A First Study of IBD vs ES Fiducial Volume Reconstruction

Janet Conrad, August 27, 2004

For the weak mixing angle analysis at the Braidwood Reactor Experiment, it is important that the fiducial volumes of the inverse beta decay (IBD) events, used for normalization, be nearly the same as the fiducial volume for the elastic scatters (ES) events, which are the signal. The concern is that the IBD events may reconstruct differently from ES due to annihilation photons which Compton scatter in the event. For example, the streamer of e^- vertices from these Compton photons may systematically pull IBD events toward the tubes.

The error on the number of ES events which comes from a difference between the ES and IBD fiducial volumes is: $(dN/N)_{fid} = 3dr/r$, where r is the fiducial radius and dr is the systematic error on the fiducial radius between the two samples. Thus, for a 2.5m fiducial radius, the two samples must have $dr < 8$mm in order for $(dN/N)_{fid} < 1\%$. In fact, 1% is a very significant error for the analysis and thus achieving substantially better than 8mm understanding of the relative fiducial radius is highly desirable.

As a start to the process of understanding this error, the purpose of this memo is to address the question: *How hard will it be to know the relative fiducial radii of ES and IBD events to a few mm?* Once the scope of the problem is established in this memo, we will seek ways to address the issues in following memos.

A hit-level Monte Carlo/Reconstruction program was written for this study. Based on this, the answer to the question will be shown to be: *it appears that the < 8mm goal can be achieved.* The study shows that ES and IBD events reconstruct to the same fiducial radius within a few mm. Quantifying "a few" requires a more in-depth study, but 3mm appears to be a reasonable goal.

1 Monte Carlo Used In Study

In the Monte Carlo simulation, the detector was divided into two volumes. For the "base" study, the attenuation length of the inner volume was 4m and

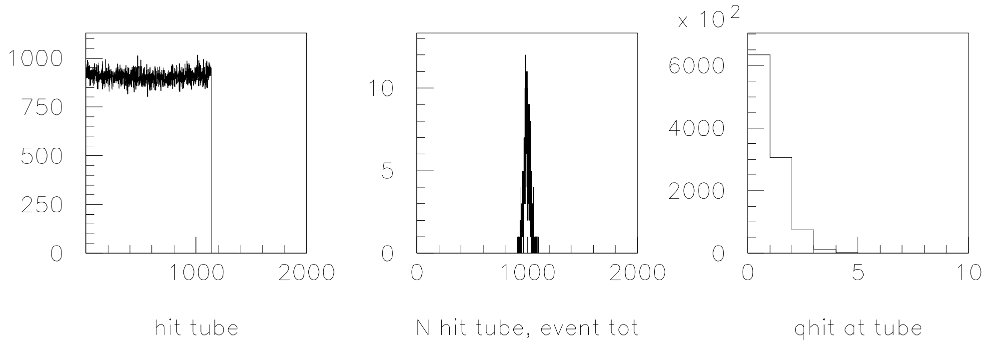

Figure 1: For ES events at (0,0,0), Left: distribution of hits across tubes; Middle: distribution of 0,1,2... hits in each tubes; Right: total hits registered.

the outer volume was 15m. Later in this memo, the effect of varying these attenuation lengths will be explored. The inner volume radius was 2.7m. The outer volume radius was 3.5m, which was assumed to be the face of the phototube. Phototube coverage was 25%. The tube radius was 10 cm.

Event vertices were generated from (0,0,0) to (0,0,2.5m) at 0.5m intervals. For the electroweak analysis, we had originally proposed a 40 cm fiducial cut from the inner edge. This would correspond to (0,0,2.3). However, we are looking at reducing this in order to increase rate. Hence the final point is at the 2.5m radius for this study.

ES events were generated as single-point vertices, although later in the memo extended vertices will be studied. The vertices were chosen throughout the inner region. Emitted scintillation light was isotropic, as is shown by the hit distributions in the tubes for vertices at (0,0,0) (Fig. 1, left). The direction of each potential hit was chosen randomly. The probability that emitted light, after attenuation in the two oil regions, produced a hit in a tube was generated according to a Poisson distribution (see Fig. 1, middle). Light could be directed at the tube more than once in the random generation process. The Monte Carlo is calibrated such that a 5 MeV e^- produced at the center of the tank represents about 1000 hits in the phototubes (see Fig. 1, right). In other words, 1 hit equals 5 keV. Later in this memo, we also consider 3 MeV events.

IBD events were generated with a central vertex followed by production of two photons. In this case the total energy in the detector was taken to be the sum of the energy of the primary vertex, plus the two 0.5 MeV photons. Hence, a 5 MeV event consisted of a 4 MeV vertex plus the two gammas. The photons would subsequently Compton scatter, as simulated using a set of routines written by Mike Shaevitz (already in use in other Braidwood code). Photons deposit energy in the form of e^- kinetic energy and scatter through an angle as given by the Compton formula. The photons corresponding to the scattered e^- kinetic energy are generated randomly and isotropically. The hits are generated according to a Poisson, accounting for attenuation. A tube can be hit by more than one photon, which may come from the same vertex of different vertices.

Fig. 2 shows three examples of Compton scattering events, all of which are generated at (0,0,0). Note the scale of the display, which shows only the central part of the detector. Each row is one event shown in three views. The size of the box indicates the amount of energy associated with the vertex. Once can see that the photons form "streamers" of vertices on either side of the central vertex. Clearly these events are very different than a single central vertex, and this is the cause for concern about variations in the reconstruction.

While the photon-induced streamers are long on the scale of the detector and with many steps, most of the final steps are at low energy. Fig. 3 shows the number of steps that a Compton photon typically takes before dropping below the 1 hit (5 keV) energy level. In the future, this 1-hit cutoff could be adjusted to the K-shell bound, which is probably closer to 2 to 3 hits, but this will not significantly change the conclusions of this memo. Fig. 3 shows the Compton length as a function of the energy of the incoming photon for each step, for 1000 photons. The size of the box indicates the number of photon vertices associated with each energy and step-length. Note the cluster of large boxes indicating many small steps at low energy. The peak at 0.5 MeV are the initial photons produced in the annihilation. By looking at the radial distance that the photons travel (which is smaller than the total distance, since photons scatter at angles), one learns how many photons exit before depositing all of their energy. Fig. 3 shows the radial distance for vertices centered at (0,0,0). There is a negligible probability for photons produced at the center to exit the inner detector region before losing all of their energy. On the other hand, 5.4% of the photons produced at a vertex of (0,0,2) will exit the detector before the energy has dropped below the 1 hit level. And at (0,0,2.5), 36% of the photons exit the inner region without depositing all

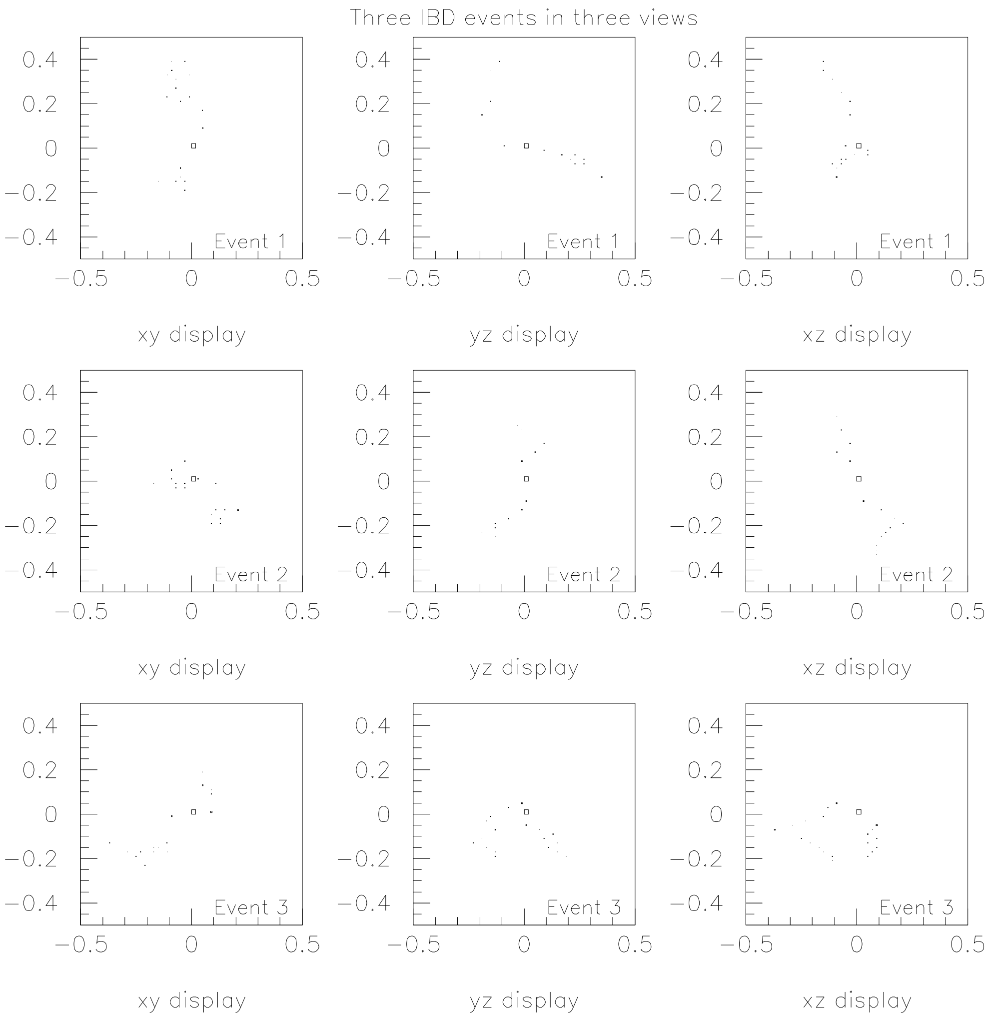

Figure 2: Displays of IBD events in the central portion of the detector. See text for details.

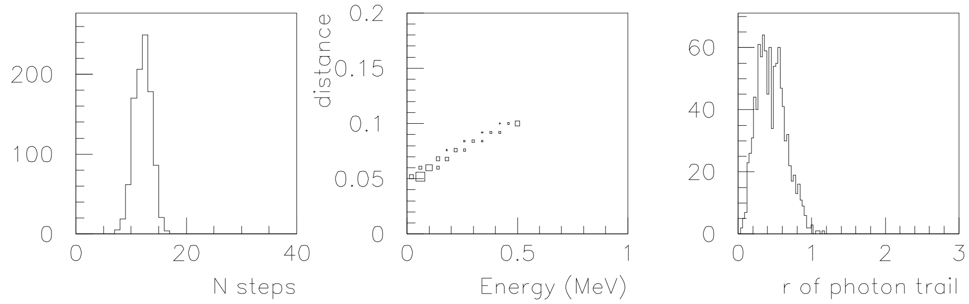

Figure 3: For IBD photons, Left: number of steps taken; Middle: step length vs. energy; Right: vector distance from vertex to end of photon trail

of their energy.

Noise hits can be added in the Monte Carlo. The "base" study assumes no noise, but a later systematics study does consider the case of additional random hits in 4% of the tubes will also be also considered here. This rate, 20 kHz, is enormous compared to the MiniBooNE noise rate of <1 kHz, and is certainly an overestimate of what we will see at Braidwood. This high rate was chosen only to make the effect of random noise on the reconstruction clearly observable.

For each study, 500 events were generated. This is only marginally sufficient statistics to answer the question, but good enough given that the goal was to "quickly" scan the space. Future studies will need to generate higher statistics

2 Reconstructing Events

The event reconstruction is fairly rudimentary. Thus, this should provide a conservative upper estimate on the difference between IBD and ES reconstruction, since the algorithm can clearly be improved.

Four parameters are used: 3 spatial coordinates and one normalization factor. The starting point for the spacial coordinates is given by the charge-weighted center in each dimension. The starting point of the normalization factor, wt, is the sum of hits in the tubes divided by the fraction of a hit which is expected to reach the tube when attenuation and normalization are considered.

The predicted number of hits in a tube, μ, is the fraction of light which will reach the tube (which is not unity due to both attenuation and solid angle) multiplied by wt. The Poisson probability for n registered hits given a prediction of μ is calculated. The negative log likelihood is the sum of the negative logs of the probabilities. This is minimized to find the best fit, using Minuit.

This algorithm produces a pull toward the phototubes for vertices near the tubes. In the future, the algorithm should be adjusted to remove this pull, but for the sake of this study, the pull itself does not matter. All that matters is that the pull for ES and IBD events be, to within a few mm, the same.

This algorithm could be made more sophisticated in the future. For example, only charge information is used. Incorporating timing information could provide substantial improvement. Also, identical algorithms are used on the ES and IBD reconstruction. In the future, one might want to account for the photon streamers in IBD events (which are tagged by their neutron capture). However since the streamers are symmetric, this should not be a large effect. This algorithm is not adjusted to account for any additional noise hits. In reality, we will measure the noise and include the expected number of hits in the reconstruction algorithm.

3 The "Base" Study

The "base" study assumes no noise hits, and inner and outer attenuation lengths of 4 and 15m, respectively. The base study compares ES and IBD events with total visible energy of 5 MeV ($\sim$ 1000 hits).

Fig. 4 shows Δz, the difference between the reconstructed and generated vertices in meters, for z-vertices between 0 (top left) and to 2.5m (bottom right) for 5 MeV ES events. The pull toward the phototubes is apparent. Fig. 5 shows these plots for IBD events. The pull is again clear.

Tab. 1 summarizes the results for the z-vertex direction. "Hist" indicates the values are taken from the Δz plot. "Fit" is the result of a Gaussian fit to the Δz distributions, which provides the peak position and σ. Note that henceforth in the discussion "mean" will refer to the histogram mean and

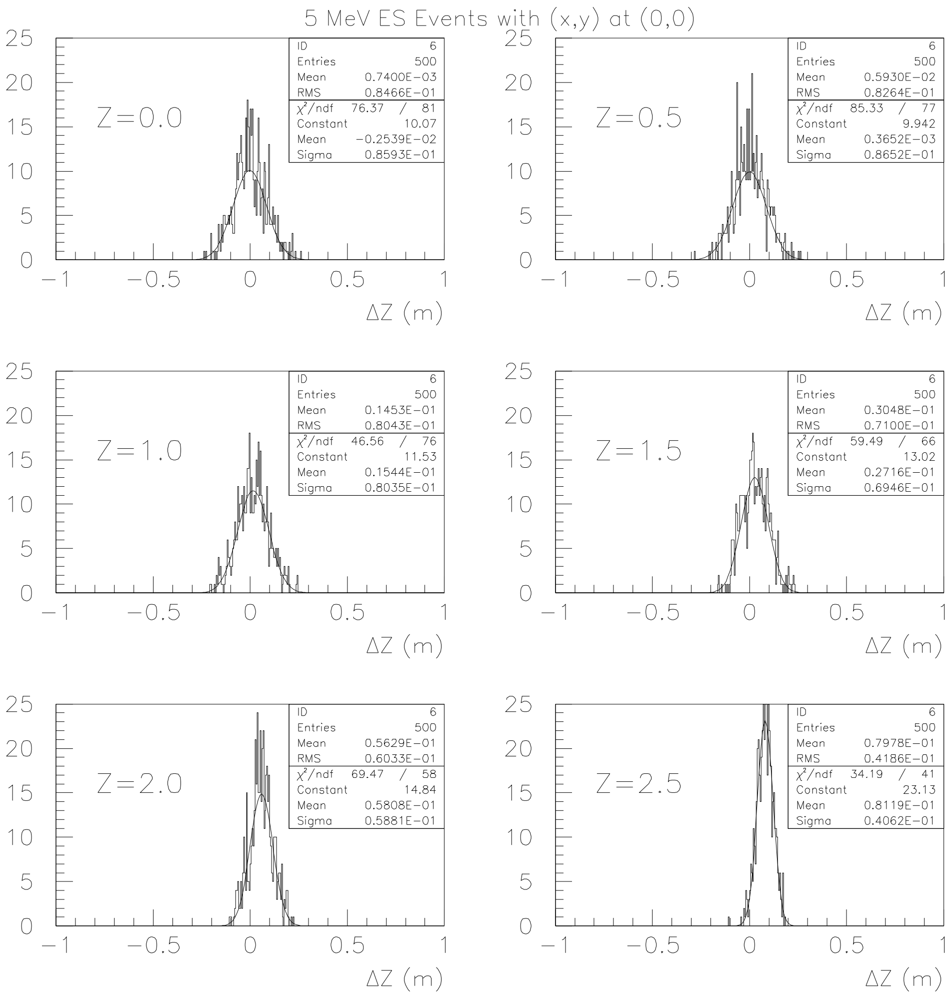

Figure 4: Δz, the difference between reconstructed and generated vertices, for ES events generated at six z positions and (x,y)=(0,0).

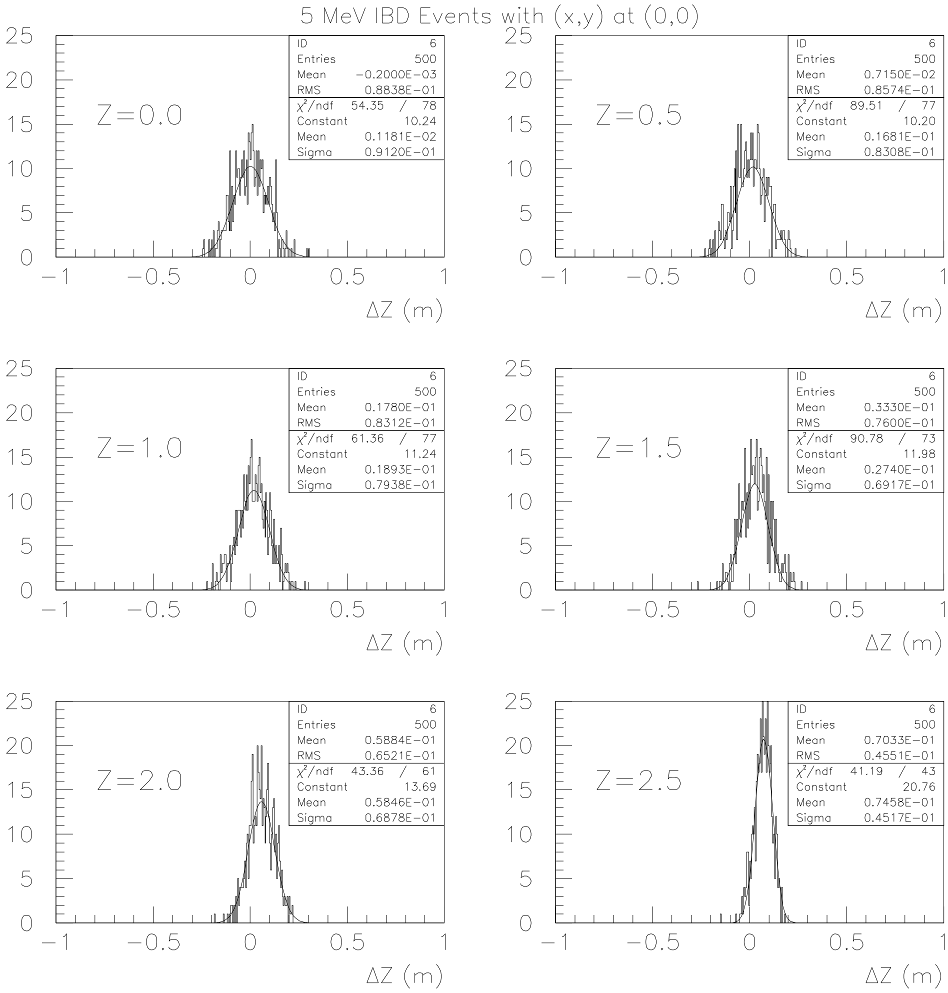

Figure 5: Δz, the difference between reconstructed and generated vertices, for IBD events generated at six z positions and (x,y)=(0,0).

z of ES	Hist mean	Hist RMS	Peak	σ
0.0m	0.0007	0.0847	-0.0025 ± 0.0044	0.0859 ± 0.0047
0.5m	0.0059	0.0826	0.0036 ± 0.0047	0.8652 ± 0.0056
1.0m	0.0145	0.0804	0.0154 ± 0.0041	0.0804 ± 0.0040
1.5m	0.0305	0.0710	0.0272 ± 0.0036	0.0695 ± 0.0031
2.0m	0.0563	0.0603	0.0581 ± 0.0030	0.0588 ± 0.0033
2.5m	0.0798	0.0418	0.0812 ± 0.0020	0.0406 ± 0.0017
z of IBD	Hist mean	Hist RMS	Peak	σ
0.0m	-0.0002	0.0884	0.0012 ± 0.0048	0.0912 ± 0.0047
0.5m	0.0072	0.0857	0.0168 ± 0.0044	0.0831 ± 0.0051
1.0m	0.0178	0.0831	0.0189 ± 0.0040	0.0794 ± 0.0044
1.5m	0.0333	0.0760	0.0274 ± 0.0036	0.0692 ± 0.0037
2.0m	0.0588	0.0652	0.0585 ± 0.0035	0.0688 ± 0.0034
2.5m	0.0703	0.0455	0.0745 ± 0.0023	0.0452 ± 0.0022

Table 1: z-vertex position study for 5 MeV ES and IBD scatters. Δz is the difference between reconstructed and generated events, in meters.

z of vertex	Difference in peaks (ES-IBD)	Difference in hist means
0.0m	-0.0037 ± 0.0065	0.0009
0.5m	-0.0132 ± 0.0064	-0.0013
1.0m	-0.0035 ± 0.0057	-0.0033
1.5m	-0.0002 ± 0.0051	-0.0028
2.0m	-0.0004 ± 0.0046	-0.0025
2.5m	0.0067 ± 0.0030	-0.0037

Table 2: Difference (ES-IBD) in peak position and histogram mean, in meters, for 5 MeV events as a function of z-vertex position.

z of vertex	x-vertex peak, ES	x-vertex peak, IBD
0.0m	0.0036	0.0060
0.5m	0.0012	-0.0050
1.0m	-0.0037	-0.0080
1.5m	-0.0021	-0.0032
2.0m	-0.0005	0.0021
2.5m	0.0044	-0.0001

Table 3: Peak position and histogram mean (both in meters) for 5 MeV events for the x-vertex as a function of z-vertex position, for ES and IBD events, respectively.

"peak" will refer to the fitted Gaussian peak. From this table, the pull is 7 cm at a 2.5m radius, or a 3% effect. The RMS improves as the vertex nears the tank-edge.

Tab. 2 gives the difference between the ES and IBD peaks and histogram means for the fits shown in Tab. 1. The systematically negative values indicate that the pull for ES versus IBD events along the direction of the z-vertex is not exactly the same. No similar systematic shift is seen in the other coordinates (see, for example, Tab. 3). For the "base" study, the shifts are at the few mm level. At 2.5m, the resulting difference lies somewhere between about 3mm and 1cm within errors. Thus, 3mm appears to be within reach, given further study and improvements to the algorithms, and also more Monte Carlo statistics. To have reached this level with the simple algorithm is very promising for the analysis!

4 Variations on the Theme

As a quick check of possible systematic effects, in this section we consider 1) lower total visible energy (3 MeV); 2) additional noise hits; and 3) adjusted attenuation length of the scintillator; 4) extension of the source, so that it appears as a tiny track. In this case, we only report on vertices at 2.5m, because this is the proposed edge of the fiducial volume. The results are summarized in Tab. 4.

The low edge of the energy window for the analysis is yet to be determined, but 3 or 3.5 MeV are likely values. Therefore, in this study, we

varied parameter	new value	ES peak	ES mean	IBD peak	IBD mean
None	(Base values)	0.0812	0.0798	0.0745	0.0703
Energy	3 MeV	0.0827	0.0775	0.0637	0.0647
Noise	4%	0.0398	0.0382	0.0302	0.0287
Low attenuation	3m	0.0815	0.0795	0.0716	0.0700
High attenuation	5m	0.0802	0.0787	0.0711	0.0703
Extended vertex	5mm	0.0815	0.0798	0.0709	0.0694

Table 4: The effect of varying parameters in the Monte Carlo. All results are for a vertex at (0,0,2.5m) and are in meters. The ES and IBD event peaks and means track each other well.

consider 3 MeV total visible energy ES and IBD events. The resulting peak and mean for ES events were 0.0827 and 0.0775 and for IBD events were 0.0637 and 0.0647 These are slightly lower than what was obtained at 5 MeV, which were 0.0812 and 0.0798 for ES and 0.0745 and 0.0703 for IBD. However, there is no significant shift in the difference between ES and IBD reconstruction. Therefore, it appears that variations in the difference across the energy window will not be very significant.

Random noise was generated in the tubes. Noise at the level observed on MiniBooNE resulted in no significant changes to either the reconstructed peaks and means or the difference between ES and IBD events. Therefore, to force a clear effect, the rate was raised by a factor of 20, resulting in random hits in 4% of the tubes. For ES at 5 MeV, the resulting peak and mean were 0.0398 and 0.0382. This large shift from the base values shows that the isotropic hits pull the vertex back toward (0,0,0). The algorithm could be adapted to correct for this effect in the future, but that is not necessary for this study. The ES results with noise can be compared to the IBD 5 MeV results with noise, which give a peak and mean of 0.0302 and 0.0287. The differences are 0.0096 (peak) and 0.0095 (mean) compared to 0.0067 (peak) and -0.0037 (mean) without noise. To the level of the statistics of this study, these differences are in agreement and indicate that even with 4% random noise the IBD events track the ES fiducial radius to a few mm.

Next, we consider the effect of decreasing or increasing the attenuation length in the scintillator for 5 MeV events with no noise. Low attenuation length was taken to be 3m and gave a peak and mean of 0.0815 and 0.0795 for ES events and 0.0716 and 0.0700 for IBD events. High attenuation length was taken to be 5m and gave a peak and mean of 0.0802 and 0.0787 for ES events and 0.0711 and 0.0703 for IBD events. These values are all in good agreement and also agree with the 4m attenuation length runs which were the base. Thus reasonable changes in attenuation length do not matter.

In reality the primary vertex will be extended, although that extension is expected to be relatively small. We model this as a 5mm track, which travels in a random direction but does not scatter, which produces hits at five equal-brightness locations. Hits are emitted isotropically. The photons are emitted from the end of the track, although this is not very relevant since the Compton length is much larger than the track extent. The result for ES scatters is a peak and mean of 0.0815 and 0.0798 and for IBD events is 0.0709 and 0.0694. After comparing this to the single-point tracks in the base study, it is fair to conclude that modeling an extended track is does not affect the relative reconstruction of ES and IBD events.

5 Conclusions

The results of this study indicate that the few mm level of relative reconstruction should be achievable. With more work, achieving about 3mm relative error appears to be possible. This adds $(dN/N)_{fid} = 0.3\%$ to the error on the number of ES events.

The next steps are to confirm this study using the G4 Monte Carlo and to consider ways of testing the relative event reconstruction using sources or spallation events in the detector. Also, the systematics must continue to be identified and pursued. Comments and suggestions are welcome!