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Towards a fast simulation of a water Cherenkov detector for gamma ray and cosmic ray experiments

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The secondary particles produced during the interaction of primary gamma rays or cosmic rays in the atmosphere can be measured using Water Cherenkov Detectors (WCD). Detailed simulations of the WCD signals produced by the interactions of the secondaries inside the detector are computationally time consuming, so a fast simulator is desirable. In this work, we use complete and detailed simulations of a water Cherenkov detector based on Geant4 to obtain a parametrization of the average signal response for different types of secondary particles as a function of the particle energy and incident angle. This parametrization is used to generate approximate signals which match the signals generated by the full detector simulation.

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1. Introduction

Arrays of Water Cherenkov Detectors (WCD) at ground have been proven to be useful to measure the particles in the air shower cascade produced by the interaction of primary gamma rays or cosmic rays in the atmosphere.

Examples of experiments using this measurement technique are, the Pierre Auger Observatory (for cosmic ray detection) [1], HAWC[2], LHAASO[3] and the future SWGO[4] (for gamma rays detection).

In the first steps of planing a cosmic ray or gamma ray detector experiment, many studies on the proposed detector performance and its relation to the scientific objectives are needed in order to find the optimal detector design able to reach the scientific objectives of the experiment with the assigned budget.

The accuracy of a very detailed simulation of the water Cherenkov detector signals produced by the interactions of the secondaries inside the detector are computationally time consuming and may not be needed in this early stage of the detector design. So a fast simulator is desirable and it could be used in detector performance studies and physics studies.

In order to get a fast simulation of the detector, the overall response of the detector will be parametrized. In this work, it is done using full detailed simulations of a water Cherenkov detector based on Geant4[5] to obtain the parametrization of the detector response. The resulting parametrization will then be used to generate approximate signals which match the signals generated by the full detector simulation.

2. Detailed simulation of a water Cherenkov detector using Geant4

The water Cherenkov detector response was simulated using GEANT4 detailed simulations[5].

As a first step, we generated simulations for a given geometry of the detector with the following characteristics:

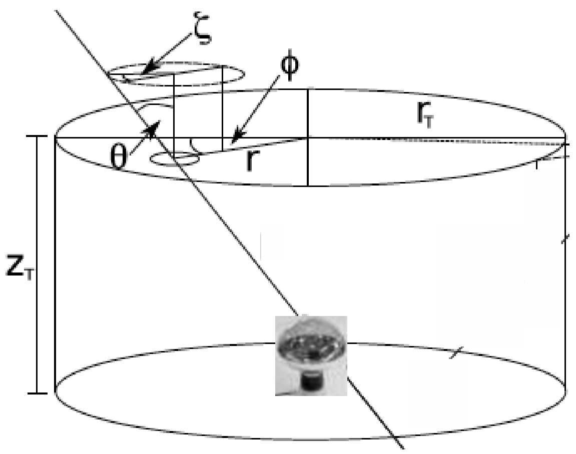

Figure 1: Detector geometry: a cylinder of height z_t= 4.5 m height and radius r_t= 3.65 m with a single central PMT positioned on the detector floor.Figure also shows how the incident particle geometry parameters are defined.

- Stainless steel cylinder 4.5 m height and 3.65 m radius, whose internal walls are covered with a UV absorbing material.
- A single 9” central PMT positioned on the detector floor, as can be seen in figure 1
- 154 tons of hyper pure water inside the detector (water level 4m)

All parameters fixing the geometry can be modified in a configuration file.

GEANT4 simulations take into account complete detail on the production and propagation of Cherenkov light within the detector:

Physical processes for particle propagation
γ: Gamma conversion, Compton scattering, Photoelectric effect
e^+e^-: Ionization, Bremsstrahlung, Annihilation, Multiple scattering
mu^+/mu^-: Ionization, Bremsstrahlung, Pair production, Multiple scattering and muon capture
Other charged particles: Ionization and multiple scattering
Decay processes ($\pi^- \to \mu^- + \bar{\nu}_{\mu^-}$, etc.)
Optical processes for the propagation of Cherenkov light
Absorption phenomena
Rayleigh dispersion
Optical processes on the interfaces (for example: glass-water for the surface of the PMT)

The simulated particles enters through the top of the detector. 1000 events were simulated for each particle type, energy and zenith angle combination with random position of particle incidence in the top of the detector. The simulation parameters were:

- type of particle: e^+,e^-,γ, μ^+,μ^-
- particle energies: 10^8 , 10^7, 10^6, 10^5 , 10^4 , 10^3 , 500 y 100 MeV
- particle zenith angles: 138, 144, 152, 164, 180 degrees
- Azimuth angle between 0 to 360 degrees
- random position of incidence in the top of the tank.

From the output of the GEANT4 simulations, the total signal is calculated as the total number of photo-electrons produced by the incident particle in the detector.

3. Results

3.1 Probability of producing a non-zero signal in the detector

The position where the particles hit the top of the detector it is shown in figure 2 from left to right for electrons incident at 1000 MeV for zenith angles: 138, 145, 153, 164, 180 degrees. Note that 180 degrees correspond to the vertical incidence of the particles. The positions of incidence of particles that produce a non zero signal are shown as black points and the ones that give a null

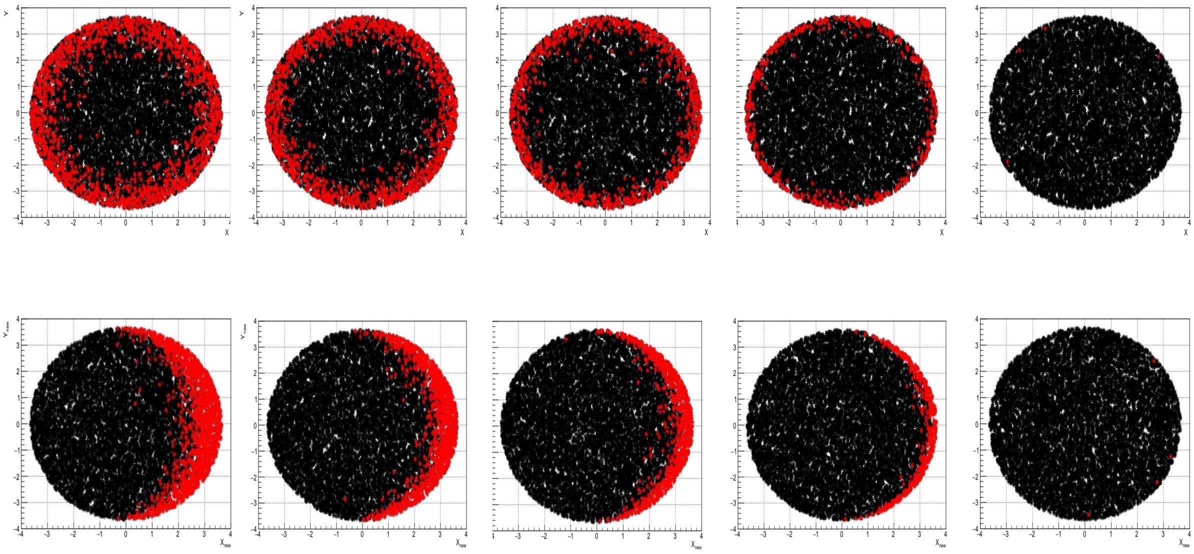

Figure 2: Position of incidence of 1000 MeV electrons that produce a non zero signal are shown as black points and the ones that give a null signal are represented as red points for electron zenith angles 138, 145, 153, 164, 180 (from left to right). In the lower panel, the coordinate system is rotated to observe all particles incident from left to right.

signal are represented as red points. In the lower panel, the coordinate system is rotated to observe all particles incident from left to right to increase the effect.

In this figure, it can be clearly observed that the regions with zero signal are on the edge of the tank and that the more vertical the particle falls on the tank, the number of null signals decreases (vertical incidence corresponds to 180 degrees).

The probability of getting no signal was calculated as the ratio between the number of particles that do not produce a signal and the total number of particles entering the detector for each type of particle at a given energy and zenith angle.

The probability of a null signal as a function of the zenith angle for a given energy and particle type is shown in figure 3 for electrons of energies 10, 100, 1000 and 10000 Mev, in figure 4 for gammas of energies 10, 100, 1000 and 10000 Mev and in figure 5 for muons of energies 100, 1000, 10000 and 100000 Mev.

In these figures, it is also observed that the more vertical the particle falls on the tank, the lower the number of null signals (vertical incidence corresponds to 180 degrees). Also, the null signal probability decrease with increasing particle energy.

The dependence of the probability of null signal with zenith angle and energy was fitted for each type of particle for future use in the fast simulator.

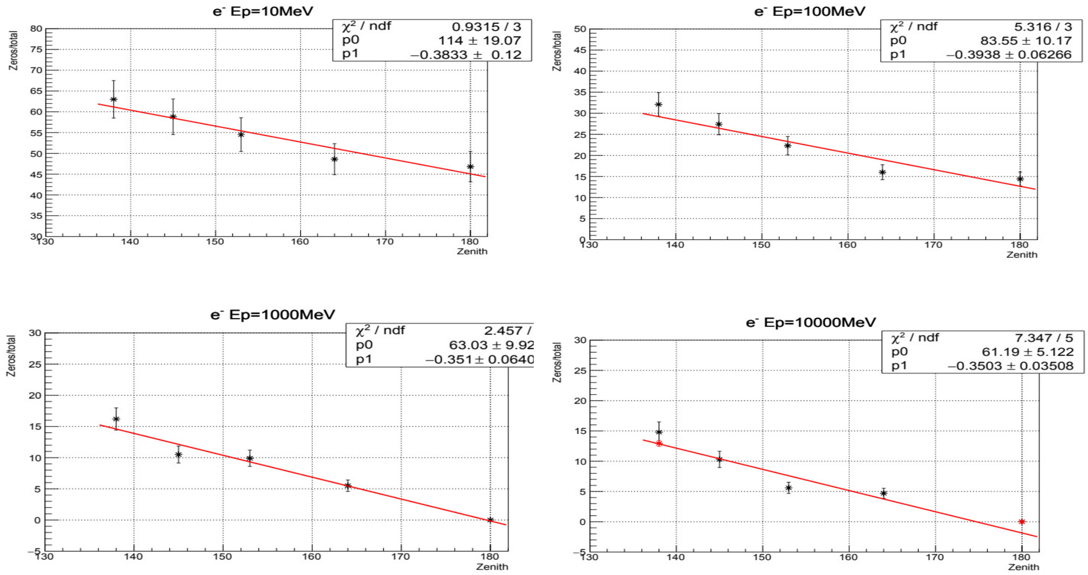

Figure 3: Fit of the zenith angle dependence for electrons incident at energies: 10, 100, 1000 and 10000 Mev (from left to right and top to bottom).

4. Parameterization of the signal

We generate histograms with the signal distribution at a given zenith angle and energy of the incident particle in the detector for each particle type. We then average over the random values of the position of incidence on the top of the detector and the azimuth angles.

The signal distribution shows two peaks, as shown in figure 6 for the three types of particles (e^+e^-,$\mu^+\mu^-$,γ). This two-peak structure in the signal distribution was also observed in gamma ray experiments like LHAASO for near vertical muons [6] . In this work they stated that the mechanism for the origin of the second peak, is produced by muons hitting directly on the PMT. As a by-product, they also proposed a method for the online charge calibration, making use of the second peak of muon signals.

As a first approach to model the signal distribution function, we propose the following functional form to fit signal distribution function:

$$Signal = f\ Landau(m_1, s_1) + (1 - f)\ Landau(m_2, s_2)$$

which is a combination of two Landau functions with different parameters m and s.

This model for the normalized signal distribution was fitted to the simulated signals using the RooFit [7] framework with 5 free parameters: f, m_1, s_1, m_2, s_2.

For a given particle type, these parameters show a dependence with energy and zenith angle, that was also fitted afterwards.

5. Summary

In this work, full detailed simulations of a water Cherenkov detector based on Geant4 were used to obtain a parametrization of the average detector response as a function of particle type, incident energy and zenith angle. This parametrization is used to generate approximate signals which match the signals generated by the full detector simulation. In this way we can build a fast simulator that will be useful for performing simulations of different detector geometries, array configurations that optimizes reconstruction and gamma-hadron separation in gamma ray experiments or for other detector performance studies in cosmic ray experiments, which are still in the early stage of the detector design.

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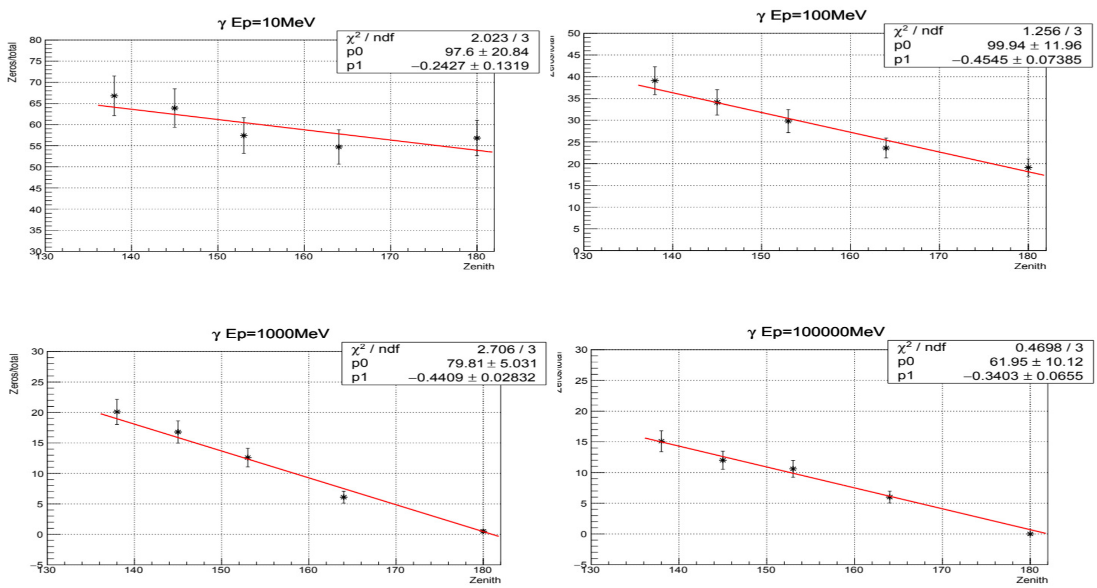

Figure 4: Fit of the zenith angle dependence for gammas incident at energies: 10, 100, 1000 and 10000 Mev (from left to right and top to bottom).

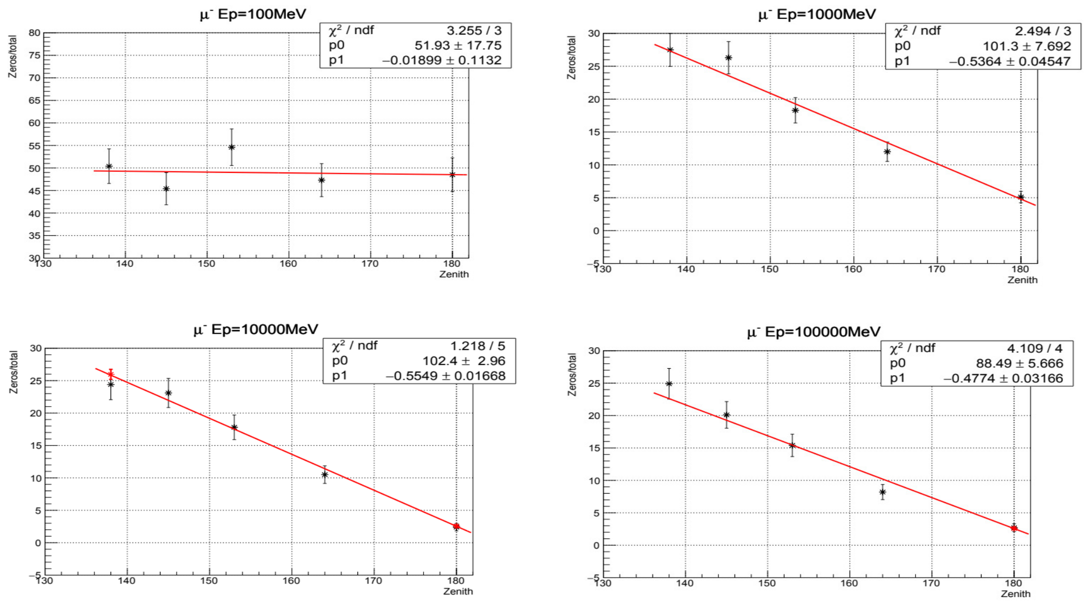

Figure 5: Fit of the zenith angle dependence for muons incident at energies: 100, 1000, 10000 and 100000 Mev (from left to right and top to bottom).

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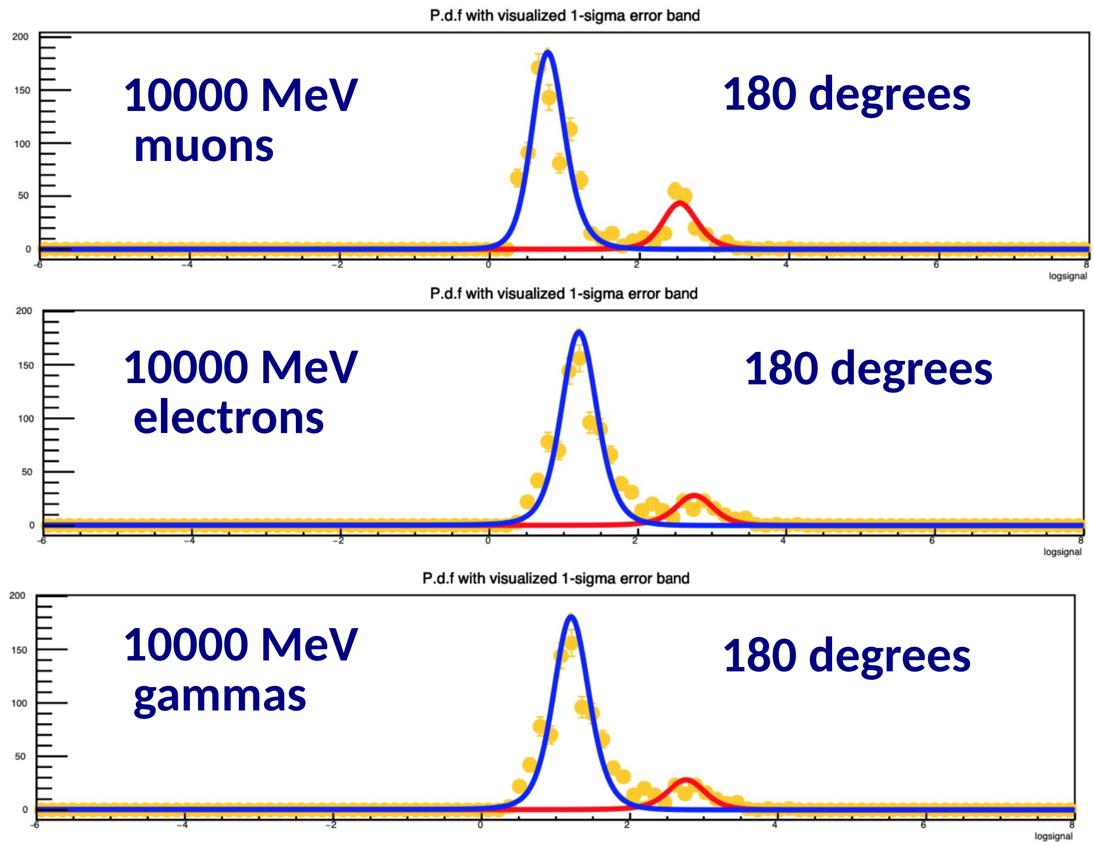

Figure 6: The average signal distribution for 10000 MeV muons, electrons and gammas for vertical incidence (180 degrees)