Single Photon Emission from Neutrino-Nucleon Coherent Scattering in Liquid Argon

Maya Moore*
University of California, Berkeley
Columbia University Nevis Laboratories REU Program
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Weak photon emission from neutral current interactions is a non-negligible background for the MicroBooNE experiment. One interaction of this type is single photon emission from neutrino-nucleon coherent scattering. In this report I outline the analysis done on coherent scattering events generated by a Monte Carlo simulation of the MicroBooNE detector. I investigate various properties of coherent photon showers such as the energy of the photon and the angle the photon makes with the neutrino beam axis. In this report I find a discriminator between coherent and incoherent events in the angle of the shower. For a simulation of 1,000 coherent events in Geant4 and DetSim, 55% of single showers have $\cos(\theta) \geq 0.85$. I present in this report an algorithm to calculate the opening angle of a shower in $\phi$ as well as in $\theta$. I also introduce the relevance this has to Dr. Avinay Bhat’s MeV blip-finding algorithm in identifying coherent and incoherent showers.

I. MICROBOONE EXPERIMENT

The MicroBooNE detector is a 170-ton liquid Argon time projection chamber located at FermiLab. The scientific objectives of the MicroBooNE experiment are to measure several neutrino-argon cross sections as well as to explore the excess of low energy events observed in a previous neutrino experiment, MiniBooNE. The MiniBooNE data revealed an excess of events at low energies which did not fit their predicted model. Due to limitations of the detector, MiniBooNE was unable to discern whether these events were from photons or electrons. Since MiniBooNE uses the Booster Neutrino Beam at Fermilab—a muon neutrino beam—the potential for an excess of electrons could suggest evidence of sterile neutrinos.

![Figure 1: Results from MiniBooNE displaying the low energy excess](image)

The MicroBooNE detector consists of a rectangular volume of liquid Argon surrounded by photomultiplier tubes. Argon is an advantageous element to use because it is dense. Since neutrino interactions are very rare, using a dense material can boost the event rate. At the end of the volume of argon are three wire planes. Two of these planes are induction planes and the third is the collection plane. As charges move past these wires they induce a voltage which gets picked up by MicroBooNE’s electronic readout system. As the charged particles traverse the liquid volume, they leave a trail of ionization electrons and scintillation photons. The ionization trail moves through the Argon at a drift velocity kept approximately constant by a large electric field maintained throughout the volume. When this trail gets picked up by the wire planes, researchers can recover information about the interaction that generated them.
MicroBooNE was designed to be able to distinguish between electrons and photons in order to explore the source of MiniBooNE’s low energy excess. The detector’s ability to distinguish between photons and electrons lies in the starting point of the electromagnetic shower both particles induce. Since the detector registers only charged particles, it can detect the electrons and positrons in the shower, but not the photon. Therefore, if there was a gap between the vertex point and the starting point of the shower one could be sure that a photon was produced at the interaction vertex.

![Image](image1.png)

**FIG. 2:** Event display from MicroBooNE (x-axis: wire ID & y-axis: time tick).

## II. THEORY

The model used for the coherent scattering simulation is based on the Alvarez-Ruso model. Alvarez-Ruso models single photon emission in NC interactions at energies relevant to MicroBooNE. Since MiniBooNE was a $\nu_\mu \rightarrow \nu_e$ oscillation experiment that could not distinguish electromagnetic showers started by a photon from those started by an electron, neutral current photon emission becomes one of the biggest backgrounds. We chose this model because it is the most thorough in its calculations. Other models ignore factors such as nuclear corrections that Alvarez-Ruso’s model takes into account. In order to extend the validity of the model to higher energies he includes the second resonance region in addition to the delta resonances. Additionally, Alvarez-Ruso is a contemporary physicist who worked with his team to implement the model in GENIE which allowed us to use the software to simulate these events. One point to note is that the model uses a cutoff at 140 MeV and so no photons are simulated at energies lower than that cutoff. This cutoff is imposed due to an infrared divergence that occurs in some of the nucleon propagator terms as the energy of the photon approaches zero.

Coherent scattering implies that the nucleus in the interaction was not altered at all by the incoming particle. The single photon analysis at Nevis Laboratories has previously been focused on the incoherent scattering in $\Delta$ baryon radiative decay. In the previous analysis, the single photon group looked at the excitation of the $\Delta(1232)$ resonance by an incoming neutrino. This delta baryon is unstable and would quickly decay back down to a proton or neutron-depending on its charge. In the process of its decay, most commonly a pion is emitted. However, a photon can also be emitted and the cross section of this decay has not been experimentally determined. Therefore, if theory underestimated this cross section it could account for the low energy excess observed in MiniBooNE.

Another source of single photons, although rare, is the coherent scattering of a muon neutrino off of an Argon nucleus. In this case, the energy of the neutrino is too low to ionize the Argon atom either by emitting a proton or a neutron. The neutrino scatters off and emits a photon in the process.

Since NC delta radiative decay emits a photon and at least one neutron, this interaction and coherent neutrino-nucleon scattering both appear as a single electromagnetic shower in our detector. Therefore, my research was targeted towards finding qualities about these single showers that would allow us to distinguish incoherent single showers from coherent single showers in the MicroBooNE detector.
III. EQUIPMENT

In conducting my research I used various software tools for the simulation and subsequent reconstruction of neutrino interactions. The first software tool I used to begin simulating coherent scattering events was GENIE. GENIE is a ROOT-based neutrino Monte Carlo event generator written in C++. GENIE simulates neutrino interactions but it does not have a time component. For example, we could tell GENIE the energy of the neutrinos in our beam and GENIE could tell us what particles will be emitted based off of known interaction cross sections. It could also tell us the momentum transfer of the interaction but it could not tell us, for instance, how far a final state photon travelled before it started showering. The data generated in GENIE’s simulation gets written to a Genie Summary Tree (‘gst’) which is an ntuple. This stores a TTree with branches that can be easily plotted in ROOT. These branches tracked information that I used to compare the behavior of coherent events and incoherent events in order to find stark differences between the interactions.

In order to simulate the time component of the analysis we use the software tool Geant4. Geant4 is officially the "simulation of the passage of particles through matter"\cite{2}. This software simulates the propagation of particles through liquid argon so that we can understand how these interactions play out over time in the MicroBooNE detector. We also use DetSim to simulate variables about our detector such as the electric field, dead wire regions, and voltage readout on the wires. This is useful because this tool is used to generate our event displays which allows us to see what is happening in the detector and it is crucial for handscanning.

The tool I used for the reconstruction stage was Pandora. Pandora uses pattern recognition to cluster hits from the Geant4 and DetSim simulation into higher level classes such as tracks or showers. From Pandora we are able to extract information like shower length and direction. This was crucial in studying the angle of the reconstructed shower. Pandora also stores metadata such as track score, which is a metric of how confident Pandora is that a cluster of hits is a track.

These tools are all integrated into an overarching framework LArSoft. LArSoft is a set of software tools for the simulation, reconstruction, and analysis of data from liquid argon neutrino experiments. Adding the software tools I previously discussed into the LArSoft framework allows us to tailor them to be useful for our experiment.

IV. MEV BLIPS

Initially I was not planning to use information about the neutron to help discriminate between incoherent single photons and coherent single photons. Since neutrons are electrically neutral, they do not leave an ionization track and so these two are theoretically visibly the same in the detector. However, although the emitted neutron itself may not be visible, it is still in the detector and it can go on and interact with other nearby Argon atoms along its path. In doing so, the neutron can excite the Argon nucleus to slightly higher energy levels. When the Argon atom relaxes back down to its ground state, a very low energy photon is released which Compton scatters and the residual electrons leave a small blip in the event displays from the detector.

I explored Dr. Avinay Bhat’s algorithm on MeV-scale reconstruction in MicroBooNE to try and use these MeV blips as a way to distinguish coherent from incoherent scattering. The MicroBooNE detector typically studies neutrino events in the range of 0.2 to 10 GeV but, due to the work of Dr. Avinay Bhat, this lower bound has been extended to energies as low as 0.1 MeV. This low-energy reconstruction should be sensitive to photons produced by a neutron through inelastic scattering with the Argon nucleus or neutron capture. In his reconstruction he lowered four main parameters in the hit-finding threshold of MicroBooNE: $N \sigma$ formation on collection and induction plane, Region of Interest (ROI) amplitude in number of electrons, and ROI average of number of electrons. For these parameters he used values of 2, 3, 100, and 300, respectively.\cite{3} To perform this reconstruction, he first takes 2D clusters in the detector and reconstructs them as 3D spacepoints by matching drift times of clusters across the three wire planes in the detector. He assumes all spacepoints are due to electrons and, in this way, converts collected charge to deposited energy. One of the difficulties he discusses in detecting MeV blips is cosmogenic background noise. Long cosmic tracks do not pose a problem but these tracks can emit $\delta$-rays and bremsstrahlung photons which have the same appearance as low energy electromagnetic blips from neutrinos and so he measures the rate of these backgrounds. He is then able to study the correlation between the neutrino vertex and the reconstructed spacepoints with low-energy deposition. His MeV scale reconstruction allows us to extend the lower limit of the energy regime which MicroBooNE is capable of detecting and allows us to search for MeV-scale electromagnetic activity caused by final state neutrons.
V. GENIE SIMULATION

The first simulation we ran through the coherent single photon simulation was with a muon neutrino beam at a constant energy of 700 MeV. This energy was chosen because it is the most probable energy of a neutrino in the beam from the actual detector. We started with this simple simulation to make sure that there were no obvious bugs in the simulation before moving forward. We then generated events for a distribution of energies that replicated the energy flux of muon neutrinos in the Booster Neutrino Beam for a more realistic simulation. I used this data to directly draw comparisons about certain parameters between the coherent single photon events and the incoherent single photon events. I began my comparison with the following variables: energy of the incoming neutrino, energy of the outgoing photon, cosine of the angle the photon makes with the beam, and the momentum transfer.

From the upper right plot in Figure 3, I was able to confirm that coherent photons did travel mostly forward especially compared to incoherent photons. I was surprised to find that the photon energy—shown in the upper right plot in Figure 3—for coherent photons peaked at a higher energy than incoherent photons. Since the neutrinos in coherent interactions are lower energy I expected the photon would be as well. However, for incoherent events, although the neutrino energy is higher, there are more final state particles. So in incoherent scattering the momentum must be conserved among more particles than in coherent scattering. I also calculated the correlation coefficient between photon energy and \( \cos(\theta) \) for both the coherent single photon and the incoherent single photon. I found these to be 0.426 and 0.655, respectively.

I also plotted the distribution in neutrino energy for both the incoherent events and coherent events and I verified that the neutrino energy for coherent events peaks at a lower value than for incoherent events. The neutrino energy for incoherent events is \( 1.175 \pm 0.5416 \) GeV. As expected, the neutrino energy for coherent events was lower at \( 0.8497 \pm 0.3760 \) GeV.
VI. PANDORA RECONSTRUCTION

I encoded the information about the photons and neutrinos from the coherent GENIE events into an HEEvent formatted text file that could be passed through Geant4, DetSim, and Pandora. This generated a file containing event displays as well as a vertexed file with information about each event. Initially, I started with a simulation of 50 events. Of these initial 50 events, 18 were reconstructed as a single shower. I handscanned through these 50 events to make sure there were no glaring errors in the simulation and reconstruction. I then analyzed a file of 1,000 coherent events. This file contained events that were simulated without overlays which means there was no cosmic background noise. Pandora reconstructed 39% of these events correctly as a single shower. I looked at this efficiency as a function of both photon energy and photon angle. I found that Pandora is better at reconstructing single showers at higher energies. For photons with energies greater than 0.45 GeV, Pandora’s reconstruction was correct 64% of the time. This is a significant increase when compared to the overall efficiency rate of 39%. I also found that Pandora is better at reconstructing forward showers. Of the events that had a cosine angle of greater than 0.85, 46% of these were reconstructed correctly. This is positive since 55% of the coherent showers had \( \cos(\theta) \geq 0.85 \).

I also explored what the most common reconstructions were. I found that the most common reconstruction was the correct one, a single shower, which occurred 39% of the time. The second most common was zero showers and zero tracks which accounted for 22% of the events. This reconstruction occurred most often because the photon left the detector or the shower was very small and so it didn’t get reconstructed. The third most common was one shower and one track which happened for 12% of showers. This misreconstruction was often due to the shower having a very straight electron/positron pair at the beginning and so the beginning of the shower was reconstructed as a track. In Figures 4-6, I attach example single shower events for each of these reconstructions.

FIG. 4: Event display on plane 2 of a single shower which was reconstructed correctly.

(a) No reconstruction overlaid.  
(b) With Pandora’s reconstruction overlaid.

FIG. 5: Two examples of single showers that Pandora did not reconstruct at all, or classified as 0g0p. In (a) the shower was not reconstructed due to dead wires. In (b) it was not reconstructed because it is small.
Figure 4 is a good single shower that got reconstructed correctly. In Figure 5a, this shower did not get reconstructed likely due to dead wire interference. The shower in Figure 5b also did not get reconstructed because it is very small and low energy. Figure 6 is a shower that got reconstructed as a shower and a track.

Of the 22.9% of events that were not reconstructed at all, about 26.6% (or 6.1% of total events) were not reconstructed because the photon left the detector. This is not a reconstruction failure but rather a simulation failure. Therefore, if you remove these events the efficiency rate of Pandora is boosted to about 41.5%. This is a lower estimate of Pandora’s efficiency rate since I did not know the exact number of events in which the photon left the detector. The values I quoted were from selecting the number of events which had zero reconstructed tracks and showers as well as no reconstructed neutrino slice. However, when handscanning, I found that there were events which had a nonzero number of reconstructed neutrino slices and yet the photon had still left the detector. This number I believe to be small and it would only further boost Pandora’s efficiency rate.

One of the major shortcomings of Pandora’s reconstructions of the single coherent showers is in the photon energy. I used the reconstructed energy on plane 2 for this comparison. I applied a 20% correction to the reconstructed energy which is approximately the value used for other MicroBooNE analyses. However, this percentage was calculated for showers with overlays, or background noise. The background hits can be clustered in with the shower and increase the overall energy of the shower. Since, the events in the simulation I was analyzing didn’t have overlays, I added an additional 10 MeV to account for this lack of background. Even with a 20% shift to the reconstructed energy plus a 10 MeV shift to account for the lack of cosmics, the reconstruction still falls 16% short of the true photon energy.

![FIG. 6: Event display on plane 2 of a single shower that was incorrectly reconstructed by Pandora as a 1g1p event.](image)

![FIG. 7: The plot in (a) depicts an overlay of Pandora’s reconstructed single shower energy on plane 2 with a 20% + 10 MeV shift and the true energy of the single photon. The plot in (b) depicts a 2D Histogram displaying the correlation between the true energy of the single photon and Pandora’s reconstructed energy of the single shower on plane 2.](image)
Pandora performs very well at reconstructing the angle information which is positive considering one of the major discriminators to identify coherent showers is the forward angle trademark. From Figure 8, Pandora always reconstructs the angle within statistical error of the true angle. There are a few cases where Pandora reconstructs the shower backwards but these make up a negligible fraction of the total events. Plotting the correlation between Pandora’s reconstruction and the truth value for \( \cos(\theta) \) it is also clear how well Pandora’s reconstruction performs.

The \( y=x \) line plotted on the 2D histogram represents a perfect reconstruction. The data is densely centered on this line which is reflective of an accurate reconstruction.

I also investigated the accuracy with which Pandora reconstructs the starting point of the shower. To do so I plotted a histogram of the distance between the simulated shower start and the reconstructed shower start in all directions–x, y, and z. The histograms for each respective coordinate are shown in Figure 9.

![Graphs showing Pandora’s accuracy in reconstructing the shower start](image)

**FIG. 8:** The plot in (a) depicts an overlay of Pandora’s reconstructed \( \cos(\theta) \) where \( \theta \) is the angle the photon makes with the beam axis and the true \( \cos(\theta) \). The plot in (b) depicts a 2D Histogram displaying the correlation between the truth value and Pandora’s reconstruction of \( \cos(\theta) \).

**FIG. 9:** Measure of Pandora’s accuracy in reconstructing the shower start through plot of distance between truth value photon end and reconstructed shower start. For truth photon end, the simulated shower start coordinates are used.

I found that the mean error in distance between simulated and reconstructed shower start is reasonable for all three
Also, as seen in Figure 8(b), a few of the events were reconstructed backwards. This could explain the events where the error is more than 20 cm in all three directions. I also noticed that the accuracy in the x and y directions is better than in the z direction. The simulation of the detector also emulated dead wire regions which interfered with Pandora’s reconstruction of the showers. The accuracy difference depending on direction can be explained by these dead wires regions in our detector. In a dead wire region, Pandora might mistake the shower start as a hit further ahead in the shower. This would cause a more noticeable impact in the z direction because our showers are mostly forward. Therefore, moving ahead in the shower one would not see as much variation in the x and y coordinates as one would in the z coordinate of the shower’s hits. One can visualize this by analyzing the event display for an event which was misreconstructed due to dead wires. Figures 10 and 11 show event displays on plane 2 and plane 0 of a shower whose start point was misreconstructed. On plane 2, there are no dead wires and on plane 0 there are dead wires.

FIG. 10: Example event display of a shower which got misreconstructed due to dead wires shown from plane 2 (no dead wires).

FIG. 11: Example event display of a shower which got misreconstructed due to dead wires shown from plane 0 (dead wires).

In Figure 11a one can see that dead wires caused interference in the shower such that Pandora reconstructed hits
in that region as unassociated, and not part of the shower. However, from Figure 10a, one can see clearly that the shower starts much further back than where it is reconstructed. One can also see how this has a more significant impact on z than on x or y. Since the shower is forward, the reconstructed shower start point in x and y is not that far from the shower’s true start x and y coordinates. However, the reconstructed z coordinate is over 30cm away from the shower’s true z coordinate.

VII. UNASSOCIATED HITS

In order to assess if the MeV blips were going to be effective in discriminating between coherent and incoherent single showers, I did a preliminary study of the number of unassociated hits for incoherent events. Specifically, I analyzed how the number of unassociated hits is affected by the momentum of the exiting neutron in NC $1g0p$ $\Delta$ radiative decay events. The number of exiting neutrons can vary from 1 to as many as 9 exiting neutrons and so I only selected events with 1 exiting neutron. I imposed this selection because I did not want the number of unassociated hits to be affected by the number of exiting neutrons in addition to the momentum. I then broke these events into three ranges depending on the momentum of the exiting neutron: low momentum ($<0.5$ GeV), medium momentum (0.5-1.0 GeV), and high momentum ($>1.0$ GeV). I also normalized the histograms to account for the fact that the number of events in each range was not equal.

![Unassociated Hits as a Function of Momentum](image)

FIG. 12: Histogram of the probability of a number of unassociated hits as a function of momentum of the exiting neutron for 1 photon 1 neutron events. The x-axis corresponds to the number of unassociated hits and the y-axis corresponds to the probability that an event has that value.

There are no higher statistics as this was purely a preliminary look to see if it was worth pursuing the MeV blip algorithm. I did notice a qualitative shift in the number of unassociated hits for each distribution. As the momentum of the neutron increases the distribution appears to shift to the right. This suggests that the exiting neutron is causing a detectable increase in the number of blips detected when it interacts with nearby Argon atoms. This information supports our idea to use blips produced by a neutron through inelastic scattering with the Argon nucleus or neutron capture to distinguish incoherent and coherent single showers.

VIII. OPENING ANGLE

Collaborators on MicroBooNE at Rutgers University reached out because they were interested in running the MeV blip-finding algorithm discussed earlier in this paper on our coherent events. This would allow us to quantitatively study if there is a significant increase in the number of blips when a neutron is emitted in the interaction compared
to an event with no neutron emission. If there is a quantitative difference then we could continue to use blips in
discriminating between coherent and incoherent events.

I then began working on an algorithm to determine the opening angle of a shower. This would allow one to define
a cone around the shower. A cone would give us a boundary between a region where we expect to find blips from the
shower and a region where blips most likely indicate the presence of a neutron. I tested this algorithm using the file
with coherent simulated events and no overlays so that there would be no background noise.

To begin implementing this, I transformed every spacepoint in a shower from Cartesian coordinates into spherical
coordinates. In the coordinate system I used in my code, $\phi$ is the azimuthal angle, $\theta$ is the inclination angle, and $r$
is the distance between a spacepoint and the reconstructed shower start. This coordinate system is shown below in
Figure 13.

![FIG. 13: Spherical coordinate system used for opening angle algorithm.]

The algorithm I implemented calculates the maximum $\phi$, minimum $\phi$, opening angle in $\phi$, maximum $\theta$, minimum
$\theta$, opening angle in $\theta$, as well as the maximum radius for a given shower.

Defining the geometry of the problem was difficult because I had to be consistently careful with how I was defining my
angle and with reference to which axis. I used the atan2 function in C++ which returns the arc tangent of two doubles
in radians from $-\pi$ to $\pi$. For showers that opened counterclockwise I added $2\pi$ to every angle which was negative so
that I now had my angles $\phi$ defined from 0 to $2\pi$. However, I ran into a bug if a shower opened up clockwise and
crossed the $y=0$ axis line on the right. When finding the minimum and maximum phis for counterclockwise showers,
I plotted a distribution of the vector of $\phi$ values and I found the first bin above a certain threshold and the last bin
above a certain threshold. The purpose of the threshold is to eliminate angles which only represent a couple hits in
order to get a more accurate picture of the opening angle. I defined the threshold to be 2.5% of the total number of
entries. If the shower was clockwise and crossed $y=0$, the first bin my algorithm would find which was above 2.5% of
entries would be 0 radians and the last bin would be $2\pi$ radians. A more clear picture of this edge case is shown in
Figure 14 and 15(a). Figure 14 depicts the shower so one can see its minimum angle is below $y=0$ which is why it gets
miscalculated in the algorithm since the angles in the code are defined to go from 0 to $2\pi$. In order to fix this I added
a piece of code that adjusts the angle definition for showers which have a positive $x$ direction. For these showers I
shift the distribution such that the mean gets translated to zero and all values in the $\phi$ vector get translated by a
distance equal to the mean modulo $2\pi$. I then subtract $2\pi$ from any angle greater than $\pi$ so that my angles are now
defined relative to the mean angle from $-\pi$ to $\pi$. This effectively shifts the histogram so there is no longer a break and
I can calculate minimum and maximum $\phi$ in the same way as for the counterclockwise showers. With the updates to
the code, it now returns correctly.
As I continued to test my algorithm I realized there was an issue in binning. I set the number of bins to a constant but the number of spacepoints in a shower can vary from tens of spacepoints to thousands. It also opened up the potential to make the binning too fine as to the point where every bin has less than 2.5% of total hits by necessity. To circumvent this, I defined the number of bins to be proportional to the number of spacepoints. The formula I used to define the number of bins was the ceiling of the number of spacepoints divided by 10.

After getting the algorithm to work successfully for individual events, I worked on up-scaling my code so that it could parse through every shower from a simulation and return critical information about the shower angles and its radius. I wrote a header function to take as input variables from the ROOT TTree and called this function for each entry that had a single shower in the vertexed file from Geant4. This function returns a vector containing the maximum phi, minimum phi, opening angle in phi, maximum theta, minimum theta, opening angle in theta, and maximum radius. Then I created a new TTree with a single branch containing this vector. I friended this TTree to the TTree from the single photon analysis ROOT file in order to easily plot variables from both.

I was then able to look at the distribution of opening angles in $\phi$ and $\theta$. I investigated the impact my cutoff was having on this distribution. I believed the cutoff was necessary due to showers with hits right around the vertex. Since the distance to the vertex is small it can skew the angle. I used a cutoff of 2.5% and 5% of the total number of entries as well as no cutoff to see how the distribution varied. The large number of entries with wide opening angles from the distribution with no cutoff shows that it is necessary to apply a cutoff.
FIG. 16: Distributions of opening angles in both $\theta$ and $\phi$ with no cutoff applied.

(a)  
(b)  

FIG. 17: Distributions of opening angles in both $\theta$ and $\phi$ with a cutoff if a histogram bin contains fewer than 2.5\% of the total number of entries.

(a)  
(b)  

FIG. 18: Distributions of opening angles in both $\theta$ and $\phi$ with a cutoff if a histogram bin contains fewer than 5.0\% of the total number of entries.

(a)  
(b)
I wanted to see if the increase in entries with larger opening angles was in fact due to space points clustered around the vertex. To visualize this I didn’t ignore any bins in my histogram as I did with the 2.5% cutoff. Instead, I only filled my histograms with space points which had a radius with respect to the vertex of 2cm or longer. This effectively ignored any hit within a 2cm radius of the vertex.

This dramatically decreased the average opening angle as compared with the distribution with no cutoff and no radius limitation. This is useful because, when looking for MeV blips, we could define a sphere around the vertex and look for blips outside of that sphere as well as blips outside of the cone defined by our opening angles in $\phi$ and $\theta$.

I also studied the correlation between the opening angle in both $\phi$ and $\theta$ and the energy of the photon. I expected, for the same reason the single photon emitted in coherent neutrino-nucleon scattering is mostly forward, that low energy showers would be mostly forward and therefore have a narrower opening angle. With high energy showers which have high momentum I expected there to be wider scattering angles and so these showers would have had wider opening angles. However, as shown in Figures 20 and 21, there was not any significant correlation.

FIG. 19: Distributions of opening angles in both $\theta$ and $\phi$ with a cutoff if a spacepoint is within a 2 cm radius of the vertex.

FIG. 20: The plot on the left depicts the correlation between the opening angle in phi and the reconstructed energy of the shower on plane 2. The plot on the right depicts the correlation between the opening angle in phi and the truth value photon energy.
FIG. 21: The plot on the left depicts the correlation between the opening angle in theta and the reconstructed energy of the shower on plane 2. The plot on the right depicts the correlation between the opening angle in theta and the truth value photon energy.

IX. CONCLUSION

Through my research I was able to identify discriminators between incoherent and coherent single showers. One of these is in the angle of the shower; coherent photons travel very forward. Another potential way to distinguish between a single photon that was emitted from a coherent interaction as opposed to an incoherent interaction is in the number of MeV blips in the detector around the shower. By defining a cone using the algorithm I completed we could count the number of blips inside the defined cone and outside. I sent a HEPevt formatted file with 10,000 simulated coherent events to our collaborators at Rutgers so that they can run their MeV blip-finding algorithm on the events. Analysis of these events with overlays will begin to tell us how effective the blips will be in discriminating between coherent and incoherent events. It will also illuminate any refinements needed for the cone method. This information will allow us to reject events with higher neutron count and help select a higher purity of the extremely rare coherent photon events.

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* Also at Physics Department, University of California, Berkeley.