Lateral distribution of EAS muons measured with the KASCADE-Grande Muon Tracking Detector

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***Abstract*. The KASCADE-Grande Muon Tracking Detector (MTD) allows to measure with high accuracy directions of EAS muons with energy above 0.8 GeV up to 700 m distance from the shower center. Lateral distribution of muon densities reflects the longitudinal development of the muonic shower component, thus comparison of experimental distributions from different detectors, as well as with the simulated results, allows to check the contemporary understanding of shower physics. Experimental results for EAS muons above 0.8 GeV obtained for the first time with the tracking detector in a wide range of distances from the core will be shown. They will be compared with the lateral distributions of muons above 0.23 GeV, measured with KASCADE Array muon scintillation counters. Comparison with the simulation results will also be shown.**

***Keywords*: KASCADE-Grande, Muon Tracking Detector, lateral muon density distributions**

I. INTRODUCTION

Ivestigations of muonic component in Extensive Air Shower (EAS) is of a primary importance for understanding air shower physics. Muons carry to the observation level nearly undistorted information about their parent particles: pions and kaons, which are the most numerous products of hadronic interactions responsible for the development of the shower in the atmosphere.

A perfect tool for such investigations is the KASCADE-Grande EAS experiment [1], being an extension of the KASCADE experimental setup [2]. It is a multi-detector system located on site of the Research Centre (Forschungszentrum) Karlsruhe in Germany at 110 m a.s.l., measuring all three EAS components: hadrons, electrons and muons (at 4 energy thresholds) in a wide range of distances (up to 700 m) from the shower core, and primary particle energies (5×10^{14}–10^{18} eV). High precision measurements of particle densities and tracks, the latter by means of a dedicated Muon Tracking Detector (MTD) [3] - at different energy thresholds allow to investigate many features of EAS and are the basis for multiparameter analyses (e.g.: [4], [5]). These features of KASCADE-Grande make it also to a very good test field for the development of other shower detection techniques, like radio detection (LOPES [6]).

II. KASCADE-GRANDE

A. The KASCADE experiment

The KASCADE experiment (Fig.1) consists of several detector systems. A description of the performance of the experiment can be found elsewhere ([2]). An array of 252 detector stations 200 m $\times$ 200 m (called the Array), is organized in a square grid of 16 clusters, and equipped with scintillation counters, which measure the electromagnetic (threshold 5 MeV) and in the outer 12 clusters, below a lead iron shielding imposing the energy

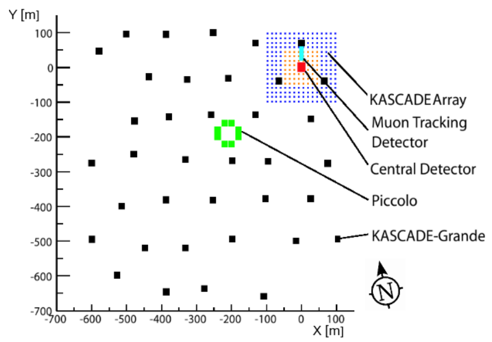

Fig. 1: The layout of the KASCADE-Grande experiment.

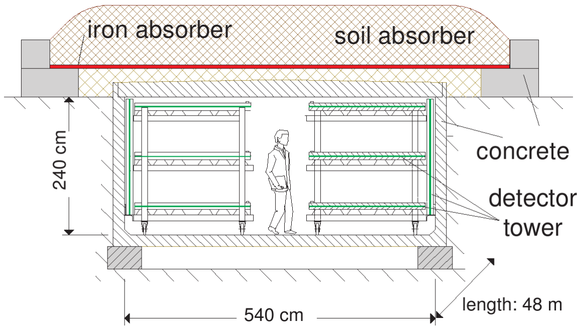

Fig. 2: Cross-section of the Muon Tracking Detector tunnel.

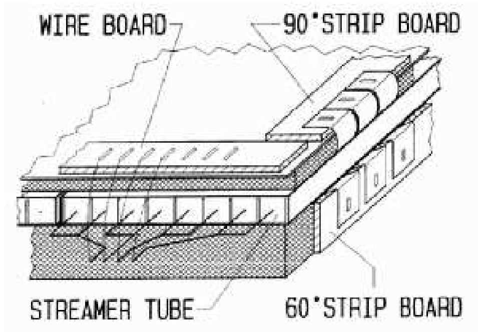

Fig. 3: The MTD module design.

threshold of 230 MeV, also the muonic parts of EAS. In its centre, a 16 m × 20 m iron sampling calorimeter (a main part of the Central Detector) detects the hadrons in the shower core [7].

Muon detectors located in the third gap of the calorimeter provide a trigger for the calorimeter and additional information about the lateral and time distribution of muons (above 490 MeV energy) near the shower core [2], [8]. Underneath the calorimeter two layers of multi-wire proportional chambers (MWPC) are used to measure tracks of muons with energy above 2.4 GeV. In the northern part of the KASCADE Array the 128 m^2 large Muon Tracking Detector is situated.

B. *Grande part of the experiment*

Grande is an extension of the KASCADE Array. It is an array of 37 detector stations organized in a hexagon grid of 18 clusters covering an area of 0.5 km^2. Each station contains 10 m^2 of plastic scintillators for registration of charged particles. In the centre there is a small trigger array of plastic scintillation stations, called Piccolo, build to provide additional trigger for the MTD and other KASCADE components.

III. THE MUON TRACKING DETECTOR

The Muon Tracking Detector is installed below ground level in a concrete tunnel. Under the shielding of 18 r.l., made out of concrete, sand and iron (Fig.2), 16 muon telescopes (called detector towers) register tracks of muons which energy exceeds 800 MeV. Each tower contains limited streamer tube (ST) detector modules: three horizontal and one vertical. All towers are connected with a gas supply system, high voltage and electronic chain readout system.

Each ST chamber houses 16 anode copper-beryllium wires in two cathode comb profiles, extruded for eight parallel ST cells of 9×9 mm^2 cross-section and 4000 mm length.

In the MTD an efficient chain-type readout system is used. Front-end electronics boards, mounted to the detector modules are acquiring signals from wires and strips. Each of three wire and nine strip boards in a module creates digital signals being used to reconstruct the tracks. Information from all modules, under certain trigger condition, is send to the acquisition system. Detailed information about the design of the MTD may be found in [3] and [9].

When a particle is passing through the modules of the tower it ionizes the gas in the streamer tubes and a streamer is created. As a result we have a large increase of charge in a small volume of the tube. This charge is inducing a certain charge in the aluminum strips above and below the tubes (perpendicular and diagonal, 60° with respect to the wires), respectively (Fig.3). Coincidence of the signal from the wires and strips in each layer is called a hit. The tracks are reconstructed out of three or two hits, in three or two modules, respectively. The algorithm is first searching for three hit tracks and the remaining hits are used next to create two hit tracks out of them.

IV. TRACKING MUONS IN EAS

Combined information of the muon tracks, direction of the shower axis and the shower core position allows to investigate the muonic component of the EAS more precisely than it is done with the scintillator array alone. With the MTD we count muons and, in addition, have very precise (better than 0.3°) information about their directions. This allows to investigate the longitudinal development of the muon component, and due to its close relation to EAS hadrons, the development of showers themselves. This investigation is done by studying quantities derived from the experimental data, like mean muon production height [10] and shower muon pseudorapidities [11]. The way shower develops in the atmosphere (and its muon component in particular) leaves its imprint in the lateral distributions of muons – also a subject of our investigations with the MTD data.

V. LATERAL MUON DENSITY DISTRIBUTIONS

Lateral distribution of EAS particles is an important characteristic of the shower cascade in the atmosphere. In particular, such distributions of EAS muons, being closely related to the hadronic shower component, are a good tool to test the quality of experimental detector setup and our understanding of shower physics. Therefore, every EAS experiment, equipped with sufficiently large muon detectors, provides such distributions. Also KASCADE experiment has done so [4] and first preliminary distributions from KASCADE-Grande were reported [12] , [13].

Usually results were obtained with arrays of shielded scintillator detectors, the most popular device in EAS experiments. With the MTD in KASCADE-Grande, for the first time with high angular resolution, it is possible to obtain lateral distributions of muons registered with the tracking devices, like limited streamer tube telescopes. Muon numbers (muon densities) are obtained by counting particle tracks instead of measuring energy deposits, as it is the case with shielded scintillator arrays.

A. *Selection of events*

This analysis is based on the showers measured in a period from March 2004 till November 2008 fulfilling the following conditions:

1) All clusters in the KASCADE-Grande array and the MTD work properly,
2) Reconstruction of shower parameters from Grande array was succesful,
3) Zenith angle of the shower $\Theta \leq 18^\circ$,
4) Shower core was reconstructed in fiducial area where $\mathrm{x_{core}} \in \langle -550\mathrm{m}; 50\mathrm{m}\rangle$ and $\mathrm{y_{core}} \in \langle -580\mathrm{m}; 20\mathrm{m}\rangle$.

B. *Calculation of the number of tracks and the area of the MTD*

The detector area is divided into 30 meter radial bins around the reconstructed shower core position (see Fig.4). Muon tracks are reconstructed from hits in two or three MTD modules and the position of each hit is known. Distance from the hit in the middle module to the shower axis is the muon distance.
The area of the detector in each distance bin is calculated in the following way:

From very precise measurements the position of every wire pair and perpendicular strip is known. Point where the wire pair is crossing the perpendicular strip is a centre of a basic detection unit (cell) in the MTD. Each cell has constant area of ~ 4 cm^2. Distance of each cell to the shower axis is being calculated and the number of cells is accumulated in each distance bin. This number

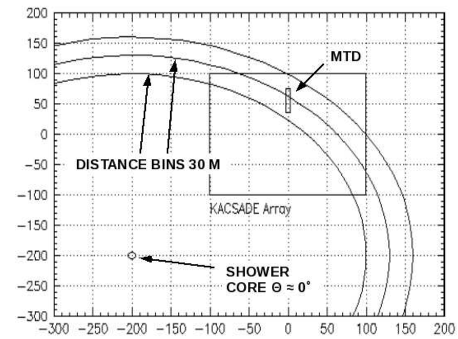

Fig. 4: 30 meter radial bins divide the MTD into parts (from one to three). In each bin the number of muons and the detector area is calculated.

of cells gives information about the detector area in that bin. The number of muon tracks in each distance bin is corrected for the reconstruction efficiency. The track reconstruction efficiency is calculated from the following formula (1):

$$\epsilon = \frac{1}{1 + \frac{N_{tr2}}{3 \cdot N_{tr3}}} \quad (1)$$

where N$_{tr2}$ and N$_{tr3}$ are two and three hit tracks respectively. Becasue of reconstruction procedure two and three hit tracks are not independent and it is necessary to introduce a proper correction factor k, given by the formula (2):

$$k = \frac{1}{3 \cdot \epsilon^3 + 2 \cdot \epsilon^2} \quad (2)$$

Typicaly $\epsilon = 0.74$ and $k = 0.4$
The density ρ_i in each distance bin is calculated as a sum of all muons from all showers corrected for reconstruction efficiency being divided by detector area corrected for zenith angle (A_{MTD}).

$$\rho_i = \frac{\sum_{j=1}^{N_s} (N_{tr2}^j + N_{tr3}^j) \cdot k}{\sum_{j=1}^{N_s} A_{MTD}^{j,i}} \quad (3)$$

where i is distance bin number, N_s is number of showers, $A_{MTD}^{j,i}$ is detector area in i^{th} distance bin for j^{th} shower.

In Fig.5 the preliminary results for the lateral muon density distributions are presented in four muon size bins: from lg(N$_\mu$)>4.9 to lg(N$_\mu$)<6.1. N$_\mu$ is derived from muon densities measured with KASCADE muon detectors and the above mentioned range roughly corresponds to primary energies from 10^{16} eV to 10^{17} eV. Together with the MTD results, represented by symbols, the lateral distributions based on the number of muons reconstructed out of energy deposits in shielded plastic scintillators of the KASCADE Array (represented by lines) are given. One can notice that the presented distributions can be compared in limited distance range (marked by full symbols and solid lines for the MTD and KASCADE distributions respectively). It is due to

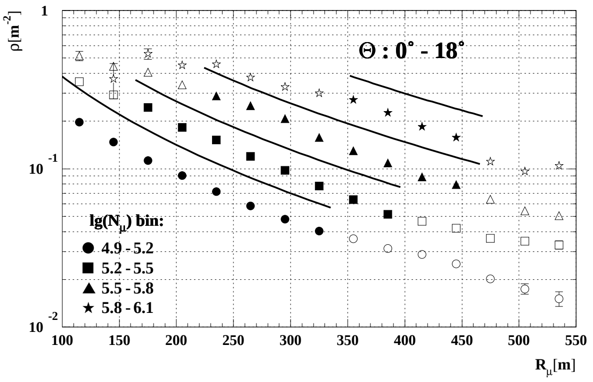

Fig. 5: Lateral muon density distributions obtained with the MTD (symbols) and with the KASCADE Array muon detectors (lines) in four muon size bins (see text).

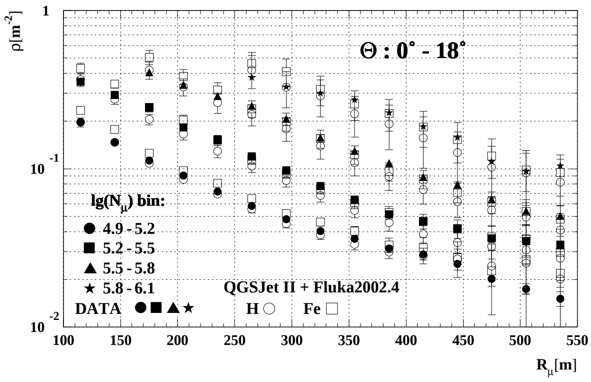

Fig. 6: Lateral muon density distributions obtained with the MTD (solid symbols) and simulations (see text).

saturation effects in the MTD when the core of the shower, initiated by high energy particle, is close to the detector. At large distances the experimental setup is not able to provide an efficient trigger. The absolute values of muon densities for both muon energy thresholds (230 MeV for the KASCADE Array and 800 MeV for the MTD) are still preliminary. Systematic uncertainties (e.g shower and track reconstruction accuracies) and efficiency corrections are under investigation. However, general shape of the distributions has been already established. It can be fitted with a Lagutin-like function (4) [15],[16]. In case of the lower energy muons the function is of the form :

$$f(r) = 0.28 \cdot r_0^{-2} (r/r_0)^{-0.69} (1 + r/r_0)^{-2.39} \times \left(1 + (r/(10 \cdot r_0))^{-2}\right)^{-1} \quad (4)$$

where r_0=320 m. For the higher energy muons registered by the MTD the distribution is steeper and can be described by similar Lagutin-like function where r_0 is smaller.

In Fig.6 comparison of the MTD distribution with CORSIKA [14] simulations of proton and iron primaries is shown. In muon size bin $\lg(N_\mu)$ from 4.9 to 5.2 the data are between simulations. In higher bins ($\lg(N_\mu)$ from 5.2 to 6.1) the data, in the distance ranges where the MTD results can be compared with KASCADE, seem to lie on top of iron distributions. Close and far away from the shower core the data points have tendency to lie on top of proton distributions. This is due to differences in track reconstruction in data and simulations. However, within our accuracies, the experimental distributions are in a good agreement with simulations.

Acknowledgements

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