# The knee of cosmic rays – news from KASCADE

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**Abstract.** The energy spectrum of cosmic rays, following over large energy ranges a simple power law, steepens at energies around 4 PeV. This so-called knee is believed to be an imprint of corresponding steepenings or even cut-offs in the energy spectra of single cosmic ray elements, thus implying a change of composition in the range between 1 PeV and 100 PeV. One of the sophisticated experiments aiming at detailed measurements in the knee region is the KASCADE [1] experiment and its successor, KASCADE-Grande [2]. In the following, existing data on the knee and their limitations are briefly discussed. Concluding, an update on the KASCADE composition analysis [3] is presented.

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## INTRODUCTION

Even though the discovery of the *knee of cosmic rays* dates back nearly 50 years, its origin is still not convincingly resolved. Many ideas have been put forth to explain this steepening in the energy spectrum of cosmic rays at approx. 4 PeV, but up to now experimental data do not allow an unambiguous discrimination between the different hypotheses. One of the main reasons for this can be found in the way, cosmic rays with energies between $10^{15}$ eV and $10^{18}$ eV are measured.

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Due to the low fluxes above energies of $10^{14}$ eV, only indirect measurements by the detection of extensive air showers (EAS), initiated in our atmosphere by the primary cosmic ray particles, are feasible. Commonly, energy and mass of the primary particle are reconstructed from measured EAS properties like electron or muon number. This ”conversion” is guided by results of Monte Carlo simulation. A main ingredient of these simulations are hadronic interaction models, describing the production of high energy secondary particles responsible for the EAS development. Since the relevant energy and kinematic regions are inaccessible in controlled lab conditions, these interaction models have to stay uncertain and differ in their predictions for EAS observables.

On the other hand, this described dependence of the analysis results on model predictions offers an opportunity for further improvement on our knowledge of hadronic interactions at high energies. Correlations between different EAS observables must be reproduced by the simulations, thus providing means to test interaction models. Furthermore, results of EAS analyses are bounded by direct measurements of cosmic rays at lower energies, where fluxes are still large enough. Together with lab experiments in the TeV-range, cosmic rays in the knee region provide important means for further development and improvement of hadronic interaction models.

In this article, a brief overview of the experimental situation at the knee is given, with special emphasis on recent results of the proton energy spectrum. Besides the demonstration of the influence of interaction models on results for the chemical composition of cosmic rays, the case of the proton spectrum indicates the current potential of EAS measurements. Following, an update on the KASCADE composition analysis [3] is given. Here, cross-checks of the analysis are focused on.

## STATUS OF THE KNEE – EXPERIMENTALISTS VIEW

### The knee in the all-particle energy spectrum

In Figure 1 some recent measurements of the energy spectrum of cosmic rays in the knee region are displayed. Results of the Gamma experiment are omitted here and in the following, since the Gamma experiment is featured in a dedicated article [4] of these proceedings. The knee is clearly visible as a steepening of the spectrum (transition from $\propto E^{-2.75}$ to $\propto E^{-3.1}$) at an energy around $4 \times 10^{15}$ eV. One of the most striking features in the figure is the high level of agreement between the different experiments, especially of these "located on the upper branch". Most notably, these recent air shower experiments are in even better agreement than direct measurements.

Just as interesting is the fact, that the derived all-particle energy spectrum is not dependent on the hadronic interaction model used in the simulations. The Tibet [6], Grapes [7], and KASCADE [3] analyses were performed twice, in one case using the QGSJet [8] model, in the other case the SIBYLL [9] model. For each experiment, the results coincide within their statistical uncertainties.

Regarding the chemical composition, the latter statement holds no longer. Here, the abundances of single elements or mass groups depend quite strongly on the interaction model used. This has been presented for example in Ref. [3]. For further demonstration, results for the cosmic ray proton spectrum will be discussed in the next paragraph.

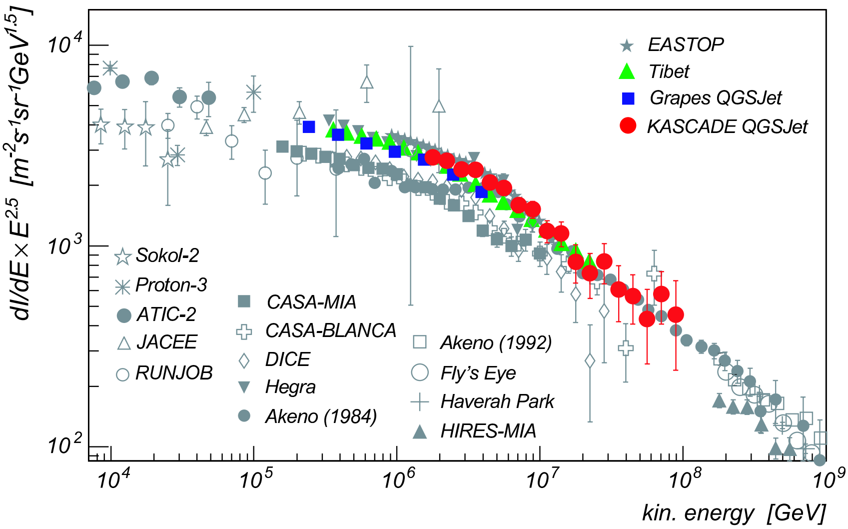


**FIGURE 1.** Measurements of the all-particle energy spectrum of cosmic rays in the knee region. For a full list of references of the data see e.g. Ref. [5].

## The cosmic ray proton spectrum around 1 PeV

The cosmic proton energy spectrum is of particular interest. For energies much smaller than 1 PeV protons are the most abundant particles in cosmic rays, resulting in measurements with high statistical accuracy. In this way, analysis results for this spectrum out of EAS data, and therefore the interaction models used, are in principle subject to strong boundary conditions.

For higher energies, where only EAS measurements are feasible, the proton spectrum is probably the only unambiguously resolvable primary spectrum. For the most EAS observables, their expectation values for EAS induced by different primary particle types scale with $\ln A$, $A$ being the particle mass. In a naive picture, neglecting intrinsic shower fluctuations, thus the resolution between two elements scales roughly like their difference $\Delta \ln A$. Since this difference $\Delta \ln A$ to the next relevant element ($p \leftrightarrow$ He, He $\leftrightarrow$ C) is largest for proton and helium, their energy spectra reconstructed out of EAS data, resemble the "true" single element spectra the most likely.

Results for the cosmic ray proton spectrum are displayed in Fig. 2. Highlighted in colours are results by air shower experiments, gray-shaded symbols correspond to direct measurements by balloons and satellites. The results of the air shower experiments span two "branches", one corresponding to results derived using the QGSJet 01 model, the other using SIBYLL 2.1. Whereas the corresponding all-particle energy spectra coincided, this is clearly not the case for the proton spectrum. For the different models, the flux at a given energy differs roughly by a factor of two.

Two features of the figure seem worth mentioning. First, for both model-based result groups a distinctive steepening in the energy spectrum is found, which causes (together

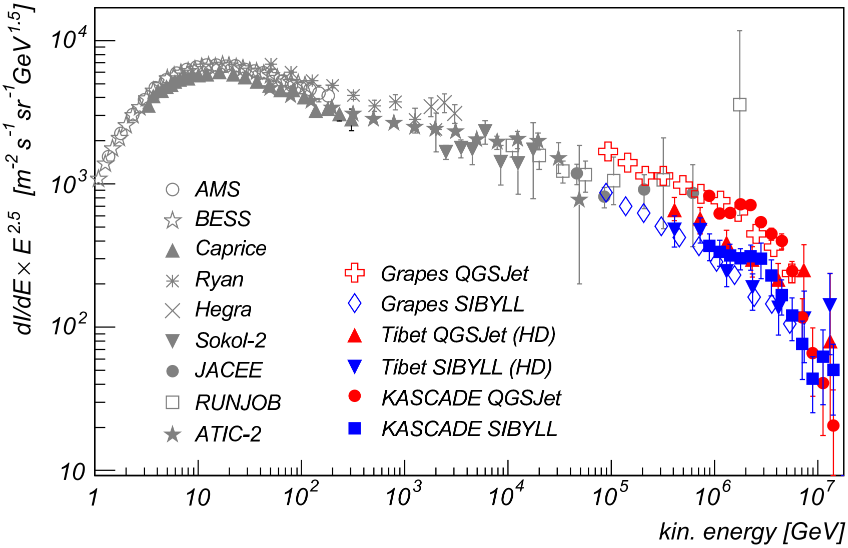


**FIGURE 2.** Compilation of some recent measurements of the cosmic ray proton energy spectrum around 1 PeV. For a full list of references of the data see e.g. Ref. [5].

with a steepening in the helium spectrum at higher energy) the steepening in the all-particle energy spectrum, i.e. the knee. Second, the difference between the two EAS ”branches”, i.e. the systematic uncertainty due to the interaction models, is now of the same order as the statistical uncertainties of the connecting direct measurements, thus demonstrating the onward improvement of the models.

In the recent past, the consistency of the air shower measurements among each other, especially concerning systematic differences between the Tibet and the KASCADE experiment, has been subject of discussion. Indeed, a closer look reveals, that in case of the Tibet results nearly no difference could be detected between QGSJet and SIBYLL spectrum. The QGSJet based proton spectrum runs in the SIBYLL branch. For Grapes and KASCADE, also small differences in spectral shape can be found. These systematic differences should not be overestimated. It has been shown [3, 10], that none of the interaction models used in the analysis describes the whole data range of even one single experiment consistently. Since the different experiments measure different observables and sample different stages of the shower development due to their different observation heights, it seems quite natural, that their results do not fully agree. Such agreement could only be expected, if ”the truth” is used in the simulations.

Nevertheless, these analyses have to be continued. The Tibet results rely on a small statistical basis and substantial efficiency corrections, which in turn depend on simulation results. For Grapes, statistics are high, but a thorough investigation of statistical and systematic uncertainties is still under way. The probable size of these systematic uncertainties can be estimated qualitatively in the KASCADE result, displayed in the left part of Fig. 4. For the KASCADE result, further cross-checks of the analysis, like consideration of data from different zenith angle ranges, have to be performed. This has been done and is presented in the remainder of this article.

## AN UPDATE ON KASCADE RESULTS

The KASCADE experiment, now part of the KASCADE-Grande experiment, is located on the area of the Forschungszentrum Karlsruhe, Germany. Main part of the installation is the $200 \times 200\ \mathrm{m}^2$ KASCADE array, measuring the lateral distribution of EAS particles. Main tasks of the array are the reconstruction of electron and muon number of each EAS, detection of its core, and determination of its arrival direction. Details of the experimental installation and the reconstruction procedures can be found in Ref. [1, 11].

### Outline of the analysis

The presented analysis is based on the number of measured EAS depending on the electron number $\lg N_e$ and the muon number $\lg N_\mu^{tr}$ (muons with core distances between 40 m and 200 m), the so-called two-dimensional shower size spectrum. For showers inside the KASCADE array and inclination below 18° this spectrum is shown as a histogram in the left part Fig. 3. The content $N_j$ of each histogram cell $j$ is

$$N_j = C \sum_{A=1}^{N_A} \int_{-\infty}^{+\infty} \frac{dJ_A}{d\lg E}\, p_A\, d\lg E. \tag{1}$$

$C$ is a normalizing constant (time, aperture). The sum is carried out over all primary particle types of mass $A$. The functions $p_A = p_A(\lg N_{e,j}, \lg N_{\mu,j}^{tr} | \lg E)$ give the probability for an EAS of primary energy $E$ and mass $A$ to be measured and reconstructed with shower sizes $N_{e,j}$ and $N_{\mu,j}^{tr}$. These probabilities $p_A$ include shower fluctuations, efficiencies, as well as reconstruction systematics and resolution. For reasons of clarity integration over solid angle and cell area is omitted in Eqn. 1, but taken into account.

Adopting this notation the two-dimensional size spectrum is interpreted as a set of coupled integral equations. It can be solved for the primary energy spectra $dJ_A/d\lg E$ by the application of unfolding algorithms. In the analysis H, He, C, Si, and Fe were chosen as representatives for five mass groups of primary cosmic ray particles. The corresponding probabilities $p_A$ were determined by Monte Carlo simulations using CORSIKA[12] and a GEANT[13] based simulation of the experiment. Details of this procedure can be found in Ref. [3].

### Using FLUKA instead of GHEISHA

In Ref. [3], the probabilities $p_A$ were determined using the high energy interaction models QGSJet (2001 version) and SIBYLL 2.1 in the simulations. In these simulations, low energy interactions ($< 80$ GeV) were modeled with the GHEISHA [14] code. To

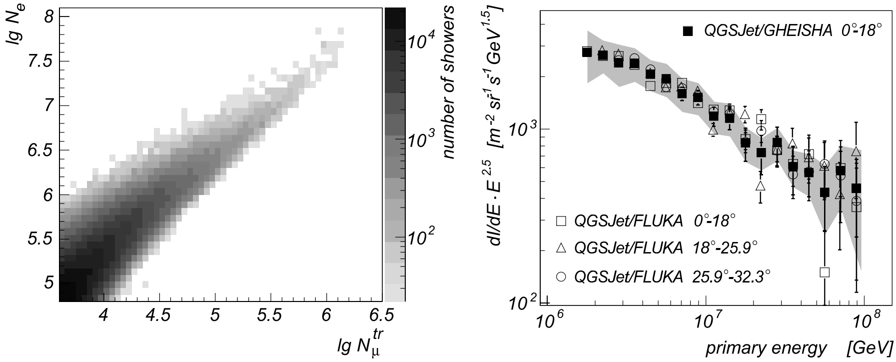


**FIGURE 3.** Left: Two-dimensional shower size spectrum as measured by KASCADE. Right: Results for the all-particle energy spectrum, using GHEISHA and FLUKA in the simulations. For FLUKA, three different data sets were considered. The shaded band gives an estimate of the methodical uncertainty of the QGSJet/GHEISHA solution.

estimate the influence of the low energy interaction model, GHEISHA was replaced in the present analysis by the FLUKA [15] package, and only the QGSJet 01 model was used. Differences between these simulations are rather small, with nearly energy and primary independent differences of $\Delta \lg N_e \approx 0.015$ and $\Delta \lg N_\mu^{tr} \approx 0.02$ (more electrons and less muons with FLUKA).

The results of the complete unfolding analysis differ for the FLUKA case only little from those of the GHEISHA case, as could have been expected from the small differences of the simulation predictions. The result for the all-particle energy spectrum is displayed in the right part of Fig. 3, where no significant differences can be found. As a further example, the results for the energy spectra of H, He, and C obtained with GHEISHA and FLUKA are compared with each other in the left part of Fig. 4. The differences between the two solution sets are small, especially when compared to the methodical uncertainties (shaded bands in the figure). In case of the heavy elements (Si, Fe) the influence is slightly larger, but still of the order of methodical uncertainties. The overall picture of the solution seems not to be affected significantly when replacing GHEISHA by FLUKA.

## Analysing data of different zenith angle ranges

In the original analysis of Ref. [3] only EAS with zenith angles smaller than 18° were considered. The analysis of more inclined shower data could serve as a consistency check, regarding the inclined shower sets as independent data sets. As the data are not described satisfactorily by the simulations (see Ref. [3]), identical results compared to the vertical data set cannot be expected. Nevertheless, strong and large differences between the solution sets would indicate a severe problem in the simulation code or the analysis technique. For such kind of cross-check the QGSJet/FLUKA analysis was repeated for two more data sets of EAS with higher inclination. In addition to the nearly

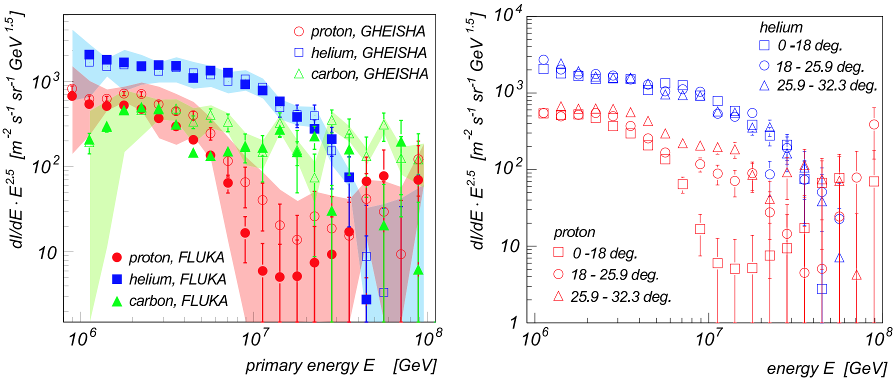


**FIGURE 4.** Left: Comparison between QGSJet/FLUKA and QGSJet/GHEISHA based results for the spectra of H, He, and C. Shaded bands correspond to estimates of methodical uncertainties for the QGSJet/GHEISHA solution. Right: Results for the spectra of H and He, based on the analysis of EAS originationg from different zenith angle ranges.

vertical showers, zenith angle intervals from 18° to 25.9° and from 25.9° to 32.3° were considered, covering an equal solid angle interval than the original sample.

The results for the all-particle spectrum coincide very well inside their statistical uncertainties, which can be seen in the right part of Fig. 3. For the underlying mass group spectra only small differences can be detected. For lack of space, only the results for H and He are discussed in the following. As can be seen in Fig. 4, inside their statistical uncertainties the spectra for Helium derived from the three data sets coincide. In the same figure, obvious systematic differences for the proton spectra at energies above the proton knee can be observed. Here, the change of index decreases with increasing zenith angle, i.e. gets less pronounced.

These observed systematic deviations of the different solution sets to each other are small. They can be understood by the interplay of increasing shower fluctuations with increasing zenith angle and shifted energy threshold due to the fixed data range in $\lg N_e$ and $\lg N_\mu^{tr}$. Therefore, no strong or unexplainable differences are found, indicating severe problems in the simulation or the analysis. Conclusions, drawn from the analysis of nearly vertical showers, remain valid and are not affected.

## SUMMARY

Cosmic ray measurements at the knee are in a good condition. At present, the agreement between the results of recent EAS experiments on the all-particle energy spectrum is quite remarkable. Furthermore, reconstruction of energy spectra of mass groups has become possible, revealing a strong dependence on the interaction models used in the necessary simulations. In case of the cosmic ray proton spectrum around 1 PeV, uncertainties related to the interaction models are the limitations to an extension of a precise measurement towards higher energies.

Nevertheless, high energy hadronic interaction models have become more and more reliable, which can be seen from converging predictions. On the other hand, air shower experiments still have to further improve and cross-check their analysis techniques in order to identify the failures and discrepancies of the models in their predictions. KASCADE has entered this phase of thorough cross-checking, so far confirming earlier results.

In the future, more precise air shower data in the knee region on the one hand, and new lab data from fixed target and collider experiments at higher energies on the other, will give the opportunity to improve the development of high energy hadronic interaction models.

## ACKNOWLEDGMENTS

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