29th International Cosmic Ray Conference Pune (2005) **5**, 87–90

Down-going and Earth-skimming showers from high energy neutrinos

Enrique Zas
Depto Física de Partículas, Campus Sur, Universidad, 15706 Santiago, Spain, and
Kavli Institue for Cosmological Physics, 5640 South Ellis Av., Chicago, IL 60637, US
Presenter: Enrique Zas: (zas@fpaxp1.usc.es), spa-zas-E-abs1-og25-oral

The rates of inclined showers produced both down-going neutrino interactions and by up-coming "tau" decays from earth skimming neutrinos are calculated with similar analytical methods as a function of shower energy. The relative contributions from different flavors and charged, neutral current and resonant interactions are compared for down-going neutrinos interacting in the atmosphere. The implications of detection by an air shower array for earth skimming events is discussed. It is shown that the relative rates of the two types of events is very sensitive to the detector behavior in the energy range between 10^7 and 10^8 GeV.

1. Introduction

High energy neutrinos incident at large zenith angles can interact deep in the atmosphere and produce extensive air showers which differ from "usual" air showers (by baryons) that interact in the upper layers [1]. Inclined shower searches by different cosmic ray experiments have already provided useful limits in neutrino astronomy [2] and future cosmic ray detectors such as the Auger Observatory have been shown to have significant effective volumes [3]. Neutrino oscillations into ν_τ have recently opened the possibility of detecting Earth-skimming τ neutrinos, that is neutrinos incident on the Earth with very large zenith angles [4]. After a charged current interaction the emerging τ travels in the Earth with little attenuation and exits to decay in the atmosphere. High energy τs can travel through several km of rock and produce detectable air showers, possibly exceeding down-going neutrinos [5, 6].

Unfortunately neutrino fluxes are small and very uncertain at high energies. Rate calculations are typically performed for different specific fluxes and experimental facilities and are difficult to compare. The differences between down-going and Earth-skimming detection modes is hidden in complex monte carlo simulations or analytical calculations. In this work I analytically calculate both down-going and Earth-skimming rates using a similar approach hoping to explore the relative merits of each mode and to provide guidance for the optimization of experimental facilities. Only two reference fluxes will be used here, chosen because of their simple and different shapes. One is a hard spectrum as can be expected from a characteristic "top-down" scenario with an $\sim E^{-1.5}$ behavior (TD) and the second is a reference E^{-2} spectrum at the Waxman-Bahcall bound without evolution [7] (WB). The results summarized here are discussed in detail in [8]. Only detection by arrays of particle detectors is addressed.

2. Down-going Rate Calculation

The differential shower rate, dN_{sh}, induced by a given neutrino flux, $\phi_\nu[E_\nu]$, interacting in an interval of atmospheric matter depth dx, is simply given by [2]:

$$dN_{sh} = \phi_\nu[E_\nu]\,[dAd\Omega dt]\,dE_\nu\; N_A dx\,\frac{d\sigma}{dy}dy \tag{1}$$

where N_A is Avogadro's number, $d\sigma/dy$ is the y-differential neutrino cross section (y is the fraction of neutrino energy transferred to the nucleus) and $[dtd\Omega dA]$ are differentials in time, solid angle and transverse area. For

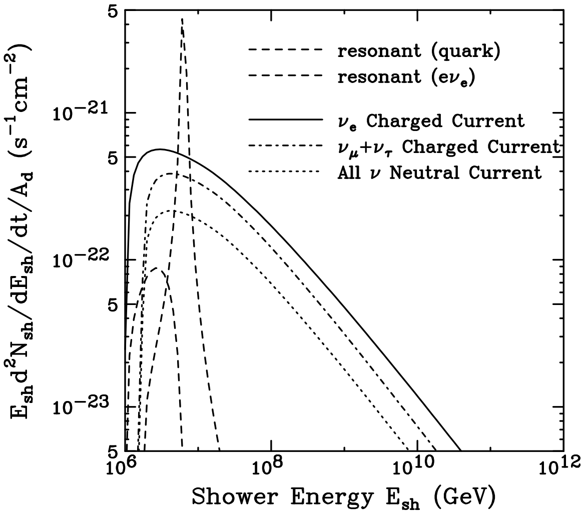

Figure 1. Shower rates produced by the labeled Deep Inelastic Scattering processes (full) and the resonant $\bar{\nu}_e e$ interactions (dashed) for the WB bound ($N_e > 10^6$). The $q\overline{q}$ and $e\overline{\nu}_e$ channels for the Glashow resonance are shown.

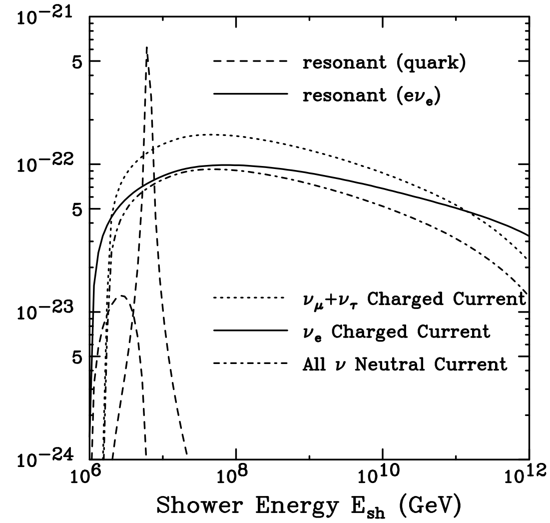

Figure 2. Same for the TD model. The processes separated are charged current $\nu_e + \bar{\nu}_e$, charged current $\nu_\mu + \bar{\nu}_\mu + \nu_\tau + \bar{\nu}_\tau$ (neglecting τ decay) and neutral current interactions for all neutrino flavors.

the cross section calculation we use the CTEQ6 set of parton distribution functions[9] throughout. The shower rate, $\phi^C_{sh}[E_{sh}]$, due to a given neutrino cannel (labeled as C) can be integrated in solid angle and impact parameter, $\vec{l}_\perp$, to give:

$$\int\int d\Omega dA \phi_{sh}[E_{sh}] = N_A \int_0^1 dy \phi_\nu[E_\nu] \left[\frac{dE^C_{sh}}{dE_\nu}\right]^{-1} \frac{d\sigma^C}{dy} \left[\int d\Omega \int_{A_d} d^2\vec{l}_\perp \int_0^{x_{max}} dx \mathcal{P}^C_{det}[y, E_{sh}, \Omega, x, \vec{l}_\perp]\right] \tag{2}$$

which in addition involves a Jacobian to account for the change of variables from neutrino energy to shower energy and the detection probability, $\mathcal{P}^C_{det}$ which must depend on E_{sh}, arrival direction, Ω, interaction depth x, on y, and on impact parameter, $\vec{l}_\perp$. If edge effects are ignored the $d^2\vec{l}_\perp$ integral simply factorizes as the array area, A_d, and introduces a "$\cos\theta$" factor in the solid angle integral of Eq. 2.

The probability $\mathcal{P}^C_{det}$ depends on detector response for showers which can be identified as deep. We assume when the zenith angle is greater than $60°$ all showers that develop in the second half of the atmosphere (in depth) can be identified as deep. This implies that the neutrino travels through the first ~ 1000 g cm^{-2} without interacting and the subsequent shower differs from a cosmic shower at the same zenith. To approximate detector response we require that showers have more than a fixed number of electrons and positrons ($N_e = 10^5, 10^6$ and 10^7) to be detected when reaching ground level. By considering small N_e values, the low energy potential of the technique is explored. Realistically this is very dependent on the detector, on the geometry, on the lateral distribution of the different particles in the shower front and on many other aspects which have been ignored. However the approximation improves as the energy of the shower rises and the array detects air showers produced close to the half-depth of the atmosphere. Results for charged current ν_e, for neutral current for all ν flavors, for charged current $\nu_\mu + \nu_\tau$ and for resonant $\bar{\nu}_e$ interactions are separately shown for the two reference fluxes in Figs. 1,2. Charged current ν_e dominates for soft fluxes because all the neutrino energy is transferred to the shower (the Jacobian is simply 1), but when all channels are added up a significant increase is shown over the dominant channel. Total rates are shown in Figs.3,4 for three different thresholds.

3. Earth-skimming Rate Calculation

The Earth skimming process implies three distinct stages, neutrino propagation in the Earth during which it attenuates and regenerates, τ propagation in the Earth during which it looses energy but it should not decay and finally decay in the atmosphere after it exits from the Earth surface. To calculate the τ rate we assume the ν_τ undergoes a charged current interaction after traveling depth $\bar{x}$ of matter producing a τ of energy E'_τ. The τ energy, E_τ, after traveling depth x can be calculated using the standard energy loss expression as [10]:

$$\frac{E+\epsilon}{E'+\epsilon} = e^{-x/\xi} \qquad \text{using} \qquad \frac{dE}{dx} = \frac{\epsilon + E}{\xi} \tag{3}$$

We take $\xi = 1.25\ 10^6$ g cm^{-2} and $\epsilon = 3000$ GeV consistent with results for the 10^8 GeV region in Ref. [11]. The neutrino flux at the interaction point is expressed as $\phi_\nu[E_\nu]e^{-g(\bar{x},E_\nu)}$ and x and $\bar{x}$ are related by the total matter depth along the Earth chord subtended by the trajectory, $x_T(\theta) = \bar{x} + x$. The function $g(\bar{x}, E_\nu)$ acts as an attenuation due to the neutrino interactions. Ignoring τ decay regeneration $g(\bar{x}, E_\nu) = \bar{x}\sigma_{eff}$ with σ_{eff} the total charged current cross section minus a term from neutral current regeneration. The survival probability after traveling depth x can be shown to be:

$$P_{\rm Surv} = \left[\frac{E}{E'}\frac{E'+\epsilon}{E+\epsilon}\right]^\eta \simeq \left[1 - \epsilon\left(\frac{1}{E} - \frac{1}{E'}\right)\right]^\eta \qquad \eta = \frac{m_\tau c^2\ \xi}{\epsilon\ \rho c \tau_\tau} \tag{4}$$

where the second approximate expression holds for $E >> \epsilon$ and the exponent, $\eta \simeq 3.2\ 10^4$, is a constant that depends on the medium density ρ, on the τ mass, m_τ, its decay constant, τ_τ, and the loss parameters ξ and ϵ. The emerging τ rate is obtained convoluting the differential neutrino flux at the interaction point, the differential cross section $d\sigma^{cc}/dy$ and the τ survival probability:

$$\phi_\tau[E_\tau, \theta] = \frac{\xi}{E_\tau + \epsilon} N_A \int_{E_\tau}^{\infty} dE_\nu \phi[E_\nu] e^{-g(x_T - x, E_\nu)} \int_{y_{min}}^{y_{max}} dy\ \frac{d\sigma^{cc}}{dy} \left[\frac{E_\tau}{E'_\tau}\frac{E'_\tau + \epsilon}{E_\tau + \epsilon}\right]^\eta \tag{5}$$

$$\text{with} \quad y_{min} = \frac{1}{E_\nu}\max[E_\nu + \epsilon - (E_\tau + \epsilon)e^{x_T/\xi}, 0] \qquad y_{max} = 1 - \frac{E_\tau}{E_\nu} \tag{6}$$

The τ flux can be integrated in solid angle, the results for the reference fluxes are the upper curves in Figs. 3,4. The figures show the differential rate in shower energy, which is assumed to be 50% of the τ energy, multiplied by E_{sh} so that the $y-$axis is roughly related to the integral flux. The target volume for neutrinos is governed by the distance the τ can travel in the Earth which can be shown to increase linearly with energy until $\sim 10^8$ GeV. This sets an important energy scale. The τ spectrum has several features worth stressing. At low energies the cross section and target volume produce a rising rate provided the spectral index is below 3 which is usually the case. Above 10^5 GeV the neutrino flux starts to get attenuated through the Earth and the rise in the spectrum flattens, at about 10^6 GeV the corresponding cross section for the neutrinos changes slope and this suppresses the spectrum for the E^{-2} of the WB bound while it flattens it for the $E^{-1.5}$ TD model. Finally at the scale $\sim 10^8$ GeV the flux drops again with approximately the same slope as the incident neutrino flux.

Finally the τ must decay in the atmosphere sufficiently near the detector so that the subsequent shower produces a detectable signal. The detection probability depends on the energy and the direction and must account for the Earth's curvature. Showers are assumed to be detected provided the electron density exceeds 0.1, 0.4 and 1 m^{-2} where the transverse plane at shower maximum intercepts ground level. This requirements limits the rate considerably as it is also shown in Figs. 3,4. These figures summarize the results. A window is shown where up-coming τ decays are shown to dominate down-going showers in the shower energy range $[10^7, 10^8]$ for the E^{-2} spectrum and $[10^7, 3\ 10^8]$ for the $E^{-1.5}$ spectrum. Depending on the detector response to showers

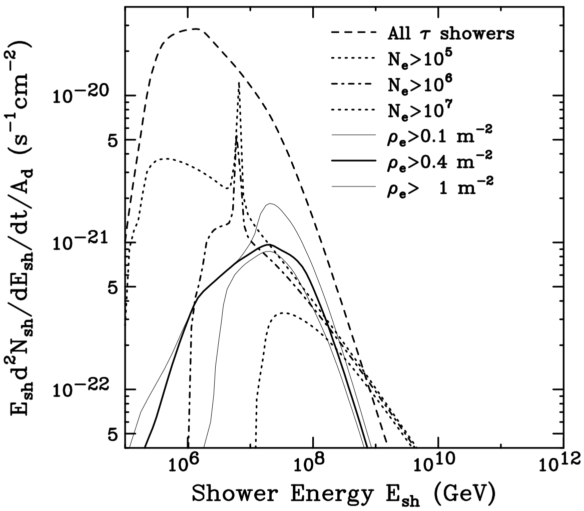

Figure 3. Shower rates for down-going neutrinos compared to earth-skimming events from τ decays for the WB bound.

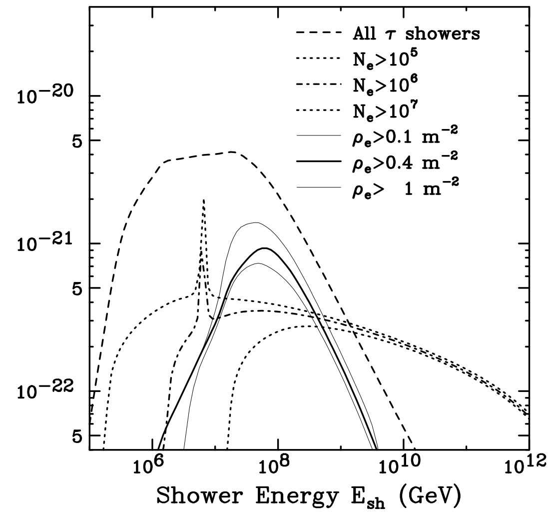

Figure 4. Same for the TD model. The dotted lines indicate the total τs entering the atmosphere.

in these intervals the two type of events can have different relative rates. The graph also sets the detection scale on this mode since a 1000 km^2 in a year of operation gives 3 10^{20}s cm^2, corresponding to order one event for the WB bound. A large difference is found between the rate of upcoming τs and those that can be detected with a ground array. Due to this difference, the duty factors for optical detection with the fluorescence or Cherenkov techniques are somewhat compensated.

4. Acknowledgements

This work was supported in part by MEC (FPA 2001-3237, FPA 2002-01161, FPA 2004-01198), by Secretaría de Estado de Educación y Univesidades, by Xunta de Galicia (PGIDIT02 PXIC 20611PN), by ESF neutrino network N-86, by Feder Funds and by the KICP under NSF grant PHY-0114422.

References

[1] V.S. Berezinsky and G.T. Zatsepin *Phys. Lett.* **B28** (1969) 423; V.S. Berezinsky and A. Yu. Smirnov, *Astrophys. Space Science* **32** (1975) 461.
[2] E. Zas, F. Halzen and R. A. Vázquez *Astropart. Phys.* **1** (1993) 297.
[3] K. S. Capelle, J. W. Cronin, G. Parente and E. Zas, *Astropart. Phys.* **8**, 321 (1998).
[4] A. Letessier-Selvon, AIP Conf. Proc. **566** (2001) 157; D. Fargion, Astrophys. J. **570**, 909 (2002)
[5] X. Bertou, P. Billoir, O. Deligny, C. Lachaud and A. Letessier-Selvon, Astropart. Phys. **17** (2002) 183
[6] J. L. Feng, P. Fisher, F. Wilczek and T. M. Yu, Phys. Rev. Lett. **88** (2002) 161102
[7] J. N. Bahcall and E. Waxman, Phys. Rev. D **64**, 023002 (2001).
[8] E. Zas, New J. Phys. **7** (2005) 130, [arXiv:astro-ph/0504610].
[9] J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. Nadolsky and W. K. Tung, JHEP **0207** (2002) 012.
[10] P. Lipari and T. Stanev, *Phys. Rev.* **D44** (1991) 3543.
[11] S. I. Dutta, M. H. Reno, I. Sarcevic and D. Seckel, Phys. Rev. D **63** (2001) 094020.