Simulation of Near Horizontal Muons and Muon Bundles for the HAWC Observatory with CORSIKA

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HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

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Abstract

The HAWC (High Altitude Water Cerenkov) gamma ray observatory observes muons with nearly-horizontal trajectories corresponding to zenith angles greater than 70^0. HAWC is located at an altitude of 4100 meters a.s.l. (70 deg. atmospheric depth of 2400 g/cm^2) on the extinct volcano, Sierra Negra in Mexico. In this poster, we summarize the CORSIKA and GEANT4 as well as toy-model based simulations performed to determine the effective area of HAWC to muons from high zenith angle cosmic ray primaries. We are developing an updated GEANT4 based detector response simulation that includes a model of the volcanoes that are located near HAWC. These simulation studies are investigating the capability to use muon multiplicity and rates to differentiate between the primary particle composition (proton or iron) and measure the primary energy

Introduction

The response of the HAWC observatory [1] to nearly-horizontal muons is complicated due to the presence of nearby volcanoes as well as instrumental effects. The minimum threshold energy required for muons to traverse the overburden depth of the volcanoes depends upon muon arrival direction. This direction dependent energy threshold enables a measurement of the energy spectrum of cosmic rays using observed muon rates as a function of arrival direction. Understanding these muon rates is also useful in the determination of backgrounds to neutrino searches [2]. We are investigating the possibility to measure the cosmic ray primary composition as well as energy spectrum using muon bundles observed with HAWC. For these analyses, the effective area as a function of arrival direction for the detection of cosmic ray primaries that produce nearly horizontal muons must be determined.

HAWC Detector and Site

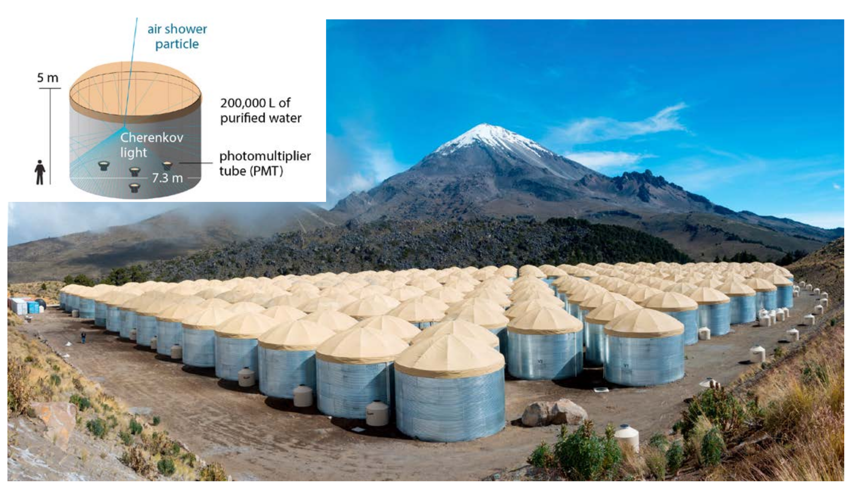

Figure 1: The HAWC detector has 300 - 4.5 m high, 7.3 m diameter tanks covering a footprint of 22,000 m2. Each tank contains 200,000 liters of purified water and is instrumented with 4 upward looking photomultiplier tubes (PMTs) .

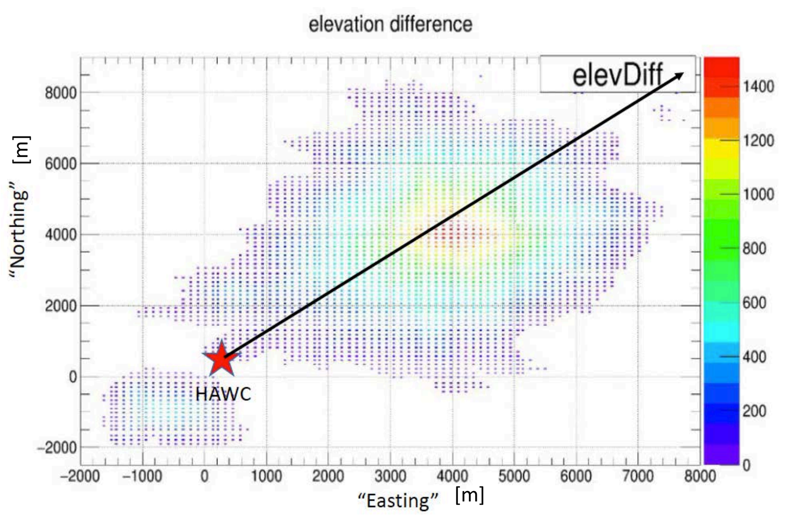

Figure 2: The HAWC site is located at an altitude of 4100m a.s.l. adjacent to two volcanoes, Pico de Orizaba (5636m) and Sierra Negra (4580m). The elevation above HAWC as a function of "Easting" and "Northing" [4] in the area surrounding HAWC. The overburden depth at the base of Sierra Negra of 7200 m.w.e results in a muon energy threshold of approximately 3.3 TeV, while at the base of Pico de Orizaba the depth of 32000 m.w.e results in a muon energy threshold of approximately 520 TeV.

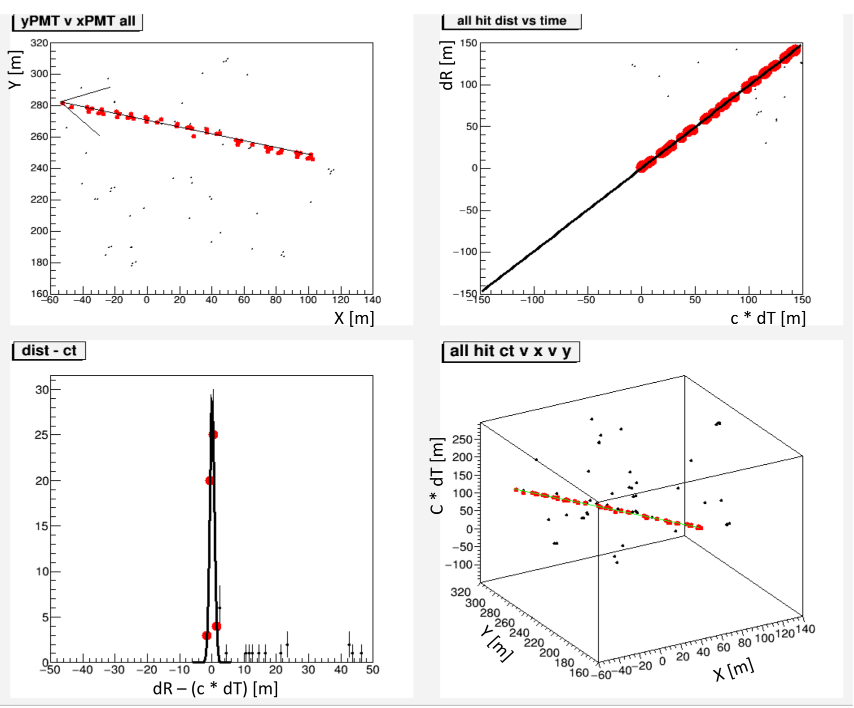

Figure 3 Nearly-Horizontal Muon Identification The procedure to identify nearly-horizontal muons traversing the HAWC detector is to identify patterns of PMT hits in time and space that are consistent with a particle moving nearly horizontally at the speed of light. The identification is done by first identifying a set of PMTs whose locations and hit times satisfy the relation distance = cΔt. Application of a Hough transformation algorithm [4] to further require isolated lines reduces the background from air shower events. A description of these algorithms and the observation of nearly horizontal muons by the HAWC gamma ray observatory is described in another report that has been submitted to this conference [5].

Overview of simulation of HAWC detector response to horizontal muons

- CORSIKA simulation software package [6] generates extensive air showers (EAS) in the atmosphere.
  - CORSIKA "tree-level" observable distributions in conjunction with geometrical considerations guides detailed simulation studies.
  - CORSIKA Data files containing trajectories and momenta of shower particles further processed by either a perfect cylindrical "toy model" or detailed GEANT4-based [7] detector model simulation.
- The "toy model" performs faster simulations to develop an understanding of the general behavior and response of a perfect detector.
- Detailed detector simulation using injected single muons determines basic instrumental response.
- The nearly-horizontal muon identification and reconstruction software processes the simulated data.
- Effect of volcano overburden determined by calculating an arrival direction dependent attenuation of the impinging muon flux due to a minimum required muon energy.
- Detector acceptance and resolution determined by a comparison of thrown and reconstructed distributions.
- A full detector simulation study, including a detailed GEANT4-based description of the volcanoes, has not yet been completed.

CORSIKA Configuration and Geometrical Considerations of EAS Generation

Extensive Air Shower (EAS) simulation with CORSIKA

- Nearly-horizontal muons detected by HAWC are produced in extensive air showers initiated at distances up to ~1400 kilometers . The CORSIKA simulation configuration must be chosen appropriately.
  - Non-flat detector using a curved atmosphere model.
  - Primary particle energy range from 100 GeV to several PeV.
  - Primary particle arrival directions probability weighted by sin(θ) ,uniform over azimuth angles.
  - Generated shower displaced parallel to original axis at distances up to $R_{p,max}$ uniformly covering circle perpendicular to shower axis.
- Muon multiplicity increases with primary particle energy. Muon energy spectrum is harder than primary.
- Muon opening angle w.r.t shower direction decreases with energy. Constrains required $R_{p,max}$.

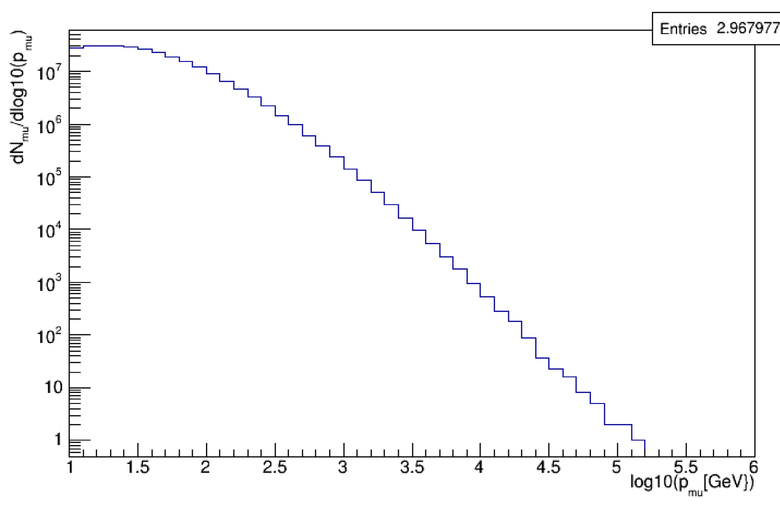

Figure 4: Muon Momentum Spectrum for a sample of 1 billion CORSIKA generated cosmic ray primaries generated in the energy range 100 GeV to 10PeV with a energy spectral index=-2.7. The muon momentum (or energy) distribution falls less steeply than the primary flux with increasing energy indicating that the muon multiplicity increases with primary energy. This increasing muon multiplicity enhances acceptance for the primary particle detection at higher energies via nearly-horizontal muons.

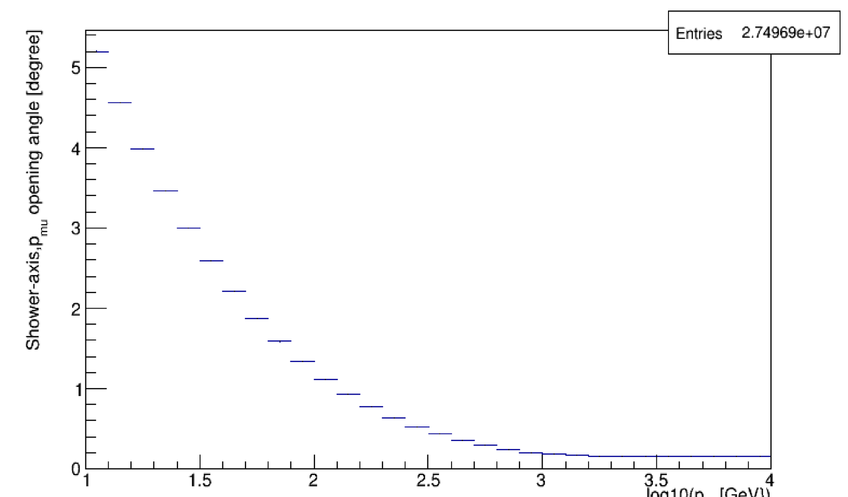

Figure 5: Average Muon Opening Angle w.r.t shower-axis for the same sample of CORSIKA generated cosmic ray primaries. For higher momenta the opening angle of muons from the shower axis decreases to be significantly less than a degree. The opening angle constrains the value required for $R_{p,max}$ to be fully efficient for detector acceptance calculations. The tighter collimation of the muon trajectories at higher energies allow bundles of muons to be observed by the HAWC detector.

Perfect "Toy Model" Detector Simulation

- CORSIKA showers are "thrown" 100 times at different radius R_p and angle ϕ on circle perpendicular to shower axis.
- Cylindrical detector has surface area and height of HAWC.
- Muon identification performed by requiring length of trajectory intersecting the cylinder be > 40m.
- Estimates effective area for primaries by multiplying detection efficiency of "perfect" detector by $\pi R^2_{p,\max}$.
- Will determine $R_{p,max}$ where detector reaches full efficiency and dependence of effective area as a function of $R_{p,max}$.
- Will estimate muon rates when combined with cosmic ray spectrum, instrumental response and overburden attenuation functions.

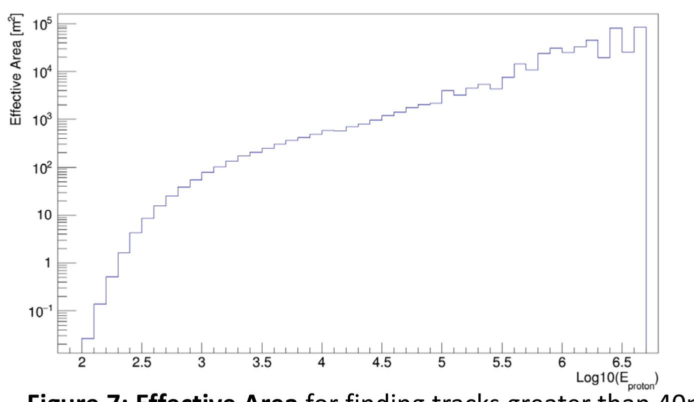

Figure 7: Effective Area for finding tracks greater than 40m in a perfect cylindrically symmetric detector as a function of cosmic ray primary proton energy for $R_{p,max}$=2km. The effective area continues to increase with $R_{p,max}$,so the actual effective area is larger than shown here and is significantly reduced by instrumental effects and Volcano overburden.

HAWCSIM Detailed Instrumental Simulation

- GEANT4-based software simulation package internally developed by HAWC.
- Fully models the instrumental response of HAWC.
- Processes CORSIKA EAS particles as well as injected single particles.
- Response to single muons will be convoluted with the effective area for a perfect cylindrical detector to obtain the effective area as a function of arrival direction including instrumental effects.

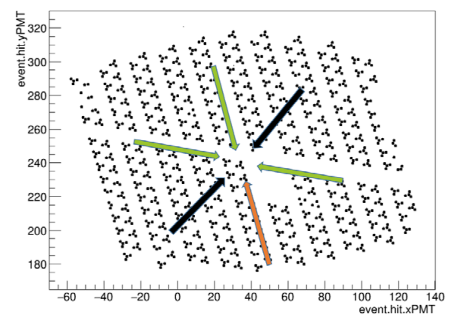

Figure 8: Location of the PMTs in the layout of the HAWC water tanks. Each set of 4 PMTs view an isolated volume of water. The azimuthal directions of enhanced response to horizontal muons are indicated by the arrows.

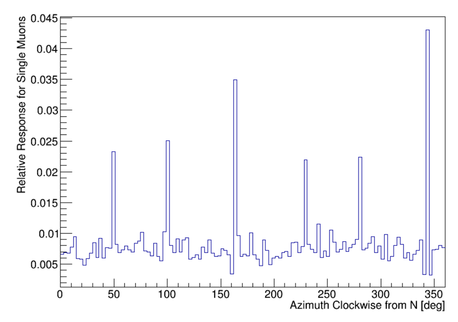

Figure 9: Relative response of identification algorithm to nearly-horizontal HAWCSIM simulated single muons as a function of azimuth angle. Note the enhanced response in the six directions corresponding to the six preferred directions of tank alignment.

Site Simulation

- Effect of overburden can be estimated by using CORSIKA generated muon momentum distribution, Figure [4], with the muon energy loss formula of the Particle Data Group [3].
- Nearly-Horizontal muon rate as a function of azimuthal angle can be estimated by combining the flux reduction factor shown in Figure 13 with instrumental azimuthal response function shown in Figure [9] normalized by an estimated muon rate impinging on a perfect cylindrical detector obtained by the Toy Model.

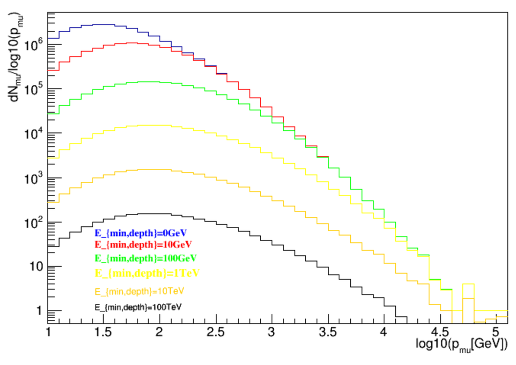

Figure 10: Initial muon momentum distribution for surviving muons after traversing various depths. Obtained by convoluting unattenuated momentum distribution shown in Figure 4 with muon survival probability for a given depth $\left(1-\exp\left(-E_{\mu}/E_{\min,\text{depth}}\right)\right)$

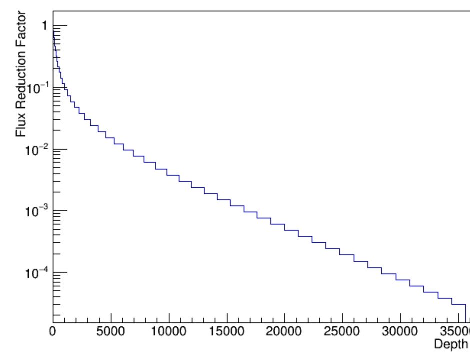

Figure 11: Muon flux reduction factor as a function of depth obtained from ratio of integrated attenuated muon energy distributions for given depth to integral of unattenuated distribution.

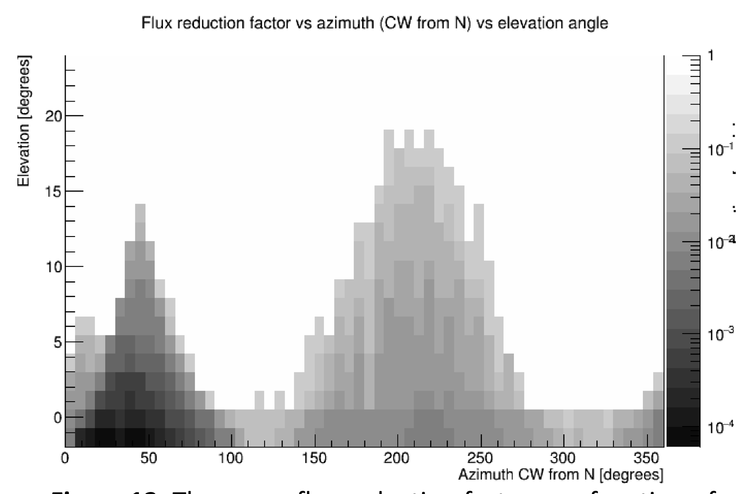

Figure 12: The muon flux reduction factor as a function of arrival direction (azimuth CW from N, elevation) due to the volcanoes Pico de Orizaba and Sierra Negra.

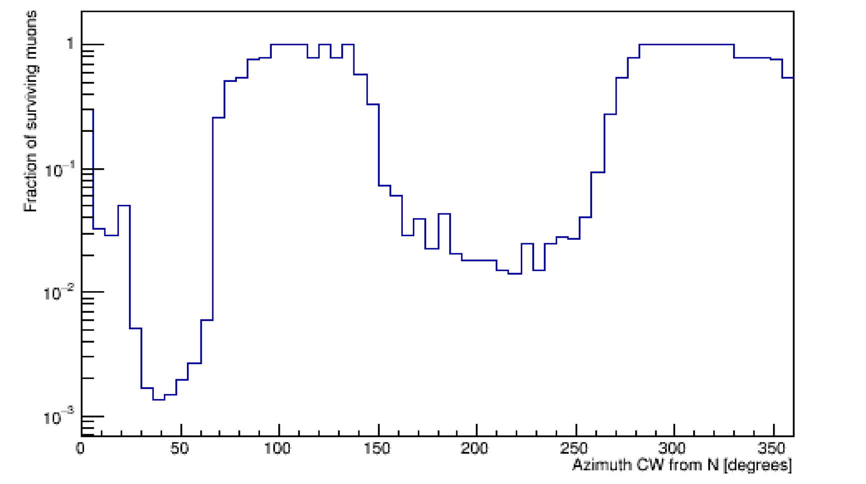

Figure 13: The muon flux reduction factor due to overburden depth as a function of azimuthal angle with elevation angles restricted to between -1^0 to 5^0.

Summary

- Guidance in the development of tools required to simulate nearly-horizontal muons obtained by studying CORSIKA generated air showers in conjunction with geometrical considerations.
- "Toy-model" simulation provides a determination of the effective area of a perfect cylindrical detector of HAWC dimensions and can be used to optimize the phase space of "thrown" events in a full GEANT4-based simulation of the HAWC detector and nearby volcanoes.
- The effect of the volcanoes on the observed muon rate as a function of arrival direction has been roughly accounted for by considering the effect of overburden depth on required minimum muon energies. A full GEANT4-based model of the volcanoes appears to be needed.
- Development of full GEANT4-based simulation of volcanoes and the techniques to extract physically meaningful energy spectra and composition measurements is at an early stage but appears promising.

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Acknowledgments

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