Study of Energy Measurement of Cosmic Ray Nuclei with LHAASO

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The Large High Altitude Air Shower Observatory (LHAASO) is a hybrid extensive air shower (EAS) array with an area of about 1 km^2 at an altitude of 4410 m a.s.l. in Sichuan province, China. It contains three sub-detectors: 1 km^2 array (KM2A) composed of 5195 electromagnetic particle detectors (ED) and muon detectors (MD); water Cerenkov detector array (WCDA) and 18 Wide Field-of-view Cerenkov Telescope Array (WFCTA). One of the main scientific goals is measuring the individual energy spectra of cosmic rays from ~30 TeV to a couple of EeV. The construction of the whole observatory will be completed by the end of 2021. In this paper, a new energy reconstruction method and result based on KM2A simulated nuclei events will be shown.

Introduction and experiment:

The measurement of energy spectra of cosmic rays is an important tool to understand the origin, acceleration and propagation of cosmic ray [1]. The energy measurement is one of the main components for the spectra measurement. WFCTA, WCDA and KM2A of LHAASO [2] measure the energy of primary particles with different techniques and independently. In this paper, a new energy reconstruction method and result based on KM2A detector will be shown.

The central part of KM2A-EDs composed of 4901 EDs (1 m^2 each) deployed in a grid with a spacing of 15 m to cover a circular area with a radius of 575 m. This central part is surrounded by an outer guard-ring instrumented with 294 EDs (30 m spacing) up to a radius of 635m. The KM2A-MD is composed of 1188 water Cerenkov tanks (36 m^2 each) deployed in a grid with a spacing of 30 m. The detectors are buried under 2.5 m of soil (~12 radiation lengths) to reduce the punch-through due to shower electromagnetic particles.

The KM2A half-array consists of 2365 EDs and 578 MDs, and takes data from Dec. 2019 to Dec. 2020. Planned layout of all LHAASO-KM2A detectors and the KM2A half-array are shown in Figure 1. The energy reconstruction method in this paper is based on the KM2A half-array detectors.

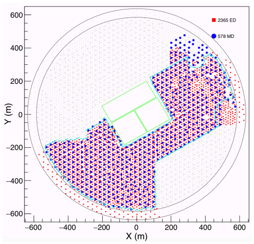

Figure 1: Planned layout of all LHAASO-KM2A detectors. The red squares and blue circles indicate the EDs and MDs of KM2A half-array.

Monte Carlo simulation:

The simulations performed include the detailed air shower development in the atmosphere, as well as the response of the KM2A detector, which is a delicately developed detector simulation program in the framework of Geant4 package. Air showers were simulated with CORSIKA (v76400) . The QGSJETII and FLUKA model for hadronic interactions were used. Five components– protons, helium, CNO, MgAlSi, and iron are generated, the mass number (noted as A below) for the CNO and MgAlSi groups is 14 and 27, respectively.

The Method:

The total number of charged particles (Nsize) from ED measurement and the total number of muons (Nμ) from MD measurement are used to reconstruct energy and do particle identification between nuclei by using the Monte Carlo samples. Both Nsize and Nμ are proportional to the energy of primary particle. However, they are also affected by other variables. For example, the zenith angle of primary particle that changes the integrated mass of atmosphere traversed, the age parameter from the fitting of lateral distribution that reflects the stage of EAS development, and also the mass of the primary particle. In this paper, the age parameter is used to correct for shower fluctuation, and the zenith angle is used to correct for different atmosphere mass. Those two effects are corrected before the energy reconstruction. The effects of the type of primary particle (or different mass) is also corrected by combining the energy measurements of Nsize and Nμ in the end.

The dependence of the Nsize and Nμ on age and zenith angle for proton samples with energy ~1 PeV are shown in Figure 2. As shown, the Nsize has a strong dependence on the age, mainly due to shower fluctuations, and small dependence on zenith angle. The dependencies of Nμ on age and zenith angle are both small. The dependencies for other energy ranges and other type of primary particles are also similar.

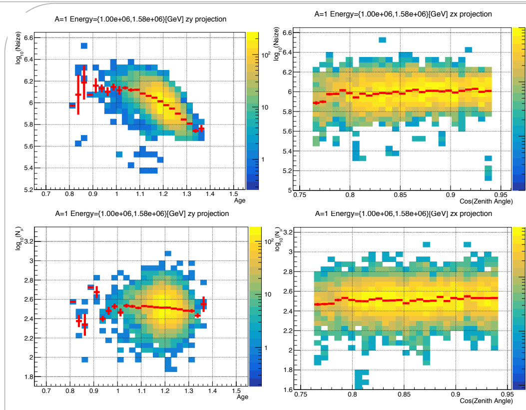

Figure 2: l The dependences of Nsize and Nμ on age and zenith angle of primary particle for proton MC sample at ~ 1PeV. Upper left: Nsize vs age; upper right: Nsize vs cos(zenith angle); lower left: Nμ vs age; lower right: Nμ vs cos(zenith angle). The red lines correspond to the mean value.

Energy reconstruction: Due to the unknown type of primary particle in real data, instead of correct the measured Nsize and Nμ to a value associated to a reference age and zenith angle. For a shower event with reconstructed age parameter and zenith angle, the mean Nsize and Nμ versus generated energy for different type of primary particles are reconstructed based on the dependencies above, which are shown in Figure 3a and 4a, when age=1.3 and zenith angle=30°. For a giving Nsize (or Nμ), based on the lines shown in Figure 3a and 4a, one energy number is reconstructed for each type of primary particle. Figure 3b and 4b show the reconstructed energy versus true logarithm mass for an event with Nsize=$10^{6.0}$ and Nμ =$10^{2.7}$.

The energy and mass of the primary particle follow both lines in Figure 3b and 4b. The mass and energy should be the x and y coordinate of the cross point of the two dashed lines. In this way, the energy and A are reconstructed simultaneously by combining the Nsize and Nμ measurements. The mass dependence of energy is corrected.

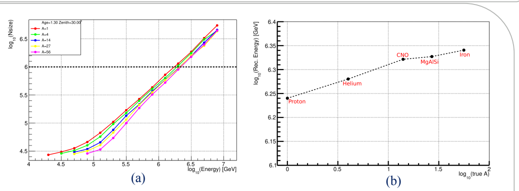

Figure 3: (a): The Nsize versus the true energy for different mass samples of MC (different colors), the dashed line indicate Nsize=$10^{6.0}$; (b): The reconstructed energy from Nsize versus the true logarithm mass of primary particle for an event with Nsize=$10^{6.0}$, based on the correlations between Nsize and true energy in (a). In both plots, age=1.3 and zenith angle=30°.

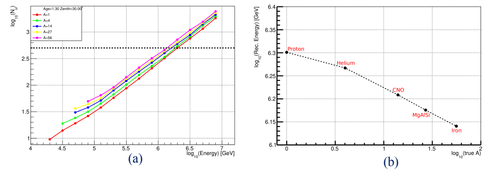

Figure 4: (a): The Nμ versus the true energy for different mass samples of MC (different colors), the dashed line indicate Nμ=$10^{2.7}$; (b): The reconstructed energy from Nμ versus the true logarithm mass of primary particle for an event with Nμ=$10^{2.7}$, based on the correlations between Nμ and true energy in (a). In both plots, age=1.3 and zenith angle=30°.

Result:

The energy resolution, bias and energy resolution function for proton, helium, CNO, MgAlSi and iron MC samples in the energy range from 300 TeV to 10 PeV are shown in Figure 5.

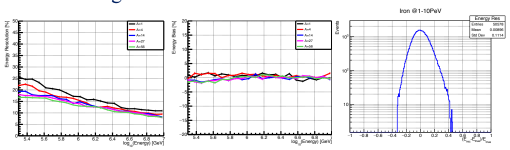

Figure 5: The parameters of the energy reconstruction method in the energy range from 300 TeV to 10 PeV. Left: the energy resolution in percentage for five mass groups; middle: the energy bias in percentage for five mass groups; right: the energy resolution function in the energy range from 1 PeV to 10 PeV of iron sample.

Refenence:

[1] B. Bartoli et al., PHYSICAL REVIEW D 92, 092005 (2015)
[2] Z. Cao et al., Chinese Physics C 34, 249 (2010)