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Production heights of muons determined with the Muon Tracking Detector of the KASCADE experiment

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Abstract. The capability of the Muon Tracking Detector to measure the radial and tangential angles of muons in extensive air showers, in combination with the shower direction as determined by the scintillator array of KASCADE experiment, has been investigated. Due to different characteristics in shower development of light and heavy primary particles the radial angle is sensitive to the mass of them. For estimating the displacement of the muon from the shower axis the tangential angle is used. The average radial angle and the muon production height have been studied as a function of shower core distance, muon number, and zenith angle. To check the consistency of the results, they have been compared to simulations, which have been done using the Monte Carlo program CORSIKA with the hadronic interaction model QGSJet.

1 Introduction

The direct measurement of the primary cosmic ray flux above the atmosphere is the most powerful method to determine the composition, but the fluxes of particles in the energy range of the knee and above are so small that it is difficult to build a detector large enough to collect a good statistical data sample of cosmic rays. A sufficient collecting sample can be easily supplied by indirect detection of the cosmic rays through measurements of the extensive air showers (EAS) produced in the atmosphere.

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The KASCADE (**KA**rlsruhe **S**hower **C**ore and **A**rray **DE**tector) (Klages et al., 1997) experiment is built of different detectors that work in an independent way and can simultaneously measure many characteristics of EAS. A Muon Tracking Detector (MTD) (Atanasov et al., 2000; Zabierowski et al., 2001) is able to identify the direction of muons.

The measurement of angles of muons in EAS can be used for studying the mass composition of the primary cosmic rays (Linsley, 1986, 1992; Ambrosio et al., 1999), as the measured average radial angles are related to the longitudinal EAS development (Pentchev et al., 1999). These angles can be transformed into the Muon Production Height (MPH) taking into account the corresponding shower core distance. The derived MPH depends on the resolution of the shower core position (a function of the position within the scintillator array, the shower size, and the shower direction) and of the measured angles.

2 The Muon Tracking Detector

The MTD is located within the KASCADE experiment in a tunnel beneath a shielding of 18 r.l., giving an 0.8 GeV energy threshold for vertical incoming muons. 16 muon telescopes (*detector towers*) are arranged in two rows. One detector tower consists of four detector modules (each 2×4 m^2), three of them positioned horizontally with a spacing of 82 cm and the fourth arranged vertically at the wall (fig. 1). The detector modules are instrumented with streamer tubes (ST) (Doll et al., 1995) which have been developed to fulfill the purpose of the MTD in the best way. Influence strips (pitch of 2 cm, width of 1.8 cm) are positioned below (angle of 60^o to the ST wires) and above (perpendicular to the ST wires) the STs. A gas mixture of Ar-CO_2-C_4H_{10} 2:78:20 volume-% was used during the time of data taking from November 2000 to April 2001.

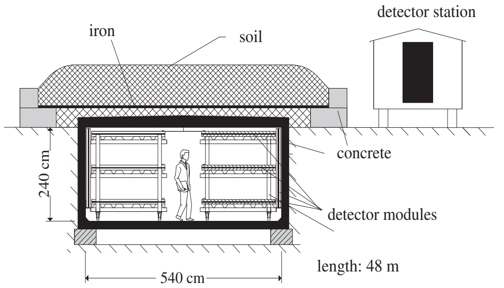

Fig. 1. Cross-section of the Muon Tracking Detector.

3 Definition of Radial and Tangential Angles

Due to the transverse momentum of the pions in EAS and multiple scattering in the atmosphere the muons form an angle in space with the shower axis. To describe the orientation of the muon track with respect to the shower axis radial and tangential angles are used (Bernlöhr, 1996).

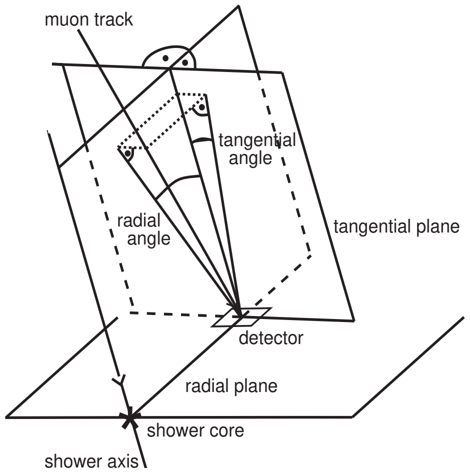

Fig. 2. Definition of radial and tangential angles.

The radial angle is defined as the angle between the direction of the shower axis and the projection of the muon track on the radial plane. The radial plane is subtended by the shower axis and the line connecting the shower core and the position, where the muon crosses the detector (fig. 2). The tangential plane is perpendicular to the radial plane, goes through the position of the muon and is parallel to the shower axis. The projection of the muon track on the tangential plane defines the tangential angle. The tangential angle gives a measure of transverse displacement of the muon direction with respect to the shower axis (Pentchev and Doll, 2001). Muons produced higher in the atmosphere may have a smaller transverse displacement (tangential angle) than those produced deeper, because of larger longitudinal momenta at the first interactions with the air nuclei.

4 Analysis

The *truncated muon number* (N_μ^{tr}), the shower direction, and the shower core postion are determined with the scintillator array of KASCADE. N_μ^{tr} is the muon size of the EAS measured by the scintillator array in the distance range from 40 to 200 m with respect to the centre. The reconstruction accuracy of the shower core position is around 3 m (depending on the shower size), of the shower angles it is better than 0.4°, and of $N_\mu^{tr} \approx 5\%$ (Weber, 1999).

For the present analysis the shower core has to be within a radial distance of 60 m around the centre of the scintillator array. As we want to investigate muons coming from high up in the atmosphere, which give some information about the place of the first interaction, the range of the tangential angle used for the analysis of the radial angle and the MPH is restricted to ± 0.7°, which corresponds to the average amount of scattering in the atmosphere and the absorber. To reconstruct radial and tangential angles with the parameters given by the scintillator array and the muon track of the MTD only such tracks have been used which hit the three horizontal modules of one tower (*3-hit tracks*).

4.1 Results from measured data

The radial angle has an asymmetric distribution (fig. 3(a)) with respect to the shower direction. Throughout this paper, a positive radial angle is assigned to a muon flying away from the shower axis. Due to the finite resolution of the detection system one should allow for some negative values. Here, radial angles down to -1° are taken into account. Most of the negative values correspond to muons which had been deflected inwards the shower axis due to multiple scattering.

Fig. 3(a) shows that for larger shower core distances the average radial angle exhibits larger values as for a fixed range of $3.25 < lg(N_\mu^{tr}) < 3.5$, muons can form larger angles originating from the same MPH.

Fig. 4 shows the median radial angle, determined including angle values starting from -1°, as a function of lg(N_μ^{tr}) for three ranges of shower core distances. With increasing lg(N_μ^{tr}) the median radial angle exhibits larger values. This behaviour is due to showers of higher energy which penetrate deeper in the atmosphere producing muons at larger average radial angles at fixed shower core distances. Another reason for the larger median radial angles with increasing lg(N_μ^{tr}) may be that it is more probable to find muons at larger shower core distances for larger lg(N_μ^{tr}). Also obvious in the different ranges of lg(N_μ^{tr}) are the larger median radial angles for larger shower core distances.

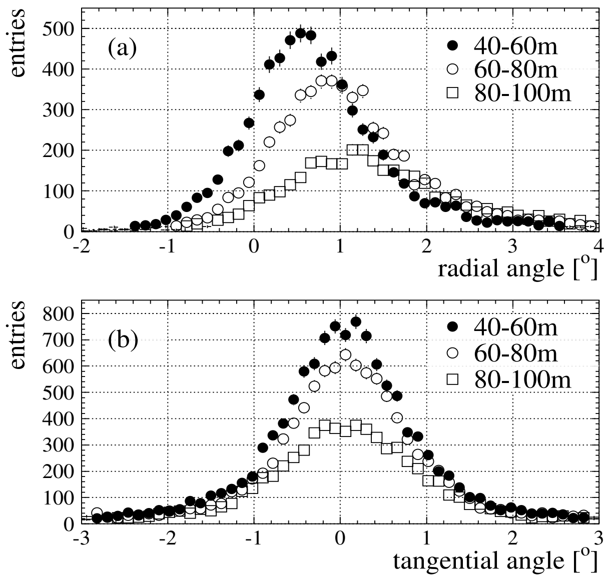

Fig. 3. Distributions of the radial angles (a) (tangential angles in the range from -0.7° to 0.7°) and the tangential angle (b) for three different ranges of shower core distance. Events with 3.25<$\lg(N_\mu^{tr})$ <3.5 and zenith angles of $0° < \Theta < 18°$ have been selected.

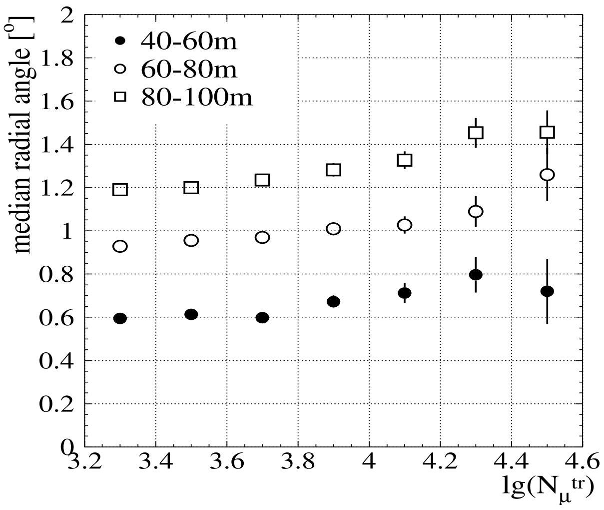

Fig. 4. Measured correlation between $\lg(N_\mu^{tr})$ and the median radial angle for three different ranges of core distance. Zenith angles of $0° < \Theta < 18°$ have been selected.

The tangential angle is symmetric around zero (fig. 3(b)), and the shape of its distribution is independent of the distance between shower core and muon. The spread of its distribution depends on the multiple scattering of the muons and on the resolution of the MTD and the scintillator array, as well as on the transversal displacement of the muon origin (fig. 5 in (Zabierowski et al., 2001)). The angular resolution of the MTD will be improved in the future (Obenland et al., 2001).

5 Comparison with Monte Carlo Simulations

Shower simulations are based on the CORSIKA program (Heck et al., 1998) in the version 5.644 with the interaction model QGSJet (Kalmykov et al., 1997). Shower simulations are followed by simulations of the scintillator array and the MTD (GEANT package, 1993). In total about 64200 proton and iron showers have been simulated in the energy range of $1 \cdot 10^{14}$ eV to $1 \cdot 10^{17}$ eV with zenith angles up to 42°. All simulations were done with an $E^{-2.0}$ differential flux spectrum and appropriate event weights (eg. $\propto E^{-0.7}$) were applied to match a desired flux spectrum. For the analysis of the simulations the same cuts as for measured data were used.

In fig. 5 the comparison of measured data, pure proton and pure iron induced showers is shown for a range of shower core distances from 40-60 m and for three ranges of $\lg(N_\mu^{tr})$ (3.25-3.5, 3.75-4, 4-4.25). With larger $\lg(N_\mu^{tr})$, i.e. larger energy, the average radial angle moves to higher values. The statistics for the Monte Carlo simulations is very limited, therefore, the data have been scaled down, in order to check if the lower and upper tails of the data distribution can be compared to the proton and iron simulations (no conclusive superposition to fit the data distributions is shown).

The low radial angle values in the data may be associated to some iron component in the cosmic ray particle flux, the large radial angle values seem to be dominated by the penetrating proton component. There is some indication, that the radial angles of the data exhibit a more pronounced tail to larger values than the model calculations. This may indicate a deeper penetration of the cosmic ray particles than can be obtained with the model calculations.

Fig. 6 shows the distribution of slant MPH for the same shower core distances and ranges of $\lg(N_\mu^{tr})$ as in fig. 5. The MPH was determined by simple triangulation and is based on a relatively accurate shower core distance. Like in fig. 5 no conclusive superposition is shown. For this future task the model distributions, because of their limited statistics, will be fitted by analytical functions like those developed by (Wibig and Wolfendale, 2000) providing the spectral shape of proton and iron distributions as a function of zenith angle, N_μ^{tr}, and shower core distance.

6 Conclusions and Outlook

It has been shown that the radial angle of muons and the reconstructed MPH are sensitive to the mass of the primary cosmic ray particles. The distributions of radial angle and MPH are available in all core distance intervals from 20-120 m, and zenith angles from 0-40° and should provide enough material to evaluate interaction model features (available in CORSIKA) and cosmic ray composition estimates.

The KASCADE-Grande upgrade (Bertaina et al., 2001), re-using scintillator counters of the EAS-TOP experiment, will enable the study of radial angles and MPH for much

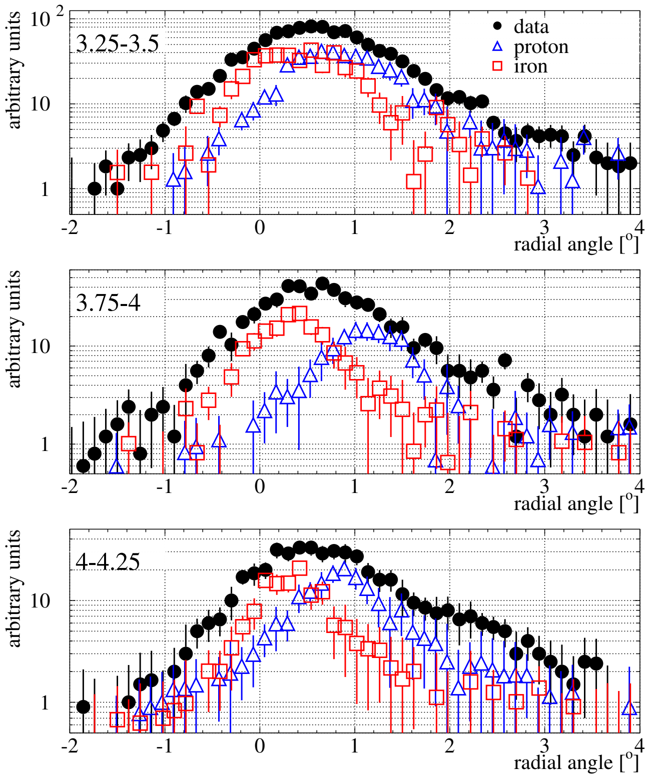

Fig. 5. Distribution of the radial angles for three different ranges of lg(N_{μ}^{tr}), shower core distances in the range of 40-60 m, zenith angles from 0-18°. Simulations are based on CORSIKA with hadron interaction model QGSJet.

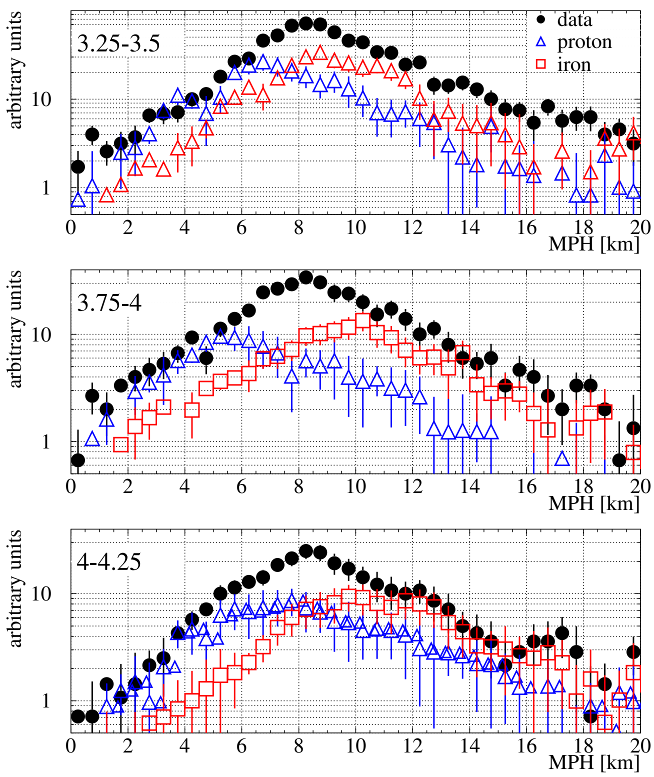

Fig. 6. Distribution of slant MPH for three different ranges of lg(N_{μ}^{tr}), shower core distances in the range of 40-60 m, zenith angles from 0-18°. Simulations are based on CORSIKA with hadron interaction model QGSJet.

larger shower core distances. This gives also the chance to investigate EAS with larger energies.

Comparisons with other experiments which use for example the Cherenkov light (Arqueros et al., 2000) or try to derive information on the elemental composition of the primary particles from the depth of shower maximum in the atmosphere and the muon and electron sizes from the ground array (Swordy et al., 2000) have to be done.

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