

Detection of tau neutrinos by Imaging Air Cherenkov Telescopes

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This paper investigates the potential to detect tau neutrinos in the energy range of 1-1000 PeV searching for very inclined showers with imaging Cherenkov telescopes. A neutrino induced tau lepton escaping from the Earth may decay and initiate an air shower which can be detected by a fluorescence or Cherenkov telescope. We present here a study of the detection potential of Earth-skimming neutrinos taking into account neutrino interactions in the Earth crust, local matter distributions at various detector sites, the development of tau-induced showers in air and the detection of Cherenkov photons with IACTs. We analysed simulated shower images on the camera focal plane and implemented generic reconstruction chains based on Hillas parameters. We find that present IACTs can distinguish air showers induced by tau neutrinos from the background of hadronic showers in the PeV-EeV energy range. We present the neutrino trigger efficiency obtained for a few configurations being considered for the next-generation Cherenkov telescopes, i.e. the Cherenkov Telescope Array. Finally, for a few representative neutrino spectra expected from astrophysical sources, we compare the expected event rates at running IACTs to what expected for the dedicated IceCube neutrino telescope.

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1. Introduction

The existing Imaging Air Cherenkov Telescopes (IACTs) such as MAGIC [1], VERITAS [2] and H.E.S.S. [3] could have the capability to detect PeV tau neutrinos by searching for very inclined showers [4]. In order to do that, the Cherenkov telescopes need to be pointed in the direction of the taus escaping from the Earth crust, i.e. at or a few degrees below the horizon. In [5], the effective area for up-going tau neutrino observations with the MAGIC telescopes was calculated analytically and found to be maximum in the range from 100 TeV to ~ 1 EeV. However, the sensitivity for diffuse neutrinos was found to be very low because of the limited FOV (the topographic conditions allow only for a small window of about 1 degree width in zenith and azimuth to point the telescope downhill), the short observation time and the low expected neutrino flux.

On the other hand, if flaring or disrupting point sources such as GRBs are observed, one can expect an observable number of events even from a single GRB if close by, as recently shown by the All-sky Survey High Resolution Air-shower (Ashra) team [6]. Also, for IACT sites with different topographic conditions, the acceptance for up-going tau neutrinos is increased by the presence of mountains [7], which serve as target for neutrino interaction leading to an enhancement in the flux of emerging tau leptons. A target mountain can also shield against cosmic rays and star light. Nights with high clouds often prevent the observation of γ -ray sources, but still allow point the telescopes to the horizon. While observation of tau neutrinos is not the primary goal of IACTs, a certain level of complementarity can be expected where switching for normal (i.e. γ -ray) observation made to tau neutrinos (i.e. mostly horizontal) pointing. Next-generation Cherenkov telescopes, i.e. the Cherenkov Telescope Array (CTA) [8], can in addition exploit their much larger FOV (in extended observation mode) and a higher effective area.

2. Method

In order to study the signatures expected from neutrino-induced showers by IACTs, a full Monte Carlo (MC) simulation chain was set, which consists of three steps. First, neutrino propagation of a given neutrino flux through the Earth and the atmosphere is simulated using an extended version of the ANIS code [9], see also [7] for more details. Then, the shower development of τ -induced showers and Cherenkov light production from such shower is simulated with CORSIKA [10]. The CORSIKA (version 6.99) was compiled with TAULEP option [11], such that the tau decay is simulated with PYTHIA package [12]. In order to simulate Cherenkov light from inclined showers for any defined Cherenkov telescopes array the CERENKOV and IACT option was also activated [14]. Finally, to consider the atmospheric depth correctly for inclined showers, the CURVED EARTH and SLANT option was also selected.

For high energies (> 1 PeV) the computing time become excessively long (scaling roughly with the primary energy). In order to reduce it to tolerable values the so-called "thin sampling" mechanism is used [13]. To cope with the vast number of secondary particles thinning and re-weighting of secondaries was used with a thinning level of 10^{-6} . The kinetic energy thresholds for explicit tracked particles were set to: 300, 100, 1, 1 MeV for hadrons, muons electrons and photons, respectively. Shower simulations were performed considering QGSJET II model for hadronic interactions in the atmosphere.

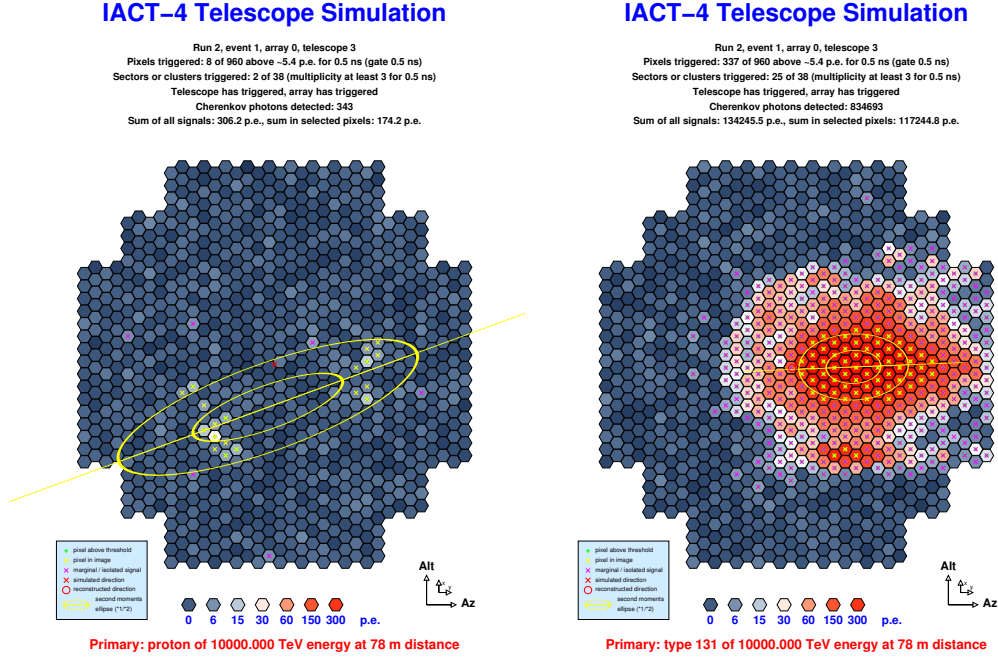


Figure 1: Example of simulated shower images with primary particle energy 10 PeV and zenith angle $\theta = 88^\circ$ as seen by IACT-4 camera with 2.5° FOV. (Left) proton interacting at the top of atmosphere, first interaction point at vertical depth below 50 g/cm^2 and detector-to-shower distance of about 1000 km; (Right) tau lepton tau decaying close to the detector, with an injection vertical depth of 760 g/cm^2 and a detector-to-shower distance of about 50 km.

We simulated showers induced by tau leptons with energies from 1 - 1000 PeV in steps of 0.33 decades and with an injection position at altitudes ranging from detector level ¹ to the top of atmosphere. The injection point spans different vertical depths from ground to top of the atmosphere with steps of at least 50 g/cm^2 . At vertical depth, 1000 showers were generated in order to study shower-to-shower fluctuations and to cover different tau decay channels. The results of CORSIKA simulations were used as input for the last step i.e. simulation of detector response. We used the Cherenkov telescope simulation package: `sim_telarray` [14]. The light collection area is simulating including the ray-tracing of the optical system, the measured transmittance and the quantum efficiency of PMT. The response of the camera electronics was simulated in detail including night-sky background and different system triggers. The `sim_telarray` simulations were performed for different configurations: H.E.S.S. like four telescopes (named here by IACT-4), and for a few CTAs arrays considered in [15] with so-called *production-1* settings. The IACT-4 can be considered as representative for current generation of IACTs. The response to τ -induced showers is found to depend weakly on the details of the optical set-up, field of view and camera electronics. Among different CTAs array configurations shown in [15] the arrays chosen were named CTA-E (59 telescopes) and CTE-I (72 telescopes), which according to [15] are the best compromise between compact and dense layout. The selected arrays have only slightly worse sensitivity for γ -rays than the full CTA array [15].

¹We used 1800 a.s.l for the simulation of current generation of IACTs and 2000 m a.s.l for CTAs.

In order to compare images at the camera plane we also simulated inclined showers induced by proton, photon and electron. At energies larger than 1 PeV, we do not expect significant background of showers initiated by photons or electrons. The proton simulations were instead used to estimate the main isotropic background for neutrino searches due to interaction of cosmic rays in atmosphere. The direction of primary protons was varied within a circular with aperture $\beta = 5^\circ$ around the fixed primary direction, i.e. the VIEWCONE option was selected in the CORSIKA simulations.

3. Results

In case of showers observed at large zenith angles the Cherenkov telescopes have to undergo a long optical path, due to a thicker layer of atmosphere. The shower maximum is located far from the observatory and the photon density at the mirrors decreases. This reduces the efficiency compared to lower zenith angles, especially at low energies. Images on the camera will be dimmer and smaller in size. As an example, in Figure 1 we show a representative shower image for a 10 PeV proton injected at the top of atmosphere and 10 PeV tau lepton injected close to the detector, respectively. As expected, the shower image on focal camera plane for tau has much larger image size and contains much more photons comparing to the proton one. Note also, that for inclined showers the hadronic and electro-magnetic component is almost completely absorbed in the atmosphere while the muonic component (muons) can reach the Earth. Thus, the shower images on the cameras from proton-induced showers will be mostly contain the muon ring (if muons propagating parallel to the optical axis) or incomplete ring (arcs) in the camera, see Figure 1 (Left) as an example.

Figure 2 (A) shows the trigger probability² for τ -induced showers with different zenith angles and energies of tau lepton in case of IACT-4 array. The calculated trigger probabilities for different zenith angles $\theta = 80^\circ, 84^\circ, 87^\circ$ are quite similar, within errors, if their plotted as a function of the distance between the injection point and the detector measured in g/cm^2 . This is understood, if we note that amount of Cherenkov light detected by telescopes depends essentially on atmospheric slant depth interval between the Cherenkov telescope and the shower maximum. At shower maximum shower has the largest lateral extension and Cherenkov light productions, thus is capable of producing the largest signal seen by IACTs telescopes. As we now, could not simulate the showers with zenith angle $\theta > 90^\circ$ in the combination of "CURVED EARTH" and IACT options, we use the zenith angle 87° to estimate the trigger efficiency for up-going tau neutrino showers. This should be reasonable assumption, because the trigger efficiency in case of τ -induced showers with the same energy should only slightly depend on zenith angle (as its confirmed by Figure 2 (A)), as long as the corresponding altitudes of shower maxima are the similar.

As expected (see Figure 2 (A)) the trigger probability increases with primary energy of lepton tau and decreasing distance to the detector. Only, at particle injection slant depths $< 1000 \text{ g/cm}^2$, measured from detector level, the trigger efficiency drops due to fact that shower maximum is

²It is defined as the number of simulated showers with positive trigger decision over the total number of generated showers. In this work, simulation was done for two level trigger, so-called Majority trigger. The first level is a camera level trigger (**L1**) defined by 3 pixels above 4 photo-electrons (p.e.) with a short time window and the second level is basically a coincidence level trigger among all telescopes in the defined array or sub-array (**L2**) and requires at least 2 neighboring triggered telescopes

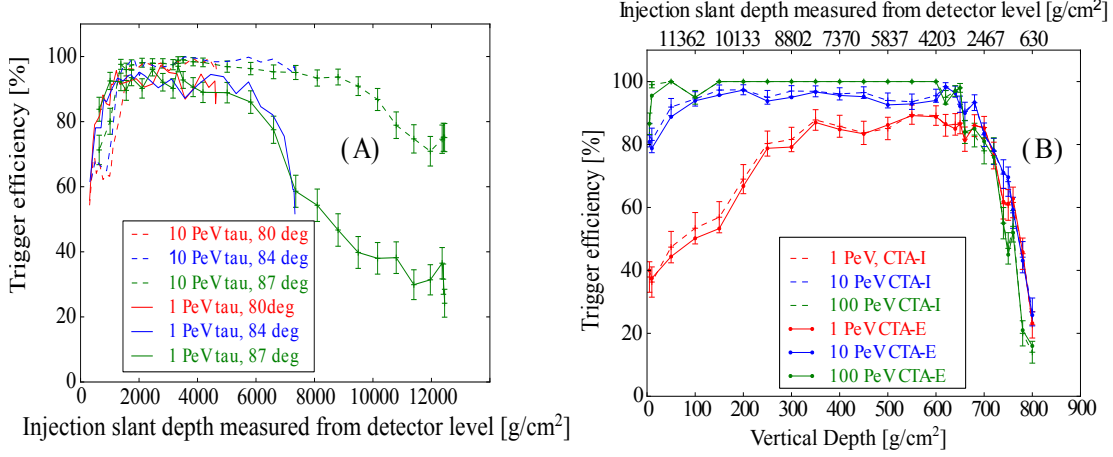


Figure 2: (A) Trigger efficiency as a function of injection slant depth with IACT-4 for different zenith angles and energies of tau lepton. Note, that for different zenith angles the distance from atmospheric border to detector level is significant different due to the Earth’s curvature. (B) Trigger probability for CTAs at a fixed zenith angle of 87° .

to close to the detector or the shower did not reach yet the maximum of shower development, decreasing amount of Cherenkov light seen by telescopes. It is also worth to mention, that below 6000 g/cm^2 the trigger probability is at the level of about 90%. In this case the corresponding geometrical distance to the detector (in meters) depends on zenith angle θ , but for $\theta = 87^\circ$ is of about $\sim 100 \text{ km}$. This gives estimate about the size of the active volume for τ -induced showers seen by IACTs.

Figure 2 (B) shows the trigger probability for considered CTAs arrays and different primary energy of lepton tau. As for IACT-4 array, the trigger probability is close increases because the higher the energy, the more Cherenkov light is produced, and the larger the number of triggered events. It is also well seen by comparing with results from Figure 2 (A), that calculation for larger CTAs array, which consists of much more telescopes with different optics and camera structures, than IACT-4 array gives basically similar fraction of triggered events. Moreover, for considered CTAs arrays, the trigger efficiency only slightly dependence on array structure. This can be explain by the fact, that for inclined shower studied in this work (with $\theta > 80^\circ$) the size of Cherenkov light pool distribution at detector level is larger than 1 km^3 , which is much more than distance between telescopes in considered arrays. Thus, the fraction of triggered events is expected to be similar and only slightly depends on density of telescopes.

The Cherenkov light forms an ellipse on the cameras. The cleaned camera image is characterized by a set of image parameters based on Hillas [16]. These parameters provide a geometrical description of the images of the showers and are used to infer the energy of the primary particle, its arrival direction and to distinguish between gamma-ray showers and hadronic showers. It is interesting to study distributions of these parameters also in the case of deep τ -induced showers, see Figure 3 (A-E). As we can see from plots, the distribution of Hillas parameters for deep τ -induced showers are quite different than corresponding distribution for p and γ -induced shower developing

³For index of refraction $n_{air} = 1.00023$ at an altitude of 1800 m, the Cherenkov opening angle is $\alpha \simeq 1.2^\circ$. Thus, for geometrical distance from the shower maximum to detector of about 50 km the Cherenkov ring radius on the ground, assuming not changes of refraction index within this distance, is given by: $50 \text{ km} \times \tan(\alpha) / \cos(\theta) = 1.04 \text{ km} / \cos(\theta)$ km for fixed zenith angle θ .

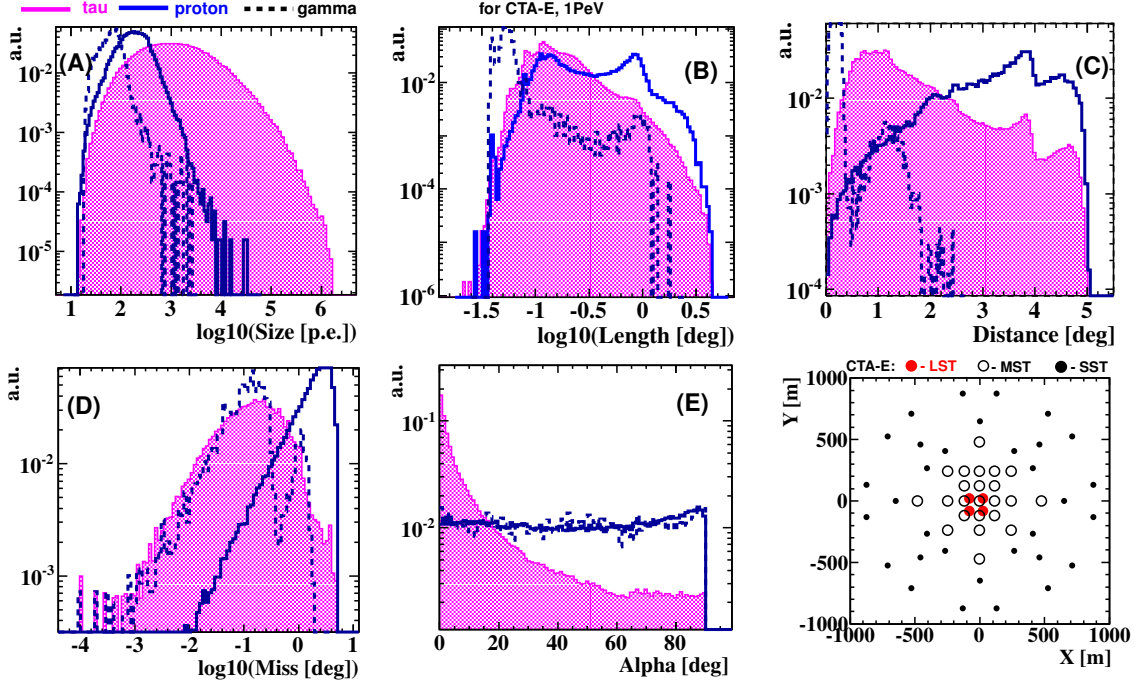


Figure 3: (A-E) Normalized distribution of Hillas parameters for τ , p and γ -induced showers and primary particle energy 1PeV, zenith angle $\theta = 87^\circ$ and CTA-E. Only deep τ -induced showers with injection depth larger than 300 g/cm^2 are shown, while for p/γ only events interacting at the top of atmosphere with the first interaction point $< 100 \text{ g/cm}^2$ (vertical depth) are considered; (F) The CTA-E layout considered in this work. The array consist of 59 telescopes, of different size i.e. Large Size Telescopes (LST) with $\sim 23 \text{ m}$ aperture, 5° FOV and 0.09° camera pixel size (red full circles), Medium Size Telescopes (MST) with $\sim 12 \text{ m}$ aperture, 8° FOV and 0.18° camera pixel size (open black circles) and Small Size Telescopes (SST) with $\sim 4\text{-}7 \text{ m}$ aperture, 10° FOV and 0.25° camera pixel size (black full circles). For more detail description of telescope properties, see Table 1 in [15].

at the top of atmosphere. In general, these parameters depend on the geometrical distance of shower maximum to the detector, which for deep τ -induced shower is much smaller than for inclined p and γ -induced showers developing at the top of atmosphere. For example, at $\theta > 80^\circ$ this distance is of about a few hundred kilometers for particle interacting at the top of atmosphere and only a few tens kilometers for deep τ -induced shower. Thus, this geometrical effect leads to rather good separation of close (τ -induced) and far-away (p , γ) events in the Hillas parameter phase space.

We found that the shape of *Distance*, *Miss* and *Alpha* distributions only slightly depend on primary particle energy and shower zenith angle (above 80°). However, as expected, for energy dependent parameters like: *Size*, *Length*, *Width* the shift of maximum of corresponding distributions to the higher values was observed, when simulation was done for the higher primary particle energies. It is also worth to mention, that the largest differences in Hillas distributions between deep τ -induced showers and p and γ -induced showers are present for *Size*, *Miss* and *Alpha* parameter. This gives possibility to use these observables in order to distinguish deep τ -induced shower from the background of inclined hadronic showers.

In order to evaluate the best set of cuts to identify deep τ -induced neutrino showers, we used the program GARCON [17], which is based on genetic algorithms to optimize cuts in a way that the signal passing rate is maximized while the background contamination is minimal. In this work, the

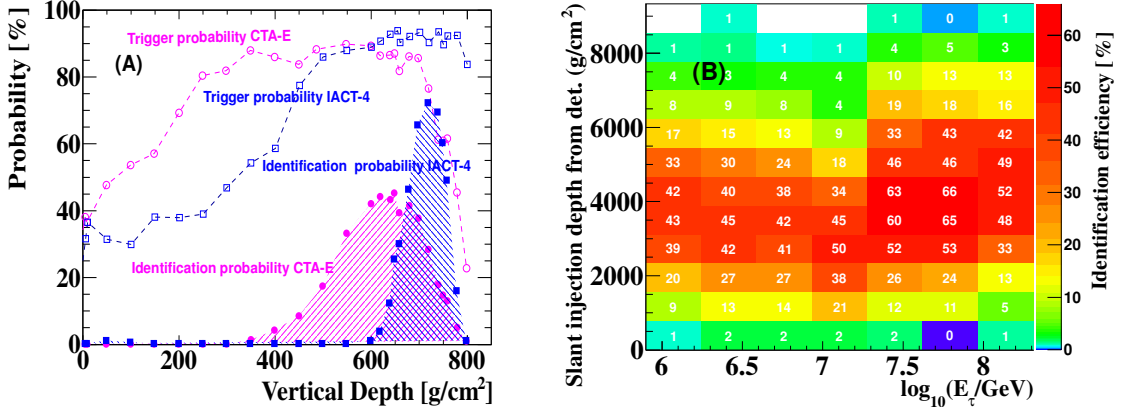


Figure 4: (A) Trigger and identification efficiency for 1 PeV τ -induced shower with zenith angle $\theta = 87^\circ$ for IACT-4 and CTA-E, (B) Identification efficiency for CTA-E as a function of lepton tau energy and injection slant depth measured from detector level.

fifth parameter phase space $\vec{x} = \{Size, Length, Distance, Miss, Alpha\}$ was used to maximize the functional $F[S(\vec{x}^{cut}), B(\vec{x}^{cut})] = S(\vec{x}^{cut})/\sqrt{B(\vec{x}^{cut})}$, where $S(\vec{x}^{cut})$ is the number of deep τ -induced showers (τ injection depth larger than 600 g/cm² i.e. ~ 43 km from detector for $\theta = 87^\circ$) passing after cuts and $B(\vec{x}^{cut})$ the number of remaining p -induced shower at top of atmosphere (p injection depth < 100 g/cm⁻²) after cuts. The set of optimized cuts on the identification observables, which lead to 0 proton events and signal efficiency of about 30%, are listed in Table 1 for IACT-4 and CTA-E.

In Figure 4 (A) the influence of cuts on the trigger probability are shown, while in Figure 4 (B) we present the dependence of identification efficiency as a function of primary energy of lepton tau. It should be pointed out, that due to larger number of triggered proton events (the larger background level for CTA-E), the optimized cuts in this case are usually harder (see Table 1) than for IACT-4. This leads to the smaller values of identification efficiency for CTA-E than IACT-4 array, at vertical depth larger than 600 g/cm². However, as expected the distribution is extended to the lower values of injection depth, up to 400 g/cm². In addition, the difference in the trigger/identification efficiency seen for vertical depth > 750 g/cm⁻² between IACT-4 and CTA-E it is cost by the different detector altitudes. The difference is only 200 m, but for zenith angle $\theta = 87^\circ$ it translates to of about 4 km difference in detector to shower distance, which in case of IACT-4 leads to the larger fraction of showers which already reached the maximum of shower development. As it also seen from Figure 4

array type	E_i^τ [PeV]	$Size$ [p.e.]	$Length$ [deg]	$Distance$ [deg]	$Miss$ [deg]	$Alpha$ [deg]	$S(\vec{x}^{cut})$ [%]	$B(\vec{x}^{cut})$ [%]
IACT-4	1	> 3110	< 0.46	< 1.09	< 0.18	< 45.1	33	0
CTA-E		> 791	< 0.27	< 2.91	< 2.12	< 13.8	24	0
IACT-4	10	$> 3.55E3$	< 0.70	< 2.19	< 0.30	< 48.7	31	0
CTA-E		$> 3.51E3$	< 0.26	< 2.97	< 0.56	< 41.4	34	0
IACT-4	100	$> 4.31E4$	< 0.78	< 1.89	< 1.81	< 12.7	30	0
CTA-E		$> 1.81E4$	< 0.33	< 2.93	< 0.22	< 13.5	33	0

Table 1: Final cuts for identification observables obtained from GARCON optimization for τ -induced showers with $\theta = 87^\circ$. E_i^τ stands for initial injected particle energy.

(A) for IACT-4 an average identification efficiency is at level of 30% for lepton tau with energy of 1 PeV. Comparing this number to the value used in our previous work [7], where an average trigger efficiency of $\sim 10\%$ was assumed, we see that more realistic trigger simulations gives at least 3 times larger value. As a consequence, this also leads to increase of event rate calculated for ν_τ in our recent work, about the similar factor, see Table 1 in [7] for more details.

4. Conclusions

In this paper, we present results of MC simulations of τ -induced air showers for IACTs and for selected CTA arrays. We calculated the trigger and identification efficiencies for τ -induced showers and study properties of images for τ -induced shower on camera focal plane, as described by Hillas parameters. In our previous work [7], we show, that the calculated neutrino rates are comparable or even larger (above ~ 30 PeV) to what has been estimated for the IceCube neutrino telescope assuming realistic observation times for Cherenkov telescopes of a few hours. However previous calculation was done for ideal detector. Instead here, we show that more realistic simulation will be lead to the larger even rate as seen by IACTs/CTAs, which make observation of τ -induced shower by the present or future Cherenkov telescopes more promising.

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