Test of High–Energy Hadronic Interaction Models using EAS Data

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Abstract

The analysis of extensive air shower (EAS) data depends strongly on simulations of the air shower development in the atmosphere. The most critical point are the hadronic interaction models used in shower simulation codes for energies far above collider energies. The investigation of the hadronic component of EAS allows a detailed study of interaction models. Using several observables of this air shower component as observed with the KASCADE hadron calorimeter a comparison between measurements and simulations is presented. The program CORSIKA with the hadronic models QGSJET, VENUS, and SIBYLL has been used for the shower simulation. It turns out that QGSJET describes the measurements best followed by the model VENUS.

1 Proem:

To investigate cosmic rays in the PeV region and above one is forced to observe extensive air showers induced in the atmosphere. To interpret the secondary particles at ground level the measured data are compared with results from Monte Carlo calculations, describing the development of the EAS in the atmosphere and the individual detectors.

The interactions of the secondary particles in the detectors at ground level are well known from collider experiments. More complex is the description of the high energy hadronic interactions of the primary particles with the air nuclei and the production of secondary particles at energies above today's collider energies.

Many phenomenological models have been developed to reproduce the experimental results. Extrapolations to higher energies, to small angles, and to nucleus–nucleus collisions have been performed under different theoretical assumptions. Many EAS experiments have used specific models to determine the primary energy and to extract information about the primary mass composition leading to partly contradictory results. Experience shows that different models can lead to different results when applied to the same data.

Therefore, it is of crucial importance to verify the individual models experimentally as thoroughly as possible. The KASCADE experiment (Klages et al. 1997) allows the detailed study of different EAS observables of the hadronic, electromagnetic, and muonic component. By comparison of measured results with data obtained from Monte Carlo calculations of the EAS development in the atmosphere using the program CORSIKA (Heck et al. 1998), different models implemented in the latter can be tested.

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2 Experimental Set up:

The fine–segmented hadron calorimeter of the KASCADE experiment allows to measure individual hadrons in the core of an EAS. The 300 m^2 iron–sampling–calorimeter is equipped with 10 000 liquid ionisation chambers in eight layers (Engler et al. 1999). A layer of plastic scintillators on top of the calorimeter and a second one below the third iron layer act as trigger for the ionisation chambers. The electromagnetic and muonic component are measured by a 200×200 m^2 array of 252 detector stations equipped with scintillation counters. More details are given in these proceedings (Hörandel et al. 1999).

3 Measurements and simulations:

About 10^8 events were recorded from October 1996 to August 1998. In 6×10^6 events, at least one hadron was reconstructed. Events accepted for the present analysis have to fulfil the following requirements: More than two hadrons are reconstructed, the zenith angle of the shower is less than 30° and the core, as determined by the scintillator array, hits the calorimeter or lies within 1.5 m distance outside its boundary. For showers with a primary energy of more than 1 PeV the core can be measured in addition using the first calorimeter layer by the electromagnetic punch-through. The fine sampling of the ionisation chambers yields 0.5 m spatial resolution for the core position. For events with such a precise core position it has to lie within the calorimeter at least 1 m distance from its boundary. After all cuts 40 000 events were left for the final analysis.

EAS simulations are performed using the CORSIKA versions 5.2 and 5.62 as described in (Heck et al. 1998). The interaction models chosen in the tests are VENUS 4.12 (Werner 1993), QGSJET (Kalmykov et al. 1993), and SIBYLL 1.6 (Fletcher et al. 1994). A sample of 2000 proton and iron–induced showers were simulated with SIBYLL and 7000 p and Fe events with QGSJET. With VENUS 2000 showers were generated, each for p, He, O, Si, and Fe primaries. The showers were distributed in the energy range from 0.1 PeV up to 31.6 PeV according to a power law with a differential index of -2.7 and within an zenith angle intervall from 15° to 20°. In addition the changing of the spectral index to -3.1 at the knee position was taken into account in a second set of calculations. The shower axes were spread uniformly over the calorimeter surface extended by 2 m beyond its boundary.

In order to determine the signals in the individual detectors, all secondary particles at ground level are passed through a detector simulation program using the GEANT package. By these means, the instrumental response is taken into account and the simulated events are analysed in the same way as the experimental data, an important aspect to avoid systematic biases by reconstruction algorithms.

4 Results:

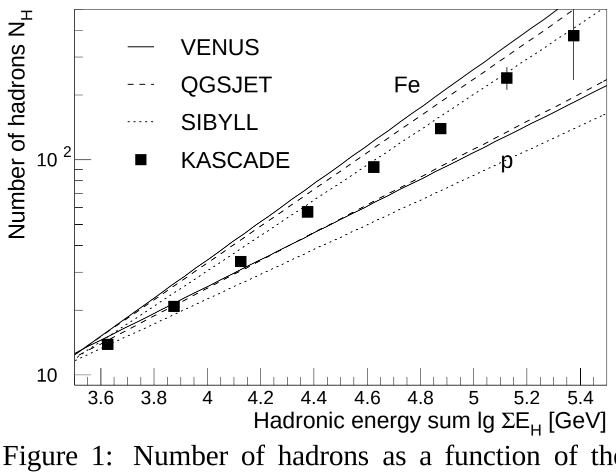

Figure 1: Number of hadrons as a function of the hadronic energy sum.

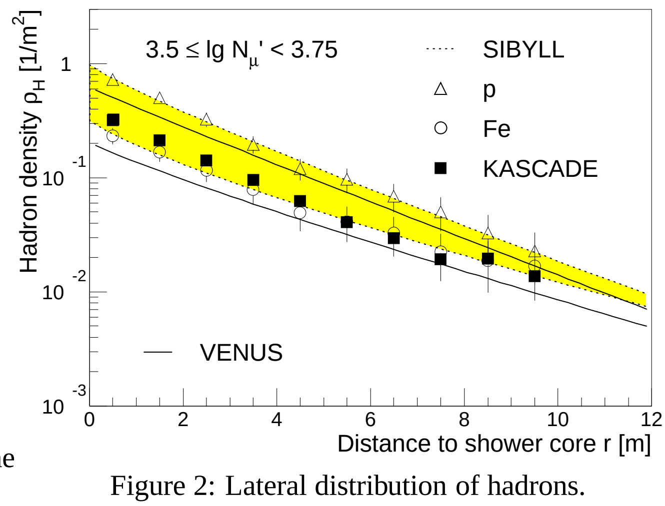

Figure 2: Lateral distribution of hadrons.

The cosmic ray mass composition is poorly known above 0.5 PeV. Therefore, the interaction models can be tested only by comparing their predictions for the extreme primary masses, namely protons and iron nuclei. If the measured observable lies in between these predictions, the corresponding model is compatible with the data, otherwise we have to exclude it.

When comparing measurements and simulations, it is necessary to divide the data into intervals of fixed shower size. For our investigations we use shower size parameters of all three components, i.e. the number of electrons and muons as well as the hadronic energy sum. For the muonic shower size a muon number obtained by integration of the muon lateral distribution in the range from 40 to 200 m is used. Several hadronic observables have been investigated (Hörandel 1998), some of them are discussed in the following.

A first example of the investigations is presented in Figure 1. The number of hadrons in each shower is plotted versus the hadronic energy sum. Results from EAS simulations with CORSIKA for primary protons and iron nuclei using different interaction models are compared with measurements. Since only hadronic observables are involved in this plot, the self consistent description of the hadronic component within the models can be tested. The abscissa covers an energy range of approximately 0.5 PeV to 15 PeV. Almost the same results are obtained by the models VENUS and QGSJET. The measurements lie well in between the proton and iron predictions, exhibiting an increase of the mean mass with rising energy. SIBYLL generates lower hadron numbers relative to the two other models. Comparison of these predictions to the measurements leads to an incredibly high and energy independent iron content of cosmic rays.

The lateral distribution of hadrons is shown in Figure 2 for a muonic shower size interval corresponding to an energy of about 1.2 PeV. VENUS and SIBYLL predictions are compared with measured results. The measurements are compatible with the VENUS calculations leaving the elemental composition to be somewhere between pure proton or pure iron primaries. QGSJET produces almost the same results and is therefore not shown. In contradiction to that, the measurements follow the lower boundary of the SIBYLL calculations, suggesting, that all primaries are iron nuclei, at this energy obviously an improbable result. The lateral distribution demonstrates, and other observables in a simular manner as reported previously (Antoni et al. 1999), that the SIBYLL code generates

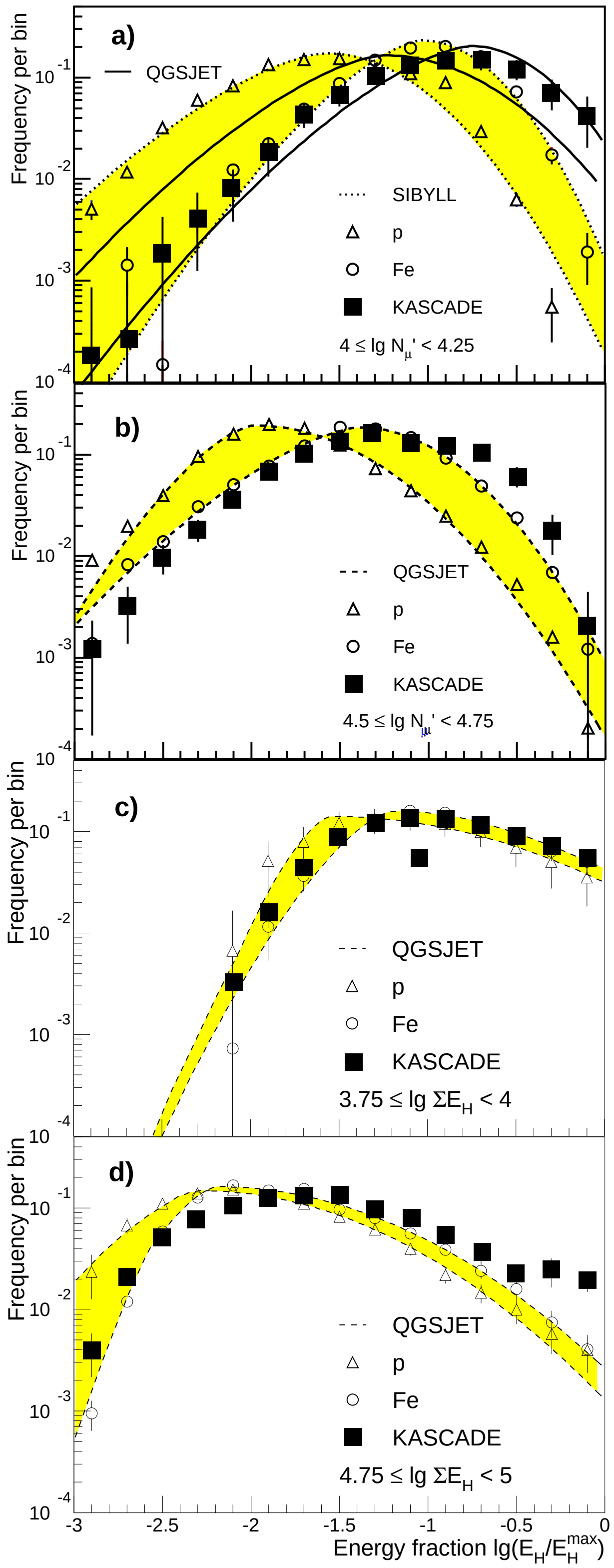

Figure 3: Frequency distribution of energy fraction for different interaction models and energy ranges.

too low muon numbers leading to a heavier elemental composition of cosmic rays. As demonstrated in Figure 1 this behaviour is not limited to muonic shower size bins, the same effect can be observed also in hadronic shower size intervals. In general VENUS produces mostly similar results as QGSJET but exhibits some deviations when the results are classified in electromagnetic shower size bins (Hörandel 1998).

A further observable is the frequency distribution of the fraction of the energy of each hadron normalised to the maximum hadron energy in a particular shower as shown in Figure 3. CORSIKA predictions for pure proton and iron nuclei using the models QGSJET and SIBYLL are compared with measured results for different energy ranges for muonic and hadronic shower size intervals. The first interval (Fig. 3a) corresponds to an energy of approximately 2 PeV, just below the knee position. The data are compatible to the QGSJET predictions, exhibiting a composition somewhere in between protons and iron nuclei. The picture shows one more example that SIBYLL is not able to describe the measurements satisfactorily. An example for a hadronic shower size bin is given in Figure 3c, the interval corresponds to about 1 PeV. It is remarkable that all investigated models predict almost the same energy fraction distributions when the data are classified in hadronic energy sum intervals, even SIBYLL is then able to describe the data. In addition shower size bins above the knee are shown in the Figures 3b and d, corresponding to 12 PeV and 8 PeV, respectively. QGSJET describes the measurements well below the knee, but above, even this models exhibits some discrepancies relative to the measurements as demonstrated for muonic and hadronic shower size bins. This behaviour is visible in other observables too (Hörandel et al. 1998).

5 Conclusion:

Three interaction models have been tested by examining the hadronic cores of large EAS. Several observables have been investigated: The lateral distribution, the lateral energy density, the differential energy spectrum, the distance distribution, the number of hadrons and their energy sum, the maximum hadron energy as well as the fraction of the energy of each hadron to the maximum hadron energy in each shower. All observables are investigated for five different thresholds of hadron energy from 50 GeV up to 1 TeV and the showers are divided into shower size intervals of all components, the number of electrons and muons as well as the hadronic energy sum. It turned out that QGSJET reproduces the measured data best, but at large shower sizes, i.e. energies above the knee even this model fails to reproduce certain observables. VENUS describes the data well, but there are deviations when binning the data in intervals of the electron number. SIBYLL has most problems to describe the data. To sum up, it can be concluded, that the results are described by the models VENUS and QGSJET reasonably well, at least up to energies of about 5 PeV.

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