A Multivariate Approach for the Determination of the Mass Composition in the Knee Region

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Abstract

New results of a multivariate analysis to determine the chemical composition obtained with the KASCADE detector are presented. Taking the information of the electron-photon, the hadron, and the muon detectors for an event-by-event analysis into account the energy dependence of the primary cosmic ray composition in the *knee* region is estimated. Bayesian nonparametric and neural network methods are used. The investigated EAS events indicate a tendency to a heavier composition above the *knee*.

1 Introduction:

The origin of cosmic rays (CR) is still fraught with insufficient knowledge and uncertainty. The analysis of the energy spectrum and the chemical composition remains one of the most important constraints on theoretical models. To infer the primary mass not only the electromagnetic but also hadronic and muonic information provided by the KASCADE detector (Klages, 1997) is used in an event-by-event examination. The novelty of this approach is the possibility to study the mass composition contingent upon the used observables. Comparing the results the differences in various observables can be investigated.

2 EAS Reconstruction:

2.1 The detector setup: The basic concept of the KASCADE experiment is to measure a large number of observables for each individual event with good accuracy and high degree of sampling. For this purpose 252 detector stations form a detector array of $200 \times 200\mathrm{m}^2$ containing liquid scintillation detectors for detecting the electromagnetic component on the top of a lead/iron absorber plate as well as plastic scintillators below the shielding. A detector coverage of more than 1% for the electromagnetic and about 2% for the muonic component EAS is achieved. In combination with a precise measurement of the hadrons using an iron sampling calorimeter, the shower core can be investigated in great detail. The main part of the central detector system is a large hadron calorimeter. It consists of a $20 \times 16\mathrm{m}^2$ iron stack with eight horizontal gaps. 10,000 ionisation chambers are used in the six gaps and below the iron stack to measure of hadronic energy in a total of 40,000 electronic channels. The third gap is equipped with 456 scintillation detectors for triggering and timing purposes. Below the iron stack two layers of multiwire proportional chambers (MWPCs) measure muon tracks and allow to study structures of the muon lateral distribution in EAS cores.

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2.2 Relevant Observables: The presented detailed analysis of EAS presented below benefits from the simultaneous measurement of a large number of quantities for each individual event. This enables multidimensional analyses for the reconstruction of the energy and the mass of the primary.

Specific EAS parameters measurable by the experiment KASCADE 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 N_h^{100GeV} with an energy larger than 100 GeV, the sum of the energy of this hadrons $\sum E_h$, the energy of the most energetic hadron $\max E_h$ (Hörandel, 1997), and the number of muons $N_\mu^\star$ with an energy threshold of $E_\mu \geq 2$ GeV measured below the central calorimeter by the MWPCs (Haungs, 1996).

Two sets of data are used. "Selection I" uses the information from the array of field stations on electrons and muons. It permits to analyse the data with good statistical accuracy but has no information from the central detector. "Selection II" uses in addition many observables measured in the central detector but has the disadvantage of a reduced data sample (Roth, 1999).

Therefore 720,000 events with an energy larger than $E \approx 5 \cdot 10^{14}\,\mathrm{eV}$ and a maximal core distance to the centre of the field array of 91 m are selected (set "selection I"). Approximately 8000 high-energetic ($E > 10^{15}\,\mathrm{eV}$), central showers are collected by cuts of N_μ^{tr} ($> 10^{3.6}$), the core location ($R_{core} < 5\,\mathrm{m}$ from the centre of the central detector system), at least one Hadron with an energy above 100 GeV and 10 muons in the MWPCs (set "selection II").

2.3 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 (Heck, 1998).

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 5 m radius from the centre of the central detector. The response of all detector components is taken into account in detail using the GEANT code. Afterwards the simulated events are treated like measured ones. Therefore measured and simulated data reconstructed with the same procedures.

3 Mass Estimation:

The number of electrons as a classical EAS measure provide a very good ability to distinguish between light and heavy particles. In analyses performed for different other observables (see refs above) it has been shown that in general the signals obtained by the central detector contain mass sensitive parameters (e.g. N_h^{100GeV}, $\sum E_h$, $N_\mu^\star$, $\ldots$). 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 the analysis of measured data using information in the centre of the 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 a Bayesian analysis described in brief in (Chilingarian, 1998) 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.

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

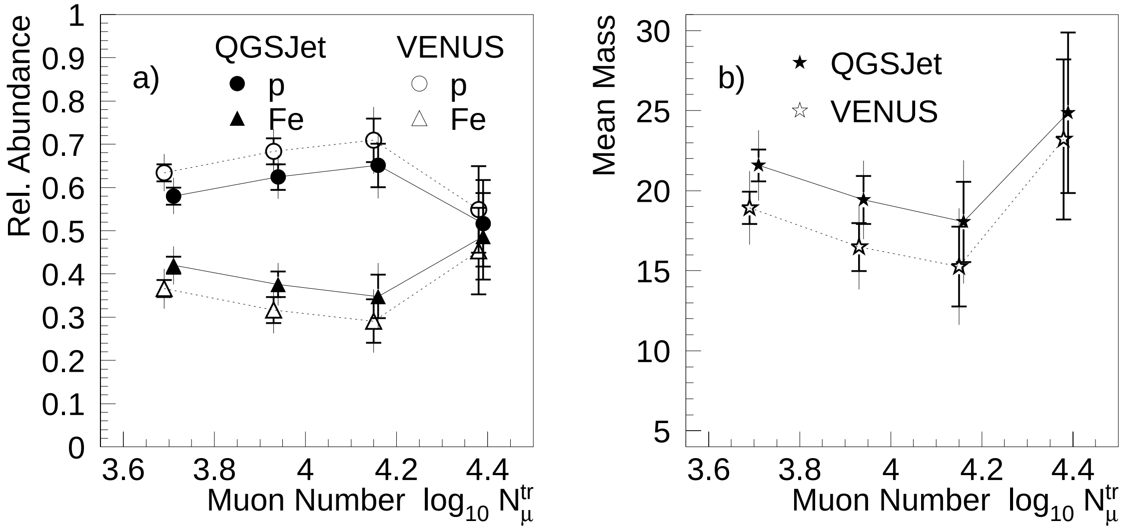

Figure 1: a) Reconstructed chemical composition for two class case and b) mean mass vs. number of muons(QGSJet and VENUS).

However, 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 fluctuations of the correlations are large. 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 $P_{i\to i}$

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
$N_\mu^\star$, $\sum E_h$	0.15	0.46	0.71
N_μ^{tr}, N_e	0.34	0.58	0.89
N_μ^{tr}, N_e, $N_\mu^\star$,$\sum E_h$	0.38	0.63	0.89

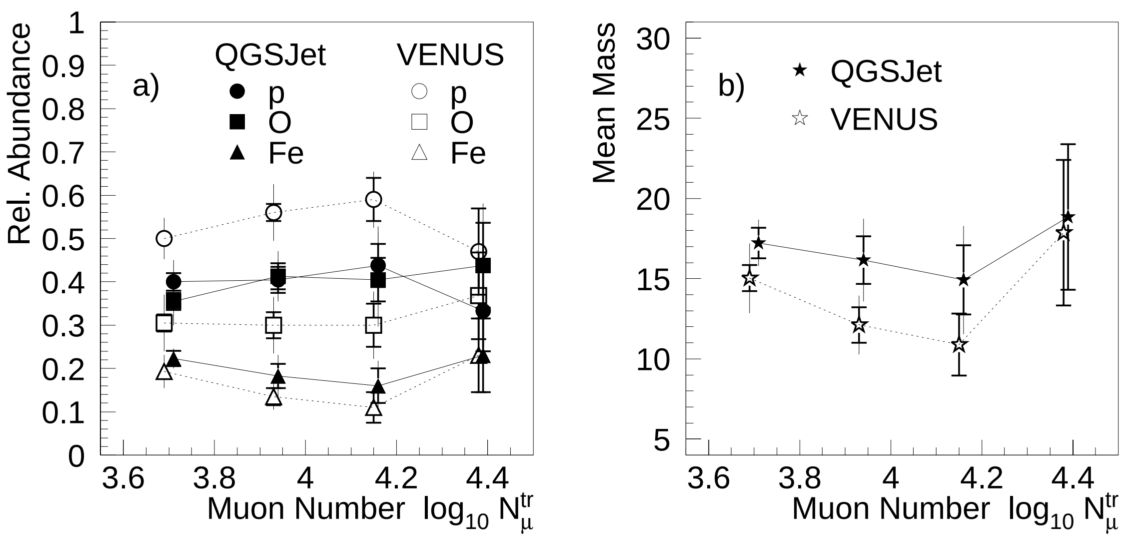

Figure 2: a) Reconstructed chemical composition for three class case and b) mean mass vs. number of muons (QGSJet and VENUS).

(see table 1) in table 2 reflects once more the increasing separability by taking into account more than two observables. Even when taking the full available information (i.e. four observables) into consideration the separability for five groups is a crucial point and must be studied in more detail.

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 (i.e. muon number) the composition is getting heavier. In 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 $\max E_h$) which show similar behaviour are combined to average values. The error of the misclassification is taken into consideration and also included as thin error lines in figures 1 and 2. Instead of only few thousand events in case of the set "selection II" the set "selection I" provides more than 700.000 events to be analysed by using only the muonic and electromagnetic components. The results of the different sets are shown in figure 3. They corroborate each other. The abscissa scale is the estimated energy which is calculated by a neural network for each single event (Chilingarian, 1999).

4 Conclusion:

The presented results on the energy dependence of the elemental composition are of preliminary character. A tendency of increasing heavy primaries beyond and a slightly decreasing before the *knee* is confirmed, like other KASCADE results. The two models indicate the same tendency on different scales of mean masses. Comparing figures 1 and 2 the mean mass depends obviously on the number of classes. One has to take as many classes as possible into account to minimise the biasing effect of too few classes, but bearing in mind the limitation of the classification accuracy.

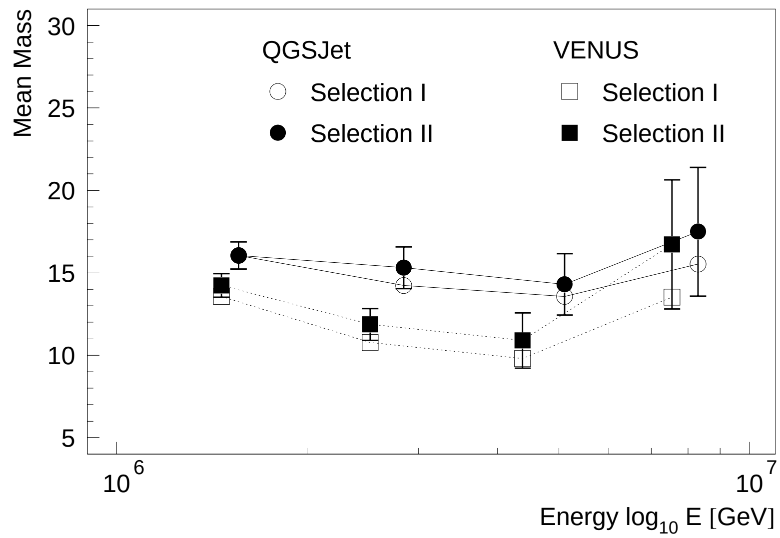

Figure 3: Reconstructed chemical composition for different data sets ("selections I+II") and the models QGSJet and VENUS vs. energy (see text for explanation).

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