Proceedings of ICRC 2001: 995 © Copernicus Gesellschaft 2001

ICRC 2001

Moon and Sun shadowing effect observed by MACRO

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Abstract.
We present the results of the analysis of the entire sample of $5.7 \cdot 10^7$ muons collected by the MACRO detector from 1989 to December 2000. We have observed the moon shadowing effect with a statistical significance of about 6.3 σ. Using the same sample of data we have detected a similar effect due to the Sun. A comparison of the shadowing effect due to these two sources will be discussed. While the displacement of the Moon shadow is in agreement with expectation, the effect due to the Sun is significantly moved to the North of the Sun position. From the latter we obtain an upper limit to the antiproton/proton flux of about 20 TeV. Based on this analysis, we have performed an all-sky survey searching for pointlike sources producing excesses of muons above the expected background. We establish upper limits of selected interesting sources.

1 Introduction

The MACRO detector is located at the Gran Sasso Laboratory (42° N, 13 ° E), 963 m above sea level, with a minimal rock overburden of 3400 hg/cm^2. In this work we present the analysis of single and double muon events collected by the apparatus from 1989 to December 2000. The entire sample used consists of $56.5 \cdot 10^6$ events. The data are used to search for the shadow cast by the Moon and the Sun in the underground muon flux and for possible pointlike sources able to produce excesses of muons in a small angular region of the sky. As reported before (Ambrosio, M. et al. , 1999) and observed by many experiments (Aglietta, M. et al. , 1991; Alexandreas, D.E. et al. , 1991; Amenomori, M. et al. , 1993; Allison, W.W.M. et al. , 1999; Cobb, J.H. et al. , 2000), the Moon shadowing effect is a widely used method to verify, using cosmic rays, the pointing capabilities of an experimental apparatus (Alexandreas, D.E. et al. , 1991; Aglietta, M. et al. , 1995) and to test its sensitivity. The analysis of the shadows of the Moon and Sun, moreover, can provide information about the Geomagnetic (GMF) and Interplanetary magnetic fields (IMF) that primary particles (mainly protons) have crossed before reaching the top of the atmosphere.

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2 Event selection

The basic requirement for this analysis is a good reconstruction quality of the event directions. Therefore we have applied a χ^2 cut of the fitting procedure used to find the trajectories of the single and double muons events. Moreover we require that a minimal number of 3 planes of the lower part of the apparatus are crossed by the track (for details about the MACRO detector description see Ahlen, S. et al. (1993)). Finally we consider only runs which lasted more than 1 hour. All these cuts reduce the uncertainties in the track direction; the angular accuracy in the pointing direction is about $0.1°$. To this value the angular displacement due to the multiple muon scattering in the rock ($0.6°$) should be added. The number of events selected after all these cuts is about $53 \cdot 10^6$ events. In order to evaluate the background, for each event we have generated also 25 events obtained by randomly coupling the directions and times for all events in the same run.

3 Moon shadowing effect

We have considered all muons having an angular distance smaller than $10°$ from the instantaneous center position of the Moon, calculated taking into account parallax corrections. The total number of events is 406400. Therefore the expected shadowing effect, due to primary cosmic rays blocked by the Moon body, consists of $406000 \cdot (\frac{0.26}{10})^2 = 274$ missing events with respect to background.

As explained in a previous paper (Ambrosio, M. et al. , 1999) we have used a binned maximum likelihood method to establish the statistical significance of the observed events. Basically we use a point spread function (PSF) which has been determined by using double muon events detected by

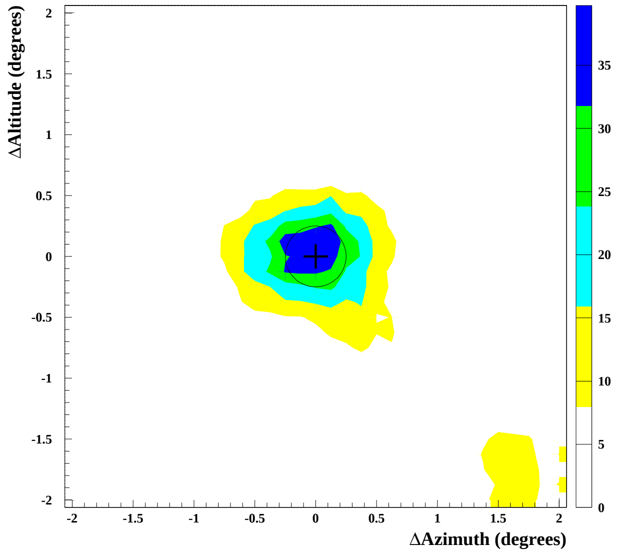

Fig. 1. χ^2 levels in the sky windows centered on the Moon position. The maximum value of χ^2 is 39.7 at (+0.°,+0.1°) corresponding to more than 6 σ signal.

the apparatus. The spread of these events is due to the muon scattering in the rock above the detector and to the uncertainties in the track reconstruction. We then perform a likelihood maximization of the map of observed events and of a map of simulated events. The latter is obtained by adding to the map of background events the effect of a chance source with unknown intensity located at the center of each bin in the map. The PSF is actually modified to take into account the finite size of the source. The result of the 2-D analysis of the map ($2^\circ \times 2^\circ$) plotted in Azimuth and Altitude coordinates and centered on the instantaneous Moon position is represented by the χ^2 map shown in Fig. 1. The maximum values found are χ^2=39.7 in the position at (0.°,+0.1°) and χ^2 above 36 within the expected Moon disk. The likelihood analysis also estimates the number of missing events producing Fig. 1 as 316 ± 51 events in agreement with expected deficit.

We have divided the sample in two subsamples called "day" and "night" by the requiring that the Moon has an angular distance from the Sun respectively smaller or greater than $90°$. This division is about equivalent to a daytime-nightime requirement on the data set similar to that used in a previous paper (Amenomori, M. et al. , 1995). The two samples contain almost the same number of events and the results of the analyses are in Fig. 2 and 3. In the "day" case the maximum deficit is located at $(-0.25°, 0°)$ and χ^2=17, in the "night" case, the maximum deficit is at the center of the Moon "nominal" disk and a χ^2=25.

We attribute the origin of the observed effect to the different shape of the geomagnetic field encountered by the primaries in the dayside and nightside part of the magnetosphere. Since the dispacement $\Delta\theta$ can be parametrized (Borione, A. et al. , 1994) as $\Delta\theta = Z \cdot 1.5°/E(TeV)$, Z being the charge of primary nuclei and E the primary energy, we conclude that the observed deflections are in agreement with the deflection angle of protons with energies of about 15 TeV and higher.

4 Sun shadowing

We have repeated the analysis using the events coming from the direction of the Sun. In principle as the Sun and the Moon have the same angular size the effect must be very similar. The total number of events selected in a 2-D window of $10°$ centered on the Sun is 395000 so that we expect to observe the same deficit obtained for the Moon. However due to the influence of the Sun's magnetic field, of the IMF and finally of the geomagnetic field, the displacement of the shadow is expected to be variable with time and larger than one observed for the Moon (Allison, W.W.M. et al. , 1999; Amenomori, M. et al. , 2000). The results of the likelihood analysis, in ecliptic coordinates, is shown in Fig. 4 and a clear deficit with maximum at (0°,+0.62°) and a χ^2=21.6, corresponding to 4.6 σ is visible. Due to the limited size of our data sample we are not able to produce detailed pictures of the shadow year by year (see Amenomori, M. et al. (1996); Allison, W.W.M. et al. (1999)). Note however that the bulk of our data are in the period 1994-2000 as shown in Fig. 5, which is a quiet phase of the solar cycle. Since MACRO is located at a high latitude, it is possible that by averaging over a long period of observations the net result is a displacement to the north as if the apparatus was mostly looking in the "away" hemisphere of the IMF. The shift is also of the expected amplitude (Amenomori, M. et al. , 1996) for 15 TeV particles.

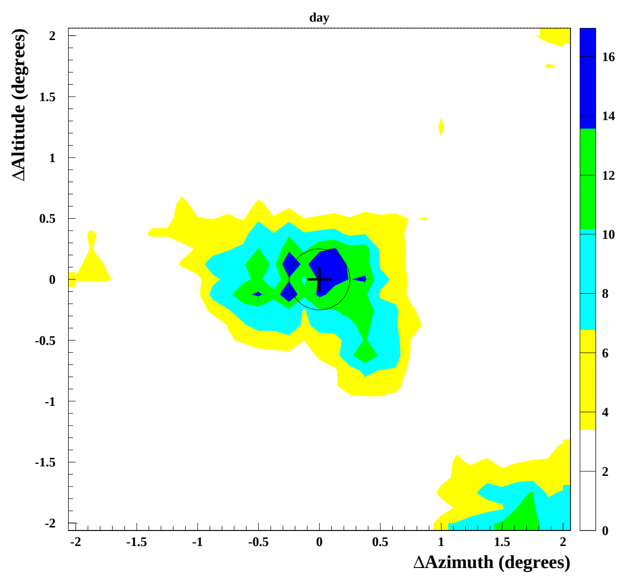

Fig. 2. χ^2 levels in the sky windows centered on the Moon position for the "day"sample. The maximum value of χ^2 is 17. at (-0.25°,0.°) corresponding to about 4 σ signal.

Table 1. DC muon flux upper limits for selected sources

SOURCE NAME	Observ. evts	Expect. evts	deviations (σ)	acceptance (m^2)	exposure time (10^6s)	Flux limit ($cm^{-2}s^{-1}$)
Mkn421	6506	6389.7	1.5	745	162	$3.7 \cdot 10^{-13}$
Mkn501	6544	6459.5	1.1	739	164	$3.4 \cdot 10^{-13}$
Crab	6808	6764.0	0.5	744	137	$3.6 \cdot 10^{-13}$
Cyg X-3	6340	6370.7	-0.4	740	164	$2.4 \cdot 10^{-13}$
Her X-1	6530	6519.0	0.14	733	159	$2.8 \cdot 10^{-13}$
3C66A	6398	6305.3	1.17	737	168	$3.4 \cdot 10^{-13}$
1ES 2344+514	6969	7003.8	-0.4	729	180	$2.3 \cdot 10^{-13}$

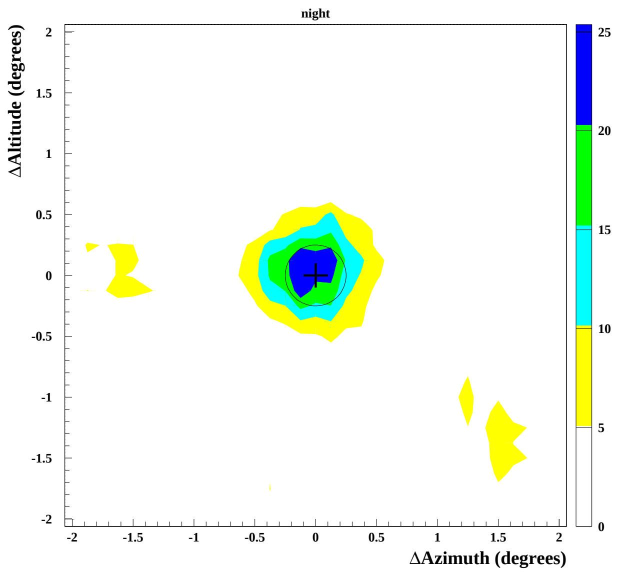

Fig. 3. χ^2 levels in the sky windows centered on the Moon position for the "night" sample. The maximum value of χ^2 is 25. at (-0.1°,0.°) corresponding to about 5 σ signal.

5 Antiproton flux limits

The displacement of the Sun shadow from the expected center position can be used to evaluate a limit on the antiproton abundance in the cosmic ray flux at the Earth. In fact if a primary antiproton flux is present, its effect should produce a displacement on the opposite direction with respect to that of the proton flux. Since we don't have a deficit in the symmetric position with respect to the Sun "nominal" center, we can estimate an upper limit for a $\overline{p}$/p flux ratio of about 1/4.6= 21.5% at a mean energy of about 20 TeV. If we take into account the He contribution (27%) to the cosmic ray primary flux, the upper limit is about 27.5 %.

6 Pointlike sources search

The positive detection of the Sun and Moon shadows lets us conclude that MACRO has good accuracy and reliability in pointing to sky directions. Therefore we have searched for possible pointlike sources by looking for excesses of events above the background in small regions ($< 1.5°$ radius) of the sky scanned by MACRO. For each angular bin we have evaluated the muon flux upper limit (95 % c.l.) (Ahlen, S. et al. , 1993). No candidate was found in the flux range between $1 \times 10^{-13} cm^{-2} s^{-1}$ and $7.5 \times 10^{-13} cm^{-2} s^{-1}$ as shown in Fig. 6. In Table 1 are shown the DC flux limits for most interesting known sources. No evidence was found for episodic emission or for modulated signals from a list of potential sources.

7 Conclusions

MACRO is the deepest detector to have a positive detection of the Moon and Sun shadowing, with a significance level of 6.3 and 4.6 σ respectively. The amplitudes of the signals are in agreement with those expected by statistics. The effect appears to be shifted with respect to the center "nominal" positions by the right amount. This result allows us to establish the good pointing accuracy and reliability of the apparatus. We have then performed a sky survey looking for pointlike

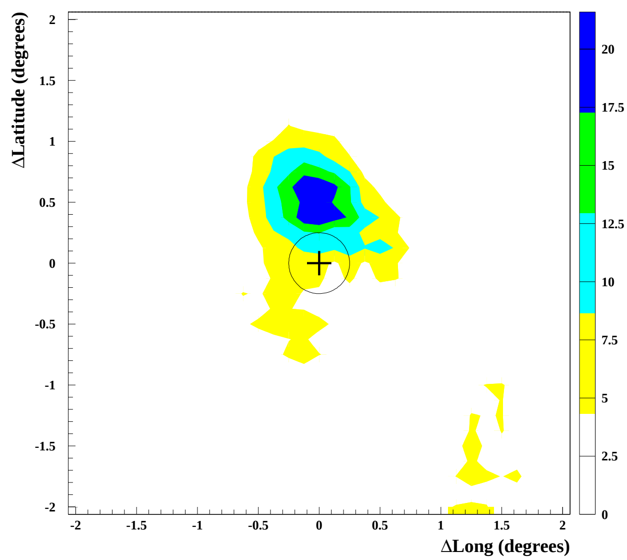

Fig. 4. χ^2 levels in the sky windows centered on the Sun position using ecliptic coordinates. The maximum value of χ^2 is 21.6 at (+0.°,+0.625°) corresponding to more than 4.5 σ signal.

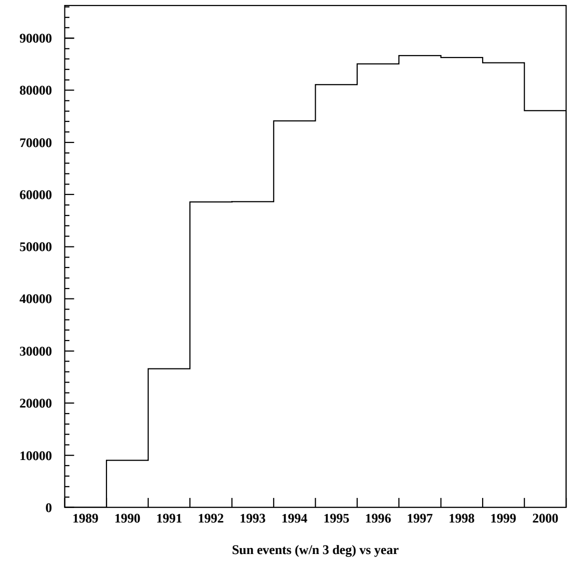

Fig. 5. Number of events within 3° from the Sun direction collected in each year of MACRO data taking.

sources and studied in detail several interesting directions. No evidence of any signal was found.

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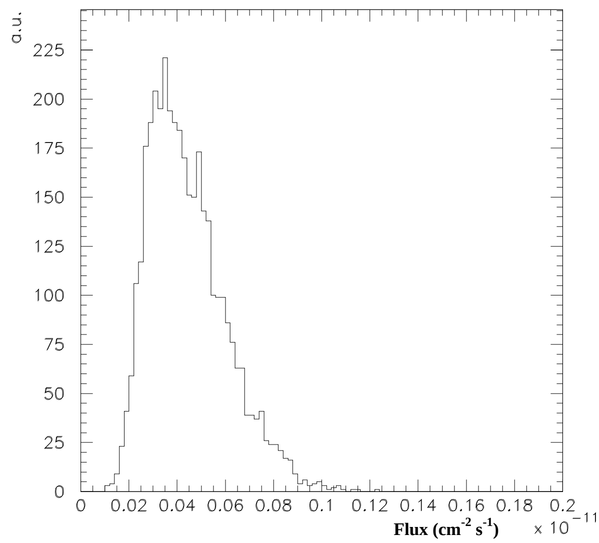

Fig. 6. Distribution of the flux upper limits at 95% c.l. for all bins in the sky.