Simulated Cherenkov Signal at Balloon Altitudes for Upward-Moving Airshowers

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Abstract

The Earth becomes opaque to neutrinos at energies greater than $\sim$ 20 TeV. However, tau neutrinos get regenerated due to the short lifetime of the tau lepton and a flux of tau neutrinos at energies $>$ 20 TeV can traverse the Earth albeit with a degraded energy spectrum. Tau neutrinos which interact in the Earth via the charged current interaction will generate tau leptons which can propagate into the atmosphere and decay. As the branching ratio for charged taus is $\sim$ 82% into an electron or hadrons, this decay will generate an upward moving airshower. If the Cherenkov signal generated by the airshower is imaged, these events can be detected.
In order to determine the flux sensitivity of an balloon-borne instrument viewing this UV signal, an airshower simulation model inspired by Hillas [1], I determine the Cherenkov photon density at an altitude of 36 km from upward moving airshowers as a function of viewing angle. The results of this simulation are presented and flux sensitivity curves are generated based upon the size of the Cherenkov spot at the instrument.

Simulation

The Cherenkov signal from an upward moving airshower is rather straight forward and has been completed using a 1-dimensional airshower simulation without including the effects of angular dispersion of the particles in the shower [2]. For this study, a Greisen parameterization is used to generate the number of particles in the shower as a function of shower step size. A 100 meter step size is used starting at the surface of the Earth and propagated upward. The atmosphere is described by the Shibata parameterization [3]. The Cherenkov signal is generated as a function of wavelength from 200 nm to 600 nm in 25 nm wavelength bins with the Cherenkov angle determined by the index of refraction of air the particular altitude of the step generation. The Cherenkov photon signal is then attenuated by taking into account Rayleigh scattering and ozone absorption [4] as determined by the amount of atmosphere and ozone between the shower step point and the altitude assumed for a balloon-borne instrument which is assumed to be 36 km in this study.
Figures 1 $\rightarrow$ 3 illustrate the Cherenkov photon density using these assumptions for showers beginning at the ground and propagating at 0 degrees, 45 degrees, and 75 degrees. Four showers were generated using the OWL hadronic airshower Monte Carlo with a 10 meter step size and

illustrate the effects of shower fluctuations. Note that the figures represent the Cherenkov photon density for the positive x-axis only but in fact have azimuthal symmetry. The angular dependence for quantities such as the shower starting point and the atmospheric grammage between a shower development point and the instrument this study is assumed to scale as $(\cos\theta_{View})^{-1}$. Also, the plane at 36 km (where photons are projected) is assumed to be oriented such that the axis of the shower is normal to this plane. The figures demonstrate a clear Cherenkov ring structure with the maximum distance represented the photons generated near the Earth's surface along with filling at the smaller radial distances from the portion of the shower nearer 36 km.
In order to take into account the angular spread of the particles in the developing shower which will smear the Cherenkov rings at the observation point, a simulation was developed using the parameterizations of Hillas [1]. First, the Cherenkov signal generated at a specific point in the shower is corrected for the energy spectrum of the charged particles in the shower. This is accomplished via a parameter which corrects the vertical component of the track length (which was determined by the 1-dimensional simulation) by the total track length of charged particles greater than a certain particle energy. This parameterization includes effects due to shower age, and decadal energy bins are used for this numerical integration. For each energy bin, the angular distribution of charged particles is determined. The effects of the Cherenkov angle are then introduced for each bin from the particle angular distribution, and the Cherenkov cone is numerically integrated over the Cherenkov azimuthal angle. A numerical integration over the azimuthal angle of the particle angular distributions completes the calculation.

Results

The effects of the energy spectrum of particles and the angular distributions of these particles are shown in Figures 4 $\rightarrow$ 7 which represent showers at 0, 45, and 75 degrees. The upper, black curves show the number of Cherenkov photons reaching a plane at 36 km after atmospheric attenuation from the 1-dimensional simulation as a function of the shower generation point. The middle, blue curves correct these for the effects of the energy spectrum of charged particles. The lower, red curves show the photons summed over a finite plane at 36 km after the full implementation of the simulation.
The Cherenkov photon density ($\gamma's/\mathrm{m}^2$) associated with the lower curves of Figures 4 $\rightarrow$ 7 representing showers at 0, 45, and 75 degrees are shown in Figures Figures 8 $\rightarrow$ 10. Note that this data is presented in as 3-dimensional lego plots along with bands of photon density on the x- and y-axes. The figures demonstrate that some of the Cherenkov ring structure has been preserved, but has been smeared and, particularly at the larger angles, has been filled-in.

References

[1] A.M. Hillas, J.Phys. G: Nucl.Phys 8, 1461 - 1473 (1982)

[2] T. Stone, Internal OWL note, (1999)

[3] T.K. Gaisser, *Cosmic Rays and Particle Physics*, Cambridge University Press, (1990)

[4] J.F. Krizmanic, 26th ICRC Proceedings, Vol. 2, 388 (1999)

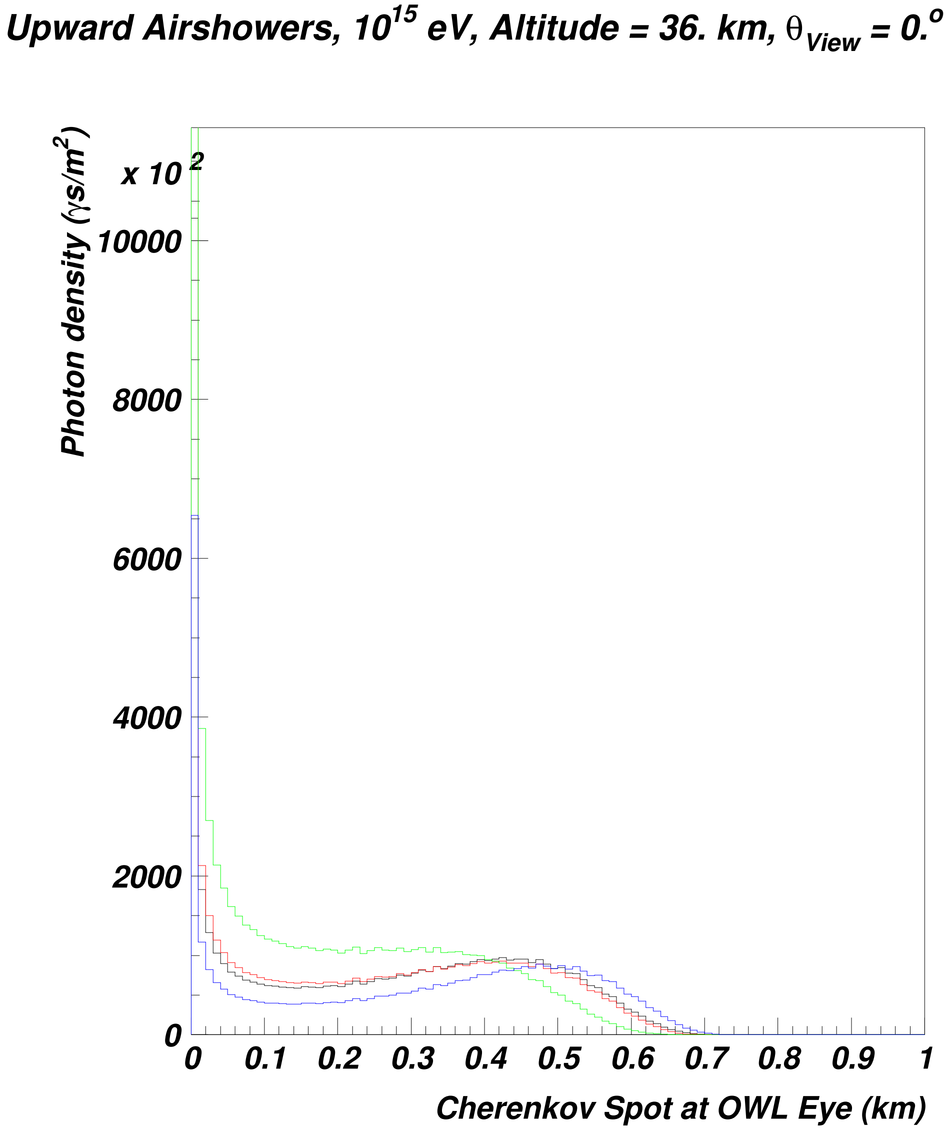

Figure 1: The Cherenkov photon density $\gamma' s/\mathrm{m}^2$) reaching the plane at 36 km center about the shower axis for four hadronic airshowers moving upward at 0 degrees from a 1-dimensional simulation.

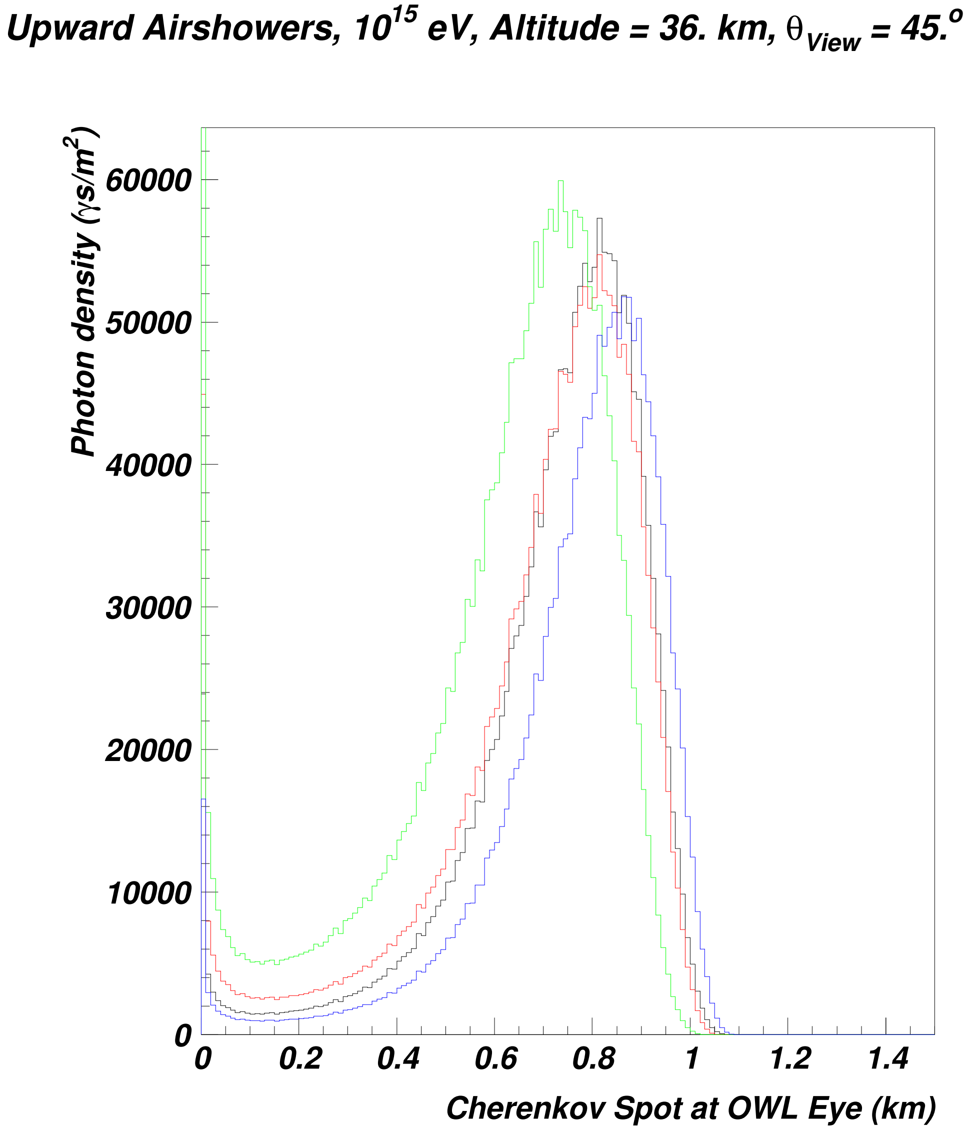

Figure 2: The Cherenkov photon density $\gamma' s/\mathrm{m}^2$) reaching the plane at 36 km center about the shower axis for four hadronic airshowers moving upward at 45 degrees from a 1-dimensional simulation.

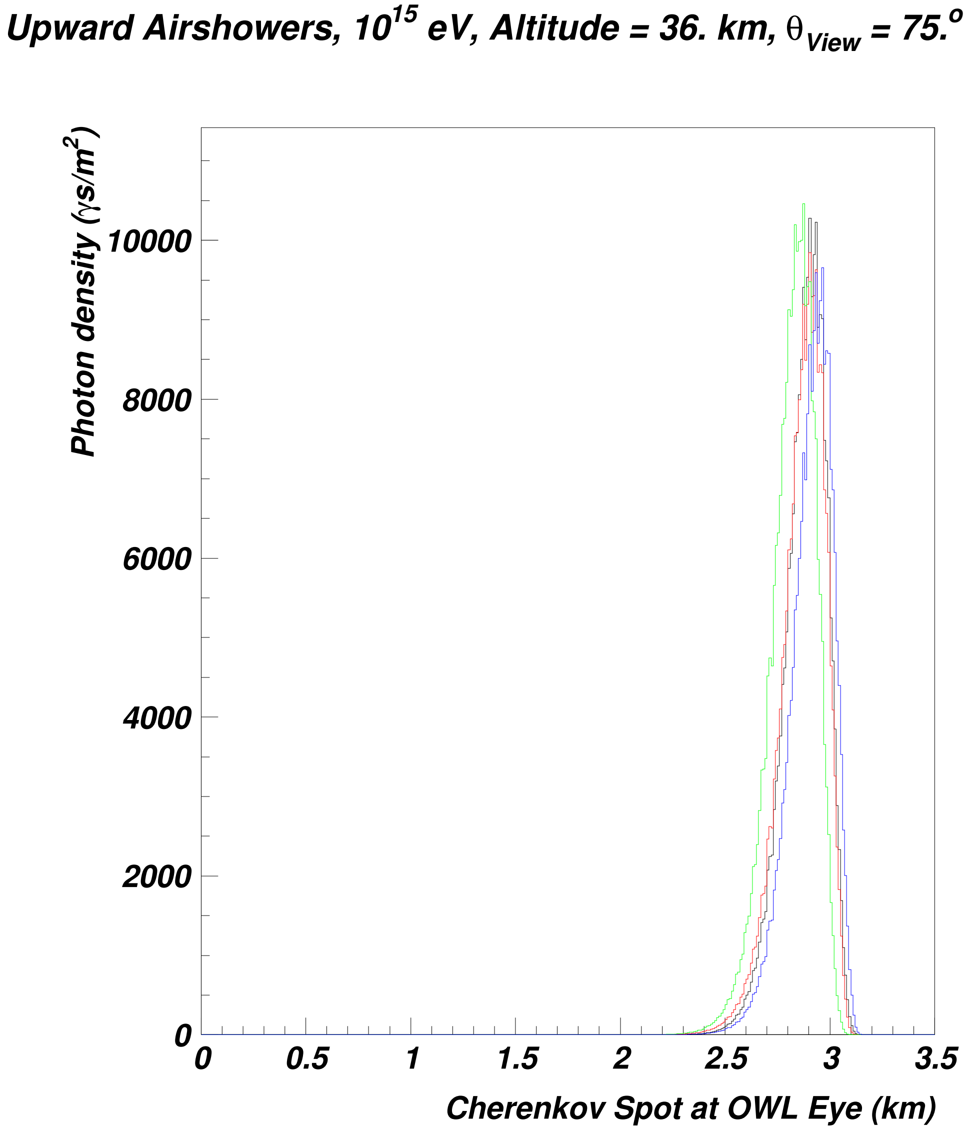

Figure 3: The Cherenkov photon density $\gamma' s/\mathrm{m}^2$) reaching the plane at 36 km center about the shower axis for four hadronic airshowers moving upward at 75 degrees from a 1-dimensional simulation.

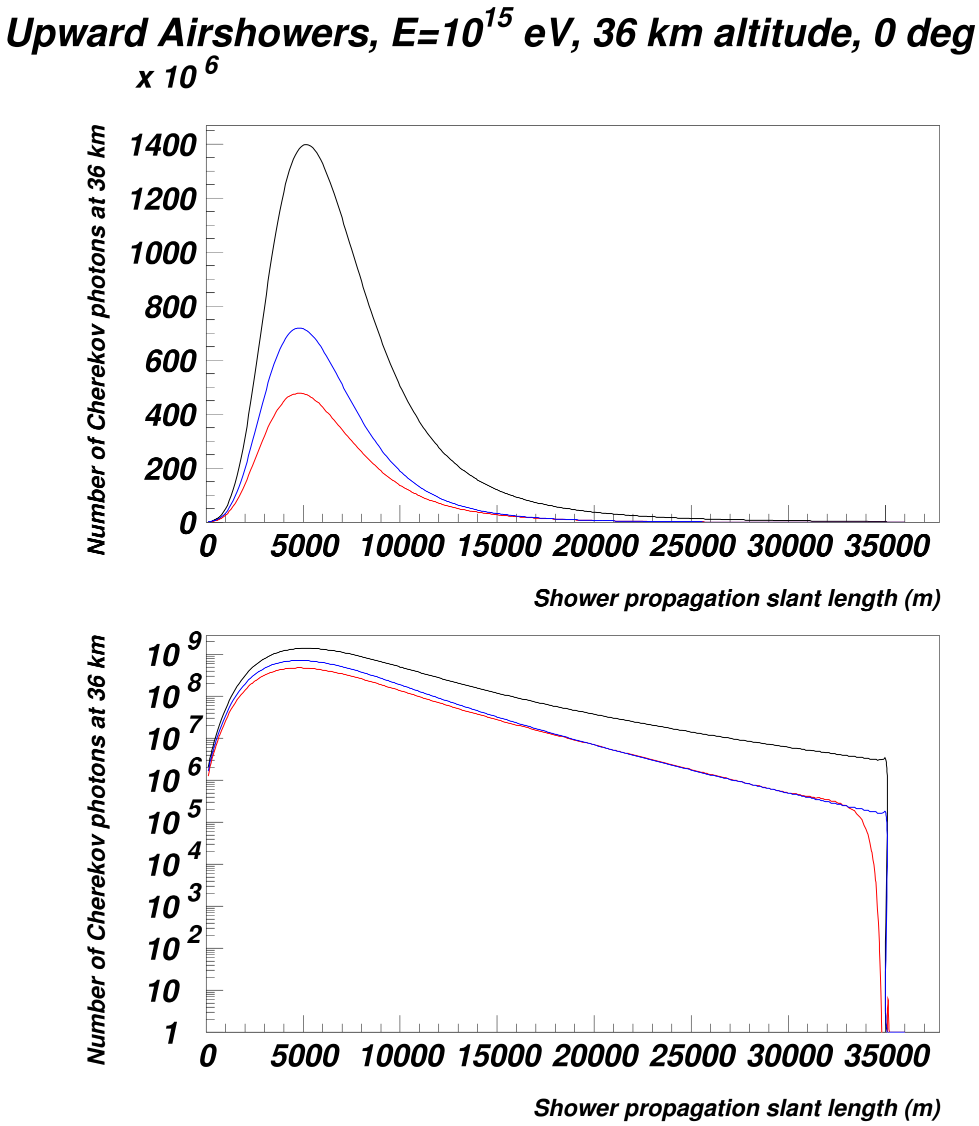

Figure 4: The absolute Cherenkov photon signal reaching the plane at 36 km as a function of generation point for an airshower moving directly upward (0 degrees). The upper (black) curve is that generated by a purely 1-dimensional shower. The middle (blue) curve represents that corrected by the Cherenkov energy and the increased track path caused by the angular distribution of particles in the shower. The lower (red) curve is the final result scored at a finite plane at 36 km and numerically integrating over the angular distributions of particles and Cherenkov angle.

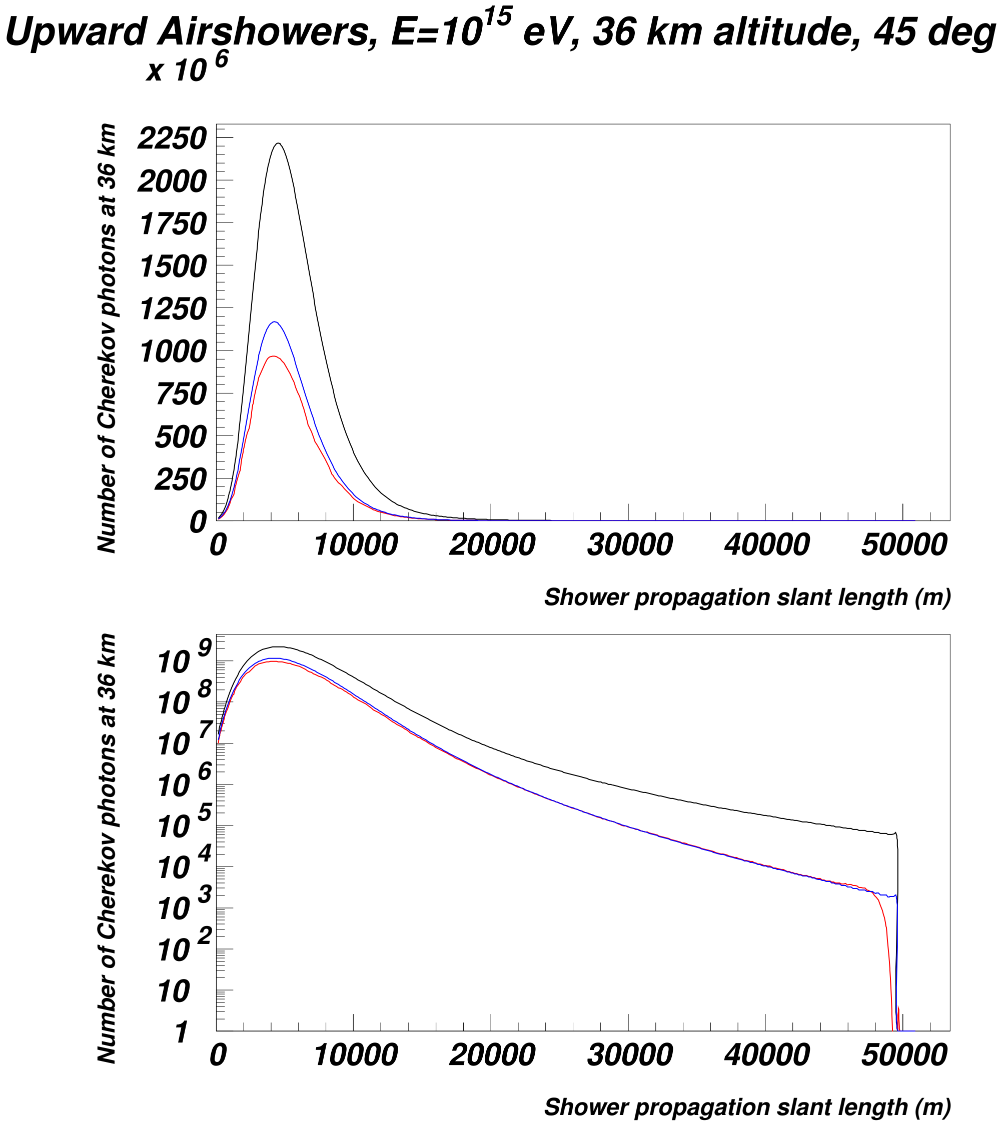

Figure 5: The absolute Cherenkov photon signal reaching the plane at 36 km as a function of generation point for an airshower moving upwards at a 45 degree angle. Note that the orientation of the plane is such as to make the shower normally incident. The upper (black) curve is that generated by a purely 1-dimensional shower. The middle (blue) curve represents that corrected by the Cherenkov energy and the increased track path caused by the angular distribution of particles in the shower. The lower (red) curve is the final result scored at a finite plane at 36 km and numerically integrating over the angular distributions of particles and Cherenkov angle.

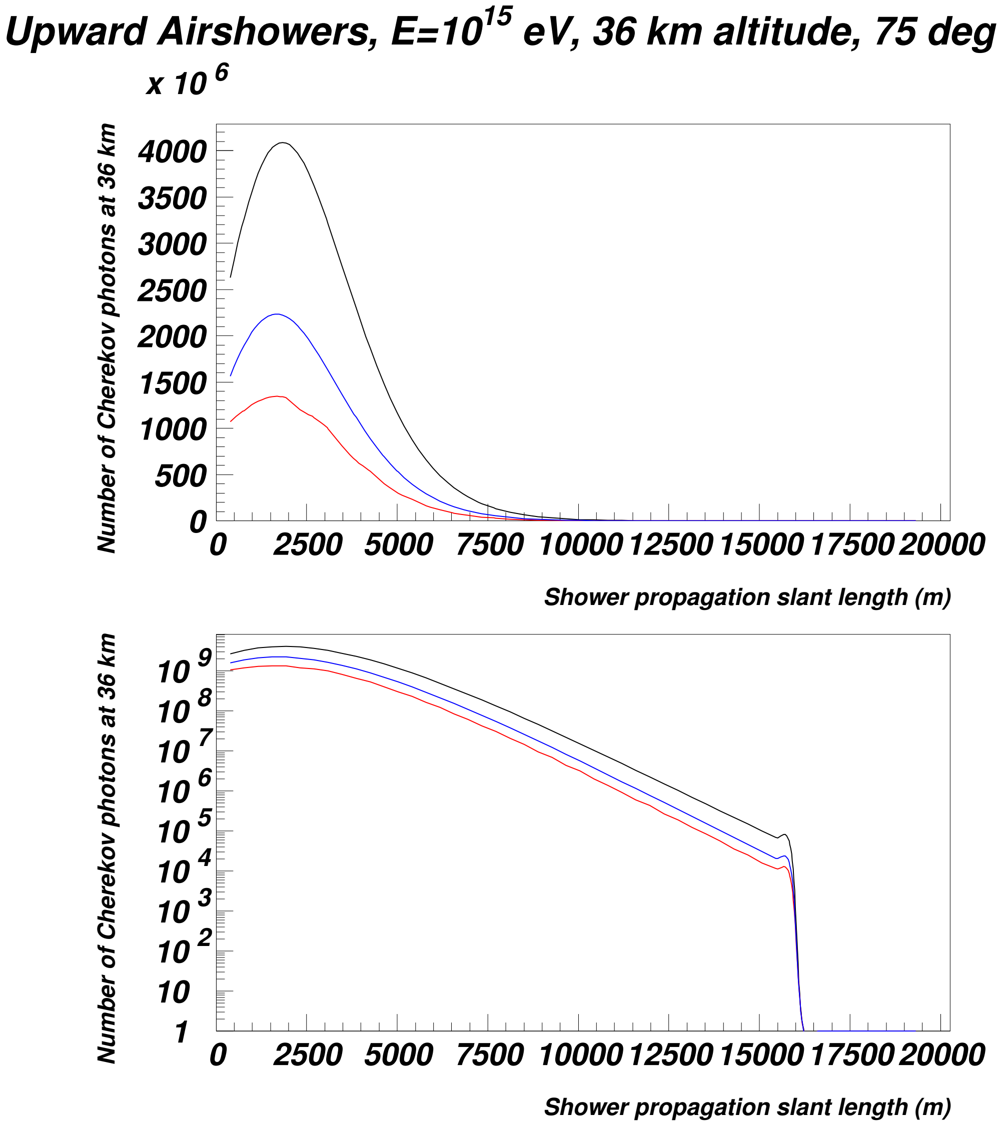

Figure 6: The absolute Cherenkov photon signal reaching the plane at 36 km as a function of generation point for an airshower moving upwards at a 75 degree angle. Note that the orientation of the plane is such as to make the shower normally incident. The upper (black) curve is that generated by a purely 1-dimensional shower. The middle (blue) curve represents that corrected by the Cherenkov energy and the increased track path caused by the angular distribution of particles in the shower. The lower (red) curve is the final result scored at a finite plane at 36 km and numerically integrating over the angular distributions of particles and Cherenkov angle.

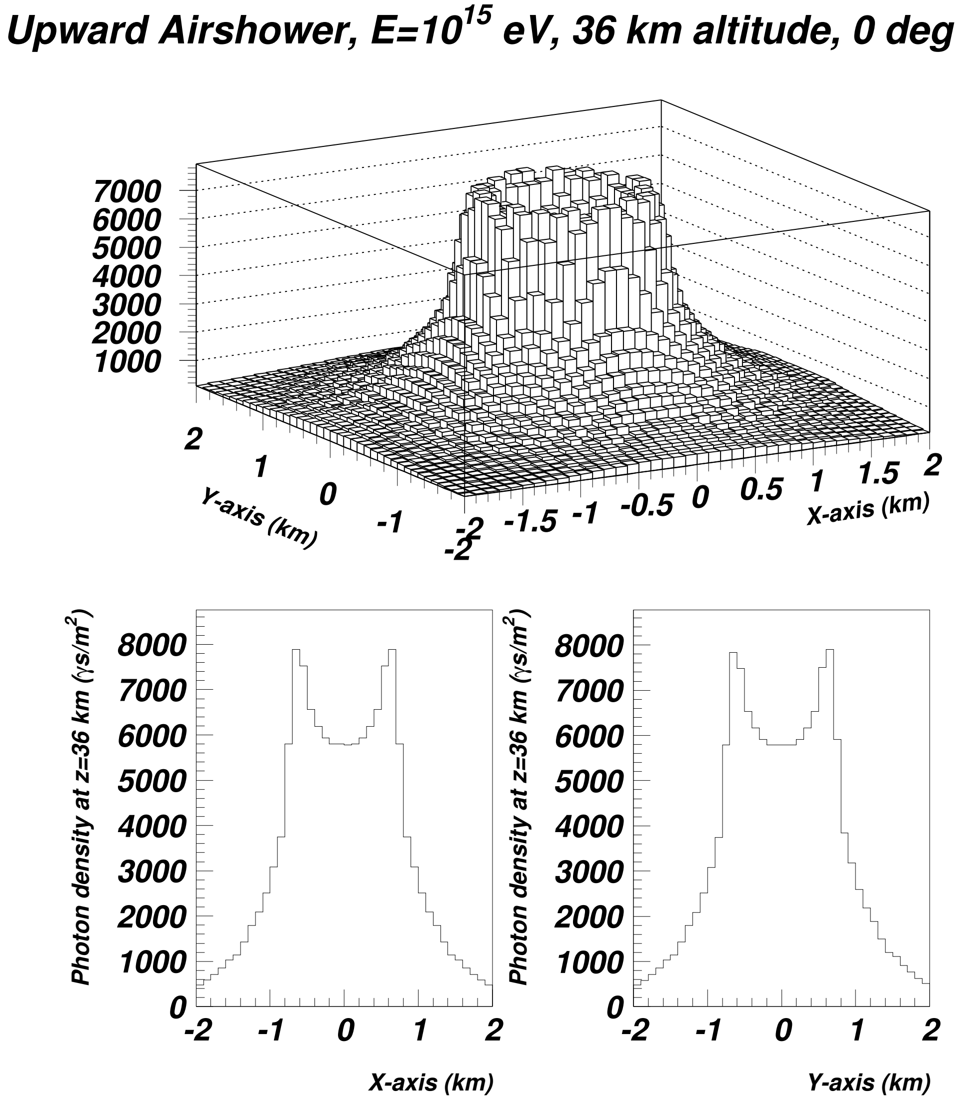

Figure 7: The Cherenkov photon density $\gamma' s/\mathrm{m}^2$) reaching the plane at 36 km center about the shower axis for an airshower moving directly upward (0 degrees). The upper figure illustrates the distribution via a lego plot while the two lower plots represent bands on the x and y axes.

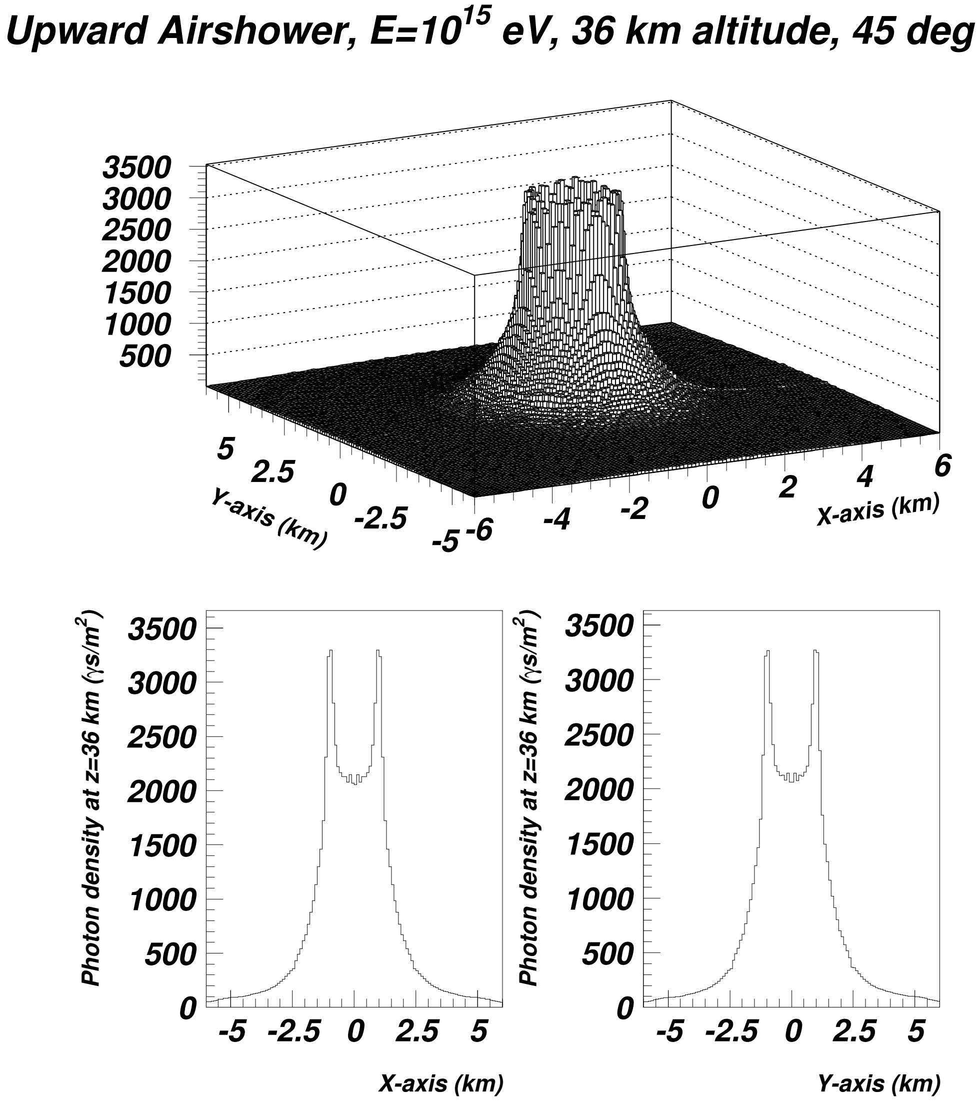

Figure 8: The Cherenkov photon density $\gamma' s/\mathrm{m}^2$) reaching the plane at 36 km center about the shower axis for an airshower moving upward at 45 degrees. The upper figure illustrates the distribution via a lego plot while the two lower plots represent bands on the x and y axes. Note that the orientation of the plane at 36 km is such as to make the shower normally incident.

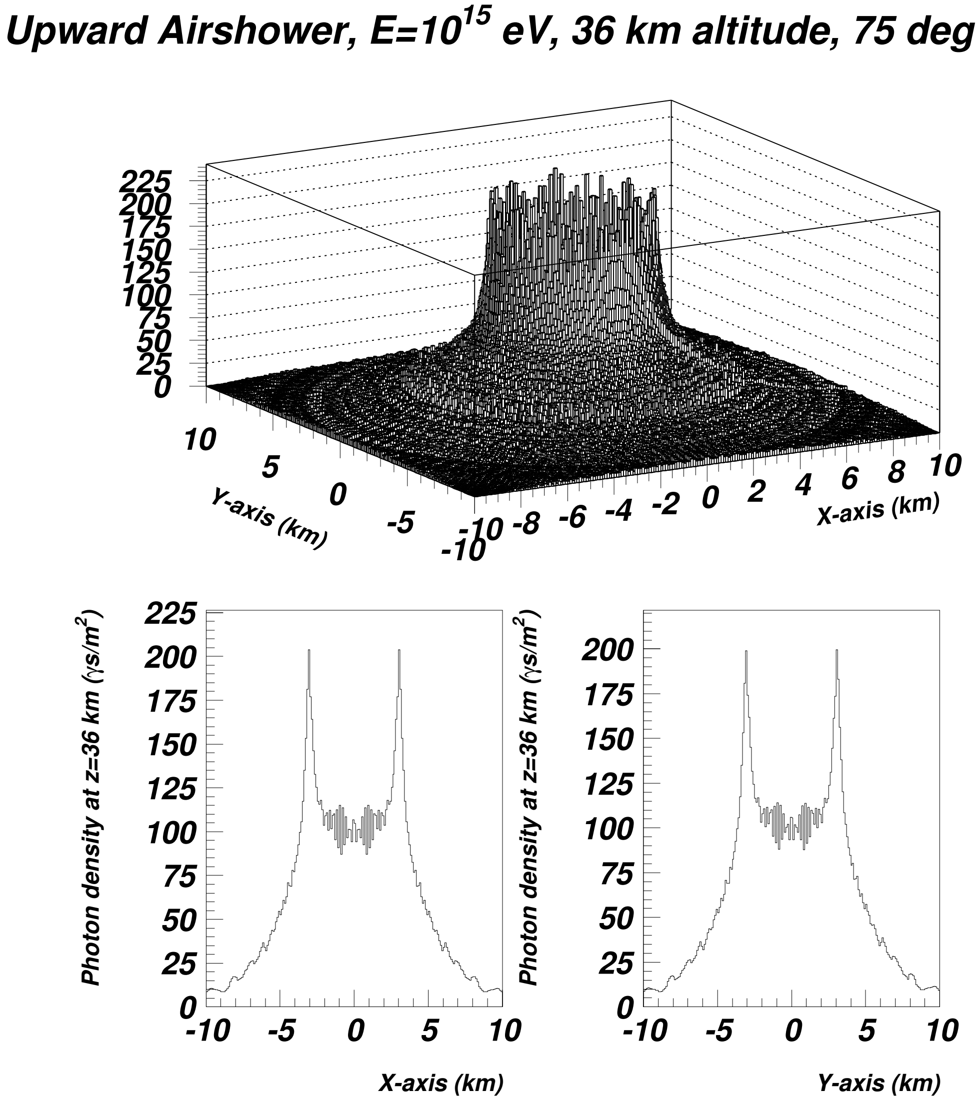

Figure 9: The Cherenkov photon density $\gamma's/\mathrm{m}^2$) reaching the plane at 36 km center about the shower axis for an airshower moving upward at 75 degrees. The upper figure illustrates the distribution via a lego plot while the two lower plots represent bands on the x and y axes. Note that the orientation of the plane at 36 km is such as to make the shower normally incident.