Weakly interacting particles viewed by fluorescence detectors

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Abstract

We estimate the acceptance of the fluorescence detectors to atmospheric showers with zenith angles larger than 60 degrees, which penetrates deeply into the atmosphere. This class of showers have the signature of UHE (Ultra High Energy) neutrinos. We have used a fast simulation version of FDSIM to study the behaviour of this class of detectors and give a lower bound to the acceptance.

1 Introduction

We report in this paper the evaluation of the acceptance of fluorescence detectors to quasi horizontal showers that develops deeply in the atmosphere. This class of showers have the typical signature of ultra high energy (UHE) neutrinos. The detection rate for deeply penetrating secondary showers, those resulting from the decay of an UHE tau-lepton deep in the atmosphere, or due to an UHE gamma-ray from the bremsstrahlung of a muon, are negligible at ultra high energies for the detectors now being built or planned\cite{1}.

The Earth is opaque to UHE neutrinos\cite{2}. However, they will interact deeply in the atmosphere, in contrast to hadrons or electromagnetic particles.

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Neutrinos have a small cross section with the matter in the atmosphere, so they have a homogeneous probability to interact at any point of it. The electromagnetic component of the normal showers, which are generated in the atmosphere, are suppressed sharply at slant depths which correspond to zenith angles of about $60^\circ$ [3].

The shower induced by a neutrino behaves very much like one induced by a hadronic particle. Showers produced by an electronic neutrino primary, will be a superposition of a purely electromagnetic shower, produced by the emerging electron, on top of the hadronic shower, and the full energy of the neutrino will be converted into tracks of the shower. On the other hand, a muonic neutrino will have a large part of its energy carried by the resulting muon, not adding much to the number of tracks of the shower. In the case when the interaction is mediated by a neutral current, the resulting shower will carry only a fraction of the original energy.

We have assumed, as a first approximation, that the purely electromagnetic component of the neutrino induced showers summed to the hadronic component can be described by the Gaisser-Hillas parametrization [4]. In this work when we refer to the energy of the shower, that corresponds to energy converted into particle tracks, which is different from the energy of the primary neutrino. To estimate an effective acceptance for specific types of neutrinos will require the convolution of the fraction of energy lost to emerging neutrinos or muons.

## 2 The atmosphere and detector simulation

We have simulated a fluorescence detector[5] with a single eye covering an azimuth range of $360^\circ$, instrumented with mirrors and cameras which are identical to those of the preliminary design of the Pierre Auger Observatory[6]. The eye is composed of 12 mirrors, each one covering a field of view of $30^\circ$ by $30^\circ$, with the lower part of the mirror raised by $2^\circ$ from the line of the horizon. The camera of each mirror has 440 pixels, each covering a solid angle of about $1.5^\circ$ squared. Each pixel has a hexagonal format and they are disposed in 22 rows with 20 pixels each. Each successive row is offset in relation to the previous one by an angle of $0.75^\circ$.

We use the Linsley parametrization for the atmosphere, based on the experimental data of the US standard atmosphere[7]. The density of the atmosphere is limited to the first 113km above the sea level and is considered zero above it in this parametrization. The vertical depth, defined by

$$ \chi_e(h) = \int_h^\infty \rho(z) \, dz, \quad (1) $$

is the quantity of matter (in g/cm$^2$) that a particle crosses as it travels vertically through the atmosphere. This quantity can be inverted to obtain
the value of the altitude $z$ (in km). The slant depth, defined by

$$\chi_s(z) = \int_z^\infty \rho(y) \, dy,$$

(2)

is the quantity of matter that a particle crosses during its actual trajectory. One may relate the slant depth to the vertical depth, for a given height, as

$$\chi_s(h) = \frac{\chi_v(h)}{\cos \theta},$$

(3)

for values of $\theta$, the zenith angle of the shower, smaller than $60^\circ$. Here one may ignore the curvature of the Earth, however, for larger values of the zenith angle we must take it into account. The height of a particle that have traveled through the atmosphere towards a point $O$, that lies at a distance $l$ from the collision point, is given by,

$$H = R \left( 1 + \frac{l^2}{R^2} + 2 \frac{l}{R} \cos \theta \right)^{0.5} - 1,$$

(4)

where $\theta$ is the zenith angle of the shower line, at the collision point $O$, and $R$ is the radius of the Earth. If $l << R$, then $H$ can be approximated by

$$H = l \cos \theta + \frac{(l \sin \theta)^2}{2 R}$$

(5)

For $\theta < 60^\circ$ the second term of the sum is negligible and we recover the usual expression for $H$. We take into account the effect of the curvature of the Earth in our results.

The simulation program generates the shower and the intensity of the light with proper wavelength distribution. The intensity of the light emitted at each stage of the shower is proportional to the number of charged particles [8], with the proportionality factor being reasonably independent of the height of the shower. It is given by

$$\frac{dN_{\gamma}}{dl} = N_f \times N_e,$$

(6)

where $N_f$ is the fluorescence yield (number of photons/charged particle/meter) and $N_e$ is the number of secondary particles produced in the shower. The phenomenon of fluorescence light production has very low efficiency, but this is compensated by the huge number of secondary particles produced in the shower. This number, which is a function of the slant depth of the point of emission, $\chi$, is given, in the Gaisser-Hillas parametrization of the longitudinal shower development [4], by

$$N_e(\chi) = N_{\max} \left( \frac{\chi - \chi_0}{\chi_{\text{max}} - \chi_0} \right)^{(\chi_{\text{max}} - \chi_0)/\lambda}$$

$$\times \exp \left( \frac{(\chi_{\text{max}} - \chi_0)}{\lambda} \right)$$

(7)

3
where $\chi$, $\chi_{\text{max}}$ and $\chi_0$ are given in units of g/cm$^2$, $\lambda = 70$ g/cm$^2$ and $N_{\text{max}}$ is the shower size at its maximum development. The light, as it travels through the atmosphere, is attenuated, either by absorption or by scattering. Absorptive processes are important in the region of wavelengths below 290 nm and above 800 nm. Between these two limits the mechanism of attenuation is dominated by Rayleigh scattering [9] (scattering by the atmosphere molecules) and Mie scattering [9][10] (scattering by natural and man-made aerosols). Rayleigh scattering is a stable phenomenon, dependent on the atmosphere density profile, which has an exponential profile that can be easily simulated. Mie scattering, on the other hand, is a highly variable phenomenon, which depends on the particle composition, its distribution and on the vertical density profile. The Mie scattering can be simulated, but its parametrization requires a continuous monitoring of the atmosphere. The transmission of light $A_{TT}$ between two points at slant depth $\chi_1$ and height $h_1$ and $\chi_2$ and height $h_2$, is separated into the Rayleigh scattering, described by

$$T_{\text{Ray}} = \exp\left[-\frac{|\chi_1 - \chi_2|}{\chi_R} \left(\frac{400}{\lambda}\right)^4\right]$$

(8)

and the Mie scattering, by

$$T_{\text{Mie}} = \exp(-\frac{h_M}{l_M \cos \theta} \left(\exp\left(\frac{h_1}{h_M}\right) - \exp\left(\frac{h_2}{h_M}\right)\right))$$

with the cumulative effect

$$A_{TT} = T_{\text{Ray}} \times T_{\text{Mie}},$$

(9)

where $\chi_R$ is the mean free path for scattering at $\lambda = 400$ nm, with a value $\chi_R = 2974$ g/cm$^2$, $\lambda$ is the wavelength of the scattered light, $l_M$ is the Mie scattering mean free path ($l_M \simeq 14$ km at $\lambda = 360$ nm), $h_M$ is the aerosol scale height ($h_M \simeq 1.2$ km) and $\theta$ is the zenith angle.

We have calculated the acceptance for a fluorescence detector with a single eye to showers at different energies and zenith angles larger than 60°. We have taken into account not only showers which hit the ground array, but also those which cross the whole volume visible to the eye, without touching the ground. Those are either horizontal showers or showers hitting the ground very far away.

To compute the neutrino acceptance of the fluorescence detector, we have required as trigger condition that at least 5 neighboring pixels are activated by the shower, with a signal to noise ratio larger than 3. We estimate the volume of atmosphere in which showers are visible to the fluorescence detector eye and generate quasi-horizontal showers in a larger volume. We generate showers that have the $\chi_{\text{max}}$ point contained within the simulation volume, and require the slant depth of initial interaction point, $\chi_0$, to be larger than a
Table 1: Fiducial volumes where the showers trigger the FD.

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Radius (km)</th>
<th>Height (g/cm²)</th>
<th>Volume (km³w.eq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{18}</td>
<td>30</td>
<td>15</td>
<td>25.7</td>
</tr>
<tr>
<td>10^{19}</td>
<td>50</td>
<td>25</td>
<td>79.3</td>
</tr>
<tr>
<td>10^{20}</td>
<td>80</td>
<td>25</td>
<td>202.9</td>
</tr>
</tbody>
</table>

minimum value $\chi_{0M}$. We then compute the fraction of showers generated in this volume, which will trigger the detector, evaluating then the acceptance of the detector in units of water equivalent volume stereo radian (km³w.eq.sr). Fluorescence detectors have a limited duty cycle, being able to operate only on clear and moonless nights, about 10% of total time. In this note, we assume a duty cycle of 100%, so that different weather conditions should be folded into the estimation. In order to compare the neutrino acceptance of fluorescence detectors to other detectors, the duty cycle must be folded in. We have simulated 15 000 showers with effective visible energies ranging from $10^{18}$ to $10^{20}$ eV, using as the fiducial volume the values shown in table 1.

We use a larger volume than the ones showed in the table 1 to make the simulation of the neutrino showers and estimate the acceptance. We set a radius of 50, 70 and 90 km for energies of $10^{18}$, $10^{19}$ and $10^{20}$, respectively, with a fixed value for the top of the volume, set at 30 km, for all of them. There is very little matter in the atmosphere above this volume.

The horizontal position of the slant depth for the maximum of the shower, $\chi_{\text{max}}$, was assigned to uniformly random points, within the cylindrical generating volume. The vertical position of $\chi_{\text{max}}$ was distributed homogeneously in g/cm². This approach is justified for UHE neutrinos, since they can interact roughly with equal probability anywhere in the atmosphere, but the interaction depends on the amount of matter crossed, not linearly on the distance traveled. The zenith angles are generated randomly in $\cos \theta$, for $\theta$ between $60^\circ$ and $90^\circ$ ($0 < \cos \theta < 0.5$) and the azimuth angles, between 0 and $2\pi$.

We have estimated the acceptance for showers with zenith angles larger than $60^\circ$, $70^\circ$ and $80^\circ$, for different values of energy, for the five different values of the minimum interaction point, $\chi_{0M}$, as $\chi_{\text{max}}$ varied randomly over the simulation volume. We show in figure 1 the results of the acceptances for showers with zenith angles greater than 60, 70 and 80 degrees when $\chi_{0M}$ is equal to 500 g/cm².

In figures 2 and 3 the acceptances for showers with zenith angles greater than $60^\circ$, $70^\circ$ and $80^\circ$, with values of $\chi_{0M}$ greater than 1250 and 2000 g/cm² are presented. For all these figures the 100% duty cycle is considered. The acceptances decrease smoothly as the values for the $\chi_{0M}$ are increased, but
Figure 1: Acceptances (in units of km$^3$.w.eq.sr for energies of $10^{18}$, $10^{19}$ and $10^{20}$ eV for showers with zenith angles larger than 60° (square), than 70° (sphere) and than 80° (triangle) and for $\chi_0M$ greater than 500 g/cm$^2$

at values of $\chi_0M$ larger than 1500 g/cm$^2$ the acceptances practically do not change as $\chi_0M$ is increased. As it was pointed in a previous paper[1], for values of $\chi_0M$ greater than 2000 g/cm$^2$, we only observe events at zenith angles between 70 degrees and 90 degrees. The reason why this happens is that, for showers with zenith angles less than 70 degrees, there is not enough slant depth along the axis for the shower to start at values deeper than 2000 g/cm$^2$ and still be able to develop and be detected above the ground (taken to be at 860 g/cm$^2$ vertical depth for the analysis here)[1].

3 Conclusions

We conclude in this note that the fluorescence detectors, as the one that will be installed at the Pierre Auger Observatory, have an acceptance to UHE neutrinos of the order than that of the surface array detectors [11][12]. In
Figure 2: Acceptances (in units of km$^3$.w.eq.sr for energies of $10^{18}$, $10^{19}$ and $10^{20}$ eV for showers with zenith angles larger than 60° (square), than 70° (sphere) and than 80° (triangle) and for $\chi_0 M$ greater than 1250 g/cm$^2$

fact this acceptance should be added to the one of the surface detector, once this class of showers are seen only by the fluorescence detector, most of them not triggering the surface detector.

From the analysis of our results we observe that in the case of events where the zenith angle is greater than 60°, even for showers with energies of $10^{18}$ eV, the acceptance of a single eye detector, with a 10% duty cycle is larger than a km$^3$.w.eq.sr. increasing to 6.6 km$^3$.w.eq.sr. at $10^{20}$ eV.

When operating in hybrid mode these detectors can increase substantially the acceptance of the Observatory. The result presented here is a lower value for the acceptance, once we have not included showers moving upwards, at low angles to the horizon. These class of showers where the neutrino interacts with the matter in the ground, near the surface will increase the values for the acceptances we have estimated here.
Figure 3: Acceptances (in units of km$^3$.w.eq.sr for energies of $10^{18}$, $10^{19}$ and $10^{20}$ eV for showers with zenith angles larger than 60° (square), than 70° (sphere) and than 80° (triangle) and for $\chi_0 M$ greater than 2000 g/cm$^2$.

References


