Nuclear Instruments and Methods in Physics Research A 742 (2014) 278–281

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Muon and neutrino collimation in extensive air shower cores

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ARTICLE INFO

Available online 6 November 2013

Keywords:
Collimation
Neutrinos
Muons
CORSIKA
QGSJET

ABSTRACT

Detailed simulations of extensive air showers have been carried out with the CORSIKA program in order to evaluate the energy brought by the different shower components at ground level and transmitted underground. A special attention is given to the angular distributions and to the collimation of beams penetrating deep underground or underwater. The natural collimation of high energy particles in extensive air shower cores results mainly from the ratio between the transverse and the longitudinal momenta of secondary particles generated in the earliest interactions. This collimation is partly conserved by the high energy muons and neutrinos. It is comparable to the magnetic focusing of charged pions and kaons decaying in tunnels of suitable length after production in accelerators. Such is the case for neutrino beams of KEK J-PARC/T2K (300 km to Kamiokande), OPERA (730 km to Gran Sasso) and MINOS (735 km to Irvine Mine).

1. Introduction

Nowadays several facilities are able to propagate inside the Earth crust neutrino beams after the decay of charged pions and kaons in tunnels of suitable length following the pion collimation with magnetic horns. Such is the case of KEK J. PARC and T2K (250 and 395 km to Kamiokande), OPERA and MINOS (732 km to Gran Sasso and Irvine Mine, respectively). This work aims to identify inside the extensive air shower (EAS) cores the natural conditions of collimation of pion beams able to replace the magnetic focusing. We have focused on the neutrino and muon EAS components penetrating deep underground. Their main features such as radial distributions, energy spectra, and angular distributions are calculated for primary cosmic-ray protons and iron nuclei in the energy range from 10^5 to 10^9 GeV. With respect to collimation, only neutrinos and muons close to the shower axis are considered.

To carry out EAS simulation, we have used CORSIKA program version 6.500 [1] coupled to the QGSJET model describing the multiple production [2]. The most important part of muons and neutrinos reaching ground level come from the decay of charged pions and kaons. CORSIKA options involved in the simulation are the following:

- Hadronic interaction model: QGSJET
- Primary particle: proton, iron
- Primary particle energy: 10^5–10^9 GeV
- Analysis concentrated on: neutrinos and muons
- Energy cutoff: 100 GeV
- EAS core: radius of 10 m.

The choice of a common lower energy threshold of 100 GeV (or above) facilitates the observation of possible features which could be correlated to the primary interaction properties.

2. Results

2.1. Neutrino and muon multiplicities

When studying the neutrino and muon multiplicities, one can notice that at low energy, we have groups of about 100 muons for 49 neutrinos in the case of primary protons (Table 1). This ratio changes to 100 muons for 37 neutrinos at higher energies. When the primary proton or iron energy increases from 10^6 to 10^9 GeV, the average ratio N_μ/N_ν increases approximately from 2.3 to 2.7. When comparing primary protons to primary iron nuclei, we observe that the ratio of the corresponding neutrino and muon multiplicities do not vary too much and remain equal to about 1.6 and 1.5, respectively, when the primary energy changes from 10^6 to 10^9 GeV.

2.2. Lateral and energy center radius distributions

The neutrino and muon lateral distributions are displayed on Fig. 1 for primary cosmic-ray protons and iron nuclei at energies of 10^7 and 10^9 GeV. When the primary particle energy increases, one

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http://dx.doi.org/10.1016/j.nima.2013.10.071

Table 1
Neutrino and muons multiplicities.

	Average N_ν			Average N_μ		
E_0 (GeV)	10^5	10^7	10^9	10^5	10^7	10^9
Proton	2.63	116	6990	5.35	295	19,040
Iron	0.83	195	10,730	3.46	456	27,870

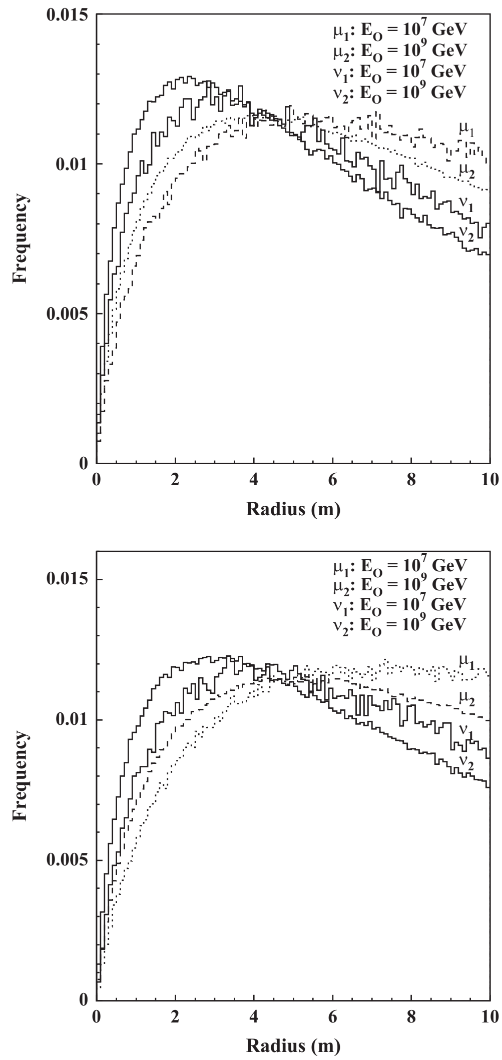

Fig. 1. Neutrino (ν) and muon (μ) lateral distributions for primary cosmic-ray protons (top) and iron nuclei (bottom) at 10^7 and 10^9 GeV.

can see that the majority of neutrinos and muons remain concentrated in the few meters from the shower axis. This result is confirmed by Fig. 2 which gives the neutrino and muon distributions of the energy center radius, R_c, at 10^8 and 10^9 GeV. R_c is given by the relation:

$$R_c = \sqrt{\left(\frac{\sum x_i \cdot E_i}{\sum E_i}\right)^2 + \left(\frac{\sum y_i \cdot E_i}{\sum E_i}\right)^2} \quad (1)$$

where (x_i, y_i) and E_i are the neutrino/muon coordinates and energy, respectively. Moreover, one can notice that the energy center radius distribution is wider for neutrinos than muons at same energies (Fig. 2). Similar results are obtained for primary iron nuclei.

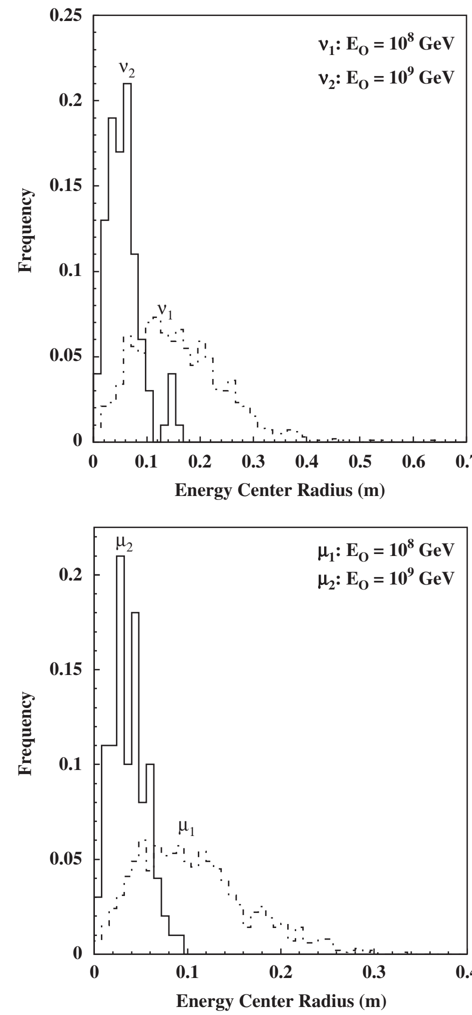

Fig. 2. Neutrino (top) and muon (bottom) energy center radius distributions at 10^8 and 10^9 GeV for primary cosmic-ray protons.

2.3. Angular distributions

Fig. 3 presents the neutrino and muon angular distributions. One can observe that the higher the energy the wider the distribution. This is due to the increase of neutrino and muon multiplicities at high energy and hence the increase of fluctuations. However, the mean zenith angle is practically constant over the entire energy range for neutrinos as well as and muons in both cases of primary protons and iron nuclei (Fig. 4). The neutrinos and muons remain very collimated around the shower axis with very small zenith angles for both primary protons and iron nuclei.

2.4. Energy distribution

Fig. 5 shows the variation of the neutrino and muon mean energy with the primary energy for protons and iron nuclei. At low energy, this quantity is approximately constant (~1 TeV) for both primary protons and iron nuclei. At very high energy (10^9 GeV), this quantity is higher for iron nuclei than protons. However, due to the large error bars, this difference is not really significant.