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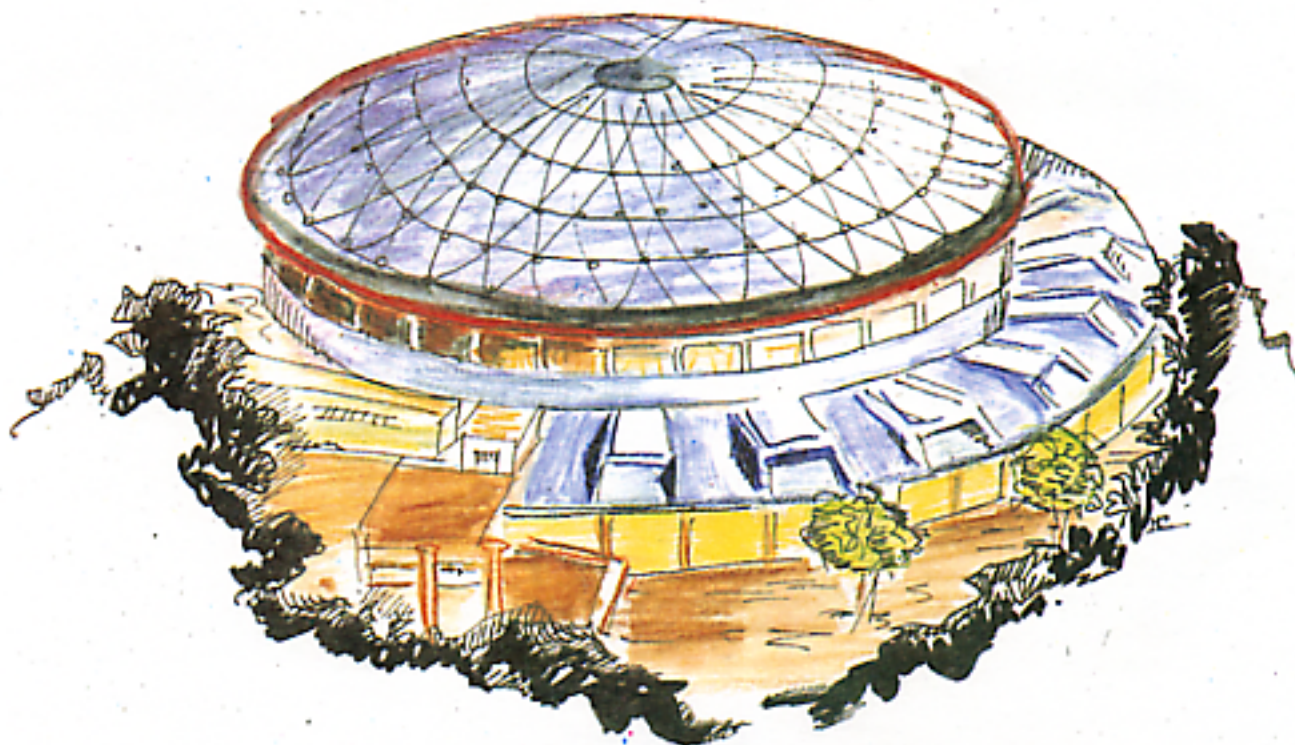
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A COSMIC-RAY VETO SYSTEM FOR THE GRAVITATIONAL WAVE DETECTOR NAUTILUS

A Cosmic-Ray Veto System for the Gravitational Wave Detector NAUTILUS

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Abstract

The ultracryogenic resonant gravitational wave antenna NAUTILUS now operating at Frascati INFN National Laboratory has been provided with a cosmic-ray veto system consisting of layers of streamer tubes. The experimental setup and performances of the system are shown. Preliminary results on the data collected during the calibration operations of the antenna are also presented together with the expected number of events from the interactions of high-energy hadrons and muons and multihadron showers with the gravitational antenna.

1. Introduction

NAUTILUS[1] , the first ultracryogenic resonant gravitational wave antenna, is now operating at Frascati INFN National Laboratory. The goal of this new-generation antenna is the detection of bursts of gravitational waves from sources located at distances up to the Virgo Cluster of galaxies. In order to clearly assign the signal detected by the antenna to g.w. bursts, the usual strategy is to make coincidences among similar detectors and to use local seismic and electromagnetic veto systems. In addition the NAUTILUS detector has been equipped with a cosmic-ray veto system consisting of

layers of streamer tubes[2] placed above and below the antenna cryostat.

The pioneering contribution on the study of the influence of high-energy particles on gravitational-wave antennas has been given in the 60's by Beron et al. at Stanford[3] [4] ; while ten years later Grassi Strini et al.[5] found a quantitative relation between the particle energy loss and the vibrational energy measured in an aluminum bar, using a 30-MeV proton beam. A plastic scintillator cosmic-ray telescope[6] has been operating at Stanford together with the cryogenic antenna in 1986 but no signals were found over the detector noise of about 20 mK. Amaldi and Pizzella[7] , and then Ricci[8] , have calculated and simulated the energy loss distribution of high-energy cosmic muons crossing a Weber-type antenna and derived the expected number of events giving a signal over a prefixed threshold. Recently, J. Chiang et al.[9] have published results of a Monte Carlo simulation of interaction of cosmic ray hadrons with a resonant gravitational wave antenna.

The planned NAUTILUS sensitivity is one order of magnitude better than that of other similar detectors; at the effective noise temperature T_{eff} of about 1 mK we expect few events per day originated by cosmic rays giving a detectable signal in the antenna, thus leading the need of a cosmic-ray monitor. In addition, the possibility to make a coincidence between cosmic ray detection and energy oscillation of the bar can give information on the sensitivity of a large aluminum bar (2300 Kg) when used as particle detector of rare events in cosmic rays[10] .

In this paper we present the experimental setup and the preliminary results on the data collection of the cosmic-ray detector assembled for NAUTILUS. We also report on the expected number of events from the interaction of high-energy hadrons and muons with the bar, by evaluating for the first time the effect due to multihadron showers. Moreover, for the simulation we have used a relation between the vibrational energy of the antenna and the energy lost by incident particles, improved with parameters suitable for low temperatures.

2. Cosmic-Ray Monitor for the NAUTILUS Gravitational Wave Detector

The cosmic-ray detector has been designed in order to optimize the detection acceptance for high-energy particles and Extensive Air Showers interacting with the antenna; it has a modular structure that allows an easy and fast disassembling during the gravitational wave detector maintenance operations. In the implementation of the cosmic-ray detector, we have been limited by the space left available by the cryostat.

The detector consists of seven layers of limited streamer tubes (LST) of which three (6×6 m^2, 24 LST each) are mounted above the cryostat (at a distance of 3.95 m from the antenna center) and four layers (6×2.75 m^2, 11 LST each) are placed on the ground level (see fig. 1). The analogic read-out of the LST wires allows a measurement of the multiplicity of the particles impinging the detector.
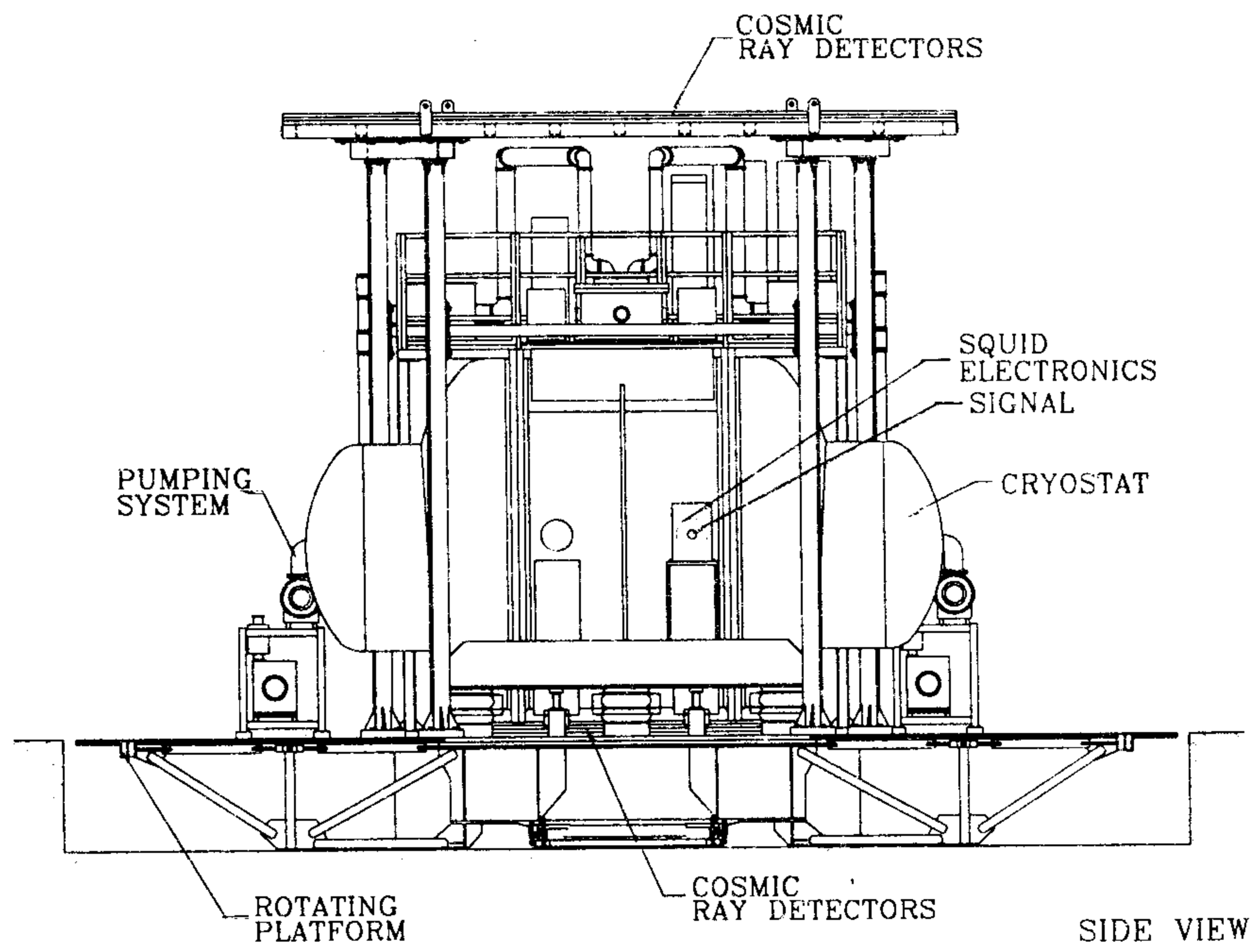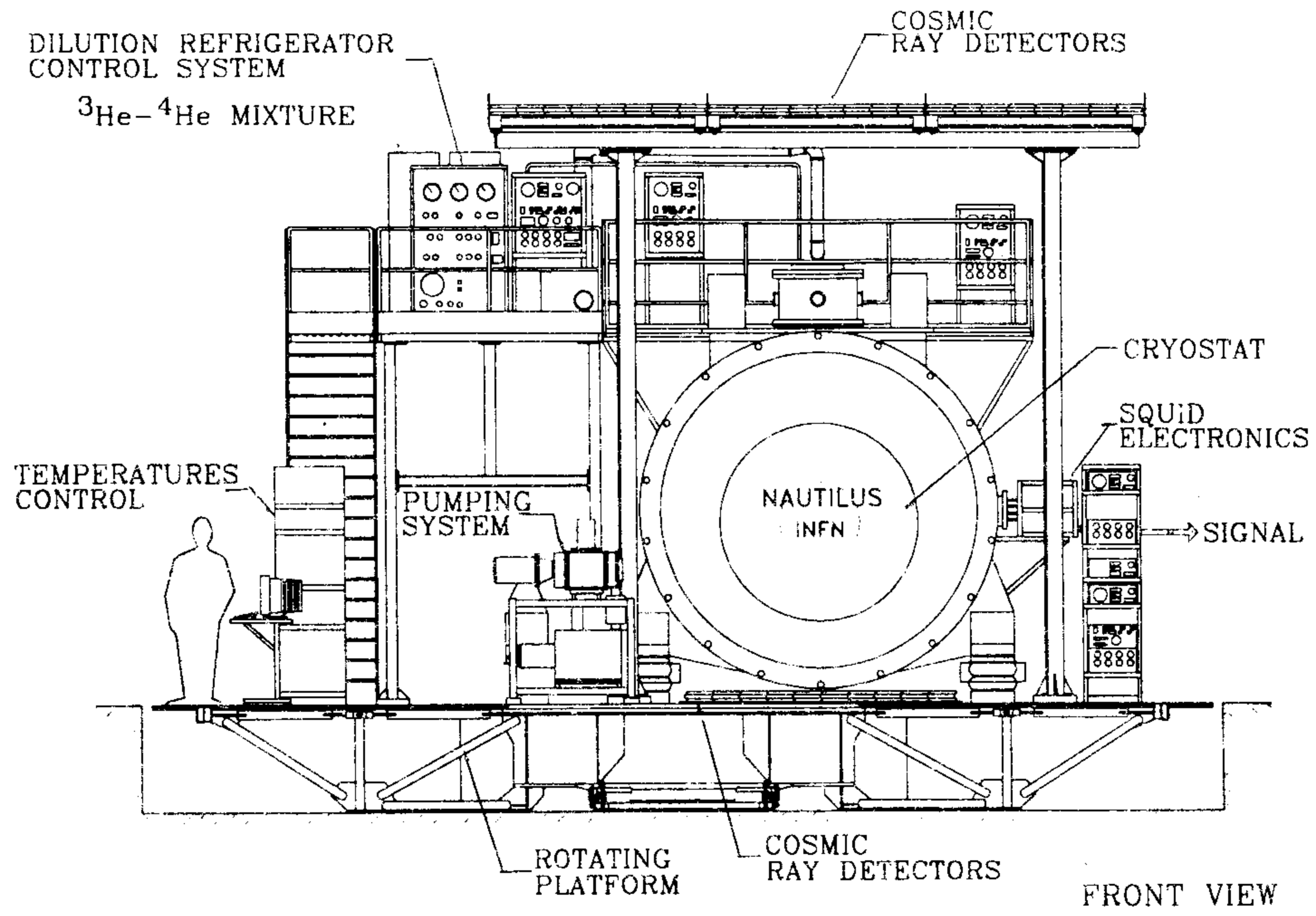
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DILUTION REFRIGERATOR
CONTROL SYSTEM

^{3}He$-^4$He MIXTURE

COSMIC
RAY DETECTORS

CRYOSTAT

SQUID
ELECTRONICS

NAUTILUS
INFN

SIGNAL

TEMPERATURES
CONTROL

PUMPING
SYSTEM

ROTATING
PLATFORM

COSMIC
RAY DETECTORS

FRONT VIEW

COSMIC
RAY DETECTORS

SQUID
ELECTRONICS

SIGNAL

PUMPING
SYSTEM

CRYOSTAT

ROTATING
PLATFORM

COSMIC
RAY DETECTORS

SIDE VIEW

Fig. 1. Layout of the NAUTILUS antenna.

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The LST are the large-size coverless plastic tubes, alredy used in the MACRO experiment[11] , (6.0 m long) operating in the limited streamer regime. Each tube consists of eight PVC-open-profile rectangular cells with a cross section of 3×3 cm^2 coated with graphite ($R \simeq 1-2$ $k\Omega/\square$). A Cu-Be anode wire with a diameter of 100 μm is strung along the center of each cell, supported every 50 cm by plastic bridges and connected through a printed circuit board to a common High Voltage bus. The profiles are inserted in an uncoated PVC sleeve. Plastic caps welded at the ends provide electrical and gas connections. The performances of these detectors as a function of High Voltage and different gas mixtures have been described elsewhere[12] ; we have intensively tested each tube against electrical failures and gas leakages, in order to ensure very stable operating conditions for the whole system.

The tubes are continously fluxed with a 60% Isobutane and 40% Ar gas mixture. This high-quenched mixture ensures a low number of after-pulses providing a better resolution in the particle multiplicity measurement. Tubes are operated at 5550 V; at this value the single streamer charge has an average value of 60 pC.
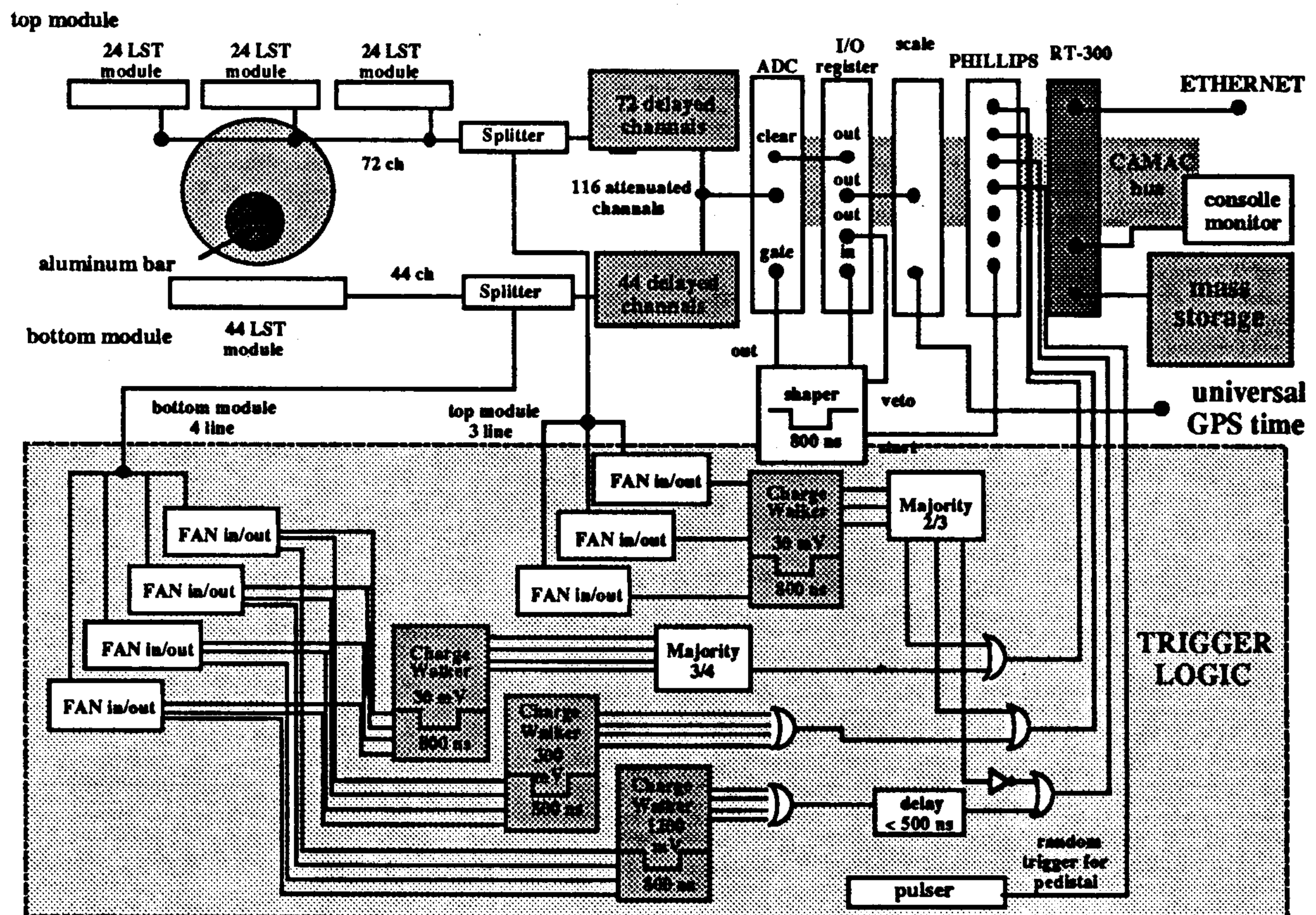

Fig. 2. Readout system.

A schematic diagram of the readout system is shown in fig. 2. Signals from the eigth wires of one tube are OR-ed together and each of these outputs is splitted in two signals:

the first one is sent to the trigger logic, while the second is attenuated (about 70 times), delayed by 500 ns and then processed by a 32-channel-ADC 12 bits (CAEN C205). The ADC gate signal is provided by the OR of the selected triggers. A typical charge distribution for muons is showed in fig. 3. The charge peak has been set at about 4 ADC channels in order to have a large dynamic range for showers. Therefore the ADC saturation threshold is approximately equivalent to 1000 particles.
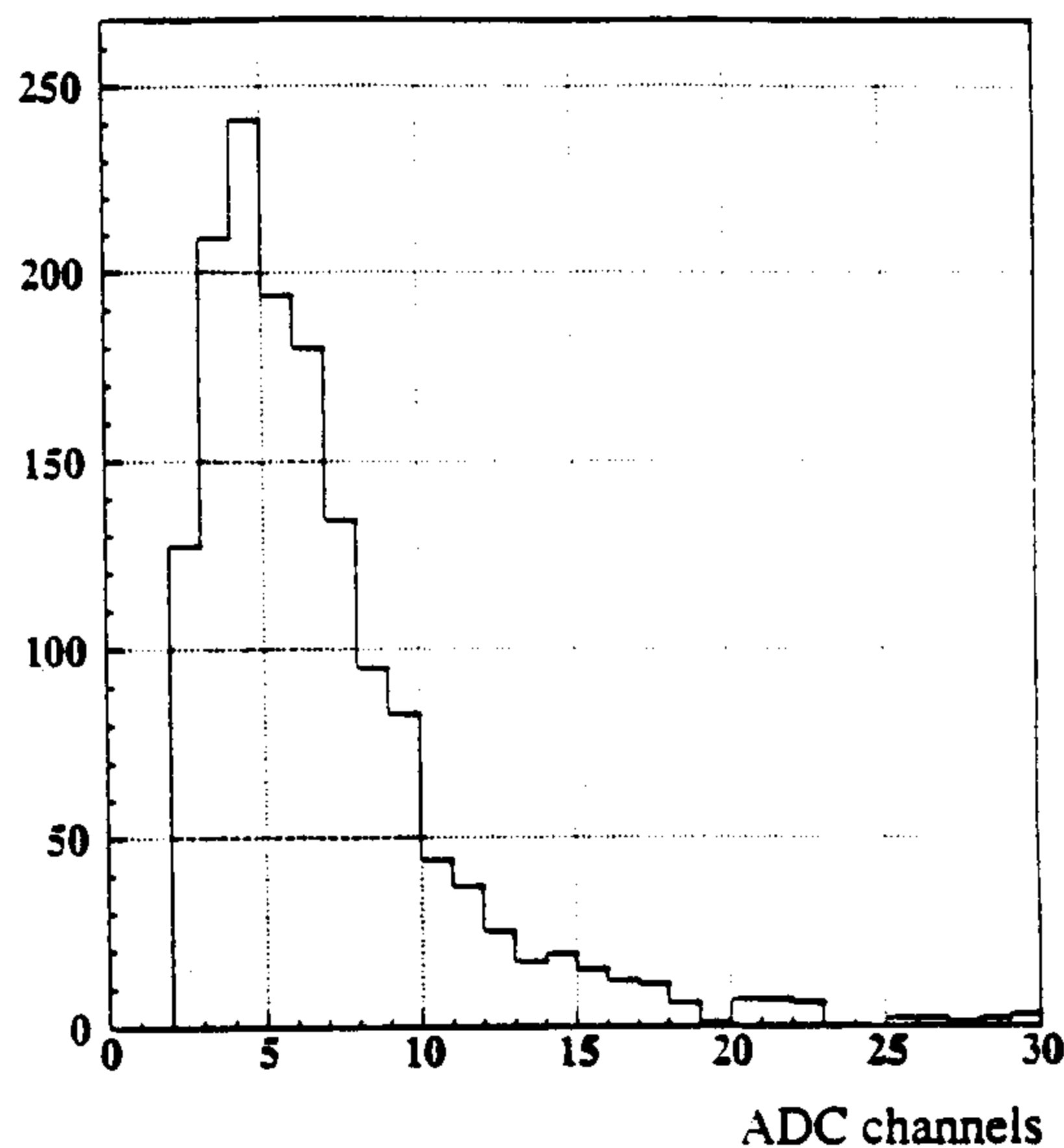

Fig. 3. A typical muon charge distribution.

The trigger logic is designed for detection of high-energy muons and hadrons interacting in the antenna or Extensive Air Showers. The analogic signals of the streamer tubes belonging to the same layer are OR-ed together and the seven outputs are fed into a NIM module (Charge Walker) developped at the Frascati Laboratory. It consists of a 4-channels charge integrator with autoreset at 500 nsec (corresponding to the maximum drift time in the tube), which provides an analogic output (1 mV/pC) and a logical signal from a comparator with a preset threshold. The width of the output signal and the threshold are settable. The threshold applied to the seven layer signals is then linearly related to the particle multiplicity detected on that layer.

Three different triggers can be selected:

The first trigger (or μ trigger) is used for a periodical calibration of the system. We require the coincidence of at least two layers on the top module and three layers on the bottom; the thresholds are set to the single particle level (30 mV). The measured rate of events is about 600 Hz.

The second trigger (or interacting particle trigger) selects those events in wich one or many particles have an interaction with the gravitational wave detector. Here we require one or more particles in at least two layers of the top module and ten or more particles in the four layers of the bottom module. The rate of this trigger is about 2 Hz.

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The third trigger (or neutral particle trigger) requires that no particles cross the top module, and that more than 20 particles cross the bottom module (the rate is about 2 Hz). Moreover we periodically use a random trigger in order to determine the ADC channel pedestals.

The data acquisition is performed by a VANTAGE 300 intelligent crate controller by Kinetic Systems operating in the CAMAC environment and built around the Digital Equipment rtVAX 300 processor. VANTAGE 300 runs the DEC VAXELN operating system[13] which is optimized for real time operations. A 16-channels-I/O REGISTER (CAEN C219) controls the ADC gates, and it is used for providing CLEAR signals and the veto logic. The acquisition throughput on mass storage is of the order of 450 Kbytes/day with a dead time of about 4%.

3. Effect of the cosmic rays and Monte Carlo simulation

A full simulation of the interaction of single hadrons and muons with the NAU-TILUS bar using the GEANT3 package[14] has been performed by improving an already existing simulation[8] .

The energy lost by a cosmic ray is converted in a local expansion of the bar due to the growth of the temperature. The relation between particle energy loss and the innovation of the vibrational energy of the bar[15] [16] can be described as follows:

$$E_n = kT_{eff} = \frac{4k}{9\pi} \frac{\gamma^2}{\rho L v^2} \left(\frac{dE}{dx}\right)^2 \left[\sin\left(n\frac{\pi z}{L}\right) \frac{\sin\left(n\frac{\pi l_0 \cos(\theta)}{2L}\right)}{n\frac{\pi R \cos(\theta)}{L}}\right]^2 \quad joule \quad (1)$$

where (see fig. 4):

E_n is the energy change deposited in the n-th vibrational mode,

T_{eff} is the minimum energy detectable expressed in kelvin, often used as measurement of the detector sensitivity

$k = 8.63 \times 10^{-11} \ MeV/K$ is the Boltzman constant,

$\gamma = 1.6$ is the value of the Gruneisen constant at low temperature,

$\rho = 2790 \ \frac{Kg}{m^3}$ is the Al 5056 density at low temperature,

$v = 5400 \ \frac{m}{s}$ is the Al 5056 sound speed at low temperature,

$L = 3 \ m$ is the length of the bar,

l_0 is the path length of the particle in the bar,

z is the coordinate measured respect to the major axis Z of the bar,

$R = 0.3 \ m$ is the radius of the bar,

θ is the angle of the incident particle respect to the major axis Z of the bar,

$\frac{dE}{dx}$ is the energy released by the particle in a unit of path length expressed in $\frac{GeV}{m}$.
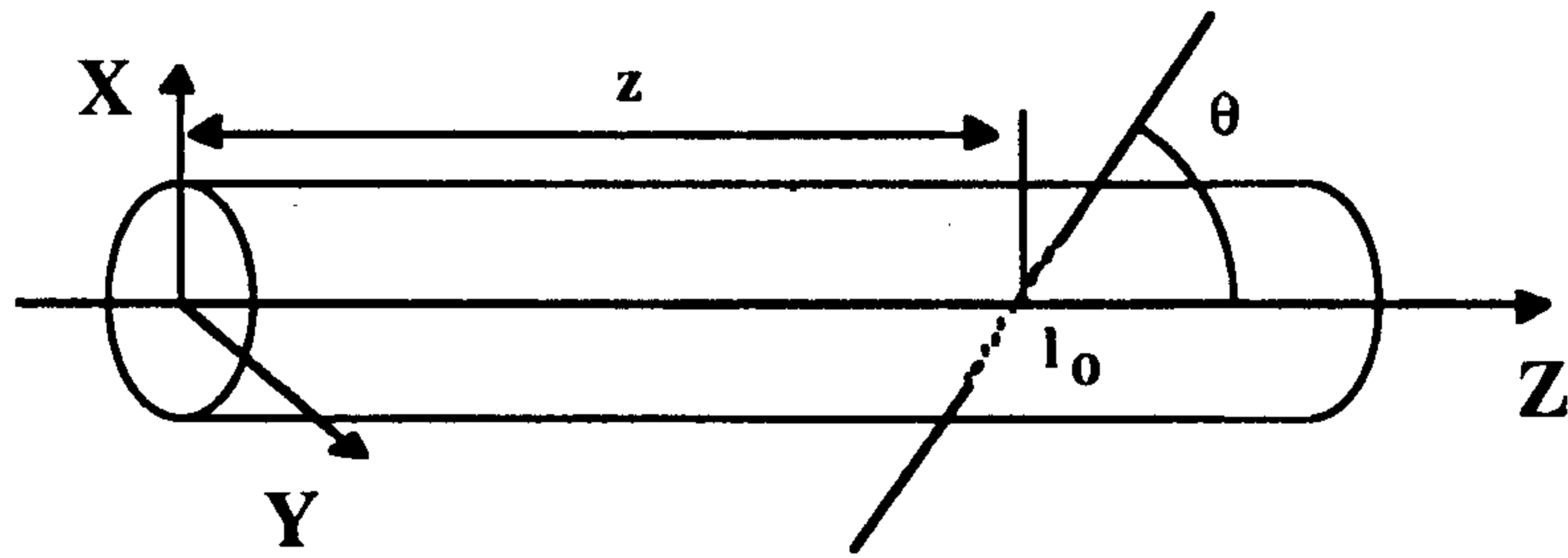
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Fig. 4. Definition of geometrical parameters.

We have used the value measured at 1 K[17] for the Gruneisen constant. As far as we know there are no measurements at the operating temperature of the NAUTILUS; moreover, the effect of the passage of cosmic rays in a superconducting medium could need further experimental investigations.

While the gravitational wave excites only the odd vibrational mode, as a consequence of its quadrupolar nature, the interacting particle can be detected also on the second longitudinal mode with the same energy detectable[9] , since relation (1) is derived for all the vibrational harmonics. In fig. 5 the bar response for the first and second armonics due to a 1 GeV cosmic ray is shown.
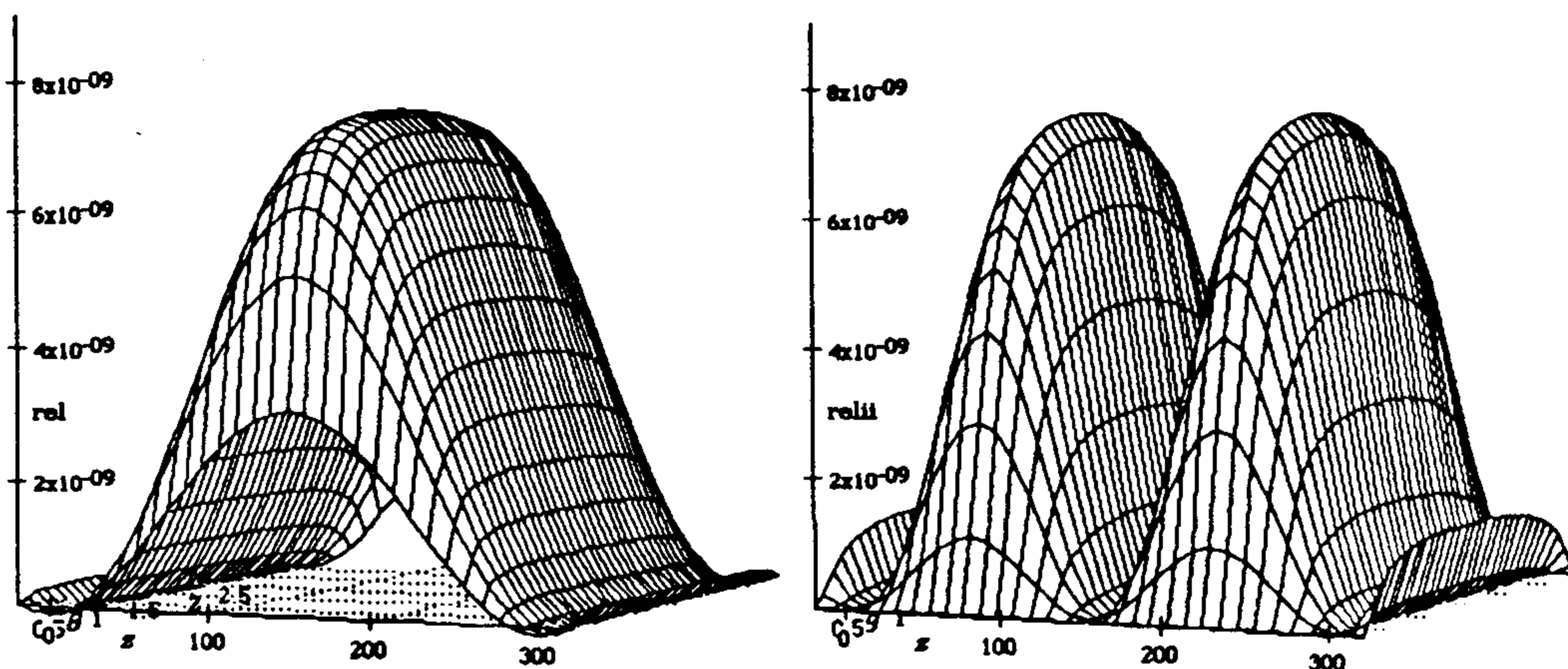

Fig. 5. Armonics response as a function of the impinging particle angle and point.

The simulated geometrical structure is shown in fig. 6; it includes the aluminum cylindrical bar, (radius 30 cm, length 300 cm), an iron cylindrical tube (4 cm thick, inner radius 34 cm, length 400 cm) which represents the vacuum can, two coaxial iron tubes (respectively 10 cm and 5 cm thick, 38.5 and 66 cm inner radius, 26.5 and 57.5 cm length) representing the equivalent thickness of the three copper shields and finally two

iron disks (5 cm thick, 90.5 cm inner radius, 152 cm outer radius) placed at ± 85 cm from the antenna center in order to account mainly for the equivalent thickness of the cryostat massive rings. A vacuum box placed under the cryostat simulates the streamer tube layers.
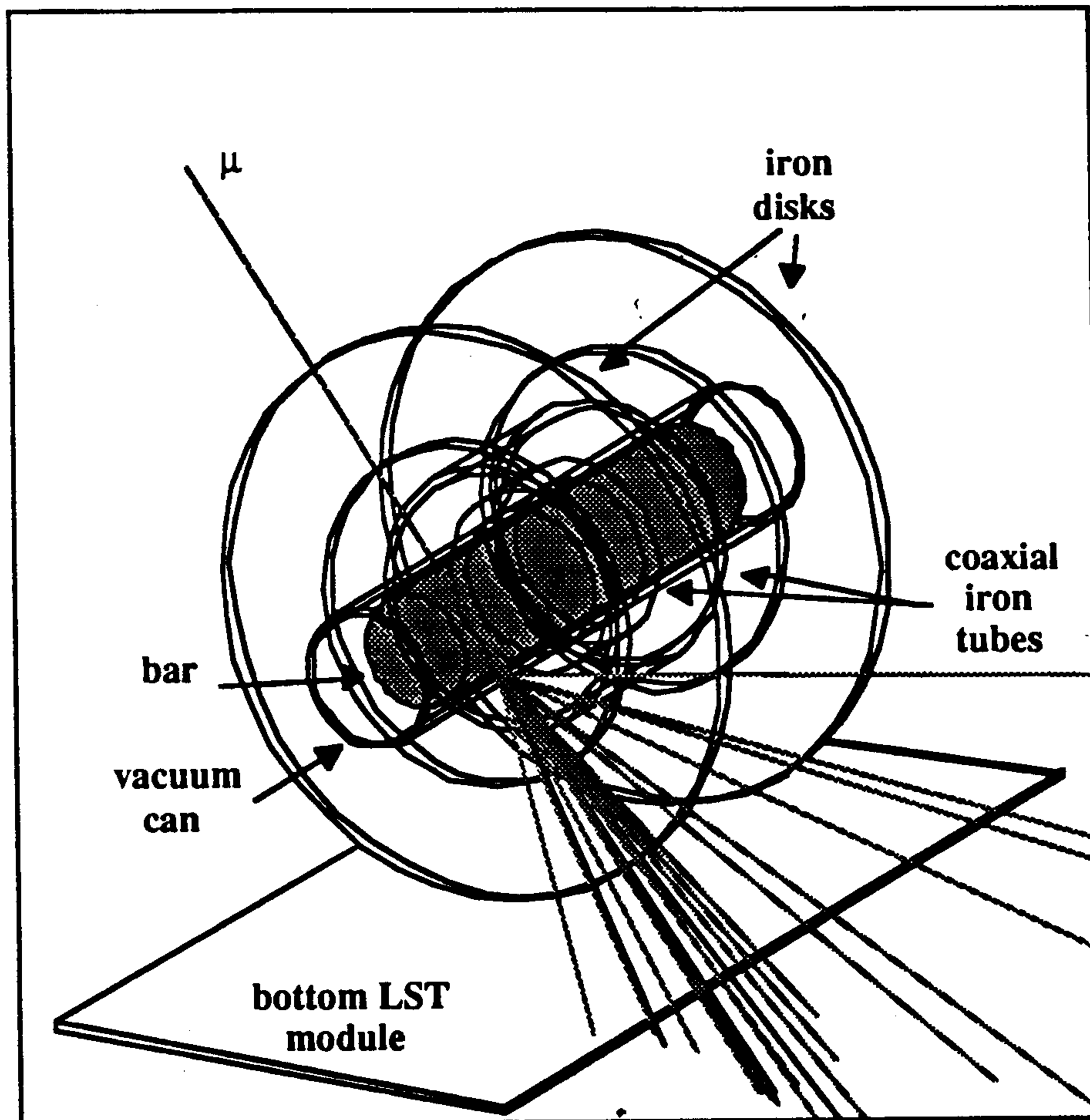

Fig. 6. Simulated interaction of 1 TeV muon in the detector.

In the evaluation of the expected numbers of detectable interactions of cosmic rays with the bar as a function of its sensitivity, a major role is played by hadron interactions. The hadron generator uses two different parametrization for the experimental data: for hadrons with energy greater than 300 GeV we have used the differential vertical spectrum at sea level given by Sihoan et al.[18] shown in fig. 7 (single charged hadrons) up to a maximum energy of 10 TeV:

$$\frac{dN}{dE} = 1 \times 10^{-10} \left(\frac{E}{300}\right)^{-2.6} \frac{hadrons}{s\ cm^2\ sr\ GeV},$$

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while below this energy we have used the Arvela et al.[19] parametrization with a minimum energy cut of 1 GeV,

$$\frac{dN}{dE} = 3 \times 10^{-4} \, E^{-2.5} \quad \frac{hadrons}{s \; cm^2 \; sr \; GeV}.$$

A factor $e^{-\frac{h}{\Lambda_N}}$, where h is the atmospheric depth crossed by the particle and $\Lambda_N \simeq 140 \frac{g}{cm^2}$, accounts for the hadron angular distribution. A 1.25 factor was also introduced, as suggested by Cowan et at.[20], to evaluate the growth of hadron rate due to neutrons. The muon interaction contribution has been evaluated using for the flux the theoretical extimation of Dar[21] shown in fig. 8, in good agreement with the available experimental data and a μ^+/μ^- charge ratio of 1.25.
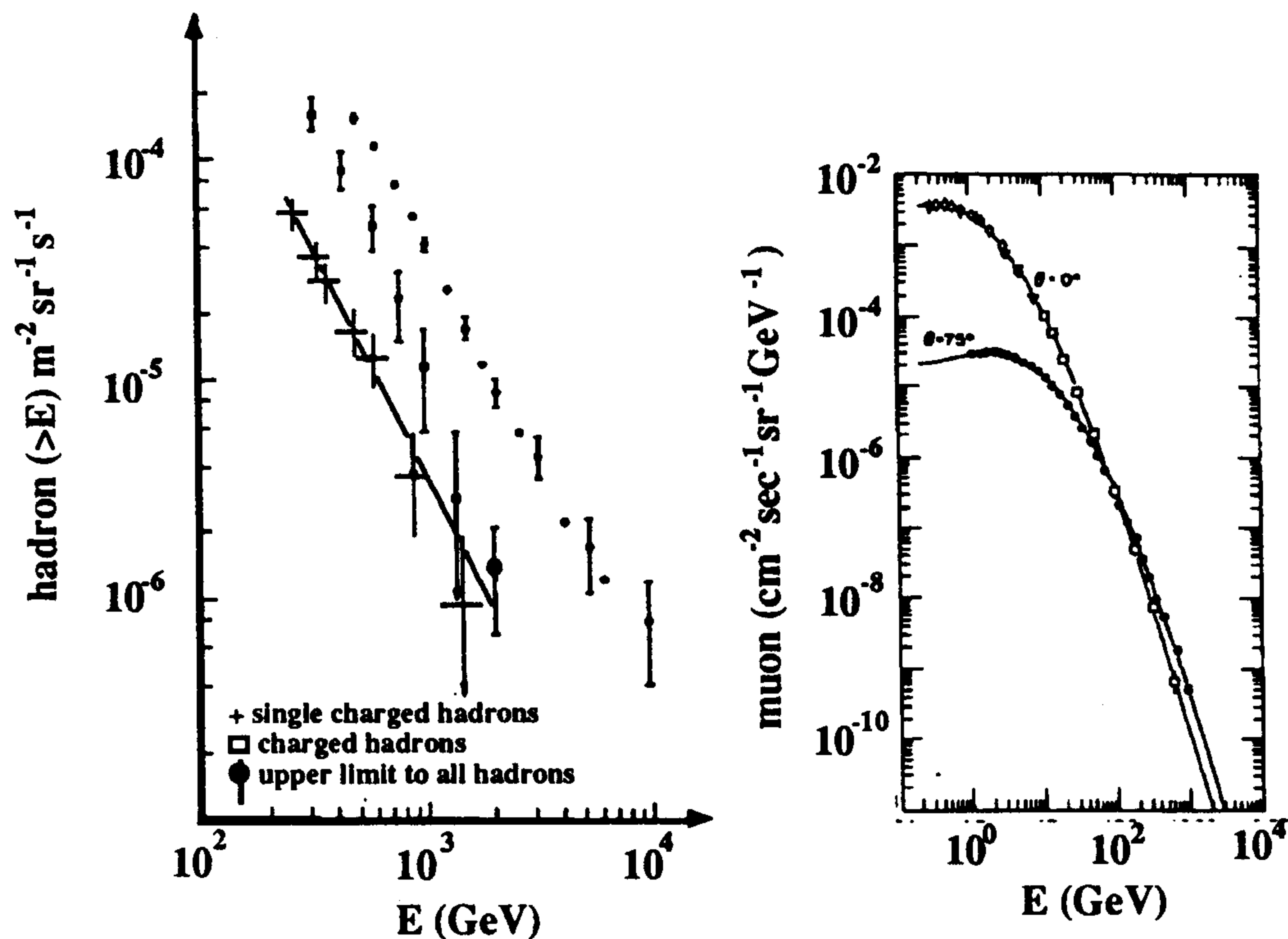

Fig. 7. Hadron flux from Sihoan et al.[18]   Fig. 8. Muon flux extimation from Dar[21] .

The particle interaction and tracking in the detector has been performed using the GEANT 3.15 package including the GEISHA simulator for the interaction of the hadrons in a shower. We have used the default energy cut values for secondary particles with the only exception for the kinetic energy cut for delta rays set to 100 KeV. The appropriate

corrections are applied to the particle fluxes to account for zenith angle distribution and NAUTILUS place height. We report in fig. 9 the results on the expected number of events per day both from hadrons and muons as a function of the minimum energy released in the bar and the related minimum vibrational energy change detectable by the gravitational detector, measured in kelvin. It is also reported an analitical extimation of the contribution due to Extensive Air Shower, as suggested by Amaldi and Pizzella[7] , and an extimation of multiple hadron events based on Arvela et al.[19] Monte Carlo results. They evaluated the flux of multihadron showers ($N \geq 10$) with a total energy greater than 1000 GeV as a function of the detector area. For a 1 m^2-detector as the NAUTILUS bar, the rate is the same of a single hadron with energy greater than 1000 GeV. Using the calculated distribution of the energy released in the bar by a hadron with a minimum energy of 100 GeV, we have then evaluated the contribution of ten hadron of the same minimum energy.
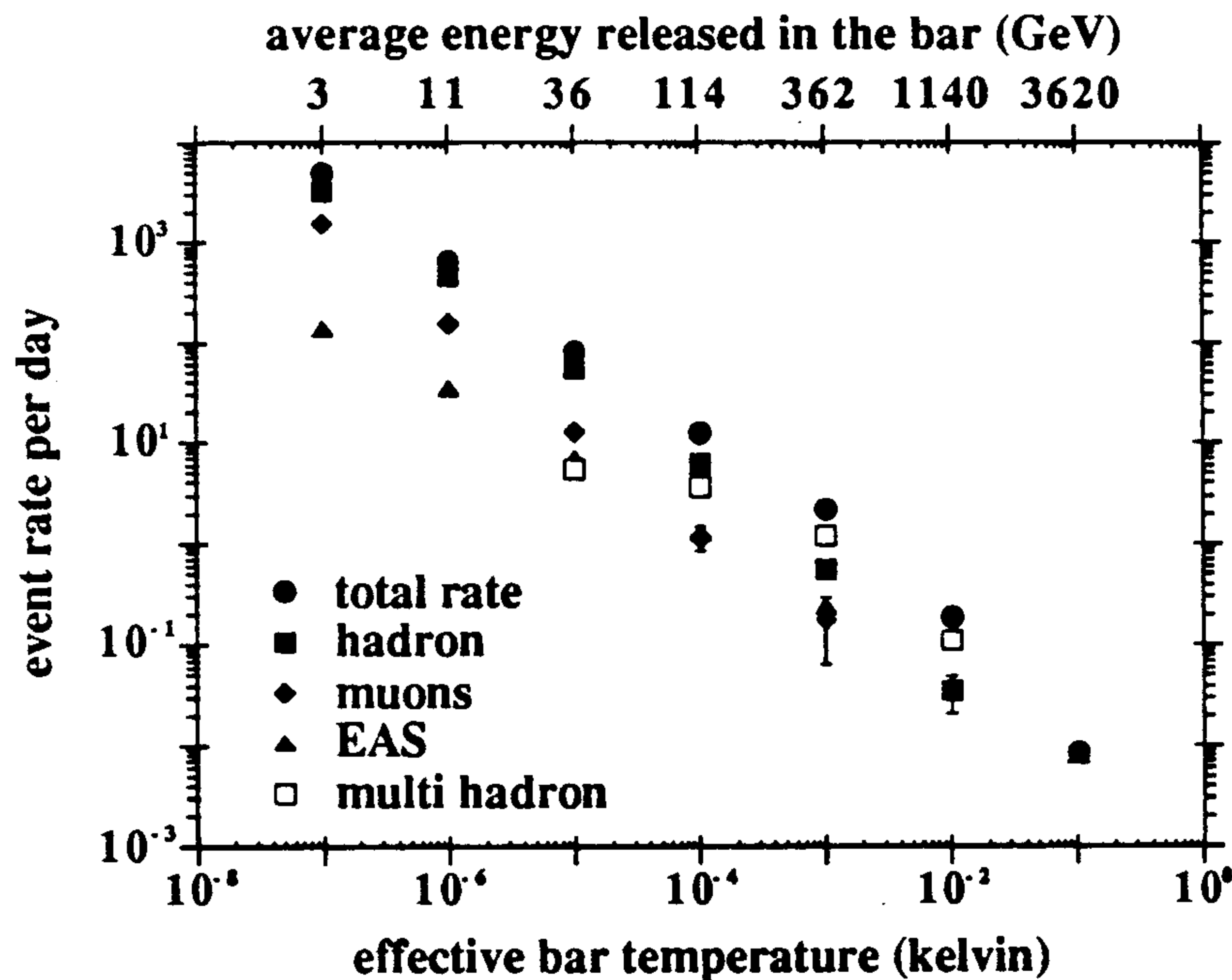

Fig. 9. Expected event rate per day.

At the sensitivity (about 5×10^{-3} kelvin) already reached in the first run of the NAUTILUS we expect in total few detectable events per day and 10 events per day at the

foreseen sensitivity of 100 μK.

Effective temperature K	events/day (muons)	events/day (hadrons)	events/day (EAS)	events/day (multi had.)	events/day (total)
10^{-7}	1540	3310	137	—	4990
10^{-6}	155	463	35	—	653
10^{-5}	12.7	55.7	7	5.5	81
10^{-4}	1.2	6.2	1.3	3.7	12.3
10^{-3}	0.18	0.56	0.24	1.2	2.2
10^{-2}	0.002	0.035	0.04	0.1	0.2

We would like to stress that there is a lack of experimental information on the flux of single and multi hadrons at high-energy and that our evaluation is based on measurements of the hadron rate up to 2×10^3 GeV and affected by large errors.

In the fig. 10 we show the expected detection efficiency for hadron and muon interaction events, at fixed values of the minimum energy released in the bar, as a function of the particle multiplicity detected in the bottom module. We clearly have a correlation between the measured charge particle multiplicity and the cut on the minimum energy relased in the bar.
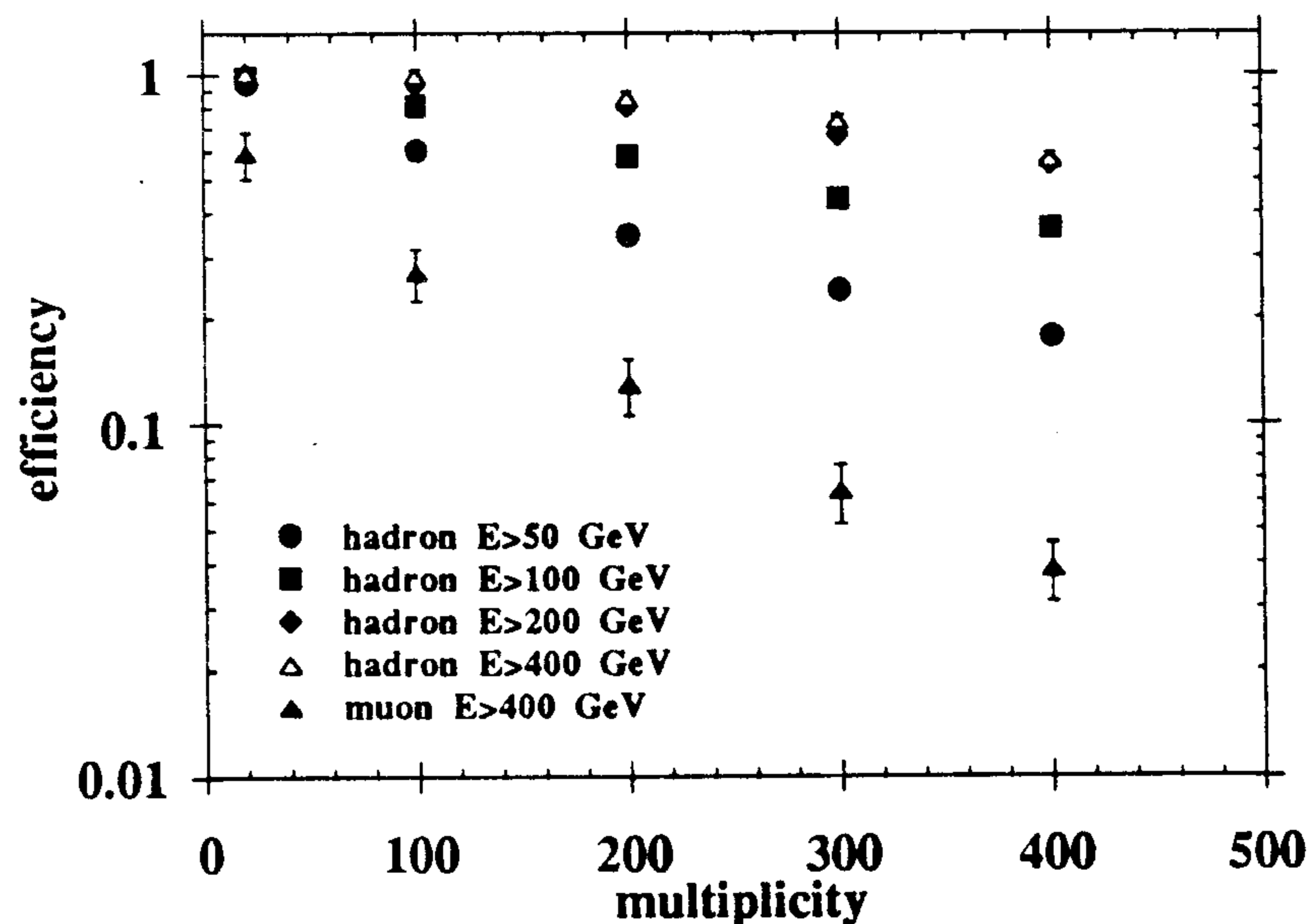

Fig. 10. Detection efficiency as function of multiplicity cut.

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4. Detector performances and calibration

In July 1993 a first cooling of NAUTILUS equipped with the cosmic-ray detector was done and the calibration of the gravitational wave antenna started; data from the cosmic-ray detector have been collected during this time of setting-up.

As preliminary results we show in fig. 11 the measured Extensive Air Shower multiplicity rate. The particle density Δ in the shower (number of charged particles per square meter) corresponds to the measured particle multiplicity in the top module. In the same figure it is also reported the best fit [22] (solid line) to the results of some cosmic-ray detectors obtained at see level. The agreement is very good.

In the low range of particle density a small effect due to the trigger request of at least 10 particles in the bottom module can be observed. Particles with low probability of interaction with the cryostat, as muons, and low energy particles, as electrons, may not exceed the threshold of 10 particles in the bottom module.

In high range of density, more than 400-600 particles per square meter, the data are affected by the ADC saturation effect.
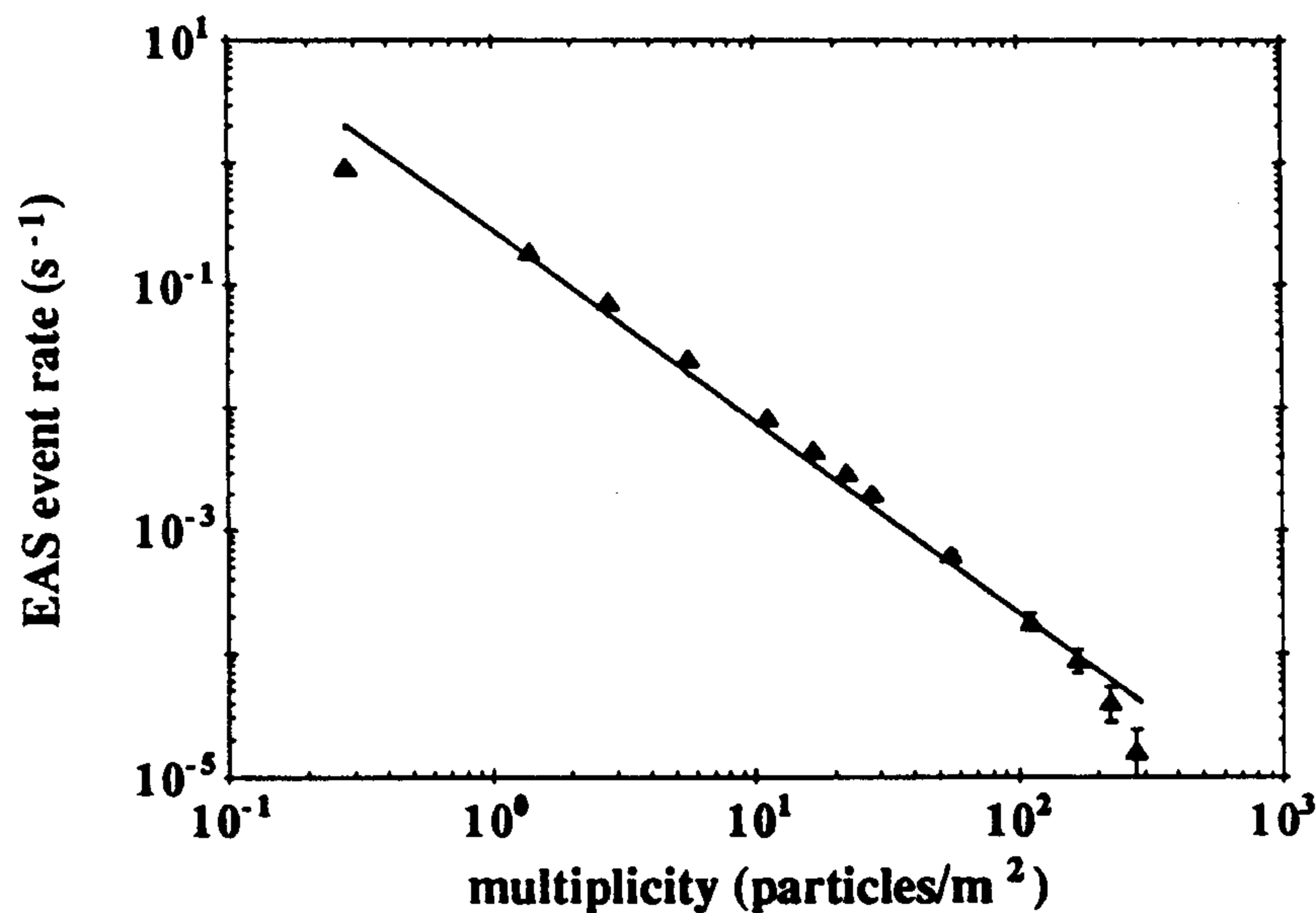

Fig. 11. Measured EAS rate.

Finally our results are not corrected for the effect due to the Laboratory height (260 m) and pressure variations.

The best fit to our data give: $H(> \Delta) = (0.354 \pm 0.006)\Delta^{(-1.55 \pm 0.01)}$ s^{-1}.

The multiplicity rate measured in the bottom module when we require only one particle (corresponding to a detected charge ranging from 0.3 to 3.0 equivalent charged particles)

and zero particle (corresponding to a value less then 0.3) in the top module is shown in fig. 12.
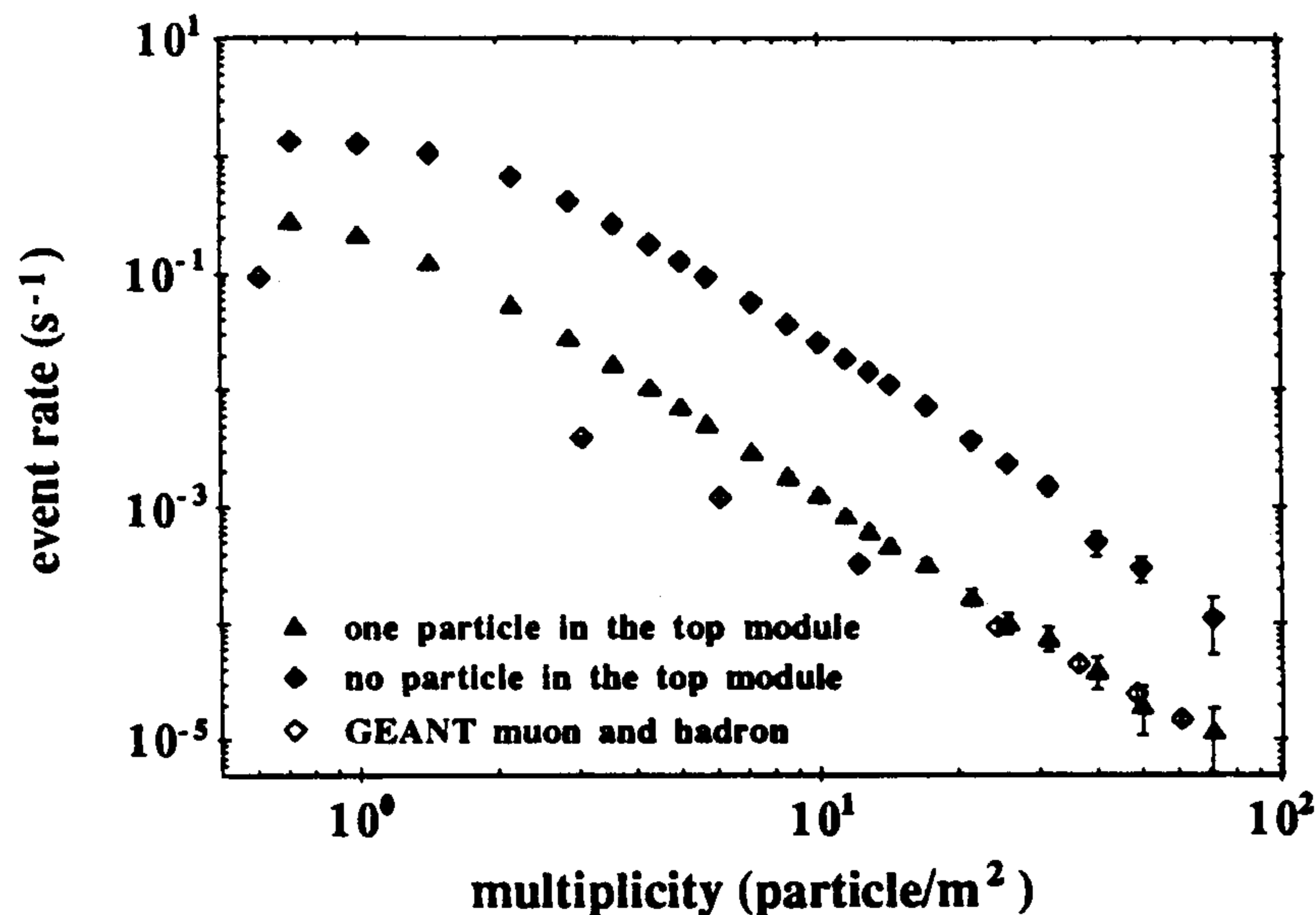

Fig. 12. Measured single particle rate in the bottom module.

Particles coming at very large angles and not interacting with the antenna are included in this category. In the figure the total Monte Carlo prediction (for hadrons and muons) is shown for comparison. The experimental points are contaminated by the background due to atmosferic showers. From this figure we can see that with a reasonable offline cut (about 4 particle/m^2) the events rate is of about 10^{-1} Hz. From fig. 10 we also see that with this kind of cut we have an efficiency of the order of 90% for hadron losing more than 200 GeV in the bar.

With a rate of events of $\simeq 10^{-1}$ Hz and a time resolution of the bar signal of the order of 100 ms[23] the dead time introduced on the NAUTILUS data taking is of the order of 10^{-2} s.

Conclusions

The first ultracryogenic gravitational wave-antenna NAUTILUS is now beginning to operate at a sensitivity never obtained before. The cosmic-ray detector assembled together with NAUTILUS has shown, in the first data taking, very good performances well in agreement with the physics requirement of the experiment as well as with the simulation results. Moreover the cosmic-ray detector with severe space constraints and

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a simple and cheap design, well fulfills the aim of the detection of events in coincidence with the gravitational detector also in absence of calorimetric measurements.

Acknowledgements

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