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The influence of properties of individual hadronic interactions on the development of extensive air showers

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To study the effects of uncertainties in the description of individual hadronic interactions on the development of extensive air showers, simulations have been carried out with the CORSIKA program, using the interaction models QGSJET and FLUKA. Within the QGSJET code, inelastic cross sections and the inelasticity of hadronic interactions have been altered within the uncertainties given by accelerator measurements. The influence of these variations on shower observables is discussed. The predictions are compared to measurements of the electromagnetic, muonic, and hadronic shower components with the KASCADE-Grande experiment.

1. Introduction

The uncertainties in the simulation of extensive air showers in the atmosphere are dominated by the limited understanding of high-energy hadronic interactions. To evaluate the effect of uncertainties in the description of individual interactions on the development of air showers, the inelastic proton-proton cross section and the elasticity of interactions have been varied within the error bounds given by accelerator measurements [1]. For the studies parameters in the hadronic interaction model QGSJET 01 [2] have been modified.

The inelastic proton-proton cross section has been lowered from 57 mbarn to 51 mbarn at 10^6 GeV. In the model a change of the proton-proton cross section influences all other hadronic cross sections as well. For example, the proton-air cross section is changed from 385 mbarn to 364 mbarn at 10^6 GeV. The lower values are in good agreement with recent measurements from the HiRes experiment [3, 4]. The variation of QGSJET 01 is labeled model 3 in the following. Another parameter to describe the interactions is the elasticity, i.e. the ratio of energy carried away by the most energetic secondary particle. For the modification with the reduced cross section (model 3) also the elasticity has been increased by about 10% – 15%, this variation is referred to as model 3a.

The influence of this changes on the integral multiplicity of high-energy muons and the average depth of the shower maximum have been described earlier [4]. In the present article the influence of the modifications on the electromagnetic, muonic, and hadronic shower components as measured by the KASCADE-Grande experiment are investigated.

Objective of the KASCADE-Grande experiment is the investigation of the origin of cosmic-rays in the energy range from several 10^{13} eV to 10^{18} eV [5, 6]. The three main components of air showers are detected simultaneously: The electromagnetic component is detected with a 200×200 m^2 and a 700×700 m^2 scintillator array. The energy, as well as point and angle of incidence for hadrons with energies $E_h > 50$ GeV are measured in a sampling calorimeter. Muons are registered with different thresholds in lead shielded detectors in the scintillator array ($E_\mu > 230$ MeV), as well as in the calorimeter with a layer of scintillators ($E_\mu > 490$ MeV) and below it with three layers of position sensitive detectors ($E_\mu > 2.4$ GeV). In addition, high-energy muons are measured by an underground muon tracking detector equipped with limited streamer tubes ($E_\mu > 0.8$ GeV).

To evaluate the impact of the modified parameters on the air shower development the simulation tool CORSIKA [7] is used. The electromagnetic component is modeled with the EGS4 code [8]. Hadronic interactions above 200 GeV are described with QGSJET 01 and with FLUKA [9] at lower energies. All particles reaching ground level are considered in a detector simulation program based on GEANT 3 [10].

2. Results

A lower cross section implies a longer mean free path for the hadrons in the atmosphere and thus a reduction of the number of interactions. A larger elasticity means that more energy is transfered to the leading particle. Both changes applied result in showers which penetrate deeper into the atmosphere. For example. the average depth of the shower maximum for protons at 100 PeV is shifted by 24 g/cm^2 due to the lower cross section and by 10 g/cm^2 due to the higher elasticity [1].

The shift of the shower maximum also affects the number of particles registered at ground level. Since the maximum moves closer to the observation level one expects an increase of the number of particles. However, reducing the number of interactions due to a lower cross section also reduces the possibility to produce secondary particles and an increase of the elasticity implies at the same time that less energy is available for multi-particle production. This means that we are faced with two competing processes influencing the number of particles observed.

The simulations reveal that an increase of the elasticity enhances the particle numbers for all species observed (electrons, muons, and hadrons). An increase is registered for both, primary protons and iron nuclei. This means the effect of deeper penetrating cascades seems to dominate. As an example, the increase of the number of muons when increasing the elasticity is illustrated in Fig. 1. Shown are the relative changes in the number of muons for model 3a relative to model 3 ($\delta N_\mu = (N_\mu^{3a} - N_\mu^3)/N_\mu^3$) for primary protons and iron induced showers as function of primary energy.

The increase of the number of muons N_μ as function of primary energy E_0 has been estimated using a Heitler model to be $N_\mu = (E_0/\xi_c^\pi)^\beta$, where $\xi_c^\pi \approx 20\ GeV$ is the critical energy for pions at which the probability for an interaction and decay are about equal [11]. The exponent β depends on the elasticity of the interaction as $\beta \approx 1 - 0.14(1 - \kappa))$. Using the energy dependence of κ for the two modifications of QGSJET [1] and introducing an energy dependent β, an increase of the number of muons as function of energy is expected as

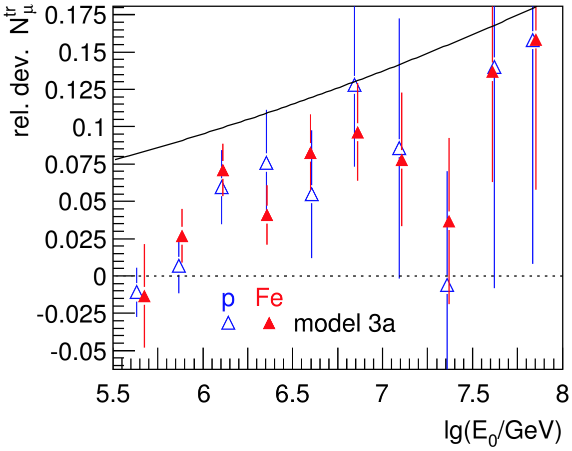

Figure 1. Relative deviation of the number of muons in model 3a relative to model 3, i.e. the change of the number of muons related to an increase of the elasticity as function of primary energy. The line indicates an estimate according to a simple Heitler model.

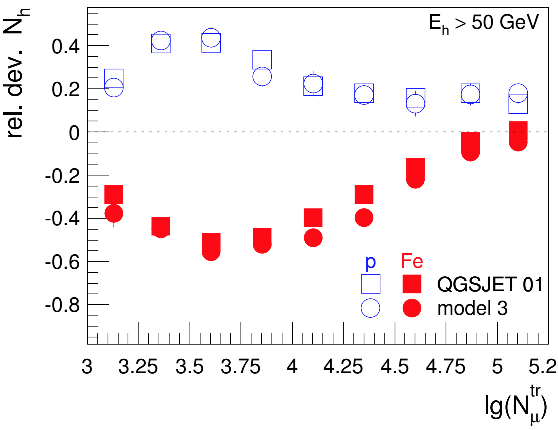

Figure 2. Relative deviation of the number of hadrons as predicted from the measured values as function of the number of muons. Predictions for primary protons and iron nuclei are shown for the original QGSJET and a variation with lower cross sections.

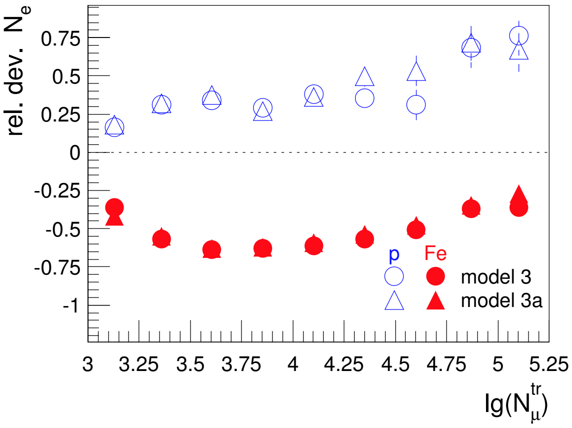

Figure 3. Relative deviation of the predicted number of electrons from the values measured by KASCADE as function of the number of muons. Shown are results for primary protons and iron nuclei for modification of QGSJET with lower inelastic cross sections (model 3) and increased elasticity (model 3a).

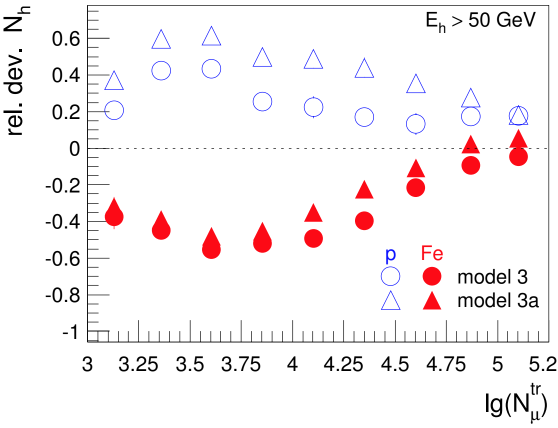

Figure 4. Relative deviation of the predicted number of hadrons from the values measured by KASCADE as function of the number of muons. Shown are results for primary protons and iron nuclei for modifications of QGSJET with lower inelastic cross sections (model 3) and increased elasticity (model 3a).

indicated by the line in Fig. 1. The general trend of the simple estimate is reflected by the detailed simulations, but the absolute values are about 5% larger for the simple estimate as compared to the full simulation.

In addition to the number of muons, also the number of electrons is increased in a similar way. This means that the data points are shifted in the N_e-N_μ plane parallel to the energy axis (i.e. along a diagonal) [12].

Consequently, there is no observable change when these quantities are reconstructed in an experiment. Fig. 3 shows the relative deviations of the predictions for proton and iron induced showers from the data measured with KASCADE-Grande as function of the number of muons. The two models shown differ in the elasticity of the hadronic interactions, but can not be distinguished in this observable. On the other hand, investigating the number of hadrons exhibits a clear difference in the order of 20% for primary protons. This is illustrated in Fig. 4, where the relative deviations of the predicted number of hadrons for two primary species from the measured data are shown. The change in the number of hadrons scales about linearly with the elasticity increase as has been seen in additional simulations assuming different values for the elasticity.

Turning to the alterations of the cross section the situation with the competing processes mentioned above becomes more complex. Reducing the cross section enhances the number of muons with energies above 230 GeV for both primary species, protons and iron nuclei. On the other hand, looking at the number of electrons and hadrons, their number increases for primary protons and decreases for iron nuclei. This behavior influences the correlation between the observed number of hadrons and the number of muons. The relative deviation of the number of hadrons predicted for two primary species from the measured values is depicted in Fig. 2 as function of the number of muons. Calculations with the original QGSJET code are compared to model 3. Due to the behavior of the individual shower components, as just described, the influence of the lower cross section is rather small for primary protons. On the other hand there is a clear and measurable difference in the order of $\sim 10\%$ for iron induced showers.

3. Conclusion

The effect of lower cross sections and higher elasticities for individual hadronic interactions on the air shower development has been investigated. It has been demonstrated that such variations yield significant differences in observable quantities, like the number of secondary particles at ground level. For a complete picture correlations between all shower components have to be analyzed. In particular, it is not sufficient to measure the correlation between the electromagnetic and muonic shower components only. Most directly the influence of properties of individual hadronic interactions can be measured investigating the hadronic air shower component and the average depth of the shower maximum.

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