Quantitative tests of hadronic interaction models with KASCADE-Grande air shower data

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***Abstract*. Quantitative tests of hadronic interaction models are described. Emphasize is given on the models EPOS 1.61 and QGSJET II-2. In addition, a new method to measure the attenuation length of hadrons in air showers is introduced. It turns out that this method is in particular sensitive to the inelastic cross sections of hadrons.**

***Keywords*: air showers, hadronic interactions, KASCADE-Grande**

I. Introduction

Measurements of air shower detectors are usually interpreted with an air shower model to obtain physical properties of the shower inducing primary particles. Modern detector installations, such as the KASCADE-Grande experiment comprise well calibrated particle detectors installed with high spatial density. The systematic uncertainties are dominated by uncertainties of the models used to interpret the data. For air shower interpretation the understanding of multi-particle production in hadronic interactions with a small momentum transfer is essential [1]. Due to the energy dependence of the strong coupling constant α_s, soft interactions cannot be calculated within QCD using perturbation theory. Instead, phenomenological approaches have been introduced in different models. These models are the main source of uncertainties in simulation codes to calculate the development of extensive air showers, such as the program CORSIKA [2].

The test of interaction models necessitates detailed measurements of several shower components. The KASCADE experiment [3] with its multi-detector set-up, registering simultaneously the electromagnetic, muonic, and hadronic shower components is particularly suited for such investigations. The information derived on properties of high-energy interactions from air shower observations is complementary to measurements at accelerator experiments since different kinematical and energetic regions are probed.

In the energy range of interest, namely 10^{14} to 10^{17} eV, the composition of cosmic rays is unknown. Therefore, primary protons and iron nuclei are taken as extreme assumptions and corresponding predictions are calculated for different interaction models. The measured data should be in between the results for the extreme assumptions. If the data are outside the proton-iron range for an observable, this is an indication for an incompatibility of the particular hadronic interaction model with the observed values.

II. Experimental set-up

KASCADE consists of several detector systems [3]. A 200×200 m^2 array of 252 detector stations, equipped with scintillation counters, measures the electromagnetic

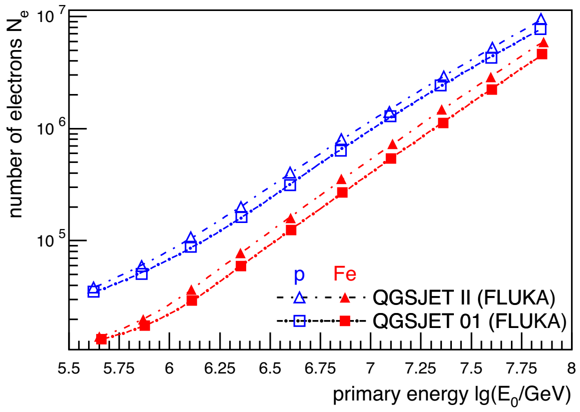


Fig. 1: Number of electrons as predicted by the hadronic interaction models QGSJET II-2 and QGSJET 01 as function of shower energy.

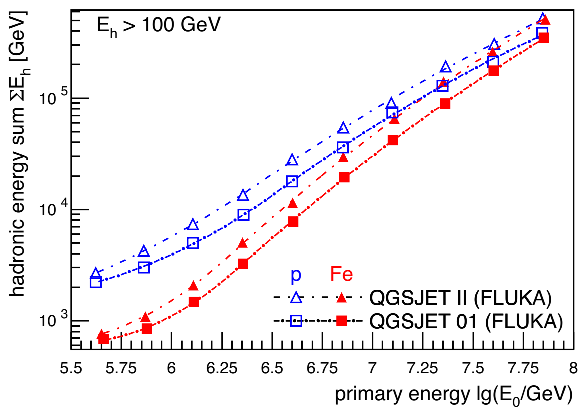


Fig. 2: Hadronic energy sum as predicted by the hadronic interaction models QGSJET II-2 and QGSJET 01 as function of shower energy.

and, below a lead/iron shielding, the muonic parts of air showers. An iron sampling calorimeter of 16×20 m^2 area detects hadronic particles [4]. It has been calibrated with a test beam at the SPS at CERN up to 350 GeV particle energy [5]. For a detailed description of the reconstruction algorithms see [6].

The shower simulations were performed using CORSIKA. Hadronic interactions at low energies ($E_h < 80$ and 200 GeV, respectively) were modeled using the GHEISHA [7] and FLUKA [8], [9] codes. Both models are found to describe the data equally well [10]. High-energy interactions were treated with different models as discussed below. 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 [11]. For details on the event selection and reconstruction, see Ref. [10], [12], [13].

III. Earlier tests

Several hadronic interaction models as implemented in the CORSIKA program have been systematically tested over the last decade. First quantitative tests [14], [15], [16] established QGSJET 98 [17] as the most compatible code. Similar conclusions have been drawn for the successor code QGSJET 01 [10].

Predictions of SIBYLL 1.6 [18] were not compatible with air shower data, in particular there were strong inconsistencies for hadron-muon correlations. These findings stimulated the development of SIBYLL 2.1 [19]. This model proved to be very successful, the predictions of this code are fully compatible with KASCADE air shower data [20], [21], [10].

Investigations of the VENUS [22] model revealed some inconsistencies in hadron-electron correlations [16]. The predictions of NEXUS 2 [23] were found to be incompatible with the KASCADE data, in particular, when hadron-electron correlations have been investigated [10].

Analyses of the predictions of the DPMJET model yield significant problems in particular for hadron-muon correlations for the version DPMJET 2.5 [24], while the newer version DPMJET 2.55 is found to be compatible with air shower data [10].

Presently, the most compatible predictions are obtained from the models QGSJET 01 and SIBYLL 2.1.

IV. Hadronic model EPOS

Recently, predictions of the interaction model EPOS 1.61 [25], [26], [27] have been compared to KASCADE air shower data [12]. This model is a recent development, historically emerging from the VENUS and NEXUS codes. The analysis indicates that EPOS 1.61 delivers not enough hadronic energy to the observation level and the energy per hadron seems to be too small. Most likely, the incompatibility of the EPOS predictions with the KASCADE measurements is caused by too high inelastic cross sections for hadronic interactions implemented in the EPOS code.

These findings stimulated the development of a new version EPOS 1.9 introduced at this conference [28]. Corresponding investigations with this new version are under way and results are expected to be published soon.

V. Hadronic model QGSJET II

Also predictions of QGSJET II-2 [29], [30], [31] have been investigated. As discussed above, QGSJET 01 is found to be the most reliable interaction code. Thus, in the following, it serves as reference model and the results can easily be compared to previous publications [16], [10]. The simulations for primary protons and iron nuclei predict about equal numbers of muons as function of energy for QGSJET II and for QGSJET 01. QGSJET II predicts about 20% to 25% more electrons on observation level at a given energy for both primary species relative to QGSJET 01, see Fig. 1. Also the number of hadrons at ground level at a given energy is larger by about 30% to 35% for proton and iron induced showers. The hadronic energy sum and the maximum hadron energy registered at observation level are shown in Figs. 2 and 3, respectively. The values predicted using

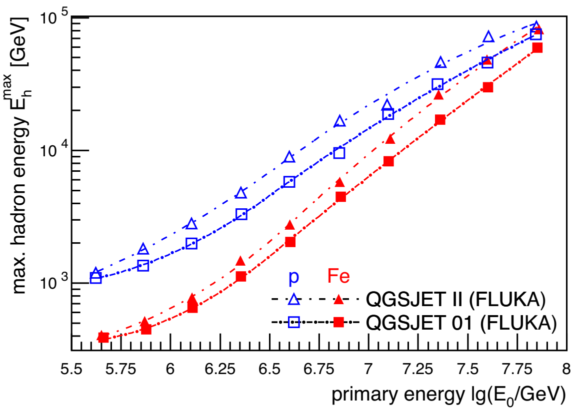


Fig. 3: Maximum hadron energy sum as predicted by the hadronic interaction models QGSJET II-2 and QGSJET 01 as function of shower energy.

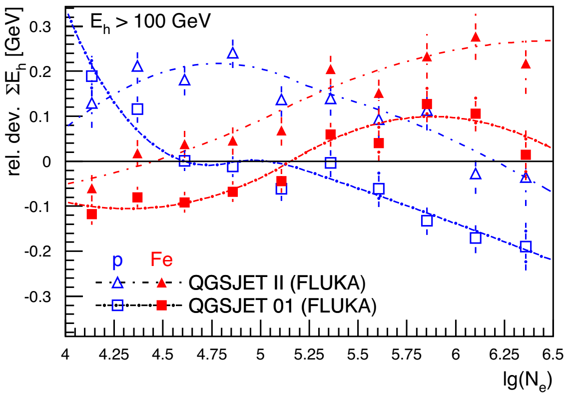


Fig. 4: Relative difference to measured values of the hadronic energy sum as predicted by the models QGSJET II-2 and QGSJET 01.

QGSJET II exceed the ones from QGSJET 01 by a significant amount (up to $\approx 40\%$), as can be inferred from the figures.

The predicted values have been compared to measured data. Investigating the hadronic energy sum and the maximum hadron energy as function of the registered muon number indicates that the predictions for QGSJET II are compatible with the measurements. The measured values are in between the predictions for the extreme assumptions for proton and iron induced showers. Also the correlation between the hadronic energy sum and the number as hadrons as well as the maximum hadron energy and the number of hadrons are compatible with the measurements.

The situation is different for the correlation between the hadronic energy sum and the number of electrons, see Fig. 4. The figure displays the relative deviation of the predicted values from the measured values, i.e. the quantity $(\sum E_h^{sim} - \sum E_h^{meas}) / \sum E_h^{meas}$ is shown. That means the data are at the "zero line". The predictions of QGSJET 01 are compatible with the data, since the values bracket the zero line. On the other hand, the predictions of QGSJET II are above the zero line for

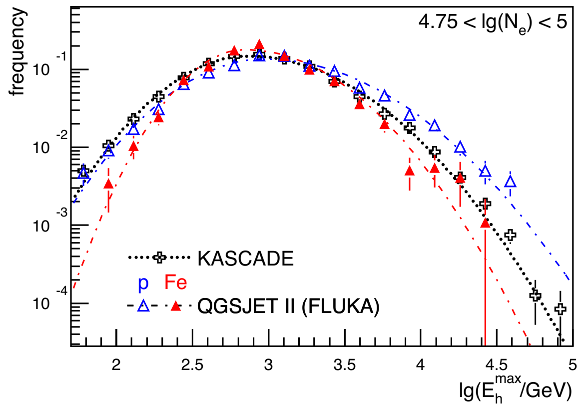


Fig. 5: Energy of the most energetic hadron reconstructed at observation level. Predictions of QGSJET II are compared to measured values.

both primary species – an unrealistic scenario.

The energy of the most energetic hadron reconstructed at observation level is depicted in Fig. 5 for an electron number interval corresponding to a primary energy of about 1 to 2 PeV. Predictions of simulations according to QGSJET II for primary protons and iron nuclei are compared to measured values. It can be recognized that for high maximum hadron energies the measured values are in between the predictions for proton and iron-induced showers. On the other hand, QGSJET II predicts too few hadrons with low energies. A similar behavior is observed for other electron number intervals.

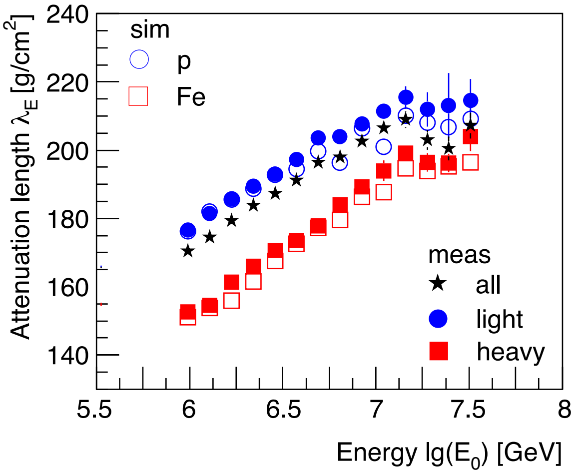
In summary, the investigations reveal incompatibilities in the hadron-electron correlation for the model QGSJET II-2.

VI. Attenuation length

Recently, a new method to determine the attenuation length of hadrons in air has been introduced, see Ref. [13]. The energy absorbed in a material within a certain atmospheric depth X is used to define an attenuation length. In this new approach we use the number of electrons N_e and muons N_μ to estimate the energy of the shower inducing primary particle E_0. The energy reaching the observation level in form of hadrons $\sum E_H$ is measured with the hadron calorimeter. The fraction of surviving energy in form of hadrons is defined as $R = \sum E_H / E_0$. The attenuation length λ_E is then defined as

$$\Sigma E_H = E_0 \exp\left(-\frac{X}{\lambda_E}\right) \quad \text{or } R = \exp\left(-\frac{X}{\lambda_E}\right). \quad (1)$$

In contrast to methods using the electromagnetic shower component, the present work focuses directly on measurements of hadrons to derive an attenuation length for this shower component. The values obtained are not a priori comparable to other attenuation lengths, given in the literature since they are based on different definitions. It should be noted that the experimentally obtained attenuation length is affected by statistical fluctuations



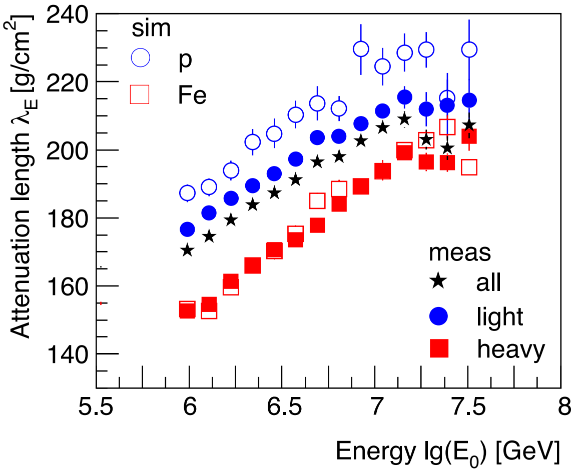


Fig. 6: Attenuation length λ_E as function of estimated primary energy. The light and heavy groups in the measurements are compared to simulations for primary protons and iron-induced showers using CORSIKA with the hadronic interaction model QGSJET 01 (*top*) and a modified version with lower cross sections and higher elasticity (*bottom*, model 3a in Ref. [32]).

during the development of the showers. However, in the present work we do not attempt to correct for this effect.

Measured values of λ_E are shown in Fig. 6. Using a cut in the $N_e - N_\mu$ plane the data have been divided into a "light" and "heavy" sample, the corresponding values for λ_E are depicted as well in the figure. Also predictions of air shower simulations for primary protons and iron nuclei, using the interaction code QGSJET 01 and a modified version with lower cross sections (model 3a in Ref. [32]) are shown. A closer inspection reveals that at high energies the λ_E values of the "light" data selection are greater than the values for proton induced showers according to QGSJET 01. This is an unrealistic behavior. Lowering the inelastic hadronic cross sections by about 5% to 8% changes the situation, see lower panel. The predicted values for protons are now above the values for the "light" selection. This demonstrates the sensitivity of the observable λ_E to hadronic cross sections applied in the simulations.

VII. Conclusions

Quantitative tests of hadronic interaction models implemented in the CORSIKA program have been performed with KASCADE-Grande air shower data in the energy range $10^{14} - 10^{17}$ eV. They indicate that the model EPOS 1.61 is not compatible with air shower data — the new version EPOS 1.9 is presently under investigation. Predictions of the model QGSJET II-2, in particular the hadron-electron correlations are not compatible with measured values. Presently, the most consistent description of all air shower observables as obtained by the KASCADE-Grande experiment is achieved by the interaction models QGSJET 01 and SIBYLL 2.1.

The newly introduced method to measure an attenuation length of hadrons is in particular sensitive to inelastic hadronic cross sections applied in air shower simulations. A comparison of values predicted by QGSJET 01 to measured values suggests that the inelastic cross sections in QGSJET 01 are slightly too large. A version with 5% to 8% smaller cross sections is more compatible with the measurements.

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