Test of hadronic interaction models with air shower data

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The description of high-energy hadronic interactions plays an important role in the (astrophysical) interpretation of air shower data. The parameter space important for the development of air showers (energy and kinematical range) extends well beyond todays accelerator capabilities. Therefore, accurate measurements of air showers are used to constrain modern models to describe high-energy hadronic interactions. The results obtained are complementary to information gained at accelerators and add to our understanding of high-energy hadronic interactions.

1 Introduction

The understanding and modeling of extensive air showers (particle cascades in the atmosphere) brings together the particle physics and astroparticle physics communities. To strengthen the connections and the scientific exchange between those communities is very fruitful for both sides and yields complementary information on the understanding of high-energy hadronic interactions.

When high-energy cosmic rays impinge onto the atmosphere they initiate cascades of secondary particles – the extensive air showers. Observations of air showers are used to indirectly infer the properties of cosmic rays at energies exceeding 10^{14} eV. The interpretation of air shower data faces a twofold challenge: the (exact) mass composition of cosmic rays is not known at those energies and, additionally, the properties of high-energy interactions taking place in air showers are partly unknown. Direct measurements of cosmic rays (fully ionized atomic nuclei) at energies below 10^{14} eV indicate that they are mostly composed of elements from hydrogen (protons) up to iron [1, 2]. The abundance of heavier elements is significantly smaller. Hence, in the following, we assume that cosmic rays comprise elements from hydrogen to iron.

We will focus on results from the KASCADE experiment [3], one of the most advanced air shower detectors in the energy range around 10^{15} eV. It has a unique set-up which allows to measure simultaneously the electromagnetic, muonic, and hadronic shower components. This is in particular valuable to test the consistency of hadronic interaction models. Since about a decade [4, 5] systematic checks of interaction models are performed with air shower data and the most stringent constraints on interaction models, derived from air shower data have been obtained with KASCADE measurements.

KASCADE consists of several detector systems. A 200×200 m^2 array of 252 detector stations, equipped with scintillation counters, measures the electromagnetic and, below a lead/iron shielding, the muonic parts of air showers. An iron sampling calorimeter of 16×20 m^2 area detects hadronic particles [6]. It has been calibrated with a test beam at the SPS at CERN up to 350 GeV particle energy [7]. For a detailed description of the reconstruction algorithms see Ref. [8].

2 Quantitative tests

The principle idea of the consistency tests of hadronic interaction models is to simulate air showers initiated by protons and iron nuclei as the two extremes of possible primary particles. The shower simulations were performed using CORSIKA [9], applying different embedded hadronic interaction models. In order to determine the signals in the individual detectors, all secondary particles at ground level are passed through a detector simulation program using the GEANT package [10]. [1] The predicted observables at ground level, such as e.g. the number of electrons, muons, and hadrons or the energy of the hadrons are then compared to the measurements. If the measured values are inside the predicted interval for proton and iron induced showers, the particular interaction model used for the simulations is compatible with the data. On the other hand, if the measured values are outside the proton-iron interval, there is a clear hint for an incompatibility between the model under investigation and the measurements.

Hadronic interactions at low energies ($E_h < 80$ and 200 GeV, respectively) were modeled using the **GHEISHA** [14] and **FLUKA** [15, 16] codes. Both models are found to describe the data equally well [11]. High-energy interactions were treated with different models as discussed below, several models have been systematically tested over the last decade.

First quantitative tests [4, 17, 5] established **QGSJET** 98 [18] as the most compatible code. Similar conclusions have been drawn for the successor code QGSJET 01 [11]. The next version of the code, QGSJET-II-2, has been investigated recently [19]. The analyses yield inconsistencies, in particular for hadron-electron correlations. An example is shown in Fig. 1. For a given interval of the number of electrons the frequency of the maximum hadron energy registered in each shower is plotted. It can be recognized that for small hadron energies, the measured values are outside the range (proton-iron) as predicted by QGSJET-II-2. Studies of the latest version, QGSJET-II-3, are in progress.

Predictions of **SIBYLL** 1.6 [20] were not compatible with air shower data, in particular there were strong inconsistencies for hadron-muon correlations [4]. These findings stimulated the development of SIBYLL 2.1 [21]. This model proved to be very successful, the predictions of this code are fully compatible with KASCADE air shower data [22, 23, 11].

Analyses of the predictions of the **DPMJET** model yield significant problems in particular for hadron-muon correlations for the version DPMJET 2.5 [24], while the newer version DPMJET 2.55 is found to be compatible with air shower data [11].

Investigations of the **VENUS** [25] model revealed some inconsistencies in hadron-electron correlations [5]. The predictions of **NEXUS** 2 [26] were found to be incompatible with the KASCADE data, in particular, when hadron-electron correlations have been investigated [11].

Recently, predictions of the interaction model **EPOS** 1.61 [27, 28, 29] have been compared to KASCADE air shower data [12]. This model is a recent development, historically emerging from the VENUS and NEXUS codes. The analysis indicates that EPOS 1.61 delivers not enough hadronic energy to the observation level and the energy per hadron seems to be too small. This is illustrated in Fig. 2: the predicted hadronic energy sum, relative to the measured

[1] For details on the event selection and reconstruction, see Ref. [11, 12, 13].

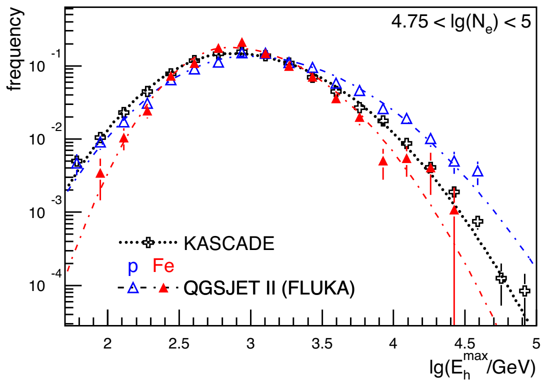

Figure 1: Energy of the most energetic hadron reconstructed at observation level. Predictions of QGSJET II are compared to measured values [19].

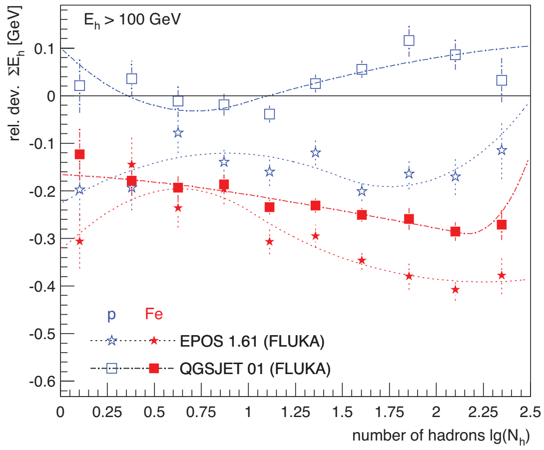

Figure 2: Relative hadronic energy sum $(\sum E_h^{sim} - \sum E_h^{meas})/\sum E_h^{meas}$ as function of the reconstructed number of hadrons for two interaction models and two primary particle species [12].

values is plotted as function of the number of reconstructed hadrons. In this representation the measured values are at the zero line. Shown are results for two interaction models and two primary particle species. The values for protons and iron nuclei for QGSJET 01 are above and below zero, respectively, as expected. However, for EPOS the predictions for both primary particle types are significantly below zero. A strong hint that the predictions are not compatible with the data. Most likely, the incompatibility of the EPOS predictions with the KASCADE measurements is caused by too high inelastic cross sections for hadronic interactions implemented in the EPOS code. These findings stimulated the development of a new version EPOS 1.9 [30]. Corresponding investigations with this new version are under way.

Presently, the most compatible predictions are obtained from the models QGSJET 01 and SIBYLL 2.1.

For a more detailed test of the interaction models one has to assume a mass composition in the simulations to compare a single simulation curve (instead of a proton-iron range) 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 [23]. Energy spectra for elemental groups in cosmic rays have been obtained by applying an unfolding procedure to the measured two-dimensional electron and muon number spectra [31]. This composition of cosmic rays has been used as input for the air shower simulations and the predicted observables at ground level have been compared to the measurements. The investigations reveal that the deviations between the model predictions and the measurements are of the order of 15% [23]. This number illustrates the present accuracy of the quantitative description of the development of air showers.

At much higher energies (exceeding 10^{18} eV) investigations of hadronic interactions are under way with data from the Pierre Auger Observatory. At present, all models investigated exhibit problems in predicting the correct number of muons in air showers [32, 33, 34, 35].

3 Uncertainties of accelerator measurements extrapolated to air shower observables

Also studies have been carried out to evaluate the effect of uncertainties in the description of individual interactions on the development of air showers. An example is the variation of the inelastic proton-proton cross section and the elasticity of the interactions within the error bounds given by accelerator measurements [36]. For the studies parameters in the hadronic interaction model QGSJET 01 have been modified. For illustration, we use here the models 3 and 3a from Ref. [36]. [2] With respect to the original QGSJET 01 code the inelastic hadronic cross sections have been lowered, e.g. the proton-air cross section at 10^6 GeV is reduced by 5% from 385 mb to 364 mb and the elasticity has been increased by about 12%.

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 transferred 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 [36].

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.

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. 3 [37]. 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 [38]. 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 [36] and introducing an energy dependent β, an increase of the number of muons as function of energy is expected as indicated by the line in Fig. 3. 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. This illustrates the sensitivity of air shower observables to properties of hadronic interactions. Another example is discussed in the following.

Recent investigations [13] revealed that the attenuation length λ_E, defined as $\Sigma E_H =$

[2] Model 3 and 3a refer to nomenclature used in Ref. [36]. For model 3 the cross section has been lowerd, and, in addition for model 3a the elasticity has been modified.

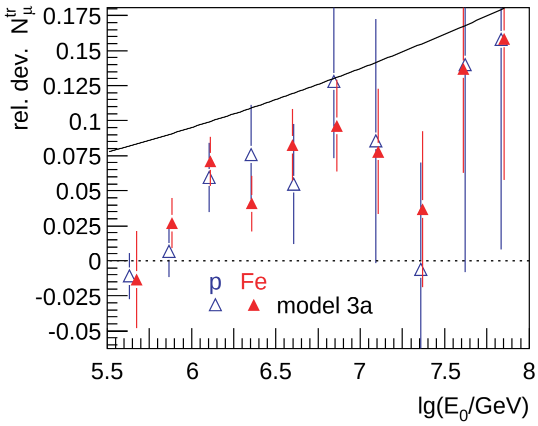

Figure 3: Relative deviation of the number of muons in model 3a relative to model 3, i.e. the change of the number of muons related to an increase of the elasticity as function of primary energy. The line indicates an estimate according to a simple Heitler model [37].

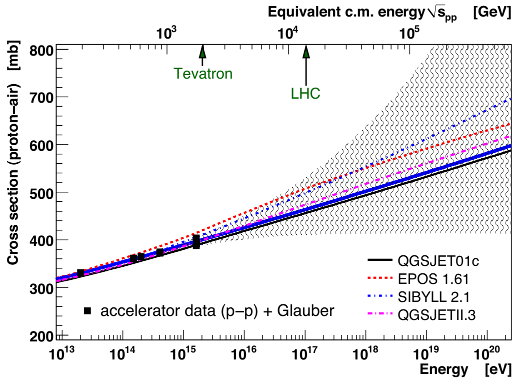

Figure 4: Uncertainties of the extrapolation of the proton-air cross section from accelerator to cosmic-ray energies [39].

$E_0 \exp(-X/\lambda_E)$ is very sensitive to the inelastic hadronic cross sections. E_0 is the energy of the primary particle and $\sum E_H$ the hadronic energy sum registered at ground level. Thus, λ is a measure for the hadronic energy transported to ground. A detailed inspection of the attenuation lengths obtained for showers induced by light and heavy elements indicates that the cross sections in the hadronic interaction model QGSJET 01 may be too large and the elasticity may be too small. A modification with altered parameters (model 3a as discussed above) improves the situation.

Also the influence of the transverse momentum $p_\perp$ in hadronic interactions on (hadronic) air shower observables has been analyzed by the KASCADE group [40]. It turned out that the geometrical distributions of the most energetic hadrons at ground level are sensitive to this parameter. The maximum geometrical distance d_{max} between the four highest-energy hadrons in each shower are sensitive to $p_\perp$. Altering $p_\perp$ in air shower simulations results in different d_{max} distributions.

4 Accelerator data needed for cosmic-ray physics

Complementary to the investigation of air showers more information about hadronic interactions is needed from accelerator experiments to fully understand cosmic rays, as discussed in the following.

Air shower measurements In high-energy interactions most energy is escaping the interaction region in the forward direction, i.e. at large pseudorapidity values η. For example, the energy flow at the LHC at $E_{cm} = 14$ TeV, corresponding to $E_{lab} \approx 2E_{cm}^2/m_p = 10^{17}$ eV, peaks at pseudorapidity values around 7 to 10. The forward region with values $|\eta| > 4$ is of great importance for air shower experiments.

Of particular interest are the total (inelastic) cross sections, the elasticity/inelasticity of the interactions, as well as the production cross sections of secondary particles and their parameter distributions, like multiplicity, transverse momentum, energy, and pseudorapidity. As projectiles protons and pions are of interest to study the elementary interactions but also beams of heavier nuclei (such as C, N, O, or Fe, being dominant in the cosmic-ray composition) are desirable. Targets are preferably air constituents, i.e. nitrogen, oxygen, (and carbon). In particular, at the LHC the study of p-p and p-N interactions is of great importance.

The uncertainties introduced in the proton air cross section by extrapolating from accelerator data to highest energies is illustrated in Fig. 4 [39]. It is obvious that LHC data will drastically reduce the uncertainties in the regime of the highest-energy cosmic rays.

Direct measurements Further input from accelerator experiments is also required for the interpretation of data from balloon borne cosmic-ray detectors, delivering unique information about the propagation of cosmic rays in our Galaxy. The systematic uncertainties of measurements of the boron-to-carbon ratio are presently dominated by uncertainties in the production cross section of boron in the residual atmosphere above the detector [41]. Boron is produced through spallation of the relatively abundant elements of the CNO group in the atmosphere. [3] Thus, the production cross sections of boron for protons and CNO nuclei impinging on nitrogen targets are of great interest at energies significantly exceeding 100 GeV/n.

5 Outlook

We are looking forward to new data from the LHC in the next few years. They will improve current models used for air shower simulations. Complementary, at energies much higher than at the LHC, data from the Pierre Auger Observatory will yield further information on high-energy hadronic interactions. A close cooperation between the high-energy physics and astroparticle physics communities will help to improve our understanding of elementary processes in nature.

Acknowledgments

It was a pleasure for me to serve together with Gianni Navarra as convener for the cosmic-ray session at the EDS 09 meeting. I thoroughly regret that Gianni Navarra passed away in August 2009 — we miss him and will always remember him.

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