The Electromagnetic Component of Inclined Showers

J. Alvarez-Muñiz, G. Parente and E. Zas
Departamento de Física de Partículas, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain

Abstract

We study the contributions of radiative processes induced by muons in inclined showers. Analytical expressions are given to calculate these effects in the absence of magnetic field effects. We find that radiative energy losses that take place in water Cherenkov detectors dominate over continuous energy loss at different energies depending on the size of the detector. For inclined showers and the Auger tanks, the sum of the track-lengths induced by the radiative processes of a 1 TeV muon represent a 50% correction to the muon track.

1. Introduction

The study of cosmic rays at the highest energies is one of the strongest priorities in astroparticle physics. The fundamental question raised on the existence of the GZK cutoff, can not yet be answered conclusively and experiments are being planned to answer this and other fundamental issues such as the spectrum, their origin and their composition. Particularly immediate is the Pierre Auger Observatory [1], now in construction, which includes a 3000 km^2 array of 1600 water-Cherenkov tanks.

It has been shown that inclined showers can be measured and will play an important role for composition studies [2]. Inclined showers are dominated by muons because the electromagnetic component of the shower gets typically absorbed high in the atmosphere. To a first approximation the electromagnetic component from the main shower can be neglected for inclined showers induced by hadrons. Simulations show that at ground level there is a residual electromagnetic contribution. This component is understood to arise mainly from muon decay in flight but radiative processes are also expected to contribute.

For inclined showers there are strong correlations between distance to shower axis and muon energy. The highly energetic muons that arrive close to shower axis are expected to contribute an electromagnetic component through radiative interactions. These can happen both in the atmosphere and also in the detectors themselves, particularly in the cases of deep water detectors such as those used in the Auger Observatory. This component will contribute to the

pp. 579–582

signal detected in extensive air shower arrays. The contribution can be studied by simulation but it becomes difficult to separate the effects of these processes from those of muon decay because of statistical thinning and of fluctuations (for the results of this approach in the case of air interactions see Ref. [3]). In this work we report on an analytical method to evaluate these effects in the absence of magnetic field.

2. Muon radiative processes in the atmosphere

Muon bremsstrahlung is the hardest process that takes place and as a result it gives rise to a succession of electromagnetic showers in the atmosphere. To compute the average EM energy density of a muonic shower due to a radiative process in the atmosphere we firstly calculate the average electron density induced by a single muon. This can be done analytically integrating the corresponding cross section with a parameterization of the electron density:

$$\rho_e^\mu(r, E_\mu) = \int dt \int_{y_{min}}^{1} dy \, \frac{d\sigma}{dy} \, \rho_{air} \, N_A \;\; N_e(yE_\mu, t) \, \rho_{NKG}(r, s) \tag{1}$$

Here $d\sigma/dy$ is the corresponding differential cross section per nucleon, E_μ is the muon energy and y the fraction of energy transferred to the shower. $N_e(E_\gamma, t)$ is the total number of electrons and positrons in a shower of energy E_γ at depth t which is multiplied by a lateral distribution function. Here we use the Greisen parameterization for the longitudinal development of the shower and the NKG lateral distribution function $\rho_{NKG}(r, s)$, with r the distance to the muon axis and s the shower age. We find that the particle density due to a single muon scales with the muon energy and as a result we can express the result in terms of a function f depending on r alone: $\rho_e^\mu(r, E_\mu) = f(r)E_\mu$.

To calculate the average contribution to the electron density in a shower due to bremsstrahlung induced by muons we convolve the particle density produced by a single muon, ρ_e^μ, with a parameterization for the muon energy density in an inclined shower, ϵ^μ.

$$\rho_e(r) = 2\pi \int dr' r' \; f(|\vec{r} - \vec{r}'|) \; \epsilon^\mu(r') \tag{2}$$

where r is the distance to the shower axis and the integral extends over the area in the transverse plane of the shower. For showers of zenith angle $\theta < 80°$ the contribution of muon bremsstrahlung in the atmosphere to the electron density equals that of muon decay for distances to shower axis always below ~ 1 m. Considering pair production would increase this distance to ~ 10 m. Particle sampling at such small distances from shower axis does not usually play an important role in large extensive air shower arrays such as the Auger detector. Moreover if the detectors measure Cherenkov light emitted in water, the typical

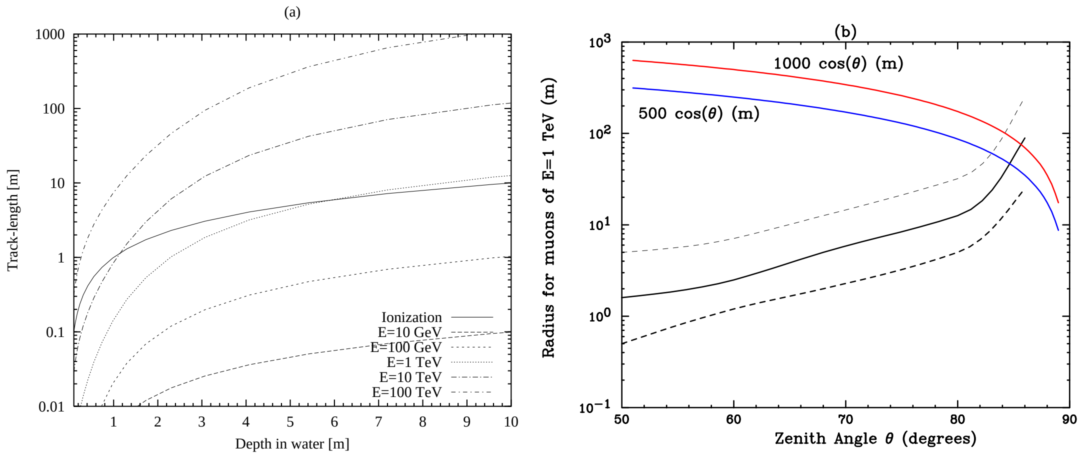

Fig. 1. (a) Muon track-length from all radiative processes for different muon energies. (b) Average distance to the shower axis of 1 TeV muons (lower solid) and one sigma deviation band (dashed)

contribution of the electromagnetic part of an inclined shower is already a small fraction of the signal induced by the muons. As a result we can ignore this effect for $\theta < 80^\circ$ and $r > 10$ m.

3. Radiative processes inside a water detector

A contribution to the signal is expected because of radiative processes of the muons inside the detector. As the signal in water Cherenkov detectors is approximately proportional to the track length of the charged particles we can calculate the track-length due to radiative processes produced by a muon of energy E_μ crossing a distance d in water as:

$$<\text{Track}> (E_\mu, d) = \int_0^d dX \int_{y_{min}}^1 dy \, \frac{d\sigma}{dy} \, \rho_{water} \, N_A \, \mathrm{T}(yE_\mu, d - X) \tag{3}$$

where y is the fraction of the muon energy carried by the photon in bremsstrahlung, by the e^+e^- shower in pair production or by the hadronic shower in nuclear interactions. The function $\mathrm{T}(E, X)$ in Eq. (3) is the integrated track-length of an EM shower of energy E when traversing a depth X in water. We use the parameterization for $\mathrm{T}(E, X)$ obtained from Monte Carlo simulation of photon showers from 10 GeV to 10 TeV using the ZHS code [4] and taking into account that the shower that develops may be only contained partially inside the detector. For nuclear interactions we consider that only a fraction of the radiated energy is converted in EM particles.

In Fig. 1a we plot the 'radiative' track calculated with Eq. (3) as a function of depth in water for different muon energies. The geometrical track, which is equal to the distance traversed by the muon, is also shown for comparison. (Note that this is a linear behavior). The track-length generated by these processes increases with muon energy as expected, however the signal induced is highly non linear for small detector sizes. For instance for a 1 m detector the radiative contribution is equal to that of the muon track for $E_\mu \sim 10$ TeV. However the energy drops by close to an order of magnitude when the detector becomes 3 m, which corresponds to the average distance of an Auger tank in the horizontal direction. In other words a 1 TeV muon traveling 3 m in the water tank induces over 1.5 m of extra track-length due to radiative processes. For 100 GeV (10 TeV) muons the corresponding track-length is 20 cm (12 m). The main contribution to the 'radiative' track comes from pair production.

For muon energies close to the critical energy one expects equal losses by continuous processes (ionization) than by radiative processes. In that case, as the Cherenkov light is proportional to energy losses, one should have the same track-length by the two mechanisms for energies around 900 GeV, the muon critical energy for water. This value is achieved asymptotically as the detector size increases.

Using the correlation between energy and distance to the shower axis in the absence of geomagnetic effects we can convert the muon energy to distance from shower core. This is shown in Fig. 1b which shows the transverse distance r for 1 TeV muons at ground level in an inclined shower as a function of zenith angle. For the Auger surface detector the typical distance to shower core for the closest detector is between 500 m and 1000 m. These distances are displayed on the figure after being projected onto the transverse plane. We have shown that radiative processes contribute significantly to the energy deposit in the tank for distances not far away from the shower axis. For example in an 80° shower 1 TeV muons lie in band centered at $r = 12$ m with a 1-sigma range $[4\ m - 30\ m]$. For this detector radiative processes in the tank dominate over radiative corrections in the atmosphere.

Acknowledgements: Work supported by grants from Xunta de Galicia PGIDT00 PXI20615PR, MCYT FPA2001-3837, and European Science Foundation Network N. 86 grant. We appreciate the support of CESGA in computing.

4. References

1. Auger Coll. see presentations in this conference.
2. Ave M. et al. 2003, Phys.Rev. D67, 043005.
3. Cillis A. N. and Sciutto S. J. 2001, Phys.Rev. D64, 013010.
4. Zas E., Halzen F., and Stanev T. 1992, Phys. Rev. D45, 362.