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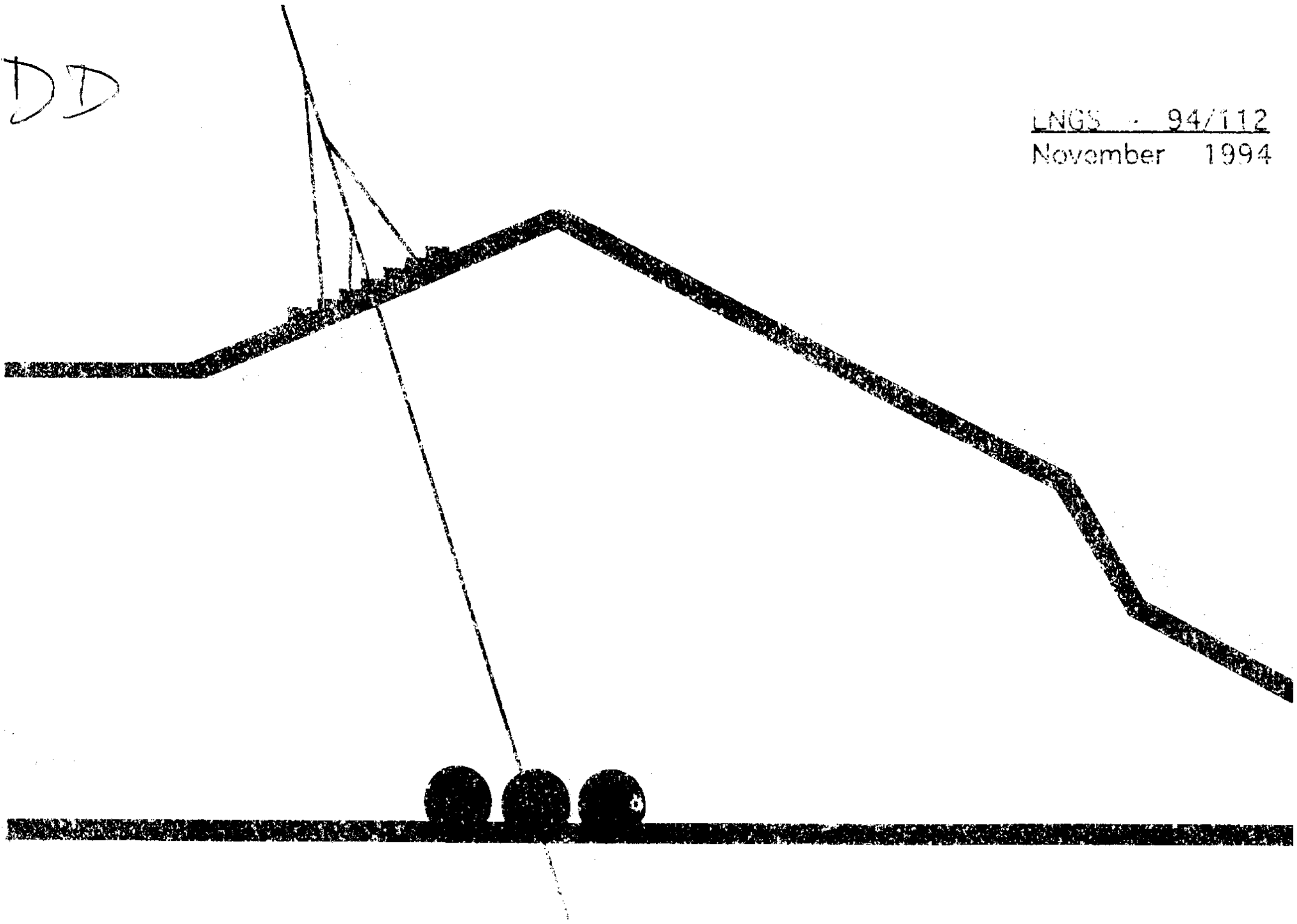

# A New Design Scintillating Fiber Calorimeter to Search for Neutrino Oscillations in Massive Underground Detectors

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## Abstract

A new design for an electromagnetic and hadronic calorimeter using the scintillating fiber technology is presented. The proposed calorimeter has been optimized for applications in massive underground experiments devoted to neutrino oscillation studies. The layout is described in details and first results on a prototype are presented. Finally, simulations showing the features of the whole calorimeter are discussed.

(Submitted to Nuclear Instruments and Methods)

# 1 Introduction

The search for neutrino oscillations [1], [2] in large volume underground experiments represents an exciting issue in the actual scenario of the elementary particle physics.

In the simplified case in which oscillations are assumed to occur between only two neutrino species, the probability of an initial $\nu_\mu$ of energy $E_\nu$ being equal to $\nu_\tau$ at a distance $L$ is

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2[\frac{1.27\Delta m^2 L}{E_\nu}]$$

where $\Delta m^2$ in eV, $L$ in meters and $E_\nu$ in MeV.

Atmospheric neutrino experiments performed in underground laboratories show an anomaly in the contained charged current neutrino interactions, interpreted as a possible signal for neutrino oscillations. In particular in water Čerenkov detectors (Kamiokande[3], IMB[4]) the ratio of $\nu_\mu$, $\nu_e$ charge current interaction (CC) is smaller than predicted by theoretical calculations.

On the other hand, calorimetric experiments such as NUSEX[5] and Frejus[6] do not see this effect. Recently Soudan II[7], an iron calorimeter detector, finds a small muon-electron ratio, in agreement with the water Čerenkov experiments, even if with small statistical significance.

The present experimental situation is far from clear, this leads to consider the possibility to realize a new generation underground experiment in order to perform precise measurements of $\mu/e$ and $\mu$ crossing, $\mu$ stopping and $\mu$ contained event ratios. This measure as a function of $L/E$ allows to explore neutrino oscillations in a wide range of $\Delta \mathrm{m}^2$ and $\sin^2 2\theta$ parameters. In fact, having been produced in the atmosphere all around the earth, the neutrinos travel distances $L$ of $10 \div 13000$ km before interacting in the underground detector. The average energy of the contained events is about 1 GeV.

Moreover, the possibility to produce high flux long baseline neutrino beams, allows to extend the range of investigation in the parameters space ( $\Delta \mathrm{m}^2$ - $\sin^2 2\theta$ ) using, for instance, a CERN – Gran Sasso neutrino beam. If $\nu_\mu \rightarrow \nu_\tau$ oscillations occur this would lead to an apparent increase in the neutral to charged current ratio (NC/CC).

Further long baseline neutrino projects are under discussion at Fermilab, Brookhaven, Serpukhov, KEK (see table 1).

| LABORATORY | TARGET | MASS kton | DISTANCE km | PROTON ENERGY GeV |
|---|---|---|---|---|
| Brookhaven | E889 detectors | 6 | 1,3,20 | 25 |
| CERN | ICARUS, Others | 5(15) | 732 | 80 to 450 |
| | Superkamiokande | 50 | 8752 | 450 |
| | NESTOR | 300 | 1676 | 450 |
| Fermilab | P822, Soudan 2 | 5 | 730 | 120 |
| KEK | Superkamiokande | 50 | 250 | 12 |
| Serpukhov | ICARUS, Others | 15 | 2192 | 600 |
| | Baikal | $1.1 \times 10^3$ | 4200 | 600 |

Table 1: Long baseline neutrino beam projects presently under study

In the following we want to discuss how a new generation experiment devoted to the study of neutrino oscillations could be realized.

# 2 Conceptual design

Both atmospheric and long baseline neutrino detection require the largest possible target mass, particle identification capability and good energy measurement. In particular, atmospheric neutrinos studies need:

- Muon-electron discrimination
- A low energy threshold and high containment energy to increase the number of events and to investigate a wide energy range.
- Isotropy of the detector: due to the quasi–isotropic distribution of atmospheric neutrinos, the complete angular acceptance is an important feature of the apparatus. Isotropy permits to detect neutrino interactions for different directions of incoming neutrinos.
- Good time resolution to measure the versus of the interaction.

Besides, long baseline neutrino investigation needs a good signature of hadronic showers in order to select neutral current events.

A fine grained calorimeter gives particle identification and good energy measurement. Equipped with fast detectors, it allows to have both the direction of the interaction and a low energy threshold in order to achieve a large event statistics.

Liquid detectors, like the ICARUS[8] liquid Argon project and the water Čerenkov experiments, like Superkamiokande[9] are the best example of isotropic apparata, where the 3-Dimensional symmetry allows full solid angle coverage.

On the contrary due to 1-D symmetry, in multilayer sampling calorimeters the angular acceptance is small and the rate of detected atmospheric neutrino events is considerably reduced. Moreover most of the incoming neutrino directions are not well detected.

In order to overcome the difficulties of liquid detectors and multilayer calorimeters, we have investigated the possibility to use a new type of detector.

In this article we propose to extend the scintillating fiber technology to large volume underground experiments. The advantages in comparison with liquid detectors are evident: solid structures are more stable and easy to handle. This technology has extensively and successfully been used in the electromagnetic calorimeter of CHORUS experiment[10], currently running on the CERN neutrino beam.

Suitably designed, a scintillating fiber calorimeter allows to reach 2-D symmetry, placing the angular acceptance of this solution ($\Delta\Omega \simeq 0.7 \cdot 4\pi$) close to the one of the liquid detector and ensuring good detection efficiencies both for long-baseline neutrino beam and atmospheric neutrinos.

# 3 Detector

The detector we propose is modular and easily extendible (Fig. 1).

Each block is 1 kton (Fig. 2) $(8 \times 6.4 \times 8)$ m$^3$ composed by Basic Modules (B.M.) $(0.3 \times 0.3 \times 8)$ m$^3$, 2 tons each, surrounded by streamer tubes and logically divided in four Basic Calorimetric Elements (B.C.E.)

This is the basic solution in which all BCE are parallel and the fibers readout provides 2 coordinates. The $3^{rd}$ coordinate, should be provided by an independent tracking system (streamer tubes).

We have used GEANT3[10] to simulate in details the proposed setup and to study the best experimental solution to detect different neutrino types, starting from few hundred MeV.

## 3.1 Basic Calorimetric Element (B.C.E.)

The basic calorimetric element can be realized as follows: the element is made by an $\sim$ 8 meters long bar of an iron-concrete mixture as radiator with scintillating fibers as active component, suitably distributed in the bar. Concrete and iron ($5\% \div 10\%$ in volume), increase the lateral spread and the multiplicity of the electromagnetic showers.

The cross section of the element is a square 15 cm side. The weight is about 0.5 tons and the thickness $2 \div 3$ radiation lengths depending on the ratio between iron and concrete. Anyway it has to be noted that these radiation lengths are completely active.

In table 2 are reported the main features of the BCE absorber.

| $\%Fe$ (Volume) | $\%Fe$ (Weight) | BCE W tons | Xo cm | $\lambda$ cm | $<\rho>$ g/cm$^3$ | $<Z>$ | $E_c$ MeV |
|---|---|---|---|---|---|---|---|
| 5 | 14 | 0.44 | 8.52 | 46.2 | 2.77 | 13.13 | 56. |
| 10 | 26 | 0.48 | 7.09 | 44.0 | 3.04 | 14.89 | 50. |
| 15 | 36 | 0.52 | 6.06 | 41.7 | 3.31 | 16.36 | 46. |
| 20 | 44 | 0.56 | 5.30 | 39.6 | 3.57 | 17.61 | 43. |

Table 2: Main features of the BCE absorber for several iron and concrete percentages

The number of fibers and their positions in the BCE element have been optimized by means of a Monte Carlo procedure. In order to guarantee the detector isotropy, the fibers are randomly located inside the bar (Fig. 3).

In each element there are 400 fibers, 2 mm in diameter, viewed at each end, in the most conservative hypothesis, by one 2" photomultiplier.

The fiber attenuation length now achievable ($5 \div 6$ m) allows to obtain a 8 m bar length.

The fibers are protected by a low cost envelope and their positions are determined by masks set 1 m apart along the 8 m bar.

In the following the main features of this element are summarized:

- 15 cm side square ($2 \div 3$ active radiation lengths)
- 400 scintillating fibers, 2 mm in diameter, as active component
- Fiber attenuation length ($5 \div 6$) m
- A mixture of concrete and iron ($5\% \div 10\%$) as radiator

At present this design seems to be quite satisfactory. It is not convenient to increase the density too much as in usual iron/lead calorimeters: apart from the cost of the radiator, the same weight and granularity readout is obtained by increasing the number of the electronic channels.

However the final choice of the bar parameters will be the best compromise among granularity, fiber numbers, weight, radiation length, light yield and cost.

## 3.2 Basic Module (B.M.)

Four of Basic Calorimetric Elements together form a module of 2 tons, 1600 scintillating fibers. Each module is surrounded by horizontal and vertical streamer tubes, $2 \times 2$ $cm^2$ in cross section, in order to provide a complete tracking of the event. In fact, by using a detailed tracking information it is possible to obtain a precise measurement of the particle path length, ($\Delta l$), in each BM to compute the specific ionization loss ($\frac{\Delta E}{\Delta l}$).

This modularity has to be repeated in order to reach a 1 kton block volume.

At the first stage the experiment can be thought as composed by $4 \div 8$ blocks ($4 \div 8$ ktons). With $300 \div 400$ MeV of energy threshold $\sim 100$ events per kton per year are expected.

Actually for a 4 kton mass apparatus the total instrumentation, fibers and PMT's, are not more than two times the KLOE calorimeter[12] of DAΦNE project at INFN Frascati Laboratories.

Due to the high fiber density, we are studying the possibility of improving the granularity of this apparatus by exploiting the full resolution capability of the fibers by means of a new readout system.

In this hypothesis we can consider the possibility to implement a different geometry. BCE dimension can be reduced and crossed BCE planes would provide x and y coordinates. In this case the streamer tubes are no more required.

# 4 Detector Performances

## 4.1 BCE prototype test

A Basic Calorimetric Element prototype, 1 m long, has been realized using 2 mm diameter POL.HI.TECH. fibers and extensively tested in a cosmic ray scintillator telescope. It is viewed at each end by one 2" Philips XP2020 photomultiplier. Setting the gain at $1.5 \cdot 10^7$ we obtain the charge distribution for minimum ionizing particles shown in Fig. 4a. This corresponds to 35 photoelectrons for each side, which typically provides $\sim$ 500 mV signal amplitude. The resolution (HWHM) is $\sim 35\%$.

Taking into account the data from single fiber charge measurement, we have simulated the charge distribution produced by muons (Fig. 4b). We find a good agreement with the experimental data.

The efficiency for cosmic ray particles crossing the BCE element, obtained ORing the signals from both sides is shown in Fig. 5 for different threshold values.

By measuring the arrival time of incoming muons in BCE element inserted in the cosmic ray telescope, we obtain the distribution shown in Fig. 6. The resulting time resolution, without taking into account pulse amplitude correction, is $\simeq$ 1 ns.

Thus the use of scintillating fiber gives to the detector a good time resolution, allowing short time coincidences as well.

In this way the accidental coincidence rate is very low and we think to implement soft triggers in order to lower as much as possible the energy threshold ($300 \div 400$ MeV), which represents an important feature for atmospheric neutrino studies. An event will be defined by not more than three elements coincidence. However, muon decays suggests a very low energy trigger based on the delayed coincidence between two elements. Besides an energy trigger for electrons could be implemented.

## 4.2 Calorimetric features

We have used the Geant3 based Monte Carlo to study the calorimetric features of the proposed setup. The simulation of the detector response is given with high accuracy, describing the granularity of the module up to the 2 mm fiber and introducing a low energy cut for radiative processes, connected to the particle propagation into the medium ($E_{th}$ = 300 keV).

Several types of absorber have been considered to study the best percentage of iron in the concrete in order to identify muons and to separate electromagnetic and hadronic showers

The simulated energy resolutions, shown in Fig. 7, are respectively $\sigma(E)/E = 0.16/\sqrt{E}$ for electromagnetic and $\sigma(E)/E = 0.7 + 0.30/\sqrt{E}$ for hadronic showers. Taking into account the total mass of the calorimeter and the resulting limited granularity these figures are rather good.

Calculations includes sampling fluctuations and detector response.

One of the Monte Carlo results provides a general requirement on the electronic readout (PMT dividers, ADC and cabling); in order to measure high charges due to energy released by electromagnetic and hadronic showers, good linearity over a factor 50 in dynamics is needed.

## 4.3 Particle identification

One of the main problems in the neutrino oscillation studies is the identification of electromagnetic and hadronic showers due to the interaction of $\nu_e$ or $\nu_\tau$, and of single muons generated by $\nu_\mu$.

The capability of the experiment to measure ionization loss ($\Delta E$) and the path ($\Delta l$) in each basic calorimetric element, many times along the track, allows particle identification using the $\frac{\Delta E}{\Delta l}$ versus range method. In particular the parameter $R/\frac{\Delta E}{\Delta l}$ is plotted in Fig. 8a for electrons and muons.

Further variables can be exploited to achieve a good discrimination power, as an example the 'over-2 mip energy'/$E_{total}$ is shown in Fig. 8b for electrons and charged pions.

The tracking system surrounding the calorimetric element improves particle identification and allows a complete calibration of the calorimeter, by means of the cosmic ray muons crossing the apparatus.

Finally, several measurements along the track (one for each basic calorimetric element), give both information about the direction of incoming neutrinos and a clean signature for stopping muons.

### 4.4 Estimated sensitivity

The apparatus can detect both atmospheric neutrinos and neutrino beam interactions. The direction and timing of the beam spill allow an efficient event identification. Besides, it will be possible to take data on atmospheric neutrino interactions during runs with the long baseline neutrino beam.

We expect after two years operations of this $4 \div 8$ kton apparatus about $1000 \div 2000$ atmospheric contained neutrino events.

The statistical significance should be rather good and the errors below the neutrino flux uncertainty.

For what concerns the long baseline, at the distance of 730 km the $\nu_\mu$ flux would be about $6 \cdot 10^4/m^2$ *per* $10^{13}$ *protons* on the beam axis.

In a fiducial region of about 2/3 of central detector volume, one expects about 5000 contained events to measure the apparent NC/CC ratio.

The result of neutrino oscillation experiments are usually plotted in in $\Delta \mathrm{m}^2$ - $\sin^2 2\theta$ plane, in which regions excluded are delimited by contour of 90% confidence level. The exclusion plots provided by this apparatus in 1 year of operation, if no oscillations are observed, are shown in Fig. 9 in comparison with the present experimental situation.

## 5 Conclusions

The scintillating fibers seem to be a promising technology to implement massive calorimeters when a fast, granular and quasi-isotropic detector is required. Due to the low cost, the concrete as radiator represents an interesting solution in underground apparata, allowing good energy measurements, as confirmed by the results of the preliminary test.

Finally, long term stability without safety problems and the extreme modularity of the proposed experiment are appealing figures, to keep in mind for future project.

## 6 Acknowledgements

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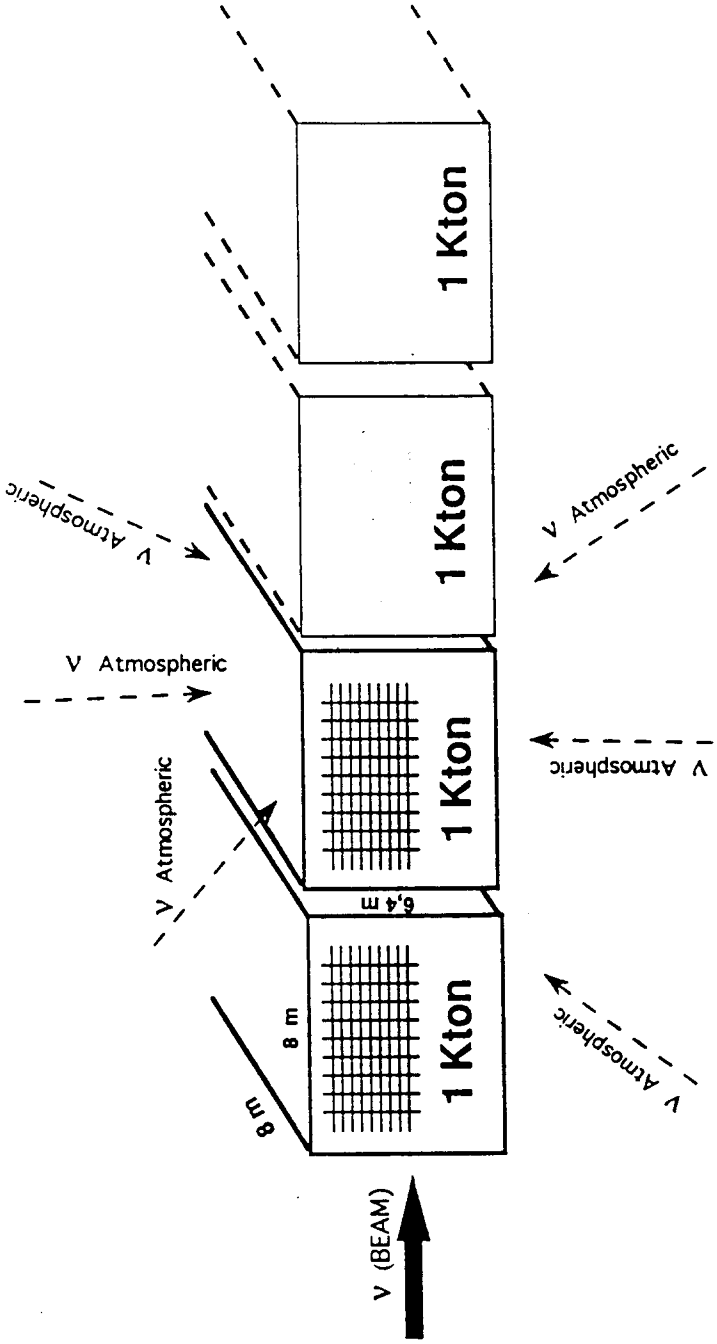


Figure 1: General detector layout for atmospheric and long baseline neutrinos

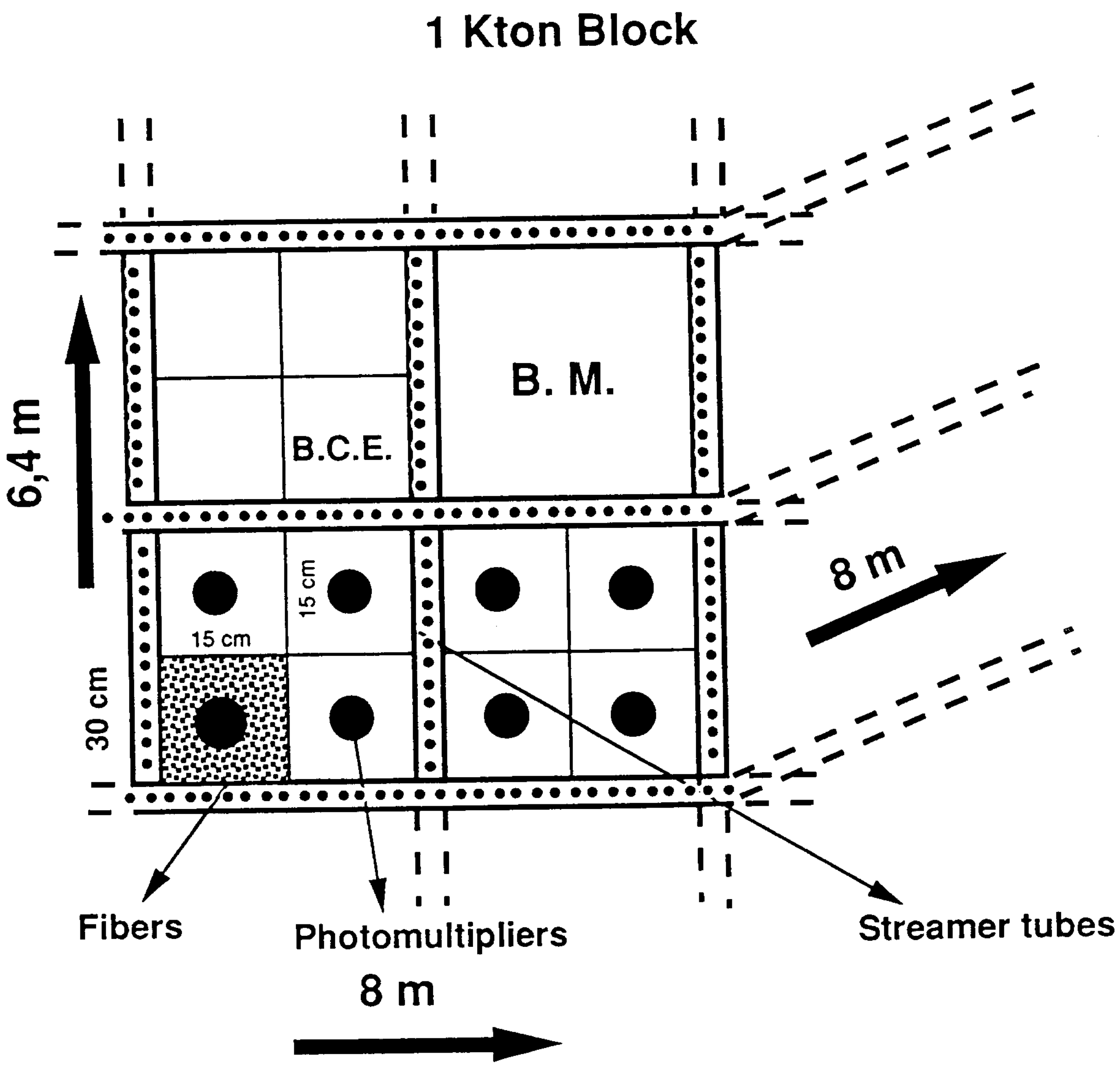


Figure 2: Details of the detector structure: in cross section is shown the Basic Calorimetric Element, made of 400 fibers and concrete, viewed at each end by a photomultiplyer. Four BCE form a BM module surrounded by streamer tubes.

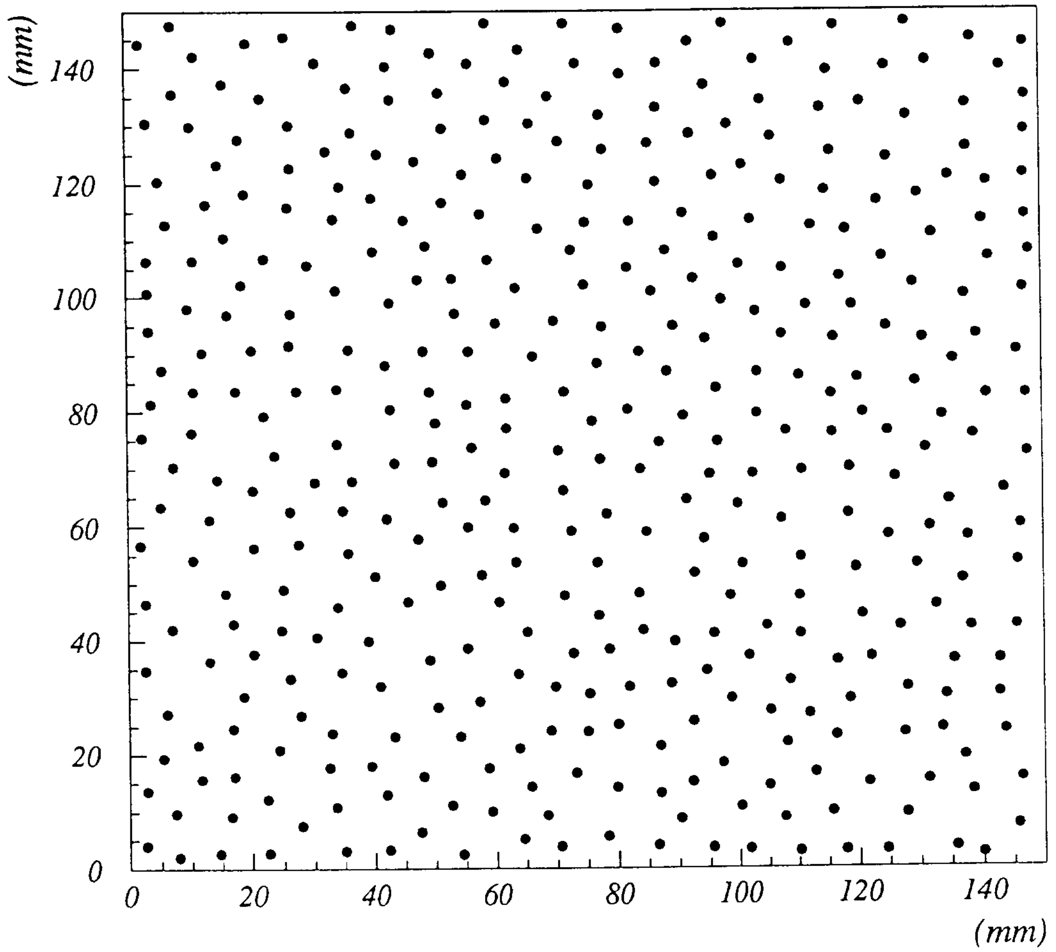
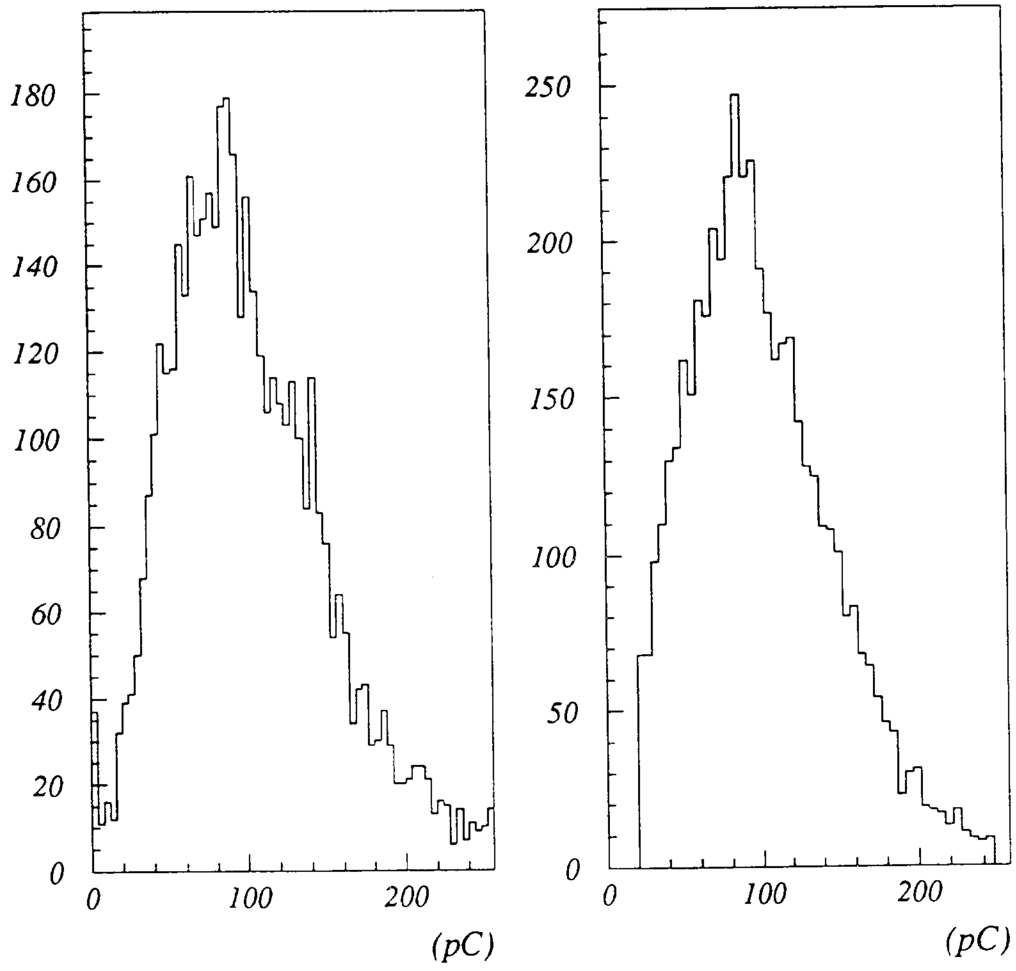


Figure 3: Cross section of the Basic Calorimetric Element: black dots represent the fiber positions in the bar



a) b)

Figure 4: Charge response of the Basic Calorimetric Element to muons crossing the cosmic ray telescope (a) The mean pulse height corresponds to 35 photoelectrons at each side. Simulated charge distribution for muons crossing the BCE (b).

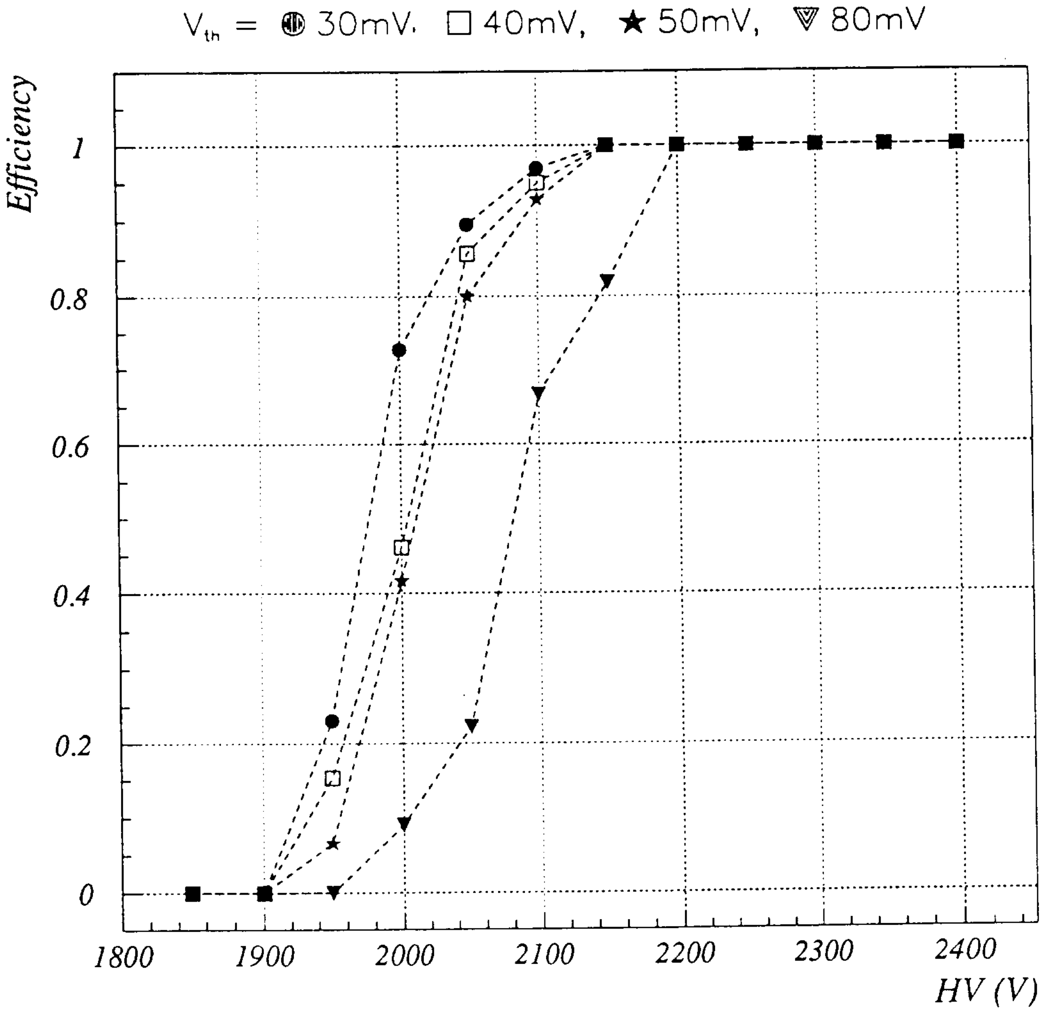


Figure 5: Efficiency of the BCE to crossing cosmic ray muons as a function of the threshold.

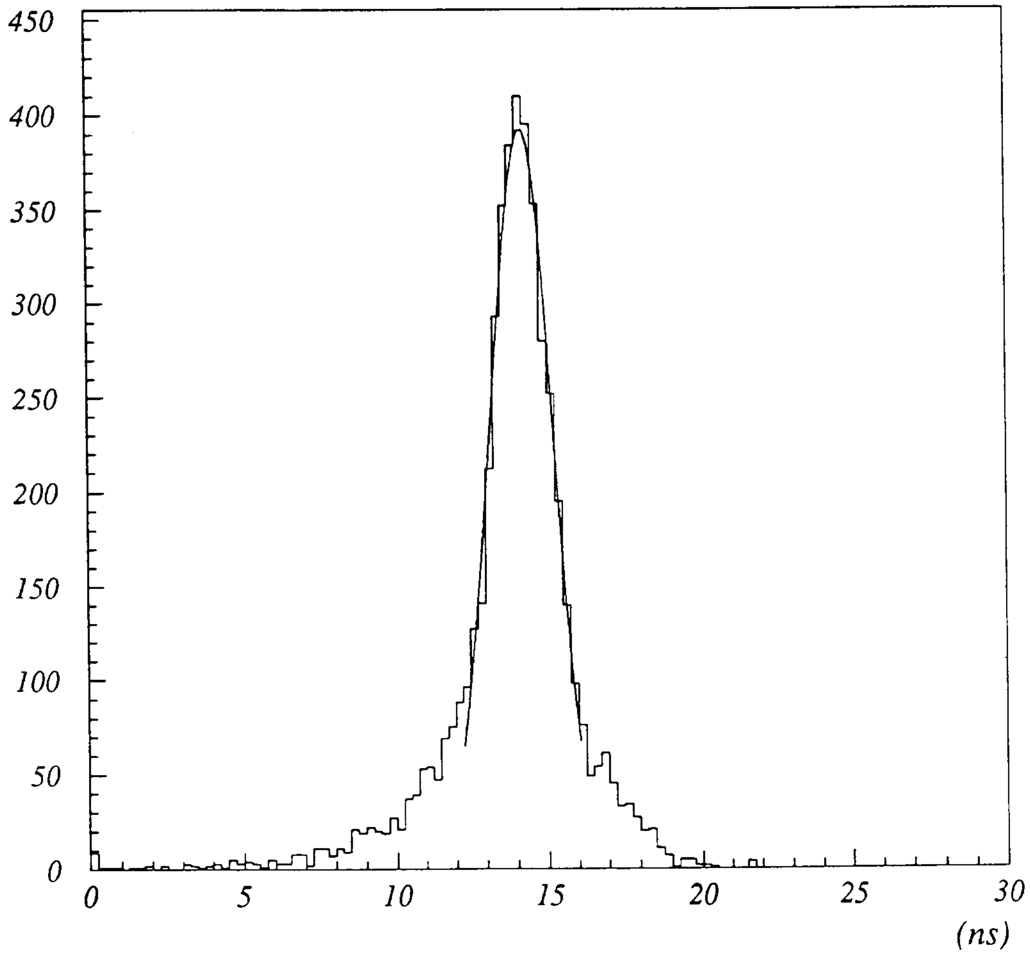


Figure 6: Time response to crossing cosmic ray muons: the gaussian fit gives a time resolution of $\sim 1$ ns.

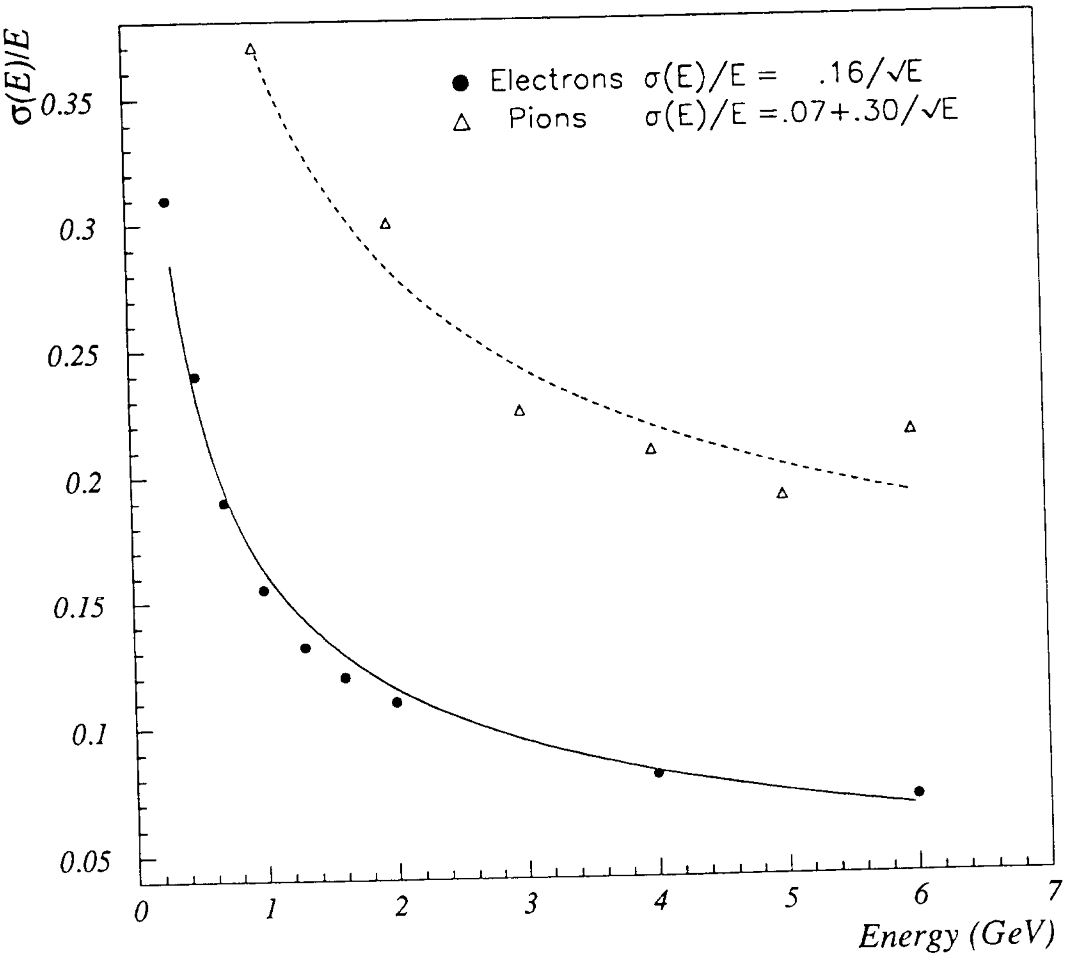


Figure 7: Energy resolution of the calorimeter as a function of energy. The curves have been obtained simulating electron and pion interactions in the apparatus. The used absorber mixture is 85% concrete, 15% Fe in volume.

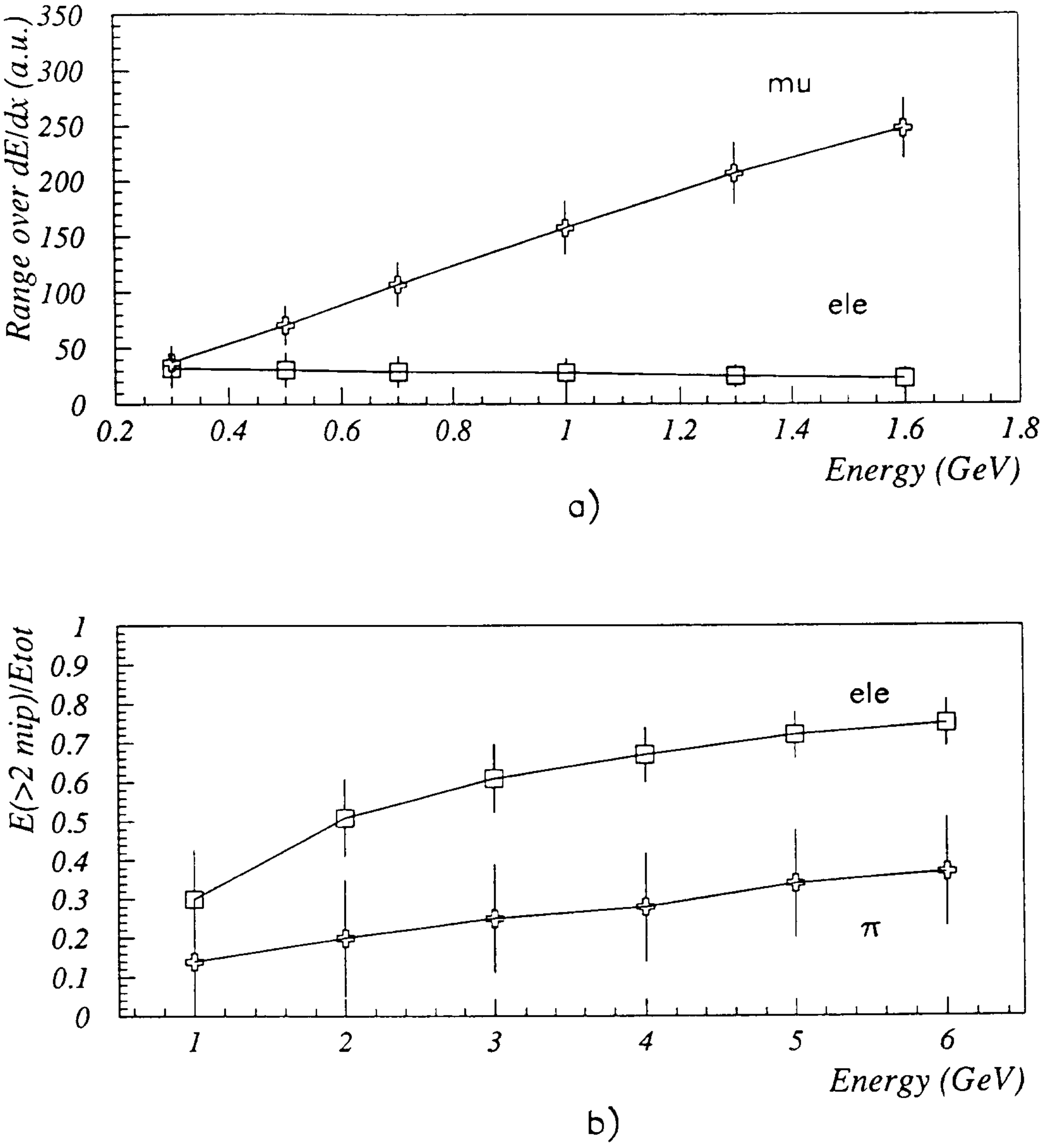


Figure 8: Two examples of simulated particle separation as a function of energy.

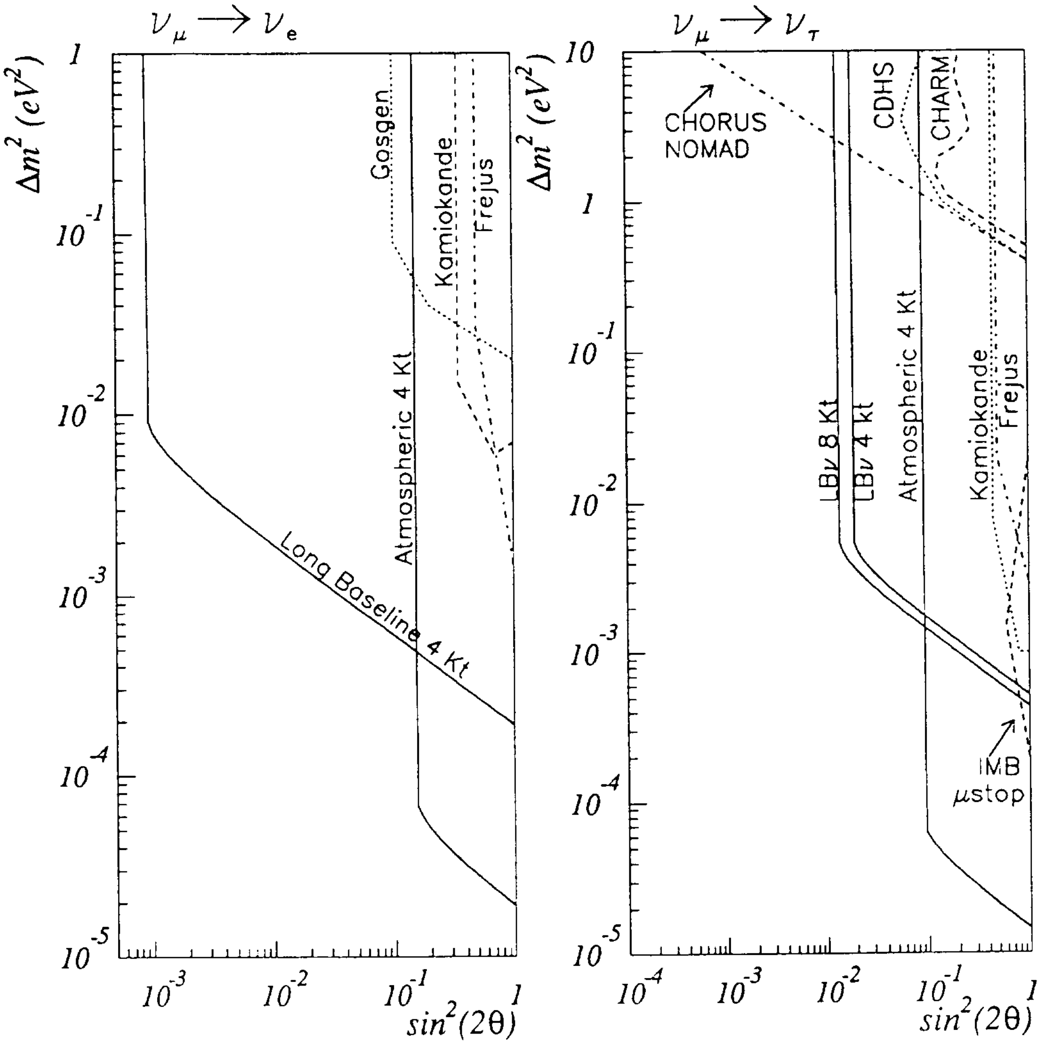


Figure 9: Sensitivity of the proposed apparatus.