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Test of Hadronic Interaction Models with the KASCADE Hadron Calorimeter

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Abstract. The interpretation of extensive air shower (EAS) measurements often requires the comparison with EAS simulations based on high-energy hadronic interaction models. These interaction models have to extrapolate into kinematical regions and energy ranges beyond the limit of present accelerators. Therefore, it is necessary to test whether these models are able to describe the EAS development in a consistent way. By measuring simultaneously the hadronic, electromagnetic, and muonic part of an EAS the experiment KASCADE offers best facilities for checking the models. For the EAS simulations the program CORSIKA with several hadronic event generators implemented is used. Different hadronic observables, e.g. hadron number, energy spectrum, lateral distribution, are investigated, as well as their correlations with the electromagnetic and muonic shower size. By comparing measurements and simulations the consistency of the description of the EAS development is checked. First results with the new interaction model NEXUS and the version II.5 of the model DPMJET, recently included in CORSIKA, are presented and compared with QGSJET simulations.

1 Introduction

At high energies ($> 10^{14}\,\mathrm{eV}$) the flux of cosmic rays becomes so low that direct measurements with balloon or satellite experiments run out of statistics. In this energy range only ground based experiments have been realized so far. These experiments cannot measure the primary particles directly, but the EAS induced by them in the atmosphere. Therefore, the interpretation of the measurements depends on the comparison with EAS simulations based on high-energy hadronic interaction models. To reduce uncertainties caused by these models it is mandatory to check the reliability of the used models. Vice versa, it is possible to obtain information about the hadronic interactions by comparing measured and simulated air showers.

When testing the interaction models in the energy range of 1 PeV–10 PeV, the problem arises that the flux and especially the mass composition of the primary cosmic rays are not well known. Therefore, in the following the measurements will be compared with the model predictions for the extreme assumption of a pure proton and a pure iron composition of the primaries. If the measured observable lies between the predictions, the corresponding model is compatible with the data, otherwise it is a hint at a problem of the model.

Recently the interaction model NEXUS and the version II.5 of the DPMJET model have been included in the CORSIKA program (Heck et al., 2001). In this analysis these models are compared with the "old" QGSJET model. An earlier comparison of QGSJET with the VENUS and the SIBYLL (Version 1.6) models has shown that QGSJET describes the measurements best (Antoni et al., 1999).

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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. A detailed description can be found in (Klages et al., 1997). The $200 \times 200\,\mathrm{m}^2$ large array of 252 detector stations, equipped with scintillation counters, measures the electromagnetic and muonic part of EAS.

In the center an iron sampling calorimeter (with an area of $16 \times 20\,\mathrm{m}^2$) detects the hadrons in the shower core. The calorimeter is equipped with 11 000 liquid ionization chambers in nine layers (Engler et al., 1999). Due to its 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

From the array measurement the position of the shower core and the angle of incidence of the EAS are reconstructed (accuracy about 2 m at 1 PeV and better than 0.5 m at 10 PeV). By integrating the measured lateral distributions of electrons and muons the total particle numbers are determined. For the muons additionally the *truncated muon number* N_μ^{tr} in the distance range 40–200 m is calculated (details in (Antoni et al., 2001)). The hadrons in the calorimeter are reconstructed by a pattern recognition algorithm, which is optimized to separate the hadrons in the shower core. Hadrons at a distance of 40 cm are separated with a probability of 50% (Engler et al., 1999). The reconstruction efficiency is about 70% at 50 GeV and rises to nearly 100% at 100 GeV. The energy resolution varies from about 20% at 100 GeV to about 10% at 10 TeV. For all analyses an energy cut of 50 GeV is applied. For the hadron number N_h and the hadronic energy sum ΣE_h hadrons up to a distance of 10 m to the shower axis are taken into account. They are corrected for missing area beyond the boundaries of the calorimeter.

Events accepted for the analysis have to fulfill the following requirements: The shower core determined by the detector array is in the calorimeter, the zenith angle is less than $30°$, the electron number N_e is larger than 10^4, the muon number N_μ^{tr} is larger than 10^3, and at least one hadron with an energy above 50 GeV is reconstructed in the calorimeter. After all cuts about 56 000 events, measured from May 1998 until April 2000, are left for the investigations.

2.3 Simulations

The EAS simulations were performed using the CORSIKA program (Heck et al., 1998). The interaction models chosen are QGSJET (version from 1997 (Kalmykov et al., 1997), CORSIKA version 5.644), NEXUS (version 2 (Drescher et al., 2000), CORSIKA version 5.946) and DPMJET (version II.5 (Ranft, 1999), CORSIKA version 6.001). For each of the models EAS simulations for primary protons and iron nuclei were performed in the energy range 10^{14}–10^{17} eV and zenith angles $0°$–$30°$. The shower core positions were distributed uniformly over the calorimeter surface extended by 2 m beyond its boundary. For each combination of models and primaries about 46 000 showers with an overall spectral index of -2.0 were simulated. For the comparison with the measurements this spectral index was converted to a -2.7 slope.[1] To determine the detector response, all secondary particles at ground level are passed through a detector simulation program based on the GEANT package.

[1] Without a knee. This doesn't influence the results significantly.

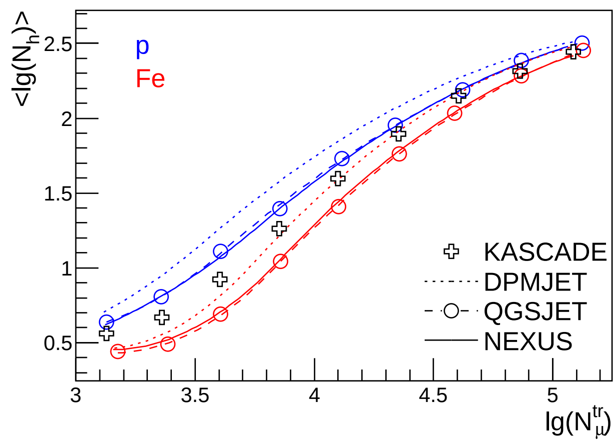

Fig. 1. Hadron number N_h versus muon number N_μ^{tr}. For reasons of better visibility for DPMJET and NEXUS only a parameterization is plotted. The muon number range $3.0 < \lg N_\mu^{\mathrm{tr}} < 5.25$ corresponds to a primary energy range 0.3–70 PeV.

3 Results

When comparing measurements and simulations, it is necessary to divide the data in intervals of shower sizes. In the following, examples of hadronic observables as functions of the electromagnetic (N_e) and muonic (N_μ^{tr}) shower sizes are discussed.

3.1 Shower Size Correlations

In figure 1 the correlation of the hadron number (N_h) and the muon number (N_μ^{tr}) is plotted. The measured data are compared with the prediction of all three models for primary protons and iron nuclei. Between the models QGSJET and NEXUS no difference can be found. Both models describe the measurements well (the measurements lie between the predictions of the models for proton and iron induced air showers). The model DPMJET however predicts a significantly larger hadron number than the other models. At large muon numbers (corresponding to high primary energies) the measured data do not lie between the model predictions. Therefore, the DPMJET model cannot describe the N_h–N_μ^{tr} correlation. In conjunction with other observables like the electron number (N_e) and the age parameter of the NKG fit to the electron lateral distribution it has to be concluded that showers simulated with DPMJET penetrate too deeply into the atmosphere.

Figure 2 shows the correlation of the hadronic energy sum (ΣE_h) and the electron number (N_e). When dividing the data in ranges of the electron number, within the individual bins proton induced showers are enriched because iron nuclei need a higher energy to yield the same electron number as proton induced showers. Hence, we expect that the measurements mainly follow the proton predictions. The QGSJET model fulfills this expectation. The deviation at higher electron numbers have not to be a hint at problems of the model. In this energy range it cannot be excluded that the primary

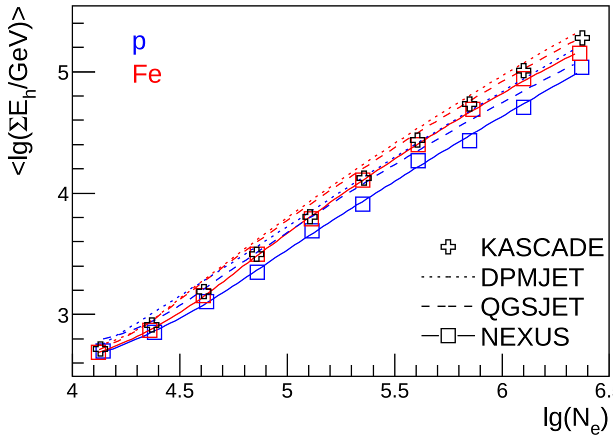

Fig. 2. Hadronic energy sum ΣE_{h} versus electron number N_{e}. For QGSJET and DPMJET only the parameterizations are plotted. The electron number range $4.0 < \lg N_{\mathrm{e}} < 6.5$ corresponds to a primary energy range 0.3–20 PeV for proton and 0.5–40 PeV for iron induced showers.

flux is dominated by iron nuclei, whereby the assumption of a proton enrichment is not longer valid. DPMJET also shows a relatively good agreement with the expectation. But, at low electron numbers the hadronic energy sum is overestimated by the model. The NEXUS model cannot describe the ΣE_{h}–N_{e} correlation at all. For all electron numbers the measurement lies on or even above the model predictions for iron induced showers. NEXUS predicts too few hadrons at constant electron numbers.

In addition to the mean values in figures 1 and 2 also the distributions of the hadron numbers and hadronic energy sums in the individual N_{μ}^{tr} and N_{e} intervals are investigated. Two examples are shown in figures 3 and 4. The shape of the distributions is, within the statistical errors, the same for all models and describes the measured data well. The main difference between the models is the shift of the mean values,

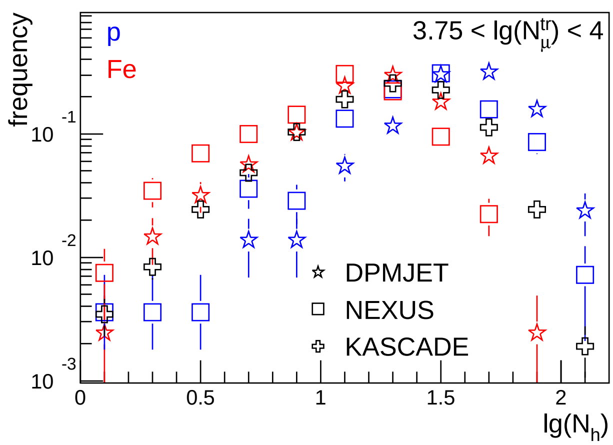

Fig. 3. Frequency distribution of the hadron number N_{h}. The muon number bin corresponds to a primary energy of about 2 PeV. The QGSJET distributions, not plotted here, are similar to NEXUS.

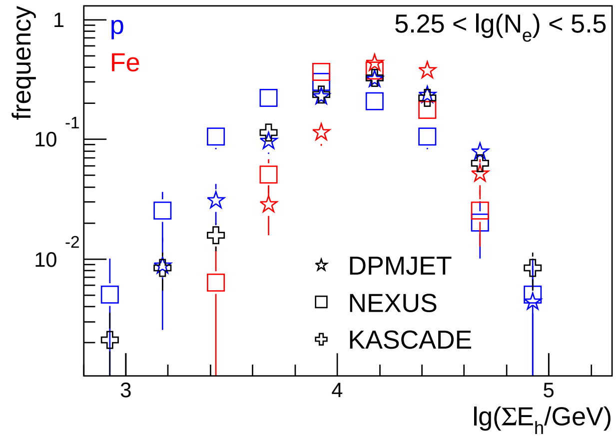

Fig. 4. Frequency distribution of the hadronic energy sum ΣE_{h}. The electron number bin corresponds to a primary energy of about 1.5 PeV for proton and 5 PeV for iron induced showers. The QGSJET distributions, not plotted here, are similar to DPMJET.

as already seen in figures 1 and 2.

3.2 Lateral Distributions

Another model test concerns the lateral distribution of the hadrons in the core of the EAS. Figure 5 shows the energy density vs. the distance to the shower core in a muon number interval. All three models describe the shape of the measured lateral distribution quite well. But, the DPMJET prediction lies too high, as already seen in figure 1.

To point out the shape of the lateral distribution, the values are normalized to the integrals of the curves (see figure 6). Again, the models describe the measured values well. The differences between the models are rather small.

3.3 Energy Spectra

Not only the lateral distribution, but also the energy distribution of hadrons can be checked. Figure 7 shows two exam-

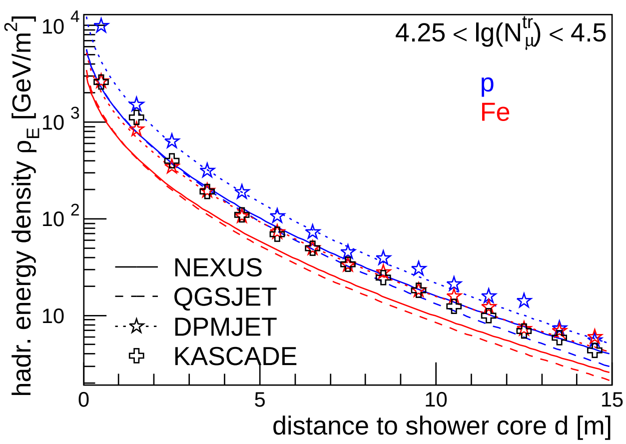

Fig. 5. Lateral distribution of the hadronic energy density. The muon number bin corresponds to a primary energy of 8 PeV.

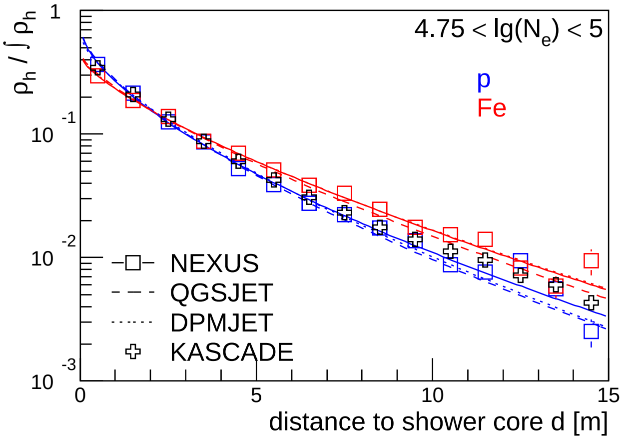

Fig. 6. Lateral hadron density.
To point out the shape of the lateral distributions, the curves are normalized to their integrals. The N_{e} bin corresponds to a primary energy of 0.7 PeV for proton and 2 PeV for iron induced showers.

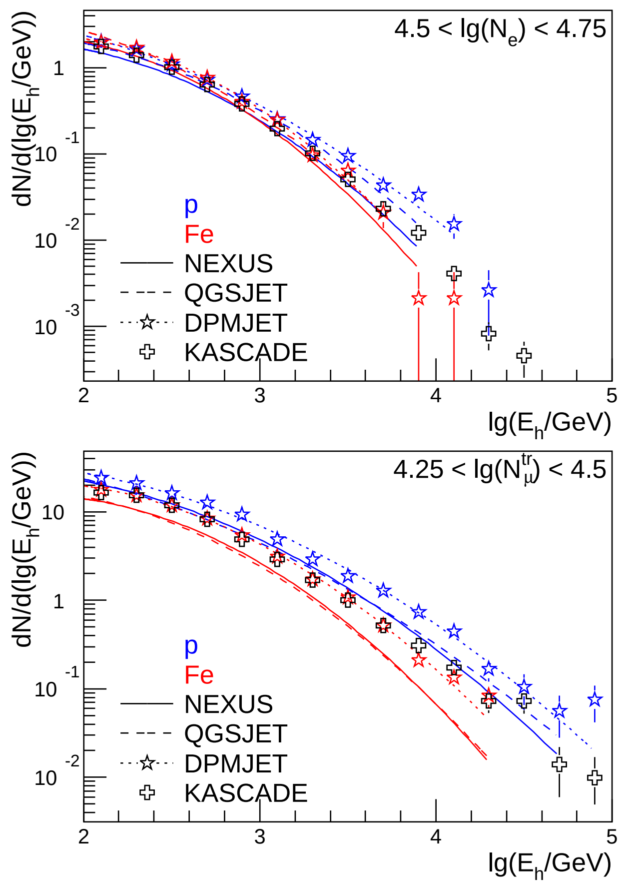

Fig. 7. Energy spectra of hadrons.
top: The N_{e} bin corresponds to a primary energy of 0.5 PeV for proton and 1.3 PeV for iron induced showers.
bottom: The N_μ^{tr} bin corresponds to 8 PeV.

ples. In the upper graph the spectra for an electron number interval are plotted. The models QGSJET and NEXUS describe the shape of the spectra quite well, the absolute values for NEXUS are again too low, whereas DPMJET overestimates the number of hadrons in the 10 TeV region for proton induced air showers. This effect was already seen in the correlation of hadronic energy sum and electron number (figure 2). At larger electron numbers this effect vanishes. In the bottom part of figure 7 the hadron energy spectra for a N_μ^{tr} interval is shown. All models describe the shape well, but DPMJET predicts a too large hadron number.

4 Conclusion

Using the hadronic shower core of EAS, measured by the KASCADE calorimeter, the interaction models NEXUS and DPMJET have been tested and compared with the QGSJET model. Several observables (number of hadrons, hadronic energy sum, frequency distributions of hadron number and energy sum, lateral distributions, and energy spectra) have been investigated as functions of the electromagnetic and muonic shower sizes. All three models describe the shapes of most distributions rather well. But, for the absolute values of hadron number and hadronic energy sum problems occur.

When dividing the data in intervals of the muon numbers, the model DPMJET overestimates hadron number and hadronic energy sum at ground level. Air showers simulated with DPMJET seem to penetrate too deeply into the atmosphere. Vice versa, when dividing the data in electron number bins, the model NEXUS predicts too small hadron numbers. There seems to be a problem in the balance between the hadronic and electromagnetic component of EAS. But, it should be stressed that both, NEXUS and DPMJET, are still under development and the problems might be specific to the used versions NEXUS 2 and DPMJET II.5.

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