EeV Hadronic Showers in Ice: The LPM effect.

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Abstract

We study the longitudinal development of hadronic showers in water and ice for energies up to 100 EeV. We present results of a hybrid Monte Carlo method developed for the purpose of simulating those showers. We show parameterizations of the longitudinal development of hadronic showers in ice and we investigate the implications of the LPM effect on shower development. The results obtained are relevant for the detection of high energy cosmic rays and neutrinos in large scale detectors that use water as Cherenkov medium.

1 Introduction

High Energy neutrino detection is one of the inminent breakthroughs in particle astrophysics (AMANDA 1998). Gamma Ray Bursts, Active Galactic Nuclei and topological defects are quite likely sites where neutrinos with energies up to 10^{19} eV may be created (Halzen 1995) and in any case high energy neutrinos have to be produced in interactions of high energy cosmic rays with matter or radiation. Neutrinos produced in interactions of the highest energy cosmic rays with the galactic plane and the Cosmic Microwave Background are practically guaranteed. Several experiments are being developped or constructed using large natural volumes of water or ice as the target medium for neutrino interactions. Most of them are conceived to exploit the long range of the muons created in charged current interactions and use Optical Modules to detect the Cherenkov light from the muons. By looking for upcoming events, the atmospheric muon background can be succesfully removed.

At high energies however the earth becomes opaque for high energy neutrinos and they should be expected to be arriving from the "downgoing hemisphere", that is from vertically downwards to little beyond the horizontal direction. To remove the background in this direction it is necessary to have energy resolution since the atmospheric muon rate drops rapidly with muon energy and provided the energy is higher than 10 PeV hardly any muons are expected. For this purpose the detection of the Cherenkov light from all the charged particles in the showers produced by high energy neutrino interactions can be of great help.

Hadronic showers are mostly started by hadrons created in the fragmentation of the nuclear debris in both charged and neutral current Deep Inelastic Scattering (DIS) neutrino interactions as well as in Z^0 resonant production. Most of the models of neutrino production, predict a ratio $\nu_\mu/\nu_e \sim 2/1$ just from naive channel counting in pion decays. In consequence $\sim 75\%$ of the potentially observable showers will be initiated in the hadronic vertex of the DIS interaction. The development of high energy hadronic showers in ice will play an important role in neutrino detection.

For energies above $E_{\rm LPM}$ (2 PeV in ice) the cross sections for pair production and bremsstrahlung are suppressed due to the Landau-Pomeranchuk-Migdal (LPM) effect. At sufficiently high energies, the characteristic interaction length becomes larger than the interatomic distances and the collective atomic potentials affect the static electric field responsible for the interaction. The LPM was earlier shown to strongly affect the development of electromagnetic showers in ice above 20 PeV (Alvarez 1997). Electromagnetic showers of those energies are significantly deviated from the Greisen parameterizations with an increase in shower length[1] with shower energy E_0 which can be approximately parameterized as $E_0^{1/3}$. In this work we study the influence of the LPM effect on the development of hadronic showers initiated by neutrino interactions in ice. Our results are also relevant for the calculation of the coherent radio pulses generated by the excess negative charge developed by showers in dense media, but this will be discussed in a separate presentation (Alvarez 1999).

[1] Defined as the length along which shower size exceeds 70% of its maximum.

2 Hadronic showers: Simulations and results

An hadronic shower can be thought of having a penetrating core containing mostly pions which continually produces electromagnetic subshowers fundamentally through π^0 decay in two photons. In dense media charged pions are expected to interact before decaying. In a simple model of shower development, we can consider that after a neutrino interaction the energy of the produced hadrons is roughly the energy transferred to the nucleus (yE_ν where E_ν is the neutrino energy in the LAB system), divided by the multiplicity of the interaction, assuming equipartition of energy. For a 1 EeV energy transfer to the hadron, the average multiplicity is $\sim$ 14 and the average energy of the photons produced by π^0 decays will be of the order of 35 PeV. These photons will initiate electromagnetic subshowers which are expected to be little affected by the LPM effect (Alvarez 1997). One can naively think that as yE_ν increases and so does the photon energy the electromagnetic subshowers will exhibit strong LPM behaviour with the typical elongations in their longitudinal development. In ice however this is not the case since π^0 interaction dominates over decay for energies above about 6.7 PeV. It is then expected that even 100 EeV hadronic showers initiated in neutrino interactions will show LPM effects in a mitigated form.

To confirm these interpretations we have simulated showers initiated in the hadronic vertex of a neutrino interaction. We have modelled the hadronic shower using the average multiplicity and the distribution of momentum of the secondaries measured in HERA (ZEUS 1999). For this purpose we have developed a fast hybrid Monte Carlo which simulates 1 dimensional showers down to a certain crossover energy, at which the subshowers produced are taken from tested parameterizations. For the purely electromagnetic subshowers we use the Greisen and NKG parameterizations. For the hadronic showers initiated by low energy protons, pions or kaons we have developed our own set of parameterizations which are valid for energies below 100 TeV. The parameterizations together with the results of the simulations for proton showers are shown in Fig. 1. The longitudinal development has been fitted to a function similar to the one used in (Gaisser 1990) of the form:

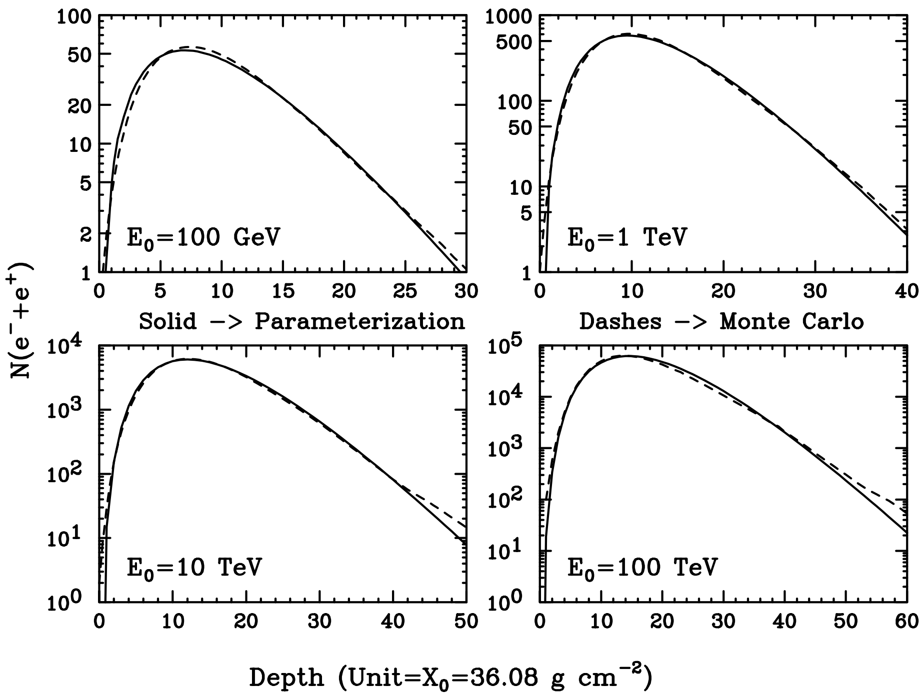

Figure 1: Longitudinal development of proton showers in ice. The solid line represents the fit to a Monte Carlo (dashed lines).

$$N(t) = S_0 \frac{E_0}{E_c} \left(\frac{X_{\max} - \lambda}{X_{\max}}\right) e^{\frac{X_{\max}}{\lambda} - 1} \left(\frac{t}{X_{\max} - \lambda}\right)^{X_{\max}/\lambda} e^{-t/\lambda} \,, \tag{1}$$

where $X_{\max} = X_0 \log \frac{E_0}{E_c}$ and S_0, X_0, λ y E_c are free parameters. Their values for different types of primaries, are shown in table I.

Primary	Proton	Pion	Kaon
S_0	0.11842	0.036684	0.0298
X_0 (g cm^{-2})	39.562	36.862	36.997
λ (g cm^{-2})	113.03	115.26	119.61
E_c (GeV)	0.17006	0.052507	0.048507

Table I: *Values of the parameters for the fit to expression 1 of the longitudinal development of hadronic showers in ice.*

We have studied hadronic showers initiated in neutrino interactions in ice for energies up to 100 EeV. We have chosen to simulate several quantities that are relevant for Cherenkov emission such as the fraction of energy going into electromagnetic subshowers, which is seen to increase with shower energy reaching values as high as 94% at EeV energies (Alvarez 1998), and the total and excess charge tracklengths, which are respectively dominated by the contribution of electrons and positrons and by the excess of electrons over positrons. For the latter purpose we have used parameterizations obtained in (Zas 1993).

In Fig. 2 we show the longitudinal development of hadronic showers. Below 1 EeV the longitudinal development "scales" with shower energy and it is not affected by the LPM effect in agreement with the interpretation given above. This is not surprising. Due to the high multiplicities involved in hadronic interactions the energy of the π^0's is considerably reduced with respect to the primary energy. The average energy of the π^0's (as produced by SIBYLL) in a proton-proton collision at 10^{19} eV in the LAB frame is of the order of 17 PeV. Moreover we have obtained that only about 10% of the π^0's of energy greater than 20 PeV, produced in proton-ice interactions, are expected to decay in ice producing photons of energy above 20 PeV. As a conclusion showers are not elongated despite being produced by primaries with energies well above $E_{\rm LPM}$.

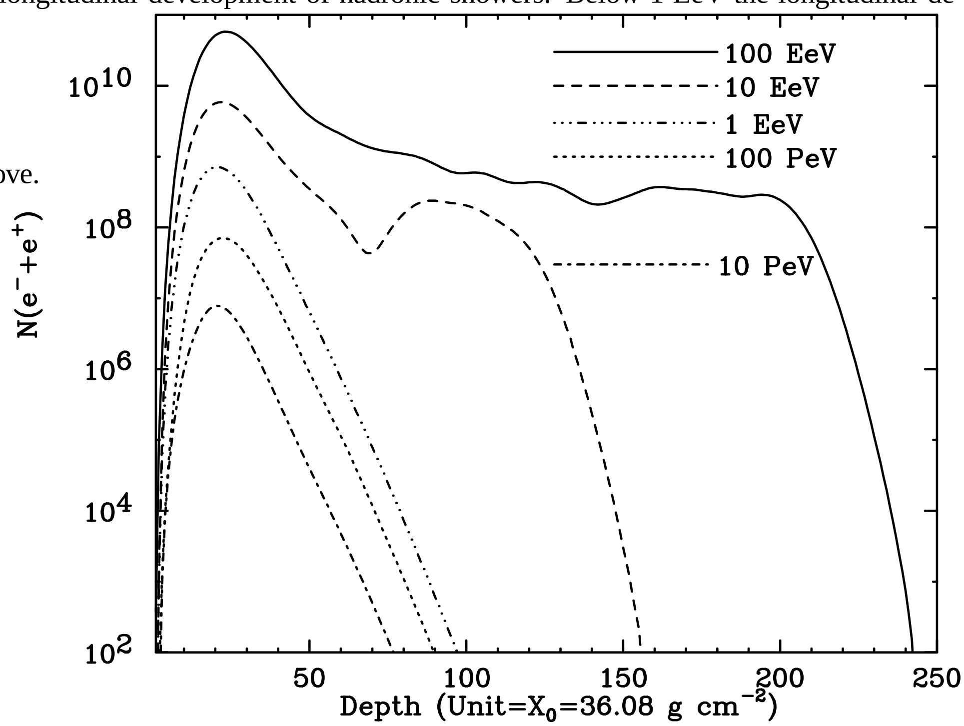

Figure 2: Longitudinal development of hadronic showers initiated by neutrino interactions in ice.

We have found that a fraction of showers above 1 EeV have deep tails characteristic of LPM showers. These tails are produced by the electromagnetic decays of resonances with short lifetimes that are created in early interactions in the shower. In particular we found that the η and η' contribute most to this effect. Although the result is model dependent, it is very interesting since if these showers are ever observed, they would provide experimental information on the production of resonances and their decays in electromagnetic particles.

The probability of having a neutrino hadronic shower with an LPM tail can be computed with the aid of Figure 3, in which we plot the integral energy distribution of the most energetic photon obtained in showers initiated in the hadronic vertex of a neutrino interaction. The plot represents the probability of having a photon with a energy ($E_\gamma = xE_0$) greater than xE_0 where E_0 is the shower energy. From the plot we can see that 10 EeV showers have a probability of 50% of having a photon with energy greater than 100 PeV which will produce a long LPM tail. Approximately the same distribution is obtained for a 100 EeV shower, from which it can be deduced that it is practically impossible to have a 100 EeV shower without LPM effect.

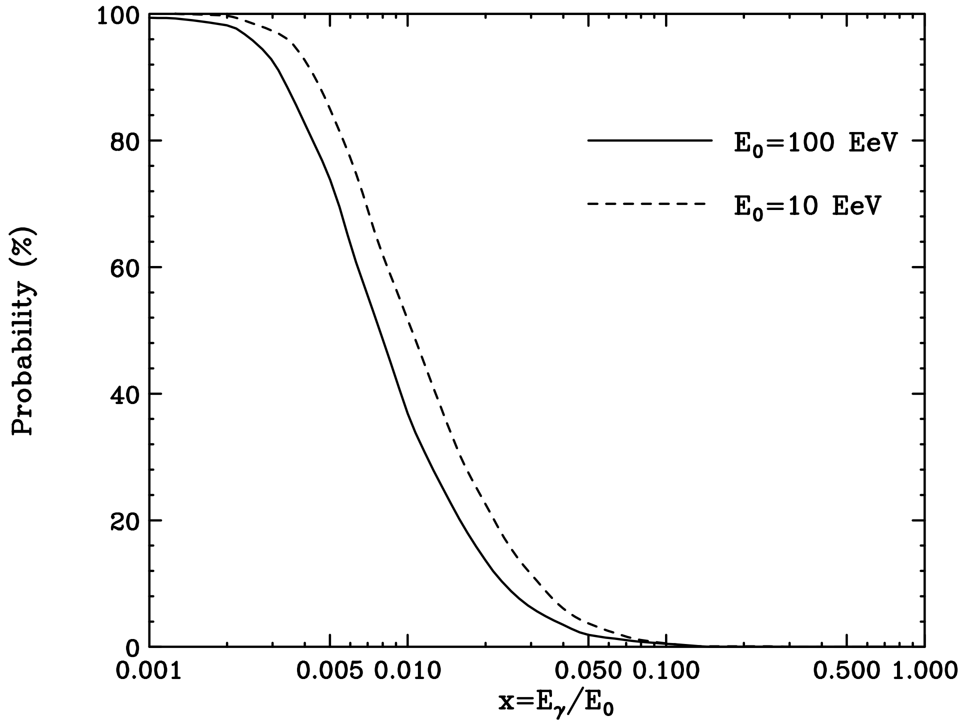

Figure 3: Probability of having a photon of energy greater than $E_\gamma = xE_0$ in a neutrino hadronic shower of energy E_0.

In summary, we have shown that hadronic showers produced in neutrino interactions are very different from electromagnetic showers being much less affected by the LPM effect. We can expect the hadronic showers induced by neutrinos of energy below 1 EeV/y where y is the fraction of energy transferred to the hadron to have a quite ordinary longitudinal development without the typical LPM tails. Our results are relevant for radio emission from hadronic showers which is treated in (Alvarez 1999)

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