PROCEEDINGS OF SCIENCE

Performance studies of the ALPACA experiment

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In the southern sky, there are many very high energy Galactic gamma-ray sources which have the possibility of cosmic-ray acceleration up to the PeV energy region (PeVatrons). Sub-PeV gamma rays are produced by interactions between PeV cosmic rays accelerated by PeVatrons and interstellar matter. Andes Large-area PArticle detector for Cosmic-ray physics and Astronomy (ALPACA), consisting of an air shower array(83,000 m^2) and underground muon detectors(3,600 m^2) located at the Mt. Chacaltaya plateau(4,740 m), near La Paz, Bolivia, observes high energy cosmic rays and gamma rays with a wide field of view in the southern sky. The performances of ALPACA for gamma-ray source are estimated with a Monte Carlo simulation in this work. As a result, we expect to significantly detect the most promising PeVatron candidate, the Galactic Center.

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1. Introduction

Galactic cosmic rays reach energies at least a few PeV, suggesting that our Galaxy contains PeV accelerating objects called PeVatron. The hadronic part of the cosmic rays which PeVatron accelerated, interacts with the interstellar gas and produces neutral pions (π^0). Neutral pions decay into two photons($\gamma\gamma$). Those photons generated in that process are expected to have 100 TeV (sub-PeV) energy ,because of having 10 percent of the energy of neutral pion. Besides, the photons emitted through this mechanism have a power law spectrum with the same index as the cosmic rays, protons, and nuclei. It is essential to study the sub-PeV gamma-ray diffuse emission because, they trace the overall distribution of cosmic ray protons in the Galaxy and suggest the position of PeVatron [**?**]. A high duty cycle and wide field of view of ALPACA is suitable for sub-PeV gamma-ray observation because of low gamma-ray flux. Alternatively, the conventional air shower array rejection power of the enormous cosmic ray background events is not high enough. However, with the muon detector array whose structure is similar to ALPACA, the TibetASγ experiment in the northern hemisphere can reject background cosmic ray events with 99.9 percent around 100 TeV region. Especially,TibetASγ can accomplish that the few hundreds TeV region is background free [**?**]. One of our main interests is the detection of gamma rays beyond 100 TeV from the Galactic Center. In 2016, H.E.S.S observed the diffuse gamma-rays around the Galactic center at the TeV energy range [**?**]. Then, H.E.S.S reported hard gamma-ray emission without a break-up. This data suggests that cosmic ray accelerator exists around it, but the H.E.S.S data is up to few tens TeV. After that H.E.S.S observation, MAGIC(2020) and VERITAS(2016) observed diffuse gamma-ray emission of the Galactic Center up to a few ten TeV [**?**][**?**].

2. MonteCalro Simulation and data analysis

The performance values for ALPACA presented in the following are derived from detailed Monte Carlo(MC) simulations of the ALPACA instrument based on the CORSIKA air shower code. The air shower generation area is inside of the circle with a 300 m radius. The point source moving on the orbit of the Galactic Center is adopted as a gamma-ray source. Besides, we assume to observe a gamma-ray source with a spectral shape following a power law with $E^{-2.32}$. As presented below(integral flux), the results are heavily dependent on the assumed spectral index. Background cosmic ray chemical composition assumed is Shibata model [**?**] with CORSIKA. The hadron interaction model is used EPOS-LHC at high energy and FLUKA at low energy. Detector response simulations are performed with GEANT. Muon detector and AS detector constructions are presented Figure left and right respectively. These layouts are above(Figure1). GEANT simulates the passage of particles through matter, allowing for arbitrary geometry and materials. In air shower array instruments simulation, 94 MeV energy deposit of scintillatingdetector is regarded as 1 particle. Similarly, 23 photoelectrons in the muon detector seem like 1 muon. In this contribution, energy reconstruction is imported with the number of particles detected. (3) The timing distribution of each air shower array instruments detecting particle(t_i) is used for estimation of incoming direction. In this method, t_i) is corrected as $t_{\mathrm{i,cor}}$, $t_{\mathrm{i,cor}} = t_{\mathrm{i}} - T(R)$ .Here,$T(R)$ is the function of distance R from the center of air shower front cone curve. Then, we introduce the value(χ^2) called "residual

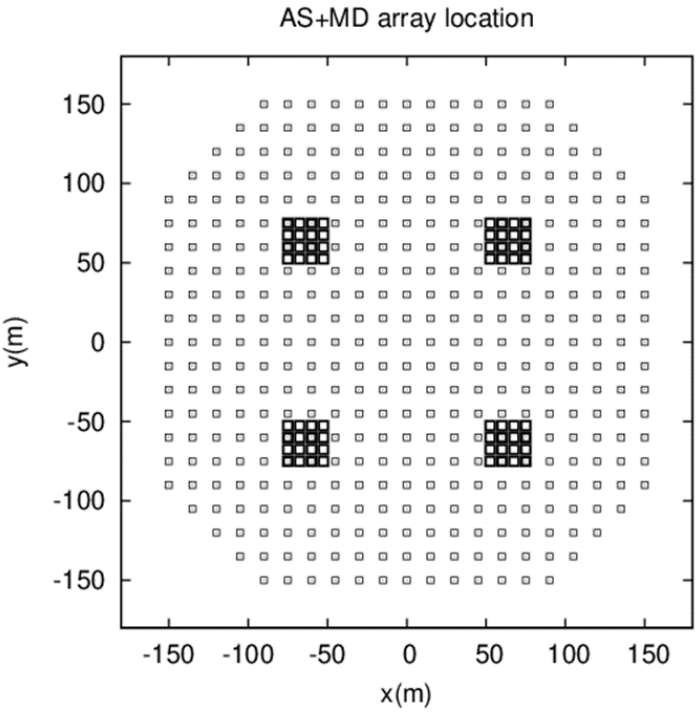

Figure 1: ALPACA configuration. Squre with bold line shows muon detectro array and open square represents air shower array.

error". Also, l, the incoming direction cosine, defined as minimum χ^2.χ^2.

$$\chi^2 = \Sigma_i w_i (l\dot{x}_i - c(t_0 - t_i)), (w_i = \frac{\rho_i}{\Sigma_i \rho_i}, x_i = (x_i, y_i, 0), c = \text{speedoflight}) \tag{1}$$

The following conditions are adopted as analysis conditions. 1 any four scintillation detectors record more than 0.8 particle density 2 the detector that records the most significant particle density is inside the inner area which is inside the air shower array, excluding the most outside instruments 3 the residual error in Equation1 is smaller than 1 meter 4 reconstructed zenith angle is smaller than 40 deg. 5 there is the Galactic Center inside the window of radius $r_{\text{win}} = 5.8° /\sqrt{\Sigma\rho}$

3. Performance of ALPACA

The angular resolution is one of the barometers showing the performance air shower array. Figure3 gives an angular resolution of ALPACA for gamma-rays. Especially, at 100 TeV region, that value is 0.2 deg as 50 percent containment. Above all, the angular resolution of ALPACA is similar to TibetASγ(0.22 deg @100 TeV) [**?**]. The number of muon detected allows us to estimate primary seeds. Figure 4 shows $(\Sigma\rho, \Sigma N_\mu)$ plot of gamma-ray and cosmic ray events. Here, ΣN_μ)is defined as the total number of muon detected. The tendency that cosmic ray events are much ΣN_μ at the same $\Sigma\rho$than gamma-ray events. We set the cut line(green line in Figure 4) and use gamma-ray events under the cutline to eliminate the enormous background cosmic ray events.

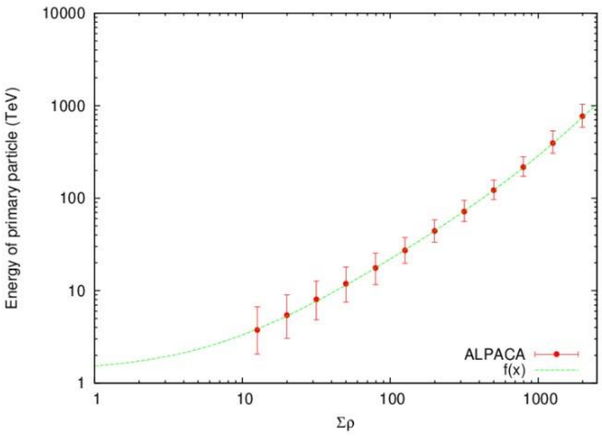

Figure 2: The relation between generated gamma-ray energy and the total number of particles detected. From Figure 2, we can estimate that $\Sigma\rho$ = 501 point corresponds to 127 TeV.

Sensitivity curves make us to understand that how long does it take to observe the Galactic Center. Figure 5 shows the sensitivity curve of ALPACA. Note that the applied definition for sensitivity requires a detection significance of 5σ per energy bin. Additional criteria are applied to require at least ten events detected gamma-rays per energy bin in the region whose background cosmic ray events are smaller than one event. In Figure5, the green line is the Galactic Center gamma-ray flux referenced H.E.S.S. observation ([**?**]) and ALPACA sensitivity curve which we calculate in this work. Then, we can expect to detect the Galactic Center gamma-ray flux at 100 TeV region about 1 year observation time.

4. Results

The effort of simulation in ALPACA plays an essential role in our future observation. In this contribution with detailed MC simulation of half ALPACA, the sensitivity curve for the Galactic Center is clarified. Then, ALPACA can be expected to observe the Galactic Center gamma-ray flux in 1 years observation, but this results is estimated under the assumption of point gamma-ray source. The understanding of the ALPACA sensitivity of the extended object is the next step.

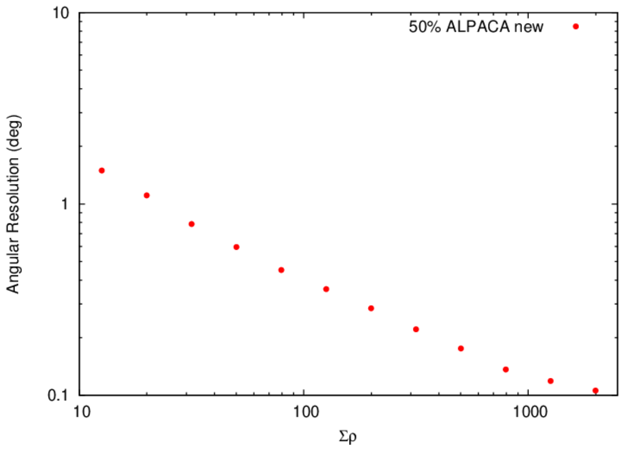

Figure 3: Angular Resolution of ALPACA to the Galactic Center

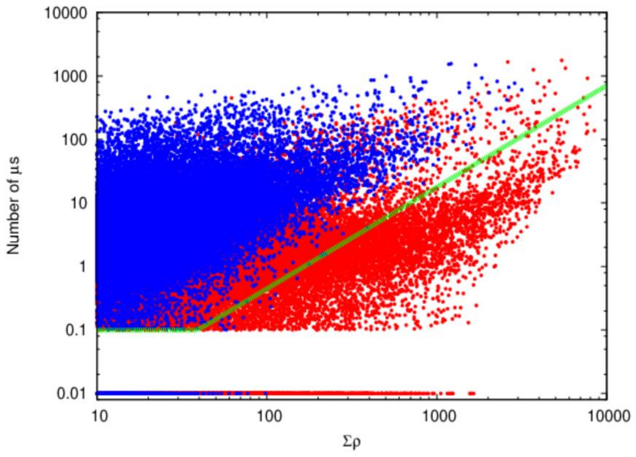

Figure 4: Red points are gamma-ray events, and blue points are CR events. In this figure, the events whose ΣN_μ is less than 0.1 accumulates $\Sigma N_\mu = 0.01$. The green line is the cutline. In data analysis process, gamma-ray events under cutl.ine are used.

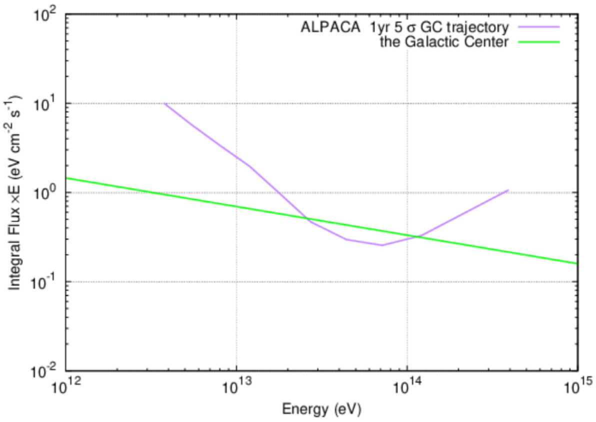

Figure 5: ALPACA sensitivity curve(purple line). Note that the definition of sensitivity curve is the gamma-ray flux to be expected to be detect with 1 yr ALPCA obserbation at 5σ.In this figure, green line is the Galactic Center gamma-ray flux referenced H.E.S.S. observation. [**?**]

5. Acknowledgments

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