Project Cherenkov
- PHYS 512 Final Project -

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1 Context: The Experiments

Ultra-low background experiments, such as those searching for WIMP dark matter, or neutrinoless double beta decay, search for energy deposits resulting from nuclear recoil scattering on a target nucleus by a GeV mass particle, e.g. [1], or a distinct peak at the end of a beta decay energy spectrum respectively, e.g. [2]. Many of these detectors are placed deep underground in order to shield them from cosmic backgrounds such as: protons, light nuclei, and muons. Unfortunately, even with several kilometers of rock overburden in the deepest of mines, there is still a residual muon flux that remains. These muons have energies in the several hundred GeV range, and can create spallation products as they interact with nuclei in the rock on their way down [3]. In this way, high energy neutrons are created that can traverse the shielding that surrounds many of these low background detectors and enter the experiment's signal region. These neutrons can either scatter off of nuclei producing WIMP-like nuclear recoil signals, or capture in the detector creating background beta emitters that can mimic a neutrinoless double beta signal. In either case, understanding the neutron production, and tagging these traversing muons can reduce the contribution of the cosmogenic neutron background to the experiments significantly. Many experiments opt to employ a water-cherenkov active muon veto. As the high energy muons passes through the water surrounding the detector they produce cherenkov light which carries directional information. Recent studies have shown that the direction of the resulting neutrons closely follow that of the muons [4]. Thus, optimizing a detector to not only tag muons but also reconstruct their tracks is interesting for the field.

The trouble arises when, traditionally, simulating these muons in Geant4 (dedicated particle tracking monte carlo software) can take ages to propagate thousands to millions of photons onto detector walls. Thus, the optimization of photosensor placement can take quite a while. This project will attempt to address the problem under various simplifications. Approximations will be made and, hopefully, will result in a fast-turn around photon propagation code (if done correctly!).

2 Project Setup

For simplicity we assume that the water tank is cylindrical, large O(10) m in diameter and height, and placed at SNOLAB in Sudbury, Ontario - a popular, and growing, laboratory for these sorts of experiments with the second lowest underground muon flux in the world [5]. We assume that a cryostat/inner detector is placed in a spherical volume that is concentric with the water shield.

We will first figure out how to best represent the muon flux through our detector. Let's take the Mei & Hime paper's flux and note first that it represents the flux as that through an arbitrarily small point in space. However, we actually want the flux through some disc sitting above our detector (in the case of Geant4, you would do this to generate the neutrons in the rock abov your detector, in this case, it's just so we understand the flux well). By generating the flux through a horizontal disc at some height, we need to make sure that either the disc is high enough above your detector such that the flux through your detector is well represented, or that your generation disc is sufficiently large in radius. In the latter case, a lot of the muons will not pass through your detector and we wast a bunch of computation. A priori, we also know that we shouldn't have a match between the flux through a disc and that through a cylinder, since muons can enter the cylinder from the walls on the side as well.

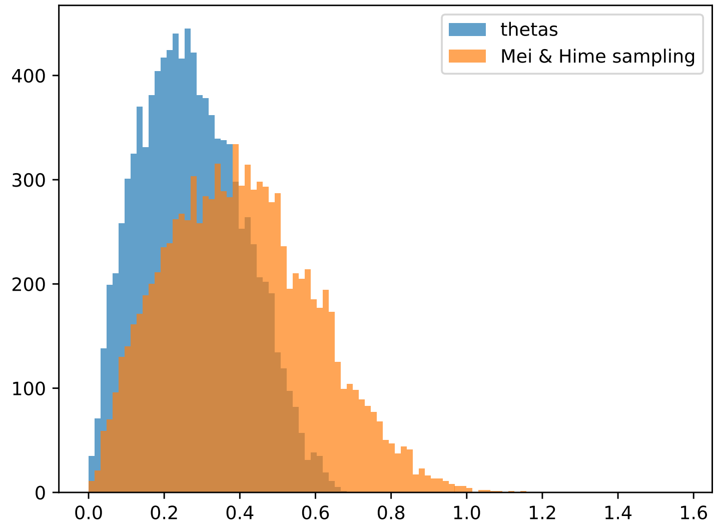

Figure 1: When your generation disc is too small, but concentric above your detector, your muon flux seems to be too straight down and not spread enough in angle.

3 Some insights

The following figures show how a changing generation disc changes the flux through our detector.

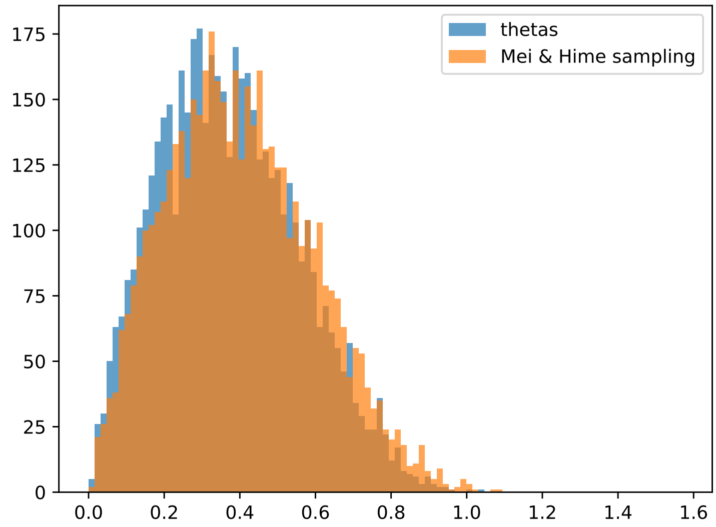

Figure 2: Once you match your generation disc radius to the radius of your detector, you start to get agreement between the angular distributions, but this is still wrong, and in this case no muons are entering from the cylinder walls only the roof.

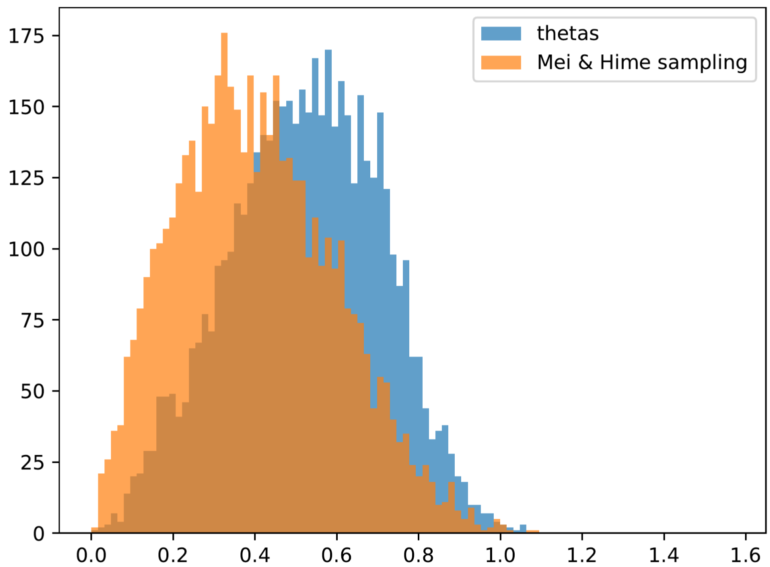

Figure 3: Finally, if your generation disc radius is good, your distributions should look like this, and not change for increasing disc sizes (holding the height and detector dimensions fixed.

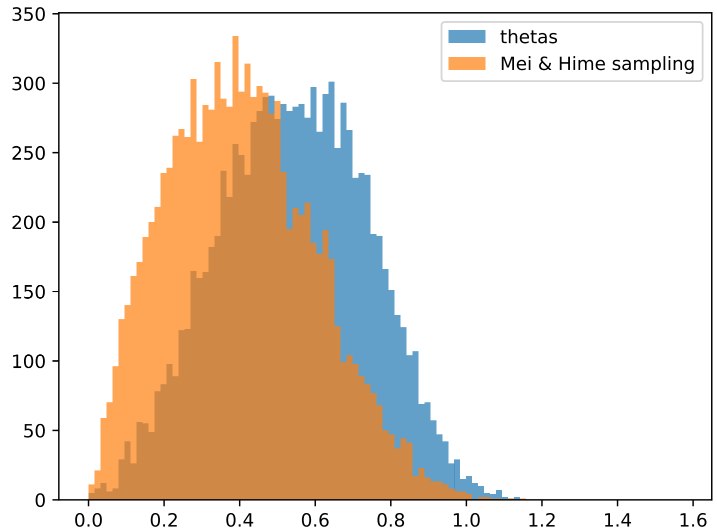

Figure 4: And here we have the same parameters but double the generation disc size. In this case, the downside is that many muons your simulate will totally miss your detector as they are generated too far from your detector and will not have a steep enough angle. It's a balancing act! just like most things...

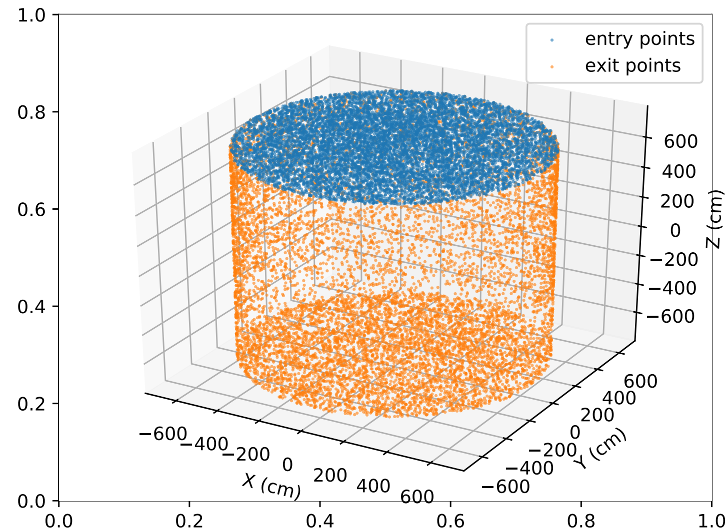

Figure 5: Here are the entry and exit points for muons when the generation disc is of the same radius as your detector. Notice how they all enter through the roof.

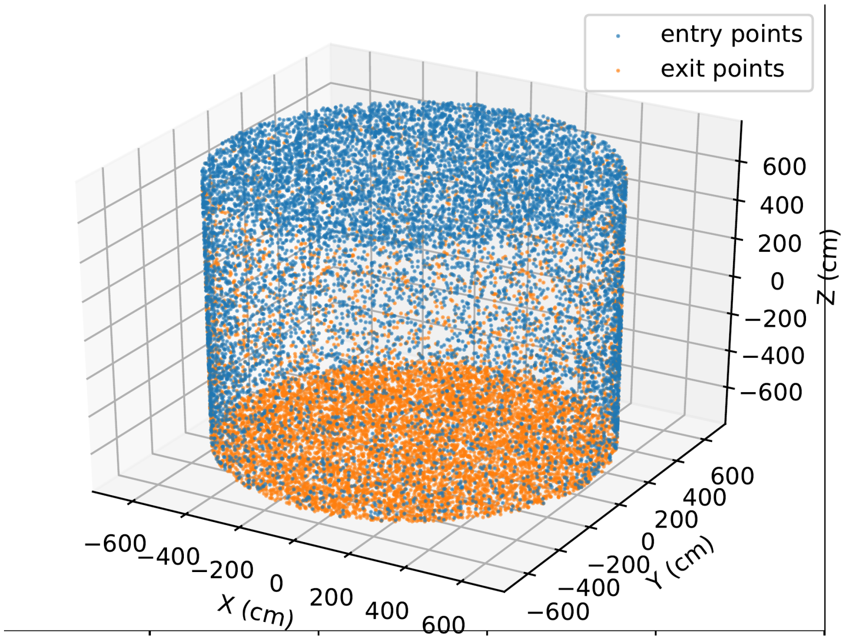

Figure 6: Here is the normal picture, muons enter from every surface, but generally leave from the floor, or at least lower than where they entered.

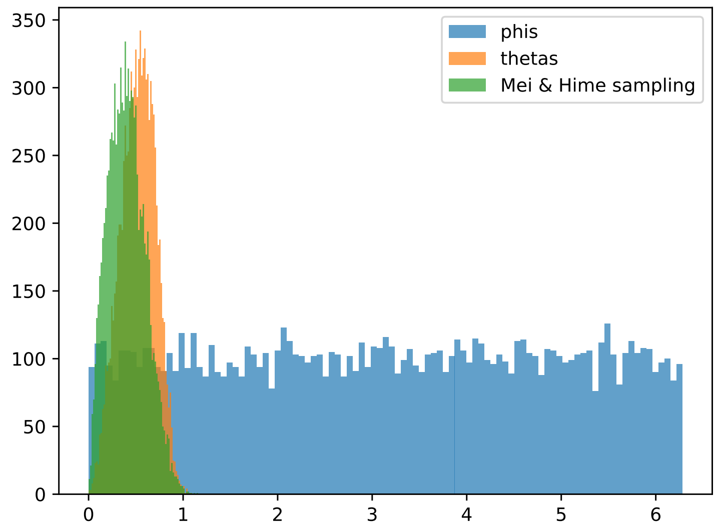

Figure 7: Finally, to make sure our simulation is OK we expect the muons to come in uniformly in phi (all around the z axis) and this is true here! Note: the phi uniformity is only true if your overburden is flat above you, i.e. you are in a mine and not a mountain. SNOLAB is in a mine and has flat overburden, so this is ok.

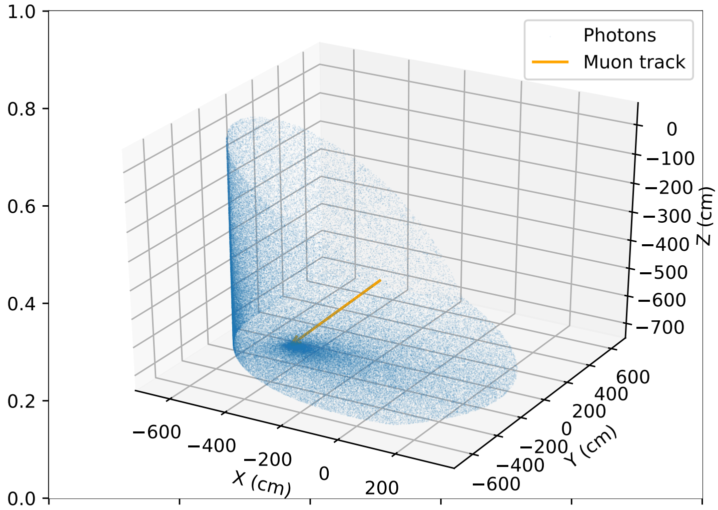

Figure 8: As the muon enters the water, it emits photons in the UV-visible via (mainly) Cherenkov radiation. This light is in a cone of 42 degrees opening angle in water. For the high energies at SNOLAB, we don't expect these muons to stop in the tank but rather go all the way through. Thus, our light should have 'filled in' circles/ellipses after a muon passage. We only consider the visible portion of the spectrum, and the variation in β due to the different muon energies does not change the Cherenkov angle much. Note: the optical scattering length in (typically) ultra-pure water is O(100 m) or so, so we ignore scattering in this simulation. Here is an example of one muon track and it's photons on the tank.

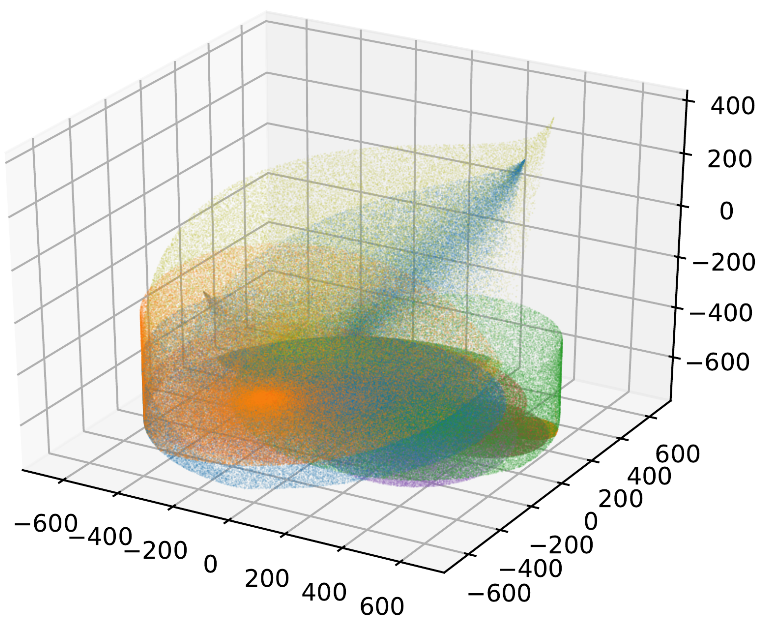

Figure 9: Even with the first ten or so events, we see that many photons tend to land on the lower part of our tank. So we should expect a much higher photon count there in the distributions.

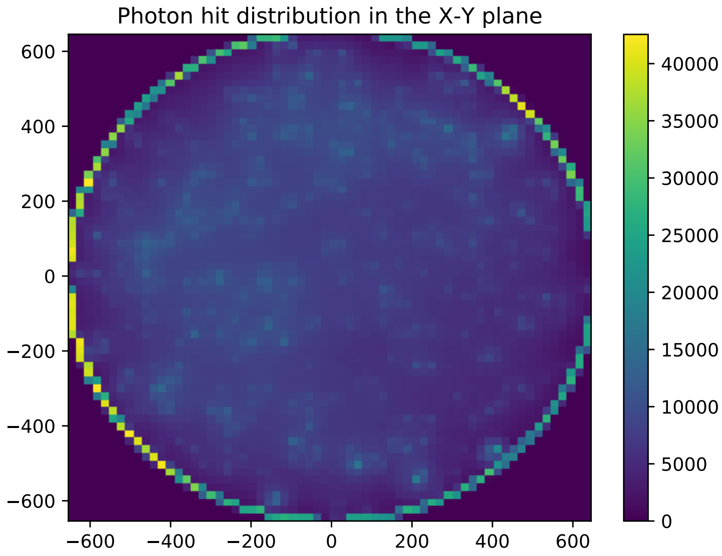

Figure 10: If we only consider the water tank/shield and forget about shadowing and reflections from the cryostat, our photon distribution on the floor looks like this, you can even make our where the muon exited the tank by the hot spots. Notice the color scale, many more photons land on the floor than the walls! Note: the bin sizes are approximately 8x8 inches - around the size of your typical water cherenkov photo-multiplier tube.

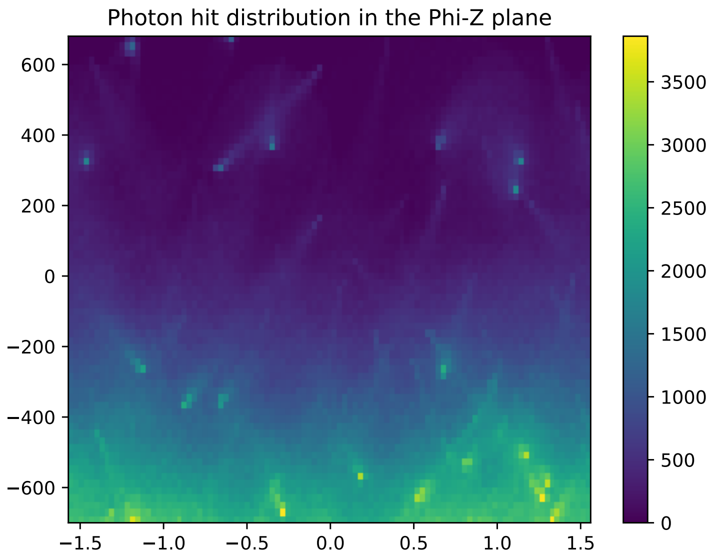

Figure 11: If we only consider the water tank/shield and forget about shadowing and reflections from the cryostat, our photon distribution on the vertical cylindrical walls look like this (Φ-Z plane, unravelling the walls of the tank). You can even make out the muon angles already by looking for the streaks by eye!

References

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[3] D.-M. Mei and A. Hime, “Muon-induced background study for underground laboratories,” *Physical Review D*, vol. 73, no. 5, p. 053004, 2006.

[4] B. Aharmim, S. Ahmed, A. Anthony, N. Barros, E. Beier, A. Bellerive, B. Beltran, M. Bergevin, S. Biller, R. Bonventre, *et al.*, “Cosmogenic neutron production at the sudbury neutrino observatory,” *arXiv preprint arXiv:1909.11728*, 2019.

[5] B. Aharmim, S. Ahmed, T. Andersen, A. Anthony, N. Barros, E. Beier, A. Bellerive, B. Beltran, M. Bergevin, S. Biller, *et al.*, “Measurement of the cosmic ray and neutrino-induced muon flux at the sudbury neutrino observatory,” *Physical Review D*, vol. 80, no. 1, p. 012001, 2009.