The time structure of the EAS muon component observed in the KASCADE experiment

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Abstract
The time structure of the EAS muon component is studied at sea level by measurements of the muon arrival time distributions using the muon facilities of the KASCADE central detector. Data have been analysed for EAS core distances up to 130 m for primary energies of the knee region. Results are presented for the distributions of various moments and the dispersion of the arrival times relative to the arrival of the foremost muon, respectively. For the muon observations at larger core distances particular studies could be performed with the question to which extent EAS muon arrival time distributions display features with information about the energy and mass composition of the primary cosmic rays.

The timing and muon identification facilities of the KASCADE central detector.

The determination of the chemical composition in the energy range of 10^{15}eV is the scientific goal of KASCADE (KArlsruhe Shower Core and Array DEtector) experiment (Klages 1997). Under this aspect the temporal structure of the muon component of Extended Air Showers (EAS) is of great interest for a detailed understanding of the EAS features, since the muon arrival time distributions map the longitudinal EAS development via the time-of-flight of muons produced in large atmospheric heights and show effects for mass discrimination of the EAS primaries (Danilova 1994, Rebel 1995, Brâncuş 1997). Using the muon detection and timing facilities of the KASCADE central detector, in particular the "trigger layer" of 456 scintilla-

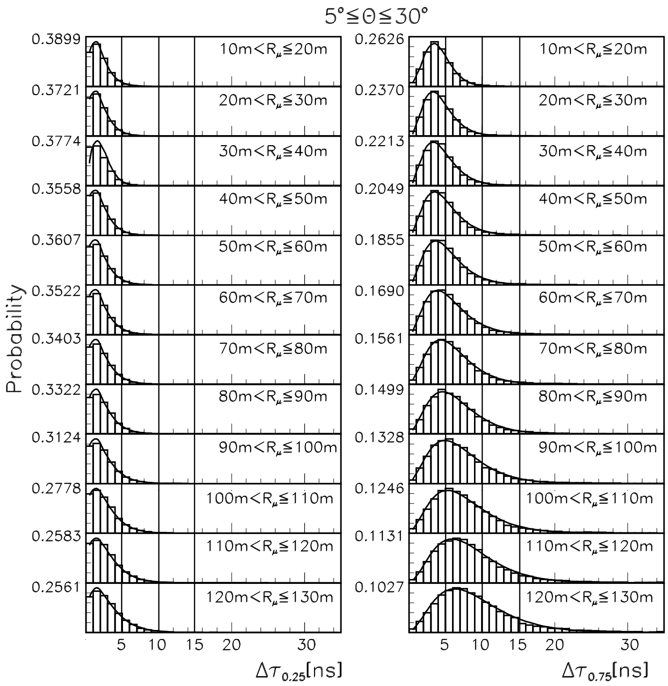

Fig. 1: *The average variation of the shape of the median distribution with the core distance, averaged on the N_μ^{tr} spectrum of the observed sample and for $5^o < \theta \leq 30^o$. The distributions are normalized to the maximum number of particle per time-bin. The lines give the fits by the Γ-form.*

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tion detectors and the position-sensitive large area multiwire proportional chambers, installed under the hadron calorimeter, the muon arrival time distributions ($E_\mu \geq 2\ GeV$) registered relative to the arrival of the foremost muon have been measured. Their dependence on various shower quantities: the distance from the shower center R_μ, the zenith angle Θ of the shower incidence and of the muon shower content N_μ^{tr} (representing the muon content with $E_\mu \geq 250\ MeV$, integrated in a limited range of 40-200 m from the center of the lateral muon distribution and considered as an identifier of the primary energy) have been studied.

Definitions of the observables and general procedures.

The experimental data have been accumulated during 900 hours in the period 30.09-3.12.1997. The total number of events of interest is about 200000 with the requirement that at least 3 timing detectors of the timing facility of the central detector must have fired per event. The muon component at energies > 2 GeV is measured as correlated signals of the trigger layer and the MWPC chambers and associated by the general KASCADE trigger event to an EAS event. Measurements of the relative muon arrival times refer to an experimentally defined zero-time, usually the arrival time T_{cor} of the shower core, used also in a first analysis of KASCADE data (Föller 1997). Time quantities like:

$$\Delta\tau_1^{glob} = T_\mu^1 - T_{cor} \text{ and}$$
$$\Delta\tau^{glob} = T_\mu - T_{cor}\ ,$$

T_μ^1 being the arrival time of the foremost muon and T_μ the mean of the distribution, referring to T_{cor} are called "global" quantities. They are affected by the reconstruction procedures of the arrival time of the electromagnetic component. Thus we prefer to analyse "local " times which refer to the arrival times of the

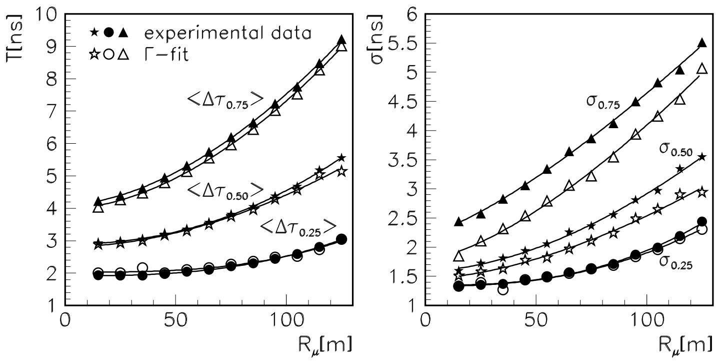

Fig. 2: *The mean values and standard deviations of the median, first and third quartile distributions extracted from the distributions (Fig.1) and compared with those from the fitting first the distributions by the Γ-form.*

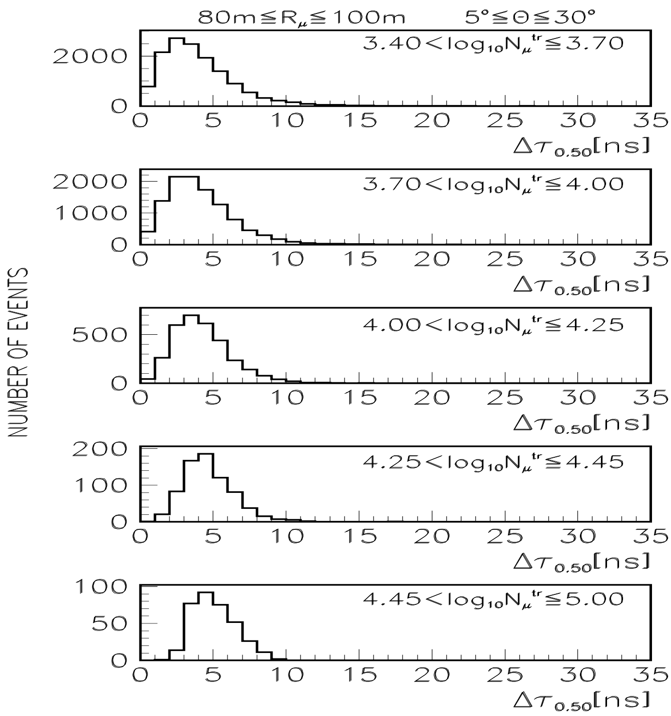

Fig. 3: *The distribution of the median values of the muon arrival time distributions observed for different $log_{10}N_\mu^{tr}$ ranges in a particular interval of the distance from the shower center.*

foremost muon, registered in the timing detector at a particular distance from the center R_μ, defined in a plane perpendicular to the shower axis:

$$\Delta\tau_\mu = T_\mu(R_\mu) - T^1_\mu(R_\mu) \; .$$

We characterize the single local arrival time distribution by different moments: the median $\Delta\tau_{0.50}$, the 1^{st} and the 3^{rd} quartile ($\Delta\tau_{0.25}$ and $\Delta\tau_{0.75}$) which pronounce different features of the $\Delta\tau_\mu$ distributions. In order to suppress faked muons from hadron events (in particular present at small R_μ) a condition of an energy deposit in the scintillator detectors $E_{dep} < 20\ MeV$ has been applied.

The EAS muon shower profile and disc thickness.

We consider the muon arrival time distributions in different intervals of the core distance $R_\mu = 10-20\ m, 20-30\ m, \ldots$ up to $130\ m$, (in some cases, with larger bins for sake of statistical accuracy), for different ranges of zenith angles and for 5 ranges of $log_{10}N^{tr}_\mu$. From the local arrival time distributions determining the mean values and the standard deviations one obtains the muon shower profile and the disc thickness. Figure 1 presents the variation of the average distributions of the 1^{st} and 3^{rd} quartiles of the muon arrival time distributions with the distance from the shower core. In studies of arrival time of the charged-particle component (Woidneck 1975) a parametrization of the observed distributions by a Γ-probability function, is given by:

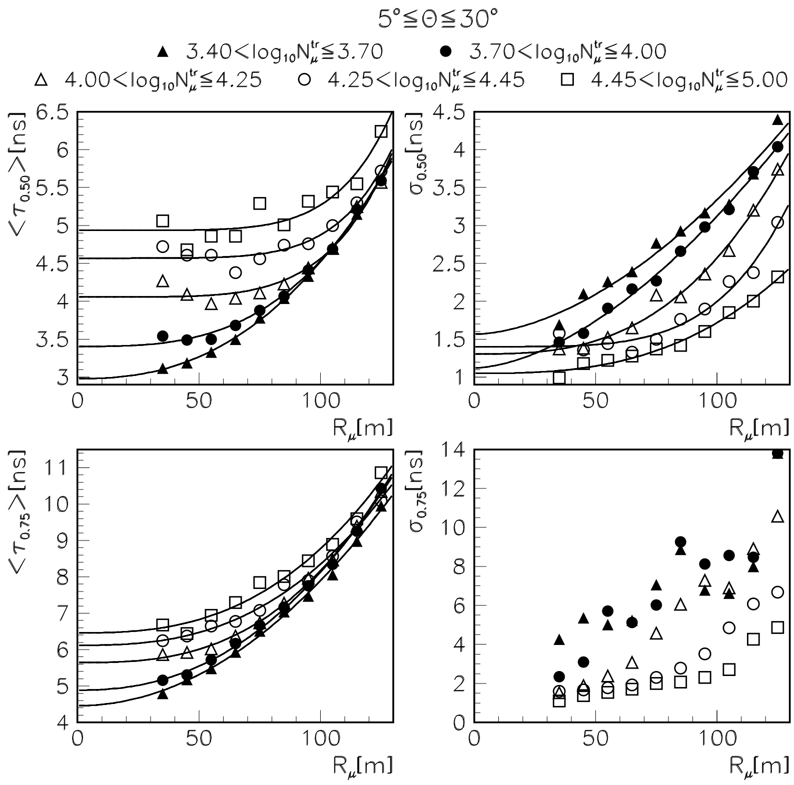

Fig. 4: *The mean values and standard deviations of the median and third quartile distributions extracted from the observed moments distributions.*

$$\Gamma(T) = aT^b exp(-cT)$$

with a mean value $< T >= (1+b)/c$ and the standard deviation $\sigma = (1+b)^{1/2}/c$

Figure 2 shows the muon shower profile and disc thickness, comparing the mean values and standard deviations extracted directly from the experimental (histograms) distributions to those from fitting first the distributions by Γ-form. Some limitations of the parametrization used are noticed, in particular for the variances, but the deviations are much smaller than that observed for the total charged particle component (Agnetta 1997). The shape of the EAS shower profiles can be approximated by a 'parabolic' form (Ambrosio 1997):

$$T(R_\mu) = t_1 + t_2(R_\mu/R_m)^\beta$$

with $R_m = 100\ m$, the scaling radius for muon lateral distribution.

The variation of muon shower profile with N_μ^{tr}.

Monte-Carlo simulations prove that for the KASCADE observation condition $log_{10}N_\mu^{tr}$ is approximately proportional to $log_{10}E_0$ and to be independent from the primary mass. We use an EAS classification by N_μ^{tr}, as an approximate energy classification, (Weber 1997) instead of by the shower sizes N_e, which would prepare samples of mixed primary energies, dominated by large fluctuations of proton induced showers (Haungs 1998). As an example Figure 3 displays the dependence of the distribution of median values of muon arrival time distributions from $log_{10}N_\mu^{tr}$, for a distance of 80-100 m from the shower core. The standard deviations of the distributions decrease with increasing primary energy $E_0(N_\mu^{tr})$, as displayed in Figure 4.

Concluding remarks.

From the present analysis of the phenomenological features of temporal structure of the muon component ($E_\mu \geq 2\ GeV$) we conclude: 1) the EAS muon disc can be characterized by the R_μ-dependence of various different moments ($\Delta\tau$, $\Delta\tau_{0.25}$, $\Delta\tau_{0.50}$, $\Delta\tau_{0.75}$); 2) the general shape of the moment distributions can be well parameterized by Γ-probability distribution function; 3) the time profiles represented by the mean and the dispersion of these moment distributions can be approximated by a quasiparabolic shape in an R_μ range up to 130 m; 4) considering the results for 5 different N_μ^{tr} values corresponding to different primary energies under and above the knee position the mean values of the muon arrival times do increase with larger N_μ^{tr}, but the disc thickness, represented by the standard deviations, decreases for larger sizes, indicating that the fluctuations get smaller for higher primary energies, particularly pronounced for the 3^{rd} quartile and possibly indicating that in the energy range after the knee the contribution of the heavy component is increasing.

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