Muon Astronomy topics with the MACRO experiment revised in 2017

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Abstract

In this paper I will present the results of a reanalysis of data of the past MACRO experiment. MACRO was located under under the Gran Sasso Laboratory and was able to detect muons coming from primaries of at least 10 TeV. This reanalysis concern the Moon and Sun shadows, the sidereal anisotropy and the Compton Getting effect. The result are compared with recent experiment like ARGO,Tibet Air shower array, ICECUBE, MINOS ecc. The number of events analized is much lower that in recent experiments, but the results could be interesting because the systematics are different and the tracking capability allows to select event with different muon multiplicity.

Keywords: Cosmic Rays, Astronomy, Muon, Gran Sasso

November 9, 2017

1. Introduction

Underground muons originate primarily from the decay of mesons produced in high energy interactions between primary cosmic ray particles and atmospheric nuclei [1]. These mesons either interact and produce lower energy hadronic cascades, or decay into high-energy muons which can be observed deep underground.

MACRO was a large acceptance, deep underground detector located in the Gran Sasso underground laboratory in Italy. MACRO's large collecting area results in large number statistics for multiple-muons. MACRO ended data taking in December 2000. The data presented in this paper have been collected in the period April 1994-December 2000 with the full MACRO, corresponding to about 41.9×10^6 single muons and and 3.08×10^6 events having at least 2 tracks.

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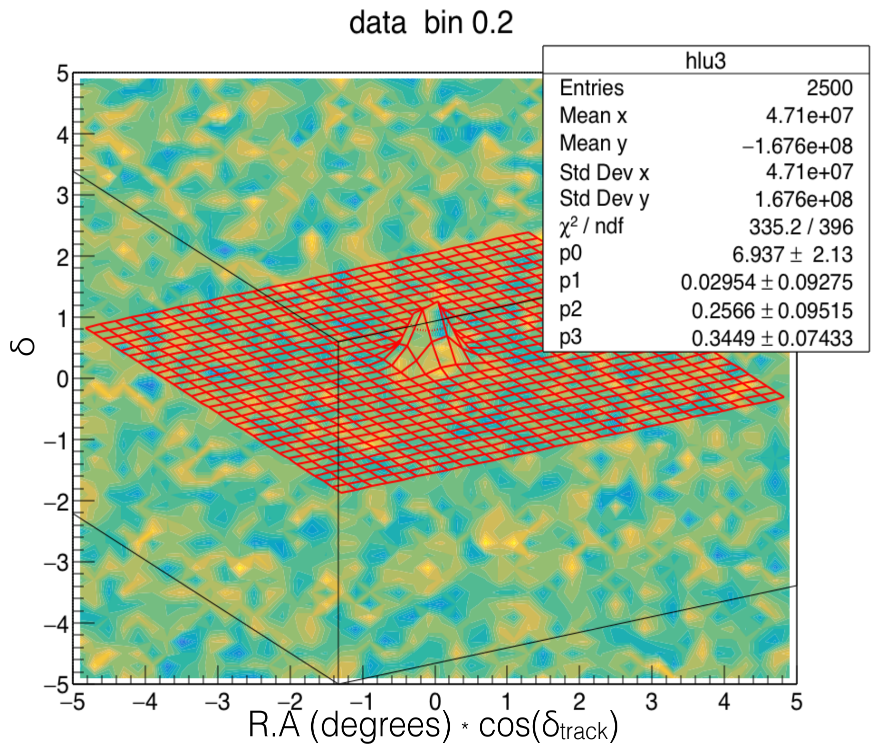

Figure 1: Moon: the number of single tracks compared to the simulation (see text) in 0.2×0.2 degree bins in right ascension times cosine of the track declination and declination. The moon is at the center. There is a change of sign to have a better figure (the excess in the figure correspond to a deficit).

2. Moon Shadow

The moon and sun shadowing effect were studied in detail in the MACRO paper [3], The purpose of this re-analisys is to check and to compare the results of [3] to the one of experiments after 2002. The angular diameter of the Moon seen from the Earth varies from a minimum of 29’ 20” to a maximum of 34’ 6” according to the distance. The average value is 0.52 degree. In a simple model in which all the cosmic rays hitting the moon are absorbed we expected that the deficit is not zero in the moon area and that the deficit is smeared by the angular detector resolution. Let us consider all the cosmic rays in a cone of 5° around the moon direction. If the angular resolution is much smaller than this cone we expect a deficit of the order $(0.26/5)^2 = 0.0027\%$ due to the moon.

The muon sample used for the present analysis includes all events collected from April 20th 1994 until the end of MACRO data taking at the end of 2000. To remove runs with hardware problems a simple selection was applied to the data requiring that the single muon rate is between 710. and 1010 events/hour.

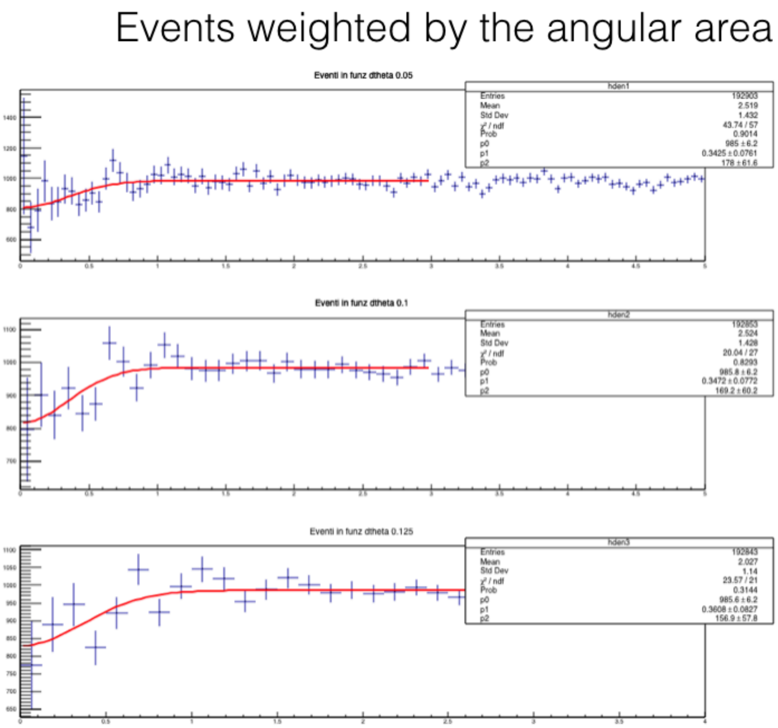

Figure 2: Moon: single muon tracks as function of the angle from the moon weighted with angular area for three different bin sizes.

The final sample totals 36×10^6 single muon tracks and 3.2×10^6 tracks due to multiple muons. Single muons and multiple muons were analyzed separately.

The moon position was computed every 2 minutes using the JPL horizon system (https://ssd.jpl.nasa.gov/?horizons).

The result of single tracks is shown in Fig. 1. On the z coordinate there is the difference between the events expected by a simulation with a statistics 100 times bigger than the data and the events of the real data set. So a deficit appears as "excess". The simulation is done using the data itself. In the simulation the azimuth and zenith of a track is is associates to the solar time of another random track. On the x axis there is the difference in right ascension times the cosine of the declination of the track. This is for uniformity with other experiments and to have bin with equal solid angles.

The plot in Fig. 1 was fitted with the product of two independent gaussian:

$$\frac{p_0}{2\pi p_3^2} \times e^{-(\frac{(Ra-p_1)^2}{2p_3^2})} \times e^{(-\frac{(\delta-p_2)^2}{2p_3^2})} \tag{1}$$

where Ra is the right ascension times the cosine of the declination and δ is the declination in degree. We assume the angular resolution p_3 is the same in Ra and δ . The result of the fit gives $p_3 = 0.34 \pm 0.07$ degrees corresponding in space to 0.48 ± 0.11 in agreement with the value 0.69 degrees expected from the study of the angular differences in multi muons events [2] and a contribution due to the moon diameter. The value of $p_1 = 0.03 \pm 0.09$ the offset in Ra is consistent with 0, while $p_2 = 0.26 \pm 0.1$ is marginally in agreement. As discuss in the original MACRO paper[3] we could have deviations effect due the geo-magnetic fields between Earth and Moon. In [3] the maximum of the Moon shadowing was found at a deviation of 0 degree in Azimuth and 0.125 degree in altitude.

The Argo experiment[7] in Tibet, located in the North experiment at a latitude of 29.5° , has studied this magnetic field effect. ARGO found that there is a very small deviation in declination and an East West effect (and therefore in right ascension) of the order of 10% less than the value $1.58° Z/E[TeV]$ expected from a simple dipole model for the magnetic field. This should correspond to a maximum deviation of the order of 0.14° under the Gran Sasso for a primary of 10 TeV.

The MINOS experiment[6], located in the North experiment at a latitude of 47.8° computed a very small displacements due to the magnetic fields between Earth and Moon for primary of energy bigger than 10 TeV (2100 Mwe). MINOS found a maximum deviation in RA of 0.02° and an average deviation in declination up to 0.02° with an average value around 0. MINOS concluded that any displacement of the moon shadow beyond 0.013° cannot be caused by the geomagnetic field, and it is unlikely that the geomagnetic field could cause an average deflection of greater than 0.01°. This result is partially in contradiction with ARGO.

The L3 experiment [5] has used the Earth magnetic field to put a limit on the antiproton flux at 1TeV.

Finally the effect of the geo-magnetic field has been computed also by the Ice-Cube experiment at South Pole [4]. The result for this location is that the cosmic ray are deviates by an amount $1.9° \frac{Z}{E[TeV]}$, mostly for the declination angle. This result confirm the order of magnitude of the deviation computed by Argo. The deviation in declination should be due to the very peculiar geographic location for a the dipole magnetic.

In conclusion the deviation observed by MACRO, if true, should not be due to magnetic field

2.1. Event deficit around Moon as function of the year

The study possible variations with the time is necessary to divide the data in smaller sets. Since the fit in two dimensions is unstable the event deficit around the moon can be determined in a better way from a plot in one dimension of the number of events as function of the angular distance from the Moon. The number of the events has been weighted with the angular area between two consecutive bin i and i-1, the weight is therefore $\pi \times ((i^2 - (i-1)^2) \times bin^2)^{-2}$ where bin is the angular bin width. This plot, shown in Fig. 2 has been fitted with the function:

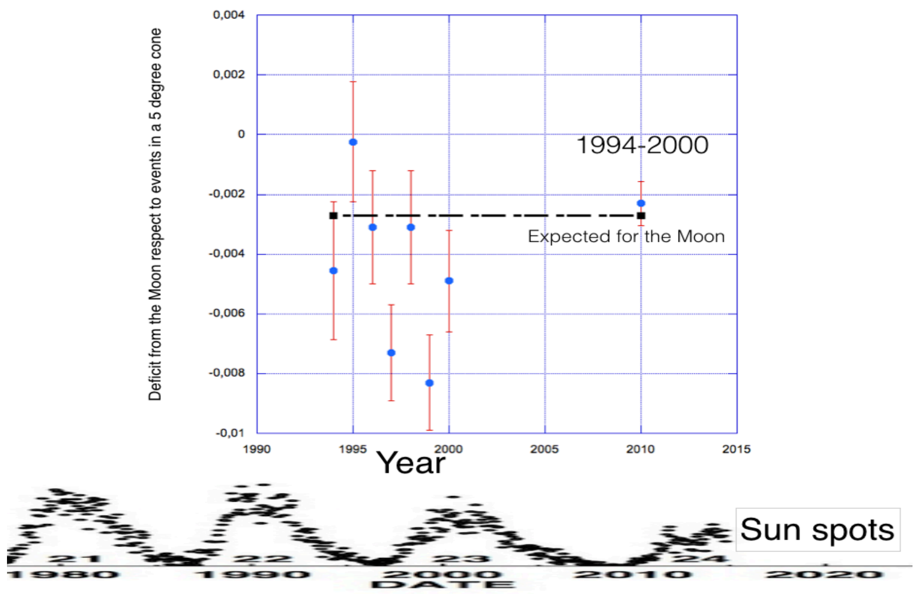

Figure 3: Moon Single muon deficit as function of Year compared to the solar spots. There is no clear correlation

$$p_0 - p_2 \times e^{\left(\frac{-\theta^2}{2p_1^2}\right)} \tag{2}$$

The result of the fit gives a deficit of events 131.3 ± 80 corresponding to $1.7 \pm 1 \times 10^{-3}$ events respect the number of events in a cone of $5°$ around the moon.

To reduce the value of the error in the deficit of the number of events the angular resolution has been fixed to $0.5°$ according to the result of the bi-dimensional fit of Eq. 1 and in agreement with the result of multiple muons. With this fit, the deficit is 179 ± 56 events corresponding to $2.3 \pm 0.73 \times 10^{-3}$ events respect the number of events in a cone of $5°$ around the moon. This value is in good agreement with the value expected 2.7×10^{-3}.

Fig. 3 shows the deficit as function of year compared to the number of solar spots. From this plot there are no hints for the correlation of the Moon deficit with solar spots. Note however that the spread of the deficits is larger than expected by statistical fluctuations, this may suggest that the shape of the moon shadow changes in a more complicated way respect to this unidimensional model.

2.2. Moon: Multiple Muons

Finally I have studied the Moon shadow in events with at lest two muons. The shadow is show in Fig 4. the deficit is 36.4 ± 14 events corresponding to

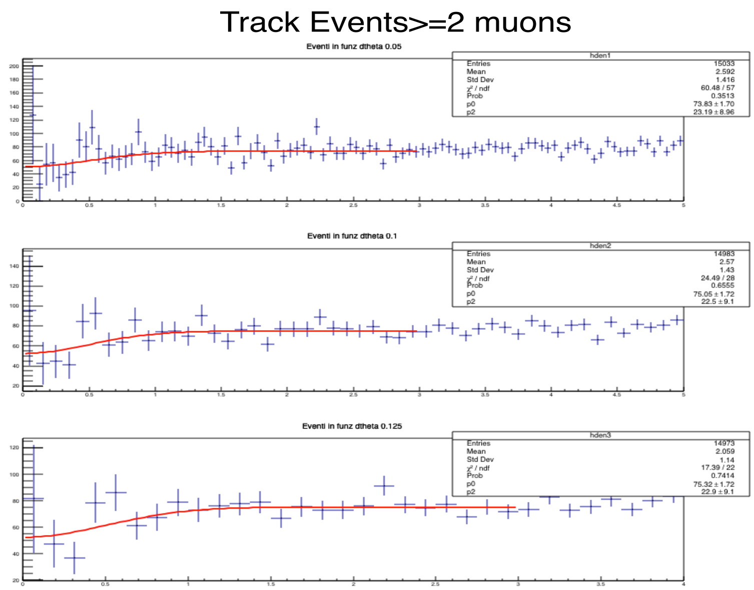

Figure 4: Moon: Multiple muon tracks as function of the angle from the moon weighted with angular area for three different bin sizes. The angular resolution is fixed at 0.5°

$6.2 \pm 2.4 \times 10^{-3}$ tracks respect the number of tracks in a cone of 5° around the moon. This number is higher than the predicted and could mean that there is something hidden. However the fit with the parameter p_1 free gives $p_1 = 0.27 \pm 0.1$ and a lower deficit 19.4 ± 19.2 events corresponding to $3.4 \pm 3.3 \times 10^{-3}$ tracks respect the number of tracks in a cone of 5°. So this difference between single and multiple muons could be due to the 30% higher energy in multiple muons, producing a sharper signal.

2.3. Moon: Day-Night

In the original MACRO paper[3] there was an hint on a possible difference due do different orientation of the Sun respect to the Moon. Selecting single muon tracks requiring an angle between Moon and Sun less then 90° the deficit is $2.4 \pm 1.0 \times 10^{-3}$ tracks respect the number of tracks in a cone of 5°. Selecting single muon tracks requiring an angle between Moon and Sun bigger than 90° the deficit is $3.1 \pm 0.98 \times 10^{-3}$ tracks respect the number of tracks in a cone of 5°. This difference is not statistically significative.

3. Sun Shadow

The Sun position was computed using the formula in [8] pag 86 verified accurate at the level of a few minute.

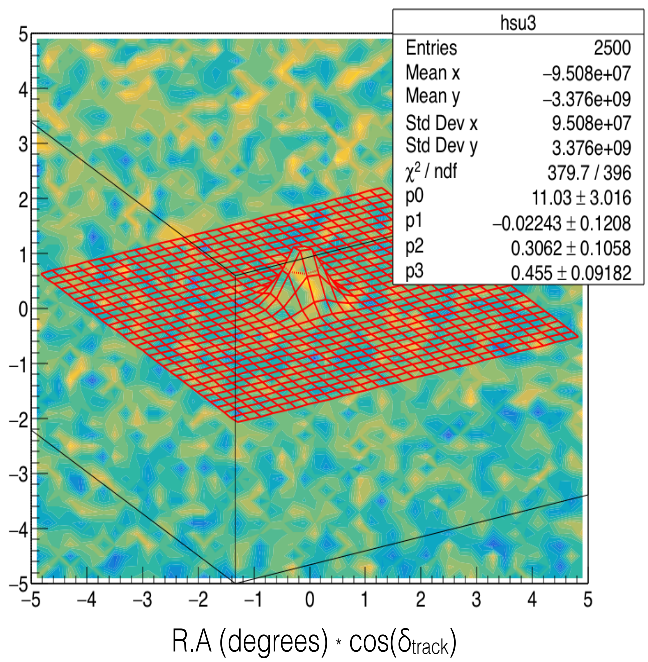

Figure 5: Sun: The number of single tracks compared to the simulation (see text) in 0.2×0.2 degree bins in right ascension times cosine of the track declination and declination. The sun is at the center. There is a change of sign to have a better figure (the excess in the figure correspond to a deficit).

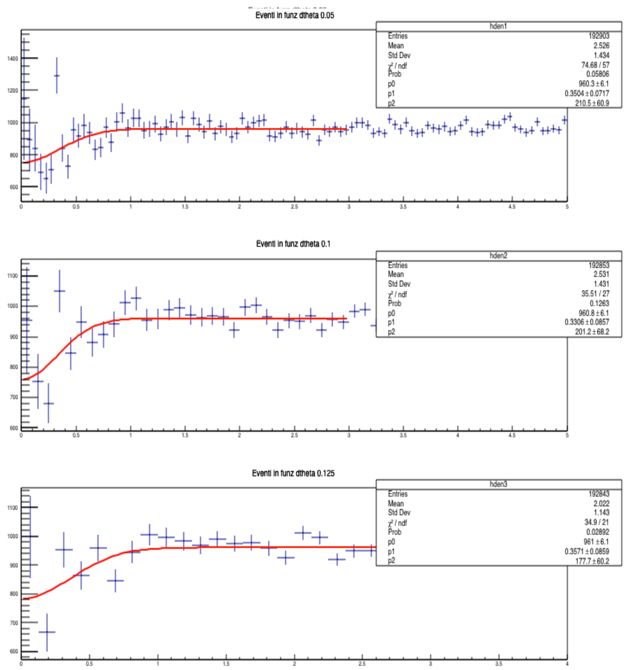

Figure 6: Sun: Single muon tracks as function of the angle from the sun divided the angular area for three different bin sizes. The chi-square probability is small because there is a point at about 0.32° much bigger than expected, this suggest that the Sun position is really shifted

The result of single tracks is shown in Fig. 5. The plot is similar to the one for the Moon. On the z coordinate there is the difference between the events expected by a simulation with a statistics 100 times bigger than the data and the events of the real data set. So a deficit appears as "excess".

As for the Moon the plot in Fig. 5 was fitted with the product of two independent gaussian (Eq.1) with the same angular resolution. The result of the fit gives $p_3 = 0.45 \pm 0.09$ degrees corresponding in space to 0.69 ± 0.12 in agreement with the value 0.69 degrees expected from the study of the angular differences in multi muons events [2] and a contribution due to the sun diameter (0.52°).

The value of $p_1 = 0.02 \pm 0.12$ the offset in right ascension is consistent with 0, while $p_2 = 0.31 \pm 0.11$ is in disagreement with 0 at 3 σ level and in agreement with the value found for the moon. This fact may suggest a common offset for the Moon and the Sun in declination. In the original MACRO paper[3] was observed a shift in the Sun position of 0.62° in ecliptic latitude, but no shift was observed for the Moon. This shift was considered due to the effect of the magnetic fields between Sun and Earth. And this is still the more reasonable

3.1. Event deficit around Sun as function of the year

The Tibet experiment [9] observed a very strong correlation of the Sun deficit with the Sun spots shown in Fig.7. The most probable energy of the primary in this experiment is 10 TeV, the most probable angular resolution is 0.9°. The deficit is reported in Fig.7. The deficit is defined as $(N_{observed} - N_{expected})/N_{expected})$ in a bin of 0.1° centered around the Sun. Note that with this definition the deficit depends from the angular resolution. For example using the same definition in MACRO we have for all the period a deficit of the order of 21% due to the better angular resolution. Fig.8 shows the deficit as function of the year measured from MACRO. The figure shows the total deficit obtained from the fit with Eq.2 respect to the number of events in a 5 degree cone. The MACRO deficit has an behavior statistically consistent with a constant value. In particular we don't observe the almost factor 3 between year 2000 and year 1996 observed by the Tibet experiment. Tibet and MACRO looks to primary of similar energies (the most probable in Tibet is 10 TeV, in Macro probably is a bit higher, but not too much). At a fist look this difference seems small to justify such conclusion, but will be necessary a full simulation using the magnetic fields between Earth and Sun.

The Minos experiment[6] observed the Sun shadow centered on $-0.29 \pm 0.13°$ in ra and $0.27 \pm 0.14°$ in declination. They don't observe significative variations of the Sun's shadow in the years 2003-2008, during this period the Tibet observed a variation in deficit from $\simeq -3\%$ to $\simeq -4\%$.

The Argo experiment[10] located in Tibet, having a median energy of 5 TeV, has found pattern similar to the one of the Tibet experiment during the years 2008-2010.

3.2. Sun: Multiple Muons

Finally I have studied the Sun shadow in events with at lest two muons. The shadow is show in Fig 9. The parameter p1 (angular resolution) is fixed to 0.5. The deficit is 17.8 ± 12 events corresponding to $3.1 \pm 2.1 \times 10^{-3}$ tracks respect the number of tracks in a cone of 5° around the Sun. This is compatible with the value of the single muons. The fit with the parameter p1 free gives similar results.

4. Compton Getting effect

The Compton Getting effect is a modulation effect of cosmic rays due to the motion of the Earth in the cosmic ray reference system. If the cosmic ray reference system is the one of the Sun, we expect a variation:

$$\frac{\Delta(I(\theta)}{I(\theta)} = (2+\gamma)\frac{v}{c}cos(\theta) \tag{3}$$

where γ is the spectral index of the cosmic ray energy distribution $E^{-\gamma}$, θ is the angle between the track and the velocity of the Earth respect to a

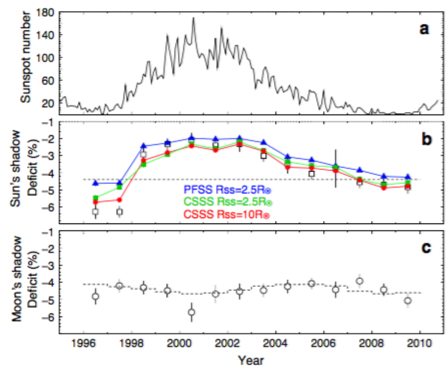

FIG. 3. Temporal variations of (a) the monthly mean sunspot number [24], (b) the deficit intensity due to the Sun's shadow, and (c) the deficit intensity due to the Moon's shadow. The open squares in the panel (b) are the observed central deficit (D_{obs}). The blue triangles, green squares, and red circles indicate the central deficits (D_{MC}) by the MC simulations assuming the PFSS ($R_{\mathrm{ss}} = 2.5R_{\odot}$), the CSSS ($R_{\mathrm{ss}} = 2.5R_{\odot}$), and the CSSS ($R_{\mathrm{ss}} = 10.0R_{\odot}$) models, respectively. The dashed lines in the panels (b) and (c) are the deficits expected from the apparent angular size of the Sun and the Moon.

Figure 7: Sun and Moon : Results of the Tibet experiment. The deficit is defined as $(N_{observed} - N_{expected})/N_{expected})$ in a bin of $0.1°$ centered around the Sun. Note that with this definition the deficit depends from the angular resolution. For example using the same definition in MACRO we have for all the period a deficit of the order of 21% due to the better angular resolution

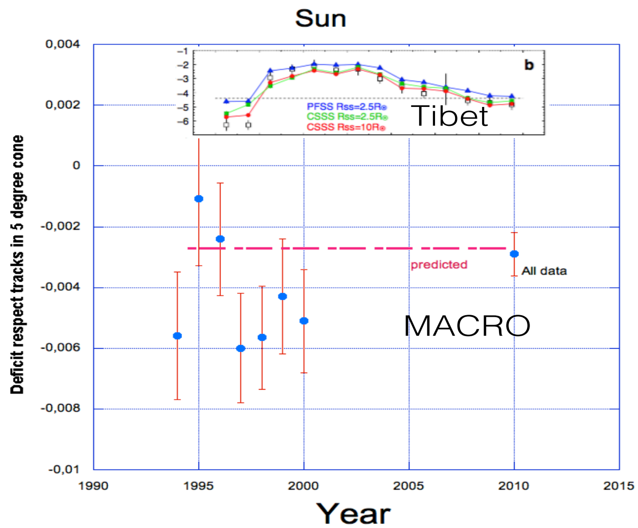

Figure 8: Sun: Results of the MACRO experiment compared with the Tibet results. For MACRO on the y axis there is the total deficit normalised to the number of events in a 5 degree cone. The MACRO deficit has an almost flat behaviour.

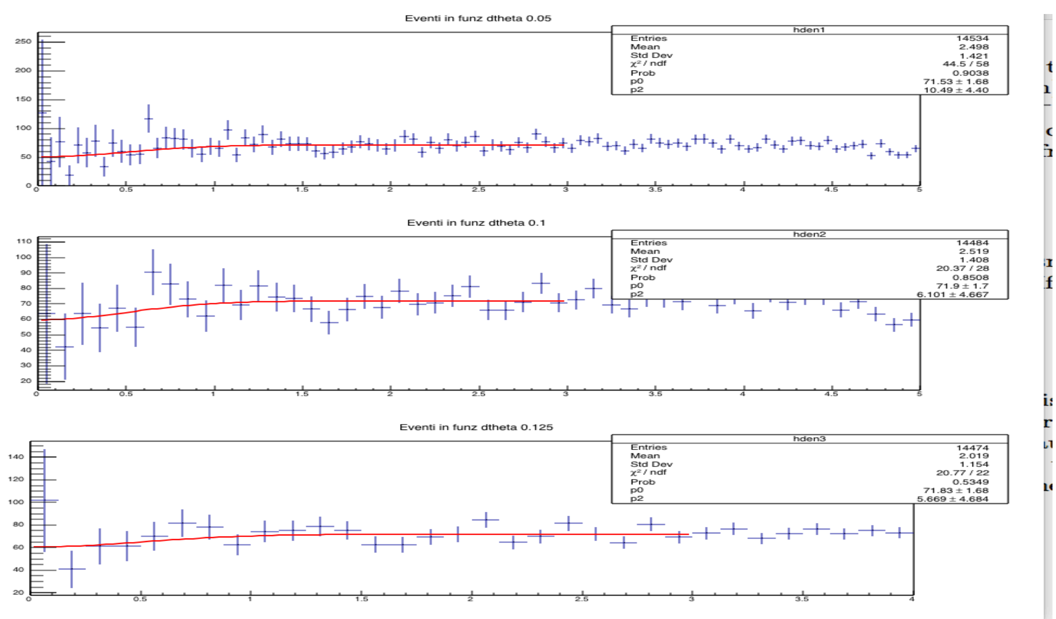

Figure 9: Sun: Multiple muon tracks as function of the angle from the moon weighted with angular area for three different bin sizes. The angular resolution is fixed at 0.5°

system with the Sun fixed[14][15]. A factor $(\gamma - 1)v/c$ is because the Doppler shift of the energy spectrum changes the number of particles that exceed the detector's energy threshold, while a factor $v/c/$ comes form the Doppler effect and another factor $2v/c$ comes form the solid angle transformation. Inmost of the older results the angle θ was the angle of the peak detector sensitivity. For a detector located at latitude λ and with a peak sensitivity in the vertical direction we expect a amplitude modulation in solar time (the solar dipole anisotropy):

$$4.7 \times 10^{-4} cos\lambda \; cos^2(i/2) \tag{4}$$

where i is the inclination of the Earth axis. The peak should be around 6 h in the local solar time, when the detector is sensitive in a direction most nearly parallel to the earths orbital velocity. Using this relation with the Gran Sasso latitude the predicted amplitude of the Solar Compton Getting is 3.4×10^{-4}.

In a more exact way the Compton Getting effect is due to the Earth rotation around the Sun with a speed of $29.8km/s$. In vectorial form the Compton-Getting effect is given at time t from

$$\delta_x = (2+\gamma)\frac{v_{x\ orb}}{c}(-sin^2(i/2)\ sin(2\omega_{orb}t)) \tag{5}$$

$$\delta_y = (2+\gamma)\frac{v_{y\ orb}}{c}(cos^2(i/2) - sin^2(i/2)cos(2\omega_{orb}t)) \tag{6}$$

$$\delta_z = (2+\gamma)\frac{v_{z\ orb}}{c} sin(i)cos(\omega_{orb}t) \tag{7}$$

where the $\delta_{\mathbf{SCG}} = (2+\gamma)\frac{\mathbf{v_{orb}}}{\mathbf{c}}$ is a vector having as direction the muon track (or the direction of the peak sensitivity) and an amplitude 4.7×10^{-4} and $\omega_{orb}t$ is the period of Earth rotation. Integrating over one day only the y component remain.

The cosmic ray reference frame could be a frame in wich the Sun moves. The Sun rotate around the galactic center with a speed of $220km/s$ pointing into galactic longitude 270° and galactic latitude 0°. So a sidereal anisotropy could generate from this motion. The amplitude should be 2.4×10^{-3} much larger than the solar. Experimental of the sidereal anisotropy data are in disagreement with this value. However the interpretation of sidereal anisotropy is complicated from the fact that in addition to the Compton Getting effect we have effects due to the Sun magnetic field and small angle anisotropy (see next paragraph).

Untile recent years the search for the Solar Compton Getting effect was based on measurement of rates as function of time. Cutler and Groom [14] have found a solar modulation with amplitude $2.47^{0.72}_{0.55} \times 10^{-4}$ and a peak at $8:18 \pm 1$ local solar time. This was considered the first evidence of the Compton-Getting modulation. But in the paper there was no correction for diurnal temperature effect.

In the paper the authors estimated that the observed modulation could be compatible with a temperature modulation of $0.07K^\circ$ with a peak at 15:00 local time. They exclude this temperature effect, because of the phase and of the amplitude, But I think that this statement was wrong.

In the following years several experiments have observed this effect with a very large statistical evidence using gamma ray telescopes[16, 17, 18]. But only

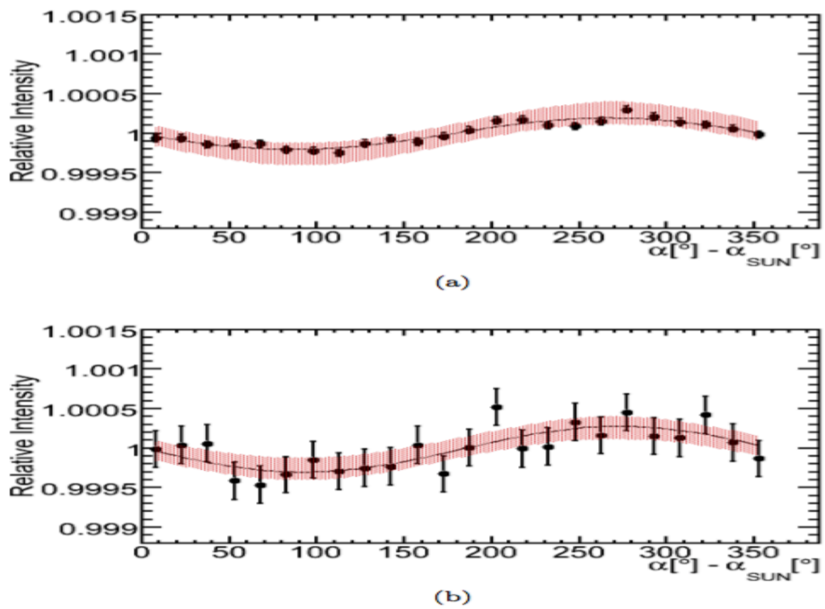

Fig. 9.— Figure (a) shows the one-dimensional projection in right ascension from the sun ($\alpha - \alpha_{sun}$) of the first energy band (20 TeV) of two-dimensional cosmic ray map in Figure 8-a. Figure (b) shows the one-dimensional projection in right ascension from the sun ($\alpha - \alpha_{sun}$) of the second energy band (400 TeV) of two-dimensional cosmic ray map in Figure 8-b. The data are shown with statistical uncertainties, and the black line corresponds to the first and second harmonic fit to the data.

Figure 10: Solar Compton Getting in Icecube

a few experiments have searched using muons. Muons and gamma rays could have different systematics, and therefore this search could be of some interest.

MACRO in the paper[19] looked to a Solar Compton Getting effect using the muon rate method in solar time. The result from the fit gives a peak at 17.8 ± 1.2hr and amplitude $0.88 \pm 0.26 \times 10^{-3}$ clearly incompatible with the Solar Compton Getting. In the paper data where compared to the variation of atmospheric temperature and the conclusion was that there was a strong evidence of an effect due to the temperature. The results presented in this paper were based on the rate measurement and computing prediction based on the direction of the peak sensitivity, however the spread in the track direction is large and with a complicated shape due to the rock of the mountain. A similar analysis was done by SuperKamiokande[22] and no evidence for a peak of the rate at 6h solar time was found.

I have repeated the same analysis and I have found the peak at 17 ± 1.6hr and the amplitude $1.46 \pm 0.26 \times 10^{-3}$. It his interesting to note that doing the same solar time analysis for multiple muons with large separation (bigger then 10m) the amplitude is $7.5 \pm 2.9 \times 10^{-3}$ and the peak at 20 ± 1.5 h, the fact that this amplitude is larger than in the single muon case is a strong indication for a diurnal atmospheric temperature effect, because the same increase was observed in the seasonal temperature analysis [21]. The temperature are given in the ref [23] every 6 hours. A rough fit the the average values of temperature in function of the solar time gives the maximum at 17.5 h with an amplitude of 0.14 $K\circ$. Assuming a value of $\alpha_T = 1$ [21] we expect a diurnal modulation of single muon a factor 2 smaller than the one found. So the conclusion is that a temperature diurnal component should be present.

A better way to analyse data would to use directly the track direction. This has been done for the first time from Icecube [22]. The result is in Fig 10

So I have done a similar analysis in MACRO plotting the differences between the right ascension of the track and the one of the Sun, results are in Fig 11. The predicted value of the Solar Compton Getting effect is: peak at 270° and first harmonic amplitude $= 3.7 \times 10^{-4}$ confirming the rough value of Eq4. The difference respect to the expected peak at 270° is due the the mountain profile. The previous values have been obtained computing the effect for each track direction and time.

Fig 11 shows data subtracted from the Montecarlo prediction. The Montecarlo uses data assigning to a track the time of another random track and simulate a run time 100 times the real data taking. The result of Fig 11 is that the phase is not consistent with the predicted value of the Compton Getting effect.

One possibility to explain this result is that this plot is modified from the seasonal and daily variations due to the temperature. In fact taking into account in the Montecarlo a seasonal temperature effect of amplitude 1.7% with peak at the day 180.3 and a diurnal variation with amplitude 0.065% and peak at 17 local time, as suggested from the daily temperature variations. The results is in Fig 12. The fit is in agreement with the Compton Getting in the solar reference system. But of course this result depends strongly from the correction of the

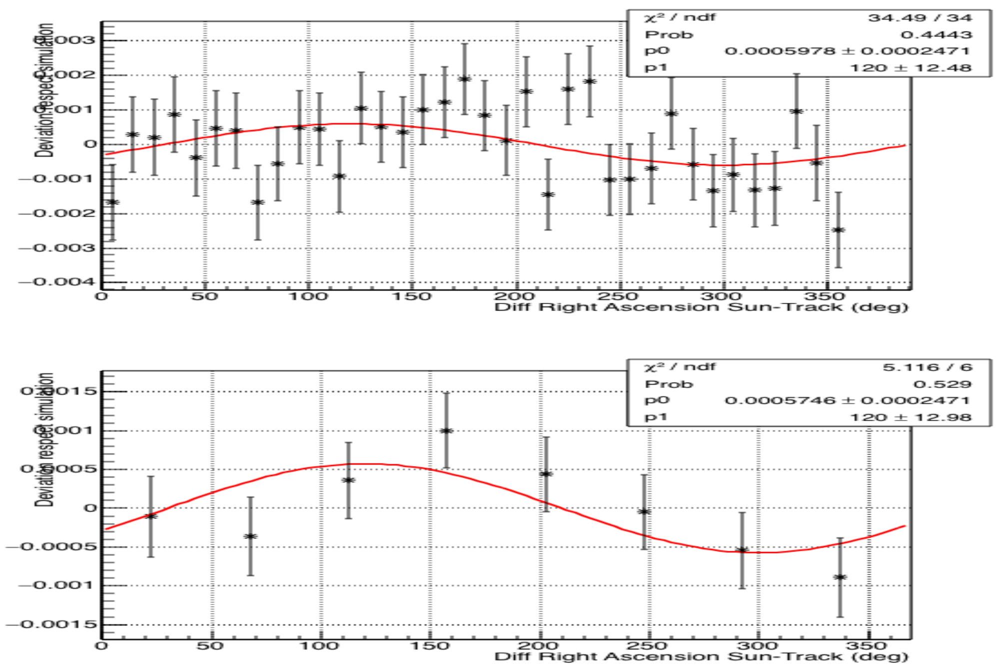

Figure 11: MACRO Compton-Getting: difference between right ascension of the Sun and of the track. Data are subtracted from the montecarlo prediction. The montecarlo uses data assigning to a track the time of another random track

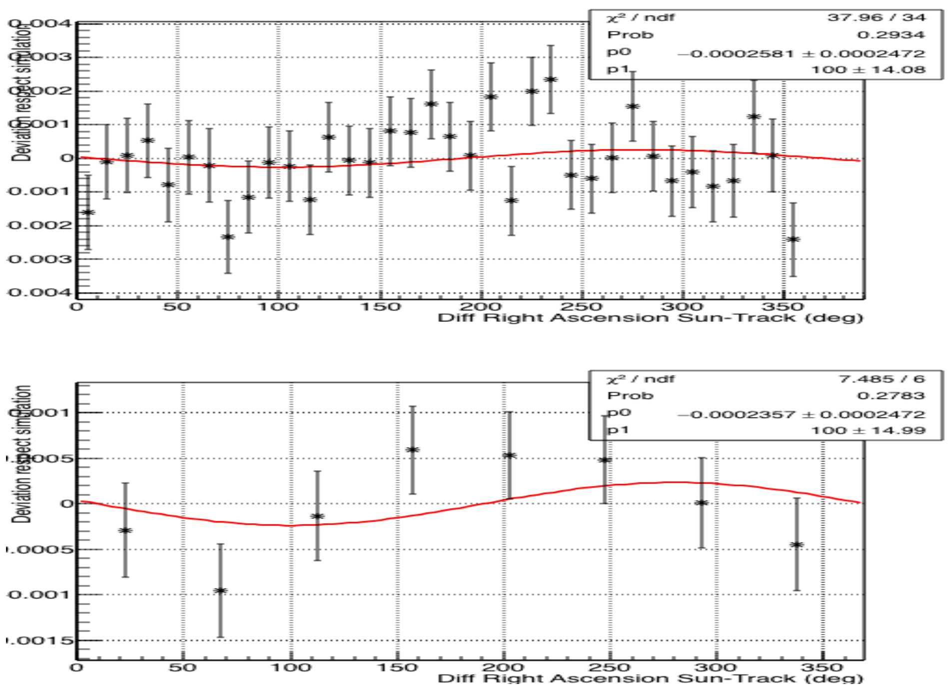

Figure 12: MACRO Compton-Getting: difference between right ascension of the Sun and of the track. Data are subtracted from the montecarlo prediction. The montecarlo uses data assigning to a track the time of another random track and a weight is assigned to take into account a seasonal modulation of amplitude 1.7% with peak at the day 180.3 and a diurnal variation with amplitude 0.065% and peak at 17 local time, as suggested from the daily temperature variations. The fit is in agreement with the Compton Getting in the solar reference system

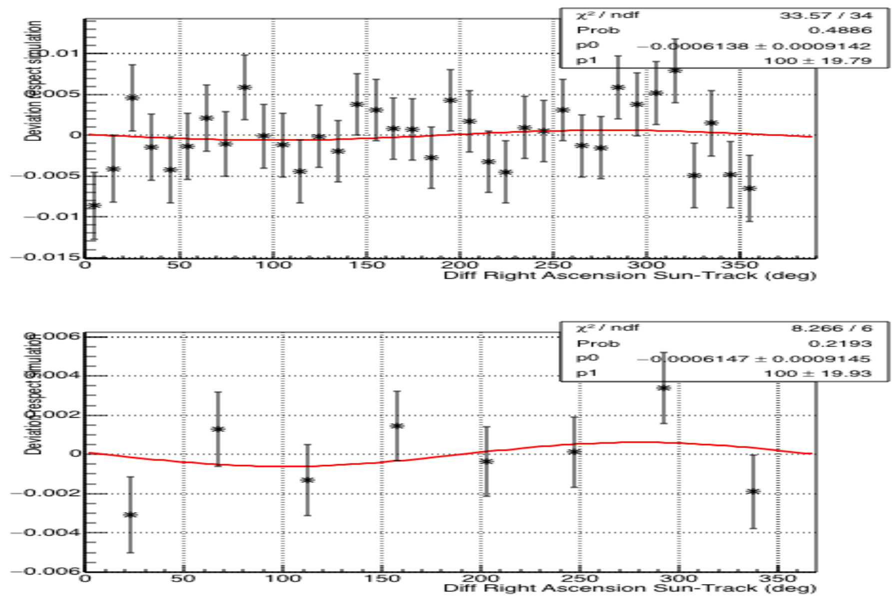

Figure 13: MACRO Compton-Getting: difference between right ascension of the Sun and of the track, for events with at least two track. Data are subtracted from the montecarlo prediction. The montecarlo uses data assigning to a track the time of another random track and a weight is assigned to take into account a seasonal modulation of amplitude 2.2% with peak at the day 180.3 and a diurnal variation with amplitude 0.084% and peak at 17 local time

atmospheric temperature variations

Finally Fig 13 shows the result for events having at least 2 muons. The statistical evidence in this case is even lower than the one for single muons, but the result of the fit is in agreement with the Compton-Getting.

5. Sidereal Anisotropy

5.1. Sidereal Anysotropy in single muon events

The sidereal anisotropy was studied in the 2002 MACRO paper[19] looking to the data rate as function of the sidereal time. The result was that an anisotropy was found with amplitude $8.2 \pm 2.77 \times 10^{-4}$ and the peak at 23.2 ± 1.3 local sidereal hour. The likelihood ratio of a a fit with a sinusoid respect to a flat distribution was 8.5. After 2002 many experiment have done similar analysis. A summary is in ref[15], see Fig. 14 . Moreover in recent years many experiments have found anomalies in small angular regions, see Fig. 15 and experiments are looking to sky maps having more information than a simple plot in sidereal time.

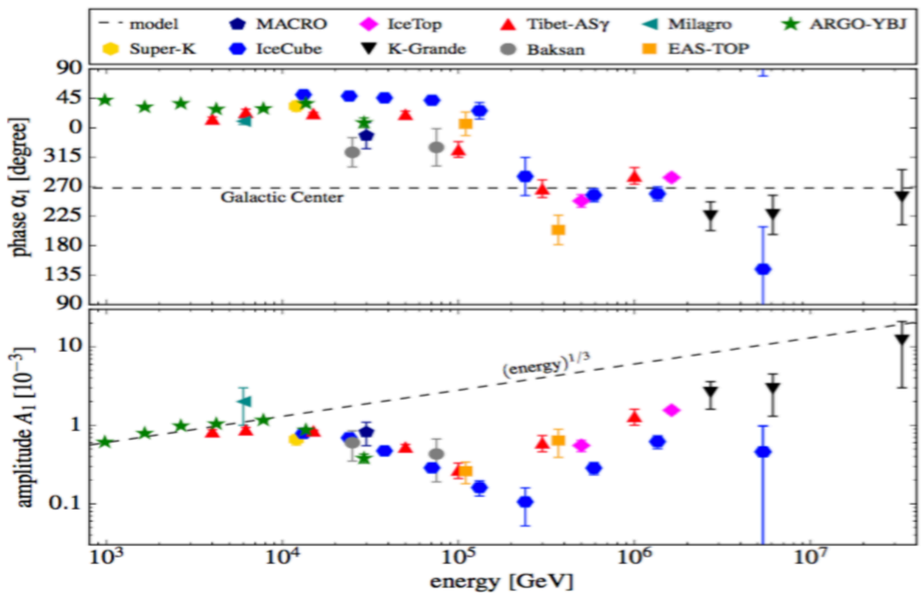

Figure 14: (Figure from ref [15]). Note that different experiment have different acceptance in declination; therefore the sidereal anisotropy could be different for example in experiment located in the North and experiment located in the South hemisphere

In this new analysis of the MACRO data therefore I use the track information looking therefore to the distribution in right ascension and declination as in Fig. 15 . and correcting data for the seasonal and daily temperature modulation. Fig. 16 shows the distribution of the declination of the single muon tracks. The acceptance extend to negative declinations, but is less than 0.5% for declinations $\leq -30^0$. Fig. 17 shows the difference between data and the Montecarlo simulation with 100 more statistics in units of standard deviation for declination $\geq -30^0$. On the x axis is the right ascension in 20° bin, on the y axis is the declination in 10° bin. it' is interesting to note that the "blue" region the one with deficit with more than 2 standard deviations are at RA of about 200° as is the plot in Fig. 14 Fig. 18 shows the projection on the x axis of Fig. 17 . The result of a fit with a sinusoid gives amplitude $=5.5 \pm 2.4 \times 10^{-4}$ and peak at $350 \pm 24°$. This result is in agreement with the points shown in Fig. 14

Fig. 19 is similar to Fig.17 but with the atmospheric seasonal temperature (annual and diurnal) effect included in the Montecarlo. The main features of this figure are similar to the one of Fig.17 and Fig.15 . Fig. 20 is similar to Fig.18 but with the atmospheric seasonal temperature effect included in the Montecarlo.The result of a fit with a sinusoid gives amplitude $=3.9 \pm 2.4 \times 10^{-4}$ and peak at $25 \pm 34°$, compatible with the one of Fig.18 but smaller than the $8.2 \pm 2.77 \times 10^{-4}$ value published by MACRO in 2002 [19].

Of course the sidereal anisotropy obtained projecting data on the RA axis is a

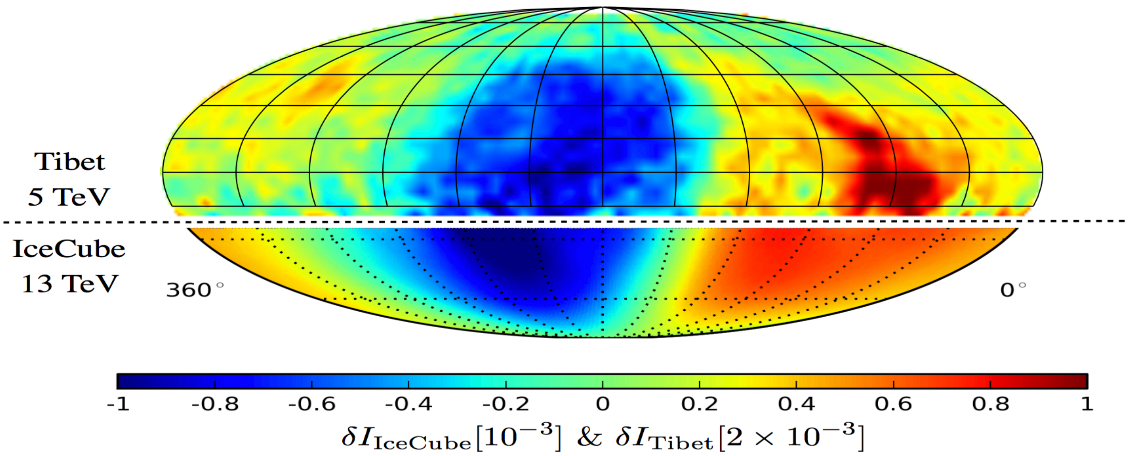

Figure 15: Combined CR anisotropy of Tibet-ASγ (units 2×10^{-3} and IceCube in the equatorial coordinate system. Note that the anisotropy map of IceCube is smoothed with a top-hat kernel with radius of 10° , which explains the absence of smaller features visible in the Tibet map. Figure from ref [15]

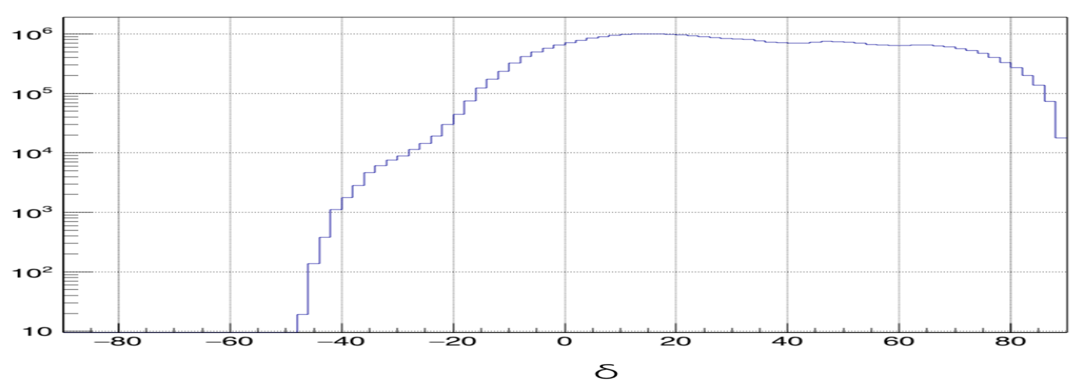

Figure 16: Distribution in declination of the single muon tracks

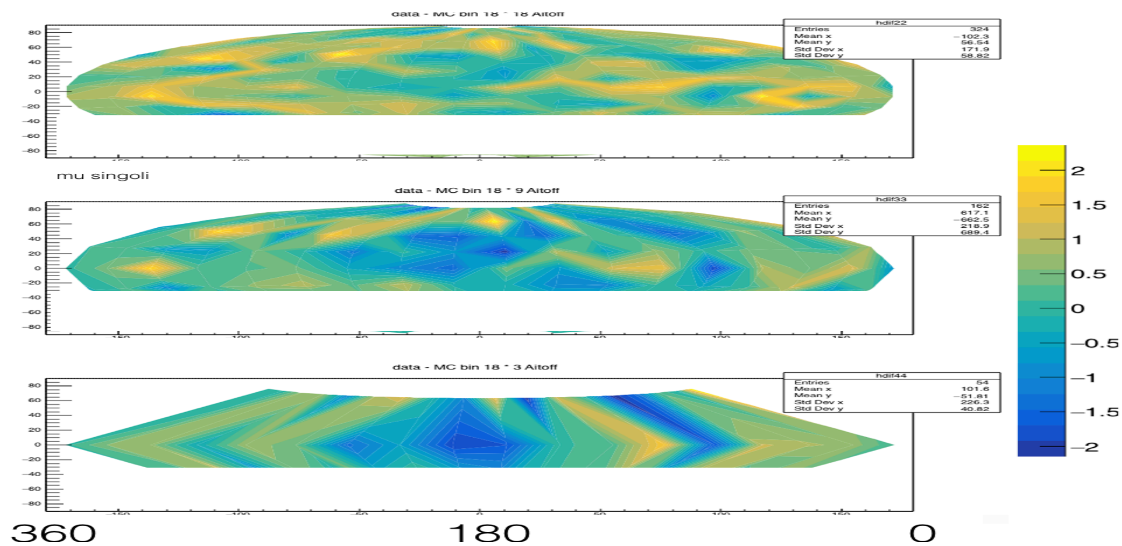

Figure 17: MACRO sidereal anisotropy: Difference between data and the Montecarlo simulation with 100 more statistics in units of standard deviation. On the x axis is the right ascension in 20° bin, on the y axis is the declination in 10°,20°,30° bin (from the top), The smoothing from the root package is applied. The main features of this figure are similar to the one of Fig.15

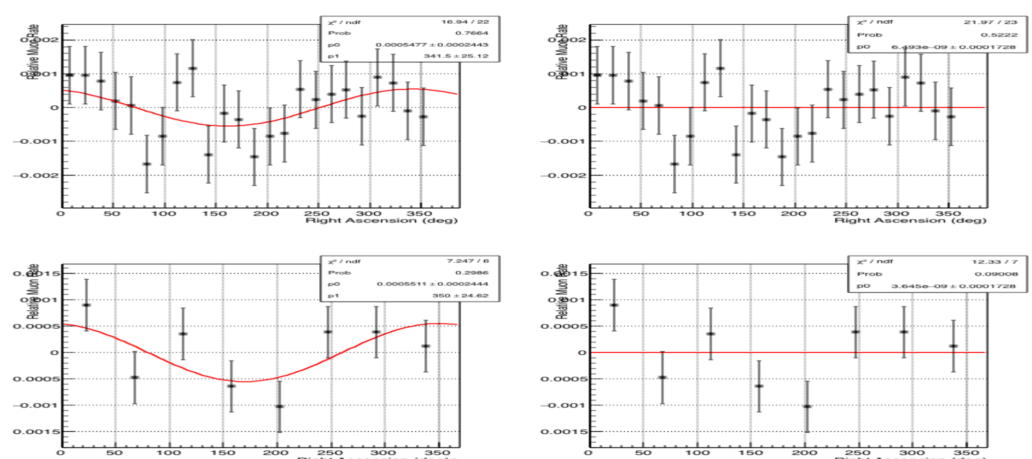

Figure 18: MACRO sidereal anisotropy: Fractional difference between right ascension of data and the Montecarlo simulation with 100 more statistics. The result of a fit with a sinusoid gives amplitude $=5.5 \pm 2.4 \times 10^{-4}$ and peak at $350 \pm 24°$

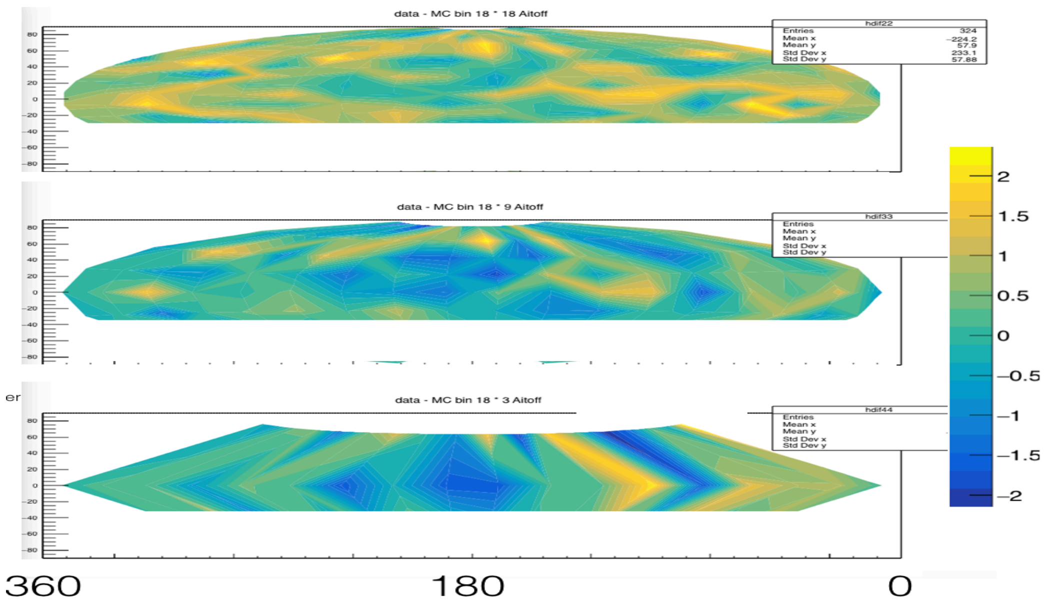

Figure 19: MACRO sidereal anisotropy: similar to Fig.17 but with the atmospheric seasonal temperature effect included in the Montecarlo. On the x axis is the right ascension in 20° bin, on the y axis is the declination in 10°,20°,30° bin (from the top), The smoothing from the root package is applied. The main features of this figure are similar to the one of Fig.15

crude approximation done for historical reasons. The bi-dimensional anisotropy has more complicated pattern dependent from the declination and from the energy.

5.2. Sidereal Anisotropy in events with at least two muons

The average energy in the two muons events is higher than the one in the single muons. This is because both muons should have enough energy to cross the rock. Also the primary composition is different. This means that the primary charge is different. The propagation through the galactic magnetic fields could therefore be different. So could be interesting to look to events with at least two muons.

The result is in Fig.21. The main features of this figure are similar to the one of Fig.15 and Fig.18 but the fluctuations are larger. The most interesting fluctuation has more than 3σ around $\delta = 10°$ and $RA = 70°$ where is the hottest spot of the Tibet experiment. The fractional excess is about 1.4%, higher than the one in the Tibet experiment. There is another large fluctuations at $\delta = -40°$ and $RA = 250°$ of about 3σ but the MACRO acceptance is very low in this region and some systematic effect could be present. This fluctuation is not shown in Fig.21 due to the low value of $\delta = -40°$.

The fit on the RA distribution Fig.22 gives amplitude $1.7 \pm 0.9 \times 10^{-3}$ and peak at $47° \pm 30°$. An increase in the amplitude with energy is expected by

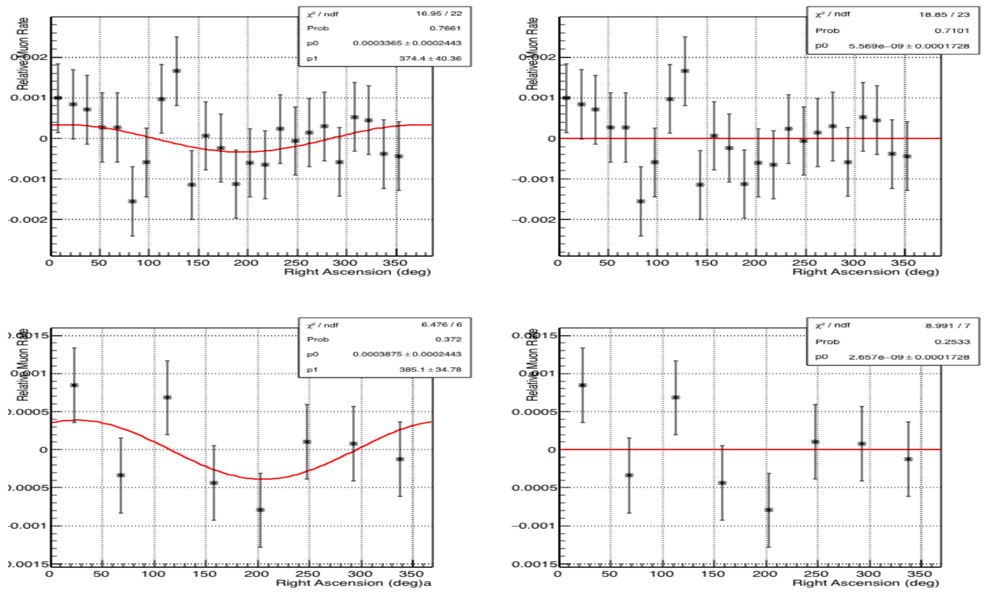

Figure 20: Similar to Fig.18 but with the atmospheric seasonal temperature effect included in the Montecarlo. The result of a fit with a sinusoid gives amplitude $=3.9 \pm 2.4 \times 10^{-4}$ and peak at $25 \pm 34°$

simple models of isotropic diffusion, but the MACRO statistical error is too large to conclude anything.

Adding the single muon data and the multiple muons the amplitude becomes $4.7 \pm 2.3 \times 10^{-4}$ and the peak is at $-6° \pm 28°$.

5.3. Sidereal anisotropy discussion

The sidereal anisotropy could be due to several effects:

1) Compton Getting if the rest frame is one fixed with the Galactic center in wish the Sun moves at velocity 220 km/s. The observable Compton Getting effect after projection onto the equatorial plane would be 2.4×10^{-3} therefore much larger than the one observed in MACRO and many other experiments, independent of energy, The peak should be at RA=138° and declination=$-48°$, therefore inconsistent with the data. Other possibilities with a much smaller amplitude are discussed in ref. [15].

2) Magnetic fields are important in the cosmic ray propagation. A strong experimental evidence for this relevance is reported by several experiments in the study of the Sun shadow. However no variation of sidereal anisotropy as function of has been found by the Tibet experiment ref. [15]. This means that at TeV energies the Sun magnetic field variation should not be important, however they could modify the small angle spots at TeV energies [24]. The large scale anisotropy could be explained by a magnetic field of the order of 5×10^{-6} and an extension of the Sun magnetosphere up to 4400 AU[24]. Other

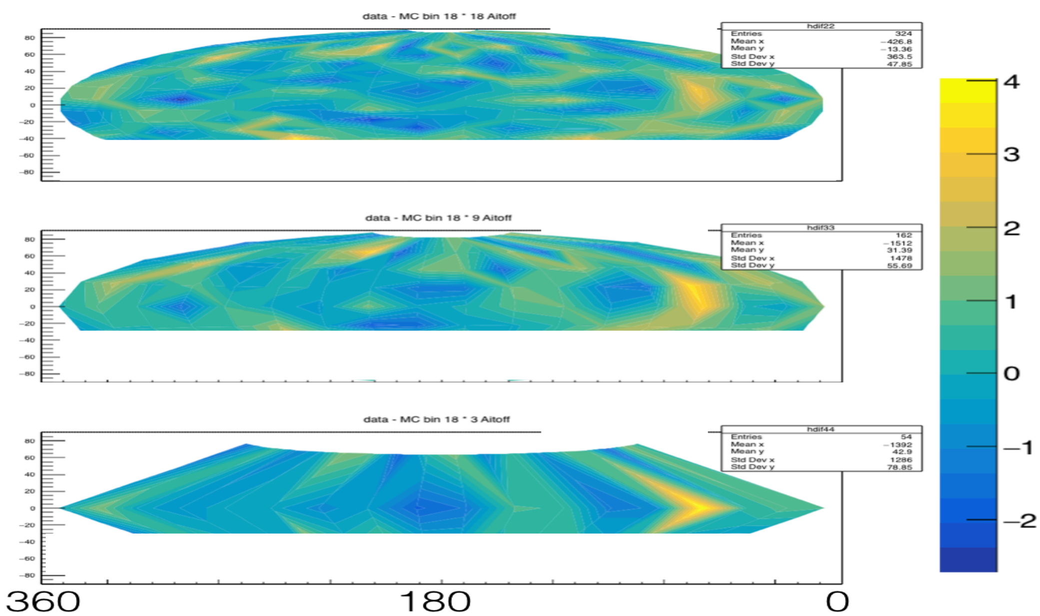

Figure 21: MACRO sidereal anisotropi with two or more tracks:. . The main features of this figure are similar to the one of Fig.19 but the fluctuations are larger. The most interesting is of more than 3σ around $\delta = 10°$ and $RA = 70°$ where is the hottest spot of the Tibet experiment. The fractional excess is about 1.4%, higher than the one in the Tibet experiment. There is another large fluctuations at $\delta = -40°$ and $RA = 250°$ but the MACRO acceptance is very low in this region and some systematic effect could be present.

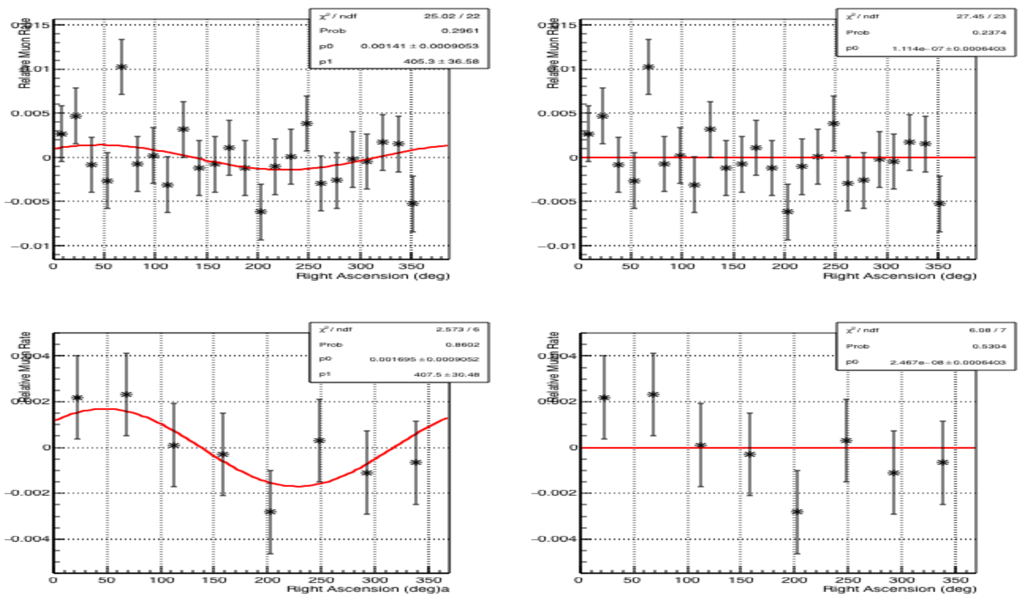

Figure 22: MACRO sidereal anisotropi with two or more tracks: Similar to Fig.20 for single muons. The fit on the RA distribution gives amplitude $1.7 \pm 0.9 \times 10^{-3}$ much higher than the one for signle muons and peak at $47° \pm 30°$.

authors suggest that both large and small scale anisotropies could be explained by galactic turbulent magnetic fields[25].

6. Conclusions and Acknowledgements

Here are the main results of this new analysis compared to the past MACRO result.

1) Sun and Moon deficit: the main result of this analysis is that the Sun's deficit doesn't depend from the year in the years 1995-2000 (and therefore from the number of Sun's spot). This result is in contrast to the Tibet result and needed to be investigated.

2) Solar Compton Getting: in the past analysis was found a modulation of the total rate with a wrong phase. In this new analysis I have used the the right ascension distributions of tracks and a correction for the atmospheric temperature variations. Now the modulation is in agreement, both in amplitude and phase, with the expected signal.

3) Sidereal anisotropy: in the past analysis was studied the modulation of the total rate. In this new analysis I have used the the right ascension and distributions of tracks and a correction for the atmospheric temperature variations. I have found a smaller sidereal anisotropy and a sky map in right ascension and declination with structures in agreement with the one of other experiments having the same threshold energy, of course with much smaller

statistics. Recent studies have shown the importance of the magnetic fields in explaining the sidereal anisotropy and the small angle structures [24] [25]. In addition to the magnetici filed effects contribution from Vela have been takn into account[26]

I gladly acknowledge precious help from Alessandro Paoloni for many useful discussions. I should also thanks all the peoples of the MACRO experiments that contribute to the construction, data collection and data analysis. A full list id in [2].

This work shows that a new analysis of data of past experiment could be very useful and that a particular attention should be given to save data and analysis programs of old experiment. ...

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