Hybrid measurement of CR energy spectrum and composition ≤ 200 TeV by using ARGO-YBJ and WFCTA

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Abstract: Two Wide Field of View Cherenkov Telescopes have been successfully running at YangBaJing Cosmic Ray Observatory near ARGO-YBJ experiment since 2008. With the information from the ARGO-YBJ experiment, the hybrid measurement of a shower is achieved by 2 different detectors. The energy spectra of individual composition below 100TeV has been measured accurately by the balloon borne calorimeter experiments such as CREEN and ATIC. In the paper, the energy spectrum of light component is presented. An absolute calibration of the energy scale for the ground based experiment will be established by comparing with the balloon borne experimental results.

Keywords: Cherenkov telescope, Energy spectrum, WFCTA.

1 Introduction

The energy spectrum of primary cosmic rays spans almost 12 orders of magnitude, from 10^9 eV to 10^{21} eV, and can be well described by a simple power law except for the situation in several small energy regions. One of these regions is the so called "knee" of the spectrum existing at around 10^{15} eV. Many experiments have observed this phenomenon; however, there still remain controversial arguments on its origin due to limited discrimination power on primary cosmic rays composition and ambiguities in nucleus-nucleus interaction modeling. The precise measurement of the energy spectrum and identification of the individual components of cosmic rays are essential to sort out the problem. Modern balloon borne experiments, such as CREAM [1] and ATIC [2], have measured the energy spectra of individual elements up to ∼100 TeV at the top of the atmosphere. Because the balloon borne detector area is constrained by the payload, the spectrum measurement should be extended to a higher energy by using a ground based air shower detector array. The spectrum should initially be measured well below 100 TeV to create an overlap with the balloon experiments, which could serve as absolute calibrations for the ground-based techniques. As one of main components of the Large High Altitude Air Shower Observatory (LHASSO) project [3, 4], Wide Field Cherenkov telescope array (WFCTA) also aims to solve the "knee" region problem.

Two prototype Cherenkov telescopes [5, 6] were deployed at Yangbaijing (YBJ) Cosmic Ray Observatory near the ARGO-YBJ experiment [7] in 2007 and started to run successfully in Cherenkov mode in August 2008. To date, millions of cosmic ray events that simultaneously trigger the telescopes and the ARGO-YBJ detector carpet array have been collected. Ground-based and full coverage ARGO-YBJ detector is good at shower geometry reconstruction and Cherenkov telescope can collect longitudinal Cherenkov emission light. Thanks to these two advantages, a good energy resolution is expected. Because of the merit of full coverage, sub-particles distribution around core position is well measured by ARGO-YBJ detector. The difference of the distribution between different primary particles is an important parameter to discriminate the composition. The information of Cherenkov image measured by Cherenkov telescope provides other important parameters, such as width parameter and length parameter. With the combination of the merits of two detectors, especially during a little lower energy region few tens of TeV, the energy spectrum measured by WFCT and ARGO-YBJ can be compared with balloon born experiments result, which can help us to understand the absolute resolution of primary energy.

The details of Two Wide Field Cherenkov Telescopes are described in Section 2. Data analysis procedure is discussed in Section 3, such as data selection and primary energy determination. The last section is the results and discussion.

2 Cherenkov Telescope

Two Cherenkov telescopes[6] are located at YBJ near ARGO-YBJ carpet detector array. The distance between two telescopes is about 50 m. One telescope is about 25 m away from the west side of the ARGO-YBJ array. The oth-

Figure 1: A photograph of the telescope with door open

er is also 25 m away from the south side. Each telescope has an filed of view (FOV) of 14° × 16°. A 4.7m^2 spherical aluminized mirror made of 20 hexagon-shape mirrors is used for each telescope. The focal plane camera is made of a 16 × 16 photomultiplier tube (PMT) array, and the pixel size is approximately 1°. The whole system including electronics system, DAQ system, slow control and monitoring system is installed in a shipping container with a dimension of 2.5 m×2.3 m×3 m, which is shown in fig.1. The container is mounted on a standard dump truck frame with a hydraulic lift elevation angle from 0° to 60°. It is easy to change the configuration of the telescope array for different observations under this portable design.

3 analysis

3.1 Monte Carlo simulation

A GEANT4-based simulation package (G4argo) is used for the ARGO-YBJ detector[8]; Cherenkov simulation tool[9] is used for WFCTA detector and Corsika (version 6735) for Cosmic ray shower generation. The comparison of the total number of photon electrons (Npe) between Monte Carlo simulation (MC) and data is showed in the fig.2; they match each other well. Other parameters, impact parameter, azimuth angle, zenith angle and so on, match each other well too.

3.2 Data selection

Two Cherenkov telescopes started to take cosmic ray events in August 2008. Up to April in 2011, after offline coincidence with ARGO-YBJ experiment, the total number of stereo events is about 509600; the total number of mono events is about 2520000. The stereo events are used to measure the energy spectrum in the paper. To get more precise and light component energy spectrum, the following procedures are applied to data selection.

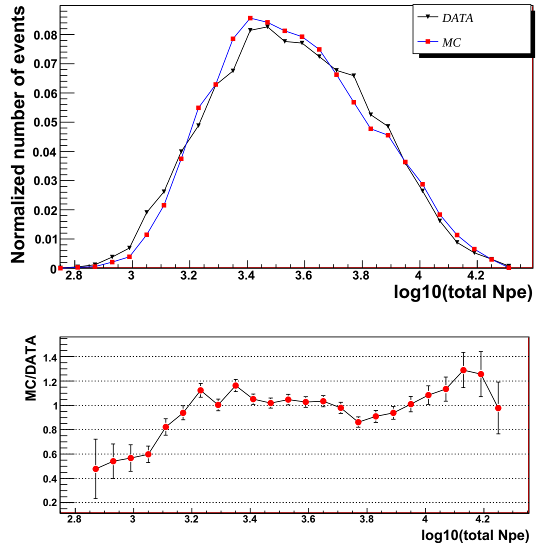

Figure 2: The total Npe of data (black) and MC (red) distribution is showed in the upon figure. Their comparison result is showed in the bottom figure.

3.2.1 Weather and Geometry selection

- Good weather selection: At present, a whole night clear observation day is used according to the everyday log file. After weather selection, about 180000 stereo events are left. Star light is a good standard light source to monitor weather condition, which is studied in the same ICRC proceeding[10]. The method can select the data by 20 minutes, so more accurate and clear data can be selected. This method will be applied into data selection before ICRC conference.

- Geometry selection: The shower core is located in ARGO-YBJ detector center array; the number of hit is greater than 1000 and space angle between shower direction and Cherenkov telescope center pointing is less than 3°. The Shower geometries information about coincident events can be got from ARGO-YBJ experiment. The core position resolution is better than 2 m and angle resolution is better than 0.3° when the shower core is located in the ARGO-YBJ center carpet and the number of hit is greater than 1000 [11]. To make sure that the full Cherenkov image is recorded by the Cherenkov telescope, the space angle should be less than 3°. After these geometry cuts, about 16282 stereo events are left.

3.2.2 Light component selection

Light component of cosmic ray induces a steeper and narrower lateral distribution than heavy component, which is well measured by ARGO-YBJ full coverage detector [12]. The parameter of density ratio, Λ=ρ(i)/ ρ(j), where ρ(i) and

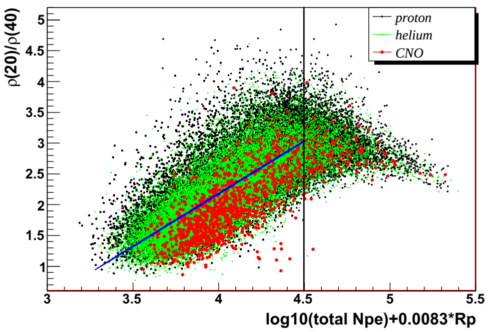

Figure 3: It is the relationship between the density ratio and the total Npe for three primary particles. The parameter of total Npe is normalized at Rp direction.

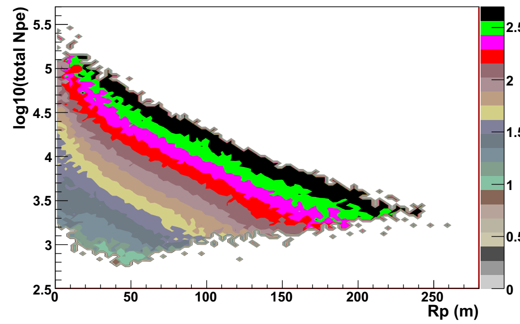

Figure 4: It is the relationship among the total Npe, the primary particle energy and Rp. The different color means different energy range

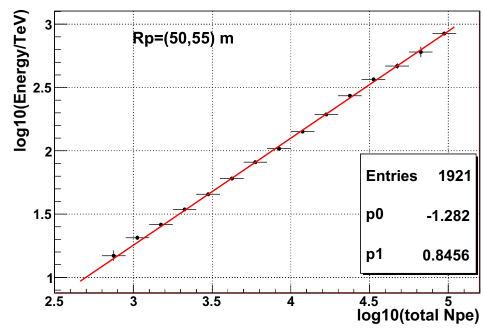

Figure 5: It is the relationship between the total Npe and the primary particle energy in a fix Rp range(50-55 m) (black dot). A linear fit is showed in a red line.

$\rho(j)$ are the average particle densities measured by ARGO-YBJ at two radial distances of i and j, is defined to describe the difference of lateral distribution between light component and heavy component. Λ is also a function of primary particle energy. The total Npe recorded by Cherenkov telescope is in proportion to primary particle energy, but the total Npe is reducing when impact distance (Rp) increases. Therefore, the normalization parameter ϵ=total Npe + 0.0083×Rp (m), which is more related to primary particle energy, is used. The relationship between density ratio and ϵ for 3 different particles is showed in the fig.3. The carbon, nitrogen and oxygen (CNO) group tends to be a smaller Λ than proton and helium at fix ϵ. Because of saturation of strips recorded by ARGO-YBJ, the Λ decreases gradually and cannot be used to discriminate compositions when $\epsilon \geq 4.5$ which relates to the primary particle energy greater than 200 TeV. By setting the cut of Λ as a function of ϵ which is showed in blue line in the fig.3 and setting no restriction when $\epsilon \geq 4.5$ (black line), light component (proton and helium) can be selected from heavy nuclei with a residual contamination from CNO at the 7% level under 200TeV of the primary particle energy. After such cut, about 7100 stereo events are used to measure the energy spectrum.

3.3 Energy determination

Cherenkov light from primary particle inducing air shower, is recorded by Cherenkov telescope into FADC count. Therefore, shower reconstruction needs to convert the FADC count into photons. A calibrated UV-LED mounted at the center of the mirror is used to calibrate the telescope [6]. This method just includes the effect of PMT and electronics. The transmission of the glass window and reflectivity of the mirrors are not taking into account. These two effects, PMT and electronics are considered as a whole effect in so called end-to-end calibration using nitrogen laser[13]. The gain of telescope is monitored by UV-LED every day. The absolute gain of telescope is got every day by using nitrogen laser calibration result and UV-LED result.

After calibration, FADC count is converted into photons or photon electrons in every event. The remainder of this section is the method of energy determination and the discussions of energy resolution and bias.

3.3.1 Method of energy determination

The total number of photon electrons recorded by Cherenkov telescope is a function of primary particle energy, impact distance and the space angle. After making sure that the full Cherenkov image is recorded by the Cherenkov telescope, the effect of the space angle can be ignored. The fig.4 shows the relationship of total Npe, primary particle energy and Rp. The total Npe gradually reduces when Rp gets larger at a fix energy range. The total Npe is in proportion to the primary particle energy at a fix Rp range (see fig.5). Therefore, a method of look-up table which consists of three parameters, total Npe, primary particle energy and Rp, can be used to reconstruct the primary particle energy. The table is generated by Monte Carlo simulation. The 0.1 step of logarithmic total Npe and the 5 m step of Rp is set in the table. After making the table, the energy of observation data can be got from the table using total Npe and Rp parameters.

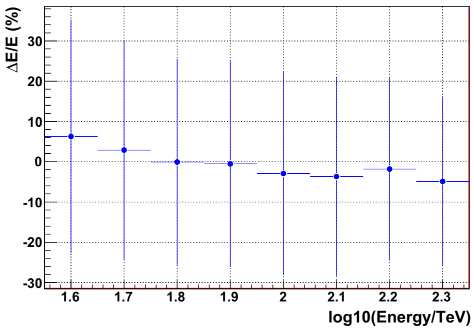

Figure 6: Energy resolution and bias.

3.3.2 Energy resolution and bias

After the reconstruction processing and data selection processing, the energy resolution is about 23% (see fig.6). The energy bias is less than 5% above 60 TeV. Because of the telescope energy threshold effect, the energy bias is getting lager in the low energy.

4 Results and discussion

Because of the saturation of ARGO strip, the composition discrimination is limited under 200 TeV. The problem can be solved by ARGO big pad analog signal[14]. The other parameter, the ratio of width and length (L/W) from Cherenkov image is also sensitive to primary particles. Here the length and width are hillas parameters[15]. The heavy component is expected to be cut more clearly by using these two parameters together. More heavy component, iron and aluminum group is expected to be more sensitive to density ratio cut than CNO[12]. More detail simulation is needed to study the combination of density ratio cut and L/W cut, and the contribution of iron and aluminum group in the light component. These will be the next task.

The interpretation of data to determine energy and mass composition is based on Monte Carlo simulation and it is difficult to study the hadronic interaction in the accelerator experiments at higher energy range. It is very lucky, the Large Hadron Collider forward (LHCf) experiment measured the single photon spectra at $\sqrt{s}$=7TeV and pseudo-rapidity ranging from 8.81 to 8.99 and from 10.94 to infinity in LHC proton-proton collisions in early 2010. Although its results show that none of the hadronic interaction models agree perfectly with the measurements, QGSJET II-03 show good agreement from 0.5 TeV to 1.5 TeV protons and agree more than the other models below 1.5 TeV protons[16]. To minimize the uncertainty caused by hadronic interaction model, QGSJET II-03 is selected in the Monte Carlo simulation.

The balloon borne experiment CREAM has measured single element precisely up to 100 TeV[1]. The energy spectrum can be compared with CREAM result at low energy range, which can help us to understand the system uncertainty from calibration, weather condition, hadron interaction model, simulation tool, energy bias, and composition model. More detail work are needed before comparison, and a preliminary result is expected to be presented at the ICRC conference.

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