Results on the cosmic ray energy spectrum measured with KASCADE-Grande

A. Haungs*, **W.D. Apel***, **J.C. Arteaga**[†,xi], **F. Badea***, **K. Bekk***, **M. Bertaina**[‡], **J. Blümer**[*,†], **H. Bozdog*** **I.M. Brancus**[§], **M. Brüggemann**[¶], **P. Buchholz**[¶], **E. Cantoni**[‡,‖], **A. Chiavassa**[‡], **F. Cossavella**[†], **K. Daumiller***, **V. de Souza**[†,xii], **F. Di Pierro**[‡], **P. Doll***, **R. Engel***, **J. Engler***, **M. Finger***, **D. Fuhrmann****, **P.L. Ghia**[‖], **H.J. Gils***, **R. Glasstetter****, **C. Grupen**[¶], **D. Heck***, **J.R. Hörandel**[†,xiii], **T. Huege***, **P.G. Isar***, **K.-H. Kampert****, **D. Kang**[†], **D. Kickelbick**[¶], **H.O. Klages***, **P. Łuczak**[††], **H.J. Mathes***, **H.J. Mayer***, **J. Milke***, **B. Mitrica**[§], **C. Morello**[‖], **G. Navarra**[‡], **S. Nehls***, **J. Oehlschläger***, **S. Ostapchenko**[*,xiv], **S. Over**[¶], **M. Petcu**[§], **T. Pierog***, **H. Rebel***, **M. Roth***, **H. Schieler***, **F. Schröder***, **O. Sima**[‡‡], **M. Stümpert**[†], **G. Toma**[§], **G.C. Trinchero**[‖], **H. Ulrich***, **A. Weindl***, **J. Wochele***, **M. Wommer***, **J. Zabierowski**[††]

*Institut für Kernphysik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany
[†]Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76021 Karlsruhe, Germany
[‡]Dipartimento di Fisica Generale dell'Università, 10125 Torino, Italy
[§]National Institute of Physics and Nuclear Engineering, 7690 Bucharest, Romania
[¶]Fachbereich Physik, Universität Siegen, 57068 Siegen, Germany
[‖]Istituto di Fisica dello Spazio Interplanetario, INAF, 10133 Torino, Italy
**Fachbereich Physik, Universität Wuppertal, 42097 Wuppertal, Germany
[††]Soltan Institute for Nuclear Studies, 90950 Lodz, Poland
[‡‡]Department of Physics, University of Bucharest, 76900 Bucharest, Romania
[xi]now at: Universidad Michoacana, Morelia, Mexico
[xii]now at: Universidade de São Paulo, Instituto de Física de São Carlos, Brasil
[xiii]now at: Dept. of Astrophysics, Radboud University Nijmegen, The Netherlands
[xiv]now at: University of Trondheim, Norway

***Abstract*. KASCADE-Grande is an extensive air shower experiment at Forschungszentrum Karlsruhe, Germany. The present contribution attempts to provide a synopsis of the actual results of the reconstruction of the all-particle energy spectrum in the range of 10^{16} eV to 10^{18} eV based on four different methods with partly different sources of systematic uncertainties. Since the calibration of the observables in terms of the primary energy depends on Monte-Carlo simulations, we compare the results of the various methods applied to the same sample of measured data.**

***Keywords*: High-energy cosmic rays, energy spectrum, KASCADE-Grande**

I. KASCADE-GRANDE

Main parts of the experiment are the Grande array spread over an area of $700 \times 700\,\mathrm{m}^2$, the original KASCADE array covering $200 \times 200\,\mathrm{m}^2$ with unshielded and shielded detectors, and additional muon tracking devices. This multi-detector system allows us to investigate the energy spectrum, composition, and anisotropies of cosmic rays in the energy range up to 1 EeV. The estimation of energy and mass of the primary particles is based on the combined investigation of the charged particle, the electron, and the muon components measured by the detector arrays of Grande and KASCADE.

The multi-detector experiment KASCADE [1] (located at 49.1°n, 8.4°e, 110 m a.s.l.) was extended to KASCADE-Grande in 2003 by installing a large array of 37 stations consisting of $10\,\mathrm{m}^2$ scintillation detectors each (fig. 1). KASCADE-Grande [2] provides an area of $0.5\,\mathrm{km}^2$ and operates jointly with the existing KASCADE detectors. The joint measurements with the KASCADE muon tracking devices are ensured by an additional cluster (Piccolo) close to the center of KASCADE-Grande for fast trigger purposes. While the Grande detectors are sensitive to charged particles, the KASCADE array detectors measure the electromagnetic component and the muonic component separately. The muon detectors enable to reconstruct the total number of muons on an event-by-event basis also for Grande triggered events.

II. RECONSTRUCTION

Basic shower observables like the core position, angle-of-incidence, and total number of charged particles are provided by the measurements of the Grande stations. A core position resolution of ≈ 5 m, a direction resolution of $\approx 0.7°$, and a resolution of the total particle number in the showers of $\approx 15\%$ is reached [3]. The total number of muons (N_μ resolution $\approx 25\%$) is calculated using the core position determined by the Grande array and the muon densities measured by the KASCADE muon array detectors [4]. Full efficiency for triggering and reconstruction of air-showers is reached at primary energy of $\approx 2 \cdot 10^{16}$ eV, slightly varying on the cuts needed for the reconstruction of the different observables.

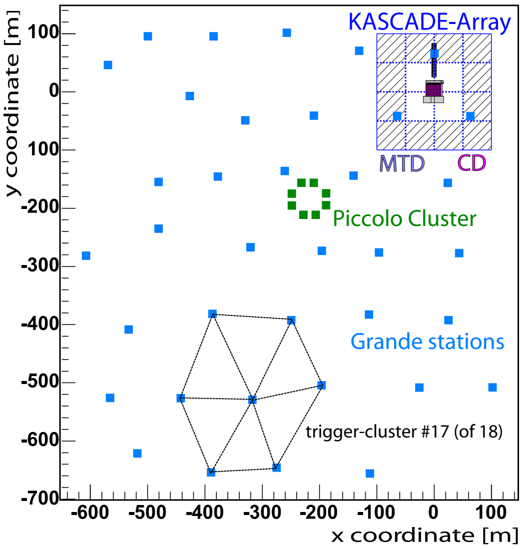

Fig. 1: Layout of the KASCADE-Grande experiment: The original KASCADE, the distribution of the 37 stations of the Grande array, and the small Piccolo cluster for fast trigger purposes are shown. The outer 12 clusters of the KASCADE array consist of μ- and e/γ-detectors, the inner 4 clusters of e/γ-detectors, only.

Applying different methods to the same data sample has advantages in various aspects: One would expect the same result for the energy spectrum by all methods when the measurements are accurate enough, when the reconstructions work without failures, and when the Monte-Carlo simulations describe correctly the shower development. But, the fact that the various observables have substantial differences in their composition sensitivity hampers a straightforward analysis. However, investigating results of different methods can be used to

- cross-check the measurements by different sub-detectors;
- cross-check the reconstruction procedures;
- cross-check the influence of systematic uncertainties;
- test the sensitivity of the observables to the elemental composition;
- test the validity of hadronic interaction models underlying the simulations.

III. Analysis

The estimation of the all-particle energy spectrum is presently based on four different methods using different observables of KASCADE-Grande:

- N_{ch}-method: The reconstructed charge particle shower size per individual event is corrected for attenuation by the constant intensity cut method and calibrated by Monte-Carlo simulations under the assumption of a dependence $E_0 \propto N_{ch}^{\alpha_{ch}}$ and a particular primary composition [5].
- N_μ-method: The reconstructed muon shower size per individual event is corrected for attenuation and calibrated by Monte-Carlo simulations under the assumption of a dependence $E_0 \propto N_\mu^{\alpha_\mu}$ and a particular primary composition [6].
- $N_{ch} - N_\mu$-method: This method combines the information provided by the two observables. By help of Monte-Carlo simulations a formula is obtained to calculate the primary energy per individual shower on basis of N_{ch} and N_μ. The formula takes into account the mass sensitivity in order to minimize the composition dependence. The attenuation is corrected for by deriving the formula for different zenith angle intervals independently and combining the energy spectrum afterwards [7].
- $S(500)$-method: The reconstructed particle density at the specific distance to the shower axis of 500 m per individual event is corrected for attenuation and calibrated by Monte-Carlo simulations under the assumption of a dependence $E_0 \propto S(500)^{\alpha_{S(500)}}$.

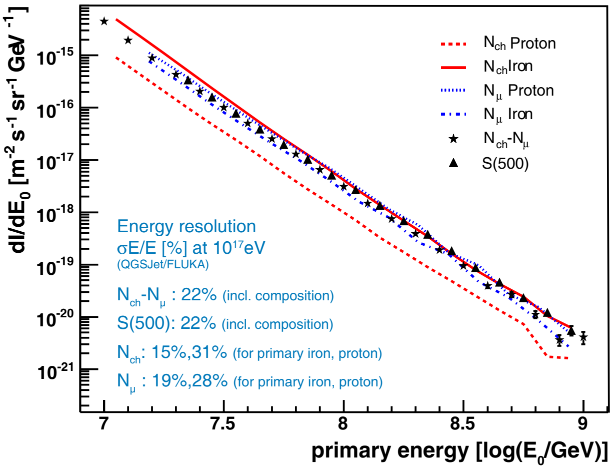

Fig. 2: Reconstructed all-particle energy spectrum by four different methods applied to KASCADE-Grande data. Given are also the energy resolution for the methods.

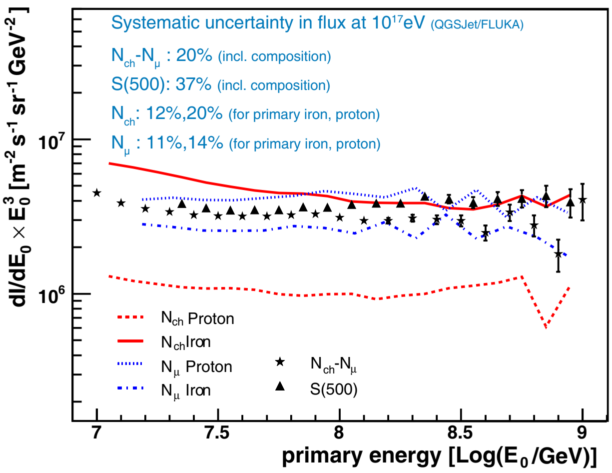

Fig. 3: Same as figure 2, but the flux multiplied by E_0^3. Values for the uncertainty in the flux determination are given for the different methods.

The distance of 500 m is chosen to have a minimum influence of the primary particle type, therefore a smaller dependence on primary composition is expected [8].

In figures 2 and 3 the resulting spectra are compiled. Due to the different procedures, the results for the first two methods are shown under proton and iron assumption, respectively, only, whereas for the other two methods the resulting all-particle energy spectrum is displayed. Figure 3 shows the same results but with the flux multiplied by a factor of $E^{3.0}$.

A. *Systematic uncertainties and attenuation*

The application of the different methods allows us to compare and cross-check the influence of various sources of systematic uncertainties. The N_{ch}-method uses the basic measurements of the Grande array only, resulting in a high accuracy of N_{ch} with better than 15% over the whole range of shower size, without any energy dependent bias. But, using only one observable, there is a large dependence on the primary elemental composition, reflected by the distance between the spectra obtained for proton and iron assumption at the calibration. The N_μ-method on the other hand is based on the muon shower size, which can be estimated less accurate (25% with a little bias dependent on the distance of the shower core to the muon detectors which is corrected for), but with a much less composition dependence. The N_{ch}-N_μ-method, due to the combination of the reconstruction uncertainty of two variables shows basically a larger uncertainty in the reconstruction, but this is compensated by taking into account the correlation of these observables at individual events. Furthermore, by this procedure the composition dependence is strikingly decreased. The $S(500)$ value by construction yields a larger uncertainty of the variable reconstruction, but has also a minor composition dependence.

For all methods, the energy resolution is estimated using full Monte-Carlo simulations and comparing the reconstructed with the simulated primary energy (for instance figure 2 gives the numbers for an energy of $E_0 = 10^{17}$ eV). Values of systematic uncertainties in the flux determination for the different methods are shown in fig. 3 (again for $E_0 = 10^{17}$ eV). These uncertainties are to a large amount due to the reconstruction of the observables, but there are additional sources of systematics which belong to all methods: e.g., concerning the Monte-Carlo statistics, the assumed Monte-Carlo spectral slope, or the fits of the calibration procedures. The different attenuation (and its handling to correct for) of the various observables ($\Lambda(N_{ch}) \approx 495 \pm 20\,\mathrm{g/cm^2}$; $\Lambda(N_\mu) \approx 1100 \pm 100\,\mathrm{g/cm^2}$; $\Lambda(S(500)) \approx 347 \pm 22\,\mathrm{g/cm^2}$ at $E_0 = 10^{17}$ eV) however, lead again to slightly different contribution to the total systematic uncertainty. The total uncertainties (energy resolution and systematics) for the various methods are discussed in refs. [5], [6], [7], [8] and can be displayed as a band surrounding the reconstructed energy spectrum (e.g., see fig. 4).

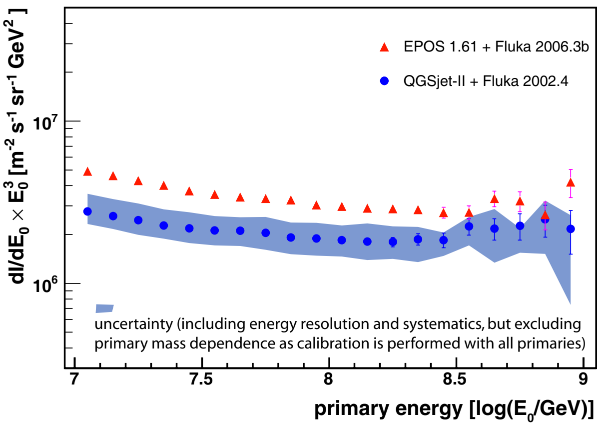

Fig. 4: Reconstructed all-particle energy spectrum with the N_{ch}-method and the calibration function obtained by assuming mixed composition, but based on two different hadronic interaction models.

B. *Discussion*

Taking into account the systematic uncertainties, there is a fair agreement between the all-particle energy spectra of the different applications (fig. 3).

Of particular interest is the fact that by using N_{ch}, the iron assumption predicts a higher flux than the proton assumption, whereas using N_μ the opposite is the case. That means that the 'true' spectrum has to be a solution in between the range spanned by both methods. If one has only the possibility of applying one method, than there is a large variance in possible solutions (everything in the range spanned by proton and iron line, not even parallel to these lines). However, more detailed investigations have shown, that a structure in the spectrum or a sudden change in composition would be retained in the resulting spectrum, even if the calibration is performed with an individual primary, only. Interestingly, over the whole energy range there is only little room for a solution satisfying both ranges, spanned by N_{ch} and N_μ, and this solution has to be of relative heavy composition - in the framework of the QGSJet-II hadronic interaction model. The narrower range for a solution provided by the N_μ-method compared to N_{ch} confirms the finding of KASCADE that at sea-level the number of mostly low-energy muons N_μ is a very good and composition insensitive energy estimator.

The results of the composition independent N_{ch}-N_μ-, and $S(500)$-methods lie inside the area spanned by the composition dependent methods, which is a very promising result. The $S(500)$-method results in a slightly higher flux than the N_{ch}-N_μ-method, but the two spectra are consistent taking into account the systematic uncertainties.

All the discussed results show a smooth all-particle energy spectrum without any hint to a distinct structure over the whole energy range from 10 PeV to 1 EeV. Another conclusion is that, taking into account the systematic uncertainties for all methods, the underlying

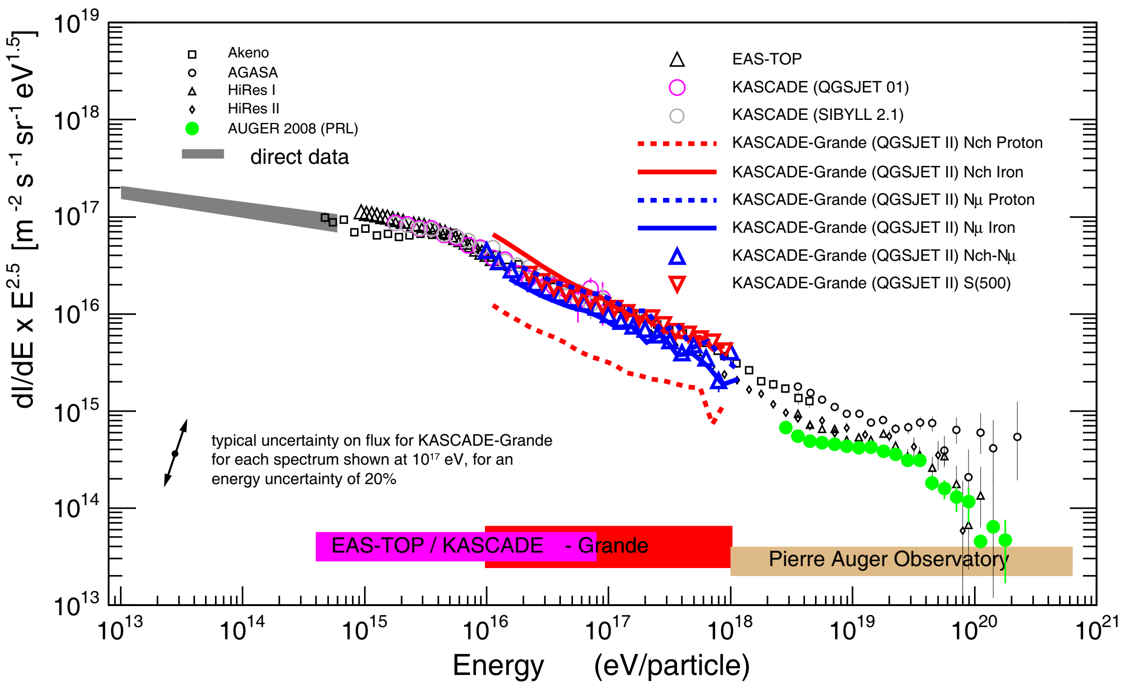

Fig. 5: Compilation of the all-particle energy spectrum obtained by four different methods applied to KASCADE-Grande data and in comparison to results of other experiments.

hadronic interaction model (QGSJet-II/FLUKA) is intrinsically consistent, i.e. the correlation between the different observables, respectively the particle components can describe the global features of our measurements.

C. *Hadronic interaction models*

By now, for all the considerations the models QGSJet-II and FLUKA [9], [10], [11] are used, only. Other interaction models would probably change the interpretation of the data. We investigated the influence of the hadronic interaction model exemplarily by performing the N_{ch}-method based on simulations with the hadronic interaction model EPOS vers.1.61 [12]. As the Monte-Carlo statistics is limited in case of EPOS, both spectra were obtained by generating the calibration curve with an equally mixed composition of five primaries (H,He,C,Si,Fe). Figure 4 compares the all-particle energy spectrum obtained with the KASCADE-Grande data set for both cases. The interpretation of the KASCADE-Grande data with EPOS leads to a significantly higher flux compared to the QGSJet-II result. Though we know, that version 1.61 of the EPOS model is not consistent with air shower data (in particular, it cannot describe the correlation of hadronic observables with the muon and electron content of the EAS [13]) this example shows that by applying and comparing various reconstruction methods on the same data set will be useful for a better understanding of the interaction processes in the air shower development.

IV. Conclusion

Applying various different reconstruction methods to the KASCADE-Grande data the obtained all-particle energy spectra are compared for cross-checks of reconstruction, for studies of systematic uncertainties and for testing the validity of the underlying hadronic interaction model. The resulting energy spectra are consistent to each other and in the overlapping energy range in a very good agreement to the spectrum obtained by the KASCADE and EAS-TOP experiments (fig. 5).

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