IOP Publishing Journal of Physics: Conference Series **60** (2007) 131–134
doi:10.1088/1742-6596/60/1/024 Proceedings of the TeV Particle Astrophysics II Workshop

HAWC: A next generation all-sky gamma-ray telescope

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Abstract. HAWC will have unprecedented sensitivity for a ground based particle detector array. It will be capable of observing the Crab at the 5σ level with each transit while simultaneously observing the entire northern sky (15 times the current Milagro detector sensitivity). The design an performance of the HAWC water Cherenkov gamma-ray observatory is presented.

1. Introduction

The HAWC observatory combines the Milagro[1] water Cherenkov air-shower detection technique with a very high altitude site. Re-deploying the existing Milagro photomultiplier tubes (PMTs) and electronics in a different configuration at an altitude above 4000m will lead to a sensitivity increase of a factor of 15 over Milagro. This dramatic improvement is due to three things: the increased altitude, the increased physical area, and the optical isolation of the PMTs. As a result of these improvements, HAWC will detect a 5 signal from the Crab Nebula in a single 4-hr transit (compared to 5 months for Milagro). Unlike imaging atmospheric Cherenkov telescopes (IACT), HAWC is capable of continuous operation and has a field of view of nearly 2 sr. The total exposure (time $\times$ solid angle) of HAWC is 2000-4000 times higher than that of a modern IACT.

This sensitivity will enable very high energy gamma ray studies that are unattainable with the current suite of instruments. HAWC will monitor (for 4 hours every day) 1/3 of the entire sky. Over a 1 year observation period HAWC will perform an unbiased sky survey with a detection threshold of 50 mCrab, enabling the monitoring of known sources, the discovery of new sources of known types, and perhaps most importantly the discovery of new classes of TeV gamma ray sources. The sensitivity of HAWC to extended sources surpasses that of IACTs for sources larger than 0.25^oo, as IACTs rely on their outstanding angular resolution for their high instantaneous sensitivity. HESS measurements clearly point to the existence of such objects within our Galaxy; since they observe many diffuse galactic sources clustered around their sensitivity limit, they may only be seeing the tip of the iceberg. HAWC's large area and exposure will permit the study of energy spectra in the range from 10-100 TeV where other instruments are photon starved. With HAWC's large FOV, it will serve as an excelent monitor for mulit-wavelenth studies with other instruements includeing X-ray, gamma-ray and particularly the neutrino telescopes such as Ice Cube that are under construction.

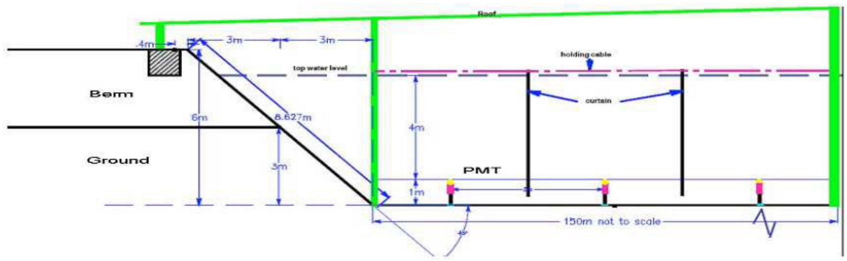

Figure 1. Cross-section of HAWC detector.

2. Detector Description

The HAWC concept builds upon experience with the Milagro detector. Milagro is the first large, uniformly instrumented, air shower array using water Cherenkov technology. The water Cherenkov technique is an excelent method for EAS detection because of its superior detection efficiency, calorimetric capability, and low cost. In contrast, gamma-ray detectors such as the Tibet ASγ [5] and the ARGO observatory[3] use a thin layer of scintillator and resistive plate chambers respectively to detect charged particles in air showers. Gamma rays, which out-number charged particle in EM showers by 5-10 times, are only detectable with the addition of a layer of lead converter. As a consequence, the ARGO detector, which is larger than Milagro and located at an elevation 1700m higher, will (upon completion) have roughly the same sensitivity as Milagro[4]. In addition, in a water detector, calorimetry of EM showers is possible, whereas thin detectors can only count particles, so HAWC can redily distingush low energy electrons and gamma rays from muons, hadrons and high energy EM particles and use this capability to distinguish between gamma-ray (signal) and hadron (background) induced showers.

The HAWC detector consists of a 150m x 150m x 5m deep reservoir lined with a polypropylene-nylon liner to contain and isolate the 125 Ml of filtered water from the ground below. The reservoir is constructed by a combination of excavation and building up soil to form a berm around the perimeter. The requirements on the slope and thickness of the berm depend on the properties of the soil and are site dependent. Milagros 900 photomultiplier tubes will be secured on a 30x30 grid with 5m spacing. Stretching between the PMTs is an opaque curtain designed to optically isolate each sensor. The PMTs will be secured to the bottom of the pond with a weight such that the top of the photocathode is 4m below the surface of the water. The PMT/weight unit will be secured to a string that extends to the surface; so that the PMT can be raised for maintenance. A concrete footing at the top of the berm will serve as anchor for a building that covers the pond. See Figure 1.

The optical isolation system consists of a series of opaque curtains placed between the PMTs. With the curtains each sensor only detects light produced within its cell. This dramatically reduces the PMT noise rate, the trigger rate from muons and background rejection capabilities of HAWC. A test of this system has been performed in Milagro over a 4x4 array of PMTs. We observed that the singles rates in the isolated PMTs dropped by a factor of three (in agreement with Monte Carlo simulations) and that when a PMT is struck it is much more likely to have information useful to the event reconstruction algorithms.

The depth of the HAWC detector was selected as a compromise between timing resolution and gamma-hadron separation. Milagro has 2 layers of PMTs: a shallow layer at 1.5m depth for shower plane reconstruction, and a deep layer at 6m depth for gamma/hadron separation. In HAWC, the functionality of these 2 layers are combined into a single layer. For gamma/hadron separation, it is important to be able to distinguish between large and small energy depositions,

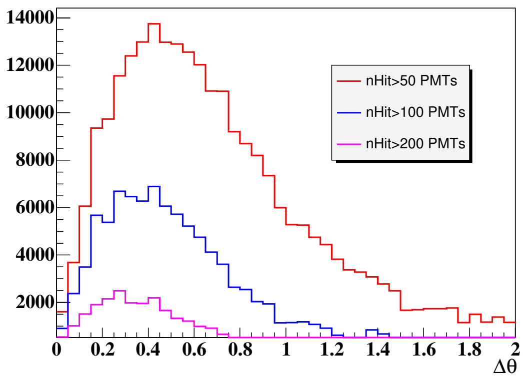

Figure 2. Angular Resolution as a function of event size.

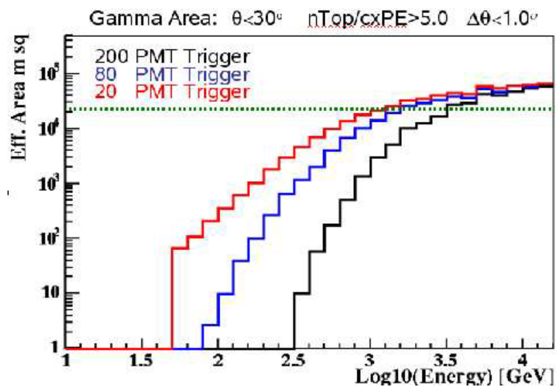

Figure 3. Effective Area of HAWC.

so the PMT needs to be sufficiently deep that EM particles have interacted prior to reaching the depth of the PMT and the produced Cherenkov light has diffused. This requires that the PMT depth is much greater than a radiation length in water (40cm). The deep layer must also be much shallower than the attenuation length of Cherenkov light in water (30m for Milagro) to maximize the detected light. Monte Carlo studies indicate that a depth of 4m or greater is sufficient for effective gamma/hadron separation and that greater depth is not advantageous. In general, the depth of the PMTs should be slightly smaller than their spacing making it possible for a PMT to view the entire surface of its cell (given the 41^o Cherenkov angle in water). Given that the depth is selected to be 4m, a separation of 5m was found to be optimal.

The location of the HAWC detector has not been finalized. Suitable sites have been identified at the YBJ laboratory in Tibet, China and near Sierra Negra in Mexico.

3. HAWC Performance

The simulation for HAWC is an extension of the Milagro simulation software package. CORSIKA[6] is used to simulate gamma ray and hadron induced atmospheric showers. A custom detector simulation using GEANT[2] is used to propagate the secondary shower particles through the HAWC detector. Cherenkov light production is simulated and individual Cherenkov photons are tracked through the detector. Detailed optical modeling of the water (absorption and scattering), reflection and absorption at surfaces, and the PMT response are included. The simulation has been thoroughly tested through comparison with Milagro data. Gamma ray and background rates are scaled from measured values in Milagro by comparing the predictions of the HAWC and Milagro simulations. By doing this, we not only remove potential systematic errors internal to the simulation from the air shower modeling, optical model, and detection efficiency, but also remove systematic errors in the measurement of gamma-ray fluxes and hadronic backgrounds provided by other experiments.

The position of the shower core on the ground is determined by fitting the distribution of the pulse amplitudes to a Gaussian profile. After the core is located, the PMT hit times are adjusted to account for the curvature of the shower front. Typically, the shower front curvature correction is 0.5^oo-1.0^o, so misidentification of the core position leads to poor angular resolution. The corrected PMT hit times are then fit to a plane to determine the incoming shower angle. The angular resolution depends on the event size. Figure 2 shows the angular resolution of the HAWC detector for three different ranges of event size. Figure 3 shows the effective area for the HAWC detector.

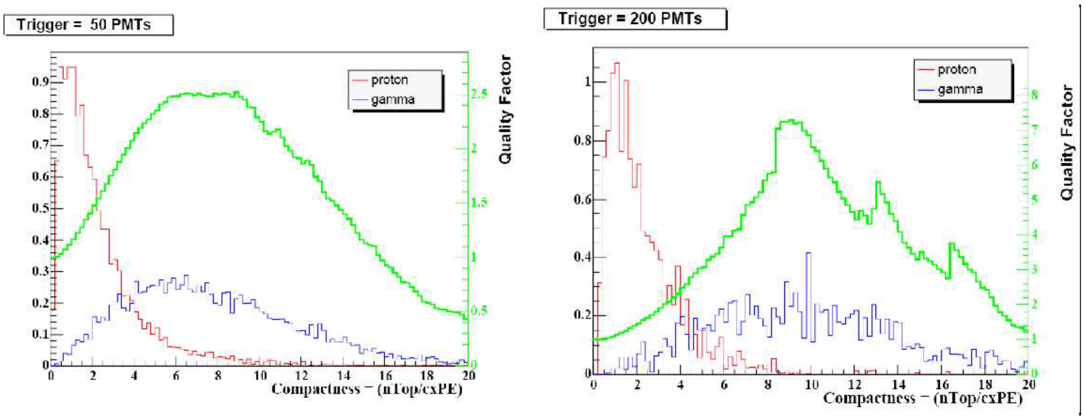

Figure 4. Gamma/hadron separation parameter distribution plotted for gamma and proton events. The Q value is plotted in green showing the increase in sensitivity achieved.

Hadronic showers are identified through the pattern of energy deposition in the detector. While gamma-ray induced showers have compact cores with smoothly falling density, hadronic showers typically deposit large amounts of energy in distinct clumps far from the shower core. This is mostly due to the presence of hadrons and muons in hadronic showers. As a simple γ/hadron discriminator, we have extended the compactness parameter, C, developed for Milagro. Here C is defined as the total number of PMTs hit with amplitudes greater than 2 PEs divided by the largest pulse amplitude that is more than 30m from the reconstructed core position. Gamma-ray induced showers, with only small hits far from the core, have large values of C. Hadron induced showers with large hits far from the core have low values for C. Figure 4 shows Compactness distribution for gamma ray and proton triggers for small (nHit¿50) and large (nHit¿200) events. The same figure shows the Q (increase in sensitivity) as a function of the cut level. The efficiency for retaining gamma ray induced events increases with increasing energy, while it drops for proton-induced events. Therefore, the background rejection capability of HAWC improves with increasing energy.

Because the sensitivity of the detector is strongly dependent on the zenith angle of the source being studied, we compute the sensitivity by estimation of the number of signal and background events collected during a single transit of the source from horizon to horizon. The transit declination of the source is 22^o and the detector is assumed to be located at a latitude of 37^o (the location of Milagro), so the minimum zenith angle for the source is 15^o. For a source transiting through the detector zenith the sensitivity is 25% higher and for a source transiting only within 25^o of zenith, the sensitivity would be 25% lower. So the results given here represent a typical sensitivity for a sky survey of $\pm 25^o$ declination. For a detector altitude assumed to be 4300m a.s.l., the altitude of the sites under consideration, HAWC will detect 50 gamma-ray events per transit with a threshold of 1.0 TeV and a significance 5 sigma.

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