Study of EAS development with the Muon Tracking Detector in KASCADE-Grande

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***Abstract*. The Muon Tracking Detector (MTD) in KASCADE-Grande allows to measure with high accuracy muon directions in EAS up to 700 m distance from the shower center. According to the simulations this directional information allows to study longitudinal development of showers by means of such quantities like muon radial angles and, derived out of radial and tangential angle values, muon pseudorapidities. Shower development depends on the hadronic interactions taking place in the atmosphere, therefore, such study is a good tool for testing interaction models embedded in the Monte-Carlo shower simulations.**

Sensitivity of the muon radial angles and their pseudorapidities to the shower development will be discussed and examples of measured distributions will be shown. Experimental results will be compared with simulation predictions showing the possibility to validate hadronic interaction models with the MTD data.

***Keywords*: KASCADE-Grande, muon tracking,**

I. Introduction

The Muon Tracking Detector (MTD) [1], registering muons above an energy threshold 800 MeV, is one of the detector components in the KASCADE-Grande EAS experiment [2] operated on site of the Research Center Karlsruhe in Germany by an international collaboration (see Fig.1). The directions of muon tracks in EAS are measured by the MTD with excellent angular resolution of $\approx\ 0.35°$. These directional data allow to investigate the longitudinal development of the muonic component in showers which is a signature of the development of the hadronic EAS core. Among the various EAS components there are only four, that are the penetrating ones: optical photons, muons, neutrinos and radio emission. As a result of their penetrating ability they provide practically undisturbed information about their origin. Out of these four, optical photons (of eV energy or smaller) as the most numerous particles, have been used most successfully so far (e.g. ref. [3]) in the study of the longitudinal shower development of individual showers. Muon information has usually been integrated over a large sample of showers and over the whole longitudinal profile.

However, muons have some advantage compared with optical photons and the radio emission: they reflect the development of the nuclear cascade with no mediation from the electromagnetic part of the shower. They are also "seen" the whole day long, not only on clear moonless nights. This feature they share with the EAS radio emission. Evident disadvantage of muons is that they are less numerous than photons and are therefore subject to large fluctuations. Moreover, being charged particles they are subjected to deflection in the geomagnetic field. Therefore, attempts to use them as an independent

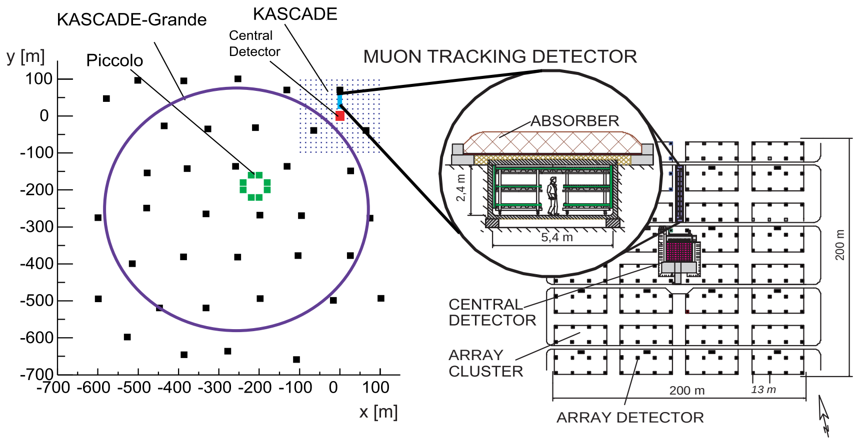


Fig. 1: Layout of the KASCADE-Grande experiment distributed over the Research Center Karlsruhe. KASCADE is situated in the North-East corner of the Center: note the position of the Muon Tracking Detector.

source of information on EAS development were rather rare in the past, but now, with the development of such sophisticated detectors as the MTD, they become more feasible and gain importance. On the other hand, muons have never been used up to now to reconstruct the hadron longitudinal development of EAS with sufficient accuracy, due to the difficulty of building large area ground-based muon telescopes.

Muons are produced mainly in decay processes of charged pions and kaons - most numerous products of the hadronic interations driving the development of EAS. The longitudinal profile of the hadronic cascade depends on the primary mass, and thus, can be used for testing the hadronic interaction models.

The most straightforward method of investigation of the longitudinal shower development is to reconstruct the muon production heights by means of triangulation [4], [5]. Results of such a research are presented on this conference by P. Doll et al. [6]. The longitudinal development of a shower has its imprint also in the lateral distribution of muon densities, presented on this conference by P. Łuczak et al. [7]. Here we will show, that the directional data of muons in EAS obtained with the MTD can be used to reconstruct such quantities like radial (ρ) and tangential (τ) angles and, as a next step, muon pseudorapidies [8], which are also sensitive to the longitudinal shower development. Therefore they can also serve to validate hadronic interaction models used in Monte-Carlo EAS simulations [9].

II. Radial, tangential angles, and muon pseudorapidity

Investigation of muons registered in the MTD is based on the two ortogonal projections of the muon angle in space with respect to the shower axis direction, namely the radial (ρ) and tangential (τ) angles. Their definition is given in Fig. 2 and their properties are discussed in [8]. Here we remind only, that the value of muon radial angle

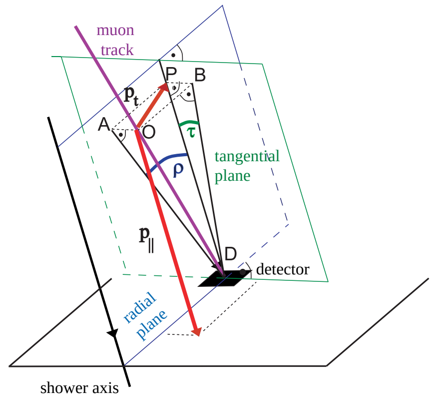


Fig. 2: Definition of radial (ρ) and tangential (τ) angles.

is dominated by the value of the transverse momentum of its parent meson.

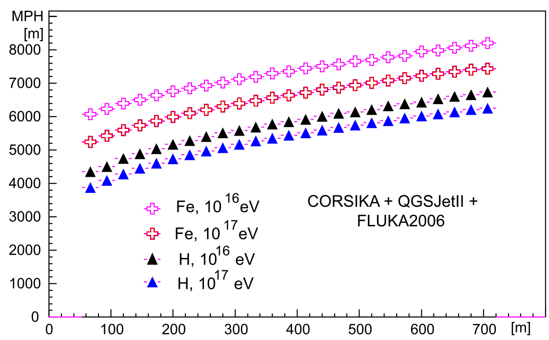
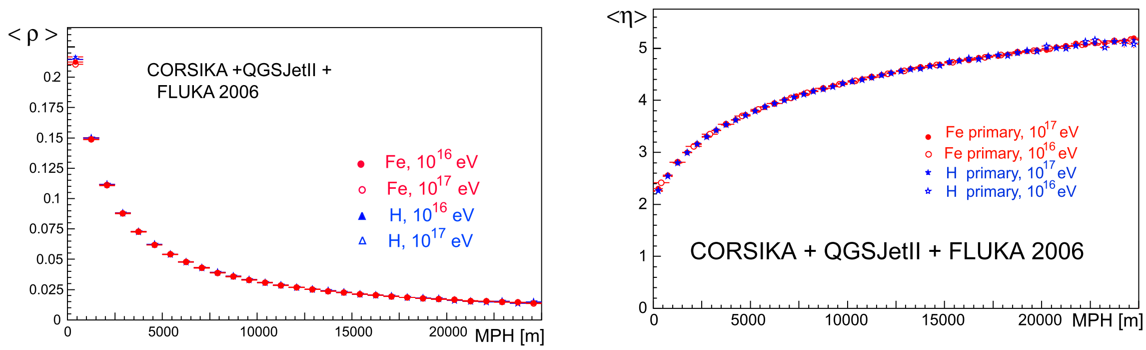


Fig. 3: Lateral distribution of the mean muon production height (MPH) in vertical showers for the two primary particle types and two energies.

In [8] it was also shown that using τ and ρ one can reconstruct the pseudorapidity of muons in the shower reference system (z-axis parallel to the shower direction): η = - $\ln \frac{\zeta}{2}$, where $\zeta = \sqrt{\tau^2 + \rho^2}$. This pseudorapidity is



(a) (b)

Fig. 4: Mean radial angle (a) and mean pseudorapidity (b) of muons registered in the MTD and produced at a given height above the detector is independent of the primary mass and energy.

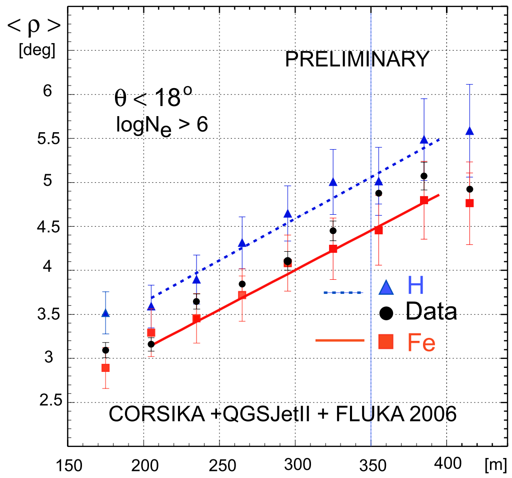


Fig. 5: Reconstructed lateral distribution of the mean radial angle compared with CORSIKA simulation results for proton and iron primaries. Lines are fits to the simulations.

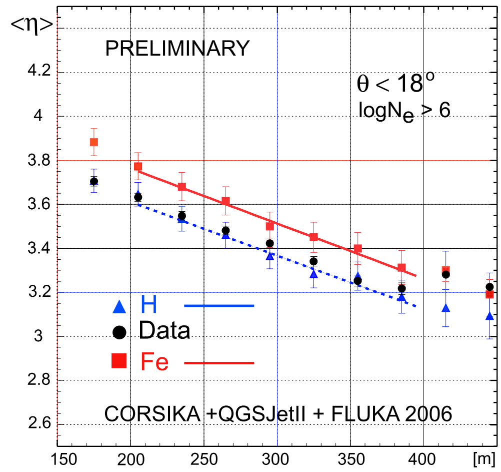


Fig. 6: Reconstructed lateral distribution of the mean muon pseudorapidity compared with CORSIKA simulation results for proton and iron primaries. Lines are fits to the simulations.

closely related with the rapidity of parent mesons [10], thus being a good tool for testing interaction models.

In Fig. 3 the sensitivity of the MTD to the longitudinal shower development is demonstrated. At each distance to the shower core registered muons have certain average production height (MPH), being dependent on the type of primary and its energy. Muons in proton induced showers are per average produced deeper than in iron showers; with increase of the primary energy mean MPH moves deeper into the atmosphere.

As it is seen from the CORSIKA [11] simulation results shown in Fig. 4 muons from a given production height carry to the observation level a certain mean value of ρ and η, irrespective to the primary type and energy. Having in mind Fig. 3 we conclude, that radial angles and pseudorapidity of muons in the showers are parameters sensitive to the longitudinal shower development. Therefore, they can be used to test the hadronic interaction models.

III. Experimental data and simulation results

The MTD data collected in the period from March 2004 to November 2008 have been used to reconstruct muon mean radial angles and mean muon pseudorapidities. Vertical showers ($\theta \leq 18°$) with the size $\lg N_e > 6$ have been selected. The fiducial area for core positions was: -550 m $\leq x_{core} \leq$ 50 m and -580 m $\leq y_{core} \leq$ 20 m.

Then the lateral distributions of those two quantities have been obtained and compared with the results reconstructed out of the simulated data for two primary species: proton and iron. The simulations were done with CORSIKA code using the QGSJETII model [12] for high energy interactions above 200 GeV and FLUKA2006 [13] below that energy.

In Fig. 5 experimental and simulated radial angle lateral distributions are compared. The comparison is done in limited ranges of muon distances to the core, where the saturation effects (seen below 150 m) and trigger inefficiencies (seen above 400 m) are not present. The lines are linear fits to the simulation results. The error bars in the simulations are still too large and the number of simulated data will be increased, thus the results are marked ”Preliminary”.

We can conclude here that the experimental data is compatible with the CORSIKA simulations done using QGSJETII - FLUKA model combination - data points are in-between the simulated ones. Similar concusions about intrinsic consistency of these models is found in [14]. We can also notice that experimental data tend to be positioned closer to the radial angles in iron initiated showers rather than proton ones.

In Fig. 6 lateral distributions of mean muon pseudorapidity for the same data sets, experimental and simulated, are compared. Here, one can also conclude that the experimental data points are bracketed by the simulated distributions showing compatibility of the simulations with the experiment, same as it is in the case of radial angles, discussed above.

However, there is one striking difference in this figure compared to Fig. 5. The data points here are closer to the proton simulation results rather than to the iron ones, as it is in the case of radial angle distribution. And for the shower sizes in our investigation one would really expect the result being shown by the radial angle distributions (at primary energies in the region of $10^{16} eV$ and above rather heavier than lighter composition is seen in the analyses of many other shower parameters).

This difference may be an indication of the features of the models. Mean radial angle distribution (Fig. 5) suggests that the transverse momentum of pions produced in hadronic interactions is reproduced by the models in a way close to the reality.

On the other hand, Fig. 6 shows that the rapidity of those pions is in simulations too large, by 0.05 - 0.1 in the mean values.

Mean radial angles and mean pseudorapidities of muons registered by the MTD in a given distance range from the shower core are quantities sensitive to the primary mass (what was shown also in section II).

However, for the investigation of the mass composition (e.g. in terms of the determination of the $<$lnA$>$ parameter) with the model combination used in this research, one should rather wait for the increased statistics of Monte-Carlo simulations.

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