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ScienceDirect
Nuclear Physics B (Proc. Suppl.) 196 (2009) 305–308
NUCLEAR PHYSICS B PROCEEDINGS SUPPLEMENTS
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Muon Production Height investigated by the Air-Shower Experiment KASCADE-Grande

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A large area ($128m^2$) Muon Tracking Detector (MTD), located within the KASCADE experiment, has been built with the aim to identify muons (E_μ >0.8GeV) and their directions in extensive air showers by track measurements under more than 18 r.l. shielding. The orientation of the muon track with respect to the shower axis is expressed in terms of the radial- and tangential angles. By means of triangulation the muon production height H_μ is determined. By means of H_μ, a transition from light to heavy cosmic ray primary particles with increasing shower energy E_o from 1-10 PeV is observed.

1. Introduction

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 [1]. Muons are produced mainly by charged pions and kaons in a wide energy range and are not always produced close to the shower axis. Multiple Coulomb scattering in the atmosphere and in the detector shielding may change the muon direction. It is evident that the reconstruction of the longitudinal development of the

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**Support by DAAD and Polish Ministry of Science and Higher Education PPP grant for the years 2007-2008 is kindly acknowledged.

0920-5632/$ – see front matter © 2009 Published by Elsevier B.V.
doi:10.1016/j.nuclphysbps.2009.09.059

muon component by means of triangulation [2,3] provides a powerful tool for primary mass measurement, giving an information similar to that obtained with the Fly's Eye experiment, but in the energy range not accessible by the detection of fluorescence light. Muon tracking also allows the study of hadron interactions by means of the muon pseudorapidity [6]. Already in the past, analytical tools have been developed which describe the transformation between shower observables recorded on the observation level and observables which represent directly the longitudinal shower development [4]. Fig. 1 in the contribution of J.Zabierowski et al. [5] to this 15th. ISVHECRI conference shows the experimental environment. Measured core position distributions for showers inside KASCADE range from 40m-140m and inside Grande from 140m-360m. These core positions stay away from the MTD more than 40m for KASCADE for shower energies $\simeq 10^{14}eV - 10^{16}eV$ and more than 140m for Grande for shower energies $\simeq 10^{16}eV - 10^{18}eV$. The shower core distribution for Grande covers full trigger efficiency in the Grande specific energy range as confirmed by investigations of muon lateral density distributions [8].

2. Muon Production Height

Usually, X_{max} is the atmospheric depth at which the electrons and photons of the air shower reach their maximum numbers and is considered to be mass A sensitive [9]. Concerning muons which stem dominantly from $\pi^{\pm}$ decays, the corresponding height where most muons are created may also provide a mass A sensitive observable. For X_{max}, Matthews [10] in a phenomenological ansatz gives for the e.m. part the elongation rate of $\sim 60gcm^{-2}$ per decade which is in a good agreement with simulations. For the X_{max} value for nuclei ref. [10] reports: $X^A_{max} = X^p_{max} - X_o ln(A)$ (X_o, radiation length in air), therefore, X_{max} from iron showers is $\sim 150gcm^{-2}$ higher than X_{max} from proton showers at all energies. With the integral number of muons for a proton or nucleus A induced shower:

$$N_\mu \sim E_0^\beta \qquad or \qquad N_\mu^A \sim A(E_A/A)^\beta \tag{1}$$

we assume that $\langle H_\mu \rangle$ exhibits a similar $\lg(N_e)$ and $\lg(N_\mu^{tr})$ dependence as X_{max} and further $\lg(N_\mu^{tr}) \simeq \lg(N_\mu)$-0.5. Note however, $\langle H_\mu \rangle$, because of the long tails in the H_μ distribution towards large heights can be systematically higher than the muon production height, where most of the muons are created in a shower. Some energetic muons may stem from the first interaction and survive down to the MTD detector plane. The almost mass A independent energy assignment in equation (2)was employed.

$$lgE_0[GeV] = 0.19lg(N_e) + 0.79lg(N_\mu^{tr}) + 2.33 \tag{2}$$

The shower development leads also to various fluctuations in those shower parameters.

For the following analysis the elongation rate was given the value $70gcm^{-2}$ per decade in $\lg(N_\mu^{tr})$. After subtracting from each track the 'energy' dependent penetration depth

$$H_\mu^A = H_\mu - 70gcm^{-2}lg(N_\mu^{tr}) + 20gcm^{-2}lg(N_e) \tag{3}$$

the remaining depth H_μ^A may exhibit the mass A dependence.

The correction with the electron size $lg(N_e)$ in equation (3) should be of opposite sign because of fluctuations to larger size for this variable (X_{max} also fluctuates to larger values).

Investigating the distribution of the parameters more closely, Fig. 1 shows $H_\mu[km]$ distributions for fixed muon number bins which vary with shower energy. The muon production heights H_μ are plotted for light and heavy primary mass enriched showers, employing the $lg(N_\mu)/lg(N_e)$ ratio to be larger or smaller than 0.84 as indicated by the solid line in Fig. 2. The distributions exhibit a striking dependence on the primary mass range and become narrower with increasing muon size, however, in a different manner for light and heavy primary mass enriched showers. Further, it is known from earlier studies, that the $lg(N_e)$ parameter exhibits fluctuations to large values in agreement with simulations while the $lg(N_\mu^{tr})$ parameter exhibits little fluctuations. In contrary, the H_μ parameter in Fig. 1 is fluctuating to large heights i.e. smaller values (gcm^{-2}). Therefore, we may argue that the fluctuations in the corrections for H_μ for the elongation rate will cancel

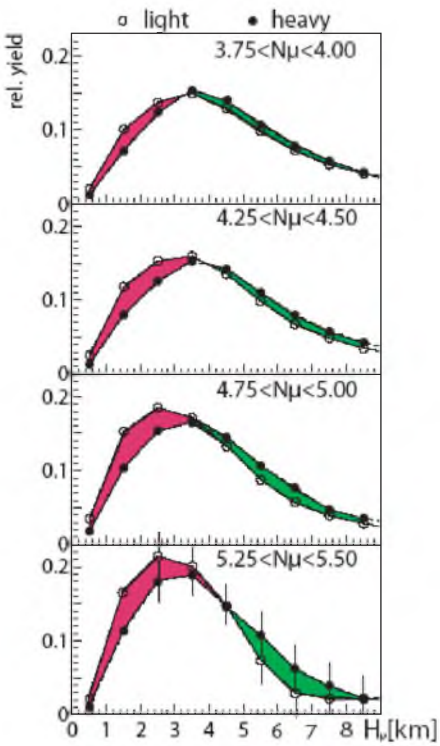

Figure 1. Muon production height distributions for different muon size lg(N_μ) bins and a shower core distance range 80m-120m and different $lg(N_\mu)/lg(N_e)$ ratio above (light)and below (heavy) the solid line in Fig. 2. Colours emphasize the strong mass dependence.

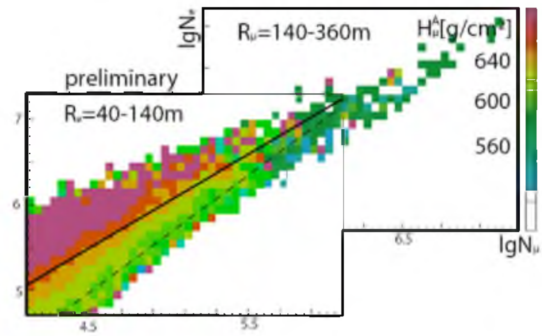

Figure 2. Effective muon production height H_μ^A in the 2-parameter presentation $lg(N_e) - lg(N_\mu)$ for $0^o - 18^o$. Pictures are overlayed for separate KASCADE and Grande analyses, respectively.

to some extent and, therefore, the resulting mass A dependent muon production height H_μ^A represents a stable mass A observable.

Fig. 2 shows the regions of different mass A dependent mean muon production height $\langle H_\mu^A \rangle$ in the 2-parameter $lg(N_e) - lg(N_\mu)$ space. H_μ^A in Fig. 2 is the mean $\langle H_\mu^A \rangle$ per muon track in the MTD and per shower. The picture shows regions of distinct $\langle H_\mu^A \rangle$ in a colour code with a $40gcm^{-2}$ step size. The borders between different regions are for some cases marked with lines which exhibit a slope in the $lg(N_e) - lg(N_\mu^{tr})$ plane. While in the middle of the distribution the slope confirms the previously employed slope $lg(N_\mu) = 0.84(\pm 0.01)lg(N_e)$ for selecting light or heavy primary particles, modified slopes may be recognized for regions away from the middle of the ridge. The slope for the $600gcm^{-2}$ line comes close to the slope of the air-shower simulations employed in [11]. Note also that the number of tracks increases with energy and exhibit a specific mass A dependent rise, which is under study.

The lines obtain their slope from the muon number-energy relation in equation (1) combined with equation (2). There, the exponent is according to ref. [10] connected to the amount of inelasticity κ (fraction of energy used up for π production) involved in the processes of the A-air collisions. A comparatively steeper slope $\beta = (1 - 0.14\kappa)$ [10], corresponds to an increased inelasticity. Such slopes may provide an extra hint for different air interactions for different primary cosmic ray species. The correction in equation (3) depending on $lg(N_e)$ and $lg(N_\mu^{tr})$ was found appropriate to get the slope of the H_μ^A profile in the 2-parameter $lg(N_e) - lg(N_\mu)$ presentation (Fig. 2). Differences between two different models in ref. [11] amount to about $20gcm^{-2}$ on the H_μ^A scale.

Sorting the $lg(N_e) - lg(N_\mu^{tr})$ events by their range in H_μ^A and employing for the same event the mass A independent equation (2) for KASCADE and a corresponding equation for Grande [7] for $lgE_o[GeV]$, energy spectra are obtained

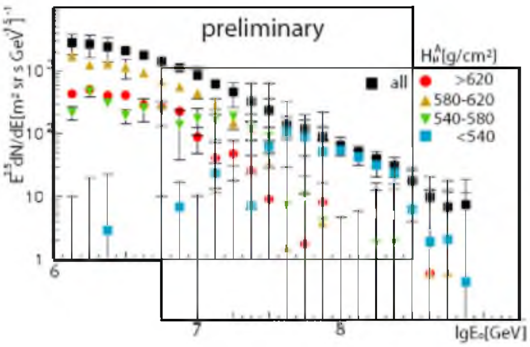

Figure 3. Energy spectra for different muon production height H_μ^A intervals for $0^o - 18^o$. Pictures are overlayed for separate KASCADE and Grande analyses, respectively.

and given in Fig. 3. The spectra do not exhibit a strong knee structure when based on the preliminary elongation rate parameters in equation (3). So far, no explicit mass range assignment is given as would be motivated by the equation $X^A_{max} = X^p_{max} - X_o ln(A)$, ($X_o$, radiation length in air). The spectra in Fig. 3 together with their preliminary error estimations are almost model independent. The preliminary spectra reveal distinct features. While low mass spectra show a rapid drop with increasing shower energy, medium mass and heavy mass spectra seem to overtake at large primary energy. Systematic errors dominate the low and high energy bins for KASCADE and Grande, respectively, and are the subject of further investigations. In the KASCADE analysis the detection threshold of the MTD may be effective and a fraction of tracks may be missing leading to a light particle mass interpretation. For the large Grande geometry some flux loss for low energy muons may lead to a bias towards large primary mass.

3. Conclusions

Triangulation of muon tracks with respect to the shower direction allows to investigate H_μ. Future analysis of other shower angle bins and a larger and improved quality data sample will provide more detailed information on the nature of high energy shower muons. Also muon multiplicities provide valuable parameters to derive the relative contributions of different primary cosmic ray particles. A natural extension towards even larger shower energies is provided by KASCADE-Grande [12]. There is a common understanding that the high energy shower muons serve as sensitive probes to investigate the high energy hadronic interactions in the EAS development [5,6]. Very inclined muons which can be studied with tracks recorded by the wall modules of the MTD are currently of vital interest.

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