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Methods to filter out high rate noises for the LHAASO-WCDA project

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For the LHAASO collaboration

The Large High Altitude Air Shower Observatory (LHAASO) will be constructed at Mt. Haizi in Sichuan Province, China. Among several detector components of the LHAASO, the Water Cherencove Detector Array (WCDA) is of great importance for low-to-middle energy gamma ray physics. The WCDA, consisting of 4 ponds, covering an area of $90,000\ \mathrm{m}^2$ in total, is sub-divided into 3600 cells by curtains, with a PMT resided in each cell. As located at 4400 m a.s.l. and $25\ \mathrm{m}^2$ area governed by each PMT, the single rate of a PMT can reach as high as 35–45 kHz, bringing a big challange for data storing and event reconstruction. In this paper, a dedicated trigger scheme and a pre-reconstruction method aiming to deal with these high rate noises are introduced. These methods are tested with the Monte Carlo simulation data, showing a fair efficiency in filtering out noises, while most of the real shower signals are kept. This method is proposed to be applied in the future LHAASO-WCDA project, put in a stage of the online processing just after the data are acquired.

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1. Introduction

In high energy astrophysics study, Gamma rays have an advantage over other charged particles because of its electric neutrality. Therefore, as a messager, gamma rays can provide more information about their original source as they are not deflected by interplanetary magnetic field and their direction of movement keeps unchanged. In experiment, the detection of Very-High-Energy (VHE, >100 GeV) cosmic gamma rays has been developed rapidly since the first detection of TeV gamma radiations from the Crab Nebula by the Whipple experiment in 1989 [1]. Generally, two kinds of detection means are often used, Imaging Air Cherenkov Telescopes (IACTs) and ground particle detector arrays. Each method has its own features. For instance, the latter has advantages such as wide-field of view and high duty cycle, so that it is more suitable in all sky survey for gamma ray sources. The Large High Altitude Air Shower Observatory (LHAASO) is such a composite ground particle detector array, which is to be constructed at Mt. Haizi in Sichuan Province, China. [2]. The LHAASO has 4 different kinds of sub-detectors, among which, water Cherenkov detector array (WCDA) [5] will focus on surveying the northern sky for steady and transient sources from 100 GeV to 30 TeV, with a very high background rejection power and a good angular resolution.

The WCDA consists of four water ponds whose size is 150 m $\times$ 150 m each, and the effective water depth is 4 m. Every water pond is divided into 900 cells with size 5 m $\times$ 5 m, partitioned by black plastic curtains to prevent penetration of the lights yielded in neighboring cells. Every cell has a photo-multiplier tube (PMT) whose size is 8-in or 9-in, positioned at the bottom to collect Cherenkov lights generated by charged secondary particles of extensive air showers.

One of the properties of the water Cherenkov technique is that, besides charged particles such as electrons, positrons and muons in an air shower, it can also detect gamma rays in a shower, which is around 10 times more in number than that of charged particles. High intenstity of low energy showers and majority of gamma rays in showers naturally brings high counting rate to PMTs. According to the prototype array of WCDA, the single counting rate of each cell can reach as high as 36 kHz [4] after subtracting the radioactive contribution, and around 40% of the rate is made up of single photo-electron (PE) signals. Cosmic muon signals, whose charge amplitude are widely distributed and centered at a level around 10 PEs, contribute part of the single counting rate as well. Taking the high altitude and 25 m^2 water area of each cell into account, the rate of these muon signals is estimated to be around 6–7 kHz. Figure 1 shows the charge distribution of some cells measured in the prototype array.

The high single counting rate and the muon signals with high amplitude would bring big trouble in the event build and event reconstruction. Many usual schemes for event trigger do not work, as spurious noise can form enormous fake events; some widely used methods for event reconstruction adopted in other air shower experiments are proved not efficient, as they are applied to deal with the WCDA simulation data. A set of proper online trigger and a pre-processing procedure are required. In order to achive this goal, a dedicated trigger scheme and an online filtering method is developed. They are to be introduced in this paper.

Section 2 of this paper will talk about the trigger scheme, which processes all the hits of the whole WCDA array of 3600 cells to form events. Section 3 will present how to further remove spurious noises in an event so that keep as clean as possible the shower hits.

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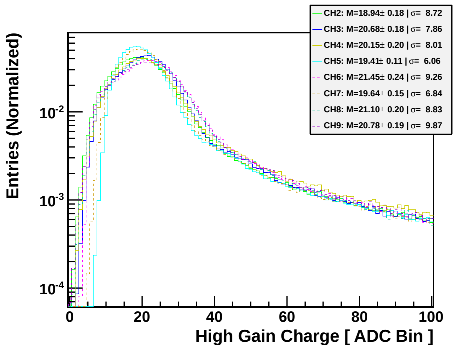

Figure 1: Charge distribution of the PMTs in the prototype array of WCDA. Only the charge signals of high gain channels are shown. The charge of a single PE signal amounts to 20 ADC counts, approximately.

2. Trigger scheme

Thanks to the accurate time synchronization protocol of the White Rabbit solution [3], the absolute time of every digitised hit of the WCDA cells is tagged, and then transmitted to a central counting room via fiber connections. A dedicated data acquiring (DAQ) system comprising of computing clusters is set up in the counting room, receiving and collecting all these hits. Those hits are split into time slices, sorted with the time information, awaiting further processing.

2.1 Scheme

Air shower particles usually concentrate a limited region around the shower core. Figure 2 shows the lateral distribution of an extensive air shower induced by an 1 TeV gamma. The left plot is the particle number distribution; The right one is the energy distribution, which somehow represents what the WCDA detector array can observe. What's all too evident to everyone is that the most shower particles and their energy distribute not far away from the center of the shower. As the numbers displayed in the figure, at least 23% of shower particles reside in a range of 30 m around the shower core, and at least 45% of the shower energy deposits in the same region. In other words, a certain area sized 60 m $\times$ 60 m should contain sufficient energy information of an shower to be detected by the WCDA array.

In the first, the whole array is subdivided logically into 81 half-overlapped trigger clusters, each of which consists of 144 cells, covering an area of 60 m $\times$ 60 m. Figure 3 is the graphical representation of the partition of the trigger clusters.

Accordingly, the trigger scheme is designed just as the following. When a PMT is fired (namely, L0 trigger from the Front-End electronics), it will output a steady signal with a normalized amplitude lasting for 250 ns. If another L0 trigger signal for the same PMT arrives, no matter during the 250 ns period or not, the signal is regarded as a new one, thus a new steady signal is produced. All of the PMT signals are processed in this way. After that, all the PMT signals in every trigger cluster are counted and summed in the falling edge of a pipeline clock of 25 ns. In any trigger cluster, if the sum of signals falls just after a rising edge, and the value of it exceeds 12, the trigger cluster and even the whole array is set to be triggered (L1 trigger), though an event

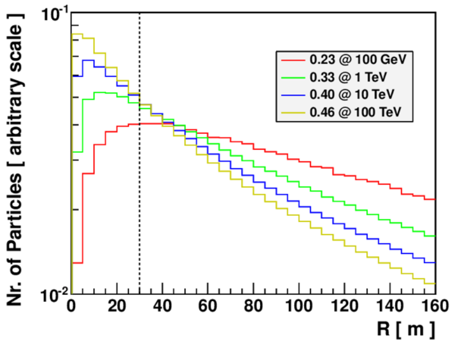

Figure 2: Lateral distribution of an extensive air shower initiated by an 1 TeV gamma. The left plot is the distribution of number of particles, and the right one is the distribution of the sum energy of particles.

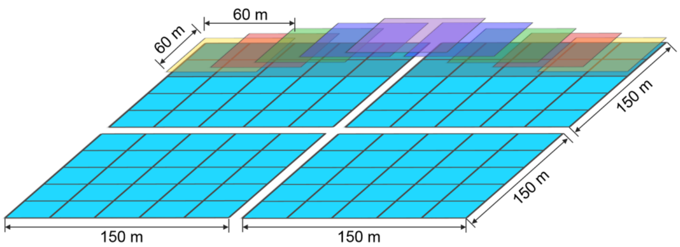

Figure 3: The partition scheme of the overlapped trigger clusters.

is formed. The trigger time of the event is just set to this falling edge, and all the hits in a time window of 2000 ns around the trigger time is stored into the event.

Note all above procedure is actually realized in a mimic way with a software program to be carried out on the DAQ computing clusters. In this sense, it is a “triggerless” scheme.

2.2 Outcome

With this L1 trigger procedure, the fake event rate due to spurious noise hits can be lowered to a level of <3 kHz. Based on an air shower and detector simulation, the trigger rate of the shower events is estimated to be 70 kHz. Further simulation results show that, with this scheme, more than 95% of the shower events with hit multiplicity ≥30 and shower core inside the array can be reserved as trigger events.

3. Online filtering

Just mentioned above, the reconstruction efficiency with a usual method declines rapidly when the real single counting noises present. A noise filtering method is to be developed. Furthermore, in order to reduce the network workload of data transmission from the experimental site to a computer center in a long distance away, the filtering method is demanded to be performed on online computers.

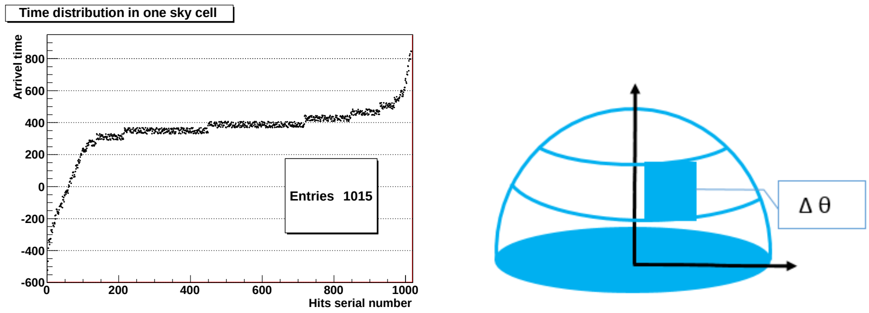

Figure 4: The left plot is the arrival time distribution of particles in one sky cell sorted in increasing sequences, y axis is arrival time, x axis is hits serial number; the right one shows the way of sky cell division.

3.1 Algorithm

The time information of each hit is the crucial parameter to reconstruct a shower. The hits from a common air shower usually distribute around the shower front, which is thin but dense in the middle, and thick but sparse in the edge. In reality the shower front is a curvature rather than a plane. But at the first step of analysis, for simplicity, an approximation of a plane is usually used. This simplification is enough good for the pre-reconstruction as described below, especially for the hits near the shower core region.

A fast iteration algorithm for all sky directions are developed here. The basic idea is to divide the whole visible sky (zenith angle from 0° to 70°) into many cells. First we define the number of equal Zenith bins in the visible sky, denoted with N_θ, and then we define the Azimuth slices. These sky cells are better in equal-sized solid angles so that no bias can be brought. Out of this consideration, once the bin size of Zenith angle $\Delta\theta = 70^\circ/N_\theta$ is chosen, the bin size of Azimuth angle is just set to $\Delta\theta/\sin\theta$. Next, these sky cells are scanned iteratively to check whether enough hits are contained in a plane perpendicular to a particular sky cell.

As to every sky cell, the time of all the hits in the event are rotated to the shower plane via a tranformation operation. After that, the hits are sorted based on their new time, from small to big. In general, the signals will manifest as a flat trend in the time distribution, as shown as the right plot in figure 4. The time gap between every two consecutive hits are calculated. If the gap is smaller than some times (X_σ) of the standard deviation of the time difference of the two hits, we regard that they may come from a same shower plane. Here the error of a hit time is evaluated from the a simulation for single secondary particles, including the effects of detector, electronics, the signal size, and the statistical representation of injecting positions and directions. If there are many consecutive hits all satisify the criteria one by one — that means there is no any break among these hits, we record the number of these hits $M(\theta,\phi)$, and also the total standard deviation $\sigma(\theta,\phi)$.

Iterating all the sky cells, and comparing the $M(\theta,\phi)$, the sky cell with the maximum M is chosen. If there are two or more sky cells having the same M, the σ is then compared, only the smallest one is kept. The sky cell remained is regarded as the most probable shower direction.

These consecutive hits for this most probable shower direction are fitted, and a further several round of dropping and picking procedures to all hits are performed, finally the fitted shower direction is obtained. The fitting results of a simulated shower event is displayed in figure 5. From it we can see that most of the hits from the shower is salvaged in spite of huge amount of noise hits in

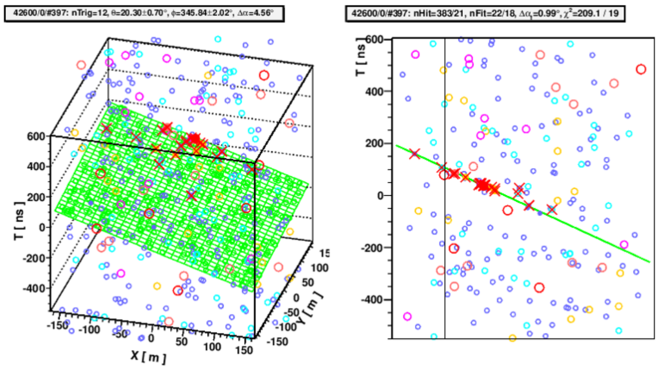

Figure 5: The plane fit of an air shower event, obtained with the fast iteration method.

the event.

During this procedure, there are two main variables. One is called N_θ which is responsible for numbers of sky cells, the other is X_σ which is used to decide whether two hits is on the same shower plane. These two parameters can be tuned to get better results statistically. The X_σ depends upon the shower energy, which can be fixed by a relationship with number of hits. So actually finally there is only one tunable parameter, N_θ, remained in the procedure. This paramter represents the number of sky cells, relating very much to the speed of the procedure. In order to achieve a rather fast speed, it shall be chosen as small as possible. But a over small value may cause either the fitting failure, or the reconstructed direction wrong. A careful treatment is very essential for a good implementation of the algorithm.

3.2 Efficiency and speed

The efficiency of this procedure for different N_θ is evaluated, as shown in figure 6. Different line style and color represents different N_θ. It shows that the events with internal shower core (the left plot) can achieve a very high efficiency; but it is not so good for all the events without core restriction (the right plot). The reason is that the shower with core outside the array are not possible to have the precise direction reconstructed as the curvature feature of the shower front; even other procedures can not easily overcome this difficulty - the phenomemon is quite general.

A further step to check the procedure is to evaluate the speed and the efficiency after a narrow time window ($\pm$100 ns around the fitted shower plane) is applied to all the hits. The latter is for the purpose of shrinking extensively the size of the raw data for a feasible transmission and storage, as the noise hits in the original 2000 ns time window can be reduced to a level of 10% with this cut. Very preliminary results are shown in figure 7. From these plots we can see that a selection of parameter $N_\theta = 20$ seems to be the minimum requirement. But more optimization of the procedure is still possible, we look forward to a more reliable speed of the process, and a better efficiency to keep more shower hits in the narrow time window.

4. Conclusion

LHAASO-WCDA is a new experiment is to be built in next 4 years. Due to its large scale,

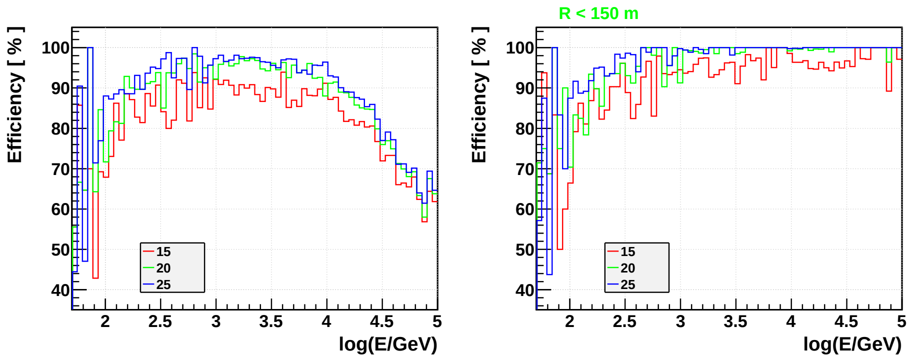

Figure 6: Reconstruction efficiency using the fast iteration method. Different color represents different value of parameter N_θ.

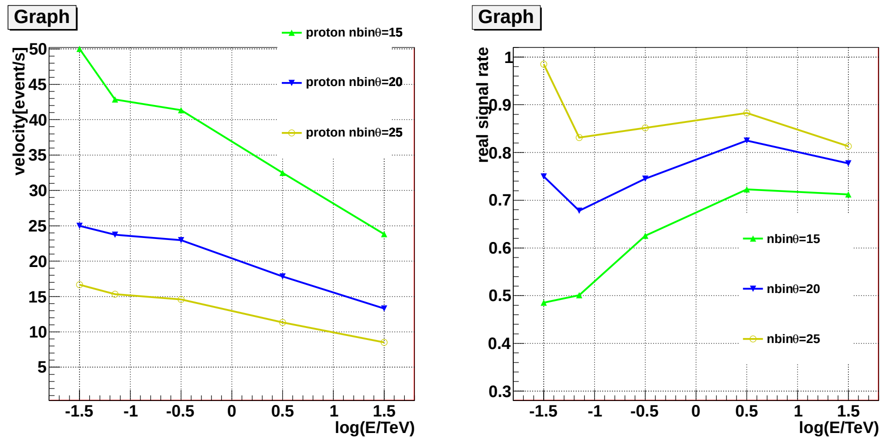

Figure 7: The speed and the efficiency of the procedure. As to the efficiency plot (left), the ratio is defined as the events with more than 85% of hits from the shower is remained in the narrowed 200 ns window.

extrodinary high single counting rate and cosmic muon influence, the event build and event reconstruction turns much different from other on-going experiments. Thanks to the triggerless design and the strong online processing power, a novel trigger scheme and an online pre-reconstruction algorithm is developed. Tested with the simulation data, the results show that the procedures are quite promising and reliable in performance. Nevertheless these procedures are still in the way of fine tuning and optimising, thus some improvements are expected in the near future.

These methods are proposed to be applied in the future LHAASO-WCDA project.

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