Sensitivity of KASCADE-Grande data to hadronic interaction models

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KASCADE-Grande is a large detector array dedicated for studies of high-energy cosmic rays in the primary energy range from 100 TeV to 1 EeV. The multi-detector concept of the experimental set-up offers the possibility to measure simultaneously various observables related to the electromagnetic, muonic, and hadronic air shower components. The experimental data are compared to predictions of CORSIKA simulations using high-energy hadronic interaction models (e.g. QGSJET or EPOS), as well as low-energy interaction models (e.g. FLUKA or GHEISHA). This contribution will summarize the results of such investigations. In particular, the validity of the new EPOS version 1.99 for EAS with energy around 100 PeV will be discussed.

1. Introduction

Studies of high-energy cosmic radiation by means of extensive air shower (EAS) techniques require a proper understanding of high-energy interactions in the Earth's atmosphere: Inferring the properties of the primary particles from EAS measurements one relies on the simulations of the air shower development, whose backbone is the hadronic cascade in the atmosphere. Significant progress has been made during recent years to interpret air shower data and main physical properties of the primary cosmic ray particles have been measured. In the energy range around 10^{15} eV, energy spectra for elemental groups and mass compositions of primary cosmic rays have been investigated. Interpretations of these extensive air shower measurements are generally related to air shower models to obtain physical properties of the shower including primary particles. Therefore, one of the goals of KASCADE-Grande is to investigate high-energy interactions in the atmosphere and to improve contemporary models to describe such processes.

The tests of hadronic interaction models require detailed measurements of several shower observables. The KASCADE-Grande experiment with its multi-detector concept of the experimental set-up, measuring simultaneously the electromagnetic, muonic, and the hadronic shower components, is particularly designed for such investigations.

The KASCADE array measures an extensive air shower in the energy range of 10^{14} to 8×10^{16} eV and consists of 252 scintillator detector stations with unshielded and shielded detectors located on a grid of 200×200 m^2 for the measurement of the electromagnetic and muonic shower components independently. In its center, an iron sampling calorimeter of 16×20 m^2 area detects hadronic particles.

The KASCADE-Grande [1] array covering an area of 700×700 m^2 is optimized to measure extensive air

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showers up to primary energies of 1 EeV. It comprises 37 scintillation detector stations located on a hexagonal grid with an average spacing of 137 m for the measurements of the charged shower component. Each of the detector stations is equipped with plastic scintillators covering a total area of 10 m^2.

2. Monte-Carlo simulations

The principal idea of the tests of hadronic interaction models is to simulate air showers initiated by protons and irons nuclei as the two extremes of possible primary particles and to compare those simulated showers with the measurements. For the air shower simulations the program CORSIKA [2] has been used, applying different embedded hadronic interaction models. To determine the signals in the individual detectors, all secondary particles at the ground level are passed through a detector simulation program using GEANT package. The predicted observables at ground level, such as e.g. the number of electrons, muons and hadrons are then compared to the measurements.

FLUKA [3] and GHEISHA [4] (E < 200 GeV and 80 GeV, respectively) models have been used for hadronic interactions at low energies. High-energy interactions were treated with different models QGSJET-II-2 [5] and EPOS 1.99 [6]. Showers initiated by primary protons and iron nuclei have been simulated. The simulations covered the energy range of 10^{14} - 10^{18} eV with zenith angles in the interval 0° - 42°. The spectral index in the simulations was -2 and for the analysis it is converted to a slope of -3. The simulated events are analyzed by the same method as the experimental data, in order to avoid biases by pattern recognition and reconstruction algorithms.

3. Investigations with KASCADE

Using KASCADE measurements, the hadronic interaction models QGSJET [7] (versions 98 and 01), SIBYLL [8, 9] (versions 1.6 and 2.1), DPMJET [10], VENUS [11] and NEXUS [12] have been investigated. First tests [13] supported QGSJET 98 as being most compatible with the KASCADE data. Similar conclusions have been later drawn for QGSJET 01 [14]. For the next model version, QGSJET-II-2 [5], some problems with the electron-hadron correlations have been observed [15]. Predictions of SIBYLL 1.6 were not compatible with air shower data, in particular there were strong inconsistencies for hadron-muon correlations. These observations improved the development of SIBYLL 2.1 [9]. The predictions of this model are very successful and fully compatible with KASCADE air shower data [14]. Investigations of the DPMJET version 2.5 yield significant problems particularly for hadron-muon correlations, while the newer version DPMJET 2.55 is found to be compatible with air shower data [14]. The predictions of the VENUS model revealed some inconsistencies in hadron-electron correlations [13]. The predictions of NEXUS 2 were found to be inconsistent with the KASCADE data in particular for the investigations of hadron-electron correlations [14]. Presently, the most compatible predictions are obtained from the models QGSJET 01 and SIBYLL 2.1.

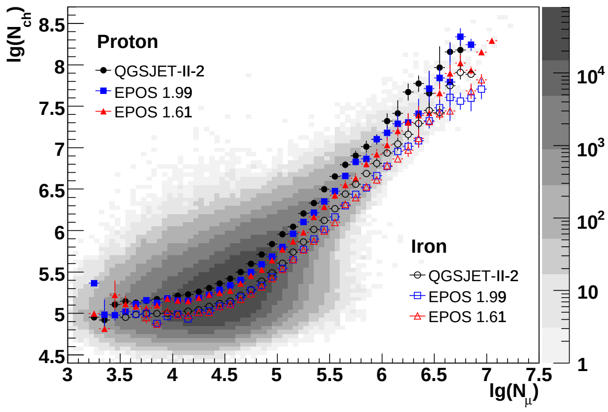

Figure 1: Two-dimensional shower size spectrum measured by KASCADE-Grande, together with proton and iron induced showers for QGSJET-II-2 and EPOS simulations.

Predictions of the interaction model EPOS 1.61 have been recently compared to KASCADE air shower data [16]. This model is a recent development, historically emerging from the VENUS and NEXUS models. This analysis indicates that the EPOS 1.61 delivers not enough hadronic energy to the observation level, and also the energy per hadron seems to be too small. Presumably, the inconsistency of the EPOS predictions with the KASCADE measurements is caused by too high inelastic cross sections for hadronic interactions implemented in the EPOS model. To solve these problems, the treatment of screening effects in nuclear collisions has been improved in EPOS. The new version EPOS 1.99 [6] has a reduced cross section and inelasticity, compared to the previous EPOS 1.61 which leads to deeper shower development.

4. Hadronic models QGSJET-II-2 and EPOS 1.99

QGSJET is essentially based on the Quark-Gluon-String model approach to high-energy hadronic interactions, including a generalization of the latter for nucleus-nucleus collisions and a treatment of semi-hard processes, using the so-called semihard Pomeron approach [7]. The new hadronic interaction model QGSJET-II accounts for non-linear interaction effects,

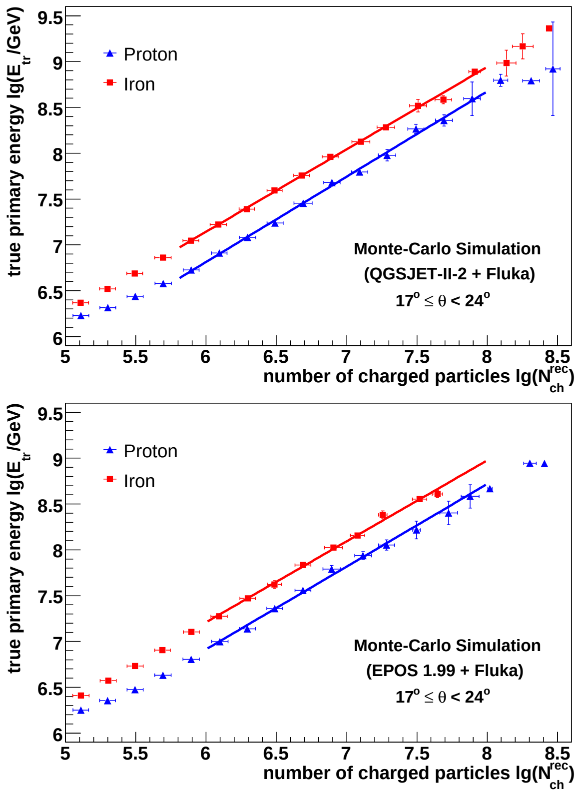

Figure 2: The primary energy as a function of the number of charged particles for assumed pure proton and iron components for QGSJET-II-2 (top panel) and EPOS 1.99 (bottom panel), respectively. The lines show the applied fits to the points.

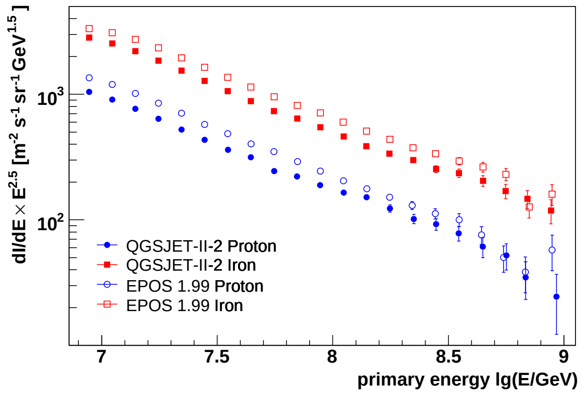

Figure 3: Reconstructed all-particle energy spectra from KASCADE-Grande shower size for assuming proton and iron composition, based on two different hadronic interaction models QGSJET-II-2 and EPOS 1.99.

which allows one to obtain a consistent description of hadronic cross sections and parton distribution functions [5]. EPOS [6] is a consistent quantum mechanical multiple scattering approach based on partons and strings, where cross sections and the particle production are calculated consistently, taking into account energy conservation in both cases.

Predictions of QGSJET-II-2 and EPOS 1.99 models have been investigated with KASCADE-Grande data. Figure 1 represents the measured two-dimensional shower size spectrum, color coded area, which includes full detector response by simulations. The symbols correspond to the primary protons and iron nuclei, as predicted by the interaction models EPOS 1.99 and QGSJET-II-2. The errors of mean values are plotted in Fig. 1. It is shown that the most probable values for EPOS are shifted toward the higher muon numbers with respect to QGSJET. This behavior implies, if EPOS predictions are used to derive the mass of primary particles from the observed data, a dominantly light mass composition. Air showers simulated with EPOS 1.99 have about 10% more charged particles and about 15% less muons than QGSJET-II-2 at KASCADE-Grande energies.

The influences of the different hadronic interaction models on the reconstructed all-particle energy spectrum was investigated by performing the reconstructed charged particle shower size method, based on simulations with the hadronic interaction models QGSJET-II-2 and EPOS 1.99. The shower size per individual event is corrected for attenuations in the atmosphere by the constant intensity cut method and calibrated by Monte-Carlo simulations under the assumption of a dependence $lgE \propto lgN_{ch}$ and a particular primary composition. To determine the energy conversion relation between the number of charged particles and the primary energy, the simulations were used. The relation of the primary energy as a function of the number of charged particles is shown in Fig. 2 for the assumption of primary protons and iron, respectively. Assuming a linear dependence in logarithmic scale of $lgE = a + b \cdot lgN_{ch}$, the fit is applied in the range of full trigger and reconstruction efficiencies. A detailed process for the energy reconstruction is given in Ref. [17].

Figure 3 shows the all-particle energy spectra obtained after applying the energy reconstruction functions as well as the appropriate correction for the bin to bin fluctuations, based on the assumption of iron and proton for QGSJET-II-2 and EPOS models. EPOS results lead to significantly higher flux (10-15%) compared to QGSJET. Since the EPOS model has for a fixed primary energy less charged particles, it assigns higher flux. As the calibration depends on simulations, other interaction models would change the interpretation of KASCADE-Grande data, so that more investigations by applying and comparing various interaction models are needed.

5. Muon density investigations

The muon density can be directly measured by KASCADE, so that the composition studies as well as the tests of hadronic interaction models with muon densities can be performed [18]. Figure 4 shows the correlation of muon density with the electron numbers and the distance from the shower axis, compared to the predictions of QGSJET-II-2 and EPOS 1.99 using proton and iron nuclei as primary particles. The muon density decreases with increasing distance from the shower axis and increases with increasing electron number. Since an equal probability trigger for protons and iron primaries as a function of distance from the shower axis is assumed, one should expect the lateral density distribution to be parallel to pure composition primaries. It shows that the lateral distributions of simulated proton and iron shower are parallel, while the measured one is not quite parallel to the both QGSJET-II-2 and EPOS 1.99 curves. However, the lateral muon density distribution has a better slope than the other models such as EPOS 1.61. The QGSJET-II-2 model could fit the data with an intermediate primary abundance between proton and iron nuclei, whereas EPOS 1.99 would require abundance of light primary particles in order to fit the data.

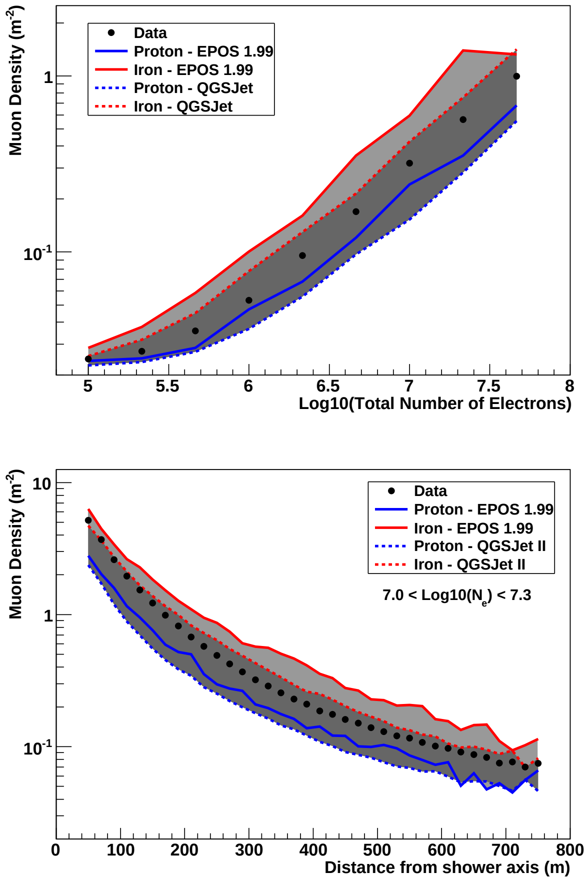

Figure 4: Muon density as a function of the total number of electrons (top panel) and lateral distribution of muons (bottom panel) compared to the predictions of QGSJET-II-2 and EPOS 1.99.

6. Conclusion

Testing of hadronic interaction models QGSJET-II-2 and EPOS 1.99 implemented in the CORSIKA program have been performed with KASCADE-Grande air shower data in the energy range of 10^{16} to 10^{18} eV. From the muon density investigations, the EPOS 1.99 model indicates that light abundances of primary cosmic ray particles would be needed to fit the data. On the other hand, the QGSJET-II-2 model describes the data with an intermediate primary abundance between proton and iron nuclei. The reconstructed all-particle energy spectra are presented by using the hadronic interaction models QGSJET-II-2 and EPOS 1.99. The resulting spectra show that the interpretation of the KASCADE-Grande data with EPOS 1.99 leads to significantly higher flux as compared to the QGSJET-II-2 result. Mored detailed investigations of EPOS 1.99 is still in work.

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