PROCEEDINGS OF SCIENCE

TA SD analysis for inclined air showers

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The origin of UHECRs is an open question which is complicated due to not very well-known deflections of the charged particles in Galactic and intergalactic magnetic fields. Finding the EeV neutrinos from astronomical sources will be a key to solve the problem of the origin. EeV neutrinos are expected to produce extensive air showers which are observable by the current operational air shower arrays. To search for neutrino-induced showers, it is important to increase both the interaction probability and background rejection power in the analysis of the inclined showers. We study a reconstruction method of the Telescope Array surface detector (TA SD) data for the neutrino-induced inclined air showers. The prime target is to improve the angular resolution for the astronomical objects. In this contribution, we present the detail of analysis method, angular resolution and total exposure of TA SD for neutrinos from the astronomical objects as a function of the declination.

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1. Introduction

Highest energy cosmic rays has been studied by the Telescope Array (TA) and the Pierre Auger (Auger) experiments, which operate in the Northern and Southern hemisphere, respectively[1]. These experiments indicate large scale anisotropy of cosmic-ray arrival direction at extremely high energies. Ultra-high energy cosmic rays are believed to be of extragalactic origin.

Since cosmic rays are charged particles, it is difficult to identify the source because their trajectories are bent by magnetic fields. It is well known that observation of neutrino is useful to identify origins of ultra high energy cosmic rays because neutrinos are not affected by magnetic fields. In this paper, performance of the TA Surface Detector (SD) array for neutrino induced air showers is discussed. We focus on the large zenith angle region to increase the probability of interaction with atmosphere. Furthermore, at large zenith angles, the first interaction points of the background (BG) hadron induced showers and the neutrino induced showers are significantly different, resulting in a difference in the shape of the shower front. This makes it easier to discriminate BGs and neutrinos than at small zenith angles.

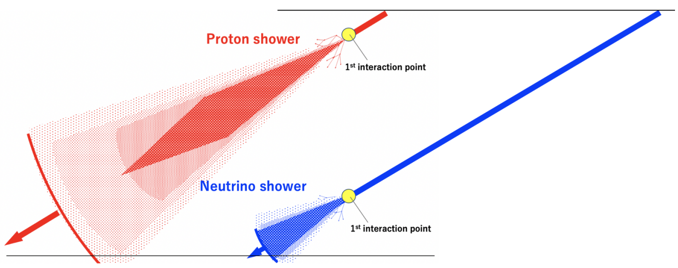

Figure 1. Schematic of proton shower and neutrino shower at large zenith angles

A visual representation of a proton shower and a neutrino shower at a large zenith angle is presented in Fig.1. For large zenith angles, BG hadron showers have already undergone interactions in the upper atmosphere, resulting in a predominant population of muons among the particles reaching the Earth's surface. In contrast, neutrino showers, even at large zenith angles, can begin to develop near the Earth's surface, leading to a significant electromagnetic component in their early interaction stages. Consequently, the shape of the shower front differs between hadron showers, which are flat, and neutrino showers, which are predicted to exhibit a curved surface with a smaller curvature radius.

The TA collaboration have investigated large zenith angle region to search ultra-high energy neutrinos[2]. They discriminated neutrino induced showers from proton induced showers using machine learning method called Boosted Decision Trees[3][4]. They use large zenith angle Monte Carlo (MC) data and define the optimum parameter. The method of this analysis was applied to the TA data and no neutrino candidate events were found. The flux upper limit of neutrinos was determined. This result is an upper limit for neutrinos from the entire sky, not neutrinos from individual objects. In this paper, we look for neutrinos from individual sources. We focused our research on determining and improving the angular resolution.

2. TA SD reconstruction of inclined air showers

The TA experiment is the largest cosmic ray observation experiment in the Northern Hemisphere, located at 113° W longitude and 39° N latitude in the desert of Utah, USA. It observes the highest energy cosmic rays at an altitude of 1430 m (875 g/cm^2 mass-overburden). The 507 surface detectors and the 36 atmospheric fluorescence telescopes are installed, divided into three station sets to the southeast, southwest and north, surrounding the TA experiment, The TA experiment started observations in 2008 and has been in operation since then. Each SD consists of two layers of 3m^2 scintillators. The lights emitted by these scintillators are converted to electrical signals by photomultiplier tubes (PMT) and recorded as waveforms. The standard analysis of the TA experiment is optimized for zenith angles below 55°. By our study, we aim to evaluate the reconstruction method for the large zenith angle region by utilizing MC data for protons and neutrinos. In this section, we outline the existing reconstruction procedure of TA SD and evaluate the anglar resolution.

2.1 MC data set

MC dataset is same as previous study[2]. The CORSIKA simulator [5] is used to generate the showers with the CURVED option. Both neutrinos and protons were considered within an energy range of 0.3 to 300 EeV. The azimuthal angles spanned from 0° to 360°, while the zenith angles ranged from 0° to 90° for neutrinos and 45° or greater for protons. For neutrinos, the initial interaction point was computed using a separate code and provided as input values to CORSIKA. In the case of protons, CORSIKA automatically determined the initial interaction point based on their interaction cross section with the atmosphere. The energy spectrum of the incident particle follows $E^{-\gamma}$ with $\gamma = 2$ for protons and $\gamma = 1$ for neutrinos. The neutrino flavor ratio is $\nu_e : \nu_\mu : \nu_\tau : \bar{\nu}_e : \bar{\nu}_\mu : \bar{\nu}_\tau = 1 : 1 : 1 : 1 : 1 : 1$. In the MC accidental muon signals are randomly injected based on the frequency of muon signals measured in TA data.

To minimize computation time, the CORSIKA shower files were reused under the specified conditions by maintaining fixed values for energy, zenith angle, azimuth angle, and initial interaction point. Only the core positions were randomized, while ensuring that the shower fell within a circular area with a radius of 21 km centered on the Central Laser Facility [6]. For the proton simulations, a total of 2403 shower files were generated. Each file was reused 54,957 times on average. Similarly, for the neutrino simulations, a total of 2237 shower files were generated. Each file was reused 27,484 times on average.

2.2 Angular resolution

Histograms displaying the angular difference between the true arrival direction and the reconstructed arrival direction for each reconstructed shower are shown in Fig.2. Here, we defined the "angular resolution" as the median value of this histogram, denoted as θ_{50}. Figure3 shows θ_{50} as a function of zenith angle threshold. The left panel shows the angular resolution of protons (stars) and neutrinos (circles) at > 45°, > 55°, > 60°, > 65°, > 70°, > 75°, and > 80°, and the right panel shows the angular resolution of neutrinos by each flavor.

In general, the proton angular resolution tends to improve with increasing zenith angles. This phenomenon can be attributed to the fact that the larger the zenith angle, the more SDs respond. Consequently, the reconstruction becomes more reliable.

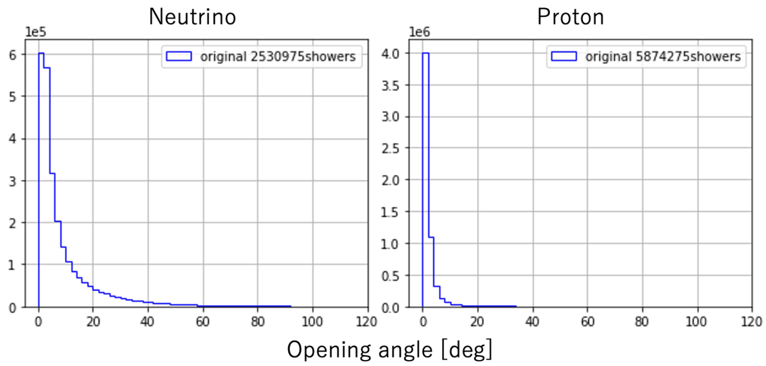

Figure 2. Opening angle distribution of neutrinos and protons using TA SD original analysis method with MC data above 45 degrees zenith angle.

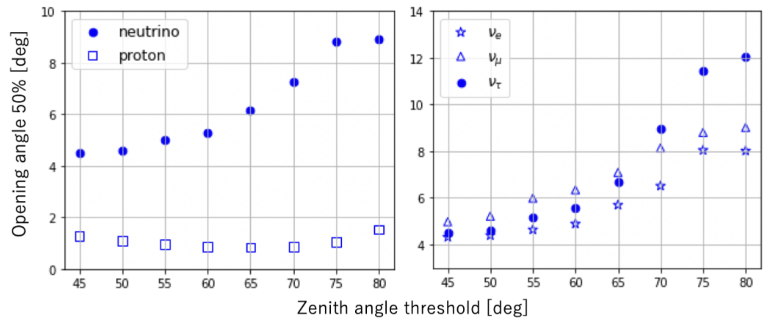

Figure 3. Angular resolution of protons and neutrinos by zenith angle in TA experimental standard analysis. The left figure shows the angular resolution of protons (stars) and neutrinos (circles) at > 45°, > 55°, > 60°, > 65°, > 70°, > 75°, and > 80°, and the right figure shows the angular resolution of neutrinos by flavor.

The angular resolutions of neutrino events are not as good as those of proton events. Also, as shown in Fig.3 (right), this trend does not depend much on the neutrino flavor. To investigate why the angular resolution of neutrinos is worse than that of protons, we examined the event display for large zenith angle neutrino events and found that there is a problem in the selection by the goodness of fit to the shower front shape. See [7] for details on fitting.

2.3 Improvement of neutrino reconstruction

The poor angular resolution of neutrino events may be due to the fact that a significant number of SDs are removed before being used for geometry fitting. This is because the shower surface fitting function used in the standard reconstruction of the TA SD is optimized to proton showers. Since neutrinos have different shower surface geometries than protons, the fit functions do not match and many SDs make the fit χ^2 worse. Therefore, for neutrino showers, more SDs are removed by the selection than proton showers. To address this issue, we investigated the angular resolution when the selection condition was made looser than in the standard.

We explored three different methods to assess the angular resolution: the original method, which is the same as the standard method used by TA (referred to as "Original"), a method that restricts the maximum number of SDs that can be excluded in the selection to two (referred to as "Loop2"), and a method that does not exclude any SDs in this selection (referred to as "No cut"). Each method was evaluated for its impact on the angular resolution.

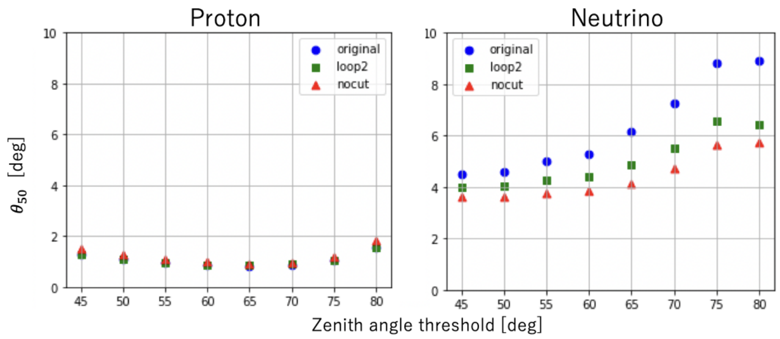

Figure 4. The changes in angular resolution when employing the Original, Loop2, and No cut methods, respectively.

The results are shown in Fig.4 as the function of zenith angle threshold. The left panel shows the results of protons and the right panel shows the results of neutrinos. The angular resolutions of the protons are independent from methods. Conversely, in the case of neutrinos, the angular resolution shows improvement by loosening the selection condition. For example, when comparing the "Original" (blue) to "No cut" (red) for angles of 80° and above, the change in the angular resolution for protons is negligible, while for neutrinos, there is an improvement of approximately 3°. The observed trend in the analysis results remains consistent across all flavors of neutrinos.

3. Neutrino detection efficiency of TA SD

In the following, we calculated the neutrino exposures in TA SD using MC data as a function of the declination δ of target object. We used the reconstruction method "No cut" that improves angular resolution for large zenith angles. The calculation method is shown in Eq.(1).

$$\varepsilon(\delta, E) = \int \epsilon(\theta, E) T(\delta, \theta) S\cos\theta \, d\theta. \tag{1}$$

Here E is the energy, θ is the zenith angle, and S is the area over which the generated showers fell, which is a circle with a radius of 21 km centered on the Central Laser Facility [6]. $\varepsilon(\delta, E)$ is the total exposure per day, $\epsilon(\theta, E)$ is the detection efficiency, and $T(\delta, \theta)$ is the observation time at each zenith angle per day. The $\cos\theta$ is the geometric effect of the detector area for inclined air showers. First, from the interaction cross section between neutrinos and the atmosphere, we obtain the interaction probability with the atmosphere for each zenith angle and energy range. Second, we obtain the detection probability by the TA SD based on the MC results. Multiplying these two, we obtain the detection efficiency $\epsilon(\theta, E)$. Then, considering the orbits of each celestial body at each declination, we determine the $T(\delta, \theta)$ which is the time duration per day during that the source object is within that zenith angle. The result is shown in Fig.5.

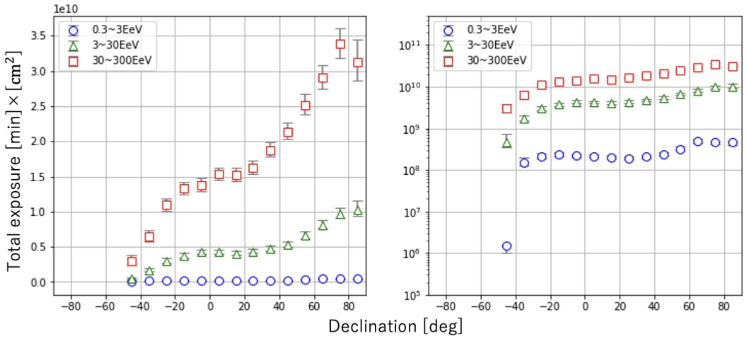

Figure 5. Total exposure per 24 hours by each declination. The left panel shown in linear scale and the right panel shown in log scale. Declination is at 10° intervals and energy ranges are divided in 0.3-3 EeV, 3-30 EeV, and 30-300 EeV.

4. Neutrino detection efficiency of TA SD from candidate sources

The formula for obtaining the expected number of neutrino events in 10-year TA SD operation is as follows.

$$N = \int \phi\,\mathrm{dE} \times \varepsilon(\delta, \mathrm{E}) \times 60\mathrm{sec/min} \times 365\mathrm{day} \times 10\mathrm{year}. \tag{2}$$

where $\int \phi dE$ is the integral neutrino flux [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$] and $\varepsilon(\delta, E)$ is the total exposure per 24 hours [$\mathrm{min} \cdot \mathrm{cm}^2$/ day]. The fluxes of NGC 1068 and TXS 0506+056 observed by IceCube [8][9] are extrapolated to the EeV energy region. For NGC 1068, in the energy ranges of 0.3 to 3 EeV, 3 to 30 EeV and 30 to 300 EeV, the expected neutrino fluxes are $6.4 \times 10^{-24}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, $4.0 \times 10^{-26}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $2.5 \times 10^{-28}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, respectively. Similarly, for TXS 0506+056, in the energy ranges of 0.3 to 3 EeV, 3 to 30 EeV and 30 to 300 EeV, the expected neutrino fluxes are $2.7 \times 10^{-18}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, $2.7 \times 10^{-19}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and $2.7 \times 10^{-20}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, respectively.

Table1 and Table2 show the expected numbers of neutrino events in 10-year TA SD operation for NGC 1068 and for TXS 0506+056, respectively. NGC 1068 has an energy flux power of -3.2, while TXS 0506+056 has a power of -2.0. In contrast, the neutrino MC data used in this study was generated with an energy spectrum of E^{-1}. To account for this difference, the calculation of the expected numbers of neutrino events is weighted by the respective energies.

Table 1: Expected number of neutrino events in 10-year TA SD operation for NGC 1068

Energy[EeV]	exposure/day [min]×[cm^2]	Flux cm^{2}s^{-1}	N_ν
0.3 ~ 3	$(4.1^{+0.20}_{-0.16}) \times 10^{8}$	6.4×10^{-24}	$(5.6^{+0.27}_{-0.22}) \times 10^{-10}$
3 ~ 30	$(5.6^{+0.37}_{-0.24}) \times 10^{9}$	4.0×10^{-26}	$(4.9^{+0.32}_{-0.21}) \times 10^{-11}$
30 ~ 300	$(1.6^{+0.09}_{-0.09}) \times 10^{10}$	2.5×10^{-28}	$(8.7^{+0.49}_{-0.49}) \times 10^{-13}$

This result indicates that the neutrinos cannot be observed in the TA SD 10-year observation when considering the energy flux extrapolated from the observations shown by IceCube [8][9]. In contrast, assuming that the spectrum of TXS 0506 has the maximum possible power (E^{-1}) within the error, we calculated the expected number of neutrino events by TA SD. The results are shown in Table3, where 0.03 events, 0.5 events and 1.9 events are expected to be observed in the energy ranges of 0.3 to 3 EeV, 3 to 30 EeV and 30 to 300 EeV, respectively.

Table 2: Expected number of neutrino events in 10-year TA SD operation for TXS 0506+056

Energy[EeV]	exposure/day [min]×[cm^2]	Flux cm^{2}s^{-1}	N_ν
0.3 ~ 3	$(3.2^{+0.20}_{-0.16}) \times 10^8$	2.7×10^{-18}	$(1.9^{+0.12}_{-0.10}) \times 10^{-4}$
3 ~ 30	$(5.0^{+0.37}_{-0.24}) \times 10^9$	2.7×10^{-19}	$(3.0^{+0.22}_{-0.14}) \times 10^{-4}$
30 ~ 300	$(1.6^{+0.09}_{-0.09}) \times 10^{10}$	2.7×10^{-20}	$(9.2^{+0.52}_{-0.52}) \times 10^{-5}$

Table 3: Expected number of neutrino events from 10 years of TA SD observations assuming that the neutrino spectrum has power of -1 from TXS 0506+056.

Energy[EeV]	exposure/day [min]×[cm^2]	Flux cm$^2s^{-1}$	N_ν
0.3 ~ 3	$(2.1^{+0.20}_{-0.16}) \times 10^8$	5.7×10^{-16}	$0.03^{+0.003}_{-0.002}$
3 ~ 30	$(4.2^{+0.37}_{-0.24}) \times 10^9$	5.7×10^{-16}	$0.5^{+0.04}_{-0.03}$
30 ~ 300	$(1.5^{+0.09}_{-0.09}) \times 10^{10}$	5.7×10^{-16}	$1.9^{+0.11}_{-0.11}$

5. Summary

In order to clarify the sensitivity of TA to neutrino point sources, we improved angular resolution of neutrino induced showers by 30 to 40% by optimizing reconstruction method for inclined air showers while maintaining the angular resolution of protons. In particular, the angular resolution of neutrinos was improved from 8.9 degrees to 5.8 degrees at zenith angles above 80 degrees. We calculated neutrino detection efficiency by TA SD as a function of zenith angle by using MC data applying new reconstruction method. Assuming neutrinos from two sources, NGC 1068 and TXS 0506+056, we obtained the number of neutrino events observed by 10-year TA SD operation. This is a first results in a TA experiment. Our research found that if we assume the best-fit value of IceCube for the neutrino fluxes [8][9], we cannot expect to detect neutrino events from candidate of origin objects by TA SD. On the other hand, with sources that has extremely hard spectrum, such as should -1, we can expect more than one neutrino detection per decade. Although we did not consider the background effect in this study, if the background value is large, we should consider applying machine-learning particle discrimination.

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