Study of longitudinal development of cosmic-ray induced air showers with LHAASO-WFCTA

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The Wide Field-of-view Cerenkov Telescope Array (WFCTA) is an important component of Large High Altitude Air Shower Observatory (LHAASO), which aims to measure the individual energy spectra of cosmic rays from ~30 TeV to a couple of EeV. The longitudinal development is one of the main tools to distinguish nuclei from each other. WFCTA is composed of 18 imaging air Cerenkov telescopes, each telescope has 32×32 pixels, covers a field of view$16^o\times16^o$ (each pixel corresponding to $0.5^o\times0.5^o$). The first telescope started in operation since February 2019, up to now, there are 18 telescopes in operation. Cerenkov photon detected by different pixels were generated at different height (or different traversed material). The distribution of dN/dθ (θ is the angle between the direction of Cerenkov photon and the direction of primary particle) is reconstructed from the image of WFCTA to study the longitudinal development of the shower (similar to dN/dX). In this paper, the dN/dθ reconstructing method and the preliminary result on the particle identification power based on this method will be shown.

Introduction and experiment:

The energy spectra of single element of Cosmic Rays (CRs) in the knee region is the key to understand the physics of knee[1]. For ground experiment, the longitudinal development of the shower (or dN/dX [2]) is one of the main tools to distinguish nuclei from each other.

LHAASO located in Haizishan, Sichuan province of China, is a hybrid experiment to detect cosmic rays. It has 18 Wide Field-of-view Cerenkov Telescopes, which are used to detect the image of Cerenkov/fluorescent radiation of Extensive Air Shower. LHAASO also has 78,000 m^2 water Cerenkov detector (WCDA), and 1 km^2 Array (KM2A). Both provide the core position and direction measurement. Theanalysis in this paper is based on the data collected by WFCTA and KM2A

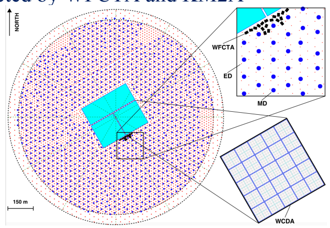

Figure 1:The layout of LHAASO experiment, WFCTA located at the center of KM2A array.

Monte Carlo simulation:

The simulations performed include the detailed air shower development in the atmosphere, as well as the response of the detectors of KM2A and WFCTA. Air showers were simulated with CORSIKA (v76400) . The QGSJETII and FLUKA model for hadronic interactions were used.

The secondary particles and Cerenkov photons reaching ground level are treated in a delicately developed detector simulation program. The program for KM2A is developed in the framework of Geant4 package, The program for WFCTA is developed based on ray tracing method.

The Method:

Detected by one telescope: a typical image of EAS detected by one telescope of WFCTA is shown in the left panel of Figure 2. The longitudinal development of the shower can be seen from the change of number of Cerenkov photons along the long axis of the image, however, the image is also affected by the viewing angle of the telescope. To study the longitudinal development with the same view angle. A virtual image from a virtual telescope is reconstructed. The direction of the virtual telescope is parallel with direction of the primary particle, while the position of the telescope stays the same.

For the signal of each SiPM from the real telescope, the direction of those photons are calculated. Then the detector simulation of the virtual telescope is performed for those photons. After those procedures, the image from the virtual telescope is obtained, which is shown in the right panel of Figure 2.

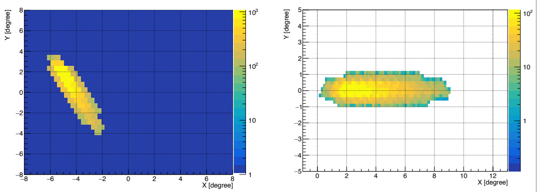

Figure 2: left: The image of Cerenkov photons detected by T1 of WFCTA; right: the image of the sameevent calculated for the virtual telescope, which points to the direction of the primary particle.

Detected by two telescopes: a typical event detected by two telescopes of WFCTA is shown in Figure 3. In Figure 3(a), part of the event is detected by telescope No. 1 (noted as T1 below, left) and T2 (right). After the same calculation procedures with the event detected by one telescope, the image from the virtual telescope is shown in Figure 3(b), the left one is the image from T1, the middle one is the image from T2, and the right one is the combined image from T1 and T2.

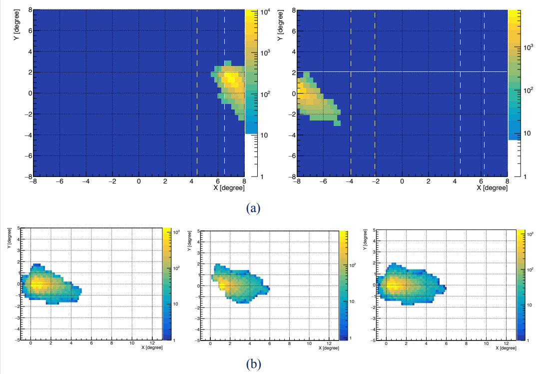

Figure 3: (a): The image of Cerenkov photons detected by T1 (left) and T2 (right) of WFCTA; (b): The image of the same event calculated for the virtual telescope, which points to the direction of the primary particle. Left: T1; middle: T2; right: T1 and T2 combined.

The longitudinal development: the projection of the combined image of the virtual telescope to the x-axis is shown in Figure 4, the left one is the event detected by single telescope, and the right one is the event detected by two telescopes. This distribution is defined as dN/dθ, where θ is the angle between the direction of Cerenkov photons and the direction of primary particle, N is the number of Cerenkov photons in the θ bin. Normally the longitudinal development function is refereed to dN/dX, where X is the atmosphere mass traversed. In principle, the θ angle is correlated with X, because different θ angle corresponding to different Cerenkov photon production height. However, based on MC simulation, it can be seen that the relationship between θ and X is also affected by other variables, for example, the mass of the primary particle. So in this paper, the new distribution of dN/dθ is used to study the longitudinal development of the shower, instead of dN/dX.

In this paper, the convolution of Gaussian function and the function of $e^{-k\theta^{\alpha}}$ is reconstructed (equation 1) to fit the data of dN/dθ. The fitting result for the same two events is also shown in Figure 4.

$$f(\theta) = Ne^{-\frac{(\theta-\mu)^2}{2\sigma^2}} \otimes e^{-k\theta^{\alpha}} \qquad (1)$$

The key parameter from equation 1 is the θ at which the dN/dθ reaches maximum (noted as θmax below), θmax will be used to do the particle identification between different nuclei.

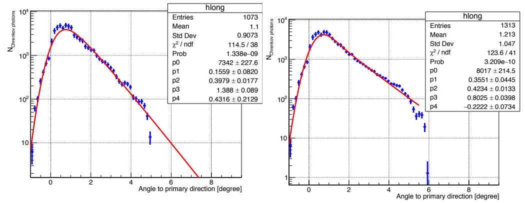

Figure 4: The distribution of dN/dθ for the two events of cosmic ray data, red line is the fitted function of equation 1. Left: the event fully detected by single telescope; right: the event detected by two telescopes, and the images are combined together.

Result:

The same procedures are performed for the MC samples, to study the particle identification power. Preliminary result of the distribution of θmax for proton and iron MC samples at around 1 PeV is shown in Figure 5.

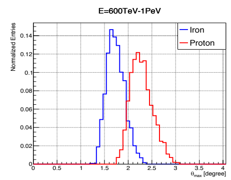

Figure 5: Preliminary result on the distribution of θmax for proton (red) and iron (blue) MC samples in the energy range from 600 TeV to 1 PeV.

Refenence:

[1] B. Bartoli et al., PHYSICAL REVIEW D 92, 092005 (2015)
[2] T. K. Gaisser, A. M. Hillas, Proc. 15th ICRC 8, 353 (1977)