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Double-layered Water Cherenkov Detector for SWGO

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The Southern Wide-field Gamma-ray Observatory (SWGO) will use the well-established and cost-effective technique of detecting Cherenkov light produced in water-filled detection units for TeV gamma-ray astronomy. Leveraging detector material reflectivity together with an optimised aspect ratio is an option to improve the performance of an array of such detector units. The double-layered Water Cherenkov Detector units comprise chambers with single photosensors in each. A reflective upper compartment enhances sensitivity to impinging secondary particles. A shallow lower compartment enables muon tagging and consequently improves the gamma hadron separation power of the observatory. Here we present detailed studies on the double-layered unit design.

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1. Introduction

The induced electromagnetic cascade produced by air showers are well suited to be observed by ground-level particle detectors providing intrinsically wide field-of-view and ~ 100% duty cycle. HAWC (High-Altitude Water Cherenkov) [1] on the flanks of the Sierra Negra in Mexico, and LHAASO (Large High Altitude Air Shower Observatory) [2] in the eastern Tibetan plateau are the two main instruments currently under operation that comprise an array of Water Cerenkov Detector (WCD) units. The detection of γ-rays higher than 0.1 PeV have already been reported by LHAASO [3] and instrumenting the Southern Hemisphere will provide unprecedented opportunities to probe the galactic plane and the southern hemisphere further [4].

Furthermore, instrumenting at a High altitude (> 4.4 km) with a high fill factor (> 80 %) will allow SWGO to be complementary in the same energy range as Imaging Atmospheric Cherenkov Telescopes (IACTs). This is extended to an outer array with a fill factor of 8% as in Fig. 1 that aims to improve sensitivity at higher energies.

SWGO (for an overview on status and prospects, see [5]) is investigating several detector technologies such as units with multiple photo-sensors [6] and an option to deploy detector units in a lake [7]. Muon identification with a separate detector element is a reasonable means of hadronic background rejection (see, e.g. [8]) for γ-ray astronomy. Here we develop the concept of a double-layered WCD design; as a potential detector unit for SWGO, comprising two isolated chambers where the lower chamber in conjunction with the upper chamber enables an effective method for gamma/hadron separation. The detector unit with optimised aspect ratio and material reflectivity will also have improved particle detection efficiency and angular resolution.

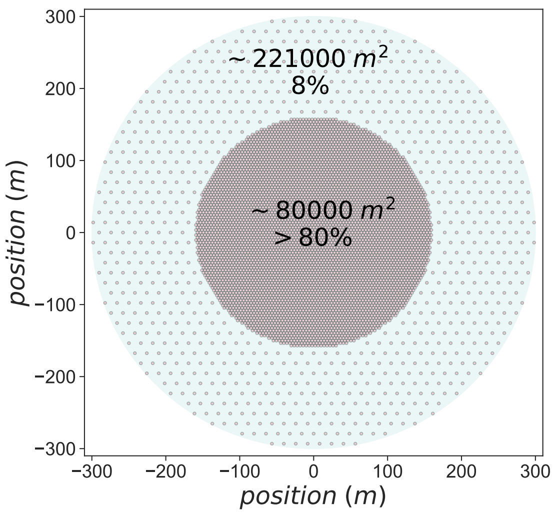


Figure 1: Sketch of the simulated array layout of cylindrical double-layered WCDs with a dense inner array (> 80%) and sparser outer array (~ 8%).

The simulations in this work use GEANT4 [9] within a simulation framework adapted from the HAWC collaboration. Air Shower simulations use the CORSIKA 7.7400 simulation package [10] where we select the hadronic interaction model QGSJet-II.04 [11] for energies above 80 GeV. UrQMD 1.3.1 [12, 13] treats the low energy hadronic interactions and for electromagnetic processes, we use the EGS4 electromagnetic model [14].

2. Unit Design

The double-layered design comprises two chambers that are isolated from each other, as shown in Fig. 2. The upper chamber is a light-tight chamber with a reflective lining and a centrally located 8” Photo-Multiplier Tube (PMT) facing upwards. The PMT orientation ensures that the prompt

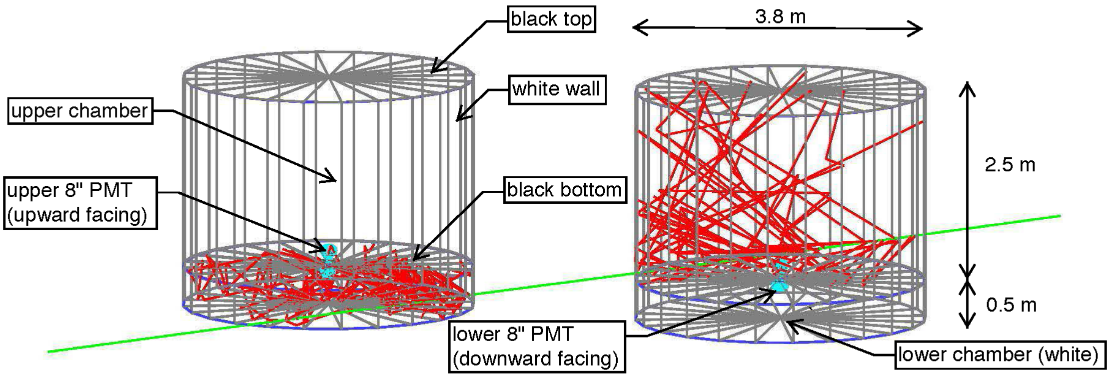
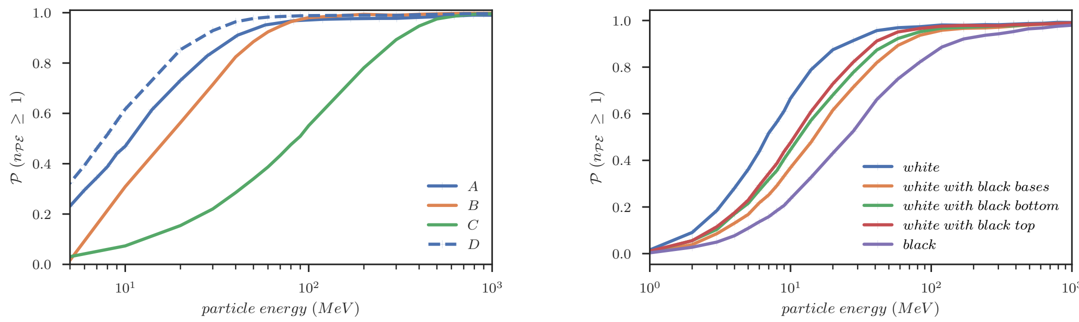


Figure 2: Cylindrical Double Layered WCD designs comprising an upper chamber ($\pi \times 1.91^2 \times 2.5\ m^3$) with white walls and black bases (top and bottom) and an entirely white lower chamber ($\pi \times 1.91^2 \times 0.5\ m^3$). The upper chamber comprises an 8" PMT facing upwards, and the lower chamber comprises an 8" PMT facing downwards. A Muon (green) passes through both units and produces photons (red). The number of photons has been limited here for illustration purposes.



(a) **(b)**

Figure 3: **(a)** Injection of vertical 5 MeV to 1 GeV γ-rays across the top surface of different WCD designs. Here we show a comparison between the upper chamber of a [A] white cylindrical double-layered WCD unit ($\pi \times 1.91^2 \times 2.5\ m^3$) with a black top and an 8" PMT, a [B] HAWC - like design ($\pi \times 3.65^2 \times 4\ m^3$) with black walls, a central 10" PMT and 3x8" PMTs', a [C] LHAASO - like black unit ($5 \times 5 \times 4.5\ m^3$) with an open top and an 8" PMT and a [D] white cylindrical double-layered WCD unit ($\pi \times 1.71^2 \times 3\ m^3$) with a black top and an 8" PMT. **(b)** Response to injection of vertical 1 MeV to 1 GeV γ-rays across the top of the upper chamber of double-layered WCD unit ($\pi \times 1.91^2 \times 2.5\ m^3$) with vertical 1 MeV to 1 GeV γ-rays with different materials.

light is detected first. The lower chamber is a similar light-tight chamber but, to ensure we collect all the energy deposited in the chamber for muon identification, it is composed of highly reflective material and a centrally located 8” PMT facing downwards.

3. Particle Detection Efficiency and Energy Resolution

The particle detection efficiency of the DLWCD is optimised by leveraging the aspect ratio and the material (reflectivity) selection. To maximise the probability of cascade production, both

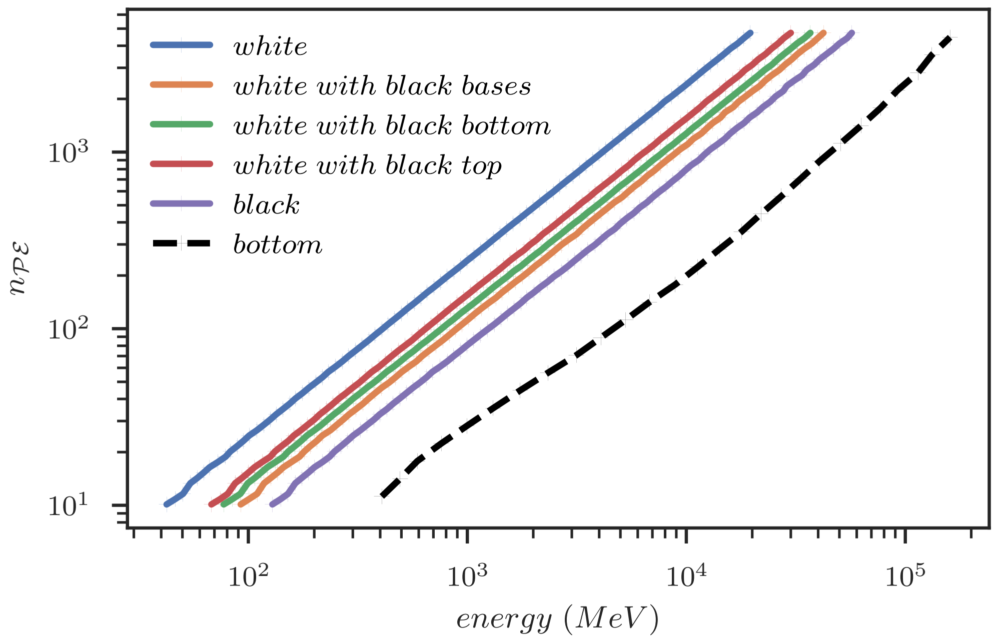


Figure 4: The number of p.e's at different electromagnetic energy for upper chambers with different materials. The dashed black line shows the corresponding value for the lower chamber.

LHAASO and HAWC have a water depth $> 10 \times x_0$, where x_0 is the radiation length of high energy $\gamma's$ in water (~ 46 cm). However, both design also uses a material with low reflectivity (black) like Polypropylene. The upper chamber of the proposed DLWCD is shallow and narrower than these designs. The chamber also comprises reflective walls, namely, Tyvek used by the Pierre Auger Observatory [15] with a combination of black bases.

To compare the detection efficiency of the DLWCD, vertical γ's were injected across the top of several design choices varying in aspect-ratio and material reflectivity (see Fig. 3). The DLWCD design, with white walls and a black top, has improved particle detection efficiency over both HAWC and LHAASO - like designs. A deeper chamber would ensure cascade production and subsequent detection of Cherenkov photons at ~ 100 MeV γs, while a narrower chamber with reflective walls improves sensitivity to lower energy γs. Reflective walls improve particle detection efficiency over non-reflective walls.

Additionally, high energy γ's close to the shower core can result in the saturation of the upper PMT. To mitigate this, since these particles can also punch through into the lower chamber, the lower PMT can extend the dynamic range (see Fig. 4).

4. Angular Resolution

In order to compare the angular resolution of the DLWCD (upper - $\pi \times 1.91^2 \times 2.5\ m^3$) of different material combinations, we simulate vertical γ initiated showers at the centre of the array shown in Fig. 1. The angular resolution is then computed in several stages.

First, after requiring a minimum of 10 unit hits, a time difference of arrival of the shower hit first arrival times for each unit are used to compute the shower direction and time. Limiting the

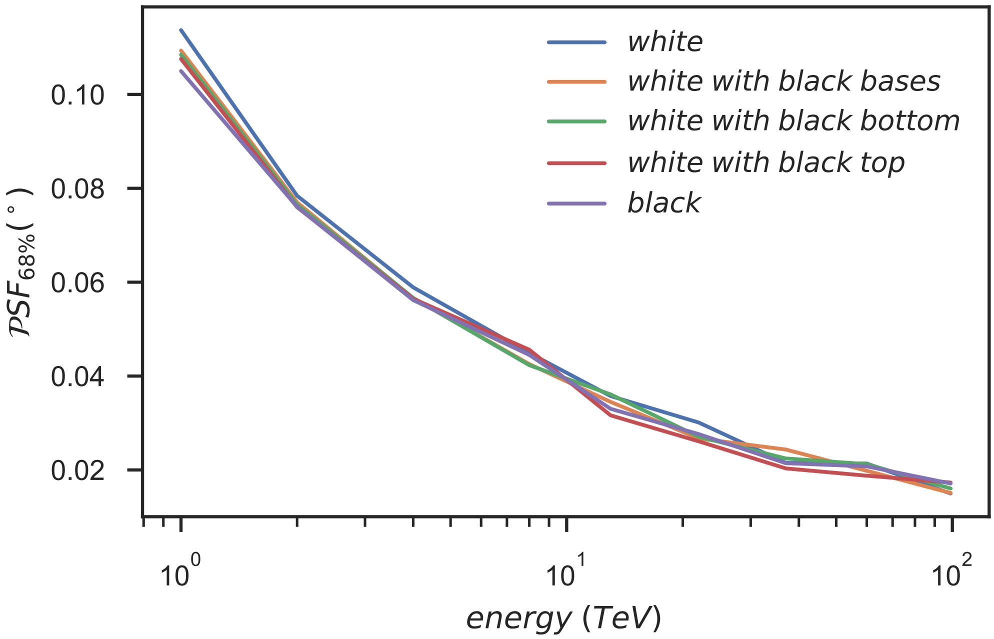


Figure 5: Angular resolution for 1 - 100 TeV vertical γ-ray's simulated with shower core at the center of an array of double-layered WCD's (upper - $\pi \times 1.91^2 \times 2.5\ m^3$) with $\sim$ 80% fill factor varying the material properties.

shower hits to 10% of the units hit with the largest charge limits the computational burden. A Landau fit to the arrival times as a function of distance to the shower core and charge is used to obtain mean and width parameters.

Given the Landau fit parameters, a 3-parameter likelihood fit (MINUIT [16]) is implemented to obtain the shower direction. The angular resolution is the 68 % containment of such showers (see Fig. 5).

We find that, as expected, as most of the first photons are the direct Cherenkov light, there is no or limited impact of the material combination on the angular resolution of the showers.

5. Gamma Hadron Separation

To evaluate the γ - hadron separation power, a Template-based maximum log-likelihood method comprising charge in the two chambers is implemented to discriminate between γ-ray and hadron induced air showers for an ensemble of γ-ray and proton-induced vertical showers of 1 to 100 TeV energy with the shower core located at the centre of the array. First, γ-ray and proton initiated showers are split into 70 – 30% training and test sets, respectively, with an exclusion region of 40 m. The exclusion region is defined to account for the high transverse momentum of $\mu^{\pm}$ and punch-through of γ & $e^{\pm}$ close to the shower core. The training set is then used to generate separate templates of charge in the upper and lower chambers for $\mu^{\pm}$ and $e^{\pm}$, & γ's. The test set is then used to identify the likelihood of a $\mu^{\pm}$ on a tank-by-tank basis.

Once $\mu^{\pm}$ are tagged, the number of such particles is counted on an event-by-event basis for both γ and hadron initiated showers for a similar number of tanks hit. The γ and p^{+} identification

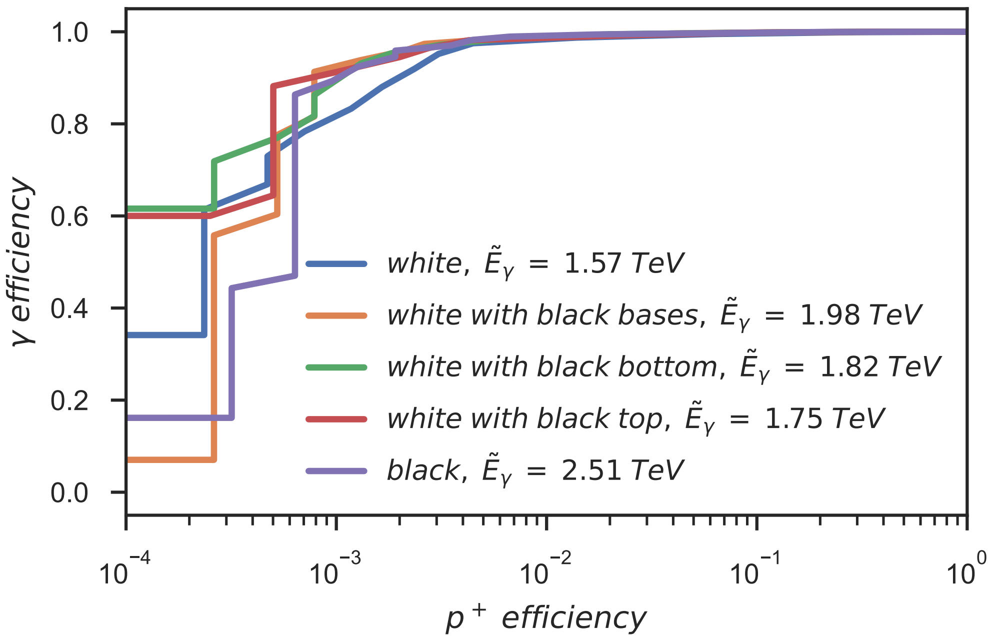


Figure 6: Gamma - Hadron separation efficiency for an array of double-layered WCD's (upper - $\pi \times 1.91^2 \times 2.5\ m^3$) with $\sim$ 80% fill factor varying material reflectivity and an exclusion region of 40 m for $547 \leq nhits < 1280$.

efficiency is shown in Fig. 6 for different material combinations and $547 \leq nhits < 1280$. Tanks with a combination of white material represent showers with a lower median γ-ray energy. As expected while there is no significant difference in the γ - hadron separation power with different material combinations, with the combination of reflective material lower energy threshold can be achieved due to an increased particle detection efficiency.

6. Conclusion

The Southern Wide-field-of-view Gamma-ray Observatory (SWGO) will use the well-established and cost-effective technique of detecting Cherenkov light produced in water-filled detection units for TeV gamma-ray astronomy. Several detector technologies such as units with multiple photo-sensors and an option to deploy detector units in a lake are currently under investigation. The double-layered WCD leverages material and aspect ratio to enhance sensitivity, achieve excellent angular resolution and gamma hadron separation.

Acknowledgements

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