Hybrid measurement of cosmic rays at the knee region with LHAASO

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Abstract: At high altitude of 4000m a.s.l., the LHAASO (Large High Altitude Air Shower Observatory) 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. The LHAASO project consists of several large area detector arrays which own different detection methods: KM2A (one km2 Array) can measure charged particles and muons, WCDA(Water Cherenkov Detector Array) can measure muons, WFCTA(Wide Field Cherenkov Telescopes Array) can measure Cherenkov lights, SCDA(Shower Core Detectors Array) can measure gamma family from pion0 at the shower cores, and PRISMA(PRImary Spectrum Measurement Array) can measure thermal neutron from pion+ and pion- at the shower cores. By advantage of these powerful hybrid detections, LHAASO is expected to offer measurement of cosmic ray spectrum and composition with high accuracy. In this presentation, a simulation of the hybrid shower detections is carried out for investigating the performance of the detection in the LHAASO array.

Keywords: cosmic ray, extensive air shower, the knee region, LHAASO

1 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±, µ±, 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.

At present a new project, LHAASO (The Large High Altitude Air Shower Observatory), is proposed to study particle astrophysics at high altitude of 4000m a.s.l., including cosmic ray knee physics [16]. 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. L-HAASO is a hybrid detection with a huge covered and sensitive area, composed of 1km² array(KM2A) with 5341m² electron detectors(ED) and 43956m² muon detectors(MD), 90000m² water Cherenkov detector array (WCDA), 28 wide field Cherenkov telescopes (WFCTA), 160m² shower core detector array(SCDA), and a new member, shower hadron detector array PRISMA(PRImary Spectrum Measurement Array)[17] (Fig. 1). 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 (Xmax) from WFCTA, gamma family from π0 at shower core from SCDA, and thermal neutron from π+ and π- at the shower cores from PRISMA. 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.

2 Configurations and performances of the Arrays

In this preliminary work, KM2A, SCDA and WFCTA are combined to simulate the hybrid detection of cosmic ray spectrum and composition.

Fig. 1: Configuration of LHAASO
2.1 KM2A

KM2A consists of ED and MD array. ED, with a sensitive area of about 5341 m², consists of 5341 square plastic scintillators with a size of 1m × 1m × 2cm, placed in triangle with a distance of 15m. Each ED is covered by one 0.5cm thick lead plate used as γ converter in order to improve angular resolution and EAS core position resolution of the array. MD, with a sensitive area of 43956 m², consists of 1221 cylindrical water tanks with diameter of 6.8m and height of 1.2m, placed in triangle with side length of 30m. Each MD is covered by overburden of 2.5m dirt, which causes muon energy threshold of 1.3GeV, to mask electro-magnetic particles in a shower contribution. A simulation work [18] indicates that, for proton, KM2A has effective area 0.8 km² at 1PeV, and energy resolution is 35% at 30TeV and 0.2° at 1PeV, and angular resolution 0.8°. During analysis [18], it is found that parameter $N_{eq}$ is not dependent on components,

$$N_{eq} = \sqrt{N_{e}N_{\mu}}$$  \hspace{1cm} (1)

where $N_{e}$ is sum of electrons in EDs in $r_{e}$=40-100m divided by $\cos \theta$, $N_{\mu}$ is sum of muons in MDs in $r_{\mu}$=40-200m divided by $\cos \theta$, $r_{e}$ is distance from hit to EAS core and $\theta$ is zenith angle of the shower. The low limit of $r_{e}$ 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 $r_{e}$ is to set a common truncation for lateral distribution. $N_{eq}$ is correlated with primary energy $E_{0}$ and independent on components (Figure 5,right). In consequence, $N_{eq}$ is a suitable parameter to scale primary energy and to separate energy range for composition discrimination.

2.2 SCDA

SCDA is a 20 × 20 detector array with area of 5000 m². Each detector is a plastic scintillator with size of 50cm × 80cm × 1cm, covered by lead with thickness of 7 radiation length. The adjacent distance is 3.75m. Aperture of SCDA reaches 5000m²sr at 1PeV and shower core position resolution is 1.2m(Fig. 3). Several parameters are obtained to study composition of cosmic ray:

- $N_{b}$: particles in one detector
- $N_{hit}$: hit detectors
- $\text{Sum}N_{b}$: Sum of $N_{b}$
- $N_{bt}$: the maximum of $N_{b}$

2.3 WFCTA

The WFCTA is one main detector of LHAASO project [16], which consists of 24 telescopes. The WFCTA is reconfigured into three observation modes: the first Cherenkov array mode focusing on the low energy (30TeV-100TeV), the second Cherenkov array mode focusing on the middle energy (100TeV-1000TeV), the fluorescence light detector array mode which allows cosmic ray spectrum and composition measurements above 100TeV where the second knee is located. Each telescope has 3232 PMTs and covers a FOV of 14° × 16°. In the first Cherenkov array mode, so called "Cherenkov imaging" mode, 24 telescopes are arranged to cover the sky with zenith angle from 0 to 33°, azimuth angle from 0 to 360°: 1 of telescopes pointing to zenith angle 0°, 8 of telescopes pointing to zenith angle 77° and 12 of telescopes pointing to zenith angle 64°. The other 3 telescopes are for addition observation. The FOV of neighborhood telescopes overlaps with each other for inter-calibration purpose. Each telescope is 75 m away from the SCDA. The configuration enables air showers with cores location inside SCDA to be well measured by the WFCTA. After reconstruction, parameters $X_{max}$ and Hillas are obtained. Aperture of WFCTA reaches 25000m²sr at 100TeV and resolution of $X_{max}$ is 40g/cm² (Fig. 4). Primary energy is determined by means of total number of photoelectrons recorded by the telescope together with the impact parameter $R_p$. Energy resolution is 20% at 1PeV (Figure 5,left). The two prototype telescopes [19] have been successfully operated at Yang-BaJing Cosmic Ray Observatory near the ARGO-YBJ array since 2008.
Fig. 5: Energy resolution vs primary energy of WFC-TA(left) and KM2A(right).

Fig. 6: Scattering plot of some parameters: $\alpha'$ from WFC-TA vs $N_e/N_\mu$ from KM2A (left) and Ntop from SCDA vs primary energy (right).

3 Hybrid detection

In this simulation, cosmic rays are generated by Corsika [20] version 6.616. The selected hadronic interaction model is QGSJETII-GHEISHA. Primary energy is from 100TeV to 10PeV. The composition of primary nuclei consists of:

- light nuclei(ln): H+He;
- moderate nuclei(mn): CNO+MgAlSi;
- heavy nuclei(hn): Fe.

Zenith angle is $24^\circ - 38^\circ$, and azimuthal angle is $77^\circ - 103^\circ$. Only events with core inside SCDA are selected.

Preliminarily, primary energy is reconstructed with $N_e$. For range $10^2 < N_{eq} < 10^3$, corresponding energy range 100TeV to 1PeV, several parameters are studied for composition separate. For example, Fig. 6 (left) gives separation with $\alpha'$ from WFCTA vs $N_e/N_\mu$ from KM2A. $\alpha'$ is shower main axis corrected by shower width W, Rp and zenith angle $\theta$:

$$\alpha' = \alpha/W - a \cdot Rp - b \cdot (\theta + 45)$$  \hspace{1cm} (2)

where a and b are correction factors from reconstruction. It is indicated that the combination of $\alpha'$ and $N_e/N_\mu$ can offer a strong capability of separation of primary composition. Moreover, WFCTA can provide some parameters for composition composition, for example, Nbtop (Fig. 6 , right).

4 Summary

A preliminary MC simulation gives a glimpse on specifications of the LHAASO array for cosmic ray physics in the knee region. The whole arrays will be combined to give a total simulation for cosmic ray detection, and more advanced analysis will be taken, such as artificial neural network. Combination with KM2A, SCDA, WFCTA, WCDA and PRISMA, LHAASO is expected to offer hybrid measurement of cosmic ray spectrum and composition with high accuracy.

References

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