Implications of the Angular Spread of Air Shower Particles for the Fluorescence Technique

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Abstract

The determination of the shower development in the atmosphere using the fluorescence technique is subject to corrections due to the angular spread of the particles in the shower which changes as the shower develops. Methods that use the longitudinal shower profile to extract the energy of the primary particle can be subject to systematic errors associated to this effect.

1. Introduction

The observation of the atmospheric nitrogen fluorescence light induced by the charged particles in an atmospheric shower (the fluorescence technique), is an alternative for ultra high energy cosmic ray detection to the ground array experiments that measure the shower front as it hits the detector plane. The technique was first explored by the Fly's Eye detector and is currently being utilized in the high resolution Fly's Eye (HiRes), in the Auger Observatory, and in planned experiments such as the Telescope Array or in satellite experiments such as EUSO and OWL [5]. Although the technique has been very successful, there are unsolved discrepancies at the 2-3 σ level in the normalization of the spectrum and the number of events above 5×10^{19} eV as measured by the HiRes experiment and the AGASA air shower array.

In this contribution we discuss the relation between the emission of fluorescence light and shower development. We argue that there are geometric effects associated to the lateral spread of charged particles in the shower that may have implications in the determination of shower energy. Similar ideas were already discussed in the past by M. Hillas [3].

2. The fluorescence technique

Fluorescence detectors use mirrors to collect the light induced by the passage of the charged particles in an atmospheric shower. Different depths in the shower development are viewed by different photo-detectors of an imaging camera in the focal plane of the mirror. The depth distribution of the collected photons

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$N_\gamma^{\rm tot}(X)$ (where X is measured along shower axis), is converted to the number of charged particles $N_e(X)$ at the corresponding depth through:

$$N_e(X) = \frac{N_\gamma^{\rm tot}(X)}{Y \Delta X} \frac{1}{g_{\rm atten} g_{\rm area}}, \tag{1}$$

where $g_{\rm atten}$ corrects for the attenuation of the fluorescence photons in the atmosphere, and $g_{\rm area}$ accounts for the collection area of the mirror (see Eq.(6.2) in Ref. [8]). ΔX is a segment of the shower viewed by the telescope and is measured along the shower axis. Y is the experimentally measured fluorescence yield for air which is assumed to be proportional to the energy loss by ionization [4].

Shower energy has been determined in the past by applying Eq. 1 to obtain the longitudinal profile which is then fitted to an adequate function and integrated [7,8]. Since the integral is performed in the direction of the shower axis, its numerical value corresponds to the sum of all the charged particle track lengths projected onto the shower axis, i.e. the *total projected track length*, which is known to be proportional to shower energy,

$$E_{\rm em} = \alpha \int_0^\infty N_e(X) dX, \tag{2}$$

Here α is a constant representing the average ionization loss and whose numerical value has been recently recalculated by Monte Carlo simulations using CORSIKA [7] yielding $\alpha \sim 2.19$ MeV/g cm^{-2}.

3. Angular spread of shower particles.

It is well established that as a shower develops the paths of charged particles become less aligned with shower axis. However, both the energy loss and the fluorescence yield are defined per unit length along the particle travel direction. As a consequence, if the fluorescence light is used to infer the number of shower particles in a given depth interval, and the fluorescence yield is assumed to be proportional to energy loss, account must be taken that the energy loss of charged particles depends on ΔL, their average track length *regardless of the particle direction* in a given depth interval ΔX measured along the shower axis.

We have calculated the ratio of ΔL and ΔX as a function of atmospheric depth by performing simulations of photon induced showers in air, using the GEANT 4 package. In Fig 1. we show the depth (shower age) dependence of f defined as the ratio of the total to the projected track lengths. It is seen that f is significantly different from 1, being $f = 1.18$ at shower maximum ($s = 1$), and increases with shower age since it can also be thought as the average value of $\sec\theta$ for all tracks, θ being the angle between the particle direction and the shower axis. We have also obtained that f is practically independent on primary energy because showers exhibit good scaling properties. Showers initiated by

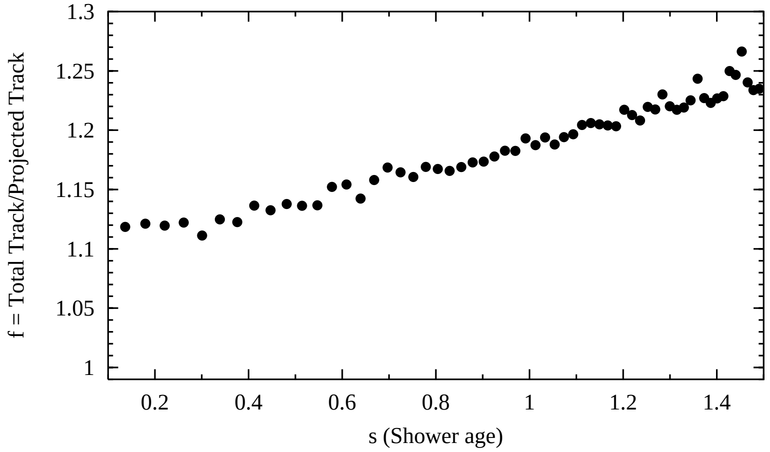

Fig. 1. Ratio of total and projected track lengths (f) in 1 TeV electromagnetic showers as a function of depth in the atmosphere (expressed as shower age $s = 3t/(t{+}2\beta)$ where $\beta = \log(E/E_c)$ and E_c is the critical energy in air and $t = X/X_0$ with X_0 the radiation length in air). The electron kinetic energy threshold used in the simulations is 10 keV.

hadrons can be considered as a superposition of photon initiated showers from π^0 decays at different depths. In fact, to a reasonably good approximation the lateral distribution of a hadronic shower around maximum corresponds to that of an electromagnetic shower of age $s \simeq 1$ [1]. Therefore, for hadronic showers, we can expect $f(s = 1) \simeq 1.18$ in a broad region around shower maximum.

The same effect has to be kept in mind in experiments that measure the photon yield ($Y_{\rm exp}$) dividing the number of emitted photons per incident electron (N_γ) by the length (d) of the visible portion of the electron beam in the direction of the beam axis [4]: $Y_{\rm exp} = N_\gamma/d$. The electrons traveling through air a distance d will be scattered, and as a result the path they travel will be longer than its projection onto the beam axis. The ratio of these two track lengths ($f_{\rm exp}$) will actually depend on the electron energy and on the distance d. To quantify its value, we have simulated electron paths in air using GEANT 4, propagating 1.4 MeV electrons a distance of 30 cm along the direction of movement of the incident electron, to roughly reproduce the conditions of the experimental setup in [4]. These simulations predict an average ratio $f_{\rm exp} = 1.02$.

Although $f_{\rm exp}$ is in general small, it should be incorporated in the yield to be used in Eq. 1, which must be corrected by a factor $f(X)/f_{\rm exp}$ (~ 1.16 at shower maximum if $f_{\rm exp} = 1.02$ is used). The deduced value of $N_e(X)$ is inversely proportional to the yield corrected by this factor. Since $f(X) > f_{\rm exp}$ for all depths, using the yield without this correction in Eq. 1 will lead to an overestimate of the shower energy. Moreover since $f(X)/f_{\rm exp}$ is depth dependent, ignoring it can lead to a misreconstructed position of shower maximum in electromagnetic showers shifted to smaller depths by ~ 4 g/cm^2. This shift is expected to be even smaller in hadronic showers since the depth dependence of $f(X)/f_{\rm exp}$ is expected to be less pronounced.

4. Conclusions and discussion

The main idea of this article refers to the relation between energy loss in a shower and the value of the projected track length. We have shown that the fact that charged particles in a shower do not travel parallel to the shower axis has important implications in the fluorescence light output. Accounting for this effect can be accomplished through a depth-dependent correction factor which is to be obtained in a detailed simulation of both the shower development and the beam experiment measuring the fluorescence yield.

We arrive at this result under the assumption of proportionality between fluorescence emission and total tracklength. A more realistic assumption is that the fluorescence emission is proportional to the energy deposited in the medium [2,6]. In this case the effect of the lateral spread of shower particles will translate into a different shift of shower energy. In addition the ratio between deposited energy and tracklength is also depth dependent [6]. In any case, the deduction of the depth development curve of the shower from the detected light needs to take into account that particles do not travel parallel to the shower axis. Our results do not help the resolution of the discrepancies between AGASA and HiRes results but imply that a detailed study, including the relation between fluorescence light, tracklength and energy deposition in hadronic showers, should be performed.

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