# Estimation of the Primary Mass with Hadronic Observables in EAS Cores

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**Abstract**

The primary cosmic-ray mass composition is estimated using the hadronic component of EAS measured by the large hadron calorimeter of the KASCADE experiment. Methods for evaluating the mean mass are described, model dependences are discussed and results are presented. The data indicate an increase of the mean mass with rising primary energy, especially beyond the *knee*.

## 1 Proem

The experiment KASCADE (Klages et al., 1997) has in its centre of array stations a large hadron calorimeter to study the core of EAS in the energy region around the *knee*. In the following, observables are presented which allow to infer the primary mass composition from particle distributions in the hadronic core. However, a correct modelling of the interactions in the atmosphere is mandatory to extract reliable conclusions about the primary mass. The procedure is very prone to even small changes in the interaction mechanism. Two interaction models, namely QGSJET (Kalmykov & Ostapchenko, 1993) and VENUS (Werner, 1993) as implemented in the EAS simulation code CORSIKA (Heck et al., 1998) are used. These two models, based on the Gribov Regge theory, have been chosen because their solid theoretical ground allows best to extrapolate from collider measurements to higher energies, forward kinematical regions and nucleus-nucleus interactions. They have been proven to describe the hadronic observables reasonably well (Antoni et al., 1999).

## 2 Experimental Set-up and Measurements

KASCADE measures all three components of an EAS simultaneously, i.e. the electromagnetic, the muonic, and the hadronic part. The latter is studied with the 320 $m^2$ large iron calorimeter which is 11 interaction lengths deep and interspersed with eight layers of active detectors. These are ionization chambers filled with the room temperature liquids tetramethylsilane and tetramethylpentane. The electrodes of $25 \times 25$ $cm^2$ size are matched to the mean lateral spread of hadronic cascades in iron and allow the resolve individual hadrons with 40 cm separation. For hadrons above a threshold energy of 50 GeV impact point, energy, and direction of incidence are reconstructed. Details of the calorimeter performance are given in (Engler et al., 1999).
For the investigations presented below, events had to fulfill the following requirements: More than two hadrons are reconstructed, the zenith angle of the shower is less than $30^\circ$ and the core, as determined by the array

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stations with a resolution of about 2 m, hits the calorimeter or lies within 1.5 m distance outside its boundary. About 40 000 showers meet these conditions.
The showers are classified according to their truncated muon size $N_\mu^{tr}$ as measured by the array. $N_\mu^{tr}$ is obtained experimentally by integrating the muon lateral distribution in the range 40-200 m. $N_\mu^{tr}$ is a good estimator of the primary energy $E_0$, because for selected showers hitting the calorimeter $E_0 \propto N_\mu^{tr\,0,98}$, nearly irrespective of the primary mass.

# 3 Simulations

Simulations were performed using the CORSIKA version 5.2 and 5.62. A sample of 7000 p and Fe events were simulated with QGSJET, and 2000 showers were generated with VENUS, each for p, He, O, Si and Fe primaries. The showers were distributed in the energy range of 0.1 to 31.6 PeV according to a power law with a differential index of 2.7 and were spread in the zenith angle in the intervall of $15^\circ$ to $20^\circ$. The shower axes were distributed uniformly over the calorimeter surface extended by 2 m beyond its boundary.

# 4 Results

In Fig.1 two examples of hadronic observables are presented which both distinctly depend on the primary mass. The graph on the left–hand shows the lateral hadron density and on the right–hand the distance distributions in *minimum-spanning trees* (MST), both for $N_\mu^{tr}$ intervalls that correspond to primary energies around 1.2 and 2 PeV, respectively. A MST connects all hadrons to each other in a plane perpendicular to the shower axis. It is that configuration where the sum of all connections weighted by the inverse energy sum of its neighbours has a minimum. Presented are results from the simulations for primary protons and Fe nuclei. The shaded area, hence, presents the region allowed for any primary mass composition. The measured data, indeed, fall in-between, and the distance to the two extrema determines the mean mass. Actually, in this way the logarithmic mass $\langle \ln A \rangle$ is obtained, because most of the observables depend only on the mass logarithmically. This can be infered from Fig.2 where the mean distance between the extrema is plotted versus $\ln A$ for the lateral hadron density, see the left–handed graph in Fig.1.

In a similar manner four other observables are investigated, namely the lateral energy density, the en-

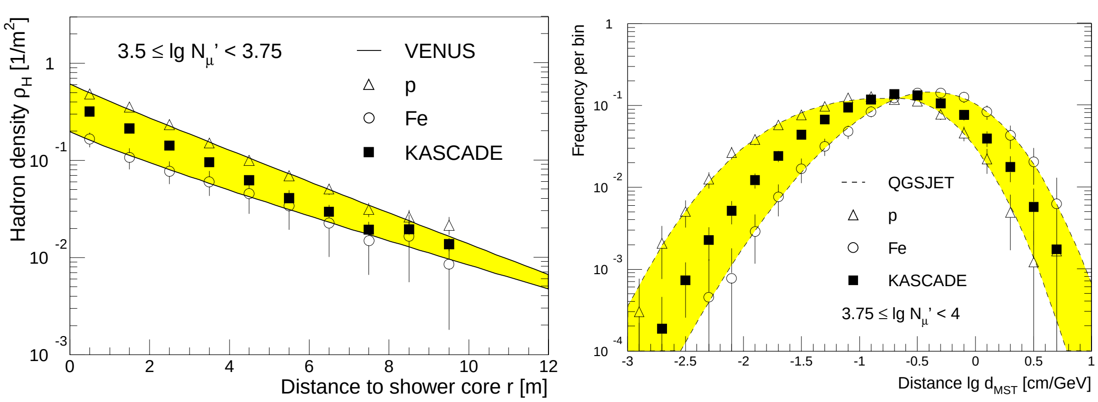


Figure 1: Lateral hadron density (left–hand) and distances in a MST (right–hand) for a muon number interval as indicated. The data are compared with simulations using VENUS and QGSJET for primary protons and iron nuclei.

ergy spectrum of hadrons, the energy of the most energetic hadron and the distribution of the fractional energy of hadrons with respect to the most energetic hadron in the shower. The latter and the MST indicate to some extent the granularity in a hadronic core, the first in energy, the second in space. For heavy primaries these two observables are expected to exhibit a rather uniform distribution whereas primary protons should show up with pronounced fluctuations.

For all six observables a mean mass parameter $\lambda$ is calculated from the distance to the two extreme compositions: $\lambda = 0$ for a pure proton and $\lambda = 1$ for a pure iron composition. Fig. 3 shows this parameter as a function of $N_\mu^{tr}$, i.e. approximately the primary energy. A steady rise with energy can be noticed for all six variables. The fluctuations, however, are large. For this reason the mean values $\langle\lambda\rangle$ of these observables and for both interaction models are combined and the corresponding $\langle \ln A\rangle$ determined.

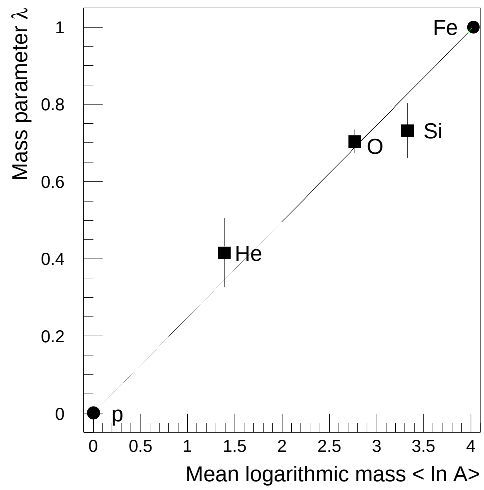


**Figure 2:** The mass parameter $\lambda$ as obtained from CORSIKA simulations using VENUS.

Fig.4 presents the results in context of a compilation of recent world data. Plotted are KASCADE figures of the present analysis using the hadrons. In addition, two further analyses are given, viz. investigations utilizing electrons and muons as measured in the array detectors (Weber et al., 1999) and a Bayes classification on an event–by–event basis employing seven observables from both the array and the central detector (Roth et al., 1999).

Direct measurements above the atmosphere are presented by the shaded area as taken from (Wiebel-Sooth, 1998). The two points at 1 PeV are extrapolations from direct measurements given in recent review talks, (Shibata 1998) and (Watson 1997). The hadron analysis yields relative high values of $\ln A$ following the trend indicated by the RUNJOB data and the measurements on the Chacaltaya. One notices that around 1 PeV the Bayes classification using all components measured in the KASCADE experiment matches the extrapolations best. The hadrons alone seem to yield a too heavy and the electrons a too light composition.

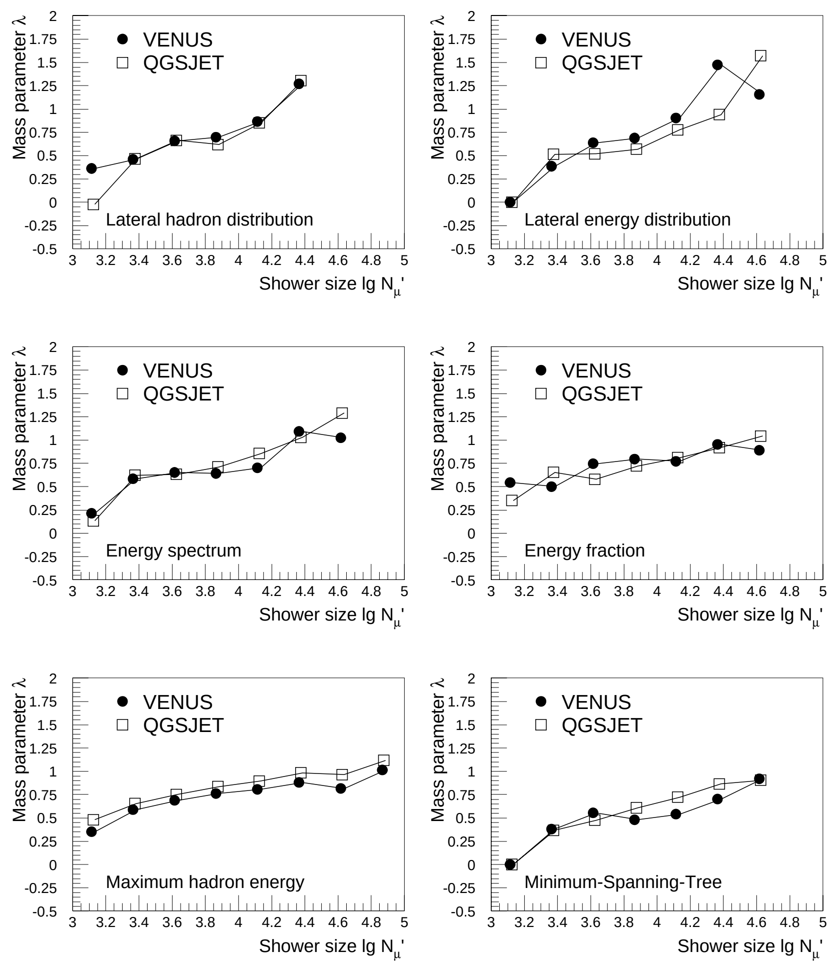


**Figure 3:** The mass parameter obtained from six observables vs. the truncated muon number. Values at $N_\mu^{tr} = 3.1$ are not corrected for trigger efficiency of the array.

Several other investigations have revealed that the simulations generate too many hadrons at observation level, see e.g. (Antoni et al., 1999) or (Risse et al., 1999). One, therefore, is tempted to conjecture that the missing hadrons are interpreted by the present analysis as a heavy composition. Vice versa the simulations seem to generate too few electrons which would account for the light composition found in the analysis using the electromagnetic component only. Whether the interaction codes really generate such an imbalance between the hadronic and electromagnetic component cannot be decided at the moment but we endeavour to study the effect by forthcoming measurements.

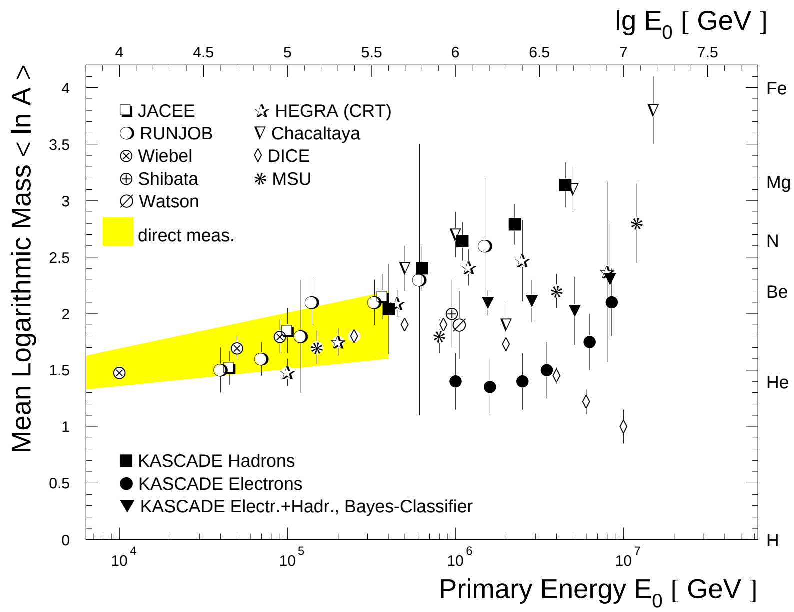


**Figure 4:** Mean logarithmic mass vs. primary energy. The shaded area represents direct measurements, compilation (Wiebel-Sooth, 1998), EAS measurements Chacaltaya (Shirasaki et al., 1997), HEGRA (Bernlöhr et al., 1998), DICE (Swordy 1998), MSU (Fomin et al., 1998).

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