MEASUREMENTS OF ARRIVAL TIME DISTRIBUTIONS OF EAS MUONS WITH THE FACILITIES OF THE KASCADE CENTRAL DETECTOR

M. Föller[1], U. Raidt[2] for the KASCADE Collaboration[*†]

[1]*Forschungszentrum Karlsruhe, Institut für Kernphysik, D–76021 Karlsruhe, Germany*
[2] *Physikalisches Institut der Universität Tübingen,Tübingen, Germany*

ABSTRACT

The central detector of the KASCADE experiment is equipped with a trigger and timing facility, which enables measurements of the arrival time distributions of muons hitting the central detector. The muons are identified with an energy threshold of 2 GeV by a setup of multiwire proportional chambers, positioned below the hadron calorimeter. The features of the muon arrival time distributions have been studied with EAS simulations. Advanced methods for the analysis of arrival times of EAS particles, based on Bayes decision rules and statistical techniques analysing nonparametric multivariate distributions, have been developed. First experimental results of the arrival time distributions of the first EAS muon, the median and mean values and the dispersion, their dependencies on and correlations with various shower variables are presented.

INTRODUCTION

The development of extensive air showers (EAS) in the Earth's atmosphere is reflected by the time structure of particles incident at observation level. Due to the high penetrability of muons, in particular the arrival time distributions of the muon component of EAS map the longitudinal development of the shower, especially at larger distances from the shower core where geometric factors are dominating. As the longitudinal structure is related to the nature and the interaction of the primary particle, the measurements of arrival time distributions and the time dispersion of the muon front provide useful information on the primary. Additionally to the $N_e - N_\mu$ correlations (and variants thereof), arrival time distributions can improve the separation of primary particles. This aspect is investigated with the detector setup of the KASCADE experiment (Klages et al., 1997). The central detector of KASCADE contains an iron sampling calorimeter for measuring hadrons. The third detector layer is equipped with a trigger and fast timing facility, consisting of 456 scintillation counters which enable the measurements of arrival times of individual muons. Muons with energies $>$2 GeV are identified with a setup of multiwire proportional chambers (MWPC) below the hadron calorimeter and correlated with the measured times of the trigger detectors.

MEASUREMENTS OF ARRIVAL TIME DISTRIBUTIONS

We analysed about 450,000 showers from a period of two months. The core position, the angle of incidence and the shower size N_e is determined by the detector array. Considering the shower reconstruction accuracy it is possible to use showers with the core inside the detector array.This leads to a maximum core distance of 100 m from the central detector. For further analysis, we require at least three muons with energies $>$2 GeV, measured simultaneously by the trigger detectors and the MWPCs. For the selected muons, it is possible to measure the arrival times with an accuracy of about 1.8 ns with the scintillation detectors. This allows the calculation of various parameters of

[*]corresponding author: e-mail: rebel@ik3.fzk.de
[†]A full list of authors and institutes of the KASCADE–Collaboration is given at the end of this volume.

arrival time distributions, e. g. mean and root mean square(rms), median, 1st quartile $t^{lok}_{0.25}$ and 3rd quartile $t^{lok}_{0.75}$. For the time zero we choose in this analysis the arrival time of the first muon in the trigger layer. As an example, Figure 1 shows the distribution of the 3rd quartiles, calculated for showers with a core distance from 80–100 m, and an inclination between $15-30^{o}$. The data sample is divided into four $log(N_e)$-bins in the range of $4.5 < log(N_e) < 5.9$.

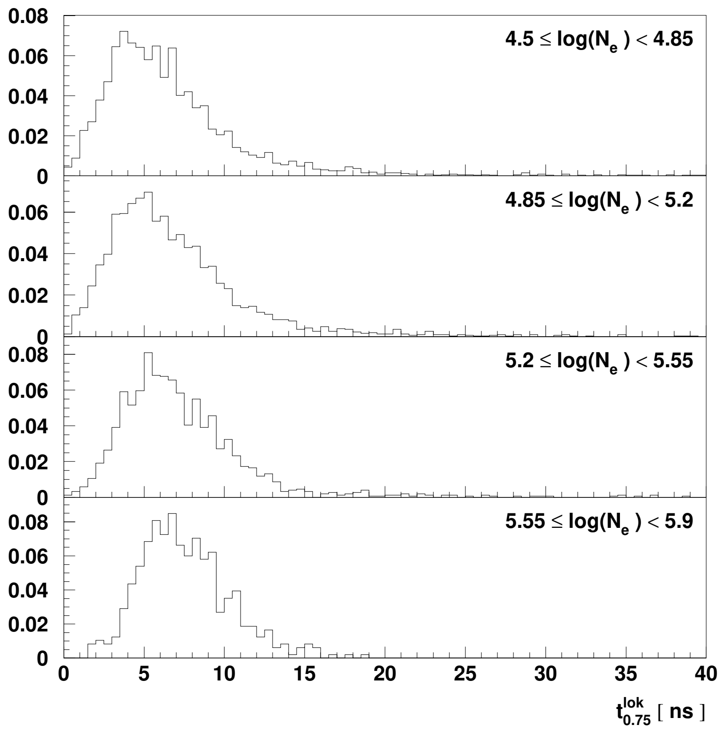

Fig. 1: Measured distributions of the 3rdquartiles with respect to the arrival time to the first muons in the trigger layer.

The rms defines the dispersion of the muon disk and depends on the distance from the shower core. The dependence can be described by $\sigma(r) = m_1 + m_2(\frac{r}{r_m})^{m_3}$ with the Moliere radius $r_m = 79$ m. The parameters m_2 and m_3 depend only weakly on shower size N_e, in contrast to m_1 which shows a strong correlation with N_e. The dependence of the arrival time distributions on atmospheric depth can be investigated by measuring the distributions at different zenith angles θ. To compare these values with the Haverah Park analysis (Blake et al., 1990, Walker and Watson, 1981) the median τ_{50} and the value $\tau_{75} = t^{lok}_{0.75} - t^{lok}_{0.25}$ are used and compared with the signal rise time T_{50} (from 10% to 50%) and T_{70} (from 20% to 70%) in a water Cherenkov detector. In radius bins between 0 and 200 m core distance $\partial\tau_m/\partial\sec\theta$ and $\partial\tau_{75}/\partial\sec\theta$ are calculated, with $1.0 < \sec\theta < 1.4$. In contrast to Walker and Watson, who use a linear fit, we find a quadratic dependence of these values from the core distance. The extrapolated value of $\partial\tau_{75}/\partial\sec\theta$ at a core distance of 300 m is in good agreement with the measurements of Blake et al..

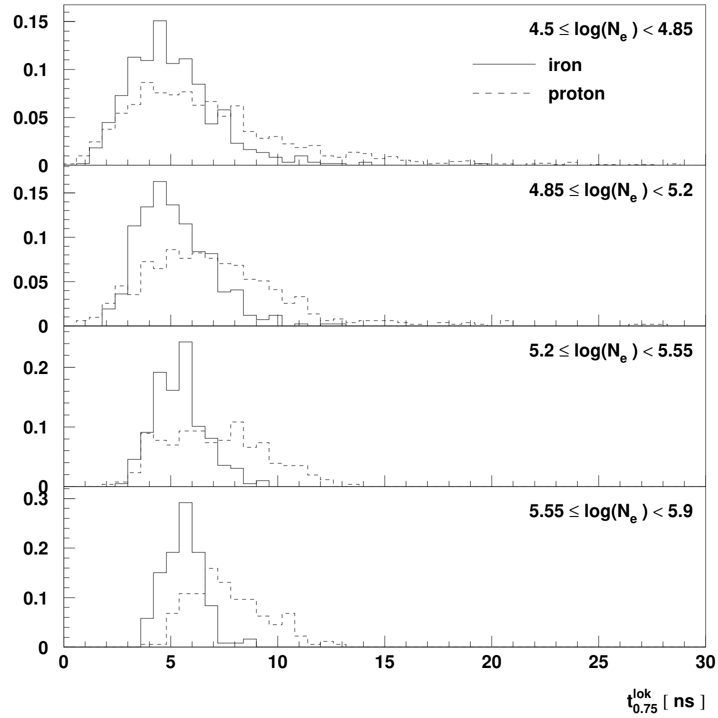

Fig. 2: Simulation of distributions of the 3rdquartiles, without detector resolution.

SIMULATIONS

For the investigation of the arrival time distribution with respect to mass separation, detailed simulations of the development of EAS are done with the program CORSIKA (Vers. 4.6) (Capdevielle et al., 1992), using the GHEISHA and VENUS packages and the EGS4 code for the e/γ component. Iron and proton showers in the energy range $5 \cdot 10^{14} - 8 \cdot 10^{15}$ eV with an inclination of 22 degrees are generated. The showers are divided into the same four $log(N_e)$-bins as the real data, considering of the energy spectrum.

Figure 2 shows the theoretical distributions (without detector resolution) of the 3^{rd} quartile at a core distance of 90 m. In fact, there is a significant difference between the distributions for proton and iron induced showers. The separation improves with higher $log(N_e)$. Because of the larger fluctuations in proton showers, this distribution is broader than the distribution of the iron induced showers. For including the detector resolution the particles, hitting the central detector in a core distance of 90 m are tracked with the GEANT package through the whole detector. The distributions of the 3^{rd} quartile, including detector resolution and muon reconstruction probability are shown in Figure 3. The differences between the distributions of iron and proton induced showers decrease in all four $log(N_e)$-bins. The same behaviour is seen for all other parameters of arrival time distribution, like 1^{st} quartile, median, mean, etc. Therefore it is difficult to separate iron and proton induced showers at a distance of 90 m to the shower core exclusively using the time data. An improvement of the separation is obtained by correlating the arrival time distributions with the number of reconstructed muons in the central detector ($E_\mu > 2$ GeV). By a $log(N_e)$ binning this number depends on the nature of the primary particle; for iron induced showers it is significantly greater than for proton induced.

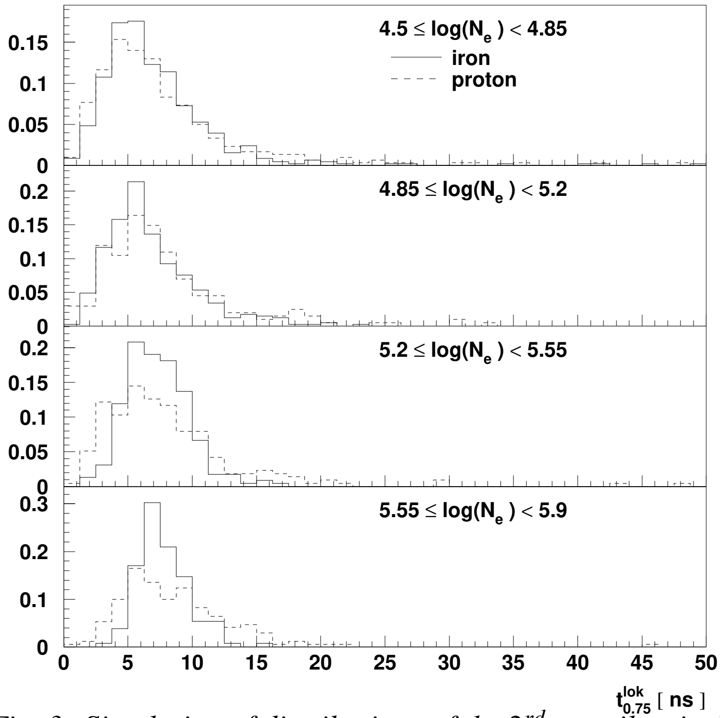

Fig. 3: Simulation of distributions of the 3^{rd} quartiles, including detector resolution.

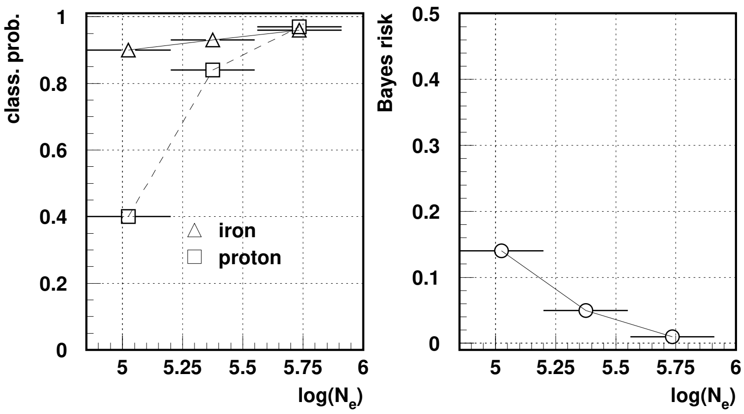

Fig. 4: Classification probability (left) and Bayes risk (right), including detector resolution.

SHOWER CLASSIFICATION

In order to classify the measured showers as a proton–like and an iron–like group we apply statistical techniques of estimation of the overlap of multivariate distributions and quantify the probability of a correct event classification by the Bayes error. The mathematical basis of this method is described in (Chilingarian, 1989) and (Chilingarian and Zazian, 1991). We use training samples of simulated iron and proton showers with full detector simulation to estimate the classification probability with the "one–leave–out–for–a–time" test. This procedure removes one element from the sample and trains the sample without it. The element is subsequently classified and returned to the sample. In addition to the probability of correct classification of iron and proton induced showers one obtains the "Bayes risk", which is an estimate of the overall classification error. As parameters for classification we select the number of reconstructed muons in the central detector and the 1^{st} and the 3^{rd} quartile of the arrival times. Figure 4 shows the results of the "one–leave–out–for–a–time" test, using proton and iron induced showers in the four described $log(N_e)$ bins. The left picture shows the probability of correct classification, the right picture the Bayes risk. Above $log(N_e) = 5.2$ more than 84% of proton induced and more than 93% of iron induced showers are classified correctly. At lower energies the multivariate distributions show a strong overlap, so that the classification probability gets worse. Therefore we have not classified the showers in the lowest $log(N_e)$ bin. Figure 5 shows the results applying the trained algorithm to the measured data. The rapid change of the proton/iron ratio below $log(N_e) = 5.2$ is caused by detector and reconstruction effects. Above $log(N_e) = 5.2$ we find an almost constant proton/iron ratio of about $(64 \pm 5)\%/(36 \pm 5)\%$.

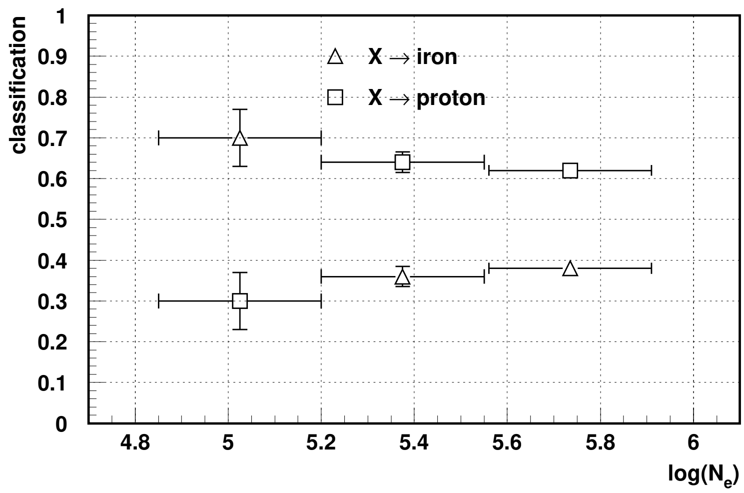

Fig. 5: Classification of the data in a proton–like and an iron–like group.

CONCLUSION

We present first measurements of EAS muon arrival time distribution using the timing facility of the KASCADE central detector and show various dependences of the time structure of the muon shower disc. The muon arrival time distributions observed in a distance of 80–100 m from the shower core prove to be sensitive to the mass of the primary, in particular when correlated with the multiplicity of the muons observed (with a threshold of 2 GeV) with the central detector. This sensitivity increases with shower size. For a classification of the measured showers into a proton–like and an iron–like group we used the Bayes decision rules. The algorithm was trained by EAS simulations, and it has been shown that the considered parameters are significant for the mass discrimination.

ACKNOWLEDGEMENTS

This work is part of various WTZ projects of scientific-technical collaboration of Forschungszentrum Karlsruhe (Germany) with IFIN-HH Bucharest (Romania), with Yerevan Physics Institute (Armenia) and with INS Lodz (Poland). It is partly supported by grants of the Romanian Ministry of Research and Technology, of the Armenian government and the Polish State Committee of Scientific Research (grant Nr. 2P03B 16612).

REFERENCES

Blake, P. R. et al.,J. Phys. G: Nucl. Part. Phys. **16**,755 (1990).
Capdevielle, J. N. et al., KFK–Report 4998, Kernforschungszentrum Karlsruhe 1992.
Chilingarian, A. A. Computer Physics Comm. **54, 381** (1989).
Chilingarian, A. A. and Zazian, G. Z., Nuovo Cim. **14**, 55 (1991).
Klages, H. O. et al., Nucl. Phys. B (Proc. Suppl.) **52B**, 92 (1997).
Walker, R. and Watson, A. A.,J. Phys. G: Nucl. Part. Phys. **7**,1297 (1981).