Test of interaction models up to 40 PeV by studying hadronic cores of EAS

(The KASCADE Collaboration)

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Abstract
The interpretation of extensive air shower measurements often requires a comparison with shower simulations in the atmosphere. These calculations rely on hadronic interaction models which have to extrapolate into kinematical and energy regions not explored by present-day collider experiments. The KASCADE experiment with its large hadron calorimeter and the detector array for the electromagnetic and muonic components provides experimental data to check such interaction models. For the simulations the program CORSIKA is used, which has several hadronic event generators embedded. For high-energy interactions \( E_{\text{lab}} \gtrsim 100 \text{ GeV} \) the models DPMJET, NEXUS, QGSJET and SIBYLL have been used. Low-energy interactions have been treated by GHEISHA and FLUKA. Different hadronic observables are investigated as well as their correlations with the electromagnetic and muonic shower components up to primary energies of about 40 PeV. Although the predictions of the more recent models are to a large extent compatible with the measured data within the range given by proton and iron primary particles, there are still significant differences between the individual models.

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1. Introduction

The astrophysical interpretation of extensive air shower (EAS) measurements in the PeV domain and above relies strongly on the hadronic interaction models applied when simulating the shower development in the Earth’s atmosphere. To estimate the uncertainties caused by these models and to improve the models it is mandatory to check their reliability. A host of data exists on particle production from p¯p colliders up to energies which correspond to 2 PeV/c laboratory momentum and from heavy ion experiments up to 20 TeV/c per nucleon. However, collider experiments do not register particles emitted in the very forward direction where the bulk of the energy flows. These particles carry the preponderant part of the energy and, therefore, are of utmost importance for the development of an EAS in the atmosphere. Since many of these particles are produced in interactions with small momentum transfers, their kinetic parameters cannot be calculated by perturbation theory of QCD, because the coupling constant is too large. Phenomenological models have to be applied instead. Several such models have been developed to describe the experimental situation. Extrapolations to higher energies, to small angles and to nucleus–nucleus collisions have been performed under different theoretical assumptions. In EAS experiments specific models have been used to determine the primary energy and to extract information about the primary mass composition from shower parameters. Experience shows that different models can lead to deviating results when applied to the same shower data (Antoni et al 2005). Hence, the understanding of the EAS development and the particle physics aspects has always been an important topic in cosmic-ray physics (see, e.g., Gaisser et al (1978) and references therein).

Also for the KASCADE experiment, it is of crucial importance to verify the individual models as thoroughly as possible. In a first publication (Antoni et al 1999), the models VENUS 4.12, SIBYLL 1.6 and QGSJET 98, as implemented in the EAS simulation code CORSIKA (Heck et al 1998), have been inspected. QGSJET was found to describe the data best. Meanwhile, the codes have been improved by their authors and additional codes are at the user’s disposal in CORSIKA (Heck et al 2001). KASCADE has used several methods to investigate hadronic interaction models: event rates (Antoni et al 2001), structures in the hadronic core of air showers (Antoni et al 2005a), muon densities at different muon energy thresholds (Haungs et al 2005, 2006) or muon pseudorapidities (Zabierowski et al 2006). In the following, the models DPMJET version II.55 (Ranft 1995, 1999), NEXUS 2 (Drescher et al 2001), QGSJET 01 (Kalmykov et al 1997) and SIBYLL 2.1 (Engel et al 1999) are investigated. In addition to these program codes used to describe high-energy interactions ($E_{\text{lab}} \gtrsim 100 \text{ GeV}$) another model is needed for lower energies. While the high-energy model controls the first few interactions of an air shower and, therefore, the overall shower development, most of the particles detected at ground are produced in low-energy interactions. In this analysis GHEISHA ($E_{\text{lab}} < 80 \text{ GeV}$) and FLUKA ($E_{\text{lab}} < 200 \text{ GeV}$) have been used as low-energy models. In case of GHEISHA two versions have been investigated: the version included in GEANT 3 (in this analysis called GHEISHA 600) and a version including correction patches (GHEISHA 2002) which improve energy and momentum conservation (Cassell and Bower 2002).

To check the reliability of the simulations it is examined how well and meaningfully the simulations resemble the measured hadronic shower observables. This can be performed within certain limits only, because the primary mass composition is scarcely known in the PeV region, and, if reported, depends strongly on the hadronic interaction model underlying the analysis. Nonetheless, direct measurements above the atmosphere indicate that most of the primary particles are atomic nuclei of the elements between hydrogen and iron and that beyond the iron group the abundance of elements drops drastically by orders of magnitude.
Hence, the experimental data should lie between the model predictions for protons (p) and iron nuclei (Fe). By investigating observables from different shower components the internal consistency of the models and the balance of the distribution of the energy to the different shower components are tested.

2. Measurements and simulations

2.1. The apparatus

The experiment KASCADE, located on the site of the Forschungszentrum Karlsruhe, 110 m a.s.l., consists of several detector systems. A description of the performance of the experiment can be found elsewhere (Antoni et al 2003). A 200 × 200 m² array of 252 detector stations, equipped with scintillation counters, measures the electromagnetic and below a lead iron shielding the muonic parts of EAS. In its center, an iron sampling calorimeter of 16 × 20 m² area detects the hadrons in the shower core. The calorimeter is equipped with 11 000 warm-liquid ionization chambers arranged in nine layers. Due to its fine segmentation (25 × 25 cm²), energy, position and angle of incidence can be measured for individual hadrons. A detailed description of the calorimeter and its performance can be found in Engler et al (1999). It has been calibrated with a test beam at the SPS at CERN (Plewnia et al 2006).

2.2. Observables and event selection

The position of the shower core and the angle of incidence of an EAS are reconstructed by the array detectors. The total numbers of electrons $N_e$ and muons $N_{\mu}$ are determined by integrating their lateral distributions. In case of muons, the ‘truncated muon number’ $N_{\mu}^{tr}$ is used for experimental reasons. It is the number of muons integrated in the distance range 40–200 m from the shower axis. For a detailed description of the reconstruction algorithms see Antoni et al (2001a). The accuracy for the determination of $N_e$ and $N_{\mu}^{tr}$ is about 10–15%. The position of the shower core is reconstructed with an accuracy better than 2 m and the angle of incidence better than 0.5°.

The hadrons in the calorimeter are reconstructed by a pattern recognition algorithm, optimized to recognize as many hadrons in a shower core as possible. Details can be found in Antoni et al (2001a). Hadrons of equal energy can still be separated with a probability of 50% at a distance of 40 cm. The reconstruction efficiency rises from 70% at 50 GeV to nearly 100% at 100 GeV. The energy resolution improves from 30% at 50 GeV to 15% at 10 TeV. The hadron number $N_h$ and hadronic energy sum $\Sigma E_h$ are determined by the sum over all hadrons in a distance up to 10 m from the shower core. A correction for the missing area beyond the boundaries of the calorimeter is applied. In the following, $N_h$ and $\Sigma E_h$ are most for a threshold of 100 GeV, but also hadronic shower sizes for higher thresholds up to 500 GeV have been investigated. The observable $\Sigma E_h$ includes also energy of hadrons which could not be reconstructed independently, because they are too close to each other. It shows up in the simulated and experimental data in the same manner.

To be accepted for the analysis an EAS has to fulfill several requirements: at least one hadron has been reconstructed in the calorimeter with an energy larger than 50 GeV, the shower core is located inside the calorimeter, the electromagnetic shower size $N_e$ is larger than $10^4$, the truncated muon number $N_{\mu}^{tr}$ is larger than $10^3$, i.e. the primary energy is greater than 300 TeV, and the reconstructed zenith angle is smaller than 30°. After all cuts about 240 000 events, measured from May 1998 until October 2005, are used for the analysis.
2.3. Simulations

The shower simulations were performed using CORSIKA with different combinations of low-energy and high-energy interaction models. The CORSIKA versions and the numbers of showers simulated for primary protons and iron nuclei are given in Table 1. The simulations covered the energy range $10^{14} - 10^{17}$ eV with zenith angles in the interval $0^\circ - 32^\circ$. The spectral index in the simulations was $-2.0$. For the analysis it is converted to a slope of $-2.7$ below and $-3.1$ above the knee with a rigidity dependent knee position (3 PeV for protons). The shower core positions are distributed uniformly over an area extending the calorimeter surface by 2 m on each side. 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 (CERN 1993). In this way, the instrumental response is taken into account and the simulated events are analyzed by the same code as the experimental data, an important aspect to avoid biases by pattern recognition and reconstruction algorithms.

The average primary energy belonging to a simulated and reconstructed number of electrons and muons is given in Figure 1. The left panel demonstrates the $N_e$ dependence on the primary mass. The lines through the points are drawn to guide the eye and represent five parameter fits. As in all figures errors of the mean values are plotted. But, in most cases, the error bars are smaller than the marker size. It is seen from Figure 1 that all models yield a nearly linear dependence, only near threshold $N_e$ rises slowly for light primaries, namely...
protons. The number of muons is expected to be a good estimator for the primary energy, since, irrespective of the individual shower development, the most abundant secondaries of the interactions are pions, for which the charged species decay to muons and arrive to a large extent at the Earth’s surface. How well $N_{\mu}^{\text{tr}}$ indicates the primary energy regardless of the primary mass can be seen in figure 1. One observes that all three models agree within 15% when the primary energy is predicted from the observed number of muons $N_{\mu}^{\text{tr}}$.

3. Results

To compare measurements and simulations the data are classified into intervals of shower sizes. Hadronic observables are discussed as a function of the muon ($N_{\mu}^{\text{tr}}$) and electron ($N_e$) numbers and the measured data are compared to the predictions of the simulations for primary protons and iron nuclei.

3.1. Low-energy models

The influence of the low-energy models FLUKA and the two versions of GHEISHA have been investigated using QGSJET 01 and SIBYLL 2.1 as high-energy models. An influence of the low-energy model on the hadronic component detected with the KASCADE calorimeter is not expected. Due to the energy threshold of 100 GeV most of the reconstructed hadrons are produced in interactions treated by the high-energy models in CORSIKA (projectile energy above 80/200 GeV for GHEISHA and FLUKA, respectively). This is confirmed by an investigation of the hadrons in dependence on the primary energy $E_0$.

Also the total number of electrons $N_e$ does not differ significantly between the low-energy models used. Only the number of muons $N_{\mu}^{\text{tr}}$ is changed when using different codes for low-energy interactions. With QGSJET 01 as high-energy model $N_{\mu}^{\text{tr}}$ is for simulations using FLUKA about 3–5% reduced compared to simulations using GHEISHA. Between the two version of GHEISHA no difference is found within the statistical uncertainties (Milke et al 2006). The difference between FLUKA and GHEISHA is reduced to about 2% when applying SIBYLL 2.1 as high-energy model.

When investigating the hadronic component of air showers in dependence on the muonic component the difference in the muon numbers $N_{\mu}^{\text{tr}}$ translates into a difference of the hadronic component, since the primary energies contributing to the same $N_{\mu}^{\text{tr}}$ interval are changed. Figure 2 shows the correlation between the hadronic energy sum $\Sigma E_h$ and the muon number $N_{\mu}^{\text{tr}}$. Using QGSJET 01 as high-energy model a small shift between the simulations using FLUKA and GHEISHA is found. In addition, results for SIBYLL 2.1 as high-energy code are plotted. The difference of the high-energy models is much larger than between FLUKA and GHEISHA.

In the following, only GHEISHA is used as low-energy model. Since for the observables investigated in this analysis no differences between GHEISHA 600 and GHEISHA 2002 are found, it is not distinguished between the two versions. If a simulation set with GHEISHA 2002 has been available (see table 1) this one has been used, otherwise GHEISHA 600.

3.2. High-energy models

With the KASCADE calorimeter several hadronic observables can be investigated. Different observables have a more or less strong sensitivity to different properties of hadronic interactions. The following observables are used in this analysis: number of hadrons $N_h$ (multiplicity in hadronic interactions), hadronic energy sum $\Sigma E_h$ (total energy in hadrons), energy of the most energetic hadron $E_{\text{max}}^h$ (elasticity), lateral distributions of the hadrons
Figure 2. Influence of the low-energy model used in air shower simulations. Shown is the correlation of the hadronic energy sum $\Sigma E_h$ and the muon number $N_{\mu}$. To make the small differences better visible, the relative deviation $(\Sigma E_{h,s} - \Sigma E_{h,m}) / \Sigma E_{h,m}$ of the simulated $(\Sigma E_{h,s})$ to the measured $(\Sigma E_{h,m})$ values are plotted. Results for two low-energy and two high-energy interaction models are shown.

Figure 3. Comparison of NEXUS 2 to the KASCADE data. On the left-hand side the correlation between the number of hadrons $N_h$ and the muon number $N_{\mu}$ is plotted. In addition, values for QGSJET 98 are shown. To improve the clarity only parametrizations of the data points are plotted for QGSJET. On the right-hand side the correlation between the hadronic energy sum $\Sigma E_h$ and the electron number $N_e$ is displayed. The shaded area is the allowed range between proton and iron for NEXUS.

(transverse momenta) and energy spectra. For all combinations of low-energy and high-energy interaction models in table 1 all hadronic observables have been investigated for several hadron energy thresholds in correlation to the muon, electron and hadron content of the air showers. In the following, only few figures can be shown exemplarily. Further examples can be found in Milke et al (2001, 2003, 2004) and Milke (2003a).

3.2.1. NEXUS. A comparison of simulation results using NEXUS 2 as high-energy interaction model to the KASCADE data is shown in figure 3. In addition, values obtained with QGSJET 98 are drawn. Since at the same primary energy both the number of hadrons $N_h$ and the number of muons $N_{\mu}$ using NEXUS are about 10% smaller than for QGSJET, the correlation between
hadrons and muons is not changed (left panel in figure 3), although the primary energies contributing to a muon number interval are different. Comparing the simulation results with the measured data one can see that the measured data are well in between the predictions for primary protons and iron nuclei. This is valid also for other hadronic observables like the energy sum $\Sigma E_h$ and the energy of the most energetic hadron $E_{h}^{\text{max}}$.

In case of the correlation between the hadronic and electromagnetic shower components the situation is different. While at the same primary energy the hadron content of the air showers is reduced for NEXUS 2 compared to QGSJET 98, the number of electrons $N_e$ is more or less unchanged. Therefore, there is a shift in the hadron–electron correlation as can be seen in the right panel of figure 3. The measured data are bracketed by the simulation results using QGSJET, but not by NEXUS. The measured data are outside the proton–iron range near the values predicted by NEXUS for primary iron nuclei. This is not plausible, since in $N_e$ intervals an enrichment of proton-induced showers is expected. For iron-induced showers fewer electrons reach ground level than for primary protons of the same energy. Therefore, for iron nuclei higher primary energies are needed to give the same number of electrons $N_e$ in the detector. Because of the steep energy spectrum of cosmic rays the heavier elements are suppressed in $N_e$ intervals. Therefore, the measured values should rather lie nearer to the proton prediction of the models than to the iron prediction. For a given $N_e$ interval NEXUS predicts a too small hadronic energy sum. This discrepancy applies also to other hadronic observables.

3.2.2. QGSJET. In figure 3, the version 98 of QGSJET has been used. In the newer version QGSJET 01 the treatment of diffractive processes has been changed. As a result, the probability for diffractive interactions is reduced. This leads to a larger mean value of the inelasticity in hadronic processes. Although the modifications are rather small, there is a large effect on the development of EAS. While the muonic component is not changed much, the hadron (10–15%) and electron (7%) content of the showers is reduced significantly. This large effect can be seen in figure 4 where the correlation between the most energetic hadron $E_{h}^{\text{max}}$ and the muon number is shown. Since both hadron and electron content of the air showers are reduced in case of QGSJET 01, the difference in the hadron–electron correlation is smaller than in the hadron–muon correlation. Overall, both model versions are within the range given by proton and iron-induced showers compatible with the measured data.
3.2.3. DPMJET. An other high-energy interaction model available in CORSIKA is DPMJET. In this analysis the two model versions 2.5 and 2.55 have been investigated. It is found that there is a large difference between the two versions. This is demonstrated in the left panel of figure 5. Plotted is the correlation between the hadron number $N_h$ and the muon number $N_{\mu}$. The older version 2.5 of DPMJET predicts about 25% more hadrons at ground than DPMJET 2.55. For the hadronic energy sum and for increasing hadron energy thresholds the effect is even larger. One observes that for muon numbers $\lg N_{\mu} > 4.3$ the measured values are no longer bracketed by the proton–iron range predicted by DPMJET 2.5. It can be concluded that the version 2.5 of DPMJET produces for a given $N_{\mu}$ too many hadrons at ground to be compatible with the data. The same effect can also be seen in the electron content of the air showers. This overestimation of hadrons and electrons is caused by a larger elasticity of hadronic interactions compared to the values of the elasticity predicted by other models. Because of this larger elasticity the air showers penetrate deeper into the atmosphere (Heck et al. 2001). Since both the hadron and the electron component of air showers are changed in the correlation between hadrons and electrons a rather small shift is found. This can be seen on the right-hand side of figure 5. For both model versions the measured values are within the range given by proton and iron-induced showers. However, for DPMJET 2.5 the measured data follow the proton line, while in case of DPMJET 2.55 rather the prediction for iron-induced showers fits the measured values. Taking the expected enrichment of proton-induced showers for electron number intervals discussed above into account, in this observable the behavior of DPMJET 2.5 seems to be more plausible. But, it is not consistent with the hadron–muon correlation.

3.2.4. Comparison of DPMJET 2.55, QGSJET 01 and SIBYLL 2.1. In figure 6, the comparison of the interaction models DPMJET 2.55, QGSJET 01 and SIBYLL 2.1 is shown. On the left-hand side, the correlation between the hadronic energy sum $\Sigma E_h$ and the muon number $N_{\mu}$ is plotted. While DPMJET and SIBYLL predict a rather similar behaviour, the values for QGSJET are smaller. This difference is caused by two effects. First, QGSJET produces more muons (5–10%) at ground for the same primary energy. Therefore, lower primary energies contribute to the same muon number interval. Second, for the same primary
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Figure 6. Comparison of the interaction models DPMJET 2.55, QGSJET 01 and SIBYLL 2.1. Shown are the correlations of the hadronic energy sum $\Sigma E_h$ with the muon number $N_{\mu}$ (left) and the electron number $N_e$ (right).

Figure 7. Frequency distributions of the hadronic energy sum $\Sigma E_h$ for a muon number interval (left) and a electron number interval (right). The shaded area indicates the allowed range between primary protons and iron nuclei for the model DPMJET 2.55.

energy fewer hadrons (10–20%) are predicted by QGSJET. Despite these differences, the measured data are well in between the proton and iron predictions by the models used.

For the correlation between the hadrons and the electrons the situation is different. The number of electrons $N_e$ for the same primary energy is smaller ($\approx 15\%$) in case of QGSJET as compared to SIBYLL and DPMJET. Therefore, the correlations between the hadronic energy sum $\Sigma E_h$ and the electron number $N_e$ do not differ significantly for the three models DPMJET 2.55, SIBYLL 2.1 and QGSJET 01, as can be seen in the right-hand side graph of figure 6. Although the primary energies contributing to a given electron number $N_e$ differ, all three models predict very similar values and are compatible with the measured data.

Not only the mean values of shower observables, as discussed above, are of interest, but also the shape of the underlying distributions. Two examples for such distributions are shown in figure 7. Plotted are distributions of the hadronic energy sum $\Sigma E_h$ for an interval of the muon number $N_{\mu}$ (left) and of the electron number $N_e$ (right). These distributions correspond
3.2.5. Lateral distributions and energy spectra of hadrons. Besides the correlations between different shower sizes also the lateral distributions and energy spectra of the hadrons are measured. In case of the lateral distributions both the number density of the hadrons and the energy density have been investigated for several hadron energy thresholds between 50 GeV and 2 TeV. It is found that all models used predict very similar shapes for the lateral distributions of the hadrons. The predicted shapes are compatible with the measured values. The only significant differences between the models are the absolute values for the hadron densities corresponding to the difference in the shower size correlations shown above. This is demonstrated in figure 8. As an example, the lateral distribution of the hadronic energy density is shown for a muon number interval corresponding to a primary energy of 4 PeV. In the left graph the absolute values of the energy densities are plotted. While DPMJET 2.55 and SIBYLL 2.1 predict a similar behaviour, the values for QGSJET 01 are smaller. On the right-hand side of figure 8 the values are normalized to the integral of the curves to compare the shape of the distributions. In this case, no significant difference between the model predictions is found. The measured shape of the lateral distribution is well in between the curves of the models for proton and iron primary particles. Although for the individual lateral distributions the models are within the proton–iron range compatible with the measured data; there are inconsistencies. For example, QGSJET requires a proton dominated composition to be compatible with the measured values for the absolute hadron energy densities in figure 8 (left-hand side), but a mixed composition to explain the measured shape of the lateral distributions (right graph in figure 8). The reason of this discrepancy can be an underestimation of the hadron content or an overestimation of the muon content of the air showers. In the latter case, smaller primary...
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energies would contribute to the muon number interval and, therefore, the hadron content would be reduced.

When investigating the energy spectra of the hadrons the situation is similar as in case of the hadron lateral distributions. Again, the shape of the distributions predicted by different interaction models is similar. The main differences are the absolute values, especially for intervals of the muon number \( N_{\mu}^p \). Within the range given by primary protons and iron nuclei the model predictions are compatible with the measured values. The energy spectra also have been analyzed for different distances of the hadrons to the shower axis. It was found that the simulations are compatible with the measurements for all distance intervals investigated (3 m width, up to 12 m distance to the shower core). An example for hadron energy spectra is shown on the left-hand side of figure 9. No significant differences between the models DPMJET 2.55, QGSJET 01 and SIBYLL 2.1 are found in the hadron energy spectra for intervals of the electron number \( N_e \).

Derived from the energy spectra are frequency distributions of hadronic energy fractions. For this observable the energies \( E_h \) of the individual hadrons are normalized to the energy \( E_{h}^{\text{max}} \) of the most energetic hadron or the energy sum \( \Sigma E_h \) of all hadrons of an event. An example for an interval of the hadron number \( N_h \) is shown on the right-hand side of figure 9. Again, the models DPMJET 2.55, QGSJET 01 and SIBYLL 2.1 predict similar shapes for these observables and are compatible with the measured data. Differences between the models are found for muon number intervals. But, all models are compatible with the measured values. The differences observed can be explained by differences in the energy of the most energetic hadron \( E_{h}^{\text{max}} \) or the hadronic energy sum \( \Sigma E_h \), as discussed above for the correlation between the hadronic and muonic shower components.

4. Conclusion

A detailed knowledge of the hadronic interactions in the atmosphere is mandatory for an astrophysical interpretation of air shower data. To check the reliability of hadronic interaction
models used in programs for the simulation of the development of EASs, data measured by the KASCADE experiment have been investigated. The measured correlations of different hadronic observables, such as number of hadrons, their energy sum, energy of the most energetic hadron, lateral distribution and energy spectra of hadrons, with the number of muons and electrons at ground level (110 m a.s.l.) have been compared to results of the CORSIKA simulation code, including detector response. Since the precise elemental composition of primary cosmic rays is unknown in the PeV energy domain, the KASCADE data have been compared to simulations of EAS induced by primary protons and iron nuclei. For the treatment of high-energy \( E_h \gtrsim 100\text{GeV} \) hadronic interactions DPMJET, NEXUS, QGSJET and SIBYLL have been used. In addition, the influence of the low-energy models GHEISHA and FLUKA have been investigated.

For the low-energy models only a small influence on the muon number is found. The total number of electrons as well as the high-energy (\( E_h > 100\text{GeV} \)) hadronic component measured by KASCADE do not differ between GHEISHA and FLUKA. The differences between the predictions of these low-energy models are small compared to the influence of different high-energy models used and could be neglected in this analysis.

In case of the high-energy models larger differences between the model predictions are found. While the shapes of many distributions are comparable for the models and compatible with the measured data, the shower sizes (number of hadrons \( N_h \), hadronic energy sum \( \Sigma E_h \), number of electrons \( N_e \) and number of muons \( N_{\mu}^{tr} \)) show significant discrepancies between the models.

For the older models (DPMJET 2.5, NEXUS 2) there are for some observables obvious discrepancies between the measured values and the model predictions, i.e. the measured data are not bracketed by the predictions for proton and iron-induced air showers. On the other hand, other observables are in agreement with the measured values for the same model. Therefore, it has to be stressed that as many observables as possible should be used when checking air shower simulations and, especially, the hadronic interaction models.

The situation is improved for the newer models (DPMJET 2.55, QGSJET 01 and SIBYLL 2.1). Within the range given by the simulation of proton and iron-induced air showers the model predictions are compatible with the measured data. Nevertheless, the models are not fully consistent. To be consistent a model has to be able to describe all observables with the same mass composition of the primary cosmic rays, taking into account the different sensitivity of individual observables to the composition. But, inconsistencies could be found, as was shown in an example for the lateral distribution of QGSJET 01 (figure 8). While the absolute values of the hadron lateral distribution require a proton rich composition, a mixed composition is suggested by the shape. Although a clear convergence of the predictions of the different models over the last couple of years can be stated, there are still significant differences (up to 30\% , e.g. in the correlation between hadronic energy sum \( \Sigma E_h \) and muon number \( N_{\mu}^{tr} \) in figure 6) between the model predictions, with a large influence on the astrophysical interpretation of measured EASs.

To further improve the situation, a possible next step could be investigations of the correlations of quantities observed at ground level, taking into account the primary elemental composition as derived from air shower data based on interpretations using the same model, thus being more precise as just being inside a proton–iron range (Milke et al 2005).

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