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Muon Size Spectrum measured by KASCADE-Grande

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The reconstruction of the muonic component of extensive air showers with KASCADE-Grande is described and the quality of the reconstruction is studied with Monte Carlo simulations and compared with data from the KASCADE experiment. Furthermore, first results of mean muon lateral distributions and muon size spectra are presented.

1. Introduction

The KASCADE-Grande[1] experiment, located at the Forschungszentrum Karlsruhe, Germany, extends the existing extensive air shower experiment KASCADE[2] by an array of 37 detector stations spread over an area of 0.5 km^2. Its major goal is to measure the possible knee of the heavy component in the primary cosmic ray energy spectrum, expected at $\approx 10^{17}$ eV. The new array comprises 18 hexagonal trigger cells (7 stations), and 100% efficiency is reached with a 7 out of 7 coincidence condition at primary energies of $\approx 3 \times 10^{16}$ eV. With this configuration it is possible to measure and reconstruct extensive air showers of primary energies up to 10^{18} eV. Each detector station houses 10 m^2 of plastic scintillators, that are sensitive to the electromagnetic and muonic component above a threshold of 5 MeV, enabling the reconstruction of the number of charged particles of an extensive air shower. The field array of the KASCADE experiment with its electron and muon detectors covers an area of 200 m × 200 m and consists of 252 stations. It provides a coverage of 490 m^2 for e/γ and 622 m^2 for muons, with an energy threshold for vertical incidence of $E_e > 5$ MeV and $E_\mu > 230$ MeV. In order to infer the energy spectra of the primary cosmic ray particles for different mass groups with unfolding techniques using the two dimensional electron-muon size spectrum, both total particle numbers have to be known.

2. Approach and accuracy

The Grande array measures the densities and arrival times of the charged particles, from which one can reconstruct the shower core and arrival direction. The total muon number is obtained in a likelihood fit to the muon densities measured by the KASCADE muon detectors, located in the outer 192 stations of the KASCADE array. To describe the lateral distribution of the muons a function similar to the one proposed in Ref.[3] for the electron component is used:

$$\rho_\mu(r) = \mathrm{N}_\mu \cdot f(r)\ , \text{with } f(r) = \frac{0.28}{r_0^2}\left(\frac{r}{r_0}\right)^{p1}\cdot\left(1+\frac{r}{r_0}\right)^{p2}\cdot\left(1+\left(\frac{r}{10\cdot r_0}\right)^2\right)^{p3} \qquad (1)$$

The parameters p1, p2, p3 were obtained to be -0.69, -2.39 and -1.0 respectively by fitting the lateral distribution function to 10^{16} eV and 10^{17} eV proton and iron induced air showers simulated with CORSIKA[4] using the interaction model QGSJet[5]. A scaling radius of $r_0 = 320$ m is used. Due to the low measured muon densities and in order to obtain stable fit results, the curvature of the lateral muon densities is kept constant and only the muon number N_μ is estimated by $N_\mu^{est} = \sum_i n_i / \sum_i (f(r_i) \cdot \mathrm{A}_i \cdot cos(\theta))$. Where n_i are the number of particles measured in a core distance r_i in an area A_i and θ is the zenith angle of the air shower. Due to punch through of the electromagnetic component close to the shower core an inner radial cut of $r_i > 40$ m is applied. A fiducial area of $500\ \mathrm{m} \times 600\ \mathrm{m}$ is defined to reduce the effect of misreconstructed core positions at the edges of the Grande array. Requiring the core of a shower to be inside this frame results in a measurement of the muon density in a radial distance of $275 - 625$ m to the shower core for $\approx 68\%$ of the showers. Typical densities for an air shower of 10^{17} eV range from 0.1 to 1 particle per m^2 in this radial range. Further quality

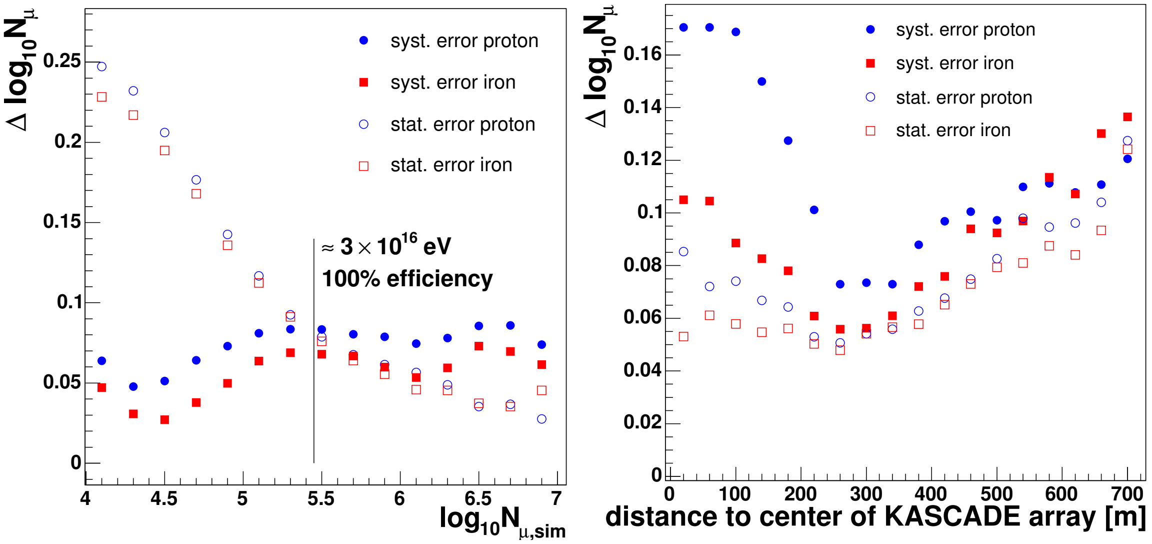

Figure 1. Uncertainties in reconstruction of total muon number depending on the muon number (left) and depending on distance to the KASCADE array (right). In the right handed figure only air showers with $\log_{10} \mathrm{N}_\mu > 5.5$ are shown.

cuts applied include the requirement of at least 16 Grande stations in an event and a cut on the age parameter s in the electron size fit (see also [6]). The systematics and uncertainties have been studied with Monte Carlo simulations using CORSIKA and the interaction model QGSJet (2001 version). The simulations comprise 380000 air showers each for proton and iron in an energy range from 10^{15} eV to 10^{18} eV and zenith angles from 0° to 42°. The simulated events have been scattered over the Grande array and tracked through a detailed GEANT[7] based detector simulation. For muon numbers larger than $\log_{10} \mathrm{N}_\mu \approx 5.5$, which corresponds to an energy of approximately 3×10^{16} eV the systematic error of the reconstructed total muon number is constant at around 15% (Fig. 1 left). It shows an offset between proton and iron of 0.01. The statistical error does not show a dependence on the primary particle. As expected, the statistical uncertainty decreases with increasing muon number. From around 20% at trigger threshold to approximately 8% at the upper limit of the energy range. Figure 1 right shows the dependency of the reconstrution accuracies on the distance of the core to the KASCADE array. In the important radial range of $275 - 625$ m, the statistical error increases from around 10% to approximately 20%. The relatively large systematic error for small distances is due to the steepness of the lateral distribution close to the shower core and to the punch through of the e/γ component close to the core. The reconstruction systematics shown in Fig. 1 are understood and will be dealt by the correct implementation of the lateral energy conversion function for the muon detectors.

3. Muon lateral distributions

Figure 2 left shows a comparison of mean muon lateral distributions from simulations with the measured data. The showers are binned in intervals of total muon number, being a good estimator of primary energy. The points for iron and proton lie very close to each other, as the shape of the muon lateral distribution is not very sensitive to the nature of the primary particle. The lateral distribution obtained from the data agrees relatively well with the simulations. The lines shown correspond to Eq.1 where N_μ is set to the measured mean muon

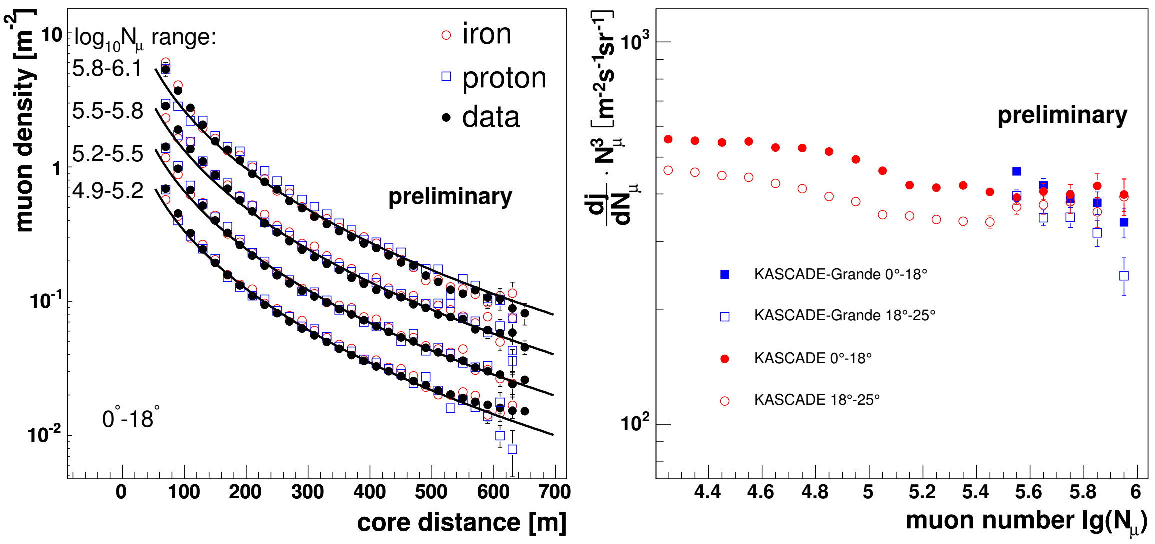

Figure 2. Left: Lateral density distributions of muons measured with KASCADE-Grande. Right: Reconstructed muon size spectrum for two zenith angle ranges

number obtained in each interval. At small radii the function has problems in describing the data, which might be due to punch through up to a range of 100 m core distance.

4. Reconstructed muon size spectrum

The shown differential muon size spectrum (Fig. 2 right) is based on a data set of 5.5×10^6 triggered events for KASCADE-Grande, taken between March 2004 and March 2005. The effective time of combined data taking of the Grande array and the KASCADE array was approximately 163 days, which is relevant for the flux determined by KASCADE-Grande. The flux for the KASCADE spectrum was obtained in approximately 1300 days of effective data taking. Both muon sizes are corrected for their systematic errors in reconstruction, derived from Monte Carlo studies. The correction applied to data from the KASCADE array in the high energy region might be too low. As one can see there is good agreement between the two measured fluxes in the overlap area in both shown zenith angle ranges. Furthermore the spectral structure shows reasonable continuation: Around a total muon number of $\log_{10} \mathrm{N}_\mu \approx 4.8$ one sees a steepening of the spectrum for the first zenith angle range, corresponding to the knee in the light component of the energy spectrum. For the second zenith angle range it is shifted lower to $\log_{10} \mathrm{N}_\mu \approx 4.6$. The steepening of the spectrum is followed by a flattening that corresponds to the relative increase of the heavy component. For more detailed statements on the shape of the muon size spectrum beyond $\log_{10} \mathrm{N}_\mu \approx 6$ more data is needed.

5. Conclusion

It has been shown that it is possible to reconstruct the total muon number with only a small fraction of radial coverage and first results look promising. The number of events measured with KASCADE-Grande above 100% efficiency are comparable to the ones measured by KASCADE, despite a factor of nearly ten in exposure time. With the above described reconstruction of the muon component together with the measured number of charged particles from the Grande array, one is able to reconstruct the electron size of an air shower measured with KASCADE-Grande (see [6]). With the information of the electron and muon size together, we expect to be able to infer the mass of the primary cosmic ray particles with an sophisticated unfolding analysis[8].

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