First results from the FINUDA experiment at DAΦNE

M. Agnello [a], G. Beer [b], L. Benussi [c], M. Bertani [c], S. Bianco [c], E. Botta [d], T. Bressani [d], L. Busso [e], D. Calvo [f], P. Camerini [g], P. Cerello [f], B. Dalena [h], F. De Mori [d], G. D'Erasmo [h], D. Di Santo [h], F.L. Fabbri [c], D. Faso [e], A. Feliciello [f], A. Filippi [f], V. Filippini [i], E.M. Fiore [h], H. Fujioka [j], P. Gianotti [c], N. Grion [k], A. Krasnoperov [l], V. Lucherini [c], S. Marcello [d], T. Maruta [j], N. Mirfakhrai [m], O. Morra [n], A. Olin [o], E. Pace [c], M. Palomba [h], A. Pantaleo [p], A. Panzarasa [i], V. Paticchio [p], S. Piano [g], F. Pompili [c], R. Rui [g], G. Simonetti [h], H. So [q], S. Tomassini [c], R. Wheadon [f], A. Zenoni [r]

[a]Dipartimento di Fisica del Politecnico di Torino, C.so Duca degli Abruzzi 24, I-10129 Torino, Italy and INFN, Sezione di Torino, via Giuria 1, I-10125 Torino, Italy

[b]University of Victoria, Finnerty Rd., Victoria, Canada

[c]INFN, Laboratori Nazionali di Frascati, Via Fermi 40, I-00044 Frascati, Italy

[d]Dipartimento di Fisica Sperimentale, Università di Torino, Via Giuria 1, I-10125 Torino, Italy and INFN Sezione di Torino, via Giuria 1, I-10125 Torino, Italy

[e]Dipartimento di Fisica Generale, Università di Torino, Via Giuria 1, I-10125 Torino, Italy and INFN Sezione di Torino, via Giuria 1, I-10125 Torino, Italy

[f]INFN Sezione di Torino, via Giuria 1, I-10125 Torino, Italy

[g]Dipartimento di Fisica, Università di Trieste, Via Valerio 2, I-34127 Trieste, Italy and INFN Sezione di Trieste, Via Valerio 2, I-34127 Trieste, Italy

[h]Dipartimento di Fisica, Università di Bari, Via Amendola 173, I-70126 Bari, Italy and INFN Sezione di Bari, Via Amendola 173, I-70126 Bari, Italy

[i]INFN Sezione di Pavia, Via Bassi 6, I-27100 Pavia, Italy

[j]National Laboratory for High Energy Physics (KEK), Oho, Tsukuba, Ibaraki, 305, Japan

[k]INFN Sezione di Trieste, Via Valerio 2, I-34127 Trieste, Italy

[l]Joint Institute for Nuclear Physics, Dubna, Moscow region

[m]Department of Physics, Shahid Beheshty University, 19834 Teheran, Iran

[n]CNR-IFSI Sezione di Torino and INFN Sezione di Torino, via Giuria 1, I-10125 Torino, Italy

[o]TRIUMF 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada

[p]INFN Sezione di Bari, Via Amendola 173, I-70126 Bari, Italy

[q]Department of Physics, Seoul National University, Seoul 151-742, South Korea

[r]Dipartimento di Meccanica, Università di Brescia, Via Valotti 9, 25123 Brescia, Italy and INFN Sezione di Pavia, Via Bassi 6, Pavia, Italy

In spring 2003 the FINUDA detector was installed at the ϕ factory DAΦNE in the Laboratori Nazionali di Frascati of INFN (Italy). In October 2003 the commissioning of the apparatus was accomplished and the first data taking started with a set of nuclear targets ^6Li, ^7Li, ^{12}C, ^{27}Al, ^{51}V. The data collection will continue until a total integrated luminosity of 250 pb^{-1} is recorded. Light and medium A hypernuclei will be abundantly produced by the strangeness exchange reaction induced by the stopped K$^-$ coming from the decay of $\phi(1020)$ mesons.

The aim of the experiment is to simultaneously measure the excitation energy spectra of the produced hypernuclei, with a resolution better than 1 MeV, the lifetime of the Λ embedded in the different hypernuclei and the partial widths Γ_π, Γ_{np} and Γ_{nn} for mesonic and non mesonic hypernuclear decays. Information on neutron-rich hypernuclei and rare hypernuclear two-body decays might be available too, with the statistics that will be collected at the end of the run.

In the present paper, first results concerning in-beam detector calibration, spectrometer performances and very preliminary hypernuclear formation and decay spectra will be presented.

1. INTRODUCTION

The FINUDA experiment (acronym for "FIsica NUcleare a DAΦNE") may be considered as a third generation experiment in hypernuclear physics. Indeed, thanks to the original design of the FINUDA apparatus and, in particular, to the large angular coverage for detection of charged and neutral particles coming from the formation and decay of hypernuclei, many hypernuclear observables like excitation energy spectra, lifetimes and partial decay widths for mesonic and non-mesonic decay can be simultaneously measured with high statistics and high energy resolution (better than 1 MeV). Furthermore, spectra corresponding to different targets can be measured at the same time, thus reducing possible systematic errors in comparing properties of different hypernuclei.

The detector was completed in 1998, but its installation on the machine was delayed due to problems related to the superconducting coil in which the detector is immersed and, mainly, to unexpected drawbacks in the commissioning of the machine. Since 2000 the peak luminosity of the collider was increased from less than $\mathcal{L}$=10^{30}cm^{-2}s^{-1} to $\mathcal{L}$=$7\cdot10^{31}$cm^{-2}s^{-1} at the end of 2002, with great reduction of the machine background.

In January 2003 the operations necessary for the insertion of the detector in the machine interaction region were started and their completion took about four months. The roll-in of the detector into the collider was done on April 28, 2003. The full detector was calibrated with cosmic rays during six weeks, with magnetic field off and on, in order to measure the alignment and to check for the performances of the different subdetectors that constitute the spectrometer. DAΦNE engineering runs were delayed to September 2003, due to a water supply shortage consequent to the exceptional hot and dry summer that affected Europe. In October 2003 the first collisions were achieved and, after few weeks of commissioning of the apparatus, the first FINUDA data taking started in November 2003 and it will continue until the end of February 2004, when a total integrated luminosity of 250 pb^{-1} will be collected.

2. THE FINUDA EXPERIMENT AT DAΦNE

FINUDA is an unconventional example of a hypernuclear physics experiment, which is typically a fixed target experiment, carried out at a (e^+, e^-) collider tuned at the formation energy of the $\phi(1020)$. The main idea [1–3] is to use the low energy K^- ($\sim$16 MeV) coming from the decay of the ϕ, slowing them down in thin targets and study the successive formation and decay of different hypernuclei produced by the strangeness exchange reaction with K^- at rest:

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

where ${}^AZ$ indicates a target nucleus and ${}^A_\Lambda Z$ the produced hypernucleus.

This technique presents several advantages when compared to the traditional ones based on K^- extracted beams. First of all, by exploiting an unique low energy and almost monochromatic K^- beam, it 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 and, for the FINUDA design, an energy resolution down to 750 keV on the hypernuclear levels may be obtained.

Furthermore, the cylindrical symmetry at the interaction region of a collider allows for the construction of a cylindrical, high-acceptance ($> 2\pi$ sr) spectrometer for the detection of the π^- coming from reaction (1). This large acceptance, joined to the excellent performances of the machine, can provide very high hypernuclear formation rates (80 hypernuclei/hour at $\mathcal{L}$=10^{32}cm^{-2}s^{-1}, with a 10^{-3} capture rate). Finally, the use of thin targets and low-mass detectors in the spectrometer, allows low energy charged particles (π^-, p, d) emitted in the weak decay of the produced hypernuclei to be detected.

2.1. The FINUDA apparatus

Fig. 1 shows a global view of the apparatus, which is contained inside a superconducting solenoid that provides a highly homogeneous magnetic field of 1.0 T, in a cylindrical volume of 146 cm radius and 211 cm length. The (e^+, e^-) colliding region, where ϕ mesons are formed and decay, is located inside the beam pipe at the centre of the experimental apparatus.

Three main regions can be distinguished inside the FINUDA apparatus. The *interaction/target region* shown schematically in Fig. 2. Here, the highly ionizing (K^+, K^-) pairs are detected by a barrel of 12 thin scintillator slabs (tofino), which surrounds the beam pipe. An octagonal array of silicon microstrips (ISIM) measures, with high spatial resolution, the interaction point of the (K^+, K^-) pairs in the thin targets, which are positioned near the external side of each element of the ISIM octagon, as shown in Fig. 2.

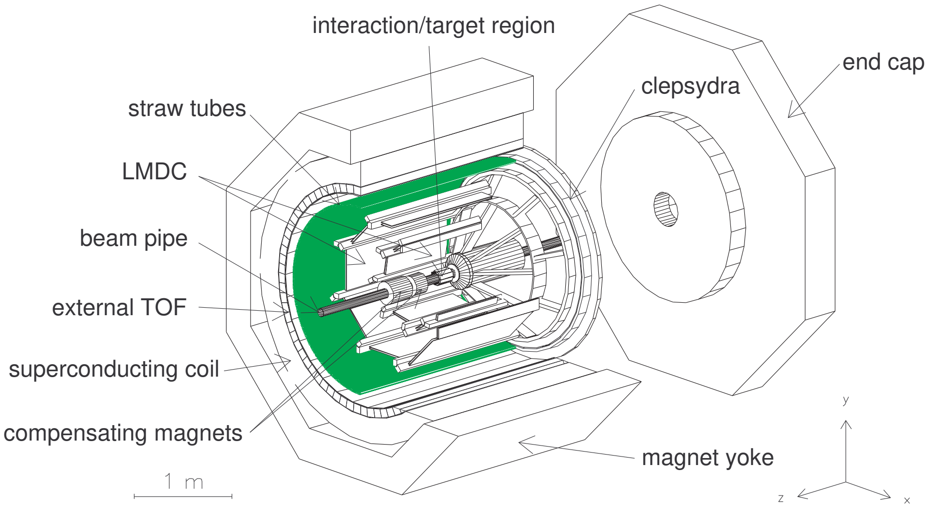

Figure 1. Global view of the FINUDA detector.

The *external tracking device* consists of four different layers of position detectors, which are placed around the detector axis with cylindrical symmetry, and are immersed in a He atmosphere to reduce the effects of the Coulomb multiple scattering. The trajectories of the charged particles coming from the targets and entering the tracking device are measured at four positions by: (i) an initial array of ten silicon microstrips (OSIM), placed close to the target array (see Fig. 2); (ii) a second and third array of eight planar low-mass drift chambers; (iii) a straw tube detector, composed by six layers of longitudinal and stereo tubes, positioned at the most external radius of the spectrometer. The design momentum resolution of the apparatus, for a typical π^- of 270 MeV/c coming from hypernucleus formation, is $\Delta p/p$=0.3% FWHM.

The *external time of flight barrel* (tofone), composed by 72 scintillator slabs, 10 cm thick, provides signals for the first level trigger and allows for the measurement of the time of flight of charged particles coming from the formation and decay of the hypernuclei. Moreover, it allows for the detection of neutrons from hypernucleus decay, with a large acceptance and an efficiency of ∼10%. Further details concerning the design and performances of the FINUDA apparatus may be found in [4–9].

2.2. The initial FINUDA physics program

As mentioned in the introduction, the physics program of the FINUDA experiment aims at the simultaneous study of both hypernuclear formation and decay. For the starting run the following targets were selected [9].

Two targets of ^6Li (isotopically enriched to 90%). The hypernucleus $^6_\Lambda Li$ is unstable for proton emission and it decays in $\sim 10^{-22}$ s into $^5_\Lambda He + p$ or into the hyperfragments $^4_\Lambda He + p + n$ and $^4_\Lambda H + p + p$, via the Coulomb assisted mechanism. Thanks to the excellent momentum resolution of the apparatus, it will be possible to clearly identify

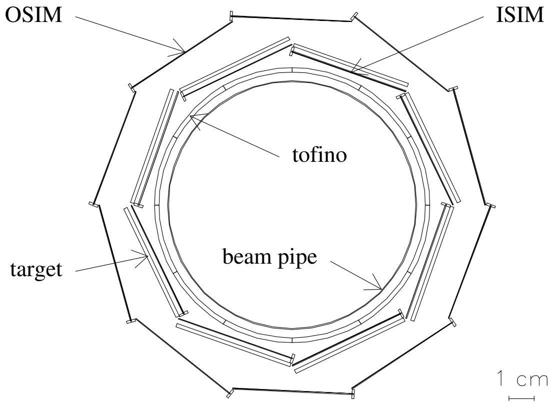

Figure 2. Schematic view of the interaction/target region.

the ${}^{5}_{\Lambda}He$ production by simply selecting the appropriate momentum range at the end point of the momentum spectrum of the π^- coming from (1). It will also be possible, with FINUDA, to recognize the formation of the ${}^{4}_{\Lambda}He$ hyperfragment by detecting its two body "rare" decays into charged products: ${}^{4}_{\Lambda}He \rightarrow d + d$ and ${}^{4}_{\Lambda}He \rightarrow p + {}^{3}H$ [10]. Finally, a very interesting reaction may occur on a ${}^{6}Li$ target: $K^-_{stop} + {}^{6}Li \rightarrow {}^{6}_{\Lambda}H + \pi^+$, which may open a window on the until now unexplored field of neutron-rich hypernuclei [11].

One target of ${}^{7}Li$. The low-lying excited spectrum of ${}^{7}_{\Lambda}Li$ is the most extensively studied with high-resolution γ spectroscopy [12]. With the FINUDA energy resolution, the ground state doublet should be clearly identified and Γ_{nn} and 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 until now, mainly at BNL and KEK [13]. For this reason, the data obtained will be mainly used for calibration purpose but, at the same time, the precision on all the measured observables will be improved. Indeed, the best excitation spectrum obtained for ${}^{12}_{\Lambda}C$ was measured with 1.45 MeV FWHM resolution.

One target of ${}^{27}Al$. Apart from a very old measurement with K^- in flight [14] with the coarse resolution of 6 MeV, no further data were produced on ${}^{27}_{\Lambda}Al$. Therefore, it would be very interesting to measure not only its excitation spectrum with high precision, but also its ground state capture rate, in order to establish whether measurement of Γ_{nn} and Γ_{np} in coincidence will also be possible for medium-high A hypernuclei.

One target of ${}^{51}V$. The excitation spectrum of ${}^{51}_{\Lambda}V$ was measured at KEK with a resolution of 1.65 MeV [13] and the peaks corresponding to the p and d single-particle orbits show possible splittings, which were tentatively attributed to a non-zero value of the Λ spin-orbit potential. The ultimate energy resolution of FINUDA, joined with the good statistics expected, would shed light on this important evidence. As for ${}^{27}_{\Lambda}Al$, the measurement of the capture rate of the ground state formation will be important as well.

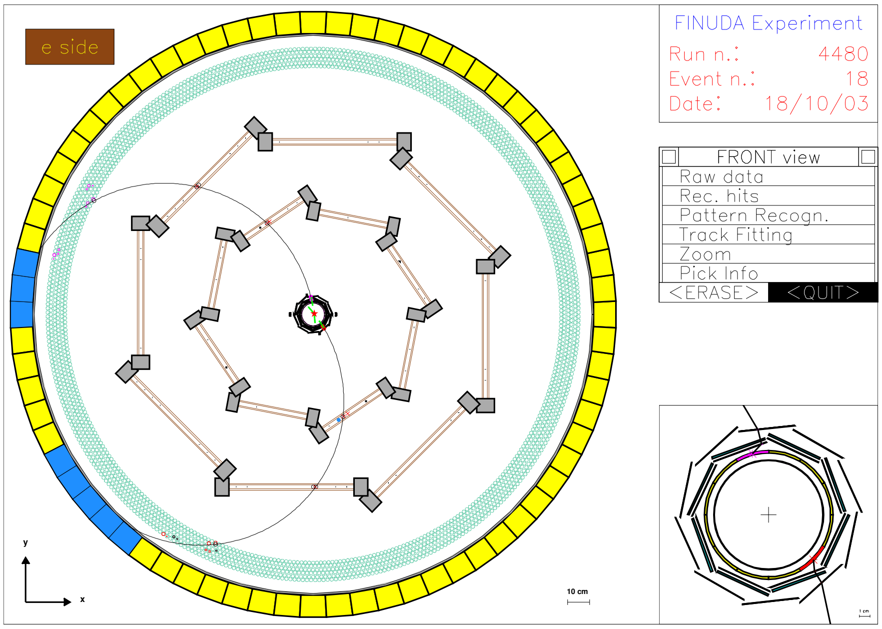

Figure 3. Event $e^+ + e^- \to \phi(1020)$, with $\phi \to K_S K_L$ and $K_S \to \pi^+\pi^-$ recorded by the FINUDA apparatus. In the picture positive tracks turn clockwise.

3. FIRST PHYSICS RESULTS

The first type of events triggered by the FINUDA apparatus were Bhabha events: $(e^+ + e^- \to e^+ + e^-)$ and $(e^+ + e^- \to e^+ + e^- + \gamma)$, that is elastic and inelastic (e^+, e^-) scattering. 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 spot, of the total beam energy, of the beam crossing angle and the evaluation of the luminosity delivered by the machine to the experiment. Using Bhabha events [15], an average luminosity of $\mathcal{L} = 2 \cdot 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ has been measured, corresponding to an integrated luminosity of $\sim 2\ \mathrm{pb}^{-1}$ per day.

By using the Bhabha trigger (two back-to-back slabs of tofino barrel fired in fast coincidence with tofone barrel), events corresponding to the formation of the ϕ followed by its decay into $K_S K_L$ and by $K_S \to \pi^+\pi^-$ were recorded too. In Fig. 3 the event display of one of these events is shown. In Fig. 4 the invariant mass of the $\pi^+\pi^-$ system calculated on events collected with the Bhabha trigger is shown. The narrow peak at 498 MeV/c^2 corresponds to the decay of the K_S. The position and width of this peak provide information on the absolute calibration and the global mass resolution of the spectrometer. The large bump on the right of the peak corresponds to the decay of the $\rho^0(770) \to \pi^+\pi^-$ coming from the ϕ decay into $\rho^0(770)\pi^0$.

The trigger selecting hypernucleus formation events [3] requires two back-to-back slabs firing on the tofino barrel (above an energy threshold accounting for the high ionization of slow kaons) and a fast coincidence on the tofone barrel. It allows (K^+, K^-) pairs, accom-

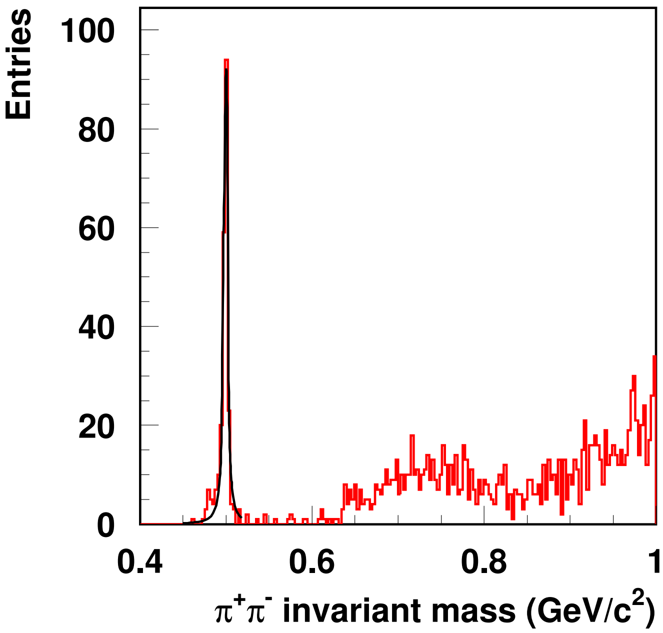

Figure 4. Invariant mass of the $\pi^+\pi^-$ system. The narrow peak corresponds to the decay of the K_S. The large bump on its right corresponds to the decay of the $\rho^0(770)$.

panied by a fast particle crossing the spectrometer and hitting the external scintillator barrel, to be selected against the physical background coming from the other decays of the ϕ or against fake events generated by the machine electromagnetic background.

Fig. 5 reports a typical candidate for hypernuclear formation event. Two tracks exit from the interaction region and cross the spectrometer: the positive one (turning clockwise) is the μ^+ coming from the decay of the K^+, the negative one, with a momentum of 260 MeV/c, is the π^- coming from the interaction of the K^- in a ^6Li target. In the inset, the vertex region with the reconstructed (K^+, K^-) trajectories is shown.

Fig. 6 shows the momentum distribution of positive tracks coming from the K^+ stopping points; 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 as $\Delta p/p$=1.1% FWHM, corresponding to about 2.5 MeV on the hypernuclear levels. This can be considered a fair starting value that should improve to the design value after the final calibrations and detector alignment.

Fig. 7 shows the scatter plot of the reconstructed y vs x coordinates of the K^- stopping points. The accumulations on the most external octagon correspond to the positions of the eight target modules, where most of the K^- stop. Accumulations on the internal slabs on the left of the octagon correspond to 10% of the K^- stopping into the ISIM modules. The asymmetry is due to the (e^+, e^-) crossing angle that determines a small total momentum of the generated ϕ in the positive x direction (beam boost). Hence, the momenta of the K^- emitted in the negative x direction are lowered.

Guessing on the data collected until now, it is possible to make an estimate of the total number of events with a K^- interacting into a target accompanied by a negative track measured in the spectrometer that will be recorded at the end of the first FINUDA data taking. The experiment should collect about 10^5 such events per target, useful for high resolution hypernuclear spectroscopy. This statistics will allow good spectroscopic studies on ^{12}C, ^{27}Al, ^{51}V and ^{7}Li targets to be performed. In addition, a survey of the rich physics possibilities offered by the ^{6}Li target should be possible too.

In Fig. 8 the momentum distribution of the π^- following the K^- interactions into the three ^{12}C targets is shown. The spectrum has been obtained from a limited sample of data already processed. The two peaks of the $^{12}_{\Lambda}C$ ground state at 275 MeV/c and of the excited state at 261 MeV/c are clearly seen.

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 positive tracks coming from the K^- interaction points in all targets. They mostly correspond to protons emitted, after the K^- interaction, by different background processes and by hypernucleus formation and decay. In this spectrum, however, π^+ coming from the formation of neutron-rich hypernuclei may also be found. The two peaks at low momentum values are given by the cut-off momenta for tracks directly entering the spectrometer from the target (forward tracks) and tracks entering the spectrometer after having crossed the interaction/target region (backward tracks). It is worth noticing the low values of these cut-off momenta.

4. FINUDA PHYSICS PROGRAM BEYOND 2003

Similar beam time allocations are expected for at least the next three forthcoming years, with a probable increase of the machine luminosity up to $\mathcal{L}$=5$\cdot 10^{32}$cm^{-2}s^{-1}. Two options are open for the FINUDA physics program beyond 2003: (i) to continue the survey on excitation energy spectra and weak decay observables for targets of medium-large A; (ii) to make a strong effort on some selected light targets, if new and interesting results will be obtained from the present survey. The item of neutron-rich hypernuclei seems, in this respect, one of the most promising.

5. ACKNOWLEDGMENTS

The authors would like to thank S. Bertolucci, Director of the LNF, for his constant support, the DAΦNE machine staff and in particular P. Raimondi for the excellent performances provided by the machine and the kind collaboration in the detector commissioning phase. They also thank A. Rotondi and P. Salvini, who made available the TRAFIT fitting package, and G. Montagna and C.M. Carloni Calame for the assistance in the implementation and use of the BABAYAGA package [15], for the simulation of Bhabha events in the apparatus. Finally, the authors are grateful to D. Pierluigi for her invaluable support to the daily life of the Collaboration.

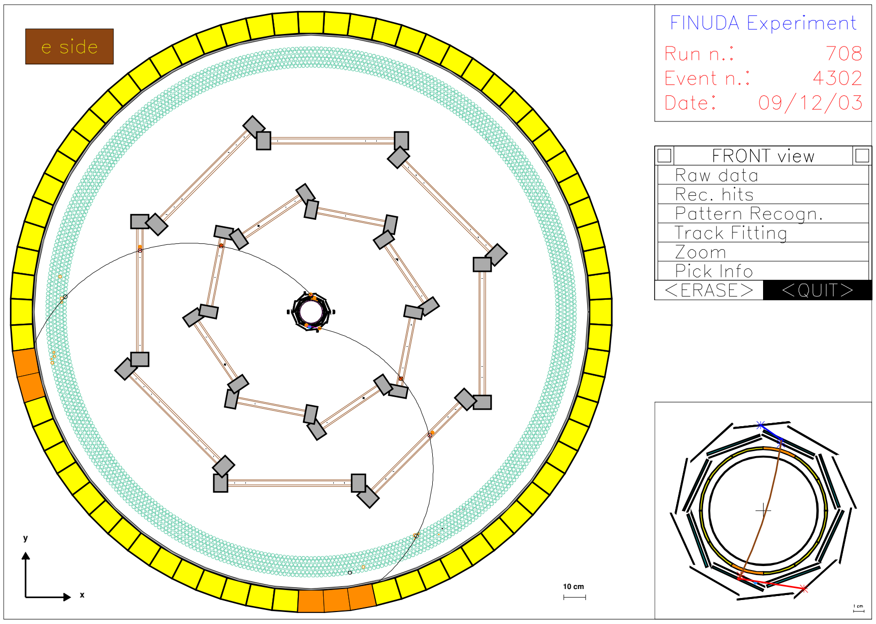

Figure 5. Candidate for a hypernuclear formation event. The μ^+ from the decay of the K^+ and a π^- of 260 MeV/c from the interaction of the K^- in a ^6Li target are seen. An enlarged view of the vertex region with the K^+K^- trajectories is shown in the inset.

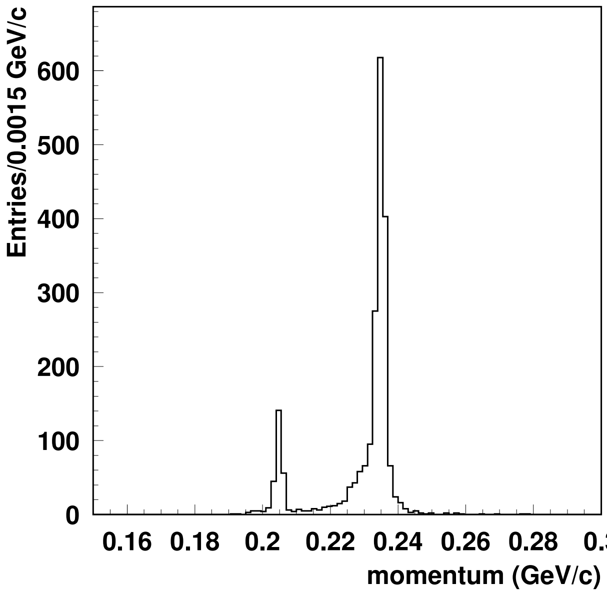

Figure 6. Momentum distribution of the positive tracks coming from the K^+ stopping points. The peak at 236 MeV/c corresponds to the two body decay $K^+ \rightarrow \mu^+\nu_\mu$, the peak at 205 MeV/c corresponds to the two body decay $K^+ \rightarrow \pi^+\pi^0$.

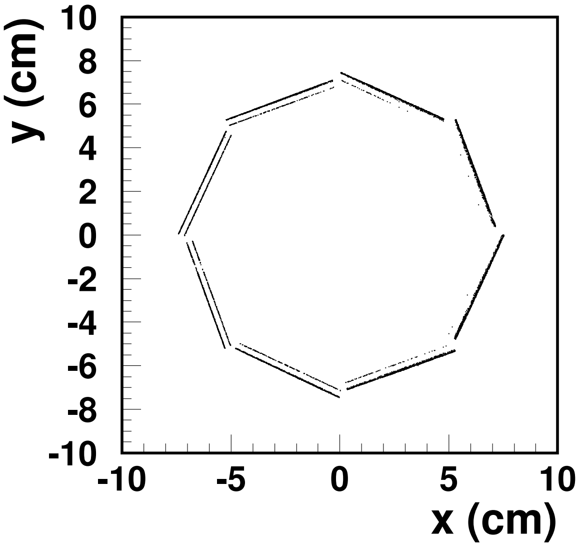

Figure 7. Scatter plot of the reconstructed y vs x coordinates of the K^- stopping points. The most external octagon corresponds to the eight target modules, where most of the K^- stop. Stops in the microstrip ISIM modules are also seen on the left side of the picture; they corresponds to about 10% of the total stops and are due to the (e^+, e^-) beam boost, which is directed in the positive x versus.

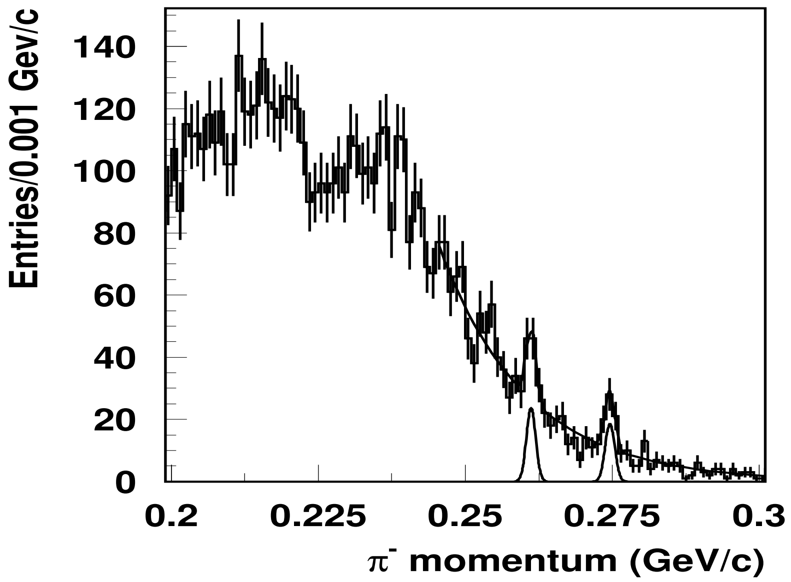

Figure 8. Momentum spectrum of the π^- coming from the K^- interaction points into the three ^{12}C targets. The two peaks of the $^{12}_{\Lambda}C$ ground state at 275 MeV/c and of the excited state at 261 MeV/c are clearly seen, with a momentum resolution of 1.1% FWHM.

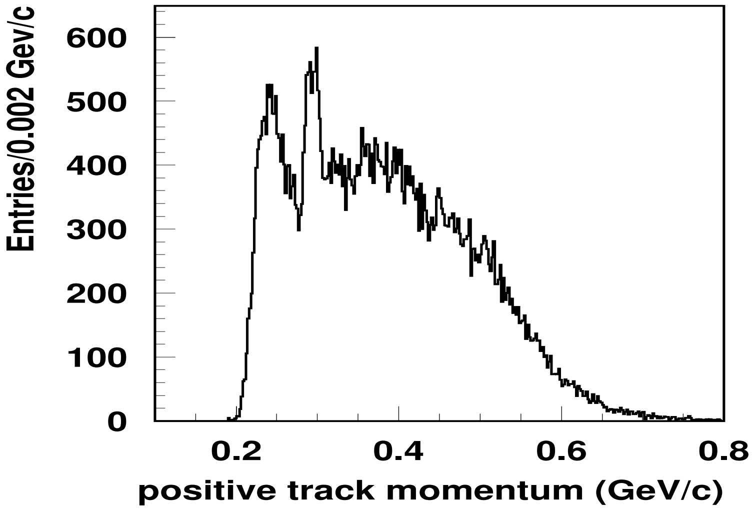

Figure 9. Momentum spectrum of the positive tracks coming from the K^- interaction points in all targets. See text for details.

REFERENCES

1. T. Bressani in Proc. Workshop on Physics and Detectors for DAΦNE, Frascati, April 9-12, 1991, ed. G. Pancheri (Laboratori Nazionali di Frascati), p.475.
2. The FINUDA Collaboration, M. Agnello et al., "FINUDA, a detector for Nuclear Physics at DAΦNE", LNF Internal Report, LNF-93/021(IR), 1993.
3. The FINUDA Collaboration, M. Agnello et al., "FINUDA Technical Report", LNF Internal Report, LNF-95/024(IR), 1995.
4. T. Bressani in Proc. Int. School of Physics "E. Fermi", Course CXXXVIII, ed. A. Molinari and R.A. Ricci, IOS Press, Amsterdam (1998), 473.
5. A. Zenoni on behalf of the FINUDA Collaboration in Physics and Detectors at DAΦNE, Frascati Physics Series Vol. XVI (1999), ed. S. Bianco et al., p.739.
6. P. Gianotti on behalf of the FINUDA Collaboration, Nucl. Phys. A691 (2001) 483c.
7. A. Zenoni and P. Gianotti, Europhysics News 33/5 (2002) 157.
8. T. Bressani in Proc. Int. School of Physics "E. Fermi", Course CLIII, ed. A. Molinari et al., IOS Press, Amsterdam (2003) 323.
9. T. Bressani, XXVIII Mazurian Lakes Conference on Physics, Krzyze, Poland, August 31 - September 7, 2003, in press.
10. A. Feliciello on behalf of the FINUDA Collaboration, Nucl. Phys. A691 (2001) 170c.
11. V. Paticchio on behalf of the FINUDA Collaboration, Nucl. Phys. A691 (2001) 119c.
12. H. Tamura et al., Phys. Rev. Lett. 84 (2000) 5963.
13. T. Nagae et al., Nucl. Phys. A691 (2001) 176c.
14. G.C. Bonazzola et al., Phys. Rev. Lett. 34 (1975) 683.
15. C.M. Carloni Calame et al., Nucl. Phys. B 584 (2000) 459.