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Investigation of Hadronic Interaction Models with the KASCADE-Grande Hadron Calorimeter

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The influence of hadronic interaction models on the simulation of extensive air showers has been studied using the correlation between the hadronic, electromagnetic, and muonic components of air showers measured with KASCADE. Both, high-energy (DPMJET, QGSJET, SIBYLL) and low-energy (GHEISHA, FLUKA) interaction models have been investigated.

1. Introduction

The interpretation of measurements of extensive air showers is usually based on the comparison with simulations of the shower development. Therefore, it is mandatory to check the reliability of the air shower simulations. This can be done by investigating the correlations between the hadronic, electromagnetic, and muonic components. The major uncertainty of the shower simulations is the description of the hadronic interactions. In the simulation program CORSIKA [1] different models are used for high-energy ($E_{\rm lab} \gtrsim 100\,\mathrm{GeV}$) and low-energy ($E_{\rm lab} \lesssim 100\,\mathrm{GeV}$) interactions. The high-energy model controls especially the first few interactions of an air shower and, therefore, the overall shower development. On the other side, most of the particles detected at ground level are produced in low-energy interactions.

In the energy range covered in this analysis ($5 \cdot 10^{14}$–$5 \cdot 10^{16}$ eV) the composition of cosmic rays is not well known. Hence, in a first step proton and iron primary particles are taken as extreme assumptions. It is then checked, if the measurements are bracketed by this hypothesis. Another possibility is to assume in the

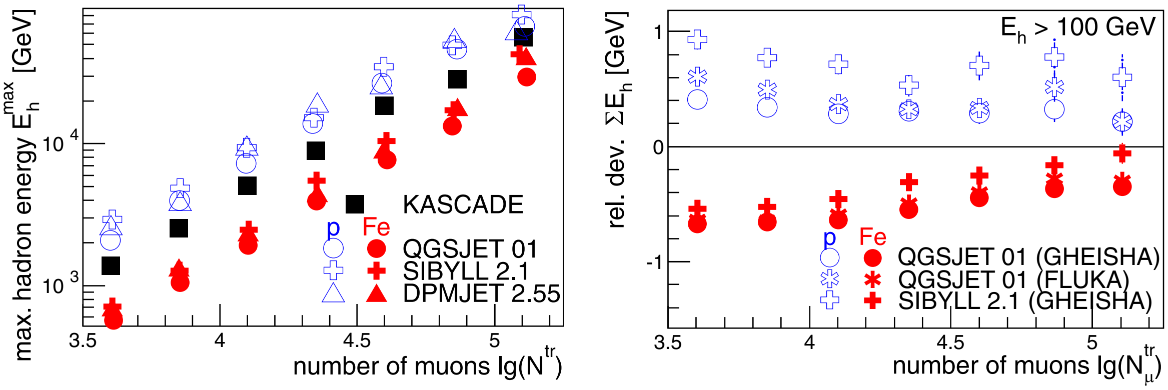

Figure 1. On the left hand side the correlations between the most energetic hadron $E_{\rm h}^{\rm max}$ and the number of muons $N_\mu^{\rm tr}$ for 3 high-energy models are plotted (GHEISHA for low energies). The right panel shows the correlation between the hadronic energy sum $\Sigma E_{\rm h}$ and $N_\mu^{\rm tr}$ for QGSJET combined with FLUKA and GHEISHA, as well as SIBYLL with GHEISHA. To make the small differences better visible, the relative deviations between simulation and measurement are plotted.

simulation a mass composition derived from the two-dimensional $N_{\rm e}$-$N_\mu^{\rm tr}$-spectrum [2] and to examine, if the simulations are able to reproduce the hadronic observables.

2. Measurement and simulation

The air shower data analysed have been recorded by the multi detector setup KASCADE [3]. A $200 \times 200\,{\rm m}^2$ array of 252 detector stations, equipped with scintillation counters, measures the electromagnetic and muonic parts of extensive air showers. They are used to determine the position and direction of the showers as well as the number of electrons ($N_{\rm e}$) and muons ($N_\mu^{\rm tr}$, distance range 40–200 m). In the center of the detector array an iron sampling calorimeter (area $16 \times 20\,{\rm m}^2$) detects hadrons. The calorimeter is equipped with 11 000 warm-liquid ionization chambers in nine layers [4]. Due to the fine segmentation ($25 \times 25\,{\rm cm}^2$) energy, position, and angle of incidence can be measured for individual hadrons ($E_{\rm h} > 50\,{\rm GeV}$).

The air shower simulations have been performed using the program CORSIKA. For the description of the high-energy hadronic interactions the models DPMJET 2.55 [5], QGSJET 01 [6], and SIBYLL 2.1 [7] have been applied. GHEISHA ($E_{\rm lab} \leq 80\,{\rm GeV}$) [8] (with correction patches [9] which improve energy and momentum conservation) and FLUKA ($E_{\rm lab} \leq 200\,{\rm GeV}$) [10] have been used to check the influence of the low-energy model. The detector response has been determined by a detector simulation program based on GEANT 3 [11].

3. Results

3.1 Test with proton and iron as extrem assumption for the primary masses

In earlier investigations [12, 13, 14] it was found, that some of the hadronic interaction models failed to describe all aspects of the shower development simultaneously. For example, NEXUS 2 [15] could not describe the correlation between hadrons and electrons, while DPMJET 2.5 overestimated the number of hadrons and electrons in dependence of the number of muons. In the meantime new versions of the interaction models are available. The differences in the model predictions have become smaller and within the range given by proton and iron as primary particles the models DPMJET 2.55, QGSJET 01, and SIBYLL 2.1 are to a large

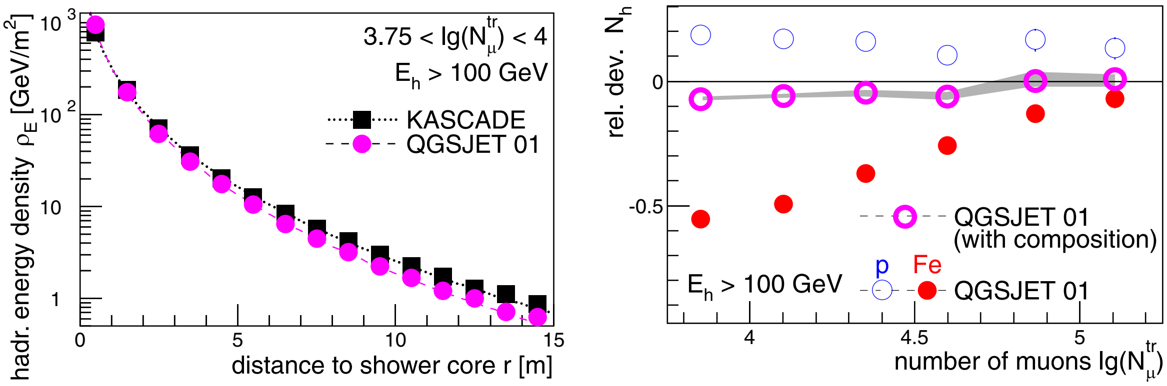

Figure 2. For the simulation using QGSJET/GHEISHA a mass composition has been assumed (see text). Shown are hadron lateral distributions (left hand side) and the correlation between hadron number N_h and muon number N_μ^tr (right hand side). The shaded band indicates the error caused by the statistical uncertainty of the assumed mass composition.

extent compatible with the measurements of the hadronic component and its correlation with electromagnetic and muonic particles. As example, on the left hand side of figure 1 the correlation between the most energetic hadron $E_\mathrm{h}^\mathrm{max}$ and the number of muons N_μ^tr is shown.

The influence of the low-energy interaction model is demonstrated on the right hand side of figure 1. Shown are simulations using QGSJET as high-energy model and FLUKA and GHEISHA for low energies. The difference is caused by different number of muons predicted by the model combinations. Since FLUKA predicts fewer muons than GHEISHA, a higher primary energy is needed for the same muon number interval. Therefore, the hadronic energy sum is increased. Due to the energy threshold for the reconstructed hadrons of 100 GeV the hadronic component itself is not influenced by the low-energy model. In addition, results for a SIBYLL/GHEISHA simulation are plotted. It can be seen that the difference between the high-energy models is still larger than between different low-energy codes.

3.2 Assuming a composition in the simulations

For a more detailed test of the interaction models one has to assume a mass composition in the simulation to compare a single simulation curve with the measured distribution. This can be done consistently by taking a mass composition derived from other observables using the same combination of low-energy and high-energy models. In the following, compositions determined by an unfolding procedure of the two-dimensional $\lg N_\mathrm{e}$-$\lg N_\mu^\mathrm{tr}$ spectrum [2] are used to check, if the models can describe the hadronic observables.

Results for the simulation using QGSJET/GHEISHA are shown in figure 2. On the left hand side an example for a lateral distribution of the hadrons is plotted. The model prediction is steeper than the measured distribution. The correlation between hadron number and muon number is plotted on the right hand side. For muon numbers $\lg N_\mu^\mathrm{tr} < 4.7$ the simulation is rather below the measurement. This is compatible with a consistency check for the unfolding of the $\lg N_\mathrm{e}$-$\lg N_\mu^\mathrm{tr}$ spectrum, which shows that QGSJET cannot describe the electron-muon data in this range consistently, while for larger muon numbers (respectively primary energies) the description becomes better. The situation for SIBYLL/GHEISHA is opposite. While for smaller primary energies the hadronic observables as well as the electron-muon data are reproduced rather well, there are discrepancies at larger muon numbers. The left panel of figure 3 shows a good agreement for measured and simulated hadron energy spectra. The correlation between the numbers of hadrons and muons (right hand side

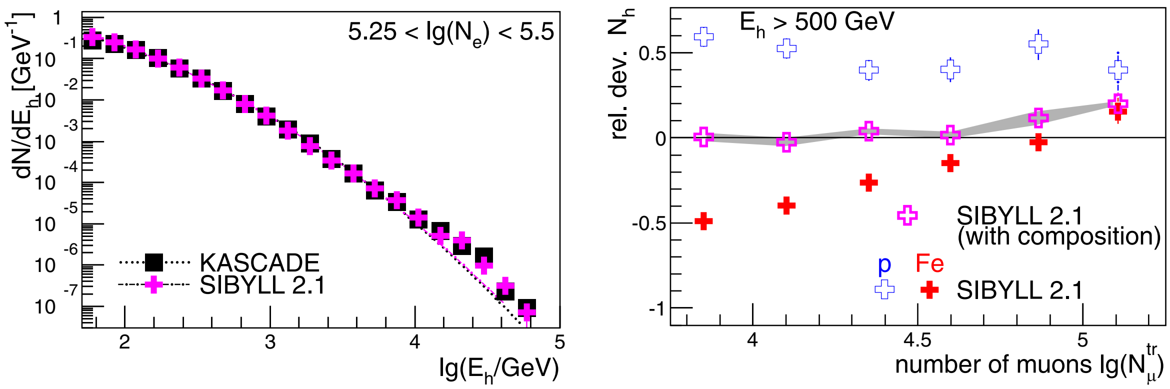

Figure 3. The left figure shows a hadron energy spectrum, the electron number interval corresponds to a primary energy around 3 PeV. On the right hand side the correlation of the number of hadrons above 500 GeV and the muon number N_μ^{tr} assuming a mass composition for the SIBYLL/GHEISHA simulation is plotted.

of figure 3) is well described by the model for small muon numbers, whereas with increasing muon number differences between simulation and measurement arise.

4. Conclusion

Although the differences between different high-energy hadronic interaction models have become smaller during the last years, there are still discrepancies, which influence the interpretation of extensive air shower measurements significantly. Also an influence of the low-energy model used is found, even though smaller than in case of the high-energy models. All models investigated so far are able to describe some aspects of the shower development, but for other shower correlations or in some energy ranges deficiencies are found.

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