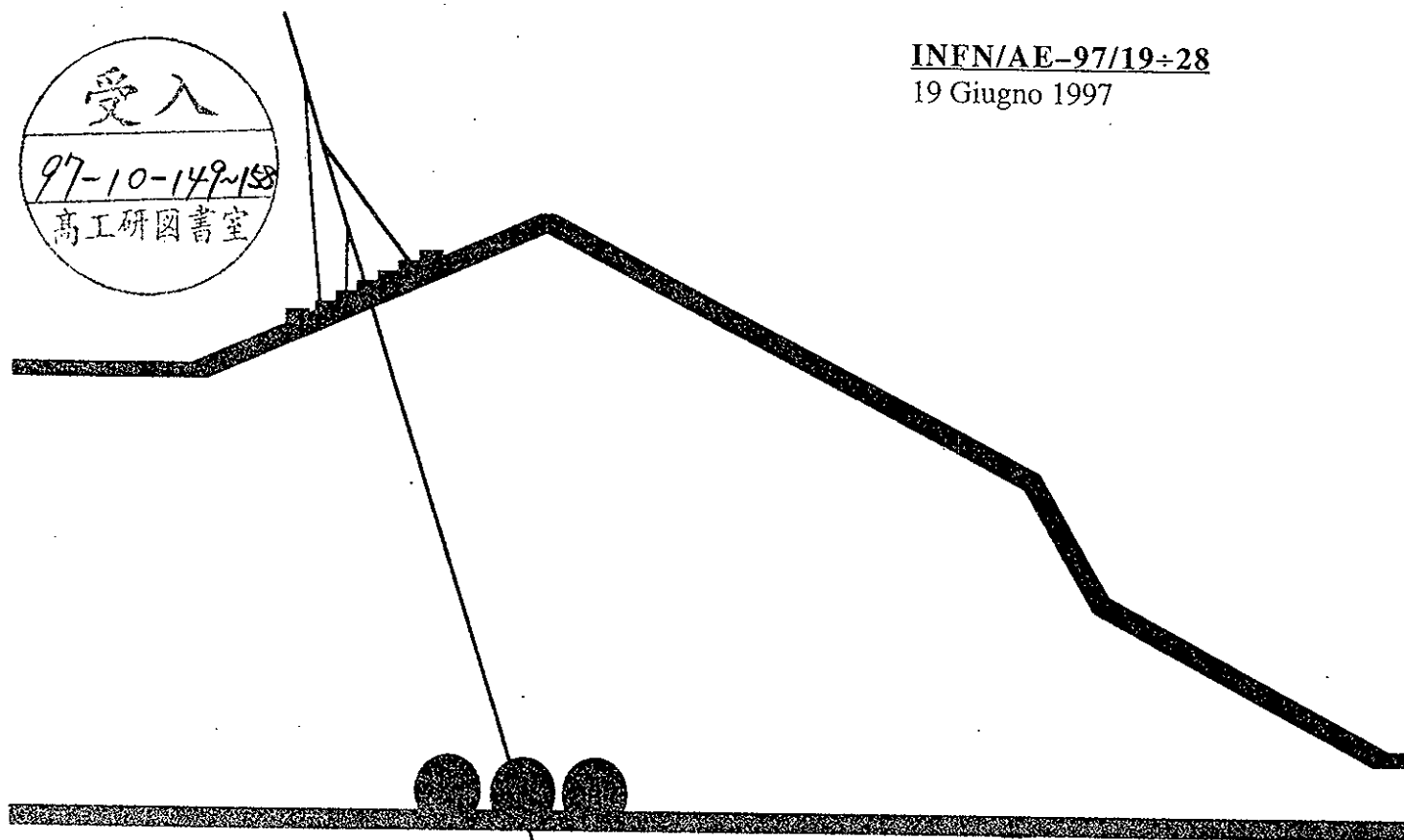




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Contributions of the MACRO Collaboration to the 1997 Summer Conferences

INFN – Laboratori Nazionali del Gran Sasso

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INDIRECT SEARCH FOR WIMPS WITH THE MACRO DETECTOR

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ABSTRACT

High energy neutrinos have been indirectly measured as upward-going muons in the MACRO detector using the time-of-flight technique. No statistically significant excess from the direction of the Earth and of the Sun have been found comparing the 364 measured upgoing muons to the expected background due to atmospheric neutrinos. Muon flux limits are given in arbitrary search cones and as a function of the neutralino mass.

INTRODUCTION

There are enough hints to suggest the existence in our Universe of a non-baryonic dark matter such as the *Weakly Interacting Massive Particles*. The luminous matter in galaxies, in fact, contributes less than 1% to the overall density of the Universe. Considerations on the structure formation and limits on the baryonic content of the Universe from Big Bang nucleosynthesis together with the aesthetical $\Omega = 1$ from inflationary theories have led to a wide list of Cold Dark Matter candidates (Jungman et al., 1996). Among them the most promising one is the neutralino, which is the Lightest Supersymmetric Particle in large regions of the supersymmetric space of parameters. In the Minimal Supersymmetric Standard Model the four neutralino mass states $\tilde{\chi}_i^0$ are linear superpositions of gaugino and Higgsino eigenstates. Their masses depend on the gauge fermion masses at the electroweak scale M_1 and M_2 , on the Higgsino mass parameter μ and on the ratio of the Higgs doublet vacuum expectation values $\tan \beta$.

The lower limit on neutralino mass $m_{\tilde{\chi}}$ resulting from combined LEP 1 ($\sqrt{s} \sim M_Z$) and LEP 1.5 ($\sqrt{s} = 130 - 136$ GeV) data, although model dependent and connected with the limits from chargino searches, exclude a lightest neutralino with mass less than $12.8 \text{ GeV}/c^2$. This limit rises to $34.1 \text{ GeV}/c^2$ for large $\tan \beta$ values when the sneutrino mass is greater than $200 \text{ GeV}/c^2$ (Buskulic et al., 1996). Moreover, combining the cosmological constraint on $\Omega_{\tilde{\chi}} h^2$ with the assumption of radiative electroweak symmetry breaking strengthens the lower limit in the case of $\mu < 0$ to 21.4 GeV for low $\tan \beta$ and to 51 GeV for $\tan \beta > 5$; in the case of $\mu > 0$ to $m_{\tilde{\chi}} > 56 \text{ GeV}$ for $\tan \beta < 3$ and $m_{\tilde{\chi}} > 36 \text{ GeV}$ for $\tan \beta < 3$ (for large sneutrino masses) (Ellis et al., 1996).

In this picture, the direct and indirect methods of detection mainly performed in underground detectors can probe complementary regions of the supersymmetric parameter space even when LEP 2 results will be available. Direct methods employ low-background detectors (e.g. semiconductors or scintillators) to measure the energy deposited when a WIMP elastically scatters from a nucleus therein. On the other hand, there are good prospects for indirect detection of neutralinos due to high energy ν radiation from WIMP annihilation in the core of the Earth and of the Sun.

THE INDIRECT SEARCH: THE MEASUREMENT OF UPGOING MUONS IN MACRO

Halo WIMPs can lose enough energy to become gravitationally trapped in the core of celestial bodies through elastic scattering in the nuclei therein. While their density builds up inside the body, their annihilation rate increases until equilibrium is achieved between capture and annihilation. High energy neutrinos are eventually produced via the hadronization and/or decay of the annihilation products (mostly fermion-antifermion pairs, weak and Higgs bosons) and can be detected as upward-going muons in underground detectors. The more the upgoing muon follows the parent direction, i. e. the higher the WIMP mass, the better the signal to noise ratio. The signal from WIMP annihilation should

be discriminated as a statistically significant excess of events in the direction of the Sun or of the Earth among the background of atmospheric neutrino induced upgoing muons. Data on upward muons from the core of the Earth and of the Sun have been measured by several experiments, notably Baksan (Boliev et al., 1996), MACRO (Ambrosio et al., 1996), Kamiokande (Mori et al., 1993), IMB (Losecco et al., 1987) and Frejus (Arpesella et al., 1988).

The MACRO detector (Ahlen et al., 1993), located in the INFN Gran Sasso Laboratory, measures upgoing muons using a system of streamer tubes for tracking (angular resolution $\sim 0.5^\circ$) and liquid scintillator counters for fast timing (time resolution ~ 500 psec) with overall dimensions of $12 \text{ m} \times 77 \text{ m} \times 9 \text{ m}$. The bottom part of the apparatus is filled with rock absorber which sets a minimum threshold of about 1 GeV for vertical muons crossing the detector. Roughly 16 million muons from about 1.4 yr of running with 1/6 of the lower detector (Mar. '89 - Nov. '91) combined with 6 months of running of the lower detector (Dec. '92 - Jun. '93) and with 2 yr of running of the full detector (Mar. '94 - Nov. '96) have been analyzed looking for upward-going muons. The results of the lower detector upgoing muon analysis have been published (Ahlen et al., 1995) and updated (Ambrosio et al., 1997).

THE SEARCH FOR A WIMP SIGNAL FROM THE EARTH AND THE SUN

We use the sample of 364 events selected in the upgoing muon analysis (Ambrosio et al., 1997).

The background to an astrophysical source of neutrinos is due to atmospheric neutrinos. We have evaluated this background using a Monte Carlo calculation we described previously (Ahlen et al., 1995).

In the case of the Sun, the times from real downgoing muons measured during data taking have been given randomly to the simulated events to evaluate their right ascension, hence taking into account drifts of detection efficiency in time. Fig. 1 shows the angular distribution of the upgoing muon events with respect to the direction of the Sun compared to the expected one from atmospheric neutrinos. The simulated distribution has been normalized by a factor of 0.765, the ratio of the events detected and expected outside the region interesting for the signal (30° from the direction of the Sun). The shape of this distribution depends on the seasonal variation of the position of the Sun with respect to the apparatus and on the livetime of the apparatus.

The exposure of the Sun has been calculated as:

$$\text{exposure} = \int_{T_{\text{start}}}^{T_{\text{end}}} \epsilon \times A(\Omega(t)) dt \quad (1)$$

where $A(\Omega(t))$ is the detector area in the direction Ω of the Sun at time t (set to zero when the Sun is below the horizon), ϵ is the detector efficiency, T_{start} and T_{end} are the beginning and the end times of the data taking. Tab. 1 shows the number of events detected and expected inside 6 arbitrary cones around the direction of the vertical of the apparatus and of the Sun. The 2 GeV threshold energy for the Sun corresponds to the value at which the area of the apparatus seen by the Sun becomes independent of energy. In the case of the Earth the threshold energy is 1.5 GeV because tracks are less slanted.

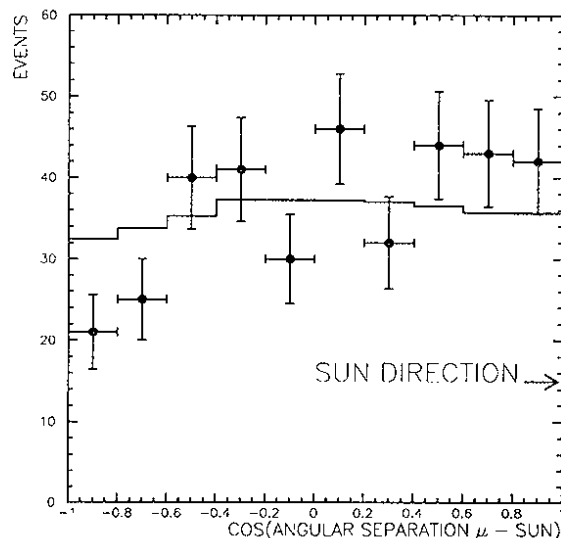


Fig. 1: Distribution of the cosine of the angular separation of upgoing muon events and the Sun position for the data and the normalized simulation.

Due to the deficit of the measured events with respect to the predicted upgoing events induced by the atmospheric neutrino background near the vertical of the apparatus (Ambrosio et al., 1997), we give conservative flux limits for the Earth assuming that the number of events measured equals the number of events expected (Barnett et al., 1996).

Table 1: Selected and expected events and 90% C.L. muon flux limits for 6 cones around the Earth and Sun directions.

EARTH				SUN		
Cone	Data	Background	Flux Limit ($E_\mu > 1.5\text{GeV}$) ($\text{cm}^{-2}\text{s}^{-1}$) Exp. = $1900\text{ m}^2\text{yr}$	Data	Background	Flux Limit ($E_\mu > 2\text{GeV}$) ($\text{cm}^{-2}\text{s}^{-1}$) Exp. = $480\text{ m}^2\text{yr}$
30°	48	87.2	2.67×10^{-14}	30	23.9	9.74×10^{-14}
25°	36	61.9	2.14×10^{-14}	18	16.7	6.04×10^{-14}
20°	23	40.2	1.72×10^{-14}	12	10.4	5.35×10^{-14}
15°	16	22.7	1.44×10^{-14}	3	6.0	2.30×10^{-14}
10°	7	10.2	1.08×10^{-14}	1	2.6	1.91×10^{-14}
5°	1	2.7	5.98×10^{-15}	1	0.7	2.26×10^{-14}

Flux limits from the study of the angular distributions

The signal of upgoing muons produced by WIMP annihilation has an angular shape that is due to several sources. As the diameter of the Sun is about 0.5° large as viewed from the Earth, the difference in angle between the center and the border of the annihilation region can be totally neglected with respect to other spreading effects. The induced muons are distributed around the neutrino direction because of the $\nu - \mu$ angle due to ν CC-interaction in the Earth and of the multiple scattering of muons in the path from the neutrino interaction point to the detector. The distribution of the $\nu - \mu$ angle is of course dependent on the shape of the neutrino energy spectrum. The energy spectrum of neutrinos produced in the annihilation of a WIMP of mass m_χ depends in principle on the details of the final states produced in the annihilation. However, the most important parameter in determining the shape of the spectrum is simply the neutralino mass, which sets the maximum neutrino energy $E_{\text{max}} = m_\chi$. In fact, the dependence of the angular spread of the muon signal on other model parameters is of the order of 1° .

The shape of the upgoing-muon signal using neutrino fluxes from χ annihilation in the Sun calculated by Bottino et al. (Bottino et al., 1995) has been evaluated and it is shown in Fig 2. The neutrino fluxes induced by 20, 40, 60 and 120 GeV neutralinos with fixed sets of model parameters and maximal mixing have been used as input to a Monte Carlo which uses the cross sections described in (Lipari et al., 1995) and propagates the muon to the detector treating the energy loss as described in (Lipari and Stanev, 1991). The 90% C.L. flux limits have been calculated in neutralino mass depen-

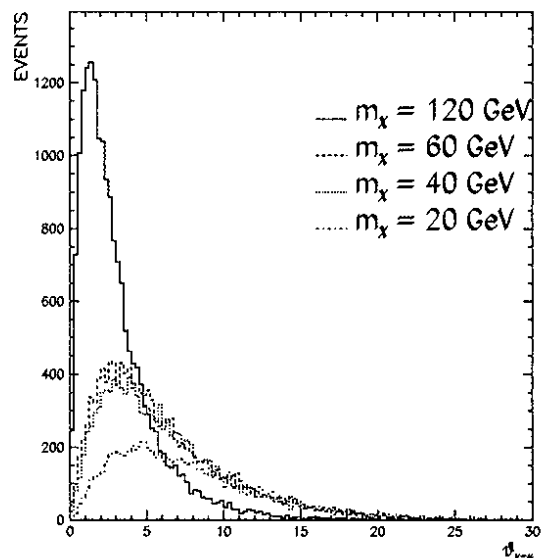


Fig. 2: Angle between the direction of the parent neutrino from χ annihilation in the Sun and the generated muon direction for different neutralino masses.

dent windows which collect 90% of the signal from the Sun (respectively 16.0° , 13.8° , 13.2° and 7.6° for $m_\chi = 20, 40, 60, 120$ GeV). The results are illustrated in Fig. 3 where the muon flux limits have been superimposed to the flux of upgoing muons from the Bottino et al. calculation as a function of m_χ .

In order to increase the sensitivity of this search, an optimization of the signal to noise ratio has been performed. The data, signal, and background angular distributions have been fitted in the region interesting for the signal using a χ^2 expression suited for Poisson-distributed data in counting experiments (Barnett et al., 1996). In this χ^2 , the signal is multiplied by a factor K . The normalization factor K of the signal is found by minimizing the χ^2 with respect to K . The resulting flux limits, shown in Fig. 3 (solid curve), have been evaluated at the 90 % C.L. as a function of the neutralino χ mass. This method is more correct than choosing *a priori* the search cone and it will certainly be improved with increasing statistics.

CONCLUSIONS

The search for a WIMP signal has been performed on the full MACRO through-going upgoing muon sample with negative results. The increased statistics and exposure have made MACRO flux limits more significant than other published results.

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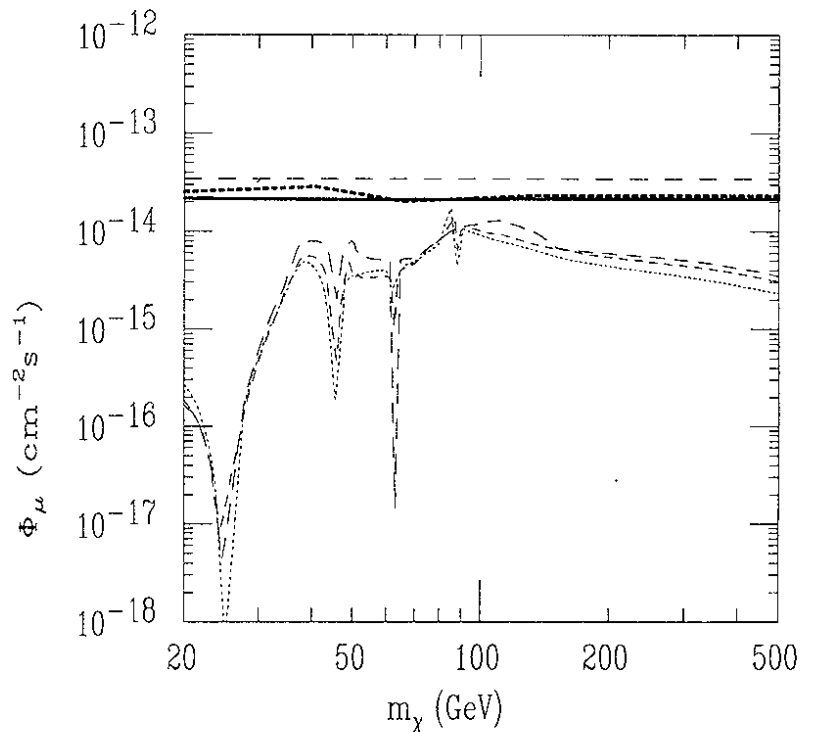


Fig. 3: The bottom three curves are predicted upgoing muon fluxes from the Sun (Bottino et al., 1995). The dotted line connects MACRO flux limits in windows containing 90% of the signal for different m_χ masses. The solid line is described in the text. The dashed line is Baksan flux limit (Boliev et al., 1996).