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KASCADE: Astrophysical results and tests of hadronic interaction models

A. Haungs[a*], T. Antoni[b], W.D. Apel[a], A.F. Badea[a†], K. Bekk[a], A. Bercuci[c], H. Blümer[ab], H. Bozdog[a], I.M. Brancus[c], C. Büttner[b], A. Chilingarian[d], K. Daumiller[a], P. Doll[a], R. Engel[a], J. Engler[a], F. Feßler[a], H.J. Gils[a], R. Glasstetter[b‡], D. Heck[a], J.R. Hörandel[b], K.-H. Kampert[ba‡], H.O. Klages[a], G. Maier[a§], H.J. Mathes[a], H.J. Mayer[a], J. Milke[a], M. Müller[a], R. Obenland[a], J. Oehlschläger[a], S. Ostapchenko[a¶], M. Petcu[c], H. Rebel[a], A. Risse[e], M. Risse[a], M. Roth[b], G. Schatz[a], H. Schieler[a], J. Scholz[a], T. Thouw[a], H. Ulrich[a], J. van Buren[a], A. Vardanyan[d], A. Weindl[a], J. Wochele[a], J. Zabierowski[e]

[a]Institut für Kernphysik, Forschungszentrum Karlsruhe, D-76021 Karlsruhe, Germany

[b]Institut für Experimentelle Kernphysik, Universität Karlsruhe, D-76021 Karlsruhe, Germany

[c]National Institute of Physics and Nuclear Engineering, P.O. Box Mg-6, RO-7690 Bucharest, Romania

[d]Cosmic Ray Division, Yerevan Physics Institute, Yerevan 36, Armenia

[e]Soltan Institute for Nuclear Studies, PL-90950 Lodz, Poland

KASCADE is a multi-detector setup to get redundant information on single air shower basis. The information is used to perform multiparameter analyses to solve the threefold problem of the reconstruction of (i) the unknown primary energy, (ii) the primary mass, and (iii) to quantify the characteristics of the hadronic interactions in the air-shower development. In this talk recent results of the KASCADE data analyses are summarized concerning cosmic ray anisotropy studies, determination of flux spectra for different primary mass groups, and approaches to test hadronic interaction models. Neither large scale anisotropies nor point sources were found in the KASCADE data set. The energy spectra of the light element groups result in a knee-like bending and a steepening above the knee. The topology of the individual knee positions shows a dependency on the primary particle. Though no hadronic interaction model is fully able to describe the multi-parameter data of KASCADE consistently, the more recent models or improved versions of older models reproduce the data better than few years ago.

1. Introduction

The all-particle energy spectrum of cosmic rays shows a distinctive feature at few PeV, known as the knee, where the spectral index changes from −2.7 to approximately −3.1 (Fig. 1). At that energy direct measurements are presently not possible due to the low flux, but indirect measurements observing extensive air showers (EAS) are performed. Astrophysical scenarios like the change of the acceleration mechanisms at the cosmic ray sources (supernova remnants, pulsars, etc.) or effects of the transport mechanisms inside the Galaxy (diffusion with escape probabilities) are conceivable for the origin of the knee as well as particle physics reasons like a new kind of hadronic interaction inside the atmosphere or during the transport through the interstellar medium.

Despite EAS measurements with many experimental setups in the last five decades the origin of the kink is still not clear, as the disentanglement of the threefold problem of estimate of energy and mass plus the understanding of the air-shower development in the Earth's atmosphere remains an experimental challenge. For a detailed discussion of the subject see a recent review [1].

The multi-detector system KASCADE (KArlsruhe Shower Core and Array DEtector) [2] approaches this challenge by measuring as much as possible redundant information from each single air-shower event. The multi-detector arrange-

*corresponding author, e-mail: haungs@ik.fzk.de
†on leave of absence from [b]
‡now at Universität Wuppertal, Germany
§now at University Leeds, UK
¶on leave of absence from Moscow State University, Russia

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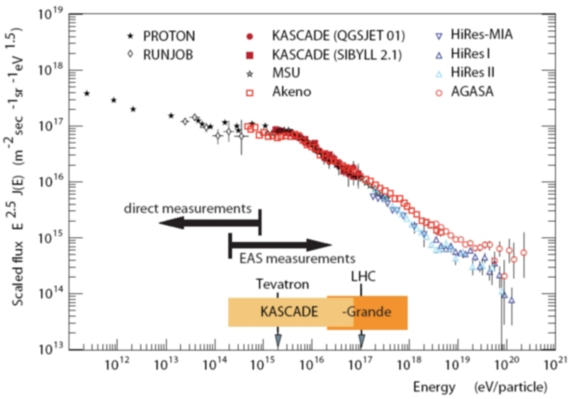

Figure 1. Primary cosmic ray flux and primary energy range covered by KASCADE and its extension KASCADE-Grande.

ment allows to measure the total electron and muon numbers of the shower separately using an array of shielded and unshielded detectors at the same place. Furthermore, the muon densities are being measured at three additional threshold energies and the hadronic core of the showers with an iron sampling calorimeter.

In the following we present the main results of KASCADE, in particular the reconstruction of energy spectra of single primary mass groups and approaches of correlation analyses to test the hadronic interaction models and to find constraints for the improvement and development of the next generation of the models. These tests provide complementary information to the data of present accelerator experiments, as air-shower data are sensitive to higher energy interactions and to a different (extreme forward direction) kinematic region.

2. The KASCADE experiment

The KASCADE experiment [2] measures showers in a primary energy range from 100 TeV to 80 PeV and provides multi-parameter measurements on a large number of observables including electrons, muons at 4 energy thresholds, and hadrons. The main detector components of KASCADE are the Field Array, the Central Detector, and the Muon Tracking Detector (Fig. 2).

The Field Array measures the total electron

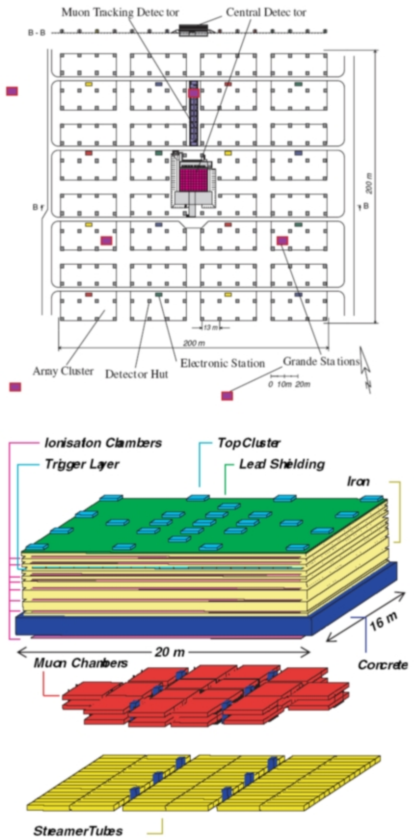

Figure 2. The main detector components of the KASCADE experiment: (the 16 clusters of) Field Array, Muon Tracking Detector and Central Detector. The location of some stations of the Grande array is also displayed. The lower part of the figure shows a sketch of the Central Detector with its different detection set-ups.

and muon numbers ($E_\mu > 240\,\mathrm{MeV}$) of the shower separately using an array of 252 detector stations containing shielded and unshielded detectors at the same place in a grid of $200 \times 200\,\mathrm{m}^2$. The excellent time resolution of these detectors allows also good determination of the arrival directions of the showers, in the search for large scale anisotropies and, if existent, cosmic ray point sources.

The Muon Tracking Detector measures the incidence angles of muons ($E_\mu > 800\,\mathrm{MeV}$) relative to the shower arrival direction.

The hadronic core of the shower is measured by a 300 m^2 iron sampling calorimeter installed at the KASCADE Central Detector: Three other components - trigger plane (serves also as timing facility), multiwire proportional chambers (MWPC), and limited streamer tubes (LST) - offer additional valuable information on the penetrating muonic component at 490 MeV and 2.4 GeV energy thresholds.

The redundant information of the showers measured by the Central Detector and the Muon Tracking Detector is predominantly being used for tests and improvements of the hadronic interaction models, inevitably needed for the interpretation of air shower data.

3. KASCADE results

First, some results which are obtained nearly independently of the influences of simulations, in particular, searches for anisotropies of cosmic rays and gamma rays will be discussed. Second, results of the main analyses of KASCADE are reported, i.e., the unfolding of the two-dimensional electron number to muon number size spectrum in energy spectra of five different mass groups, and the dependence of the results on the hadronic interaction models. Finally, specific tests of the hadronic interaction models using data of the Central Detector and the Muon Tracking Detector of KASCADE are discussed.

3.1. Search for anisotropies and point sources

Investigations of anisotropies in the arrival directions of the cosmic rays give additional information on the cosmic ray origin and of their propagation. Depending on the model of the origin of the knee one expects large-scale anisotropies on a scale of 10^{-4} to 10^{-2} in the energy region of the knee and depending on the assumed structure of the galactic magnetic field. For example in Fig. 3 (upper panel) the predictions from calculations of Candia et al. [3] are compared with the limits of anisotropy given by KASCADE results [4]. The KASCADE limits were obtained by investigations of the Rayleigh amplitudes and phases of the first harmonics. Taking into account possible nearby

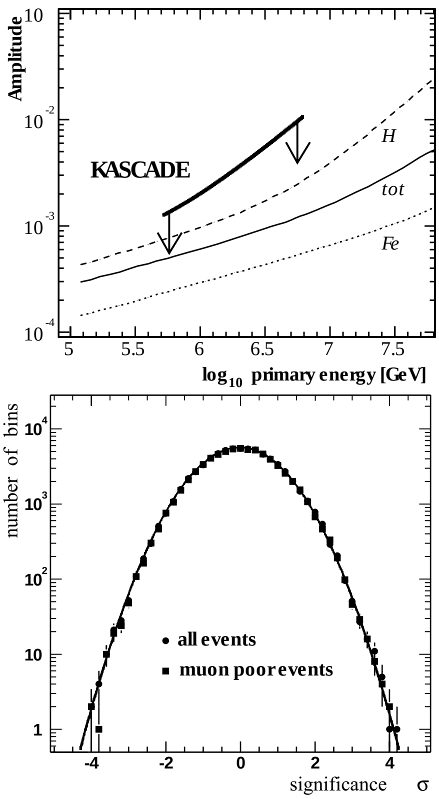

Figure 3. Upper part: Rayleigh amplitude of the harmonic analyses of the KASCADE data [4] (limit on a 95% confidence level) compared to theoretical predictions [3]. Lower part: Significance distributions for searching point sources on the sky map seen by the KASCADE experiment [6].

sources of galactic cosmic rays like the Vela Supernova remnant [5] the limits of KASCADE already exclude particular model predictions. But for a complete picture the investigations have to be performed with air shower samples of the different mass groups which need a higher statistical accuracy of measurements.

Some interest for looking to point sources in the KASCADE data sample arises from the possibility of unknown near-by sources, where the deflection of the charged cosmic rays would be small or by sources emitting neutral particles like high-energy gammas or neutrons. Due to their small decay lengths the latter ones are of interest for near-by sources only. Fig. 3 (lower panel) shows

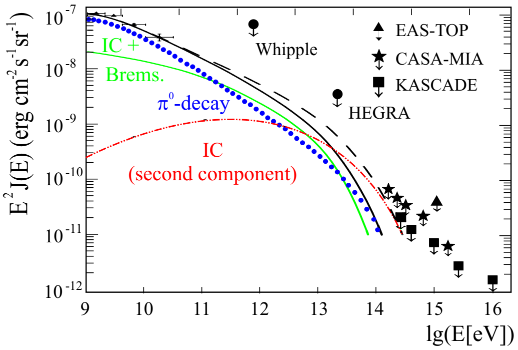

Figure 4. Derived limits on the gamma flux compared to limits of other experiments and theoretical spectra from [8].

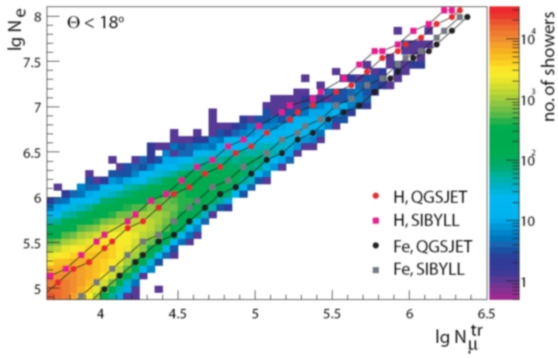

Figure 5. Two dimensional electron (N_e) vs. muon (N_μ^{tr} = number of muons in 40-200m core distance) number spectrum measured by the KASCADE array. The lines display the most probable values for proton and iron primaries obtained by CORSIKA simulations employing different hadronic interaction models.

the distribution of significances for a deviation of the flux from the expected background for all bins of the visible sky of KASCADE. Shown are the distributions for the full sample of air showers as well as for a sample of "muon-poor" showers which is a sample with an enhanced number of candidates of γ-ray induced events. No significant excess was found in both samples [6].

With a similarly obtained sample of enhanced gamma candidates an analyses is performed to estimate limits [7] on the diffuse high-energy gamma ray flux. Fig. 4 shows the flux compared to obtained limits from other experiments and theoretical spectra from [8]. By increasing the statistics and/or improving the selection procedures the KASCADE results will reach the sensitivity to prove such theoretical calculations.

3.2. Energy spectra of individual mass groups

The content of each cell of the two-dimensional spectrum of electron number vs. muon number (Fig. 5) is the sum of contributions from the individual primary elements. Hence the inverse problem $g(y) = \int K(y,x)p(x)dx$ with $y = (N_e, N_\mu^{\mathrm{tr}})$ and $x = (E, A)$ has to be solved. This problem results in a system of coupled Fredholm integral equations of the form

$$\frac{dJ}{d\,\lg N_e\ d\,\lg N_\mu^{tr}} = \sum_A \int_{-\infty}^{+\infty} \frac{d\,J_A}{d\,\lg E} \cdot p_A(\lg N_e\,,\, \lg N_\mu^{tr}\ \mid\ \lg E) \cdot d\,\lg E$$

where the probability p_A is a further integral with the kernel function $k_A = r_A \cdot \epsilon_A \cdot s_A$ factorized into three parts. The quantity r_A describes the shower fluctuations, i.e. the distribution of electron and muon number for given primary energy and mass. The quantity ϵ_A describes the trigger efficiency of the experiment, and s_A describes the reconstruction probabilities, i.e. the distribution of reconstructed N_e and N_μ^{tr} for given true numbers of electrons and muons. The probabilities p_A are obtained by parameterizations of Monte Carlo simulations for fixed energies using a moderate thinning procedure as well as fully simulated showers as input of the detector simulations.

The application of the unfolding procedure to the data is performed on the basis of two different hadronic interaction models (QGSJET 01 [9], SIBYLL 2.1 [10]) as options embedded in CORSIKA [11] for the reconstruction of the kernel functions [12]. By applying the above described procedures to the experimental data energy spectra are obtained as displayed in Fig. 6.

Knee like features are clearly visible in the all particle spectrum, which is the sum of the unfolded single mass group spectra, as well as in the spectra of primary protons and helium. This demonstrates that the elemental composition of cosmic rays is dominated by light components below the knee and dominated by a heavy compo-

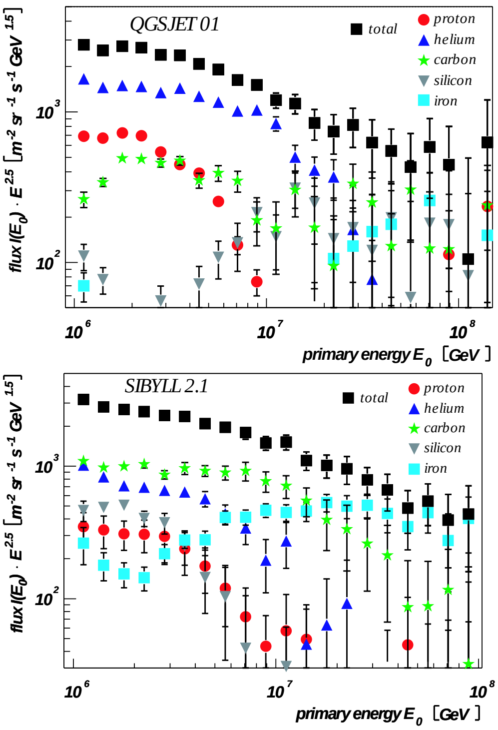

Figure 6. Result of the unfolding procedure. Upper part: based on QGSJET 01; Lower part: based on SIBYLL 2.1.

nent above the knee feature. Thus the knee feature originates from a decreasing flux of the light primary particles. This observation corroborates results of the analysis of muon density measurements at KASCADE [13], which are performed independently of the unfolding procedure.

3.3. Inaccuracies of hadronic interaction models

Comparing the unfolding results based on the two different hadronic interaction models, the model dependence when interpreting the data is obvious. Modeling the hadronic interactions underlies assumptions from particle physics theory and extrapolations resulting in large uncertainties, which are reflected by the discrepancies of the results presented here. The most prominent difference lies in the larger contribution of heavier primaries in case of the SIBYLL model, especially at high energies. To understand the differences between the results based on the two different models and to judge the validity of the models in general detailed investigations of the results are performed. In Fig. 5 the predictions of the N_e and N_μ^{tr} correlation for the two models are given in case of proton and iron primaries. It is remarkable that all four lines have a more or less parallel slope which is different from the data distribution. There, the knee is visible as kink to a flatter N_e-N_μ^{tr} dependence above $N_\mu^{tr} \approx 4.2$. The heavier primary contribution to the results based on the SIBYLL model is due to predictions of a larger ratio of muon to electron number for all primaries. Comparing the residuals of the unfolded two dimensional distributions for the different models with the initial data set we conclude [14] that at lower energies the SIBYLL model and at higher energies the QGSJET model are able to describe the correlation consistently, but none of the present models gives a contenting description of the whole data set. Also a preliminary analysis using the FLUKA [15] code instead of GHEISHA [16] as low energy interaction model shows no conspicuous improvement of the situation.

Crucial parameters in the modeling of hadronic interaction models which can be responsible for these inconsistencies are the total nucleus-air cross-section and the parts of the inelastic and diffractive cross sections leading to shifts of the position of the shower maximum in the atmosphere, and therefore to a change of the muon and electron numbers as well as to their correlation on single air shower basis. The multiplicity of the pion generation at all energies at the hadronic interactions during the air shower development is also a 'semi-free' parameter in the air-shower modeling as accelerator data have still large uncertainties.

3.4. Tests with hadronic observables

Arbitrary changes of free parameters in the interaction models will change the correlation of all shower parameters. Tests using KASCADE observables, which are measured independently of such used in the unfolding procedure, may give further constraints, e.g. by investigating correlations of the hadronic shower component with electron or muon numbers. The aim is to provide hints for the model builder groups how the parameters (and the theory) should be modified in order to describe all the data consistently.

The applied method here is to evaluate the measured data relative to simulations (including the detector response) of proton and iron primaries. The measurements have to lie between these extreme values, otherwise the simulations cannot describe this specific observable correlation. Direct comparisons between data and simulations are not possible due to the unknown composition of the primary particles generating the air showers.

These kinds of tests are performed for a large set of interaction models employed in the simulation package CORSIKA [11]. In ref. [17] first results of these tests were published investigating the models VENUS 4.12 [18], SIBYLL 1.6 [19], and QGSJET 98 [9]. The general conclusion was that QGSJET described the data best at that time, whereas strong hints could be given that SIBYLL 1.6 generates too few muons. These results triggered improvements of the model leading to the newer version SIBYLL 2.1 [10]. Later [20], NEXUS 2 [22], SIBYLL 2.1 and QGSJET 01 [21] were investigated with the result that the differences between the models got smaller. Whereas QGSJET 01 and SIBYLL 2.1 can now describe the KASCADE hadronic observables, NEXUS calculations predict too little hadronic energy at the observation level. Present investigations comparing the data with DPMJET 2.55 [23], QGSJET 01, and SIBYLL 2.1 confirm that these three models can describe the hadronic observables and their correlations with the electron and muon component within the sensitivity of the KASCADE experiment (Fig. 7), at least in the energy range below 10 PeV.

The tests will be continued with new models, e.g. QGSJET II [25], and with better statistical accuracy at higher primary energies. Additionally another approach will be followed: To change specific parameters in one certain model (QGSJET 01) and to investigate the change of the correlations of measurable observables [26] and compare them with the data.

A different window to the hadron-muon correlation is the investigation of the KASCADE trigger rates [27]. Here, in particular primaries of lower energies and their behavior in the atmosphere is approached. By this, indications for an underestimate of the non-diffractive inelastic cross-section in the models are given.

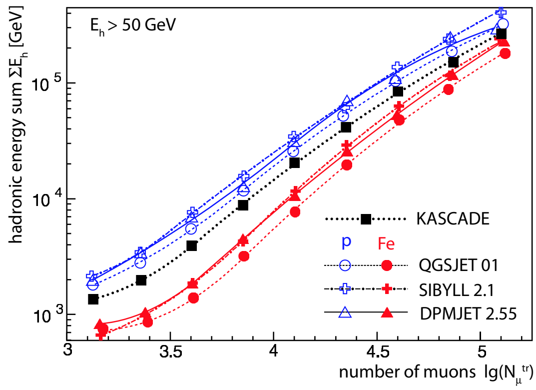

Figure 7. Correlation between the reconstructed hadronic energy sum and the number of muons.

3.5. Tests with muon densities

The tests described in the last sections are sensitive to the high-energy interaction models used in EAS simulations. Measurements of muon densities for different energy thresholds, here 2.4 GeV and 490 MeV detected by the KASCADE Central Detector are more sensitive to low-energy interaction models like GHEISHA [16], UrQMD 1.1 [28], or FLUKA [15] (see also ref. [24]). The ratio of muon densities measured at fixed core distances are determined by the muon energy spectrum in air-showers, which is a different approach to test the models than investigating the total number of muons [29]. Fig. 8 displays the ratio of the muon densities for two thresholds in dependence of the muon number (truncated muon number) measured by the KASCADE array ($E_\mu^{thr} = 240\,\mathrm{MeV}$). The range of N_μ^{tr} corresponds to the primary energy range of $10^6 - 10^7$ GeV. Compared is the distribution of the data with predictions (including full detector response and reconstruction procedures) for various high-energy and low energy model combinations. None of the models can reproduce fully the measurements, especially at higher muon number, i.e. higher pri-

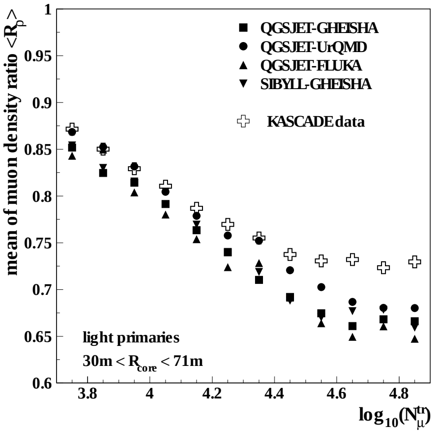

Figure 8. Distributions of the muon density ratio for KASCADE data in comparison with predictions for various model combinations.

mary energy, but the behavior of the UrQMD model seems to be more consistent than FLUKA or GHEISHA. The next generation of CORSIKA will include QGSJET II [25] as a new model, which shows in first calculations a significantly different behavior of the muon component.

3.6. Tests with muon pseudorapidities

Another approach to test the hadronic interaction models via the muon component is possible due to the excellent angular resolution of the KASCADE Muon Tracking Detector (≈0.35°). Measuring the relative angles τ and ρ between single shower muons and the shower axis the pseudorapidity $\eta = ln\frac{2p_\parallel}{p_t} \approx -ln(\sqrt{\tau^2+\rho^2}/2)$ can be calculated. Fig. 9 shows the correlation of the pseudorapidity of the muons measurable in the MTD and of the parent hadrons [30]. The rapidity distribution of hadrons generated in high-energy hadronic interactions is still an open question and an important parameter for the model building.

3.7. Tests of the shower development

Investigating further shower observables at KASCADE like the muon arrival time distributions [31], the electron and muon lateral distributions or the muon production heights [32] enable to scrutinize the shower development itself rather than the hadronic interactions. In sum-

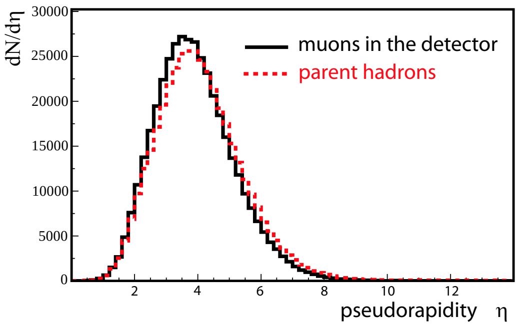

Figure 9. Pseudorapidity distribution predicted by CORSIKA/QGSJET simulations for muons detectable in KASCADE and for the parent hadrons of the same muons.

mary, within the given sensitivity of KASCADE CORSIKA describes the shower development reasonably well and no significant deviations were found.

4. Conclusions and outlook

Measurements with the multi-detector setup KASCADE provide plenty of high quality data to investigate the physics of the knee in the cosmic ray energy spectrum. By analyzing these data no significant large scale anisotropy is found in the energy region of the knee and no point source candidates could be identified, neither for charged cosmic rays nor for a sample with an enhanced number of gamma-ray candidates. Concerning energy reconstruction, conclusive evidence has been given that the knee is caused by a decrease of the flux of light primaries, where the knee positions show a dependence on the primary mass group. Systematic uncertainties for the estimate of the elemental composition are dominated by the inadequacy of the hadronic interaction models underlying the reconstruction of energy spectra of single mass groups. Hence, still there are only weak constraints for detailed astrophysical models to explain the knee in the primary cosmic ray energy spectrum.

Indications for the inadequate description of the hadronic interactions in the atmosphere are also given by additional KASCADE data analyses taking the advantage of the multi-detector information, i.e. investigations of the hadron component in air-showers or of muon properties measured for different muon energy thresholds. These investigations of observable correlations have shown that none of the present hadronic interaction models is able to describe all the KASCADE data consistently (on a level of a few percent). Recently some efforts were made to sample the information from accelerator experiments and cosmic ray investigations [33] to improve the hadronic interaction models.

The multi-detector concept of the KASCADE experiment has been extended to KASCADE-Grande [34], accessing higher primary energies up to 10^{18} eV which will prove the existence of a knee-like structure for heavy elements. In future, by having the data of the KASCADE-Grande experiment and by further improving the hadronic interaction models better constraints especially at higher primary energies are expected. Thus cosmic ray physics at energies around the knee remains a vital field of research with high scientific interest.

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