Accounting for Cosmic Muons in the Hyper-Kamiokande Outer Detector

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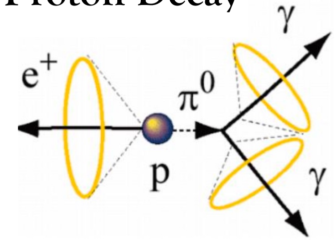
Hyper-Kamiokande

Hyper-K is the future of water Cherenkov neutrino detectors.
It has 8.4 times the fiducial volume of its predecessor, Super-Kamiokande
Separated into 2 optically separated regions; Inner Detector (ID) and Outer Detector (OD)
ID detects neutrino events form many sources to answer many physics questions:

Hyper-K Access Tunnel

Astrophysical Neutrinos

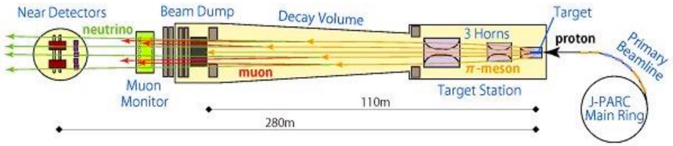
Proton Decay



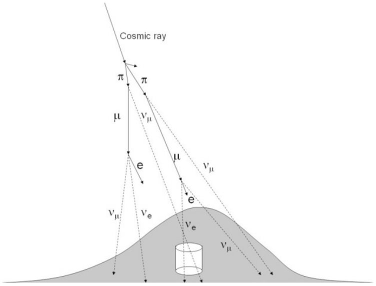
Physics program of Hyper-K

- Neutrino Oscillations
- Proton Decay
- Supernova Neutrinos
- Dark Matter

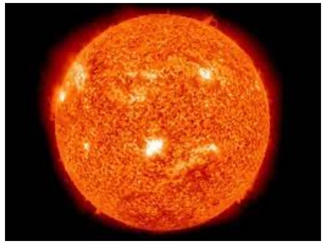
Beam Neutrinos from J-PARC

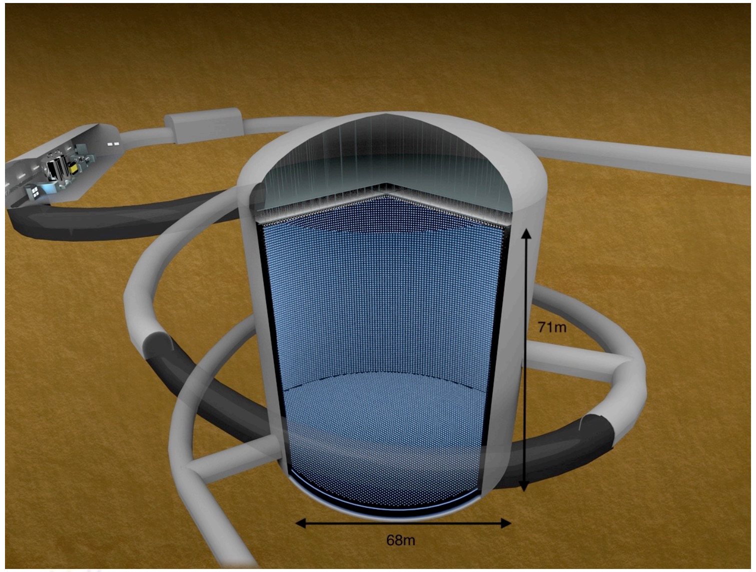


Atmospheric Neutrinos



Solar Neutrinos





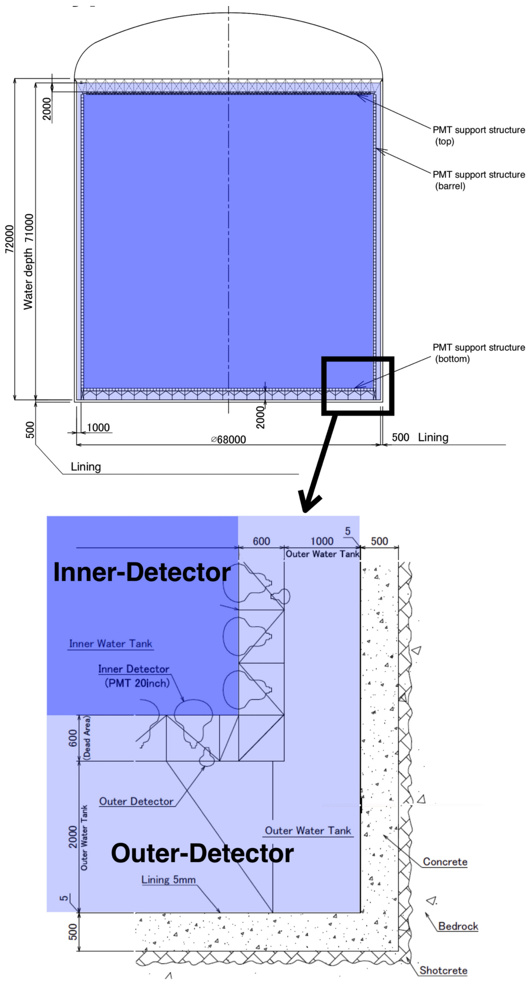
71m Height
68m Diameter
188kton FV
20,000 ID 20” PMTs
>7,000 OD 3” PMTs

The Hyper-K Outer Detector

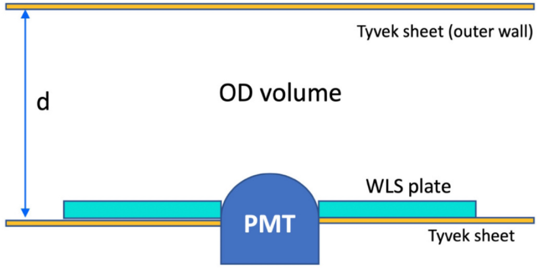
The role of the OD is to limit background sources so that there is a better distinction between candidate neutrino events which, only interact with the ID, and other incoming particles. The main background source are cosmic-ray muons, which are produced when high energy primary cosmic rays (protons) interact with the upper atmosphere, creating a cascade of secondary particles, mainly pions, which decay into muons.

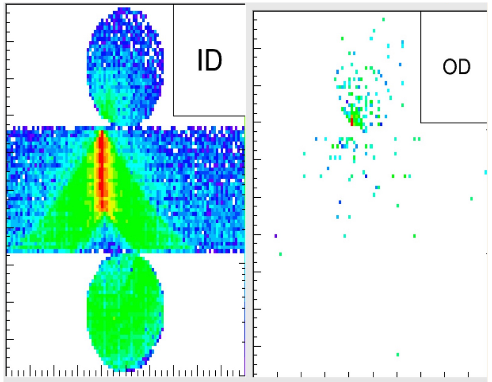
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

The sparseness of OD PMTs mean additional features are needed. Cherenkov photons are reflected by Tyvek sheets so that the PMT collection efficiency is maximised. OD PMTs are mounted in the middle of Wavelength Shifting (WLS) plates, so any UV photons that hit the plate, will be absorbed and re-emitted at longer wavelengths to match the PMTs optimum quantum efficiency (QE)



These cosmic-muons interact with the water in the OD (which is 1m thick on the barrel and 2m thick on the top/bottom caps) and the ID, which is shown by this event display:



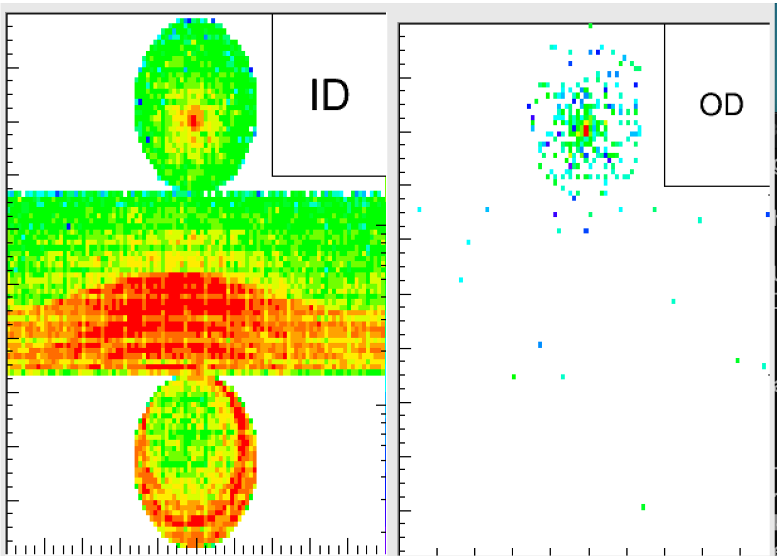


The cosmic muon flux will be ~45 Hz, corresponding to ~4 million muons per day. This means the veto efficiency must be extremely high (99.9999%) and so an effective algorithm is required to trigger on these events

Center of Mass Clustering

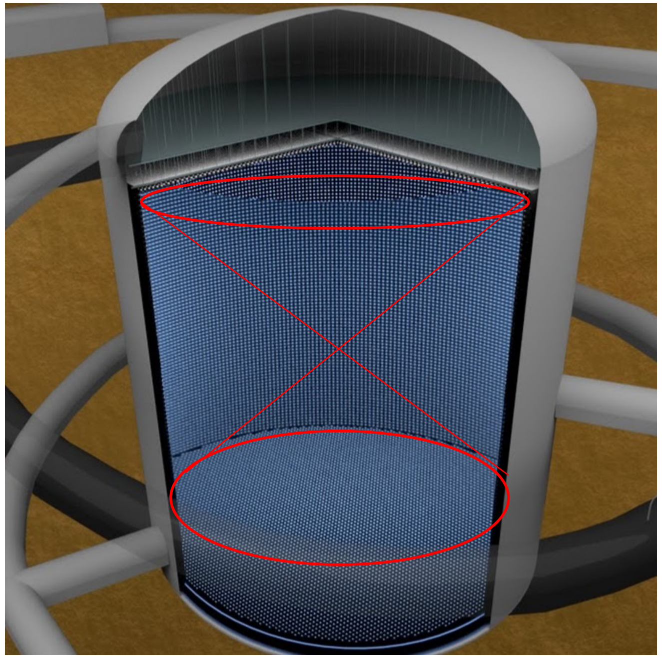
- Using the event display, the OD cluster that we want can be seen. I have employed a Centre of Mass Clustering to get the cosmic muons' positions. I take the average positions of all the OD PMTs which are triggered by a certain muon event.

- For stopping muons with an energy < 16 GeV, this will end up being somewhere in the middle of Hyper-K. therefore I project that through the origin of the detector, onto the OD surface.



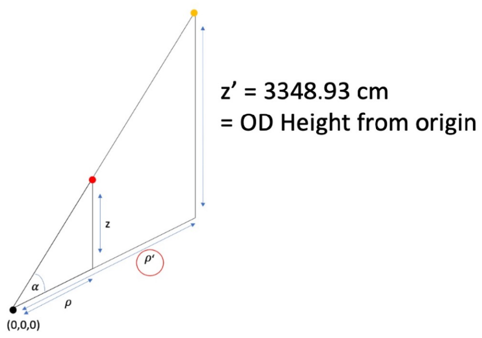
Projecting onto the OD

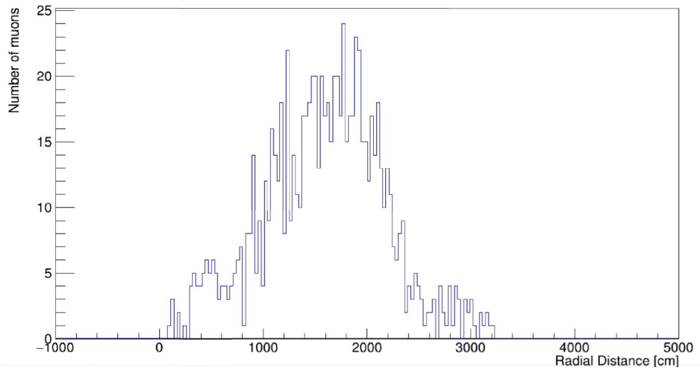
- If one imagines two cones inside the detector, as shown inside the image of Hyper-K, any muon which is reconstructed inside the top (bottom) cone is projected onto the OD top (bottom) cap. Anything outside of these cones is projected onto the OD barrel.



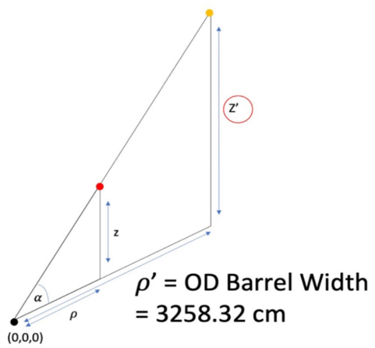
Projecting onto the OD

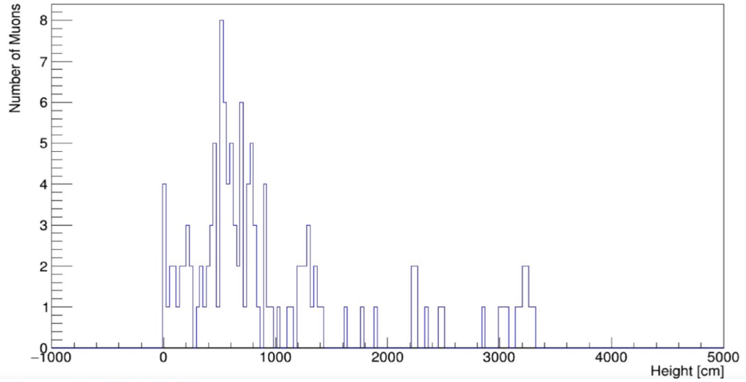
- Points which need to be projected onto the Top will have a new radial position which can be calculated using similar triangles





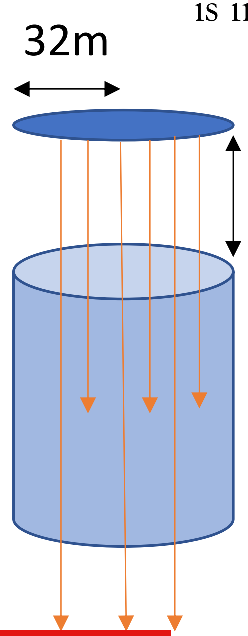
- Similarly, points which need to be projected onto the Barrel will have a new height



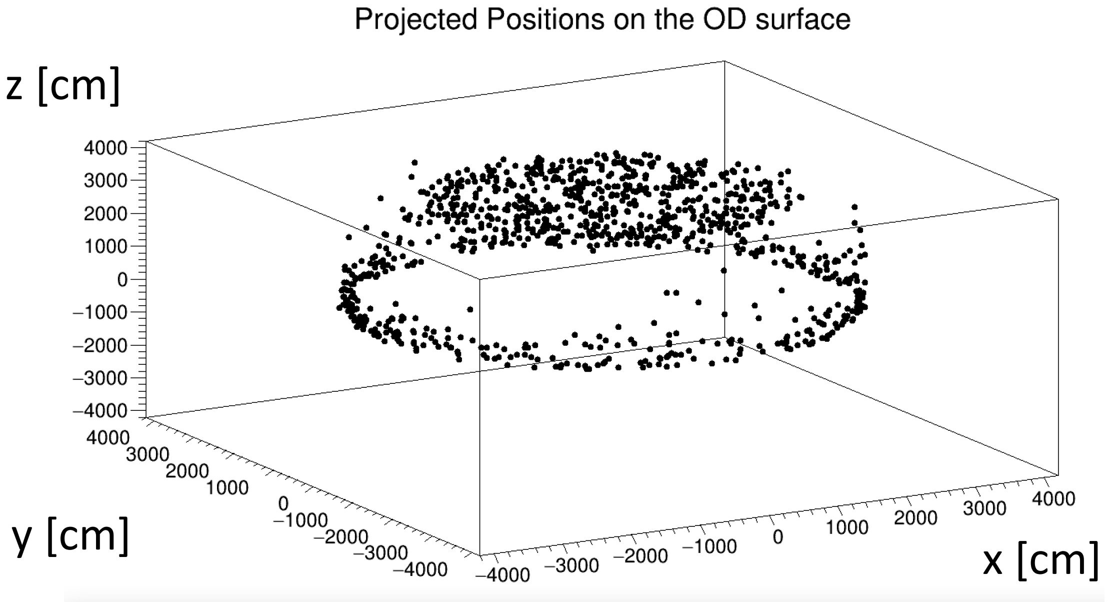


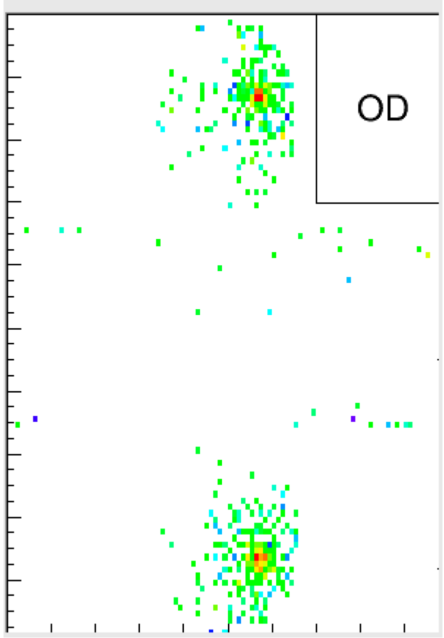
Through Going Muons

- Through going muons have energies greater than around 16 GeV
- The original algorithm as it was would have projected all of the through going muons onto the barrel, because the geometric center of mass of through going muons is slap bang in the middle of the tank. This is incorrect!



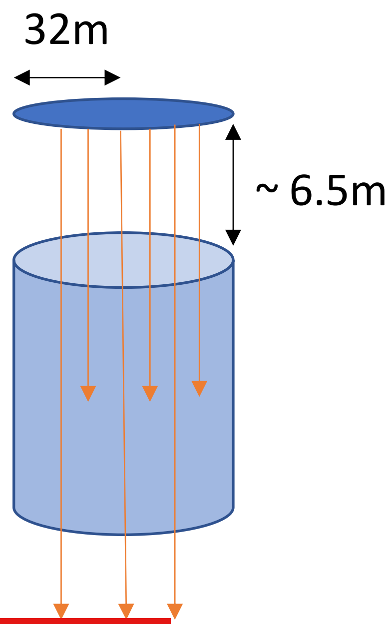
This simulation is 5,000 stopping muons (10 GeV) and 5,000 through going muons (20 GeV) coming from the same plane and direction as before

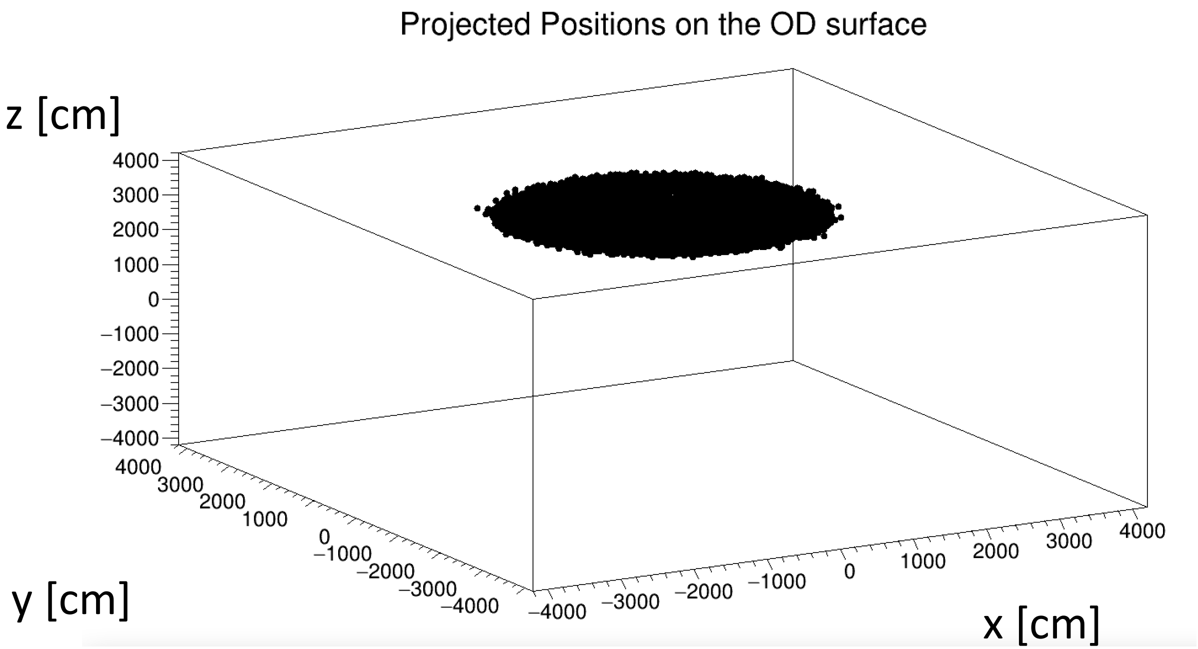




Through Going Muons

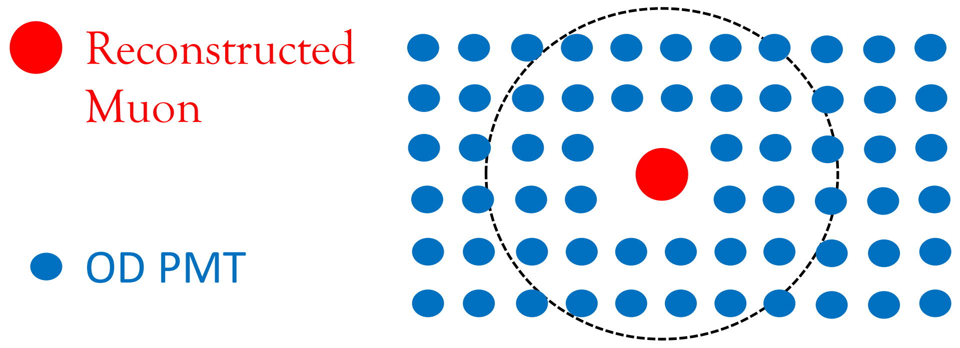
- To deal with these through going muons, I defined them specifically to be muons which made hits on both the OD top cap and on the OD bottom cap. For these muons, I specifically only took the top cap hits into account, when calculating the center of mass. Below shows the corrected plot of the muons' reconstructed positions

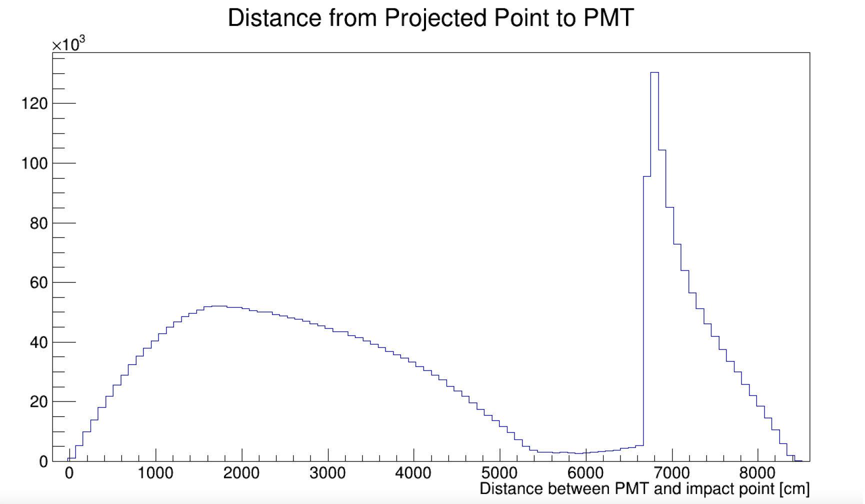




Through Going Muons

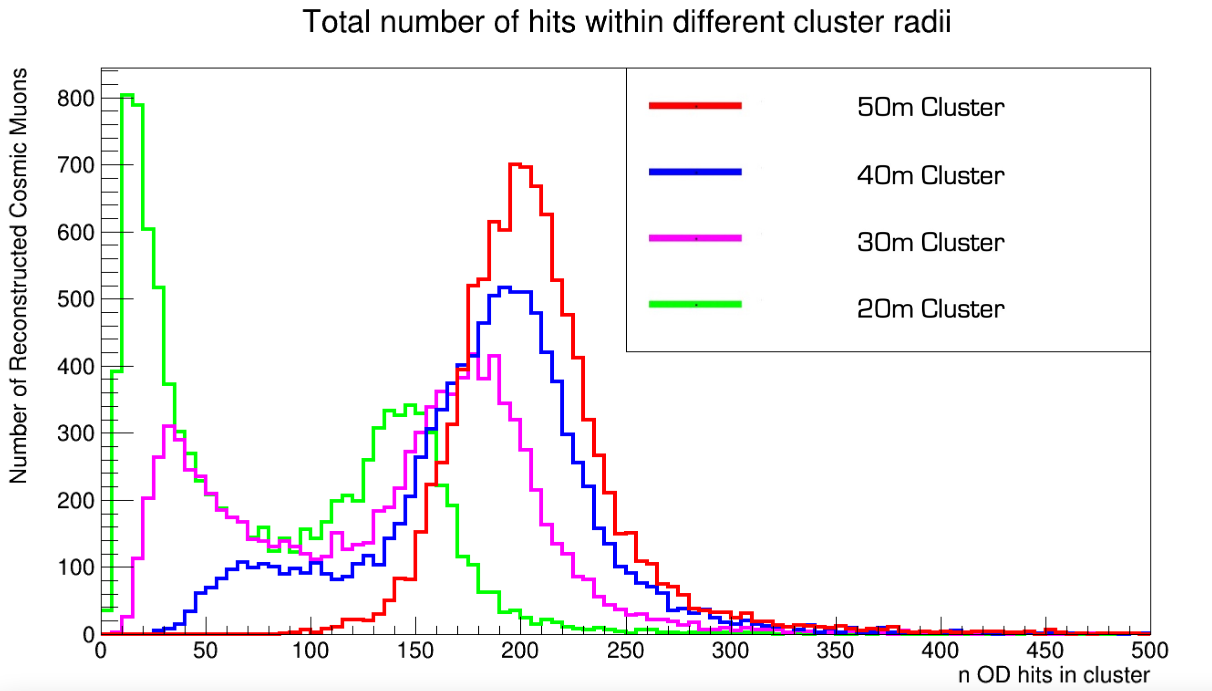
- Calculate the distance to each OD PMT, then do a spherical cut-off
- I distinguish between stopping and through going muons using a time cut. The average hit time for through going muons will be skewed, because of the hits which occur at a much later time on the bottom cap.
- Not only do I cluster around the reconstructed positions on the top, but I also create a separate cluster of hits on the bottom, which will be useful for distinguishing between different muon events.
- This plot shows the distances from each reconstructed muon, to each PMT which is affected by that event





Preliminary Results

- If there are more than a certain number of hits within this cluster, then noise can be ruled out, and the event is a cosmic muon which can be vetoed! This plot shows the number of hits which are encompassed by different cluster radii

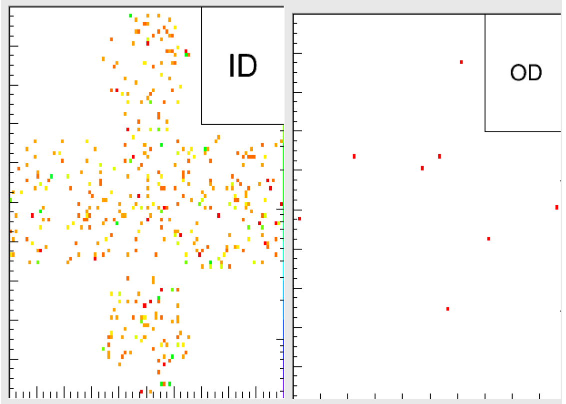


Preliminary Results

- The key piece of information which can be gained from the previous plot is the Efficiency. This is done for each different cluster radius, and is calculated by taking the area under the curve from a threshold number to the maximum of the graph, and dividing it by the total area under the curve.

$$Efficiency = \frac{\int_{nHits\ Threshold}^{500} Cluster\ Radius\ Histogram\ for\ x\ m}{\int_{0}^{500} Cluster\ Radius\ Histogram\ for\ x\ m}$$

- The nHits threshold number which is used for a lower bound of the numerator is optimised by looking at a background simulation, which only has PMT dark noise (where some PMTs record hits for no reason), and working out what the minimum number of hits is for an actual event. This is because dark noise events only cause a handful of PMTs to go off



Preliminary Results

- The trigger rate can then be calculated. Since this is all Monte Carlo, the frequency of how much dark noise is simulated can be set, and was set to 2 microseconds.

$$\text{Trigger Rate} = \frac{Efficiency}{2\mu s}$$

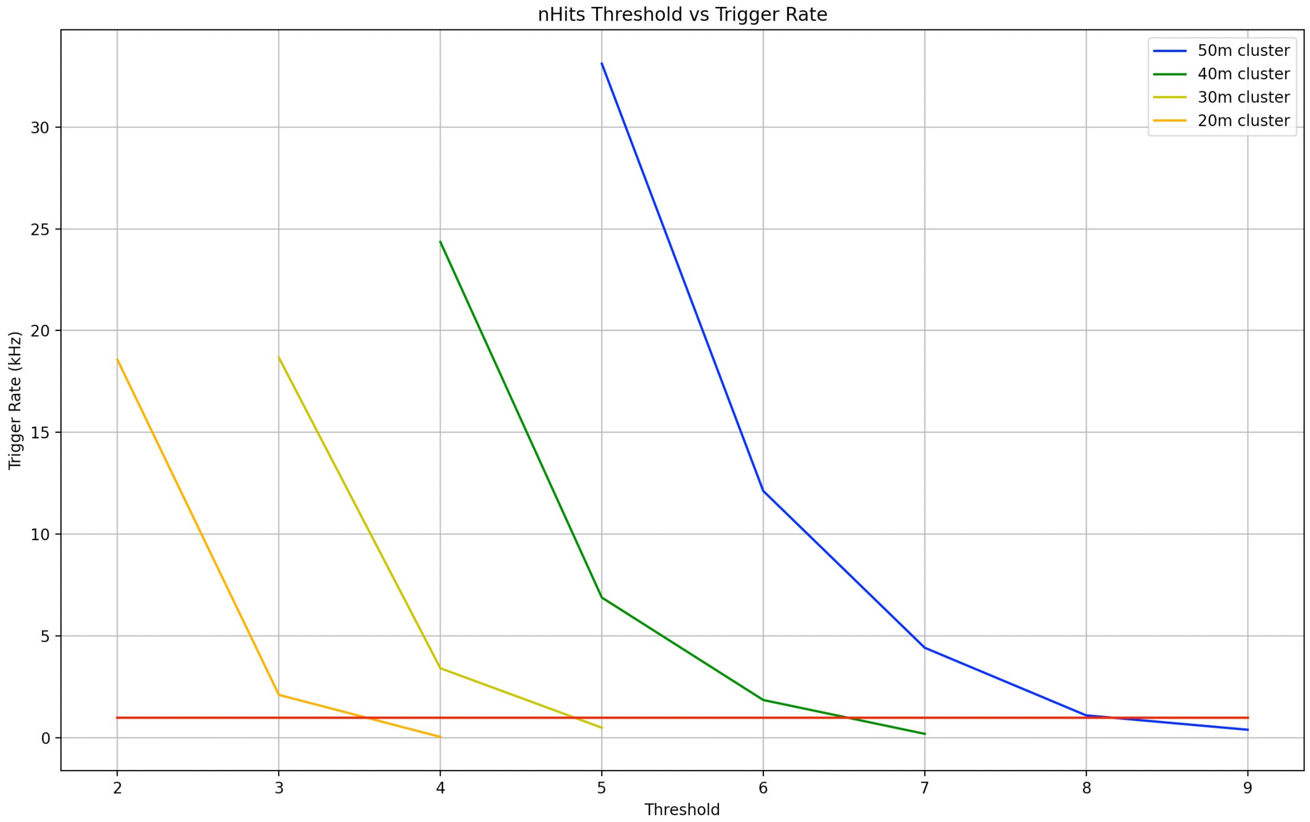
- So the maximum efficiency needed to get a trigger rate $\lesssim$ 1kHz (which at the moment is the maximum that won't overwhelm the DAQ) is 0.002 (i.e. only 0.2% of events are triggered when they shouldn't be)

- The optimal nHits threshold to obtain a trigger rate of $\lesssim$ 1kHz can be calculated for different cluster radii

- To re-iterate, this part of finding the trigger rate, so that I could find the optimal nHits threshold, was done using the background simulation which was all dark noise

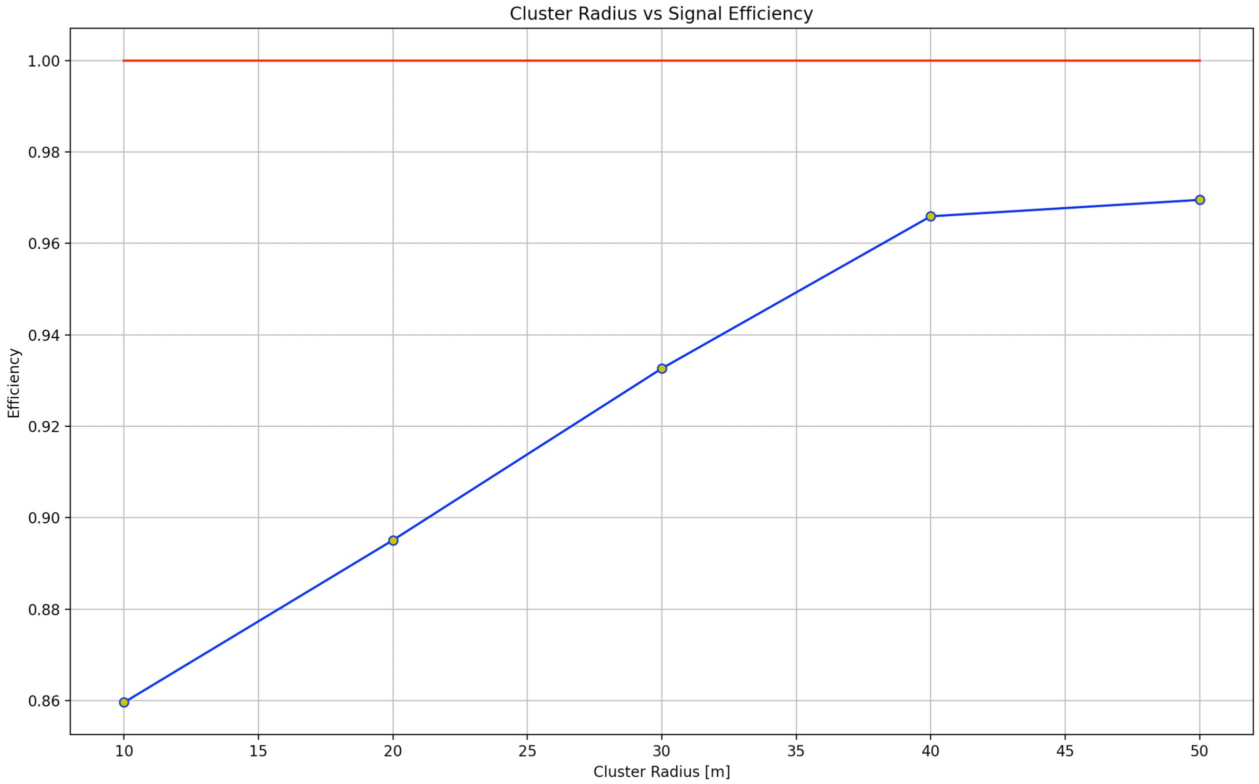
Preliminary Results

- This trigger rate can be plotted against the corresponding nHits threshold for each cluster radius:



Preliminary Results

- Finally, using these optimal thresholds on the signal simulation, with simulated cosmic muons, gives an optimal signal efficiency for each cluster radius:



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Preliminary Results

- For this particular MC simulation, because the signal efficiency begin to level off at 40m, the optimal cluster radius is 40m. From the nHits vs Threshold plot, the optimal nHits threshold for a 40m cluster is 7 !

- The plot on the previous page shows the efficiency for these values to be around 96% for just stopping muons

- Plugging these values into the efficiency formula…

$$Efficiency = \frac{\int_{nHits\ Threshold}^{500} Cluster\ Radius\ Histogram\ for\ x\ m}{\int_{0}^{500} Cluster\ Radius\ Histogram\ for\ x\ m}$$

- …for the through going simulation, this method gives an even greater efficiency of over 99%, for the 10,000-muon sample, after I correctly altered the algorithm and reconstructed those muons properly

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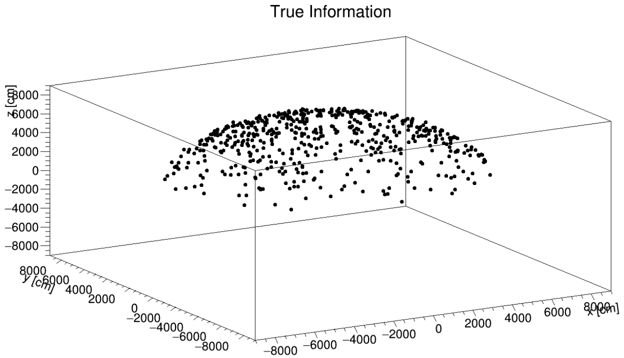
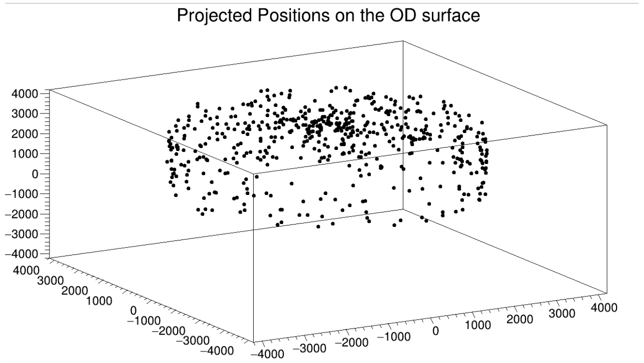
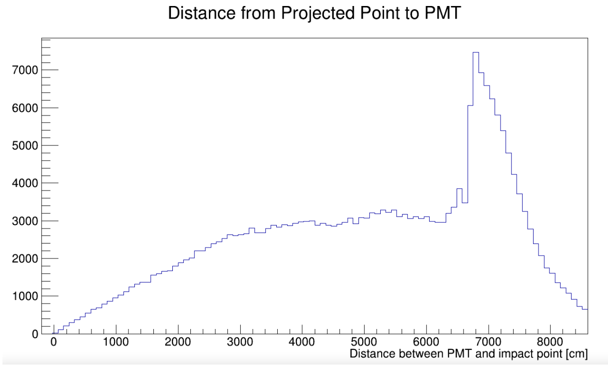
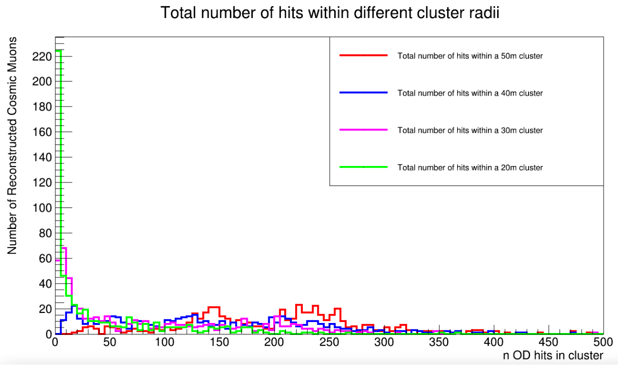
Next Steps

- The best test of my clustering algorithm is real Cosmogenics. This study is still on going, and uses Super-K data which has been modified to account for the different amount of rock above Hyper-K compared to Super-K





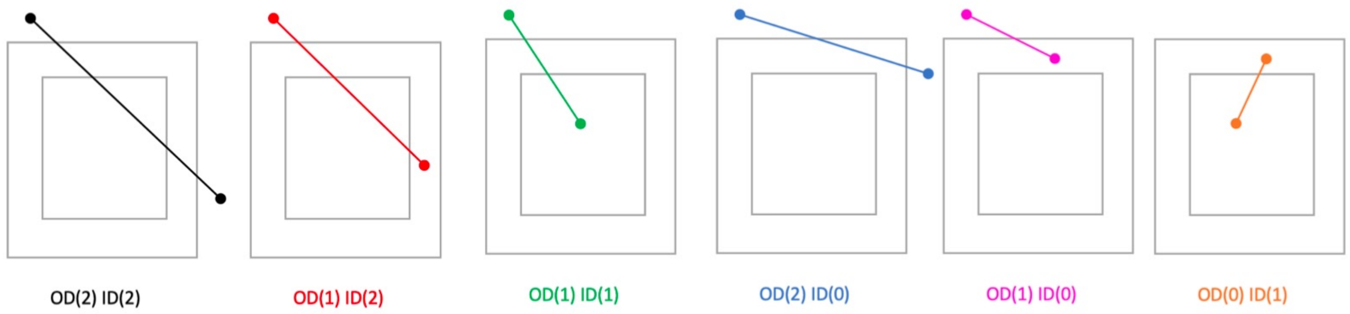




Next Steps

- Corner Clippers are events which just clip the corners of the OD tank and go through. This means that they have 2 cluster, but these clusters are geometrically very close to each other, which makes it tough to distinguish between the incoming and the outgoing clusters. They are also close in time, so some outside the box thinking is needed.

- I am currently investigating ways to optimize the separation of these clusters, by combining all information at my disposal including charge, time and position information



Summary

- Hyper-K is the next generation of water Cherenkov detector, which is being built to further our understanding of neutrinos and to try and answer some of the most fundamental questions in physics
- The Outer Detector's role is to veto cosmic muons which are a background to the neutrino events of interest
- My clustering algorithm uses a center of mass approach to use PMT information to reconstruct the positions of these muons, and then cluster around these positions to encompass some of the PMTs which re associated to each muon
- In different cases, different numbers of clusters need to be considered, and so far, I can get a trigger efficiency of upwards of 99%
- The next steps will be to focus on corner clippers, and optimize the cuts to increase the triggering efficiency

Thank you for listening!

Kamiokande
1983 start

2002

Super-Kamiokande
1996 start

2015

Hyper-Kamiokande
2020 construction
2027 start

???

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