Muon Production Height from the Muon Tracking Detector in KASCADE

C. Büttner[1], 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], 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], J. Zabierowski[5]

(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

The Muon Tracking Detector (MTD; E_μ^{th}=0.8 GeV) [5] of the KASCADE-Grande experiment enables the analysis of the longitudinal shower development by means of the Muon Production Height (MPH). The analysis employes radial and tangential angles of the muon track with respect to the shower direction, and the distance of the muon hit to the shower core. Comparing analysed MPH distributions with Monte Carlo simulations (CORSIKA) [6] an increase of $\langle ln\ A \rangle$ of the primary cosmic rays with $\lg(N_\mu^{tr})$ is observed.

1. Radial and Tangential Angles

Due to transverse momentum of pions in EAS, causing a displacement of the origin of muons from the shower axis, and due to multiple scattering in the atmosphere, muons form an angle in space with the shower axis. To describe the orientation of muon tracks with respect to the shower axis, radial and tangential angles are employed [3]. Zabierowski et al. [8] investigate a transformation of those angles into a pseudorapidity type quantity for shower muons. Both angles are studied with respect to $\lg(N_\mu^{tr})$ which corresponds to the total number of muons that are within 40-200m of the KASCADE array and which represents [7] an approximate energy estimator of the primary cosmic ray.

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The tangential angle provides a measure of the transverse displacement of the muon direction with respect to the shower axis. The tangential angle distribution is symmetric around zero and exhibits a narrow Gaussian distribution sitting on a broad distribution. The narrow component is attributed to the combined effect of the MTD-Array angle resolution. CORSIKA simulations allow to derive the contribution from multiple scattering in the atmosphere for muons which amounts to 0.5-0.2° for muon energies between 1-10GeV. For large values of lg(N_μ^{tr}) of about 5, the width of the narrow Gaussian approaches 0.3°. To reduce the influence of low energy particles the tangential angle was limited to ±0.7° for the analysis.

The distributions of radial angles are asymmetric as shown in Fig. 1 (left) because the radial angle is directly correlated with the MPH. With larger muon number lg(N_μ^{tr}), i.e. larger energy [7], the mean radial angle Fig.1 (right) moves to higher values as the shower maximum develops deeper into the atmosphere.

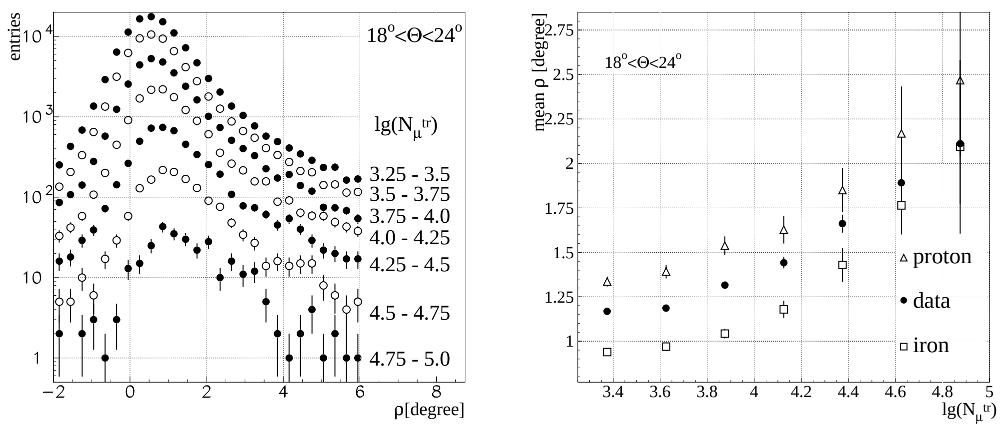

Fig. 1. Radial angle distributions and their mean value dependence on $lg(N_\mu^{tr})$

1.1. Analysis

Shower simulations are based on the CORSIKA program (version 5.644 with QGSJet(1998) and version 5.948 with NEXUS2) and are followed by simulations of the detector elements of the Array and the MTD. In the energy range of 10^{14}eV to 10^{17}eV with zenith angles up to 42° about 560000 showers each for proton, and iron have been simulated in the case of QGSJet and about 360000 showers each in the case of NEXUS. All simulations were done with an $E^{-2.0}$ differential flux spectrum [4] and appropriate event weights (e.g. $\propto E^{-0.7}$) were applied to match the spectrum in the energy region below the knee.

As QGSJet and NEXUS exhibit only few percent differences in the observables presented here, Figs. 1 and 2 (right) show only comparisons with NEXUS calculations. The Monte Carlo simulations show that, in average, proton induced EAS penetrate deeper in the atmosphere than iron induced EAS at same primary energy. The distributions of radial angles that are plotted in Fig. 1 exhibit a tail to negative values but for calculation of MPH (h_μ in Fig. 2) only positive values of radial angles are used. Further analyses should investigate the influence of negative radial angles on MPH distributions, also with respect to the finite angle resolution of the MTD-Array system.

2. Production Height

The MPH is calculated by triangulation, and taking into account the displacement (tangential angle) of the muons from the shower axis. In Fig. 2 MPH distributions and their mean value dependence on $lg(N_\mu^{tr})$ are shown. The measured distributions (left) are described by weighted distributions of proton and iron simulations. The measured mean values Fig. 2 (right) exhibit a trend from the the proton to the iron simulations with increasing $lg(N_\mu^{tr})$.

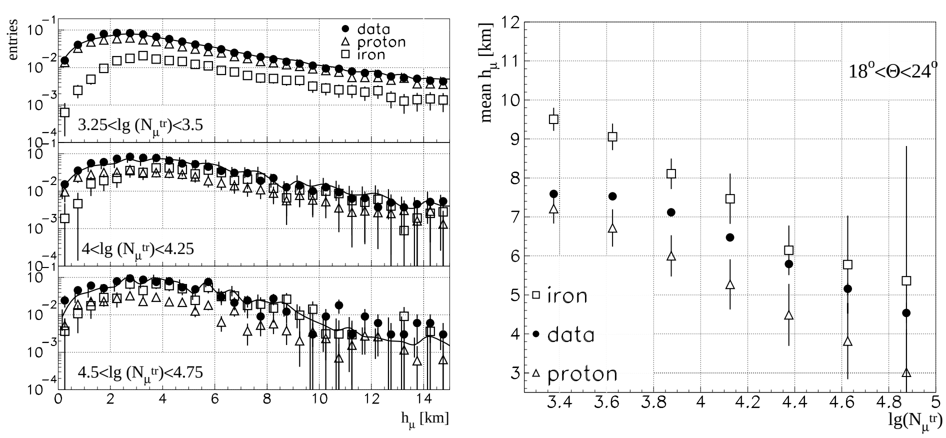

Fig. 2. Production height distributions and their mean value dependence on $lg(N_\mu^{tr})$

3. Production Depth

Comparing the mean radial angles in Fig. 1 (right) and the mean h_μ (MPH) in Fig. 2 (right) with CORSIKA simulations, an increase of $\langle ln\ A\rangle$ of the primary cosmic rays with $lg(N_\mu^{tr})$ is derived as presented in Fig. 3 (left). Badea et al. [2] investigate the influence of the muon track observables on the cosmic ray composition in a Bayesian approach.

In Fig. 3 (right) an atmospheric depth – calculated by using the MPH and the values of the US-standard-atmosphere – in dependence on primary energy [7] is shown. The mean muon production depth (MPD) can be compared with the mean atmospheric depth deduced from Čerenkov light [1], which is assumed to represent the depth of the maximum shower development. Those experiments seem to reveal a deeper maximum shower development than the findings with the MTD. The muon tracking analysis may be more sensitive to higher energy interactions in the earlier steps of the shower development. The experiments lie between the boundaries of the simulations, each.

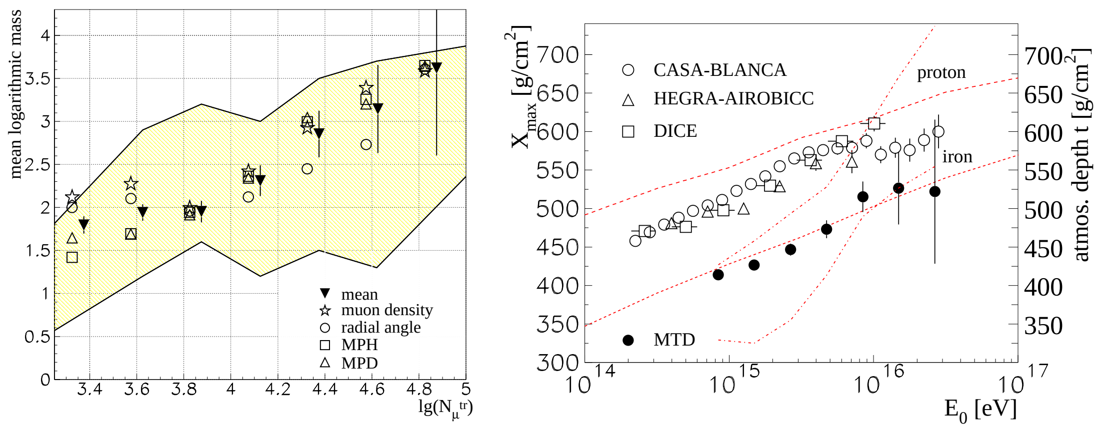

Fig. 3. Mean mass (preliminary) within the range of previous analyses and X_{max} and muon production depth within model (QGSJet) predictions, each.

4. Conclusion

The MTD of the KASCADE-Grande experiment enables the analysis of the longitudinal shower development by means of the MPH. In the meantime the MTD has been upgraded for improved track resolution valuable for high energy muons which are selected by narrow tangential angle cuts.

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