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Energy reconstruction of cosmic rays at large zenith angles using a combined neural network

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In this work, we develop a combined neural network, CNN+MLP, to reconstruct cosmic-ray energy of events at large zenith angles detected by Square Kilometer Array of Large High Altitude Air Shower Observatory (LHAASO-KM2A). We use two sets of input features for neural network training, both of which are reconstruction parameters from LHAASO-KM2A. There are two steps: first, a CNN identifies the cosmic-ray composition; second, the results are passed to an MLP for energy reconstruction. The results from the neutral network demonstrate that the method achieves good performance in both energy resolution and bias; in the zenith angle range of 50°-60°, the overall energy resolution is better than 18% at 10 PeV, and the bias is limited within 5% for individual mass groups. We also carry out simulation test of the method by comparing the input true spectrum and the reconstructed one.

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1. Introduction

The cosmic-ray energy spectrum is one of the most important keys for solving the mysteries of the cosmic-ray origin, acceleration, and propagation. Currently, the satellite-based experiments have directly measured the energy spectrum of proton and helium up to 100 TeV[1][2]. Since the cosmic ray spectrum follows a power-law distribution, the flux decreases rapidly with increasing energy, making the ground-based experiments necessary for indirect measurements beyond 100 TeV.

Due to the good linear correlation between the cosmic-ray energy and detector measurements (such as the numbers of muons and electrons) at small zenith angles, traditional methods for energy reconstruction and spectrum measurement in ground-based extensive air shower (EAS) arrays are generally applicable only to events at zenith angles below 40°.

The Large High Altitude Air Shower Observatory (LHAASO) precisely measured the cosmic ray spectrum in the 0.3–30 PeV range within the zenith angle of 10°–30°, identifying the "knee" at ~3.67 PeV and suggesting that this feature is primarily dominated by light mass groups[3].The KASCADE experiment, with data at θ <18°, and its extension, KASCADE-Grande, with data at θ <40°, measured the all-particle spectrum. KASCADE observed a knee-like structure at ~4 PeV (QGSJet-01) and ~5.7 PeV (SIBYLL), while KASCADE-Grande reported spectrum hardening around 20 PeV and a significant steepening feature at ~80 PeV[4][5].

This study focuses on the analysis of events at large zenith angles. First, when the energy reaches a certain high level, the excessive number of secondary particles from vertical events can easily lead to saturation in the detector array, at large zenith angles, the deeper atmosphere absorbs more secondary particles, enabling extensive air shower (EAS) arrays to potentially detect higher-energy cosmic-ray events. Second, extending the zenith angle range to larger angles enhances the statistic of data sample.

In recent years, artificial neural networks (ANNs) have achieved remarkable success in predictive systems, pattern recognition, and other fields due to their exceptional capabilities in adaptive learning, nonlinear processing, and multivariate analysis, making them a research hotspot across various disciplines. Neural networks are capable of learning the relationship between array reconstruction parameters—such as electromagnetic and muon numbers—and the primary particle energy. They demonstrate strong adaptive capabilities in handling the effects caused by variations in parameters such as zenith angle and shower core position.

Building upon these technical advantages, this study developed an energy reconstruction method for cosmic rays at large zenith angles (50°–60°).

2. Method

We develop a convolutional neural network (CNN) for predicting the primary particle type, with the results serving as an intermediate quantity for energy reconstruction. Then, a multi-layer perceptron (MLP) neural network is built for energy reconstruction. The simplified architecture is shown in Figure 1.

The analysis employs two distinct feature sets as the network inputs: The first set—including number of electromagnetic particles within 40-200 m from the shower core (N_e), number of

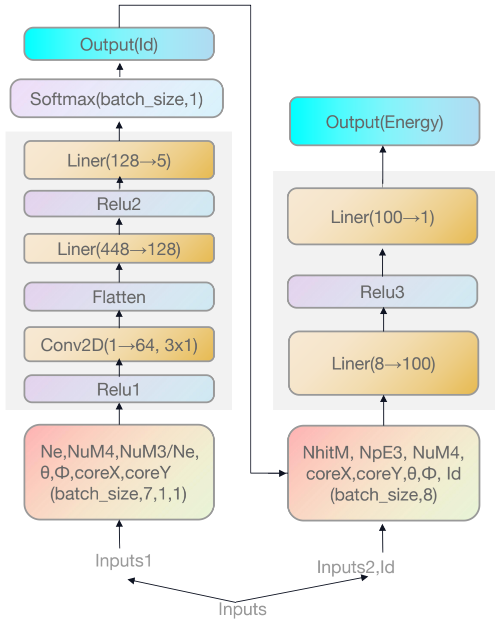

Figure 1: Architecture of the Neural Network

muons within 15–400 m from the shower core (NuM4), NuM3/ N_e (NuM3 is number of muons within 15–200 m from the shower core), zenith angle (θ), azimuth angle (ϕ), shower core position (coreX,coreY)—is used as input features for composition prediction(Id). The predicted Id is incorporated as an intermediate variable into the energy prediction network. The second set—number of electromagnetic particles within 40-200 m from the shower core (N_e), number of muons within 15–400 m from the shower core (NuM4), zenith angle (θ), azimuth angle (ϕ), ratio of the triggered muon detectors and electron detectors (NhitM/NhitE), shower core position (coreX,coreY), and particle type(Id)—served as input features dedicated to the energy prediction.

The simulation is produced by a combination of CORSIKA, GEANT4, and KM2AMCrecV3, with the selected interaction models: QGSJetII-04 (for the high-energy interactions) and FLUKA (for the low-energy interactions). Five types of nuclei are used: proton, He, N (denoted by CNO), Al (denoted by MgAlSi) and Fe. We select events that trigger the array for training. The simulated energy range spans from 100 TeV to 100 PeV, roughly following an E^{-2} spectral distribution, with zenith angles from 50°–60°, azimuth angles from 0°–360°, and shower core position falling within 280–450 m from the array center. The total number of events is $8{\times}10^5$ after trigger. The events are divided into training, validation, and test sets, with a ratio of 48.75% (training) : 16.25% (validation) : 35% (test).

3. Result

The energy reconstruction performance is evaluated on the test set. The energy resolution and reconstruction bias, derived from a Gaussian fit to the $(E_{\mathrm{rec}} - E_{\mathrm{true}})/E_{\mathrm{true}}$ distribution using H3a spectrum-normalized weights, serve as quantitative metrics for assessing the reconstruction quality. The result is as follows:

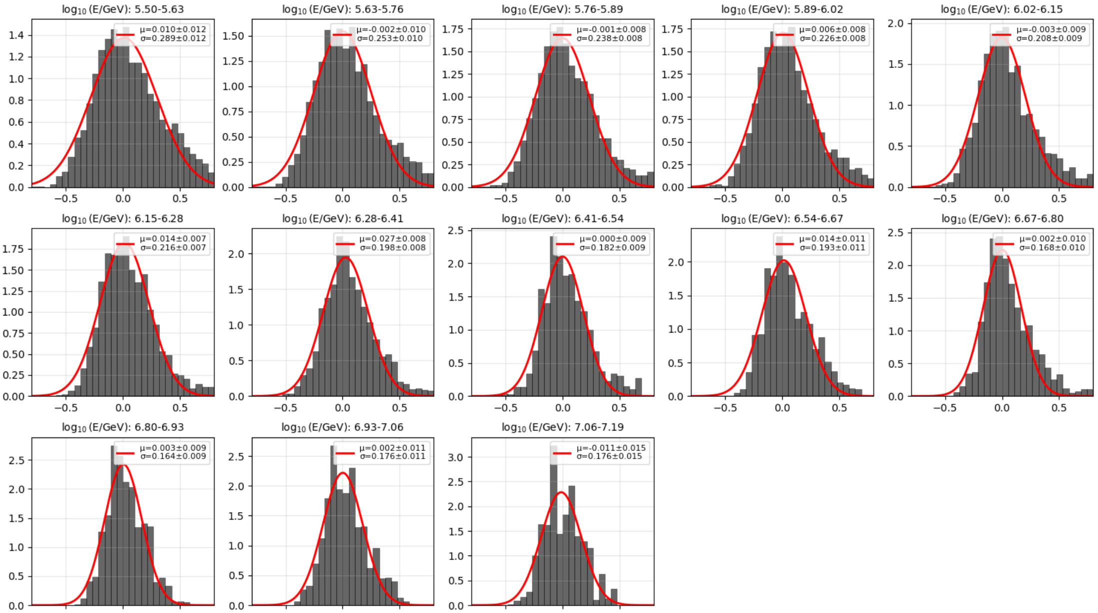

Figure 2: The all-particle $(\mathrm{E_{rec}} - \mathrm{E_{true}})/\mathrm{E_{true}}$ distribution using H3a spectrum-normalized weights with energy from 100 TeV to 16 PeV. The vertical axis represents the probability density weighted by H3a. The red lines show the Gaussian fit.

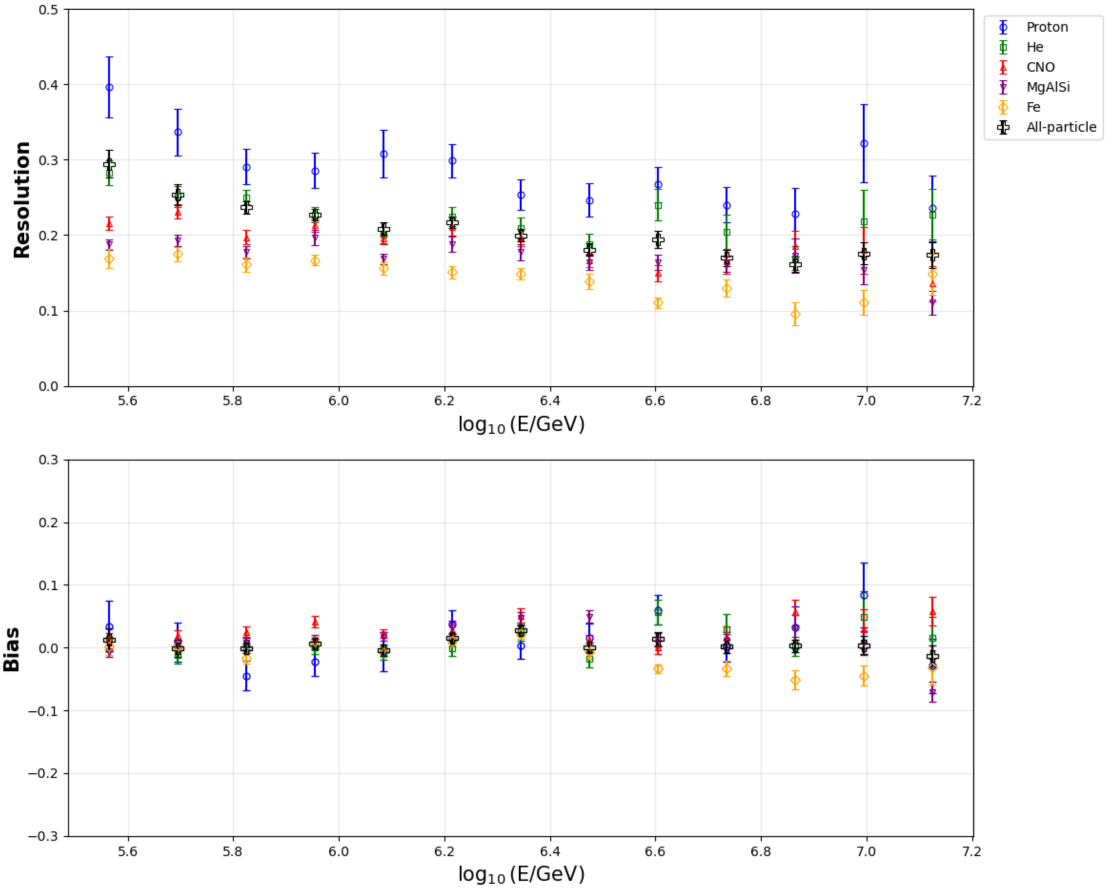

Figure 3: Top: the reconstructed energy resolution for individual and all chemical mass groups; bottom: the reconstructed energy bias for individual and all chemical mass groups.

1. In Figure 2 and 3 we show the results of energy reconstruction. The simulation results show that the energy resolution improves with increasing energy, achieving a resolution better than 18% at 10 PeV. The reconstruction bias for individual mass groups, and all mass groups, are predominantly within 5%. The results demonstrate a small dependence of the method on the primary particle type.

2. In Figure 4 we show the discrepancy between the input spectrum and the reconstructed spectrum of all-particle and individual mass groups. For the all-particle spectrum, the reconstructed flux is slightly overestimated at lower energy, while the reconstructed spectrum agrees well with the input spectrum above 600 TeV. For individual mass groups, the proton spectrum exhibits a noticeable overall underestimation, the results of other mass groups generally fluctuate around 100%.

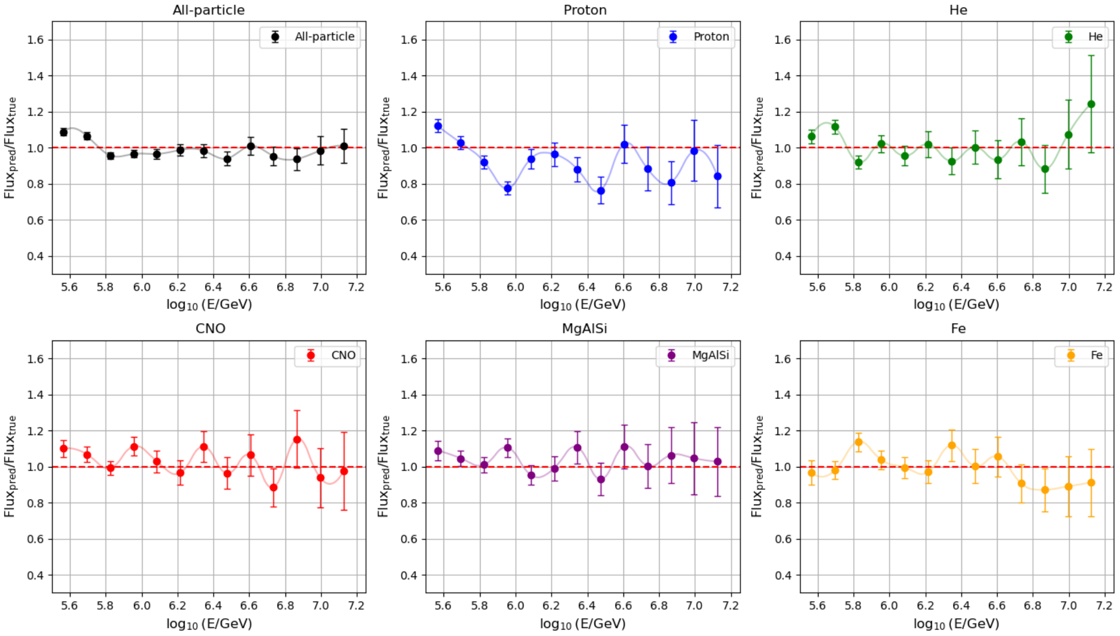

Figure 4: Test-set spectral deviations: predicted vs. true. The error bars represent statistical uncertainties.

4. Conclusion

We develop an energy reconstruction method using a combined neural network for large-zenith-angle events from LHAASO-KM2A. The results demonstrate that the energy reconstruction with this method exhibits a small composition dependence, with a reconstruction bias of 5% for all mass groups predominantly. Assuming the H3a composition model, the energy resolution is better than 18% at 10 PeV. The reconstructed all-particle energy spectrum aligns well with the input spectrum, indicating the potential of the neural network approach for energy reconstruction and spectrum measurement. The current analysis does not account for the influence of hadronic interaction models on the reconstruction. Future work will focus on: (1) rigorous uncertainty quantification, (2) methodology refinement, (3) extending the method to the 100 PeV - 1EeV range.

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