

Ultra High Energy ν_τ detection at Pierre Auger Observatory

G. Miele^a, L. Perrone^b, O. Pisanti^a

^aDipartimento di Scienze Fisiche, Università di Napoli “*Federico II*” and Istituto Nazionale di Fisica Nucleare – Sezione di Napoli, Complesso Universitario di Monte S. Angelo, Via Cinthia, I-80126 Napoli, Italy.

^bFachbereich C, Sektion Physik, Universität Wuppertal, D-42097 Wuppertal, Germany.

Earth-skimming UHE tau neutrinos have a chance to be detected by the Fluorescence Detector (FD) of Pierre Auger Observatory if their astrophysical flux is large enough. A detailed evaluation of the expected number of events is here performed for a wide class of neutrino flux models.

Neutrinos with energy above 10^{17} eV are expected to originate from the interaction of UHE cosmic rays with the Cosmic Microwave Background (CMB) *via* the π -photoproduction, $p + \gamma_{CMB} \rightarrow n + \pi^+$, the so-called *cosmogenic neutrinos* [1]. The prediction for such a flux have been exhaustively discussed in several papers (see for example Ref.s [2,3]).

High energy neutrinos are hardly detected, as they are almost completely shadowed by Earth and rarely interact with the atmosphere. In this framework, an interesting strategy for ν_τ detection has been proposed in literature (see [4] for a complete list of references). For energy between 10^{18} and 10^{21} eV the τ decay length is not much larger than the corresponding interaction range. Thus, an energetic τ , produced by Charged Current (CC) ν_τ interaction not too deep under the surface of the Earth, has a chance to emerge in the atmosphere as an upgoing particle. Unlike τ 's, muons crossing the rock rapidly loose energy and decay. Almost horizontal ν_τ , just skimming the Earth surface, will cross an amount of rock of the order of their interaction length and thus will be able to produce a corresponding τ , which might shower in the atmosphere and be detected.

A detailed estimate of the number of possible upgoing τ showers which the Fluorescence Detector (FD) of Pierre Auger Observatory could detect is presented in Ref. [4], where the predictions are analyzed with respect to their dependence on

different neutrino fluxes and by using a new estimate of neutrino-nucleon cross sections. In the present paper a brief review of the main results obtained in Ref. [4] is reported.

Ultra High Energy protons, with energy above $\sim 10^{20}$ eV, travelling through the universe mostly loose their energy *via* the interaction with CMB radiation. The large amount of charged and neutral pions produced will eventually decay in charged leptons, neutrinos (*cosmogenic neutrinos* [1]), and high energy gamma rays.

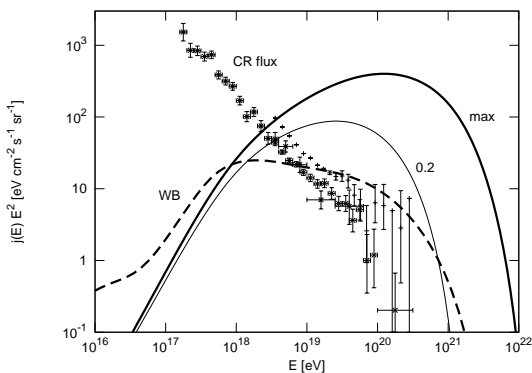


Figure 1. Cosmogenic neutrino fluxes as a function of energy.

At the GeV energy range the extragalactic diffuse gamma-ray background was measured by the EGRET experiment. This measurement provides an upper bound for possible neutrino fluxes from pion production. In particular, it gives the expected maximum flux of cosmogenic neutrinos from an initial spectrum of measured UHE protons. It is worth noticing that, since at least part of UHECR are protons, the existence of cosmogenic neutrinos is guaranteed, even if their flux is very uncertain. In Figure 1 the GZK neutrino flux for three possible scenarios is plotted. The thick solid line gives the case of an initial proton flux $\propto 1/E$, by assuming in addition that the EGRET flux is entirely due to π -photoproduction (GZK-H). The thin solid line shows the neutrino flux when the associated photons contribute only up to 20% in the EGRET flux (GZK-L). The dashed line stands for the conservative scenario of an initial proton flux $\propto 1/E^2$ (GZK-WB). In this case the neutrino flux is compatible with the so-called Waxman-Bahcall limit.

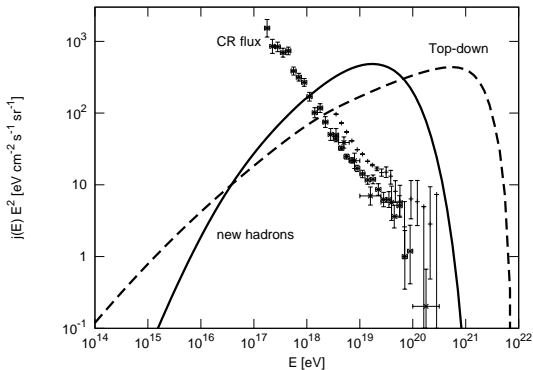


Figure 2. Neutrino fluxes in exotic UHECR models.

Most of the models trying to explain highest energy cosmic rays ($E > 10^{20}$ eV) in terms of exotic particles, predict a large associated flux of neutrinos. In Figure 2, the expected neutrino flux

for two of such scenarios is plotted. One of them is the model of *new hadrons* (NH), with mass $M \sim 2 - 5$ GeV, capable of generating UHECR events above GZK cutoff. In SUSY theories, for example, the new hadrons are bound states of light bottom squarks or gluinos and, once produced in suitable astrophysical environments, can reach the Earth without significant energy losses. In spite the production of new hadrons is a subdominant process, it generates a large number of neutrinos (see Figure 2).

The dashed line in Figure 2 shows the neutrino flux for a Topological Defects model (TD) (for a review see [5]). In this case UHECR events with energy $E > 10^{20}$ eV are explained in terms of γ 's which are produced in the decay of heavy particles with mass of the order of 10^{22-23} eV. As in the previous case, the associated neutrino flux for this kind of models is extremely large.

At energy above 1 GeV the interaction between neutrinos and the atoms of the rock is dominated by the process of *Deep Inelastic Scattering* (DIS) on nucleons. Detectable leptons are produced through Charged Current interaction $\nu_l(\bar{\nu}_l) + N \rightarrow l^-(l^+) + X$. The total cross sections can be written in terms of differential ones as follows

$$\sigma_{CC}^{\nu N}(E_\nu) = \int_0^{1 - \frac{m_l}{E_\nu}} \frac{d\sigma_{CC}^{\nu N}}{dy}(E_\nu, y) dy, \quad (1)$$

where E_ν is the energy of the incoming neutrino, m_l is the mass of the outgoing charged lepton and y is the inelasticity parameter, defined as

$$y_{CC} = 1 - \frac{E_l}{E_\nu}, \quad (2)$$

with E_l the energy of the outgoing charged (for CC) or neutral (for NC) lepton. In the present analysis we have used the CTEQ6 [6] parton distribution functions in the DIS factorization scheme. The Q^2 -evolution is realized by the next-to-leading order Dokshitzer-Gribov-Lipatov-Altarelli-Parisi equations.

Figure 3 shows a comparison between a CTEQ4-based parametrization of CC cross section and the corresponding calculation performed with CTEQ6. A substantial agreement is found up to 10^9 GeV, whereas a discrepancy of at most

30% at 10^{12} GeV is observed (CTEQ4 prediction being larger). In this range of energy the uncertainty due to the lack of knowledge of parton distribution functions is expected to be overwhelming.

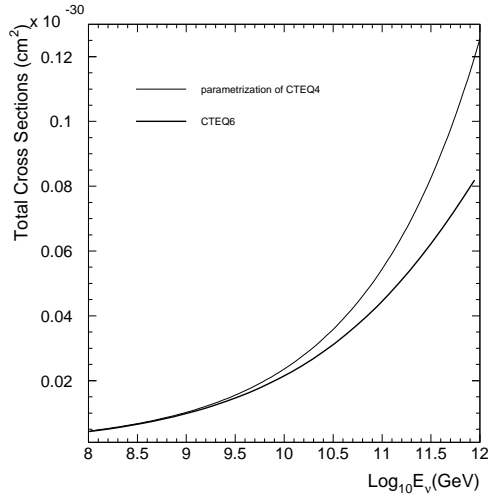


Figure 3. The total ν_τ -nucleon CC cross sections based on both CTEQ4 [7] and CTEQ6 [6] are reported.

Following the formalism developed in Ref. [8], let Φ_ν be an isotropic flux of $\nu_\tau + \bar{\nu}_\tau$. The differential flux of charged leptons emerging from the Earth surface with energy E_τ is given by

$$\frac{d\Phi_\tau(E_\tau, \Omega)}{dE_\tau d\Omega} = \int dE_\nu \frac{d\Phi_\nu(E_\nu, \Omega)}{dE_\nu d\Omega} \times K(E_\nu, \Omega; E_\tau), \quad (3)$$

where $K(E_\nu, \theta; E_\tau)$ is the probability that an incoming neutrino crossing the Earth with energy E_ν and nadir angle θ produces a lepton emerging with energy E_τ (see Figure 4). In Eq.(3), due to the very high energy of ν_τ , we can assume that in the process $\nu_\tau + N \rightarrow \tau + X$ the charged lepton is produced along the neutrino direction.

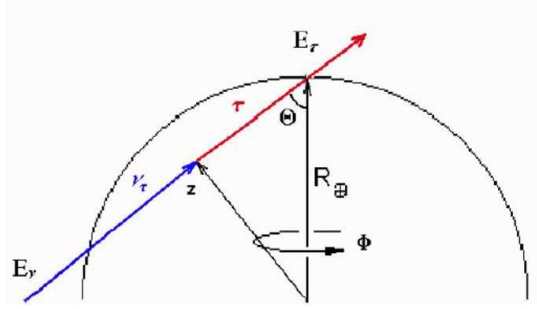


Figure 4. A neutrino ν_τ crosses the Earth with energy E_ν at a nadir angle θ and azimuth angle ϕ . Then it travels a distance z before converting into a charged lepton τ , which emerges from the Earth surface with energy E_τ [8].

This process can occur if and only if the following conditions are fulfilled:

- the ν_τ with energy E_ν has to survive along a distance z through the Earth;
- the neutrino converts into a τ in the interval $z, z + dz$;
- the created lepton emerges from the Earth before decaying.

By using the expressions for all the above probabilities one obtains

$$K(E_\nu, \theta; E_\tau) = \frac{\sigma_{CC}^{\nu N}(E_\nu) N_A}{E_\tau (\beta_\tau + \gamma_\tau E_\tau)} (F(E_\nu, E_\tau))^\xi \times \exp \left\{ -\frac{m_\tau}{c\tau_\tau \beta_\tau \rho_s} \left(\frac{1}{E_\tau} - \frac{1}{E_\tau^0(E_\nu)} \right) - 2R_\oplus \cos \theta \sigma_{CC}^{\nu N}(E_\nu) \rho_s N_A \right\}, \quad (4)$$

where $\xi \equiv \omega + \sigma_{CC}^{\nu N}(E_\nu) N_A / \beta_\tau$. As extensively discussed in Ref. [4] the parameters $\beta_\tau \simeq 0.71 \cdot 10^{-6} \text{ cm}^2 \text{ g}^{-1}$ and $\gamma_\tau \simeq 0.35 \cdot 10^{-18} \text{ cm}^2 \text{ g}^{-1} \text{ GeV}^{-1}$ fairly describe the τ energy loss in matter. Moreover, the tau lepton, once produced, carries an average energy $E_\tau^0(E_\nu) = (1 - \langle y_{CC} \rangle) E_\nu$.

Eq. (4) leads to the total rate of upgoing τ 's showering on the Auger detector, and thus *poten-*

tially detectable by the FD:

$$\begin{aligned} \frac{dN_\tau}{dt} &= 2\pi S D \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \int_{E_\tau^{th}}^{E_\tau^0(E_\nu)} dE_\tau \\ &\times \int_{\cos\theta_{min}}^1 \frac{d\Phi_\nu(E_\nu)}{dE_\nu d\Omega} K(E_\nu, \theta; E_\tau) \\ &\times \left(1 - \exp \left\{ -\frac{H m_\tau}{c\tau_\tau E_\tau} \right\} \right) \varepsilon \cos\theta d(\cos\theta) , \quad (5) \end{aligned}$$

where we have used the isotropy of the considered neutrino flux. In Eq.(5) the quantity $S = 3000 \text{ km}^2$ is the geometrical area covered by the Auger apparatus, $D \sim 10\%$ is the duty cycle for fluorescence detection, $E_\tau^{th} \simeq 10^{18} \text{ eV}$ is the energy threshold for the fluorescence process, and E_ν^{min} is the minimum neutrino energy capable of producing a τ at detection threshold. The quantity E_ν^{max} is the endpoint of the neutrino flux.

The exponential term in the r.h.s. of Eq.(5) accounts for the decay probability of a τ (showering probability) in a distance H from the emerging point on the Earth surface.

In Eq.(5) the integration over $\cos\theta$ can be easily performed and this yields to the definition of the *effective aperture* of the apparatus, $A(E_\nu)$, as

$$\frac{dN_\tau}{dt} = D \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \frac{d\Phi_\nu(E_\nu)}{dE_\nu d\Omega} A(E_\nu) . \quad (6)$$

In Figure 5 the quantity $A(E_\nu)$ is plotted versus the neutrino energy for different values of E_τ^{th} and H .

The number of τ -shower Earth-skimming events expected per year at the FD detector for the different neutrino fluxes result to be: 0.02 (GZK-WB), 0.04 (GZK-L), 0.09 (GZK-H), 0.11 (TD), 0.25 (NH).

As well known, neutrino induced extensive air showers (see Ref. [9] for an extended discussion) can be disentangled by the ordinary cosmic ray background only for very inclined and deep showers. An estimate of the expected number of down-going events within 30 km from the FD detector results to be comparable with the upgoing one only for zenith angles larger than 70° .

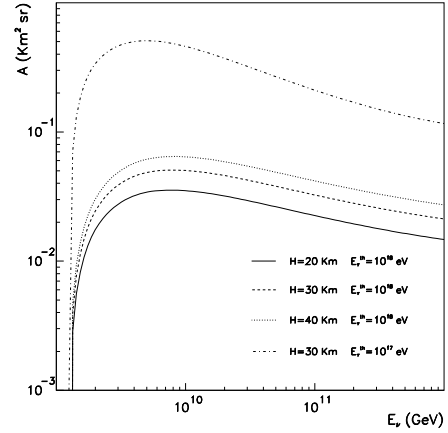


Figure 5. The *effective aperture* $A(E_\nu)$ is here plotted for $E_\tau^{th} = 10^{17} \text{ eV}$ and $H = 30 \text{ km}$, and for $E_\tau^{th} = 10^{18} \text{ eV}$ with $H = 20, 30, \text{ and } 40 \text{ km}$, respectively.

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