Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 4 (HE part 1), pages 207–210

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Separation of the electromagnetic and the muon component in EAS by their arrival times

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Abstract: KASCADE-Grande is a ground based multi-detector experiment measuring extensive air showers in order to study the primary cosmic ray energy spectrum in the energy range from 10^{14} eV to 10^{18} eV. A Flash-ADC based data acquisition system in KASCADE-Grande allows to study the temporal structure of extensive air showers. Muons in extensive air showers are thought to arrive on average earlier than the particles of the electromagnetic shower component. The separation of electrons and muons according to their arrival times poses an alternative to the measurement of the shower muon content with muon detectors [1]. Approximately one year of KASCADE-Grande data have been analyzed to study the arrival times of the electromagnetic and the muonic shower components.

Introduction

The differences in the shower development of the electromagnetic and the muonic shower components suggest an arrival time difference between electrons and muons at the observation level. According to the model of the shower development, muons are on average produced higher in the atmosphere and move under the production angle with respect to the shower axis rectilinearly towards the observation point. 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. Furthermore, electromagnetic particles which are produced at the early phase of the shower development are absorbed in the atmosphere before they reach the observation level. Therefore, the bulk of electromagnetic particles, which are detected at sea level, are produced deeper in the atmosphere or at a later stage of the shower development. At

this point, the energy available for the production of secondaries has already decreased. Hence, the average kinetic energy of the electromagnetic particles is smaller than the kinetic energy of the muons. The resulting effect of the different development of the electromagnetic and the muonic shower components is that muons arrive earlier at the observation level than particles of the electromagnetic shower component. The difference in the arrival time increases with the radial distance from the shower core.

Analysis

In order to study particle arrival times with KASCADE-Grande [2, 3, 4, 5], data from a Flash-ADC based data acquisition system have been analyzed [6]. The FADC system comprises 16 FADC modules of 8 bit resolution and a sampling frequency of 1 GHz. The 16 FADC modules are installed in eight detector stations of the KASCADE detector array. The two modules per station are connected to the electromagnetic and the muonic detectors in order to measure the electromagnetic and the muonic shower components separately. The FADC modules digitize the full shape of the photomultiplier signal. In this way the arrival times of shower particles at the detectors are being stored since the detector signal corresponds to a convolution of the particle arrival time distribution with the single particle detector response. This means that an extraction of the particle arrival time distribution is possible by applying an unfolding algorithm if the single particle detector response is known.

The single particle detector response has been determined by averaging single particle events from usual air shower data. A single particle detector response has been determined for the e/γ- and the μ-detector separately. The single particle detector response is used to construct the response matrix for the Gold unfolding algorithm. Figure 1 shows an example of an FADC pulse shape and the result of the unfolding.

The data used to study the arrival times of shower particles were recorded during approximately one year between January 2005 and February 2006. The minimum requirement for a data taking run to be analyzed was that at least the KASCADE array, the Grande array and the Flash-ADC system participated in the data taking. From these runs only showers were selected which had their shower core reconstructed within a fiducial area of 600 m$\times$600 m around the center of the Grande array, and which triggered at least 20 Grande detector stations. To assure a high quality of the reconstructed shower observables only showers which had a zenith angle smaller than 30° were used for the analysis. In total, approximately 290,000 extensive air showers measured by KASCADE-Grande entered the analysis. The used events belongs to primary energies of approximately 10^{16} eV –10^{18} eV. The signals in these selected air showers were only used for the analysis if no saturation occured and the KASCADE array time measurement of the corresponding detector stations was available.

The signals which passed these quality requirements were unfolded as described above. The resulting arrival time distributions were filled into overall particle arrival time distributions. In order to study the temporal structure of the shower component in dependence on the distance from the shower center, the overall arrival time distributions were created for 13 intervals of the distance from the shower core. As an example, the arrival time distributions of electrons and muons are shown in figure 1. As the detectors for the electromagnetic shower component are located above the detectors for the muonic shower component, the arrival time distributions of electrons contain also the arrival times generated by muons passing the electromagnetic detector. This contribution had to be subtracted on a statistical basis by subtracting the muon arrival time distribution from the electron arrival time distribution after scaling down the muon arrival time distribution by the ratio of the electron detector area and muon detector area. As an example, the resulting particle arrival time distributions of electrons and muons are shown on the right hand side of figure 1 for the distance interval $R = (250 - 300)$ m.

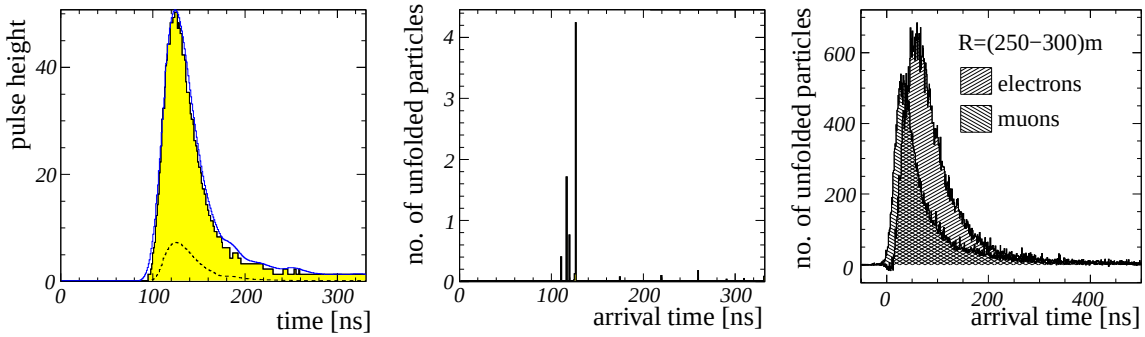

Figure 1: *Left:* The histogram depicts an example of an unfolded FADC signal pulse (from a μ-detector) belonging to a multi-particle transition. The dashed line corresponds to the average MIP detector response, which was used to generate the response matrix. The continuous line represents the forward folded solution which is the product of the unfolded arrival time distribution and the response matrix. *Middle:* Corresponding unfolded particle arrival time distribution. *Right:* Example of overall particle arrival time distributions in the distance interval $R = (250 - 300)$ m.

Results

The arrival time distributions are used to generate the time profile of the electromagnetic and the muonic shower fronts. The mean value of the distributions represents the most probable arrival time of the corresponding particle type. The shower front profile of the electromagnetic and the muonic component is shown in figure 2. The thicknesses of the shower disks of both components by means of the standard deviation of the corresponding arrival time distributions are depicted in figure 3. The time

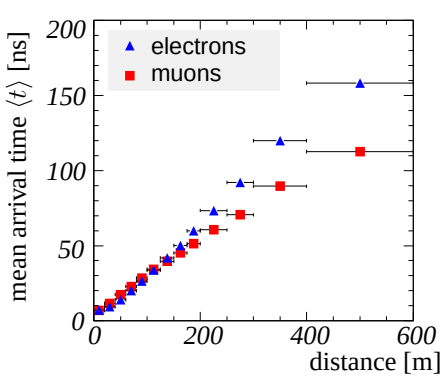

Figure 2: Mean arrival time of electrons and muons as a function of the core distance according to the mean values of the particle arrival time distributions.

profile indicates that for $R > 200$ m muons start to arrive earlier at the observation level than electrons. The relative difference in the average arrival time increases with increasing core distance as expected.

The difference in the average arrival time above $R = 200$ m allows the determination of an arrival time cut in order to separate electrons and muons. This time cut on the particle arrival time is defined as the average of the distributions' mean values. As the muons represent the early shower component, particles with an arrival time smaller than the arrival time cut are considered muons whereas particles with a later arrival time are considered electrons. The particle arrival time cut as a function of the core distance is shown in figure 4. Due to the large spread of the particle arrival times the muon selection obtained by this definition is not 100 % clean, but will also contain misclassified early electrons. In order to determine the expected purity of the muon selection the arrival time cut was applied to the arrival time distributions and the muon purity was calculated as the ratio of the number of muons to the total number of particles before the arrival time cut. The purity of the muon selection is shown in figure 5. The error band in both pictures reflects the sum of statistical and systematic errors and is dominated by the systematic error. The systematic error is mainly caused by the uncertainty of the reconstructed arrival time of the shower core

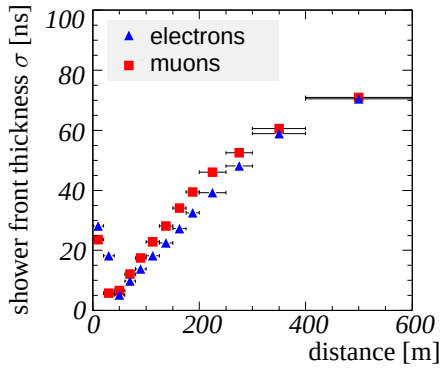

Figure 3: Thickness of the electromagnetic and muonic shower front as a function of the core distance in terms of the standard deviation of the particle arrival time distributions.

and the alignment of the unfolded particle arrival times relative to the shower core arrival time.

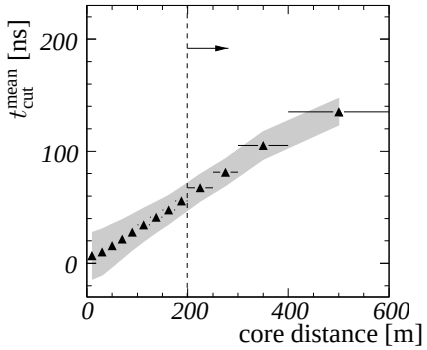

Figure 4: Separation cut values calculated from the mean values of the particle arrival time distributions with the systematic uncertainties represented by the error bands. The dashed lines represent the core distance above which a separation of electrons and muons according to their arrival times becomes feasible.

Discussion

The analysis of particle arrival times of the electromagnetic and muonic shower component with data from the KASCADE-Grande experiment has shown that muons have on average an earlier arrival time at the observation level than electrons. This difference in the arrival time can be used for an alternative method to determine the muon content in extensive air showers. Experiments without dedicated muon detectors but with time resolving data acquisition electronics are able to separate muons from electrons according to their arrival time to a certain extent.

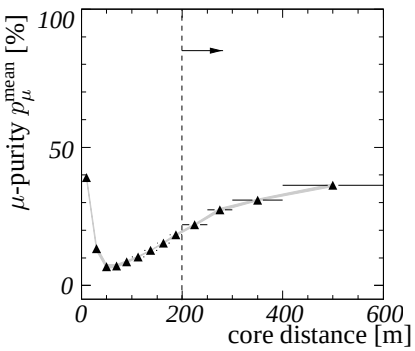

Figure 5: Muon purities calculated from the mean values of the particle arrival time distributions with the systematic uncertainties represented by the error bands. The dashed lines represent the core distance above which a separation of electrons and muons according to their arrival times becomes feasible.

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