Analysis of EAS observables of the KASCADE experiment by nonparametric methods for determining energy and elemental composition of cosmic rays

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Abstract

The KASCADE experiment measuring a larger number of EAS observables with an improved sampling of the electron-photon, hadron, and muon components than previous experiments provides data accurate enough for an event-by-event analysis of the energy dependence of the primary cosmic ray flux in the energy range of $10^{14} - 10^{16}$ eV. Bayesian nonparametric and neural network approaches enable to estimate the primary cosmic ray flux and the elemental composition. The major feature in the observed PeV energy region, the so called *knee* seems to be reproduced. The investigated EAS data indicate a tendency to a heavier composition above the knee.

Introduction.
The knowledge of the energy spectra of different components of primary cosmic rays in the knee region is of vital importance for testing alternative hypotheses of the cosmic ray (CR) origin and acceleration. The manifold interpretations of CR experiments have their causal connection in the inadequate knowledge about the characteristics of hadronic interactions above accelerator energies. Moreover uncertainties in the CR composition, caused by strong fluctuations of the shower parameters give rise to this ambiguities.
The presented detailed analysis of EAS benefits from the simultaneous measurement of a large number of observables for each individual event. Specific EAS parameters measurable by the experiment KASCADE (Klages 1997) are used, like the number of electrons N_e, the truncated number of muons N_μ^{tr} (Glasstetter 1997; Weber 1997), the number of hadrons with an energy larger than 100 GeV N_h^{100GeV}, the deposited energy in the iron sampling calorimeter (Hörandel 1997) $\sum E_h$, and the number of muons $N_\mu^\star$ with an energy threshold of $E_\mu \geq 2$ GeV measured below the central calorimeter (Haungs 1996). The techniques presented by Chilingarian (Chilingarian 1998) on the basis of nonparametric multivariate methods (neural networks, Bayesian decision making) are developed and applied to infer the mass and the energy of primary particles on an event-by-event analysis.

Simulations.
Simulations have been performed with the models VENUS, and QGSJet in the energy range $10^{14} - 3.16 \cdot 10^{16}$ eV using the CORSIKA code version 5.2 (Heck 1997). The

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zenith angle was chosen between 15° and 20°. For each primary (p, He, O, Si, and Fe) approximately 2000 EAS events have been simulated, distributed in the energy range with an decreasing particle flux. The core of the EAS lies within a 5 m radius away from the centre of the central detector. The response of all detector components is taken into account in great detail using the GEANT code. The number of simulated events is limited by to the available computer power.

Energy and mass sensitive observables.
The number of electrons as a classical EAS measure provide a very good ability to distinguish between light and heavy particles. Just so in analyses done for different other single

Table 1: The classification rates $P_{j\to i}$ for three groups of primary nuclei using different sets of observables (VENUS model).

$N_\mu^\star$, $\sum E_h$.

	p	O	Fe
$P_{p\to i}$	0.58	0.27	0.15
$P_{O\to i}$	0.34	0.33	0.32
$P_{Fe\to i}$	0.22	0.30	0.48

N_μ^{tr}, N_e.

	p	O	Fe
$P_{p\to i}$	0.68	0.26	0.06
$P_{O\to i}$	0.21	0.49	0.30
$P_{Fe\to i}$	0.09	0.31	0.60

N_μ^{tr}, N_e, $N_\mu^\star$, $\sum E_h$.

	p	O	Fe
$P_{p\to i}$	0.71	0.24	0.05
$P_{O\to i}$	0.18	0.52	0.30
$P_{Fe\to i}$	0.07	0.26	0.67

Table 2: Geometric mean of correct classification as a measure of separability for different groups of primaries(VENUS model).

	5 groups	3 groups	2 groups
$N_\mu^\star$, $\sum E_h$	0.154	0.462	0.708
N_μ^{tr}, N_e	0.341	0.584	0.887
N_μ^{tr}, N_e, $N_\mu^\star$,$\sum E_h$	0.38	0.626	0.894

detector components (see refs above) it is shown that in general the signatures obtained by the central part of the KASCADE detector arrangement are mass sensitive parameters (N_h^{100GeV}, $\sum E_h$, $N_\mu^\star$, ...). The truncated number of muons N_μ^{tr} (the integration of the lateral distribution function limited to the range of the fit region caused by the array layout), however, is considered as a good energy estimator as it shows only marginal sensitivity to the mass of the primary particle according to simulations (Weber 1997). Due to the limited statistics of simulated and measured events (approximately 2500 events according to the simulations) the analysis of measured data using information in the centre of the

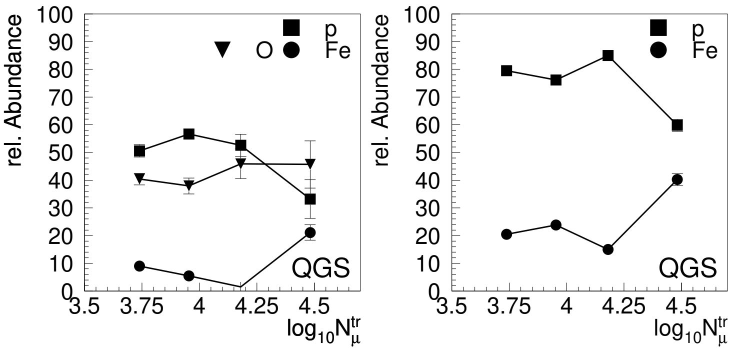

Fig. 1: **QGSJet model:** Relative abundance of primary particles vs. truncated muon size N_μ^{tr}. A Bayesian analysis was applied using two (right) and three (left) classes.

EAS core is restricted to at most three types of primaries: light (p), medium (O), and heavy (Fe).

Table 1 shows, as an example, the nearly energy independent classification rates from the Bayesian analysis for three groups of primaries, which are calculated for different sets of observables. They represent the possibility of correct classification $P_{i\to i}$ (or misclassification $P_{i\to j}$). As expected the combination of all observables together provides the best classification. However, even the increase of the $P_{i\to i}$ from the set $\{N_\mu^{tr}, N_e\}$ to the set $\{N_\mu^{tr}, N_e, N_\mu^{\star}, \sum E_h\}$ is not very large, because the correlations of these parameters are strongly model dependent. Hence, applying different models in a nonparametric analysis can lead to completely different results. The geometric mean $\sqrt[N]{\prod_{i=1}^{N} P_{i\to i}}$ of the diagonal elements $P_{i\to i}$ in Table 2 reflects once more the increasing separability by taking into account more than two observables. Even when taking the full information into consideration the separability for five groups is a crucial point and must be studied in more detail.

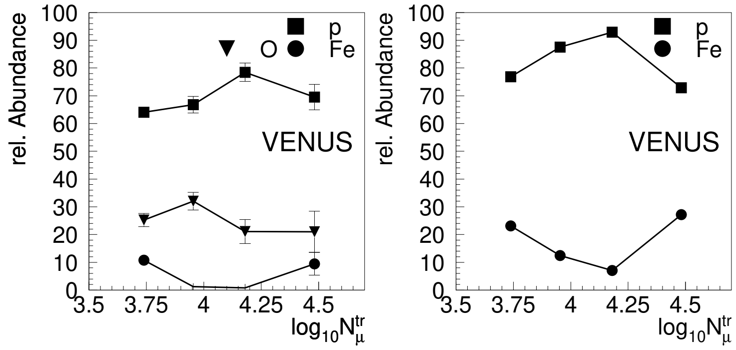

Fig. 2: **VENUS model:** Relative abundance of primary particles vs. truncated muon size N_μ^{tr}. A Bayesian analysis was applied using two (right) and three (left) classes.

Mass and energy estimation.

As shown in Figures 1 and 2 there is a tendency to have a lighter composition in the knee region ($log_{10}\ N_\mu^{tr} \approx 4.1$) using the Bayesian decision making procedure independently of the applied model and the number of chosen groups to divide in (2 or 3). At higher energies the composition is getting heavier. In the case of VENUS the composition seems to be in general lighter than in the QGSJet case. Results of different combinations of observables (N_μ^{tr}, N_e, $N_\mu^{\star}$,$\sum E_h$, and E_h^{max}) which show similar behaviour are combined to average values. The result for three groups applying the neural network (Figure 3) method corroborates the Bayesian one. The error of the misclassification is taken into consideration only by the Bayesian procedure.

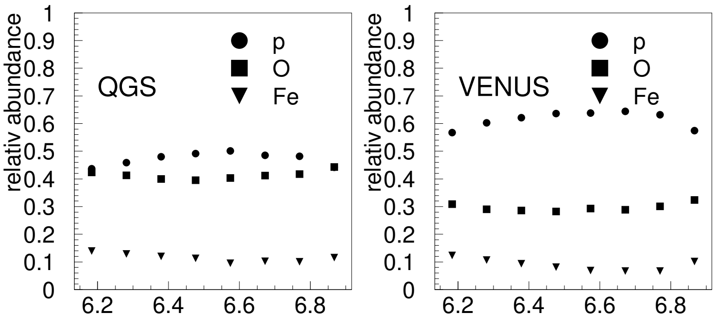

Fig. 3: Relative abundance of primary particles vs. estimated energy of a neural network analysis for three classes (QGSJet and VENUS model).

Instead of only 2400 events in the Bayesian case in the neural net case there were ca. 460.000 events processed by using only the N_μ^{tr}, N_e observables. This provides the opportunity to use the large amount of data taken by the KASCADE detector field. The abscissa scale is the estimated energy which is calculated by a neural network. The lack of Monte-Carlo simulations in the high-energy region prevents the estimation of energies larger than $8 \cdot 10^{15}$ eV. Therefore, the increase of the heavier components in Figure 3 is not as strong as indicated in Figures 2 and 3 ($log_{10}\, N_\mu^{tr} = 4.5 \approx 1 \cdot 10^{16}$ eV). The errors given in the Figures 1,2, and 3 are of statistical nature only. Systematic errors like finite number of groups and efficiencies are of the order of 5-15%. The all-particle energy spectrum resulting from different networks shows strong model dependence ($\gamma_{QGSJet} = -2.61$ and $\gamma_{VENUS} = -2.77$). The slope difference 0.16 between the models below the knee is even larger than the methodical errors of 0.05.

Conclusion.

The presented results on the energy dependence of the elemental composition are of preliminary character. The major feature of the observed energy region (the abrupt change of the composition) seems to be reproduced. The two models indicate the same tendency on different scales of relative abundances.

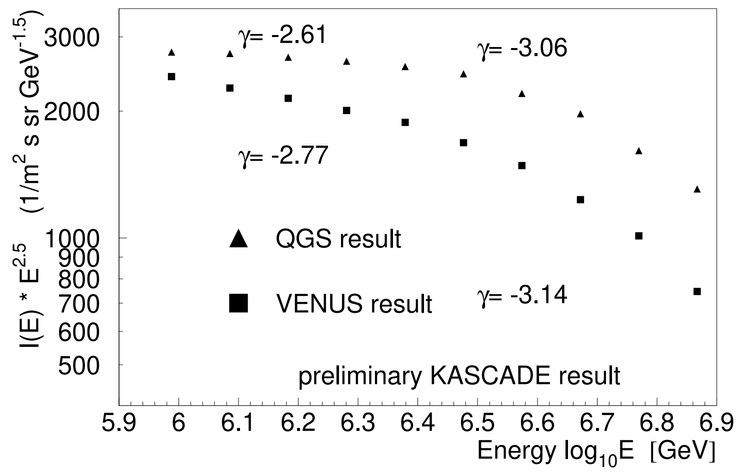

Fig. 4: All-particle energy spectrum as a result of a neural net analysis (QGSJet and VENUS data trained networks were used).

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