Performance of Small Photomultiplier Tubes with Wavelength Shifting Plates for an SWGO-like Water Cherenkov Detector Using Geant4

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Introduction

Water Cherenkov detectors (WCDs) detect high-energy particles via Cherenkov radiation in water, traditionally using large photomultiplier tubes (PMTs). This study explores a novel design using smaller PMTs combined with wavelength-shifting (WLS) plates to enhance photodetection efficiency and reduce costs. The WLS plates increase the light capture area and direct photons to the PMT's photocathode edge.

Geant4 Monte Carlo simulations were used to optimize the design, comparing it to larger PMTs in a double-layered WCD, specifically for muon detection in a Southern Wide Field Gamma-ray Observatory (SWGO) –like WCD.

The Design

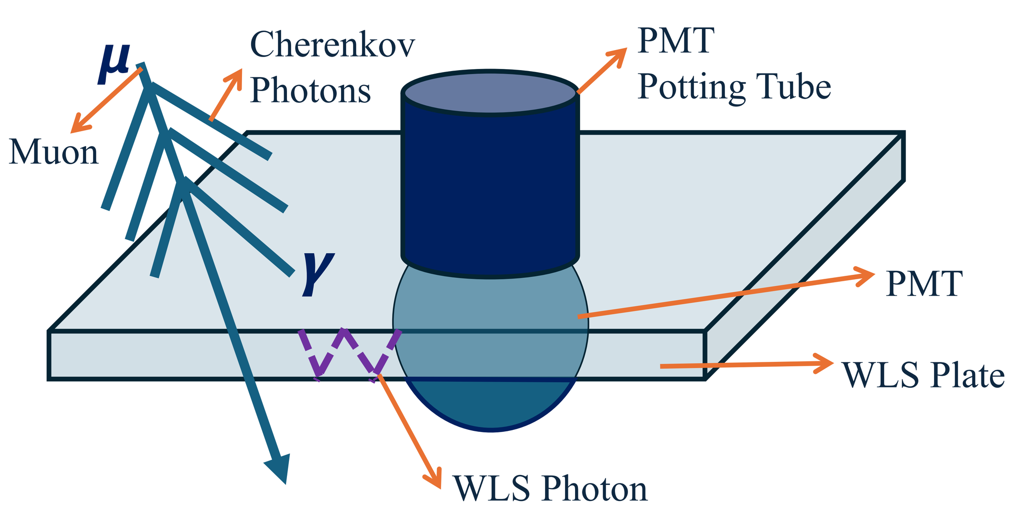

Figure 1 – Schematic of PMT embedded in the center of a WLS plate, demonstrating the light guiding affects.

- 3-inch photomultiplier tube (PMT) embedded in the center of a wavelength shifting (WLS) plate.
- WLS plate captures Cherenkov photons and acts as a light guide.
- Captured UV photons are shifted to a longer wavelength, to better match the PMTs quantum efficiency.
  - The WLS plates can be doped to adjust the wavelength emission spectrum.
- The edges of the WLS plate are polished and reflective to further guide the captured photons towards the PMTs photocathode.

Results and Analysis

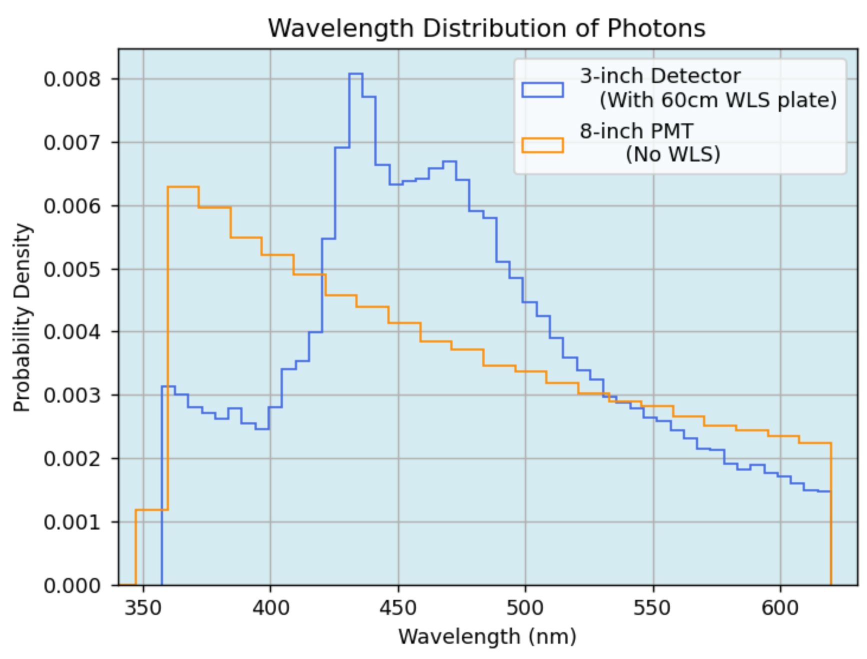

Figure 4 – Wavelength distribution for a 3-inch PMT with WLS plates and an 8-inch PMT, showing the region of shifted emission in the WLS plate.

- By doping the WLS plate, the emission spectrum of the shifted photons can be adjusted to match the PMT's quantum efficiency.
  - This would ensure that more photons have a chance of being detected.
  - Resulting in a higher light yield with the WLS plates.

- Time profiles differentiate electrons from muons; electrons are absorbed faster and produce fewer Cherenkov photons[1].
- Electrons' photons reach the PMT sooner due to fewer reflections in the tank – as shown by the earlier peak in Figure 5 to the right.
- WLS plates do not affect the timing differences used to distinguish between electrons and muons.

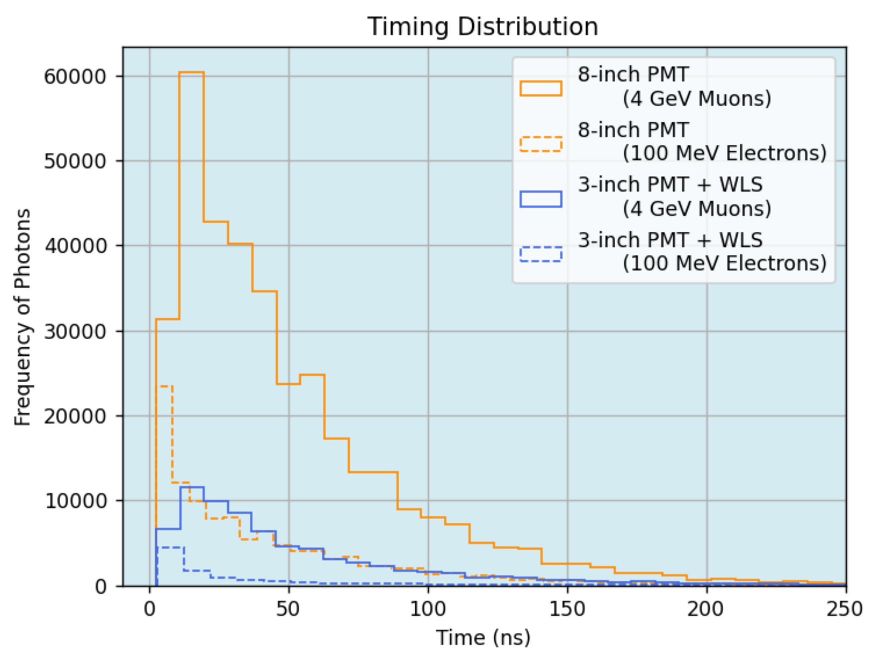

Figure 5 – Timing distribution between electrons and muons for a 3-inch PMT with WLS plates and an 8-inch PMT.

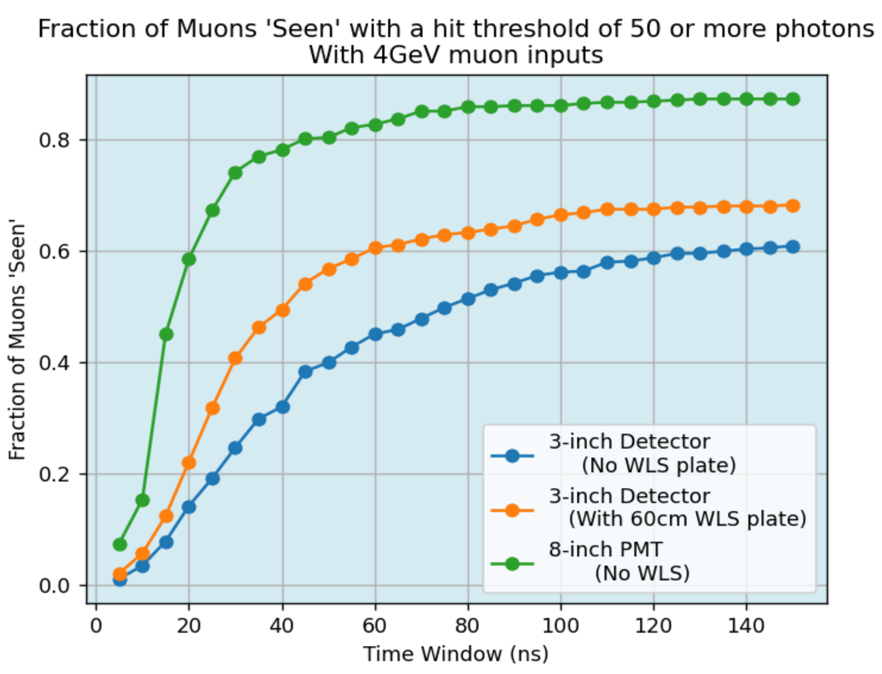

Figure 6 – Fraction of muons detected using a 50-photon threshold, for a 3-inch PMT with and without WLS plates and an 8-inch PMT.

- Photons with longer path lengths due to multiple tank reflections, take more time to reach the PMT.
- The photon threshold needed to recognize a muon can depend on the detector unit you use[2].
- An example threshold of 50 photons was used to determine the muon detection efficiency.
- As the time window increases, the detection rate plateaus around 80 ns for the 8-inch PMT, or 100 ns for the 3-inch PMT with WLS
- At 80 ns the 8-inch PMT detects ~85% of all the events.
- The 3-inch PMT detects 51% of all events, increasing to 63% with WLS plates.

Research Objectives

- Measure the impact of the WLS plates on the photodetection efficiency of smaller PMTs.
- Compare to determine if this design can replace a traditional 8-inch PMT, in an SWGO-like WCD.
- Optimize for a cost-effective design.

Simulation

- In Geant4, a water Cherenkov tank was modeled.
- A downward-facing PMT was placed at the top of the tank.
- Simulated 1,000 muons, each with 4 GeV energy, from random positions and directions.
- 506 muons successfully penetrated the tank.
- Modeled a 3-inch PMT with and without WLS plates (60 cm x 10 mm, PMMA).
- Compared the performance of the 3-inch PMT to an 8-inch PMT

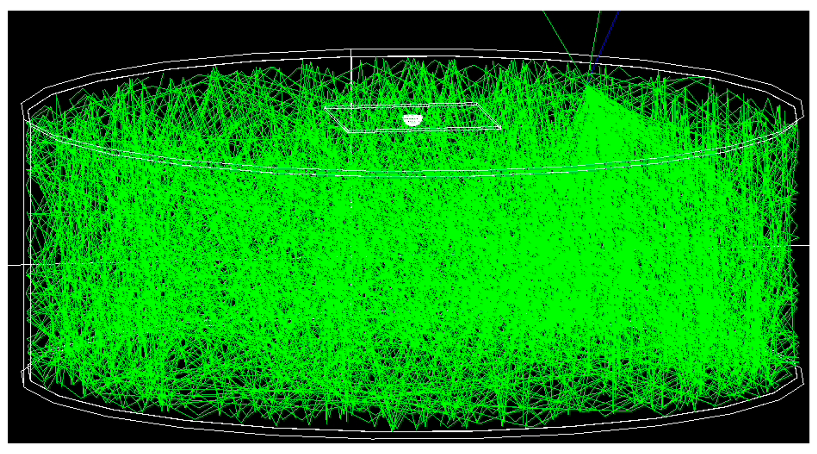

Figure 2 – An example simulation output in Geant4 using a muon to show the Cherenkov photons trajectories inside the WCD tank.

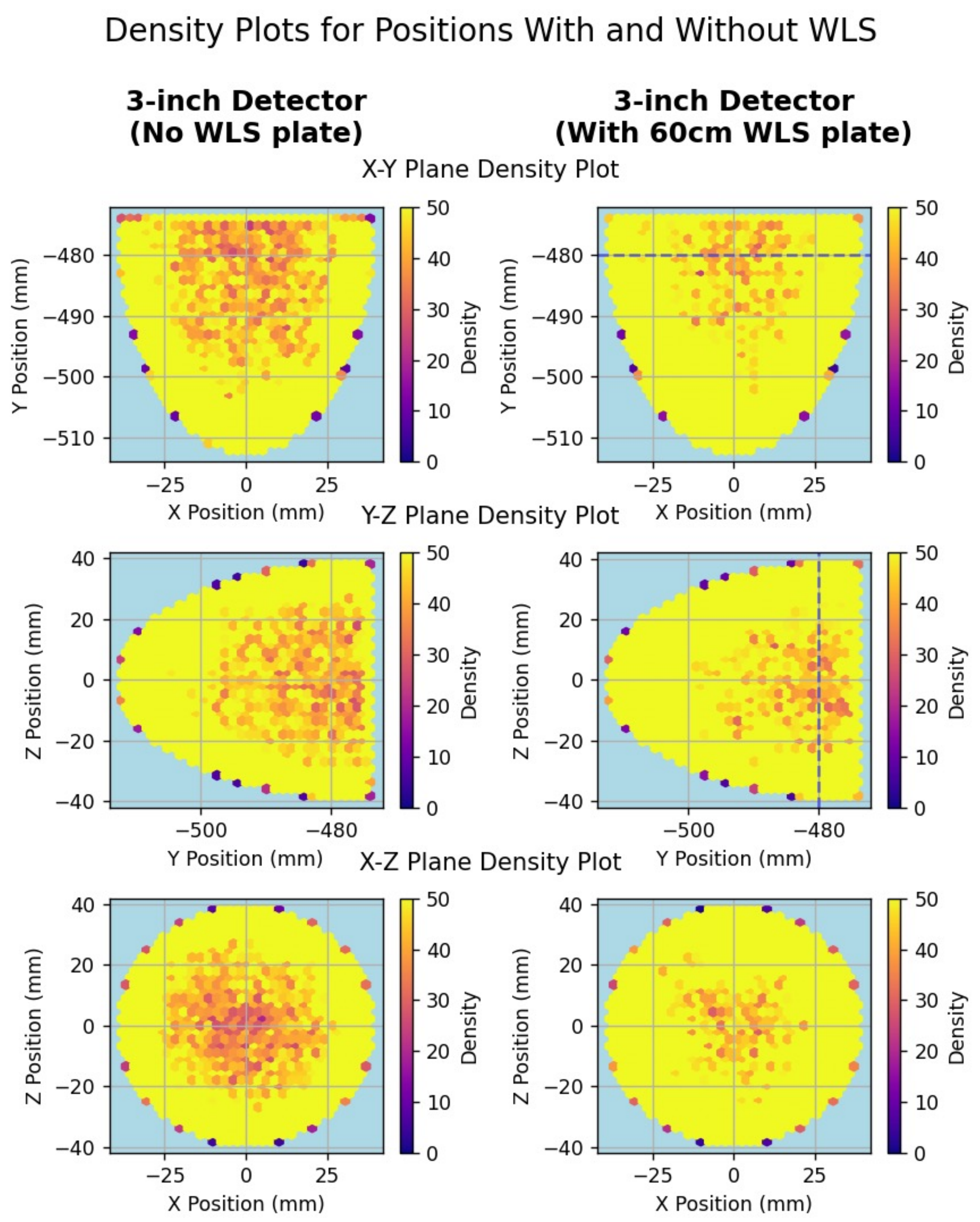

Figure 3 – Photon hit density plots for a 3-inch PMT with WLS plates (on the left) and an 8-inch PMT (on the right), for each axes plane.

- The hit efficiency across all three scenarios was compared.
- Adding WLS plates to the 3-inch PMT resulted in an average light yield increase of approximately 15%.
- However, the 3-inch PMT experienced 80% fewer photon hits per event compared to the 8-inch PMT.
- Despite the 8-inch PMT's higher hit efficiency, the smaller 3-inch detector might still be sufficient for a SWGO-like WCD.

Summary and Future Work

- Explored smaller 3-inch PMTs with wavelength-shifting (WLS) plates and compared with larger 8-inch PMTs in a water Cherenkov detector.
- WLS Plates increased light yield by ~15% and optimized photon redirection.
- WLS plates can shift UV photons to longer wavelengths to better match the PMT's quantum efficiency.
- The 3-inch PMT with WLS plates detected 22% fewer muon events than the 8-inch PMT using a 50-photon threshold.
- Timing profiles distinguish muons from electrons; electrons have a narrower timing resolution and a lower mean time than muons.
- The WLS plates did not affect the particle timing structures.

- Optimise the design with different WLS plate geometries and materials
- Study the requirements for accurate hadronic rejection for SWGO.
  - What are the trade-offs between lower detection efficiency and cost efficiency?
- Compare simulations results with experimental data, to test reliability of results.

References

[1] Liu, J. et al., 2017. Measurement of cosmic ray muon flux using the Daya Bay detector. [online] arXiv. doi:10.48550/arXiv.1708.09500
[2] Bevington, P.R. and Robinson, D.K., 2003. Introduction to Experimental Particle Physics. Cambridge University Press.