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The lateral distribution of Cherenkov light in 10–100 TeV primary proton showers

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Abstract. A measurement of the lateral distribution of Cherenkov light in Extensive Air Showers (EAS) mainly originated by 20 - 80 TeV primary protons has been performed at the Gran Sasso laboratories by the EAS-TOP and MACRO arrays. The seven-telescope EAS-TOP array 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. The selection of EAS through a high energy muon allows the selection of a beam strongly dominated by primary protons ($E_o > 1.3$ TeV/nucleon) and therefore facilitates the comparison with simulations. Measurements are compared with the results of simulations based on the CORSIKA-QGSJET code and provide an experimental validation of the code itself.

1 Introduction

The detection of EAS Cherenkov light is widely exploited at TeV energies mainly for gamma ray astronomy applications. However, the energy calibration and the response function of such instruments has to be derived indirectly, through Monte Carlo simulations, mainly due to the impossibility of localizing the EAS core at such energies and selecting the primary particle. The EAS-TOP and MACRO arrays at Gran Sasso Laboratory offer a unique opportunity to measure the lateral distribution of Cherenkov light in the 10 - 100 TeV energy range by associating the Cherenkov light collected by the EAS-TOP array with the TeV muon reconstruction, and consequently the EAS core geometry, through the MACRO array. Due to the shower selection through at least a high energy muon ($E_\mu > 1.3$ TeV, i.e. $E_{primary} > 1.3$ TeV/nucleon), in the energy range of sensitivity of the EAS-TOP Cherenkov telescopes (threshold energy $E_{oc} > 10$ TeV), the selected primaries are mainly protons. Measurements are compared with the results of simulations based on the CORSIKA-QGSJET code, and provide an experimental validation of the code itself.

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2 The detectors

The Cherenkov array of EAS-TOP (Aglietta et al. , 1993) 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 a parabolic mirror (0.5 m^2 area, 40 cm focal length) for a total field-of-view (f.o.v.) of 0.16 sr, the f.o.v. of each individual photomultiplier being 2.3×10^{-2} sr. The two sets of 7 PMs of each detector work at different voltages ($\Delta V \approx 200$ V, providing High Gain and Low Gain channels) to increase the dynamic range of the telescope.

The Cherenkov events are identified by the coincidence, in a time window of 30 ns, between any two photomultipliers having the same geometrical position on the focal plane of the two mirrors of the same telescope. (We denote such PMs as corresponding PMs). The trigger threshold is $N_{phe}^{th} = 200$ photoelectrons /mirror corresponding to $E_{oc} \approx 10$ TeV; the trigger rate being 7 Hz/telescope.

MACRO, in the underground Gran Sasso Laboratory 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. The lower part of the MACRO detector has dimensions $76.6 \times 12 \times 4.8$ m^3. A detailed description of the apparatus can be found in MACRO Collaboration (1993). In this work we consider only muon tracks, which are required to have at least 4 aligned hits in both views of the horizontal streamer tube planes over the 10 layers composing the whole detector. The angular resolution for muon tracks is less than one degree, dominated by multiple scattering in the overburden rock.

The two experiments are separated by a thickness of rock ranging from 1100 up to 1300 m, depending on the angle (Fig. 1). The corresponding minimum energy for a muon to reach the depth of MACRO ranges from $E_0 \approx 1.3$ to $E_0 \approx$

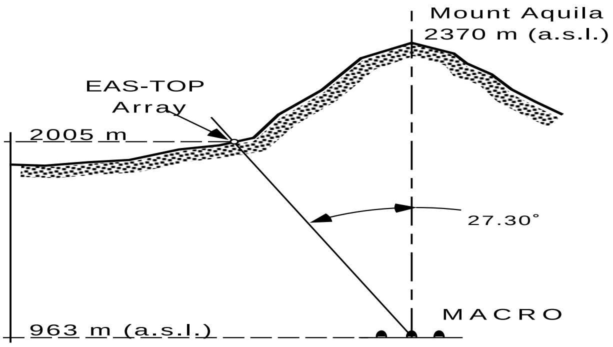

Fig. 1. Location of EAS-TOP and MACRO arrays.

telescope	events	hours	ev/h
X	801	110.75	7.23
U	475	90.14	5.27
Q	601	92.16	6.52
T	453	79.67	5.69

Table 1. Coincidence events for the 4 telescopes used in analysis.

1.8 TeV. Event coincidence is established off-line, using the absolute time given by a GPS system with an accuracy better than 1 μs.

The two experiments have run in coincidence in the bright moonless nights in the period 1998-2000. Here we report on the analysis done for the period September 1998 - September 1999 using 4 telescopes (named X,U,Q and T), when the two experiments were in coincidence for a live time of $\Delta T = 125.3$ hours corresponding to an exposure ≈ 300 day m^{2}sr. In that period MACRO reconstructed 14779 events in the angular field $24^o < \theta < 40^o$ and $153^o < \phi < 198^o$, corresponding to the region in zenith and azimuth covered by the Cherenkov telescopes. 1665 events have been found in coincidence with Cherenkov data in a window of $\Delta t = 7 \mu s$, the expected accidental contamination being 1.2 events. In Table 1 the statistics for each telescope in use has been reported, while in Fig. 2 the coincidence peak in time (top) and the relation between the μ reconstructed direction, and the f.o.v. of the triggered PM (bottom) is shown. As it can be seen from Fig. 2 (bottom) the correlation between the field of view of the triggered corresponding PMs and the reconstruction of the muon direction is quite good. Such a correlation allows the selection of the PM pointing in the f.o.v. of the arrival direction of the muon as reconstructed by MACRO.

3 Data reduction

From the point of view of the muon reconstruction, the standard MACRO procedure (MACRO Collaboration , 1992) provides an accuracy of 0.95^o (due to the instrumental uncertainties and the muon scattering in the rock) that combined with the muon lateral spread leads to an uncertainty on the EAS core location of ≈ 20 m.

Concerning Cherenkov light, the data treatment is summarized in the following.

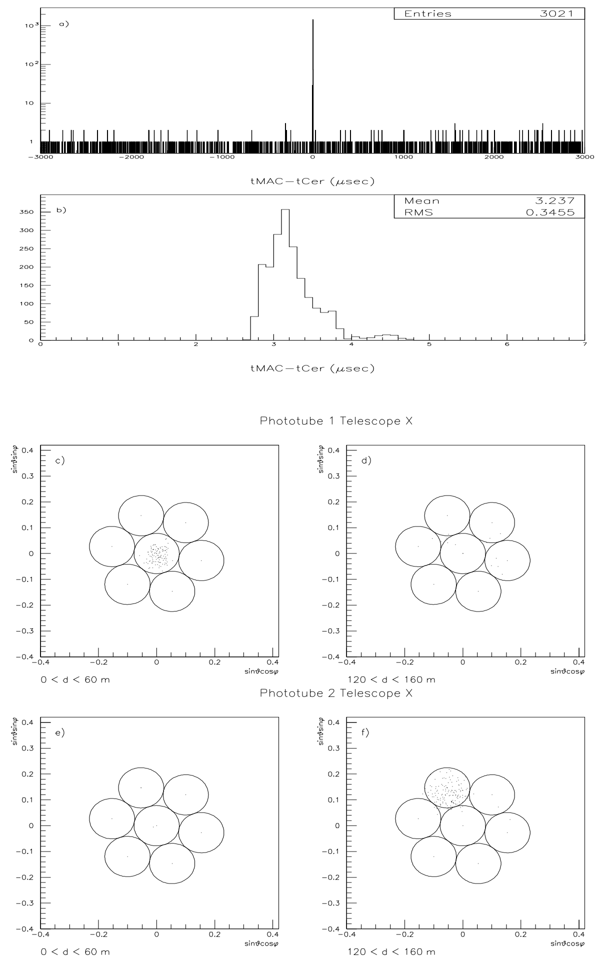

Fig. 2. top) Temporal distribution of coincidence events using a window of $\Delta t = 6ms$ (a) or $\Delta t = 7\mu s$ (b). bottom) Directional reconstruction of μ (dots) for two different ranges of distances from the telescope: $d < 60m$ (c,e) , $120 < d < 160m$ (d,f), together with the fields of view of the PMs (represented by the circles). As it can be seen the central PMs (PM 1) select μ with $d < 60m$ (c), while a couple of lateral ones (PM 2) selects μ in the $120 < d < 160m$ range on a specific angular window (f). Only very few times this correspondance is wrong (d-e).

1 *Pedestal subtraction.* The variable luminosity of the sky during the night has been taken into account by measuring and subtracting from the ADC readout an on-line pedestal obtained every 300 s as the charge value with the highest rate in each PM spectrum (i.e. corresponding to absence of signal).

2 *Long term variations (sky luminosity and mirror reflectivity).* The number of photoelectrons (phe_{001}) corresponding to a fixed rate (0.01Hz) where the detector is fully efficient has been used to correct for long term variations. All the data set (≈ 1 year) has been divided into 3 subperiods and for each subperiod an average value ($\overline{phe_{001}}$) has been calculated for each phototube. The average value of the second and third period has been normalized to the first one. The spread of the points so corrected for each night represents the fluctua-

tion on the sky transparency on a night by night basis. Such fluctuation has been evaluated to be $\sigma_{sky} \approx 15\%$.
3 *PMs' gain.* The PMs' gain has been calibrated by using the single photoelectron technique. A systematic error on the absolute gain of $\sigma_g \approx 12\%$ has been estimated.
4 *Absolute normalization.* The PMs' outputs of the 4 telescopes used in the present analysis have been normalized among each other. The central phototubes and separately the lateral ones have been normalized by averaging the $\overline{phe_{001}}$ values. The width of such distributions has been chosen as the systematic error in the absolute value of photoelectrons detected. It has been found to be $\sigma_c \approx 12\%$ for the central PMs and $\sigma_l \approx 7\%$ for the lateral ones.

The fluctuations in the response of PMs were deduced from the comparison of the outputs of the HG and LG channels (the corresponding PMs) and were found to be $\sigma(phe) = 16\%$ as an average of central ($\sigma(phe)_c = 17\%$) and lateral PMs ($\sigma(phe)_l = 15\%$).
5 *Photoelectron - photon conversion.* The conversion from phe to photons has been calculated taking into account: sky transparency ($A(\lambda)$), mirror reflectivity ($\eta(\lambda)$) and quantum efficiency ($\epsilon(\lambda)$) of the PMs. For the sky transparency, the Rayleigh and aerosol scatterings have been estimated following Hayes and Latham (1975), assuming for the aerosol ones the same absolute absorbtion as Cerro Tololo (Chile, 2200m a.s.l.). The mirror reflectivity has been measured and varies from $0.85 < \eta < 0.92$ depending on λ. By taking into account the quantum efficiency of the PM (Philips , 1990), the efficiency in the conversion of phe to photons has been evaluated:

$$\overline{\epsilon} = \frac{\int_{\lambda_1}^{\lambda_2} \epsilon(\lambda) \cdot \eta(\lambda) \cdot A(\lambda) \frac{d^2N}{dld\lambda} \cdot d\lambda}{\int_{\lambda_1}^{\lambda_2} \frac{d^2N}{dld\lambda} \cdot d\lambda} = 0.11 \quad (1)$$

with $\lambda_1 = 290$ nm and $\lambda_2 = 630$ nm.
6 *Light collection efficiency.* The geometric efficiency of the light collector and the efficiency in collecting the Cherenkov light has been studied using a Monte-Carlo simulation (see Section 4). Such a simulation showed that the Cherenkov light associated with a μ whose distance from the telescope is $r < 60$ m or 120 m $< r < 190$ m for the central or lateral PMs respectively, has on average a collection efficiency $\epsilon(\theta, \phi) > 50\%$. Therefore only events belonging to these two regions and whose direction (θ, ϕ) has an efficiency $\epsilon(\theta, \phi) > 50\%$ have been used in the analysis. In particular, on a event by event basis, the number of photons collected (ph_c) on the PM has been corrected for the average efficiency found by the above simulation for such direction ($ph = ph_c/\epsilon(\theta, \phi)$). Considering that the muon arrival direction is known with an error $\sigma_{ang} \approx 1^o$, an indetermination $\sigma_\epsilon \approx 11\%$ has been evaluated (on average) for the efficiency used in the individual event reconstruction.
7 *Normalization of the corona acceptances.* For comparing the event rates of different telescopes and of the same telescope at different distances (r) the acceptance of each circular corona of radius r for each telescope has been calculated. For this purpose all the μ data reconstructed by MACRO in the angular window of EAS-TOP have been used. In particular the normalization coefficient $c_\Phi(tel, r1, r2)$ for each telescope (tel) at the distance $r_1 < r < r_2$ has been renormalized to the flux $\Phi(I, 40, 60)$ of telescope I in between $40 < r < 60m$:

$$c_\Phi(tel, r_1, r_2) = \frac{N_\mu(tel, r_1, r_2)}{S(r_1, r_2) \cdot T(tel)} \cdot \frac{1}{\Phi(I, 40, 60)} \quad (2)$$

where $N_\mu(tel, r_1, r_2)$ is the number of μ collected in the corona whose area is $S(r_1, r_2)$ in the time $T(tel)$. The statistical error on the coefficient c_Φ has been found to be $\sigma_{c_\phi} < 2\%$.

A list of the main sources of error with an estimation of their values has been reported in Table 2. Taking into account the different components, a systematic error of $\sigma_{sys} \approx 21\%$ has been evaluated.

Origin	Nature	value(%)
fluctuations in corresponding PMs	stat.	16
fluctuations in sky luminosity	sist.	15
normalization among the PMs	sist.	12c - 7l
normalization of coronae acceptance	stat.	<2
error on PMs' gain	sist.	12
error on the mirror efficiency	stat.	11
error on the spectra from the c.i.c. (*)	stat.	variab.

Table 2. Summary of the different sources of errors. (*) The costant intensity cut (c.i.c.) technique is described in Section 5.

4 The simulation

The Cherenkov light lateral distribution was calculated from simulated showers generated with the version 5.61 of the CORSIKA code (Knapp and Heck , 1998), with the QGSJET hadron interaction model. Both proton and Helium nuclei were considered as primary particles, with discrete energies between 10 and 400 TeV. Zenith and azimuth angles were chosen randomly inside the telescopes' field of view ($30^o < \theta < 40^o$ and $175^o < \phi < 185^o$). In fact, the shape of the lateral distribution is strictly related to the shower zenithal angle (Fig. 3), and the measurement refers to an average zenith angle of 35^o. The coincidence with the muon underground detector MACRO selects those showers which produce at least a muon of energy higher than 1.3 TeV. This requirement is not included in the present simulation, and it would imply a reduction of $\approx 20\%$ of the absolute photon densities. The final set consisted of 100 showers for each energy value.

5 The lateral distribution

The lateral distribution was constructed using the technique of the constant intensity cut (c.i.c.). The integral spectra of each telescope for different coronae has been created, normalized in area and time and summed up with the corresponding ones of the other telescopes. As shown in Fig. 4,

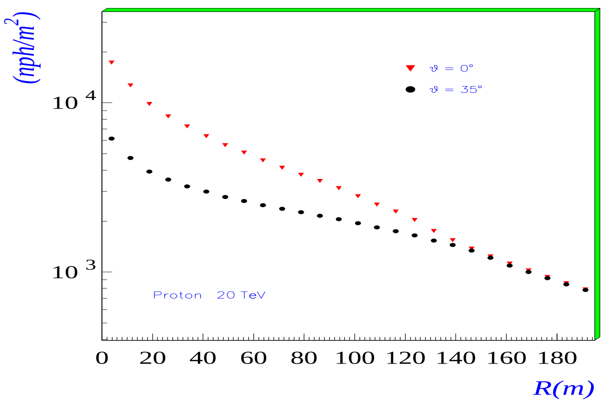

Fig. 3. Ldf-shape dependence on the zenithal angle; 20 TeV proton-initiated showers at 35 and 0 degrees zenithal angle.

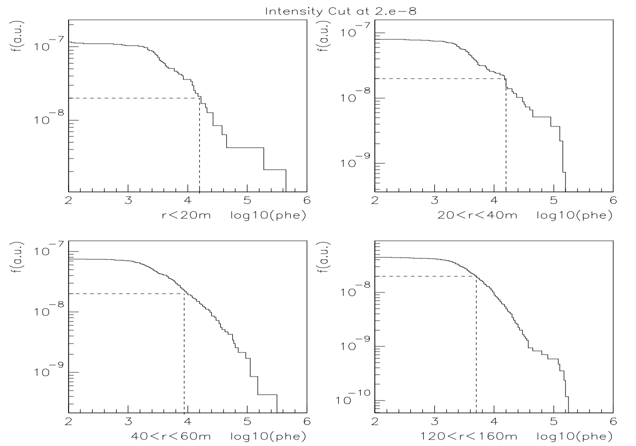

Fig. 4. Integral spectra and constant intensity cut technique.

frequencies where the telescopes were completely efficient were chosen for 4 different coronae. The number of photons corresponding to the same rate in the 4 different coronae were used to construct a lateral distribution. In this way it is implicitly assumed that events that happen with the same rate in the four regions are of the same energy. The frequency cuts applied are in agreement, inside the systematic errors, to the proton primary flux at the energies they are compared. On this assumption several lateral distributions have been constructed and compared to the proton simulated ones in the 20-80 TeV region where the experimental points are made with a sufficient statistic. (Twenty TeV represents in fact the threshold for constructing the lateral distribution). As it can be seen from Fig. 5, the experimental points match very well with the proton simulated ones. The agreement is slightly worse at core distances r = 10 m due to the fact that this point is particularly sensitive to the underground muon reconstruction accuracy. The error on the x axis represents the bin size, while on the y axis only the statistical error is shown. A 20% systematic error should be added, whose effect would result in scaling all the curves without changing their shape.

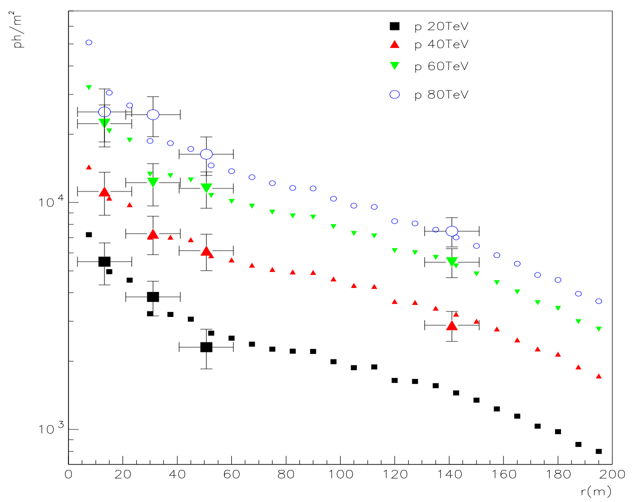

Fig. 5. Measured C.l. lateral distributions compared with simulated ones ($290 < \lambda < 630$ nm).

6 Conclusions

A measurement of the lateral distribution of Cherenkov light in EAS in the energy range 20 - 80 TeV for primary protons 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 muon triggering condition provides a primary beam with energy $E_0 > 1.3$ TeV/nucleon, dominated by protons. The Helium contamination in the 20 TeV bin is less that 30 $\%$ even assuming its larger contribution. Incidentally, the calculated shapes of Cherenkov light lateral distributions for proton and Helium primaries are within 15 $\%$. 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. An experimental validation of the simulation code has thus been obtained.

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