TIME CORRELATIONS OF HIGH ENERGY MUONS IN AN UNDERGROUND DETECTOR

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Abstract

We present the result of a search for correlations in the arrival times of high energy muons collected from 1995 till 2000 with the streamer tube system of the complete MACRO detector at the underground Gran Sasso Lab. Large samples of single muons (8.6 million), double muons (0.46 million) and multiple muons with multiplicities from 3 to 6 (0.08 million) were selected. These samples were used to search for time correlations of cosmic ray particles coming from the whole upper hemisphere or from selected space cones. The results of our analyses confirm with high statistics a random arrival time distribution of high energy cosmic rays.

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1 Introduction

It is generally expected that high energy (HE) galactic cosmic rays (CRs) have a random arrival time; but it was also suggested that CRs coming from a nearby pulsar, a nearby supernova-like event, etc. could show modulation effects [1]. Some early experiments reported non-random components in the arrival times of HE cosmic rays [2], but higher precision measurements did not see any effect, see e.g. ref. [3].

MACRO was a large multipurpose detector installed in hall B of the Gran Sasso National Laboratories (LNGS) at the minimum depth of overburden rock of 3200 mwe (average depth of 3600 mwe). The detector had a modular structure consisting of six supermodules (SMs) each of dimensions 12 m x 12 m x 9.3 m. It was made of three horizontal layers of liquid scintillation counters, 14 horizontal layers of streamer tubes, one horizontal layer of nuclear track detectors and seven layers of rock absorbers. The vertical sides were closed by six layers of streamer tubes and one layer of scintillators. The complete detector was thus a nearly ”closed box” with a total length of 76.7 m [4]; it had a lower part 4.8 m high, with 10 horizontal layers of streamer tubes, two layers of scintillators and seven layers of rock absorber. The upper part (”attico”) contained also the electronics. The main goals of the experiment were the search for rare particles, like magnetic monopoles and nuclearites [5], the study of atmospheric neutrino oscillations [6] and the study of downgoing HE muons [7][8].

In this paper we present a high statistics study of the time distributions of downgoing HE single, double and multiple muons measured from 1995 till 2000 with the streamer tube system. The investigation concerns also the time distributions of muons coming from selected directions in the sky.

For each muon arriving at time $t_0$, we studied the distribution of the time intervals elapsed from $t_0$ till the arrival times $t_1$, $t_2$, $t_3$, $t_4$, $t_5$ of the next five muons: $(t_1-t_0)$, $(t_2-t_0)$, $(t_3-t_0)$, $(t_4-t_0)$ and $(t_5-t_0)$. The present statistics is larger by at least a factor of 20 than those of previous underground experiments [2][3].

The data selection is discussed in Section 2, the time correlations in Section 3 and the conclusions in Section 4.

2 Data selection and tests analyses

For this analysis we selected runs according to the following criteria:

a) Run duration greater than two hours, (the average run duration was about
5 hours).
b) Muon rates $R$ in the range $840 \leq R \leq 960$ muons per hour (corresponding to deviations of less than $2\sigma$ from the average).
c) Acquisition dead time smaller than 0.4% for each of the 3 microvax computers.
d) No errors in the atomic clock (The arrival time of muons was measured with an atomic clock with a precision of about $1\mu s$ absolute and $0.5\mu s$ relative).
e) No trigger problems.
f) No problems with the streamer tube gas system.
g) Streamer tube efficiencies of the wires and strips larger than 90% and 86%, respectively (the average wire efficiencies for each selected run is about 94%).

Further selection criteria:
A single muon event should have a track with multiplicity equal to one, both in the wire and strip streamer tube views; double muon events must have 2 tracks in the wire and strip views and multiple muons have multiplicities from 3 to 6 and reconstructed on both wire and strip views.

2035 runs passed the cuts for a total number of $8600 \times 10^3$ single muons, $460 \times 10^3$ double muons and $80 \times 10^3$ multiple muons.

The primary cosmic ray energy for events with a single muon is larger than 20 TeV. For events with two (multiple) muons the mean primary energy is larger than 200 TeV (1500 TeV).

The distribution of single muon rates per hour (taken when the full apparatus was running) is shown in Fig. 1a. The average run duration was about 5 hours. Fig. 1b shows the number of runs versus the muon rate of each run. For the whole apparatus the average rate was 899 muons/hour.

In Fig. 1a we notice that the counting rate per run shows a regular variation with run number (time). This is the signature of the seasonal variation of the muon flux due to density and temperature changes of the upper atmosphere. This effect was discussed in detail in [9]. In ref. [10] the daily variations in solar and sidereal times were discussed. These analyses demonstrate the high sensitivity of the detector to study very small ($10^{-3}$ in magnitude) time variations of the muon flux.

3 Time correlation analyses

As already stated, it is expected that galactic CRs have a random arrival time distribution because of the direction reshuffling of charged CR particles by random interstellar magnetic fields. But there may be some mechanisms
which introduce time correlations. One could expect to observe clusters in time for events generated by charged or neutral particles coming from intermittent emissions by nearby sources.

For random arrivals, the time distribution may be fitted to the Gamma function of order M [11]

$$G(t; \lambda, M) = N\lambda \frac{(\lambda t)^{M-1}e^{-\lambda t}}{(M-1)!},$$

(1)

where, $1/\lambda$ is the mean value of the time difference between two consecutive muons and N is a normalization factor. For M=1 Eq. (1) reduces to an exponential:

$$G(t; \lambda, M = 1) = N\lambda e^{-\lambda t}$$

(2)

After each trigger there was a dead time of about 100 ms (when the whole
apparatus was operational). The effect of this dead time is evident in the \((t_1-t_0)\) distribution for \((t_1-t_0) < 100\) ms, Fig. 2. In the present analysis we do not apply any correction for this dead time, but discarded the first point of the distribution in the fitting procedure. The correction was made in a previous analysis of a sample of 0.4 million muons by re-populating the data with events lost during the dead time [3].

3.1 All sky analyses

Fig. 3a shows the distribution of the time separation between two consecutive single muons \((t_1-t_0)\) with \(0^\circ \leq \text{zenith} \leq 72^\circ\) and \(0^\circ \leq \text{azimuth} \leq 360^\circ\). The distribution for double and for multiple muons are shown in Fig. 3b and 3c, respectively. The three distributions are clearly exponential indicating the random nature of the bulk of the cosmic ray arrival times. A fit of the data for \((t_1-t_0)\) was made to Eq. (2): it yields the parameters quoted in Table 1.

In Fig. 4 and 5 are presented the higher order correlations: \((t_2-t_0)\), \((t_3-t_0)\), \((t_4-t_0)\) and \((t_5-t_0)\) for single and for double muons, respectively. The experimental distributions are compatible with the higher order Gamma functions, that is with random arrival times.
3.2 Analyses in narrow cones

We repeated the same analyses on time correlations for muons arriving from defined directions in azimuth and zenith. In this case the detector is used as a "multiple telescope" to observe different restricted regions of the sky, see Table 1 and Fig. 6. Cones (1) and (2) were chosen to have maximum muon intensities in the angular distributions on azimuth and zenith; cone (3) was chosen to cover the declination region centred on the direction of Cyg-X3. The pointing ability of the detector was checked in ref. [12] using the Moon and the Sun shadows of CRs. A search for astrophysical point sources was made.
Fig. 4. (a) \((t_2-t_0)\) (triangles), \((t_3-t_0)\) (circles) and (b) \((t_4-t_0)\) (triangles), \((t_5-t_0)\) (circles) time correlations for single muons. The dashed lines represent the fits to the Gamma functions of order 2, 3, 4 and 5, respectively.

using downgoing muons and none was observed, see ref. [13].

The first cone has \(25^\circ \leq \text{zenith} \leq 45^\circ\) and \(20^\circ \leq \text{azimuth} \leq 40^\circ\), the total number of selected single muons is \(280 \times 10^3\). For the second cone, \(25^\circ \leq \text{zenith} \leq 45^\circ\) and \(140^\circ \leq \text{azimuth} \leq 160^\circ\), we selected \(350 \times 10^3\) single muons. For the third cone, we have chosen \(60^\circ \leq \text{azimuth} \leq 100^\circ\) and \(260^\circ \leq \text{azimuth} \leq 300^\circ\) and \(30^\circ \leq \text{zenith} \leq 50^\circ\) and the number of selected single muons is \(520 \times 10^3\). The right ascensions and declinations for single muons coming from the selected cones were calculated using the local coordinates and the times of events. In Fig. 6. are presented the declination bands for selected muons. The open circles indicates the galactic plane.
Fig. 5. (a) the \((t_2-t_0)\) (triangles), \((t_3-t_0)\) (open circles) and (b) \((t_4-t_0)\) (triangles), \((t_5-t_0)\) (open circles) time correlations for double muons. The dashed lines represent the fits to the Gamma functions of order 2, 3, 4 and 5, respectively.

Fig. 7 shows the \((t_1-t_0)\) time distributions for single muons in cone 1 (black points), in cone (2) (triangles) and in cone (3) (open circles).

All data show the exponential character of the \((t_1-t_0)\) distributions; higher order correlations agree with Eq. (1). It is thus concluded that the arrival times of our selected muons are consistent with random arrival time distributions.

Table 1 gives the results of the various fits of the \((t_1-t_0)\) experimental distributions to the exponential form, Eq. (2).
Fig. 6. Distributions of single muons coming from selected cones in declination and right ascension. The open circles indicates the galactic plane.

3.3 Kolmogorov-Smirnov test

In order to search for possible structures in the time arrival distributions, we have also used the Kolmogorov-Smirnov test [14], which compares the cumulative distribution $F(x)$ of the experimental data with the expected random distribution $H(x)$. The measure of the deviation is $d = \max |F(x) - H(x)|$, where $F(x)$ and $H(x)$ are the cumulative distributions of $f(x)$ (data) and $h(x)$ (expected), respectively. In terms of this quantity, $F(x)$ agrees with $H(x, \lambda)$, where $\lambda$ is taken from the data, with a probability of compatibility between the expected and measured distributions given by

$$P_k(d > \text{observed}) = Q_{ks}(\sqrt{Nd})$$

where

$$Q_{ks}(x) = 2 \sum_{j=1}^{+\infty} (-1)^{j-1} e^{-j^2 x^2}$$

The probabilities of the tests for the $(t_1 - t_0)$ distributions are given in the last column of Table 1. They are consistent with random distributions, although, in the case of the Cygnus X3-centered cone 3, some disagreement (at the level
Fig. 7. Distributions of the time between two consecutive single muons coming from cone 1 (black circles), cone 2 (triangles) and cone 3 (open circles). The lines represent the fits to Eq. (2).

Table 1
Results of the fits (parameters $N, 1/\lambda$, $M$ and $\chi^2/\text{DoF}$) of the time correlation data $(t_1-t_0)$ to the Gamma Function of order 1, Eq. (2), for single, double and multiple muons coming from the all sky and from 3 narrow cones. The last column gives the probability of the Kolmogorov-Smirnov test.

| Selection | $N \times 10^3$ | $1/\lambda$ (s) | $M$ | $\chi^2$/DoF | Pr. K-S |
|-----------|-----------------|----------------|-----|--------------|---------|
| Single $\mu$ | 8638±4          | 4.03±0.01       | 1.002±0.003 | 1.00       | 0.99    |
| Double $\mu$   | 456.5±0.9       | 73.3±0.3        | 1.008±0.004 | 1.36       | 0.95    |
| Multiple $\mu$ | 180.2±0.3       | 196.0±0.4       | 0.93±0.07  | 0.98       | 0.99    |
| Cone 1         | 276.3±0.6       | 121.58±0.03     | 1.003±0.004 | 1.02       | 0.99    |
| Cone 2         | 353±1           | 95.9±0.1        | 1.003±0.006 | 0.82       | 0.77    |
| Cone 3         | 522±1           | 63.82±0.3       | 1.004±0.004 | 0.91       | 0.38    |

of $1\sigma$) could produce the low K-S probability. This could originate in a possible enhancement of the event rate for $DT=500$ s (see Fig. 7), but the available statistics is too poor to reach clear conclusions.
4 Conclusions

We have presented new high statistics data on the arrival time distributions of downgoing cosmic ray muons with energies larger than 1.3 TeV at the top of the Gran Sasso mountain. The data were obtained with the streamer tube system of the MACRO detector in its complete configuration.

Single, double and multiple muons arriving from the whole upper hemisphere and also from selected space cones were considered.

No significant deviations from random arrival time distributions were observed.

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