



Time structure of the EAS electron and muon components measured by the KASCADE–Grande experiment

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Abstract

Extensive air showers measured by the KASCADE–Grande experiment at the Forschungszentrum Karlsruhe are studied with respect to the arrival times of electrons and muons at observation level. The mean and the spread of the arrival time distributions have been used to determine the average time profile of the electromagnetic and muonic shower disk. For core distances $R > 200$ m particles of the muonic shower component arrive on average earlier at observation level than particles of the electromagnetic shower component. The difference increases with the core distance from $\Delta\langle t \rangle = (12.9 \pm 0.2)$ ns at $R > 200$ m to $\Delta\langle t \rangle = (47 \pm 1)$ ns at $R = 500$ m, where the width of the muonic and electromagnetic shower disks are comparable. This difference in arrival time is used to separate the electrons and muons dependent on the distance from the shower center. This is intended to be used by experiments with time resolving detectors.

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1. Introduction

High energy cosmic particles can be studied by analyzing the extensive air showers (EAS) of secondary particles they generate in the atmosphere. These EAS can be measured by sampling the shower disk of particles at ground level with detector arrays. The number of muons is an important ingredient for the reconstruction of the energy and identity of the primary particle.

Most often the measurement of muons requires the operation of dedicated μ -detectors. This increases the number of detectors of an EAS array. Furthermore, the μ -detectors have to be shielded against the electromagnetic shower component in order to measure the number of muons with high purity. Therefore, the use of dedicated μ -detectors is cost intensive for large detector arrays. Modern EAS detector arrays, however, are equipped with fast time resolving electronics to sample the time development of the detector responses which offers an alternative method to determine the muon content of EAS. The different development of the electromagnetic and the muonic component of EAS causes a difference in the arrival times of electrons and muons at the observation level. Therefore, an alternative to the use of dedicated muon detectors is the separation of the muon and electromagnetic components by an adequate cut on the particle arrival time.

Differences in the shower development of the electromagnetic shower component and the muonic shower component lead to an arrival time difference between electrons and muons at the observation level. Muons are on average produced higher in the atmosphere and scatter far less than electrons do. Their paths to the ground are nearly straight lines. The electromagnetic particles are on average produced deeper in the atmosphere and close to the shower axis. They reach the observation point by multiple scattering creating longer path lengths and thus longer times of flight. In addition, the average kinetic energy of the electromagnetic particles is smaller than the kinetic energy of the muons. The resulting effect of the different development is that muons arrive earlier at the observation level than particles of the electromagnetic shower component [1–5]. The difference in the arrival time increases with the radial distance from the shower core. Numerous experiments have studied the particle arrival time distributions but being limited to either small core distances, e.g. KASCADE [6,7], GREX/COVER_PLASTEX [8], AKENO [9,10], or small statistics, e.g. MSU EAS Array [11], Vulcano Ranch [12] or Yakutsk [13]. The development of the shower components and its effect onto the particle arrival times have been studied theoretically by means of calculations and simulations (e.g. [3,14–16] and references therein) most recently based on the Monte Carlo program CORSIKA [17] or AIRES [18].

This paper extends the results of differences of the mean arrival times of the electronic and muonic EAS components, observed by KASCADE [4] to larger distances from the shower axis, and for a lower muon energy threshold. The time structure of the EAS disk is analysed separately

for the electromagnetic and the muonic component up to core distances of $R = 600$ m. A Flash-ADC (FADC) based data acquisition (DAQ) system installed in eight stations of the detector array of KASCADE samples detector signals of the e/γ - and the μ -detectors, respectively. Global shower parameters are reconstructed from data of the Grande array of KASCADE–Grande. The arrival times of the shower particles are extracted from the detector signals using an unfolding algorithm. The results show the expected earlier arrival of muons at the observation level. In Section 2 the experimental setup of the KASCADE–Grande experiment will be explained. Section 3 gives a description of the observables used in the analysis and an outline of the analysis procedure. In Section 4 the time profiles of the electromagnetic and muonic shower disks obtained from the unfolding of the detector signals are presented and compared with predictions according to Ref. [10].

2. The Grande array and the timing facility of KASCADE–Grande

The KASCADE–Grande experiment [19] measures EAS initiated by primary cosmic ray particles with energies between 100 TeV and 1 EeV. It consists of the original KASCADE [20] (KARlsruhe Shower Core and Array DEtector) experiment, the Piccolo trigger array and the Grande detector array. A schematic overview of the KASCADE–Grande experiment and its subdetectors is depicted in Fig. 1.

The KASCADE experiment is itself made up by subdetectors. Its main part consists of a 200×200 m² sized detector array of 252 scintillator stations arranged on a grid with 13 m spacing. The KASCADE array consists of 4 inner and 12 outer clusters of 15 or 16 detector stations, respectively. Stations of the inner clusters contain scintillation detectors for the electromagnetic shower component, only. Stations of the outer clusters contain scintillation detectors for the electromagnetic and the muonic shower component. The μ -detectors are shielded with 10 cm lead and 4 cm iron against the electromagnetic shower component. The shielding corresponds to an energy threshold of $E_{\text{kin}} = 230$ MeV for vertical muons.

The Grande array consists of 37 scintillation detector stations distributed over an area of 700×700 m² with an average spacing of 137 m. Each station has a sensitive area of 10 m² and measures the charged component of EAS.

The time measurement of KASCADE–Grande is based on two clocks common to all subdetectors provided by a clock generator generating time stamps for each event. The first clock is a 1 Hz clock (GT: Global Time), the second one a 5 MHz clock (TL: Time Label) dividing each second into 200 ns bins. While the counters for the 1 Hz clock cycles run steadily the clock counters for the 5 MHz clock cycles are being reset every second by the 1 Hz clock signal.

The important time resolving detector part for the present analysis is the FADC system [21] of the KASCADE

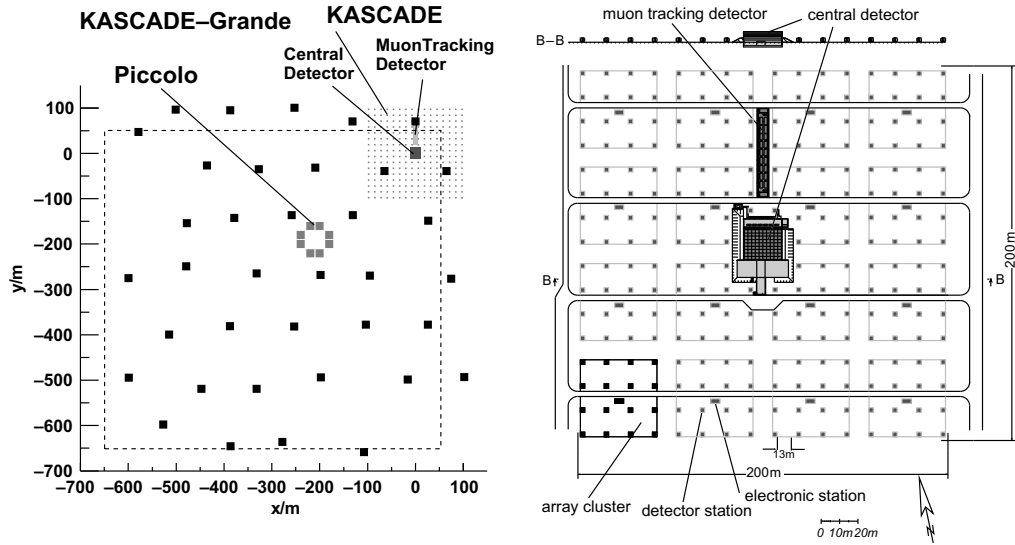


Fig. 1. (Left) Schematic top view of the KASCADE-Grande experiment [19]. The dashed square indicates the fiducial area used for this analysis. (Right) The KASCADE experiment and its subdetectors [20]. The figure also shows the organization of the KASCADE array into 16 clusters of 16 or 15 stations. The highlighted lower left cluster is cluster 1, where the FADC system is installed.

array. It samples the full pulse shapes produced by the photomultiplier tubes attached to the scintillators of the KASCADE detector array. The FADC system consists of 16 FADC-modules, each with a sampling frequency of 1 GHz and 8 bit resolution. The 16 modules are installed in eight detector stations in cluster 1 of the KASCADE detector array (Fig. 2, see also Fig. 1). Since one FADC module (station 16) was found to not operate properly only the data from seven FADC modules are used in the analysis. In each of the detector stations the analog sum signals of both the e/γ - and the μ -detector are sampled separately by the FADC-system.

The photomultipliers (PMTs) of the KASCADE detectors are connected to the input of discriminators in the electronics station belonging to each array cluster. In case the

photomultiplier signal exceeds an adjustable threshold a logic signal is generated which starts a TDC with a precision better than 1 ns. The next signal from the experiment's common 5 MHz clock stops the TDC. The TDC value is converted into nanoseconds and represents in first approximation the time between the detection of the first particle of the shower front in the detector and the 5 MHz clock. Thus the global time of the transition of the first particle through the detector is known with a precision of 1 ns.

In the case of the Grande array the photomultipliers are connected to discriminators in the Grande detector stations. If the signal exceeds the threshold of an individual station a trigger signal is produced by the discriminators and sent to the central data acquisition station of the Grande array. In this station a 128 channel multi-hit

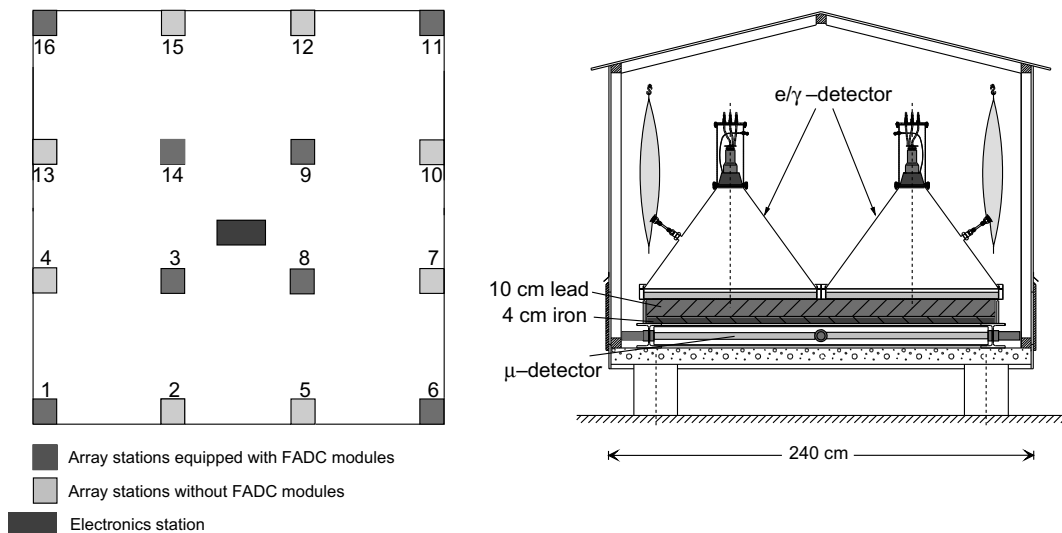


Fig. 2. (Left) Distribution of KASCADE array stations equipped with FADC modules in cluster 1. The numbering scheme of the stations within the cluster is also shown. (Right) Schematic view of a sample array detector station.

TDC with 0.8 ns resolution stores the arrival time of this first trigger signal. The TDC is stopped by the trigger signal of each further station exceeding the threshold. Up to January 2005 the measured arrival times had no connection to the TL or the GT and only relative times between the station events were measured. Since then an additional TDC channel measures the times of the 5 MHz clock signal ($t_{\text{TDC}}^{\text{TL}}$). In this way the time difference between the arrival times of the trigger signals at the TDC and the 5 MHz clock is known which allows also in case of the Grande array to calculate the global time of each detector event.

3. General procedures

3.1. Definition of observables

The characteristics of EAS are defined as shown in Fig. 3. The shower axis corresponds to the trajectory of the incident primary cosmic ray particle extrapolated towards the observation level. The shower plane is the plane perpendicular to the shower axis with R as the radial distance from the shower core. The shower disk refers to the curved disk of secondary shower particles propagating towards earth. Two shower fronts are expected, one of the electromagnetic particles and the other from the muons.

3.2. Measurements and shower reconstruction

As a first step global shower parameters are reconstructed from the raw data of the 37 detector stations of the Grande array [22,23]. The used parameters for the present analysis are the position and arrival time of the shower core, the arrival direction, the shower age, and the shower size.

The modules of the KASCADE Flash-ADC system are being operated in ring-buffer mode. They digitize the detector signals continuously until they are stopped by an external trigger signal provided by KASCADE–Grande. Each

FADC module stores 8 μs of the sampled detector signals. In order to decrease the amount of data permanently the FADC data is processed in order to perform a zero suppression. This is achieved by looking for particle signals in the buffered FADC data. The beginning of a signal is defined as two adjacent samples above a threshold signal height $h = \mu + 3 \times \sigma$ in units of FADC channels. The threshold is determined for each module at each run start from the data of the first 20 events. Here μ denotes the mean value of all samples of the first 20 events, and σ the corresponding standard deviation. When a signal is found by the DAQ software it is stored together with 100 leading and trailing pedestal samples.

To smooth signal deformations caused by random noise and characteristics of the electronics, the FADC signals are processed with a median filter. Furthermore, for each signal a pedestal estimation is performed using its first 80 time bins. The mean value of these 80 bins is taken as pedestal of the corresponding signal and is subtracted from the full signal. Fig. 4 shows as an example FADC signals after the application of the filter and the pedestal correction.

3.3. Synchronization of the KASCADE and the Grande array

The analysis presented in this paper aims at analyzing particle arrival time distributions especially for larger distances from the shower axis. Therefore, the showers measured by the Grande array are of special interest. These showers require a coincident measurement of the KASCADE and the Grande array. Both detector arrays can be thought of as two separate experiments running in parallel. A joint analysis of arrival times, using the data of both arrays, requires their time synchronization.

In order to find the time offset between both arrays regular EAS data has been used. A subsample of nearly vertical EAS was selected which contains EAS having the maximum energy deposit measured in Grande station 7

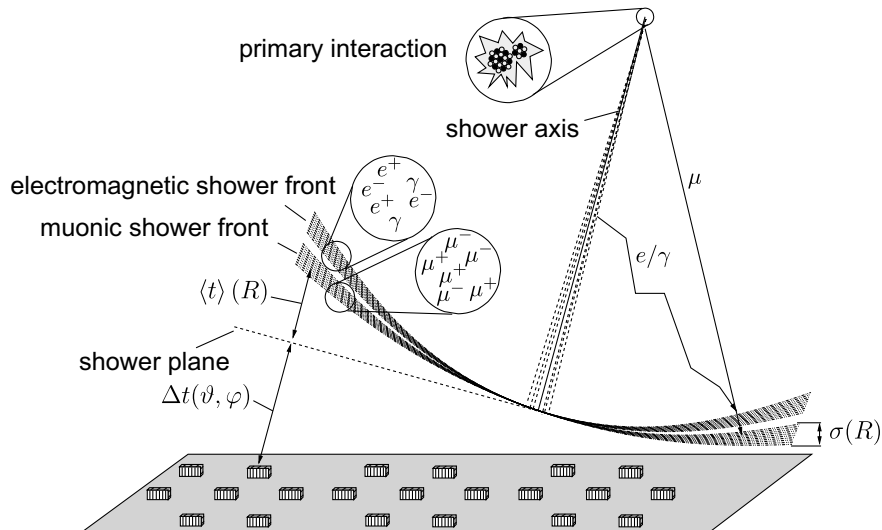


Fig. 3. Scheme of the shower development in the atmosphere (see text for details).

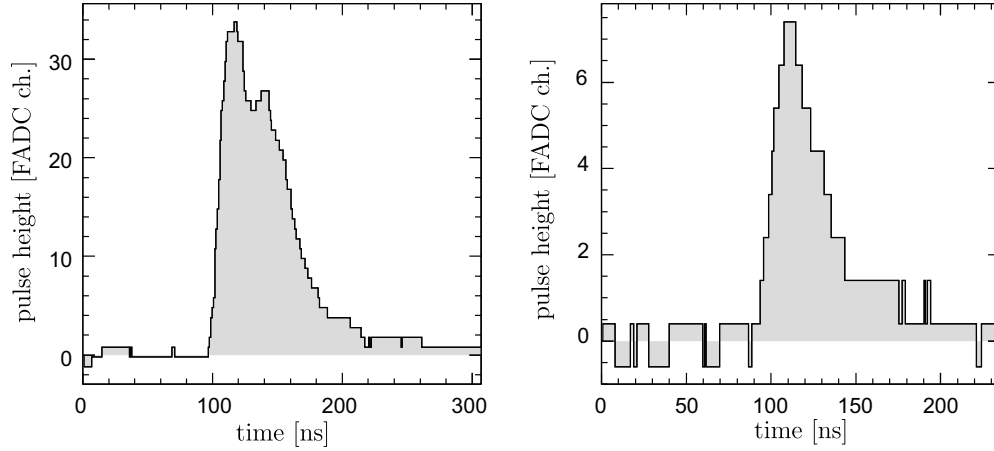


Fig. 4. Examples of filtered FADC signals with subtracted pedestal for a single event. (Left) processed detector signal of the e/γ -detector. (Right) processed detector signal of the μ -detector.

indicating that the shower core is close to this station. This station is located inside the KASCADE array and surrounded by four KASCADE detector stations. The measured arrival times of the shower plane calculated separately in the KASCADE time reference system and in the Grande time reference system are subtracted from each other in order to determine the relative time shift Δt_{Offset} between the arrays. This time shift stems from signal propagation delays of the trigger and clock signal distribution. In order to minimize contributing arrival time differences between the detectors caused by shower inclination the arrival times of the shower plane measured by the four KASCADE detector stations are averaged beforehand.

Deficiencies in the measurement of the TDC value of the 5 MHz clock cycle belonging to the Grande event time label (see Section 2) cause that under certain conditions one 5 MHz clock cycle is blocked at the input of the TDC. In these cases the offset between both arrays is underestimated by 200 ns. This effect is depicted on the left hand side of Fig. 5. The offset has been calculated separately between both detector types (μ and e/γ) of the KAS-

CADE array and the Grande array. It is however possible to decide on a shower-to-shower basis which offset should be used in order to synchronize both arrays. The offset distributions cover only a certain range of measured TDC values as shown on the right hand side of Fig. 5. The measured TDC value $t_{\text{TDC}}^{\text{TL}}$ of a specific shower can therefore be used to judge which offset has to be used. Showers for which the TDC value $t_{\text{TDC}}^{\text{TL}}$ lies within the region of TDC values where both offset distributions overlap cannot be used. In this region the assignment of the correct offset value is ambiguous. The offset values are extracted as the mean value of a Gaussian fitted to the peaks of the distributions.

3.4. Extracting particle arrival times from FADC signals via deconvolution

A measured FADC signal pulse $S(t)$ is described by a convolution of the true arrival time distribution $T(t)$ and the single particle system response $S_1(t)$

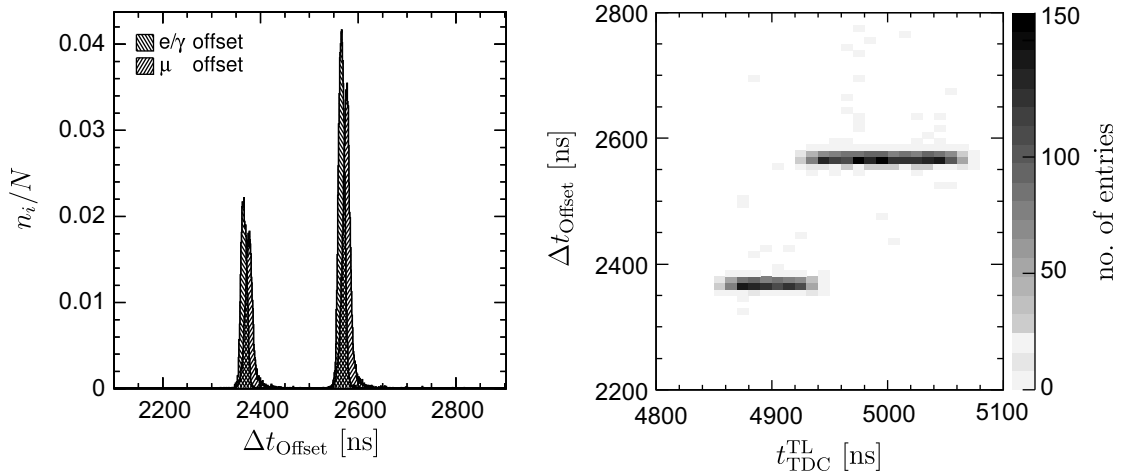


Fig. 5. (Left) Distributions of the time offsets between the Grande and the e/γ - and μ -detector of the KASCADE array. For comparison the bin contents n_i of the distributions were normalized by the total number of entries N . (Right) Offset value Δt_{Offset} vs. TDC measurement $t_{\text{TDC}}^{\text{TL}}$.

$$S(t) = \int_0^t T(t') S_1(t - t') dt'. \quad (1)$$

If the response $S_1(t)$ is known, it is possible to apply an unfolding algorithm to extract the true arrival time distribution $T(t)$ from the measured signal pulse. In order to process discrete or binned data, the integral equation is approximated by a matrix equation with the integral replaced by a sum over all bins and the signal $S(t)$ and the time distribution $T(t)$ rewritten as data vectors $\vec{s}$ and $\vec{t}$ resulting in the equivalent formula

$$\vec{s} = R\vec{t}. \quad (2)$$

Herein R denotes the response of the detection system in matrix representation. Its columns are defined by the single particle detector response in vector representation $\vec{s}_i$.

An adequate unfolding method to solve this equation is the Gold algorithm [24]. The iteration equation of the Gold algorithm is given by

$$t_i^{k+1} = \frac{t_i^k}{\sum_{j=1}^N R_{ij} t_j^k} \times s_i. \quad (3)$$

The initial guess of the solution vector $\vec{t}$ is improved step-by-step that it approaches the measured data $\vec{s}$ when being multiplied with the detector response matrix R . As seen in Eq. (3), the solution is positive for positive measurements s_i . For this reason and because the algorithm is fast as well, the Gold algorithm is chosen to unfold the PMT signals sampled by the KASCADE FADC system. For the application of the Gold algorithm on FADC signal pulses, the elements of the solution t_i^k represent the elements t_i of the reconstructed particle arrival time distribution $T_{\text{rec}}(t)$ obtained after k iterations.

A mandatory input for the deconvolution is the detector response matrix R . It has to be constructed from the single particle detector response signal $S_1(t)$, in the following referred to as average minimum ionizing particle (MIP) detector response. Since two types of detectors are being read out by the FADC system, two separate average MIP detector responses, one for the e/γ -detectors and one for the μ -detectors, have to be determined. The detector response is not a constant function which can be determined a priori. It varies during normal operation of the experiment due to changing run conditions like temperature, variations in voltage supply, etc. Therefore, it has to be measured as an average detector signal pulse of many single particle signal pulses recorded during the regular operation of the experiment.

In order to determine the average MIP detector response of the e/γ -detector and μ -detector, only e/γ - or μ -signals were used which have been measured by detector stations with at least $R = 400$ m or $R = 200$ m distance to the shower core, respectively. Here, the density of the corresponding particle type reaches one particle per m^2 or even less. In this way the use of signals from multi-particle detections is minimized. In order to prevent a broadening of the

average MIP detector response, it is necessary to match the leading edges of the contributing signal pulses. In each signal pulse, the point on the leading edge is determined where the signal pulse height reaches half of the maximum amplitude with respect to the pedestal. The FADC signal pulses are then summed with respect to this point.

The path length of a particle traversing the scintillator is minimal for vertical particles and increases by the geometric factor $(\cos \vartheta_P)^{-1}$. The inclination angle ϑ_P is not measured separately for each individual particle by KASCADE-Grande. In a first order approximation the particle's inclination angle ϑ_P coincides with the inclination ϑ of the EAS. Hence, to account for the change in path length within the scintillator material and the related increase in energy deposit, each signal pulse is scaled by the factor $\cos \vartheta$ before it enters the average MIP detector response in order to cancel the effect of the inclination. The resulting average MIP detector responses of the e/γ - and μ -detector are shown in Fig. 6. The average MIP μ -detector response shows a bump on the right hand side of its peak. Its origin is unknown but signal reflections at cable connections or a ringing of the PMTs are possible sources.

The last important input for the unfolding is the number of iterations which has to be used to achieve a solution of high quality. Therefore, a subsample of FADC signals is unfolded and an overall particle arrival time distribution is generated by summing up all solutions. Characteristics of this distribution are compared as a function of the number of iterations used for the unfolding. It turns out that increasing the number of iterations beyond 600 has no effect on the characteristics of the overall distribution, and therefore, the number is set to 600.

For each FADC signal pulse to be unfolded a dedicated response matrix is generated. Since the average MIP detector response corresponds to vertical particles, it is scaled by $(\cos \vartheta)^{-1}$ before it is filled into the matrix to account for the effective increase in detector thickness for inclined particle tracks. In addition, it is scaled by a calibration factor to adjust the average MIP detector response to the actual performance of the detector which provided the FADC signal pulse. The calibration factor is calculated as the ratio of the actual run specific detector gain and the detector gain averaged over all runs. To exploit the full resolution achievable by this method, rounding to integer particle numbers is avoided at the unfolding. It was found that the mean arrival times do not change by allowing only integer numbers, but the distributions are distorted.

In Fig. 7 example signal pulses are shown together with the corresponding particle arrival time distribution resulting from the deconvolution of these signal pulses.

3.5. Corrections

The particle arrival time distributions resulting from unfolding the single FADC signals are used to generate overall arrival time distributions for various intervals of

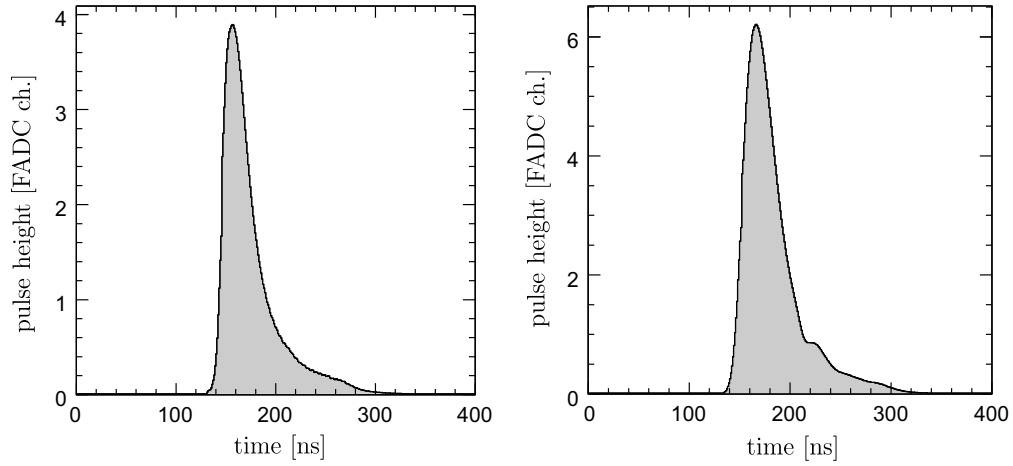


Fig. 6. Average detector response for a single particle transition as extracted from regular EAS data. (Left) The average MIP e/γ -detector response. (Right) The average MIP μ -detector response.

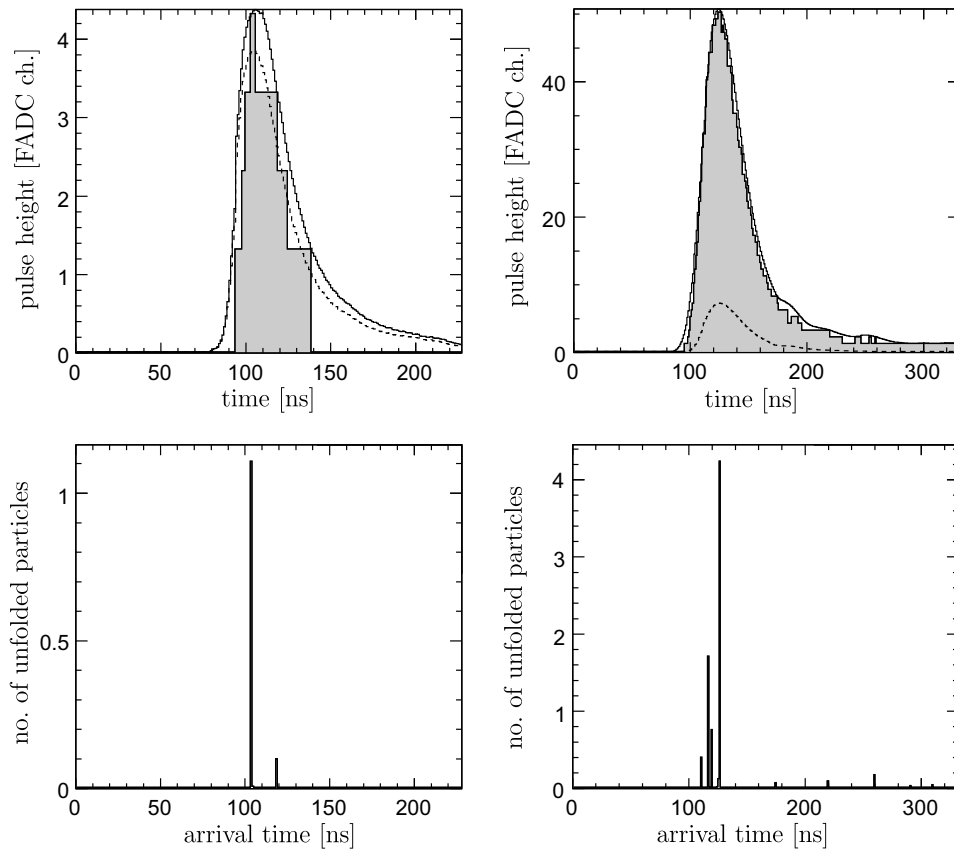


Fig. 7. Examples of unfolded FADC signal pulses. (Upper left) The histogram depicts the FADC signal pulse (from a e/γ -detector) to be unfolded. The size of the signal pulse suggests a transition of a single particle. The dashed line corresponds to the average MIP detector response, which was used to generate the response matrix. The continuous line represents the forward folded solution which is the product of the unfolded arrival time distribution and the response matrix. (Lower left) Particle arrival time distribution unfolded from the signal pulse above. (Upper right) The same as the upper left picture but with a FADC signal pulse (from a μ -detector) belonging to a multi-particle transition. (Lower right) The particle arrival time distribution calculated from the signal pulse above.

the distance to the shower core and other shower parameters. Before the single solutions are summed up they are aligned with respect to the shower plane where several steps are necessary.

First, the time information measured by the detector, i.e. the arrival time of the first particle of the shower front segment hitting the corresponding detector, is transformed into shower disk coordinates. By subtracting the recon-

structured shower core arrival time the arrival time of the first particle is referred to the shower plane. The DAQ software of the FADC system transfers also leading pedestal samples of the detector signal which represent an offset to the unfolded particle arrival times. To determine this offset, the FADC signal pulse is examined to locate the time of arrival of the first particle. A test of the search algorithm on simulated FADC signals shows a particle density dependent misidentification of this position. The deviation is parameterized as a function of the FADC pulse height. The parameterization is used to correct the reconstructed offset to be subtracted from the unfolded particle arrival times before they are filled into the distributions. The correction is in the order of 10 ns close to the shower axis and decreases with core distance.

Simulations show that there is a discrepancy between the true and the reconstructed arrival time of the shower core, due to the deviation of the parameterized shape of the shower front used in the reconstruction of the shower direction from its actual shape. This mismatch is parameterized as a function of the electron shower size. For the alignment of the unfolded particle arrival times relative to the shower plane the parameterization is used to calculate a shower dependent correction to the reconstructed shower core arrival time. This correction is added to the unfolded particle arrival times. The correction is in the order of 10 ns at all distances.

3.6. Data selection

Since EAS measured by the Grande array are studied with the FADC system which is installed in the KASCADE array, the minimum requirement for the data is, that all three subdetectors, the KASCADE array, the Grande array and the KASCADE FADC system, participated in the measurements. The data of approximately one year are analyzed. In order to ensure a high quality of the shower observables the following cuts are applied:

- A successful reconstruction of the global shower observables is required.
- The EAS has triggered at least 20 Grande detector stations. This translates into a minimum primary energy of about $E = 10^{16}$ eV. At 3×10^{16} eV the Grande array reaches full trigger and reconstruction efficiency [25].
- The reconstructed shower core coordinates are within the fiducial area.
- EAS with a zenith angle $\vartheta > 30^\circ$ are discarded from the analysis due to an increasing systematic difference between the reconstructed and the true arrival time of the shower core for larger zenith angles.
- EAS with a $t_{\text{TDC}}^{\text{TL}}$ value which does not allow an unambiguous determination of the correct time offset are not analyzed.

After applying these selection criteria a total number of 291,245 EAS remain for the analysis, comprising 829,050

FADC pulse signals from the e/γ -detector and 494,656 FADC pulse signals from the μ -detector, respectively. These pulse signals are subject to further selection criteria: Saturated and thus deformed FADC signals predominantly measured close to the shower core are excluded from the analysis by applying an upper cut on the signal amplitude at 240 FADC channels. In some cases the time information from an array detector station is missing in the data. Without this time information, the particle arrival times unfolded from a FADC signal pulse provided by this station cannot be aligned with respect to the shower plane. Therefore, FADC signal pulses are discarded if no time information is provided by the corresponding array station. In total 651,133 (78.5%) FADC signal pulses from the e/γ -detector and 359,541 (72.7%) FADC signal pulses from the μ -detector remain after application of these additional requirements.

4. Results

4.1. Particle arrival time distributions

The particle arrival time distributions are reconstructed separately for both particle types. In order to study the difference in the arrival time of the electromagnetic and muonic shower component as a function of the core distance, the particle arrival time distributions are binned in 13 unequal intervals of the core distance taking into account the decrease in statistics at larger distances. Example arrival time distributions of electrons and muons are shown in the upper part of Fig. 8 for two ranges of the core distance. Since the e/γ -detector is located above the μ -detector, it also measures passing muons which are detected by the μ -detector. Therefore, the arrival time distributions of the electromagnetic component also contain the arrival times of the muonic shower component, i.e. they represent the arrival time distributions of the total charged component. In order to correct for this contribution, the muon content has to be subtracted from the arrival time distribution of the total charged component, which can only be achieved on a statistical basis. The distribution of the muonic component is scaled down by a factor $f = A_{e/\gamma}/A_\mu = 0.4848$ before the subtraction. This factor arises from the difference between the size of the detection area of the e/γ -detector $A_{e/\gamma}$ and the μ -detector A_μ , assuming that detector area and detection efficiency are linearly correlated. In the lower part of Fig. 8 the effect of this correction on the arrival time distributions of the electromagnetic component is illustrated. The slopes of the leading edges of the arrival time distributions are slightly decreased which shifts the maxima of the distributions to larger arrival times. The correction by the μ -content is applied to the arrival time distributions of the electromagnetic component for all intervals of the core distance. Only the corrected distributions are used for further analysis.

Fig. 9 shows the corrected distributions for two ranges of the distances from the shower core, two different energy

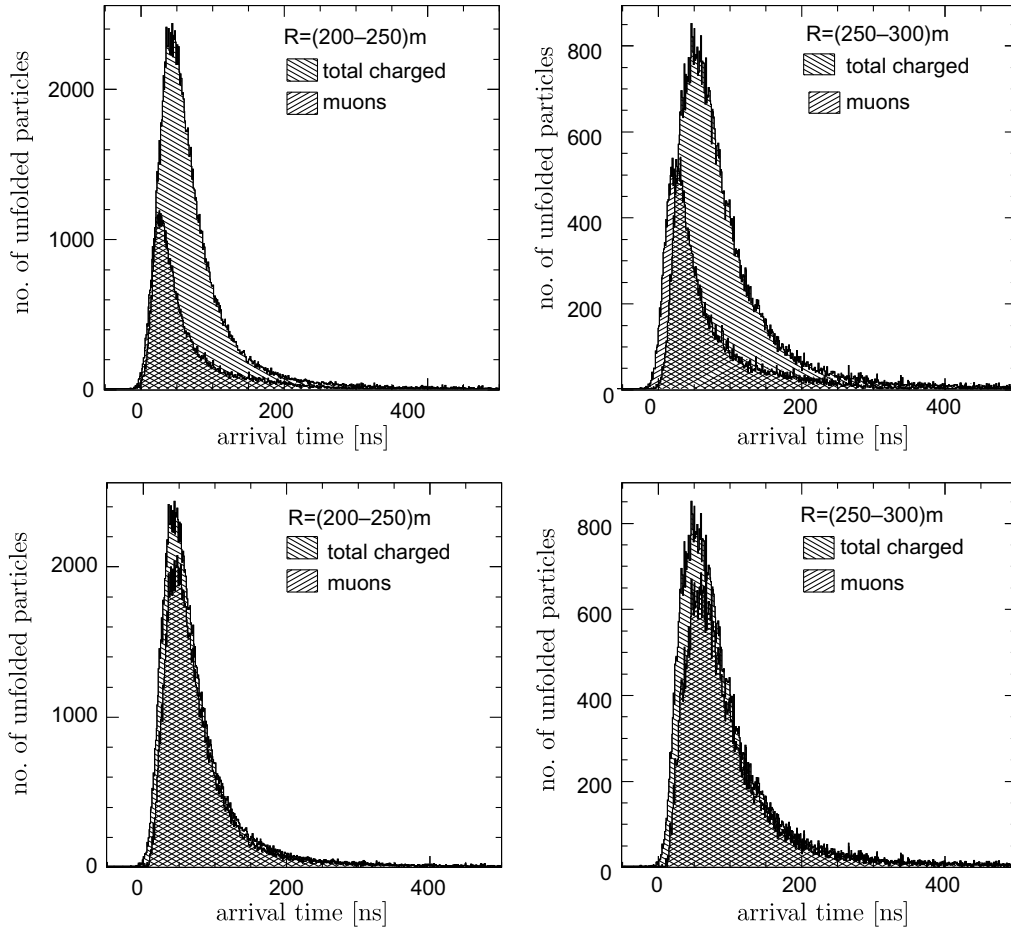


Fig. 8. (Top) Example arrival time distributions of the total charged and muonic shower component, respectively, for two intervals of the distance to the shower core. (Bottom) Illustration of the effect of the subtraction of the μ -content from the distribution of the total charged component for the same distributions.

ranges and two ranges of the zenith angle. The primary energy is coarsely estimated via the formula [23] $\log_{10}(E_{\text{est}}/\text{GeV}) = 0.313 \cdot \log_{10}N_e + 0.666 \cdot \log_{10}N_\mu + 1.24/\cos\vartheta + 0.580$, used to separate the arrival times into wide intervals over the energy range of KASCADE-Grande.

4.2. Time profiles

The particle arrival time distributions are used to reconstruct the time profiles of the electromagnetic and the muonic shower disk. In the present analysis fits to the distributions with a given function (e.g. with the often used Γ -function) are avoided due to the fact that they are not describing the distributions very well [26]. The mean arrival times for electrons $\langle t \rangle_{e/\gamma}$ and muons $\langle t \rangle_\mu$ are depicted as a function of the core distance R on the left hand side of Fig. 10. The statistical errors are the errors on the mean $\sigma/\sqrt{N-1}$, with σ being the standard deviation of the distribution and N the number of unfolded particles in the distribution. The statistical errors are smaller than 1 ns and therefore not visible in the figure. The error band depicts the overall systematic uncertainties dominated by the

unknown precision of the parameterizations of the correction to the reconstructed shower core arrival time and the correction to the reconstructed position of the first particle within the FADC pulse signals (see Section 3.5). For a conservative estimation the time profile of the shower disk was repeatedly calculated with only one correction at a time. The difference to the values with both corrections was then taken as systematic uncertainty of the corresponding correction. Furthermore, in order to check the systematic effect of the uncertainty of the average MIP detector response's amplitude all signals are unfolded with average MIP detector responses with a variation of $\pm 10\%$ in their amplitude. The difference between the resulting time profile and the unmodified values is included in the overall systematic error. Furthermore, uncertainties of the reconstructed position of the shower core propagate into the calculated particle arrival times via the transformation into shower disk coordinates. The average uncertainty of the shower core position in KASCADE-Grande amounts to about $\sigma = 8\text{ m}$ for the relevant energy range. This value is used as spread for a two-dimensional Gaussian in order to smear the reconstructed core position of an EAS before the transformation into shower disk coordinates is applied.

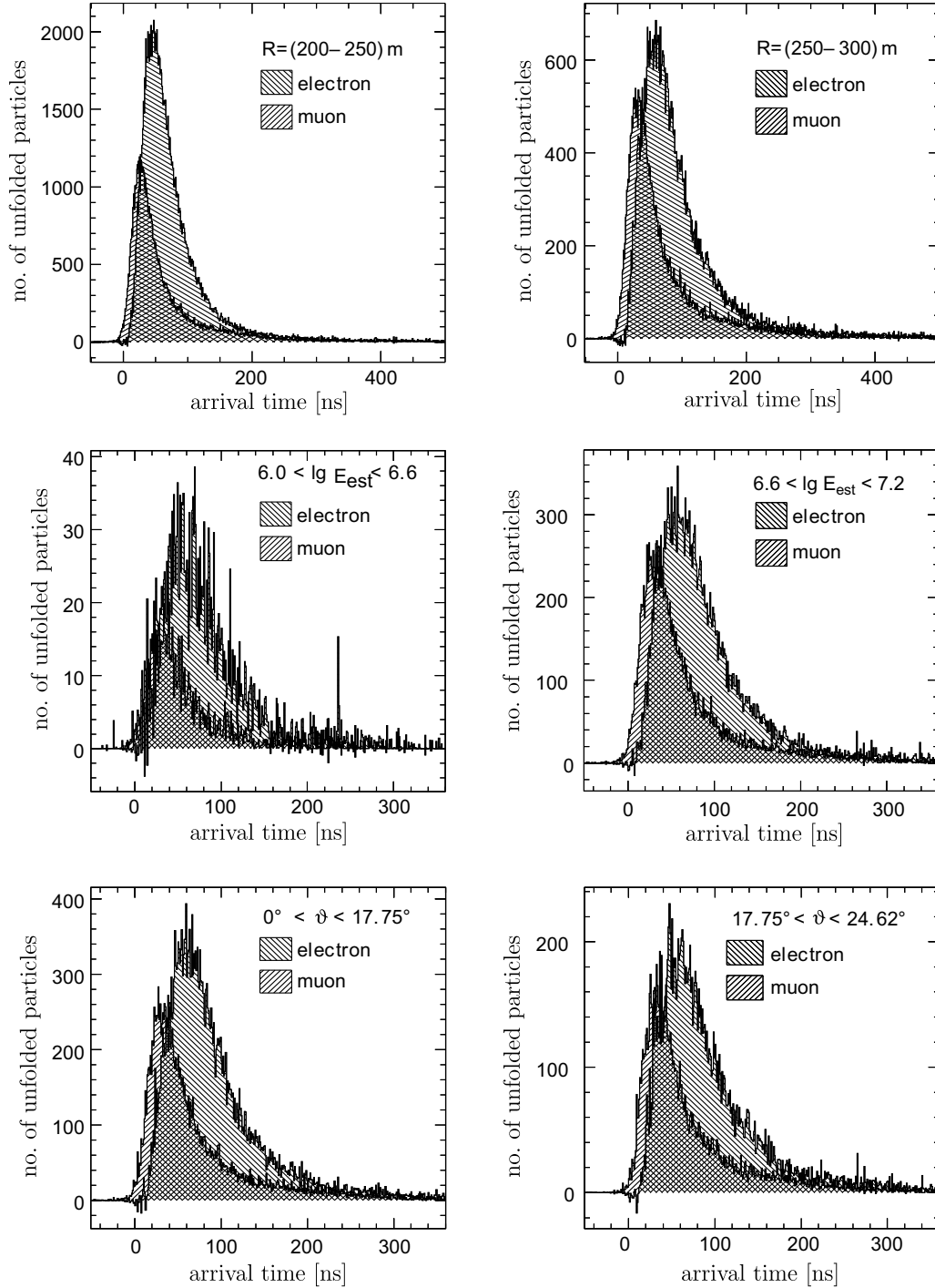


Fig. 9. Examples of particle arrival time distributions of the electromagnetic and muonic shower component. (Top) For two different ranges of the core distance. (Middle) For two energy intervals ($R = (250\text{--}300)\text{m}$). (Bottom) For two intervals of the zenith angle ($R = (250\text{--}300)\text{m}$).

The effect of this smearing onto the mean arrival times is in the order of 1 ns. Nevertheless, the original values are corrected by the deviations. All contributions to the systematic uncertainties described above are added quadratically to an overall systematic error which is in the order of 12 ns and depicted as the error band in Fig. 10.

The time profile of the shower components shows that beyond a core distance of about $R = 200 \text{ m}$ muons arrive

on average earlier at ground level than electrons. Although the error bands of the time profiles overlap the earlier arrival of muons is guaranteed. The error bands represent the systematic uncertainties which affect both shower front time profiles identically. These uncertainties represent possible changes in the absolute mean arrival times without altering the relative time difference between both shower components. The relative time difference between the aver-

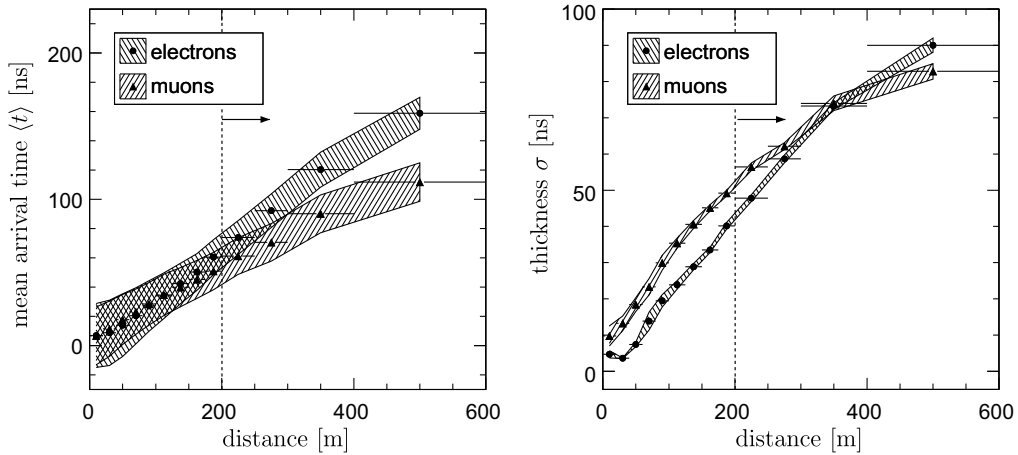


Fig. 10. (Left) Mean arrival time of electrons and muons as a function of the core distance according to the mean values of the particle arrival time distributions. The horizontal bars indicate the widths of the core distance intervals. (Right) Thickness of the electromagnetic and muonic shower disks as a function of the core distance in terms of the standard deviation of the particle arrival time distributions. The dashed lines represent the core distance above which a discrimination between electron and muon arrival times becomes possible (see text).

age arrival times of electrons and muons increases as expected with the distance to the shower core.

Close to the shower core up to a core distance of approximately $R = 200$ m the maximum difference in the average arrival time amounts to 4 ns. Signals from the μ -detectors exhibit deformations of unknown origin next to the peaks of the signals (see Fig. 6). Since the size of the deformations are proportional to the size of the signal they are more pronounced in large signals which are measured predominantly close to the shower core due to the high density of secondary particles. After the unfolding the deformations enter the particle arrival time distributions as fake muons since their size exceeds the size of the average MIP μ -detector response. This broadens the distributions as can be also seen by means of the thicknesses of both shower fronts on the right hand side of Fig. 10. This effect also shifts the average arrival time of muons to later values. Hence, the present setup allows discrimination between electron and muon arrival times only above core distances $R \geq 200$ m. Here the average signal amplitude is low enough that the deformations are taken into account by the shape of the average MIP μ -detector response used in the unfolding algorithm.

Above $R = 200$ m the difference $\Delta\langle t \rangle$ between the average arrival time of both shower fronts increases from initial $\Delta\langle t \rangle = (12.9 \pm 0.2)$ ns to $\Delta\langle t \rangle = (47 \pm 1)$ ns. Up to $R = 200$ m, the thickness of the muonic shower disk is on average 10 ns larger than the thickness of the electromagnetic shower disk caused by the effects described above. This difference decreases for distances $R > 200$ m. For core distances $R > 400$ m, the width of the average muonic shower disk is approximately 5 ns smaller than the width of the average electromagnetic shower front.

The results shown in Fig. 10 are in agreement with earlier works, particularly when taking into account the higher energy thresholds for muons in AKENO [10] and the KASCADE central detector used in Ref. [4]. Low energy muons

are in average generated deeper in the atmosphere, therefore a noticeable difference of the shower fronts develops only at larger core distances.

Fig. 11 shows the development of the shower front time profiles for different intervals of the estimated primary energy $\log_{10}(E_{\text{est}})$. The mean arrival times show an increase to later arrival times with increasing energy. The result that muons arrive earlier than electrons above a core distance of $R = 200$ m holds for all three energy ranges ($\Delta\langle t \rangle \approx 20$ ns at $R = 250$ m). The increase in the mean arrival time with the primary energy is caused by the different statistics in the particle arrival time distributions. For a specific particle type the particle arrival time distribution at large core distances is broader for EAS with higher energies. The tail is more pronounced than for EAS with lower energies as also indicated by the increase in shower front thickness with primary energy. This is due to the larger extension of the EAS with higher energies. The particle density at fixed core distance is higher and hence also the probability that delayed particles are measured by the detector. For EAS with lower energies the particle density at large core distances is low. The density of particles with a delay to the foremost part of the shower front is even lower. Correspondingly, the probability that delayed particles hit the detector is lower. Therefore, the tail of the distribution is less occupied. Furthermore, the measured particles of the low energy EAS stem from the foremost part of the shower front, where the particle density and thus also the probability that a particle hits the detector is higher. Hence, the decrease of the mean arrival time is an effect of low statistics at large core distances for EAS with low energy E_{est} . In this analysis no conclusion can be drawn about a systematic dependence of the mean arrival time on the primary energy. A detailed analysis requires more data at large distances from EAS with low energy.

Also the zenith angle dependence of the shower disk time profile has been checked. No significant variation of

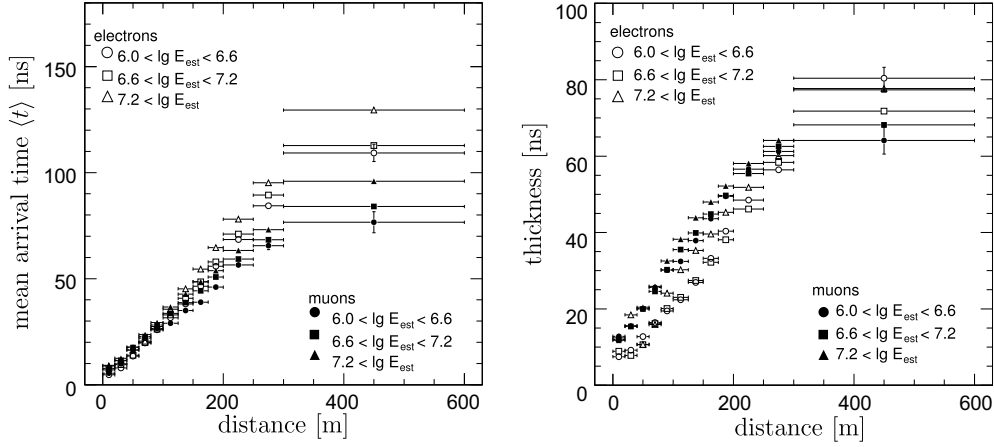


Fig. 11. (Left) Mean arrival times of the e/γ- and μ-shower fronts for three ranges of the estimated primary energy. (Right) Thicknesses of the e/γ- and μ-shower fronts for three ranges of the estimated primary energy.

the shower disk profile is visible as expected for zenith angles below $\vartheta = 30^\circ$.

4.3. Estimation of the muon number using a particle arrival time cut

The values of the mean arrival times are used to determine an arrival time cut t_{cut} for secondary particles for each core distance interval. This cut is intended to separate the muonic and the electromagnetic shower components. Since muons arrive earlier, all particles measured with $t < t_{\text{cut}}$ are considered muons. Accordingly, all particles with $t \geq t_{\text{cut}}$ are considered part of the electromagnetic shower front. As indicated by the time profile of the shower fronts, the validity of an application of the cut for $R < 200$ m is unknown. Therefore, the results will focus on core distances $R > 200$ m. The separation cut t_{cut} is calculated as the average of the mean arrival times of electrons and muons at the core distance R

$$t_{\text{cut}}(R) = \frac{1}{2} \times (\langle t \rangle_{e/\gamma}(R) + \langle t \rangle_{\mu}(R)). \quad (4)$$

The statistical error of the separation cut values t_{cut} is calculated via error propagation using the errors of the mean values $\langle t \rangle_{e/\gamma}$ and $\langle t \rangle_{\mu}$. On the left hand side of Fig. 12 the arrival time cut $t_{\text{cut}}(R)$ is shown as a function of the core distance. The statistical errors are smaller than the markers (typically 0.2 ns). The error band shown represents the systematic uncertainties. They are determined analogously to the systematic error of the shower front time profile depicted in Fig. 10.

Due to the spread of the particle arrival times, as indicated by the thicknesses of both shower fronts, a 100% clean separation of muons from electrons is not achievable. Instead, the estimated muon number using a cut on the particle arrival time will be contaminated by electrons with an arrival time $t < t_{\text{cut}}$. Therefore, applying the separation cut will result in a certain purity of the reconstructed muon

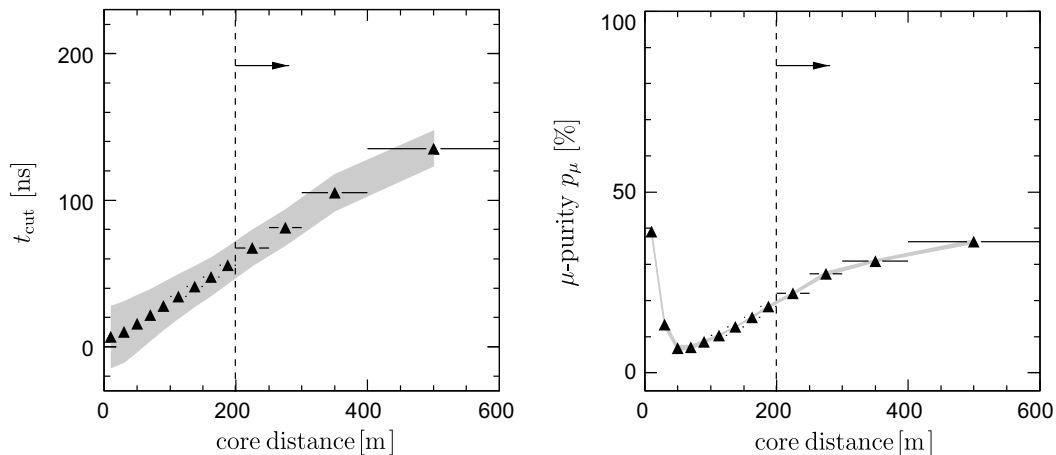


Fig. 12. Separation cut values (left) and muon purities (right) with the systematic uncertainties represented by the error bands. The dashed lines represent the core distance above which a separation of electrons and muons according to their arrival times becomes feasible.

number, depending on the exact separation cut value. Hence, the muon purity p_μ

$$p_\mu(R) = \frac{n_\mu(t < t_{\text{cut}})(R)}{n_\mu(t < t_{\text{cut}})(R) + n_{e/\gamma}(t < t_{\text{cut}})(R)} \quad (5)$$

is calculated for the separation cut values. Here, $n_\mu(t < t_{\text{cut}})$ denotes the sum of unfolded particles of the muon arrival time distribution with an arrival time smaller than t_{cut} . The parameter $n_{e/\gamma}(t < t_{\text{cut}})$ denotes the sum of unfolded electrons with an arrival time smaller than t_{cut} . The error of the muon purity is calculated via error propagation using the statistical errors $\sqrt{n_\mu}$ and $\sqrt{n_{e/\gamma}}$. The purity is shown in the right part of Fig. 12. The statistical errors are in the order of 0.5% and smaller than the markers. The error band indicates the overall systematic uncertainty. Because the arrival time difference of electrons and muons increases with the distance from the shower core, the purity does as well. The purity has to be applied as a correction factor to estimate the true number of muons.

5. Summary and conclusions

Photomultiplier signals from several KASCADE scintillator stations digitized by a Flash-ADC based data acquisition system have been used to extract particle arrival time distributions with respect to the arrival time of the shower core. A typical detector signal represents the particle arrival time distribution convolved with the detector response function. The particle arrival time distribution can be reconstructed by applying an unfolding algorithm using an average single particle detector signal as detector response function. The FADC data acquisition system is connected separately to the e/γ - and the μ -detectors of the KASCADE array detector. The unfolded particle arrival times have been used to construct μ - and e/γ -arrival time distributions for core distances up to 600 m. The mean and the spread of the arrival time distributions have been used to determine the average time profile of the electromagnetic and muonic shower disk. For $R < 200$ m the particle arrival times are biased by detector effects and no statement about relative arrival times of electrons and muons can be given. At core distances of $R > 200$ m the muonic shower component arrives on average earlier than the electromagnetic shower component. The difference in average particle arrival time for $R > 200$ m increases with the core distance from initial $\Delta\langle t \rangle = (12.9 \pm 0.2)$ ns to final $\Delta\langle t \rangle = (47 \pm 1)$ ns at $R = 500$ m. The width of the muonic and electromagnetic shower disks are comparable. Up to $R = 250$ m the muon shower disk is slightly thicker by $\Delta\sigma \approx 8$ ns due to deficiencies in the experimental setup and probably not by physics reasons. The difference in the width decreases at larger core distance. For $R > 400$ m the electromagnetic shower disk is broader by $\Delta\sigma \approx 6$ ns.

The difference in the average arrival times of electrons and muons can be used in order to determine a cut on

the particle arrival time for an alternative determination of the muon content of EAS. Muons are identified as particles with an arrival time smaller than the cut on the particle arrival time. Since also electrons have smaller arrival times, the muon selection has a certain purity which has to be corrected for.

The potential of the method evolves with increasing distance to the shower core and is thus especially interesting for larger EAS arrays. The data analyzed stem from KASCADE detector stations which cover in total 12.6 m² (e/γ -detector) or 25.9 m² (μ -detector). For large EAS arrays without dedicated μ -detectors it could be worthwhile to operate fine segmented detectors of comparable size for electromagnetic particles and muons. Equipped with fast time resolving electronics they would be able to measure the particle arrival times directly minimizing systematic uncertainties. The data can be taken in parallel to the regular EAS data and the results could later be used for the offline determination of the electromagnetic and the muonic content of the EAS.

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