The Role of Measurements of Muon Arrival Time Distributions for the Mass Discrimination of High Energy EAS

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1. Introduction

The temporal structure of the shower disc, especially of the muon component at higher muon energies, arises from geometrical (path length) effects, at least at sufficiently large distances from the shower axis. Thus the arrival time distributions of muons, measured on ground relative to the arrival time either of the shower center (global delays) or of the first locally registered muon (local delays) can be rather directly related to the height of production of the parent pions and kaons and do map the longitudinal EAS development. They are correlated with angle-of-incidence distributions of the muons. Advanced Monte Carlo (MC) simulations of the EAS development provide a good basis for the understanding of the observed distributions in terms of the longitudinal EAS development and mass composition of primary cosmic rays, respectively, or for testing the ingredients (particle propagation, hadronic interaction models) of the MC simulations.

This report compiles the main features of muon arrival time distributions measured with the Central Detector of the KASCADE experiment or studied on basis of corresponding MC simulations using the Monte Carlo EAS simulation program CORSIKA. The experiences with the KASCADE detector setup, restricted to arrival time observations at distances $R_\mu \lesssim 100$ m from the EAS axis

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are summarized. An outlook to the role of studies of the temporal EAS structure with KASCADE-Grande [3] is given. There muon arrival time distributions gain considerable importance with respect to the mass discrimination power [2].

2. Summary of KASCADE results

The timing facility of the KASCADE Central Detector, an "eye" of 456 pixels of scintillator elements, distributed over 16×20 m^2 with a coverage of 68% of the area, registers the timely sequence of the arriving muons, additionally identified with position sensitive MWPC installed in the souterrain of the Central Detector with an energy threshold of 2.4 GeV and with a minimum multiplicity, spanning the single-event arrival time distribution. From the single distribution various quartiles $\Delta\tau_q$ e.g. the median $\Delta\tau_{0.50}(R_\mu)$, are deduced. The distributions of these quartiles is considered to be representative for the temporal EAS structure and the fluctuations. For details see ref. [1, 2].

At shower sizes observed with KASCADE the muon multiplicity registered for single shower events is relatively low which causes some difficulties to define the shower front by the foremost muon. Thus the quartile values additionally fluctuate with the multiplicity i.e. the number of muons (or the muon density $\rho_\mu^*(R_\mu)$) registered by the MWPC at $E_{thr} = 2.4$ GeV. It turns out that reduced quantities $\Delta\tau_q/\rho_\mu^*$ widely cancel such type of fluctuations. The main results of experimental studies and analyses of muon arrival times from KASCADE investigations are [1, 2]:

- As simulations show the mass discrimination effects at primary energies around the knee and $R_\mu < 100$ m in terms of arrival time differences are in the order of few nanoseconds. The effects, increasing with the primary energy and the distance R_μ are considerably obscured by the finite time resolution of the apparatus.
- Nevertheless the experimentally observed results, expressed in distributions of various quartiles $\Delta\tau_q$ and by EAS time profiles (i.e. variation of $\langle\Delta\tau_q/\rho_\mu^*\rangle$ and of the dispersions) are in very good agreement with the results of extensive MC simulations adopting a reasonable mass composition.
- Nonparametric analyses of multivariate distributions correlating the EAS time observables with other observables (shower size N_e, the approximate energy estimator N_μ^{tr} ....) display the minor role for mass discrimination under the conditions of KASCADE, though the good agreement of the phenomenological features considerably enhances the consistency of KASCADE analyses.

3. Expected features of muon arrival time distributions of high-energy EAS observed with KASCADE-Grande

The situation concerning the sensitivity to the primary mass is expected to get improved considerably with KASCADE-Grande observations [3].

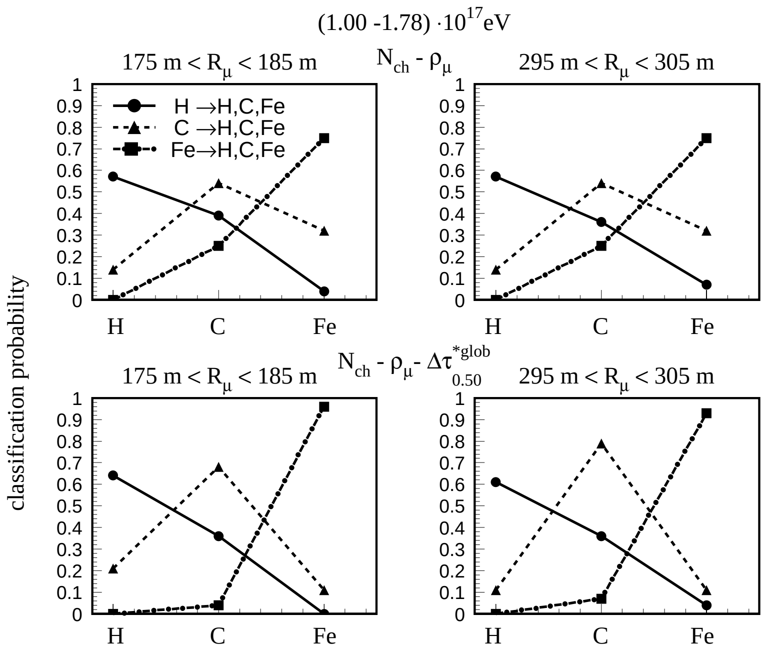

Fig. 1. The effect of the global time parameter $\Delta\tau_{0.50}^{glob}(R_\mu)$ on the true and false classification by the $\mathrm{N}_{ch} - \rho_\mu(R_\mu)$ correlation shown for two distances R_μ and the primary energy range $(1.0 - 1.78) \cdot 10^{17}$ eV.

This expectation is based on extensive MC analyses, inspecting correlations and applying nonparametric statistical analysis techniques to multivariate distributions for the KASCADE-Grande case specifying the improvement of the Bayes risk values of classification. Since KASCADE-Grande will measure only a partial muon number N_μ^{part} (registered with the muon detectors of the embedded KASCADE array), for sake of simplicity the muon density $\rho_\mu(R_\mu)$ (with the observation threshold E_{thr}= 240 MeV) is used to represent N_μ^{part}. Fig.1 displays the true- and misclassification probabilities resulting from the application to a sample of proton, C and Fe induced EAS, classified by use of the correlation of the total number of charged particle N_{ch} with $\rho_\mu(R_\mu)(\propto N_\mu^{part})$ and compared to the result from the $\mathrm{N}_{ch} - \rho_\mu(R_\mu) - \Delta\tau_{0.50}$ correlation. There are improvements of the classification probabilities of the heavy ion induced EAS, which are of considerable significance for reconstruction of the mass composition.

4. Observations of muon arrival time distributions as consistency test

The experimental procedure measuring the muon arrival times imply various conditions about the energy threshold of the muons observed in a certain distance R_μ and a certain multiplicity threshold for being accepted for the reconstruction. Hence specific subsamples of all registered EAS events are selected. The distortions of the mass composition vary with the distance from the EAS center due to different lateral (and energy) distributions of the EAS particles. In order to reconstruct the original mass composition efficiency (acceptance) corrections have to be introduced, dependent on the observation distance R_μ, on the primary energy, on the multiplicity of the muons etc.. Such corrections invoke necessarily MC calculations with the requirement: The reconstruction of the primary mass composition from each sample observed with the variation of R_μ (and of the multiplicity threshold) must lead to identical composition results within the uncertainties.

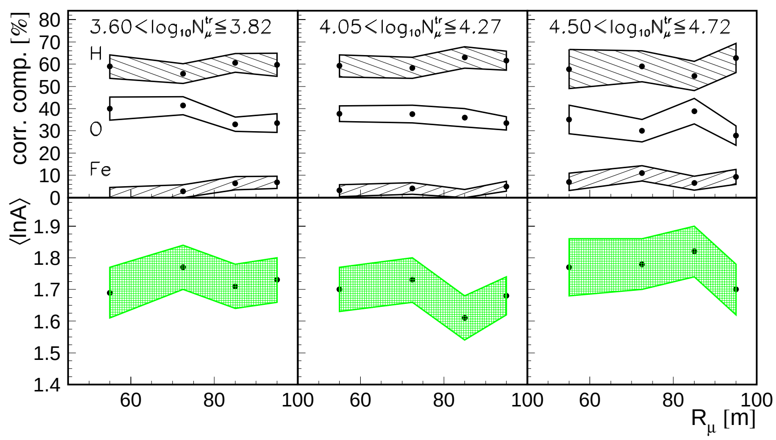

Fig. 2. Variation of the efficiency corrected mass composition and $\langle \ln A \rangle$ deduced from experimental observations at different R_μ.

The procedure has been applied to KASCADE data [2] using the QGSJet model as generator of the CORSIKA MC simulations (Fig.2). The deduced mass composition is in fair agreement with the other results of KASCADE and corroborates the increase of $\langle \ln A \rangle$ beyond the knee.

5. Concluding remarks

The results considering the KASCADE-Grande case tentatively demonstrate that muon arrival time measurements will play a significant role approaching a detailed understanding of the high-energy EAS. The procedure of the consistency test, first applied to KASCADE data can be further refined [4]. Global arrival time distributions turn out to be not significantly improving the sensitivity to the primary mass as compared to local distributions.

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