LHAASO simulation: cosmic ray observation in the knee region

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***Abstract*. At Yangbajing, with altitude of 4300m a.s.l., the LHAASO site is an ideal location for energy spectrum and composition measurements for cosmic rays above 50TeV because developing maxima of air showers are 1-2km above the ground. Using a $1km^2$ array composed of electron detectors, muon detectors, water Cherenkov detectors, wide field Cherenkov telescopes and shower core detectors, multiple parameters of air showers are measured event by event so that the primary particles are expected to be identified effectively. A simulation of the hybrid shower detection, including electrons, muons and X_{max} is carried out for investigating the performance of the detection in the LHAASO array. Energy resolution, composition discrimination, efficiency and event rate are estimated for the hybrid observation.**

***Keywords*: cosmic ray, the knee region, hybrid observation**

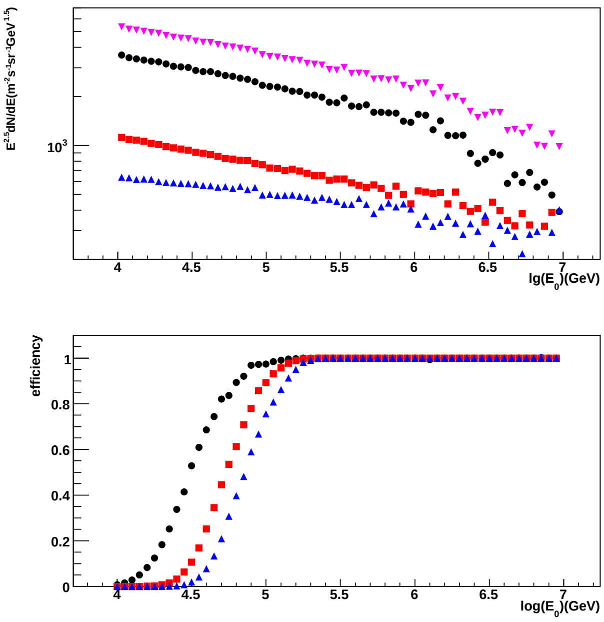

Fig. 1: a(upper): primary spectrum; b(lower): trigger efficiency vs primary energy. Reverse triangle: all particles. Dot: LN. Square: MN. Triangle: HN.

I. Introduction

Origin and acceleration mechanism of cosmic rays is a fundamental problem of particle astrophysics, and the knee region in the primary energy spectrum of cosmic rays is very sensitive to it. Because cosmic rays flux in the knee region is much low, measurement of primary energy and composition of cosmic rays mainly depends on the ground-based experiments detecting extensive air showers (EAS) generated from cosmic rays interacting with atmospheric nuclei. In last thirty decades, several detector arrays were built up near sea level [1-7] or on the mountain [8-14]. At some levels almost all of the experiments are hybrid detection of secondary particles such as $e\pm$, $\mu\pm$, hadron, Cerenkov light and so on in EAS. A hybrid detection is able to obtain several parameters of EAS simultaneously and in consequence primary energy and composition of cosmic rays reliably. From then on, there were many progresses in the observations, but measurements of compositions still differ in uncertainty of about 30% , and are hadronic interaction model-dependent (e.g., [1,15]). The next generation of cosmic ray experiments should be particular about providing high ability on particle separation and high statistics which is important way to solve the problem.

Yangbajing, with altitude of 4300m a.s.l., is an ideal location for measuring energy spectrum and composition of cosmic rays in the knee region, since the altitude is close to the maximum of EAS development in the knee region so that fluctuation in EAS is little compared with low altitude position, and measurement is less mass dependent. There have been two experiments for the knee region, ARGO-YBJ [8] with RPC target array and Tibet-ASγ [9] with electron array and burst detectors for EAS cores. At present a new project, LHAASO (The Large High Altitude Air Shower Observatory), is proposed to study particle astrophysics at Yangbajing [16], including cosmic ray knee physics. LHAASO is a hybrid detection with a huge covered and sensitive area, composed of 1km^2 array(KM2A) with 5000m^2 electron detectors(ED) and 30000m^2 muon detectors(MD) [17], 90000m^2 water Cherenkov detector array (WCDA)[18], 28 wide field Cherenkov telescopes (WFCA)[19], and 5000m^2 shower core detectors(SCDA)[20]. Multiple parameters of air showers are measured event by event: electrons from ED and WCDA, muons from MD and WCDA, depth of maximum of EAS longitudinal development (X_{max}) from WFCA, and burst at core from SCDA. Under such a powerful hybrid detection, the primary particles are expected to be identified effectively at high level. In this paper, a preliminary Monte Carlo simulation is made to study specifications of LHAASO as a hybrid detection in the knee region.

II. Simulation Setup

In this simulation, cosmic rays are generated by Corsika [22] version 6.616. The selected hadronic interaction model is QGSJETII-GHEISHA. Primary energy is from 10TeV to 10PeV. The composition of primary nuclei consists of:

- light nuclei(LN): H+He;
- moderate nuclei(MN): CNO+MgAlSi;
- heavy nuclei(HN): Fe.

Primary energy spectrum of each component is set as [21](Figure 1a). Zenith angle is $0-45°$, and azimuthal angle is $0-360°$. Observation level is at YangBaJing.

The configuration of KM2A is set as [17] except for two differences: distance between adjacent EDs is 22m, and MDs are organized into modules of which each has 4×4 MDs and distance of 100m from adjacent ones. Detector of ED and MD is plastic scintillator with dimension of $1m \times 1m \times 2cm$ and $5m \times 5m \times 2cm$ respectively. Each ED is covered by one 0.5cm Pb plate used as γ converter to increase efficiency for improvement of angular resolution and position resolution. Each MD is covered by overburden of 2.8m dirt, which has muon energy threshold is 1.3GeV, to mask electro-magnetic particles in a shower contribution.

As to detector response, at this moment, a MC simulation on unit detector (ED+MD) in KM2A is carried out to reproduce detector geometry and materials based on this simulation, a parametrization look-up table is conducted to consider all fired detector response. Simulation of ED γ converter and MD overburden is made individually with GEANT4 [23] and is parameterized for detector i as :

$$N_{ei} = N_{ei}(ID, E, \theta) \tag{1}$$

and

$$N_{\mu i} = N_{\mu i}(ID, E, \theta, R) \tag{2}$$

respectively, where for one input particle, ID is identification, including γ, $e\pm$ and $\mu\pm$, E is energy, θ is zenith angle, and R is distance to the center of the detector. Trigger is set as any 20 ED hits in time window 600ns, and readout time window is $10\mu s$. Noise from single cosmic muon in ED and MD is 1000Hz/m^2 and 300Hz/m^2 respectively. In order to decrease single muon noise in MD, number of muons in MD is counted in a time window $\pm 30ns$ around the peak time of electrons in ED during offline analysis. X_{max} is read out from Corsika data directly and added by fluctuation of 50g/cm^2. The other detectors including WFCA, SCDA and WCDA are not simulated. After an EAS event is created, there are three parts of measurements obtained: number of electrons and time in EDs, number of muons and time in MDs, and X_{max} of the event.

III. Analysis and Results

A. Reconstruction

From these measurements, procedure of data analysis is as follows: A shower Front with a conical shape is reconstructed from positions and arrival time in fired

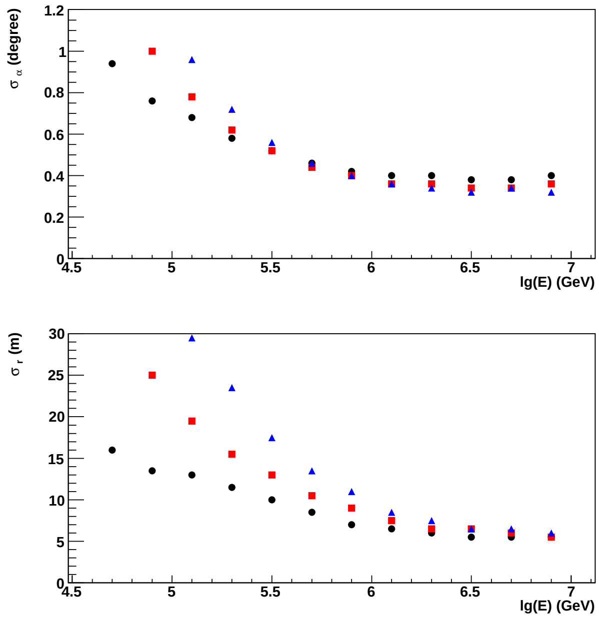

Fig. 2: a(upper): angular resolution vs primary energy; b(lower): Core position resolution vs primary energy. Dot: LN. Square: MN. Triangle: HN.

EDs, and fitted in least square method to gain EAS direction with χ^2 after minimization

$$\chi^2 = \sum \frac{(t_i - t_0 - ax_i - by_i - \alpha r_i/c)^2}{\sigma_i^2} \tag{3}$$

where t_i, x_i, y_i and σ_i is arrival time, x, y coordinates and time resolution at detector i respectively, r_i is distance from detector i to the core, c is light speed, α is slope parameter of conical front, t_0, a and b are three parameters of fitting. Then zenith and azimuthal angle can be figured out by

$$\theta = sin^{-1}(c\sqrt{a^2+b^2}) \tag{4}$$

$$\phi = tan^{-1}(\frac{a}{b}) \tag{5}$$

EAS core position, size and age can be reconstructed from electrons in EDs by fitting lateral distribution with the NKG function [24][25] in maximum likelihood method

$$\rho(\frac{r}{r_M}) = C(s)\frac{N_e}{2\pi r_M^2}(\frac{r}{r_M})^{s-2}(1+\frac{r}{r_M})^{s-4.5} \tag{6}$$

where r is distance from the core, r_M is Moliere radius (=133m at YangBaJing), ρ is density of electrons at r, N_e is size, s is age of the shower and C(s) is normalization factor.

Position of weight center of electron hits is used as initial value of the core position, and several iterations of both direction and lateral distribution reconstruction are proceeded to obtain optimized direction, core position, size and age. During analysis, only events with distance of 500m from shower core to the array center are selected.

B. Specifications

Trigger efficiency (Figure 1b) is more than 80% above 50TeV, 80TeV and 100TeV for LN, MN and HN respectively. Total event rate is estimated about 200Hz. Angular resolution (Figure 2a) is $1°$ and $0.4°$ at 50TeV and 1PeV respectively for LN, decreasing with primary energy increasing. For MN and HN, angular resolution is worse at low energy but similar with one for LN at high energy. Resolution of core position (Figure 2b) is 15m and 6m at 50TeV and 1PeV respectively for LN, improved with energy increasing. For MN and HN, core position resolution is worse at low energy but close to one for LN at high energy.

During analysis, it is found that parameter $N_{e\mu}$ is not dependent on components,

$$N_{e\mu} = \sqrt{N_e N_\mu} \qquad (7)$$

where N_e is sum of electrons in EDs in r_c=40-100m divided by cosθ, N_μ is sum of muons in MDs in r_c=40-200m divided by cosθ, r_c is distance from hit to EAS core and θ is zenith angle of the shower. The low limit of r_c is to remove punch-through effect near the core which is caused by high energy γ and electrons and creates local showers with much high number of charged particles in detectors. The high limit of r_c is to set a common truncation for lateral distribution. From Figure 3a, for secθ ~1-1.1, it is indicated that $N_{e\mu}$ is correlated with primary energy E_0 :

$$E_0 = 2.7 \times 10^3 N_{e\mu}^{2.34} \qquad (8)$$

and independent on components. In consequence, $N_{e\mu}$ is a suitable parameter to scale primary energy and to separate energy range for composition discrimination. Resolution of energy is about 30% and 18% at 100TeV and 1PeV respectively for LN, decreasing with primary energy increasing(Figure 3b).

C. composition separation

three parameters are used to separate composition: N_e, N_μ and X_{max}. During this study, it is found that two combinations of the parameters are more sensitive to composition: N_e/N_μ and $N_e X_{max}/N_\mu$ which are also mutually independent. For example (Figure 4), for secθ ~1-1.1 and $N_{e\mu}$ ~(100,300), that is E_0 ~300TeV-1PeV, in the range of $N_e/N_\mu > 1.3$ and $N_e X_{max}/N_\mu > 750$, ratio of LN to total LN, i.e., selection efficiency of LN is 82.0%, and ratio of LN to events in the region, i.e., selection purity of LN is 80.7%. In another region, $N_e/N_\mu < 0.8$ and $N_e X_{max}/N_\mu < 350$, selection efficiency of HN is 26.9% ,and selection purity of HN is 70.1%. Therefore LN and HN can be selected with a certain efficiency and purity. It is indicated that composition can be discriminated effectively with several measurement parameters.

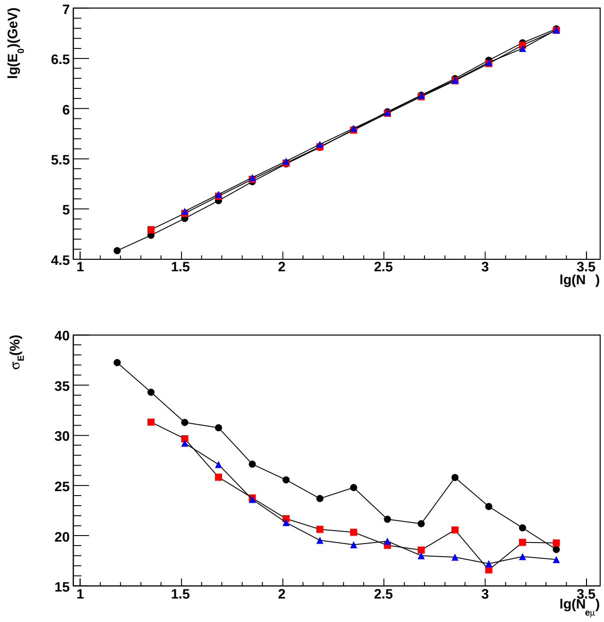

Fig. 3: for secθ ~1-1.1, a(upper): primary energy vs $N_{e\mu}$; b(lower): energy resolution vs $N_{e\mu}$. Dot: LN. Square: MN. Triangle: HN.

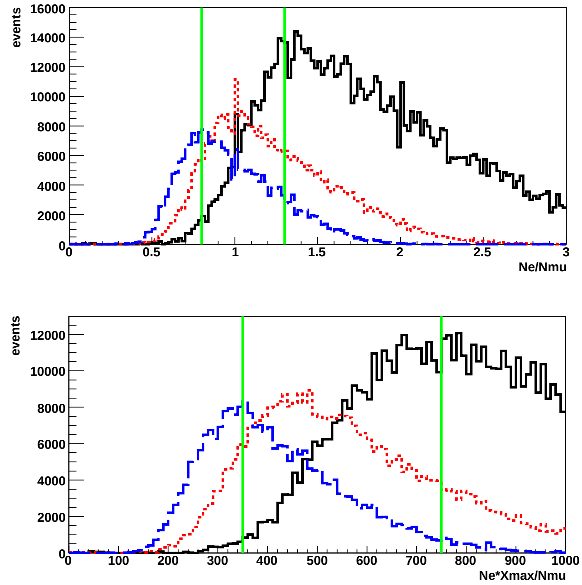

Fig. 4: For secθ ~1-1.1 , $N_{e\mu}$ ~(100,300), (E_0 ~300TeV-1PeV), a(upper): distribution of N_e/N_μ; b(lower): distribution of $N_e X_{max}/N_\mu$. Solid line: LN. Dot line: MN. Dash line: HN. Vertical line: separation for different components.

IV. Summary and Discussion

A preliminary MC simulation gives a glimpse on specifications of the LHAASO array for cosmic ray physics in the knee region. Even such a first-level simulation have shown reliability of efficiency, angular resolution, core position resolution, energy resolution and composition discrimination. More simulation will be proceeded, such as detailed detector simulation, combination with SCDA, WFCA, WCDA, and even the ARGO and ASγ array which may reach to lower energy range to match with the space direction measurement, different hadronic interaction models, and optimization of configuration of detectors and arrays, and so on, to reach the complete feature of the LHAASO project.

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