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Basic simulation study on the discrimination between primary electrons and gamma rays for the next generation IACTs

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The discrimination between primary electrons and gamma rays is an open question for Imaging Atmospheric Cherenkov Telescops (IACTs) even in the Cherenkov Telescope Array (CTA) era. If the discrimination will be realized in the energy band around a few hundred GeV, the sensitivity for the observation of very-high-energy gamma rays will be improved by about an order of magnitude than that achieved by the CTA. Though the discrimination was tried by existing IACTs, the definitive methods have not been found yet. To figure out the problem, we have started basic simulations assuming an ideal detector that obtains the information on both the incident positions and directions for each Cherenkov photon. From the study, we recognized first that it is possible to discriminate only the Cherenkov photons generated around the point where incident particles first interact with the atmosphere, if the shower axis can be determined at accuracy. If the incident particle is an electron or positron, such Cherenkov photons are called the direct Cherenkov photons. On the other hand, if the primary is a gamma ray, they are the Cherenkov photons produced by the first electron-positron pair in an extensive air shower. We collectively call them the "first Cherenkov photons". Second we recognized that the ground pattern of the "first Cherenkov photons" for the electron is different from that for the gamma ray, which makes discrimination between these particles possible.

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1. Introduction

Observations with gamma rays are very important to study high-energy phenomena in the universe such as acceleration mechanism of cosmic rays. For this reason, various observation instruments of gamma rays have been developed and various experiments have been conducted. The observation methods can be divided into two main types. One is the direct detector such as Fermi LAT[1] and EGRET[2], which were installed in satellites. As shown in Fig.1, such type of detectors consists of anti-coincidence detector for charged particles, the tracker layer to convert incident gamma ray to electron-positron pair, and the calorimeter to measure the energies of the pair under the tracker layer. In the tracker layer, the trajectory of the pair is obtained and then incident direction of the gamma rays can be measured. Moreover, it can be also used to distinguish the types of incident particles such as electrons and gamma rays. This is because the gamma rays do not hit the anti-coincidence detector and the trajectory appears from the middle of the tracker layer. Therefore the primary electrons can not be the background for the gamma rays. However, it is difficult to obtain the large effective area more than several square meters because of the installation on satellite.

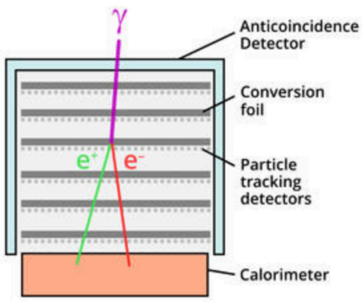

Figure 1: This picture shows the schematic view of the Fermi LAT. It consists of anti-coincidence detector, the converter/ particle tracker, and calorimeter.

The other type is ground-basedindirect detectors, such as Imaging Atmospheric Cherenkov Telescopes [3] and surface particle detectors.[3]. When gamma rays enter the atmosphere, an extensive air showers are produced due to electromagnetic cascade. Because the produced electrons and positrons can run faster than the light in the atmosphere, Cherenkov photons are generated. In the case of incident gamma rays with the energy above ~20 GeV, number of Cherenkov photons reaching the ground is sufficient to distinguish from the night sky background (NSB). Attempts to observe gamma rays using telescopes collecting Cherenkov photons began in the 1970s. By the installation of telescopes with large size of mirrors on the ground, it can obtain an effective area several tens of thousands times larger than that of satellite detectors. Moreover, the stereoscopic observation by an array of multiple telescopes much contributed to the improvement of the angular resolution and the reduction of background from cosmic-ray protons. Therefore, IACTs such as the CTA[4] lead the world in the observation of gamma rays with energies above 100 GeV up to a few tens of TeV.

However, the discrimination between primary electrons and gamma rays is an open question for IACTs even in the CTA era. If the discrimination will be realized in the energy band around

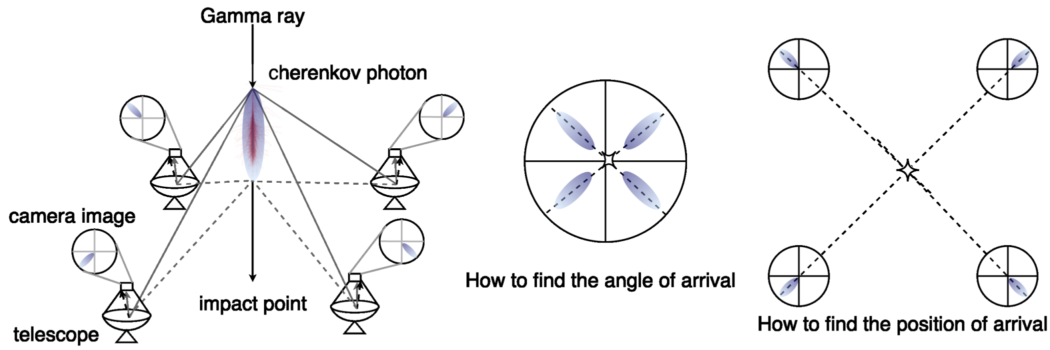

Figure 2: The Schematic view of Cherenkov telescope array. The image of air shower is detected by each telescope. By analyzing these images, the shower axis and the impact point are recognized. Moreover, these data can be used to discriminate the air shower for gamma rays from that for protons.

a few hundred GeV, the sensitivity for the observation of very-high-energy gamma rays will be improved by about an order of magnitude [5]. Despite the advantage, discrimination method with the current IACTs has not been established yet. The reason is that the shape of the air shower from primary gamma ray is almost same as that from primary electron because both primary particles cause the electromagnetic cascade. However, there is one significant difference between them as shown in Fig.3. If the incident particle is an electron, the electron itself should emit Cherenkov photons in a conical shape near the top of the atmosphere. On the other hand, in case of primary gamma rays, Cherenkov photons are emitted immediately after the first pair production, by both of the electron and the positron in a conical shape. We collectively call them the "first Cherenkov photons". So if we could extract this first Cherenkov photons and examine the image, it would be possible to discriminate between gamma rays and electrons. However, the number of first Cherenkov

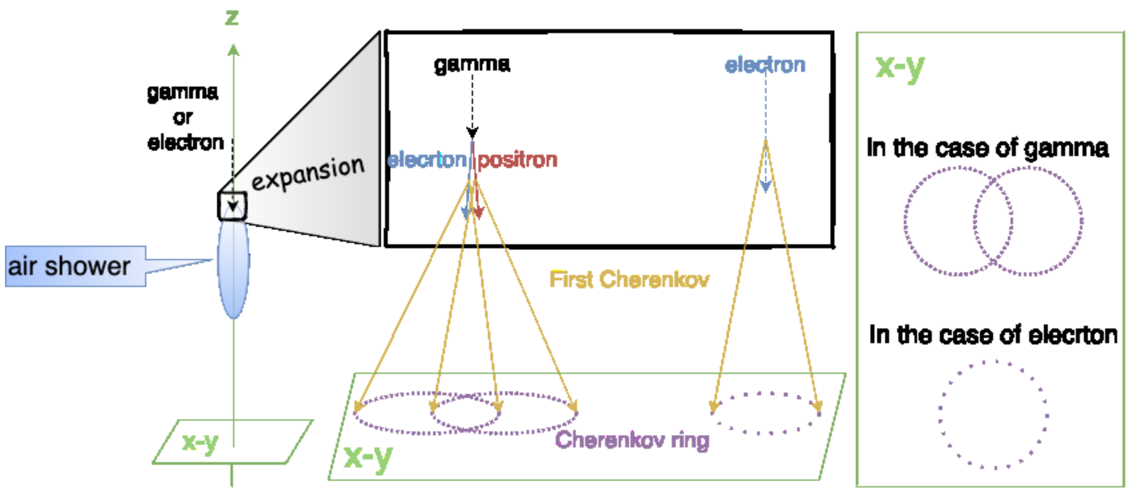

Figure 3: The air shower due to primary gamma rays and electrons. If we could detect only the first Cherenkov photons on the ground, we will see one ring image for primary electrons and two ring image for primary gamma rays, respectively.

photons is thousand times fewer than that of Cherenkov photons emanating from lower altitudes. Therefore, unless a method is established to extract the first Cherenkov photon, the discrimination is impossible. First The analysis of Direct Cherenkov photon has been already performed with current Cherenkov telescopes [6], but it is in the limited use case of heavy nuclei, since the amount of Cherenkov photons emitted is proportional to the square of the charge (Z^2) of the primary.

Conventional IACTs can only obtain the information on the incident direction and the time of arrival on the ground for each photon. And from them, the information of the shower axis can be obtained. In addition to those, if the incident position of each photon can be measured at accuracy, by tracing back the photons with the incident position and direction and by examining their intersection with the shower axis, it should be possible to determine the altitude at which each photon was generated. This means that only the first Cherenkov photon can be extracted, which in turn may make it possible to discriminate between primary electrons and gamma rays. To investigate if the above idea is valid, we first performed a computer simulation in a very simple case. In this paper, we present the results.

2. Simulation and Analysis Methods

Using the CORSIKA Version 7.5600[7] and including QGSJET01 and GHEISHA as hadronic interaction model, we conducted the air shower simulation with CERENKOV option. The contents of the input file given to the CORSIKA are shown below. Simulations were performed with 2,000 injections for each of electrons and gamma rays. The incident energy is fixed to 500 GeV and the incident direction is also fixed to vertical. As for the atomosphere profile, we use the standard model in the United States. The geomagnetic fields are set to be the one for Central Europe (CORSIKA default setting). Observation level was set to be 110m a.s.l.. We assume that the flat detector with the area of 25 square kilometer is installed. The parameter of "STEPFC" is related with the multiple scattering length for electrons and positrons. Though the value is usually set to be 1.0 with CERENKOV option, we modified the CORSIKA source code to set this value to be much shorter (0.01), in order to realize more accurate simulation. Atmospheric extinction of the Cherenkov photons were not considered in the simulation.

```
nshow 2000                       maxprt 1
prmpar 1                         parout T T
erange 500.0 500.0               datbas T
eslope 0.0                       plotsh T
thetap 0.0 0.0                   cerary 1 1 500.0 500.0 500000.0 500000.0
phip  0.0 0.0                    cerfil T
atmod 1                          cerqef F F F
magnet 20.4 43.23                obslev 11000.0
longi T 20.0 T T                 stepfc 0.01
direct tk                        exit
```

When this simulation is run, information on the large number of Cherenkov photons generated for each shower particle is written to a file. The information on one photon bunch is the incident direction, the incident position, number of photons, and the arrival time. Using these information, the candidates of the first Cherenkov photons are extracted from the total photons by the following multi-step filtering.

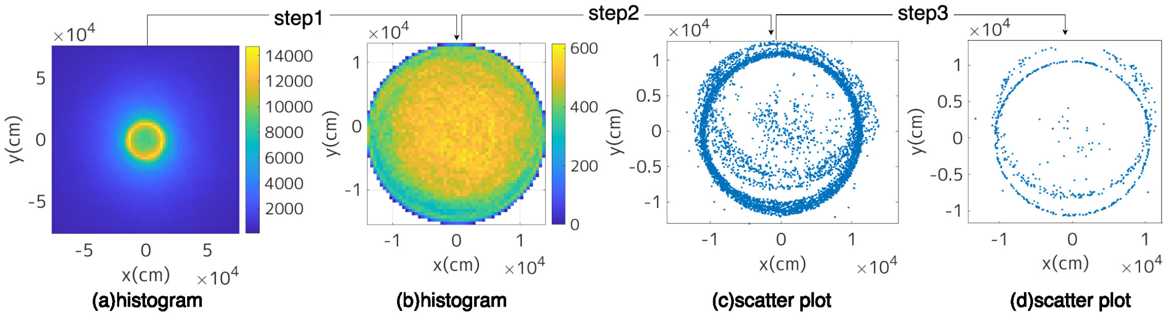

Figure 4: Ground image of photons remaining after each filtering.(Figure for one event only.) In the case of an event which the ideal ring was taken. (a) : All observed photons. (b) : Photons selected in step 1. (c) : Photons selected in step 2. (d) : Photons selected in step 3.

Step1: The leftmost figure in Fig.4 shows the position of all Cherenkov photons falling onto the ground. Fig.5 also shows the distribution of the distance of all photon positions from the light pool center and the distribution of the zenith angles of the photon direction. Photons at distances smaller than the maximum bin were extracted. Moreover, because the incident angle of the first Cherenkov photons is almost 0 deg, we extracted only photons with smaller incident angle than the maximum of the angular distribution. The distribution of photons passing through these selections is shown in (b).

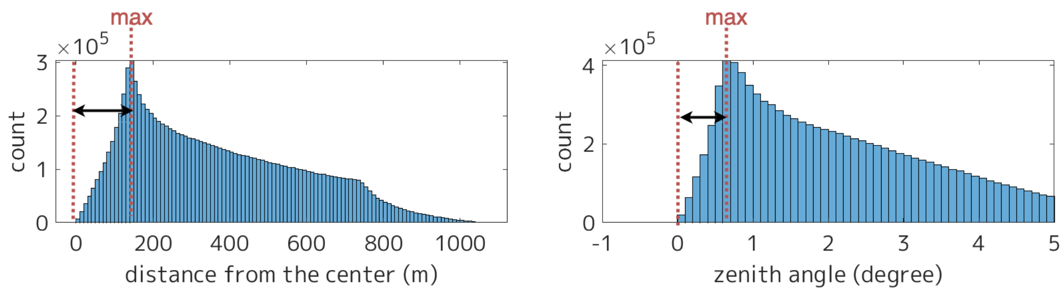

Figure 5: The distribution of the distance from the light pool center to the falling position and that of the incident angle for each photons. Though these are examples for a gamma ray, the shape of the histograms is also similar to that of electrons.(Figure for one event only.)

Step2: With the extracted photons by Step1, the trajectory of each photon is defined by the following equation.

$$\frac{x - x_0}{v_x} = \frac{y - y_0}{v_y} = \frac{z - z_0}{v_z} \tag{1}$$

(x_0, y_0, z_0) and (v_x, v_y, v_z) are the falling position of the photon and the direction cosine vector, respectively. Then we calculated the intersection of this line with the plane $x = 0$.

Though the intersection for two lines of photon trajectories should be calculated, there are two reason to calculate the intersection with the plain. First, there are so many photons passing through Step 1 and then the calculation of the intersection between two lines for every combination is very time consume, so we need to introduce a pre-selection stage. The second reason is as follows. Since the charged particles emitting the First Cherenkov photons mostly move along the plane $x = 0$ when the incident direction of primary particles is vertical because geomagnetic direction vector is in $y = 0$ plane, the trajectory of the First Cherenkov photons should have an intersection with the $x = 0$ plane. The Fig.6 shows the distribution of the intersection on the plane of $x = 0$. The left and right figures correspond to the case of incident gamma rays and that of incident electron, respectively. Though there is an outlier seen for gamma-ray case in Fig.6, it is spurious intersection and then it can be removed. Because the candidates of the first Cherenkov photons should be emitted from the highest position, we extracted 6000 photons in order of its altitude in the intersection plot.[1]. The image due to only for the extracted photons is shown in the (c) of Fig.4. As you can see in this figure, photons are distributed on the circle. It indicates that the first Cherenkov photons are much contained in the extracted photons.

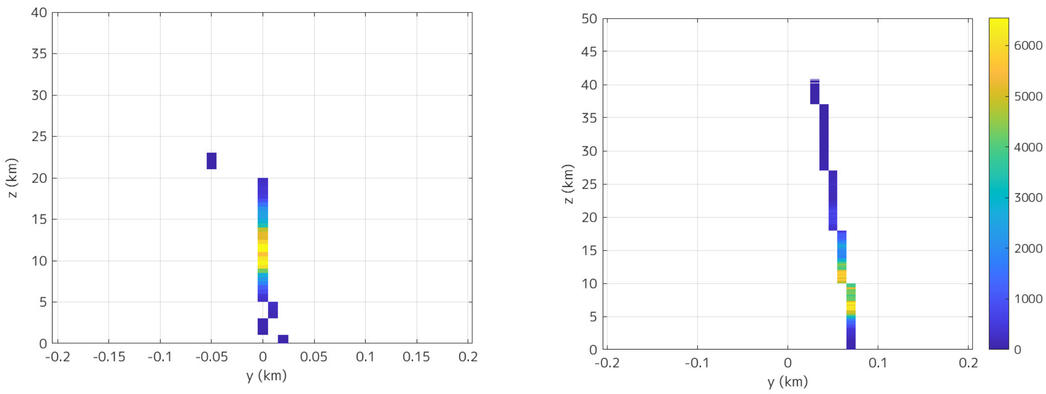

Figure 6: The distribution of the intersection on the plane of $x = 0$. The left and right figures correspond to the case of incident gamma rays and that of incident electron, respectively.(Gamma rays and electrons, one event each.)

Step3: Finally, using the equation for extracted each photon, the intersection position for two photons were investigated. In case that 6000 photons are extracted in the former step, the calculation is carried out about 18 million times ($\approx 6000 \times (6000 - 1)/2$). However, the two lines are generally most likely to be in a twist position and then the exact intersection point can not be calculated. Therefore, we first calculated the distance between the two lines when they were closest to each other. If the distance is less than 500 meters, we considered the two photons as parts of first Cherenkov photons. The figure (d) in Fig.4 shows the ground image due to the extracted photons by such process. Because we can know from the simulation the actual generating altitude of the photons extracted by the above three filters, we investigated

[1]The value of 6000 is adjusted depending on the incident energy.

that first Cherenkov photons can be correctly extracted by the analysis method as described above.

Fig.7 shows the ground images of the photons through three filters for a primary gamma ray and electron, respectively. For these events, in the case of primary electrons, the number of photons are less than that in the case of primary gamma rays. It is due to that the altitude where first Cherenkov photons are generated is comparatively high. Moreover, in the case of the gamma rays, the image with two rings can be dimly seen.

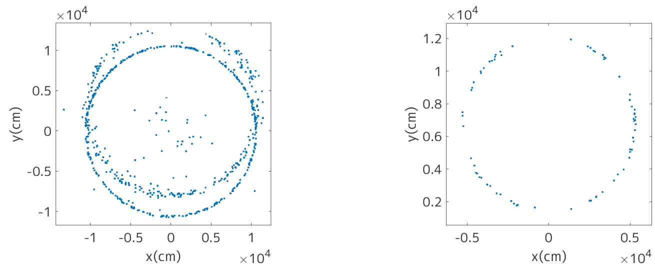

Figure 7: The left and right figures show the images through three filters for a primary gamma ray and electron, respectively. In the image for the gamma ray, there are dimly two rings.(Gamma rays and electrons, one event each.)

3. Discrimination with Convolutional Neural Network

To make the difference between the two images stand out more, the image with (x, y) is the converted to that with (r, θ), which are $\sqrt{x^2 + y^2}$ and $\arctan(y/x)$, respectively. Then we tried to discriminate two types of images with Convolutional Neural Network (CNN).

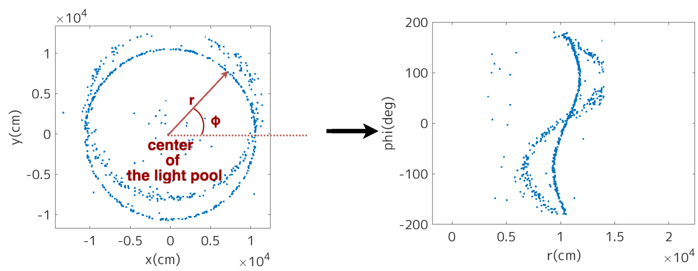

Figure 8: As the preparation to apply the CNN, the final image in Fig.4 is converted to the coordinates of (r, θ).

Now we have 2000 images such as the right figure in Fig.8 for both incident gamma rays and electrons. Each 1000 images for both them were used as the data for learning of CNN and the rest images were used to investigate the discrimination ability as the test data. The CNN was carried out in use of MATLAB[8]. The number of layers for the convolution and the pooling are 3 and 2, respectively. As the results, Correct discrimination was achieved in 95% of the 2000 test data.

Though we tried the CNN changing the parameters such as the number of layers and the number of epoch, the probability is almost stable. Then, the justification for the discrimination is generally good. However, the probability of recognizing a gamma ray as an electron was higher than the probability of mistakenly recognizing an electron as a gamma ray.

4. Conclusion and Future Works

Aiming at the development of the next-generation IACT's capable of discrimination between primary gamma rays and electrons, we have carried out the computer simulation assuming the detector capable of obtaining the information on the incident position with the number of photons, the incident direction, and the arrival time. Assuming the incident energy of 500 GeV and vertical injection, we have developed the method of the discrimination. In use of the filtering method, the "first Cherenkov photons" can be extracted for both primary electrons and gamma rays. Moreover, we have accomplished 95% as the probability of correct discrimination between electrons and gamma rays. Now we only have the simulation fixing the incident energy to 500 GeV and the incident direction to vertical. In near future, we will carry out the simulation changing the incident energy and direction. Since we will develop a photo-sensor with SiPMs detecting all four information, we will have the simulation by the Cherenkov telescope assuming the photo-sensor.

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