PROCEEDINGS OF SCIENCE

Latest Results of KASCADE-Grande

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The KASCADE-Grande experiment has significantly contributed to the current knowledge about the energy spectrum and composition of cosmic rays for energies between the knee and the ankle. Meanwhile, post-LHC versions of the hadronic interaction models are available and used to interpret the entire data set of KASCADE-Grande. A new, combined analysis of both arrays, KASCADE and Grande, were developed increasing significantly the accuracy of the shower observables. Latest results from the analysis of the entire data set as well as recent activities related to scientific outreach of the KASCADE-Grande experiment are presented.

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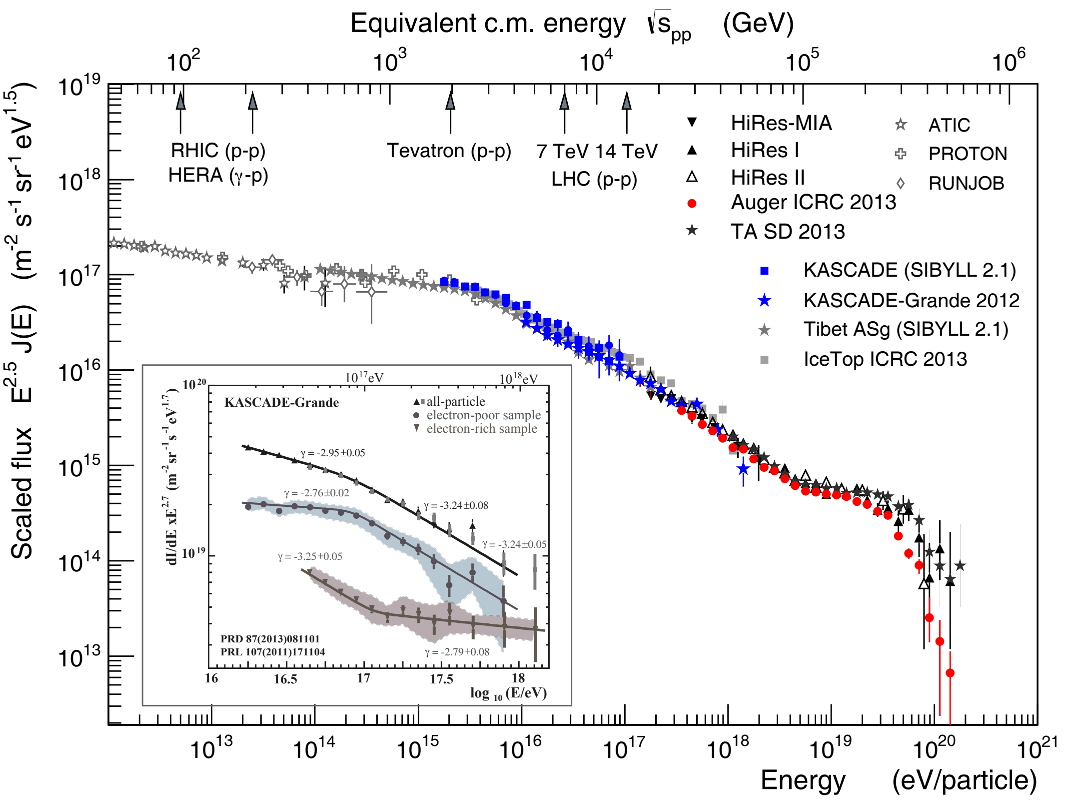

Figure 1: The all-particle energy spectrum [8] obtained with KASCADE and KASCADE-Grande (based on the QGSJet-II model and unfolded, i.e. corrected for the reconstruction uncertainties). Shown are the spectra in comparison with results of other experiments. In addition, the corresponding interaction energy at accelerators are indicated. The inlet shows the all-particle, electron-poor, and electron rich energy spectra from KASCADE-Grande. References are given in the figure.

1. KASCADE-Grande

The Extensive Air Shower (EAS) experiment and cosmic-ray facility KASCADE finally stopped the active data acquisition end of 2012 after 20 years of measurements. KASCADE, its extension KASCADE-Grande as well as the radio test experiments LOPES and CROME are meanwhile fully decommissioned. The collaboration, however, continues the detailed analysis of the high-quality air-shower data. In addition, with KCDC, the KASCADE Cosmic-ray Data Center, we provide to the public the scientific data via a customized web page.

The multi-detector experiment KASCADE [1], located in south-west Germany in the valley of the river Rhine (49.1°n, 8.4°e, 110 m a.s.l.), started operation in 1993 and was extended to KASCADE-Grande in 2003. Main parts of the facility were the KASCADE array covering $200 \times 200\,\mathrm{m}^2$ with unshielded and shielded detectors, a large-size hadron calorimeter, and additional muon tracking devices as well as the later installed Grande [2] array spread over an area of $700 \times 700\,\mathrm{m}^2$. The radio antenna field LOPES [3, 4, 5] and the microwave experiment CROME [6, 7] were also concise components of the experimental set-up of KASCADE-Grande. The entire facility was in operation

until end of 2012.
The main goal of the measurements was the estimation of energy and mass of the primary particles in a wide energy range around the knee. Most of the analyses are based on the combined investigation of the charged particle, the electron, and the muon components measured by the detector arrays of Grande and KASCADE. We aimed mainly at data analyses of the KASCADE and KASCADE-Grande experiments by the determination of the chemical composition in the primary energy range $10^{14} - 10^{18}$ eV by reconstructing individual mass group spectra (Fig. 1). We believe that structures observed in these individual spectra provide stronger constraints to astrophysical models of origin and propagation of high-energy cosmic rays than the all-particle spectrum or mean mass determination.

2. Combined analysis on the basis of post-LHC interaction models

Combining the KASCADE and KASCADE-Grande arrays already at the shower reconstruction improves the quality of the number of charged particles and the number of muons considerably: 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 [9]. By that, the accuracy of the electron shower size at 10^5 electrons improves from about 6% to about 4 to 5% for the combined reconstruction, reaching an accuracy of better than 3% towards higher energies and the improvement in the muon reconstruction results from about 25% to 17%. The new 2-dimensional shower size spectrum (Fig. 2) contains 4.384.896 reconstructed events covering more than three orders of magnitude in primary energy (see also [10]).
The method from the Grande stand alone data analysis (k-parameter method, where k is basically

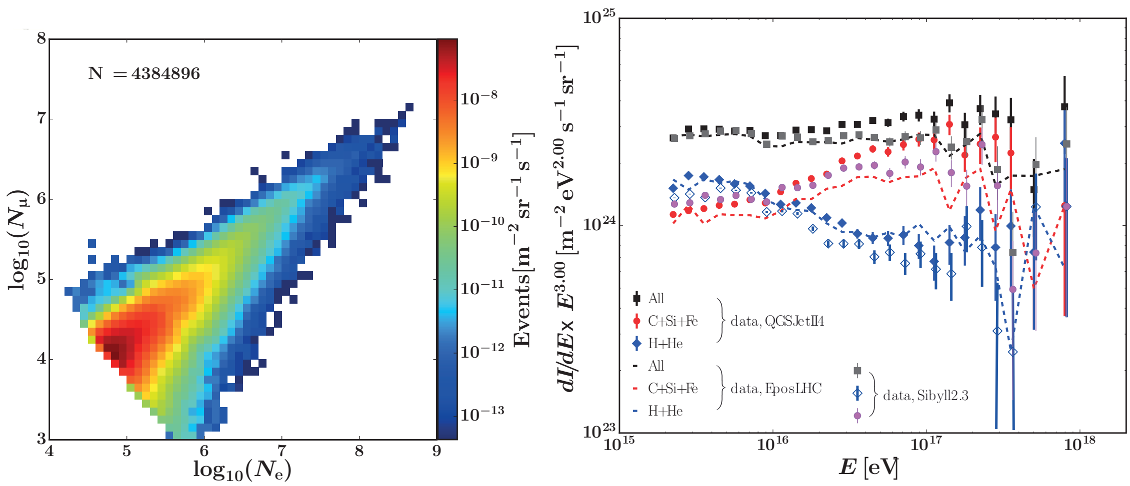

Figure 2: Left: The two-dimensional shower size spectrum for data obtained by a combined shower reconstruction of data from the KASCADE and the Grande arrays [9]. Right: The resulting all-particle, light and heavy spectra for three different hadronic interaction models.

the electron-muon ratio of the individual showers taken into account the incident zenith angle) was applied 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

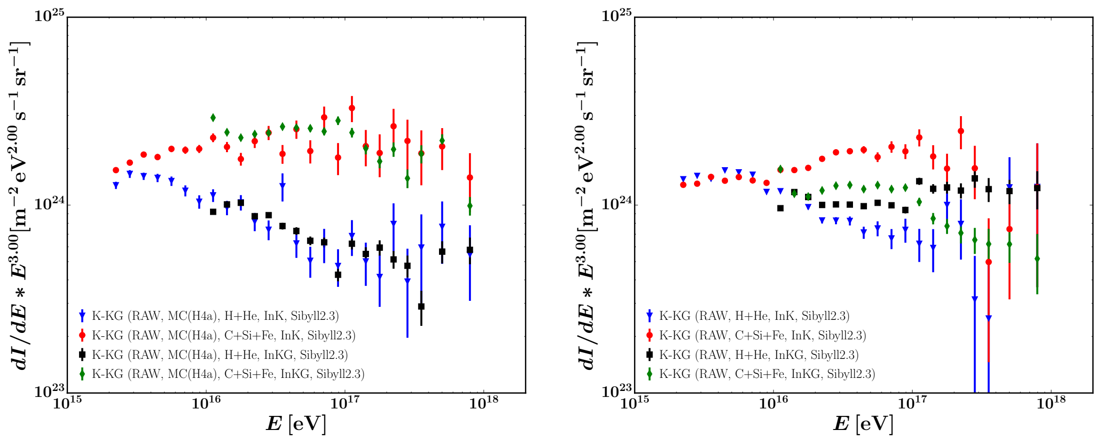

Figure 3: The reconstructed spectra for the heavy and light component are shown for data simulated using Sibyll 2.3 as the hadronic interaction model and H4a as the astrophysical model (left) and for measured data using calibrations based on Sibyll as the hadronic interaction model (right). The spectra have been obtained with the combined reconstruction, however, separately for the two data sets defined by the core being located in KASCADE and KASCADE-Grande, respectively.

simulations is needed which is obtained for each hadronic interaction model, separately. Always the same hadronic interaction model was used to define the separation value (the cut in the parameter 'k') and to interpret the full data set.

Considering the results based on CORSIKA simulations [11] and the models QGSJet-II-04 [12, 13], EPOS-LHC [14] and SIBYll 2.3 [15, 16] and EPOS-LHC, the spectra confirms 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. 2). However, again, also for the 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 [10]). A set of data was generated with the true, i.e. simulated spectra of the five elements H, He, C, Si, and Fe corresponding to the predictions of an astrophysical model (H4a [17]) which is relatively close to the obtained results. In addition, the unique feature of KASCADE-Grande allows for cross-checking the results by dividing the data in 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 ($300-700\,\mathrm{m}$) from the shower core. If we now apply 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. 3) proving

the internal consistency of the model, at least. However, applying the reconstruction to the two measured samples, independently, the spectra show significant differences. Figure 3 shows this in case of the Sibyll 2.3 model, but we found similar differences also for the other two models. 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 EAS or too few at larger distances. I.e. the lateral distribution of muons is predicted to be too flat.
That the feature of the shower muons show a deficiency in the interaction models is proven by another analysis which studies the attenuation of muons in the Earths' atmosphere [18, 19]. There we found that none of the models studied describes the observed attenuation length.

3. Study of the diffuse gamma ray flux

Using the KASCADE and KASCADE-Grande arrays, upper limits on the diffuse gamma ray flux are obtained [20] by selecting and studying muon-poor air shower events. An update on this analysis has been performed by including a larger set of data and simulations as well as a detailed study of the systematic uncertainties on the obtained limits. The figure 4 shows the latest result on these investigations in comparison with other experiments in this energy range. The upper limit

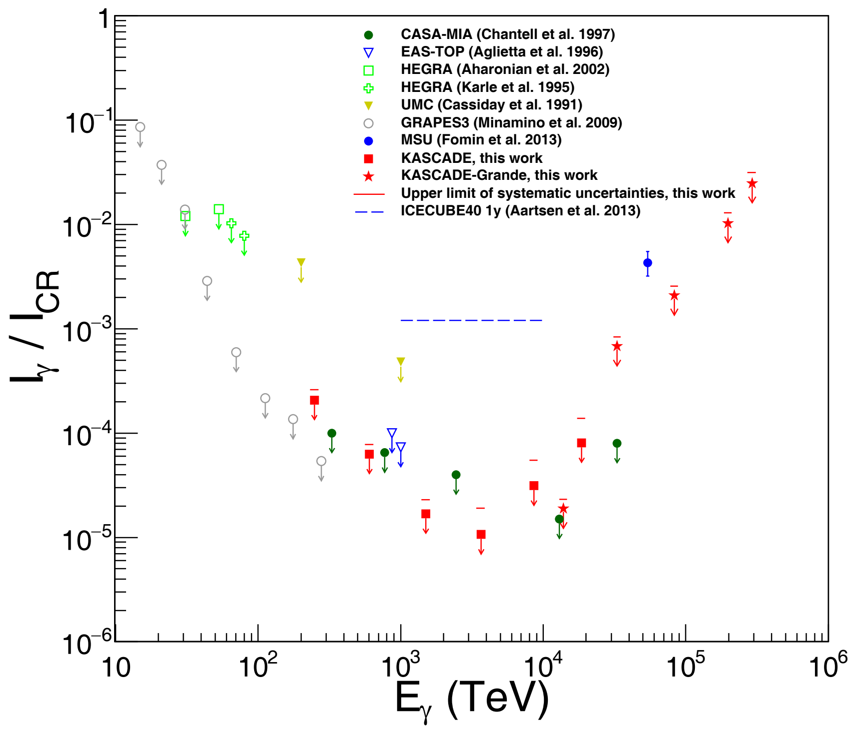

Figure 4: Measurements of the fraction of gamma rays relative to cosmic rays in the energy range from 10^{13} eV to 10^{18} eV in comparison with other experiments. The red squares and stars represent the results from KASCADE (90% C.L.) and KASCADE-Grande (90% C.L.), respectively, with systematic uncertainties.

of the fraction of γ rays from the KASCADE and Grande measurements are partly presently the lowest upper limits, which can be used to set constrains on theoretical predictions, e.g., on the distance of sources for neutrino excess models or, above 100 PeV, the limit to the background rate of muon-poor showers in the search for the galactic disk enhancement of cosmic rays.

4. The KASCADE Cosmic-ray Data Center: KCDC

The KASCADE facility operated several large-area detectors for the measurement of EAS for more than 20 years. The major goal of KCDC [21] is the installation and establishment of a public data centre for high-energy astroparticle physics. KCDC fulfills three basic requirements needed to address the general public:
KCDC is a data provider: There is free and unlimited open access to KASCADE and KASCADE-grande cosmic-ray data, where a selection of fully calibrated and reconstructed quantities as well as energy deposits at individual detectors per individual air shower is provided. The access relies on a reliable data source with a guaranteed data quality.
KCDC is an information platform: For a meaningful usage of KCDC, a detailed experiment description as well as sufficient meta information on the data is provided for any kind of data analysis. This is accompanied by a reasonable description of the physics background as well as tutorials, which focuses on a level for teachers and pupils.
KCDC is a long-term digital data archive: To constitute a sustainable piece of work, KCDC serves also as archive of software and data for the collaboration as well as for the public.
KCDC has recently been updated by a new release (see also [22] at these proceedings) presenting a lot of new functionality, data and meta-data. Interested colleagues are invited to visit KCDC under `https://kcdc.ikp.kit.edu`.

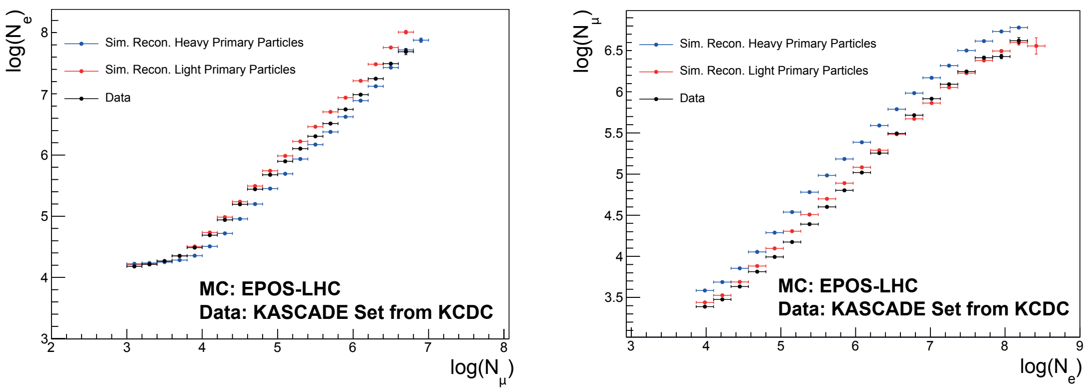

Figure 5: Comparison of the reconstructed shower electron number and muon number between EPOS-LHC simulated events and data. The KASCADE measured events are taken from the data base released in KCDC. Light means Proton plus Helium simulations, heavy Silicon plus Iron ones. The two profiles depend on the same data set with same cuts on simulations and data. A $\log(N_\mu)$ of ≈ 4.2 corresponds to 1 PeV primary energy.

The web portal KCDC is also used by the collaboration as log-term data archive of the 20 years measurements at the KASCADE facility. An example is show in figure 5, where we compare the EPOS-LHC hadronic interaction model with data from the original KASCADE array. Seeing deficiencies of this model in the high-energy regime (KASCADE-Grande) the question was if the

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model can describe the data at and below PeV energies, where the pre-LHC models were able to describe the measurements reasonably well. A simple quantitative cross-check of the model is possible by inspection of the correlation between reconstructed shower sizes in mean value and fluctuation: If we plot the shower size (N_e) as function of the muon number (Fig. 5, left) than the data are in between the simulations for light and heavy primaries, i.e. a solution for a physics-wise reasonable elemental composition is possible. However, if we plot the muon number as function of the shower size (Fig. 5, right), the model predicts to many muons than a mixed composition would allow. This preliminary analysis hints to deficiencies of EPOS-LHC in describing the air showers already at primary energies around 1 PeV and will be continued.

5. Outreach: Cosmic Revelation

Using some of the dismantled KASCADE scintillator detectors we set-up a small air shower array, called Mini-KASCADE, which is mobile and flexible in its arrangement and still can trigger and reconstruct online extensive air shower with reasonable resolution (Fig. 6, left). A first application of Mini-KASCADE was in autumn 2016 in the frame of an art and science project of KASCADE together with the artist Tim Otto Roth [23]. The general idea of Cosmic Revelation [24] is to make invisible cosmic rays visible. Mini-KASCADE installed at the roof of a large building with stairwells is steering flashers in the stairwells as well as a light intense sky beamer. The sixteen detectors from Mini-KASCADE measured the cosmic radiation in real time. The four stairwells that form the four corners of the SV SparkassenVersicherung headquarters in Stuttgart were lit up in red. Smaller showers let now and then flashes these stairwells by white light. On the roof a bright narrow light beam reached up to the sky, pointing out that this illumination comes from the earth's atmosphere, and pointing back the direction of the incoming high-energy event (Fig. 6, right).

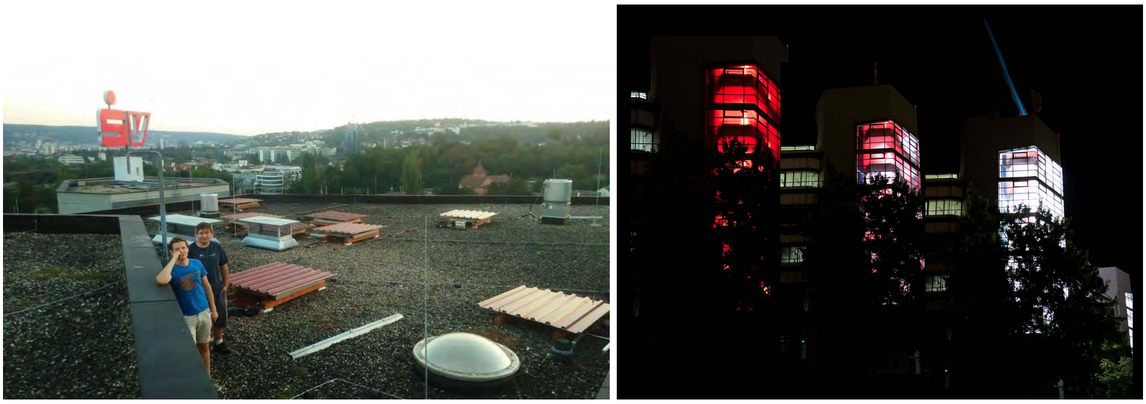

Figure 6: Left: Mini-KASCADE installed at the roof of a large building in Stuttgart, Germany. Right: the building illuminated by flashers and a sky-beamer in real time when Mini-KASCADE has recorded an high-energy extensive air shower..

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