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Nuclear Physics B (Proc. Suppl.) 61B (1998) 180–184

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Performance of the MACRO Detector at Gran Sasso: Moon shadow and seasonal variations

The MACRO collaboration *
presented by N. Giglietto

The MACRO underground detector at Gran Sasso has recorded about 30 million muon events in the period 1989-1995. We have analyzed these data to look for time variations and to study the pointing capabilities of the apparatus in the search for astrophysical point sources. We have observed a 3% seasonal variation of the high energy muon rate, due to atmospheric temperature variations, in agreement with theoretical predictions. We report also the detection of the moon shadowing effect with a statistical significance of 3.7 σ. The results obtained straighten the possibility that a "muon astronomy" using underground experiments is possible.

1. INTRODUCTION

One of the pecularity of MACRO as a muon telescope is its excellent angular resolution. Moreover, it has a large collecting area and thus relatively large statistics when compared to other deep underground detectors. We present an update of the results on the study of atmospheric effects on the underground muon flux recorded by our detector [3]. It is also important to establish the pointing accuracy of the apparatus. We have therefore looked for the shadow of the Moon cast by high energy primary cosmic rays, which for MACRO have E>12 TeV. The analysis confirms the good pointing capability of the detector and gives confidence in MACRO's ability as a muon telescope.

2. SEASONAL VARIATIONS OF THE UNDERGROUND MUON FLUX

Underground muons originate primarily from the decay of mesons produced in high energy interactions between primary cosmic rays and atmospheric nuclei. As shown decades ago [1, 2], fluctuations in atmospheric temperature lead to variations in the muon intensity observed at ground level and underground. However, there have been relatively few experimental underground measurements of these effects and those that have been made were not always in agreement with theory [1,2].

Because of its large collecting area and great depth, MACRO is a powerful tool to investigate the atmospheric temperature effects on the underground muon rate, although the expected amplitude is of few percent. Data were collected during a 4 year period starting in January 1991, when all the six lower supermodules with streamer tubes became operational.

Specific cuts are used to remove systematic effects on the evaluation of the muon rate. Fig. 1-a shows the monthly variations of the muon counting rate.

The effect has been analyzed assuming the relation:

$$\frac{\Delta R_\mu}{\overline{R}_\mu} = \alpha_T \frac{\Delta T_{eff}}{\overline{T}_{eff}}, \tag{1}$$

where we have introduced an "effective temperature" T_{eff} that takes into account the non-uniform variation of the temperature along the entire atmospheric mass column above the detector. T_{eff} is obtained via a weighted average of the temperatures measured at different isobaric levels

$$T_{eff} = \sum_i w_i T_i \tag{2}$$

α_T is a temperature coefficient. We have chosen for $w(i)$ the expression:

$$w_i = \frac{exp^{-h(i)/\lambda}/h(i)}{\sum_i exp^{-h(i)/\lambda}/h(i)}, \tag{3}$$

*see last page for the complete author list

0920-5632/98/$19.00
PII S0920-5632(97)00559-8

with $\lambda = 160$ g/cm^2[3].
The temperature data were provided by the Ispettorato Telecomunicazioni ed Assistenza Volo dell'Aeronautica Italiana. For the years 1991-1993, the data were obtained at 7 atmospheric depths (700 g/cm^2, 500 g/cm^2, 300 g/cm^2, 150 g/cm^2, 70 g/cm^2, 45 g/cm^2, 35 g/cm^2, 25 g/cm^2) four times daily: 0^h, 6^h, 12^h and 18^h. In 1994, there were only two flights per day, for most of the year, at 11^h and 23^h. The depth sampling during these flights however was much finer. To be consistent with the previous years we used only data at depths ≤ 700 g/cm^2.

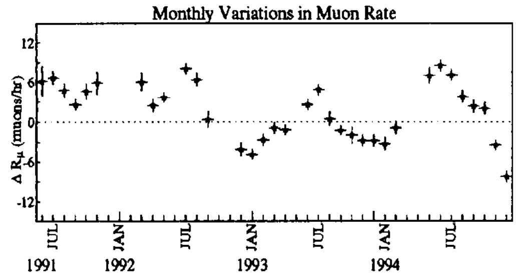

Figure 1. a) Monthly variations in the muon rate, $\Delta R_\mu = (R_\mu - \overline{R}_\mu)$. R_μ is the monthly rate and $\overline{R}_\mu = 364.8$ muons/hr is the average monthly rate computed for the December 1992-1994 data set. The errors are dominated by statistical errors in the rates.

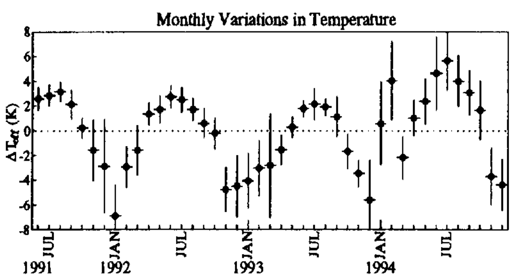

Figure 1. b) Monthly variations in the effective temperature, $\Delta T_{eff} = (T_{eff} - \overline{T}_{eff})$, where T_{eff} is the average monthly effective temperature distribution and $\overline{T}_{eff} = 217.8K$ is the mean effective temperature for the complete data set (1991-1994). The errors on the data points are taken as the standard deviations in the T_{eff} distribution for that month.

The total number of single muons analyzed in the period 1991-1994 is 5.3×10^6 after run cuts. We computed for each month the mean value of the effective temperature. In Fig. 1a-b are shown the monthly rate values of $\Delta T_{eff} = T_{eff} - \overline{T}_{eff}$, where T_{eff} is the mean effective temperature and $\overline{T}_{eff} = 217.8K$ the average effective temperature computed for the complete data set.

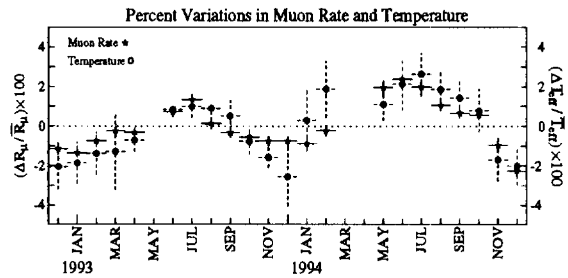

Figure 2. The superposition of the percentage monthly variations in the muon rate, $\Delta R_\mu/\overline{R}_{mu}$ (%), and the average monthly variations in the effective temperature, $\Delta T_{eff}/\overline{T}_{eff}$ (%) for the December 1992-1994 data set.

In Figure 2 we superpose the percentage variations in the effective temperature onto the percentage fluctuations in the muon rate.

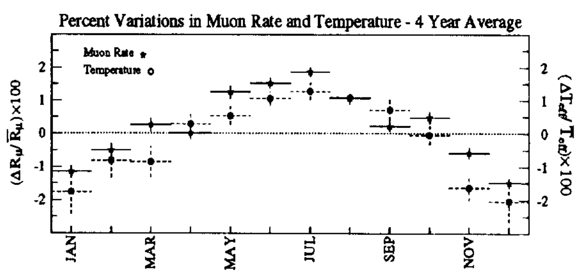

Figure 3. The superposition of the percentage monthly variations in the muon rate, $\Delta R_\mu/\overline{R}_{mu}$ (%), and of the percentage monthly variations in the effective temperature, $\Delta T_{eff}/\overline{T}_{eff}$ (%) for the total data set, 1991-1994

To quantify the significance of the correlation in Fig. 3, we have computed both the correlation coefficient and the chance probability that the variations in the muon rate and the effective temperature are uncorrelated (null hypothesis). The regression analysis of the available monthly data yields $\alpha_T = 0.98 \pm 0.12$ in the total data set. The value of the temperature coefficient $\alpha_T/\overline{T}_{eff} \times 100 \simeq 0.45 \pm 0.06\%/K$ is consistent with theoretical expectations [1,4].

3. MOON SHADOWING EFFECT

To demonstrate the pointing accuracy of MACRO, we have searched for the shadow of the Moon in high energy primary cosmic rays. The analysis of 30×10^6 single muons recorded from 1989 to 1995 has been performed in two ways: the first one is a classical approach, the second one is a maximum likelihood method. The first method consist in a comparison between the density of the observed events versus the angular distance from the center of the calculated Moon position, and a simulated event distribution[5] . The result of this analysis is shown in Fig. 4.

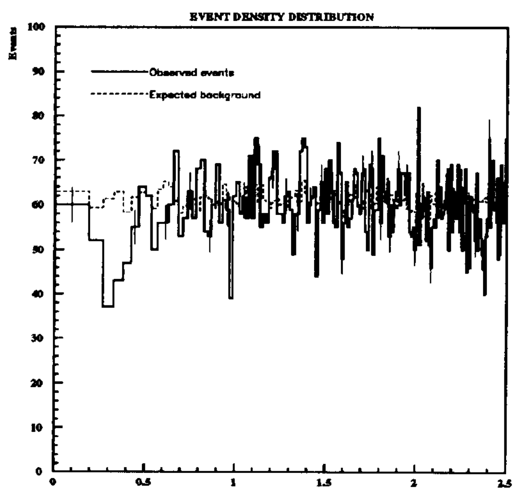

Figure 4. Muon event density observed vs the angular distance from the Moon; the simulated expected events (dashed line) are superimposed

The maximum deviation occurs at 0.25°; the observed deficit at 0.6° is equal to 98 events on a background of 700 ± 26 events ($3.7\ \sigma$) while the deficit within 1° is 120 events on a background of 1170 ± 46 events ($2.85\ \sigma$).

The second analysis was done in two dimensions using the maximum likelihood method of COS-B [6]. This method is based on the *a priori* knowledge of the point-spread function and searches for a source of unknown intensity, in this case a source of negative intensity.

The intrinsic angular resolution of the detector is 0.2°[7]. However the multiple Coulomb scattering in the rock overburden introduces an energy dependent spread of the muons with respect to the original direction. The overall spread has been estimated from the distribution of the angular separation of double muons; the overall angular resolution is about 1°.

The analysis was done on 72 different windows containing each 17 by 17 bins (0.25 degrees wide in equatorial coordinates): the first window is centered on the instantaneous position of the moon ($\alpha_{moon}, \delta_{moon}$); the others are displaced by 5°, thus covering the entire range of 360°.

We have calculated, for each bin, the likelihood function for the poissonian process [8]: $\mathcal{L}(x_s, y_s, I_s) =$

$$2 \sum_{i=1}^{N_{bin}} \left[N_i^{th} - N_i^{obs} + N_i^{obs} \ln \left(\frac{N_i^{obs}}{N_i^{th}} \right) \right], \qquad (4)$$

where N_i^{obs} is the number of the observed events in each bin and N_i^{th} is given by the expression:

$$N_i^{th} = N_i^{back} + I_s \cdot PSF_{x_s,y_s}(x_i, y_i) \qquad (5)$$

being N_i^{back} is the calculated number of background events in each bin, $PSF(x,y)$ the point spread function and I_s the intensity of a possible source at (x_s, y_s). For each bin the most likely intensity of a source in that position is obtained by minimizing $\mathcal{L}$ and varying I_s as a free parameter.

The probability of a background fluctuation is theoretically given by the cumulative χ^2 distribution with one degree of freedom for $\lambda = \mathcal{L}(\tilde{\alpha}, \tilde{\delta}, 0) - \mathcal{L}(\tilde{\alpha}, \tilde{\delta}, I_s^{min})$ with

$$\tilde{\alpha} = \alpha - \alpha_{moon} \qquad \tilde{\delta} = \delta - \delta_{moon}$$

A contour plot of the λ variable for the moon window is shown in Fig. 5. The maximum value is $\lambda = 14.2$ (3.7σ) on the position ($-0.25°$,$0.°$) where is the maximum deficit. The observed displacement is compatible both in value and in the direction with the displacement of the primary protons due to the geomagnetic field.

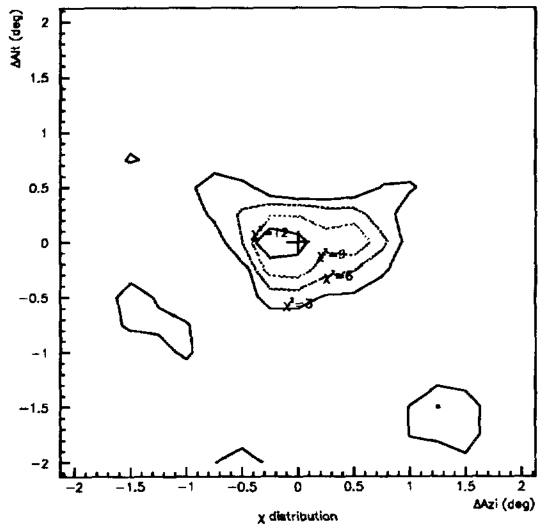

Figure 5. χ^2 values in the window centered on the moon, obtained by the maximum likelihood procedure. Four levels are shown starting from $\chi^2 = 3$ with a step of 3. The maximum value of $\chi^2 = 14.2$ is in the position (-0.25°,0°)

Since we find only 1 bin in the other 71 windows, having $\lambda \geq 14.2$, the *a priori* probability of finding a fluctuation that mimics the shadow of the moon in the expected position is 0.02%, a result consistent with the significance level given by the first analysis.

4. CONCLUSIONS

The determination of the positive temperature coefficient for atmospheric effects on the muon intensity recorded by MACRO appears to be consistent with the expectations.

We have found evidence of a deficit in the arrival distribution of muons about the nominal position of the moon (0.25° displaced) with a significance of 3.7 σ both in the one-dimensional and two-dimensional analyses showing also a good statistical consistency between the two methods.

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The MACRO Collaboration

M. Ambrosio[12], R. Antolini[7], G. Auriemma[14,a], R. Baker[11], A. Baldini[13], G. C. Barbarino[12], B. C. Barish[4], G. Battistoni[6,b], R. Bellotti[1], C. Bemporad[13], P. Bernardini[10], H. Bilokon[6], V. Bisi[16], C. Bloise[6], T. Bosio[7], C. Bower[8], S. Bussino[14], F. Cafagna[1], M. Calicchio[1], D. Campana[12], M. Carboni[6], M. Castellano[1], S. Cecchini[2,c], F. Cei[13,d], V. Chiarella[6], A. Corona[14], S. Coutu[11], L. De Benedictis[1], G. De Cataldo[1], H. Dekhissi[2,e], C. De Marzo[1], I. De Mitri[9], M. De Vincenzi[14,f], A. Di Credico[7], O. Erriquez[1], R. Fantini[2], C. Favuzzi[1], C. Forti[6], P. Fusco[1], G. Giacomelli[2], G. Giannini[13,g], N. Giglietto[1], M. Goretti[4,14], M. Grassi[13], P. Green[m], A. Grillo[7], F. Guarino[12], P. Guarnaccia[1], C. Gustavino[7], A. Habig[8], K. Hanson[11], A. Hawthorne[8], R. Heinz[8], J. T. Hong[3], E. Iarocci[6,h], E. Katsavounidis[4], E. Kearns[3], S. Kyriazopoulou[4], E. Lamanna[14], C. Lane[5], D. S. Levin[11], P. Lipari[14], G. Liu[4], R. Liu[4], N. P. Longley[4,n], M. J. Longo[11], G. Ludlam[3], F. Maaroufi[2,e] G. Mancarella[10], G. Mandrioli[2], A. Margiotta-Neri[2], A. Marini[6], D. Martello[10,], A. Marzari-Chiesa[16], M. N. Mazziotta[1], D. G. Michael[4], S. Mikheyev[7,i], L. Miller[8], P. Monacelli[9], T. Montaruli[1], M. Monteno[16], S. Mufson[8], J. Musser[8], D. Nicoló[13,d], R. Nolty[4], C. Okada[3], C. Orth[3], G. Osteria[12], O. Palamara[10], S. Parlati[7], V. Patera[6,h], L. Patrizii[2], R. Pazzi[13], C. W. Peck[4], S. Petrera[10], N. D. Pignatano[4], P. Pistilli[10], V. Popa[2,l], A. Rainó[1], J. Reynoldson[7], F. Ronga[6], U. Rubizzo[2,c], A. Sanzgiri[15], F. Sartogo[14], C. Satriano[14,a], L. Satta[6,h], E. Scapparone[7], K. Scholberg[4], A. Sciubba[6,h], P. Serra-Lugaresi[2], M. Severi[14], M. Sitta[16], P.F. Spada[2], P. Spinelli[1], M. Spinetti[6], M. Spurio[2], R. Steinberg[5], J. L. Stone[3], L.R. Sulak[3], A. Surdo[10], G. Tarlé[11], V. Togo[2], V. Valente[6], E. Vilela[2,o], C. W. Walter[4] and R. Webb[15]

1. Dipartimento di Fisica dell'Università di Bari and INFN, 70126 Bari, Italy
2. Dipartimento di Fisica dell'Università di Bologna and INFN, 40126 Bologna, Italy
3. Physics Department, Boston University, Boston, MA 02215, USA
4. California Institute of Technology, Pasadena, CA 91125, USA
5. Department of Physics, Drexel University, Philadelphia, PA 19104, USA
6. Laboratori Nazionali di Frascati dell'INFN, 00044 Frascati (Roma), Italy
7. Laboratori Nazionali del Gran Sasso dell'INFN, 67010 Assergi (L'Aquila), Italy
8. Depts. of Physics and of Astronomy, Indiana University, Bloomington, IN 47405, USA
9. Dipartimento di Fisica dell'Università dell'Aquila and INFN, 67100 L'Aquila, Italy
10. Dipartimento di Fisica dell'Università di Lecce and INFN, 73100 Lecce, Italy
11. Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA
12. Dipartimento di Fisica dell'Università di Napoli and INFN, 80125 Napoli, Italy
13. Dipartimento di Fisica dell'Università di Pisa and INFN, 56010 Pisa, Italy
14. Dipartimento di Fisica dell'Università di Roma "La Sapienza" and INFN, 00185 Roma, Italy
15. Physics Department, Texas A&M University, College Station, TX 77843, USA
16. Dipartimento di Fisica Sperimentale dell'Università di Torino and INFN, 10125 Torino, Italy

a Also Università della Basilicata, 85100 Potenza, Italy
b Also INFN Milano, 20133 Milano, Italy
c Also Istituto TESRE/CNR, 40129 Bologna, Italy
d Also Scuola Normale Superiore di Pisa, 56010 Pisa, Italy
e Also Faculty of Sciences, University Mohamed I, B.P. 424 Oujda, Morocco
f Also Dipartimento di Fisica, Università di Roma Tre, Roma, Italy
g Also Università di Trieste and INFN, 34100 Trieste, Italy
h Also Dipartimento di Energetica, Università di Roma, 00185 Roma, Italy
i Also Institute for Nuclear Research, Russian Academy of Science, 117312 Moscow, Russia
l Also Institute for Gravity and Space Sciences, 76900 Bucharest, Romania
m Sandia National Laboratory, Albuquerque, NM 87185, USA
n Swarthmore College, Swarthmore, PA 19081, USA
o Also Inst. de Pesquisas Energéticas e Nucl., Pinheiros 05422-970 São Paulo, Brasil