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Complete List of Authors:	Atik Yilmaz, Şeyma; Abant İzzet Baysal Üniversitesi Fen Edebiyat Fakültesi, Physics Yilmaz, Ali; Giresun Üniversitesi, Electrical and Electronics Engineering Denizli, Haluk; Abant İzzet Baysal Üniversitesi Fen Edebiyat Fakültesi, Physics Oyulmaz, Kaan; Abant İzzet Baysal Üniversitesi Fen Edebiyat Fakültesi, Physics
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Energy cut-off effect in CORSIKA on the detected particles of $\pi\pi^0$ decay channel

Şeyma Atik Yılmaz*

Department of Physics, Abant İzzet Baysal University, 14280, Bolu, Turkey.

Ali Yılmaz†

Department of Electrical and Electronics Engineering,

Giresun University, 28200, Giresun, Turkey.

Haluk Denizli‡

Department of Physics, Abant İzzet Baysal University, 14280, Bolu, Turkey.

Kaan Yüksel Oyulmaz§

Department of Physics, Abant İzzet Baysal University, 14280, Bolu, Turkey.

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Abstract

CORSIKA (COsmic Ray SIMulations for Kascade) has various features in the creation of the extensive air showers with several characteristics where the users can configure the input card to achieve the desired result. ECUT is a parameter defined as the low energy cut-off of the particle kinetic energy for hadrons, muons, electrons and photons. We investigate the effect of the different ECUT values on the detected particles in 10^7 GeV - 5×10^8 GeV primary particle energy range where $\pi^-\pi^0$ decay channel chosen with 5 km shower development length. The selected ECUT values in this study are 0.05 GeV and 0.1 GeV for both hadrons and muons while 0.05 GeV for electrons and photons. The effect of the reducing by half on the energy cut-off value is studied for the detector array located on an inclined plane which is planned for upward τ detection.

I. INTRODUCTION

In the astroparticle physics, the detection of high energy cosmic rays is very appealing subject since it reveals the information of their origin and their sources. The experiments like SUGAR (Sydney University Giant Air-shower Recorder)¹, AGASA (The Akeno Giant Air Shower Array)², KASCADE (Karlsruhe Shower Core and Array Detector)³, Pierre Auger Observatory⁴, etc. are constructed to observe these energetic horizontal cosmic ray showers with an array. There are studies in the literature⁵ to observe primary particles with zenith angle greater than 90° . In our study, we have constructed the array on an inclined plane⁶ to take the advantage of the technique called *Earth Skimming Strategy*. In this technique Ultra High Energy (UHE) ν_τ traveling through the Earth interacts with the rock before it leaves the Earth crust and produces τ particle via Charge Current (CC) interaction. Secondary particles coming from τ decay produce an upward-going horizontal shower while traveling through the atmosphere^{7,8}. Hence the $\pi^-\pi^0$ has the highest branching ratio in the τ decay channels, it is chosen to study the effect of ECUT on the array.

II. SIMULATIONS

Simulations for the study of the Ultra High Energy Cosmic Ray (UHECR) showers are done by CORSIKA⁹ (modified version of 6.99) with using QGSJET (Quark Gluon String model with JETs for high-energy hadronic interactions) and GHEISHA (Gamma Hadron Electron Interaction SHower code for hadronic collisions up to 100 GeV) physics models without thinning procedure. Two set of ECUT values selected for this study are 0.05 GeV for muons, hadrons, electrons and photons and 0.1 GeV for muons and hadrons while 0.05 GeV for electrons and photons. Primary particle angles ranges between $92.0^\circ - 92.5^\circ$ for θ (zenith angle measured between the particle momentum vector and the negative Z-axis) and between $0.0^\circ - 0.5^\circ$ for ϕ (azimuthal angle measured between the positive X-axis and the horizontal component of the particle momentum vector). Shower development length is selected as 5 km and the shower energy is between 10^7 GeV - 5×10^8 GeV. The energy ranges grouped as low ($\sim 10^7$ GeV) and high ($\sim 10^8$ GeV) having 9 showers in each. The showers are observed on a plane at a mountain slope which has a 30° inclination. On this plane there are 640 stations (16×40) and each station has 2 scintillators (40×20 cm²),

separated by 160 cm, which are pointing 2.5° below the horizon. The stations are separated 30 m from each other and the array is in 0.5 km^2 area. Both plate area and separation of stations are chosen after careful studies of the array to maximize the efficiency in this energy range.

III. RESULTS

The array constructed on an inclined plane to catch the Earth-skimming neutrinos with a large zenith angle. Generated showers with different arrival directions, ECUT sets and shower energies are analyzed in terms of number of particles (total, γ , $e^\pm$, $\mu^\pm$) on the observation plane, detected by full detector array and detectors around the shower center and the width of the shower (in y and z) evaluated by the hits on the detectors along the inclined plane where 640 stations are located and reconstruction of shower directions (zenith and azimuthal angles).

FIG. 1. For low energy scale the number of particles for (a) all, (b) $\mu^\pm$ and (c) the shower diameters in y-z directions for 0.1 GeV ECUT, (d) total number of particles, (e) $\mu^\pm$ number of particles and (f) the shower diameters in y-z directions for 0.05 GeV ECUT.

Figure 1a and 1b show total number of particles (all types), and muons (and antimuons) on an inclined plane (blue), on an array (red) and on an array around center (green) for low energy scale in the case where ECUT is 0.1 GeV for hadrons and muons. In Figure 1c,

FIG. 2. For high energy scale the number of particles for (a) all, (b) $\mu^\pm$ and (c) the shower diameters in y-z directions for 0.1 GeV ECUT, (d) total number of particles, (e) $\mu^\pm$ number of particles and (f) the shower diameters in y-z directions for 0.05 GeV ECUT.

diameter of showers in y and z from the detected particles in the stations are plotted for each showers. On average diameter in y and z directions are approximately 140 m and 136 m, respectively. Figure 1d, 1e and 1f are for ECUT value of 0.05 GeV for hadrons and muons. Comparing these figures indicated that decreasing ECUT by half result in 10%, 5% and 6% of increase at total number of particles on the mountain plane, on the array and around center of array, respectively. The number of $\mu^\pm$ decreases on mountain plane when the energy cut-off is reduced by half. On detector array and around the center of array the number of $\mu^\pm$ within the error while the reducing by half of the ECUT for hadrons and muons. The average diameter of 9 different showers obtained from total number of particles increases 30 m in y direction and 4 m in z direction while the energy cut-off decreases. Also the area of the showers increases as 19% approximately with the decreasing of energy cut-off on hadrons and muons.

In high energy scale, the number of particles (total and $\mu^\pm$) on the detection plane and the diameters of showers are shown in a, b, and c of Figure 2 for ECUT value equals to 0.1 GeV and in d, e and f of Figure 2 when ECUT value equals to 0.05 GeV. The number of total particles changes with the decreasing of the energy cut-off value from 0.1 GeV to 0.05

GeV about 3% of increasing on the mountain surface, 6% of increasing on the detector plane and 6% of increasing around the center of the detector array. The decrease on the energy cut-off value increases the number of $\mu^\pm$ on the mountain surface and the detector array while around the center of array is not changing. Reducing the energy cut-off by half does not effect the size of the shower determined by the array on the inclined plane when trigger is set to require at least 5 hits in the stations. Also the diameter of the showers in y and z directions are 250 m and 203 m, respectively. The increase in y direction as 20 m and the decrease in z direction as 10 m, so the area of the showers increases as 4% approximately with the decreasing of energy cut-off on hadrons and muons. At the low energy scale, the area increases more than at the high energy scale due to the smaller increase on the diameter in y direction and the decrease in the z direction.

FIG. 3. The simulated arrival directions; $\theta_{calculated}$ for hadrons ECUT (a) 0.1 GeV, (c) 0.05 GeV in low energy scale, (e) 0.1 GeV, (g) 0.05 GeV in high energy scale, $\phi_{calculated}$ for hadrons ECUT (b) 0.1 GeV, (d) 0.05 GeV in low energy scale, (f) 0.1 GeV and (h) 0.05 GeV in high energy scale.

The calculated arrival directions found by using the MINIUT which is a system for function minimization. MINIUT provide to calculate χ^2 function of the space (x_i, y_i, z_i) and time (t_i) variables.

$$\chi^2 = \sum_i^N w_i (n_x(x - x_i) + n_y(y - y_i) + n_z(z - z_i) - c(t_i - t_0))^2$$

The result gives the direction vector of EAS as (n_x, n_y, n_z) then this vector transferred

to the spherical coordinates to calculate θ and ϕ . These calculated arrival directions of the simulated showers are shown in Figure 3. The arrival directions are not affected significantly by changing the energy cut-off on hadrons and muons. In the low energy scale $\theta_{calculated}$ is 0.14° off for 0.1 GeV hadron ECUT and 0.11° off for 0.05 GeV hadron ECUT while $\phi_{calculated}$ is 0.18° off for 0.1 GeV hadron ECUT and 0.05° off for 0.05 GeV hadron ECUT. In the high energy scale $\theta_{calculated}$ has 0.12° off for 0.1 GeV, 0.16° off for 0.05 GeV and $\phi_{calculated}$ has nearly 0.03° off for both hadron ECUT values.

IV. CONCLUSION

The main goal for this study is to reduce the energy cut-off for both hadrons and muons then to observe more muons in the array and checking the performance of the array in terms of particle distributions, shower diameter and arrival direction. The results show that the total number of particles relatively changed when energy cut-off reduced by half. We also see that energy cut-off is more effective in the high energy range ($\sim 10^8$ GeV) than in the low energy range ($\sim 10^7$ GeV) as one can expect. Number of muons in the simulated showers with higher energy increases as the energy cut-off is reduced by half. This effect is not noticeable due to low statistics in the showers with lower energy. $\theta_{calculated}$ and $\phi_{calculated}$ from shower observables are not affected significantly by changing the energy cut-off on hadrons and muons.

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* seyma.atik@ogr.ibu.edu.tr

† aliyilmaz@giresun.edu.tr

‡ denizli_h@ibu.edu.tr

§ kaan.oyulmaz@gmail.com

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