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The Cosmic Ray Spectrum of Light Component above 10TeV measured by LHAASO experiment

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One of main scientific goal of Large High Altitude Air Shower Observatory (LHAASO) is to measure individual cosmic ray spectra from 30 TeV to several EeV. The absolute energy scale obtained from the moon shadow measured by WCDA will be transferred to WFCTA at around 10 TeV. So it is important to measure the energy spectra of pure proton and proton&helium from 10 TeV to 100 TeV. The first and the second SiPM based Cherenkov telescopes of LHAASO have successfully put into operation in January and May 2019, respectively. The first water Cherenkov pool (150 $m \times 150$ m) of LHAASO (WCDA-1) also began operation in February. The combined detection of showers with WCDA-1 and Cherenkov telescopes enables LHAASO to improve the resolution of reconstructed energy, shower direction, shower core location and composition identification. The energy threshold of WFCTA is well below 10 TeV. The preliminary analysis results of the data are presented in the paper with comparison with the corresponding simulation of the air showers their detection by the telescopes.

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1. Introduction

The measurement of individual cosmic ray spectra is an important tool to investigate cosmic ray acceleration and propagation mechanisms. Experimental results, the "knees" of the proton is below 1 PeV or above 1 PeV are still unclear [1, 2]. This is caused by the lack of effective identification of individual composition and accurate absolute energy scale determination in the ground-based experiments. Large High Altitude Air Shower Observatory (LHAASO) [3, 4], located in Haizishan Daocheng, Sichuan province of China, is a hybrid experiment to detect cosmic rays. The height of LHAASO is 4410 m above sea level. LHAASO has 18 Wide Field-of-View Cherenkov Telescopes (WFCTA), 78,000 m^2 water Cherenkov detector (WCDA), and 1km^2 complex array (KM2A) including 5195 scintillator detectors and 1171 m^2 μ detectors. Using the depth of shower maximum, ratio of length to width of Cherenkov image, the number of μ, the number of particles in the shower core, cosmic ray single elements above 30 TeV can be separated from all particles.

One of main scientific goals of LHAASO is to achieve the consecutive measurement of single element energy spectrum from 30 TeV to several EeV. In order to achieve this goal, it is necessary for the telescope to make hybrid observations with WCDA in the energy region from 10 TeV to 100 TeV. In this stage, the absolute energy scale obtained from the moon shadow measured by WCDA will be transferred to WFCTA. The number of particles in the shower core and μ information measured by WCDA. Hillas parameters of Cherenkov image are composition sensitive parameters. WCDA can provide the geometric information of the air shower and the shower detector plane reconstructed by WFCTA can be used to improve the accuracy of shower core location and shower direction reconstruction. The accurate energy spectra of proton and helium from 10 TeV to 100 TeV can be obtained by using a multi parameter analysis. One water Cherenkov pool (150 $m \times 150$ m) of WCDA and two Cherenkov telescopes are running at LHAASO site now. The comparison of detections measured by WFCTA between data and simulation is presented in this paper.

2. Experiment

The first Cherenkov telescope has successfully put into operation at the end of January 2019 and the second Cherenkov telescope also puted into operation in May 2019. In this stage, two Cherenkov telescopes point to the zenith angle of 0° for low energy measurement. The first water Cherenkov pool of WCDA of LHAASO began operation in February. Two Cherenkov telescopes are put at the southwest corner of the pool (Fig. 2).

WCDA-1, seperated into 900 cells, has an area of 150 $m \times 150$ m. The size of each cell is 5 $m \times 5$ m with one 8 inches PMT plus one 1.5 inches PMT in each cell. The 1.5 inches PMT is put close to the eight-inch PMT to enhance the dynamic range of the detector. Each Cherenkov telescope [5] consists of an array of 32×32 light concentrators and Silicon photomultipliers (SiPMs), 1024 channels of readout electronics system and a spherical aluminized mirror with an area of 5 m^2. The field of view (FOV) of each Cherenkov telescope is $16^\circ \times 16^\circ$ and one pixel size is approximately $0.5^\circ \times 0.5^\circ$. The telescope is mounted on a dump-truck frame with a pitching rotation system. The portable design of the telescope can rearrange the telescope array easily for carrying out spectrum and composition measurements of cosmic rays in different energy ranges.

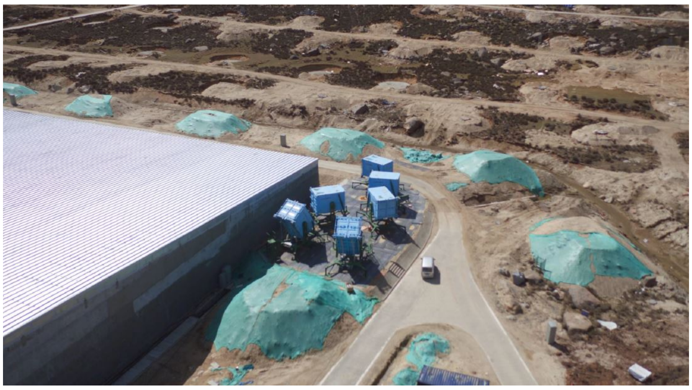


Figure 1: The layout of six Cherenkov telescopes is shown and two Cherenkov telescopes are working now. The Cherenkov telescopes are put at the southwest corner of the pool of WCDA.

3. Data Analysis and Results

3.1 Data

To understand the data well, we choose datas at four clear and no moon nights, 02 April 2019, 28 May 2019, 29 May 2019 and 30 May 2019. In these four days, 182,325 events were detected by the Cherenkov telescope and WCDA. The amount of cloud is monitored by an infrared cloud monitor. Fig. 2 shows the condition of cloud at 22:50 of 2019-05-28. The lower infrared bright temperature represents the fewer clouds. The red frame in the figure shows the field of view of the telescope. Datas at cloudy time are also exclusived. Besides, a further offline trigger was applied by WFCTA. Removing the sipms whose signal is less than 45 N_{pe} Table 1 shows the numbers of coincidence events detected by WFCTA and WCDA on condition of no clouds and without moon. After the clear weather selection, 153,880 coincidence events are left.

date	number of events	number of events without clouds
02 April 2019	3,853	3,853
28 May 2019	58,524	50,164
29 May 2019	49,870	49,025
30 May 2019	70,078	50,838
All	182,325	153,880

Table 1: The number of events detected by WCDA and WFCTA

A hybrid event is shown in Fig. 3. The Cherenkov image after clean is shown in Fig. 3(a). The red dotted line is the length direction of the image, which is the shower-detector plane. The shower direction and shower core location should be in the plane. The resolution of shower direction and core reconstructed by WCDA will be improved by using this plane. The Fig. 3(b) shows the trigger time of each cell in first Cherenkov pool of WCDA. It represents the arrival time of the shower and the arrival direction can be obtained by the fitting arrival time. The direction of coincidence events are almost vertical because Cherenkov telescopes point to the zenith angle of 0°. The azimuth angle can not be reconstructed well by WCDA for vertical events. The cross-point show in the image is the direction reconstructed by WCDA. The azimuth angle is freedom, which can be any

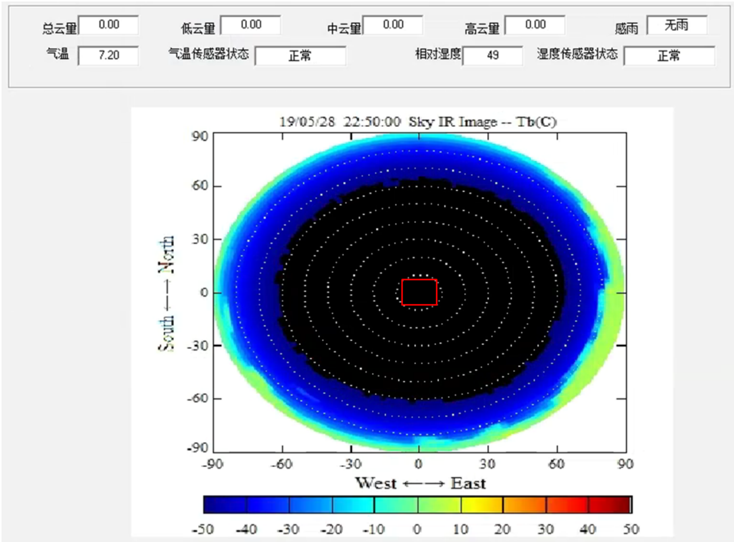


Figure 2: The bright temperature distribution measured by an infrared cloud monitor at 22:50 on 28 May 2019. The lower bright temperature represents the fewer clouds. The black color in the figure means bright temperature less than $-50°C$. The field of view of this monitor is zenith 0° to 90°, azimuth 0° to 360°. The contours in the figure represent different zenith. The zenith degree of the innermost circle is 10°, the outmost one is 90°. The red frame in the figure shows the field of view of the telescope.

value in the blue circle. Information from the Cherenkov image can help to improve the situation. The intersection of the blue circle and the red line represent the direction of the shower.

The Fig. 3(c) shows the number of photo-electrons (N_{pe}) measured by 8 inches PMT and the Fig. 3(d) shows the number of photo-electrons measured by 1.5 inches PMT. Their lateral distributions of N_{pe} is shown in Fig. 3(e). The whole event combined the N_{pe} of 8 inches PMT and the N_{pe} of 1.5 inches PMT is shown in Fig. 3(f). The shower core position can be obtained by centroid method. Information from the Cherenkov image can help to improve the resolution of the shower core. The core should be in the shower plane reconstructed by the Cherenkov telescope.

3.2 Simulation

The simulation of LHAASO-WFCTA can be divided into two steps. The first step is to simulate air showers initiated by cosmic rays by using CORSIKA program with version 74005 and the second step is to simulate the process of Cherenkov photons in the telescope. In the CORSIKA program, EGS4 model is chosen for electromagnetic process and QJSJET-II04 and FLUKA models are chosen for high and low energy hadronic process, respectively. Due to the telescopes of LHAASO-WFCTA at this stage is pointed to zenith, the energy threshold is about 10 TeV, so the events are sampled with energy range from 1 TeV to 500 TeV, index -1. Due to the FOV of the telescope is 16° × 16°, the events are sampled with zenith range from 0° to 13°, azimuth range from 0° to 360°. The cores of the events are sampled uniformly within 400 $m \times 400$ m. In this step, the absorption and scattering of Cherenkov photons in the atmosphere and the quantum efficiency of the SiPMs are considered. Five composition groups, proton, helium, CNO, MgAlSi and iron, are generated in order to study the ability to separate light nuclei from all particles.

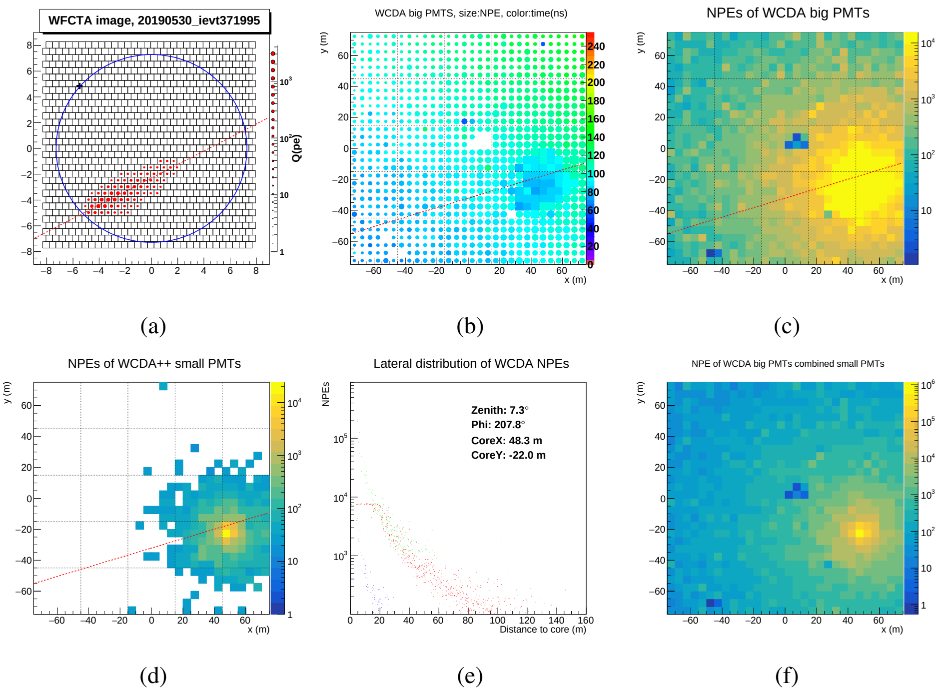


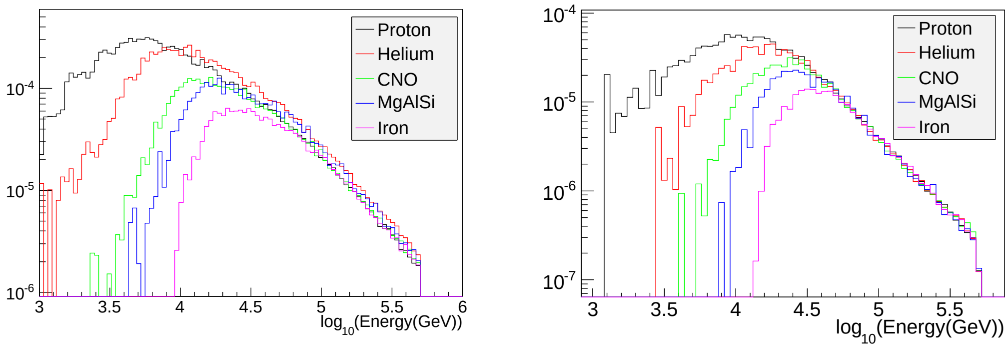
Figure 3: An exhibition of a hybrid event: (a) A Cherenkov image measured by the telescope. (b) The arrival timing map of an event detected by WCDA. (c) N_{pe} map measured by 8 inches PMTs of WCDA. (d) N_{pe} map measured by 1.5 inches PMTs of WCDA. (e) The lateral distributions of N_{pe} measured by WCDA. (f) N_{pe} map combined the signal of 8 inches PMTs and 1.5 inches PMTs. The blue circle in (a) is the zenith angle reconstructed by WCDA, and the black point on this circle is the shower direction reconstructed by WCDA. The red line in (a) represents the shower detector plane. The line in (b), (c) and (d) is the line cross the telescope and shower core reconstructed by WFCTA.

The second step is the simulation of LHAASO-WFCTA. In this step, the process of photons in the telescope, the roughness of reflecting mirrors, the filter, the winston cones, the SiPMs and trigger patterns are simulated. In order to reduce the energy threshold, considering compactness distribution of emission angular of Cherenkov photons, events with three adjacent triggered SiPMs are triggered. The trigger energy threshold of proton is about 7 TeV as shown in Fig. 4(a).

3.3 Analysis

Before analysis, image clean should be done firstly. In the process of image cleaning, only triggered SiPMs with 3 neighbors are saved. After image cleaning, collection efficiency of photons with different incident angles, the un-linearity of SiPMs are corrected and then the Hillas parameters are calculated.

Belowing selection criteria are used to make sure a full observation of the Cherenkov images. Firstly, the number of servived pixels after image cleaning should be more than 5, the centroid of the image should be less than 6°. The simulated energy spectrum are normalized to the index -2.7. The energy spectrum after event selection with the criteria discussed above for different composition groups are shown in Fig. 4(a). The peaks of the energy distributions after event selection show the analysis energy threshold of the telescope. According to the Fig. 4(b), the threshold energy for proton is about 10 TeV, while the threshold energy for iron is about 30 TeV.



(a)		(b)

Figure 4: (a) Energy distributions of thriggered events in simulation. (b) Energy distributions with the selection criteria for different composition groups. The peaks of the energy distributions show the energy threshold of the telescope.

The total photons named as *Size* in the image is a good energy estimator, but it is Rp dependent. Here Rp is for the perpendicular distance of telescope and shower core positions. In the hybrid observation, cores and the arriving directions of showers can be obtained by LHAASO-WCDA. The Rp resolution is about 3 m achieved by LHAASO-WCDA. After Rp correction, the energy resolution obtained by the *Size* is about 23% at 100TeV as shown in Fig. 5.

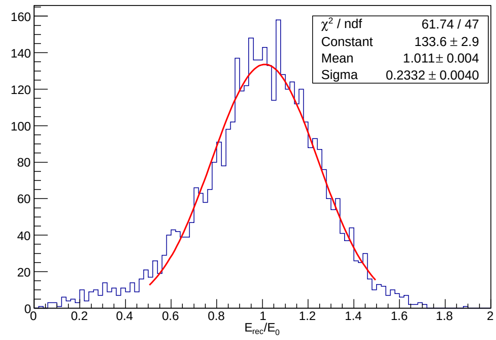


Figure 5: The energy resolution of the telescope at 100 TeV.

3.4 Data and Simulation Comparison

Datas on 28 May 2019 detected by WFCTA are chosen to compared with simulation. Image clean method is the same as simulation (Sec. 3.3): single trigger threshold of 45 pe and triggered SiPMs with 3 neighbors, isolated tube cleaning. The data selection criteria is that the Cherenkov image gravity center is less than 6°, the fired pixels after image cleaning is more than 5. The selection criteria is the same as simulation in Sec. 3.3. After the data selection, about 51,909 events are selected. The results of data and simulation comparison of total N_{pe} in Cherenkov image is shown in Fig. 6(a), number of fired tubes is shown in Fig. 6(b), length of Cherenkov image is shown in Fig. 6(c), and N_{pe} measured by single channel is shown in Fig. 6(d). The simulation is consistent with data in 10%. The simulation can also be used to study the coincidence events from the results of data and simulation comparison.

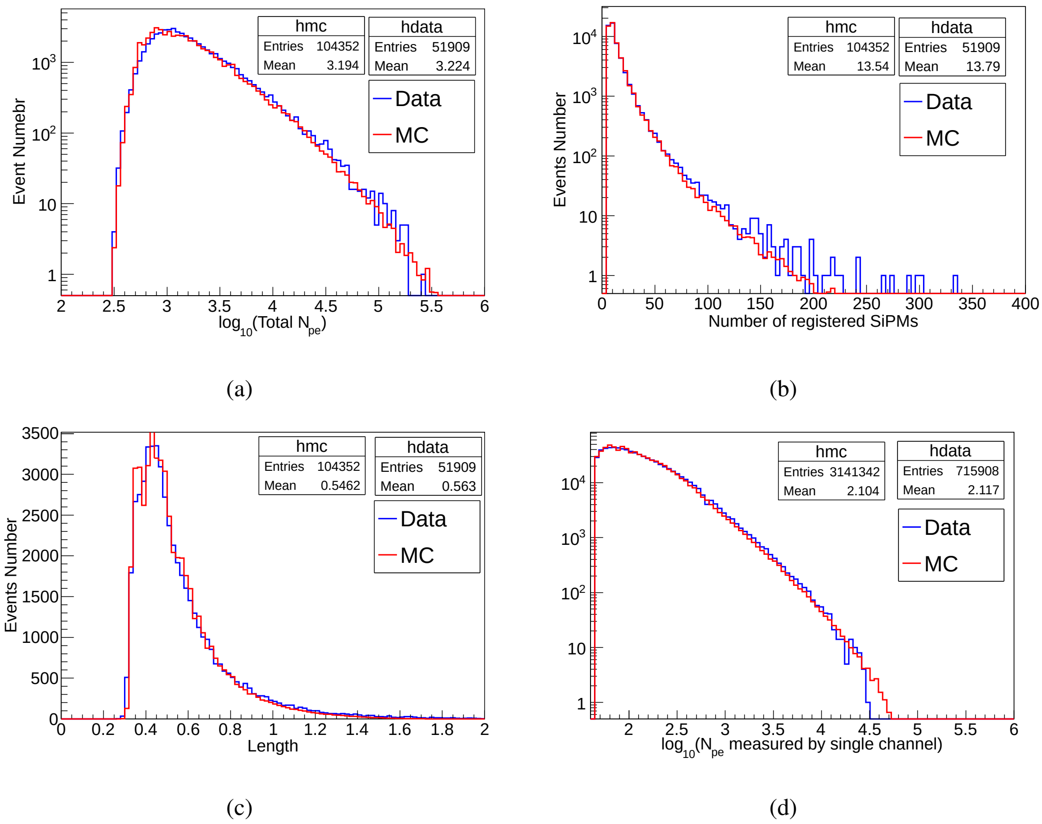


Figure 6: (a) Data and simulation comparison of total N_{pe} in Cherenkov image. (b) Data and simulation comparison of number of registered SiPMs. (c) Data and simulation comparison of length of Cherenkov image. (d) Data and simulation comparison of N_{pe} measured by single channel.

4. Conclusion and Discussion

Tow out of the 6 deployed Cherenkov telescopes beside the firstly built pond of 3 water Cherenkov detector arrays have been put in operation for scientific observation at LHAASO site. Among the four days selected in this paper, more than 180,000 events triggered both the telescopes and WCDA-1 have been collected within a coincident window of 20,000 ns. The geometrical reconstruction of those coincident events, shower arrival direction and core location, is expected to be further improved by combining the both measurements. This is still under development. The resolution of arrival direction is 0.3° and of core location is 2 m, by using WCDA-1 alone. According to the simulation of the air shower and the data, the distributions of number of registered pixels, N_{pe} in each pixel, the total N_{pe} in shower images and their elongation lengths reasonably agree with the data in the comparison. It is found that the threshold of WFCTA is well below 10

TeV. The energy scale is expected to be established by compare with the events of WDCA-1 which used in the moon shadow measurement overlapping in the range from few TeV to 30 TeV. The moon shadow measurement using WCDA-1 has been used to obtain the absolute energy scale by measuring the shifts of the shadows at different eneries, see the other LHAASO paper [6] in this proceedings. Part of Hillas parameters of the shower image measured by the telescopes and enrgy flux in the shower core and μ-content measured by WCDA-1 and MD array will be used in a multi parameter analysis algorithm to identify the single element from all showers. For the selected low contamination event set, the shower energy reconstruction is expected to be improved. This is under development as well. For the simulation events, the energy resolution is 23% around 100 TeV without the composition selection.

5. Acknowledgements

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