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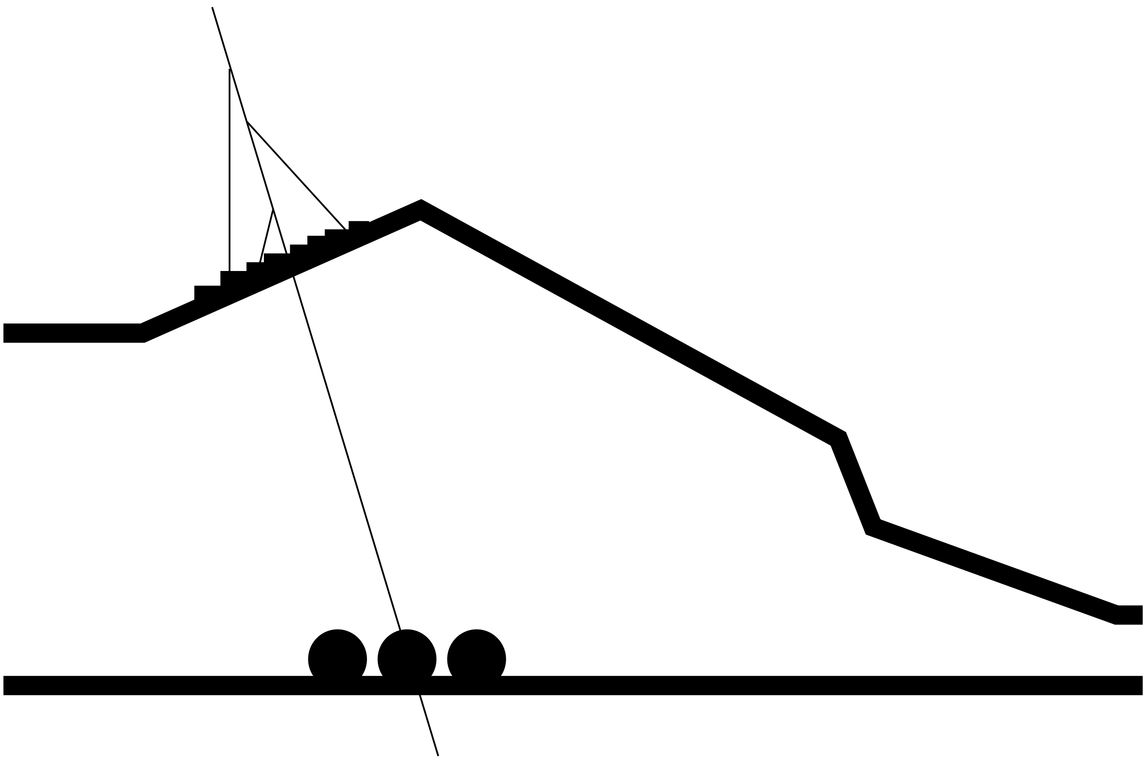

Study of UHE Cosmic Neutrinos through Horizontal Extensive Air Showers

The EAS-TOP Collaboration

Neutrino Mixing: Meeting in Honour of Samoil Bilenky's 70th Birthday
Torino, Italy ; 25 - 27 March, 1999
Submitted to World Scientific

INFN - Laboratori Nazionali del Gran Sasso

INFN - Istituto Nazionale di Fisica Nucleare

Laboratori Nazionali del Gran Sasso

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Study of UHE Cosmic Neutrinos through Horizontal Extensive Air Showers

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Abstract

The study of cosmic neutrinos at energies $E_\nu \geq 10^4$ GeV will be one of the most challenging tasks for the next generation of experiments in Astrophysics. Detectors will operate in well shielded laboratories. An alternative low background channel is provided by the observation of the Extensive Air Showers (EAS) at very large zenith angles produced in the atmosphere by penetrating particles. The status of such observations from the technical and physical points of view is discussed following the most recent results of the EAS-TOP array. The origin of the Extensive Air Showers observed al large zenith angle ($\theta \geq 75^0$) is identified as mainly due to muon dominated showers produced by UHE cosmic rays interacting at very large distance in the atmosphere. The obtained upper limit to the diffuse neutrino intensity is $I_\nu(E_\nu > 10^5$ GeV$) < 8.5 \times 10^{-9}$ cm^{-2}s^{-1}sr^{-1} (90 % c.l.). In case of neutrino mixing such limit would be reduced of $\approx 30\%$.

1 Introduction

The detection of UHE neutrinos ($E_\nu \geq 10^4$ GeV) from cosmic sources will represent an important step in Astrophysics. Their flux is predicted following cosmic ray acceleration processes and cosmic ray fluxes. The main candidates as such possible sources, AGNs, have been detected over the whole e.m. energy range [1], and recently at TeV gamma-ray energies [2]. The detection of neutrinos will provide a proof, or disproof, of cosmic ray acceleration at such sources (and maybe help in solving the problem of cosmic ray origin at the highest energies). Moreover direct information on the physical conditions in their inner regions unaccessible from gamma-ray data will possibly become available.

UHE neutrino experiments require large volume detectors, shielded against the "cosmic ray noise", i.e. underground [3], underwater [4, 5, 6, 7], underice [8] installations. The foreseen dimensions of such detectors (≈ 1 km^3 [9]) with the quoted experimental requirements indicate the challenge imposed to experimentalists from technical and engineering points of view.

High energy cosmic ray particles are currently detected from the cascades (Extensive Air Showers, EAS) they induce in the atmosphere. The qualities of their geometrical reconstructions have strongly improved in the last few years (e.g. providing resolutions on their arrival directions $\sigma_\theta \approx 0.5^0$), while the combination of measurements of different components provides constraints on their primaries.

The observation of Extensive Air Showers in nearly horizontal direction provides a possible "well shielded laboratory" for the detection of penetrating particles: cosmic neutrinos [10], high energy muons [11], possible weakly interacting particles or neutrinos [12] produced in the decays of cosmological superheavy particles.

The low background at large zenith angles is provided by the large atmospheric depth ($x > 3000$ g cm^{-2} at $\theta \geq 75^0$) and by the exponential attenuation (with $\Lambda_{EAS} \approx 220$ g cm^{-2}) of the air shower electromagnetic component, which implies a decrease of the air shower counting rate with $\Lambda_c \approx 130$ g cm^{-2}.

The experimental requirement for such detectors is an excellent angular resolution in order to reject the high level background provided at smaller zenith angles by the hadronic c.r. showers (see e.g. fig. 5). On the other side the nature of the observed events in horizontal direction has to be well understood and monitored.

Detection of events at large atmospheric zenith angles (Horizontal Air Showers, HAS) has been reported in the seventies by Böhm and Nagano [13] and their interpretation was not straightforward, due to the contradiction between the expected and detected muon contents.

An analysis of HAS and upper limits to the UHE neutrino flux ($E_\nu \geq 10^5$ GeV) have been reported by the EAS-TOP array [14]. At $E_\nu \geq 10^8$ GeV upper limits have been set by the Fly's Eye experiment [15]; the possibilities connected at the highest energies with the Auger project are currently discussed [16].

We discuss here the experimental status of the observations of HAS following the recent results of the EAS-TOP experiment, both from technical point of view, and concerning the identification of their origin; constraints to the UHE cosmic neutrino flux are derived.

2 Neutrinos as sources of Horizontal Air Showers and physical background

Neutrinos produce showers through:

CC-interactions:

$$(\bar{\nu}_l)\nu_l + N => l^{\pm} + hadrons \tag{1}$$

NC-interactions:

$$(\bar{\nu}_l)\nu_l + N => (\bar{\nu}_l)\nu_l + hadrons \tag{2}$$

where l = e, μ or τ;
and resonance production [17, 18]:

$$\bar{\nu}_e + e^- => W^- => hadrons \tag{3}$$

where the resonant neutrino energy is:

$$E_0[GeV] = m_W^2/2m_e = 6.410^6 \tag{4}$$

In absence of neutrino mixing, the event rate for a neutrino intensity I_ν and processes (1) and (2) is

$$f_\nu = \int d\Omega \int dt \int dE_{em} A_{em}(E_{em}, t, \theta) \sum_{\nu,k} \int dE_\nu I_\nu \frac{d\sigma_{\nu k}(E_\nu, E_{em})}{dE_{em} dt} \tag{5}$$

where: E_{em} is the energy transferred to the e.m. shower in $\nu - N$ interaction, t is the atmospheric depth of the interaction, A_{em} the effective detector area; index ν indicates summation over the neutrino flavours ($\nu = \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$), and k over CC and NC interactions (k = CC, NC).

The shape of neutrino spectrum has been calculated [19] for ν_μ and $\bar{\nu}_\mu$ from AGNs. These fluxes must be accompanied by ν_e and $\bar{\nu}_e$ fluxes of the same origin: the asymptotic flavour ratio for $p - \gamma$ neutrino production being: $I_{\nu=\nu_e+\bar{\nu}_e} = 0.45 I_{\nu=\nu_\mu+\bar{\nu}_\mu}$ [20]. The differential $\nu - N$ cross sections are calculated using the parametrization of the quark distribution in nucleons [21] with extrapolation for vary small x [22].

For resonant events (3), the calculation of the event rate is analogous to (5), with the following expression for the production rate of showers with the resonant energy E_0 (per target electron):

$$\nu_{res}(E_0) = 2\pi\sigma_{eff} E_{\bar{\nu}_e} I_{\bar{\nu}_e}(E_0) \tag{6}$$

where $\sigma_{eff} = 3.10^{-32}$ cm^2 is the effective cross section.

In case of neutrino mixing, if all neutrino species would be nearly equally present at the earth ($I_{\nu=\nu_e+\bar{\nu}_e} \approx I_{\nu=\nu_\mu+\bar{\nu}_\mu} \approx I_{\nu=\nu_\tau+\bar{\nu}_\tau}$), the summation in (5) has to be extended to ν_τ and $\bar{\nu}_\tau$. Additional e.m. energy would be provided to the showers through channel (1) (mainly through the τ decay). The efficiency of the technique in the detection of UHE cosmic neutrinos would thus be improved of $\approx 30\%$.

Indicatively the sensitivity of Extensive Air Shower experiments to a diffuse neutrino intensity is:

$$I_\nu \approx (T \times A_{eff} \times \Omega(>\theta_{min}) \times \sigma(E_\nu) \times X_{oss} \times N_{Av})^{-1} \tag{7}$$

where:

T = exposure time (including a factor $f \approx 0.1 - 0.2$ for detectors exploiting optical emission, as e.g. Fly's Eye);

X_{oss} = detector depth sensitivity;

θ_{min} = minimum angle free from backgound contaminations ($\approx 75^0$);

A_{eff} = effective detector area in the inclined direction;

N_{Av} = Avogadro number.

For an exposure time $\Delta t \approx 1$ yr, as order of magnitude of the sensitivities of the different detectors, neglecting backgrounds, we obtain:

EAS-TOP:

$I_\nu^{sens}(E_\nu > 10^5 \text{ GeV}) \approx 5.10^{-9}\ \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$;

Fly's Eye:

$I_\nu^{sens}(E_\nu > 10^8 \text{ GeV}) \approx 10^{-13}\ \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$;

Auger:

$I_\nu^{sens}(E_\nu > 10^{10} \text{ GeV}) \approx 10^{-16}\ \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$.

Concerning the physical background, its main sources are due to the atmospheric muons and their interactions.

(a) High energy single muons can interact through bremmstrahlung (which dominate 10:1) or deep inelastic scattering and initiate showers at the appropriate depth for detection. Such showers are essentially electromagnetic, since the remnant muons from the initial shower (whose typical primary energy is not much larger than the muon one) are dispersed over a very large area (see fig. 1a).

(b) Ultra high energy cosmic rays interacting at the top of the atmosphere, at very large zenith angles (and therefore distances from the detector $l_d \approx 100$ km), produce a 'large' amount of muons, through the pion decays (favoured, at large angles, with respect to pion interactions due to the low atmospheric density at the interaction altitude). Such showers are therefore composed essentially of muons since the e.m. component is fully absorbed (see fig. 1b).

Neutrino induced showers (fig. 1c) have some intermediate typology, being more similar to conventional c.r. Extensive Air Showers or to events (a), when a large amount of their energy is transferred to the electromagnetic cascade. Arrays must therefore have the possibility of discriminating between the different typologies of events through μ/e identification.

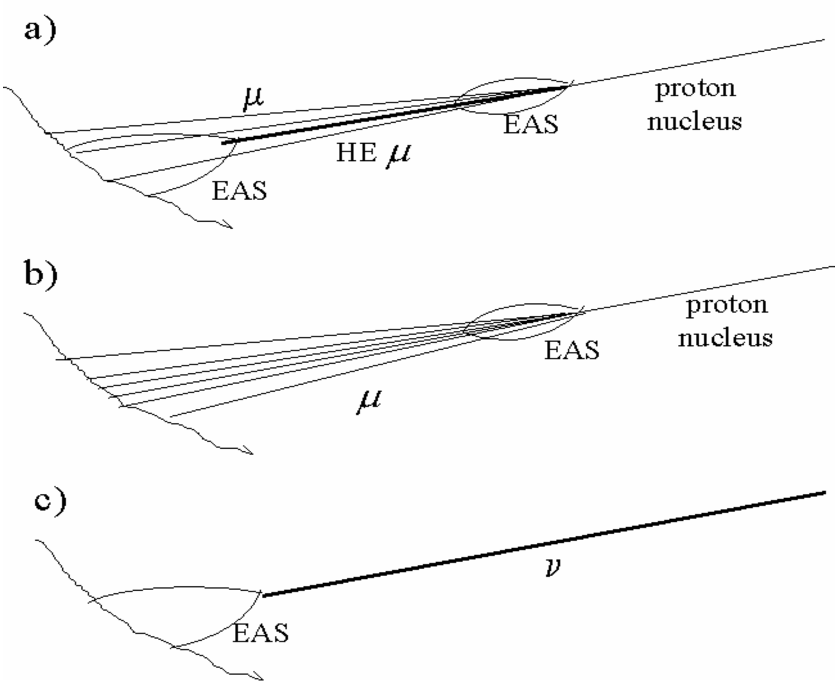

Figure 1: Possible sources of Horizontal Air Showers: a) "local" high energy muon interactions, b) muon dominated showers, residuals from an UHE c.r. interaction at very large distance, c) neutrino events.

Figure 2: Aerial view of part of the EAS-TOP array during winter time. The e.m. modules are visible out of the snow; the muon detector is located inside the shed on top of the picture.

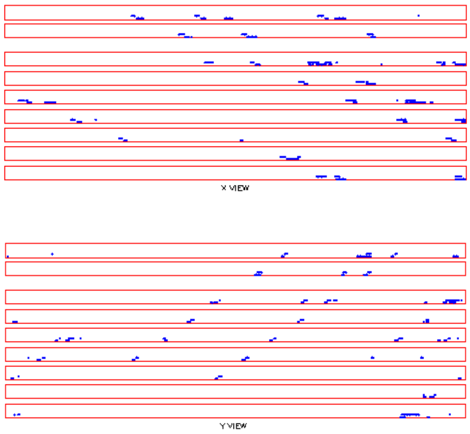

Figure 3: Muon detector: hits from muon tracks seen on orthogonal projections. The average muon angles are $\theta = 74.2^0, \phi = 169.2^0$. The drawing is not on scale: dimensions are 12 m in lengths, 3 m in height.

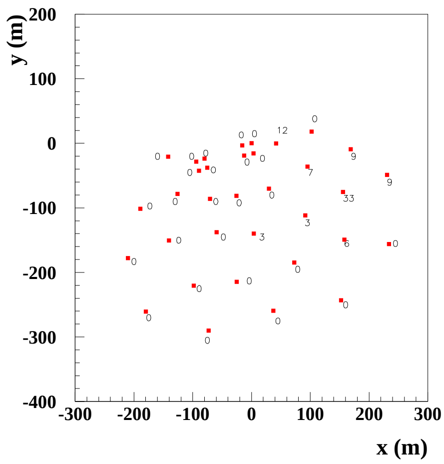

Figure 4: Scintillator detector: number of equivalent vertical $m.i.p.$s in each module. The arrival direction is: $\theta = 77.2^0, \phi = 169.1^0$.

3 The EAS-TOP array

The EAS-TOP array [24] is located at Campo Imperatore (2000 m a.s.l.), above the underground Gran Sasso Laboratories. It includes detectors of different EAS components; in the present analysis we are interested in the total ionizing (electromagnetic + muons) and muon components.

Each detector acts as an independent triggering source in order to select electromagnetic rich showers (HAS) or muon rich showers (Horizontal Muon Bundles, HMB).

The detector of the total ionizing component [25] is made of 35 modules of plastic scintillators (10 m^2 each) distributed over an area $A \sim 10^5$ m^2 on the slope of *Mount Aquila* (average slope $\simeq 15°$), see fig. 2. The triggering condition for the events under discussion is provided by the firing of a subarray made of 6 (or 7) contiguous modules, the central one recording the largest number of particles. The energy threshold of each module is set at 30 % of the energy loss of a vertical minimum ionizing particle ($\Delta E_{m.i.p.}$). Arrival directions are measured from the time of flight technique between the different modules, with accuracy $\sigma_\theta^{EAS} \approx 0.8°$ for vertical incidence ($\sigma_\theta^{EAS} \approx 0.5°$ for events with core internal to the edges of array and shower size $N_e \geq 10^5$ particles). On scintillator triggers, the muon detector data too are acquired.

The μ-detector is a tracking module (140 m^2 area) made of 18 layers of streamer tubes (with section 3 $\times$ 3 cm^2 and 12 m length) and 8 layers of iron absorbers (13 cm thick). The read-out is performed on orthogonal x and y views . The energy threshold for vertical incidence is $E_{th}^{\mu} \approx 1$ GeV ($E_{th}^{\mu} \approx 2$ GeV at $\theta = 75°$). Arrival directions are obtained from the reconstruction of the muon tracks, the angular resolution being $\sigma_\theta^{\mu} \approx 0.6°$ [26]. The

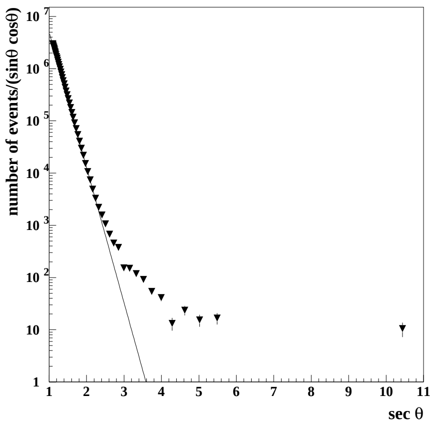

Figure 5: The zenith angle distribution of a sample of EAS as measured by the EAS-TOP e.m. array.

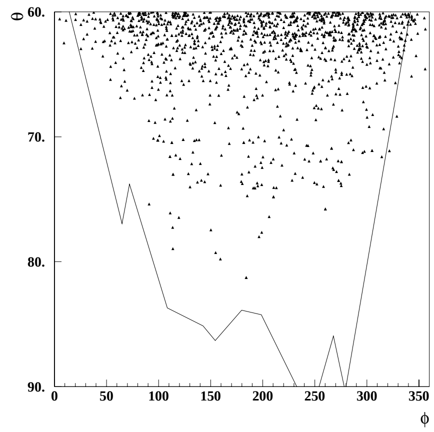

Figure 6: Arrival directions of EAS and the mountain profile seen by EAS-TOP.

effective area for muon counting at $\theta = 75°$ is $A_\mu = 50\ \ m^2$. Two vertical (3.0×12.0 m^2) streamer tube layers on the northern and southern sides of the detector in coincidence with a subset of horizontal layers provide the HMB trigger. Horizontal Muon Bundles (HMB) with $N_\mu \geq 3$ and $\theta \geq 75°$ are detected with geometrical acceptance $\Gamma \approx 25\ \ m^2$ sr.

The display of an event as observed in the muon tracking and scintillator detectors is shown in fig.s 3 and 4 respectively.

While, due to shielding, in the muon detector only muon tracks are observed, in the scintillator modules all ionizing components are measured.

4 HAS: angular distribution and muon content

At zenith angles $\theta > 65°$ an excess of events (HAS) is observed above the rate of EAS as expected from their attenuation length in the atmosphere [14, 27, 28] (see fig. 5).

The physical nature of the anomalous arrival directions of HAS is confirmed by the absence of events from the direction of the sky shaded by the top of the mountain on which the array is located (see fig. 6).

Moreover, the dependence of the barometric effect on the zenith angle, shown in fig. 7 [1], clearly shows a deviation from the $sec\theta$ behaviour for $sec\theta > 2$. This can be explained by the presence of a "non-attenuated" EAS component that amounts to $\approx 30\%$ of the total EAS flux at 70°, and dominates at larger zenith angles.

The comparison of the zenith angle measurements of the scintillator and muon detectors is shown in fig. 8 (for such analysis, as well as in the following, a cut in the

[1] The barometric coefficient $\beta = \frac{1}{n}\frac{dn}{dx}$ (n = counting rate, x = atmospheric pressure) is related to zenith angle θ as: $\beta(\theta) = \beta(0^0) sec\theta$.

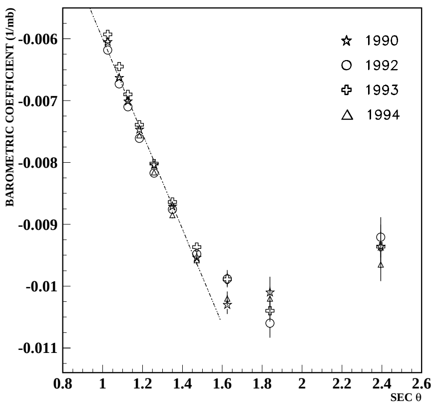

Figure 7: Barometric coefficient for different zenith angles measured by *EAS-TOP*.

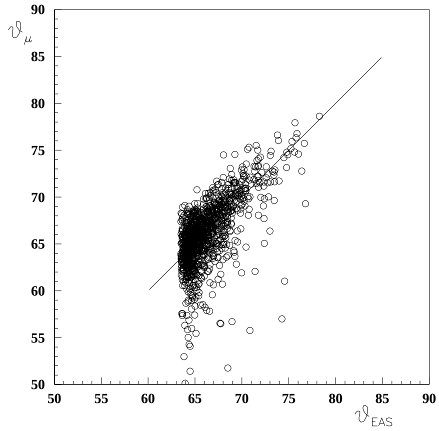

Figure 8: Scatter plot of the event directions obtained by the e.m. and muon detectors.

e.m. reconstruction $\chi^2 \leq 1/\text{d.f.}$, introducing an efficiency $\epsilon \geq 85\%$ has been applied). The agreement of the two measurements is quite good, and the presence of events with $\theta \geq 75°$, which cannot be explained by errors in the angular reconstruction, is confirmed.

To study the origin of such events from their muon content, we concentrate our attention on events with $\theta \geq 75°$, for which the contamination from cosmic ray "conventional" showers is $\approx 1\%$.

In 575 common observation days of the two detector, 37 events have been recorded. Very few of such showers have a negligible content of muons (2 over 37 have zero muons in the μ-detector) i.e. could be μ-poor as expected for μ induced showers in the atmosphere (events quoted (a) in sect. 2). In fact they correspond to events with rather low energy losses in the scintillators, compatible with the absence of muons in the tracking module respectively at 1. and 3.5 s.d.. For all other events, the muon density ($\rho_\mu \approx \bar{n}_\mu / A_\mu \approx 0.3$ muons m^{-2}) is comparable with the total density of charged particles measured by the scintillator modules (comparison is done by using the data of scintillators located at the same distance as the muon detector from the module with highest recorded number of particles, assumed as approximate shower core location). The charged particle density as measured by the scintillator detector ($\Delta E/\Delta E_{m.i.p.}$) and the muon density measured by the tracking detector at the same distances from the shower axis are compared in fig. 9: all experimental points lay inside a ± 2 s.d. interval around the 1 to 1 correlation line. This is expected from "pure" muon showers, indicating a marginal content of electrons.

5 Horizontal Muon Bundles (HMB)

HMB ($N_\mu \geq 3$ and $\theta \geq 75°$) have been detected during 474 observation days at a rate of 8.4 events day^{-1}. Their frequency distribution for different muon multiplicities is shown in fig. 10.

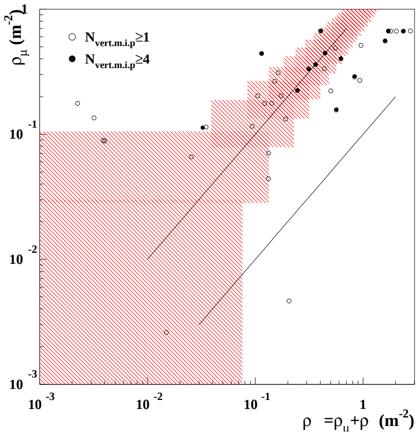

Figure 9: Particle density as measured by the scintillator and tracking detectors. 1 s.d. error boxes are shown. ρ_μ is "saturated" at 0.7 m^{-2}. Empty (full) symbols represent events at 1 (4) vertical m.i.p. level. The $\rho_\mu = 0.1\rho_{ch}$ line is also shown: hadron and neutrino initiated showers are expected to populate the region at the right of such line.

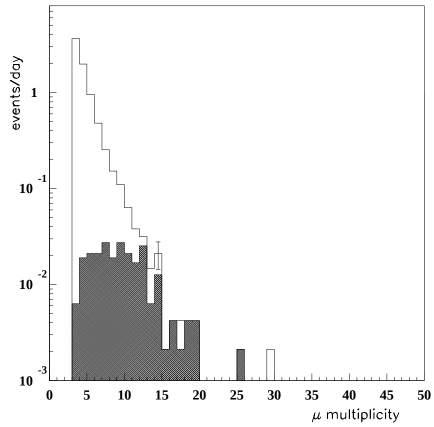

Figure 10: Rate of Horizontal Muon Bundles of different multiplicities. The shaded area corresponds to events in coincidence with the e.m. detector.

These events can be easily interpreted as EAS originated at large distance in the atmosphere, in which the e.m. component has been completely absorbed and the remnant muons are observed.

The expected rate of such events has been calculated by using a simulation code to propagate very inclined Extensive Air Showers in the atmosphere (CORSIKA [29], which includes the geomagnetic field and QGSJET hadron interaction model). Inside the uncertainties on the primary spectrum and composition, the experimental event rate and multiplicity distribution can thus be fairly well explained. It appears that events with detected muon multiplicities $N_\mu \geq 10$ are due to primaries with typical energy $E_0 \approx 10^{17}$ eV, detected at core distances $r \approx 500$ m, the total muon number for such events being $N_\mu \geq 10^4$.

The dashed istogram of fig. 10 represents the events which fire the scintillator trigger too. It is interesting to notice that, as the muon multiplicity increases, the two experiments (HAS and HMB) coincide. For $N_\mu \geq 10$ about 50% of HMBs could be as well considered HASs: the muon triggers include the scintillator triggers. This means that very large zenith angle muon bundles are mostly responsable for the excess of events in the EAS angular distribution (HAS). For smaller muon multiplicities the density threshold in the individual scintillator ($\rho_{th} \approx 0.2$ m^{-2}) reduces, as expected, the scintillator trigger rate.

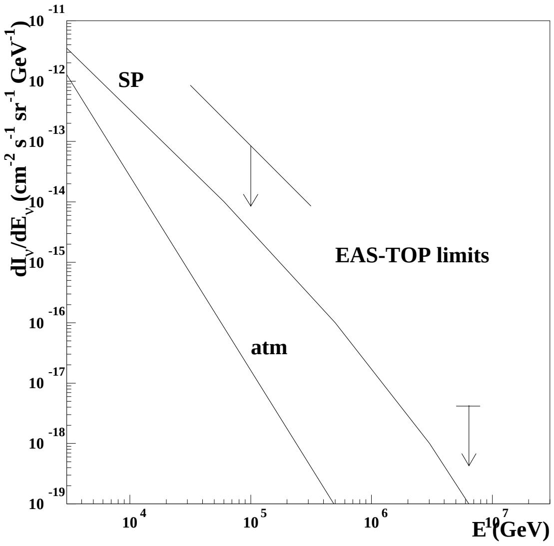

Figure 11: Upper limits to the intensity of the cosmic neutrino flux obtained from the EAS-TOP HAS analysis. 'SP' represents the expected flux from Szabo and Protheroe, 'atm' the flux of neutrinos produced by c.r. interactions in the atmosphere.

6 Conclusions

The muon content of scintillator triggered events (showing that the muon density includes the total density of the ionizing components), and the rate of muon bundle triggers (that for large enough muon densities correspond to the scintillator triggers) lead to the conclusion that HAS are largely dominated by muon showers. The e.m. component in such case is essentially due to local muon interactions with small energy losses (delta rays, direct pairs).

Muon showers are generated by high energy primaries interacting very far in the atmosphere (i.e. events quoted (b) in the introduction).

From the point of view of the technique, beside an optimum angular resolution, the possibility of measuring the e.m. and muon components provide a fundamental tool for identifying candidate neutrino primaries.

UHE cosmic neutrinos through reactions (1) - (3) produce showers with muon content "lower" or "similar" to ordinary c.r. showers. In fig. 9 a $\rho_\mu = 0.1\rho_{\mu+e}$ line is drawn, as an upper limit to the muon content of c.r. hadron, and therefore neutrino induced showers. Also in fig. 9 the muon density vs. (muon+electron) density is shown for events with energy losses triggering the scintillators above the 1 effective particle level at $\theta \geq 75^0$. For none of such events the quoted limit is exceeded, i.e. the e.m. component is 10 times larger than the muon one, as would be expected also for neutrino induced events. From such upper limit in the 575 days of common operation of the muon and e.m. detectors, we derive as upper limit to the diffuse neutrino intensity (at 90 % c.l.):

$$I_\nu(E_\nu > 10^5 GeV) < 8.5 \times 10^{-9} cm^{-2} s^{-1} sr^{-1}. \quad (8)$$

For the differential flux in the energy range $E_0 \approx 10^5$ GeV, and for a spectrum $S(E_\nu) \propto E_\nu^{-2}$ we obtain:

$$\frac{dI_\nu}{dE_\nu} < 8.5 \times 10^{-14} (\frac{10^5}{E_\nu})^2 cm^{-2} s^{-1} sr^{-1} GeV^{-1} \quad (9)$$

and for resonant events (for $E_{\bar{\nu}_e} = 6.410^6$ GeV):

$$\frac{dI_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} < 4.3 \times 10^{-18} cm^{-2} s^{-1} sr^{-1} GeV^{-1}. \quad (10)$$

Concerning neutrino flavours, the technique is complementary to the underwater one (mainly based on muon detection), being more sensitive to channels providing a large amount of energy to the e.m. component (i.e. e.g. to the ν_e flux).

In case of neutrino mixing, limits (8) and (9) should be reduced of $\approx 30\%$.

In fig. 11 upper limits (9) and (10) are shown together with the calculated intensities of ref. [19].

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