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The muon charge ratio in cosmic ray air showers

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Abstract: The muon charge ratio of the lateral muon density distributions in single Extended Air Showers (EAS) is studied on basis of Monte Carlo simulations, in view of proposals to measure this observable in coincidence with EAS observations. Differences of the azimuthal variation of the muon densities of opposite charges and the azimuthal variation of the muon charge ratio appear to be very much pronounced, dependent on the direction of the EAS incidence and the position of the observer in respect to the Earth's magnetic vector. The influence of the geomagnetic field, which induces comparable effects in radio emission from EAS, is obviously of great interest for understanding the shower development.

Introduction

The flux, the energy spectrum and the charge ratio of atmospheric muons, resulting from the decay of pions and kaons which are produced in collisions of primary cosmic rays with the air molecules, have been studied extensively over wide range of energies at sea level as well as on high mountain altitudes and during balloon ascents. The studies comprise several aspects, in particular they provide information on the composition of cosmic rays and on characteristic features of the hadronic interaction and of the influence of the geomagnetic field on the primary and secondary components of cosmic radiation. The investigations show that the ratio of the number of positive to negative atmospheric muons $R_{\mu}^{atm} = N_{\mu^+}/N_{\mu^-}$ is experimentally varying between the values of about 1.2 -1.3 [1]. As detailed analyses [2] show, the excess of the positive charge reflects mainly the excess of protons of primary cosmic rays and less eventual small differences of the production of positive and negative parent particles of the muons. The Earth's magnetic field influences the flux of primary cosmic rays entering the Earth atmosphere leading to the well-known East-West asymmetry and the latitude effect. In addition the geomagnetic field bends the trajectories of the charged particles of the secondary cosmic rays which get curved. The effect is particularly dominant for the muon component which is less affected by Coulomb scatterings processes. This leads to the East-West effect of the muon charge ratio: the observation that the ratio of positive and negative atmospheric muons proves to be different for muons arriving the spectroscopic device from West from those arriving from East direction (see [3], [4]). The finding originates from the fact that in the East-West plane due to different bendings, muons of positive and negative charges have different path lengths from the locus of production to the observer. Hence the decay probability of low energy muons is differently modified.

The features are slightly different for the muon charge ratio in Extensive Air Showers (EAS) whose axes have well defined angles (θ,Φ) of incidence, not only relative to the zenith direction, but also relative to the vector of the magnetic field of the Earth. The total charge ratio integrated over all muons of the EAS is only determined by the hadronic interaction and the decay of the parent particles, and no more by the composition of cosmic rays. However, due to various effects the lateral distribution $\rho(r, \phi)$ of the density of positive and negative muons and its charge ratio $R_{\mu}(r, \phi)$ vary radially (with the distance r from the EAS centre) as well as azimuthally (with the EAS intrinsic azimuth ϕ, counted clockwise in the horizontal

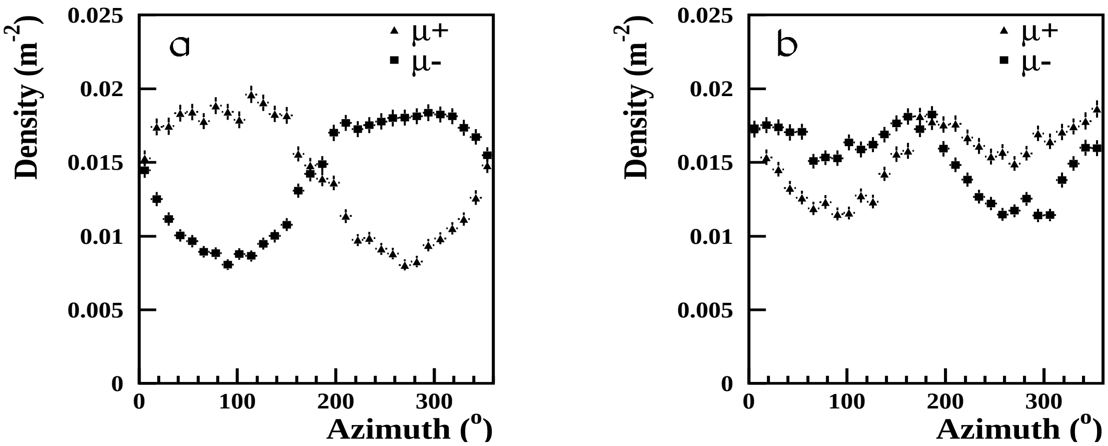

Figure 1: The mean azimuthal μ^+ and μ^- - distributions of proton induced inclined EAS (θ = 45^o) incident from (a) North and (b) South with the primary energy of 10^{15} eV at a distance of 45-50 m from the shower axis.

plane from the axis defined by the direction from the shower center towards North).

In this paper we study in particular the azimuthal variation of the lateral density distribution of EAS muons of both opposite charges separately and the resulting variation of the muon charge ratio. The studies are based on EAS simulations using the Monte Carlo simulation code CORSIKA (vers. 6.0) [5] (E_μ^{thres}=100 MeV). In order to be specific we demonstrate the main features by considering p and Fe induced EAS, with the primary energy of 10^{15} eV, incident with a zenith angle θ = 45^o, but comparing different azimuthal directions of incidence, in particular from North and from South. The magnetic inclination of observation locus (Karlsruhe) is adopted to be about 65^o with the magnetic field pointing downwards. The studies are in context of various actual [6] and future attempts [7] to measure the muon charge ratio with a spectroscopic device coupled to EAS observation by small detector arrays.

Azimuthal asymmetries in the lateral distribution of charged EAS particles

The origin of azimuthal asymmetries of the lateral distributions of charged EAS particles is mainly attributed to the attenuation and to geometrical effect of showers with inclined incidence. Assuming that the EAS starts from infinity and neglecting any influence of the geomagnetic field for the moment, we have cylindrical symmetry around the shower axis. For inclined showers incident to the observation plane, charged particles arriving first ("early" azimuthal region) experience less attenuation than particles arriving later ("late" azimuthal region) due to larger travel distances. Additionally there appear effects from the projection of the normal shower plane to the observational plane. It should be noted that the attenuation of the particle density is largely obscured and counter-balanced, when the measured particle densities are reconstructed from the measured energy deposits in scintillation detectors, since the dependence of the energy deposit per particle from the angle of particle incidence works in opposite direction.

Influence of the geomagnetic field on the azimuthal lateral μ^+ and μ^- - distributions

Figures 1 and 2 display some selective examples of the results for proton induced EAS observed in the observational plane as function of the azimuth an-

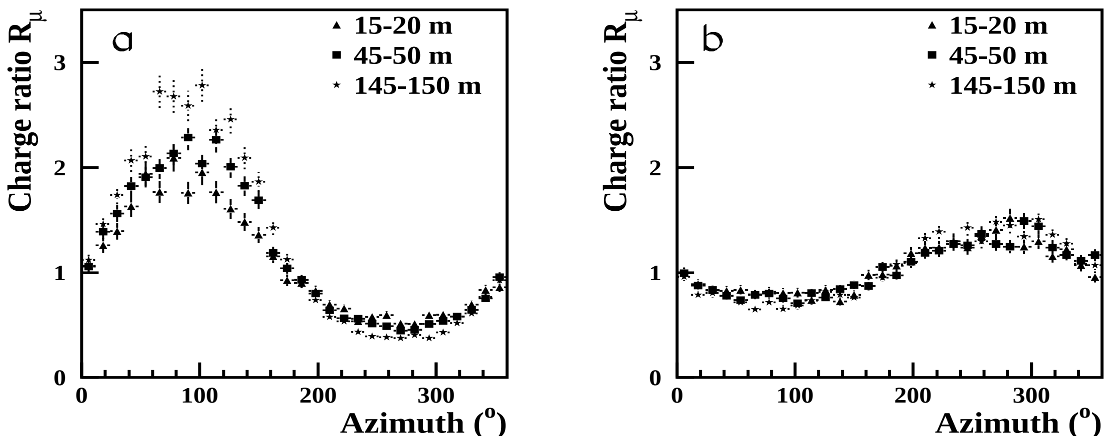

Figure 2: Azimuthal variation of the charge ratio $R_\mu(r, \phi)$ of the mean muon density distribution of proton induced inclined EAS (θ = 45^o) incident from (a) North and (b) South with the primary energy of 10^{15} eV at various distances $r(m)$ from the shower axis.

gle ϕ. Fe induced showers show similar features. The asymmetry for EAS incident from various directions can be explained by different relative angles to the Earth magnetic vector. When the geomagnetic field is switched off, the azimuthal μ^+ and μ^- - distributions show practically only the variation due to geometric and attenuation effects, for μ^+ and μ^- similar, so that the charge ratio value stays with $R_\mu(r, \phi)$ =1. Obviously differences in the π^+ and π^- productions remain rather small at the considered energies (and within the invoked hadronic interaction model: QGSJET). This finding is underlined by the value of $R_\mu(r, \phi)$ integrated over all distances and azimuth angles R_μ = 1.028 ± 0.002 for the cases shown in Figure 2.

The influence of the geomagnetic field and the separation of μ^+ and μ^- increase with the path length (slant depth) of the muon trajectories in the atmosphere. Hence the $R_\mu(r, \phi)$ variation gets more pronounced with increasing distances from the shower core, with the threshold (Fig.3) of observed muon energies (since muons of higher energies stem dominantly from earlier generations) and with the zenith angle EAS incidence (see Fig.4). Recently this feature has been regarded in view of a separation of positive and negative muons by the Earth's magnetic field [8] , for the case of very inclined showers of primary energies high enough so that the muon component observed at ground remains sufficiently intensive for observation.

Concluding remarks

EAS simulations show that the lateral density distributions of the positive and negative muons are varying not only with the (radial) distance from the shower axis, but also with the azimuth relative to the plane of the incident shower. The reasons are different. In addition to the attenuation effects of charged particles of inclined showers in the atmosphere by the variation of the travelling distances, the geomagnetic field affects dominantly the travel of positive and negative muons with deflections in opposite directions. The geomagnetic effects depend on the direction of the EAS axis relative to the Earth's magnetic vector. This leads to an azimuthal variation of the muon charge ratio of the muon density distribution. In the extreme case of very inclined showers (with long slant depths) the Earth field might be used as magnetic separator. Obviously these features which are not yet experimentally explored [6], [7] in a systematic way, are of great interest for the understanding of the EAS development. It should be mentioned that some findings for the muon component induced by the geo-

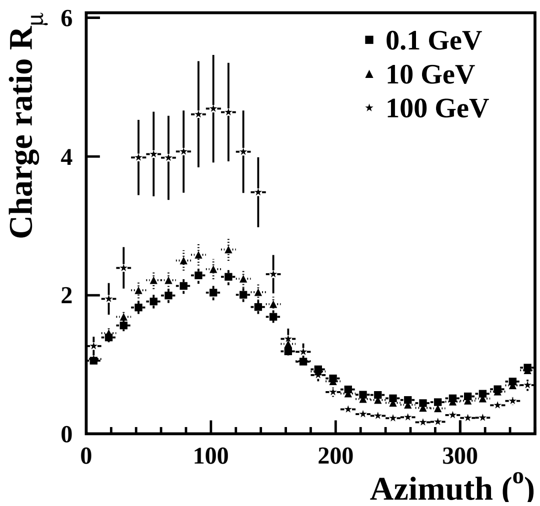

Figure 3: Azimuthal variation of the charge ratio R_μ of the muon density distribution of proton induced EAS of inclined incidence (θ = 45^o), incident from North with the primary energy of 10^{15} eV, observed at a radial distance of 45-50m. Comparison of different detection thresholds.

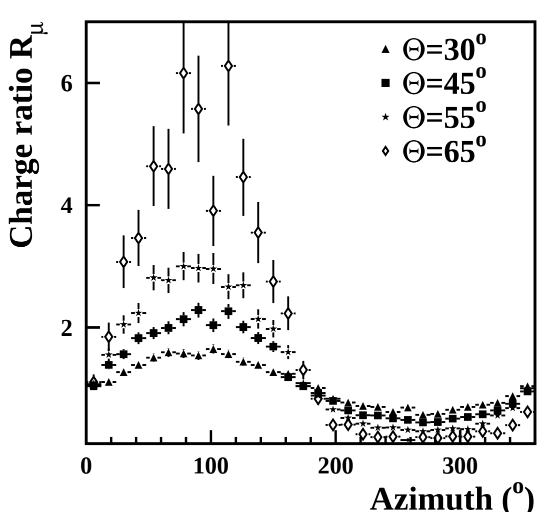

Figure 4: Azimuthal variation of the charge ratio R_μ of the muon density distribution of proton induced EAS with different zenith angles incident from North with the primary energy of 10^{15} eV , observed at a radial distance of 45-50m. Comparison of different zenith angles of incidence.

magnetic field resemble features observed for the radio emission from EAS [3, 4]. Furthermore the quantitative results would also provide some detailed information about the hadronic interaction, in particular when observing higher energy muons.

Acknowledgements

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