# Monte-Carlo Simulation of Horizontal Air Shower

M. A. Huang, C. C. Hsu, and P. Yeh
*Department of Physics, National Taiwan University, Taipei 106, Taiwan, R.O.C.*

**Abstract**

The neutrino induced air showers occur mostly in near horizontal direction, where the existing air shower simulation codes have difficulties. We devise a method to simulate horizontal air showers. We find that the heavy attenuation of Čerenkov photons from shower core makes the muon tails of hadronic part of the showers visible. This information may aid the identification of the shower initiating particle.

## 1. Introduction

At energies above $10^{15}$ eV, cosmic neutrinos coming from near horizontal directions may produce extensive air showers (EAS). Some Earth-skimming neutrinos could even produce up-going showers. Realistic EAS simulation is crucial for experiments searching for very high energy neutrinos.

Most of the current EAS simulation codes are designed for cosmic rays experiments. These codes normally use plane geometry, therefore the slanted depth diverges when the zenith angle $\theta \approx 90°$ for near horizontal showers. Some EAS codes impose limit on the range of $\theta$, or introduce a modified geometry, such as *curved* option in CORSIKA [1] and *curved Earth* in AIRES [2]. Even with these modifications, they still can not simulate up-going EAS.

One alternative is using a three-dimensional coordinate system with the center of Earth as the origin, similar to the 3-D atmospheric neutrino simulation codes like COSMOS [3]. However, these codes focus on the neutrinos. Changing the coordinates system in existing EAS codes or adding production of Čerenkov /fluorescence photon to atmospheric neutrino simulation codes are both labor intensive and difficult.

We devised a method to simulate horizontal or up-going EAS and implemented it in CORSIKA. Some results of simulated Čerenkov photons are presented.

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## 2. Modifications of CORSIKA

To avoid divergence at $\theta \approx 90^\circ$, we take a horizontal direction as the $z$ axis, which in normal CORSIKA program points to the zenith. We also made necessary changes on density $\rho$, index of refraction $n$ and photon attenuation length $\ell$ of air.

The air density can be simplified as a constant for horizontal showers. We take $\rho = 10^{-3}$ g/cm$^3$, the nominal density at 2.5 km above sea level.

The index of refraction of air plays two roles in Čerenkov photon productions [4]: Čerenkov angle $\theta_c = \cos^{-1}(1/n)$ and Čerenkov photon production efficiency $dN/ds \propto (n-1)^2$. For horizontal air showers $n$ can also be approximated with a constant. we modified the source code of the Bernlöhr package [4] to return $n = 1.00021$.

The photon attenuation includes effects from ozone layer at 10-20 km, molecular (Raleigh) scattering at all altitude and aerosols (Mie) scattering near ground. The last two sources dominate for the horizontal propagation of photons. The default CORSIKA table of absorption coefficients $c(\lambda, h)$ is supplied by the Whipple group. We use the Whipple model to derive the mean attenuation length $\ell(\lambda)$ at altitude $h = 2.5$ km with the help of the surviving probability $P(\lambda)$:

$$P(\lambda) = e^{-c(\lambda,3)}/e^{-c(\lambda,2)} = e^{-X_{2:3}/\bar{\rho}\ell(\lambda)} \tag{1}$$

where $X_{2:3} = \int_{h=2}^{3} \rho\, dh$ is the vertical depth from 2 km to 3 km and $\bar{\rho}$ is the average air density we use. With $\ell(\lambda)$ in hand, the absorption coefficient in horizontal direction is simply $c(\lambda, h) = d/\ell(\lambda)$ where $d$ is the distance from photon production site to the detector.

The photon attenuation length is shown in Figure 1 with a comparison to the model that HiRes experiment is using [6]. We noticed that the HiRes model describes a more transparent atmosphere. For this study we use the Whipple model.

## 3. Results from the Simulation

Tau neutrinos skimming through the Earth could produce $\tau$ leptons via charged current interaction inside the Earth. Approximately 87% of $\tau$ lepton decays contain electrons or hadrons in the final state, which initiate extensive air showers. We inject electrons and pions with energy $10^{15}$ eV and locate detectors at 40 km deep into the air in the horizontal direction, similar to the geometry of the NuTel experiment [7]. To study the lateral profile, the Čerenkov photons are sampled by an array of telescopes lying on a plane perpendicular to the shower axis. Figure 2 shows the lateral distribution of Čerenkov photon density at the detector plane. A Čerenkov ring with radius $\approx 700$ m is visible for the electron shower. The ring is formed by Čerenkov photons emitted near the shower maxima

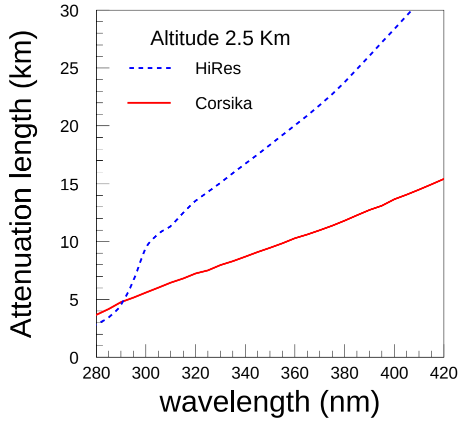


**Fig. 1.** The mean horizontal attenuation length for photons at an altitude of 2.5 km. The dashed line is the HiRes model and the solid line is the Whipple model used in this study.

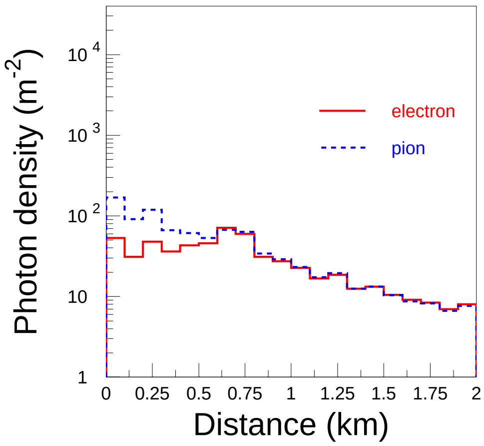


**Fig. 2.** The lateral profile of photon density of electron shower (solid line) and pion shower (dash line). Both electrons and pions are injected at distance 40 km away from detector in horizontal direction.

approximately 35 km away. However, the pion shower does not show such a ring. electron shower and pion shower exhibit similar photon densities outside the ring position. The excess of Čerenkov photons inside the ring radius for the $\pi^-$ shower is produced by *muons* produced by the hadronic interaction of shower particles with air, and is a typical signature of hadron showers. This signature is less significant in down-going air showers due to less attenuations for photons emitted around the shower maxima.

Figure 3 shows the production distance of Čerenkov photons which survive the air attenuation and arrive at the detector. It is seen that the shower maxima produce similar number of Čerenkov photons for both $e^-$ and $\pi^-$ showers. The striking feature is the "tail" of more and more photons as the production position approaches detector plane.

By examing the charged particles in the same showers, we found that the photons in the tail are produced by muons from pion decays. These muons, with typical energy above 10 GeV, radiates Čerenkov photons and suffer little ionization energy loss. The number of produced Čerenkov photons per unit length is almost constant. This together with attenuation effect explains the behavior of the tail.

It is clearly seen that the hadronic showers produce far more Čerenkov photons from the muon tail than the electron showers. This feature may help on the identification of the primary particles.

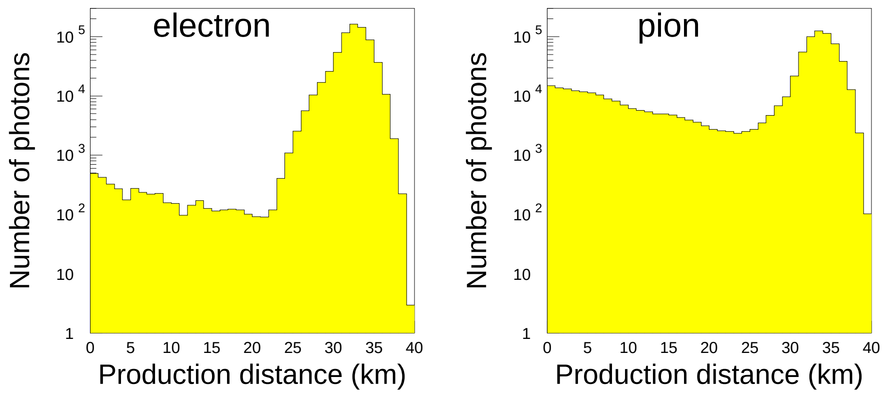


**Fig. 3.** The photon production distance of electron shower (left) and pion shower (right) for photons that arrive at the detector. See text for details.

## 4. Conclusion

We have implemented the necessary modifications in CORSIKA to simulate horizontal air showers. The result shows that heavy attenuation of Čerenkov photons from shower maxima makes the muon tail of hadronic showers visible. With carefully placed detectors this can provide information for identification of the particles that initiates the shower. In conjunction with other information, this can be used to distinguish very high energy $\nu_\tau$ from $\nu_e$ and $\nu_\mu$.

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