# Investigation of the Muon Pseudorapidities in EAS with the Muon Tracking Detector of the KASCADE Experiment

J. Zabierowski[5], T. Antoni[1], W.D. Apel[2], F. Badea[1,a], K. Bekk[2], A. Bercuci[2,a], H. Blümer[1,2], H. Bozdog[2], I.M. Brancus[3], C. Büttner[1], A. Chilingarian[4], K. Daumiller[1], P. Doll[2], R. Engel[2], J. Engler[2], F. Feßler[2], H.J. Gils[2], R. Glasstetter[1,b] A. Haungs[2], D. Heck[2], J.R. Hörandel[1], A. Iwan[5], K-H. Kampert[1,2,b] H.O. Klages[2], G. Maier[2], H.J. Mathes[2], H.J. Mayer[2], J. Milke[2], M. Müller[2], R. Obenland[2], J. Oehlschläger[2], S. Ostapchenko[1,c], M. Petcu[3], H. Rebel[2], M. Risse[2], M. Roth[1], G. Schatz[2], H. Schieler[2], J. Scholz[2], T. Thouw[2], H. Ulrich[2], J. van Buren[2], A. Vardanyan[4], A. Weindl[2], J. Wochele[2]

*(1) Institut für Exp. Kernphysik, Universität Karlsruhe, 76021 Karlsruhe, Germany*
*(2) Institut für Kernphysik, Forschungszentrum Karlsruhe, 76021 Karlsruhe, Germany*
*(3) National Institute of Physics and Nuclear Engineering, 7690 Bucharest, Romania*
*(4) Cosmic Ray Division, Yerevan Physics Institute, Yerevan 36, Armenia*
*(5) Soltan Institute for Nuclear Studies, 90950 Lodz, Poland*
[a] *on leave of absence from (3)*
[b] *now at: Universität Wuppertal, 42097 Wuppertal, Germany*
[c] *on leave of absence from Moscow State University, 119899 Moscow, Russia*

## Abstract

High angular accuracy of muon track measurements in KASCADE Muon Tracking Detector (MTD), together with the high precision in determination of the shower direction and shower core position, allow to investigate the pseudorapidity of muons in EAS using the concept of radial and tangential angles. Preliminary results of the pseudorapidity distribution of muons registered by the KASCADE experiment are presented. Mean muon pseudorapidity values at different stages of the longitudinal development of the EAS cascade are calculated using additionally the reconstructed muon production height provided by the MTD data. Experimental results are compared with Monte Carlo simulations.

## 1. Introduction

The KASCADE experiment [1] with its large Muon Tracking Detector (MTD) [4] allows to measure directions of muons in air showers using the concept of tangential ($\tau$) and radial ($\rho$) angles [2,3]. This directional information, as shown in [9], gives also possibility to investigate momentum components of shower muons and, in particular, their pseudorapidities. The parameter $\zeta$, a certain combination of $\tau$ and $\rho$ introduced in [9], is equal to the ratio of transversal to longitudinal momentum components of the muon with respect to the shower direction (for

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pp. 29–32

$|\tau| \leq 0.4$ rad and $|\rho| \leq 0.4$ rad):

$$\zeta \equiv \sqrt{\tau^2 + \rho^2} = \frac{p_t}{p_\parallel} \tag{1}$$

Hence, the pseudorapidity $\eta$ of muons with energy $> 0.8$ GeV (MTD threshold) can be expressed as follows:

$$\eta = \ln \frac{2 \times p_\parallel}{p_t} \approx -\ln \frac{\zeta}{2} \tag{2}$$

## 2. Results and discussion

For the analysis KASCADE data registered in the period between November 2000 and October 2002 have been used. In addition, showers simulated with CORSIKA [7] (v.5.644 using QGSJet98 [8] and v.5.946 using neXus2 [5] - with GHEISHA [6] for low energy hadronic interactions in both cases) and full detector Monte Carlo (CRES 1.15/08) were used for testing model predictions. All simulations were done with differential energy spectrum index -2.0 and events were weighted to match the experimental spectrum index -2.7 in the energy region below the knee. No knee structure was assumed here. Muon tracks were measured in the range 20 - 160 m from the shower axis. Only showers with zenith angle $\theta \leq 22°$ were considered.

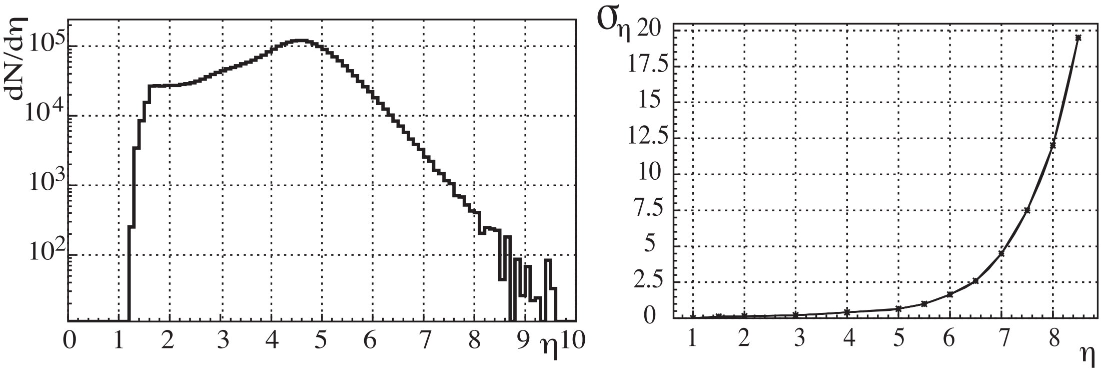

**Fig. 1.** Pseudorapidity distribution of EAS muons registered in MTD (left) and error in determination of $\eta$ as a function of $\eta$ value (right).

In Fig. 1. pseudorapidity ($\eta$) distribution of muons (in shower coordinates) registered by KASCADE for all $N_\mu^{tr}$ values is plotted. With respect to the pure CORSIKA results [9] the 20 m distance limit reduces the number of entries in the range of high rapidities and cuts away values above 9.5. In the lower end of the distribution the limits on $\tau$ and $\rho$ values, as well as 160 m muon-shower core distance limit, show their influence. Even with very good KASCADE resolution of shower direction ($\approx 0.2°$) and muon track ($\approx 0.35°$) the errors in determination of $\eta \geq 6$ (see Fig. 1) become prohibitively large. However, due to large statistics,

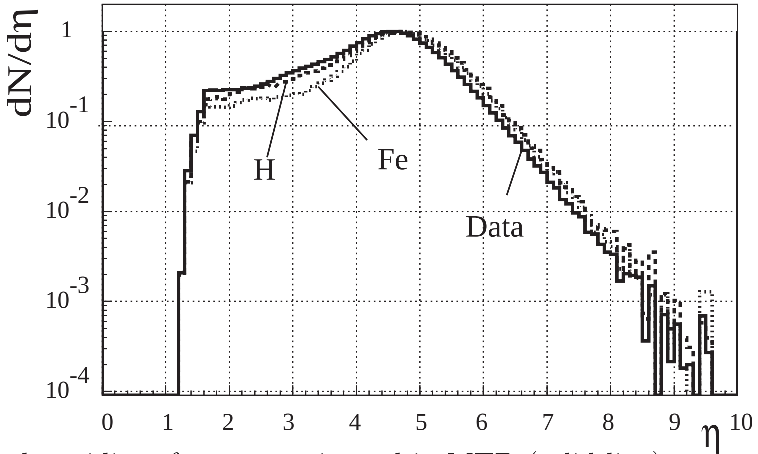

**Fig. 2.** Pseudorapidity of muons registered in MTD (solid line) compared with simulations using QGSJet model for two primary types: protons (dashed) and iron nuclei (dotted).

errors of mean values are still very small and up to $\eta \approx 8.5$ mean pseudorapidity can be investigated. As an example, in Fig. 2., the pseudorapidity distributions of EAS muons for all $N_{\mu}^{tr}$ values (normalized to the maximum) were compared with the simulations. No differences between results of the two models used were found, so only QGSJet distributions are shown. One observes a shift of the experimental distribution towards lower values with respect to the simulated ones. It may indicate, either underestimation of the mean muon transverse momentum in the parent meson decay reaction or/and overestimation of the longitudinal momentum component of created muons. In the large psedorapidity region (above the maximum) one finds no sensitivity of this variable to the primary mass. On the contrary, below $\eta \leq$4.5 simulations predict different behaviour of the distribution for protons and iron nuclei.

The pseudorapidity distribution of muons registered on ground is only slightly shifted towards lower values with respect to the distribution at creation. Therefore, it may be a useful probe of high energy hadronic interactions in which pions and kaons are produced, decaying next in a weak process into muons.

For this reason it may be of interest to investigate the pseudorapidity profile of muons in the longitudinal development of showers. The muon production height (MPH) can also be calculated using $\zeta$ parameter, which is a measure of the muon angle to the shower axis, and the event geometry. Mean values of MPH, as shown in ref.[9], are very well reproduced by this method. In Fig. 3. experimental longitudinal profiles of mean muon pseudorapidity in EAS for two $N_{\mu}^{tr}$ ranges are shown. Up to the ≈10 km where, due to the large statistics of muons, accuracy in determination of MPH is better than 100 m, the logarithmic dependence of $\eta$ on MPH is observed with a change in slope at altitude ≈ 2 - 3 km. Above ≈10 km the errors become much larger and it is hard to make any quantitative conclusions.

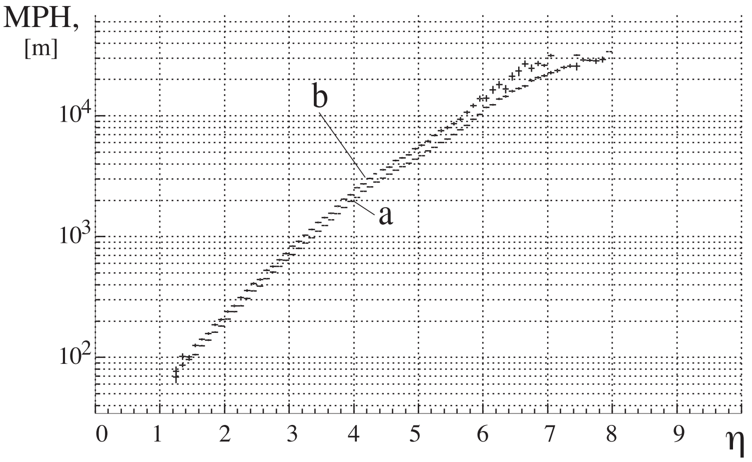

**Fig. 3.** Relation between mean muon pseudorapidity and their mean production height for experimental data with $N_\mu^{tr}$=3.8-4.0 (a) and $N_\mu^{tr}$=4.4-4.6 (b)

## 3. Conclusions

Precise measurements of muon directions with respect to the shower axis allow to investigate muon pseudorapidities in EAS and to test hadronic interaction models (high and low energy). Muon pseudorapidity profiles in the longitudinal development of EAS may give another point of view on the extended air shower physics. Presented distributions are just a few examples out of large variety of possible investigations of muon pseudorapidity in EAS (dependence on the zenith angle, shower size, primary type and energy etc.). Tests of other models like newer versions of QGSJet and neXus are of particular interest also. The investigation of high $\eta$ values requires muons registered close to the shower core, which is very difficult. In the KASCADE-Grande setup, due to the larger muon-shower core distances available, there will be much more statistics in the region of low $\eta$ values and higher muon production altitudes can be accessed for investigation of longitudinal shower development with reasonable errors.

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1. Antoni T. et al., KASCADE Collaboration, 2003, NIM A, submitted
2. Bernlöhr K. 1996, Astropart. Phys. 5, 139
3. Büttner C. et al., 2003, Proc.28$^{th}$ ICRC, these proceedings
4. Doll P. et al., 2002, NIM A 488, 517
5. Drescher H.J. et al., 2001, Phys. Rep. 350, 93
6. Fesefeldt H. Report PITHA-85/02, RWTH Aachen, 1985
7. Heck D. et al., 1998, FZKA 6019, Forschungszentrum Karlsruhe
8. Kalmykov N.N. and Ostapchenko S.S. 1993,Yad. Fiz. 56, 105
9. Zabierowski J., Daumiller K. and Doll P., astro-ph/0211568, to appear in Nucl. Phys.B (Proc.Suppl), 2003