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SIMULTANEOUS OBSERVATION OF EXTENSIVE AIR SHOWERS AND DEEP UNDERGROUND MUONS AT THE GRAN SASSO LABORATORY

MACRO and EASTOP Collaborations

INFN - Laboratori Nazionali del Gran Sasso

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Printed and Published by
Servizio Documentazione
dei Laboratori Nazionali di Frascati

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Abstract

Combined measurements of extensive air showers at the surface and high energy muons deep underground have been initiated at the Gran Sasso laboratory. The underground detector is the first supermodule of MACRO (Area= 140 m^2, depth=3100 m.w.e., E_μ>1.7 TeV) and the surface detector is the EAS-TOP array (altitude 2000 m a.s.l., total enclosed area A~ 10^5 m^2). We discuss the correlation technique, the comparison between the shower parameters as determined by the two detectors, the characteristics of the reconstructed events and give indication of physics possibilities using this promising technique.

1. Introduction

One of the most important problems in high energy cosmic ray physics is the study of primary flux at energies above Eo=10^{15}-10^{16} eV where a steepening, or "knee", of the all-particle primary spectrum is observed[1]. In this range of energy the experimental data are still poor and many questions, as the astrophysical origin of the "knee" or the chemical composition of the spectrum, are still left without a quantitative answer. A precise knowledge of the abundances and spectral indexes of the different mass groups of nuclei is of extreme importance in order to have a better understanding of the sources of cosmic rays, and their propagation and acceleration mechanisms in our galaxy. In the high energy region, only indirect measurements of primaries are possible at the present time. Two techniques can be exploited in this field: i) the measurement at ground level of secondary e.m. cascades (Extensive Air Showers) generated by the interaction of a primary particle with the atmospheric nuclei[2], by sampling the shower front with large area surface arrays; ii) the measurement of penetrating high energy muons in underground experiments[3]; these muons detected deep underground are the high energy remnants of the primary interaction.

These two research lines have been pursued mostly by independent experiments, not correlated with each other. The advantage in an event by event combined experiment is that it is possible to isolate the very high energy region of the primary spectrum and simultaneously measure more physical parameters related to those events. For example, the main uncertainty in the analysis of multi-muon events in underground experiments is the fact that the contribution to a given muon multiplicity comes from primaries whose energies span at least two decades in a differential energy spectrum which is falling as $E_0^{-2.7}$. The composition is therefore difficult to unfold and the sensitivity can be enhanced by correlating the underground multi-muon events with the measurement of the shower size on the surface. This then determines the primary energy for these events to within a factor of two independent of composition. As a consequence it is possible to measure muon multiplicities in fixed shower size windows, corresponding to comparable total energies for all nuclear species.

The Gran Sasso Laboratory[6] (LNGS) offers unique possibilities to accurately perform combined measurements. Previously two experiments have been reported that demonstrate the possibility of making coincidences, but with less extensive detectors[4,5]. New experiments now in operations at LNGS can provide data on simultaneous observations of EAS and underground muons, with large acceptance and combined reconstruction capability never reached by the past experiments.

In this paper we report the first results obtained by the joint collaboration of the surface EAS-TOP experiment, at 2000 m. above the sea level, and the underground MACRO experiment, at a depth of 3100 m.w.e.. We show the detection features achieved by the two combined experiments, discussing in particular their capability for good reconstruction of cosmic ray events.

2. The experimental apparata

Fig. 1 shows the location of the surface array and of the underground laboratory with respect to each other. MACRO is located in the Hall B of the Gran Sasso underground laboratory (latitude 42° 27' North, longitude 13° 34' East), at an altitude of about 963 m above sea level (a.s.l). The EAS-TOP array is located above the Gran Sasso underground laboratory, at 27.5° with respect to vertical of MACRO, in correspondence to the minimum thickness of rock, at the altitude of 2005 m a.s.l..

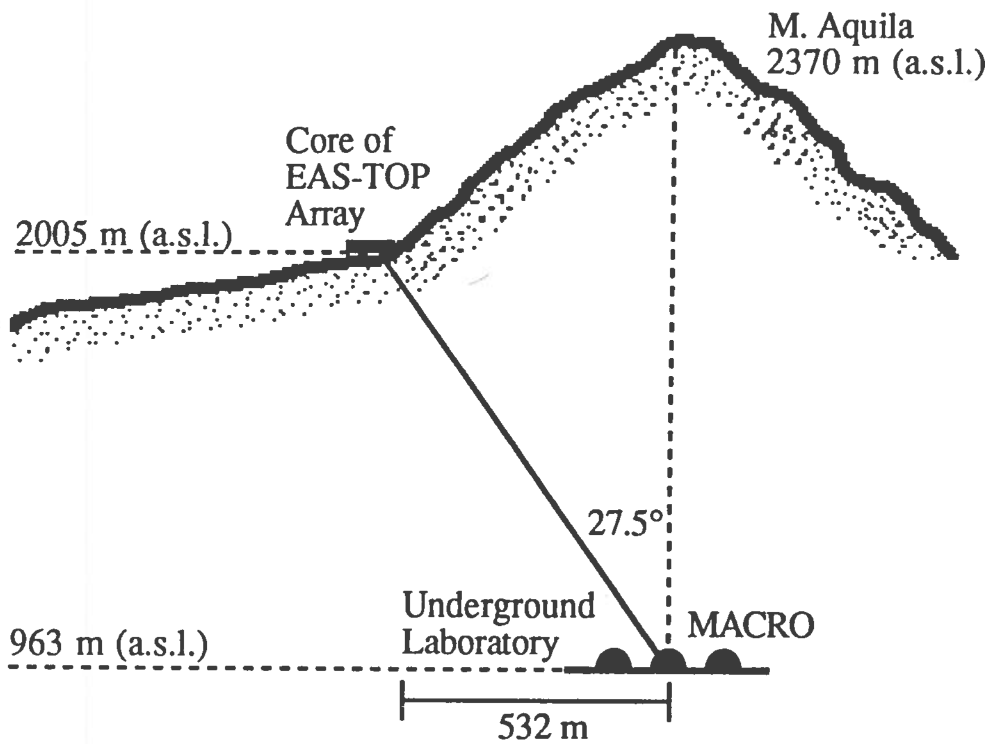

FIG. 1 - Locations of the two arrays at the LNGS.

The shower detector in EAS-TOP[7] (Fig. 2) consists of 29 stations separated by 17 m near the center, and 80 m at the edges of the field, each one containing a 10 m^2 module of scintillator. However in the period corresponding to the data presented here, only 22 stations where operational. The total covered area is about 10^5 m^2. Each 10 m^2 module consists of 16 scintillation counters. Four modules use liquid scintillator, the others NE102A plastics. At present each scintillator is viewed by one PMT for timing and amplitude measurements and the gain is equalized to measure a number of particles $n \leq 100$. Typically, at n=50, the error on the determination of the number of particles is about 20%.The threshold of each module is set to an amplitude equivalent to 0.3 minimum ionizing particles.

FIG. 2 - Photographic view of the EAS-TOP array

For triggering purposes EAS-TOP is organized in 7 hexagonal overlapping subarrays of 6 or 7 modules interconnected with each other. The subarrays operate independently. Any coincidence within 500 ns of all the modules within a subarray, triggers the data acquisition of the whole apparatus. In this configuration the measured trigger rate is ~5 Hz. Data are taken by means of a micro VAX connected through a radiotelephone link to the INFN national network. The absolute timing of the events is provided by a quartz clock (absolute precision ~100 μs), adjusted by the time standard provided by the Italian national broadcasting company. The EAS-TOP array is able to determine the main shower characteristics with the following resolutions at

$E_0 = 10^{15}$ eV: ~1° for the direction measurements, a few meters for the core location; ~20% for the shower size Ne; and 10% for the shower age s (the Nishimura-Kamata-Greisen[10] formalism is used for lateral distribution function: $\rho(r) \propto Ne\,(r/r_1)^{s-2}\,(r/r_1 + 1)^{s-4.5}$ with r_1 roughly equal to 100 m at our observation level). The present trigger scheme gives a calculated efficiency increasing from ~10% at $Ne=10^4$, corresponding roughly to 100 TeV, to full efficiency at $Ne \sim 10^5$ for showers having the core within the geometrical area defined by the array. The effective detection area depends on the energy, and ranges from 10^4 to over 10^5 m^2, increasing with energy.

The MACRO detector is a large area multipurpose experiment[8]. It is designed as a modular array of liquid scintillation counters, plastic streamer tubes, and track-etch detectors. When complete it will fill a box-shaped volume with 12x78 m^2 base and 9 m height. The first "supermodule" of MACRO (12x12x5 m^3, see Fig. 3) has been operated since the beginning of 1989. It consists of a horizontal sandwich of two scintillation counter layers for timing, 10

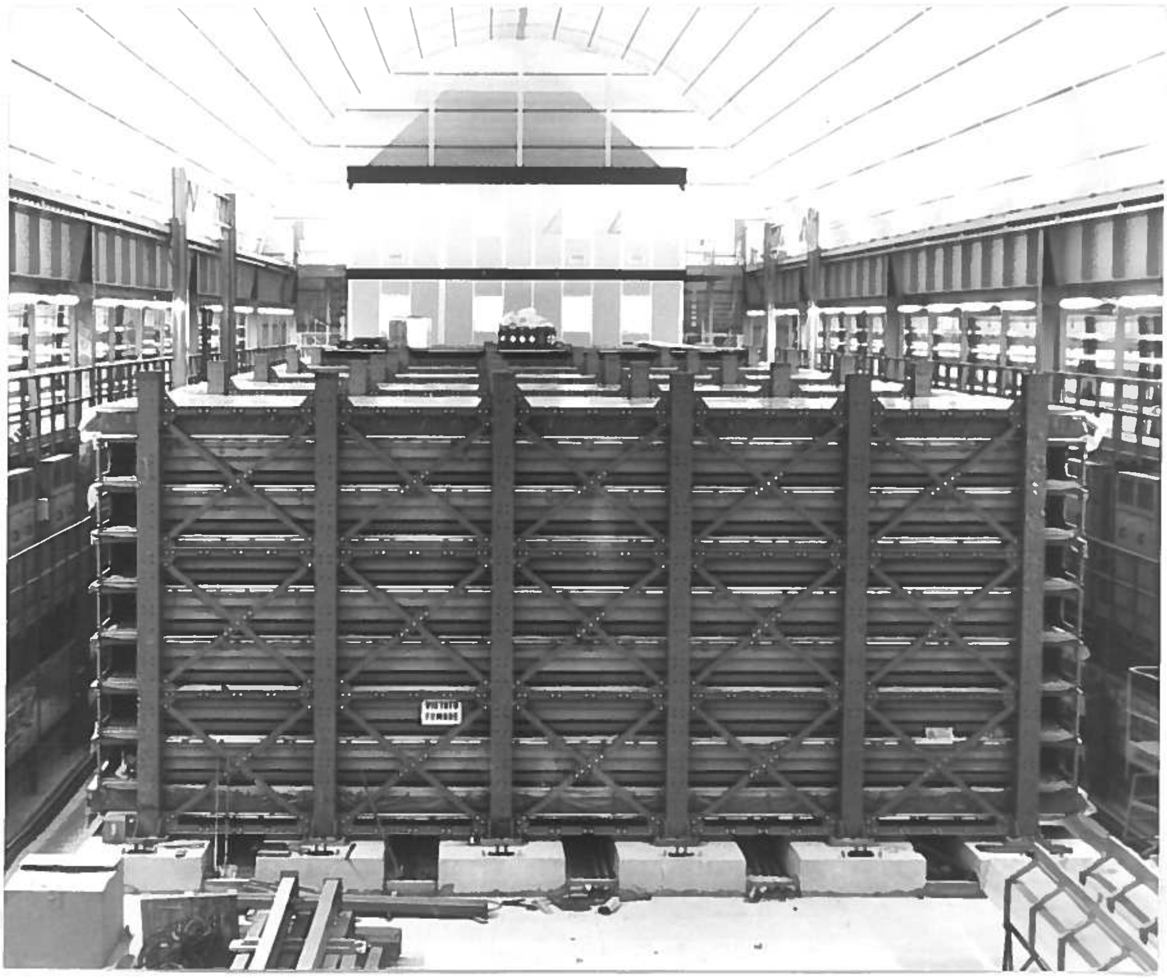

FIG. 3 - Photographic view of the first three supermodules of MACRO (total length 38 m). The first of these supermodules was used in the data reported here.

streamer tube layers for tracking, and one track-etch multilayer (CR39 and Lexan with an aluminum absorber) to identify highly ionizing particles. Passive absorbers (iron and $CaCO_3$) are in between the sensitive layers, to identify penetrating particles, setting a threshold for through-muons pointing at EAS-TOP at 1.2 GeV. Only two sides of the first supermodule are presently closed by one layer of scintillation counters and six layers of streamer tubes.

The streamer tube layers consist of 8-tube PVC chambers, with dimensions 25x3 cm^2 x 12 m. The individual cell cross section is 3x3 cm^2, with 100 μm anode wire and graphite cathode. They operate in the limited streamer mode. Two-dimensional localization is performed by 3 cm wide pick-up strips at an angle of about 30°. The achieved space accuracy is about 1 cm, resulting in an angular accuracy of ~ 0.2° in the two projected views.

The liquid scintillation counters are 75 cm wide, 26 cm thick, and 12 m long. They are viewed at each end by two PMTs. The trigger energy threshold is ~10 MeV, the timing accuracy 1 ns.

Different muon triggers operate independently in MACRO, based on streamer tubes and scintillators, alone or in combination. The measured rate of muons with a selected minimum track length of 180 cm, is ~2 per minute. Data are taken through CAMAC managed by microVAX, operating in VAXELN system, under the control of a VAX 8200. The absolute timing of the events is provided by a rubidium clock (absolute precision ~1 μs). The clock stability is periodically checked with the radio signal in the external laboratory.

EAS-TOP is seen by MACRO in the angular range 25°-37° in zenith, and 160°-200° in azimuth. The rock depth between the two experiments ranges from 3100 to 3500 meters water equivalent (m.w.e.), depending on the angle. The corresponding energy threshold for a muon to be detected underground is E_μ =1.7 - 2 TeV. The time of flight between the two sites, for a relativistic particle, is ~3 μs.

3. Data selection

The two experiments have been running simultaneously in the period from the 23rd of March to the 29th of May 1989, for a total live time of 1107 hours.

No physical link at present exists between EAS-TOP and MACRO, so the correlation of data is established off-line, on the basis of the absolute timing and the directional capabilities of the detectors. Fig. 4 shows the distribution of the time difference between the reconstructed events of MACRO and EAS-TOP, when looking for time coincidence within a 6 ms window, for a sub-sample of 637 hours. No directional cuts are applied at this stage. The peak of correlated events is clearly seen, above the background of accidentals. The correlation peak is well fitted by a gaussian, with a mean value of 3.2 ms (due to a different internal zero-setting of the two clocks), and σ ~ 90 μs. The time resolution is slightly better than expected by the design features of the quartz clock.

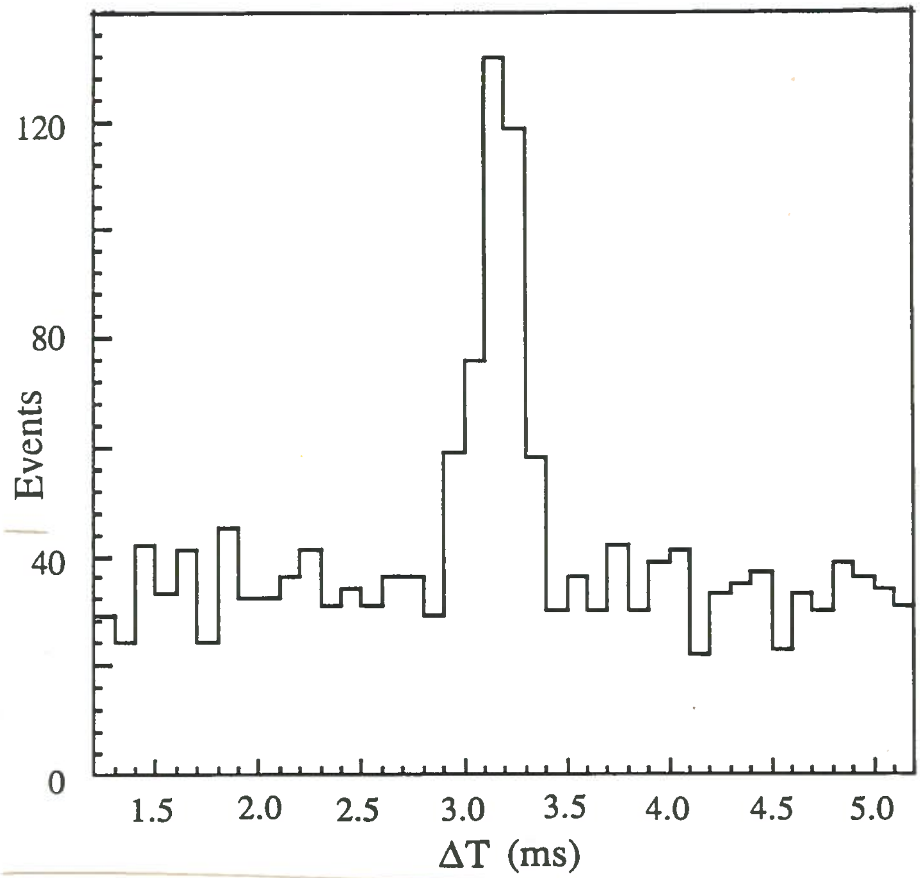

FIG. 4 - Time difference distribution of the reconstructed events of EAS-TOP and MACRO in coincidence within 6 ms.

The accidental coincidence background can be largely cut by means of directional criteria. Fig. 5 shows the same Δt distribution of Fig. 4 when a non stringent angular cut $\psi \leq 10°$ is applied to the angle in space between the two reconstructed directions. It can be seen that even in this preliminary analysis only a few events are lost with this cut. The area under the correlation peak within $\pm 3\sigma$ in time corresponds to 8.0 ± 0.7 correlated events per day. The estimated accidental contribution is ~ 4%. In the following we shall mantain the requirement $\Delta t = 3.2 \pm .3$ ms to define a coincidence.

With this selection the total number of coincidences found in the whole data sample is 347. The measured coincidence rate is in rough agreement with a preliminary calculation based on the commonly used models of cosmic ray spectrum and composition, the dependence on energy of the effective area of EAS-TOP, the acceptance cone between the two detectors, and the parametrization of muon propagation in the rock as a function of energy for each primary mass group[9]. The coincidence rate has remained constant, within the statistical error, during the entire measurement period, as shown in Fig. 6, where the coincidence rate is shown for different days of the run.

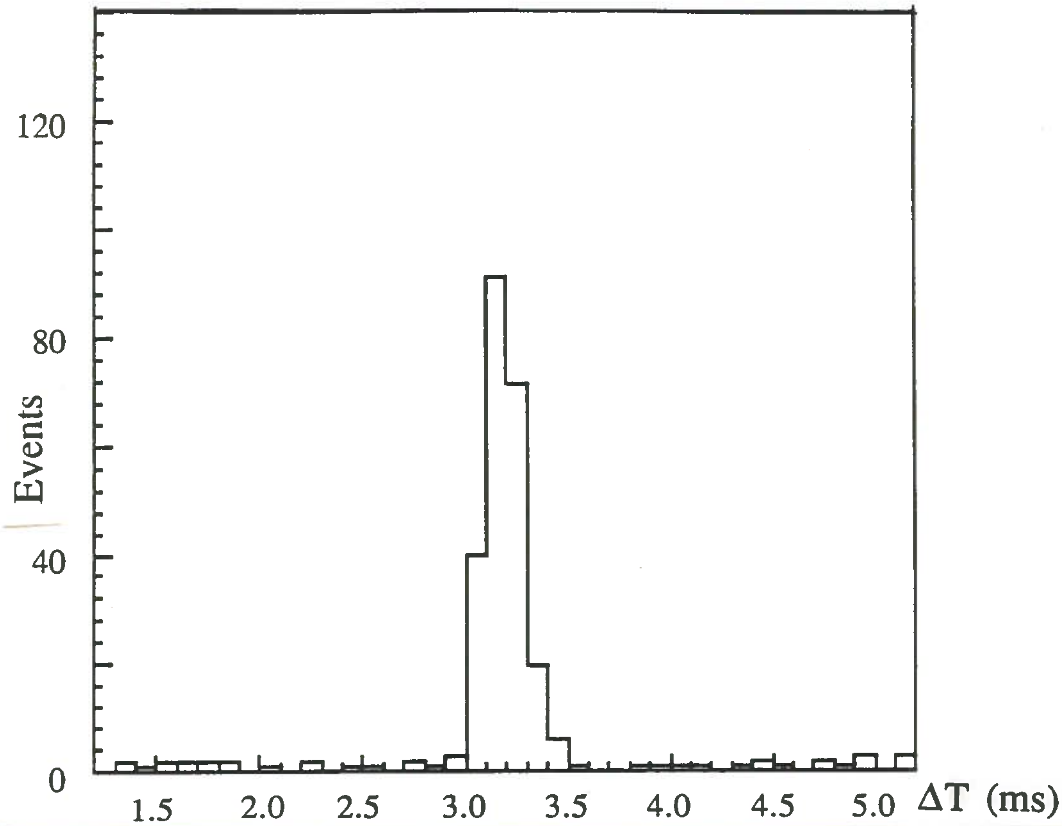

FIG. 5 - Same as Fig. 4, when an angular cut $\psi \leq 10^{\circ}$ is applied to the angle in space between the two reconstructed directions.

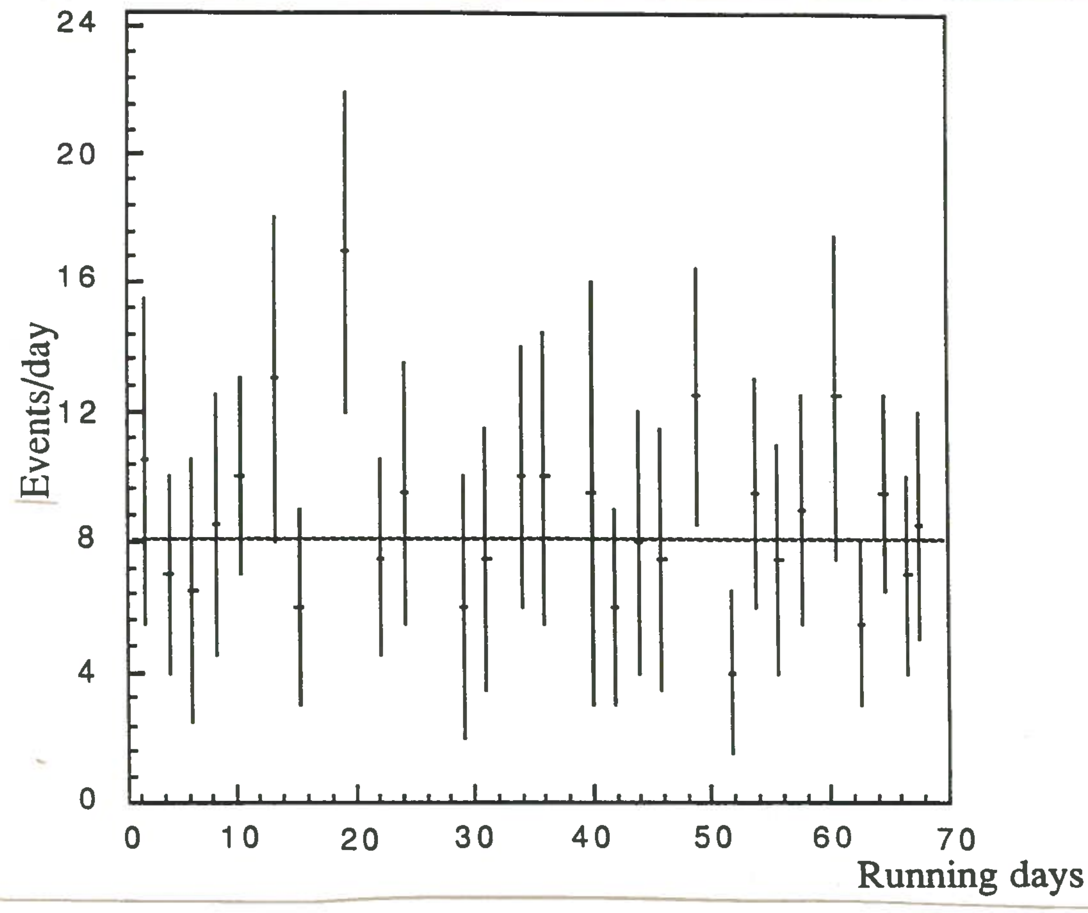

FIG. 6 - Rate of correlated events (day^{-1}) as measured in different days of run.

4. Spatial and angular resolution of the correlated events

The reconstruction of the direction of the shower and its core location are obtained independently by the two experiments. EAS-TOP uses the different arrival times of the electrons to fit the direction of the showers, and the number of particles in each counter to determine the core location, the shower size, and the lateral distribution of the particles. MACRO uses the tracking of the underground muons to define the arrival direction of the showers; in addition the extrapolation of the tracks of singles muons (or of the center of gravity of multi-muons) up to the EAS-TOP plane gives a measurement of the core location.

The achievable accuracies in the event reconstruction depend on physical and instrumental effects. In the case of EAS-TOP the main physical uncertainty is given by the time and density fluctuations of the particles inside the shower disk; this is more relevant far from the shower axis and at the lower energies. The instrumental accuracy is mainly related to the TDC system, which must be carefully and frequently calibrated.

In the case of MACRO the tracking system is able to define the arrival direction of a muon with high and stable accuracy, but one has to take into account the multiple scattering of muons in the rock, beyond sparse high-p_t interactions, which give an angular resolution $\sigma_\theta \sim 0.6°$ on the whole. This has been estimated by the distribution of the angle between different tracks in muon bundles. The accuracy in the shower core location by MACRO depends also on the possibility of sampling the muons far from the shower axis. This can introduce a few meters bias at low detected muon multiplicity, but which rapidly vanishes as multiplicity increases. Taking into account all the possible effects, including the back-pointing on the surface, the estimated accuracy in the shower core location for single muon events in MACRO, at EAS-TOP level, is ~ 20 m, decreasing to a few meters at higher muon multiplicities.

In Fig. 7 a), b), and c) we show an example of coincidence event as reconstructed by EAS-TOP and MACRO respectively: in a) the measured number of particles is shown for each module; in b) the lateral distribution function of the shower is fitted to the measured particle densities: from this fit the shower size, age, and core location are derived; in c) the underground muon event is shown as seen in the two projections of the MACRO supermodule. The muon tracks are fitted with straight lines.

In order to have a first understanding of the reconstruction capabilities of the two combined experiments, as far as the spatial parameters of the showers are concerned, we have restricted our selection to the "internal trigger" events. These are the events in which the largest number of particles is recorded by an EAS-TOP counter not belonging to the edge of the array. In our whole sample, corresponding to the 1107 hours of run, the number of internal trigger events is 93 out of a total of 347.

Fig. 8 a) , b) and c) show the distribution of the projected angular difference along X (West-East direction), along Y (South-North direction), and of the angle in the space between the reconstructed directions for the two experiments, when a loose cut $\Delta X, \Delta Y \leq 60$ m is applied to the difference of the measured core location coordinates (90 events out of 93).

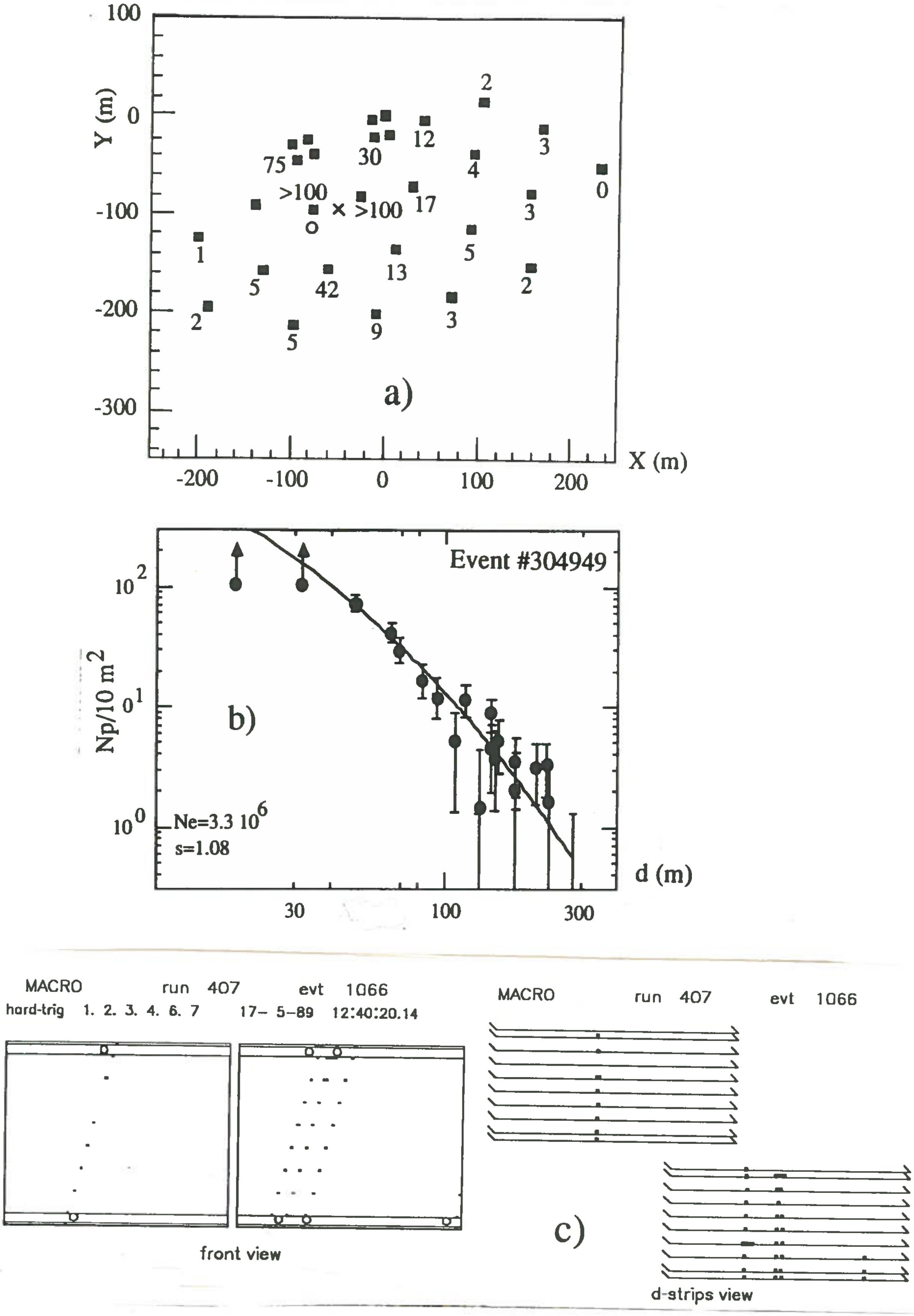

FIG. 7 - Example of a coincidence event as seen by the two experiments: a) number of detected particles in each counter of EAS-TOP, the shower core location as measured by the two experiments are also shown (MACRO: circle, EAS-TOP: cross); b) reconstructed lateral distribution function, the fitted size and age of the shower are also shown; c) the two views in the digital tracking of MACRO representing the underground multi-muon event detected in coincidence. The straight line fits are not reported to allow a better visualization of the hit streamer tubes.

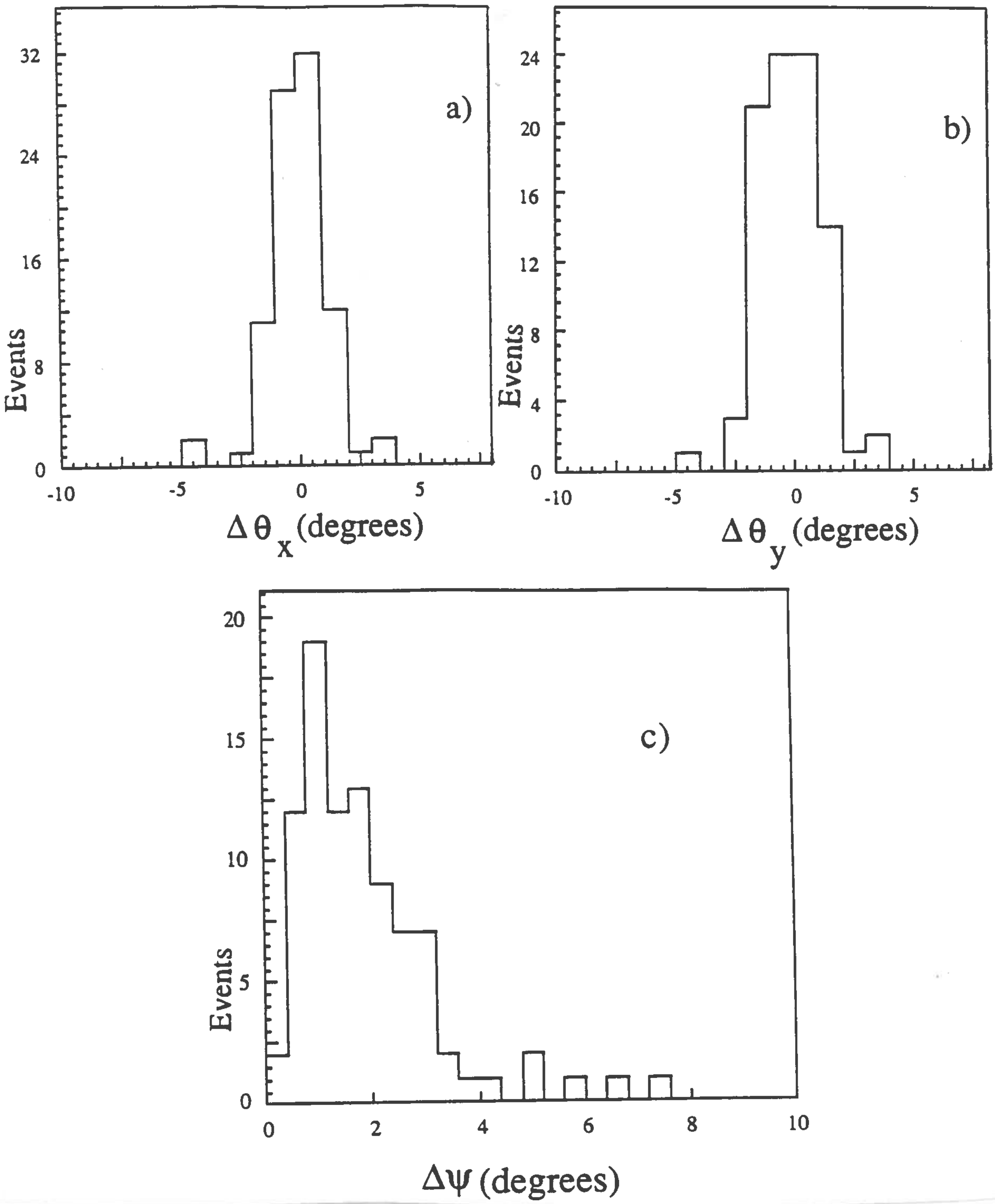

FIG. 8 - a) Angular difference between the the directions by the two experiments for the coincident internal trigger events, projected along the West-East direction, and b) the South-North direction; c) angle in space between the two reconstructed directions.

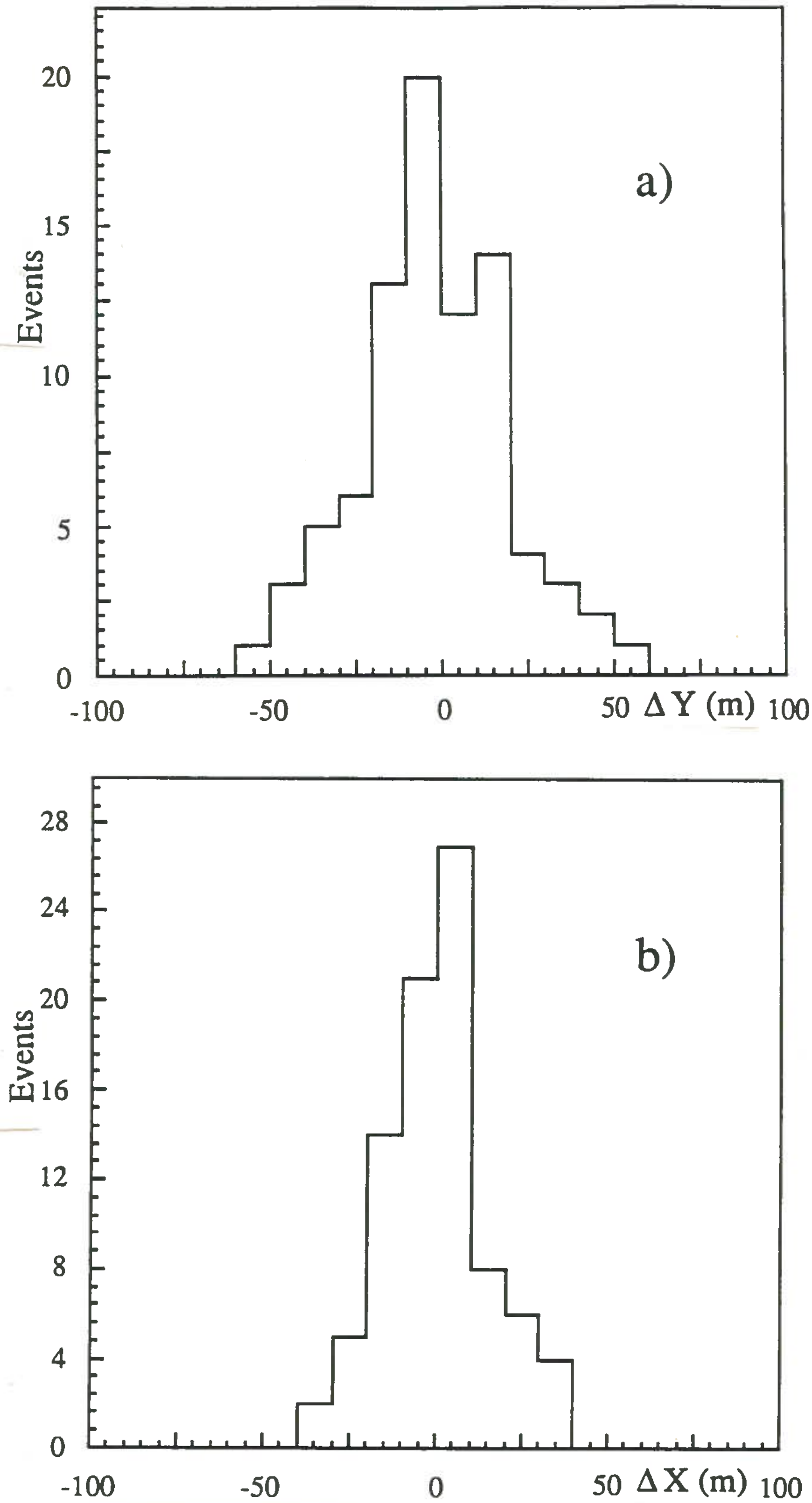

FIG. 9 - Difference of the reconstructed core location, for the coincident internal trigger events ($\psi \leq 5^o$), projected on two orthogonal axes on a plane perpendicular to the direction EAS-TOP - MACRO.

The measured resolutions are $\sigma_{\theta x}$=1.0° and $\sigma_{\theta y}$ =1.2°. The average $\Delta\theta_x$ is 0.04 ± .10, and the average $\Delta\theta_y$ is -0.20 ± 0.12, showing that no appreciable systematic effects are seen in the angular reconstruction. The corresponding resolution in the angle ψ in space is σ_ψ = 1.5°: it defines the accuracy in the relative pointing between MACRO and EAS-TOP. In the following we shall consider as coincidences the events passing the 95% cut $\psi \leq 5°$ (87 out of 93).

Fig. 9 a) and b) show the distribution of the difference in the shower core location by the two experiments, as projected along two orthogonal axes in a plane perpendicular to the direction EAS-TOP - MACRO. X is again the West-East direction. A resolution of 21 and 15 meters is found respectively, in agreement with the expectations depending on the geometry of the surface apparatus. If a cut is introduced both in the shower size ($Ne \geq 10^5$) and in muon multiplicity ($N_\mu \geq 2$), the above resolutions improve down to 11 and 6 m respectively. However the collected data are not sufficient, at present, to analyse in detail the dependence of the geometrical reconstruction parameters on the event size.

As expected, slightly worse resolutions are obtained when also including edge events in the analysis.

5. Correlation of Physical quantities

Fig. 10 shows the muon multiplicity distribution for the 87 selected internal trigger events. It must be compared to the total multiplicity distribution as measured by MACRO in single. This is reported in the same figure, normalized at N_μ=1: it refers to a sample of muons corresponding to 1740 hours of run, with $\theta \leq 70°$. The different ratio of multiple to single muons in the two cases is a direct reflection of the higher primary energy threshold in the coincidence experiment.

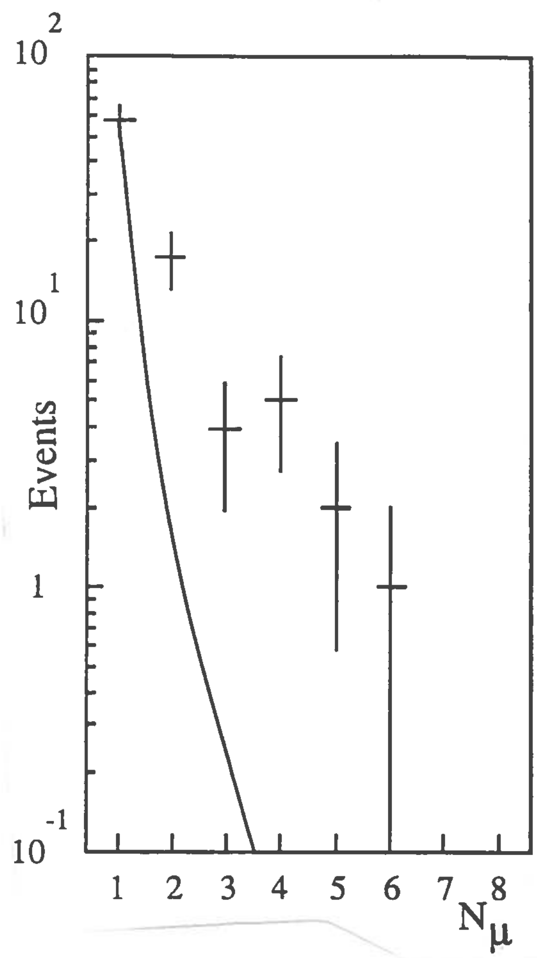

FIG. 10 - Muon multiplicity distribution as observed in MACRO for the coincident internal events. The continuous curve is the muon multiplicity distribution as observed in MACRO, in single, from any direction ($\theta \leq 70°$) for a period of 1740 hours of live time, normalized at N_μ=1.

Fig. 11 shows the measured logNe distribution for the internal trigger sample. The shape of the distribution for $Ne<10^5$ is affected by the EAS-TOP trigger, and by the request of detecting at least one muon in MACRO. The above result shows that this correlation experiment has a good sensitivity in the energy region of the knee of the primary spectrum ($Ne = 2\div5\cdot10^5$). The size distribution measured by EAS-TOP in single operation is superimposed. Since in this case there is no request for high energy muon production, the distribution is shifted toward lower shower size.

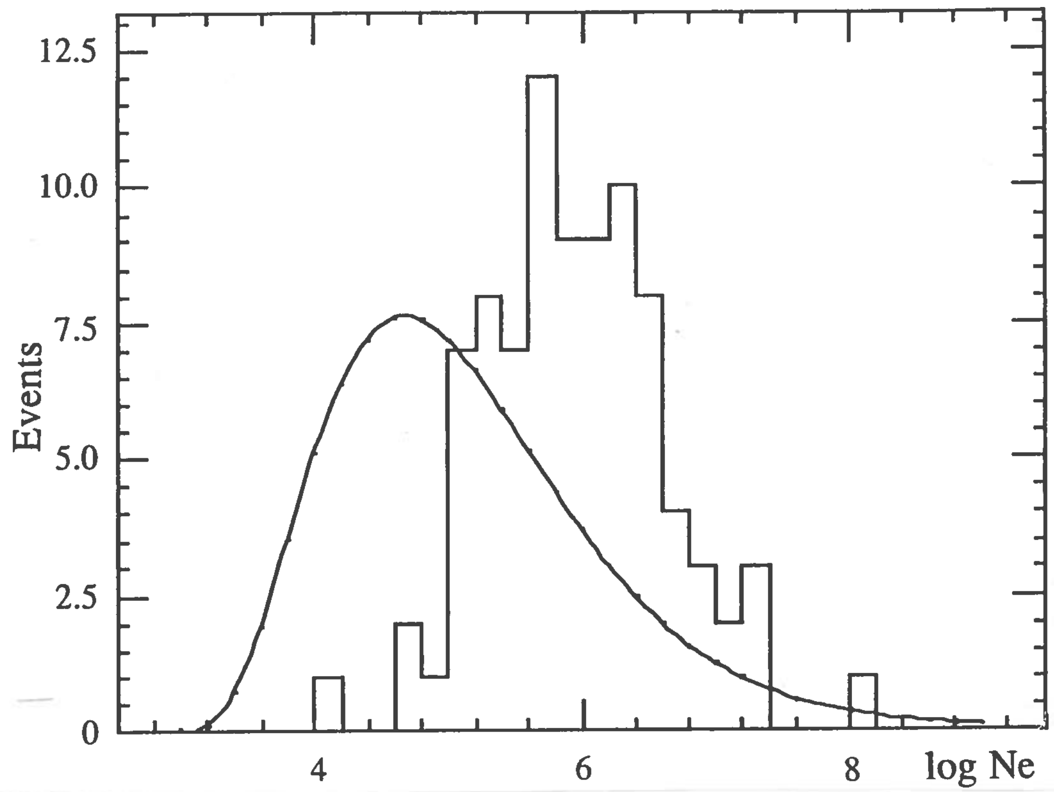

FIG. 11 - Distribution of logNe as measured by EAS-TOP for the coincident internal trigger events. The continuous line is the shape of the same distribution as measured by EAS-TOP in single operation, normalized at the same number of the events.

We have also tested the MACRO core location as an input to the EAS-TOP reconstruction code for the shower size. In Fig. 12 the reconstructed size is plotted versus the same quantity as obtained with the EAS-TOP data alone, when the multiple muon events are selected in order to minimize the errors in the core location. The obtained result confirms the assumption of the accuracy in the back-pointing of the underground muons. This can be of great importance in the analysis of the edge events.

We show in Fig. 13 the muon multiplicity distribution for the lower (logNe<4.8) and higher (logNe>5.2) intervals of EAS size. Within the obvious statistical limits the trend is similar to that shown previously in Fig. 10 and in Fig. 14 described in the next section: higher primary energy corresponds to longer high multiplicity tail.

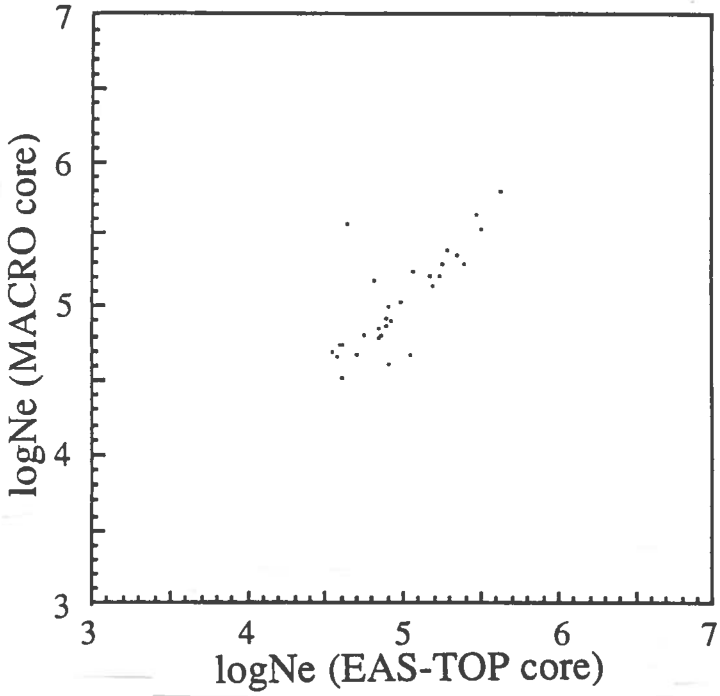

FIG. 12 - Shower size reconstructed using the core location given by MACRO for multiple muon events vs. the same quantity reconstructed by EAS-TOP alone.

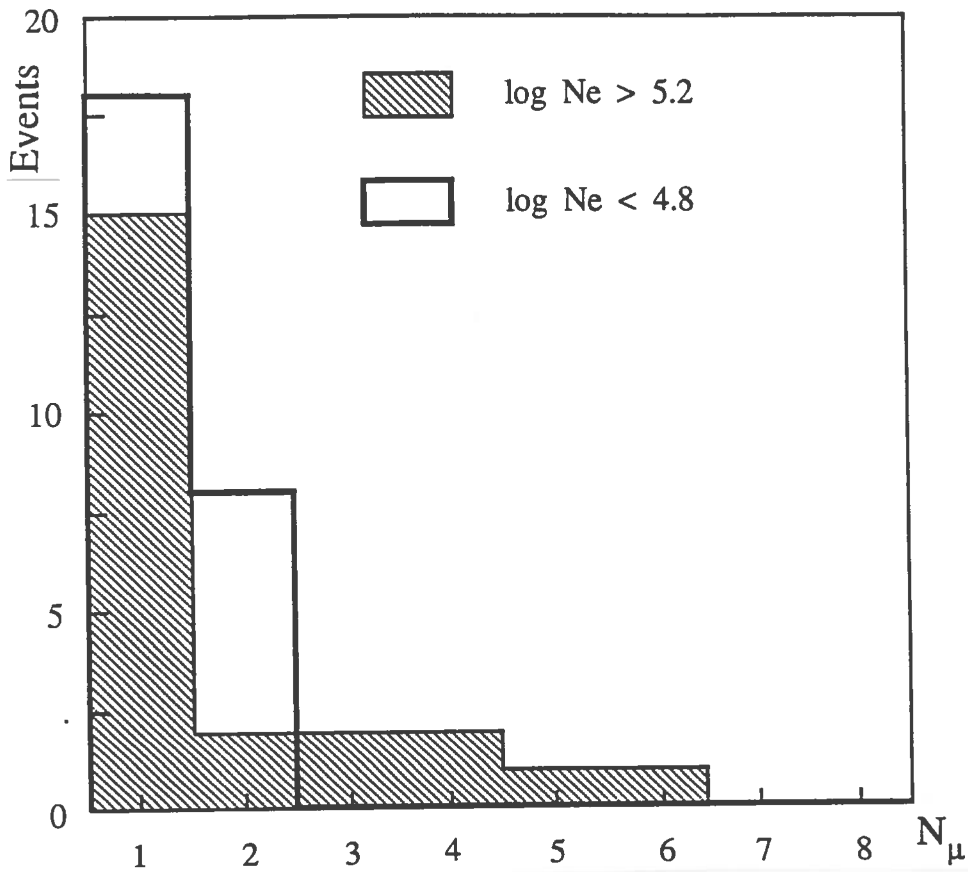

FIG. 13 - Muon multiplicity distributions as observed by MACRO for coincidence events with log Ne > 5.2 and log Ne < 4.8 .

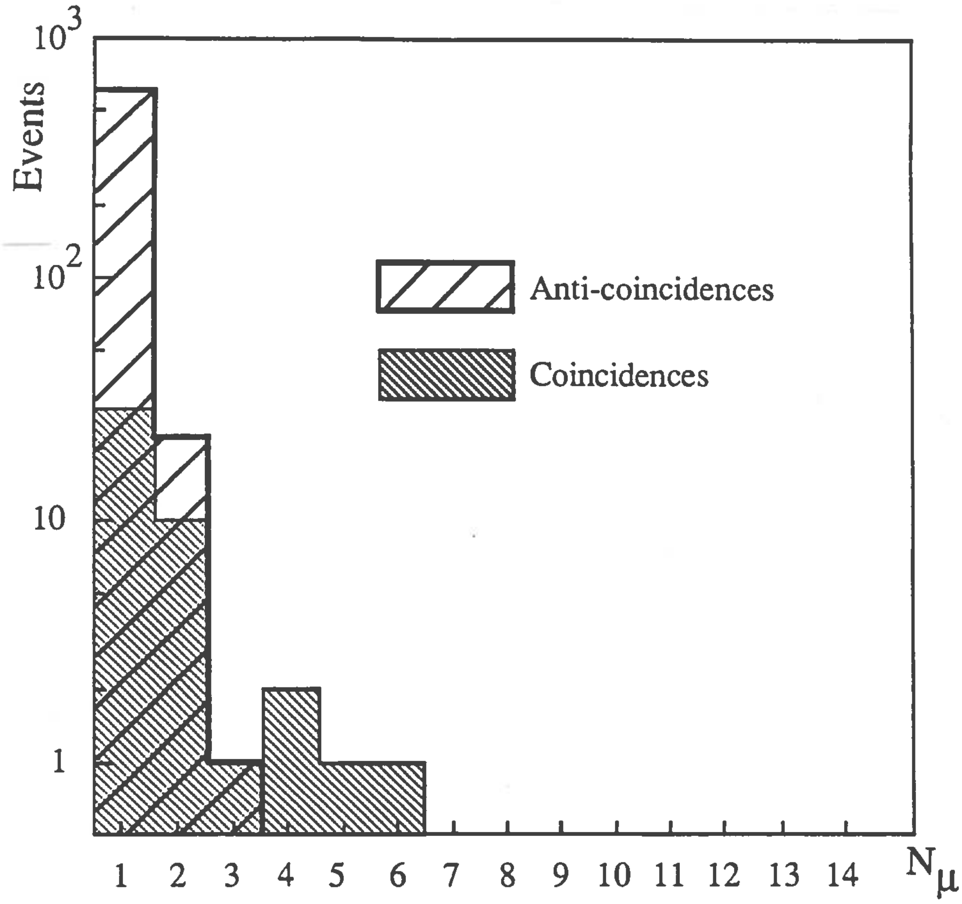

FIG. 14 - Muon multiplicity distributions as observed by MACRO for events pointing to the fiducial region for coincident events, and anti-coincident events.

The evaluation of the effect of the finite size of the apparatus is crucial for the physics analysis of the correlation between the underground muon multiplicity and the EAS shower size. A detailed Montecarlo simulation is now in progress to quantify this effect and to compare the data with different composition models.

6. Anti-correlated events

Physical information can be obtained also from anti-correlated events. These are those events in which MACRO points to EAS-TOP but no coincidence is found, the shower energy being under threshold. These events come from the lower energy region of the measurable spectrum, around $E_0=10^{13}-10^{14}$ eV. Here the primary composition is better known than at higher energies. Furthermore, here the underground muons are mainly produced by the light nuclei (p and α). Therefore this measurement can provide an independent check of the analysis coming from the coincidence data.

A fiducial area of 10^4 m^2 has been chosen well inside the internal region of EAS-TOP, at least 50 m far from the edge of the array. In the total period of analysis, an anti-coincidence/coincidence ratio of 624/44 has been found in the fiducial region. The statistical error (~20 %) does not permit any definite conclusion now.

Fig. 14 shows the muon multiplicity distributions as measured in the fiducial region for coincidence superimposed to the same distribution for anti-coincidence events. The anti-coincidences are mostly low-multiplicity events: the higher multiplicities (≥4) have been all detected as coincidence events, as one should expect, since they correspond to higher energies.

7. Conclusions

The presented results show that the coincidence experiment at the Gran Sasso Laboratory between EAS-TOP and MACRO has achieved good detection and operation efficiency. In particular a good geometrical reconstruction of the events has been obtained, without systematic effects. This allows the simultaneous detection of underground muons and EAS, thus resulting in a powerful new tool for the analysis of cosmic rays at very high energy. In this respect the two combined experiments have already shown their potential capability to perform accurate measurements in the most interesting region of the primary spectrum.

Furthermore the coincidence measurements provide a reciprocal check between the two experiments, which is very useful also for the single operation of each apparatus.

Many improvements are also scheduled in the future: MACRO is going to increase by a factor of 6 its active surface by putting other supermodules into operation, and EAS-TOP will lower the energy threshold by a factor 3 and increase its sensitivity at high energy. Furthermore an optical fiber system for the calibration of the EAS-TOP scintillators is envisaged and the absolute time resolution will be brought to ~1 μs. After 3 years of running we expect to increase our statistics by a factor 100, thus hopefully allowing a discrimination between different composition models.

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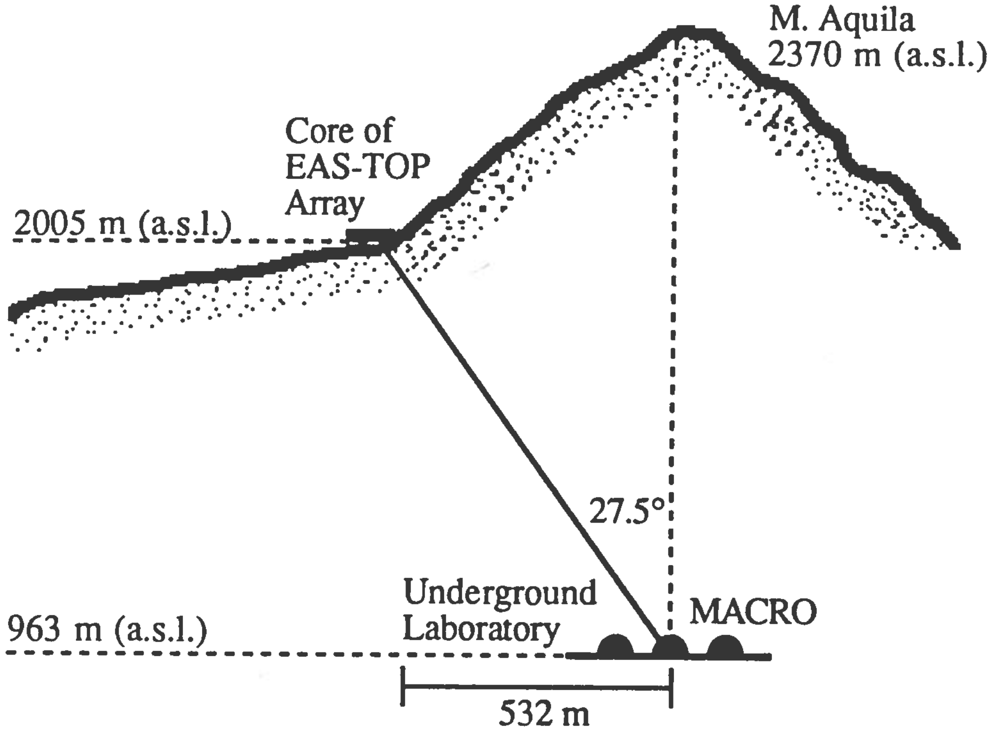

M. Aquila
2370 m (a.s.l.)
Core of
EAS-TOP
Array
2005 m (a.s.l.)
27.5°
Underground
Laboratory
MACRO
963 m (a.s.l.)
532 m

Fig. 1

Fig. 2

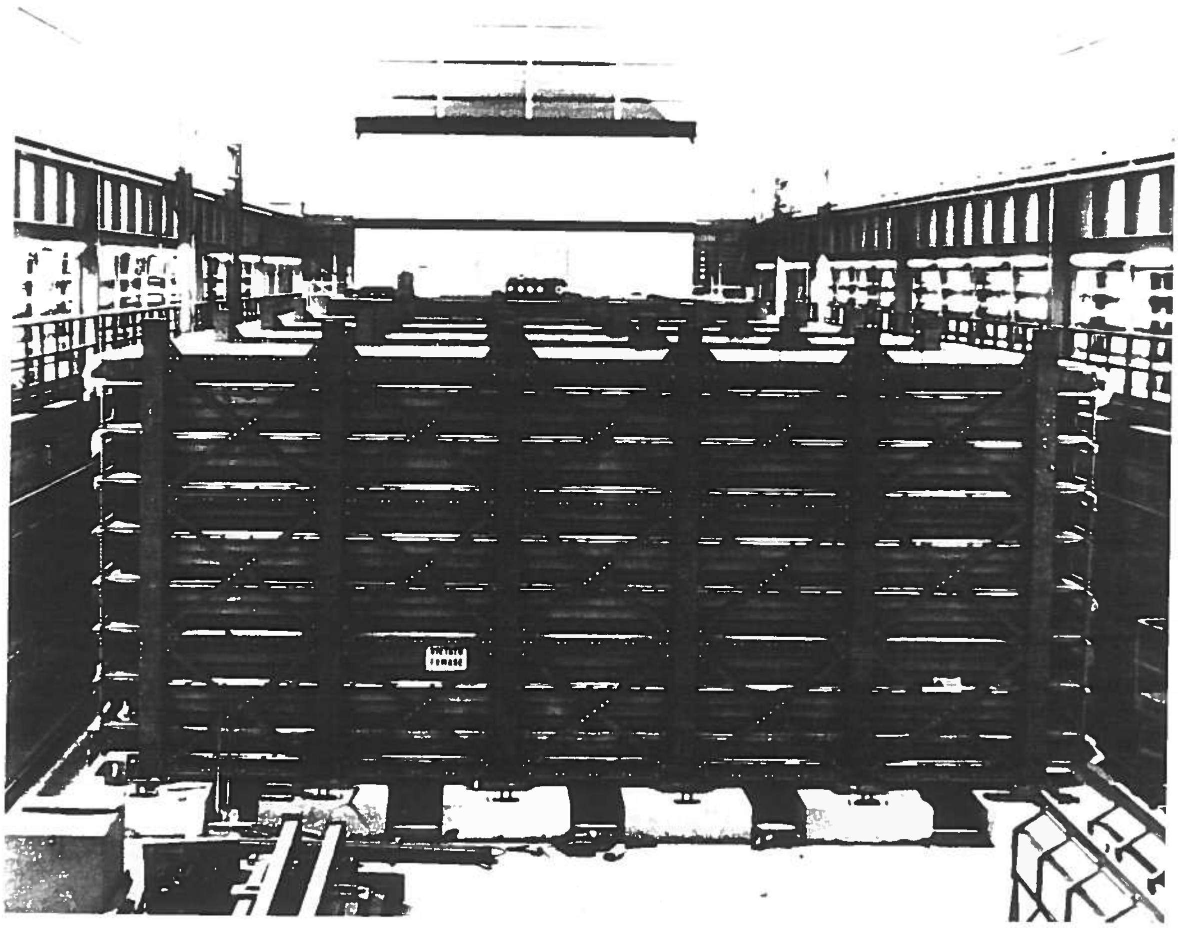


Fig. 3

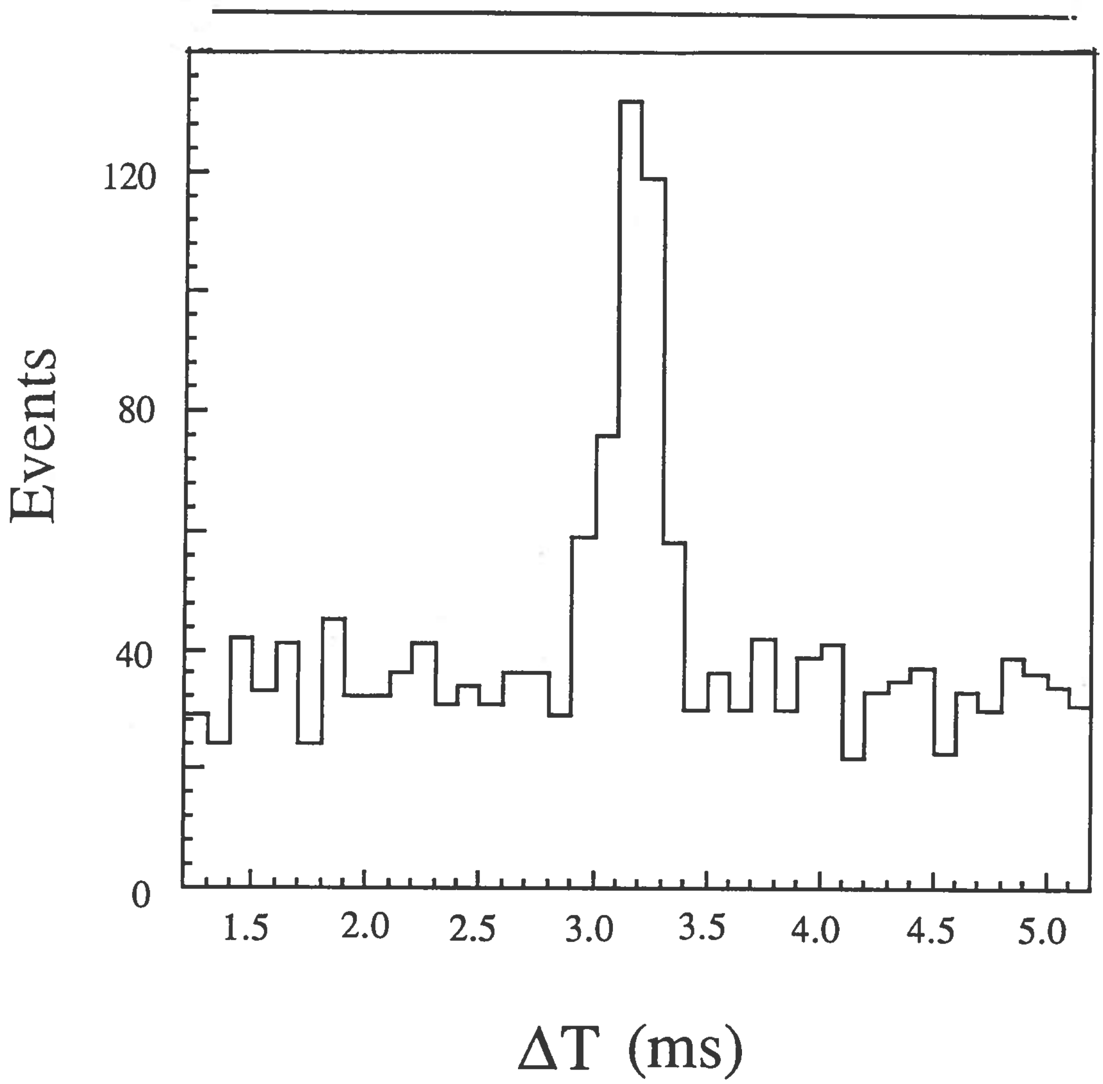


Fig. 4

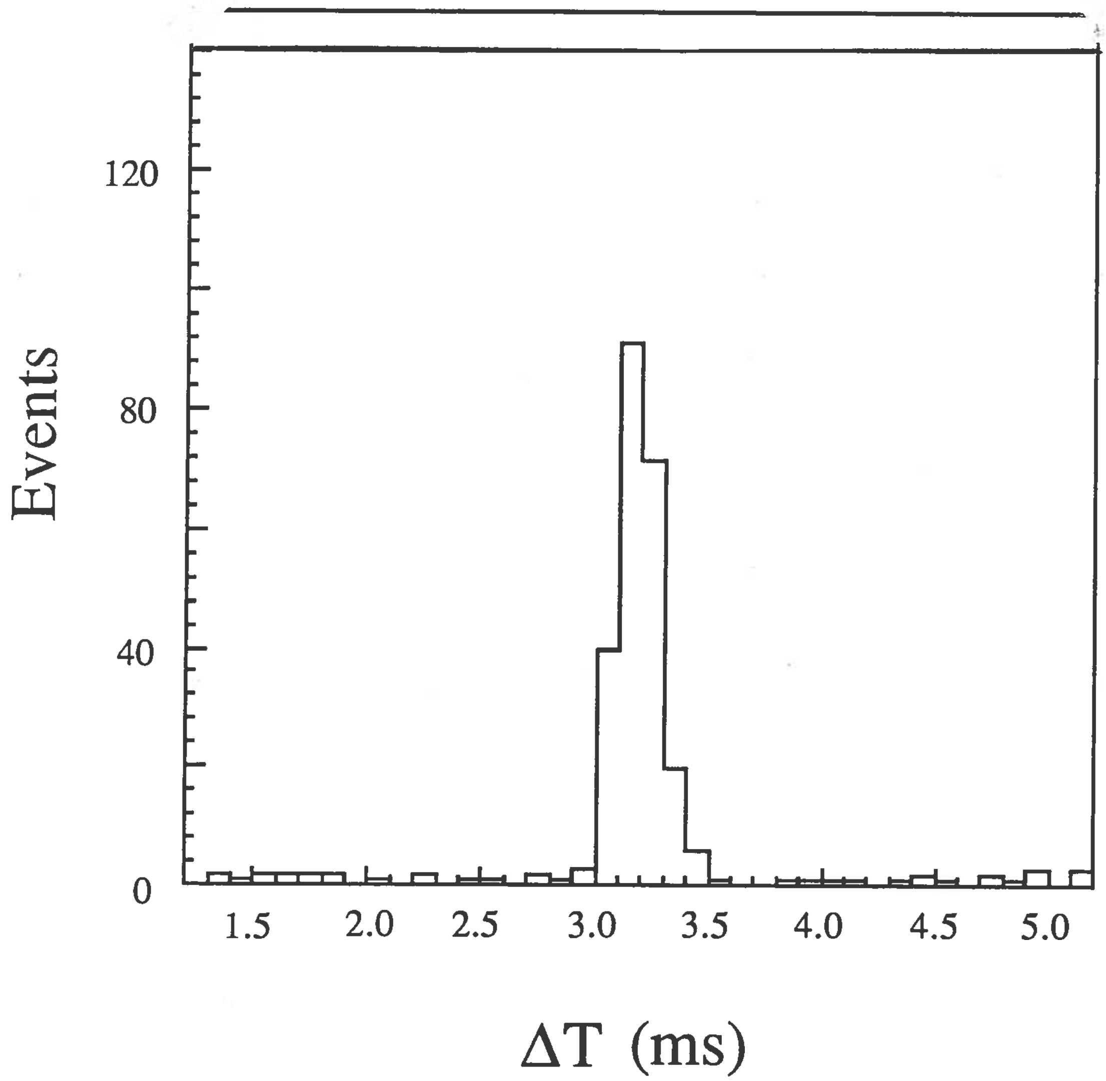


Fig. 5

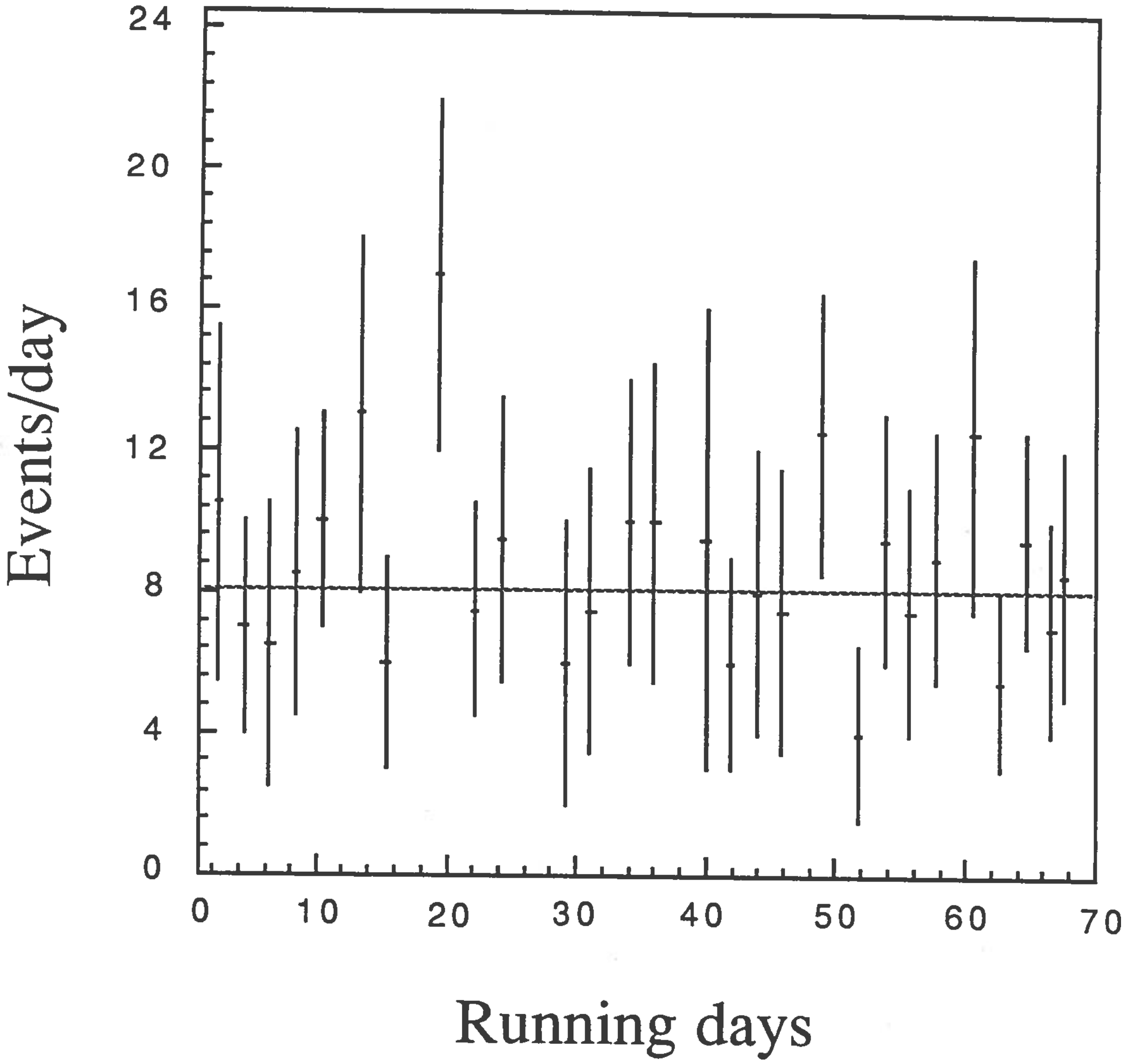
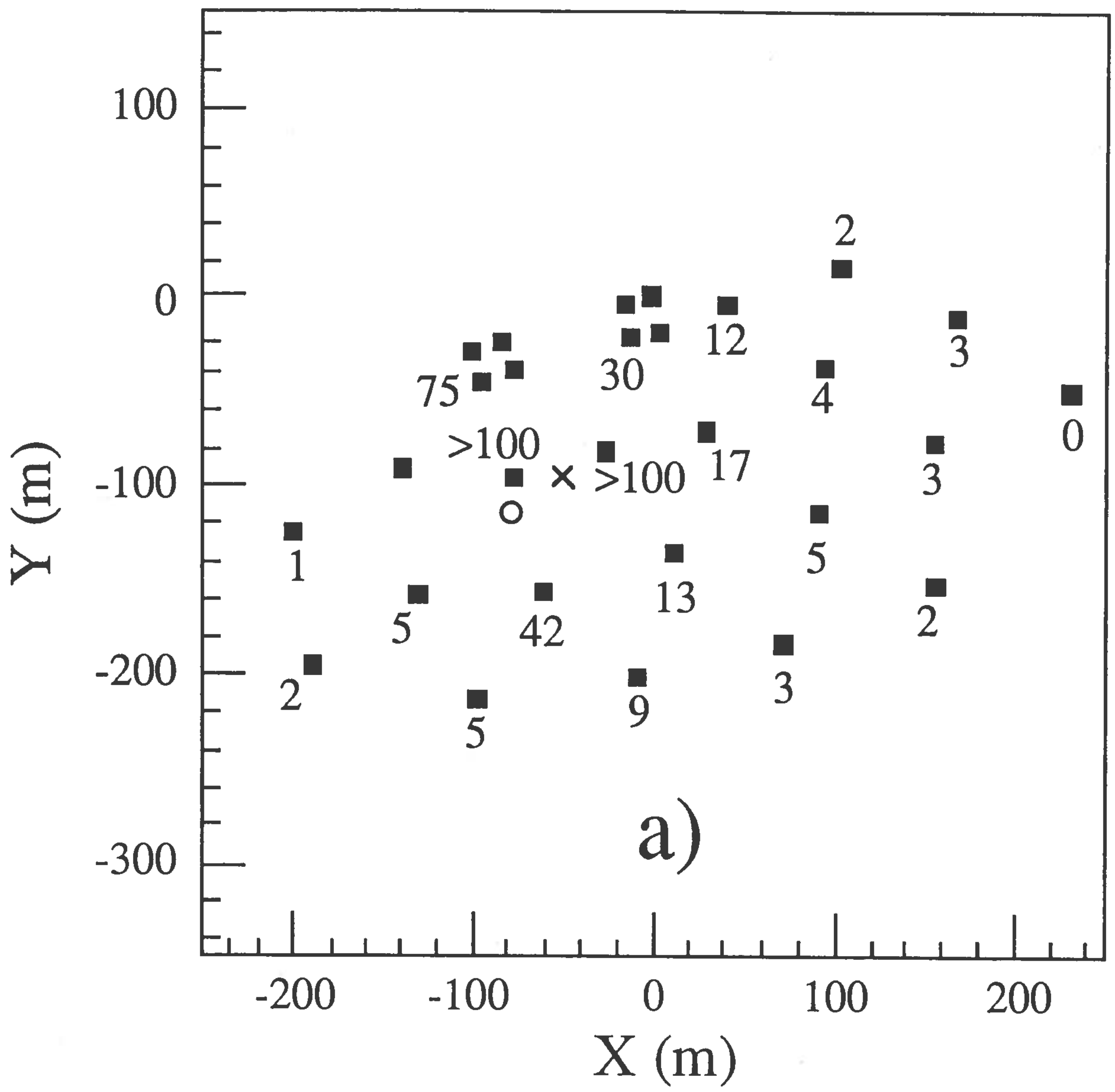
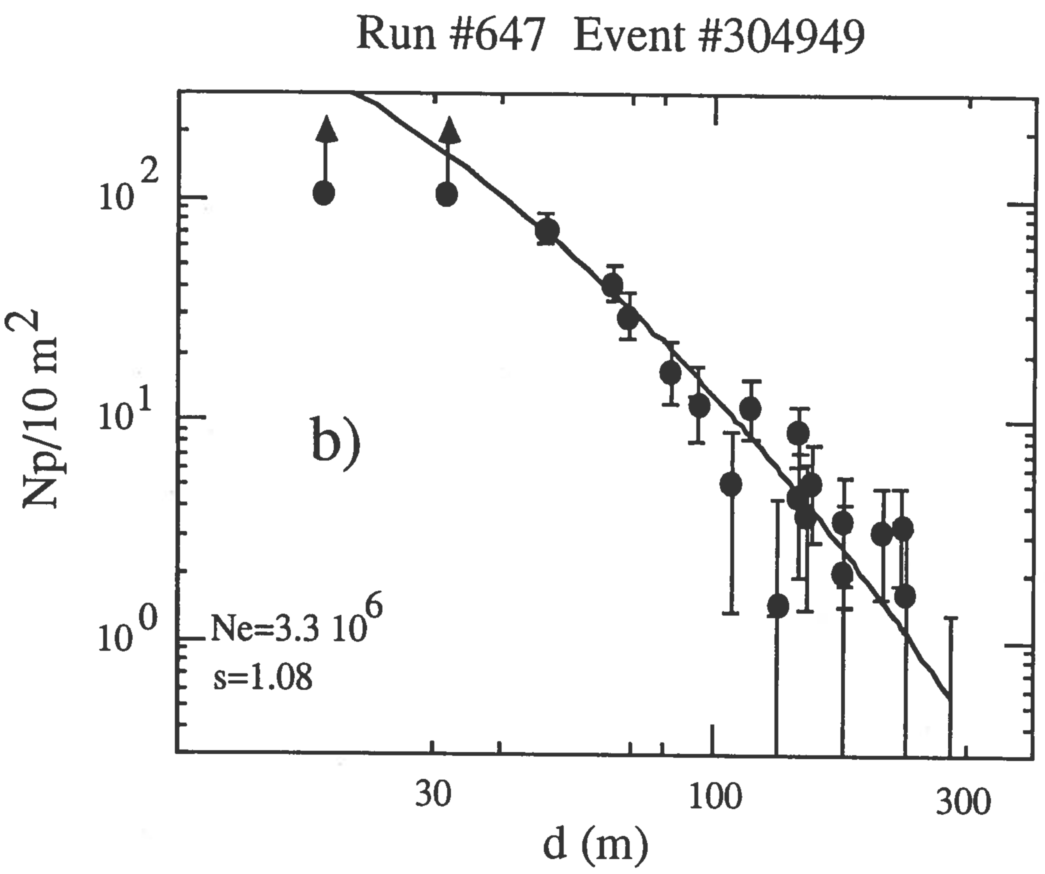


Fig. 6



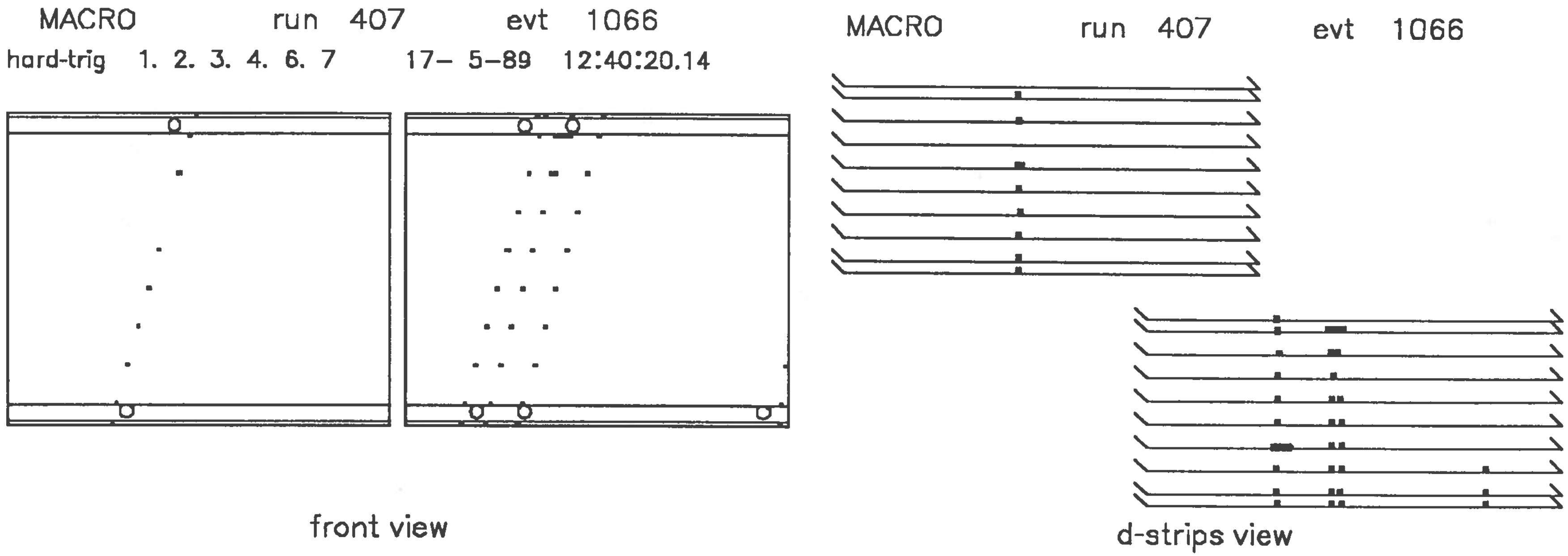
100
0
-100
-200
-300
Y (m)
-200
-100
0
100
200
X (m)
a)
2
12
3
30
75
4
0
>100
>100
17
3
1
5
5
13
42
2
2
3
9
5

Fig. 7



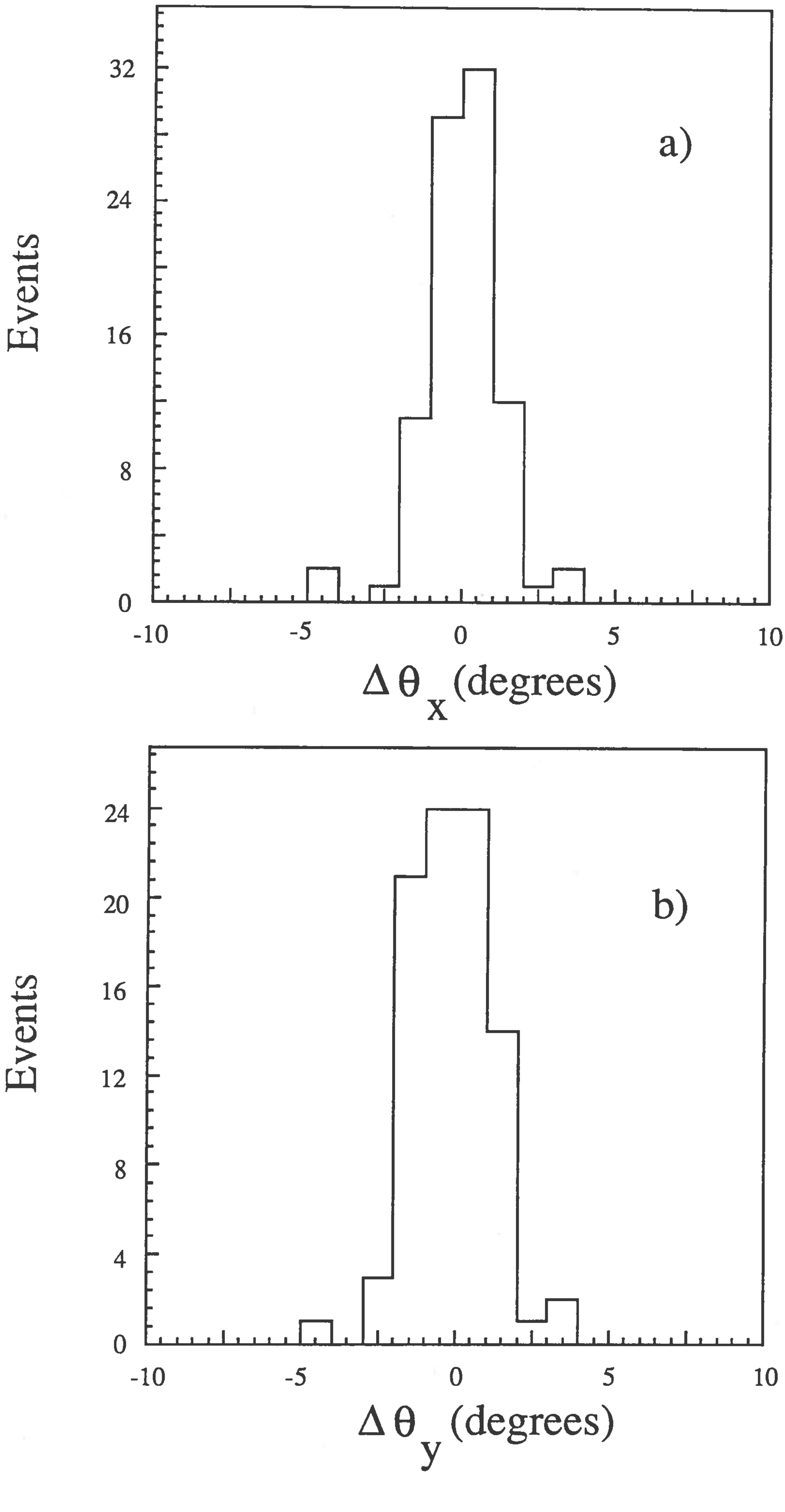
Run #647 Event #304949
10^2
10^1
10^0
Np/10 m^2
b)
Ne=3.3 10^6
s=1.08
30
100
300
d (m)

Fig. 7


MACRO run 407 evt 1066
hard-trig 1. 2. 3. 4. 6. 7 17- 5-89 12:40:20.14
front view
MACRO run 407 evt 1066
d-strips view

c)

Fig. 7



a)
Events
32
24
16
8
0
-10
-5
0
5
10
Δ θ x (degrees)
b)
Events
24
20
16
12
8
4
0
-10
-5
0
5
10
Δ θ y (degrees)

Fig. 8

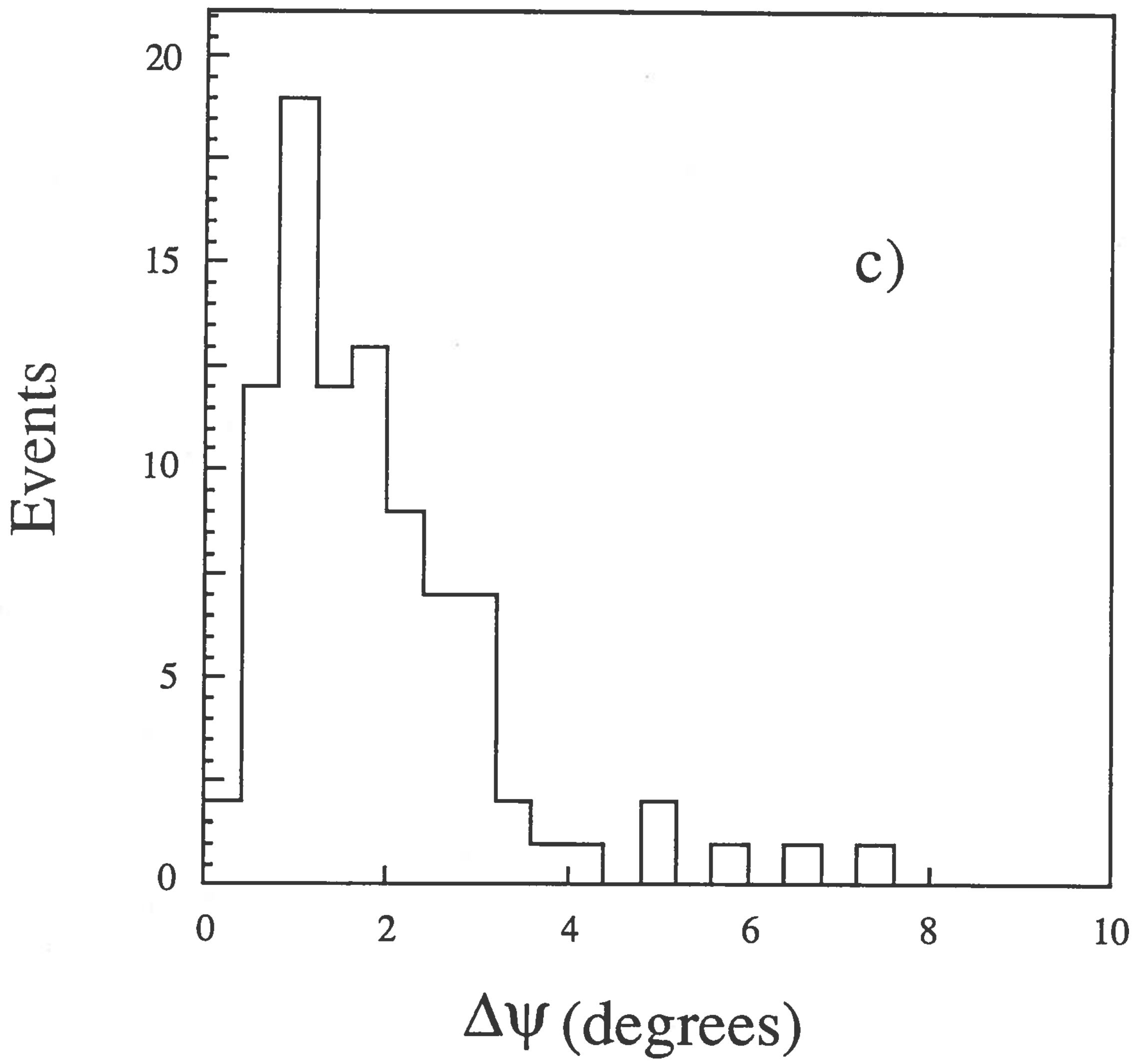
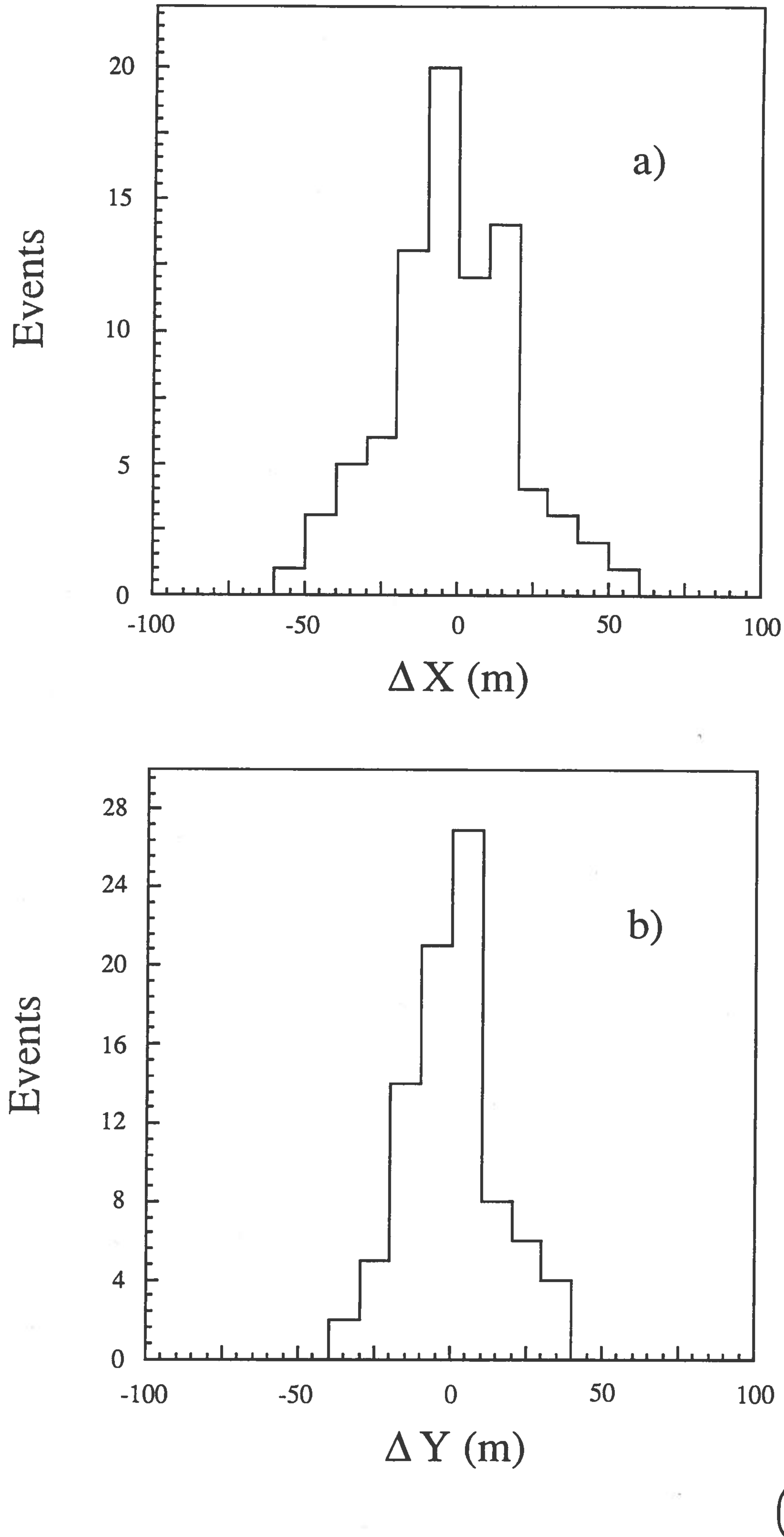


Fig. 8



a)
Events
20
15
10
5
0
-100
-50
0
50
100
ΔX (m)
b)
Events
28
24
20
16
12
8
4
0
-100
-50
0
50
100
ΔY (m)

Fig. 9

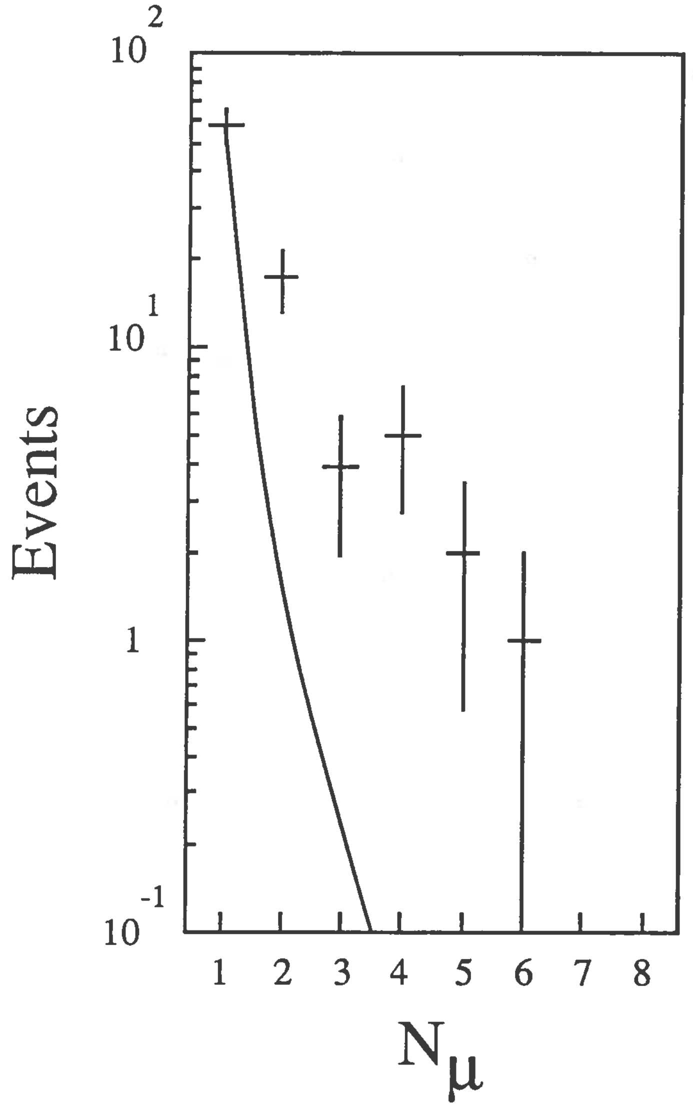


Fig. 10

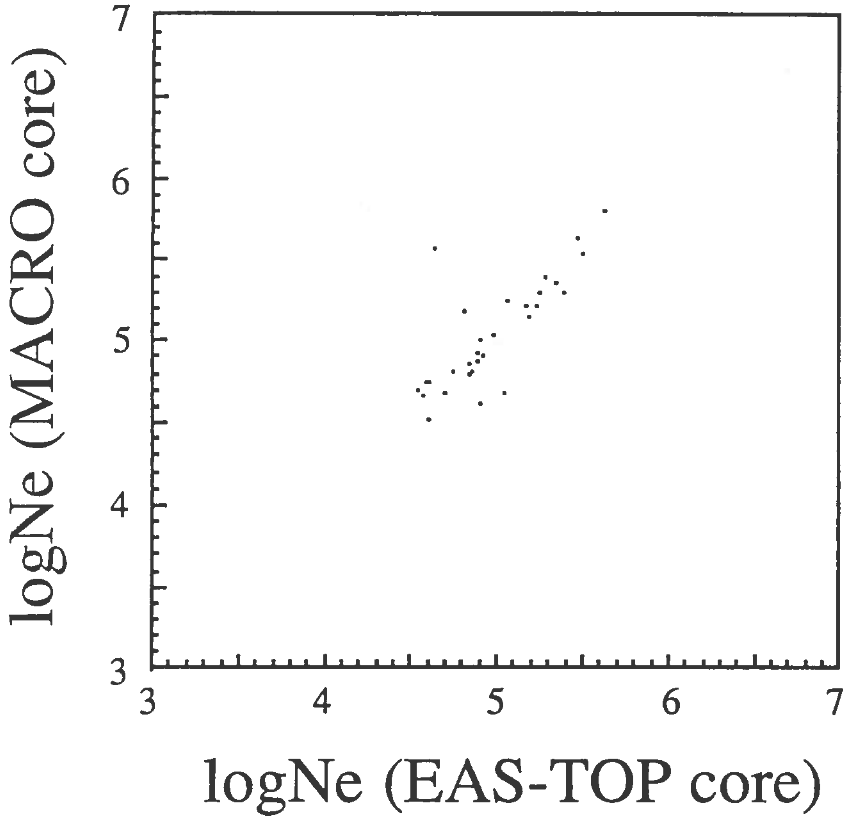


Fig. 11

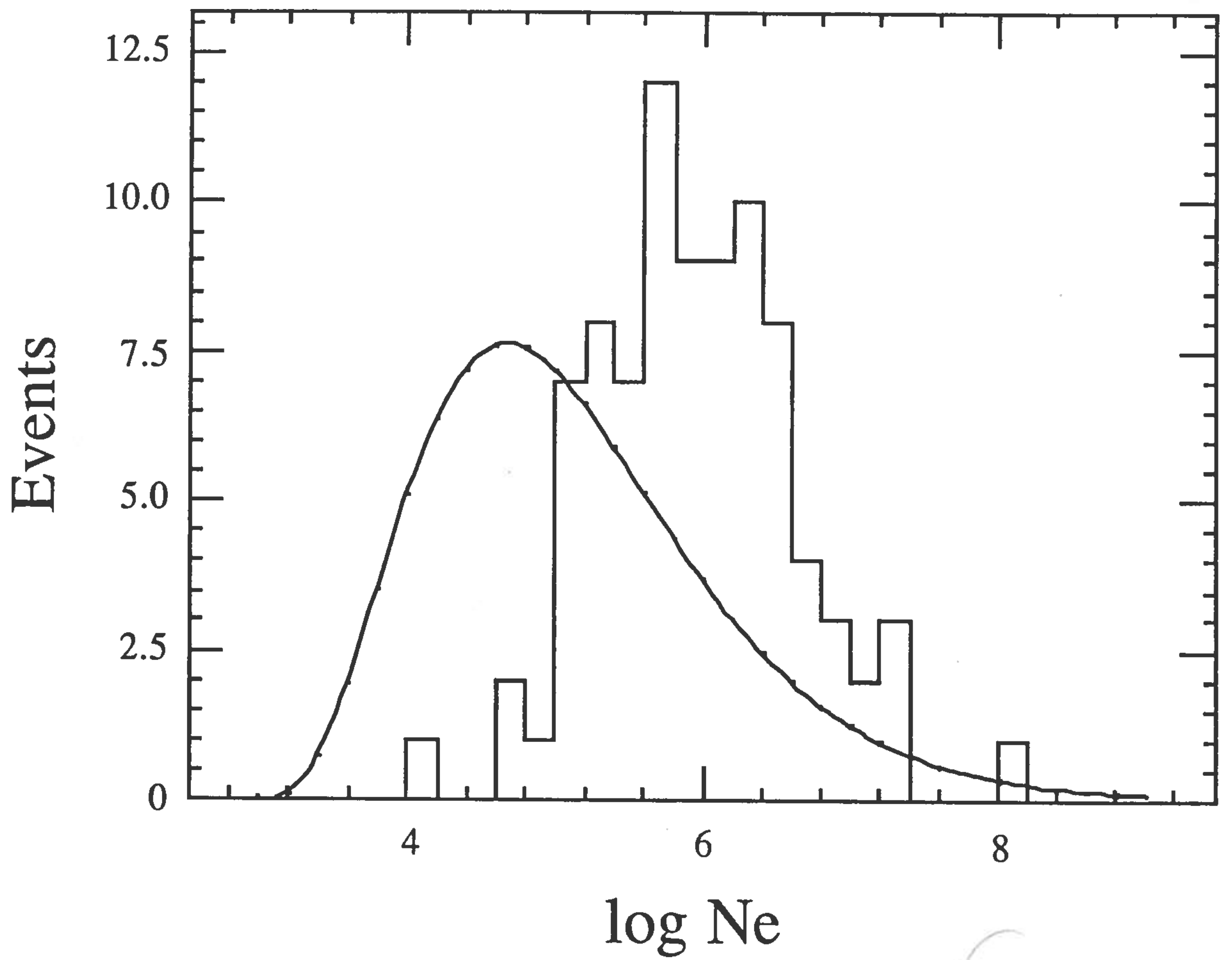


Fig. 12

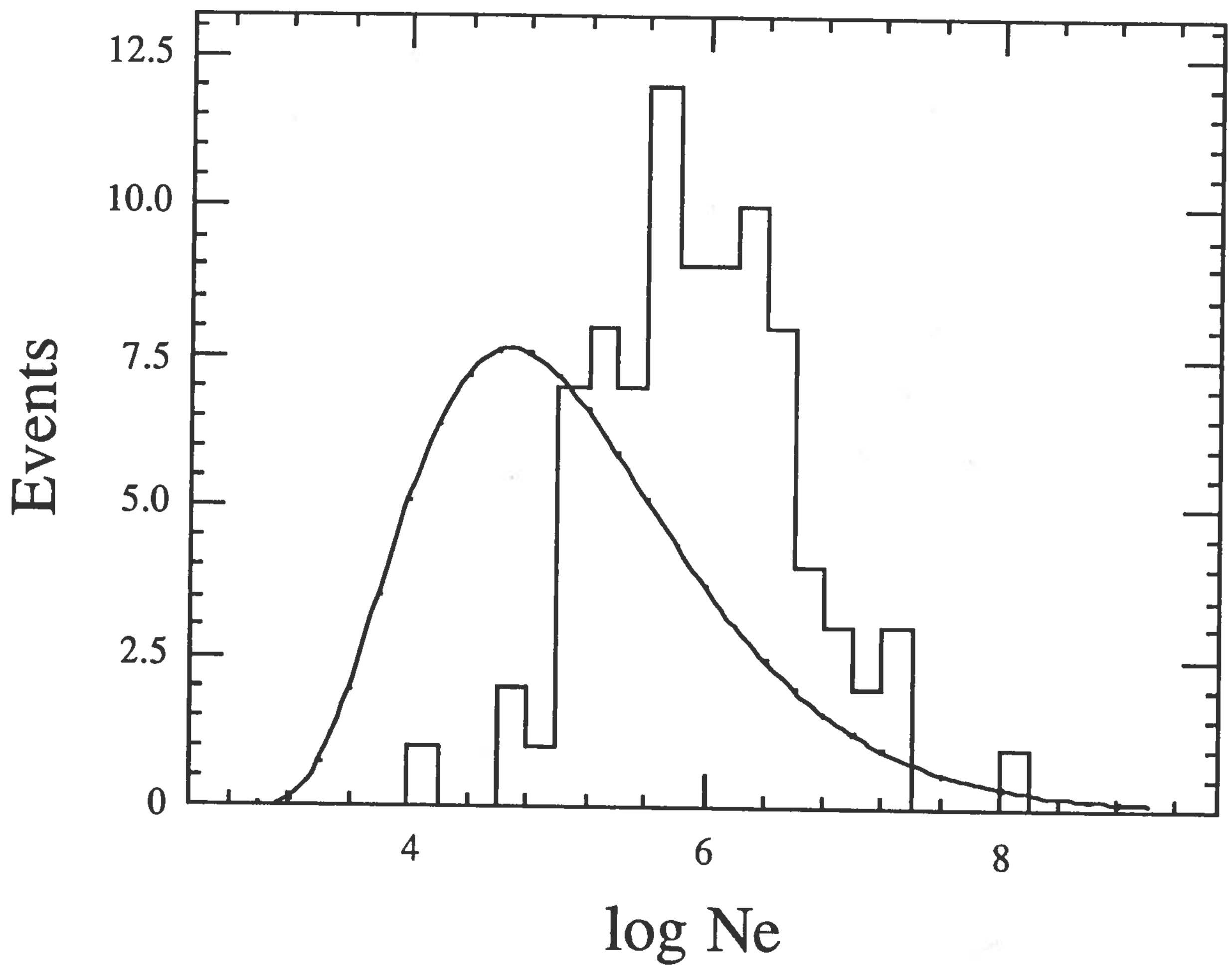


Fig. 12

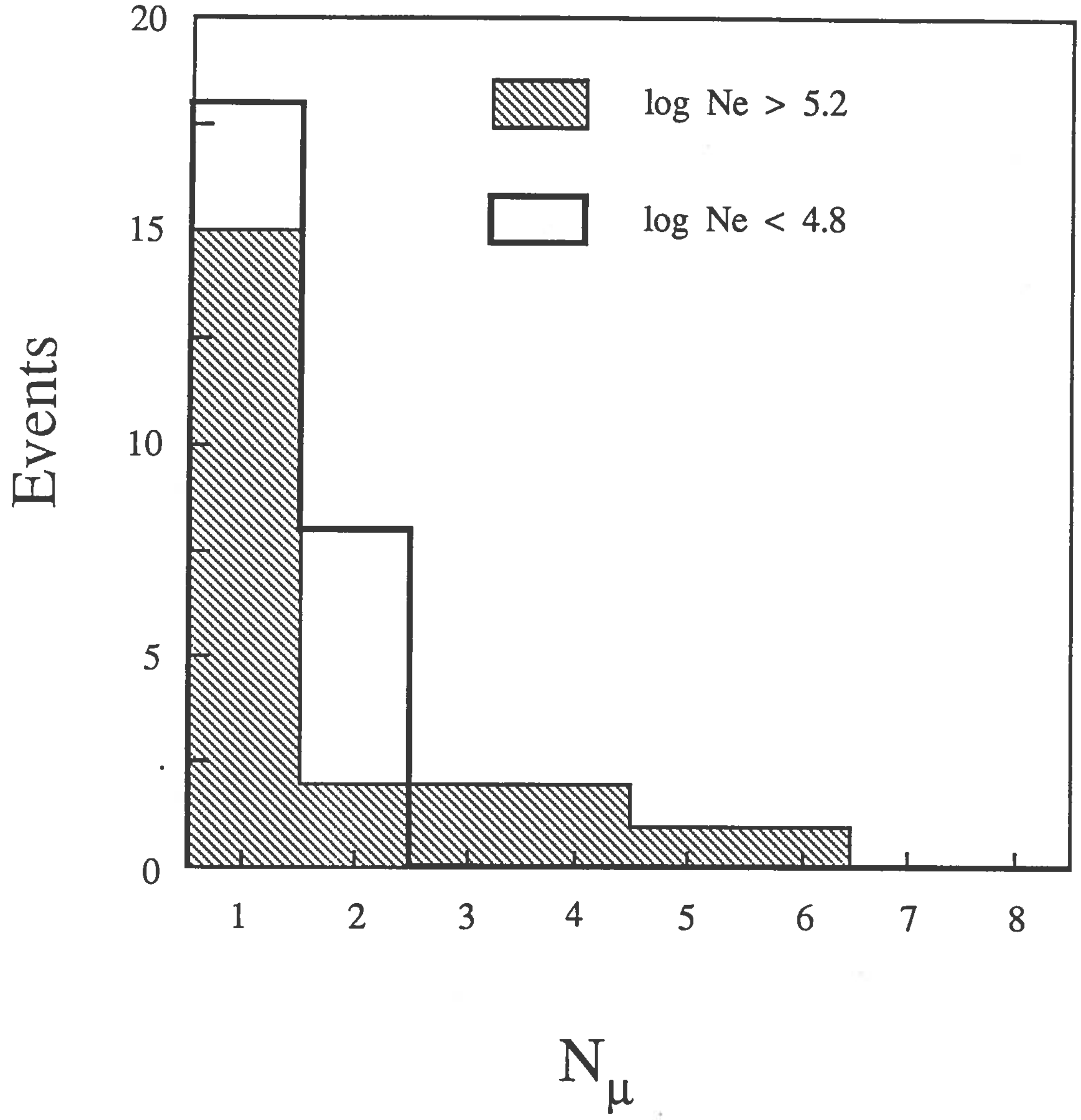
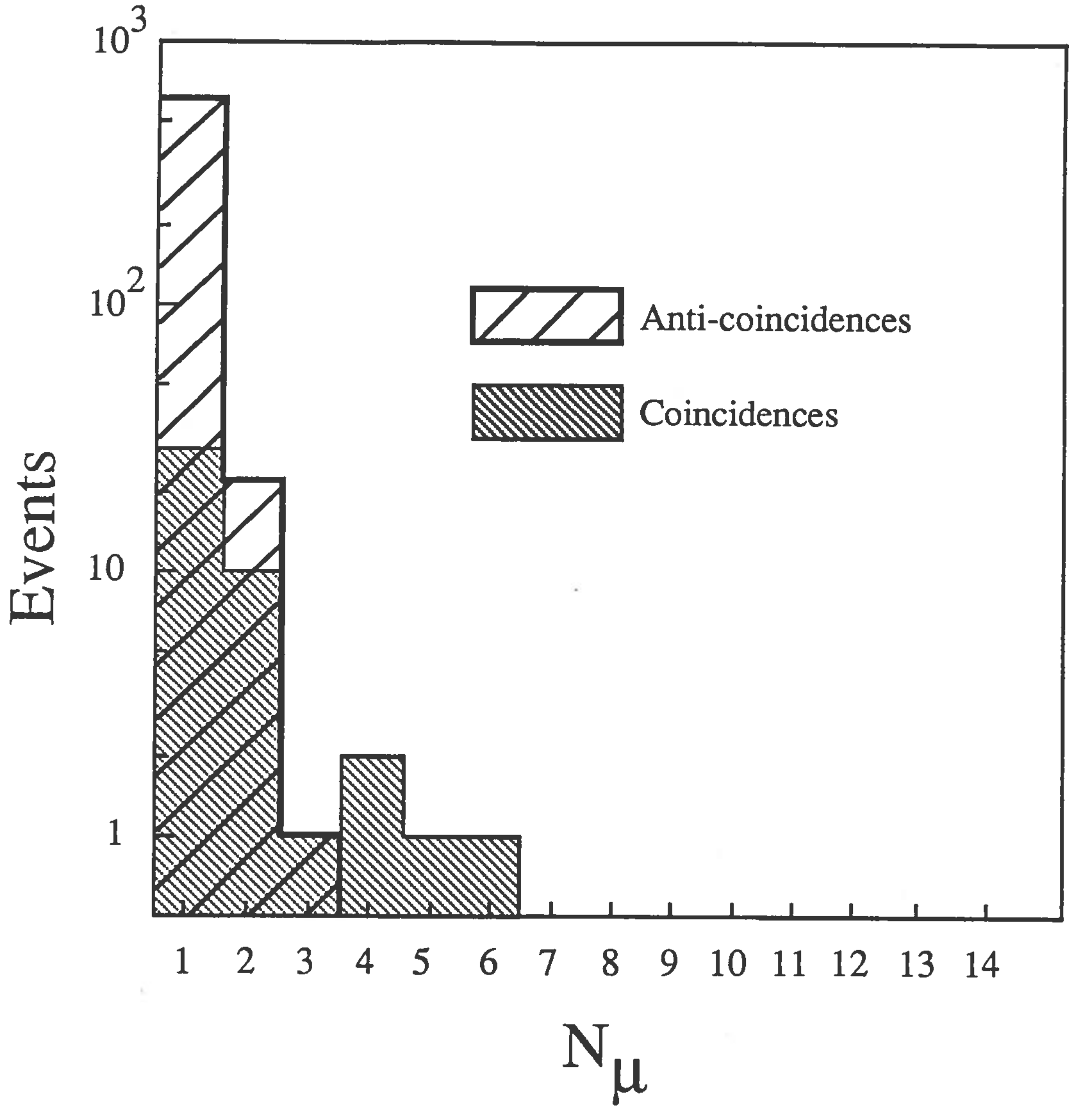


Fig. 13



10^3
10^2
10
1
Events
Anti-coincidences
Coincidences
1 2 3 4 5 6 7 8 9 10 11 12 13 14
N_μ

Fig. 14

ERRATA CORRIGE - pagg. 14/15 -
INFN/AE-89/7 (31 Agosto 1989)

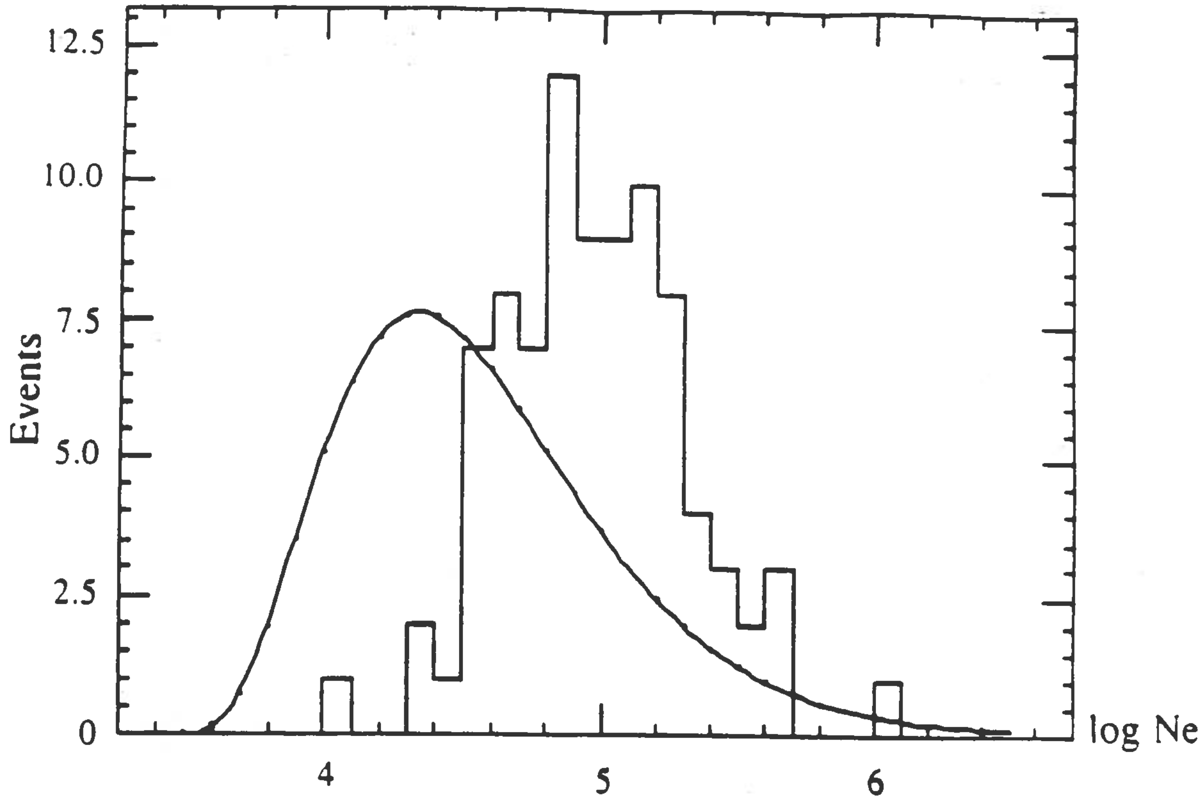


FIG. 11 - Distribution of logNe as measured by EAS-TOP for the coincident internal trigger events. The continuous line is the shape of the same distribution as measured by EAS-TOP in single operation, normalized at the same number of the events.

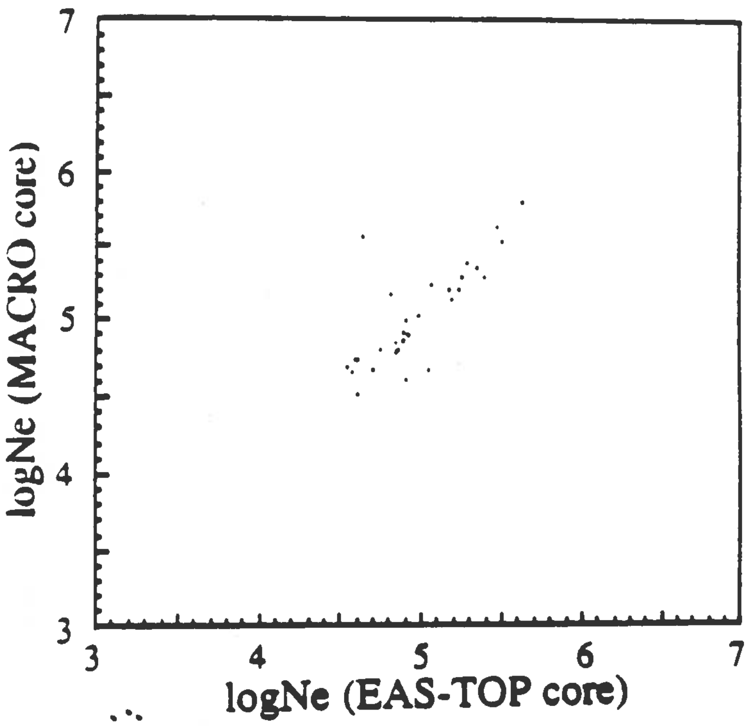


FIG. 12 - Shower size reconstructed using the core location given by MACRO for multiple muon events vs. the same quantity reconstructed by EAS-TOP alone.