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Nonparametric determination of energy spectra and mass composition of primary cosmic rays for slant depth

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Abstract. The data measured by the KASCADE (KArlsruhe Shower Core and Array DEtector) experiment are the basis for a multi-component analysis with the aim to determine the mass composition of the primary cosmic rays in the knee region. We discuss the methods used for estimating mass and energy of primary particles by utilizing neural network and nonparametric classification methods. By applying such techniques, measured data have been analyzed in an event-by-event mode and the mass and energy of individual EAS inducing particles are reconstructed. Results of all-particle energy spectra and relative abundances for different groups of primary particles are presented on basis of the electron and muon size data measured for different slant depths. The analyses of measured data indicate a transition to a heavier composition above a knee energy of ca. 5 PeV. It turns out that the mass composition depends on the particular set of observables (e.g. electron size N_e, truncated muon size N_μ^{tr}, hadron size N_h, most energetic hadron $E_h^{\max}$,...) being considered simultaneously in the analysis. Though different sets of observables result in a qualitativly similar mass composition, quantitatively this leads to conspicuous differences. In this way the limitations of a particular interaction model are revealed and the necessity of detailed studies of correlations of EAS observables as a test of the hadronic interaction model is demonstrated.

1 Introduction

The basic astrophysical questions in high-energy cosmic rays (CR) relate to the sources, the acceleration mechanisms and the propagation of CR through space. In particular, the observation of the change of the power law slope (the *knee*; Kulikov and Khristiansen (1959)) of the all-particle spectrum at an energy of a few times 10^{15} eV has induced considerable interest and experimental activities. Nevertheless, despite of many conjectures and attempts, the origin of the knee phenomenon has not yet been convincingly explained.

Due to the rapidly falling intensity and low fluxes, cosmic rays of energies above a few 10^{14} eV can be studied only indirectly by observations of extensive air showers (EAS) which are produced by successive interactions of the cosmic particles with nuclei of the Earth's atmosphere. EAS develop in the atmosphere as avalanche processes in three different main components: the most numerous electromagnetic (electron-photon) component, the muon component and the hadronic component. The properties of EAS are usually measured with large ground-based detector arrays. In most experiments only one or two components are studied. The KASCADE experiment (Doll et al., 1990; Klages et al., 1997) studies all three main components simultaneously and a large number of shower parameters are registered for each event. The determination of the primary's mass and energy, however, are obscured by the considerable fluctuations of EAS development.

Due to the complexity of this process the analysis of the EAS variables to deduce the properties of the primary particle relies on the comparison with Monte Carlo simulations (MC) of the shower development, including the detector response. Usually only one or two EAS parameters are measured and various simplified procedures are used to describe the relation between the observed EAS properties and the nature and energy of the primary particle. The simplification often implies the use of parameterizations of the aver-

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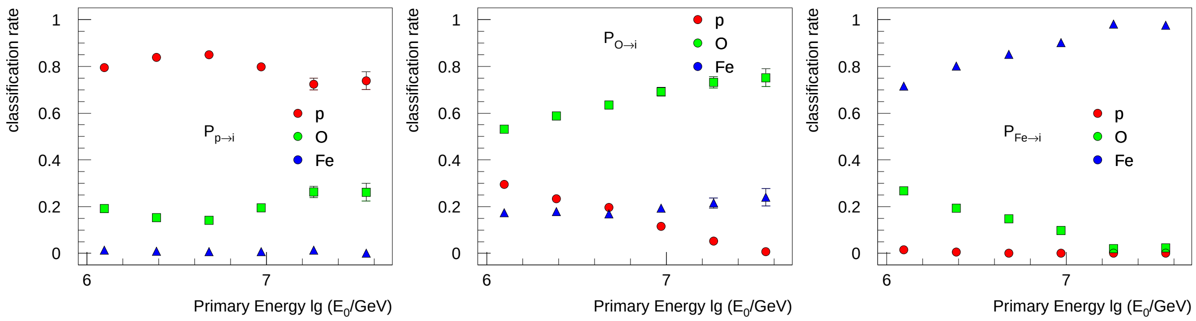

Fig. 1. Classification rate for three classes (p,O and Fe). The used observables are $N_\mu^{\rm tr}$ and $N_{\rm e}$.

age behavior, which may bias the results and limit the accuracy because fluctuations are neglected or not properly accounted for. For the analysis of multivariate parameter distributions and accounting for fluctuations more sophisticated methods are needed. The Bayesian methods and the neural network approaches, currently in vogue, meet these necessities. The methods facilitate an event-by-event analysis. Non-parametric procedures (Chilingarian, 1989) yield not only an estimate of the primary energy and mass composition, but they also allow to specify the uncertainty of the results in a quantitative way. For a detailed description of the applied methods see Antoni et al. (in press).

In the following we report on an investigation of the primary energy spectrum and mass composition in the energy range of $10^{15} - 5 \times 10^{16}\,$eV, based on the analysis of c. 4,000,000 EAS events. A subset of approximately 8000 showers with cores near the center of the hadron calorimeter yields information on all three components and has been studied in more detail. The simulated showers have been calculated with the program CORSIKA (Heck et al., 1998) and have been convoluted with the apparatus response using the GEANT code (CERN Long Writeups, 1993).

2 Simulation and reconstruction

The CORSIKA code incorporates several high-energy interaction models and is continuously under improvement. In particular, we consider the latest version of QGSJet (Kalmykov and Ostapchenko, 1993). QGSJet is a model based on the Gribov-Regge theory, and extrapolates the interaction features in a well defined way into energy regions which are far beyond energies available at accelerators, and especially into the extreme forward direction. For the low-energy interactions CORSIKA includes the GHEISHA code (Fesefeldt, 1985). The influence of the Earth's magnetic field on charged particle propagation is taken into account. As density profile of the atmosphere the U.S. standard atmosphere is chosen.

Samples of c. 300,000 proton, oxygen and iron-induced showers have been simulated. The energy distribution follows a power law with a spectral index of -1.5 in the energy range of $10^{14}\,$eV to $10^{17}\,$eV. The zenith angles are distributed in the range $[0^\circ, 35^\circ]$. The centers of the showers are spread uniformly over the area of the detector array. In addition, simulations are used where the shower core exceeds the surface of the hadron calorimeter by 2 m on each side. The signals observed in individual detectors are determined by tracking all secondary particles down to observation level and passing them through a detector response simulation program based on the GEANT package (CERN Long Writeups, 1993).

The reconstruction of the EAS observables which has been described in detail elsewhere (Haungs et al., 1996; Antoni et al., 2001; Unger et al., 1997; Hörandel, 1998; Weber et al., 1999), applies an iterative procedure for reconstructing the shower size parameters. At the end the algorithms deliver reconstructed observables like the electron and truncated muon sizes $N_{\rm e}$, $N_\mu^{\rm tr}$ (Weber et al., 1999), observables of the multiwire proportional chambers (Haungs et al., 1996) $N_\mu^\star$, D_{-6}, D_6 as well as hadronic observables like the reconstructed number of hadrons $N_{\rm h}^{E>100\,\rm GeV}$, the energy of the most energetic hadron observed in the shower $E_{\rm h}^{\rm max}$, and the energy sum of all reconstructed hadrons $\sum E_{\rm h}$ (Unger et al., 1997; Hörandel, 1998).

3 Mass composition and energy determination

Due to the finite number of simulated EAS and the correspondingly limited statistical accuracy it is hardly reasonable to use the full set of observables simultaneously to achieve a reliable result about mass composition. Hence we consider simultaneously only a few observables.

Each simulated or measured event is represented by an observation vector $x = (N_{\rm e}, N_\mu^{\rm tr}, \ldots)$ of the n observables. Applying the technique described elsewhere (Antoni et al., in press) the likelihood (probability density distribution) $\hat{p}(x|\omega_i)$ of an event x for each class $\omega_i \in \{\rm p, O, Fe\}$ can be calculated, i.e. the probability of an event x belonging to a given class ω_i. The classification rates $P_{ij} = \hat{P}_{\omega_i \to \omega_j}$ give the

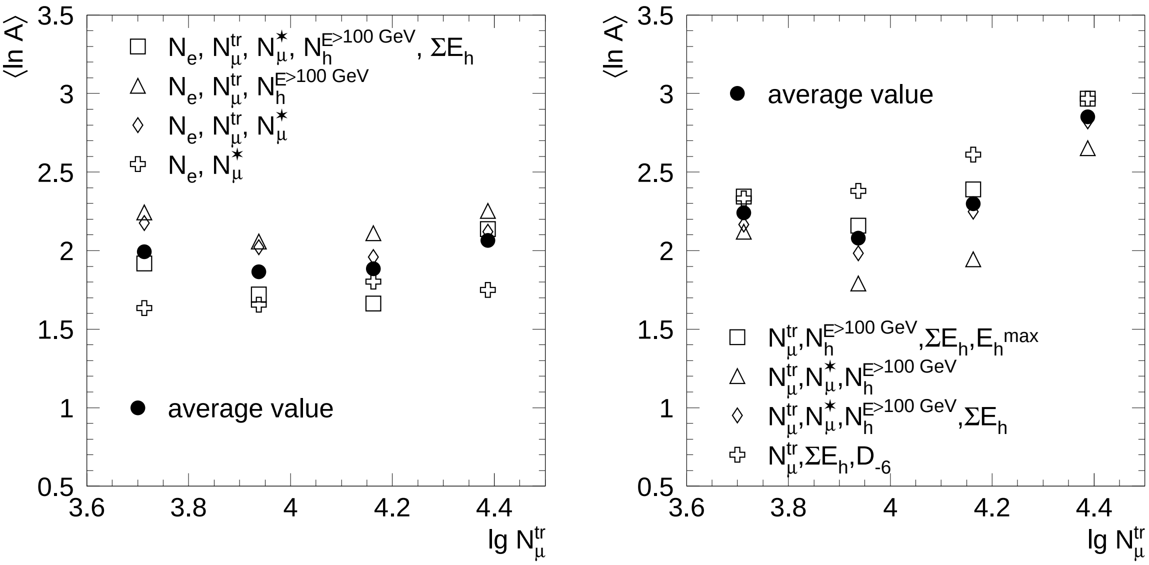

Fig. 2. Mean logarithmic mass $\langle \ln A \rangle$ resulting from the analysis of different sets of observables vs. $\lg N_\mu^{\mathrm{tr}}$ (QGSJet prediction). The sets displayed on the right do not include the observable N_{e}. The error bars are omitted to simplify the presentation of the synopsis, but are not larger than 25%. The knee energy corresponds to $\lg N_\mu^{\mathrm{tr}} \approx 4.15$.

fraction of correctly, P_{ii}, and wrongly, P_{ij} ($i \neq j$), classified events. An example for three mass classes is given in Figure 1. Of course, the sum of each row has to be 100%. Taking into account these classification rates the relative abundances of the different sets of observables included in the analysis are calculated and comprised in the determined mean logarithmic mass (see Figure 2). Of course, this procedure to calculate $\langle \ln A \rangle$ is to some extent arbitrary, but this is always implicit, when $\langle \ln A \rangle$ is used. In Figure 2 only the subset of showers is used where the shower core is within a circle of 6 m relative to the centre of the calorimeter. Remarkably, all sets omitting the electron size N_{e} (right graph) result in a heavier composition and a more pronounced increase above the knee. As the electron size has the strongest mass sensitivity, as well as the smallest fluctuations, the mass compositions are predominantly determined by N_{e} and N_μ^{tr} (left). Compositions resulting from sets of less sensitive observables differ from these values (right).

The fact that different combinations of observables taken into account in the analysis, lead apparently to different mass compositions (shown in Figure 2), reveals inadequacies of the reference model, i.e. that the degree of the intrinsic correlations for different observables differs from those of the real data. Otherwise the determined mass compositions should be identical within the statistical errrors.

To estimate the primary energy E the most important parameters are N_{e} and N_μ^{tr}, where N_μ^{tr} carries most of the information. Thus we use as data basis all data of the array. Due to the large computing time requirements we do not apply the Bayesian algorithms here and use instead neural networks only. In principal there are no basic arguments to prefer one particular method. Previous publications have demonstrated the consistency and equivalence of neural network and Bayesian methods in EAS analyzes (Roth, 1999; Chilingarian et al., 1997). Detailed studies show that the neural network estimator reconstructs the energy without any bias independently of the primary particle. Only the spread of the estimated energies varies from proton (largest) to iron (smallest). Figure 3 presents the reconstructed energy spectra of measured data resulting from the analysis of three different angular intervals. Within the errors no systematic discrepancy can be stated. The best-fit results are $\langle \gamma_1 \rangle = 2.76 \pm 0.003 \pm 0.03$, $\langle \gamma_2 \rangle = 3.1 \pm 0.02 \pm 0.06$ and $\langle E_{\mathrm{knee}} \rangle = 5 \times 10^6 \mathrm{GeV}$, including statistical errors as well as the methodical error derived from different training parameters of the neural network. It is obvious that the statistical errors are considerably smaller than the systematic uncertainties resulting from the small number of simulated events and from interaction models.

In the present status of our analysis procedure it is hardly possible to introduce more than three classes for the reconstruction of the mass composition. If this were to be attempted additional observables had to be included. A finer binning of the energy scale (beyond the energy resolution $(\Delta E/E)_{\mathrm{est}}$) for the spectra of single masses would require to deconvolute the resolution effects. In the actual analysis this step has not been performed and only the mean logarithmic variation of the mass composition (and no detailed energy spectra of the different mass classes) are presented in Figure 4. Remarkably, within the errors no systematic dis-

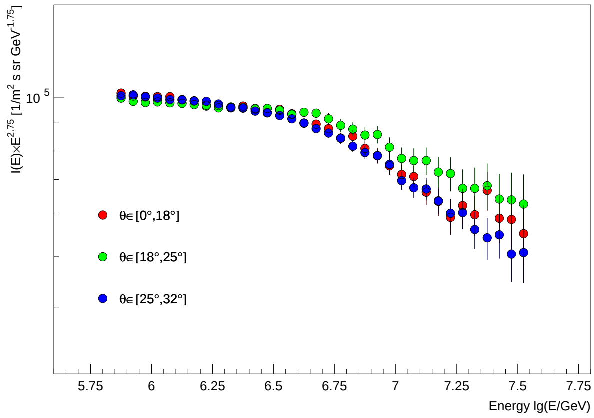

Fig. 3. Differential energy spectra resulting from the analysis of data of the KASCADE experiment using a neural network for three different zenith angle intervalls. The network was trained with CORSIKA showers using QGSJet. The used observables are N_μ^{tr} and N_{e}.

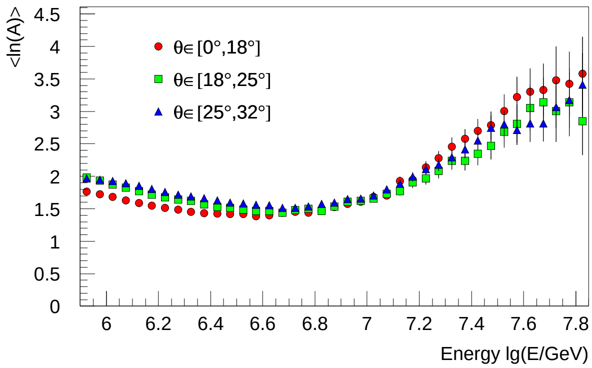

Fig. 4. Mean logarithmic mass as a function of primary energy from a neural network analysis, see legend of Figure 3.

crepancy can be stated, either. To analyze the data beyond this limit we need, in the simplest case, to construct from the misclassification matrices a matrix $A_{\mathrm{AA'};\mathrm{EE'}}$ deconvoluting mass and energy resolution effects. Hence, we cannot infer any significant fine structure from the all-particle energy spectrum beyond the resolution of $(\Delta E/E)_{\mathrm{est}}$.

4 Conclusion

It should be stressed that the present study emphasizes the methodical aspects of how to infer energy spectrum and mass composition of CR. A final answer requires improved statistical accuracy both in experiment and simulation and, first of all, a reduction of systematic uncertainties due to the incomplete knowledge of high-energy interactions. Nevertheless, our findings on spectrum and mass composition are compatible within the methodical accuracy to the results of other experiments.

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