NICHE detector and analysis results

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Introduction

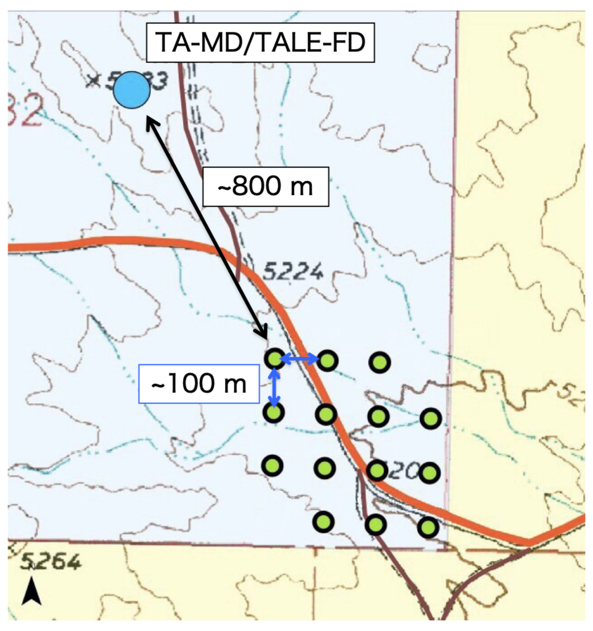
The mass composition of cosmic rays is very important to clarify their origin, because it must be strongly related to their sites of origin, mechanisms of particle accelerations, and propagation from the sources to the Earth. There is a general agreement as regards cosmic ray composition that the fraction of the heavier component increases with energy around the knee region, $10^{15} - 10^{16}$ eV [1].
In air shower experiments, the types of primary nuclei that induce air showers can be inferred from the longitudinal developments of the showers thanks to the differences in the interaction cross-sections with the atmosphere.
The results from the previous experiments show that the cosmic-ray mass ⟨lnA⟩ increases with energy indicating a heavy-dominant composition at the knee. This is consistent with the rigidity-dependent stochastic particle acceleration models for cosmic ray sources that predict the maximum reachable energies $E_{max} \propto Z$. On the other hand, it has been predicted that galactic cosmic ray sources such as supernovae cannot accelerate particles to energies greater than $\sim 10^{18}$ eV, and therefore we conclude that cosmic rays with such high energies are of extra-galactic origin. In this case, protons and other lighter components would be dominant in this higher energy region, since heavier nuclei suffer from photo-disintegration processes by interaction with the cosmic microwave background photons during long distance propagation. In fact, from recent measurements of the cosmic ray composition in the ultra-high energy region ($E > 10^{18}$ eV) using the air fluorescence detection technique, a proton-dominant composition has been reported at 10^{18} eV [2, 3, 4]. Therefore, we can expect a drastic change in the cosmic-ray mass composition in the energy range of 10^{16} to 10^{18} eV, *i.e.* from the heavier galactic components to the lighter extra-galactic components. The aim of the NICHE (Non-Imaging CHErenekov) experiment is to measure the mass composition of cosmic rays in this transient region.

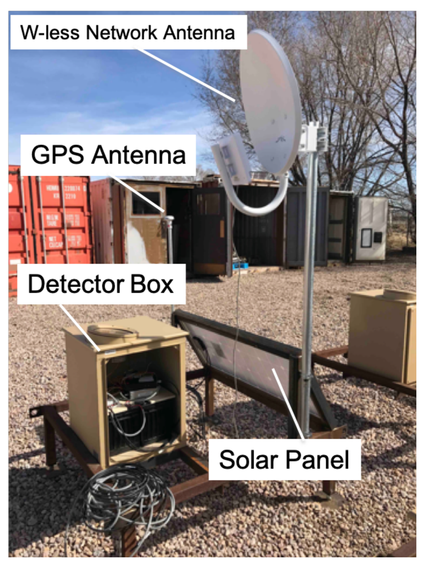
NICHE at the TA site

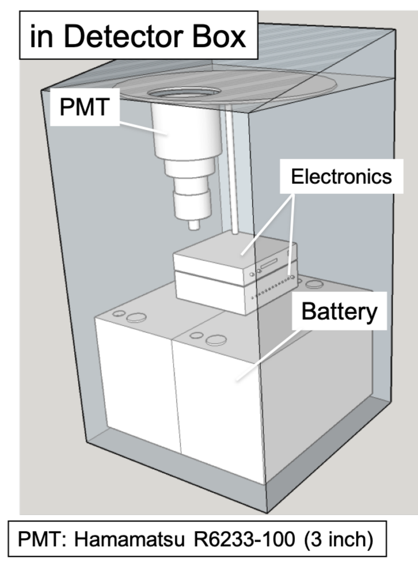
A *Kakenhi* Grant by Japan Society for the Promotion of Science (JSPS) was approved in 2014 for four years, and a prototype array of 14 CDs has been developed. This array will be called j-NICHE to distinguish it from other NICHE endeavors. The detectors are deployed ~ 800 m away from the MD site with 100 m spacing to detect air Cherenkov lights generated by showers with $E \geq 3$ PeV together with the MD and the TALE FDs.

A j-NICHE counter detects Cherenkov light by a 3-inch photomultiplier tube (PMT, Hamamatsu R6233-100) whose the output signal is passed through FADC(200MHz, 12 bits) and stored as a digital in a micro-SD card.
A Winston cone of opening half-angle 45° is attached above PMT to collect more inclined lights.

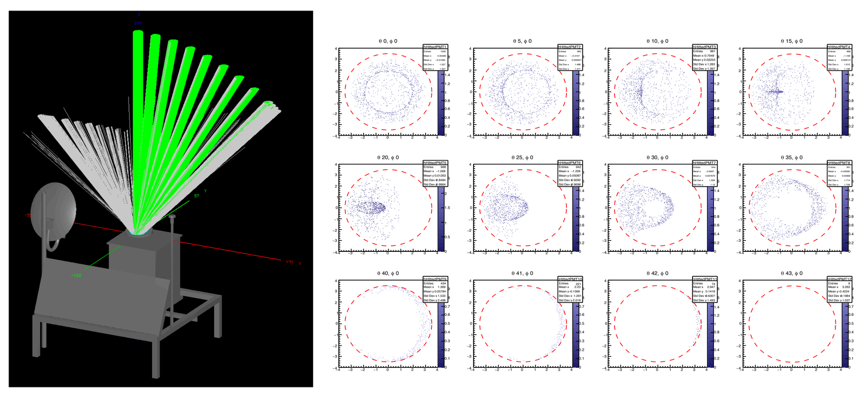
We found the most of rays with $\theta = 43°$ can not be seen by PMT according to the result of ray-tracing simulation for a NICHE detector using ROBAST[5]: 1,000 rays are generated by changing zenith angle $\theta = 0°$ to $43°$ at azimuthal angle $\phi = 0°$ (to east) and note that the dashed red line is the boundary of PMT photocathode area.







The result of ray tracing using ROBAST



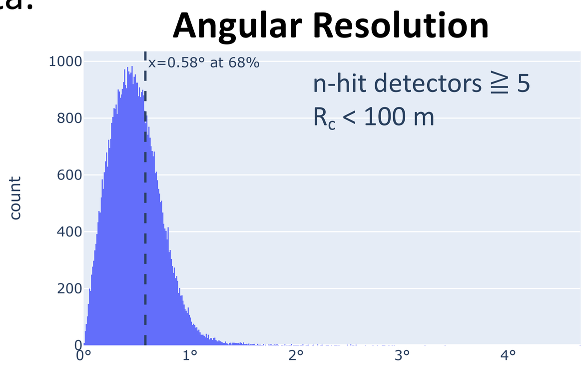
NICHE operation is held for a whole dark night from the end of the astronomical twilight to the beginning of the next astronomical twilight, thus carried out at the same time as MD-FD operation. Main PC at MD-FD building connects each detector via wire-less communication using SSH and sends a command and gets a corresponding result using Expect. Preparations of observation begins 30 minutes before the astronomical twilight, connecting and initializing every detectors and turning on HV with a shutter closed. Data taking starts till 15 minutes before the end, after opening a shutter at the beginning, and then data collecting and backup are executed. NICHE observation has regularly started in May 2018 when 10 counters were deployed then, but all the counter is done in Sep 2018.

Reconstruction Methods

We have developed reconstruction methods based on MC air-shower simulation result.
CORSIKA[6] generates 100-proton/100-iron showers uniformly in the energy range of 10^{15} to 10^{16} with arrival direction (zenith angle θ is 0° to 40°and azimuthal angle is 0° to 360°) and its intensity follows $\sin\theta\cos\theta$ distribution.
Each shower is reused 980 times with translating core position on the ground so that the total number of events is 980,000.

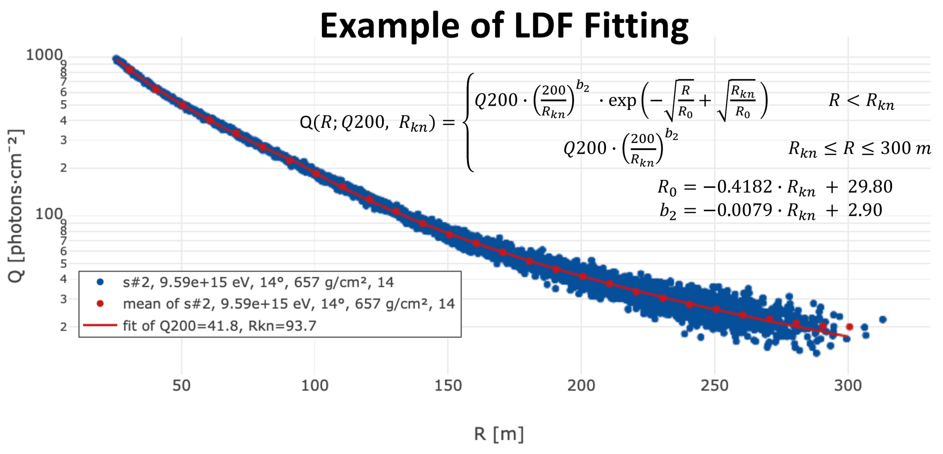
Shower arrival directions are determined by fitting detector-hit timings with a plane going with light speed in atmosphere, which results that opening-angle distribution between true and reconstructed arrival direction calculated using CORSIKA shows 0.58° at 68% of the data.

Angular Resolution

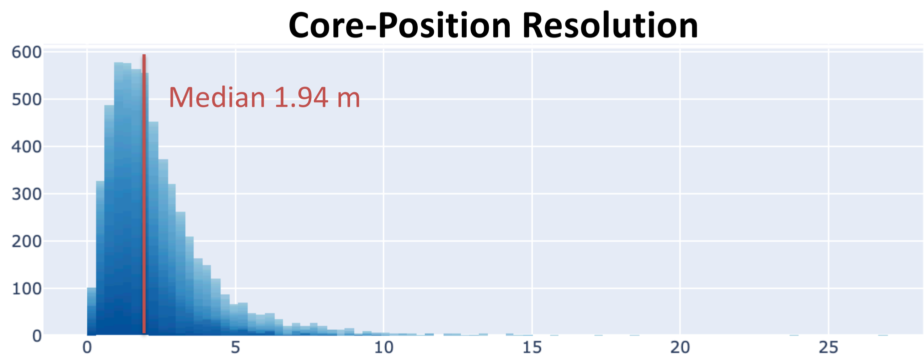


Shower core positions are determined by searching the positions on the shower planes determined above where each weighted MSE of Lateral Distribution Function (LDF) is minimized.
We use the modified LDF of the Tunka-experiments one[7] for the NICHE experiment.

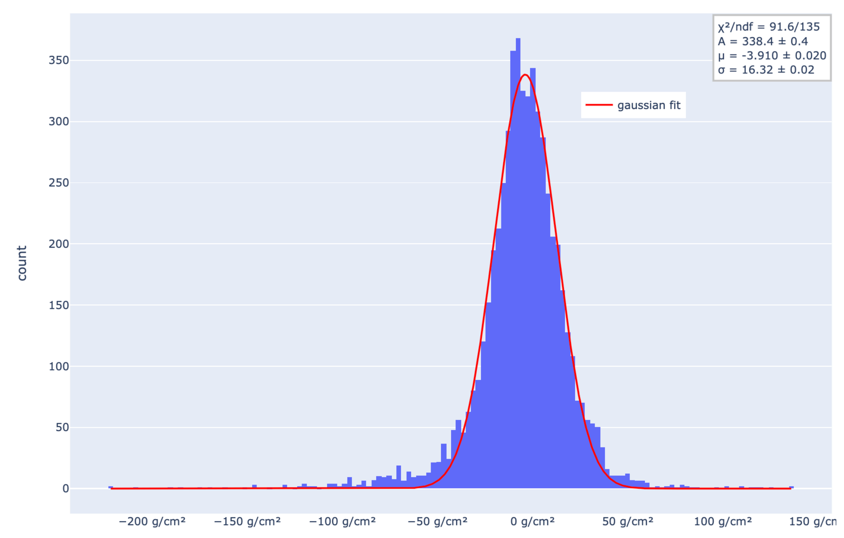
Example of LDF Fitting

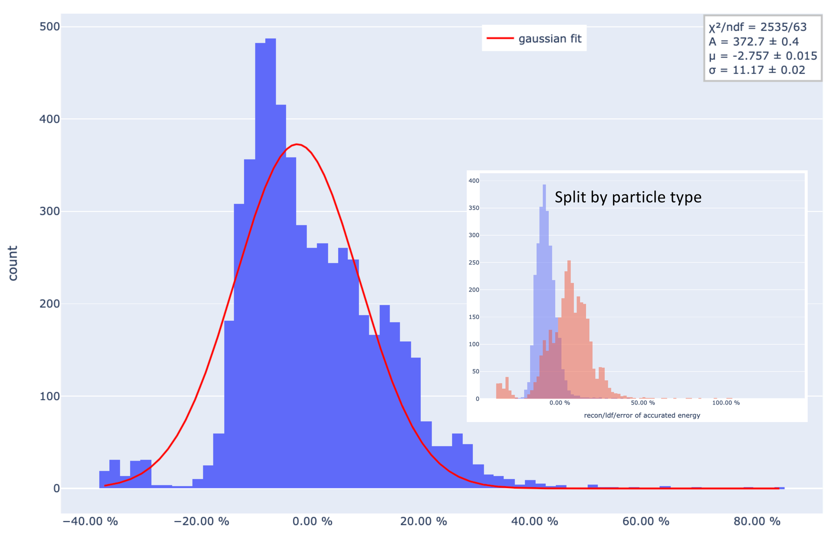


Core-Position Resolution



E_0 and X_{max} are derived from the pre-calculated relations of the LDF parameters Q_{200} and R_{kn} respectively.
absolute error of X_{max} is 16.3 g/cm² and relative error of E_0 is 11.2%.

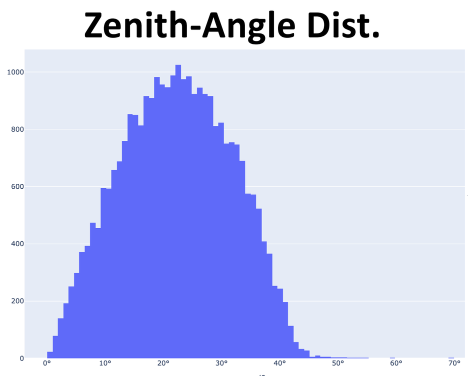




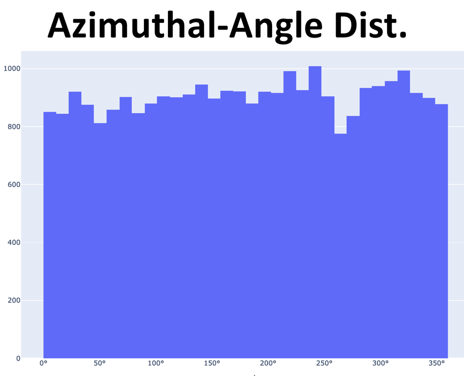
Observation Reconstructions

Observation duration for data analysis is for 7 months March to September in 2019.
In this periods, all 14 detectors were available at maximum but only 10 detectors are used in this analysis for technical reasons. The total number of shower events is 88,296.

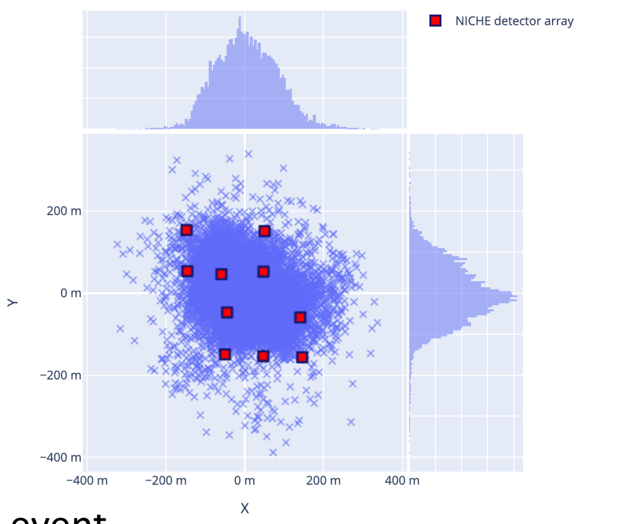
Zenith-Angle Dist.



Azimuthal-Angle Dist.



Core-Position Dist.



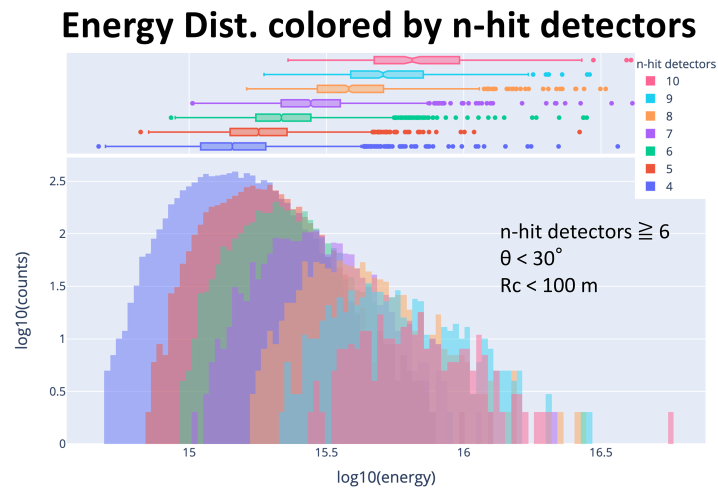
Distributions of reconstructed arrival direction and core position is determined by the methods.

Energy and X_{max} have been calculated using LDF event by event.

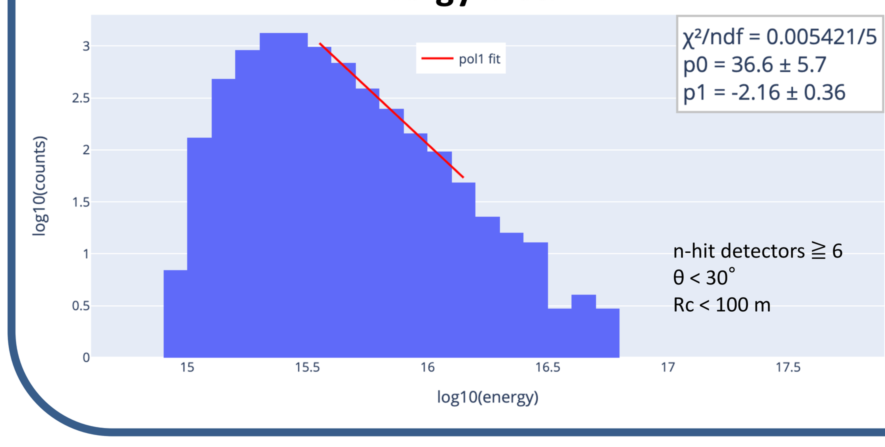
We got preliminary energy and X_{max} distributions as shown below.
In the energy distribution, the bin width of energy distribution is $\log E = 0.1$.
We found an index of power law in the energy range of $10^{15.55}$ eV to $10^{16.15}$ eV is -3.2 without any correction, but this result is reasonable comparing to other experiments like Tunka experiment.

X_{max} distribution is fitted with a mixed X_{max} distribution of proton and iron, that results its distribution is explained by mixed shower events of 31% proton and 69% iron.
However, there are the avoidable number of the events where are shower developed at maximum more shallowly than 400 g/cm².
This must be investigated more carefully.

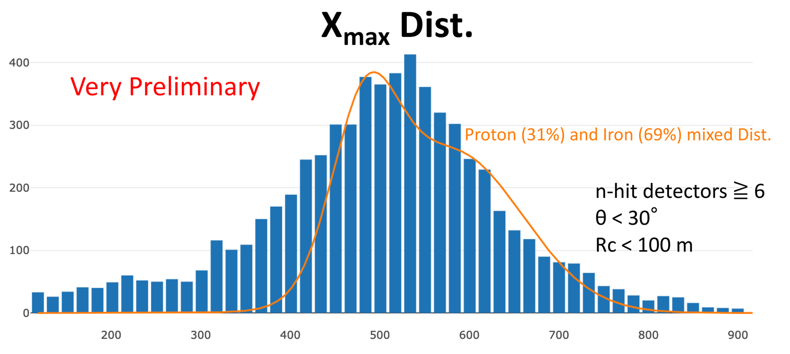
Energy Dist. colored by n-hit detectors



Energy Dist.



X_{max} Dist.



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