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Study of the trigger mode of LHAASO-KM2A

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ABSTRACT

The Large High Altitude Air Shower Observatory (LHAASO), built 4410 m a.s.l. near Daocheng, in the Sichuan province of China, is a new-generation complex EAS array. The Square Kilometre Array (KM2A), one of LHAASO's three detector arrays, is composed of 5195 electromagnetic particle detectors and 1171 muon detectors, which are distributed in an area of 1.3 km^2. A lower trigger threshold would increase the number of low-energy showers detected, although this would also import many noise events because of the numerous KM2A detectors. In this work, the KM2A trigger logic adopted a software trigger system. A toy simulation was developed to estimate the chance coincidence rate of noise hits. Taking into account the characteristics of real cosmic ray shower events, the trigger logic was investigated by adjusting the space and time windows simultaneously using the detector simulation sample. In order to improve trigger efficiency and reduce the effect of noise, an optimized trigger criterion was achieved. The KM2A threshold energy can be reduced to 5 TeV. The performance of KM2A with this trigger criterion is presented. The expectation on observation of sun shadow and cosmic ray large-scale anisotropy are also shown.

1. Introduction

Cosmic rays, spanning a very large range of energies from 1 MeV to 100 EeV, are the most energetic particles in the universe. They consist mainly of charged nuclei that can be deflected by the galactic magnetic field during propagation from their sources to detectors on Earth. This makes it difficult to identify the original sources, even though the cosmic rays with energy up to 10^{15} eV are believed to originate from galactic compact objects, e.g., supernova remnants. One of the main goals of cosmic ray physics is to identify the sources of high-energy cosmic particles.

Neutral high-energy gamma rays, produced by collisions between cosmic ray hadrons and ambient media, are important probes to detect the "smoking gun" of cosmic ray origination. Up to now, more than 3000 GeV gamma-ray sources have been detected by the satellite-based detector Fermi-LAT [1], and more than 190 very high energy (VHE) gamma-ray sources have been observed by ground-based detectors.[1] One of the important types of ground-based detector arrays is composed of imaging atmospheric Cherenkov telescopes (IACTs), such as H.E.S.S., MAGIC, and VERITAS. The other is the extensive air shower (EAS) arrays such as Milagro, ARGO-YBJ, and HAWC. Most of these gamma-ray sources can be naturally interpreted as the inverse Compton emission of high-energy electrons in the interstellar radiation field [2]. The corresponding synchrotron radiation of the electrons have been widely detected in the X-ray and radio wave bands. Because of the energy limitations of electron emission, gamma rays near 100 TeV are important for diagnosing hadronic origination [3], which is rarely explored by current ground-based detectors.

The Large High Altitude Air Shower Observatory (LHAASO) project [4,5] is a complex EAS array that is built at Haizi Mountain (4410 m a.s.l.) in Sichuan province, China. One of the most important science motivations is to extend the current VHE gamma-ray observation from approximately 20 TeV to approximately 100 TeV; this is implemented by the Square Kilometre Array (KM2A), a sub-array of LHAASO. In addition to gamma-ray astronomy, KM2A will also be devoted to studying a wide range of fundamental issues in cosmic ray and astroparticle physics, such as the energy spectrum of individual cosmic ray elements, large-scale cosmic ray anisotropy, and solar physics.

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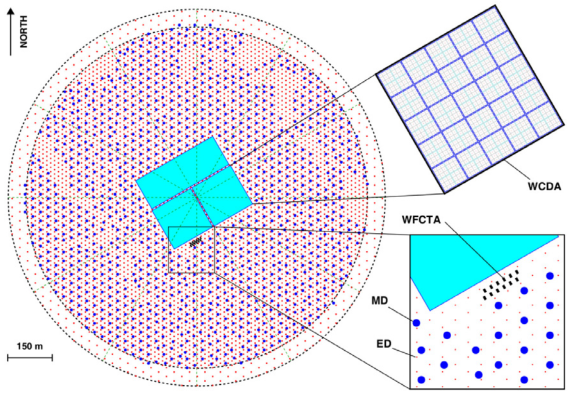

Fig. 1. Layout of LHAASO detectors.

In the past and current EAS arrays, the trigger logic is usually implemented in electronic hardware on the basis of the arrival time of hits and the detector multiplicity, e.g., ARGO-YBJ [6], Milagro[7], and HAWC [8]. The trigger threshold is determined by the noise rate of the detector unit and trigger time window, and is limited by the capability of the electronics in the data acquisition (DAQ) system. For example, the trigger threshold of HAWC is set to approximately 70 PMTs to limit the data rate to 40–60 MB/s, which the baseline the electronics can manage [8]. The trigger system of KM2A fully adopts a software trigger system. This will allow complex trigger logic using space-time information to select events as low-energy as possible, on the basis of shower topology.

An EAS contains many secondary particles that can fire multiple detectors (one fire is denoted as one “hit” in the following text) in a short time period. At the same time, one detector can also be fired by random signal particles, and multiple detectors have a certain possibility to be fired coincidentally in a short period (this is denoted as a “noise event” in the following text). KM2A is composed of more than 5000 electromagnetic particle detectors, which will import many noise events. Therefore, trigger logic is needed to reject noise events and select real EAS events. The study of the KM2A trigger mode is essential for its physical aims. Good trigger logic can help us improve the sensitivity of LHAASO on sun shadow and cosmic ray anisotropy at energies of 5–20 TeV. We discuss this further in Section 5.

2. The KM2A detector and simulation

2.1. The KM2A detector

LHAASO is a major instrument for VHE gamma-ray astronomy and cosmic ray physics. It is a complex EAS array and consists of three sub-arrays: KM2A, the 78,000 m^2 Water Cherenkov Detector Array (WCDA), and the Wide-Field Air Cherenkov Telescope Array (WFCTA). The layout of LHAASO detectors is shown in Fig. 1. WCDA is mainly designed for gamma-ray astronomy in the energy range of 0.1 - 20 TeV, and KM2A for energy above 20 TeV. WFCTA is designed mainly for cosmic ray physics.

As the major array of LHAASO, KM2A contains 5195 electromagnetic particle detectors (EDs) and 1171 muon detectors (MDs). The EDs, each with an area of 1 m^2, are arranged on a triangular grid of 15-m spacing, covering an area of 1 km^2 in the central region. The spacing is enlarged to 30 m in the surrounding region, which extends the whole KM2A area to approximately 1.3 km^2. Each ED consists of 4 plastic scintillation tiles covered by a 0.5-cm-thick lead plate to convert the gamma rays to electron-positron pairs and improve the angular resolution of the array. The EDs detect mainly the electromagnetic particles in the shower, which are used to reconstruct the primary direction, core location, and energy. In the present study, only the EDs were taken into account in the trigger logic. To test the KM2A design, a prototype engineering array of approximately 1% of KM2A was constructed at Yangbajing, Tibet, China [9]. The resulting ED performance fully met the design requirements. More details regarding the ED and its performance can be found elsewhere [10,11]. According to the engineering array result, the noise rate is approximately 2 kHz for each ED.

The MDs, each with an area of 36 m^2, are arranged on a triangular grid of 30-m spacing in the central 1-km^2 region. Each MD includes a cylindrical water tank with a diameter of 6.8 m and a height of 1.2 m. The tank is buried under 2.5 m of soil to shield electromagnetic particles in the shower. The MDs are used mainly to detect the muonic component of showers, which is used to discriminate between gamma and hadron. Two prototype MDs were constructed in the engineering array in 2012 and 2014, respectively. More details about the MD and its performance can be found elsewhere [12]. According to the prototype MD result, the noise rate is 6 kHz.

2.2. Detector simulation

The EAS process was simulated by CORSIKA [13] version 7.4005, with an $E^{-2.0}$ spectrum from 1 TeV to 1 PeV. The zenith angles were sampled within $0^\circ - 60^\circ$. The cores were sampled within a large enough circular area with a radius of 1000 m centred on KM2A. For detector response, the parameterized method presented in [14] was adopted here. That is, the single ED and MD detectors were simulated by GEANT4 [15] individually at first. Then, a look-up table was made to parameterize the number of generated particles corresponding to different injected particles. One particle is parameterized to photo-electrons and is sampled with a Landau distribution according to the real signal recorded by the KM2A engineering array [9]. In addition to these, random noises from a single secondary cosmic ray in the EDs and MDs were also taken into account with noise rates of 2 kHz and 6 kHz for the ED and MD, respectively. Finally, these signals were digitized to hits according to the electronic performance used in the KM2A engineering array. For the ED, the time resolution was set to 2 ns with a dead time of 8 ns [16] for each hit. For the MD, the time resolution was set to 10 ns with a dead time of 600 ns.

3. Method

When a VHE gamma ray (or cosmic ray nucleus) enters the atmosphere, it interacts with atmospheric nuclei, inducing electromagnetic cascades (or hadron cascades). Because the particles in the EAS are ultra-relativistic and the dominant physical processes are sharply peaked forward, the EAS arrives at ground level in a thin front only a few metres thick. The lateral extent of the showers is in the hundreds of metres. The lateral and time distributions are shown in Fig. 2, which shows that the particle density is significantly correlated with the distance to the shower core.

In past EAS arrays, the trigger logic was usually implemented using the arrival time of secondary particles; for example, the ARGO-YBJ requires the number of fired detectors to be at least 20 within 420 ns [17]. The detector area of KM2A is much larger than that of ARGO-YBJ. Many noise events would be reserved if we only used the trigger logic that consisted of a simple multiplicity count of the number of fired EDs. In fact, the extension of showers with primary energy around 20 TeV (see Fig. 2) is smaller than the area of KM2A. Different from previous cosmic ray experiments, the DAQ of LHAASO is designed to collect all the data of detectors and then a software is used to implement the trigger logic. More details about this system can be found in [18]. This software trigger system will allow a complex trigger logics. Therefore, in addition