TEST OF HADRONIC INTERACTION MODELS WITH KASCADE*

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The interpretation of extensive air shower (EAS) measurements depends on the comparison with EAS simulations. These calculations rely on hadronic interaction models which have to extrapolate into kinematical and energy regions not covered by present-day collider experiments. Therefore, it is necessary to check the reliability of the interaction models used. For the EAS simulations the program CORSIKA is used with several hadronic event generators embedded. Different observables, measured with the KASCADE experiment simultaneously for each air shower event, are investigated as well as their correlations. The consistency of the models applied is checked by comparison of experimental and simulated results.

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1. Introduction

The energy spectrum of cosmic rays extends up to 10^{11} GeV. It can be described by a power law with a change of the spectral index from -2.7 to -3.1 at about 4×10^6 GeV, the so called "knee" (see also [1]). Up to energies of few 10^5 GeV cosmic rays can be measured directly with experiments on satellites or high floating balloons. Because of the steeply falling flux as function of energy, these experiments run out of statistics at higher energies. The detector sizes and exposure times necessary to measure at higher energies can only be realized with ground based experiments so far. These experiments do not measure the primary particles directly, but the extensive air showers (EAS) induced in the atmosphere. Therefore, the interpretation of the measurements depends on the comparison with simulations of EAS.

The most critical aspect of these simulations is the description of the interactions of the hadronic shower particles with the nuclei in the atmosphere. The interaction models used have to extrapolate into energy and kinematical regions beyond the limit of present-day collider experiments. The highest energy available at a collider (2 TeV, Tevatron) corresponds to an EAS energy of 2×10^6 GeV, *i.e.* just below the knee. In addition the very forward region is usually not covered by detectors at colliders. But these particles emitted with high energies and small transverse momenta in the forward direction dominate the development of EAS.

Therefore, it is mandatory to check the reliability of the EAS simulation programs used and especially the hadronic event generators embedded. This can be done by measuring as many air shower components as possible simultaneously and investigating the correlations between different shower components. By comparing measurements and simulations the reliability of the hadronic interaction models can be checked. The most relevant free parameters of the models are the proton-air cross sections, the multiplicity and transverse momentum distributions of the secondary particle production, and the diffractive part of the cross sections (see also [2]).

2. Measurement and simulation

2.1. The experiment KASCADE

The experiment KASCADE[1] [3] is located on the site of the Forschungszentrum Karlsruhe (Germany), 110 m a.s.l. It was designed to measure EAS in the energy range 10^5 GeV–10^8 GeV. The main aims of KASCADE are the determination of energy spectra for individual mass groups of cosmic rays to investigate the knee in the energy spectrum and the test of hadronic interaction models used for the interpretation of EAS measurements.

[1] **Ka**rlsruhe **S**hower **C**ore and **A**rray **De**tector

KASCADE consists of several detector components to measure the electromagnetic, muonic, and hadronic shower components simultaneously. The $200 \times 200\,\mathrm{m}^2$ large detector array with 252 detector stations equipped with scintillation counters measures the electromagnetic and below a lead iron shielding (20 radiation lengths, energy threshold $E_\mu > 230\,\mathrm{MeV}$) the muonic component. By a fit to the measured lateral distributions of the shower particles the number of electrons N_e, the number of muons N_μ^{tr} (in the distance range 40–200 m), and the shower core position are determined. In addition, there is a $128\,\mathrm{m}^2$ large muon tracking detector ($E_\mu > 800\,\mathrm{MeV}$) consisting of three horizontal and two vertical layers of limited streamer tubes [4].

In the center of the array a $20 \times 16\,\mathrm{m}^2$ large hadron calorimeter is installed [5]. It is a 11.4 hadronic interaction lengths thick iron sampling calorimeter with 9 active layers equipped with liquid ionization chambers. Due to the fine segmentation in $25 \times 25\,\mathrm{cm}^2$ channels energy, position, and direction of incidence of individual hadrons can be reconstructed ($E_h > 50\,\mathrm{GeV}$). In the third absorber gap a layer of scintillation counters is installed as trigger and for the measurement of muons with an energy threshold of 490 MeV. Below the absorber of the calorimeter two layers of multiwire proportional chambers and a layer of limited streamer tubes are installed to measure tracks of muons above 2.4 GeV.

2.2. Simulations

For the extensive air shower simulations the program CORSIKA [6] is used. CORSIKA describes the transport of the individual particles through the atmosphere and processes such as the decay of instable particles, ionization losses, and multiple scattering. Electromagnetic interactions are handled by EGS4 [7]. For the hadronic interactions different interaction models have been included. At high energies ($> 80\,\mathrm{GeV}$ laboratory energy) the models DPMJET [11], NEXUS [9], QGSJET [8], SIBYLL [10], and VENUS [12] can be used. For low energy interactions the models GHEISHA [13], UrQMD [14], and recently also FLUKA are available.

3. Results

3.1. Hadronic observables

The closest connection to the hadronic interactions in the atmosphere is given for high-energy hadrons in the central region of EAS. Therefore, the hadrons measured in the calorimeter of the KASCADE experiment provide important information about hadronic interactions [15, 16]. Since the mass composition of primary cosmic rays is not known in the energy range of the knee, the measured observables cannot be compared with the simulations directly. Instead, the measured data are evaluated relative to simulations of proton and iron primaries. The measurements have to lie between these extreme values, otherwise the simulations cannot describe the measured data since nuclei heavier than iron are not expected to be abundant among primary cosmic rays.

Many hadronic observables like the number of hadrons N_h, the energy sum of hadrons ΣE_h, the most energetic hadron $E_h^{\max}$, lateral distributions $\rho_\mathrm{h}(r)$, and energy spectra dN/dE_h have been investigated. Several energy thresholds (50 GeV–2 TeV) are applied and energy spectra are calculated for different distance ranges. All observables are evaluated in correlation with the number of muons, electrons, and hadrons in the air showers [17].

Two examples for shower size correlations are shown in Fig. 1. On the left-hand side the correlation between the hadronic energy sum ΣE_h versus the number of muons N_μ^{tr} is plotted. The measured data are between the proton and iron curves for the models QGSJET 01, SIBYLL 2.1, and NEXUS 2. The right-hand graph shows the correlation between the energy of the most energetic hadron $E_h^{\max}$ and the number of electrons N_e. Since the electromagnetic shower component is continously regenerated by the hadrons in an EAS in this case no or only small differences between proton and iron simulations can be found for the individual models. But there are significant differences between the predictions. QGSJET and SIBYLL reproduce the measurements well, whereas with NEXUS calculations too little hadronic energy is obtained.

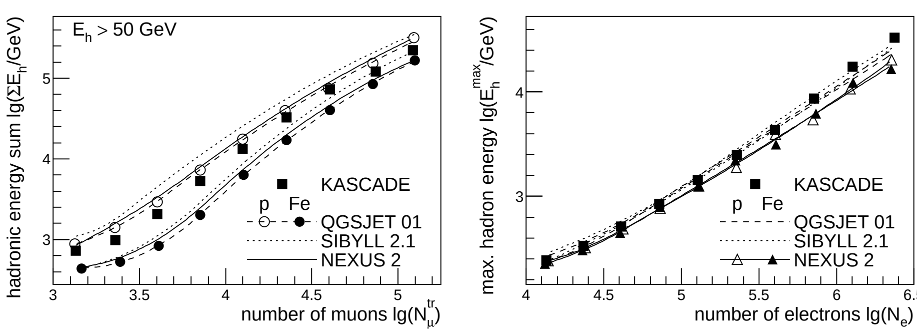

Fig. 1. Left-hand side: Correlation between the hadronic energy sum ΣE_h and the number of muons N_μ^{tr}. Right-hand side: Correlation of the most energetic hadron $E_h^{\max}$ and the number of electrons N_e. To improve the visibility, for some of the models only parameterizations are shown.

Fig. 2 shows examples for hadron lateral distributions and energy spectra. All three models are compatible with the measured data. By investigating many hadronic observables it is found that the models QGSJET and SIBYLL can describe the measured data. The measurements lie between the prediction of the models for proton and iron induced EAS. Contrary, NEXUS presently cannot reproduce all distributions. The model has problems to describe the correlation of the hadronic observables with the electromagnetic shower component.

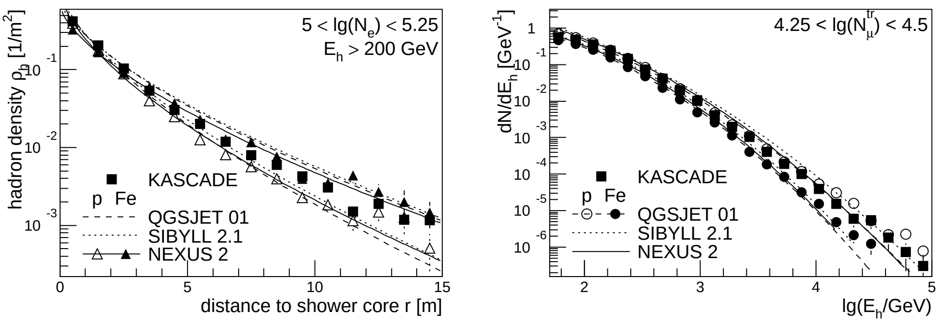

Fig. 2. Left-hand side: Hadron lateral distributions for an electron number interval corresponding to primary energies between 10^6 GeV (p induced showers) and 3×10^6 GeV (Fe induced showers). Right-hand side: Energy spectra of hadrons in a muon number interval (approx. 7×10^6 GeV).

3.2. Structure of the hadronic core of EAS

Another investigation of the high-energy hadrons in the core of EAS deals with their spatial structure which is sensitive to the transverse momentum distributions of the interactions [18]. At primary energies around and above the knee the observation of aligned geometrical structures in air showers has motivated many experimental and theoretical investigations including discussions about sensitivity to special interaction features such as jet formation or hints to new physics (see *e.g.* [19,20] and references therein). The alignment of particles (or particle families) is commonly described by a parameter λ_4 quantifying the angular correlation between the four most energetic particles

$$\lambda_4 = \frac{1}{24} \sum_{i \neq j \neq k}^{4} \cos 2\varphi_{i,j}^{k} \qquad (1)$$

with the angle $\varphi_{i,j}^{k}$ between the lines connecting the particle k to i and j. λ_4 varies between $-1/3$ (isotropic) and $+1$ (perfect alignment). Events are usually termed elongated for $\lambda_4 > 0.8$.

In Fig. 3 a good agreement between measurements and simulations can be found. No significant differences between proton and iron induced showers are observed. To investigate the correlation between the λ_4 parameter and jet production in high-energy interactions the azimuth angles of the four hadron positions were chosen randomly. If the lateral distribution of the hadrons is not modified by this procedure the distributions of the parameter λ_4 do not change. Even an unphysical modification of p_t in the simulation causes only marginal modifications of the distributions.

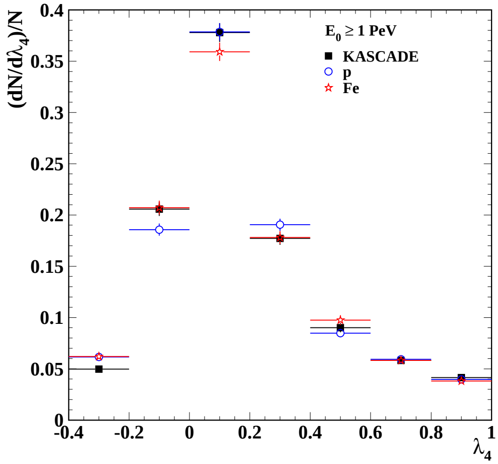

Fig. 3. Distributions of the alignment parameter λ_4. KASCADE measurements are compared with QGSJET 01 simulations.

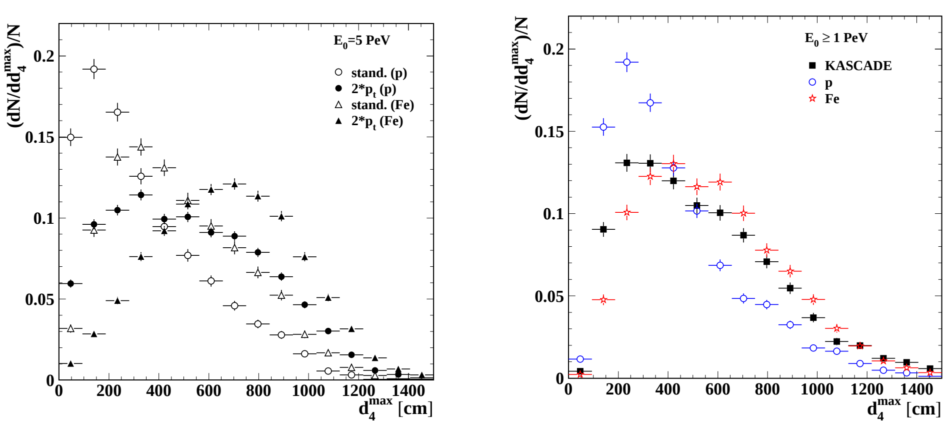

Fig. 4. Distributions of the parameter $d_4^{\max}$. Left hand side: Comparison of standard QGSJET 01 simulations and QGSJET with p_t increased by a factor two. Right hand side: Comparison of measurement and simulation.

The parameter λ_4 depends only on the angles between the hadrons, but not on the distance between them. Therefore, a parameter $d_4^{\max}$ was introduced which is defined as the maximum distance between one of the four hadrons considered to the geometric center of the three others. This parameter shows a clear correlation with p_t as can been seen on the left-hand side of Fig. 4. In the right graph of Fig. 4 the comparison of the measurements and simulations is shown. A clear separation between proton and iron induced events is visible with the KASCADE data in between.

3.3. Muon densities

The observables discussed so far are sensitive to the high-energy interaction models used in EAS simulations. By using measurements of muon densities for different energy thresholds the influence of low-energy hadronic interaction models ($E_{\text{lab.}} < 80\,\text{GeV}$) can be investigated [21]. A parameter found to be sensitive to the interaction models is the ratio of muon densities $R_\rho = \rho_\mu^{2400}/\rho_\mu^{490}$ measured per single air shower in the multi-wire proportional chambers below the KASCADE hadron calorimeter (ρ_μ^{2400}, $E_\mu > 2.4\,\text{GeV}$) and the scintillator layer in the third gap of the iron absorber of the calorimeter (ρ_μ^{490}, $E_\mu > 490\,\text{MeV}$).

In Fig. 5 the dependence of the mean values and the fluctuations (width of distributions) of the density ratios on the number of muons N_μ^{tr} ($E_\mu >$ 230 MeV) is shown. The measured data are compared with simulations using different combinations of high-energy and low-energy interaction models. As can be seen none of the model combinations can reproduce the measured

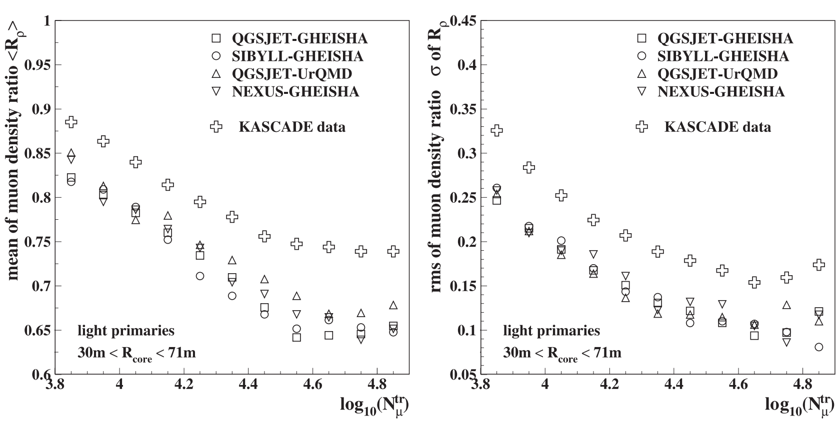

Fig. 5. Muon density distributions. On the left-hand side the mean values of the R_ρ distributions are shown, on the right-hand side the corresponding RMS values. The range of muon numbers shown corresponds to primary energies 10^6–10^7 GeV.

data reasonably well. The next generation of CORSIKA will include FLUKA and neXus 3 as new models which show in first tests a significantly different behaviour of the muon component (see [22]).

4. Summary

By measuring simultaneously the hadronic, muonic, and electromagnetic components of EAS the experiment KASCADE offers good possibilities to check the reliability of EAS simulations used to interpret the measured data. Both the low-energy and the high-energy hadronic interaction models used in simulations can be tested by investigating the correlations between many different observables. Up to now none of the models applied is able to describe all aspects of EAS simultaneously. Additional information from accelerator and cosmic-ray experiments are needed to improve both the high-energy and the low-energy hadronic interaction models.

REFERENCES

[1] A. Haungs *et al.*, *Acta Phys. Pol. B* **35**, 331 (2004), these Proceedings.

[2] R. Engel, H. Rebel, *Acta Phys. Pol. B* **35**, 321 (2004), these Proceedings.

[3] T. Antoni *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A513**, 490 (2003).

[4] P. Doll *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A488**, 517 (2002).

[5] J. Engler *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A427**, 528 (1999).

[6] D. Heck *et al.*, CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers FZKA 6019, Forschungszentrum Karlsruhe (1998).

[7] W.R. Nelson *et al.*, The EGS4 Code System SLAC Report 265, Stanford Linear Accelerator Center (1985).

[8] N. Kalmykov *et al.*, *Nucl. Phys. B (Proc. Suppl.)* **52B**, 17 (1997).

[9] H.J. Drescher *et al.*, *Phys. Rep.* **350**, 93 (2001).

[10] R. Engel *et al.*, Proc. 26$^{\mathrm{th}}$ ICRC, Salt Lake City, USA vol. 1, 1999, p. 415.

[11] J. Ranft, `hep-ph/9911213`.

[12] K. Werner, *Phys. Rep.* **232**, 87 (1993).

[13] H. Fesefeldt, Report PITHA–85/02, RWTH Aachen (1985).

[14] M. Bleicher *et al.*, *J. Phys. G: Nucl. Part. Phys.* **25**, 1859 (1999).

[15] T. Antoni *et al.*, *J. Phys. G: Nucl. Part. Phys.* **25**, 2161 (1999).

[16] T. Antoni *et al.*, *J. Phys. G: Nucl. Part. Phys.* **27**, 1785 (2001).

[17] J. Milke *et al.*, Proc 27$^{\mathrm{th}}$ Int. Cosmic Ray Conf., Hamburg, vol. 1, 2001, p. 241; J. Milke *et al.*, *Nucl. Phys. B (Proc. Suppl.)* **122**, 388 (2003).

[18] A. Iwan *et al.*, Proc. 28$^{\mathrm{th}}$ ICRC, Tsukuba, Japan, vol. 3, 2003, p. 1595.

[19] A.S. Borisov *et al.*, *Nucl. Phys. B (Proc. Suppl.)* **52B**, 218 (1997); J.N. Capdevielle, S.A. Slavatinsky, *Nucl. Phys. B (Proc. Suppl.)* **75A**, 12 (1999).

[20] F. Halzen, D.A. Morris, *Phys. Rev.* **D42**, 1435 (1990).

[21] A. Haungs *et al.*, Proc. 28$^{\mathrm{th}}$ ICRC, Tsukuba, Japan, vol. 1, 2003, p. 37.

[22] D. Heck *et al.*, Proc. 28$^{\mathrm{th}}$ ICRC, Tsukuba, Japan, vol. 1, 2003, p. 279.