



## Study of CR primaries and their cascades at $E_0 = 10 \div 100$ TeV through EAS-TOP and MACRO

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A measurement of the lateral distribution of Cherenkov light in Extensive Air Showers (EAS) at  $E_0 = 10 \div 100$  TeV and a study of the compatibility of the photon number spectra with the expectations from the direct measurements of  $p$  and  $\alpha$  spectra and the Corsika-QGSJET propagation code in the atmosphere have been performed at the National Gran Sasso Laboratories by the EAS-TOP and MACRO arrays. The telescope array of EAS-TOP has been used as the Cherenkov light detector. The muon tracking system of MACRO in the deep underground Gran Sasso Laboratories ( $E_\mu > 1.3$  TeV) served as the EAS detector, including core localization and arrival direction.

### 1. INTRODUCTION

The EAS-TOP and MACRO arrays at the Gran Sasso Laboratories offer a unique opportunity of measuring the lateral distribution of Cherenkov light in the  $10 \div 100$  TeV energy range by associating the Cherenkov light collected by the EAS-TOP telescopes with the TeV muon reconstruction, and consequently the EAS core geometry, through the MACRO array. In this paper we report on the measurements of the Cherenkov light lateral distribution compared with the results of simulations based on the CORSIKA-QGSJET code providing an experimental validation of the code itself. Moreover the technique allows a study of the primary composition and a comparison with the direct existing measurements in a overlapping region. Due to the shower selection through the high energy muon ( $E_\mu > 1.3$  TeV, i.e. primary energy  $E_0 > 1.3$  TeV/nucleon), in the energy range  $10 \text{ TeV} < E_0 < 40 \text{ TeV}$  (10 TeV being the Cherenkov telescopes' threshold energy) the selected primaries are mainly protons, while for  $40 \text{ TeV} < E_0 < 100 \text{ TeV}$  they include both  $p$  and  $\alpha$  particles.

### 2. DETECTORS AND DATA REDUCTION

The Cherenkov array of EAS-TOP ([1]) consists of 7 telescopes 60-80 m apart from each other. Each telescope loads two wide angle detectors equipped with 7 photomultipliers (PMs) ( $d = 6.8$  cm each) on the focal plane of parabolic mirrors ( $0.5 \text{ m}^2$  area, 40 cm focal length) for a total field of view (f.o.v.) of 0.16 sr.

MACRO, in the underground Gran Sasso Laboratories at 963 m a.s.l., 3100 m w.e. of minimum rock overburden, is a large area multi-purpose apparatus designed to detect penetrating cosmic radiation. A detailed description of the apparatus can be found in [2]. In this work we consider muon tracks, having at least 4 aligned hits in both views of the horizontal streamer tube planes over the 10 layers composing the whole detector.

The two experiments are separated by a thickness of rock ranging from 1100 m up to 1300 m, depending on the angle. The corresponding minimum energy for a muon to reach the depth of MACRO ranges from 1.3 to 1.8 TeV. Event coincidence is established off-line, using the absolute time provided by a GPS system with an accuracy better than  $1 \mu\text{s}$ .

The two experiments have run in coincidence in the bright moonless nights in the period 1998 - 2000. Here we report on the analysis performed using 5 telescopes in coincidence for a live time

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$\Delta T = 208$  hours corresponding to an exposure  $\Gamma \approx 815 \text{ day} \cdot \text{m}^2 \cdot \text{sr}$ . In such period MACRO reconstructed 35814 events in the angular field  $16^\circ < \theta < 58^\circ$  and  $127^\circ < \phi < 210^\circ$ , corresponding to the region in zenith and azimuth covered by the Cherenkov telescopes. 3830 events have been found in coincidence with Cherenkov data in a window of  $\Delta t = 7 \mu\text{s}$ , the expected accidental contamination being 3.0 events.

From the point of view of the muon reconstruction, the standard MACRO procedure [2] provides an accuracy of  $0.95^\circ$  (due to instrumental uncertainties and the scattering in the rock) that combined with the muon lateral spread leads to an uncertainty on the EAS core location of  $\Delta x_c \approx 20 \text{ m}$ .

Concerning Cherenkov light, the data treatment is summarized in [1] where sky luminosity and mirror reflectivity's variations, PMs' gain calibration, absolute normalization among PMs, photoelectron - photon conversion and light collection efficiency are taken into account. Considering all the different components, a systematic error of  $\sigma_{sys} \approx 21\%$  has been evaluated.

### 3. THE SIMULATION

The Cherenkov light lateral distribution was calculated from simulated showers generated with the CORSIKA code version 5.61 ([3]) and QGSJET hadron interaction model. Both protons and Helium nuclei were considered as primary particles, with discrete energies between 20 and 120 TeV. Zenith and azimuth angles were chosen randomly inside the telescopes' fields of view ( $30^\circ < \theta < 40^\circ$  and  $175^\circ < \phi < 185^\circ$ ). The requirement of having a muon with energy  $E_\mu > 1.3 \text{ TeV}$  implies a reduction of  $\approx 20\%$  of the absolute photon densities and this effect has been taken into account. Proton and Helium lateral distributions show a similar shape with a 10 - 20 % difference in intensity depending on the energy.

### 4. THE ANALYSIS

The lateral distribution was constructed using the constant intensity cut technique (c.i.c.) [1]. Photon integral spectra corresponding to 6 differ-

ent coronae ( $r \in [0,20], [20,35], [35,50], [125,145], [145,165], [165,185] \text{ m}$ ) where the central or the lateral PMs were fully efficient have been considered for each telescope, normalized in area and time and summed up with the corresponding ones of all telescopes. The number of photons corresponding to the same rate in the 6 different coronae was used to construct a lateral distribution. Frequencies were selected according to the following expression:

$$f(E > E_o) = \int_{E_o}^{\infty} \frac{dN_p}{dE} \cdot p_p^\mu(E) dE + \int_{E'_o}^{\infty} \frac{dN_{He}}{dE'} \cdot p_{He}^\mu(E') dE' \quad (1)$$

where  $E_o$  and  $E'_o$  represent respectively the proton and helium energies giving the same lateral distribution. The following values have been chosen for protons: 20, 40, 60, 80, 100 and 120 TeV.  $\frac{dN_p}{dE}$  and  $\frac{dN_{He}}{dE}$  are the differential primary spectra: the JACEE and RUNJOB data have been used as reported in tab. 1. Finally  $p_p^\mu$  and

Table 1  
JACEE and RUNJOB [4] primary spectra.

el.	JACEE	RUNJOB
p	$0.111 \times E^{-2.8}$	$0.126 \times E^{-2.8}$
He	$7.86 \cdot 10^{-3} \times E^{-2.68}$	$4.42 \cdot 10^{-3} \times E^{-2.8}$

Units are:  $\text{m}^{-2}\text{s}^{-1}\text{sr}^{-1}\text{TeV}^{-1}/\text{n}^{-1}$ .

$p_{He}^\mu$  represent the probability for a primary  $p$  or  $\alpha$  to produce a muon with energy  $E_\mu > 1.3 \text{ TeV}$  in the MACRO detector. Such contribution has been calculated through the CORSIKA-QGSJET code in the atmosphere and detector using the Gran Sasso Interface program (CORCSI) for muon propagation in the rock. As it can be seen from Fig. 1, the experimental points match very well with the simulated ones according to the JACEE proton and helium spectra. The error on the  $x$  axis represents the uncertainty on the EAS core position, while on the  $y$  axis statistical and systematic errors are summed up in quadrature. The systematic error is of the order of 20% and its effect is to scale all the curves without changing their shape.

The C.I. yield associated with the underground

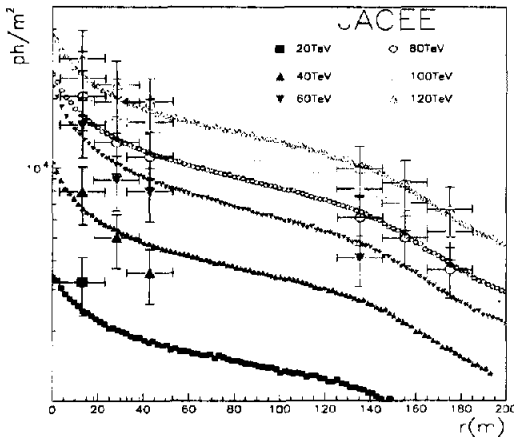


Figure 1. Measured C.I. lateral distributions compared with simulated ones ( $290 < \lambda < 630$  nm) using the JACEE spectra.

muon reconstruction provides a technique to discriminate among different primary spectra. In fact the agreement is worse when frequencies are calculated using RUNJOB spectra of Tab. 1 (see Fig. 2). This has to be ascribed to the lower contribution of the  $\alpha$  component in the RUNJOB spectra.

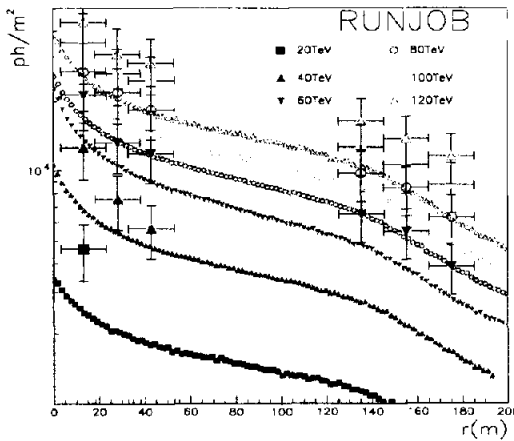


Figure 2. Same as fig. 1 using the RUNJOB spectra.

## 5. CONCLUSIONS

A measurement of the lateral distribution of Cherenkov light in EAS in the energy range  $20 \div 120$  TeV has been performed at the Gran Sasso Laboratories by the EAS-TOP and MACRO arrays. The EAS and its geometry are selected through the muon detected deep underground by MACRO ( $E_\mu > 1.3$  TeV). The measurements are performed by means of the Cherenkov light detector of EAS-TOP at Campo Imperatore (2000 m a.s.l.). The measurement is compared with the results of simulations based on the CORSIKA-QGSJET code. Simulated and real data show a good agreement, inside 20% systematic uncertainties.

The shape of the l.d.f. reflects the rate of energy release in the atmosphere, (i.e. the properties of the interaction, the primaries being dominated by the lightest components due to the TeV muon trigger requirement) while the absolute scale is mostly related to the event rate, i.e. the primary  $p$  and  $\alpha$  spectra. The agreement of both of them (see fig. 1) shows both the adequacy of the CORSIKA-QGSJET code in describing the cascades in this energy range and of the JACEE flux in the  $20 \div 120$  TeV region. The contribution of fluctuations and of the CNO component have been successively studied and they do not affect these conclusions.

## REFERENCES

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