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Measuring Charge Efficiency of Large PMTs in LHAASO-WCDA using Shower Muons that Hit Small PMTs

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The Water Cerenkov Detector Array (WCDA) is a component of the Large High Altitude Air Shower Observatory (LHAASO), comprising 3,120 cells, each equipped with a large PMT (8" for pool1 and 20" for pool2 and pool3) and a small PMT (1.5" for pool1 and 3" for pool2 and pool3). The large PMTs are used to measure the time and charge of secondary particles produced by extensive air showers (EAS), while the small PMTs extend the measurement range of charge. As the performance of these PMTs varies from one to another and changes over time, it is crucial to measure their performance in real-time. In this report, we present a method that uses single muons from air showers itself to measure the charge efficiency of large PMT. To do so, we select shower muons that hit in the vicinity of small PMTs, whose position and direction can be predicted, to study the response of large PMTs. By simulating the charge that the muon would produce on the large PMTs in the same cell, based on its position and direction, we can calculate the charge efficiency of the large PMTs. We found that the measurement efficiency is consistent with the lab sample, and that the average charge spectra of large PMTs from simulations and data agree within a 10% uncertainty. Using this method, we obtained an average efficiency, and will study the efficiency of individual large PMTs later.

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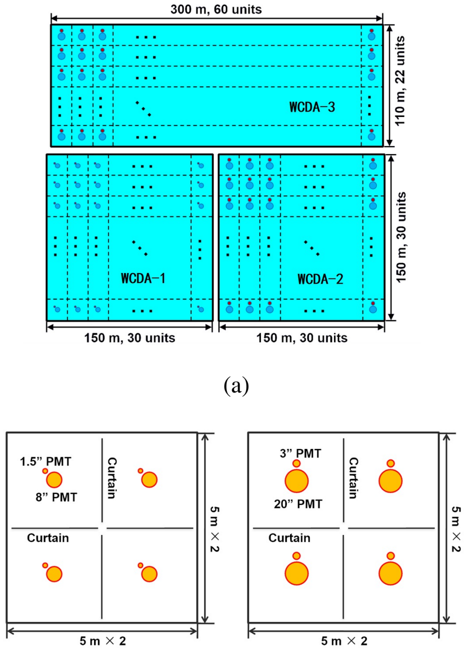
1. Introduction

LHAASO-WCDA is a ground-based experiment for very high energy gamma ray observation, which has continuously operating time and wide field of views, making it one of the most sensitive TeV energy air shower detectors in the world. It is located at an altitude of 4410m, on the Mt. Haizi (29°21’27.6" N, 100°08’19.6" E), in Daocheng, Sichuan Province, China. The WCDA covers an area of 78,000 m^2 and consists of three water pools, as shown in figure 1. WCDA-1 and WCDA-2 are square water pools with dimensions of 150m × 150m, while the WCDA-3 pool has dimensions of 300m × 110m. Each pool is divided into 5m × 5m cells, with a total of 3120 cells. Cells are separated by curtains to avoid the photon signals from one cell interfering others. Each cell contains a large PMT and a nearby small PMT to expand the dynamic range of charge measurements. For the type of large PMT, Hamamatsu CRS-365 PMTs(8" diameter) serve in WCDA-1, while NNVT GDB-6203 PMTs(20" diameter) are used in the WCDA-2 and WCDA-3. On the other hand, HZC XP-3960 (1.5" diameter) PMTs are used as small PMTs in WCDA-1, and HZC XP-72B22 (3" diameter) PMTs are used in the other two pools. The detailed information about the PMTs in LHAASO-WCDA can be find in reference[1]. With two PMTs in each cell, we are able to measure the charge of secondary particles with a range of 1 to 10^6 photon electrons (Pe).



(a)

(b) (c)

Figure 1: (a) A sketch map for WCDA.The blue points represent for large PMTs and red points show the position of small PMTs. (b) Sketch map of cells in WCDA-1. (c) Sketch map of cells in WCDA-2 and WCDA-3.

Charge signals represent the amount of photons that are detected by PMT. Deviations in the charge between data and simulation can result in significant errors, especially for energy reconstruction and estimation of effective area. However, the performance of each PMT in the array varies and changes over time. In the simulation of WCDA, an important factor that have to be taken into account is the non-uniformity of PMT photon-cathode surface, which will affect the simulation of PMT charge response. If we have a robust method to measure the surface efficiency of PMTs, the system error of WCDA will be well reduced. Considering the structure of LHAASO-WCDA, we propose a novel real-time method for the PMT surface efficiency measurement.

Muons penetrate deep into the water and are more isolated in showers front compared to electromagnetic particles, making them easier to distinguish from other signals. Additionally, muons only undergo a few specific physical processes in water, such as Cerenkov radiation and ionization, which has been studied for a long time and can be calculated accurately. Thus, a natural idea has been proposed that getting the surface efficiency by comparing the pure muons from shower itself between data and simulation.

2. Method

We propose to use the charge of muons that have definite trajectory as a standard light source to measure the surface efficiency of PMTs. A problem is that a single line light source is obviously not precise enough to measure the efficiency of each position on the photo-cathode, so we study the PMT response to many different muon trajectories, and use the charge spectrum of the Cerenkov photon between MC and Data on the PMT surface to fit the surface efficiency.

Muons in showers usually are produced in the upper air when the primary particles are still very high, and therefore the incident direction of these muons are approximately the same as the primary particles[2]. Furthermore, small PMTs scarcely receive large charge signals due to their small photo-cathode area, and the large signals are very likely from nearby muons instead of electromagnetic signals. In other words, if we apply a higher charge threshold on small PMTs, we can select muons that hit in the vicinity of the small PMT. By using the reconstructed shower direction and the position of small PMTs, the muon trajectory can be completely determined. Through detailed simulation of the trajectory, we can measure the efficiency of PMT surface with considerable accuracy.

However, we still have a challenge that how to select these muons from so many secondary electromagnetic particles. To pick up the muons that satisfy our needs, here we choose selection criteria from aspects below:

- We need to ensure showers are good enough for correct direction reconstruction. This is fulfill by using the cut on the zenith angle of showers and the valid firing cells numbers (Nq05t30).The variable Nq05t30 is defined as the number of fire cells with charge greater than 5 Pe and time residual within ±30ns.
- It is crucial to verify that the muons are indeed in the shower front. This can be achieved by analyzing the time residual between the signal and the reconstructed shower front, thereby effectively filtering out most of the noise.
- Muons traverse through the water without significant absorption, making the condition of small PMT firing an effective method for muon selection. Moreover, if the charge recorded by the small PMT is sufficiently large, it strongly suggests the presence of a muon in close vicinity.

- Due to the discrete lateral distribution of muons in shower front, the proportion of muons increases in regions far away from the central of the showers. We choose the hits that far away from the EAS core to avoid pollution from electromagnetic particles.
- Muons trigger minimal cascade of showers in the air, resulting in their signals being isolated from those generated by electromagnetic particles in the shower front. This isolation enables the use of a cut criterion wherein none of the surrounding detection cells are on fire to select the muon.

The specific selection cuts are shown in sec 4. We use the shower simulation of Mk version to check these cuts that we do pick the muons out at a purity level of 70%, and specific results are shown in figure 2 (a). After all these selections, our standard light source can be finally obtained. The charges of these selected muons can be well simulated, and we can get the efficiency by comparing the charge in data and simulation.

3. Data and Simulation

We employ the Mk version of reconstructed data collected over a 30-day period in November 2021 to select muons. To simplify and speed up our analysis,We use WCDA-1 as an example to illustrate our method. The Mk version has been checked and used for a long time, which is a stable reconstruction version of WCDA at present. Here we choose the events that have best quality in direction reconstruction:

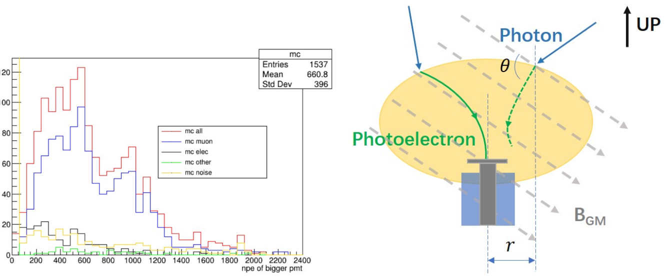
- $Nq05t30 \geq 100$
- Zenith Angle < 60°

As for the simulation of muons in water, we employ the Geant4-based LHAASO-WCDA simulation software, G4WCDA, version 4.3. Because the purity of muons picked from data is high enough, we replace the shower simulation with single muon simulations to speed up the simulation. The single muon simulations allow us to only focus on the response of a single cell in WCDA-1. Additionally, we confine the range of muons to hit within a 20 cm radius near the small PMT to increase its firing rate. In the simulation, we set the initial energy of muons according to the muon energy spectrum described in reference[3], with muon energies restricted between 0.1 GeV and 1 TeV. Furthermore, the simulated muons were generated within a zenith angle range of 0 to 60° and an azimuth angle range of 0 to 360°.

4. Analysis

We now apply the muon selection to the data mentioned in sec 3. The criteria are specified as follow :

- Distance to Shower Core > 40 m
- -30 ns < Residual Time < 30 ns



(a) (b)

Figure 2: (a) The charge distribution of hits selected from the shower simulation, using the selection cuts in 3. It shows the shape and proportion of the charge from different secondary particles, which proves the purity of muon selected by our method is about 72%. (b) Geomagnetic effect to the surface efficiency of a PMT. As the angle between the trajectory of the photo-electron and the direction of the Earth's magnetic field increases, the charge of PMT will decrease.

- Charge of Small PMT > 40 Pe
- Charge of large PMT > 20 Pe
- The four adjacent cells have no signals

For the charge results of simulated muons on large PMTs, we apply the same selection cuts to avoid the biases. Since showers selection is unnecessary in the simulation, selection cuts are simplified to the following:

- Charge of Small PMT > 40 Pe
- Charge of large PMT > 20 Pe
- The four adjacent cells have no signals

Muons with zenith angle larger than 40° may light up adjacent cells, so the isolation selection is also required for MC. After muon selection, we adjust the surface efficiency of the large PMT in the simulation to closely match the charge distributions with the data. Considering the varying charge responses of muons from different directions on the large PMT, we categorize the muons into groups based on their directions, with each group representing a 10° interval in zenith angle and azimuth angle. For each angle, the charge distribution from 0 to 1800Pe is normalized and composed into a histogram with one bin for every 30Pe, and we calculate the χ^2 value between the charge spectrum of simulation and data. The sum of χ^2 values in all 6×36 angle bins is used as the fitting loss function, as shown in Equation 1. The zen and azi in equation 1 is the sequence number of zenith group and azimuth group and the c is the sequence number of bins in a charge spectrum.N is the ratio of hits numbers in this charge bins to the total hits numbers at this angle, and σ is the statistic error of N difference between data and simulation.

$$\chi^2 = \sum_{zen}\sum_{azi}\sum_{c}\left(\frac{N_{data,zen,azi,c} - N_{mc,zen,azi,c}}{\sigma_{zen,azi,c}}\right)^2, \qquad zen = 0, 1 \ldots 5, azi = 0, 1, \ldots 35, c = 0, 30, \ldots 1800 \tag{1}$$

Considering that Cerenkov photons emitted by the muon that will hit on different areas of the PMT surface, we adjust the photo-cathode surface efficiency at different areas to maximize the agreement between the simulated and data charge spectrum at each angle. Apart from the original efficiency model of PMT surface, we need to consider the geomagnetic effects. The geomagnetic field severely influences the trajectory of photo-electrons, and has a complex effect to the PMT charge, as shown in figure 2 (b).

We can assume that the efficiency is only proportional to the $sin\theta$, and ignore the higher-order effects. The θ is the angle between the photo electron trajectory and the magnetic field.

The most obvious feature of surface efficiency is the edge effects. The edge effects of PMT refer to the decrease in efficiency near the equatorial plane of PMT due to manufacture and other factors, which has been confirmed through measurements in lab. With the efficiency and geomagnetic model, we can give a preliminary efficiency model by several parameters, which largely reduce the time of fitting. Specific efficiency model are shown in equation 2.

$$\varepsilon(\theta, r) = A \times (1 - b \times c^{r}) \times (1 - \alpha \times sin(\theta)) \tag{2}$$

In this equation, $\varepsilon(\theta, r)$ refer to the surface efficiency of PMT, and r refers to the distance between the surface position and the central axis of the PMT. The parameters to be fitted are as follows: A is the scale factor of the overall efficiency, b and c are the parameters used to fit the edge effect, and α is the proportion coefficient of the geomagnetic effect. This equation 2 is a simplified attempt to explain the surface efficiency, and we will study the PMT model in detail later. The fitting program nlopt is used to find the minimum value of the loss function.

5. Results

For each PMT in simulation, the $\varepsilon(\theta, r)$ is served as the surface efficiency. In the MC simulation, We add a process before the digital simulation part. When a photon hit on the PMT, its survival probability is decided by $\varepsilon(\theta, r)$. And the parameters in equation 2 are fitted and shown in Table 1.

Table 1: Fitting parameters of surface efficiency of WCDA-1.

Parameters	A	b	c	α
Fitting Results	1.060	5.255e-02	7.923	-0.481

The figure 3 shows the muon charge spectra between data and MC with and without the efficiency correction applied in some angles. The figure 4 shows the charge peak difference in all angle bins. With the surface efficiency, the simulated muon charge agrees better with the data at all angles. Next, we apply the surface efficiency of PMT to the shower simulation to see if the correction makes the simulation more consistent with the data. The effect of correction on the simulation of gamma rays is studied by comparing the data and simulation from crab, and the effect of correction on hadron cosmic rays is studied by comparing the data and simulation of cosmic rays.

For gamma observations, we use the method based on ref [4] to observe the crab. During the comparison, we focus on 2 representative parameters: $Nq05t30$, the maximum charge at core

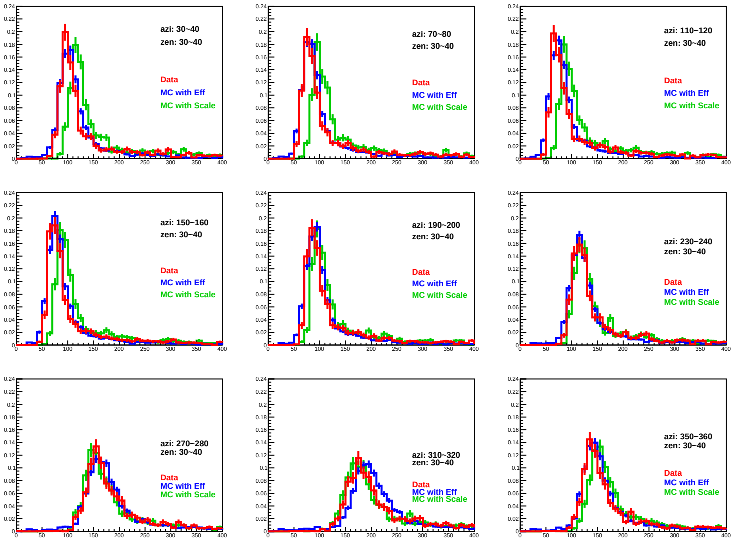


Figure 3: A simple comparison of muons charge in part of angles between data (blue lines) , MC with simple efficiency (scaling of 0.7) (green lines) and MC with surface efficiency (red lines).

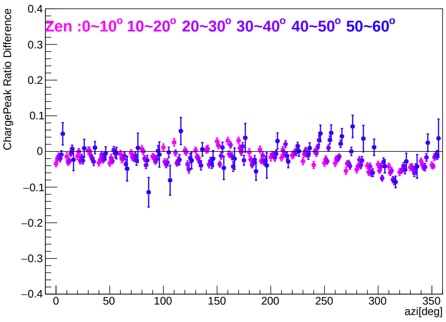
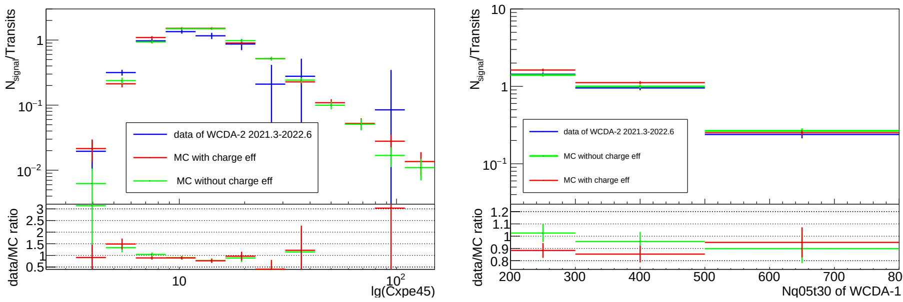
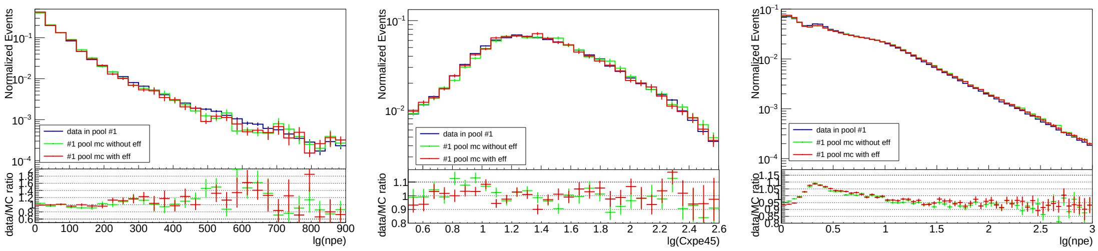


Figure 4: The difference of charge peak ratio between data and MC with surface efficiency in different angles. Muon charge peaks between MC and data at each angle can be reduced within 10%.



(a) (b)

Figure 5: Comparison between data and MC simulation of Crab using WCDA-1.(a) The maximum charge at core distances of 45m ($Cxpe45$) in WCDA-1 (b) the number of fire cells with charge greater than 5 Pe and time residual within ±30ns($Nq05t30$).



(a) (b) (c)

Figure 6: Comparison between data and MC simulation of cosmic rays using WCDA-1.(a)$Nq05t30$ in WCDA-1 (b)$Cxpe45$ in WCDA-1 (c) charge spectrum of WCDA-1.

distances of 45m ($Cxpe45$), respectively, for the purpose of data-simulation comparison. The comparison results are presented in the figure 5. The efficiency correction has little effect on $Nq05t30$, but improves the consistency in the distributions of $Cxpe45$.

Furthermore, we select cosmic ray data from November 1, 2021, for the data-simulation comparison of cosmic rays(in figure 6). The comparison includes the distribution of $Nq05t30$, $Cxpe45$, and the charge spectrum of cosmic rays, and the distribution results are all optimized.

6. Conclusion

We have developed a method that enable us to obtain the surface charge efficiency of large PMTs using muons that hit small PMTs. This method proves valid for serving as an effective means to verify the charge stability of LHAASO-WCDA. By applying the surface efficiency, the difference in muon charge peaks between simulation and data at each angle can be reduced to within a 10% margin, and this improvement enhances the agreement between data and simulation in both cosmic rays and gamma rays samples. In future, we plan to study the efficiency model precisely and use this method to monitor the PMT every month.

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