

## Reconstruction of coincident events between LHAASO and ENDA

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In the investigation of the "knee" region within the cosmic ray energy spectrum, energy determination and composition separation are of paramount importance. The Electron-Neutron Detector Array (ENDA) is designed to detect not only electrons in the proximity of the extensive air shower (EAS) core, but also thermal neutrons generated in the ground by secondary hadrons which constitute the "backbone" of EAS and carry vital information regarding the primary cosmic rays. ENDA-64, consisting of 64 detectors, is employed inside the Large High Altitude Air Shower Observatory (LHAASO). Hybrid detection of EAS using LHAASO and ENDA can provide a full secondary particle measurement of EAS including electrons, muons, atmospheric Cherenkov light, and hadrons, exhibiting a unique capacity for separating primary components and accurately measuring energy. ENDA-64 consists of 4 clusters, and each cluster is configured as a  $4 \times 4$  matrix of 16 detectors. The inter-detector distance is approximately 4.5 m, compared to 15 m for the electromagnetic component detectors (ED) of LHAASO-KM2A. Moreover, ENDA-64 can measure electrons over a higher dynamic range than ED. By selecting EAS events with cores falling inside ENDA, a comprehensive analysis of coincident events between LHAASO-KM2A (farther from the EAS core) and ENDA (closer to the core) enables full lateral electron distribution acquisition, ultimately enhancing the precision of core position, size, and age reconstruction.

## 1. Introduction

The cosmic ray energy spectrum spans over ten orders of magnitude in energy and more than thirty orders in flux intensity, generally following a power-law distribution. Around  $4 \times 10^{15}$  eV, known as the “knee” region, the spectral index changes from  $-2.7$  to  $-3.1$ . Accurately understanding the composition and spectral behavior of cosmic rays near the knee is crucial for revealing their acceleration mechanisms and propagation processes. In extensive air showers (EAS), the hadronic component serves as the primary manifestation of strong interactions from primary cosmic rays. It forms the “skeleton” of the shower and carries vital information about the mass, energy, and origin of the primary particles. However, direct detection of hadrons at the ground level is challenging. An alternative strategy is to detect thermal neutrons generated near the shower core by hadronic interactions, allowing indirect inference of the nature of primary cosmic rays. For this target, inside The Large High Altitude Air Shower Observatory (LHAASO)[1], the Electron and Neutron Detector Array (ENDA) [2] is deployed to measure secondary hadrons of EAS in conjunction with LHAASO, thereby enhancing the ability to determine energy and discriminate composition of the primary cosmic rays. One key job is to obtain important parameters such as size, age, core position of cosmic ray EAS by reconstruction using combination between ENDA and LHAASO.

## 2. Experimental Setup

LHAASO is located at Mt. Haizi (4410 m a.s.l.,  $600 \text{ g/cm}^2$ ,  $29^\circ 21' 27.56''$  N,  $100^\circ 08' 19.66''$  E) in Daocheng, Sichuan province, P.R. China. LHAASO consists of  $1.3 \text{ km}^2$  array ( KM2A ) of electromagnetic particle detectors ( ED ) and muon detectors ( MD ), a water Cherenkov detector array ( WCDA ) with a total active area of  $78,000 \text{ m}^2$ , 18 wide field-of-view air Cherenkov telescopes ( WFCTA ) and a newly proposed electron-neutron detector array ( ENDA ) covering  $10,000 \text{ m}^2$ . Each detector is synchronized with all the other through a clock synchronization network based on the White Rabbit protocol. The observatory includes an IT center which comprises the data acquisition system and trigger system, the data analysis facility. At present, ENDA consists of four clusters, each comprising 16 electron-neutron detectors arranged in a  $4 \times 4$  matrix layout with a distance of 4.5 meters between adjacent detectors, shaping a diamond pattern, so called ENDA-64 [3] [4]. In this paper, only coincident events between ENDA and EDs are taken into account.

## 3. Reconstruction Method

The shower core refers to the intersection point between the shower axis and the ground-based detector array. Based on the arrival time and electron density information recorded by ground detectors, the shower direction, core position, size and developmental age can be reconstructed. In our analysis, because poorer timing precision 20 ns of ENDA than 2ns of EDs, we just directly use direction reconstructed by EDs without using timing record of ENDA. Electrons detected by both ENDA and EDs are used during reconstruction.

The initial value of the shower core position is obtained by using the weighted method:

$$X_0 = \frac{\sum_i w_i x_i}{\sum_i w_i}, \quad Y_0 = \frac{\sum_i w_i y_i}{\sum_i w_i} \quad (1)$$

where,  $(X_0, Y_0)$  denotes the estimated core position coordinate in the LHAASO coordinate system,  $(x_i, y_i)$  represents the coordinate of the fired detector, and  $w_i$  is weight of each fired detector. Although the weighted method is simple, its accuracy is limited so that the core positions generally are moved within the detector array and accumulate on the detectors, so this method is used only to provide an initial estimation. In practise, an optimised weight is adopted [5]:

$$\omega_{ij} = N_i \times e^{-\frac{1}{2} \left( \frac{dr_j}{r_a} \right)^2} \quad (2)$$

where,  $N_i$  is number of electrons recorded by the  $i$ th detector,  $r_a$  is adjacent distance between detectors which is 4.5 m and 15 m for ENDA and EDs respectively, and  $dr_j$  is distance from the detector to the  $j$ th iteration result of core position. In the first iteration,  $dr_j = 0$ . The initial value of size uses sum of electrons detected by ENDA and ED, and The initial value of age is set 1.2 .

The lateral distribution of electrons can be traditionally described by the NKG function[6][7].

$$\rho_{NKG}(r) = N_e \cdot \frac{\Gamma(4.5 - s)}{2\pi r_m^2 \Gamma(s) \Gamma(4.5 - 2s)} \cdot \left( \frac{r}{r_m} \right)^{s-2} \left( 1 + \frac{r}{r_m} \right)^{s-4.5} \quad (3)$$

where  $r$  is the distance from the shower core,  $\rho_{NKG}(r)$  is electron density at  $r$ ,  $N_e$  is electron size,  $s$  is the shower age,  $r_m$  is the Molière radius, and  $\Gamma$  is the  $\Gamma$  function. Based on it, a modified NKG function is adopted to improve description near the detectors[8]:

$$\rho(r, s_m) = m^{-2} \rho_{NKG} \left( \frac{r}{r_m} \right), \quad m = 0.78 - 0.21s \quad (4)$$

the maximum likelihood method is taken to fit the lateral distribution by using the modified NKG function. The actual number of electrons detected by each detector follows a Poisson distribution:

$$P(n_i | \lambda_i) = \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!} \quad (5)$$

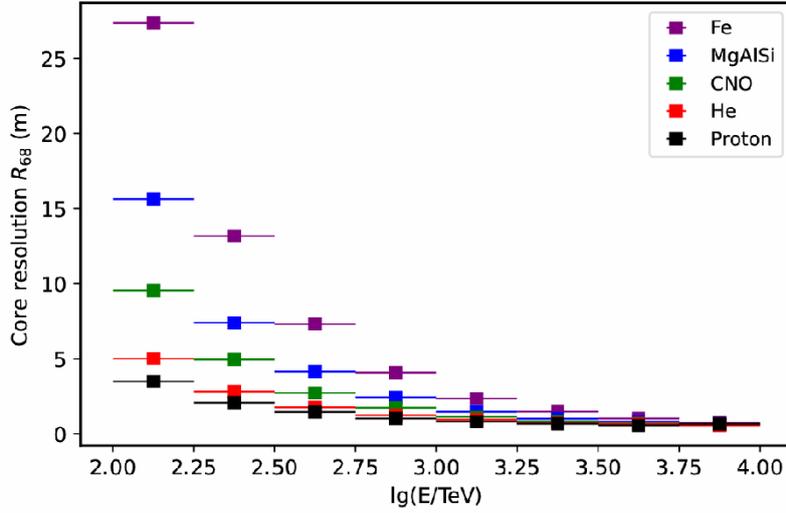
Here,  $-\lambda_i$  is the expected number of particles, and  $n_i$  is the actual number of particles detected by the detector. and the likelihood function is:

$$\mathcal{L} = \prod_i P(n_i | \lambda_i) = \prod_i \frac{\lambda_i^{n_i} e^{-\lambda_i}}{n_i!} \quad (6)$$

Fitting range is within distance 5 - 80 m from the shower core. After fitting, core position, size and developmental age are obtained.

#### 4. Results

In the simulation, EAS of cosmic ray, including proton, He, CNO, MgAlSi, and Fe, are generated by CORSIKA [9] version 7.640. The selected hadronic interaction models include QGSJETII for the high energy range and GHEISHA for the low energy range. The whole primary energy range is set from 100 TeV to 10 PeV. The zenith angle range is set from  $0^\circ$  to  $40^\circ$ , the azimuthal angle range is set from  $0^\circ$  to  $360^\circ$ , and the observation level is set at 4400 m above sea level. The low energy cut-off of the secondary hadrons is set as 1 GeV, and the low energy cut-off of the secondary



**Figure 1:** The shower core position resolution  $R_{68}$  (m) in different components and different energy.

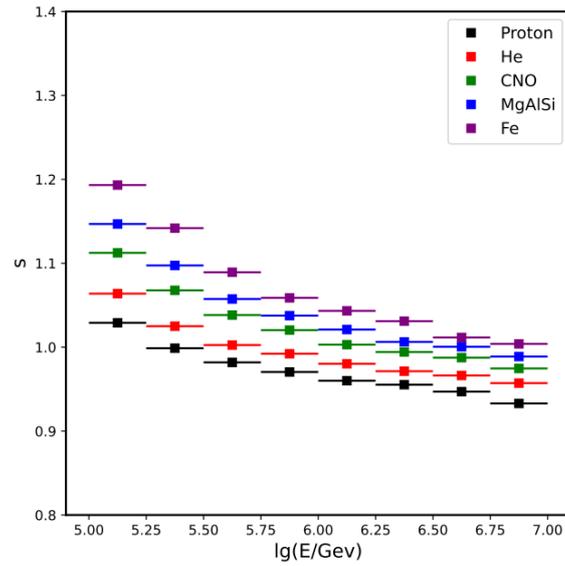
electromagnetic components and muons is set as 0.01 GeV. Response to secondary particles in EAS is simulated with GEANT4 [10] version 10.4.

It can be seen from Fig. 1 that the shower core position resolution  $R_{68}$  (m) changes with different components and different energy. Higher energy, higher core position resolution. At 10 PeV, core position resolution of all components can reach 0.66 m. Besides, lighter nuclei, higher core position resolution. At 100 TeV, core position resolution of proton and Fe is 3.5 m and 27 m respectively.

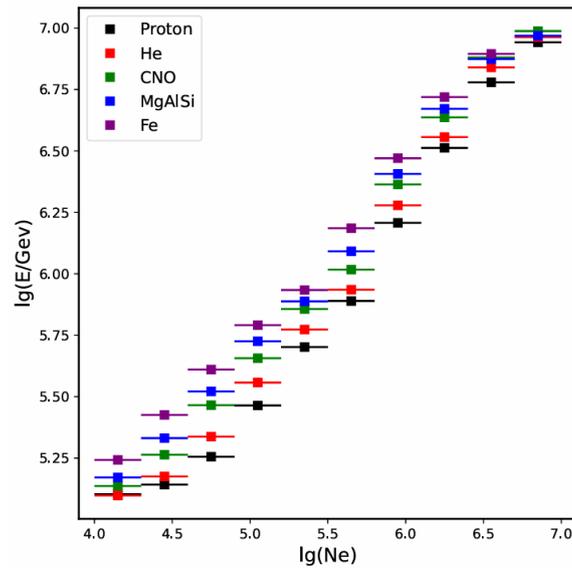
Moreover, relation between shower size  $N_e$  and age  $s$  and primary energy  $E$  and components are obtained (Fig. 2 and Fig. 3) respectively. It indicates that size is correlated with energy and age is anti-correlated with energy. Besides, both size and age are all good at composition separation. From relation between size and age (Fig4), we can see that anti-correlation between size and age are different between different components.

## 5. Summary

This study investigates the reconstruction of cosmic ray air showers in the "knee" region based on joint simulation data from LHAASO-KM2A and ENDA. ENDA enable effective detection of electrons near the shower core, meanwhile EDs detect electrons far from the shower core. The lateral distribution of electrons of both ENDA and EDs are fitted. The analysis focuses on the reconstruction accuracy of key parameters including shower core position, size, and age. Because ENDA has a more compact deployment, by combining measurements from ENDA and KM2A, the accuracy of the lateral distribution reconstruction are improved. The results are significant for accurate measurement of cosmic ray light component energy spectrum by using ENDA-64 and LHAASO in the near future.



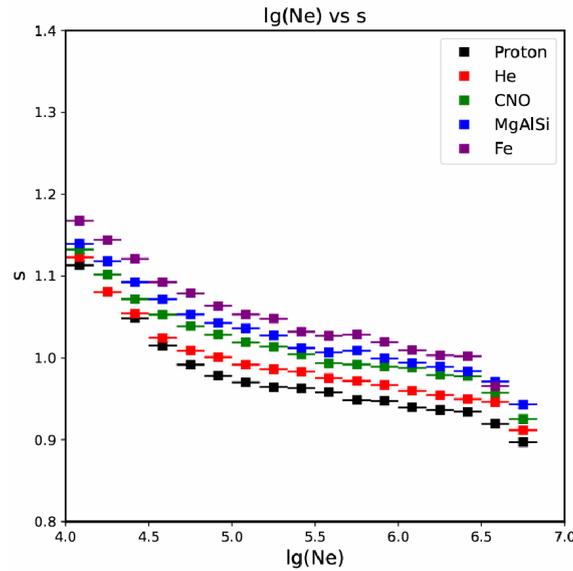
**Figure 2:** Relation between primary energy  $E$  and age  $s$  for different components.



**Figure 3:** Relation between primary energy  $E$  and size  $N_e$  for different components.

## 6. Acknowledgements

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**Figure 4:** Relation between size and age for different components.

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