29th International Cosmic Ray Conference Pune (2005) **6**, 297–300

Studies of different LDFs for primary energy estimation and mass discrimination of cosmic rays by the EAS lateral charged particle distribution as observed by KASCADE-Grande

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On basis of simulation studies the reconstruction quality and some features of the lateral distribution of charged particles from extensive air showers (EAS) have been explored as observed with the KASCADE-Grande detector array in the primary energy range of 10^{16} eV - 10^{18} eV. Special emphasis is put on the study of observables serving for energy determination and mass discrimination of the cosmic rays primaries.

1. Introduction

The lateral distribution of various charged particles is a basic quantity of extended air showers (EAS) observed with ground arrays. In present work we explore the quality of its reconstruction for the detector layout of KASCADE-Grande [1] and study salient features of the reconstructed average distribution $S(r)$. The detection efficiency and the response of the detector have been taken into account by a dedicated reconstruction program SHOWREC [2] recently developed and designed for EAS of vertical and inclined incidence as observed with the KASCADE-Grande array. It calibrates the detector signals of the KASCADE-Grande stations in terms of charged particles densities. The reconstruction quality is studied by comparing "true" and reconstructed simulated distributions, and various parameterizations (LDFs) have been scrutinized with respect to the reproduction of $S(r)$ in the radial range of KASCADE-Grande observations (about $r \leq 700$ m). It turns out the region of the lateral charged particles distribution around $r = 500$ m (dominated by the muon component) indicates the energy of the primary particles, nearly independent of the mass, while the region about 100- 200 m (dominated by the electron gamma component) is sensitive to the primary mass.

2. EAS simulations

A set of showers with random angles of incidence, induced by H, C and Fe primaries have been simulated with CORSIKA Monte Carlo program (version 6.023) [3], using QGSJET model for describing the high-energy hadronic interaction for various energy ranges between $(1.00 - 1.78)10^{16}$ eV up to $(5.62 \cdot 10^{17} - 1.00 \cdot 10^{18})$ eV. The results are "distorted" by the SHOWREC program taking into account the detector responses and reconstruction features, thus providing quasi-experimental observables.

3. Reconstruction of the lateral particle density distribution by the program SHOWREC

The reconstruction procedures are based on the simulation of the energy deposit per charged particle (muons and electrons) in the Grande detector stations deduced with the code GEANT [4], and evaluated as function of the distance from the shower axis by introducing a lateral energy correction function. From the reconstructed number of charged particles, found for each detector station of the Grande array the reconstructed charged particle density S(r) in the plane normal to the shower axis has been deduced. The distribution and number of the original CORSIKA charged particles hitting each detector are also recorded for sake of comparison and controlling the reconstruction performance. The present study extensively compares the features of the "true" density $\rho_{ch}(r)$ with the reconstructed density $S(r)$. The charged particle distributions (either the sampled CORSIKA distributions $\rho_{ch}(r)$ or the reconstructed distribution $S(r)$) adopt an a-priori anticipated form of the lateral distribution function (LDF) used for the interpolation of the charged particle density between the detector stations.

Different parameterizations of the LDF have been scrutinized, in particular the NKG function [5], the Linsley - LDF [6], the Lagutin - LDF [7] and a description as sum of polynomials [8]. Adopting adequate values for the scaling radius R0, the shape parameters of these forms and the total number of charged particles (normalisation of the LDF) have been determined by a fitting procedure. Actually none of the studied LDF describes the reconstructed lateral distribution perfectly over the whole r - range. Hence average EAS observables would be best determined by fitting the average lateral distribution in restricted ranges, e.g. $< S^{500} >$ or equivalently $< N_{ch}^{500-600} >$ (the integrated particle number between $r = 500$ and 600 m), and $< S^{200} >$ (or equivalently $< N_{ch}^{100-200} >$, the integrated particle number between $r = 100$ and 200 m). However these fits provide generally minor quality when extrapolated beyond the fitting range. Such a procedure deriving relevant EAS observables from fits to the observed lateral distributions over restricted lateral ranges would not be efficiently feasible for analyses of single showers on an event by event basis. Fortunately the fitted Linsley and Lagutin LDF do reproduce the reconstructed average lateral distribution $S(r)$ over large r-ranges with sufficient accuracy increasing with the primary energy.
In addition to the question how well a particular LDF reproduces the observed $S(r)$ is the question how well a certain quantity derived from the reconstructed lateral distribution reflects the "true" value.

Fig.1 displays a comparison of the reconstructed observables S^{200} and $N_{ch}^{100-200}$, respectively. These observables show some features, particularly useful for mass discrimination.

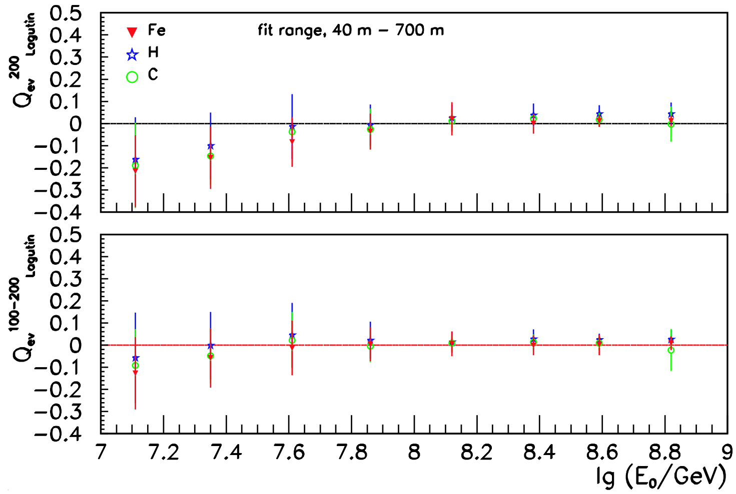

Figure 1. Energy variation of the reconstruction quality displayed by the quantity $Q(r) = (O(S_{rec}) - O(\rho_{ch}(r))/O(\rho_{ch}(r))$ for the reconstructed observables $O = S^{200}$ and $N_{ch}^{100-200}$, respectively. The displayed quantity Q_{ev} is the average over many single showers of the sample, comparing the reconstructed observable with the "true" (i.e. undistorted CORSIKA) value.

4. Energy estimation by S^{500}

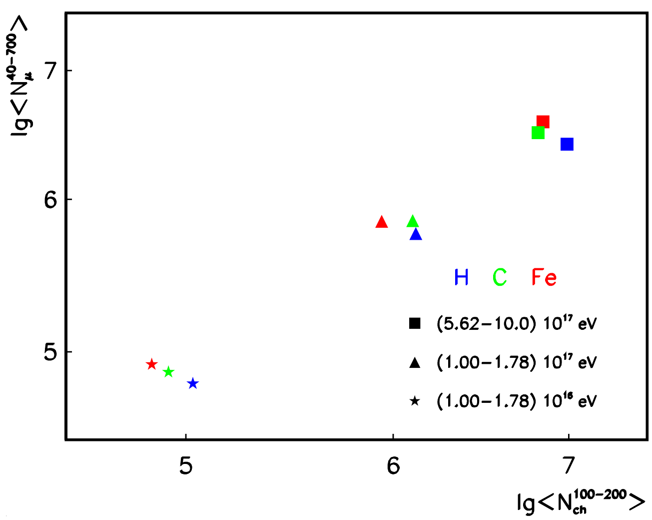

Figure 2. The $N_{ch}^{100-200}$ - N_{μ}^{40-700} correlation of the averaged lateral distributions for various primaries and primary energy ranges.

While the KASCADE experiment is able to use a combination of the shower sizes of the electromagnetic and muon components for the energy determination, KASCADE-Grande [1] relies - in the present layout - on the observation of the charged particles, in general without discrimination between muons and electrons. This feature suggests to consider the procedure first suggested by Hillas et al. [9] to exploit the information of the lateral distribution $S(r)$ in the region of 500-600 m distance from the shower core. The results of the analysis display a linear energy dependence of the average reconstructed $\log < S^{500} >$ for proton and iron induced EAS, exhibiting a rather weak dependence on the primary mass and a slight dependence on the angle of shower incidence. It should be noted that the reconstruction quality of S^{500} and $N_{ch}^{400-600}$, respectively gets reduced (within the error bars up to 50%) at lower primary energies. This is due to the reduced efficiency of the apparatus observing charged particles of lower energy EAS at $r \approx 500\,\mathrm{m}$. This feature, however, is included in the energy calibration of $< S^{500} >$ and $< N_{ch}^{400-600} >$, respectively .

5. Observables for mass discrimination

A particular aim is to explore EAS features which may carry information about mass composition in the primary energy range 10^{16} eV to 10^{18}, i.e. within the energy range of the KASCADE-Grande experiment. The shape parameter η of the Linsley LDF shows some mass discrimination power. Promising and more pronounced discrimination features of $< S^{200} >$ get evident by well reconstructed values of $< S^{100/200} >$ or alternatively $< N_{ch}^{100-200} >$. The studies of the correlation distributions with various EAS observables exhibit pronounced mass discrimination features when correlating S^{200} ($N_{ch}^{100-200}$) with the muon density observed at adequate distance from the shower axis or with an adequately reconstructed muon number. In the present status we use as muon number (N_{μ}^{40-700}) a value reconstructed from the number of muons expected from the CORSIKA simulations hitting the Grande detectors (and using an adequate LDF for fitting the distribution in the range $r = 40 - 700$ m, see also ref. [10]).

6. Conclusions

1. The reconstructed averaged charged particle density in a range of distances of 500 m and 600 m from the shower core is only very weakly dependent on the primary mass and can be used as good energy identifier for EAS observed with KASCADE-Grande array.
2. Magnitude and shape of $< S(r) >$ in the region $r \approx 200$ m show a distinct dependence of the primary mass. The S^{100}–N_{μ} correlation proves to be a powerful mass discriminator. This feature has been shown for the average lateral distributions of the charged particles and muons (reconstructed for the layout of KASCADE-Grande).
3. These results suggest the application in event-by-event analyses where the mass discrimination can be quantitatively specified by nonparametric statistical multivariate analyses providing the true - and mis-classification probabilities for the mass assignments [11].

The methods worked out for the analysis of lateral distributions of charged EAS particles have been started to get applied to the analysis of real showers.

Acknowledgements
This work is supported by a grant of the Deutsche Forschungsgemeinschaft (grant: GZ436RUM).

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