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The influence of the detector system on the measurements of muon arrival times in Extensive Air Showers (EAS)

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Abstract. Arrival time distributions of EAS muons carry information about the production profile of the EAS muonic component. The measured distributions are affected and distorted by various interwoven effects which arise from the time resolution of the timing detectors, from fluctuations of the reference time and the number of detected muons spanning the arrival time distribution of a single EAS event. The origin of these effects is discussed and correction procedures which involve detailed simulations are proposed.

1 Introduction

The temporal structure of the EAS muon component reflects the longitudinal EAS profile, and muon arrival time distributions map the distribution of the muon production heights, in particular, when observed at large distances from the shower axis. Thus muon arrival time distributions should carry some information on the mass of the EAS primaries, unless the intrinsic fluctuations of the muon generation processes and limitations of the detector response do obscure the discriminating features. In fact, experimental muon arrival time distributions have experienced various intriguing distortions which depend not only on the time resolution of the timing detectors, but also on the observed muon multiplicity, i.e. on the number n of registered muons spanning the arrival time distribution of the particular EAS event. Measurements of muon arrival time distributions, correlated with other EAS parameters are a current subject of the KASCADE experiment (Brancus et al., 1998; Antoni et al., 2001; Haeusler, 2000; Badea, 2001).

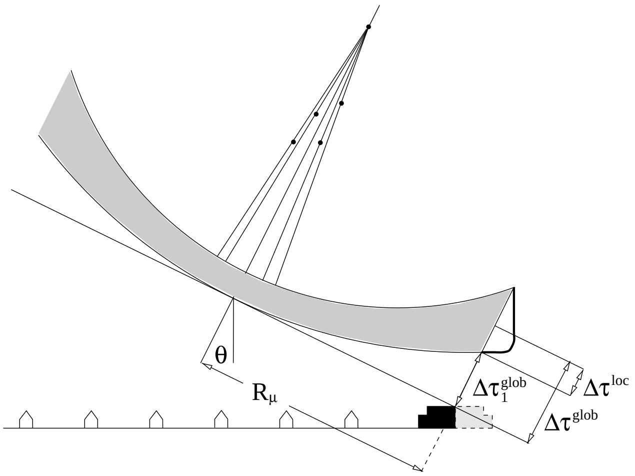

Fig. 1. Characterisation of the EAS temporal structure by global and local arrival times.

In this context we study muon multiplicity effects, entangled with the response and time resolution of the apparatus and demonstrate procedures, used to reveal from measured data the basic time structure of the observed EAS.

Arrival times of muons, registered by the timing detectors at a certain distance R_μ (in the shower plane) from the shower axis refer to a defined zero time (Fig. 1). For the reference zero the arrival time τ_c of the shower centre could be

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used (global arrival times). However, there are often difficulties to reconstruct this time with sufficient accuracy. Hence alternatively local arrival times are considered which refer to the arrival time of the foremost muon, registered locally. In event-by-event observations the single EAS relative arrival time distributions can be characterised by mean values $\Delta\tau_{mean}$ and by various quartiles like the median $\Delta\tau_{0.5}$, the first and the third quartiles $\Delta\tau_{0.25}$ and $\Delta\tau_{0.75}$, which pronounce different features of the single distributions. The variation of the distributions of these quartiles, in particular of their mean values and variances, with the distance R_μ from the shower centre, is called the EAS time profile. In case of global time parameters it informs about the curvature of the shower disk and the shower thickness, while local quantities characterise only the structure of the shower thickness. The following discussion is mainly focused on the implications of observations of local time quantities.

2 Fluctuations of the arrival time of the foremost muon

Following the considerations of (Villiers et al., 1986) it can be argued that the arrival time $\Delta\tau_1$ of the foremost muon (relative to a fictitious zero time, representing the muon front, approximated by a sample with a large number n of muons), its expectation value and fluctuations depend on the particular value of the multiplicity n. Fig. 2 shows muon arrival time distributions accumulated from many showers with the expectation values $\langle\Delta\tau_1(n)\rangle$ of the arrival time of the foremost muon for subsamples of different multiplicities.

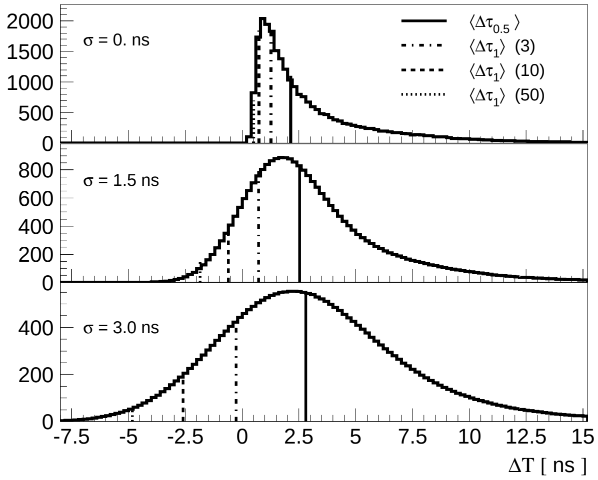

Fig. 2. Muon arrival time distributions $\tau_1(n) - \tau_c$ with the multiplicity dependence of $\langle\Delta\tau_1(n)\rangle$ and the influence of the time resolution. The shown distributions stem from the accumulation of 100 simulated Fe and 100 simulated proton induced EAS (zenith angle of incidence 0°) of $3 \cdot 10^{15}$ eV, observed in the range $70\,\mathrm{m} \leq R_\mu < 80\,\mathrm{m}$.

With increasing n and in the case of infinite time resolution ($\sigma = 0$ ns) of the timing detector $\langle\Delta\tau_1(n)\rangle$ approaches the fictitious arrival time of the shower front (which appears for small R_μ and the infinite time resolution near τ_c). In addition to the fluctuations of the arrival times of the first muon due to the registered multiplicity (which in reality involves also the influence of the detector response) there is the influence of the finite time resolution. It broadens the observed distributions and smears out the original asymmetry. As an example also the expectation for the (global) median $\langle\Delta\tau_{0.5}\rangle$ is shown. The averaged global median does not depend much on the time resolution. In contrast the local quantities underly the trends of $\langle\Delta\tau_1(n)\rangle$, i.e they increase with the multiplicity and with the time resolution. These features are illustrated in Fig. 3 and lead to local shower profiles which are distinctly influenced by the detector qualities (time resolution and response for the muon multiplicity).

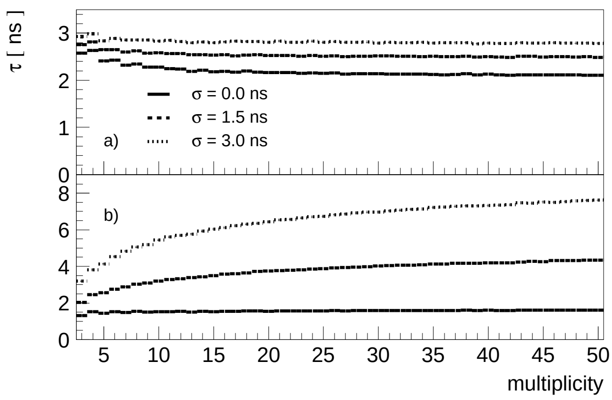

Fig. 3. Multiplicity and time resolution dependence for the mean values of global a) and local b) time parameters of single muon arrival time distributions.

The influence is very pronounced in the central region with the largest multiplicities. As displayed in Fig. 4 for different primary energies and proton and iron showers, the profiles approach the ideal case at larger distances from the core (> approx. 250 m), where the time resolution gets less important, but features discriminating different primaries in global profiles are disappearing (Brancus et al., 2001).

3 How to account for muon multiplicity effects

In actual experimental observations of muon arrival time distributions like in the KASCADE experiment the profiles are derived from EAS events, including all different multiplicities (n > n_s), as registered by the timing detectors. Due to the lateral distribution of the EAS muon component the average (registered) multiplicities in an EAS are depending on R_μ. They depend also on the type and energy of the primary, and even if the energy is approximately specified, the

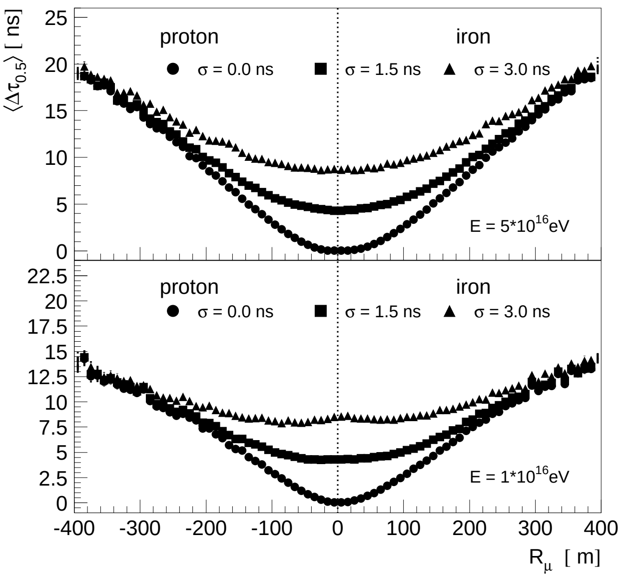

Fig. 4. Local time profiles of proton and iron induced EAS for different primary energies and different time resolution, virtually registered with a detector eye of 400 detectors of 0.5 m^2 (approximately like the timing facility of the KASCASDE central detector).

observed time profiles originate from a superposition of various multiplicities, varying with the distance from the shower core. That feature leads to interference effects, distorting the predicted quasi-parabolic shape of the time profile. Fig. 5, which displays measured EAS time profiles (Brancus et al., 1998), exhibits this effect.

In principle, it would be desirable to extract the shower profile for each multiplicity separately. However, this attempt would meet serious problems of the statistical accuracy of the results. The main problem, however is that the appearance of the distortions depends on the response qualities of the particular detector arrangement, so that measurements by different detectors are hardly directly comparable. There are various ways to approach a representative result about the EAS time structure from measurements of local quantities.

- The standard concept to compare experimental results with theoretical predictions are procedures simulating the experimental conditions and response folded with the predictions and comparing the resulting distributions with the measured results. This will give an impression about agreement or disagreement and on the undistorted time profiles, but does not immediately enable the comparison with other experiments of different (often unknown) quality and conditions.
- The measured time parameters, deduced for each event from the single muon arrival time distributions registered with varying multiplicity, get scaled to a chosen reference value of the multiplicity by a correction according to predictions by simulation calculations (indicated for the case of the mean value $\Delta\tau_{mean}$ by a calibration curve in Fig. 3). The appearance of time profiles depends on the choice of the reference multiplicity. The correction procedure needs detailed simulation calculations of muon arrival time distributions of the kind shown in Fig. 2. The procedure has been successfully applied in recent KASCADE experiments (Antoni et al., 2001; Haeusler, 2000).
- The observation that for global time quantities the influences of the multiplicity and the time resolution are less pronounced, suggests to relate the muon arrival times to the arrival time of the shower centre by simulating the time difference between the arrival time τ_1 of the local foremost muon and the arrival τ_c of the EAS core. In this way (Badea, 2001) the local quantities are transformed into pseudo-global time parameters, which display the EAS time structure rather realistically, but invoke EAS simulations, specified in detail. While only the shape of the arrival time distributions enters in the above multiplicity calibration procedure, the transformation to pseudo-global quantities stresses also the absolute time difference $\tau_1 - \tau_c$.

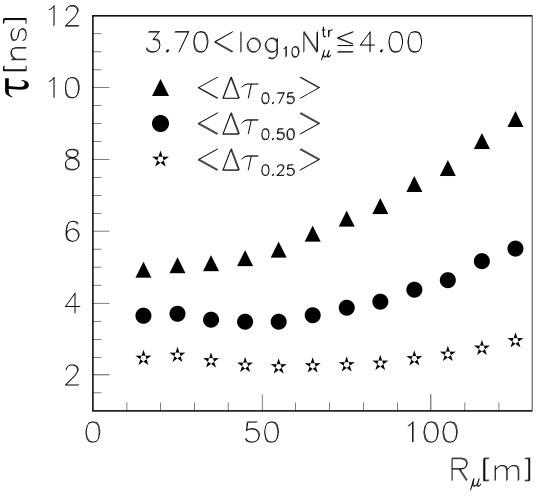

Fig. 5. The variation of the mean values of the median, first and third quartile distributions with the distance from the shower axis, extracted without multiplicity correction for an EAS sample within a particular range of $\log_{10} N_\mu^{tr}$ (indicating the primary energy range of approx. $1.6 \cdot 10^{15}$ eV to $3.2 \cdot 10^{15}$ eV) (Brancus et al., 1998).

Finally Fig. 6 presents a result of an experimental investigation (Haeusler, 2000) of EAS time profiles using the KASCADE detector. For different ranges of the truncated muon number N_μ^{tr} (used as approximate energy estimator) and with a consistent correction for the multiplicity dependence, the experimental results are compared with CORSIKA (Heck et

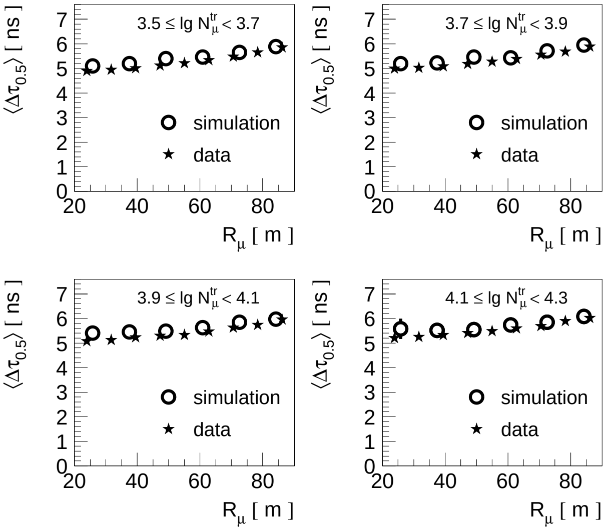

Fig. 6. Local EAS shower profiles ($\langle \Delta\tau_{0.5} \rangle$), corrected for the multiplicity dependence, as compared with predictions of EAS simulations using the Monte Carlo code CORSIKA (Heck et al., 1998), for different EAS muon sizes (corresponding to an energy range from $6 \cdot 10^{14}$ eV to $6.3 \cdot 10^{15}$ eV).

al., 1998) simulations, adopting a mass composition p:O:Fe = 1:1:1.

4 Conclusions

Measured muon arrival time distributions which refer to the arrival time τ_1 of the first locally registered muon, experience some distortions which arise from the superposition of different muon multiplicities spanning the observed distributions, entangled in an intricate way with the response of the experimental detector set-up. There are various procedures to correct for such effects and to display the measured results for a sensible comparison with theoretical predictions or other experiments. The procedures, weakly dependent on the used interaction model and adopted mass composition, invoke explicitely EAS Monte Carlo simulations.

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