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Muon spectra reconstructed from inclined air showers measured by KASCADE-Grande

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Abstract: Inclined air showers (i.e. showers with zenith angle above 40 degrees) are registered by the KASCADE-Grande experiment, which is designed to address fundamental questions about the origin, composition and acceleration mechanisms of primary cosmic rays between 10^{14} and 10^{18} eV. Despite the aggravate reconstruction due to the thin scintillation detectors used in KASCADE-Grande these inclined events are valuable since they offer a good opportunity to both, study the penetrating component of the air showers and cross-checks of hadronic interaction models. Working in this direction, a first analysis of the KASCADE-Grande data from inclined events has been performed. In particular, the muon spectra have been reconstructed for different zenith angle intervals and features of the resulting spectra have been studied and confronted with expectations from Monte Carlo simulations.

Introduction

The main objective of the KASCADE-Grande experiment is the search for a knee in the heavy component of the cosmic ray spectrum. The presence or not of this feature will shed light on the origin of the cosmic rays in the energy region of $10^{14} - 10^{18}$ eV. The experiment studies this region of the cosmic ray spectrum indirectly, by observing the extensive air showers produced by cosmic rays in the atmosphere. For this purpose, KASCADE-Grande makes use of an $0.5\,\text{km}^2$ array of $37 \times 10\,\text{m}^2$ plastic scintillator detectors, which measures the arrival time and the density of charged particles in the shower front [1]. The advantage of the experiment is that it can directly measure the penetrating component of the air shower by using the array of $192 \times 3.2\,\text{m}^2$ shielded scintillator detectors of the original KASCADE observatory [2].

KASCADE-Grande is sensitive to air showers up to 70^o degrees of zenith angle, but only showers

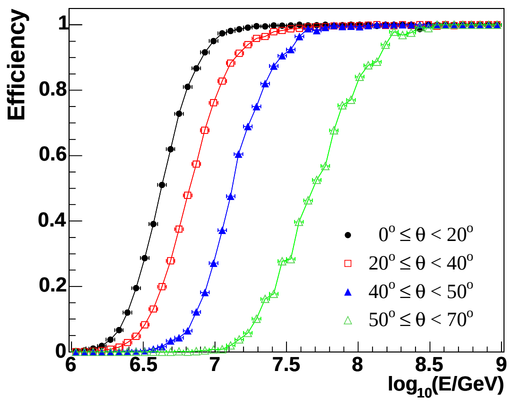

Figure 1: KASCADE-Grande triggering and reconstruction efficiency as a function of primary energy for different zenith angle intervals.

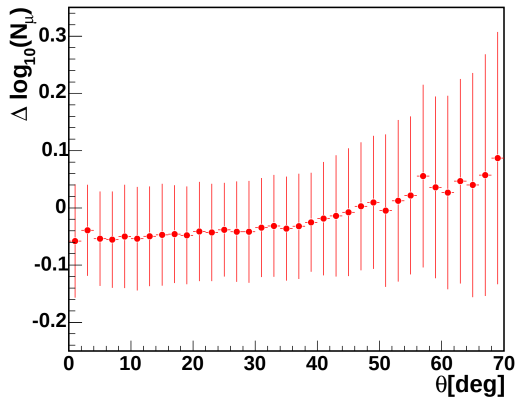

Figure 2: Zenith angle dependence of the systematic error for the reconstructed muon number.

below 40^o have been used up to now in the general analyses. Before using the data on inclined showers (i.e., on events above $\theta = 40^o$) a very good understanding of the precision of the employed reconstruction techniques in this zenith angle range is required. This task has recently begun, led by the different opportunities that the study of inclined showers offers, e.g.: 1) to increase the statistics of the experiment, 2) to understand in more detail the penetrating component of the shower, which is dominant in these kind of events, and 3) to cross-check hadronic interaction models, taking advantage of the close relation existing between the hadronic processes and the production of muons in the shower. In the following, the results of a first analysis of the penetrating component of inclined showers measured with the KASCADE-Grande experiment will be discussed.

Efficiency and systematics

To study the systematics and performance of the KASCADE-Grande detector at different zenith angles, both the air shower and the secondary particle interaction with the detector were carefully simulated. The air showers were generated with CORSIKA [3], employing the high-energy hadronic interaction model QGSJET II [4] for the range $\theta = 0^o - 70^o$, the energy interval $E = 10^{15} - 10^{18}$ eV and different primaries with equal abundances: H, He, C, Si and Fe. A power law cosmic ray flux with spectral index $\gamma = -2$ was used to generate the air showers. The cosmic ray events were isotropically distributed and their core homogeneously scattered over the entire Grande array. The same reconstruction procedure used for the experimental data was applied to the simulations.

The total muon number, N_μ, in the air shower is estimated from a log-likelihood fit to the measured muon densities at the KASCADE muon detectors [5]. On the other hand, the arrival direction of the shower is obtained from a χ^2 fit to the arrival times of the shower front to the KASCADE-Grande stations [6]. In this fit, sampling effects, fluctuations and the curvature of the shower front are properly modeled based on Monte Carlo simulations following [6], but with the difference that for inclined showers also muons are taken into account when parametrizing the shower front dependence on the zenith angle.

Several quality cuts were applied to the simulated data. A fiducial area of $0.4\,\text{km}^2$ with octagonal shape, centered at KASCADE-Grande, was chosen for the analysis to avoid showers with misreconstructed cores. Additionally, only events that triggered more than 19 Grande stations and passed successfully the charged particle reconstruction were considered. Cuts on the electron number N_e and the electron age parameter, s, were also introduced. For events with $\theta < 50^o$, the cut $N_e > 10^5$ was imposed. The same cut can not be applied to showers with higher zenith angles, in other case

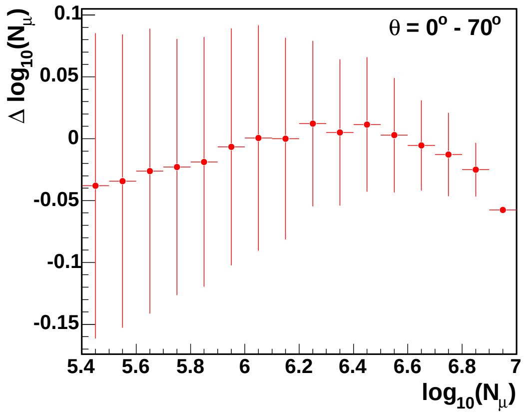

Figure 3: Systematic error in the estimation of the muon number shown as a function of the reconstructed N_μ.

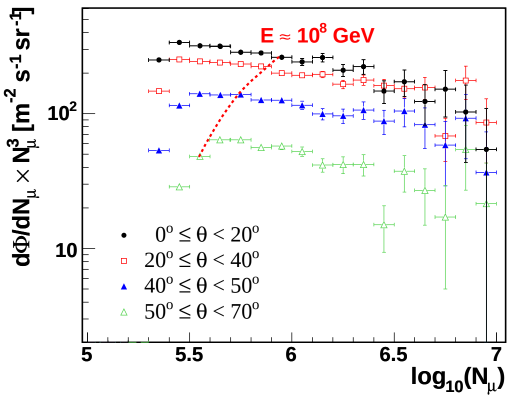

Figure 4: Reconstructed muon number spectra from KASCADE-Grande data on vertical and inclined showers. The intersections between the dotted line and the spectra give the respective muon numbers at which the expected primary energy is $E \approx 10^{17}$ eV.

the Grande detector loses efficiency. Instead, the cut $N_e > 10^4$ was employed. A final condition $N_\mu > 10^{5.4}$ was applied overall. With these cuts, it is found that the energy threshold at which the KASCADE-Grande detector achieves its full efficiency increases from $E = 10^{7.3}$ GeV for vertical showers up to $10^{8.5}$ GeV for very inclined ones (see Fig. 1).

Regarding the KASCADE-Grande pointing resolution, the analysis of the simulated data showed that it is better than 0.6^o inside the whole zenith angle interval $\theta = 0^o - 70^o$. For the systematic error in the reconstruction of the muon number, the result was $\Delta \log_{10}(N_\mu) \leq 0.1$ (with reference to Figs. 2 and 3), which was estimated as the difference between the true $\log_{10}(N_\mu)$ and the reconstructed one. The uncertainty in the shower core position, on the other hand, was found to be less than 40 m. The achieved accuracy in the reconstruction of N_μ and θ for inclined showers is good enough to perform a more detailed analysis of these events.

Muon size spectra

For the present work, 81593 events were subject to analysis. These events were selected from a vast set of experimental data collected by KASCADE-Grande, from which it resulted an effective time of observation of about 498 days. The selection was done by imposing the quality cuts described in the preceding section and discarding those experimental runs where one or more of the muon detector clusters of KASCADE were not active. Around 22% from the set of quality events were classified as inclined showers.

Before reconstructing the muon spectra, the muon number of each event was corrected for its systematic uncertainties through a correction function obtained from simulations. This function takes into account the dependence of the N_μ systematic uncertainty on the zenith angle (see Fig. 2), core position and $\log_{10}(N_\mu)$ (with reference to Fig. 3).

The resulting muon number spectra from the KASCADE-Grande data analysis for different zenith angle intervals are shown in Fig. 4 multiplied by N_μ^3. Clearly the threshold behavior for the different zenith angle ranges are seen. At this stage, the lack of statistics prevents us to perform a detailed analysis on the shape of the muon number spectra for $N_\mu \geq 10^{6.4}$.

Comparison with simulations

In Figure 5, the observed muon number spectra are confronted with expectations from simulations. In both cases, the same reconstruction techniques

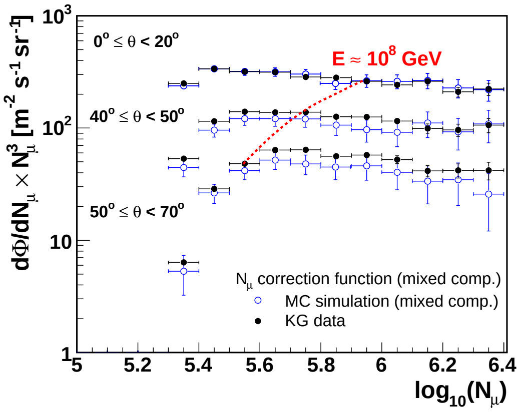

Figure 5: Comparison between the reconstructed muon spectrum from experimental data and simulations at different zenith angle ranges.

were applied. The simulated data set here employed was similar to the one described in section 2, but multiplied with an appropriate weight function, according to the energy of the event, in order to reproduce an energy power law spectrum with $\gamma = -3$. To compare the measured and simulated N_μ spectra, the latter ones had to be multiplied by a common normalization factor, which was chosen in such a way that for the range $\theta < 20^o$, the muon spectra obtained from the experimental and simulated data have the same magnitude. The analysis is restricted to the interval $\log_{10}(N_\mu) = 5.4 - 6.4$ in order to avoid statistical fluctuations, in particular, due to a low number of inclined events at high energies.

Small differences in magnitude between the measured and expected N_μ spectra for inclined showers are revealed in Fig. 5. The difference is also present for the range $\theta = 20^o - 40^o$ (not shown in Fig. 5 for clarity reasons), and grows from 12% at this zenith angle interval up to 20% for $\theta = 50^o - 70^o$. When iron nuclei or protons are used as primaries in the simulations, the above systematic trend is also observed, only the magnitude of the differences changes slightly. A lower muon number in the predictions from Monte Carlo simulations (CORSIKA/QGSJET II) for inclined showers than in the measurements or a reconstruction bias could be responsible for the observed differences. To find the reasons behind these discrepancies more analyses are needed.

Conclusions

It was shown that the KASCADE-Grande detector is sensitive to very high energy inclined air showers ($40^o \leq \theta < 70^o$), which can be well reconstructed. Besides that the angular resolution of the detector and the achieved accuracy reconstruction of N_μ are sufficient to allow detailed analyses with inclined air showers in KASCADE-Grande. From a first analysis of measured inclined showers the muon number spectra, corrected by the corresponding N_μ systematic uncertainties, were reconstructed. These fluxes were compared with expectations from simulations based on CORSIKA/QGSJET II. After normalizing the simulated N_μ spectra with a common factor, which allowed us to match the measured and simulated fluxes for $\theta < 20^o$, a systematic difference between the experimental and the simulated spectra was found, which increases with the zenith angle. The origin of this discrepancy has to be investigated.

Acknowledgments

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