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Characterization of inclined showers induced by neutrinos

M. Ave[1]**, L. Cazón**[2]**, R. A. Vázquez**[2]**, and E. Zas**[2]

[1]Dept. of Physics and Astronomy, University of Leeds, Leeds LS2 9JT, UK
[2]Dept. de Física de Partículas, Universidade de Santiago, 15706 Santiago de Compostela, Spain

Abstract. We have simulated neutrino showers for different energies, incident angles and interaction depths. Parameterizations for the lateral distribution function and for the number of particles at ground level are given. Effect of geomagnetic deviations of muon density patterns for neutrinos are compared to cosmic rays.

1 Introduction

The origin of the high energy cosmic rays ($E > 4 \times 10^{19}$ eV) is one of the most important open problems in astroparticle physics. Models abound for the explanation of these cosmic rays and the best way to discriminate between these models is that of composition. Most models also predict an associated neutrino flux. In spite of the implicit uncertainties in these predictions, a measurement of the high energy neutrino flux would allow to discriminate and strongly constrain whole classes of models for the origin and propagation of the highest energy cosmic rays.

The observation of inclined showers has been suggested long ago (Berezinsky and Zatsepin , 1969) as a possible technique to measure the high energy neutrino flux (and in general, of any other deeply penetrating particle). By searching for inclined showers deep showers initiated by such particles should be different from showers induced by ordinary cosmic rays. These start early in the atmosphere and are largely attenuated before reaching the ground. Limits for neutrino fluxes have already been published using the non-observation of inclined showers (D.J. Bird et al., 1993; Blanco-Pillado et al., 1997).

Nowadays, with the advent of a new generation of array detectors (Zas, 2001) the detection of neutrino induced horizontal showers can become a reality (K.S. Capelle et al., 1998). The challenge requires not only the measurement and reconstruction of inclined showers (a problem which by itself is rather demanding, and that has delayed the field for several years) but also the discrimination between ordinary (*i.e.* proton, nuclei or photon induced) inclined showers from those induced by neutrinos. Most of the differences between neutrino and cosmic ray showers are a consequence of the difference in the first interaction point. Neutrinos have a low cross section and therefore interact with an essentially uniform distribution in atmospheric depth. The acceptance of any detector to neutrino events will therefore greatly depend on the accuracy with which deep showers can be identified.

This article is an attempt to quantify these effects and produce useful parameters to discriminate both types of showers. It reports on preliminary studies and parameterization of the properties of the muon component of neutrino induced showers neglecting geomagnetic field effects. It has been shown that magnetic effects can be implemented *a posteriori* (M. Ave et al., 2000, 2001b). A more complete study, including the electromagnetic component will be presented elsewhere (M. Ave et al., 2001a). In section 2 we will study the global properties such as total number of muons and the energy spectrum as a function of the depth. In section 3 we will study the possible geometric effects which may alter the circular symmetry of the shower. In section 4 we will study several effects which have to be taken into account for a description of the showers and we will give examples of the lateral distribution of muons for neutrino showers. Finally we will close in section 5 by giving some conclusions.

2 Global properties

An ordinary cosmic ray shower of a high zenith angle has an “early” first interaction point with two main effects. Firstly, it produced at high altitudes and therefore, particles have to travel through large amounts of matter before reaching the ground. Most of the electrons and photons in a shower are due to electromagnetic subshowers induced by photons from neutral pion decays. Shower maximum is produced at a characteristic depth of around 1000 g cm^{-2}, after which the

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Correspondence to: R. A. Vázquez
(vazquez@fpaxp1.usc.es)

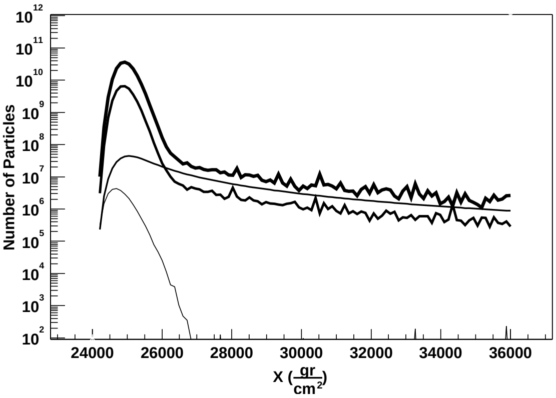

Fig. 1. Total number of photons (upper thick line), electrons (lower thick), muons (medium), and pions (thin) as a function of depth for a neutrino induced shower initiated at depth ~ 24000 g cm^{-2} and in a constant density atmosphere. The initial energy is 10^{19} eV.

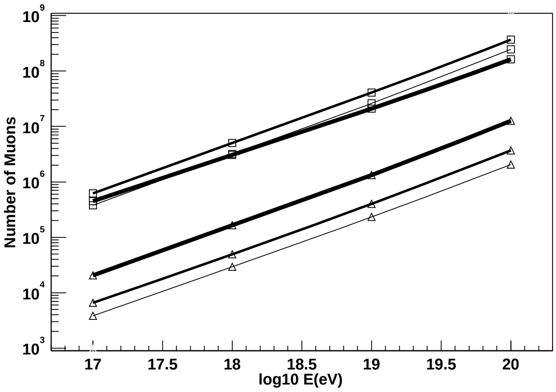

Fig. 2. Number of muons as a function of primary energy for a neutrino induced shower initiated at depth 250, 500, 750 g cm^{-2} (thin, medium, thick lines) for zenith angles 60° (upper curves, squares) and 85° (lower curves, triangles). The number of muons for 85° has been divided by 10 to make the figure clearer.

front is exponentially absorbed. The muonic component of the shower can travel however to ground level provided the muons have sufficient energy dominating the shower front at depths well beyond shower maximum. Secondly the muons can be very much deflected by the geomagnetic field because they have to travel very long distances. This produces strong characteristic distortions of the muon density profiles which have been the object of specific studies (M. Ave et al., 2000).

Neither of these two effects occurs for a sufficiently deep shower as can be induced by a neutrino. A deep shower will have an important electromagnetic component, at ground level, with a number density that will exceed by a large factor that of the muons. The magnetic deflections will be small, of the same order as in a vertical shower and the axial symmetry of the shower will be approximately preserved. As a result the particle densities in the *transverse plane*, that is a plane perpendicular to shower axis at ground level, will be circularly symmetric.

We have simulated inclined showers initiated at different depths in the atmosphere using the Monte Carlo code Aires (Sciutto, 1999). We use a proton primary in all cases, *i.e.* we assume that a neutrino shower can be approximated by a proton shower which starts at a slightly earlier depth. The approximation is enough for our present purposes. The primary energy was varied between 10^{17} to 10^{20} eV and we have used a thinning level of 10^{-5} which gives smooth enough distribution for muons.

In Fig.1 we show the longitudinal development of a 10^{19} eV shower developed in a constant density atmosphere and injection point at 24000 g cm^{-2} of depth. The electrons and photons are absorbed but there is a residual component which is "fed" by muon decay and interaction. The mild attenuation of the muon number is controlled by muon decay and energy loss.

The number of muons as a function of energy for different injection depths and zenith angles are shown in Fig.2. The dependence on primary energy of the number of muons at ground can be seen to be approximately independent of zenith angle and injection depth and can be parameterized as E^{β} where $\beta \sim 0.9$ is a constant. The approximation is better the larger the zenith angle. In Fig.3 the number of electrons and positrons as a function of energy for the same zenith angles and injection depths is also shown. Here the number of electrons depends with energy and injection depth in a more complicated fashion and can not be well parameterized by such a simple scaling law. This is because a 60° shower at an injection depth of 750 g cm^{-2} gives a shower maximum very near ground level.

The total number of muons and their energy spectrum can be easily understood with a toy model for muon propagation. Let's assume that muons propagate in a constant density atmosphere and loose energy continuously. If we start with N muons of energy E_0, after traversing a distance l the number of muons will decrease according to:

$$\frac{dN}{dl} = -\frac{N}{\lambda(E)} \tag{1}$$

where $\lambda(E) = E/m_\mu\tau$ is the decay distance of a muon of energy E, τ and m_μ are respectively the muon decay time and mass. The muon energy decreases mainly through approximately continuous ionization losses according to:

$$E(x) = E_0 - \alpha x \tag{2}$$

where $x = \rho_0 l$ is the depth traveled by the muon, ρ_0 is the air density, and $\alpha \sim 2$ MeV [g cm^{-2}]$^{-1}$ is the stopping power for air. Integrating the above equation we obtain

$$N(x) = N_0(1 - \frac{\alpha x}{E_0})^{\kappa} \tag{3}$$

where $\kappa = \frac{m_\mu}{\alpha\rho_0\tau} \sim 0.8$ using the atmospheric density at sea level. This simple equation correctly predicts the behavior of the total number of muons and the average energy. If muons

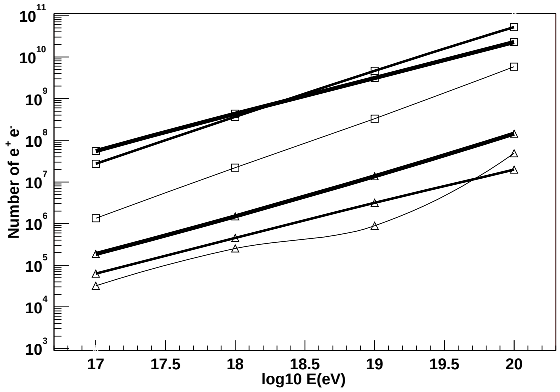

Fig. 3. Number of electrons as a function of primary energy for a neutrino induced shower initiated at depth 250, 500, 750 g cm^{-2} (thin, medium, thick lines) for zenith angles 60° (upper curves, squares) and 85° (lower curves, triangles).

are produced initially with a spectrum $dN/dE = AE^{-\beta}$ after going through a matter depth x the spectrum becomes:

$$\frac{dN}{dE} = A(\alpha x)^{-\beta}(1+\xi)^{-\beta-\kappa}\xi^{\kappa} \tag{4}$$

where $\xi = E/(\alpha x)$. The spectrum gets cutoff at low energy because of muon decay. At the low (high) energy limit the spectrum behaves as E^{κ} (is unmodified). This is shown in Fig.4 where the muon spectrum is shown as a function of the energy for different zenith angles. From this equation we obtain that the total number of muons behaves as:

$$N = \int_0^{\infty} dE \frac{dN}{dE} = K(\alpha x)^{1-\beta} \tag{5}$$

where K is a constant. This results agrees well with the calculations using Monte Carlo and implies, for instance, that for not too large zenith angles the total number of muons goes as $\cos\theta^{\beta-1}$. Also we get that the average energy of muons is given by:

$$< E >= c\,\alpha\,x \tag{6}$$

where c is a number of order unity. This estimate also agrees well with the results of a more detailed Monte Carlo.

3 Geometric effects

The analysis of asymmetries is an important ingredient in the identification of conventional showers as was pointed out in the introduction. Even in the absence of geomagnetic field, the lateral distribution function presents asymmetries due to several effects. Clearly there is an asymmetry because the shower which is assumed to be axially symmetric is projected onto the ground plane. This is trivial and can be eliminated by a projection. We are referring to residual asymmetries when the effects of the projection are eliminated which are best studied in the transverse plane. It is important to study the origin of these asymmetries in order to understand the differences between neutrino and proton induced showers.

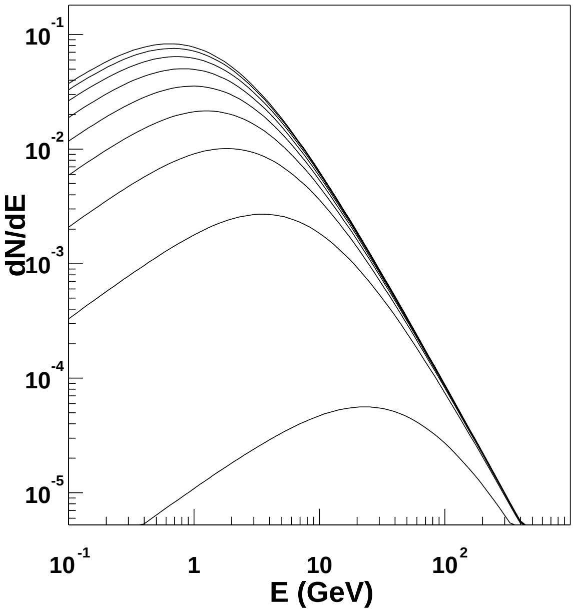

Fig. 4. Energy spectrum of muons for different propagation distances. Muons with a fixed spectrum, E^{-2}, are injected at an altitude of $h = 10$ km and propagated at a zenith angle $10, 20, 30, \ldots, 90^{\circ}$ from top to bottom.

Let's assume an inclined shower produced at altitude h above the ground level and at zenith angle θ. The distance from production point to the ground is taken to be l. We will set the y–axis in the transverse plane in a direction defined by its intersection with a plane perpendicular to the ground that contains the shower axis. Assuming the transverse plane goes through the impact point of the shower axis, when a particle has $y > 0$ it will reach the transverse plane before reaching the ground, while for $y < 0$ the particles find ground level before reaching the transverse plane.

For inclined showers, even neglecting the geomagnetic field effects, the muon lateral distribution function (LDF) is not circularly symmetric. The residual asymmetry is mainly due the differential decay of muons: For instance, at a zenith of 60° there is a 13% asymmetry in the number of muons arriving with $y > 0$ compared with those arriving at $y < 0$, this number increases to 43% for 85° and injection depth of 23 km. The asymmetry in a horizontal axis is however negligible in the absence of magnetic field. We have checked that this asymmetry is well reproduced by just considering the above mentioned effects. Muons in the $y > 0$ part travel more distance than in the $y < 0$ part to reach the ground and therefore we expect less. Defining the asymmetry as $A = (N_+ - N_-)/(N_+ + N_-)$, where $N_{\pm} = N(y <> 0)$ we find, using the above estimate for the number of muons

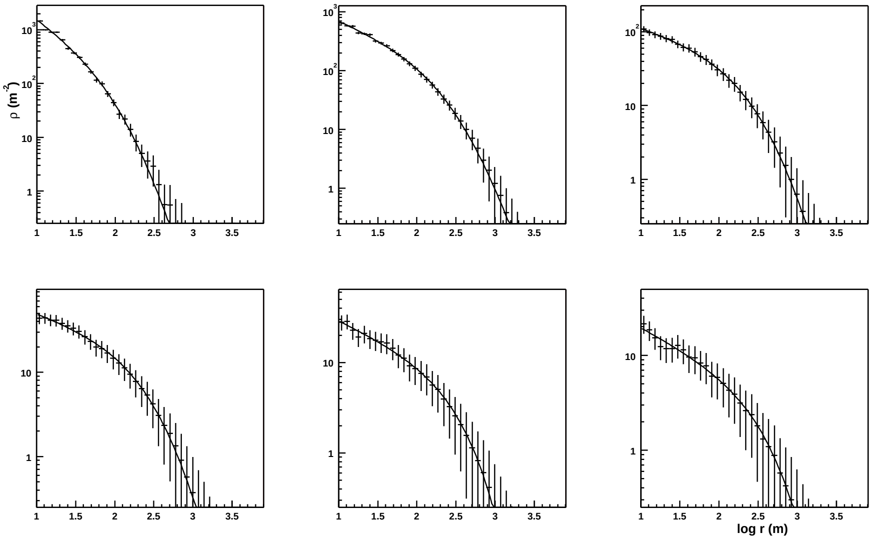

Fig. 5. Muon lateral distribution function for a 10^{19} eV shower for depths 457, 1528, 2600, 3671, 4742 and 5814 g cm^{-2}. A constant atmospheric density corresponding to ground level has been assumed.

as a function of the distance:

$$A = (1-\beta)\frac{R_m \tan\theta}{l} \qquad (7)$$

where l is the distance traveled by the muons and R_m is a characteristic distance for the lateral spread of the shower. For large zenith angles this asymmetry increases and can become quite large.

There are a number of additional asymmetries which have not been taken into account in the above estimate. The most important one is a shadow effect due to the Earth's curvature and is relevant only for zeniths above $\theta \sim 80^\circ$ and for particle densities at large distances to the shower axis. There is at least an additional asymmetry due to the actual gradient of density in the atmosphere. It also applies in the y-direction but it is expected to be negligibly small.

4 Lateral distribution of muons for neutrino induced showers

Taking into account the above estimates we have described the muon lateral distribution functions (LDF) for neutrino induced showers in the transverse plane. They can be fitted using a NKG type function and the exponents can be calculated. In Fig.5 we show the results of the fit for several depths. As the shower penetrates to further depths the muon LDF becomes flatter at first, a well known effect, but once a given depth is reached, the lateral distribution hardly changes with depth. This can be understood combining the above estimate and the fact that the average muon energy is inversely related to its distance to shower axis (this is discussed for proton showers in (M. Ave et al., 2000, 2001b)). We obtain:

$$\frac{dN}{dr} = \frac{A(\alpha x)^{1-\beta}}{R_m}\left(\frac{r}{R_m}\right)^{\beta-2}\left(1+\frac{r}{R_m}\right)^{-\beta-\kappa} \qquad (8)$$

where here $R_m = p_t/(\alpha\rho_0)$ is the characteristic lateral spread and p_t is the transverse momentum of the produced muon. Our simple model predicts the muon LDF to be of an NKG form. The coefficients are seen to be independent of depth along shower axis. This is indeed a feature observed in the simulations and can be seen on Fig.5.

5 Conclusions

We have developed a toy model for the development of the muon density patterns at ground level produced by the hadronic shower resulting from a neutrino interaction. This is considered as a first step into the search for discriminating features between inclined showers produced by neutrinos deep into the atmosphere and those produced by ordinary cosmic rays.

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