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UHE and EHE neutrino induced taus in the Earth

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Abstract. The propagation of extremely energetic ν_τ's and τ's through the Earth is studied by means of a detailed Monte Carlo simulation. All major mechanisms of $\nu_\tau$interactions and τ energy loss as well as all its relevant decay modes are properly taken into account. The probability for τ's emerging from the Earth is determined for several energy thresholds.

1 Introduction

The Earth is completely transparent to neutrinos in the GeV energy range but it is expected to become opaque for sufficiently high neutrino energy. As to muon neutrinos, the charged current (CC) interaction length inside the Earth equals Earth's diameter for energy around 40 TeV (Gandhi et al., 1996). It has been recently pointed out (Fargion, 1997; Halzen ad Saltzberg, 1998; Iyer et al., 2000; Becattini and Bottai, 2001) that the behavior of τ-neutrinos, whose existence should be guaranteed in a neutrino-oscillation scenario, should be significantly different from ν_μ and ν_e. Whilst muon and electron neutrinos are practically absorbed after one CC interaction, the τ lepton created by the ν_τ CC scattering may decay in flight before losing too much energy, thereby generating a new ν_τ with comparable energy. Hence, ultra high energy τ-neutrinos should emerge from the Earth instead of being absorbed. At the same time some of the τ produced in the Earth, because of their relative long decay length at high energy, could emerge from the Earth surface and eventually decay inside the atmosphere (fig. 1). Such kind of events could be detected by atmospheric shower detectors as upward going showers. For a correct evaluation of the energy of τ's emerging from the Earth, it has to be taken properly into account ν_τ interactions as well as τ energy loss and decay. In the present work a detailed Monte Carlo calculation of $\nu_\tau - \tau$ system propagation through the Earth has been performed for energy up to 10^{22} eV including the τ energy loss.

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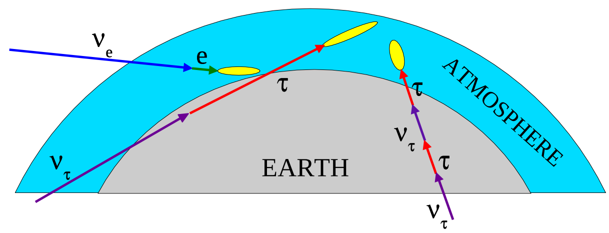

Fig. 1. Graphical examples of atmospheric showers induced by neutrinos. Electron neutrinos in atmosphere will give the most strength signature. Upward going ν_τ's could be detected as upward going showers induced by τ decay.

2 Simulation

The Montecarlo simulation has been performed following neutrinos and charged leptons along their path inside the Earth. The Earth model considered is the preliminary the Earth model of A.M. Dziewonski and D.L. Anderson, 1981. During particle propagation the occurrence of interactions relevant for energy loss, decay or leptons production has been simulated by a unidimensional approach. The only secondary particles which have been followed are the ν_τ's produced by τ decays and τ's arising from ν_τ charged current interactions. Deep inelastic neutrino-nucleon scattering is the dominant interaction of energetic neutrinos into conventional matter. Charged and neutral current differential cross sections used in this work (see Becattini and Bottai 2001 for more details) have been calculated in the framework of QCD improved parton model. We have used the parton distribution set CTEQ3-DIS(H. Lai et al., 1995) with NLO-DGLAP formalism used for Q^2 evolution of parton distributions $q(x, Q^2)$ and assuming for very low momentum fraction x the same functional

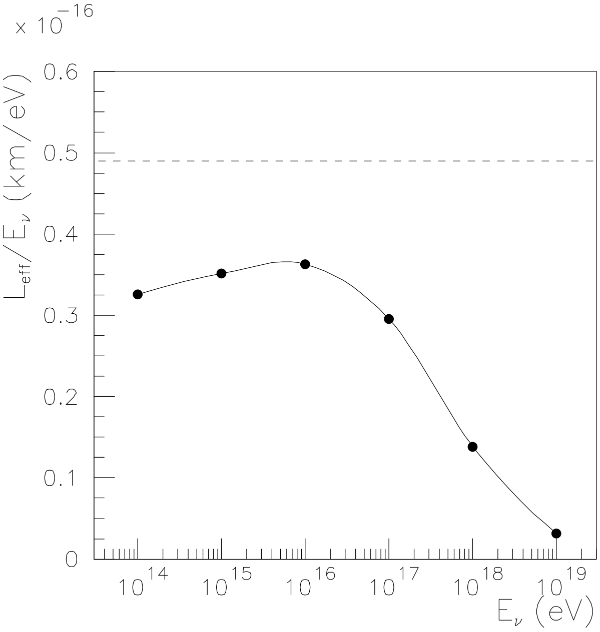

Fig. 2. Effective depth for creation of exiting τ's. The dotted line shows the expected result for no interacting τ's created with the same neutrino energy and decaying after one τ decay length.

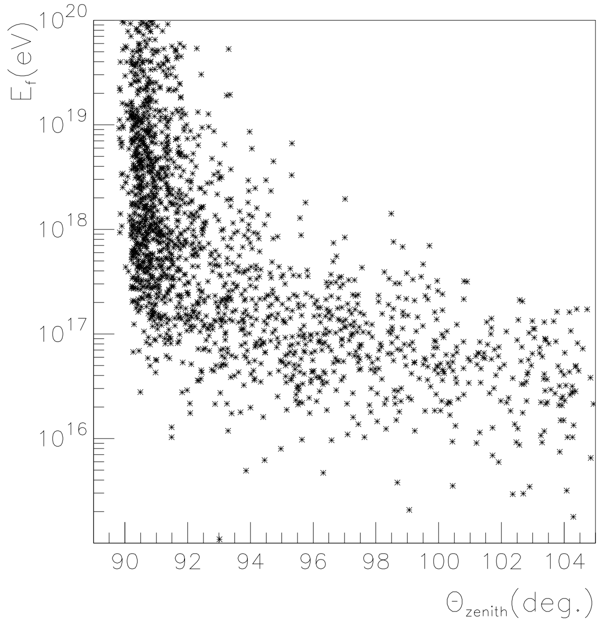

Fig. 3. Scatter plot for final energies of emerging τ's (E_f) versus emerging zenith angles. The simulation has been performed at $E_\nu = 10^{20}$eV for an isotropic flux

form measured at $x = \mathcal{O}(10^{-5})$. The electromagnetic interactions of muons with matter, at the actually considered energies, are dominated by radiative processes rather than ionisation. The cross sections for electromagnetic radiative processes of τ are lower than muon's but radiative interactions still remain the dominant process for τ energy loss. The cross sections used for radiative electromagnetic interactions of τ leptons are based on QED calculation for bremsstrahlung (Petrukhin and Shestakov, 1968), for direct pair production (Kokoulin and Petrukhin, 1970) and for photonuclear interactions (Bezrukov and Bugaev, 1981) by replacing muon or electron mass with τ mass (only formulae with explicit lepton mass dependence in the original paper have been considered). For all above processes we have implemented stochastic interactions for $\nu = (E_f - E_i)/E_i \geq 10^{-3}$ and a continuous energy loss for $\nu = (E_f - E_i)/E_i \leq 10^{-3}$, where E_i and E_f are the τ energies before and after the interaction respectively.
It is worth mentioning that bremsstrahlung cross section scales as the inverse square of lepton mass whereas direct pair production approximately scales according to m_e/m_l (Tannenbaum, 1991). As a consequence, the dominant processes of τ lepton energy loss are direct pair production and nuclear interactions rather than bremsstrahlung photon radiation. The τ decay has been simulated by using the TAUOLA package (Jadach et al., 1993)

3 Results and conclusions

Tau neutrinos interacting in proximity of the Earth surface can produce τ's which in turn can survive until they exit from the ground. The τ decay length, at first approximation, can be used to fix the order of magnitude of the depth below the Earth surface to be considered active for such events (*effective depth*). At energies below 10^{18}eV , for which the neutrino interaction length in the Earth crust is $\geq$ 400km, the neutrino interactions inside the last part of the Earth crust are approximately homogeneously distributed. Even if the correct results for τ fluxes emerging from the Earth will be given as they come out from a detailed and complete montecarlo simulation, it is interesting to evaluate the *effective depth* in the approximation considered above for quite low energy and homogeneous distributed interactions. For that reason we have simulated ν_τ CC interactions coming from vertical neutrinos and homogeneously distributed in the Earth below the surface. For each neutrino energy we can define the effective depth as the limit :

$$L_{eff} = \lim_{L \to L_{Earth}} \; L \cdot \epsilon(L)$$

where L is the maximum depth considered for the simulation of neutrino interactions and $\epsilon(L) = \frac{exiting\ \tau's}{neutrino\ interactions}$. The results of such simulations are shown in fig. 2 where they are compared with the simple approximation for L_{eff} given by the value of τ decay length with $E_\tau = E_\nu$.

At low energy L_{eff}/E_ν slowly rises with E_ν because the fraction of energy carried by the τ increases with energy in the CC ν_τ interactions. Above $\approx 10^{17}$eV the effect of τ energy loss becomes important, the degradation of τ's energy prevents them to reach the surface and consequently L_{eff}/E_ν drops down.

In order to evaluate the fluxes of exiting τ's the results given for L_{eff} should be used together with neutrino total

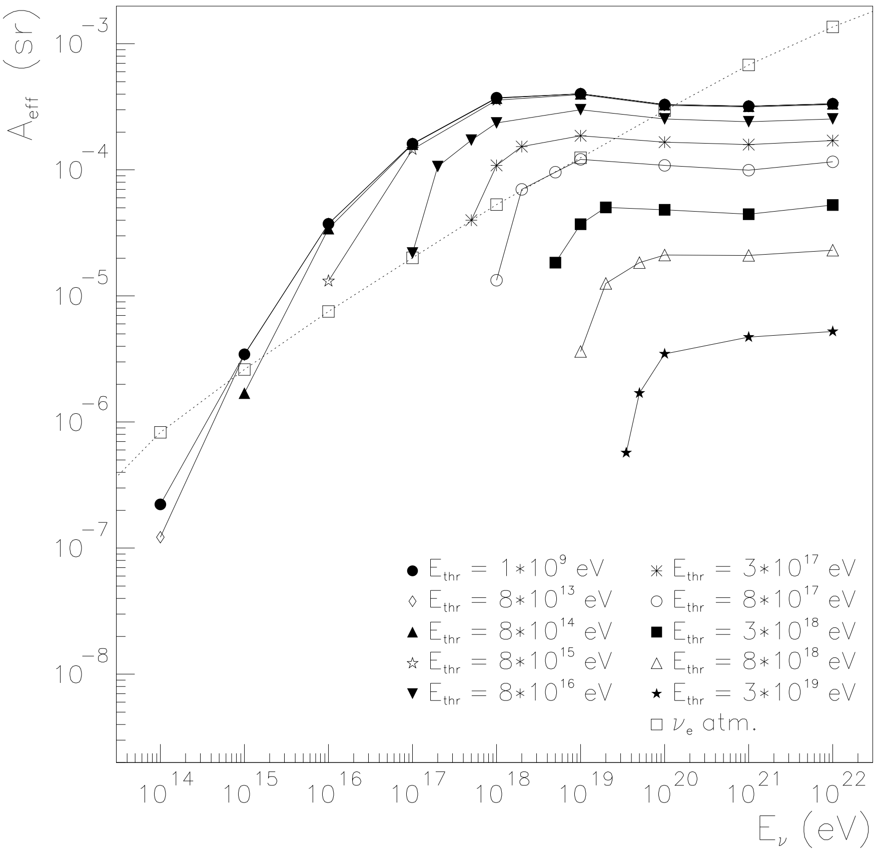

Fig. 4. Effective aperture for τ exiting from the Earth surface for different energy threshold. Also the effective aperture for events induced by downward going neutrino interactions in the atmosphere overhanging the Earth surface is shown

cross sections and neutrino fluxes as they should appear close to the surface after having crossed the whole Earth (Becattini and Bottai 2001). Such a procedure can be avoided using the results of a complete simulation following leptons propagation from the entering point on the Earth surface to the exiting one. The simulation performed takes into account all physical phenomena described in the previous section and properly considers the degradation in energy of the ν_τ-τ system during its propagation inside the Earth in the energy range $10^{12}eV \leq E_{\nu_\tau;\tau} \leq 10^{22}eV$. Once a neutrino is injected into the Earth surface, the probability that such a particle will emerge above a given energy threshold as a τ strongly depends on the amount of crossed matter and hence on the zenith angle of the emerging particle. Because of the rise with energy of neutrino cross sections and due to several energy degradation processes involved in the propagation, particles at extreme high energy are expected to emerge only as almost horizontal events. In fig 3 the result of a simulation at extreme high energy using an isotropic flux of neutrinos hitting the Earth with energy $E_\nu = 10^{20}$eV is presented. Most of τ's having zenith angles larger than 94^0 emerge with energies in the 10^{16}eV-10^{17}eV range, where the tau decay length is comparable with tau radiation length. Since for $E_\nu = 10^{20}$eV the ν interaction length in the crust reaches $\approx$ 70km, for high zenith angles with total path length larger than some hundreds of kilometers neutrinos interact quite soon, far away from the Earth surface, and the produced τ's lose energy or decays (eventually being regenerated from the new ν_τ) before exiting from the Earth. Due to this mechanism the energy of the ν_τ-τ system decreases as the zenith angle increases (fig 3). As the energy of the ν_τ-τ system decreases the probability of τ decay increases while the probability of ν_τ CC interaction which generates a new τ decreases. Hence the probability for a ν_τ to exit as a τ drops, in case of $E_\nu = 10^{20}$eV, for zenith angles larger than 100^o. For primary energy lower than $E_\nu = 10^{20}$eV the behavior of the ν_τ-τ system is similar but shifted to larger values of zenith angles. At lower energy the ν interaction length increases and even at larger zenith angles the first ν_τ interaction can happen close to the surface, hence without a significant energy degradation of the ν_τ-τ system before emerging from the Earth.

The results given in fig 4 can be used for simple calculation of the number of τ's exiting from a given Earth surface for any given isotropic extraterrestrial neutrino flux. For each neutrino energy E_ν we define an effective aperture $A_{eff}^{E_{th}}(sr)$:

$$A_{eff}^{E_{th}}(sr) = \int P(\nu_\tau \rightarrow \tau(E_\tau \geq E_{th})) \cdot |cos(\Theta_{zenith})| \, d\Omega$$

where $P(\nu_\tau \rightarrow \tau)$ is the probability that a given ν_τ hitting the Earth surface will exit as a τ, Θ_{zenith} is the zenith angle

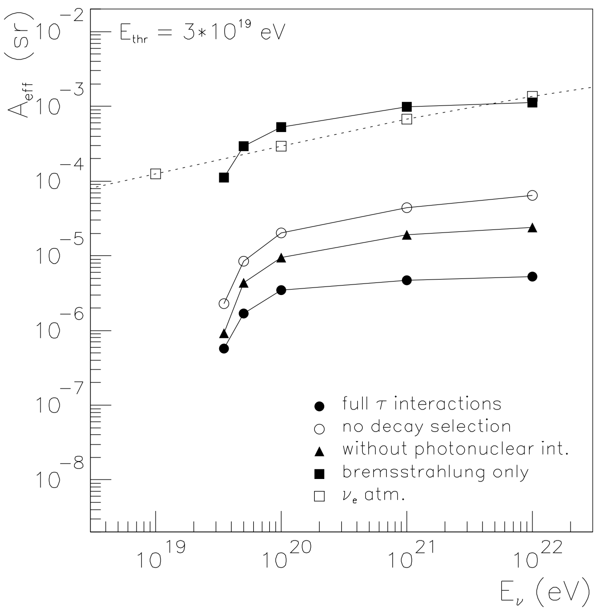

Fig. 5. Effective aperture for different τ energy loss mechanisms and in case of standard τ energy loss without any decay selection. The energy threshold is $E_{th} = 3 \cdot 10^{19} eV$

of the emerging particles. The convolution of this $A_{eff}^{E_{th}}(sr)$ with a typical isotropic tau neutrino flux $\frac{dN}{dE_\nu}$ will give the total number of exiting τ's per unit surface and unit time above a given energy threshold E_{th} :

$$N_\tau(E_\tau \geq E_{th}) = \int \frac{dN}{dE_\nu} \cdot A_{eff}^{E_{th}}(E_\nu)\, dE_\nu$$

where we also have imposed the condition that the exiting τ must decay within an atmospheric slant depth larger than $600 g/cm^2$ in order to develop a detectable EAS. For each detector monitoring an Earth surface S the number of upward going τ's above threshold per unit time will be given by the product $S \cdot N_\tau(E_\tau \geq E_{th})$. In fig 4 it is also displayed the previously defined effective aperture $A_{eff}(sr)$ for CC interactions for downward going electron neutrinos inside the atmosphere. In this case the convolution of $A_{eff}(sr)$ with an extraterrestrial isotropic neutrino flux will result in the number of neutrino interactions inside the atmosphere overhanging the unit surface per unit time. In case of $A_{eff}(sr)$ for atmospheric interactions we did not consider any threshold condition since the whole neutrino energy is transferred to the produced EAS. The effective aperture $A_{eff}(sr)$ for atmospheric interactions in fig 4 rises with energy according to the rise of neutrino cross section. For quite low energy the rise of $A_{eff}(sr)$, in case of exiting τ's , is steeper because the rise of ν cross section and the rise of τ decay length both contribute to increase the probability of τ's escaping from the Earth. This probability continues its fast rise as far as the increase of the ν cross section enhances the production of τ's. Around $E_\nu = 10^{18}$eV the cross section of neutrinos is so high that the probability for neutrinos to have at least one interaction is close to one for most of zenith angles. Above this energy the rise of neutrino cross section does not further contribute to increase the number of produced τ's but for a very narrow region of almost horizontal events. At the same time the rise of cross section above 10^{18}eV induces neutrinos to interact far from the exiting surface and hence the ν_τ-τ system undergoes a higher degradation of energy. Moreover the increase of τ decay length prevents most of the extreme high energy events to produce a detectable shower inside the atmosphere (only τ' decaying within 600g/cm^2 slant depth are retained). Due to these mechanisms the value of $A_{eff}(sr)$ at extreme high energy gets an almost flat beheaviour with energy and strongly depends on the requested τ energy threshold.

The comparison between emerging τ's and neutrino interactions in the atmosphere leads to the conclusion that the enhancement effect of neutrino interaction in the Earth is effective in the energy range 10^{15}eV-10^{20}eV in case of low energy threshold, while for very high energy thresholds ($E_{th} \geq 10^{19}$eV) the number of emerging τ's from a given Earth surface is much lower than the number of neutrino interactions in the atmosphere above the same surface.

The effect of τ energy loss has been found to be very important for extreme high energies. In fig 5 the values of $A_{eff}(sr)$ for an energy threshold of $3 \cdot 10^{19}$eV are given for normal τ energy loss, for nuclear interaction switched off and for only bremsstrahlung contribution to energy loss. Such very important differences in the results demand further investigations about the extrapolation of τ cross sections at extreme high energies.

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