Simulations of Cherenkov Events by Cosmic ray Muons

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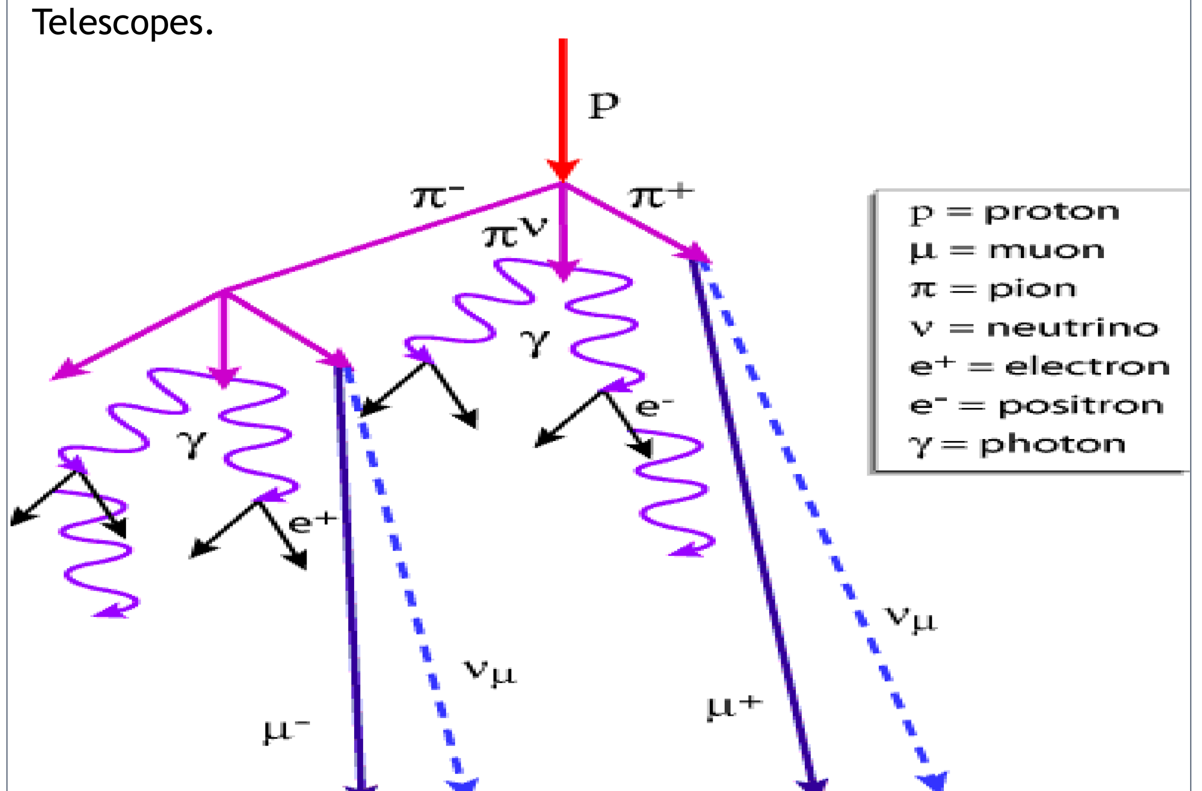
Introduction

Cosmic rays are high energy particles with energies on the order of 10^{18} eV and above, which easily exceeds that of particles generated in even the most powerful man-made particle accelerators.

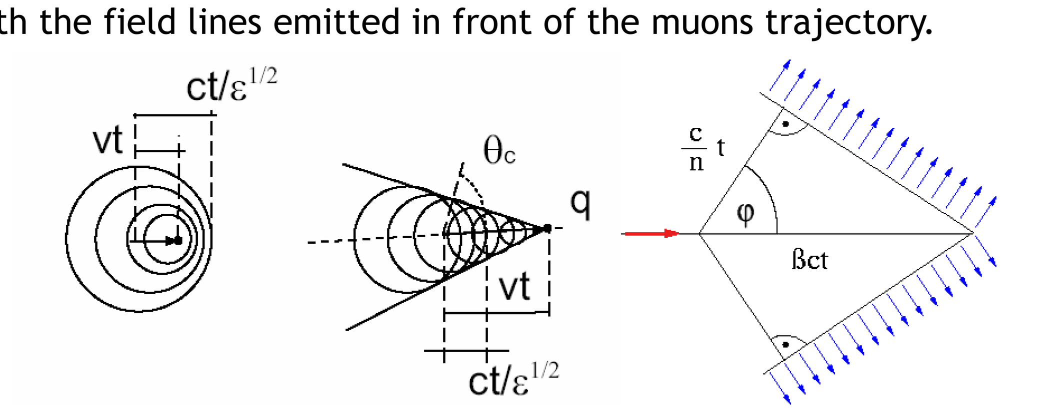
The resulting cascade of ultra-relativistic particles are capable of travelling through the atmosphere, generating an air shower which can contain many different components such as a hadron component, an electromagnetic component, a neutrino component, a meson component and a resultant muon component.

In the diagram, a Cosmic ray proton collides with a component of the atmosphere and generates a jet of pions. Pions are unstable, with a very short half-life so they decay rapidly into a subsequent shower of muons, gamma rays and neutrinos. The muons, moving at ultra-relativistic velocities are able to survive the trip to the Earth's surface by extension of the muon's half-life due to the time-dilation effects of special relativity. Because the muon is travelling through the atmosphere at ultra-relativistic speeds, it will create a burst of electromagnetic radiation by the Cherenkov Effect which can observed with ground based detectors, such as Cherenkov Telescopes.



Theory of Cherenkov Radiation.

High Energy charged particles, such as muons, can travel at a phase velocity faster than the electric field lines they produce in the air can catch up with them, hence the field lines appear "frozen" in space with respect to the muon. These apparently "frozen" field lines will destructively interfere with the field lines emitted behind the muon trajectory while the field lines constructively interfere with the field lines emitted in front of the muons trajectory.



The constructive interference creates a burst of electromagnetic radiation which is the called the Cherenkov Effect. The Cherenkov photons released are emitted in a cone in the direction of the muon trajectory. In media with non-complex refractive index the Cherenkov Cone is emitted in the direction of the muon's motion.

The photons emitted along the muon's path in this way are emitted at an angle, known as the Cherenkov angle, which determines the angular dependence of Cherenkov photons as seen from the observer.

The condition for the Cherenkov Effect to occur must be that the value of the refractive index,n, times β,(v^2/c^2), must be greater than 1.

$$\sin\varphi = \frac{1}{n\beta}$$

Russian Physicist Pavel Alekseyevich Cherenkov first described Cherenkov radiation experimentally, and Ilya Frank and Igor Tamm developed the Frank-Tamm equation which describes the theory of how Cherenkov radiation is generated by calculating the number of Cherenkov photons produced at a given energy and over what frequencies of light will be produced by a particle in terms of the charge of the particle, its velocity compared to the change in the position of the electric field lines in the medium and the permittivity of the electric fields(or refractive index) of the medium.

$$\frac{d\mathcal{E}_f}{dz} = \frac{q^2}{v^2}\int^{\omega_0} d\omega\,\omega\left(1-\frac{1}{\epsilon\beta^2}\right)$$

$$\frac{dN}{dz} = 2\pi\alpha\left(1-\frac{1}{(\beta\cdot n(z))^2}\right)\cdot\int_{\lambda_{low}}^{\lambda_{high}}\frac{1}{\lambda^2}d\lambda,$$

Cherenkov Simulation

In order to simulate Cherenkov events for a single charged particle it requires a knowledge of how many Cherenkov photons can be emitted, on average, at a given point in the atmosphere and at a given kinetic energy of the particle.

In the simulation, the result output by the Frank-Tamm formula, the expected number of Cherenkov photons, acts as a mean in a Poisson function, λ, which generates a random number of photons for each Cherenkov event, k, in the atmosphere up to the result output by the Frank-Tamm formula from which it maximizes k.

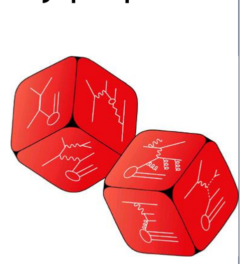
$$f(k;\lambda) = \frac{\lambda^k e^{-\lambda}}{k!},$$

The refractive index changes over a series of loops which depends on the initial height of the muon, the critical energy for a Cherenkov event to happen, the total muon energy at a given height, the density of the air and the refractive index at sea level which signals the end of the loop.

The energy given off by the muon at a given refractive index changes as the refractive index changes which itself changes as the height of the muon changes. By dividing the atmosphere into slices, each with a boundary and having the refractive index change at this boundary the mean number of Cherenkov photons can be found which will be looped in a Poisson distribution up until the muon has stopped and reached sea level.

The change in refractive index over slices means that the Cherenkov angle will also change for photons emitted at these boundaries, hence the Cherenkov photons will branch out in a cone in fixed rings which will be such that the most Cherenkov photons are emitted at the largest Cherenkov angles.

Once the functions are set up to emit Cherenkov photons in this way, it is then possible to generate a Monte carlo distribution of the Cherenkov angles for each bundle of photons and generate a random free angle for each photon. Then the distribution of photons on the ground can be viewed on a graphics display, the radius of the Cherenkov cone can be found and the positions of the photons can be constructed to form a graphical image of the cone for display purposes.



Monte carlo methods are also used to collect the Cherenkov photons over a given area, the aperture Of the Cherenkov telescope. A matrix can simulate the Photons as they are reflected in a parabolic geometry and detected over an interval of space defined by the focal point of the PMT camera. The PMT surface should display a realistic distribution of a standard Cherenkov event.

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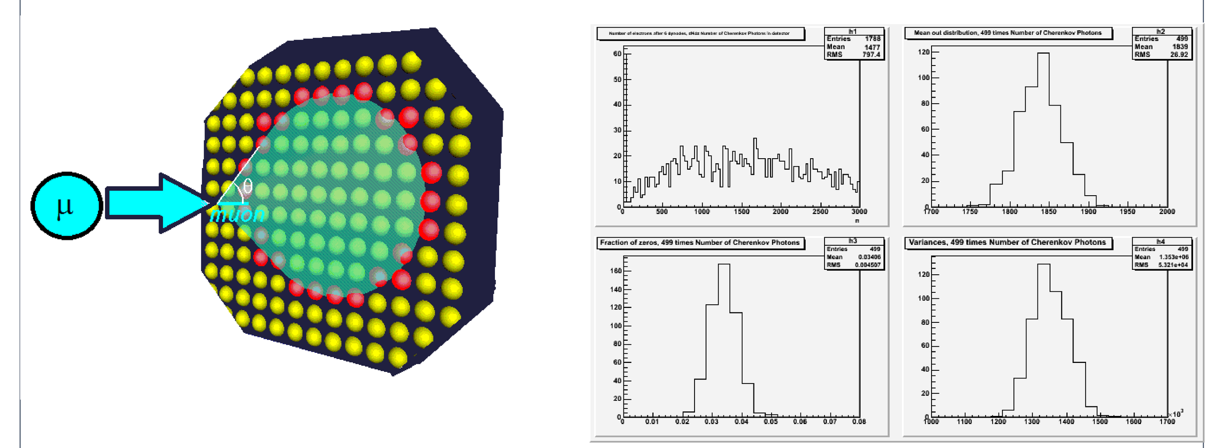
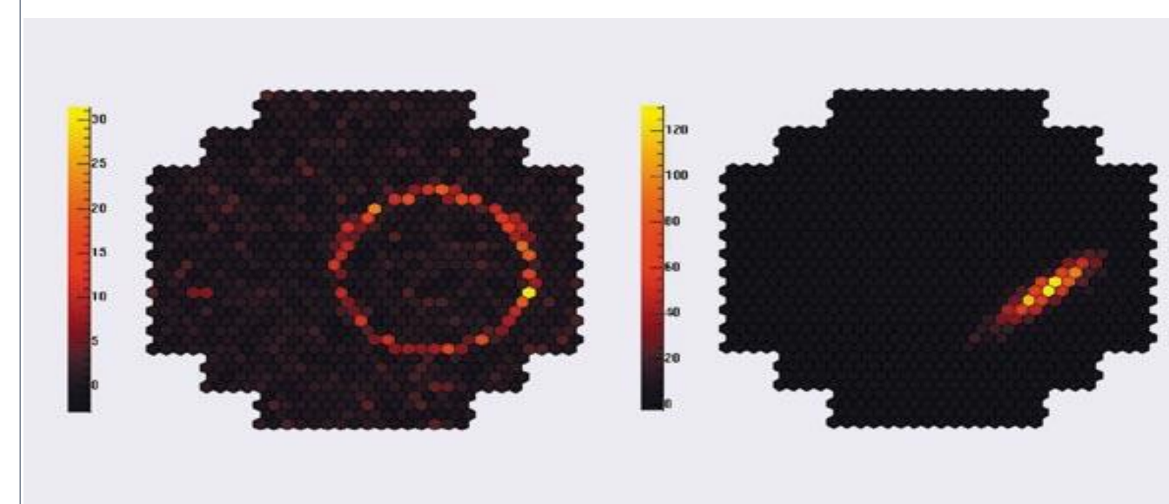


Simulation Results.

The Simulation images are compared with experimental evidence from Cherenkov Telescopes and Ring Imaging Cherenkov Detectors to prove they are accurate descriptions of a Cherenkov event.

PMT detector cameras which are mounted at the focal point of the parabolic mirror collecting the light in a Cherenkov telescope, such as those used in the VERITAS and HESS arrays, record the Cherenkov event as a full ring if the entire Cherenkov. cone enters the detector or as an ellipse if the Cherenkov cone was only. glimpsed at an angle.

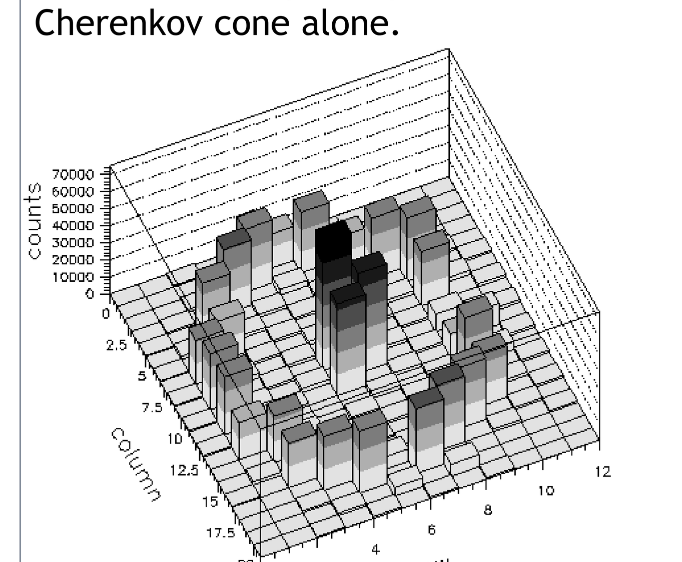


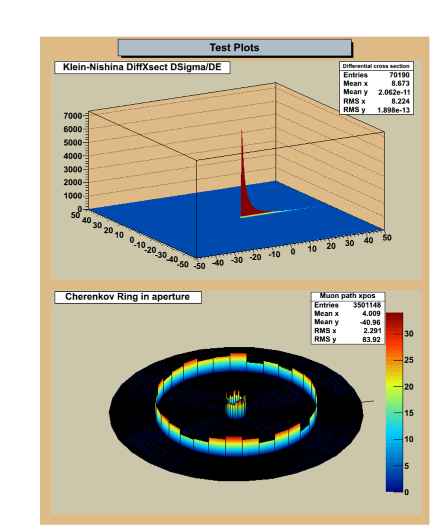
The Simulation results show these effects and in the case of the ellipse resolve them with more consistency with the distribution of Cherenkov photons on the ground so they are consistent with recorded events.

Ring Imaging Cherenkov(RICH) Detectors such as those used in particle accelerators and in the AMS-2 module on the International Space Station must be able to resolve other effects as the muon's energy is split from it.

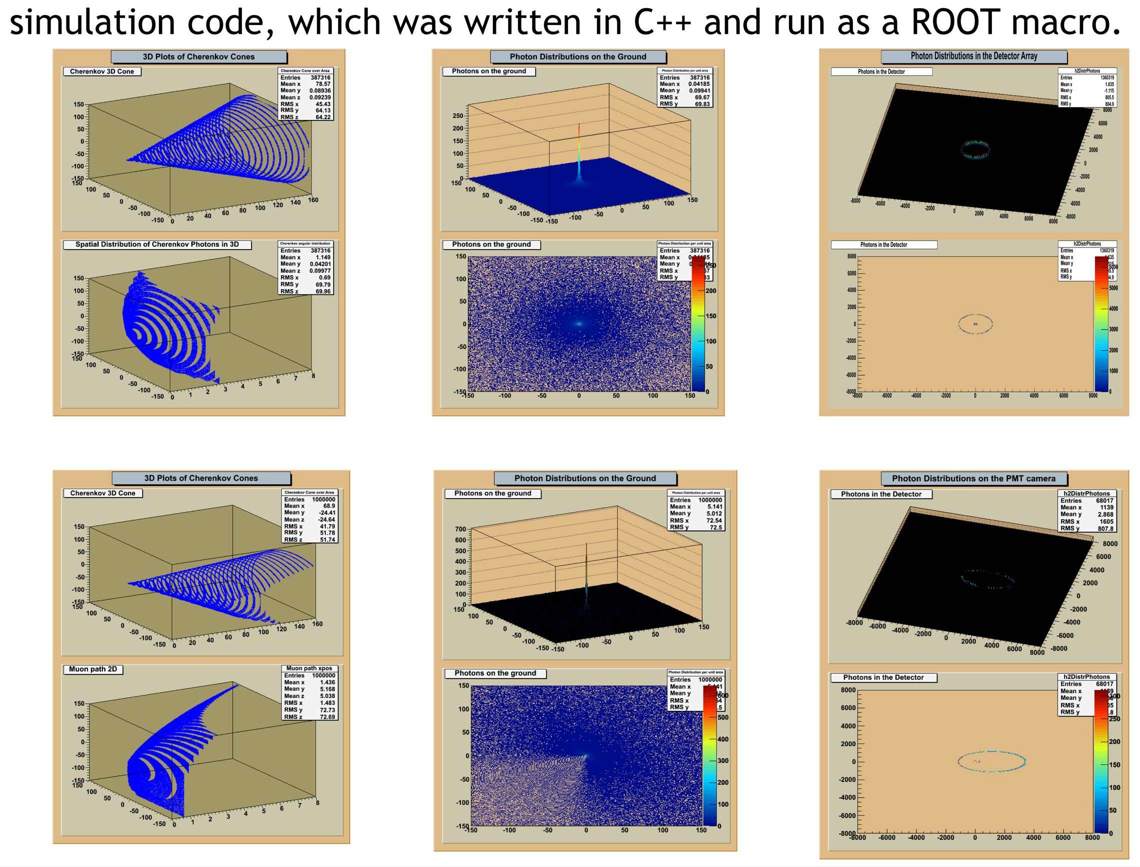
Brehmstrahlung photons, which are hard to pinpoint on Cherenkov Telescopes, have to be detected by RICH detectors as used in particle accelerator experiments to detect high energy processes. The Brehmstrahlung photons emitted as the muon interacts with the nuclei of atoms in the atmosphere would make a significant contribution, as would ionisation and an introduction of conversion electrons. These can be viewed on the simulation if required.

The brehmstrahlung photons also appear as rings but closer to the core of the shower, the identification of brehmstrahlung photons is important for this as it allows to pin point the position of the particle in a cascade or jet of particles with more accuracy than looking at the Cherenkov cone alone.





Below are some of the simulation images are generated with the simulation code, which was written in C++ and run as a ROOT macro.



Identification of the Cherenkov cone and ring image is important, as computer codes, which can either do geometric transformations(Hoff Transform) or are based on A.I. techniques such as neural nets, can recognize rings and if an extension is used, such as a code which performs the Sellmeire formula over a given wavelength of light detected, the velocity of the particle can be instantly computed. These codes are often very powerful and need powerful computers to run on.

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