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Understanding cosmic ray air showers at large zenith angles

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Abstract. Particle density distributions are essential for the analysis of the showers generated in the atmosphere by cosmic rays of ultra high energy. Several useful parameterizations of lateral distribution of particles (LDF) have been used by different experiments to study showers produced at low zenith angles. Very inclined showers are of particular interest since they would increase the acceptance of any air shower array. We present an approach to analyze lateral distributions of electrons and muons produced by high energy cosmic ray particles. The proposed LDF fit very well the data obtain by MC simulations. Studies of the evolution of LDF parameters with the atmospheric depth are also presented.

1 Introduction

The lateral distribution function of electrons and muons of an extensive air shower(EAS) produced by ultra high energy cosmic ray particles at ground, is a very important observable because the energy of the primary can be derived from them.

Much of our interpretation of the extensive air shower phenomenon involves the LDF in one way or another. For example, the dependence of the shower size with the age parameter is expected to contain information about the primary composition and characteristic of high energy interactions. Both shower size and age parameter are estimated by using the LDF. It is therefore important to know the analytical form of the structure function that correctly describes the lateral distribution.

The ground patterns produced by inclined showers are difficult to analyze because they lose the circular symmetry usually used for interpretation of low zenith angle showers density profiles(Pryke , 1998).

The asymmetry of ground densities in inclined showers is dominated by a purely geometrical projection effect(Bertou and Billoir, 2000) with the additional asymmetry due to the longitudinal development.

In this paper we present a study of the dependence of the LDF parameters with atmospheric depth corresponding to semi-analytical lateral distribution functions for vertical showers. The results obtained are use to calculate the corresponding LDF for inclined showers.

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2 Electron lateral distribution function

The lateral structure function derived for a pure electromagnetic cascade by (Greisen , 1960) (Kamata and Nishimura , 1958) has been much used both in theoretical developments (3D extensive air shower simulation) and in the description of experimental results (Antoni et al., 2001) (Nagano , 1984):

$$\rho(r) = \frac{N_e}{r_m^2} f(r) \quad (1)$$

$$f(r) = \frac{\Gamma(4.5-s)}{2\pi\Gamma(s)\,\Gamma(4.5-2s)}\left(\frac{r}{r_m}\right)^{s-2}\left(1+\frac{r}{r_m}\right)^{s-4.5} \quad (2)$$

$$s = = s_{nkg} = \frac{3}{1+\frac{2\ln(\frac{E_0}{\epsilon_0})}{t}} \quad (3)$$

$$t = \frac{\int_z^{\infty}\rho_{atm}(z)dz}{X_0} \quad (4)$$

N_e is the total number of electrons, ϵ_0 is the critical energy , E_0 is the primary energy, r_m is the Moliere radius and X_0 is the radiation length in air. s is the age parameter which is related to the shower stage of development.

The lateral distribution of electromagnetic showers in different materials scales well with the Moliere radius :

$$r_m = E_s\frac{X_0}{\epsilon_0} \sim \frac{1}{\rho_{atm}} \quad (5)$$

$$r_m = r_m(t_0)\frac{\rho_{atm}(t_0)}{\rho_{atm}(t)} \approx r_m(t_0)\frac{t_0}{t} = r_{nkg} \quad (6)$$

E_s is the scale energy given by $E_s = m.c^2\frac{4\pi}{\alpha}$.

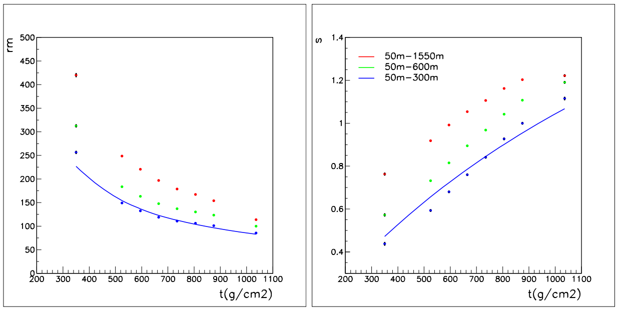

Fig. 1. (left)-Variation of r_m fitting in different ranges of r, s fixed to s_{nkg}(eq.3). The full line corresponds to r_{nkg}(eq.6). (right)-Variation of s fitting in different ranges of r, r_m fixed to r_{nkg}.

The Moliere radius r_m is a characteristic unit of length in the scattering theory, the geometrical value of r_m is inversely proportional to the density of the medium. For an isothermal atmosphere it will be inversely proportional to the vertical depth t (eq.6).

Vertical proton showers at 10^{19} eV were generated using AIRES + QGSJET with an effective thinning 10^{-8}.

Nishimura-Kamata-Greisen formula(NKG) eq.(1-4) can describe the simulated LDF at different observing levels. Reduced χ^2 are in the range 1-5 with better fits near the shower core. r_m values depend on the fitted region if s is fixed to the theoretical value (eq.3).

On the other hand, fitting the region close to the shower core ($r \leq 300$ m), $r_m \sim \frac{1}{\rho_{atm}}$ as expected. Deviations from this behavior appear at larger distances from the core as a consequence of using a fixed value of s. The age parameter depends on the axial distance $s = s(r)$.

In Fig1., the variation of r_m and s with atmospheric depth is shown. The r dependence of the parameters is evident.

The shower size can be reproduced rather well if the fit is performed at small distance from the shower core. The normalization of the NKG function depends on r if $s = s(r)$ is used.

Our studies of vertical showers confirm, as proposed by (Bourdeau et al., 1980), that a modified NKG formula should be used:

$$\rho(r) \quad = \quad \frac{N(r)}{r_m^2} C(s) (\frac{r}{r_m})^{s(r)-2} (1 + \frac{r}{r_m})^{s(r)-4.5} \qquad (7)$$

In this work, we use as a first approximation,

$$s \quad = \quad s_{nkg}(t) = \frac{3}{1 + \frac{\eta\, 2\, ln(\frac{E_0}{\epsilon_0})}{t}} \qquad (8)$$

where η takes into account the above mentioned deviations.

2.1 Inclined showers

In this section we present a first attempt to extend these solutions to inclined showers. In the case of an homogeneous atmosphere, one have rotational invariance and the solution is the same as the vertical induced shower but evaluated in the coordinates of the rotated system :

$$x' \quad = \quad x \cos\theta + z \sin\theta = x_a \cos\theta \qquad (9)$$

$$y' \quad = \quad y = y_a \qquad (10)$$

$$z' \quad = \quad z \cos\theta - x \sin\theta = \frac{z}{\cos\theta} - x_a \sin\theta \qquad (11)$$

The (x_a, y_a) coordinates are the Cartesian coordinates of the particles measured from the intersection between the shower axis and a plane parallel to the ground.

The structure function will be the same as eq.2 but evaluated at :

$$t' \quad = \quad \frac{\int_{z'}^{\infty} \rho_{atm}(z) dz'}{X_0} \qquad (12)$$

with z' along the shower axis direction.

Actually, the structure of an air shower is quite complex but following (Pryke , 1998; Dova et al., 1999), an inverted cone seems to be a reasonable first approximation. If the cone angle $\tan\alpha$ is assumed nearly independent of z then, the particle density distribution for an inclined shower is given by eq.7-8 with slant depth t' including the azimuthal angle dependence.

$$\frac{z}{\cos\theta} - L \quad = \quad (z' - L)\,(1 - \frac{r'}{(z' - L)} \tan\theta \cos\phi) \qquad (13)$$

$$\tan\alpha \quad = \quad \frac{r'}{(L - z')} \qquad (14)$$

$$\frac{dz}{dz'} \quad = \quad \cos\theta\,(1 - \tan\alpha\, \tan\theta\, \cos\phi') \qquad (15)$$

$$\frac{t}{t'} \quad = \quad \cos\theta\,(1 - \tan\alpha\, \tan\theta\, \cos\phi') \qquad (16)$$

Proton air showers at 10^{19} eV were generated with AIRES + QGSJET at zenith angles between $\theta = 30°$ and $\theta = 70°$ with an effective thinning level of 10^{-8}.

For single showers, two-dimensional density distributions r-ϕ were built at all predetermined observing levels for different particles.

The distributions were fitted using the modified NKG formula including the zenith angle dependence.

The proposed density distribution fits well e^+e^- at all observing levels for $\theta \leq 70°$. At zenith angles greater than $70°$ the electromagnetic component is attenuated before reaching the ground and the formula fits only up to a slant depth $t' \sim 1950 gr/cm^2$

It is well known that in very inclined showers due to the greatly enhanced atmospheric slant depth, the electromagnetic component is almost completely absorbed and at ground the shower consist mainly of muons (Ave et al., 2000).

Fig.2 and Fig.3 show the r(left) and ϕ(right) projections of the two-dimensional distributions for $50°$ and $70°$ inclined showers respectively at a given atmospheric depth.

3 Muon lateral distribution function

A semi-analytical form of the structure function was proposed by (Vernov et al., 1968):

$$\rho_\mu(r) \quad = \quad N_\mu(t) f_\mu(r)$$

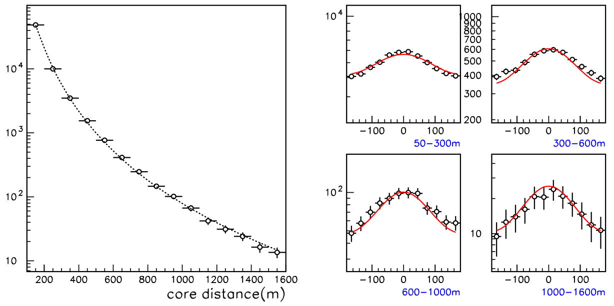

Fig. 2. 50° inclined shower two-dimensional fit of NKG function with fixed r_m at $595 gr/cm^2$.

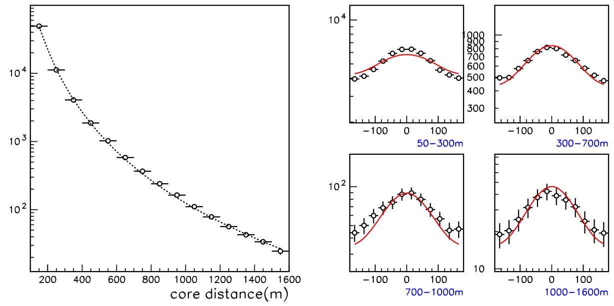

Fig. 3. 70° inclined shower two-dimensional fit of NKG function with fixed r_m at $350 gr/cm^2$.

$$f_\mu(r) \;=\; C\,(\frac{r}{r_0})^{-\gamma}\exp(-\frac{r}{r_0})) \tag{17}$$

with $\gamma = 0.4$ and $r_0 = 80m$. It has been widely used in the evaluation of the experiments of the Moscow group (Vernov et al., 1968).

A dependence of the parameters according to shower development must be expected for the lateral distribution of the muons as it is the case for the electromagnetic component.

Shower muons are less attenuated in traversing the atmosphere and little affected by Coulomb scattering. Its spread is determined by the direction of emission of the parent particle and hence increases while the shower propagates downwards, whereas reproduction, especially of energetic muons, becomes negligible. Thus, the lateral distribution of older showers will be flatter than that of less attenuated events. A shower age dependence of the muon structure function has been considered in relation with the parameter γ (Alessio et al. (1980) and references therein).

Murthy et al. (1968) used Vernov distribution to describe the electron lateral distribution with:

$$\gamma \;=\; 2.25 - s_{nkg} \tag{18}$$

$$s \;=\; \frac{3}{1+\frac{2\ln(\frac{E_0}{\epsilon_c})}{t}} \tag{19}$$

Fitting Vernov distribution to the simulated muon lateral distribution of a $10^{19} eV$ vertical proton shower, we found that the γ parameter dependence with atmospheric depth is well described by :

$$\alpha \;=\; 2 - s_\mu \tag{20}$$

$$s_\mu \;=\; \frac{3}{1+\frac{2\beta}{t}} \tag{21}$$

with β as a free parameter.

It can be argued (Bosia et al., 1972; Bergamasco et al, 1976) that, if the parent particles had been created with a p_T distribution:

$$p_\perp \;=\; N\,\frac{p_\perp}{p_0}\exp(-\frac{p_\perp}{p_0})\frac{dp_\perp}{p_0} \tag{22}$$

the sea level lateral distribution will resemble the Vernov law, with r_0 related to the mean transverse momentum $< p_T >$, the mean energy of muons $< E_\mu >$ and to the mean height of production $< H >$:

$$r_0 \;=\; \frac{2}{3} < H > \frac{< p_\perp^\mu >}{< E_\mu >} \tag{23}$$

The mean height of origin of muons $< H >$ depends on the pion decay probability as well as the relative importance of the various pion generations. The increase of $< H >$ with increasing muon energy is determined by the pion decay probability since muons with higher energies come from pions requiring lower densities of atmosphere for decaying, then it is reasonable to assume :

$$< H > \sim \frac{1}{\rho_{atm}} \tag{24}$$

$$r_0 \;=\; \frac{2}{3} < H > \frac{< p_\perp^\mu >}{< E_\mu >} \sim \frac{1}{\rho_{atm}} \tag{25}$$

$$r_0 \;=\; r_0(t_0)\frac{\rho_{atm}(t_0)}{\rho_{atm}(t)} \approx r_0(t_0)\frac{t_0}{t} \tag{26}$$

Although these expressions are semi-quantitative approximations, they can serve as a basis for an order of magnitude assessment of the variation of the parameters of the lateral spread.

The Vernov structure function for an inclined shower is then the same of eq.16 but evaluated at :

$$t' \;=\; \frac{t}{\cos\theta\,(1-\tan\alpha\,\tan\theta\,\cos\phi')} \tag{27}$$

(28)

The modified Vernov LDF successfully fits the Monte Carlo simulation data at all zenith angles. The behavior of the fitted parameters will be described in detail elsewhere.

Fig.4 and Fig.5 show radial and azimuthal angle projections of the muon density from two-dimensional fits to the data for 50° and 70° zenith angles respectively.

4 Summary and conclusions

We have studied in detail the structure of vertical and inclined showers. Starting from semi-analytical LDF we analyzed the

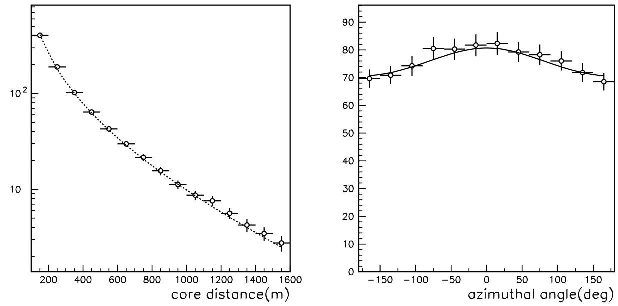

Fig. 4. 50° inclined shower two-dimensional projections of the muon LDF fit at $850 gr/cm^2$.

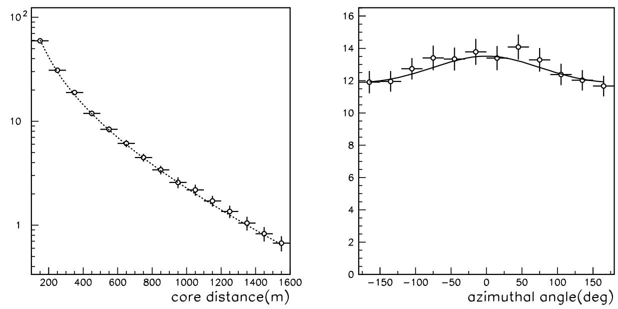

Fig. 5. 70° inclined shower two-dimensional projections of the muon LDF fit at $850 gr/cm^2$.

atmospheric depth dependence of the shower parameters for vertical showers. This is an essential point to properly modified the corresponding vertical LDF in order to describe inclined showers.

The parameterizations obtained for electron and muon lateral distribution functions fit well the simulation data at different zenith angles.

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