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Muon Production Height in the Air-Shower Experiment KASCADE-Grande

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Abstract: 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, transition from light to heavy cosmic ray primary particle with increasing shower energy E_o from 1-10 PeV is observed.

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 telescopes [1]. Muons are produced mainly by charged pions and kaons in a wide energy range. They must not always be produced directly on the shower axis. The multiple Coulomb scattering in the atmosphere and in the detector shielding also change the muon direction. It is evident that the reconstruction of the longitudinal development of the muon component by means of triangulation [2, 3] provides a powerful tool for primary mass measurement and for the study of high-energy hadron interactions with the atmospheric nuclei, giving the information similar to that obtained with the Fly's Eye experiment, but in the energy range not accessible by the detection of fluorescent light. Muon tracking allows also the study of hadron interactions by means of the muon pseudorapitity [4]. 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 the longitudinal shower development [5]. Fig. 1 shows the experimental environment.

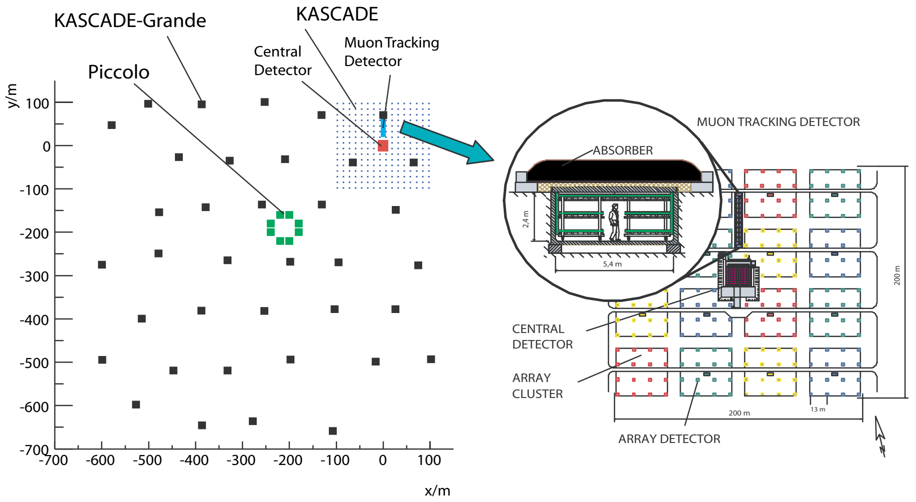

Figure 1: Schematic view of the KASCADE-Grande experiment with some details on the Muon Tracking Detector (MTD).

Muon Production Height over Electron and Muon Size

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 [6]. 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 [7] in a phenomenological ansatz gives for the e.m. part the elongation rate of $85gcm^{-2}$ per decade (lg=log10) which is in a good agreement with simulations. For the X_{max} value for nuclei ref. [7] 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:

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

and

$$X_{max} \sim lg(E_0) \qquad (2)$$

we assume that $\langle H_\mu \rangle$ exhibits a similar lg(N_e) and lg(N_μ^{tr}) dependence as X_{max}. Note however, $\langle H_\mu \rangle$, because of the long tails in the H_μ distribution towards small (gcm^{-2}) 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 elongation rate D_μ becomes

$$D_\mu = \delta\langle H_\mu \rangle / \delta lg N_\mu^A \qquad (3)$$

The almost mass A independent energy assignment in equation [4] was employed.

$$lgE_0[GeV] = 0.19lg(N_e) + 0.79lg(N_\mu^{tr}) + 2.33 \qquad (4)$$

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

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

$$H_\mu^A = H_\mu - 70gcm^{-2}lg(N_\mu^{tr}) + 20gcm^{-2}lg(N_e) \qquad (5)$$

the remaining depth H_μ^A should be giving the mass A dependence.

The correction with the electron size $lg(N_e)$ in equation [5] should be of opposite sign because of fluctuations to larger size for this variable (X_{max} also fluctuates to larger values).

Investigating in a closer look the distribution of the parameters involved in the correction for H_μ^A for

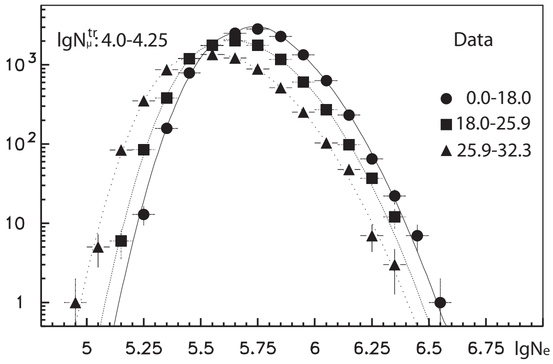

Figure 2: lg(N_e) size spectra for lg(N_μ^{tr})=4.0-4.25 and three zenith angle ranges.

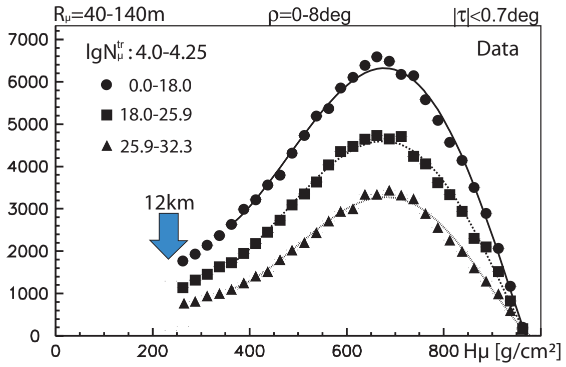

Figure 3: H_μ spectra for lg(N_μ^{tr})=4.0-4.25 and three zenith angle ranges.

the elongation rate, Fig. 2 shows how the electron size distributions for fixed muon number bin and three zenith angle bins vary with angle. In a similar way Fig. 3 shows muon production height distributions for the same shower parameters (below 12km were the errors are small). 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. 3 is fluctuating to smaller values (gcm^{-2}). Therefore, we may argue that the fluctuations in the corrections for H_μ for the elongation rate will cancel to some extent and, therefore, the resulting mass A dependent muon production height H_μ^A represents a stable mass A observable.

Fig. 4 shows the regions of different mass A dependent mean muon production height $\langle H_\mu^A \rangle$ in the 2 parameter space $lg(N_e) - lg(N_\mu^{tr})$. H_μ^A in Fig. 4 is the mean $\langle H_\mu^A \rangle$ per shower and any muon track in the MTD. The picture shows regions of distinct $\langle H_\mu^A \rangle$ in a color 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 $lg(N_\mu^{tr}) = 0.74(\pm 0.01) lg(N_e)$ 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 [8]. Note also that the number of tracks increase 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 [4]. There, the exponent is according to ref. [7] 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 $\beta = (1 - 0.14\kappa)$ [7], corresponds to an increased inelasticity. The correction in equation [5] 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 $lg(N_e) - lg(N_\mu^{tr})$ presentation (Fig. 4). Differences between 2 lines amount to $40gcm^{-2}$. Differences between two different models in ref. [8] 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 [4] for $lgE_o[GeV]$, energy spectra are obtained and given in Fig. 5. Sofar no explicit mass range assignment is given as would be motivated by the equation $X_{max}^A = X_{max}^p - X_o ln(A)$. The spectra in Fig. 5 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 and are a subject of further investigation. In the present analysis the

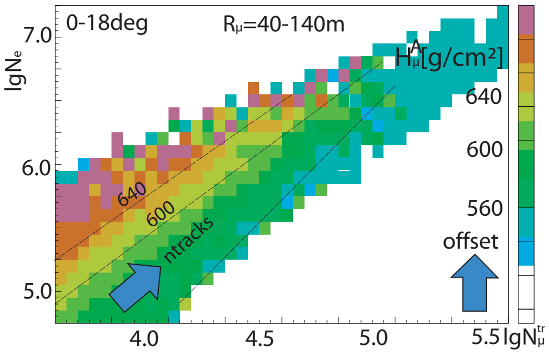

Figure 4: $lg(N_e) - lg(N_{\mu}^{tr})$ matrix with effective muon production height H_{μ}^{A} along the z-axis.

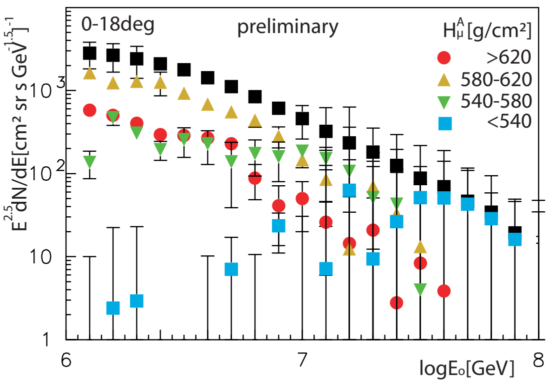

Figure 5: Energy spectra for different mass A groups which produce muons at different effective muon production height H_{μ}^{A}.

detection threshold of the MTD may be effective and a fraction of tracks may be missing leading to a light particle mass interpretation.

Conclusions

Triangulation allows to investigate H_{μ}. Future analysis of other shower angle bins and of larger and improved quality data sample will provide a 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 will be provided by KASCADE-Grande [9]. There is a common understanding that the high energy shower muons serve as sensitive probes to investigate [4] the high energy hadronic interactions in the EAS development. Very inclined muons which can be studied with tracks recorded by the wall modules of the MTD are currently of vital interest.

Acknowledgements

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