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STUDY OF A LARGE ARRAY TO DETECT ULTRA-HIGH ENERGY TAU NEUTRINO*

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The PeV cosmogenic neutrino is still an interesting argument. Since cosmogenic neutrinos interact weakly with matter, the detection of their direction will precisely point out the source in the space. In this paper, we show the results of the simulation of tau lepton air showers induced by high-energy neutrinos detected by an array of stations designed to use the Earth Skimming method improved by the "mountain chain screen" strategy. Both track time stamp and position information of the stations on the array are used to reconstruct the shower to estimate the direction and the number of events. The studied array consists of 640 stations (40×16) spread over an area of $0.6\,\mathrm{km}^2$ starting from 1500 m above the sea level (a.s.l.) on a 30° inclined plane of the mountain. When we extrapolate to 3 years and 10 km^2, we estimate 13 tau lepton events in an energy interval of 10 PeV to 1000 PeV detected using the present upper limits of tau neutrino flux.

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1. Introduction

The observation of Ultra-High Energy (UHE) neutrinos generated in both distant galactic and extragalactic sources such as pulsars or supernova remnants has been a major challenge in astroparticle physics. The neutrinos with an energy of 10^{17} eV or more, generated by the interaction of Ultra-High

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Energy Cosmic Rays (UHECRs) with the Cosmic Microwave Background (CMB) are called cosmogenic neutrinos [1]. Due to the low neutrino flux and the small detection probability, a very large scale detector array (surface or volume) is required to get a detectable rate. For this purpose, many large array experiments based on different techniques have been constructed [2–8].

Recently, the IceCube Collaboration [9] has reported 28 neutrino candidate events in the energy range of 30 to 1200 TeV. They also claimed the detection of a high-energy neutrino event, IceCube-170922A, with an energy of ~ 290 TeV in correlation with other telescopes showing a multimessenger physics. The arrival direction of this neutrino was consistent with the location of a known γ-ray blazar, TXS 0506+056, observed to be in a flaring state [10].

The cosmogenic neutrino, such as tau neutrino (ν_τ), may interact along the chord of the Earth or inside a mountain chain and creates a tau lepton (τ) by the charged-current (CC) interaction. When the τ emerges from the rock before it decays, it produces an extensive air shower developing at a very large angle near to the horizon [11, 12]. The observations can be achieved using surface detectors, Cherenkov light telescopes, fluorescence detectors or radio signals. Some of the proposed experiments in the literature are Ashra-1 [13], MAGIC telescopes [14], Telescope Array (TA) [15], and IceCube [16, 17].

The Ashra-1 detector aims to observe the Cherenkov lights from τ showers with the Earth Skimming method for PeV–EeV energy range [13]. An upper limit of neutrino flux has been measured by MAGIC telescopes in the 1 PeV to 3 EeV energy interval for ν_τ-induced showers arising from the ocean [14]. In Antarctica, radio antennas are placed to the ground and point at the high mountains to detect the skimming ν_τs too [18]. All these proposed experiments have no evidence of τ events except for a possible τ candidate in IceCube [16, 17]. To detect the horizontal and upward ν_τ showers, we propose a surface detector array on an inclined plane to improve the detection acceptance of τ shower using the time of flight (TOF) and e/mu separation [19, 20]. In this study we also include a chain of mountains in front of the array and evaluate the wideness of the valley.

This paper shows the results of a large array named "TAUshoWER", (TAUWER) which has the geometrical advantage of using both the Earth Skimming method to detect the τ showers produced below the horizon and a mountain chain in front of the array to enlarge the acceptance. The array geometry is discussed in Section 2, while the simulation of the decaying τ air showers, the selection criteria for decay length from emerging point and the result of the probability calculations for tau-neutrino interaction are given in Section 3. An analytical approach to the estimation of the event number to be observed with this array is presented in Section 3.1. Reconstruction of the showers is given in Section 3.2 and Section 3.3. Section 3.4 contains a discussion of the trigger. Finally, we summarize our results and conclude with a number of expected events/year.

2. Design of the array

To detect the τ showers produced by the tau-neutrino interaction with rock along its path in the Earth crust or a mountain in front of the array, we propose a large surface array in which stations point below the horizon to detect particles produced by large angle showers. The best way, as discussed in Section 3, to detect ν_τ is to use a large amount of matter by pointing down the horizon and a mountain chain in front of the array to increase the interaction probability of ν_τ. Therefore, we propose to install stations on an inclined mountain surface. In this paper, we consider a grid of 640 stations (40×16) placed 30 m apart and located on a 30° inclined plane of the mountain between 1500 m and 2250 m above the sea level and covering a surface of 0.6 km^2 as shown in figure 1. Each station, *named tower*, is composed by two scintillator tiles ($40 \times 20 \times 1.5\,\mathrm{cm}^3$) 160 cm apart and read

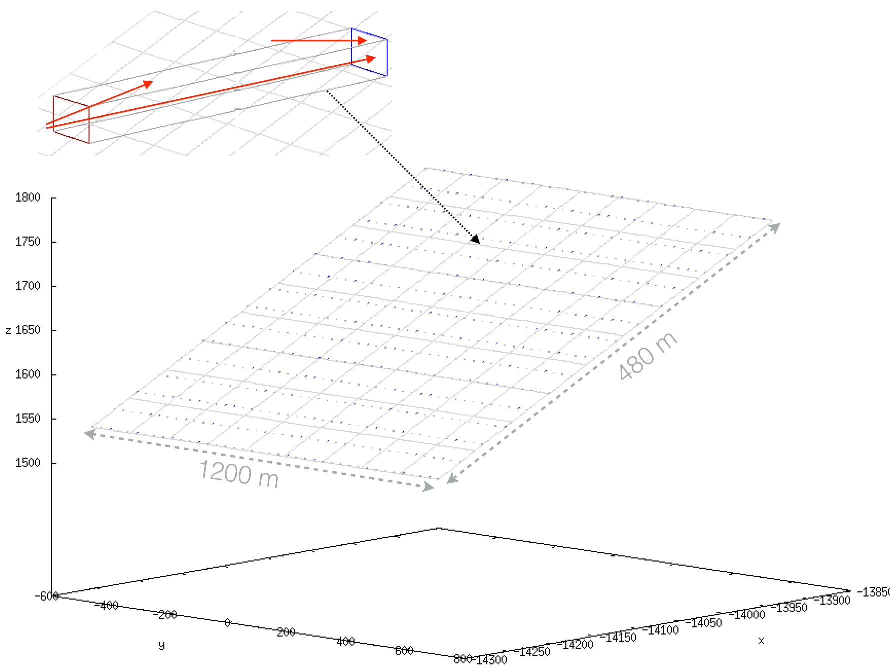


Fig. 1. Schematic drawing (scaled) of the array. The array consists of 640 stations placed on the 30° inclined plane (mountain surface) in the matrix form of 16 rows and 40 columns which are separated by 30 m apart.

by 3×3 mm^2 silicon photomultiplier (SiPM) placed on one side, which permits to select the particle direction using the time-of-flight (TOF) method. If a layer of lead 2.5 cm thickness is installed in front of the rear tile, it is possible to separate the muons from the electromagnetic particles [20]. The stations point below the horizon (approximately 2.5°) to measure upward-moving showers coming from ν_τ interactions with the Earth crust and at the same time can detect showers produced in the mountain chain. Shower direction is selected by the TOF computed with the two scintillating plates. The layout of the array studied in this paper covers a surface of 0.6 km^2 which can be increased according to the shape of the mountain.

3. Evaluation of τ events escaped from the rock

The detection of high energetic ν_τ which are coming nearly horizontal to the Earth surface has a chance to create a τ via a charge-current (CC) interaction or neutral-current (NC) interaction. It may survive and emerge from the surface to initiate a shower in the atmosphere. In order to take advantage of both the valley and mountain to improve the detection probability, each station in the array is placed on the mountain slope and directed to the horizon. The shower detection probability depends on not only the τ initial energy but also on the traveling distance of the τ after the ν_τ interaction inside the Earth crust. Therefore, we have considered a mountain in front with 60 km thickness which corresponds to the maximum travel distance for τ with an energy of 1000 PeV to escape from the rock before it decays as shown in the sketch of the proposed experiment for this study (figure 2). The incoming ν_τ travels a distance $(L - x)$ along the Earth crust and interacts with the rock as depicted by the asterisk symbol, "$*$" and produces τ by the CC interaction. The τ travels a distance x before emerging from the rock. L^* is the distance between the point where τ initiates the shower and the center of the array. In this study, we have required that τ shower is produced in the atmosphere.

To evaluate the expected τ events detected by the array, we first generated events using the TAUOLA code [21] considering several decay modes of the τ in the energy range of 10–1000 PeV. We have considered the decay modes (π^-, $\pi^-\pi^0$, $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$, $\pi^-\pi^+\pi^-\pi^0$) that covers 64% of the τ branching ratio to study the optimization and identification performance of the expected ν_τ induced showers by the TAUWER array.

Consequently, CORSIKA (version 6.99) [22] has been modified and compiled to simulate very inclined showers at an observation plane which is considered to be 30°. The produced air showers, induced by the decay products of τ, were initiated at 1500 m a.s.l. and developed up to the detector level (2250 m a.s.l.) for 4 different distances starting from the τ decay

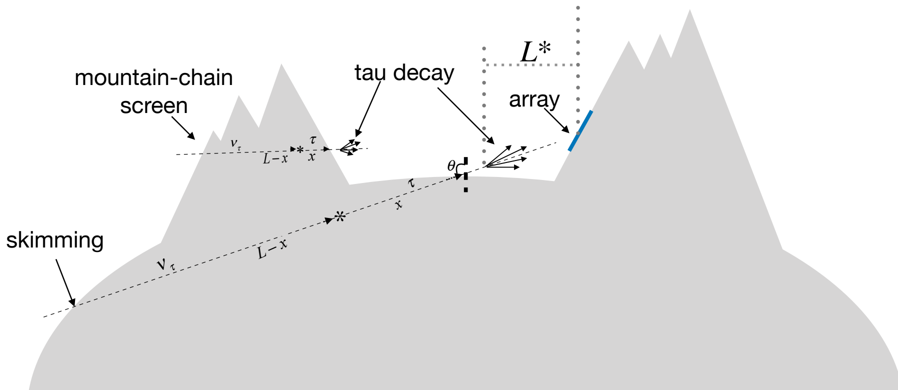


Fig. 2. In this layout (not in scale) the array accepts τ shower produced by the charged-current interaction skimmed neutrinos by the Earth crust and a mountain in front of the array. $L - x$ is the interaction distance for the ν_τ, the interaction point is shown by an asterisk symbol "$*$", x is the traveling distance for the τ. L^* is the distance of τ decay point from the center of the array.

point to the center of the array, L^* (3 km, 5 km, 7 km and 10 km), as shown in figure 2. 1000 showers have been simulated at different energy for this study. QGSJETII [23] and GEISHA [24] are selected for high- and low-energy interaction models, respectively. The "CURVED EARTH" and "SLANT" options are activated to make a more realistic simulation for correctly including the atmospheric depth. The "COAST" option is selected for reading and converting CORSIKA binary files. Since the computing time of the showers increases with the energy, the "thinning" strategy has been also used in shower productions. The CORSIKA output file provides position (x, y and z), arrival time and momentum (P_x, P_y, P_z, and P_{tot}) information of each particle crossing on the observation plane. Using this information, the trajectory is reconstructed for each particle and counted when it passes through the scintillating tiles. In this proposed layout, it is also important to identify the best distance of the plane of the array from the τ decay point to intercept the maximum shower evolution to make more efficient the shower detection and in the same time evaluate the best valley wideness.

The determination of the optimum wideness for the valley is evaluated using the particle density measured on the array plane for different decay paths of the τ in air. Figure 3 shows the averaged number of the $e^{\pm}$ per shower detected on the array plane for $\pi^-\pi^0$ modes at different energies (10–1000 PeV) as a function of L^*, the distance of the τ decay point to the center of the array. The number of muons is about 5% of the number of electrons and almost flat as a function of the distance of τ decay point in the air.

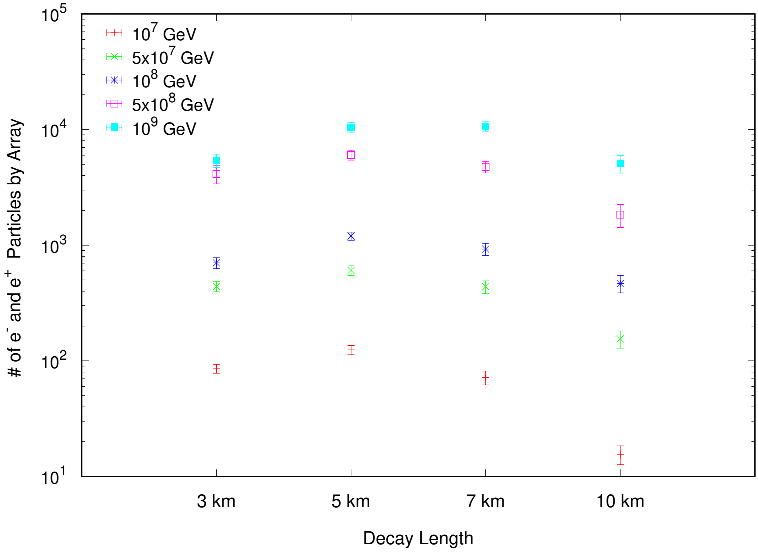


Fig. 3. Averaged number of $e^{\pm}$ per shower (among 180 simulated showers) detected on the array as a function of L^*, a distance of τ decay point to the center of the array, for different energies (10^7, 5×10^7, 10^8, 5×10^8, 10^9 GeV) at $\pi^-\pi^0$ decay mode.

It shows that the number of $e^{\pm}$ from the $\pi^-\pi^0$ decay mode and different τ energy on the detector plane is maximum when the τ decay point is at a distance of 5–7 km from the center of the array. A similar distribution is also obtained by π^-, $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$ and $\pi^-\pi^+\pi^-\pi^0$ decay modes. The decrement on the density of $e^{\pm}$ at 10 km is due to the energy loss of $e^{\pm}$ in the atmosphere. Since the density of the detected particles is higher at 5–7 km, 7 km decay lengths from the emerging point to the array center is used for further analysis in this text. To obtain the expected number of τ neutrino detected by the array, we have to evaluate the probability of escaping the τ from the Earth crust, P_{escp}. The probability of ν_τ interacting along the $L-x$ path at the $*$ point inside the rock is given as

$$P_{\mathrm{int}} = \int_0^{L-x} \mathrm{e}^{-l/L_{\mathrm{int}}} \frac{\mathrm{d}l}{L_{\mathrm{int}}}\,, \tag{1}$$

where L_{int} is the neutrino interaction length, $\mathrm{d}l$ is the short distance the interaction happens. The neutrino cross section for the charged-current interaction within 10% as follows according to CTEQ6.6M [25] and its energy dependence varies as ${E_\nu}^{0.348}$, where E_ν is the ν_τ energy. By this parameterization, we have an interaction length of τ about 700 km for 10 PeV and

3000 km for 200 PeV. The neutrino NC cross section is 2.4 smaller than that of the CC interaction which means the interaction length of neutrino is about two times greater than that of the charged-current channel. Since the NC interaction probability is not high before the CC interaction, the neutrino has the same energy as it enters the Earth shell when it interacts as CC. In this study, we consider CC interactions of ν_τ where the τ lepton is produced with 80% of the ν_τ energy [26] as well as the NC interaction.

On the other hand, the probability the τ escapes from the Earth shell is given by the probability the neutrino interacts along its path times the survival probabilities of τ lepton in the shell with initial energy as a function of the distance it travels, given as

$$P_{\text{escp}} = P_{\text{int}} \times \exp\left[-\int_{L-x}^{L} \left(ct_0 \left(\exp\left[-\beta_0/\beta_1 + \left(\beta_0/\beta_1 + \ln\left(E_i/E_0 \right) \right) \right] \right. \right. \right. \\ \left. \left. \left. \times \exp\left[-\beta_1 \times \rho_{\text{rock}} \times l \right] E_0 \right) / m_\tau \right)^{-1} \mathrm{d}l \right], \tag{2}$$

where l is the distance the τ traveled, c is the speed of light, t_0 is the mean life time of τ lepton, β_0 is the energy loss parameter from Bremsstrahlung, pair production and photonuclear interaction with $E_0 = 10^{10}$ GeV, E_i is the energy of τ lepton when it is generated, $\rho_{\text{rock}} = 2.65 \times 10^{15}$ (g/km^3) is the density of the standard rock, and m_τ is the mass of τ lepton, β_1 is the photonuclear coefficient as a function of neutrino energy [25, 27, 28]. The maximum distance the τ lepton travels at the energy of 1000 PeV is about 60 km. That means the neutrino interaction should happen in the Earth shell of 60 km thickness to produce a tau lepton which has a probability to escape from the Earth crust. The survival probability (P_{surv}) of τ corresponds to the exponential factor in Eq. (2) and decreases while τ lepton moves away from the interaction point in the Earth shell.

3.1. Estimation on the number of detected ν_τ events

As discussed in Section 3, we evaluated the ν_τ interaction length and its probability P_{int} based on the study given in Ref. [26], besides that, the approaches are used from Ref. [29] to calculate the τ's P_{surv} and then the escape probability, P_{escp}, after the τ travels through the Earth and the mountain chain 60 km thickness at PeV energies. Table I shows the P_{escp} of the τ calculated for different neutrino initial energies and escaping directions from the Earth crust using formula (2). The τ crossing the mountains are produced at 90° in θ. No specific profile of the mountain has been studied.

TABLE I

The escape probability of τ as a function of θ and ν_τ energy. In the first row there is reported the probability considering a mountain screen 60 km thickness. These values where computed using a neutrino cross section for charged currents according to CTEQ6.6M.

θ[°]/ Energy [PeV]	10	20	50	100	200	300	500	1000
Screen	6.850×10^{-4}	3.168×10^{-3}	9.430×10^{-3}	1.546×10^{-2}	2.220×10^{-2}	2.651×10^{-2}	3.245×10^{-2}	4.164×10^{-2}
91	3.114×10^{-6}	2.038×10^{-5}	9.056×10^{-5}	1.900×10^{-4}	3.276×10^{-4}	4.203×10^{-4}	5.381×10^{-4}	6.669×10^{-4}
92	3.799×10^{-6}	2.149×10^{-5}	7.418×10^{-5}	1.212×10^{-4}	1.525×10^{-4}	1.570×10^{-4}	1.456×10^{-4}	1.061×10^{-4}
93	3.383×10^{-6}	1.659×10^{-5}	4.472×10^{-5}	5.729×10^{-5}	5.323×10^{-5}	4.434×10^{-5}	3.023×10^{-5}	1.330×10^{-5}
94	2.670×10^{-6}	1.138×10^{-5}	2.408×10^{-5}	2.435×10^{-5}	1.686×10^{-5}	1.145×10^{-5}	5.806×10^{-6}	1.571×10^{-6}
95	1.978×10^{-6}	7.340×10^{-6}	1.226×10^{-5}	9.851×10^{-6}	5.124×10^{-6}	2.855×10^{-6}	1.084×10^{-6}	1.825×10^{-7}
96	1.411×10^{-6}	4.571×10^{-6}	6.056×10^{-6}	3.883×10^{-6}	1.527×10^{-6}	7.009×10^{-7}	2.006×10^{-7}	2.114×10^{-8}
97	9.818×10^{-7}	2.784×10^{-6}	2.938×10^{-6}	1.510×10^{-6}	4.515×10^{-7}	1.712×10^{-7}	3.704×10^{-8}	2.453×10^{-9}
98	6.709×10^{-7}	1.667×10^{-6}	1.405×10^{-6}	5.810×10^{-7}	1.324×10^{-7}	4.150×10^{-8}	6.798×10^{-9}	2.830×10^{-10}

By using the present cosmogenic neutrino flux upper limit [30–32], $\Phi(E)$, we evaluate the expected number of τ events in the TAUWER array according to the following formula:

$$N_\tau = \int_{E_{\min}}^{E_{\max}} \Phi(E) P_{\mathrm{escp}}(E) \left(\varepsilon_{\mathrm{acc}}\left(E, \Theta, \Phi, L^*\right) \times \beta_\tau\right) \mathrm{d}E \Delta t \Delta A \Delta \Omega \,, \qquad (3)$$

where β_τ is τ branching ratios for π^-, $\pi^-\pi^0$, $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$ and $\pi^-\pi^+\pi^-\pi^0$ decay modes, $\varepsilon_{\mathrm{acc}}$ is the efficiency of detector array acceptance. Δt is the time interval of one year, $\Delta A = 0.6$ km^2 area and $\Delta\Omega$ is the solid angle that watched the showers emerging below the horizon within 8° in θ and the showers emerging from the chain of mountains in front of the array of 2° in θ. To evaluate the number of detected events, we take into account two scenarios: Earth Skimming and the screen strategies produced by a mountain chain in front of the array.

The expected number of events by the TAUWER array was estimated using the latest neutrino flux upper limit reported by the IceCube experiment [30–32]. The results of different scenarios, only skimming strategy and screen strategy, are summarized in Table II. The expected number of events as a function of two different neutrino flux upper limits are 0.18 and 0.43 events in km^2 per year for skimming and skimming-screen strategy, respectively. If the integrated time is 3 years [32] and the surface of array is 10 km^2, the number of expected events for the TAUWER array is about 13 events. The presence of 'screen' increases the detected number of events about a factor of three. That is explained by higher probability of interaction of the ν_τ that travels a longer path when it is skimmed by the Earth crust.

TABLE II

The expected number of events in km^2 per year for the TAUWER array using the analytic method and DANTON simulation code corresponding to the different upper limit fluxes. With the DANTON simulation, we computed only skimming events.

Flux [GeV cm^{-2}s^{-1}sr^{-1}]	Scenario	Energy range [PeV]	N_{event} CTEQ6.6M	N_{event} DantonSim
2×10^{-8} (all flavor) [30]	Skimming	[10–1000]	0.0437	0.0885
	Screen	[10–1000]	0.1273	
	Skimming + Screen	[10–1000]	0.1710	
5.1×10^{-8} (ν_τ flavor) [32]	Skimming	[10–1000]	0.1116	0.2257
	Screen	[10–1000]	0.3245	
	Skimming + Screen	[10–1000]	0.4361	

The P_{escp} computed using the analytic method has been compared to that evaluated using a specific code DANTON that simulates the tau-neutrino interaction in the Earth crust and the τ decay giving the τ decay point in the air [33]. Using this code, we obtained the total P_{escp} of τ for energy greater than 200 PeV, in average by a factor 2.5 higher than the P_{escp} evaluated with the analytic method. This discrepancy is mainly due to the different PDFs used in the neutrino cross-section parametrization. To evaluate the expected τ lepton, we can use the geometrical acceptance computed in our study because the tau decay point coordinates in DANTON have an average distance from the array of 8 km and a momentum distribution similar to which was used in the analytic method. By using the upper limit fluxes [30, 32], we obtain 0.21 and 0.55 events per km^2 per year with the DANTON simulation code.

3.2. Arrival τ shower direction

The direction of the τ air shower is calculated with a common method used in literature [34] based on the minimization of the direction vectors of each track by using Minuit [35]. The momentum of each particle is used to obtain the direction vectors (n_x, n_y, n_z) of the shower in Eq. (4).

$$\chi^2 = \sum_i^N w_i \left(n_x \left(x_i - x_{\text{core}}\right) + n_y \left(y_i - y_{\text{core}}\right) + n_z \left(z_i - z_{\text{core}}\right) - c \left(t_i - t_{\text{core}}\right)\right)^2 , \tag{4}$$

where t_i is the arrival time of $e^{\pm}$, x, y and z its coordinates on the array plane, x_{core}, y_{core}, z_{core} the coordinates of the core of the shower evaluated with the maximum weighted density of the particles on the inclined plane. t_{core} is estimated from the closest station taken into account of the distance from the core. The active stations are selected by requiring at least two particles on the *tower* and used in the evaluation of the shower direction for different showers where the primary particle has an energy range of 10 PeV–1000 PeV and it is the decay point 7 km apart from the array plane

Figure 4 shows both zenith and azimuthal angles evaluated for a sample of 27 showers in the energy range between 10 and 1000 PeV. The arrival directions θ and ϕ are estimated with an error of 0.16° and 0.045°, respectively.

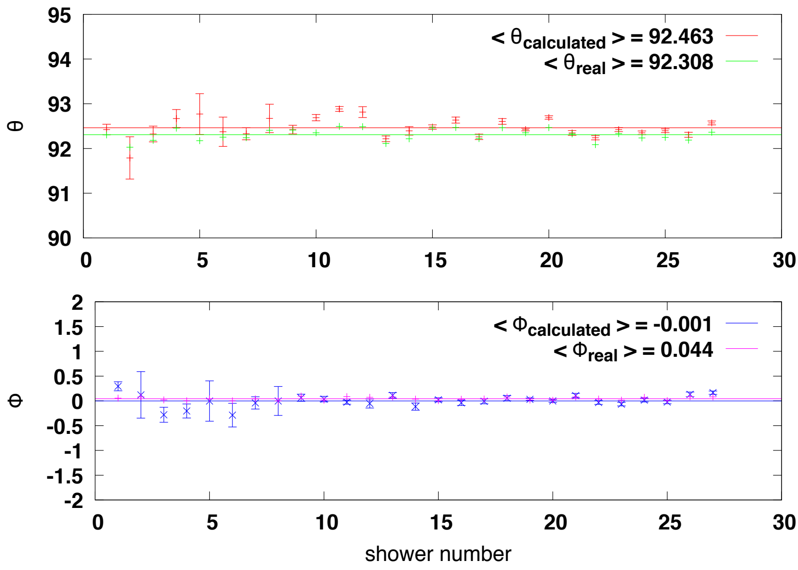
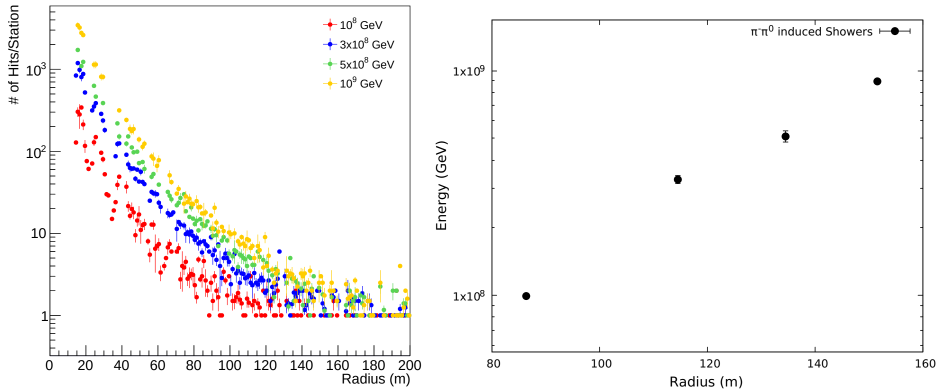


Fig. 4. Zenith (top) and azimuthal (bottom) angles evaluated from the active station for different showers where decay length from the emerging point is 7 km and primary energy ranges from 10 PeV to 1000 PeV. Active stations are selected by requiring at least two hits on the tower.

3.3. τ shower energy reconstruction

The center of the shower is estimated from the most triggered stations and hits per station as a function of distance from the shower core given in figure 5 (a). This figure shows the number of hits per station as a function of distance for different energy intervals between 10 and 1000 PeV where at least one hit on a single tile is required. The core of the shower is evaluated from the stations having at least 5 hits. The radius of the shower is obtained by requiring 4 subsequent stations having hits ranging from 1 to 4 and register the first one as the radius (edge) of the shower. Figure 5 (b) shows the energy *versus* its corresponding radius. It is clearly seen that there is an exponential behaviour between energy and radius in the range of the interested energy region.



(a) (b)

Fig. 5. (a) The number of hits per station *versus* the distance from the shower core for different τ energies; (b) the energy of τ showers as a function of the shower radius.

3.4. Trigger decision

The average timing spectrum for $e^{\pm}$ between 10 PeV and 1000 PeV for all hadronic channels of τ shower that hit any scintillator in the 640 stations has been studied. The timing spread of the stations is computed by using the arrival time of all hits in the station and identifying the earliest one which is selected as time reference to find a delay time in a (4×4) subarray around the center of the shower. The maximum time difference between the first and last hit produced by the τ shower on the array plane must be in the time interval of 0.3 μs. From these simulation studies, the signature of τ shower is given by a cluster of station with the highest density of $e^{\pm}$ and the maximum number of hits in a single station for τ shower between 10 PeV and 1000 PeV ranges from 450–3500, in the time interval of 10–20 ns. Compared this requirement to the vertical EAS events collected in a test made at the Karlsruhe Institute of Technology (KIT) [19], the atmospheric background can be easily suppressed if we require 250 hits, defined as trigger T1. The second level trigger T2 can be defined as requiring at least 450 hits on each station of a sub-array (2×2) in a time window of 88 ns. This criterion (/trigger) leads to a selection of a shower with an energy of 10^8 GeV or greater.

4. Conclusions

We have simulated τ decay modes (π^-, $\pi^-\pi^0$, $\pi^-\pi^+\pi^-$, $\pi^-\pi^0\pi^0$, $\pi^-\pi^+\pi^-\pi^0$) that covers 64% of the τ branching ratio in the energy range of 10–1000 PeV to determine the performance of the TAUWER array. It shows that the energy of the showers between 100 and 1000 PeV can be reconstructed in terms of the radius as discussed in Section 3.3. The arrival direction is also determined with an accuracy of 0.16° in the same energy range. The atmospheric background can be easily rejected by requiring T1 trigger, while a second level trigger, T2, selects showers with 10^8 GeV or greater energies. We have estimated the ν_τ conversion to τ and τ propagation through the rock including both skimming and screen strategies with the TAUWER detector array, which is ranging between 5–13 tau lepton events in the energy range of 10–1000 PeV for 3 years of the integrated time period and an array surface of 10 km^2 using the analytical method. We obtained 6–16 tau lepton skimmed events by using the DANTON simulation for the same time period, array surface and in the same energy range. The number of events skimmed by the Earth crust using this simulation code is higher of a factor of two due to the neutrino cross section. The effect of the screen in front of the array increases the expected number of events by a factor of three.

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