Rates of Horizontal Tau Air-Shower observable by satellites

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Abstract

Up-going and Horizontal Tau Air-Shower, UpTaus and HorTaus, may trace Ultra High Energy Neutrino Tau Earth Skimming at the edge of the horizon. We show that such events even for minimal GZK neutrino fluxes could be detected by space telescopes such as the EUSO project: These Horizontal Tau Showers will track very long fan-like, multi-finger showers whose signature would be revealed by EUSO, OWL experiments. Moreover the additional imprint of their young secondaries ($\mu^\pm$ and $\gamma$ bundles with $e^\pm$ pair flashes) might allow to disentangle their nature from the old UHECR secondaries in horizontal showers. Indeed at large zenith angles, the number of $\mu^\pm$ and secondary $\gamma$'s from old, Ultra High Energy Cosmic Rays becomes comparable. On the contrary up-ward muon bundles from UpTaus and HorTaus may arise within a young shower with a larger gamma-muon ratio ($\sim 10^2$). Such a very characteristic imprint maybe observed by Crown detectors on Mountain, planes or balloons in space, as well as by $\gamma$ satellites in Space. We estimate the UpTaus and HorTaus rate from the Earth and the consequent event rate of $\mu^\pm$ bundles, whose flux at $92^\circ - 97^\circ$ exceed the up-going muon flux induced by the atmospheric neutrino.

Key words:
Cosmic Rays, Air-Showers, Neutrino, Tau, Muons

1 Introduction

The study of ultra high energy upward and horizontal $\tau$ air showers produced by $\tau$ neutrino interactions within the Earth crust has been considered in recent years as an alternative way to detect high energy neutrinos. The problem of $\tau$ neutrinos crossing the Earth is indeed quite complicated because of the complex terrestrial neutrino opacity at different energies and angles of arrival. In addition, several factors have to be taken into account, such as the amount
of energy transferred in the $\nu_\tau - \tau$ lepton conversion, as well as the $\tau$ energy losses and interaction lengths at different energies and materials. This makes the estimate of the links between the input neutrino - output $\tau$ air shower very difficult. Such a prediction is further complicated by the existence of a long list of theoretical models for the incoming neutrino fluxes (GZK neutrinos, Z-burst model flux, $E^{-2}$ flat spectra, AGN neutrinos, topological defects). Many authors have investigated this $\nu_\tau$ signature, however the results are varied, often in contradiction among themselves, and the expected rates may range over a few orders of magnitude (Fargion, Aiello, & Conversano 1999; Fargion 2002; Bertou et al. 2002; Feng et al. 2002; Bottai & Giurgola 2003, Tseng et al. 2003; Bugaev, Montaruli, & Sokalski 2004; Fargion et al. 2004; Jones et al. 2004; Yoshida et al. 2004). So far, the majority of the current studies on this topic is based on Monte-Carlo simulations assuming a particular model of the incoming neutrino flux. Some author have chosen ad hoc the crossing depth of the tau; other considered ad hoc maximal distance for the tau in flight. Most of the authors focus on the UpTaus tracks in underground detectors. In previous works we have presented a very simple analytical and numerical derivation (as well as its more sophisticated extensions) which takes into account, for any incoming angle, the main processes related to the neutrinos and $\tau$ leptons propagation and the $\tau$ energy losses within the Earth crust (see Fargion et al. 2004a, Fargion et al. 2004b for details). Our numerical results are constrained by upper and lower bounds derived in more simple and tested approximations. We have shown how the effective volumes and masses are more severely reduced at high energy and we included as a further constraint the role of the air dilution at high altitude, where $\tau$ decay and the consequent air-shower may (or may not) take place. We showed (Fargion et al. 2004a) that our results give an estimate of the $\tau$ air-shower event rates that exceeds earliest studies but they were comparable or even below more recent predictions (Yoshida et al. 2004). Secondly, we pointed out that the consequent $\mu^\pm$, $e^\pm$, $\gamma$ signature of HorTaus largely differs from that of horizontal UHECR backgrounds (Fargion et al. 2004b).

In this paper we introduce in the calculation of the number of events an additional suppression factor related to the altitude at which air showers are observed. This guarantees the optimal extension and the largest flux for the shower to be detected at each observational $h$ altitude. In particular we apply all our previous results to the calculation of the expected number of events at different altitudes in the atmosphere, with a particular attention to the EUSO telescope. EUSO is a space born detector that will be located at an altitude of about 400 km on the International Space Station (ISS), aimed at the the detection of UHECR. It consists of a wide angle UV telescope that will look downwards towards the Earth atmosphere to detect the fluorescence signals induced by UHECR showers in the atmosphere. Its aperture is such to cover a surface as large as $1.6 \times 10^5$ km, therefore it will encompass AGASA-HIRES and Auger areas. EUSO is scheduled to be launched in the 2009. Its ability to observe within the downward atmosphere layer the long tracks of horizontal
showers may show their peculiar opening, by geomagnetic fields, into three main fingers defined by their charges: (muon and electron pairs of opposite charge bent in opposite arcs and rectilinear $\gamma$ paths for tens and hundreds of km distances).

2 How to estimate the Earth-Skimming Volume-Mass

To calculate the effective volume we assume that the neutrino traversing the Earth is transformed in a tau lepton at a depth $x$, after having travelled for a distance $(D(\theta) - x)$. The column depth $D(\theta)$ defined as $\int \rho(r)dl$, the integral of the density $\rho(r)$ of the Earth along the neutrino path at a given angle $\theta$ is shown in Fig. 2. The angle $\theta$ is included between the neutrino arrival direction and the tangent plane to the earth at the observer location ($\theta = 0^\circ$ corresponds to a beam of neutrinos tangential to the earth’s surface) and it is complementary to the nadir angle at the same location. The probability for the neutrino with energy $E_\nu$ to survive until a distance $(D(\theta) - x)$ is $e^{-(D(\theta)-x)/L_\nu}$, while the probability for the tau to exit the Earth is $e^{-x/l_\tau}$. On the other hand, as we will show in the next section, the probability for the outcoming $\tau$ to emerge from the Earth keeping its primary energy $E_\tau$ is $e^{-x/L_\tau}$ (where $e^{-x/L_\tau} \ll e^{-x/l_\tau}$ at energy $E_\tau > 3 \times 10^{17}$ eV). By the interaction length $L_\nu$ we mean the characteristic length for neutrino interaction; as we know its value may be associated to the inverse of the total cross-section $\sigma_{T_\nu} = \sigma_{CC} + \sigma_{NC}$, including both charged and neutral current interactions. It is possible to show that using the $\sigma_{CC}$ in the $e^{-(D(\theta)-x)/L_\nu}$ factor includes most of the $\nu_\tau$ regeneration along the neutrino trajectory making simpler the mathematical approach (Fargion et al. 2004a).

The effective volume per unit surface is given by

$$V_{Tot}(E_\nu) = \frac{V_{Tot} \oplus(E_\nu)}{2\pi R_\oplus^2} = \int_0^{\frac{\pi}{2}} \int_0^{D(\theta)} e^{-(D(\theta) - x)/L_\nu} e^{-x/l_\tau} \sin \theta \cos \theta d\theta dx$$

where $A$ is any arbitrary surface above the corresponding effective volume. For instance this expression has been first estimated for all the Earth. In this case $A$ is just half of the terrestrial surface, due to the request of selecting only the upward direction. Under the assumption that the $x$ depth is independent of $L_\nu$ and $l_\tau$, the above integral becomes:

$$V_{Tot}(E_\tau) = \frac{l_\tau}{1 - \frac{l_\tau}{L_\nu}} \times \int_0^{\frac{\pi}{2}} \left( e^{-(D(\theta)/l_\tau)} - e^{-(D(\theta)/l_\tau)} \right) \sin \theta \cos \theta d\theta$$
where the energy of the neutrino $E_\nu$ has been expressed as a function of $E_\tau$ via the introduction of the parameter $\eta = E_\nu / E_{\tau f}$, the fraction of energy transferred from the neutrino to the lepton. At energies greater than $10^{15}$ eV, when all mechanisms of energy loss are neglected, $\eta = E_\nu / E_{\tau f} = E_\nu / E_\mu \simeq 1.2$, meaning that the 80% of the energy of the incoming neutrino is transferred to the newly born $\tau$ after the $\nu - N$ scattering (Gandhi 1996, 1998), (Fargion et. all 2004a)). Once the effective volume is found, we introduce an effective mass defined as

$$M_{Tot} A = \rho_{out} V_{Tot} A$$

(1)

where $\rho_{out}$ is the density of the outer layer of the Earth crust: $\rho_{out} = 1.02$ (water) and 2.65 (rock).

The expression of the effective volume in the most general case becomes (see Fargion et al 2004 for details)

$$\frac{V_{Tot}(E_\tau)}{A} = \left( \frac{L_{\tau(\beta)}(E_\tau)}{1 - \frac{L_{\tau(\beta)}(E_\tau)}{L_{\nu CC}(\eta E_\tau)}} \right) \times \frac{2}{\pi} \int_{0}^{\pi} e^{-L_{\nu CC}(\eta E_\tau) \rho(\theta) \sin \theta \cos \theta} d\theta$$

(2)

where the interaction length $L_{\tau(\beta)}$ (shown in Fig. 2 and compared to $l_\tau$) guarantees a high energy outcoming $\tau$ even if outcoming from a thinner Earth crust (see Fargion et al. 2004 for a more detailed discussion of $L_{\tau(\beta)}$).

We remind that the total neutrino cross section $\sigma_\nu$ consists of two main component, the charged current and neutral current terms, but the $\tau$ production depends only on the dominant charged current whose role will appear later in the event rate number estimate. The interaction lengths $L_{\tau \beta}, L_{\nu CC}$, depends on the energy, but one should be careful on the energy meaning. Here we consider an incoming neutrino with energy $E_{\nu i}$, a prompt $\tau$ with an energy $E_{\tau i}$ at its birth place, and a final outgoing $\tau$ escaping from the Earth with energy $E_{\tau f}$, after some energy losses inside the crust. The final $\tau$ shower energy, which is the only observable quantity, is nearly corresponding to the latter value $E_{\tau f}$ because of the negligible $\tau$ energy losses in air. However we must be able to infer $E_{\tau i}$ and the primary neutrino energy, $E_\nu$, to perform our calculation. The effective volume resulting from Eq. 2 calculated for a detector with a 1 km$^2$ acceptance area is displayed in Fig. 3.

3 From the GZK neutrino flux to Tau-Air Shower rate for EUSO

After having introduced the effective volume we can estimate the outcoming event number rate for EUSO for any given neutrino flux. The consequent event
rate for incoming neutrino fluxes may be easily derived by:
\[
\frac{dN_{ev}}{d\Omega dt} = \left( \int \frac{dN_\nu}{dE_\nu d\Omega dAdt} \sigma_{N_\nu}(E) dE \right) n_\rho V_{Tot}
\]  
(3)

where \( L_{\nu CC} = (\sigma_{N_\nu} n)^{-1} \), \( \Phi_{\nu} = \frac{dN_\nu}{dE_\nu} E_\nu = 5 \cdot 10^{-18} \left( \frac{E_\nu}{10^{19} eV} \right)^{-\alpha+1} \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1} \)
describes as a flat spectrum (\( \alpha = 2 \)) most of the GZK neutrino flux and as a linearly increasing spectrum (\( \alpha = 1 \)) the Z-burst model; \( \rho_r \) is the density of the most external layer (either rock or water). The assumption on the flux may be changed at will and the event number will scale linearly according to the model.

In Fig. 4 we show the expected number of event for EUSO where we have included the Earth’s atmosphere and we have used \( L_{\tau(\beta)} \), so that we may express the results as a function of the final \( \tau \) lepton energy.

As one can see from Fig. 4, at energy \( E = 10^{19} \text{ eV} \) the general expected event rate is given by:
\[
N_{ev} = 5 \cdot 10^{-18} \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1} \left( \frac{V_{eff} \rho_r}{L_{\nu CC}} \right) (2\pi \eta_{Euso} \Delta t) \\
\times \left( \frac{\Phi_{\nu} E_\nu}{50 eV \text{cm}^{-2} \text{sec}^{-1} \text{sr}^{-1}} \right) \eta^{-\alpha} \left( \frac{E_\tau}{10^{19} \text{eV}} \right)^{\alpha+1}
\]

Such number of events greatly exceed previous results by at least two orders of magnitude (Bottai et al. 2003) but are comparable, but below more recent estimates (Yoshida et al. 2004).

4 The Tau air showers and secondary \( \mu \) differential rates

The differential number of events is given by
\[
\frac{dN_{ev}}{d\Omega dt} = \Phi_{\nu} \rho_r V_{eff} L_{\nu CC}
\]  
(4)

We introduce now a differential expression of the number of events which allows to calculate the number of events as a function of the angle \( \theta \). We shall introduce a suppression factor that cares the finite length of the horizontal atmosphere (Fargion et all. 2004a).

We can rewrite the expression of the effective volume given in Eq. 2 as a
differential volume for each arrival angle $\theta$:

$$\frac{dV}{d\theta d\phi d\Omega dA} = \left[1 - e^{-\frac{L_0}{\tau}}\right] \times l_\tau(E_\tau) \frac{e^{-\frac{D(\theta)}{L_{\nu CC}}}}{\left(1 - \frac{l_\tau(E_\tau)}{L_{\nu CC}}\right)} \sin \theta \cos \theta$$  

(5)

and we obtain the following expression for the differential rate of events

$$\frac{dN_{ev}E}{dEd\Omega d\theta d\phi dt dA} = \Phi_{\nu_0} \eta^{-\alpha} \left(\frac{E_\tau}{E_{\nu_0}}\right)^{-\alpha+1} \rho_\tau \left[1 - e^{-\frac{L_0}{\tau}}\right] \frac{l_\tau(E_\tau)}{L_{\nu CC}} \frac{e^{-\frac{D(\theta)}{L_{\nu CC}}}}{\left(1 - \frac{l_\tau(E_\tau)}{L_{\nu CC}}\right)} \sin \theta \cos \theta$$

with $\eta = 1.2$ and $E_{\nu_0} = 10^{19}$ eV.

If we now integrate on the solid angle $d\Omega$ (half side) we obtain the above formula multiplied by a factor $2\pi$.

Given the $\tau$ number of events we can calculate the rates of $\mu$, $e^\pm$ pairs and $\gamma$, which originates as secondary particles from the $\tau$ decay. The number of muons is related to the total number of decaying pions and according to Matthews (2001) is given by

$$N_\mu \simeq 3 \cdot 10^5 \left(\frac{E_\tau}{P eV}\right)^{0.85}$$  

(6)

$$N_{e^+e^-} \simeq 2 \cdot 10^7 \left(\frac{E_\tau}{P eV}\right)$$  

(7)

$$N_\gamma \simeq 10^8 \left(\frac{E_\tau}{P eV}\right)$$  

(8)

and we obtain finally

$$\frac{dN_{ev}^i}{d\theta d\phi dt dA}(E, \theta) = N_i \cdot \frac{dN_{ev}^\tau}{dE d\theta d\phi dt dA}(E_\tau)$$  

(9)

We show in Fig. 5 the average differential rate of $\tau$'s and the secondary $\mu^\pm$, $e^\pm$ and $\gamma$ bundles from the decay of $\tau$ leptons. We find that the muon signal at the horizon, related to Earth skimming tau neutrinos is above $10^{-12} - 10^{-11}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. One should notice that the muonic background produced by atmospheric neutrinos (CR $\rightarrow \mu^\pm$ $\rightarrow \nu_{atm}$ $\rightarrow \mu^\pm$) below the horizon approaches the value $\Phi_{\mu atm} \simeq 2 \cdot 10^{-13}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, which is at least one order of magnitude lower than what we have obtained from our calculation for minimal GZK $\nu_\tau$ fluxes (see Fig. 5).
Moreover this muonic shower would have a significant $\gamma$ component, with a high number of photons - $N_\gamma / N_\mu \sim 10^2$ (Cillis & Sciutto 2001; see also Fig. 15 in Cronin 2004) - because of the $\tau$ decay channels into both charged and neutral pions.

On the other hand, horizontal UHECRs will not represent a source of contamination for our signal because the horizontal $\gamma$’s produced in the hadronic shower inside the atmosphere would be exponentially suppressed at large slant depth ($X_{\text{max}} > 3000$ g cm$^{-2}$) and large zenith angles ($\theta > 70^\circ$) (Cillis & Sciutto 2001). Only $\mu^\pm$ can survive when propagating through the atmosphere at large zenith angles. Such muons would also be source of parasite $\gamma$ signal - due to the $e^\pm$ pair produced in the $\mu^\pm$ decay in flight - but the gamma-to-muon-number ratio would be now approximately $\ll 1$.

Therefore, this difference would allow to distinguish gamma-rich HorTaus from common horizontal gamma-poor UHECR events to reveal UHE earth-skimming $\nu_\tau$’s.

For a more precise approach to the calculation of the rate of events one has also to take into account that the number of events varies as a function of the height $h$ at which the observer is located to detect the muonic, electronic and gamma shower. Therefore we introduce an additional factor

$$\frac{dN_{\text{ev}}^\mu}{d\theta d\phi dt dA}(E, \theta, h) = \left(1 - e^{-h/h_s}\right) \frac{dN_{\text{ev}}^\mu}{d\theta d\phi dt dA}(E, \theta)$$

where the parameter $h_s$ that we have introduced as

$$h_s = R_\tau(E_\tau) \sin \theta + \frac{X_{\text{max}}(E_\tau)}{\rho_r} \sin \theta$$

(10)

defines the optimal height where the shower can reach its maximal extension at the corresponding energy $E_\tau$. This is the sum of the height reached by the $\tau$ in the atmosphere before its decay ($R_\tau \sin \theta$), where we have neglected $\tau$ energy losses in the atmosphere, and the altitude reached by the secondary particles of the shower which is related to the parameter $X_{\text{max}}$. Note that $R_\tau = 4.9(E_\tau/10^{17} \text{ eV})$ km and $X_{\text{max}}/\rho_r = 5.7 + 0.46 \ln(E_\tau/10^{17} \text{ eV})$ km. Here we have considered the air density $\rho_r = 1.25 \times 10^{-3}$ g cm$^{-3}$ constant and equal to the value at the sea level. At low energies ($10^{15} - 10^{16}$ eV) the second term is dominant and $\rho_r$ can be considered as constant because the $\tau$ lepton travels for less than 1 km before it decays. At higher energy ($10^{17} - 10^{19}$ eV) the first term is dominant, and we can neglect the way the exact value of $\rho_r$ changes with the altitude. In Fig. 6 we show the differential number flux (per unit area, energy and time) at different altitudes of $\mu$ leptons originated by $\tau$ decay. We have performed this calculation assuming an input GZK neutrino flux and that the Earth outer layer is made of rock (left panel) and water (right panel). We show how the expected number of events increase with the altitude of the observer.
In particular at $h = 40-20$ km, roughly the altitude of the atmosphere layer where HAS or HORTAUs are expanding to maximal power and where EUSO is following the UHECR showers, the differential number flux of muons and electromagnetic showers reach already its maximal asymptotic value.

In Fig. 7 we display the differential number flux (per unit area, solid angle and time) of the secondary $\mu^\pm$ pair (from HORTAUs) as a function of the aperture $\theta$ which describes the line of sight below the horizon (i.e. $\theta = \theta_{\text{zenith}} - 90^\circ$). Again we have assumed an input GZK neutrino flux and an Earth outer layer made of rock. The two panels correspond to two different $E_\tau$ energies: $E_\tau = 10^{17}$ ev (Fig. 7, left panel) and $E_\tau = 10^{18}$ ev (Fig. 7, right panel).

Again we show that at higher altitudes the muon, (as well as the gamma flux) from HORTAUs is high and that satellites orbiting around the Earth at a few hundreds of kilometers may better search Earth skimming tau-air showers secondaries, if they will turn their focus on the Horizons edges of the Earth, where they are mostly produced (See Fargion et all. 2004c)

5 Conclusions

Horizontal showers from normal hadrons (or gammas) are strongly depleted of their electromagnetic component because of the large slant depth ($X_{\text{max}} > 3 \times 10^4$ g cm$^{-2}$), while horizontal tau air showers are not. Indeed ”young” HorTaus either of hadronic (67%) or electromagnetic (33%) nature at their peak shower activity are expected to have a large $N_\gamma/N_\mu$ ratio, greater than $10^2$ (but with a characteristic energy ratio $E_\gamma/E_\mu < 10^2$). Old horizontal showers would have $N_\gamma/N_\mu \approx 1$. This difference would allow to distinguish and disentangle HorTaus from horizontal UHECR events, even in absence of good angular resolution, opening a new perspective in the UHE neutrino Astronomy. The secondary fluxes of muons and gamma bundles made by incoming GZK neutrino fluxes and their HorTau showers, is well above the noise (by one-two orders of magnitude) made by up-going atmospheric muons. The neutrino signals at energies much above EeV may be even better probing the expected harder neutrino Z-Burst model spectra [3, 22].

The peak fluences we find in the $\mu$ and $\gamma$ component at the horizon ($\pm 5^\circ$) will give a signal well above the background produced by atmospheric $\nu$'s. We have not discussed the albedo muons whose fluxes measured by Nemo-Decor experiments, $\phi_\mu \lesssim 10^{-9}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$, are made mostly by single tracks [19]. Because pair (or triple) bundle muons are much rarer ($\phi_{\mu\text{pair}} < 10^{-4}\phi_{\mu\text{single}} \approx 10^{-13}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$), the search and detection of muon bundles by GZK HorTaus at a minimal rate of $10^{-12}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ (over an area of $10^2$ m$^2$) will lead, in a year, to about 30 muons possibly clustered in five - ten multiple bundles. These events will be reinforced by hundreds or thousands of associated collinear gamma flashes. A detector with an area of few tens or hundreds
of square meters pointing to the horizon from the top of a mountain would be able to reveal the GZK $\nu_\tau - \tau$ young showers (Iori, Sergi & Fargion 2004). The characteristics of a prototype twin crown-like array detector to be placed on mountains, balloons, or satellites (Fargion2001a) will be discussed in detail (Fargion et. all. 2004c)). The simultaneous sharp $\gamma$ bundle at $\phi_\gamma \sim 10^{-9} \div 10^{-11}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ and the ”burst” of electron pair at $\phi_{e^+e^-} \sim 10^{-9}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ would give evidence of unequivocal $\tau$ signature.

It should be reminded that the neutrino interaction enhancement by TeV new Physics would produce also an increase of hundreds or thousands time in Hor-Taus beyond a mountain Chain (like Auger) than standard weak interactions would do. Therefore Auger (a)must soon detect the Andes Shower Shadows toward the far away west side because of their absorption inside the mountain;(b) Auger must reveal the absence (or) the birth of young (Fargion,Aiello Conversano 1999), (Bertou et all. 2002), HorTaus created by tau born inside the the mountain themselves; they will be more abundant if New Physics at TeV is inducing larger neutrino-nucleon interactions. In a few years Auger might anyway be able to observe the expected GZK neutrinos inducing Hor-Taus at EeV energies. In conclusion we showed that an orbiting telescope such as EUSO experiment will be able to see at least half a dozen of events of Hor-Taus mainly enhanced along the Continental Shelves or Mountain edges. To conclude we want to remind that inclined-vertical PeVs $\tau$ air showers (Up-Taus) would nearly always be source of $\gamma$ ”burst” surviving the atmosphere opacity. These sharp UpTaus (with their companion HorTaus above and near EeVs) might be observed by satellites as brief Terrestrial Gamma Flashes (TGF). Indeed we identified a possible trace of such events in BATSE record (taken during the last decade) of 78 upgoing TGF possibly associated with galactic and extragalactic UHE neutrino sources (Fargion 2002).

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Fig. 1. Horizontal Upward Tau Air-Shower (HorTauS) originated by UHE neutrino skimming the Earth: fan-shaped jets arise because of the geo-magnetic bending of charged particles at high quota ($\sim 23 - 40$ km). The shower signature may be observable by EUSO just above the horizon. Because of the Earth opacity most of the UpTau events at angles $\theta > 45 - 50^\circ$ will not be observable, since they will not be contained within its current field of view (FOV).

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Fig. 2. **Left:** Column depth as a function of the incoming angle having assumed the multi-layers structure given by the Earth Preliminary Model. **Right:** Comparison between $L_{\tau(\beta)}$ and $l_{\tau}$ for rock and water. As one can see from the picture, $L_{\tau(\beta)}$ is shorter than $l_{\tau}$ at energies above $10^{17}$ eV, thus it corresponds to a smaller effective volume where $\tau$’s are produced while keeping most of the primary neutrino energy. The energy label on the x axis refers to the newly born tau for $L_{\tau(\beta)}$: $E_{\nu\tau}$.

Fig. 3. Effective mass for UpTaus and HorTaus per km square unit area including the suppression factor due to the finite extension of the Earth’s atmosphere (an horizontal length of 600 km). The curves obtained (the red line for an Earth outer layer made of water and the pink line for the rock) are compared with a simplified model of the Earth, considered as an homogeneous sphere of water (green line) and rock (blue line). Here we used the interaction length $L_{\tau(\beta)}$ and the volume is expressed as a function of the final tau energy. Note that above $10^{-2}$ km$^2$ the effective mass-volume in the energy range $3 \times 10^{15} - 10^{19}$ eV is larger than the volume of the atmospheric layer, whose ability to convert downward neutrino in observable air shower is negligible. Only horizontal neutrino interaction in the atmosphere may be detected, at a much lower rate than the HorTaus ones.
Fig. 4. Number of EUSO Event for HorTaus in 3 years record as a function of the outgoing lepton tau ($L_{\tau(\beta)}$ as interaction length), including the finite extension of the horizontal atmospheric layer. At energy $E_{\tau} = 10^{19}$ eV, the event number is $N_{ev} = 3.0 \ (\phi_{\nu}E_{\nu}/50 \ eV \ cm^{-2} \ s^{-1} \ sr^{-1})$ for the water and $N_{ev} = 6.0 \ (\phi_{\nu}E_{\nu}/50 \ eV \ cm^{-2} \ s^{-1} \ sr^{-1})$ for the rock. The resulting number of events has been calculated for an initial GZK neutrino flux: $\propto E^{-2}$.

Fig. 5. Left: The differential number of event rate of $\tau$ leptons (HorTaus) for an input GZK neutrino flux. As in previous Figures we are assuming that $\tau$’s are escaping from an Earth outer layer made of rock. Note the discontinuity at $\theta \simeq 1$ rad, due to the corresponding inner terrestrial higher density core (see Fig. 2). Right: The differential number of event rate of the secondary muons produced by the decay in flight of $\tau$ leptons in the Earth’s atmosphere: HorTaus. As in previous Figures we are assuming an input GZK neutrino flux and that $\tau$’s are escaping from an Earth outer layer made of rock.
Fig. 6. **Left:** The differential number flux (per unit area, energy and time) of the expected number of events of $\mu$ leptons from $\tau$ decay at different altitudes as a function of the energy of the incoming neutrino $E_\nu$. Here we have assumed an input GZK neutrino flux and an Earth outer layer made of rock. **Right:** The differential rate of the expected number of events of $\mu$ leptons from $\tau$ decay at different altitudes as a function of the energy of the incoming neutrino $E_\nu$. Here we have assumed an input GZK neutrino flux and an Earth outer layer made of water. The higher the observatory the larger the flux, and for $h = 400$ km it can even exceed the "noise" due to the atmospheric upgoing muons ($\Phi_{\mu, atm} \sim 2 \times 10^{-13} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$).

Fig. 7. The average differential number flux (per unit area, solid angle and time) of secondary muons from HorTaus at different altitudes as a function of the aperture $\theta$ which describes the line of sight below the horizon (i.e. $\theta = \theta_{\text{zenith}} - 90^\circ$). The flux has been calculated for two values of the energy of the $\tau$: $E_\tau = 10^{17}$ eV (left panel) and $E_\tau = 10^{18}$ eV (right panel). We have assumed an input GZK-like neutrino flux and an Earth outer layer made of rock. Note the discontinuity of the angular spectrum in the left panel, due to the sharp density contrast of the Earth at $\theta \simeq 1$ rad and the asymptotic behaviour for $h \gg 1$ km. Because the Earth is nearly opaque to EeV $\nu_\tau$, only Earth-skimming neutrinos nearly horizontally are visible. The discontinuity in the spectrum at $\theta \sim 1$ rad occurs also at energies as large as $10^{18}$ eV (right panel), but at a lower flux, thus it is not included in this figure.