KASCADE-GRANDE RESULTS AND FUTURE PROSPECTS FOR THE TRANSITION ENERGY RANGE OF COSMIC RAYS*

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Investigations of the energy spectrum as well as the mass composition of cosmic rays in the energy range of PeV to EeV are important for understanding both, the origin of the galactic and the extragalactic cosmic rays. The multi-detector arrangement of KASCADE and its extension KASCADE-Grande was designed for observations of cosmic ray air showers in this energy range. The experimental installation was completed in 2013, however, the collaboration continues to analyse the recorded data. In this contribution, we discuss the status and results of recent analyses in particular in view of tests of the validity of hadronic interaction models used for the interpretation of measured air-shower data.

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1. Introduction

The cosmic-ray air-shower experiments KASCADE [1] and KASCADE-Grande [2] were located at the Karlsruhe Institute of Technology, Karlsruhe, Germany (49.1° north, 8.4° east, 110 m a.s.l.). The data accumulation was fully completed at the end of 2013 and all experimental components have been dismantled.

KASCADE (Fig. 1) and KASCADE-Grande measured the energy spectrum, mass composition, and the arrival direction of cosmic rays in the primary energy range of PeV to EeV. Important results can be summarised as: The all-particle energy spectrum shows a knee-like structure due to a steepening of spectra of light elements [3] at few times 10^{15} eV as well as a concave behaviour just above 10^{16} eV, and a knee-like feature due to heavy primaries at around 10^{17} eV [4, 5]. In addition, an ankle-like structure is observed just above 100 PeV in the energy spectrum of light primary cosmic rays [6] (Fig. 2, left panel).

Fig. 1. Photo of the KASCADE array (2005).

The analysis of the measurement data requires an understanding of the high-energy interactions in the Earth's atmosphere, as the reconstruction of the properties of the primary particles relates to simulations of the air-shower evolution. Therefore, it is necessary to continue analysing the KASCADE and KASCADE-Grande data also after the completion of the measurements, for example, to perform tests of new and extended hadronic interaction models and thus to reduce the systematic uncertainties of the analyses. To simplify these possibilities technically, we have made the entirety of the measurement data available in an open portal, the KASCADE Cosmic Ray Data Centre (KCDC) [7].

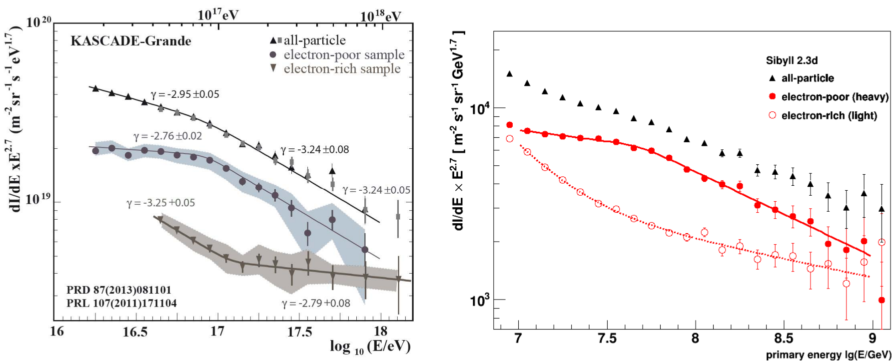

Fig. 2. Left: The main results from KASCADE-Grande. It shows the spectra obtained on basis of the QGSJet-II model (references inserted). Right: The resulting energy spectra of heavy and light primaries based on the Sibyll 2.3d model [8].

2. Test of new interaction model Sibyll 2.3d

Recently, a new version of the Sibyll hadronic interaction model was published (version Sibyll 2.3d [9]) and we used the full data set of KASCADE-Grande to investigate the features of this model. Based on the new hadronic interaction model Sibyll 2.3d and the shower size measured by KASCADE-Grande, the energy spectra of different mass groups were reconstructed. All known features (Fig. 2, left panel) of the energy spectra (observation of a heavy knee at around 10^{17} eV and flattening of the light component at about 10^{17} eV) are confirmed by this analysis (Fig. 2, right panel).

Comparing the shower size of the new model Sibyll 2.3d with other models, it is observed that it produces a higher number of muons. This increases in the analyses slightly the abundance of lighter primaries compared to other models. This means that this model gives the lowest flux of heavy primaries of all models, *i.e.* the lightest composition. Another observation is that the spectral slope of light primaries for Sibyll 2.3d changes more smoothly below 10^{17} eV compared to the results from other models. Detailed studies including estimation of systematic uncertainties and the correction of shower fluctuations are in progress.

3. Combined analysis and test of hadronic interaction models

Combining the KASCADE and KASCADE-Grande arrays already at the shower reconstruction improved considerably the quality of the determination of the shower size and number of muons [10]. Events located in the Grande array gain additional 252 density measurements, and events located in the KASCADE array gain 37 additional measurements compared to the individual fits to the lateral densities. The resulting 2-dimensional shower size spectrum (Fig. 3) contains more the four million reconstructed events covering more than three orders of magnitude in primary energy (see also [11] and references therein).

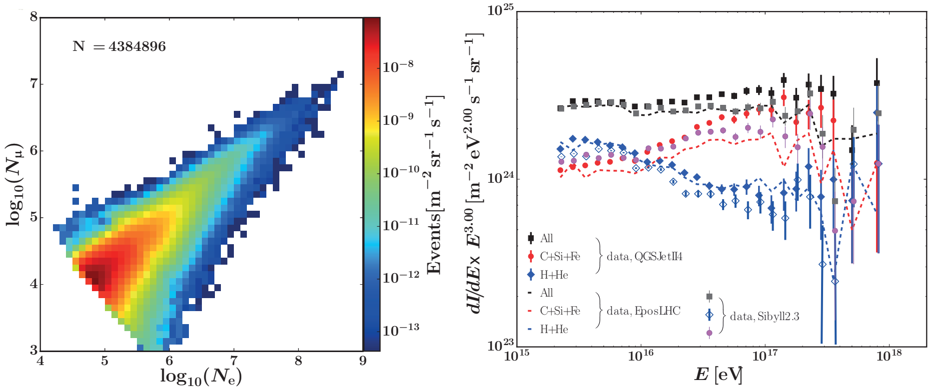

Fig. 3. Left: The two-dimensional shower size spectrum for data obtained by a combined shower reconstruction of data from the KASCADE and the Grande arrays [10]. Right: The resulting all-particle, light and heavy spectra for three different hadronic interaction models [11].

An analysis was applied to unfold the two-dimensional shower size spectrum and to obtain the all-particle energy spectrum, as well as the spectra of the heavy- and light-induced air showers. For the calibration of the energy and mass of the primary particle, a set of simulations is needed which is obtained for different hadronic interaction models, separately. Considering the results based on CORSIKA simulations and the post-LHC models QGSJet-II-04, EPOS-LHC, and Sibyll 2.3, the spectra confirm the observation of all features found earlier, *i.e.* the light and heavy knees at approx. 3 and 100 PeV, respectively as well as the hardening at approx. 10 PeV and the light ankle at approx. 100 PeV (Fig. 3, right panel). However, again, also for these post-LHC models, the relative abundances of the light and heavy generated spectra differ quite significantly from model to model. It is interesting to note that comparing the spectra of the light component agrees better for the different models than those of heavy primaries. This can be interpreted as a hint that the proton–proton interactions are better described in the post-LHC models than the nucleus–nucleus interactions.

To learn more about the source of the differences in interpreting the same data with different hadronic interaction models, we deepened the analysis (here the case of Sibyll 2.3 is shown, for the other models see [12]). A set of data was generated with the simulated spectra of the five elements H, He, C, Si, and Fe corresponding to the predictions of the astrophysical model H4a which is relatively close to the obtained results. The unique feature of KASCADE-Grande allows for cross-checking the results by dividing the data into one set containing events located within KASCADE (InK) and another set limited to events located in KASCADE-Grande (InKG). Doing this, we obtain the muon number by measuring muons close to the shower core in one sample, for the other sample by measuring muons far (300–700 m) from the shower core. Now applying the full (including the detector response) simulated data to the above-mentioned reconstruction, we expect to get back the right answer, *i.e.* the input spectra for both event samples. This worked within the systematic uncertainties for the studied interaction model (Fig. 4, left panel) proving the internal consistency of the model, at least. This is similarly true for all models investigated. However, applying the reconstruction to the two measured data samples, independently, the spectra show significant differences (Fig. 4, right panel, for one model as an example). It is obvious that a systematic deficiency appears for the model to describe the muon content of the showers consistently. Either there are too less muons predicted in the center of the shower or too few at larger distances.

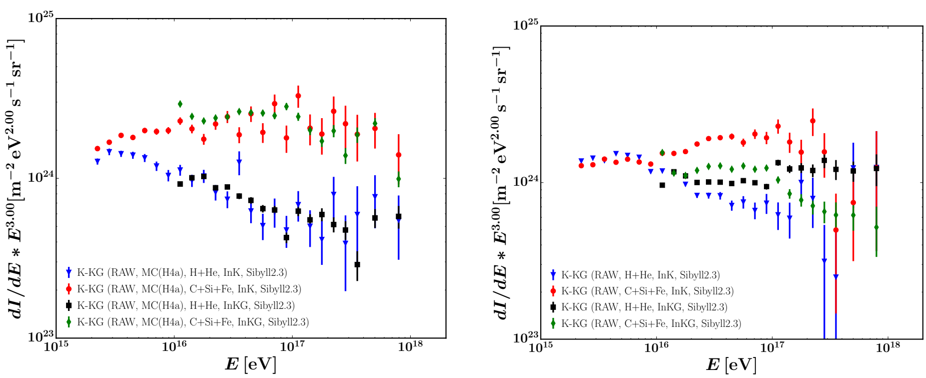

Fig. 4. The reconstructed spectra for the heavy and light component are shown for data simulated using Sibyll 2.3 as the hadronic interaction model and H4a as the astrophysical model (left), and for measured data (right) [12].

4. Muon studies

The analysis of the muon content in extensive air showers (EAS) with primary energies above 10 PeV from measurements of several experiments seems to reveal important discrepancies between the data and the predictions of modern high-energy hadronic interaction models [14]. In particular, the studies point out an excess in the measured number of shower muons over expectations, which seems to increase with the primary energy. To investigate this anomaly with KASCADE-Grande, we have performed an analysis of the data from the experiment to estimate the muon content in cosmic-ray-induced air showers as a function of the primary energy [13]. Then, we compared these muon estimations with the predictions of the hadronic interaction models QGSJET-II-04, EPOS-LHC and Sibyll 2.3 and Sibyll 2.3c (Fig. 5).

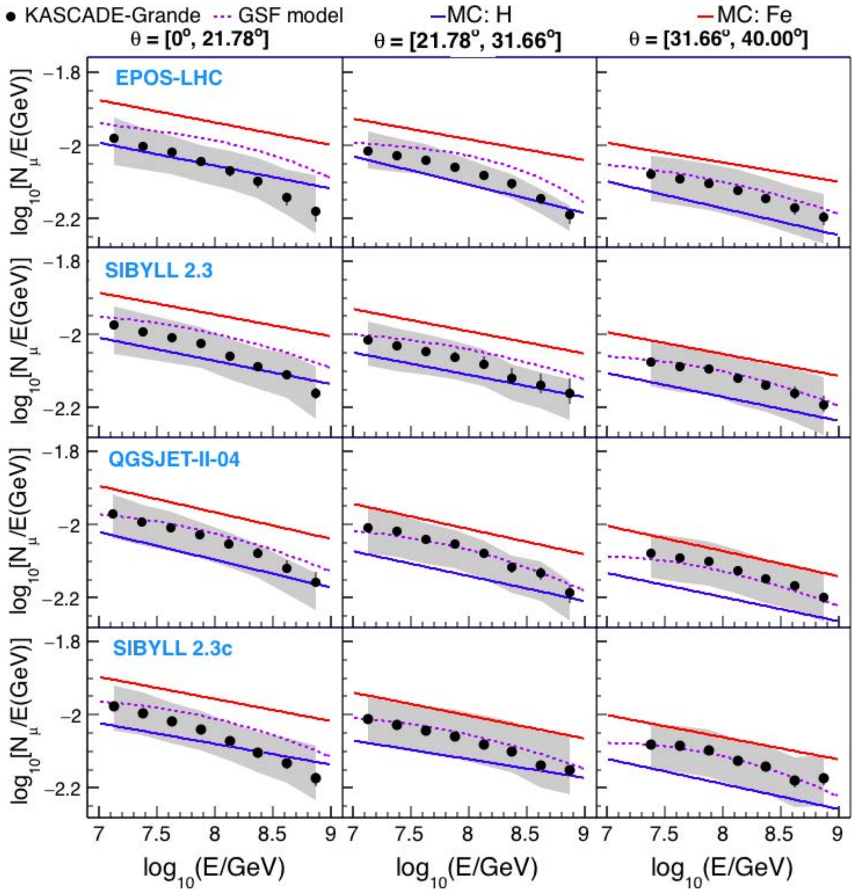

Fig. 5. Experimental (points) and simulated (lines) mean values of muon number *versus* energy in the framework of several post-LHC hadronic interaction models. Each column corresponds to a different zenith angle bin. The vertical error bars on the experimental plot represent statistical errors, while the grey band, the total systematic uncertainty [13].

None of the high-energy hadronic interaction models studied here is able to describe consistently the KASCADE-Grande data on the muon number for all zenith angles and energies. As a conclusion, we can state that the attenuation of the number of muons with the zenith angle is smaller in data than in simulations. These observed anomalies could imply that the energy spectrum of muons from real EAS at production site for a given primary energy is harder than the respective model predictions.

5. KCDC

KCDC, the 'KASCADE Cosmic-ray Data Centre'[1], is a web-based interface where initially the scientific data from the completed air-shower experiment KASCADE-Grande was made available for the astroparticle community as well as for the interested public. Over the past 7 years, we have continuously extended the data shop with various releases and increased both the number of detector components from the KASCADE-Grande experiment and the data sets and corresponding simulations [7, 15]. It is also important to mention LOPES [16], the radio detection experiment integrated in KASCADE-Grande, whose data are also made available via KCDC. With the latest releases we added a new and independent data shop for a specific KASCADE-Grande event selection and by that created the technology for integrating further data shops and data of other experiments, like the data of the air-shower experiment MAKET-ANI in Armenia. In addition, we made available educational examples how to use the data, more than 100 cosmic ray energy spectra from various experiments, and recently attached a public server with access to Jupyter notebooks.

It is important to note that KCDC is a platform serving both, the scientific community of the research field and the society. Outreach profits from open data, therefore KCDC is a platform for both, open data and outreach.

6. Future strategy (Snowmass process)

Investigations of the energy spectrum, mass composition and arrival directions of cosmic rays in the energy range of PeV to EeV are important for understanding the origin of both galactic and extra-galactic cosmic rays. The origin of the highest energy Galactic cosmic rays is still not understood, nor is the transition to EeV extra-galactic particles. Enhancements of existing air-shower arrays as well as new installations are in progress to achieve measurements with better accuracy and higher statistics. In a Letter of Interest (LoI) for the Snowmass21 process [17] the scientific motivation and current results at this energy range are presented, and the foreseen experimental improvements are discussed.

[1] https://kcdc.iap.kit.edu

The increased accuracy, exposure and sky coverage provided by the various experiments, including data from KASCADE-Grande available to everyone through KCDC, will bring unprecedented sensitivity to the scientific questions raised in this LoI. This will raise the contribution of galactic cosmic rays to multimessenger astrophysics to a new level and offer a real opportunity to finally discover the most energetic accelerators in our Milky Way.

This contribution is dedicated to Heinigerd Rebel, who passed away on 02.02.2022. Heinigerd was one of the founding fathers of the KASCADE experiment and thus of astroparticle physics in Karlsruhe. In our memories he will always be associated with the KASCADE experiment.

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