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Test of interaction models with the KASCADE hadron calorimeter

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The interpretation of extensive air shower measurements often requires the comparison with EAS simulations. These calculations rely on hadronic interaction models which have to extrapolate into kinematical and energy regions not covered by present-day collider experiments. The KASCADE experiment with its large hadron calorimeter and its detectors for the electromagnetic and muonic components provides experimental data to check hadronic interaction models. For the EAS simulations the program CORSIKA with several hadronic event generators embedded is used. Different hadronic observables are investigated as well as their correlations with the electromagnetic and muonic components. Comparing the interaction models QGSJET 98, NEXUS II, and DPMJET II.5, it is found, that QGSJET describes the data best.

1. Introduction

EAS simulation programs use phenomenological models to describe the hadronic interactions in the atmosphere. This results in uncertainties in the simulations which introduce systematic errors in the interpretation of EAS measurements. To reduce these ambiguities it is necessary to check the reliability of the interaction models used. When testing the models in the energy range 1–10 PeV by comparing measured and simulated EAS the problem occurs that the mass composition of the primary cosmic rays is not well known. Therefore, the measured data are compared with the extreme assumption of pure protons and pure iron nuclei in the simulation. As long as the data are between the simulated values for both primaries the simulation is compatible with the data, otherwise it is a hint at a problem in the simulation. In the EAS simulation program CORSIKA [1] several hadronic interaction models are at the users disposal. The models NEXUS II [2] and DPMJET II.5 [3] are tested and compared with the model QGSJET 98 [4]. An earlier comparison of QGSJET with VENUS and SIBYLL (version 1.6) [5] and a test of NEXUS, DPMJET, and QGSJET [6] has shown that QGSJET describes the measurements best.

2. Measurement and simulation

2.1. The experiment KASCADE

The experiment KASCADE, located on the site of the Forschungszentrum Karlsruhe (Germany), 110 m a.s.l., consists of several detector systems [7]. The $200 \times 200\,\mathrm{m}^2$ array of 252 detector stations, equipped with scintillation counters, measures the electromagnetic and muonic part of EAS. In its center an iron sampling calorimeter (with an area of $16 \times 20\,\mathrm{m}^2$) detects the hadrons

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in the shower core. The calorimeter is equipped with 11 000 warm-liquid ionization chambers in nine layers [8]. Due to the fine segmentation ($25 \times 25\,\mathrm{cm}^2$) energy, position, and angle of incidence can be measured for individual hadrons.

2.2. Observables and event selection

The hadrons in the calorimeter are reconstructed by a pattern recognition algorithm optimized to seperate the particles in the shower core. Hadrons of equal energy at a distance of 40 cm are seperated with a probability of 50 %. The reconstruction efficiency rises from 70 % at 50 GeV to nearly 100 % at 100 GeV. The energy resolution improves from 20 % at 50 GeV to 10 % at 10 TeV. The hadron number N_h and hadronic energy sum ΣE_h are determined by the sum over all hadrons in a distance up to 10 m from the shower core. A correction for missing area beyond the boundaries of the calorimeter is applied. The position of the EAS is reconstructed by the array. The total numbers of electrons and muons are determined by integration of their lateral distributions. In case of the muons the *truncated muon number* N_μ^tr in the distance range 40–200 m is used [9].

To be accepted for the analysis EAS have to fullfil the following requirements: At least one hadron is reconstructed in the calorimeter with an energy larger than 50 GeV, the shower core is inside the calorimeter, the electron number N_e is larger than 10^4, the muon number N_μ^tr is larger than 10^3, and the zenith angle is smaller than 30°.

2.3. Simulations

For the EAS simulations CORSIKA with the models QGSJET 98, NEXUS II, and DPMJET II.5 have been used. For each model protons and iron nuclei have been simulated in the energy interval 10^{14}–10^{17} eV and zenith angle range 0–35°. The shower core positions are distributed uniformly over an area extending the calorimeter surface by 2 m on each side. The spectral index is -2.0 in the simulation. For the analysis it is converted to a -2.7/-3.1 slope with a rigidity dependent knee position (3 PeV for protons). The detector response is determined by tracking all secondary particles at ground level through a detector simulation program based on GEANT.

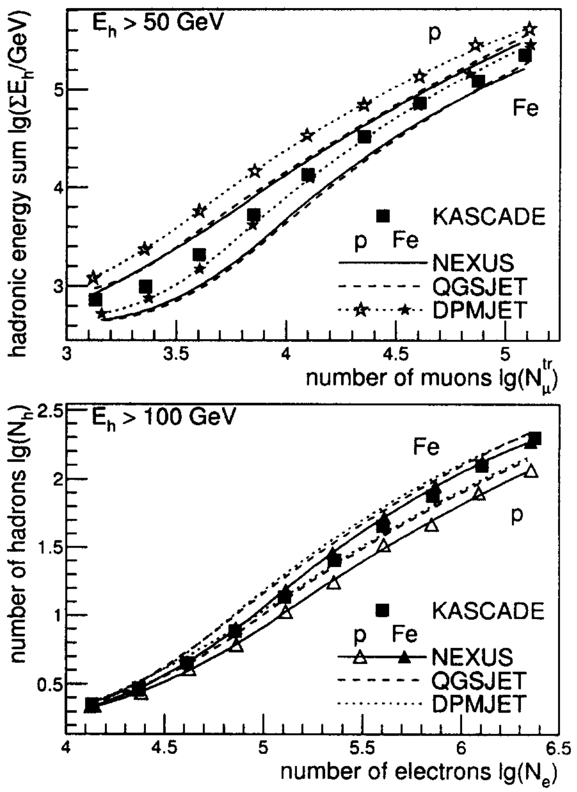

Figure 1. Shower size correlations. Top: Hadronic energy sum vs. muon number. The N_μ^tr range corresponds to primary energies from 0.3 to 70 PeV. Bottom: Hadron number vs. electron number (0.3–20 PeV for protons, 0.5–40 PeV for iron nuclei). To improve the clearness simulated data points are plotted for one model only.

3. Results

To compare measurement and simulation the data are divided into intervals of shower sizes. In the following, examples of hadronic observables are discussed as function of the electromagnetic (N_e) and muonic (N_μ^tr) shower sizes. The measured data are compared to the proton and iron predictions of the simulations.

3.1. Shower size correlations

Figure 1 (top) shows the correlation of the hadronic and muonic components of EAS. The models NEXUS and QGSJET predict very sim-

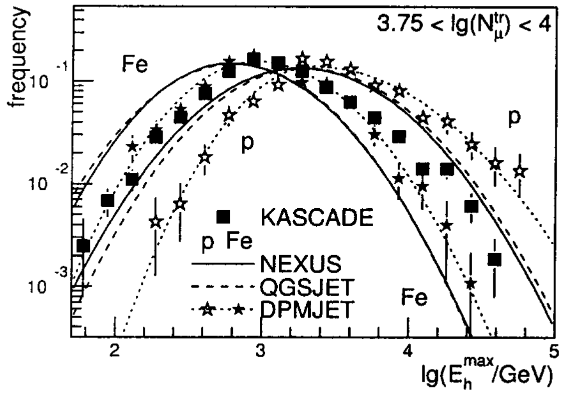

Figure 2. Frequency distributions of the most energetic hadron $E_{\mathrm{h}}^{\max}$. The muon number interval corresponds to a primary energy of 2 PeV.

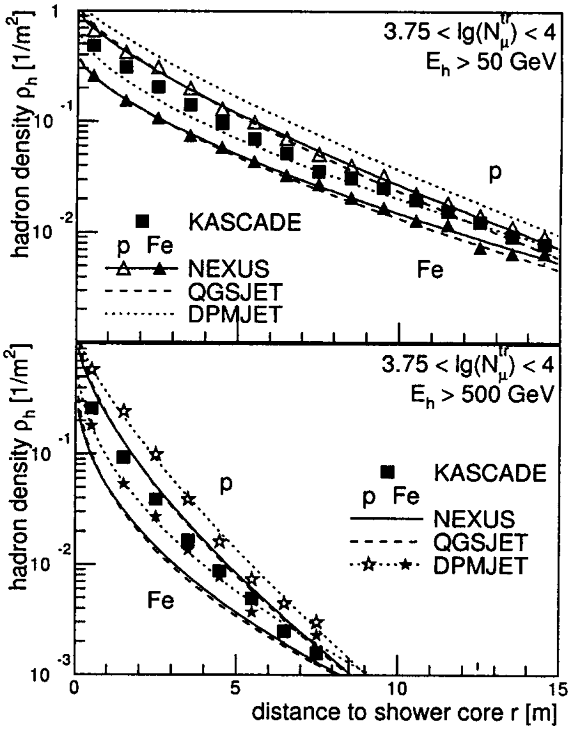

Figure 3. Lateral distribution of hadrons. Shown are two different hadron energy thresholds.

ilar values. The measured data lie between the proton and iron predictions of the models. DPMJET however predicts much larger values of the hadronic energy sum than the other models. At large N_μ^{tr}-values the measured data are not between the model predictions. Therefore, the model cannot describe the ΣE_{h}-N_μ^{tr}-correlation correctly. Showers simulated with DPMJET penetrate too deep into the atmosphere. This is probably caused by an overestimation of the elasticity in pion nucleus interactions [10].

The correlation of the hadronic and electromagnetic shower components is plotted in figure 1 (bottom). Dividing data in N_{e}-bins enriches proton induced showers, since primary iron nuclei need a higher energy to produce the same electron number at ground. Therefore, it is expected that the proton predictions of the models should follow the measurements. DPMJET and QGSJET fullfil this expectation, but NEXUS underestimates the hadron number for a given electron number. The measured data coincide with the iron prediction of the model. NEXUS cannot describe the correlation of the hadronic and electromagnetic component of EAS.

In addition to the mean values of the shower sizes also their frequency distributions can be investigated. Figure 2 shows as example the distribution of the energy of the most energetic hadron in a muon number interval. The shapes of the distributions are similar for all three models and describe the measured data well. Only the mean values are shifted corresponding to the differences in the shower size correlations.

3.2. Lateral distributions

The lateral distributions of the hadrons in the shower core are described rather well by all three models. Distributions for two different hadron energy thresholds are shown in figure 3. The shape is similar for all models. Only the absolute values differ significantly between the models as already seen on the base of the shower size correlations.

3.3. Energy spectra

The shape of the energy spectra of the hadrons is described well by all three models (figure 4). But, depending on the shower size used for the binning, the absolute values differ corresponding to the differences in the shower size correlations.

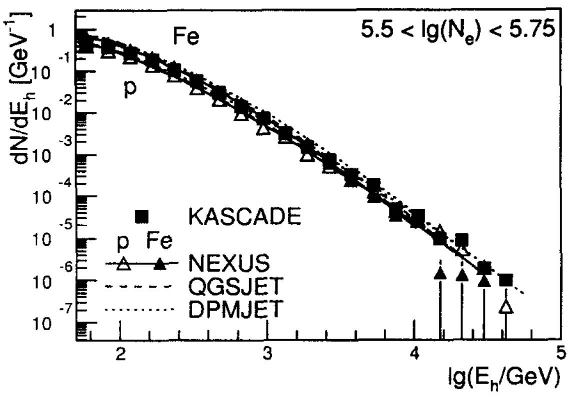

Figure 4. Energy spectra of hadrons. The electron number bin corresponds to a primary energy of 2.5 PeV for protons and 8 PeV for iron nuclei.

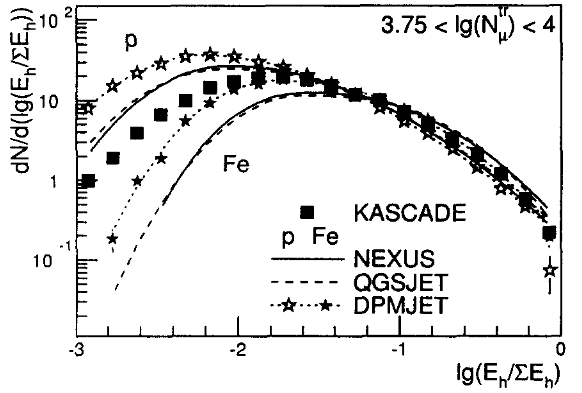

Figure 5. Distributions of hadronic energy fractions. The energies of the hadrons are normalized to the energy sum of all hadrons of a event.

In addition to the energy spectra itself, the distributions of energy fractions are investigated. The energy fractions are given by the energies of the individual hadrons of an event normalized to the most energetic hadron or the energy sum of all hadrons in this event. An example for the latter is shown in figure 5. NEXUS and QGSJET predict very similar values. The DPMJET curves are shifted to the left. This is caused by the larger values of the hadronic energy sum predicted by DPMJET.

4. Summary

The hadronic interaction models NEXUS II, DPMJET II.5, and QGSJET 98 have been tested by comparing measured hadronic shower cores with results from EAS simulations. Several hadronic observables have been investigated as function of the muonic and electromagnetic shower sizes.

Overall, it can be concluded that QGSJET describes the measured data best. The measurements are between the extreme assumptions of primary protons and iron nuclei. DPMJET exhibits problems with the correlation between the hadronic and the muonic EAS components. Showers simulated with DPMJET penetrate too deep into the atmosphere and the hadronic component is overestimated for a given muon size. Vice versa, NEXUS cannot describe the correlation between the hadrons and the electrons in the showers. The hadronic component is underestimated for a given electron number.

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