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EXPERIMENTAL STUDY OF UPWARD STOPPING MUONS IN NUSEX

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ABSTRACT

A search for upward going stopping muon events has been performed using the NUSEX detector. The experimental flux, $(1.31 \pm 0.46)\ 10^{-13}\ \mu/cm^2$ s sr, is in good agreement with the theoretical expectations of muon production from atmospheric neutrinos. The experimental limit on the flux of muons produced by high energy neutrinos from the Sun is compared to the expectations based on cold dark matter hypothesis, and mass limits on different candidates are set.

1. - INTRODUCTION

The measurement of the atmospheric ν_e to ν_μ ratio reported by the Kamiokande collaboration exhibits a relative deficit of ν_μ interactions in the low energy tail of the spectrum. Since authors are unable to explain these data as a result of systematic detector effects, this discrepancy has been interpreted as an evidence for possible neutrino oscillations [1].

On the other hand, no evidence for neutrino oscillations was found in the data from NUSEX, Frejus and IMB experiments[2,3,4]. In these observations, the experimental ratio $(\nu_\mu + \bar{\nu}_\mu) / (\nu_e + \bar{\nu}_e)$ for events which are fully contained in the fiducial volume of the apparatus is in good agreement with predictions within statistics.

Motivated by these results, we performed an indirect measurement of the muon neutrino flux, through the detection of upward-going muons produced by charged current interactions in the surrounding rock and subsequently stopping in our detector. The median energy of atmospheric neutrinos producing stopping muons is about 7 GeV, to be compared to a value of 100 GeV to produce through-going events. The large path of neutrinos coming from the opposite side of the Earth makes the study of these events very sensitive to small values of the oscillation parameters.

Upward going muon events can also be produced by a directional flux of high energy neutrinos coming from the annihilation of possible dark matter candidates gravitationally trapped into the Sun[5]. In the considered neutrino energy region, the expected solar neutrino flux from dark matter is enhanced with respect to the atmospheric background; a comparison between solar and atmospheric fluxes can discriminate among different dark matter candidates.

In both oscillation search and dark matter studies, the measurement of the upward-going stopping muon flux thus provides a complementary information to that obtained from the analysis of contained events and through-going muons.

2. - APPARATUS AND EVENT SELECTION

The NUSEX detector has been in operation since June 1982 in the Mont Blanc tunnel, at a vertical depth of 5000 hg/cm^2; a detailed description of our detector can be found elsewhere[6].

Briefly, it is a 3.5 m cubic size tracking calorimeter consisting of 134 horizontal iron planes 1 cm thick, interleaved by limited streamer tubes active planes, 1 cm^2 section. The coordinates on each plane are read by means of X and Y strips respectively parallel and perpendicular to the tubes; the spatial resolution is 1 cm, the angular one is 1 and 2 mrad in zenithal and azimuthal angles respectively. A trigger is generated when either 4 or 3+2 or three non consecutive pairs of planes are hit.

In the following analysis, we have considered 5.64 years of running time, during which we detected 48868 muon events, with a single muon frequency of 1 per hour. In order to select upward muons stopping inside the fiducial volume of the detector, all the events were firstly visually scanned, looking for one prong events in the apparatus with nadir angle $\Psi < 87^o$ and having one vertex contained in the fiducial volume. At least 10 planes crossed are needed to define a muon, which track is considered to stop in the fiducial volume if its potential path crosses at least 7 more active planes.

The timing resolution of our detector does not permit time of flight measurements, but its fine granularity allows us to easily recognize the path of a particle at the end of range; in about 35% of the cases, the stopping muon can also be identified by the delayed signal of the positron from its decay. A further quantitative test on the track flight direction was performed by an analysis of the progressive multiple scattering angle along the track[7].

With more than 95% efficiency, we finally got 8 positively identified upward-going muons stopping inside the fiducial volume defined above. The total exposition for these events is 194 m^2 y. The above selection criteria correspond to a muon residual energy of 0.2 to 2 GeV.

The experimental flux results to be (1.31 ± 0.46) 10^{-13} μ/cm^2 s sr. We point out that if the same reduction factor found in the experimental muon neutrino flux from Kamiokande holds in the higher energy region we are considering , only 4 upward going muon events should have been seen in our detector.

3. - NEUTRINO OSCILLATION SEARCH

In order to investigate the neutrino oscillation hypothesis, the experimental upward going muon flux has been compared with the expected one from atmospheric neutrinos in absence of oscillations.

The number of expected events in the effective live time T is given by [8]:

$$N_\mu = T N_A \int_{\Psi=0}^{87^o} \int_0^{2\pi} d\cos\Psi \, d\Phi \, S(\Psi,\Phi) \int_o^\infty dx \int_{E_\mu}^\infty dE_\nu \int_{E_\mu}^{E_\nu} dE_\mu \left(\frac{d\Phi_{\nu_\mu}}{dE_\nu d\Omega} \frac{d\sigma_{\nu_\mu}}{dE_\nu} + \frac{d\Phi_{\bar\nu_\mu}}{dE_\nu d\Omega} \frac{d\sigma_{\bar\nu_\mu}}{dE_\nu} \right) P(E_\nu, E_\mu, x)$$

where N_A is the Avogadro number, x the distance to the interaction point in rock, $S(\Psi,\Phi)$ the detector area projected onto a plane perpendicular to the direction (Ψ,Φ). $P(E_\nu,E_\mu,x)$ is the probability that a muon of energy E_μ comes to stop in the detector after propagating a distance x. This has been evaluated by Monte Carlo simulation of the muon transport through the rock[9].

The charged current interaction of ν_μ is described in the frame of the usual parton model approximations, but accounting for the QCD evolution of the quark distributions as suggested by Quigg et al [10].

$\frac{d\Phi_{\nu_\mu}}{dE_\nu d\Omega}$ is the predicted spectrum of neutrinos at the detector. For the low energy region, the flux specifically calculated[11,12] for our experimental location has been used; it takes into account the effects of geomagnetic field, solar modulation on the neutrino flux and muon polarization. The high energy neutrino flux (E_ν > 3 GeV) was instead taken from Volkova[13]. Together, they give a detailed description of the atmospheric neutrino fluxes from 100 MeV up to the highest energies. The absolute flux normalization error is estimated to be ± 20%.

From this calculation, the expected flux of upward going stopping muons results to be 9.62 10^{-14} μ/cm^2 s sr; the experimental flux derived from our events appears to be in good agreement with the theoretical expectations within the quoted errors. The poor statistics does not allow a comparison between the experimental and expected angular distributions; nonetheless, the number of upward (Ψ=0-60^{o}) and horizontal upward (60-87^{o}) events appears to be in agreement with that expected.

In the case of $\nu_\mu - \nu_e$ oscillations, the expected flux of upward muon neutrinos would be reduced; however, since cosmic rays have a non negligible flux of ν_e, the loss of ν_μ due to $\nu_\mu \rightarrow \nu_e$ is partially compensated by the gain from $\nu_e \rightarrow \nu_\mu$. Thus the spectrum of neutrinos at the detector will be given by

$$\frac{d^2\Phi_{\nu_\mu}}{dE_\nu d\Omega} = \frac{d^2\Phi_{\nu_\mu}}{dE_\nu d\Omega}(E_\nu,\Psi)\left(1 - P_{\nu_\mu \rightarrow \nu_e}(E_\nu;\Psi)\right) + \frac{d^2\Phi_{\nu_e}}{dE_\nu d\Omega}(E_\nu,\Psi)\, P_{\nu_e \rightarrow \nu_\mu}(E_\nu,\Psi)$$

where $\frac{d^2\Phi_{\nu_\mu}}{dE_\nu d\Omega}$ and $\frac{d^2\Phi_{\nu_e}}{dE_\nu d\Omega}$ are the differential muon and electron neutrino expected fluxes in absence of oscillations. $P_{\nu_\mu \rightarrow \nu_e} = P_{\nu_e \rightarrow \nu_\mu}$ is the probability for $\nu_\mu \leftrightarrow \nu_e$ oscillations. Analogous relations hold for antineutrinos.

In a region where matter density is constant, the oscillation probability is given by

$$P_{\nu_\mu \rightarrow \nu_e}(E_\nu,\Psi) = P_{\nu_\mu \rightarrow \nu_e}(E_\nu,\Psi) = \sin^2 2\Theta_m \sin^2\left(\frac{\pi L}{L_m}\right)$$

where L_m is the matter oscillation length, Θ_m the mixing angle for rotating the weak eingenstates into the mass eigenstates basis.[14,15]

$$\sin^2 2\Theta_m = \frac{\sin^2 2\Theta_\nu}{\sin^2 2\Theta_\nu + (L_\nu/L_o \mp \cos 2\Theta_\nu)^2}$$

with $L_\nu = \frac{4\pi p}{\delta m^2}$ vacuum oscillation length, Θ_ν = mixing angle in vacuum, δm^2 = mass squared difference between the two neutrino mass eigenstates, p=neutrino momentum. $L_o = \frac{2\pi}{\sqrt{2}\, G_F\, n_e}$; G_F is the Fermi constant and n_e is the electron number density. Assuming $\delta m^2 > 0$, the above formula shows that the transition probability for neutrinos has a resonance at $L_\nu/L_o = \cos 2\Theta_\nu$, even if the intrinsic mixing angle is small, while oscillations are suppressed for antineutrinos. The opposite would happen for $\delta m^2 < 0$.

A constant value was used in our calculation for the radial density distribution in the Earth, even if it actually exhibits a complex structure; in fact, most of the upward going neutrinos path through the mantle of Earth without hitting the core.

The ratio $R = N_{\mu}^{osc}/N_{\mu}$, between the number of expected muons in presence and in absence of oscillations was then computed; the calculated R is independent from the absolute normalization of the neutrino fluxes. This ratio is shown in Fig. 1. The spectrum of neutrinos contributing to upward going stopping muons is shown in Fig. 2; its shape depends only weakly on the nadir arrival angle of neutrino.

From our data, we finally get a lower limit to the experimental flux of muons of 8.44 10^{-14} μ/cm^2 s sr (90% C.L.); this give a ratio $R^{exp} = 0.88$ when using the expected atmospheric neutrino flux of 9.62 10^{-14} μ/cm^2 s sr quoted above.

Even allowing for a 20% increase in the expected flux, our result turns out to be consistent with an excluded region $\delta m^2 \geq 10^{-2}$ eV^2.

4. - DARK MATTER

The dark matter hypothesis was introduced in order to understand the details of Galaxy formation, the nature of galactic halos around spiral galaxies, the overall mass density of the Universe if inflation theory is correct.

Possible scenarios for solving the dark matter problem involve cold dark matter particles with $m_x > 3$ GeV. Relic WIMPs with average velocities of about 300 Km/s can be trapped by elastic scattering in massive objects like the Sun. Their annihilation results in a spectrum of particles of which only high energy neutrinos can escape. The high energy neutrino flux depends on the nature of the dark matter particle [16].

The flux of neutrinos from dark matter has been computed by many authors for different dark matter candidates at various mass values[16-18]: generic and closure higgsinos, photinos, superstring relics, Dirac and scalar muon neutrinos.

As an example, the differential flux $\frac{d\Phi(\nu_{\mu} + \bar{\nu}_{\mu})}{dE}$ of neutrinos from generic higgsinos (full line) is shown in Fig. 3 in comparison to the expected atmospheric $(\nu_{\mu} + \bar{\nu}_{\mu})$ flux (dashed lines) in a cone of 15^{o} centered in the Sun; in Fig. 4, one can see the corresponding energy spectrum of neutrinos contributing to upward going stopping muon events. It has to be noticed that in the energy range we are investigating, the solar flux exceeds the atmospheric one.

6 muon events out of 8 have been detected during the time spent by the Sun below the horizon; none of these is found within 15^{o} of the source. In fact, due to the interaction scattering angle from incident neutrinos and to the muon multiple scattering in rock, muons would not be expected to point directly to the source. Simulations also show that the above acceptance angle is enough to enclose more than 95% of the muon events.

These data have been interpreted according to the statistical analysis suggested by Protheroe[19] and previously used to set limits from contained events and through-going muons detected in Kamioka, Frejus and IMB experiments[21-23].

This approach allows one to set limits on the ratio R between on-source and off-source events, taking into account fluctuations in both sets of data. Furthermore, the use of this ratio cancels possible systematic errors in the experimental rates.

Following the procedure of ref. 19, we found a 90% C.L. upper limit on R of 0.39.

The comparison with the expectation for R is shown in Fig. 5 for the different considered dark matter candidates. Scalar neutrinos can be entirely excluded; upper limits on the generic higgsinos and Dirac neutrino masses are found to be 9 GeV and 13 GeV respectively. These results are in good agreement with the ones found by using contained events and through-going muons with $E_\mu > 2$ GeV (IMB, Frejus and Kamioka combined data); however, it should be stressed that in order to draw any firm conclusion many uncertainties affecting the calculation of the expected fluxes must be solved[20].

As already pointed out[24,25] , these results together with the SLC, LEP and UCSB/LBL ones completely rule out Dirac neutrinos as dark matter candidates; Majorana neutrinos are also excluded at least for $m < 78$ GeV.

5. - CONCLUSIONS

The detection of upward going muons produced in the surrounding rock and stopping inside the fiducial volume of an underground detector allows to explore the atmospheric muon neutrino flux in an energy range ($<E> = 7$ GeV) usually inaccessible from the analysis of contained or through-going muon events.

In particular, this allows to enhance the signal to background ratio in searches for high energy neutrinos from the Sun due to the annihilation of dark matter particles.

The flux of upward going muons stopping in the NUSEX detector has been found to be consistent with the calculated expectation with no ν_μ - ν_e oscillations; this conclusions is in agreement with that independently reached by analyzing contained events. However, even allowing for a 20% increase in the calculated flux, our result is consistent with an excluded region $\delta m^2 \geq 10^{-2}$ eV^2.

The same set of data has been analyzed to search for any correlation with the Sun position. No events pointing to the source have been found, in such a way allowing to place constraints on the mass of dark matter candidates.

Scalar neutrinos of any mass, generic higgsinos and Dirac neutrinos with masses greater than 9 and 13 GeV respectively are excluded.

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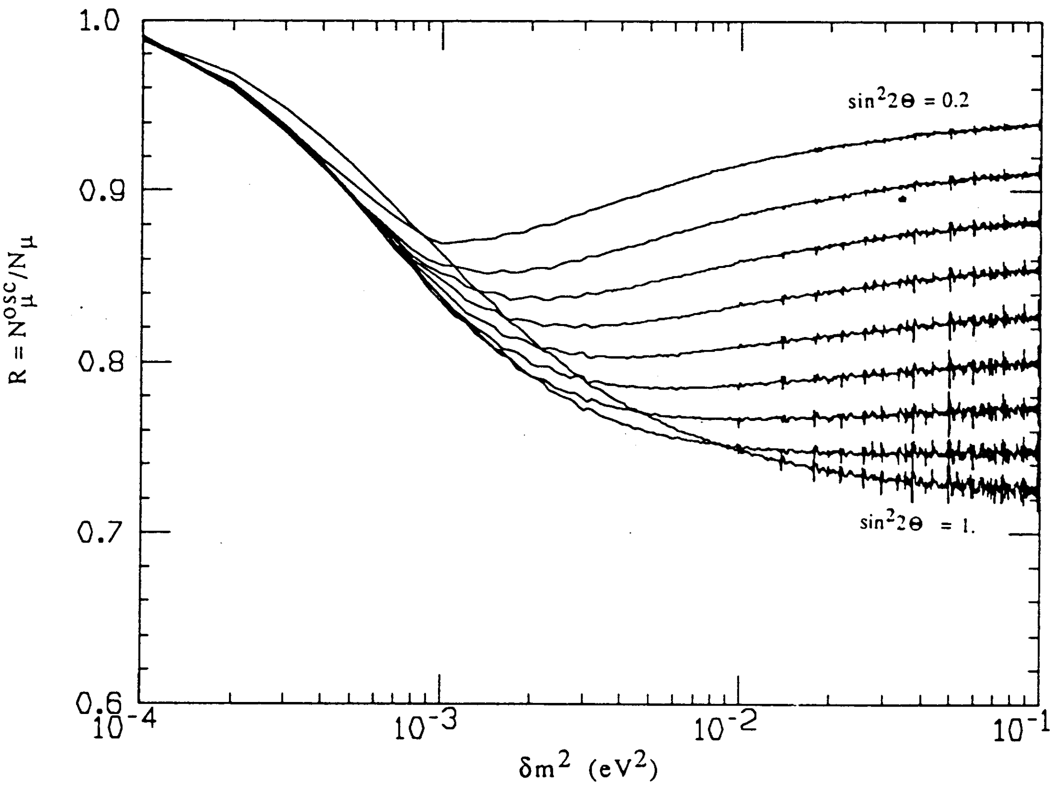

FIG. 1 - Ratio $R = N^{osc}_{\mu}/N_{\mu}$ between the number of expected muons in presence and in absence of oscillations as a function of δm^2. The different curves refer to values of $\sin^2 2\Theta = 0.2$ to 1.

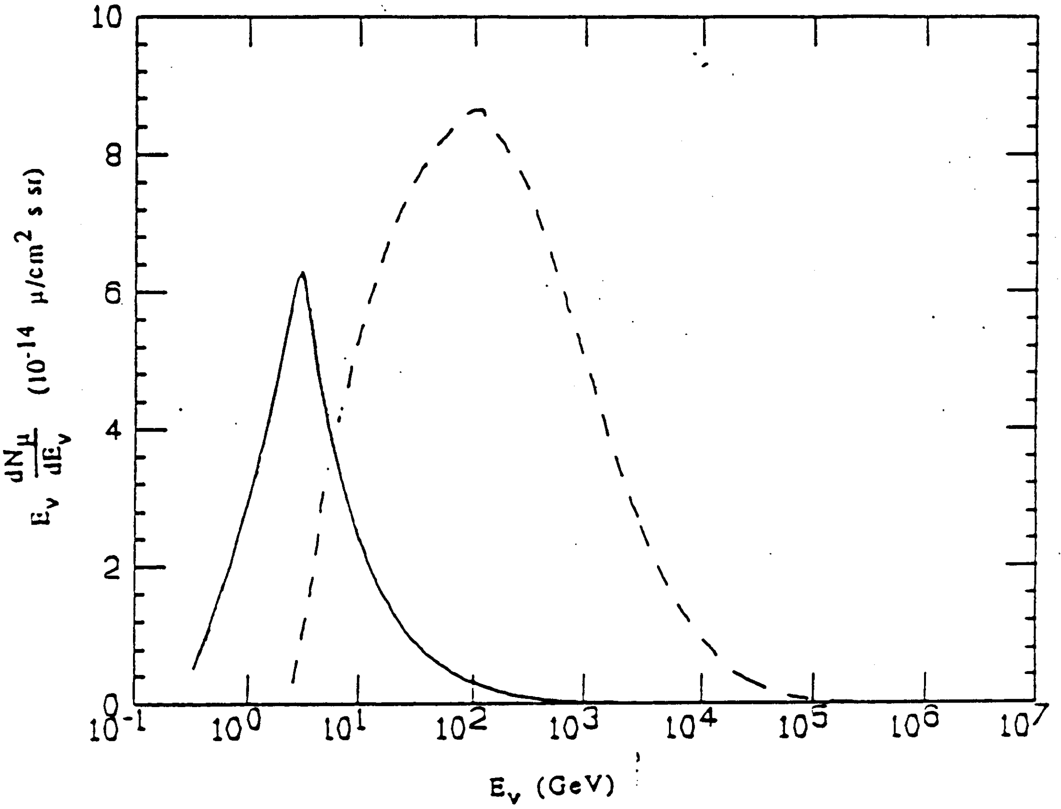

FIG. 2 - Energy spectrum of atmospheric neutrinos contributing to the upward-going stopping muons detected in NUSEX (full line). For comparison, the spectrum of neutrinos contributing to through-going muon events is shown (dashed line).

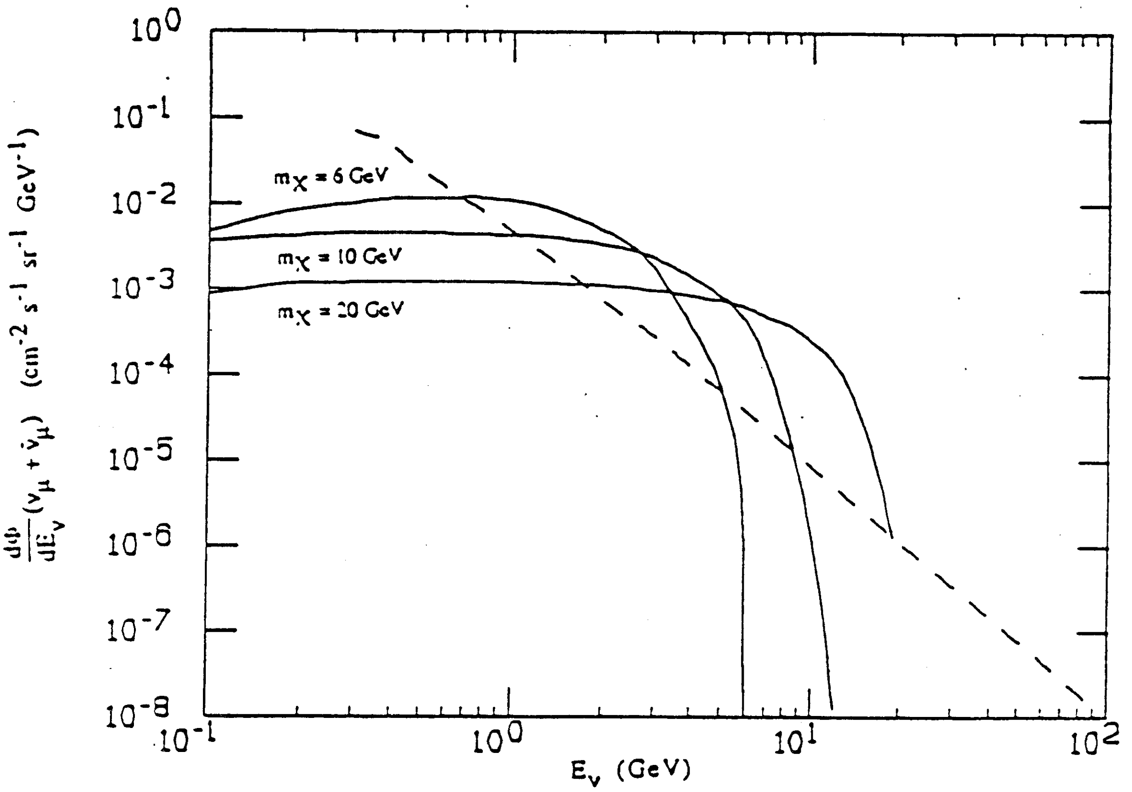

FIG. 3 - Differential flux $\frac{d\Phi(\nu_\mu + \bar\nu_\mu)}{dE}$ of neutrinos from generic higgsinos (full line) of mass 6,10,20 GeV . For comparison, the expected atmospheric $(\nu_\mu + \bar\nu_\mu)$ flux (dashed lines) in a cone of 15° centered in the Sun is also shown.

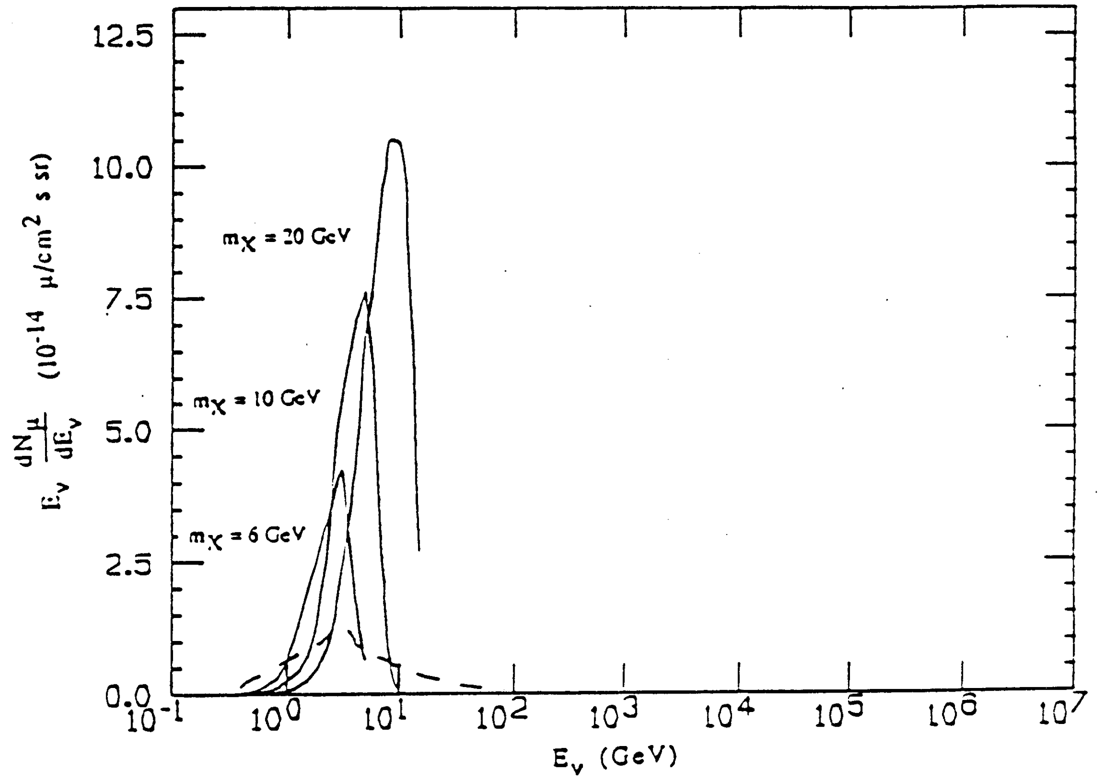

FIG. 4 - Energy spectrum of neutrinos from generic higgsinos of mass 6, 10, 20 GeV contributing to the upward-going stopping muons. The contribution of atmospheric neutrinos is shown as a dashed line.

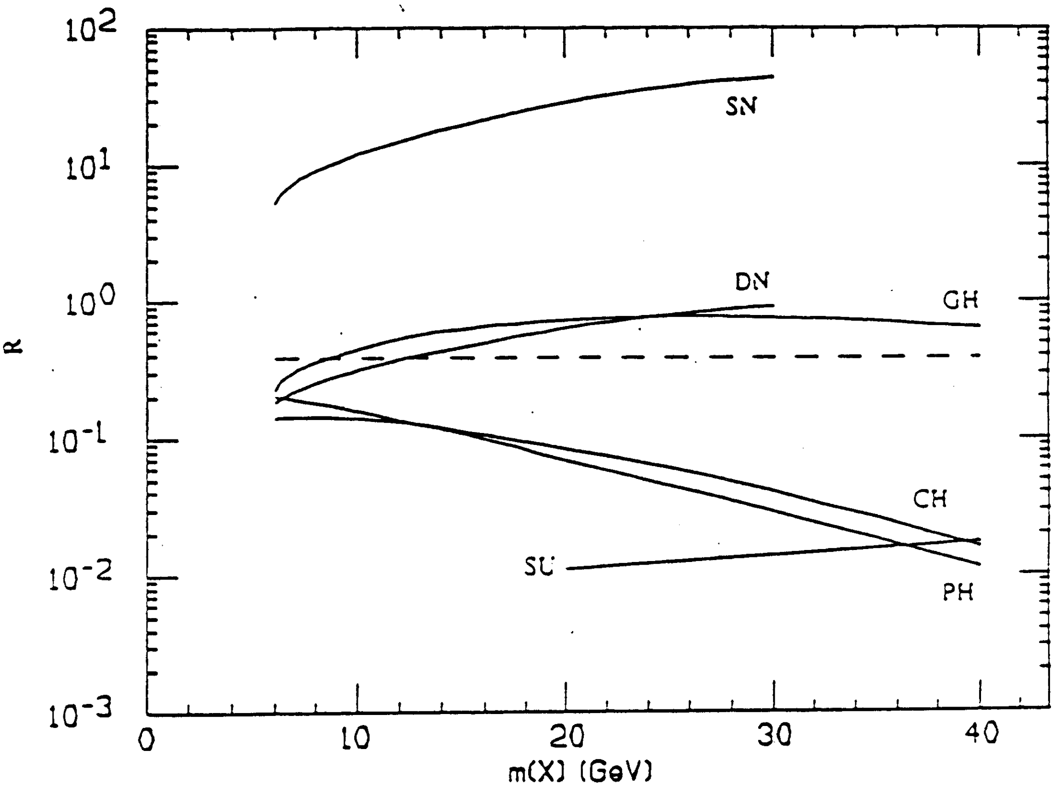

FIG. 5 - Ratio R between on-source and off-source events versus the dark matter mass for different candidates. The experimental 90% C.L. upper limit on R is shown as a dashed line. The various investigated possibilities are indicated as GH = generic higgsinos, CH = close higgsinos, PH = photinos, SU = superstring relics, DN = Dirac neutrinos, SN = scalar muon neutrinos.