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The aperture for UHE tau neutrinos of the Auger fluorescence detector using a Digital Elevation Map

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Abstract

We perform a new study of the chances of the fluorescence detector (FD) at the Pierre Auger Observatory to detect the tau leptons produced by Earth-skimming ultra high energy ν_τ's. We present a new and more detailed evaluation of the effective aperture of the FD that considers a reliable fiducial volume for the experimental set up. In addition, we take into account the real elevation profile of the area near Auger. We find a significant increase in the number of expected events with respect to the predictions of a previous semi-analytical determination, and our results show the enhancement effect for neutrino detection from the presence of the near mountains.

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Neutrinos constitute one of the components of the cosmic radiation in the ultra high energy (UHE) regime. Since we have detected ultra high energy cosmic rays (UHECR), the presence of a secondary UHE neutrino flux is guaranteed as a result of the π-photoproduction, due to the interaction of hadronic UHECR with the cosmic microwave background. The detection of these *cosmogenic neutrinos* [1,2], in addition to a possible primary neutrino flux, would provide precious information on the physics and position of their powerful astrophysical sources. On the other hand, copious neutrino fluxes are also predicted in more exotic *top-down* scenarios where relic massive particles, produced at the first moments of the Universe, decay into UHE lighter particles, among which neutrinos and photons are expected. In any case, the detection of UHE neutrinos would significantly contribute to unveiling the still unknown origin of UHECR.

Due to the very low expected fluxes and the small neutrino-nucleon cross section, neutrinos with energies of the order of 10^{18} eV and larger are hardly detectable even in the new generation of giant array detectors for cosmic radiation, like the Pierre Auger Observatory (Auger, in short) [3,4]. The detection of UHE neutrinos inducing inclined air showers was recently reviewed in [5]. In particular, a promising strategy concerning the detection of the tau leptons produced by Earth-skimming UHE ν_τ's has been analyzed in a series of papers [6]–[19]. UHE τ's, with energies in the range 10^{18-21} eV, have a decay length not much larger than the corresponding interaction range. Thus, if a UHE ν_τ crosses the Earth almost horizontally (Earth-skimming) and interacts in the rock, the produced τ has a chance to emerge from the surface and decay in the atmosphere, producing a shower that in principle can be detected as an up-going or almost horizontal event.

The aim of this letter is to perform a new, more refined, estimate of the effective aperture of the fluorescence detector (FD) at Auger to Earth-skimming UHE ν_τ's. A calculation of the number of possible up-going τ showers detectable with the FD has already been performed in ref. [15] by using a semi-analytical computation. Our analysis represents a considerable improvement with respect to the estimate of this last work, since it uses a different method for calculating the number of ν_τ/τ events, which now includes a class of tracks neglected in the previous calculation.

An additional improvement in our analysis comes from considering the effects of the topology around the Auger observatory site, by using a Digital Elevation Map (DEM) of the area around the experiment. A detailed DEM of the Earth surface is provided by ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) [20] which is an imaging instrument that is flying on Terra, a satellite launched in December 1999 as part of NASA's Earth Observing System. The available elevation map, GTOPO30, is a global digital model where the elevations are regularly spaced at 30-arc seconds. We show in Fig. 1 a 3D map of the relevant region around Auger. We will use this DEM to produce a realistic and statistically significant sample of possible ν_τ/τ tracks crossing the fiducial volume of Auger, that will be used later to evaluate the real aperture of FD at Auger.

We will define the Auger *fiducial* volume as that limited by the the six lateral surfaces Σ_a (the subindex $a = W$, E, N, S, U and D labels each surface through its orientation: West, East, North, South, Up, and Down), and with $\Omega_a \equiv (\theta_a, \phi_a)$ a generic direction of a track entering Σ_a, as shown in Fig. 2. We have considered a simplified Auger area, given by a 50×60 km rectangle (an approximation to the real one, see ref. [4]), while the height of the fiducial

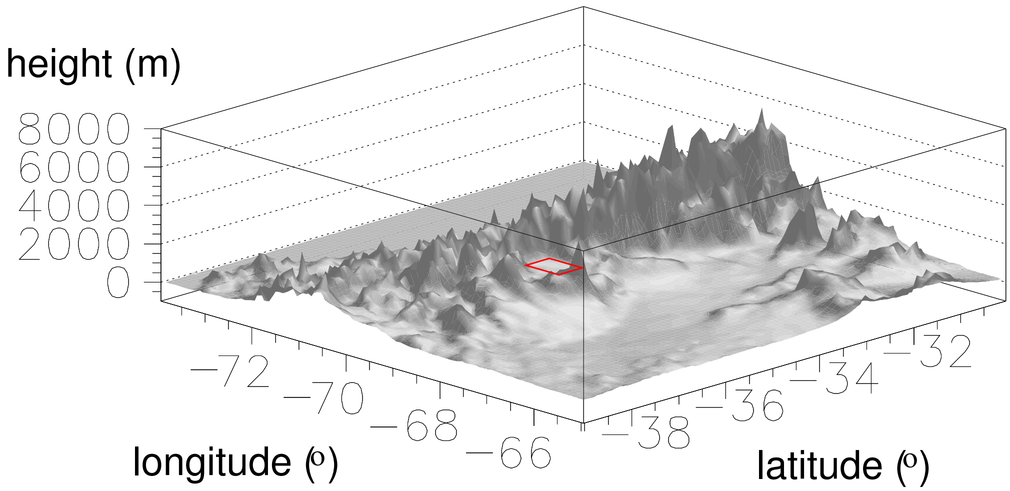

Fig. 1. A 3D map in longitude and latitude of the area around Auger with the elevation (not to scale) expressed in meters. The Auger position and surface, approximated to a rectangle, is indicated in red.

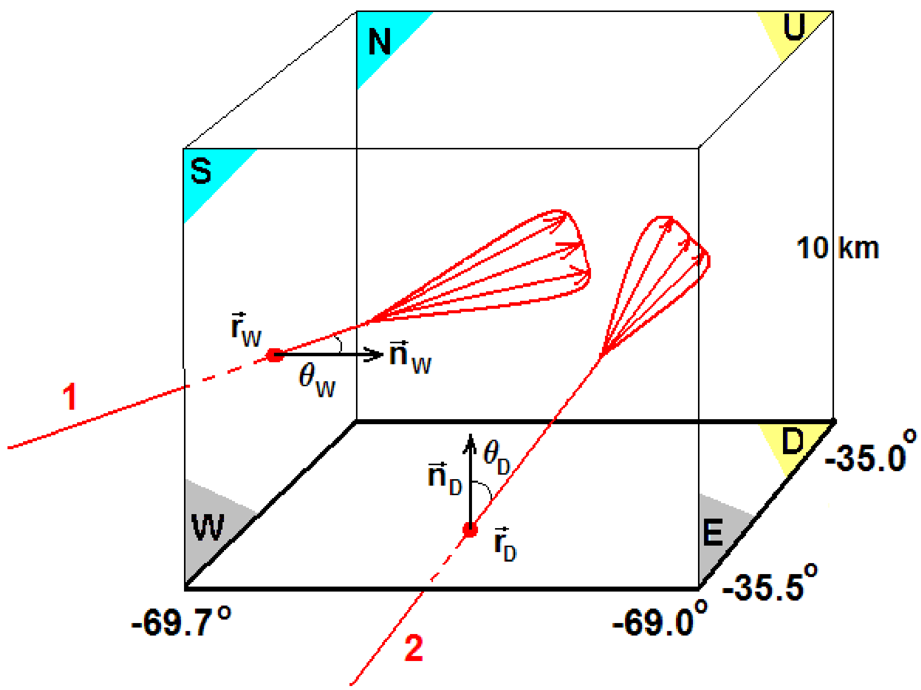

Fig. 2. A simplified scheme of the Auger fiducial volume is represented (height not to scale). The lateral surfaces are labelled by their orientation. Two examples of entering tracks are also shown.

volume was fixed to 10 km in order to be within the range of detection of the FD eyes. This is a conservative estimate, since we expect that the effective fiducial volume for the detection at the FD will be larger.

Let Φ_ν be an isotropic flux of $\nu_\tau + \overline{\nu}_\tau$. By generalizing the formalism developed in ref. [13], the number of τ leptons emerging from the Earth surface with energy E_τ, going through Σ_a and showering in the fiducial volume per unit of time (thus potentially detectable by the FD), is given by

$$\left(\frac{dN_\tau}{dt}\right)_a = D \int d\Omega_a \int dS_a \int dE_\nu \; \frac{d\Phi_\nu(E_\nu)}{dE_\nu \, d\Omega_a} \times \int dE_\tau \; \epsilon(E_\tau) \; \cos(\theta_a) \; k_a(E_\nu \, , E_\tau \, ; \vec{r}_a \, , \Omega_a) \quad , \tag{1}$$

where D is the duty cycle and $\epsilon(E_\tau)$ is the detection efficiency of the FD, respectively [3]. The minimum energy for the τ leptons, 10^{18} eV, is chosen taking into account the energy threshold for the flourescence process [15]. The kernel $k_a(E_\nu \, , E_\tau \, ; \vec{r}_a \, , \Omega_a)$ is the probability that an incoming neutrino crossing the Earth with energy E_ν and direction Ω_a, produces a lepton emerging with energy E_τ, which enters the fiducial volume through the lateral surface dS_a at the position $\vec{r}_a$ and decays inside this volume (see Fig. 2 for the angle definition). In Eq. (1), 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.

As already shown in details in ref. [15], this process can occur if the following conditions are fulfilled,

1) the ν_τ with energy E_ν has to survive along a distance z through the Earth;
2) the neutrino converts into a τ in the interval $z, z + dz$;
3) the created τ emerges from the Earth before decaying with energy E_τ;
4) the τ lepton enters the fiducial volume through the lateral surface Σ_a at the point $\vec{r}_a$ and decays inside this volume.

1) The probability P_1 that a neutrino with energy E_ν crossing the Earth survives up to a certain distance z inside the rock is

$$P_1 = \exp\left\{ -\frac{z}{\lambda^\nu_{CC}(E_\nu)} \right\} \quad , \tag{2}$$

where

$$\lambda^\nu_{CC}(E_\nu) = \frac{1}{\sigma^{\nu N}_{CC}(E_\nu) \, \varrho_s \, N_A} \tag{3}$$

is the charged current (CC) interaction length in rock ($\varrho_s \simeq 2.65$ g/cm^3). A detailed discussion of an updated evaluation of the neutrino-nucleon cross section, $\sigma^{\nu N}_{CC}(E_\nu)$, can be found in ref. [15]. The dependence of λ^ν_{CC} on the particular track direction can be safely neglected, since it is well known that the interesting events are almost horizontal and thus the experienced Earth density is essentially[1] equal to ϱ_s.

2) The probability for $\nu_\tau \to \tau$ conversion in the interval $[z,\, z+dz]$ is

$$P_2\, dz = \frac{dz}{\lambda^{\nu}_{CC}\,(E_\nu)} \quad . \tag{4}$$

3) The probability P_c that a charged lepton survives as it loses its energy travelling through the Earth is described by the coupled differential equations

$$\frac{dP_c}{dz} = -\frac{m_\tau}{c\,\tau_\tau\, E_\tau}\, P_c \ , \tag{5}$$

$$\frac{dE_\tau}{dz} = -\left(\beta_\tau + \gamma_\tau\, E_\tau\right)\, E_\tau\, \varrho_s \ . \tag{6}$$

Here $m_\tau = 1.77$ GeV, $\tau_\tau \simeq 3.4 \times 10^{-13}$ s denotes the τ mean lifetime, whereas the parameters $\beta_\tau \simeq 0.71 \times 10^{-6}$ cm^2 g^{-1} and $\gamma_\tau \simeq 0.35 \times 10^{-18}$ cm^2 g^{-1} GeV^{-1}, as discussed in ref. [15], fairly describe the τ energy loss in matter (for further references and a recent discussion, see [21]). We denote the transferred energy as $E^0_\tau = E^0_\tau(E_\nu) = (1 - \langle y_{CC}\rangle)E_\nu$ (see ref. [15] for details). By solving Eq.s (5) and (6) at the emerging point on the Earth surface one has

$$P_c = \left(F(E_\nu, E_\tau)\right)^\omega\, \exp\left\{-\frac{m_\tau}{c\tau_\tau\beta_\tau\varrho_s}\left(\frac{1}{E_\tau} - \frac{1}{E^0_\tau(E_\nu)}\right)\right\} \ , \tag{7}$$

$$E_\tau = \frac{\beta_\tau\, E^0_\tau(E_\nu)\, \exp\left\{-\varrho_s\, \beta_\tau(z_{\rm max} - z)\right\}}{\beta_\tau + \gamma_\tau\, E^0_\tau(E_\nu)\left(1 - \exp\left\{-\varrho_s\, \beta_\tau(z_{\rm max} - z)\right\}\right)} \ , \tag{8}$$

where

$$F(E_\nu, E_\tau) \equiv \frac{E^0_\tau(E_\nu)(\beta_\tau + \gamma_\tau E_\tau)}{E_\tau(\beta_\tau + \gamma_\tau\, E^0_\tau(E_\nu))} \ , \qquad \omega \equiv \frac{m_\tau\, \gamma_\tau}{c\tau_\tau\beta^2_\tau\varrho_s} \ . \tag{9}$$

The quantity $z_{\rm max} = z_{\rm max}\,(\vec{r}_a\,, \Omega_a)$ represents the total length in rock for a given track entering the lateral surface Σ_a of the fiducial volume at the point $\vec{r}_a$ and with direction Ω_a.

The energy E_τ of the exiting lepton must be consistent with Eq. (8). This condition is enforced by the presence of a δ-function in the final expression of

[1] We neglect the fact that UHE neutrinos may traverse a significant amount of water (as those from the West), which could enhance the arrival of UHE tau neutrinos at the largest energies, see e.g. [14].

the probability P_3,

$$P_3 = P_c \;\delta \left(E_\tau - \frac{\beta_\tau \, E_\tau^0(E_\nu) \, \exp\left\{-\varrho_s \, \beta_\tau (z_{\max} - z)\right\}}{\beta_\tau + \gamma_\tau \, E_\tau^0(E_\nu) \left(1 - \exp\left\{-\varrho_s \, \beta_\tau (z_{\max} - z)\right\}\right)} \right) \quad . \tag{10}$$

4) Once the τ lepton has emerged from the Earth surface, its showering probability is determined by the total distance it has to travel for reaching the fiducial volume. If we denote with $\lambda_{\text{out}} = \lambda_{\text{out}} \, (\vec{r}_a \, , \Omega_a)$ the total length travelled in the atmosphere by the τ before reaching the point $\vec{r}_a$ on the surface Σ_a, and with $\lambda_{\text{in}} = \lambda_{\text{in}} \, (\vec{r}_a \, , \Omega_a)$ the length of the intersection of the track with the fiducial volume, the decay probability inside the fiducial volume is given by

$$P_4 = \exp\left\{ -\frac{\lambda_{\text{out}} \, m_\tau}{c\tau_\tau \, E_\tau} \right\} \left(1 - \exp\left\{ -\frac{\lambda_{\text{in}} \, m_\tau}{c\tau_\tau \, E_\tau} \right\} \right) \quad . \tag{11}$$

Collecting together the different probabilities in Eq.s (2), (4), (10) and (11), we have

$$k_a(E_\nu \, , E_\tau \, ; \vec{r}_a \, , \Omega_a) = \int_0^{z_{\max}} P_1 \, P_2 \, P_3 \, P_4 \; dz \quad . \tag{12}$$

Since the flux can be reasonably assumed isotropic, namely

$$\frac{d\Phi_\nu(E_\nu)}{dE_\nu \, d\Omega_a} = \frac{d\Phi_\nu(E_\nu)}{dE_\nu \, d\Omega} \qquad \forall a \;, \tag{13}$$

we can rewrite Eq. (1), summing over all the surfaces, as

$$\frac{dN_\tau}{dt} = D \int dE_\nu \; \frac{d\Phi_\nu(E_\nu)}{dE_\nu \, d\Omega} \, A(E_\nu) \;\; , \tag{14}$$

where the effective aperture, $A(E_\nu) \equiv \sum_a A_a(E_\nu)$, is the sum of each surface contribution,

$$A_a(E_\nu) \equiv \int dE_\tau \, K_a(E_\nu \, , E_\tau) \;\; , \tag{15}$$

and

$$K_a(E_\nu \, , E_\tau) = \int d\Omega_a \int dS_a \; \cos\left(\theta_a\right) \; \epsilon(E_\tau) \, k_a(E_\nu \, , E_\tau \, ; \vec{r}_a \, , \Omega_a)$$

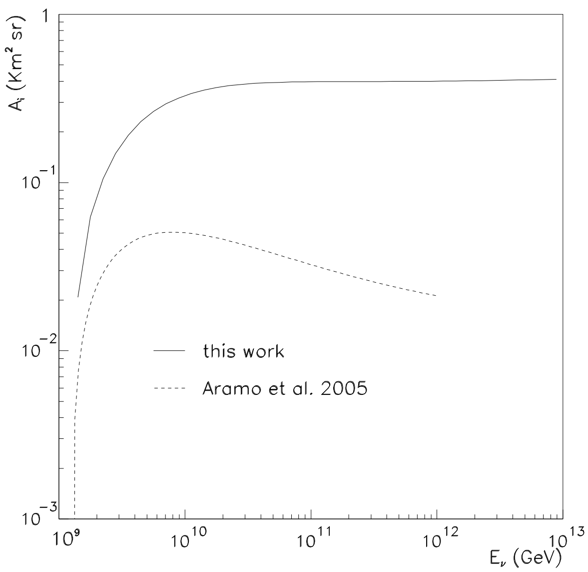

Fig. 3. The total effective aperture $A(E_\nu)$ is plotted versus the neutrino energy (solid line). The dashed line corresponds to the same quantity as obtained in ref. [15] for $H = 30$ km.

$$= \int d\Omega_a \int dS_a \, \cos(\theta_a) \, \epsilon(E_\tau) \int_0^{z_{\max}} P_1 \, P_2 \, P_3 \, P_4 \, dz \quad . \tag{16}$$

In order to get the explicit expression for $K_a(E_\nu \, , E_\tau)$ an extremely involved integration has to be performed, which requires the computation of all the properties for each track $(\vec{r}_a, \, \Omega_a)$, taking into account the DEM of the Auger site. To this aim a suitable approach is based on the following procedure: we use the available DEM of the Auger area to isotropically generate a large number of oriented tracks (let us say N) which cross the Auger fiducial volume. If we denote with N_a the subset of the N tracks which enter through surface Σ_a, then the kernel $K_a(E_\nu \, , E_\tau)$ can be well approximated by the expression

$$K_a(E_\nu \, , E_\tau) \approx 2\pi \, \epsilon(E_\tau) \, \frac{S_a}{N_a} \sum_{i_a=1}^{N_a} \cos(\theta_{i_a}) \; k_a(E_\nu \, , E_\tau \, ; \vec{r}_{i_a} \, , \Omega_{i_a}) \quad . \tag{17}$$

We show in Fig. 3 the aperture $A(E_\nu)$ as a function of the neutrino energy (solid line), compared with the results of ref. [15] (dashed line). Remarkably, an enhancement factor approximately of one order of magnitude is found with respect to the semi-analytical results of ref. [15]. The origin of the difference between the two calculations can be explained in the following way. In ref. [15] an event is rejected if the τ takes more than 30 km to decay; this means that almost horizontal events (where the τ emerges from the Earth far from the lower surface of the experiment, travels more than 30 km before entering in the

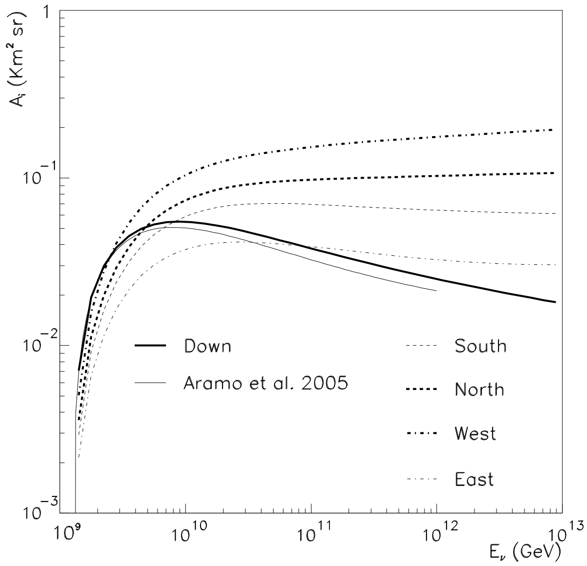

Fig. 4. The effective apertures $A_a(E_\nu)$ defined in Eq. (15) are plotted versus the neutrino energy. The thin solid line corresponds to the same quantity as obtained in ref. [15] for $H = 30$ km.

fiducial volume, and then decays inside it), preferred by the lateral surfaces due to the $\cos(\theta_{i_a})$ term in Eq. (17), were not included in the calculation of ref. [15], while they are present in this analysis. In Fig. 4 the different contributions from each surface are plotted together with the results of ref. [15] (thin solid line). As one can notice, the contribution coming from the tracks going through the Down surface (thick solid line) is in nice agreement with our previous calculation. Moreover, it is possible to distinguish a North-South effect and, more consistent, a West-East effect.

It is worth observing the different high energy behavior of the aperture corresponding to the D surface, A_D, with respect to the others. The increase of the neutrino energy would select the almost horizontal tracks, which however are depressed, for the D-surface only with respect to the lateral ones, by the factor $\cos(\theta_{i_D})$.

We can use the expression in Eq. (14) to obtain the yearly number of τ showering events at the FD of Auger (assuming a duty cycle $D = 10\%$). In Table 1 these rates are reported for the same UHE neutrino fluxes considered in section 2 of ref. [15] (see in particular figs. 1 and 2), and described in a series of papers [22,23,24,25,26,27,28]. The three GZK fluxes refer to three possible scenarios for cosmogenic neutrinos, which are those produced from an initial flux of UHE protons. Instead the NH (New Hadrons) and TD (Topological Defects) cases are two examples of exotic models capable of generating the UHECR above 10^{10} eV, with large associated neutrino fluxes. For each neutrino flux (fixed column), we list the total number of yearly events as well as

	GZK-WB	GZK-L	GZK-H	NH	TD
Surface D	0.016	0.040	0.095	0.246	0.100
Surface S	0.012	0.037	0.098	0.214	0.094
Surface N	0.015	0.046	0.125	0.267	0.120
Surface W	0.022	0.066	0.181	0.380	0.174
Surface E	0.008	0.024	0.061	0.139	0.060
Total	0.074	0.213	0.560	1.245	0.548
Ref. [15]	0.02	0.04	0.09	0.25	0.11

Table 1
Yearly rate of Earth-skimming events at the FD for the different neutrino fluxes considered in ref. [15]. The number of τ's showering into the fiducial volume that enter through each lateral surface are reported, as well as the total number of events for each flux. For comparison, we include the corresponding results from ref. [15].

the contributions from each lateral surface.

Some comments are in turn. The number of events crossing the bottom surface is in fair agreement with the previous analytical result of ref. [15]. However, the total number of events is a factor 4-6 larger (depending on the model considered), showing that the main contribution to the number of events is coming from almost horizontal showers, where the τ emerges from Earth surface far away from the Auger fiducial volume and decays inside it. The enhancement factor depends on the different features of the fluxes used in the analysis. For example, for the three GZK models in Table 1, this factor ranges from 3.7 to 6.2, corresponding to a hardening of the differential fluxes in energy (see Figs. 1 and 2 of ref. [15]). Instead, the enhancement is roughly the same for the last two models in Table 1 despite the fact that they have a different spectrum in the high energy range, due to the suppression of the very high energy neutrino events which escape without showering.

As one can see from Table 1, a significant difference in the number of events exists between the Surfaces W (facing the Andes) and E, which shows a *mountain* effect. This enhancement is mainly due to the largest amount of rock encountered by horizontal tracks coming from the west side. If we define, as a measure of the effect of mountains, the difference of the number of expected events entering the volume from W-surface and E-surface, divided by their average, the effect can be quite remarkable (even order 30%). This effect would also be larger by comparing the exclusive apertures, but in this case the difference in the apertures, which is larger for larger neutrino energy, should compel the fast decreasing with energy of neutrino fluxes. Of course, on the total number of events this 30% effect is diluted because it concerns only one surface among four lateral ones. Moreover, a similar but smaller effect (of order $\sim$ 20-25%) is

	GZK-WB	GZK-L	GZK-H	NH	TD
ν_e	0.034	0.098	0.277	0.565	0.276
ν_τ	0.009	0.018	0.036	0.113	0.043
Total	0.043	0.116	0.313	0.678	0.319

Table 2
Yearly expected number of down-going events at the FD, due to the showering of ν_e and ν_τ inside the Auger fiducial volume. The different predictions refer to the same fluxes of Table 1 and to a zenith angle larger than 60°.

also present in the difference between the number of events from the Surfaces N (facing the higher part of the *cordillera*) and S.

In conclusion, the largest contribution through the surfaces E, W, S and N makes the total number of yearly Earth-skimming events larger than the previous estimates of ref. [15]. This in turn increases the detection chances of UHE ν_τ at the FD of Auger, which seem realistic even for conservative neutrino fluxes like GZK-WB, considering that data will be taken over many years of observation.

In analogy with the analysis of ref. [15], we report in Table 2 the expected numbers of yearly down-going events at FD, produced by UHE ν_e and ν_τ showering inside the fiducial volume [2] . The numbers are calculated in a similar way to the Earth-skimming case, but with a different kernel in Eq. (12),

$$k_a(E_{\nu_\alpha}, E_\alpha; \vec{r}_a, \Omega_a) = \delta\left(E_\alpha - E^0_\alpha(E_{\nu_\alpha})\right)\; P_1^{\nu_\alpha}\; P_2^{\nu_\alpha} \tag{18}$$

where $\alpha = e, \tau$ and $E^0_\alpha(E_{\nu_\alpha})$ is the transferred energy to the charged lepton. For a ν_e we have

$$\begin{aligned} P_1^{\nu_e} &= \exp\left\{-\frac{\lambda_{\rm out}}{\lambda^\nu_{CC}(E_{\nu_e})}\right\} \\ P_2^{\nu_e} &= \int_0^{\lambda_{\rm in}} dz\, \frac{\exp\left\{-z/\lambda^\nu_{CC}(E_{\nu_e})\right\}}{\lambda^\nu_{CC}(E_{\nu_e})} = 1 - \exp\left\{-\frac{\lambda_{\rm in}}{\lambda^\nu_{CC}(E_{\nu_e})}\right\}\;, \end{aligned} \tag{19}$$

which take into account the probability that the neutrino survives until the fiducial volume producing an electron which initiates a shower inside the detector. Instead, for a ν_τ we have

[2] From the study of ν_e,ν_μ–induced shower in the atmosphere of ref. [29] it is argued that high energy ν_μ's have a very small probability of inducing a shower before reaching the ground.

$$
\begin{aligned}
P_1^{\nu_\tau} &= 1 - \exp\left\{-\frac{\lambda_{\rm in}\, m_\tau}{c\tau_\tau\, E_\tau}\right\} \\
P_2^{\nu_\tau} &= \int_0^{\lambda_{\rm out}} dz\, \frac{\exp\{-z/\lambda_{CC}^\nu(E_{\nu_\tau})\}\ \ \exp\{-(\lambda_{\rm out}-z)\, m_\tau/(c\tau_\tau\, E_\tau)\}}{\lambda_{CC}^\nu(E_{\nu_\tau})} \\
&= \frac{\exp\{-\lambda_{\rm out}/\lambda_{CC}^\nu(E_\nu)\} - \exp\{-\lambda_{\rm out}\, m_\tau/(c\tau_\tau\, E_\tau)\}}{[\lambda_{CC}^\nu(E_\nu)\, m_\tau/(c\tau_\tau\, E_\tau)] - 1}\ ,
\end{aligned}
\tag{20}
$$

which take into account the probability that the neutrino produces a τ which survives until the fiducial volume and initiates a shower inside the detector.

In this letter a new and more detailed computation of the aperture for Earth-skimming ν_τ of the fluorescence detector at the Pierre Auger Observatory has been performed. The evaluation has been carried out by using a different approach with respect to the previous semi-analytical one of ref. [15] and taking into account the real elevation profile of the area around Auger. The obtained results show an increase of the effective aperture, and correspondingly of the number of the expected events. This larger result is mainly due to the contribution of almost horizontal Earth-skimming τ's, emerging from the Earth surface far away from Auger but decaying inside its fiducial volume. Remarkably the presence of mountains near Auger leads to an enhancement factor on the total number of events of the order 1.3-1.6. As previously shown (see e.g. the discussion in [5]), our results indicate that the number of UHE neutrino events at Auger is comparable for showers induced by down-going UHE neutrinos and by the decays of τ's produced by Earth-skimming UHE ν_τ's.

It is worth observing that the efficiency of the FD detector, whose parameterization we have used in Eq. (1), can be considered as oversimplified and that one should expect a behaviour of FD much more complicated with energy and/or geometry of the event. Unfortunately, a complete and exhaustive analysis of this issue is still absent and thus not available for any analysis like ours. Nevertheless, our predictions can be considered as a first but probably useful step in the right direction, which should motivate more study inside the Auger collaboration for example in order to obtain a reliable efficiency of FD with energy and for horizonal showers.

Possible future improvements of the present work should take properly into account the response of the flourescence detector, as well as the real geometry of the Auger area and the fact that some of the UHE ν_τ/τ tracks could partly traverse water.

Acknowledgments

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