Cosmic Rays in the PeV Energy Range: KASCADE-Grande

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Recent results from the multi-detector set-up KASCADE on measurements of cosmic rays in the energy range of the so called knee (at $\approx 3\,$PeV) are presented. The multidimensional analysis of the air shower data indicates a distinct knee in the energy spectra of light primary cosmic rays and an increasing dominance of heavy ones towards higher energies. This provides, together with the results of large scale anisotropy studies, implications for discriminating astrophysical models of the origin of the knee. To improve the reconstruction quality and statistics at higher energies, where knee-like features of the heavy primaries are expected at around 100 PeV, KASCADE has recently been extended by a factor 10 in area to the new experiment KASCADE-Grande.

1. Introduction

The all-particle energy spectrum of cosmic rays shows a distinctive discontinuity 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 hardly 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. Two classes of theories (diffusion or acceleration based) predict knee positions occurring at constant rigidity of the particles. On the other hand, the hypothesis of new hadronic interaction mechanisms at the knee energy, as for example the production of heavy particles in *pp* collisions, implies an atomic mass dependence of the knee positions. It is obvious that only detailed measurements and analysis of the primary energy spectra for the different incoming particle types can validate or disprove some of these models.

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 arrangement 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. Additionally muon densities at further three muon energy thresholds and the hadronic core of the shower by an iron sampling calorimeter are measured. Recently KASCADE was extended in area by an factor 10 to the new experiment KASCADE-Grande. KASCADE-Grande allows now a full coverage of the energy range around the knee, including the possible second knee at around 100 PeV. (see Fig. 1).

From KASCADE [2] measurements we do know that at a few times 10^{15} eV the knee is due to light elements [4], that the knee positions depend on the kind of the incoming particle and that cosmic rays around the knee arrive our Earth isotropically [5, 6].

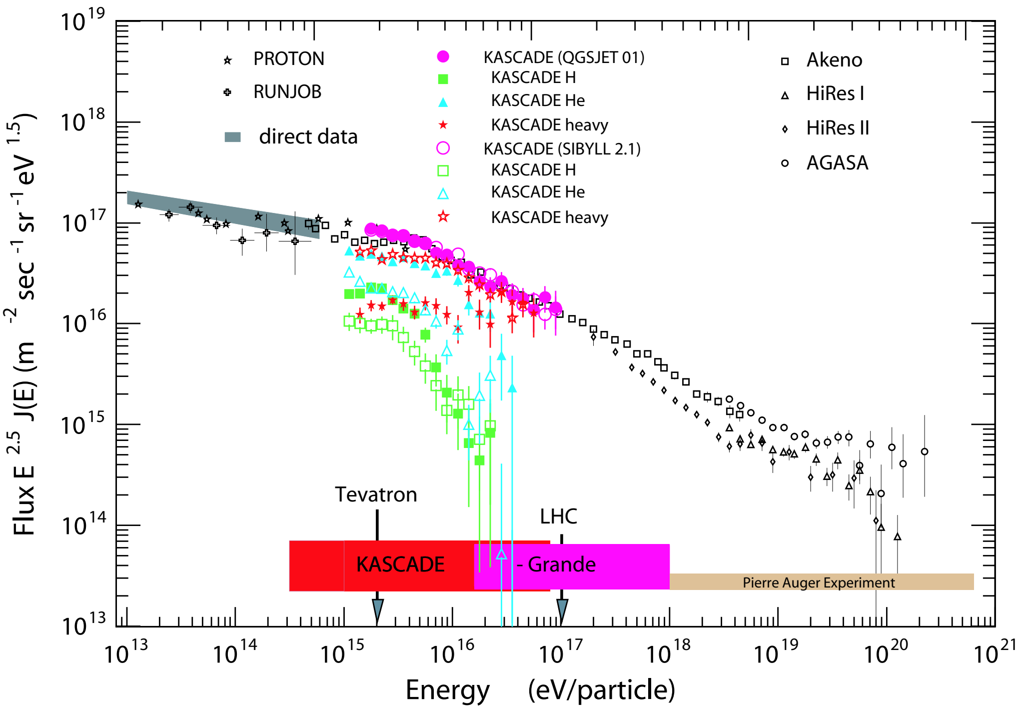

Figure 1: Primary cosmic ray flux and primary energy range covered by KASCADE-Grande. Results of the KASCADE data analyses are also shown (see text).

KASCADE-Grande [7, 8], measuring higher energies, will prove, if exists, the knee corresponding to heavy elements. Additionally KASCADE could show that no current hadronic interaction model which are unavoidably needed for the interpretation of air shower data, describes very well cosmic ray measurements in the energy range of the knee and above [9]. These model uncertainties are due to the lack of accelerator data at these energies and especially for the forward direction of collisions. Multi-detector systems like KASCADE and KASCADE-Grande offer the possibility of testing and tuning the different hadronic interaction models.

With its capabilities KASCADE-Grande is also the ideal testbed for the development and calibration of new air-shower detection techniques like the measurement of EAS radio emission [3].

2. The KASCADE Experiment

The KASCADE experiment [2], located at the Forschungszentrum Karlsruhe, Germany, (49°n, 8°e, 110 m a.s.l.) measures showers in a primary energy range from 100 TeV to 80 PeV and provides multi-parameter measurements on a large number of observables concerning 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.

The Field Array measures the total electron 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 decent investigations of the arrival directions of the showers in searching large scale anisotropies and, if exist, cosmic ray point sources.

The Muon Tracking Detector ($128\,\mathrm{m}^2$) measures the incidence angles of muons ($E_\mu > 800\,\mathrm{MeV}$) relative to the shower arrival direction. These measurements provide a sensitivity to the longitudinal development of the showers.

The hadronic core of the shower is measured by a $300\,\mathrm{m}^2$ 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, respectively.

The whole KASCADE setup is readout if a certain multiplicity of the array detector stations or of the trigger plane is firing, leading to a trigger rate of $\approx$ 4 Hz.

The redundant information of the showers measured by the Central Detector and the Muon Tracking Detector is prevailingly used for tests and improvements of the hadronic interaction models.

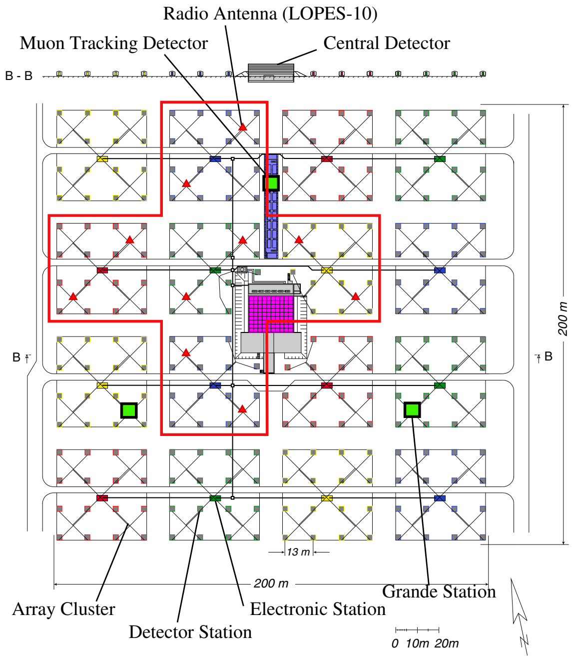

Figure 2: The main detector components of the KASCADE experiment: (the 16 clusters of) Field Array, Muon Tracking Detector and Central Detector. The location of 10 radio antennas is also displayed, as well as three stations of the Grande array.

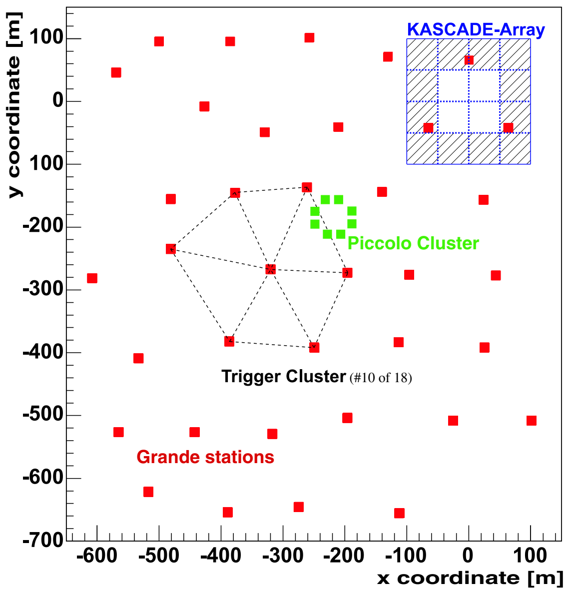

Figure 3: Sketch of the KASCADE-Grande experiment.

3. The KASCADE-Grande Experiment

The multi-detector concept of the KASCADE experiment has been translated to higher primary energies through KASCADE-Grande [10].

The 37 stations of the Grande Array (Fig. 3) extend the cosmic ray measurements up to primary energies of 1 EeV. The Grande stations, 10 m^2 of plastic scintillator detectors each, are spaced at approximative 130 m covering a total area of ~ 0.5 km^2. There are 16 scintillator sheets in a station read-out by 16 high gain photomultipliers; 4 of the scintillators are read-out also by 4 low gain PMs. The covered dynamic range is up to 3000 mips/m^2. A trigger signal is build when 7 stations in a hexagon (trigger cluster, see Fig. 3) are fired. Therefore the Grande Array consists of 18 hexagons with a total trigger rate of 0.5 Hz.

Additionally to the Grande Array a compact array, named Piccolo, has been build in order to provide a fast trigger to KASCADE ensuring joint measurements for showers with cores located far from the KASCADE array. The Piccolo array consists of 8 stations with 11 m^2 plastic scintillator each, distributed over an area of 360 m^2. One station contains 12 plastic scintillators organized in 6 modules; 3 modules form a so-called electronic station providing ADC and TDC signals. A Piccolo trigger is built and sent to KASCADE and Grande when at least 7 out of the 48 modules of Piccolo are fired. Such a logical condition leads to a trigger rate of 0.3 Hz.

To improve further the data quality a self-triggering, dead-time free FADC-based DAQ system will be implemented in order to record the full time evolution of energy deposits in the Grande stations at an effective sampling rate of 250 MHz and high resolution of 12 bits in two gain ranges [11]. This will lead to an intrinsic electron-muon separation of the data signal at the Grande Array.

4. KASCADE results

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. The limits of large-scale anisotropy analyzing the KASCADE data are determined to be between 10^{-3} at 0.7 PeV primary energy and 10^{-2} at 6 PeV [5]. These limits were obtained by investigations of the Rayleigh amplitudes and phases of the first harmonics. Taking into account possible nearby sources of galactic cosmic rays like the Vela Supernova remnant [15] 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 in measurements.

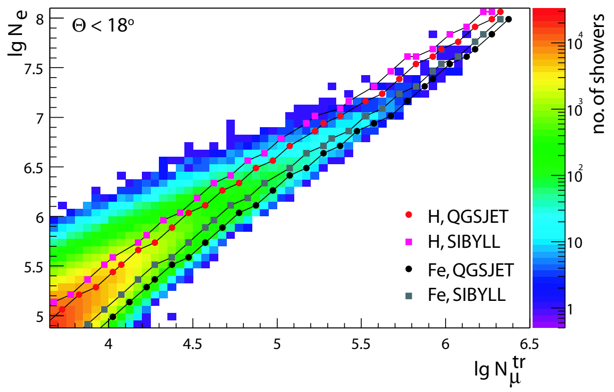

Figure 4: Two dimensional electron (N_e) vs. muon ($N_\mu^{\rm tr}$ =number of muons in 40-200m core distance) number spectrum measured by the KASCADE array. The lines display the most probable values for proton and iron primaries obtained by CORSIKA simulations employing different hadronic interaction models.

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. Investigated were the full sample of air showers as well as 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 was performed to estimate limits on the diffuse high-energy gamma ray flux in the energy range from 0.3 to 10 PeV [16]. The limits are found to be close to the theoretically predicted diffuse γ-ray spectra from [17].

Energy spectra of individual mass groups:

The KASCADE data analyses aims to reconstruct the energy spectra of individual mass groups taking into account not only different shower observables, but also their correlation on an event-by-event basis. The content of each cell of the two-dimensional spectrum of reconstructed electron number vs. muon number (Fig. 4) is the sum of contributions from the individual primary elements. Hence the inverse problem $g(y) = \int K(y,x)p(x)dx$ with $y = (N_e, N_\mu^{\rm tr})$ 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 $N_\mu^{\rm tr}$ for given true numbers of electrons and muons. The probabilities p_A are obtained by Monte Carlo simulations on basis of two different hadronic interaction models (QGSJET 01 [18], SIBYLL 2.1 [19]) as options embedded in CORSIKA [20]. By applying the above described procedures (with the assumption of five primary mass groups, only) to the experimental data energy spectra are obtained as displayed in Fig. 1. The resulting spectra for primary oxygen, silicon, and iron are added in the figure for a better visibility.

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 proton and helium. This demonstrates that the elemental composition of cosmic rays is dominated by light components below the knee and dominated by a heavy component above the knee feature. Thus the knee feature originates from a decreasing flux of the light primary particles.

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. In Fig. 4 the predictions of the N_e and N_μ^{tr} correlation for the two models are overlayed to the measured distribution 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 on 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 [9] 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.

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

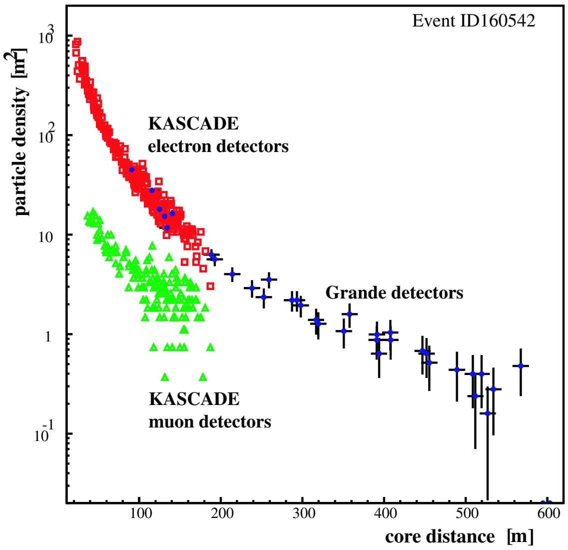

Figure 5: Particle densities in the different detector types of KASCADE-Grande measured for a single event.

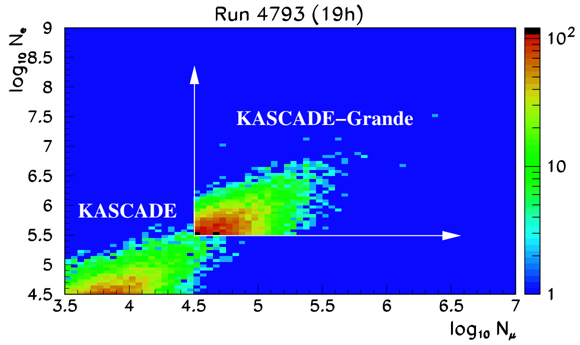

Figure 6: Comparison between KASCADE and KASCADE-Grande data for a combined test-run.

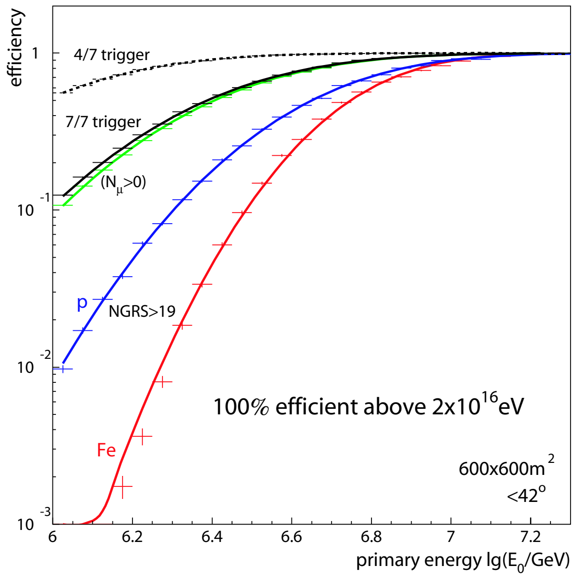

Figure 7: Efficiency of the Grande array (details see text).

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 [12].

5. First Measurements with KASCADE-Grande

Fig. 5 shows, for a single event, the lateral distribution of electrons and muons reconstructed with KASCADE and the charge particle densities measured by the Grande stations. This example illustrates the capabilities of KASCADE-Grande and the high quality of the data. The KASCADE-Grande reconstruction procedure follows iterative steps: shower core position, angle-of-incidence and total number of charged particles are estimated from Grande Array data; the muon densities and with that the reconstruction of the total muon number is provided by the KASCADE muon detectors. The reconstruction accuracy of the shower core position and direction is in the order of 4 m (13 m) and 0.18° (0.32°) with 68% (95%) confidence level for proton and iron showers at 100 PeV primary energy and 22° zenith angle [13]. The statistical uncertainty of the shower sizes are around 15% for both, the total numbers of electrons and muons. The critical point of the KASCADE-Grande reconstruction is the estimation of the muon number due to the limited sampling of the muon lateral distribution by the KASCADE muon detectors. The systematic uncertainty for the muon number depends on the radial range of the data measured by the KASCADE array and the chosen lateral distribution function.

At the KASCADE experiment, the two-dimensional distribution shower size - truncated number of muons played the fundamental role in reconstruction of energy spectra of single mass groups. In Figure 6 the correlation of these two shower sizes for both cases, KASCADE and KASCADE-Grande measurements are compared for a 1-day test-run. For the same run time, due to its 10 times larger area compared with KASCADE, the Grande Array sees a significant number of showers at primary energies ∼10 times higher. Hence, Figure 6 illustrates the capability of KASCADE-Grande to perform an unfolding procedure like in KASCADE.

Figure 7 shows the efficiency characteristics of the KASCADE-Grande array. For internal tests of the detector stations a 4/7 trigger is performed at the hexagons. The efficiency of the 7/7 trigger are also shown which is only small decreasing if additionally is required that the muon number has to be reconstructed with the information of the muon detectors of the original KASCADE array. To reduce efficiently the amount of data a software cut will be applied with the requirement of at least 10 Grande stations ($NGRS > 19$) have to be fired. A hundred percent efficiency is than reached for all primary particle types for energies above $2 \cdot 10^{16}$ eV, providing still a large overlap with the KASCADE energy range. The limit at high energies for Grande is due to the limitation in area and not saturation of the detectors, as even at primary energy of 10^{18} eV only one station in average is saturated.

6. Conclusions

The extension of KASCADE to the KASCADE-Grande experiment, accessing higher primary energies, is expected to prove the existence of a knee-like structure corresponding to heavy elements. KASCADE-Grande keeps the multi-detector concept for tuning different interaction models at primary energies up to 10^{18} eV. KASCADE-grande also provides the perfect environment detecting radio emission in extensive air showers. This is the aim of the LOPES project and subject of a further paper at these proceedings [3].

Acknowledgments

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