Search for WIMPS using Upward-Going Muons in MACRO

T. Montaruli[1] **for the MACRO Collaboration**
[1]*Istituto Nazionale di Fisica Nucleare, Bari, I-70126, Italy*

Abstract

We present updated results on the search for a neutrino signal from the core of the Earth and of the Sun induced by Weakly Interacting Massive Particles (WIMPs). In this paper we concentrate on neutralinos as WIMP candidates. The 971 and 642 events used respectively for the search from the Sun and from the Earth are compatible with the background of atmospheric neutrinos. Consequently we calculate flux limits for various search cones around these sources. Limits as a function of the neutralino mass are given and compared to the supersymmetric (SUSY) models.

1 WIMPs from the Earth and the Sun:

We describe an indirect method to look for non-baryonic dark matter WIMPs. The best WIMP candidate is the lightest SUSY particle (LSP) which in the Minimal Supersymmetric Standard Model (MSSM) is expected to be stable if R-parity is conserved and hence should be present in the Universe as a cosmological relic from the Big Bang. The linear combination of Higgsinos and gauginos, the neutralino χ, is currently considered the best candidate for cold dark matter since its couplings and mass range naturally give the relic density required to explain halo dark matter. Neutralinos are described by 3 parameters in the MSSM assuming the GUT relation between gaugino masses: one of the gaugino masses, the Higgsino mass parameter μ and the ratio of the Higgs doublet vacuum expectation values $\tan\beta$. Moreover, if universality is assumed, the MSSM phenomenology is described by these parameters, the universal trilinear scalar coupling A, the degenerate scalar mass m_0 and the mass of the pseudoscalar neutral Higgs m_A. Experimental searches at LEP set a lower limit on m_χ at ~ 32 GeV and suggest an upper limit at ~ 600 GeV if one requires that the neutralino cosmological abundance $\Omega_\chi h^2 \leq 0.3$ (Ellis, 1999). This upper limit is not yet achievable by the forthcoming LEP and Tevatron runs. Direct and indirect searches at underground detectors explore SUSY parameters and are complementary to the future LHC measurements. Direct searches look for a signature of a direct scattering of a WIMP from a nucleus in the detector. The DAMA experiment (~ 100 Kg NaI(Tl)) sees an indication of an annual modulation of the rate which could be due to the Earth's motion around the Sun and the change of the Earth's velocity relative to the incident WIMP. The 19511 kg day data favor at 99.6$\%$ c.l. the presence of an annual modulation signal which, if interpreted in terms of WIMPs, implies a mass of $m_W = (59^{+17}_{-14})$ GeV (Bernabei et al., 1999). This indication should be checked using different techniques, such as the indirect detection of trapped WIMPs inside the core of the Earth and of the Sun. The signature would be an excess of neutrino events resulting from WIMP-WIMP annihilations around the direction of the vertical of the apparatus and of the Sun beyond the known atmospheric ν background (Jungman, Kamionkowski & Griest, 1996). MACRO measures neutrinos indirectly as upward-going muons and has presented results of the WIMP search in Ambrosio et al., 1998a, to which we refer for details. We update this search including the data collected during Mar. 98-Feb. 99.

2 MACRO Updated Results on WIMPs:

The MACRO detector at the Gran Sasso Laboratories, with overall dimensions of $12 \times 76.6 \times 9$ m^3, detects upward-going muons through the time-of-flight measurement using 600 tons of liquid scintillator inside 12 m long boxes (time resolution ~ 500 psec). A system of around $20,000$ m^2 of streamer tubes reconstructs tracks with angular resolution $\leq 1^\circ$. The lower part of the apparatus is filled with rock absorber setting a 1 GeV threshold for vertical μs. The upward-going muon measurement relative to the construction period of MACRO (Mar. 89 - Apr. 94: 1.38 yr of running of 1/6 of the lower apparatus and 0.41 yr of the lower detector, inefficiencies included) is described in Ahlen et al., 1995. Since then, MACRO is in its full configuration (3.93 yr, inefficiencies included) and further results are in Ambrosio et al., 1998a and Ambrosio et al., 1998b.

For the WIMP search for the Earth we use the sample of 642 throughgoing upward muons selected with the requirement that the track crosses at least 200 g/cm^2 in the MACRO rock absorber, which reduces the background due to soft πs produced at large angles by downward-going μs to $\sim 1\%$ (Ambrosio et al., 1998c). Releasing this cut, we use 971 upward-going μs for the search for the Sun because background rejection is not so critical for moving sources and the increase in exposure offsets the slight increase in background.

For the Earth, the expected background due to interactions of atmospheric νs in the rock below MACRO is evaluated with a full Monte Carlo described in Ambrosio et al., 1998b using the Bartol ν flux (Agrawal et al., 1996), the GRV(94) DIS parton distributions (Glück, Reya & Vogt, 1995) and the muon energy loss as in Lohmann et al., 1985. We estimate a total uncertainty in the calculation of upward-going muon fluxes of 17%. For the Earth we have even considered a $\nu_\mu \to \nu_\tau$ oscillation scenario with parameters $\Delta m^2 = 0.0025$ eV^2, $\sin^2 2\Theta = 1$ as suggested by the flux measurement reported at this conference (Ronga et al., 1999). For the Earth search, the expected number of atmospheric induced events in the no oscillation scenario is (including the contribution due to ν-interactions inside the bottom part of the apparatus which are selected as throughgoing muons) 835 ± 142 and in the oscillation scenario 581 ± 99.

EARTH					SUN		
Half-cone	Data	Back-ground events	Norm. factor	Flux Limit ($E_\mu > 1.5$ GeV) (cm^{-2} s^{-1})	Data	Back-ground events	Flux Limit ($E_\mu > 2$ GeV) (cm^{-2} s^{-1})
30°	102	150.2	0.83	2.01×10^{-14}	69	58.9	6.38×10^{-14}
24°	70	96.2	0.80	1.56×10^{-14}	41	37.3	4.06×10^{-14}
18°	44	53.0	0.78	1.28×10^{-14}	22	20.9	2.77×10^{-14}
15°	32	36.8	0.77	1.03×10^{-14}	14	14.5	2.07×10^{-14}
9°	12	13.7	0.77	6.58×10^{-15}	5	5.3	1.42×10^{-14}
6°	4	6.2	0.77	5.07×10^{-15}	2	2.3	1.07×10^{-14}
3°	0	1.6	0.77	2.89×10^{-15}	2	0.6	1.35×10^{-14}

Table 1: Observed and atmospheric ν-induced background and 90% c.l. μ flux limits as a function of half-cone angles around the Earth core and the Sun. For the Earth, the expected background events are multiplied by the ratio of observed to expected events outside each cone. The Earth results are for the no oscillation scenario. The average exposure for the Earth is 3272 m^2 yr and for the Sun 1116 m^2 yr.

For the Sun we have compared the 971 measured events with a different simulation with respect to that used for the Earth. This is obtained by mixing randomly the local coordinates of measured upward-going events and times gathered during the entire data-taking. This method takes into account the contribution of events produced by internal ν-interactions in the MACRO absorber. In Fig. 1(a) we show the angular distributions of the measured and expected events from atmospheric neutrinos for the Earth and the Sun. For the Sun this distribution depends strongly on time due to the motion of the Sun. In Fig. 1(b) we show the muon flux limits for 10 search cones from 3° to 10°. In the case of the Earth, the expectation from atmospheric νs in the region of interest for the signal is larger than the data; we then evaluate flux limits multiplying the expected number of events by the ratio of the data to the expectation outside the cone where we look for the signal. This normalization is motivated by the high uncertainty in the normalization of upward-going muon flux calculations, whereas the shape error in the flux distribution is a few percent only. Moreover, since the number of detected events is less than the normalized expected events, we set conservative flux limits assuming that the number of measured events equals the number of expected ones (Caso et al., 1998). With this normalization, Earth limits considering ν-oscillations agree with the ones in the case of no oscillations within 7%. On the other hand, for the Sun, having used data to evaluate the expected numbers from atmospheric νs, oscillation effects are automatically included in the given limits. In Table 1 we show measured and expected events and flux limits for some of the cones calculated assuming a minimum μ energy of 1.5 GeV and 2 GeV for the Earth and the Sun, respectively. The minimum energy for the Sun is higher because tracks pointing toward it are more slanted than vertical tracks pointing to the core of the Earth and hence cross a larger amount of MACRO absorber. The average exposures (live-time times detector area in the direction of the expected signal from the source of WIMP annihilation) for cones between 3° and 30° is 3272 m^2 yr for the Earth and 1116 m^2 yr for the Sun. We estimate a maximum error of 5% on flux limits assuming these minimum energies for flux limit calculation with respect to a calculation which takes into account the dependence of the acceptance of the apparatus and of the neutrino fluxes from $\chi - \bar{\chi}$ annihilation.

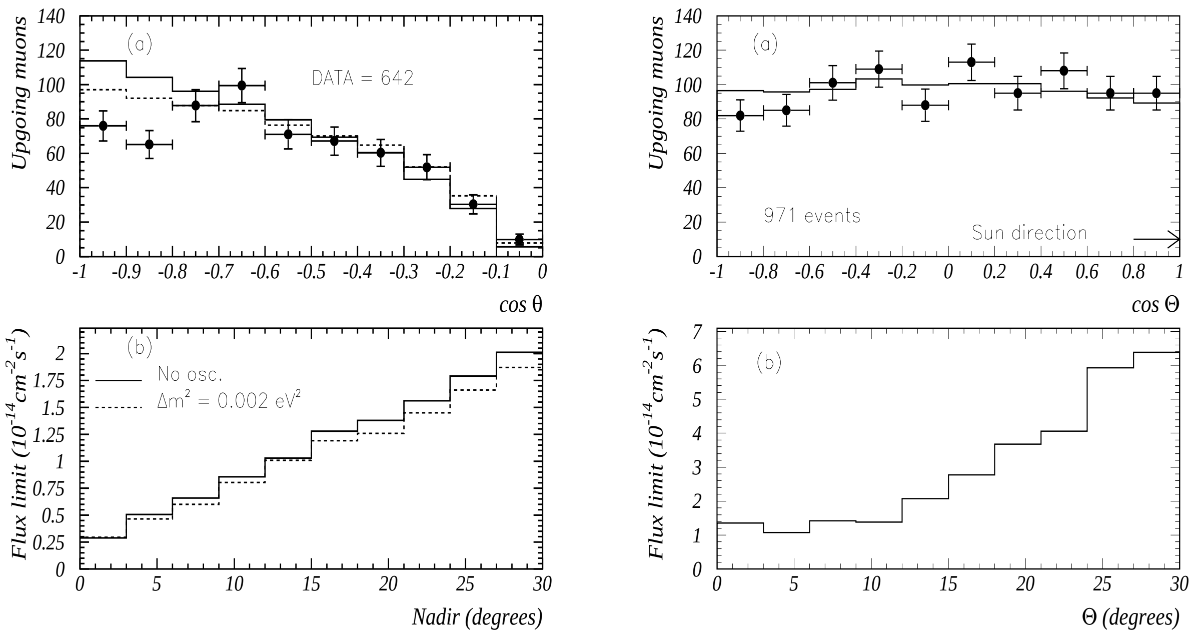

Figure 1: (a) On the left: zenith angular distribution of measured and expected events for the Earth search. Solid and Dotted lines: expectations for atmospheric νs for no-oscillations and $\nu_\mu \to \nu_\tau$ oscillations with $\Delta m^2 = 0.0025$ eV^2; black circles: data. The expected distributions are multiplied by the ratio R of the measured events over the expected ones outside the largest window $30°$ ($R = 0.83$ for the solid line and 1.15 for the dashed line). On the right: distribution of the cosine of the angle from the Sun direction. (b) μ flux limits (90% c.l.) vs. the half-width of the cone from the source direction.

We calculate flux limits assuming the neutralino is a WIMP candidate. We estimate search cones considering the angular distribution of upward-going muons around the direction of neutrinos from neutralino annihilation which mainly depends on the neutralino mass using Bottino et al., 1995 flux calculations. We choose to calculate flux limits in those cones which include 90% of the expected signal. We estimate that extreme assumptions on the annihilation channels (the final states are fermion pairs, gauge/Higgs bosons) produce a maximum variation of flux limits of about 17%. The Bottino models are shown as dots (model parameters are described in detail in Ambrosio et al., 1998b) and circles in Fig. 2 as a function of neutralino mass for the Earth and the Sun and a minimum muon energy of 1 GeV. The solid lines represent MACRO flux limits corrected for the 90% collection efficiency of the cones and including correction factors to translate limits in Table 1 to the 1 GeV threshold used in the calculation. These factors are maximum for low neutralino masses (1% for the Earth and 10% for the Sun at $m_\chi = 60$ GeV). As shown in detail in Ambrosio et al., 1998b, MACRO's experimental limit from the Earth rules out a considerable number of SUSY configurations based on the interpretation of the DAMA/NaI data (Bottino et al., 1999), even assuming neutrino oscillations of the atmospheric ν background. It should anyway be considered that even if the MACRO flux limits vary within 7% if the oscillation or no oscillation hypothesis is assumed, $\nu_\mu - \nu_\tau$ oscillations with the already quoted parameters could lower neutrino flux calculations from neutralino annihilation by at most a factor of two (Fornengo, 1999). In the case of the Sun, MACRO has less overlap in sensitivity for low neutralino masses with direct searches because the indirect search is more sensitive to spin-dependent scattering.

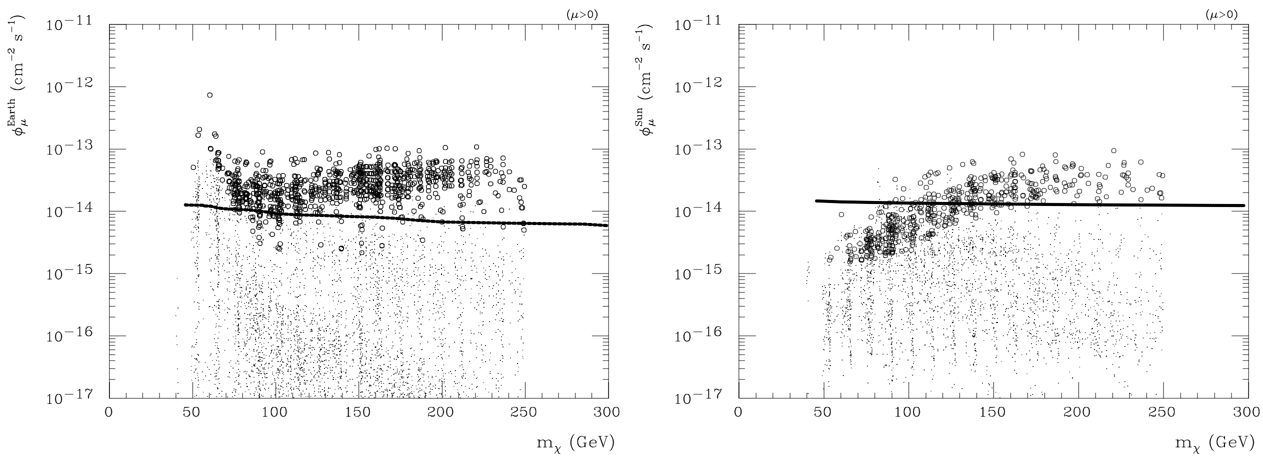

Figure 2: On the left: dots are upward-going μ fluxes vs m_χ for $E_\mu^{th} = 1$ GeV from the Earth for various model parameters (Bottino et al., 1995); solid line: MACRO flux limit (90% c.l.). Open circles: models excluded by direct measurements (Bernabei et al., 1996). On the right: the same as on the left for the Sun.

References

Agrawal, V., Gaisser, T.K., Lipari, P. & Stanev, T., 1996, Phys. Rev. 53 1314
Ahlen, S., et al., MACRO Collaboration, 1995, Phys. Lett. B357, 481
Ambrosio, M., et al., MACRO Collaboration, 1998a, subm. to Phys. Rev. D15 and hep-ex/9812020
Ambrosio, M., et al., MACRO Collaboration, 1998b, Phys. Lett. B434, 451
Ambrosio, M., et al., MACRO Collaboration, 1998c, Astrop. Phys. 9, 105
Bernabei, R., et al., 1996, Phys. Lett. B389, 757
Bernabei, R., et al., 1999, Phys. Lett. B450, 448
Bottino, A., et al., 1995, Astrop. Phys. 3, 65
Bottino, A., et al., 1999, Astrop. Phys. 10, 203
Caso, C., et al., Review of Particle Physics, 1998, Eur. Phys. J., C3, 1
Ellis, J., 1999, astro-ph/9903003
Fornengo, N, 1999, hep-ph/9904351
Glück, M., Reya, E. & Vogt, A., 1995, Z. Phys. C67, 433
Jungman, G., Kamionkowski, M., & Griest, K., 1996, Phys. Rep. 267, 195
Lohmann, W., et al., 1985, CERN Yellow Rep., CERN-EP/85-03
Ronga, F., for the MACRO Collaboration, 1999, these Proceedings