^0$, respectively. From the width of the μ^+ peak, the present momentum resolution of the apparatus can be estimated $\Delta p/p$=1.1% FWHM, corresponding to about $\Delta E \sim 2.5\,MeV$. This value is 3-4 times higher than the design value; however, the apparatus calibrations were not final not was the detector alignment.

The scatter-plot of Fig. 7 shows the reconstructed coordinates of the stopping position of negative kaons. The segments of the external "octagon" are the actual positions of the eight targets, where most of the negative kaons stop. The internal "octagon" is ISIM

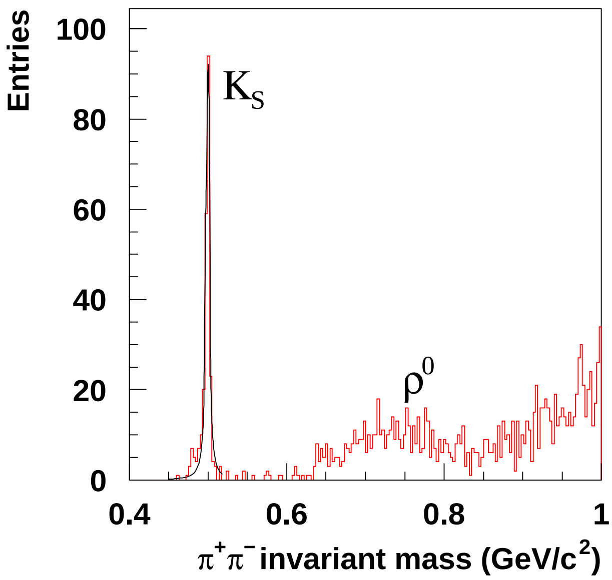

Figure 4. Invariant mass of the $\pi^+\pi^-$ system. The narrow peak is the $\pi^+\pi^-$ invariant mass distribution of the $K_S \to \pi^+\pi^-$ decay. The bump at its right corresponds to $\rho^0(770)$.

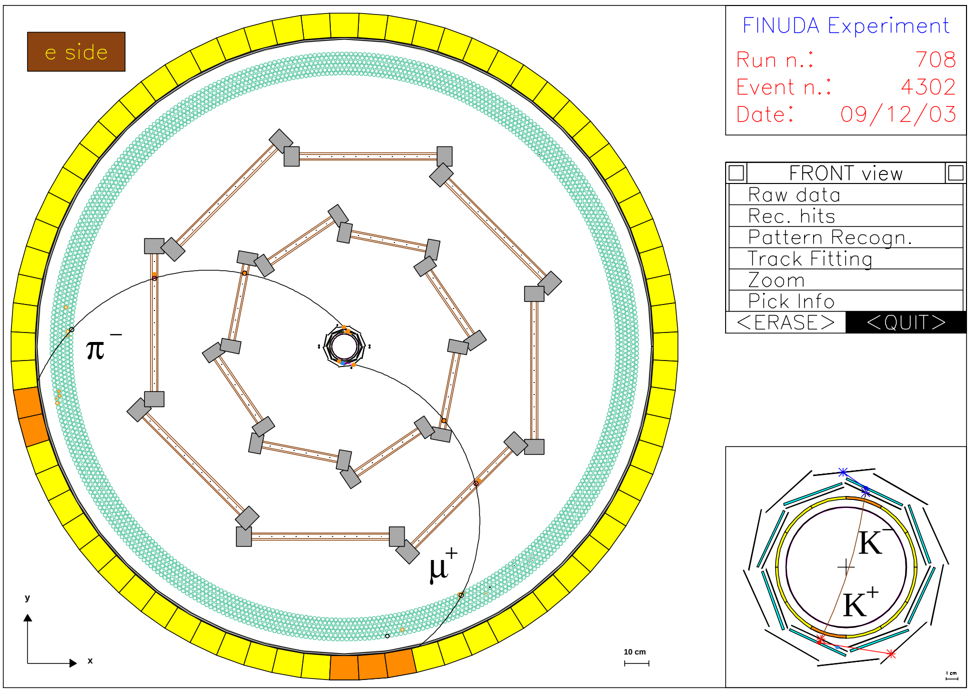

Figure 5. Reconstruction of a hypernuclear event. Muons from K^+ decays and π^-'s from $K^-\ {}^6Li$ interactions can be seen. In the inset, an enlarged view of the vertex region with the K^+ and K^- trajectories is shown. K^+ K^- stop into two targets.

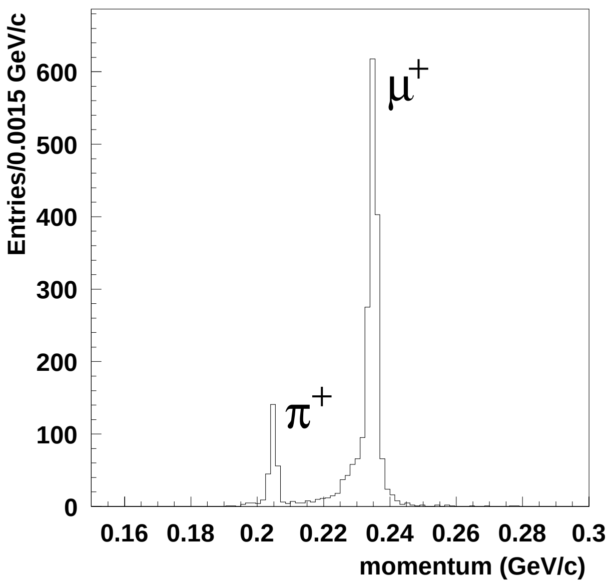

Figure 6. Momentum distribution of the positive-polarity events which follows the decay of kaon at rest. The peak at 236 MeV/c corresponds to the two body decay $K^+ \rightarrow \mu^+\nu_\mu$, while the peak at 205 MeV/c corresponds to the two body decay $K^+ \rightarrow \pi^+\pi^0$.

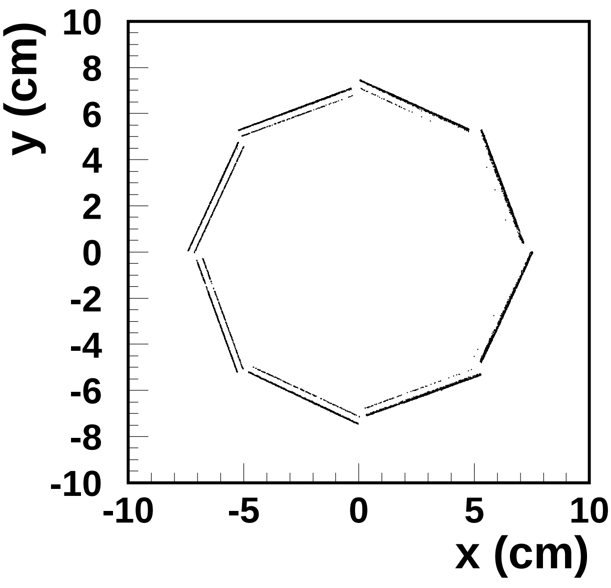

Figure 7. Scatter plot of the reconstructed coordinates of negative kaons stopping in the targets. The external "octagon" corresponds to the eight target, where about 90 % of the K^- stop. The ISIM modules are also populated of negative kaons, which is due to the crossing angle ($\sim 12.5\, mrad$) of (e^+, e^-) beams in the interaction region.

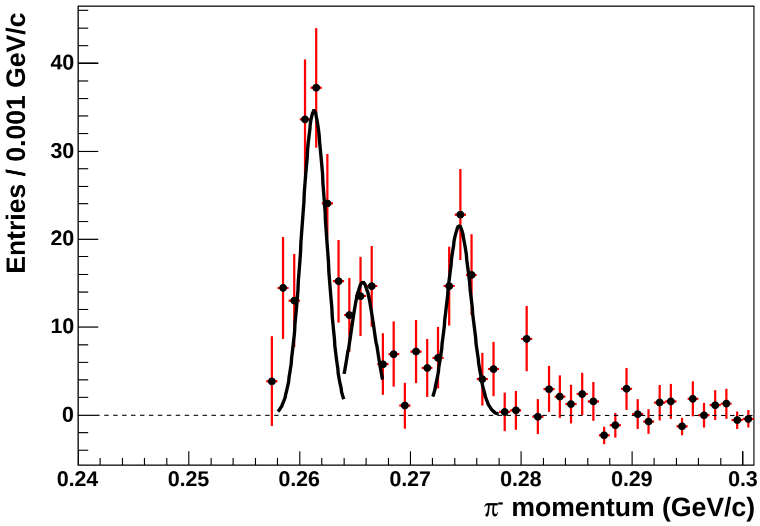

Figure 8. Momentum distribution of negative pions from the $K^-_{stop} + {}^{12}C \rightarrow {}^{12}_{\Lambda}C + \pi^-$ reaction. The ground state of ${}^{12}_{\Lambda}C$ peaks at $\sim$ 275 MeV/c, and the two excited states peak at $\sim$ 266 MeV/c and $\sim$ 261 MeV/c, respectively. The data are preliminary; in fact, the momentum resolution is 1.1 % (FWHM), and the statistics is just few percent of the expected statistics.

modules, about 10 % of negative kaons stop. The modules of ISIM are populated by a varying density of K^-'s. This is due to the (e^+, e^-) crossing angle that boosts ϕ's toward the positive x direction.

By extrapolating the data so far collected and analyzed, it is possible to make an estimate of the total number characterized by a K^-_{stop} and a negative track crossing the entire spectrometer. The experiment will collect about 10^5 of such events per target, which will be useful for hypernuclear spectroscopy analyses.

The π^- momentum distribution of the π^- is shown in Fig. 8 for the ${}^{12}C$ target. The ground state of ${}^{12}_{\Lambda}C$ peaks at $\sim$ 275 MeV/c, and the two excited states peak at $\sim$ 266 MeV/c and $\sim$ 261 MeV/c, respectively. The data are preliminary; in fact, the momentum resolution is 1.1 % (FWHM), and the statistics is just few percent of the expected statistics.

With the number of events available at the end of the present data taking, different hypernuclear decay observables will be measured with good statistics. As a preliminary result, Fig. 9 reports the momentum spectrum of the tracks with positive polarity, which follow the K^-A interaction, where A includes all the targets used. They are mostly protons; however, the low-momentum part of the distribution includes a valuables number of positive pions. This opens the door to analysis different from Λ-hypernuclei. The two peaks at low momenta are given by the cut-off to tracks directly entering the spectrometer from the target (forward tracks) and to tracks entering the spectrometer after having

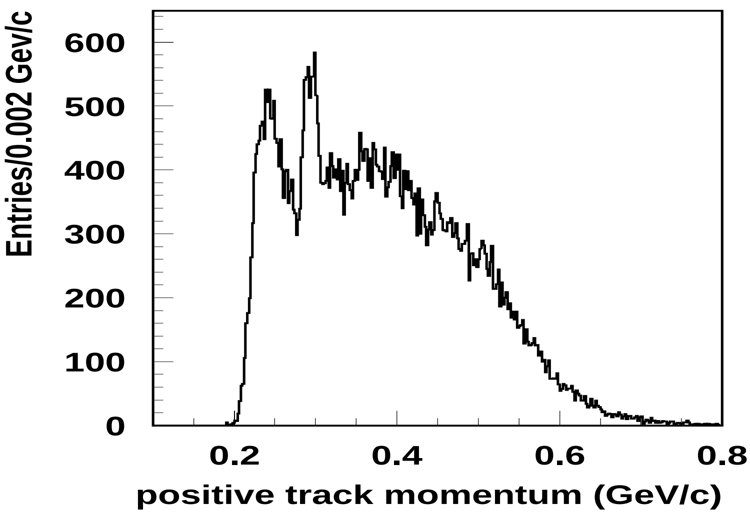

Figure 9. Momentum spectrum of events with positive polarity, which follows the $K^-_{stop}A$ interaction. See text for details.

crossed the interaction/target region (backward tracks). Finally, it is worth noticing the low values of these cut-off momenta.

3. CONCLUSION

The preliminary data analysis shows that FINUDA can fulfil the hypernuclear formation and decay studies. Moreover, the statistics expected will allows for more exotic studies; as for example, rare hypernuclear two-body decays (Fig. 10).

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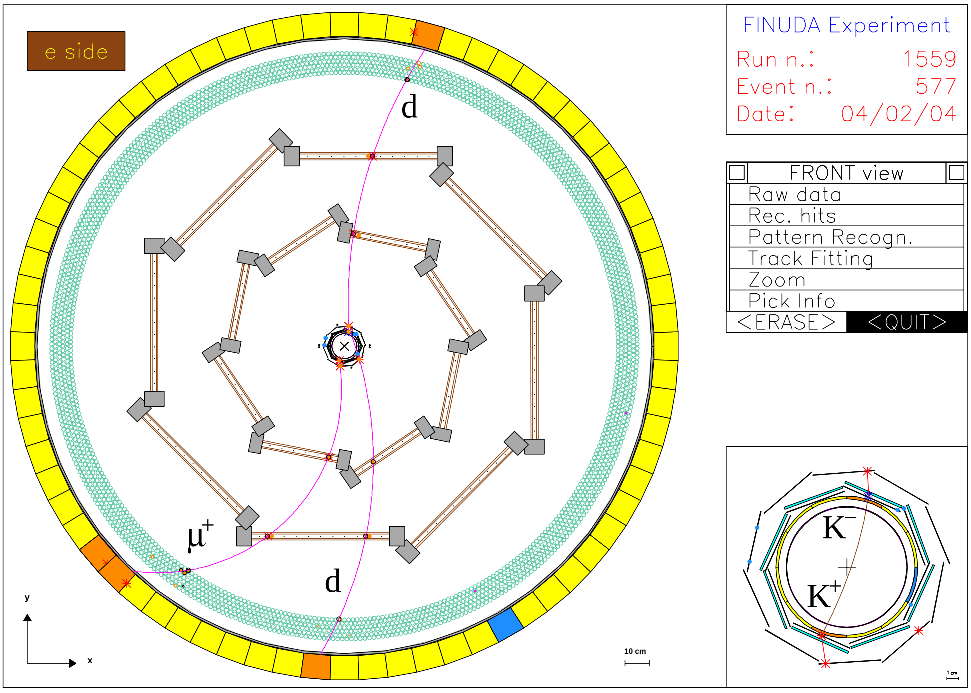

Figure 10. Candidate event for a rare hypernuclear two-body decay, never observed before. The ${}^{4}_{\Lambda}He$ hyperfragment (from ${}^{6}_{\Lambda}Li$) decays in two almost back-to-back deuterons.