Muon tracking in KASCADE-Grande: Lateral distributions of EAS muon densities

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***Abstract*— The KASCADE-Grande Muon Tracking Detector allows to measure with high accuracy ($\sim 0.3^{o}$) muon directions in Extensive Air Shower up to 700 m distance from the shower centre. According to the simulations within such a distance, in showers initiated by primaries with energies 10^{16}–10^{17} eV, nearly all muons reaching the observation level are subject of investigation.**

Study of lateral distributions of muon densities allows to investigate not only the longitudinal development of the Extensive Air Shower but also to check performance of the Muon Tracking Detector. Measuring muon tracks and their angles with respect to the shower direction it is possible to study also such quantities like mean muon production heights and muon pseudorapidities. They are not only sensitive to the longitudinal shower development but are a tool for testing hadronic interaction models and investigating cosmic ray mass composition.

The description of the detector, its capabilities to investigate the longitudinal development of muonic component in EAS, especially by means of studying lateral distributions of muon densities, will be presented. Preliminary results of these distributions will be shown.

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 cascade in the atmosphere.

Perfect tool for such investigations is the KASCADE-Grande EAS experiment, being an extension of the KASCADE experimental setup [1], [2]. It is a multi-detector system located on the 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) [2]. 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] and [6]). These features of KASCADE-Grande make it also to a very good test field for the development of other shower detection techniques, like radio detector (LOPES [7]).

II. KASCADE-GRANDE

A. The KASCADE experiment

The KASCADE experiment consists of several detector systems. A description of the performance of the experiment can be found elsewhere ([1]). A 200 m $\times$ 200 m array of 252 detector stations (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 superimposing the energy threshold of 230 MeV, also the muonic parts of EAS. In its centre, a 16 m $\times$ 20 m iron sampling calorimeter (Central Detector) detects the hadrons in the shower core. The calorimeter is equipped with 11 000 warm liquid ionization chambers arranged in nine layers. Due to its fine segmentation (25 cm $\times$ 25 cm), energy, position and angle of incidence can be measured for individual hadrons. A detailed description of the calorimeter and its performance can be found in [8].

Muon detectors located in the third gap of the calorimeter provide trigger for the calorimeter and additional information about the lateral and time distribution of muons (above 490 MeV energy) near the shower core [1], [9]. Underneath the calorimeter two layers of multi-wire proportional chambers (MWPC) are used to measure tracks of muons with energy

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TABLE I
COMPONENTS OF THE KASCADE-GRANDE EXPERIMENT

Detectors	Detected EAS particles	Area	Energy threshold
KASCADE Array:			
Liquid scintillators	Charged particles, photons	490 m^2	5 MeV
Plastic scintillators	Muons	622 m^2	230 MeV
Grande array:			
Plastic scintillators	Charged particle, photons	37×10 m^2	5 MeV
Piccolo	Charge particles, photons	80 m^2	5 MeV
Central Detector:			
Ionization chambers	Hadrons	9×304 m^2	50 GeV
Plastic scintillators	Muons	208 m^2	490 MeV
Streamer tubes	Muons	247.5 m^2	2.4 GeV
MWPC	Muons	2×129 m^2	2.4 GeV
Plastic scintillators	Electrons	23 m^2	5 MeV
MTD:			
Limited streamer tubes	Muons	4×128 m^2	800 MeV

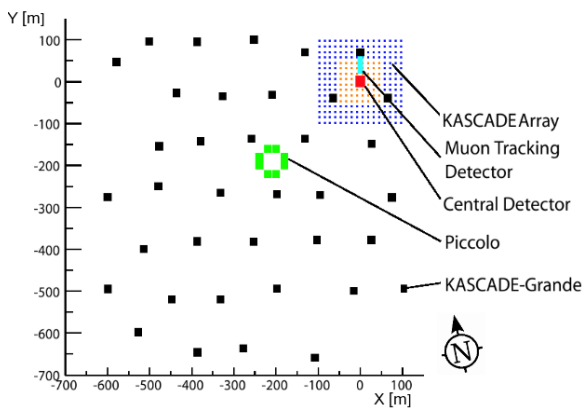

Fig. 1. The layout of the KASCADE-Grande experiment.

above 2.4 GeV.

In the North part of the KASCADE Array (see Fig.1) 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 above the energy threshold of 5 MeV. 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. The layout of the KASCADE-Grande experiment is shown in Fig.1. In Table I one finds a list with total size of each detector group, type of detected particles and their detection energy thresholds.

III. THE MUON TRACKING DETECTOR

The Muon Tracking Detector is installed below ground level in a concrete tunnel. Under the shielding, 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 detector modules: three horizontal and one vertical (see Fig.2 and Fig.3). All towers are connected with a gas supply system, high voltage and electronic chain readout system. Detailed information about the design of the MTD may be found in [3] and [10]. When a particle is passing through the modules of the tower it ionizes the gas in the streamer tube 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

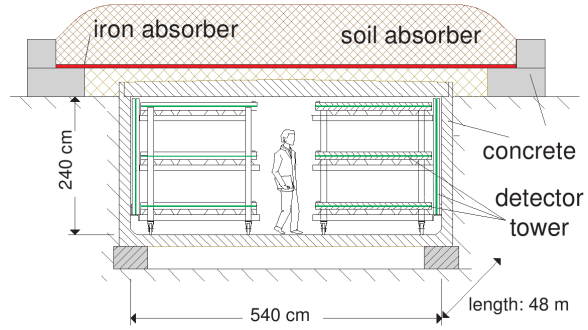

Fig. 2. Scheme of the Muon Tracking Detector tunnel.

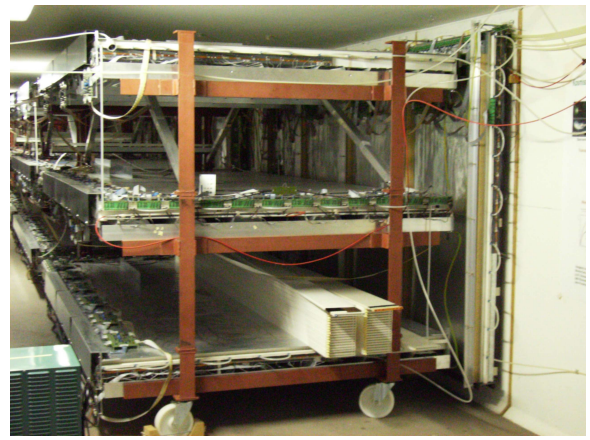

Fig. 3. The MTD tower. Steel crates hold three horizontal modules, a vertical module is between the crate and the tunnel wall.

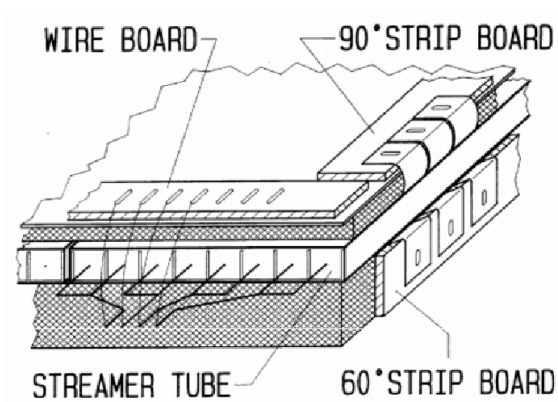

Fig. 4. The MTD module design.

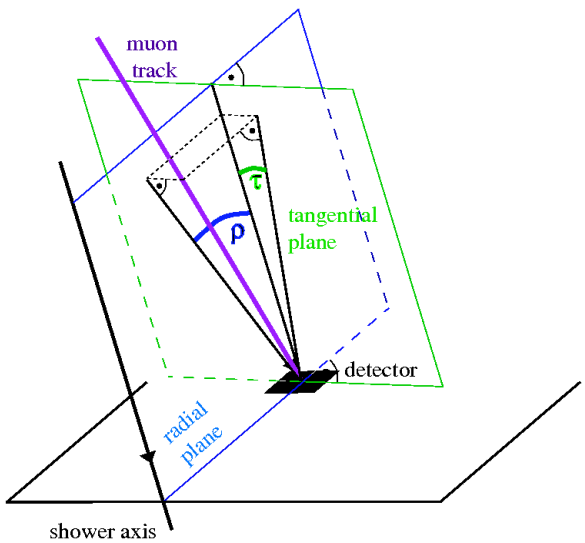

Fig. 5. Definitions of radial and tangential angles [11].

a certain charge in the aluminum strips above and below the tubes (perpendicular and diagonal, 60° with respect to the wires), respectively (Fig.4). Coincidence of the signal from 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.

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^o) 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 and shower muon pseudorapidities on the observation (detector) level. 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. Mean muon production height is a primary mass sensitive parameter, while muon pseudorapidity is a tool for testing hadronic interaction models and composition study, as well. Analysis of muon directions for the above mentioned studies utilizes the concept of tangential (τ) and radial (ρ) angles [11] derived from the measured muon and shower directions in the way depicted in Fig.5.

Determination of the muon production height H_μ [12] is done by triangulation, based on the muon radial angle and the distance of the muon to the shower core position. An example of some results of this analysis, taken from [13], is shown in Fig.6, where the regions of different mass-A dependent mean muon production heights $\langle H_\mu^A \rangle$ are shown in the 2-parameter space.

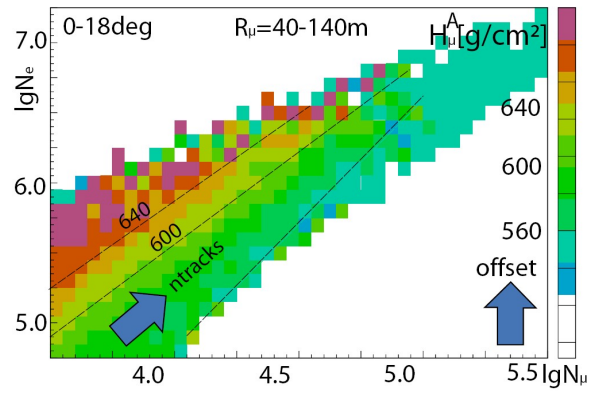

Fig. 6. $\lg(N_e)$–$\lg(\langle H_\mu^{tr} \rangle)$ matrix with effective muon production height H_μ^A along the z-axis. Muon multiplicities (ntracks) increase with the shower size (see [13]).

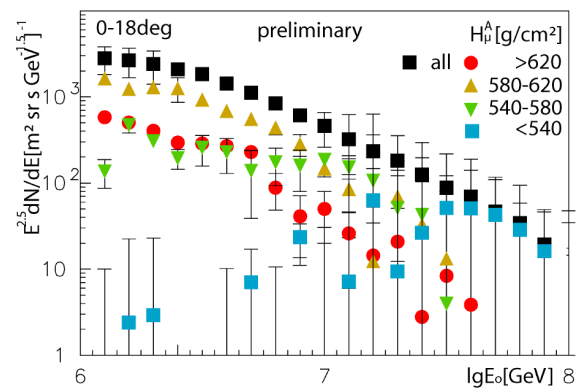

Fig. 7. Energy spectra for different H_μ^A groups which produce muons at different effective muon production height.

In this figure N_e is a total electron number in a shower and H_μ^{tr} is the, so called, truncated muon number (see in [1]). The picture shows regions of distinct $\langle H_\mu^A \rangle$ in a color code with a step size of 40 gcm^{-2} . H_μ^A is derived from H_μ after correction for the elongation rate in the form: $H_\mu^A = H_\mu - (\alpha \lg(H_\mu^{tr}) + \beta \lg(H_e)$. Applying to the distribution of Fig.6 the procedure described in [13] the energy spectra were obtained and shown in Fig.7.

Study of muon pseudorapidities utilizes both, tangential and radial angles of registered muons. As it was shown in [11], a certain combination of τ and ρ is equal to the ratio of transversal to longitudinal momentum components of the muon with respect to the shower direction. And this ratio determines the muon angle of incidence with respect to the shower direction, i.e., muon pseudorapidity η in shower coordinate system: $\eta = -\ln(\zeta/2)$, where

$$\zeta = \sqrt{\rho^2 + \tau^2} = p_t/p_{||} \quad (1)$$

Investigation of muon pseudorapidities gives a direct insight into hadronic interactions taking place in the atmosphere because, as simulations show, it is closely related to the pseudorapidity of their parent mesons [14]. The relation between pseudorapidity distribution of muons registered in EAS and

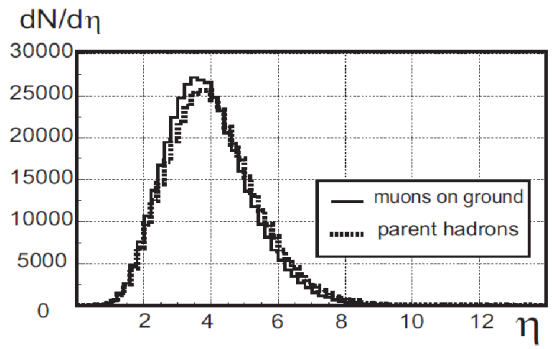

Fig. 8. Pseudorapidity distributions of muons and parent hadrons

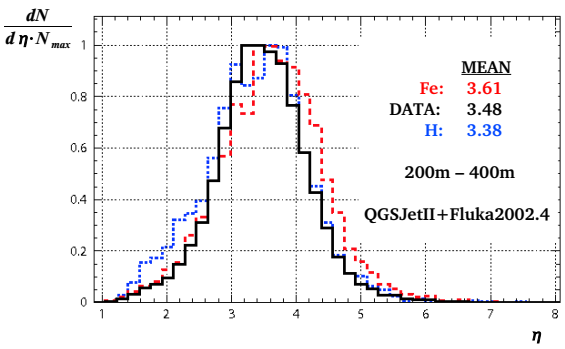

Fig. 9. Muon pseudorapidity distribution measured in a ring 200÷400 m from the shower centre and compared with CORSIKA simulation predictions for iron and proton (dashed and doted line, respectively) primary originated showers.

corresponding distribution for parent hadrons is shown in Fig.8.

For this investigation high precision in the determination of muon and shower directions is required which is fulfilled in case of the MTD and the KASCADE-Grande. Therefore, pseudorapidity distributions of muons registered in the MTD have been studied by the KASCADE-Grande and used as a test tool for interaction models used in Monte Carlo EAS simulations [14], [15], [16].

In Fig.9 an example of such distributions is shown. It is a preliminary distribution of muon pseudorapidity reconstructed from the MTD data measured in a certain range of distances to the shower core together with the predictions of the CORSIKA [17] simulations for proton and iron primary particles. It is seen, that experimental values are bracketed by simulated ones, what indicates that in this particular case the interaction models describe the data reasonably well, and one may try to draw some conclusions on the cosmic ray mass composition.

V. LATERAL MUON DENSITY DISTRIBUTIONS

Lateral distribution of EAS particles is an important characteristics 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

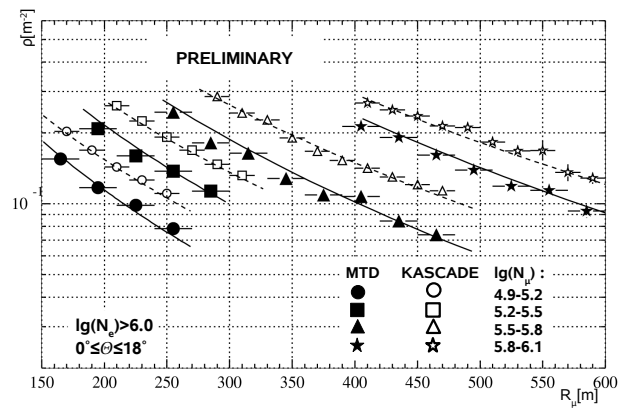

Fig. 10. Lateral muon density distributions obtained with the MTD (solid symbols) and with the KASCADE Array muon detectors (open symbols) in four muon size bins. A Lagutin-like function is represented by solid and dashed lines for MTD and KASCADE distributions, respectively (see text).

distributions. Also KASCADE experiment has done so [4] and first preliminary distributions from KASCADE-Grande were reported [16].

Most results were obtained with arrays of shielded scintillator detectors 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 is the case with shielded scintillator arrays.

In Fig.10 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_μ 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 full symbols, the lateral distributions based on number of muons reconstructed out of energy deposits in shielded plastic scintillators of the KASCADE Array (represented by open symbols) are given. 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. Some analysis details 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 ([18],[19]). In case of the lower energy muons the function is of the form :

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

where r_0=320 m. For the higher energy muons registered by the MTD (where the energy cut-off is 800 MeV) the

distribution is steeper and can be described by similar Lagutin-like function where r_0 is lowered. The lines running over solid and open points in Fig.10 are obtained with these formulas.

VI. Conclusion

Lateral muon density distribution in a wide distance range has been obtained from tracks of the particles. Because of different energy thresholds KASCADE and MTD distributions are separated and have different slopes.

Acknowledgements

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