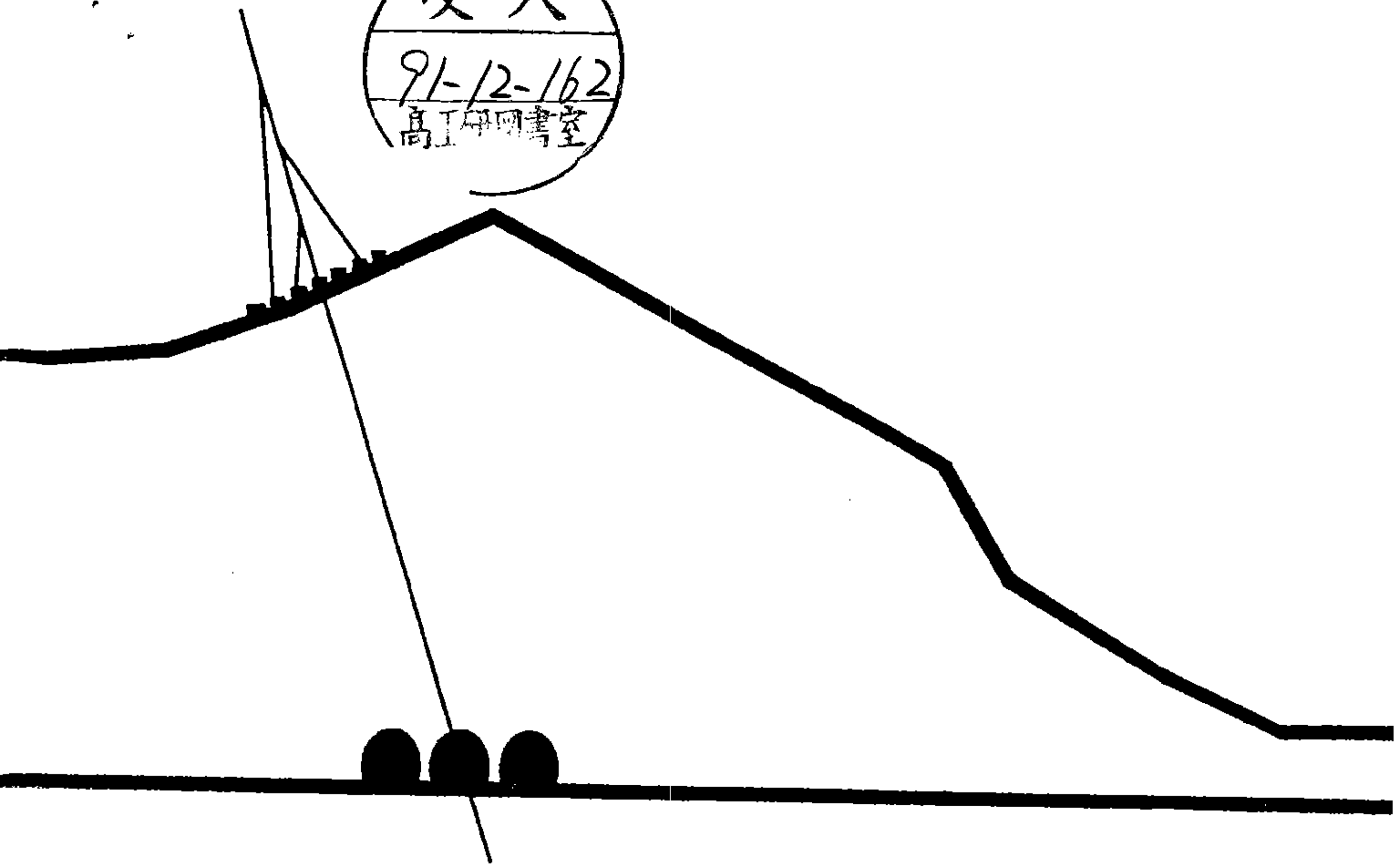

LNGS - 91/06
October 1991

Measurements of Electromagnetic and TeV Muon Components of Extensive Air Showers by EAS-TOP and MACRO

LNGS - 91/07
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Study of High Energy Cosmic Rays through the Measurement of the Electromagnetic and TeV Muon Components of Extensive Air Showers by EAS-TOP and MACRO

CONTRIBUTIONS TO THE 22nd ICRC

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(HE 4.2-5)

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1 Abstract

The simultaneous observation of the electromagnetic and TeV muon components of extensive air showers by the EAS-TOP and MACRO detectors, respectively, is described for a period of 100 days in 1990. The two detectors and their combined resolutions are briefly reviewed and muon multiplicity distributions for various detector configurations are presented.

2 Introduction and General Detector Characteristics

The study of primary cosmic rays at high energies ($E_0 > 10^{14}$ eV) is hampered by low fluxes. To improve upon past studies requires the combined measurement of different parameters of extensive air showers. The correlation of the total electromagnetic shower size at ground level (N_e) with the muon bundle characteristics deep underground provides an important tool in the study of this subject.

MACRO[1] is located in Hall B of the underground Gran Sasso National Laboratories in Italy. For the period of time reported here, two supermodules were in operation, resulting in a rectangular parallelepiped shape of dimensions $24 \times 12 \times 4.8$ m^3. Muon tracking in MACRO for this analysis was provided by 10 horizontal layers of streamer tubes with a spatial accuracy of ~1 cm, resulting in an angular reconstruction accuracy in two projected views of better than 0.6°, the mean angular deviation due to multiple Coulomb scattering in the rock above the detector. A muon was defined as at least four aligned hits in the streamer tubes.

EAS-TOP[2] is an array of 29 modules of scintillation counters, each of area 10 m^2, distributed over an area of 10^5 m^2. It is located at an altitude of 2005 m above sea level, on the mountain above the underground laboratory, at an average angle of 33° with respect to the vertical of MACRO. The minimum trigger requirements are four contiguous modules firing, corresponding to a primary energy threshold ~50 TeV. For a primary energy $E_0 \geq 200$ TeV ($N_e \geq 3 \times 10^4$) and core inside the edges of the array, the angular reconstruction accuracy is $\sim 0.8°$, the core location is determined to a few meters and the total shower size to $\Delta N_e/N_e \sim 20\%$.

The relative location of MACRO and EAS-TOP is shown schematically in Fig. 1. The rock overburden above MACRO in the direction of EAS-TOP varies between 3100 and 3500 m of water equivalent, corresponding to muon energy thresholds of 1.3 and 1.6 TeV. The angular range of EAS-TOP as seen by MACRO is 25° to 37° in zenith and 160° to 200° in azimuth. The two detectors had run simultaneously for 46 days of live time in 1989, and the results were reported elsewhere[3]. We present here the analysis of data gathered between July 18 to December 14, 1990, for a total live time of 100.0 days. There had been several improvements made for the 1990 run, both to EAS-TOP (a more accurate clock, lowering the trigger threshold, operating all 29 modules, as opposed to 22 in 1989) and to MACRO (doubling the size from 1 to 2 supermodules).

3 Data selection and combined reconstructions

For both detectors, the timing of each event was provided by independent rubidium clocks, accurate to 1 μs. The selection of coincident events was performed off-line on the basis of this timing. Relative clock drifts were corrected (also off-line) by using relativistic muons to define the coincidence peak, run by run. Fig. 2 shows the distribution of time differences between the reconstructed events of EAS-TOP and MACRO. The curve is a gaussian fit with a standard deviation of 0.69 μs. A 3σ cut at ± 2.1 μs was applied to define a coincidence. An example of one of the more spectacular coincident events thus defined is shown in Fig. 3. Accidental coincidences caused a background of 22.6$\pm$0.1 events per μs. Overall, 7644 events satisfied the 3σ cut, including an estimated 95.0$\pm$0.3 accidental coincidences (1.2%), for a constant trigger rate of 75.5$\pm$0.9 real coincidences per day.

Events recorded by EAS-TOP were classified according to the trigger criteria. In what follows, the analysis is restricted to so-called "internal" events, i.e. events for which the core of the shower lies within the boundaries of the array. This category was further divided into high energy and low energy internal events, where a high energy event hit at least 6 contiguous counters, and a low energy event hit at most one counter located on the edges of the array but satisfied the minimum trigger requirement. The corresponding primary energy thresholds were roughly 100 TeV and 50 TeV.

Out of the 7644 coincident events, 582 were high energy internal events. For this trigger configuration, a background of 3.2$\pm$0.5 accidental coincidences (0.5%) was expected; out of the 582 events, 2 were eliminated as background by obvious angular mismatches. For 90% of the remaining events, the independent reconstructions agreed to better than 3.9° in absolute direction in space and 55 m in core location, indicative of consistent reconstruction procedures. 434 of the 7644 coincidences were low energy internal events.

The distribution of muon bundle multiplicities N_μ as seen by MACRO for high energy and low energy internal events is shown in Fig. 4. Paper OG6.1-2 of these proceedings discusses in detail the MACRO analysis of muon bundle multiplicities.

An anticoincident event is defined as a MACRO event pointing back to a small fiducial area of about 10^4 m^2 well within the perimeter of EAS-TOP and which did not trigger the array. This corresponds to a primary energy below the threshold of EAS-TOP. Also plotted on Fig. 4 are the multiplicity distributions for anticoincident events and those coincident events reconstructed by MACRO to point back to the same fiducial area. There were 2915 anticoincident events recorded, compared with 670 coincident events pointing back to the fiducial area.

4 Conclusions

The coincidence technique based on timing measurements guarantees a high efficiency of operation with extremely low levels of background, which can be identified from the geometrical information. In the current EAS-TOP trigger configuration, the efficiency for detecting the electromagnetic component of extensive air showers for which the high energy muons point back to the array is good ($\sim$ 19%) and is 100% for $N_\mu \geq 4$. As is apparent from Fig. 4, the general features of muon multiplicity distributions agree with

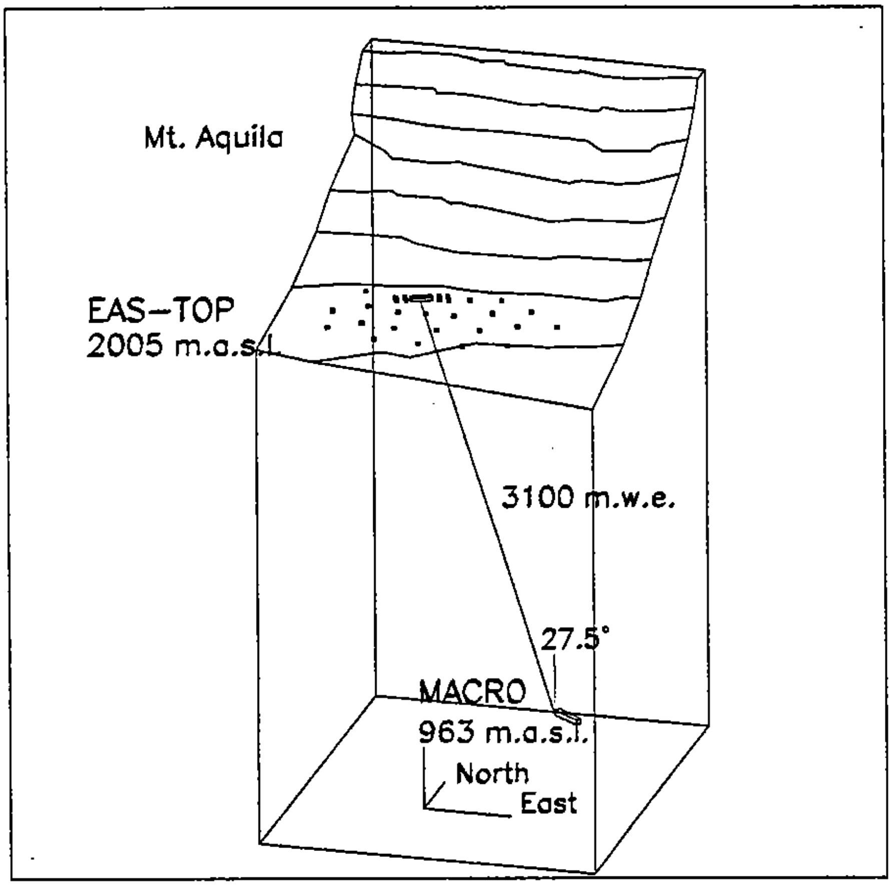

Figure 1: Relative locations of EAS-TOP and MACRO.

expectations over a primary energy range from less than 50 TeV up to more than 1000 TeV, namely that with increasing shower size, and thus increasing primary energy, there is an increase in the contribution of high muon multiplicities. Work is in progress to increase the statistical sample by including external events in the analysis. In paper OG6.1-23 of these proceedings, we examine the data defined above in a more quantitative way.

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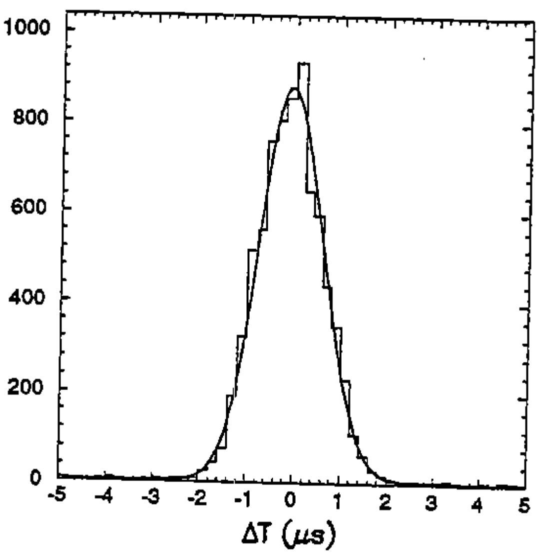

Figure 2: Time difference distribution between EAS-TOP and MACRO events.

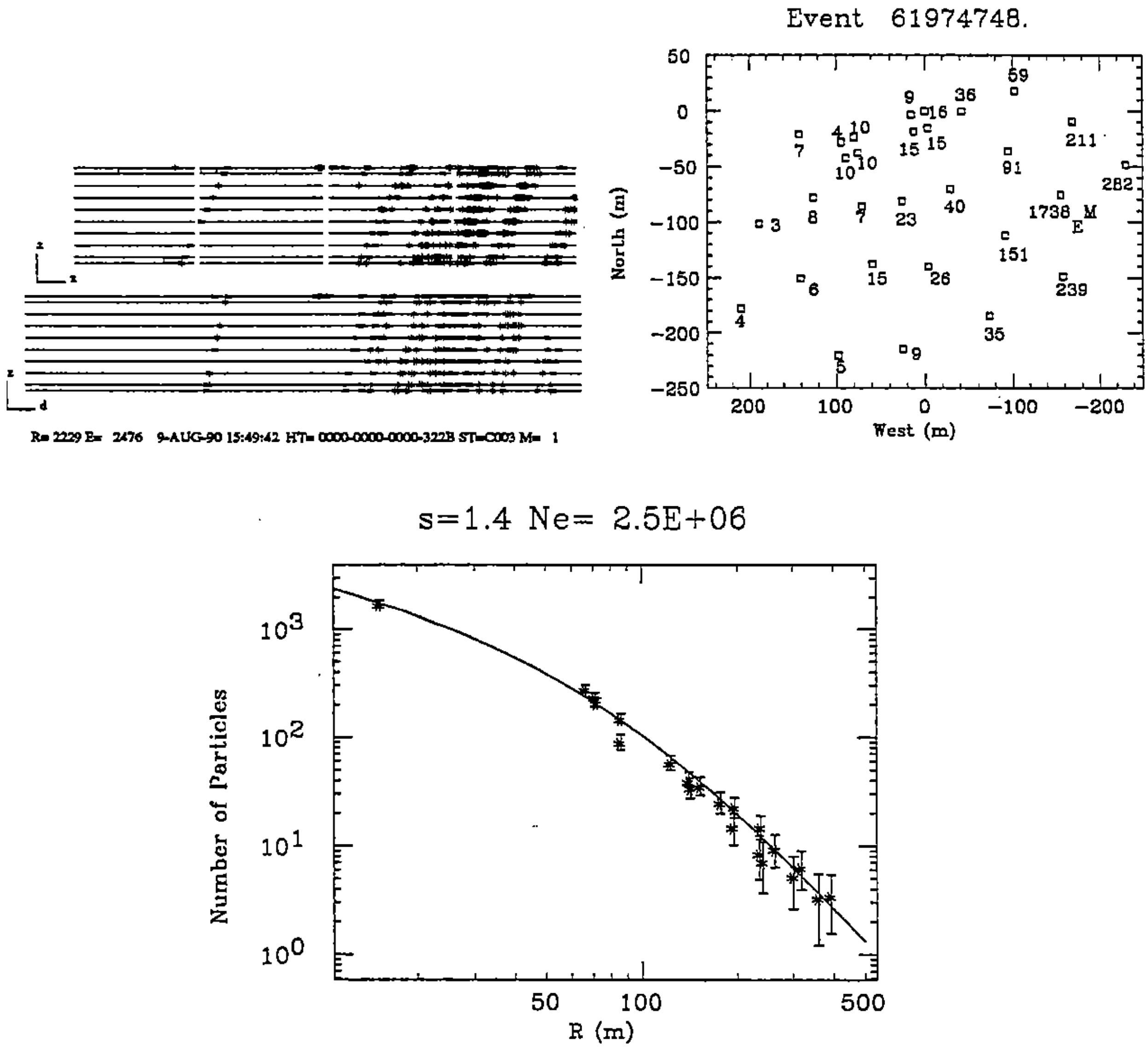

Figure 3: a) A coincident event as seen by MACRO (23 muons). The resolution is much better than what is apparent on the figure since the hits were drawn larger to make them more clearly visible. b) The same event as seen by EAS-TOP. E and M refer to the EAS-TOP and MACRO core locations. Numbers next to each counter are the number of particles sampled. c) EAS-TOP reconstructed lateral distribution. The function is from NKG

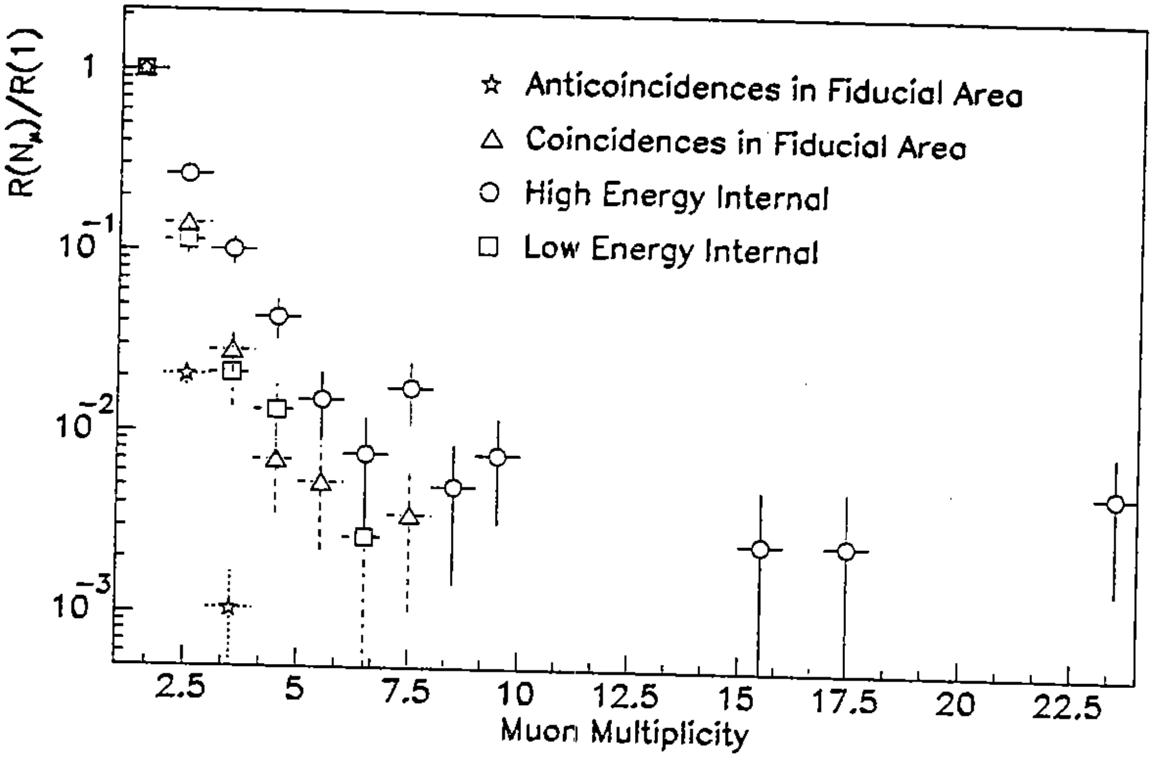

Figure 4: Multiplicity distributions normalized to the rates of single muons for various trigger configurations. For multiplicities without data points, no event had been recorded.

Study of high energy cosmic rays through the measurement of the electromagnetic and TeV muon components of extensive air showers by EAS-TOP and MACRO

(OG 6.1-23)

The MACRO collaboration

The EAS-TOP collaboration

1 Abstract

Deep underground muons and the electromagnetic component of Extensive Air Showers are measured by the MACRO and EAS-TOP detectors at the Gran Sasso Laboratories. A first analysis of the physical parameters N_μ and N_e related to the study of the primary composition at $E_0 = 10^{14} - 10^{16}$ eV is presented.

2 Introduction

The detectors of the electromagnetic component at EAS-TOP[1] and of the high energy muons at MACRO[2] operate as a multicomponent detector of Extensive Air Showers with the main aim of studying the primary cosmic ray composition at high energies[3]. They are located at the Gran Sasso Laboratories at altitudes of 2005 and 963 m a.s.l. respectively at a mean zenith angle of 33°. The mean slant depth of MACRO in the EAS-TOP direction is 3200 m w.e., corresponding to a muon energy threshold of 1.4 TeV. Two supermodules of MACRO ($24 \times 12 \times 4.8\ m^3$) are in operation in which a muon is defined as at least 4 aligned hits out of 10 horizontal layers of streamer tubes. In the present analysis we discuss coincident events with the core inside the edges of the EAS-TOP array ($A_{int} = 4 \times 10^4\ m^2$, high energy internal events). Shower size and core location are obtained by fitting the measured electron densities with the NKG lateral distribution function formula; the resolution for shower size at $N_e = 10^5$ is $\delta N_e/N_e$= 20%.

Event selection and reconstruction are discussed in paper HE 4.2.5 of these Proceedings. In this paper we present a first analysis of the physical parameters N_μ and N_e of 580 events collected under uniform conditions from July 18th, 1990 to December 14th, 1990, for a total combined live time of 100 days.

3 Simulation

We compare the experimental data with the preliminary results of a Monte Carlo simulation. The physics generator is taken from ref. 4 based on a p-p and p-p hadronic interaction model developed according to collider results up to $\sqrt{s}$ = 900 GeV. Nucleus interactions are treated in the context of the superposition model. The mean values and fluctuations of Ne are from ref. 5; the slope of the electromagnetic lateral distribution function is sampled from the experimental distribution. As a first approach, we have treated shower size and muon multiplicity independently. However there exists an anticorrelation effect as discussed in ref. 5, which affects $\log_{10} N_e$ by at most 10% at 100 TeV, decreasing at higher energy. A simulation describing the full experimental setups for each detector, including trigger scheme and measured fluctuations, is then carried out producing data of the same format as that of real events. Simulated data are then analyzed using the same reconstruction procedures as for real events. We have simulated pure p and Fe compositions with a statistical sample corresponding to a live time 10 times larger than the experimental one, and a particle spectrum compatible with the experimental data of ref. 6,7, the same for both compositions:

$$F(\ 50 < E_0 < 2000\ TeV)\, dE_0 = 2.7 \times 10^4 E_0^{-2.65}\, dE_0 \quad m^{-2} s^{-1} sr^{-1} GeV^{-1}$$
$$F(\ 2000 < E_0 < 5 \times 10^5\ TeV)\, dE_0 = 4.3 \times 10^6 E_0^{-3.00}\, dE_0 \quad m^{-2} s^{-1} sr^{-1} GeV^{-1}$$

4 Data Analysis

The coincidence rate for simulated events ranges from 3.8 (pure Fe) to 7.7 (pure p) ev/day, to be compared with the experimental one f=5.80 ± 0.24 ev/day (uncertainties in the primary energy spectrum and interaction model currently affect the simulated data by at most 25%). A plot of the $\log_{10} N_e$ spectrum for the real coincident events is given in figure 1, together with the expectations for the extreme pure compositions p and Fe. Simulated data are normalized to the total live time. Figure 2 shows the experimental muon multiplicity spectrum compared with Monte Carlo predictions. Muon multiplicity distributions for events with shower sizes in three $\log_{10} N_e$ intervals, chosen to give the same statistical sample are reported in figure 3. The mean experimental N_μ value for each $\log_{10} Ne$ interval is plotted versus $\log_{10} N_e$ in figure 4. In this plot, which is less sensitive to the primary spectrum, the experimental points lie between the two extreme cases, as expected for a mixed primary composition. This is also the case for the absolute rates and the general trends of figure 3.

5 Conclusions

The measured coincidence rate, the shower size spectrum and the muon multiplicity distribution, within the experimental fluctuations, are consistent with the expected ones for a mixed composition, showing that the model is adequate and the two experiments have been well simulated. In spite of this general consistency, a quantitative statement on primary mass abundances is not possible at this time due to limited statistics and the need to further refine the simulation model by making full consistency checks with all the experimental data, thereby reducing systematic uncertainties. The next coincident run will start next autumn with a total surface area of 860 m^2 for MACRO and $A_{int} \simeq 6 \times 10^4$ m^2 for EAS-TOP. In such conditions the statistical errors in the measured parameters will be reduced to 10% in the whole range (including the region above the knee in the primary spectrum) in about 1 year of combined live time.

6 Acknowledgements

We wish to thank the Director of the Gran Sasso National Laboratories and the whole staff of the Labs for their continuous cooperation. An important contribution to this analysis has been provided by M.Carboni.

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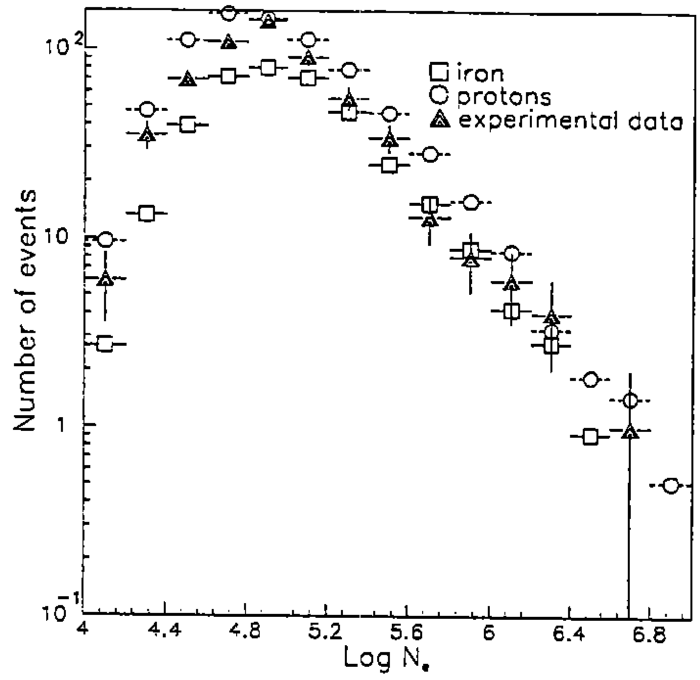

Figure 1: Measured and expected shower size spectrum for coincident events. For sake of clearness errors on Monte Carlo data are not shown (see text)

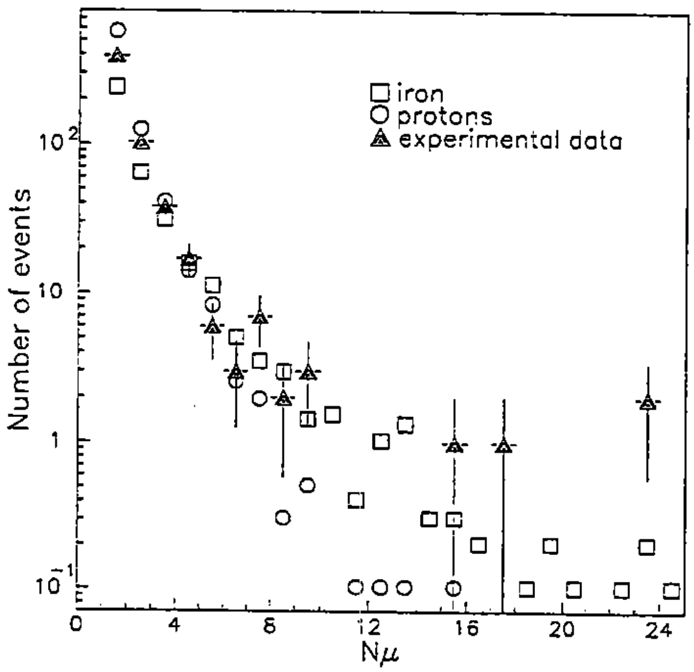

Figure 2: Measured and expected muon multiplicity distribution for coincident events

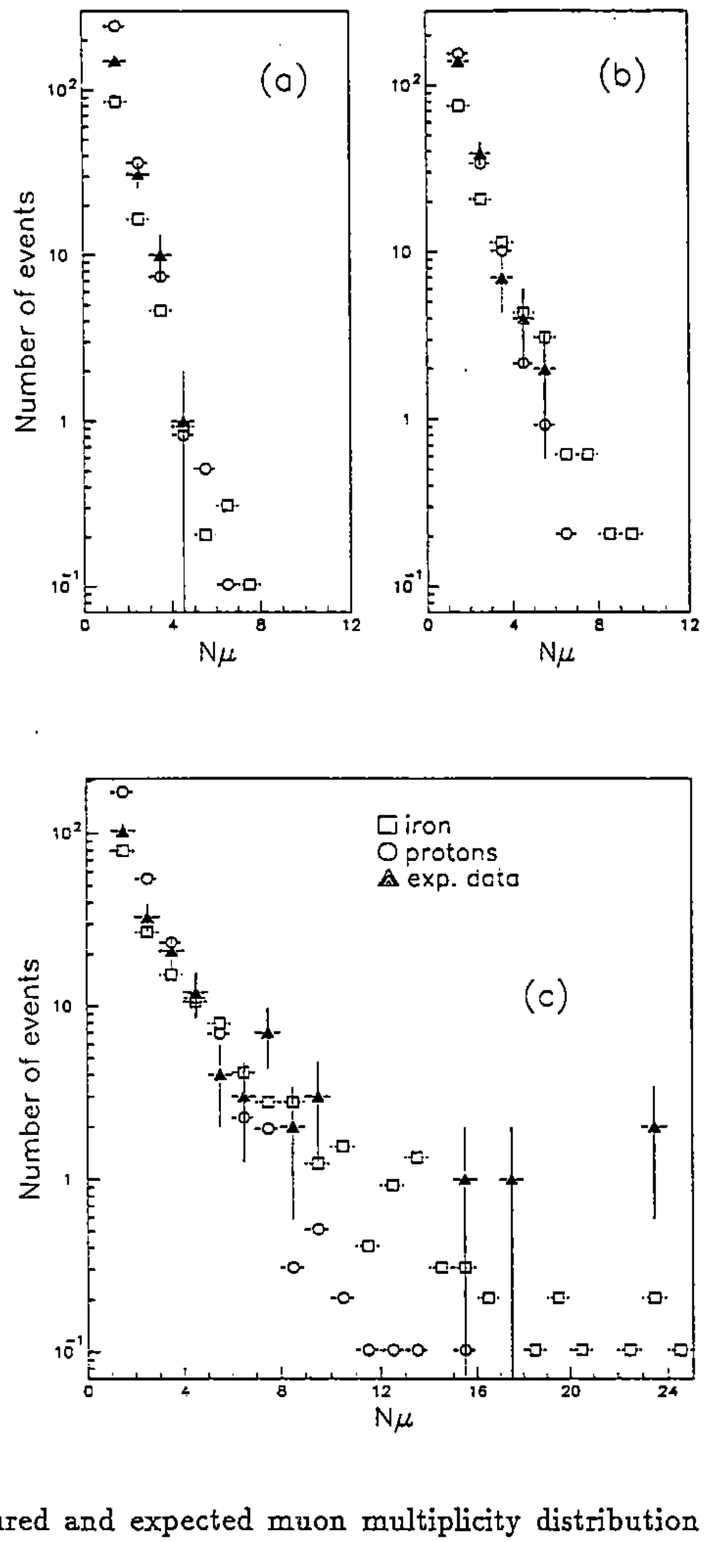

Figure 3: Measured and expected muon multiplicity distribution for three shower size intervals (a) $\log_{10} Ne < 4.75$; (b) $4.75 < \log_{10} Ne < 5.04$; (c) $\log_{10} Ne > 5.04$. for multiplicities without data points no event had been recorded

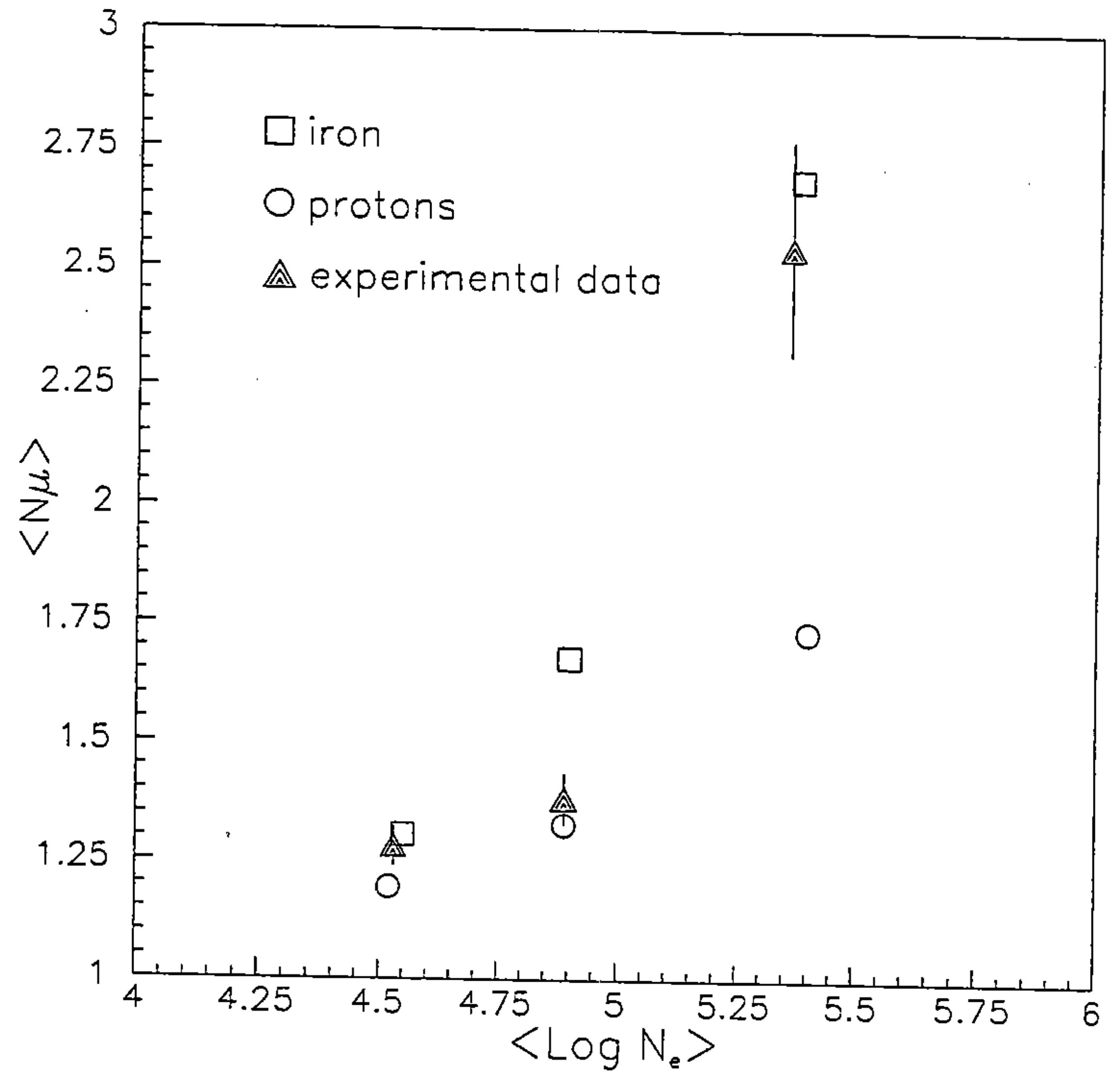

Figure 4: Correlation between $< N_\mu >$ and N_e for experimental data and pure composition models