Cutting ^{208}Tl Background for the $\sin^2\theta_W$ analysis

Janet Conrad, December 19, 2004

1 The Problem

In the memo proposing to measure $\sin^2\theta_W$ we presented the following on ^{208}Tl:

We calculate the contribution to the background from ^{232}Th assuming 5×10^{-17} g/g. In 13×10^6 g per detector, there is 6.5×10^{-10} g of ^{232}Th per detector. The mass is 232 g/mol; thus we have about 3×10^{-12} moles or about 1.75×10^{12} ^{232}Th isotopes/detector. The half-life is 1.4 $\times10^{10}$ years, yielding 265 events decay during the run. We double this for two detectors to obtain 530 events. We then take 35% for the branching of ^{208}Tl to ^{208}Pb, to obtain 185 events. These events will be reconstructed with the combined energy of the emitted γ and the β. Combining these energies, we find that 51% are expected to reconstruct within the 3 to 5 MeV window. The total is therefore 93 events in the two near detectors.

At this rate, the background is two orders of magnitude from impacting the analysis (*i.e.* we can tolerate 5×10^{-15} g/g before the background from contamination becomes significant). Thus it looked like this was not an issue. However, since this paper was written, the question was raised: *What if the Gd has much higher Th contamination?*

This could be a very big problem. Minfang's talk at LRT2004 conference (go to http://lrt2004.snolab.ca/ and select "Program and slides") quotes a Th contamination for Gd_2O_3 from IHEP as $(440\pm32)\times10^{-9}$ g/g, which, when scaled for the 0.1% concentration in the detector gives $(440\pm32)\times10^{-12}$ g/g, which is far too high for this analysis. However, it is unclear whether this was the best IHEP could achieve or whether this was good enough for what they wanted to achieve. They may have been able to do better. As stated in Minfang's talk, we actually will use $GdCl_3$, and the purity measurements for this are not yet available, but Minfang states they are aiming for $< 1\times10^{-9}$ g/g. We have heard in our meetings from Dick and Minfang that there have been attempts to purify Yb, a similar metal to Gd, which which have reached the level of 10^{-10} g/g. Given a 0.1% concentration the level of Th background would be 10^{-13} g/g, which is still not sufficient. As stated in the proposal, we need to do R&D in order to further purify Gd or find other methods for cutting this background.

This memo concentrates on "other methods." It shows that ^{208}Tl events can be identified through hit timing. With a realistic scintillator (either PPO, which is used in Borexino, or Butyl PBD, which was used in LSND) a rejection factor > 100 of ^{208}Tl events can be obtained while maintaining 90% of the ES events. We also discuss a look-back to identify the ^{208}Tl from its parent decay. This removes another factor of > 10. Thus, in this study, a possible factor of > 1000 reduction has been identified.

This is meant to be a proof-of-principle. To do this study, the simple Monte Carlo developed for the fiducial volume studies was used. In the future, this analysis will need to be done using ReactorFSim or a GEANT Monte Carlo. In the end, all of the claims discussed here must be demonstrated in-situ in the far detectors.

2 All About ^{208}Tl...

% Decay	Mode	Type
49%	1.8 MeV β + 0.6 MeV γ + 2.6 MeV γ	1
22%	1.5 MeV β + 0.3 MeV γ + 0.6 MeV γ + 2.6 MeV γ	2
25%	1.2 MeV β + 0.3 MeV γ + 0.3 MeV γ + 0.6 MeV γ + 2.6 MeV γ	3
	1.2 MeV β + 0.3 MeV γ + 0.9 MeV γ + 2.6 MeV γ	4
	1.2 MeV β + 0.6 MeV γ + 0.6 MeV γ + 2.6 MeV γ	5
	1.2 MeV β + 1.2 MeV γ + 2.6 MeV γ	6
4%	1.0 MeV β + 0.2 MeV γ + 0.3 MeV γ + 0.3 MeV γ + 0.6 MeV γ + 2.6 MeV γ	7
	1.0 MeV β + 0.5 MeV γ + 0.3 MeV γ + 0.6 MeV γ + 2.6 MeV γ	8
	1.0 MeV β + 0.5 MeV γ + 0.9 MeV γ + 2.6 MeV γ	9
	1.0 MeV β + 0.3 MeV γ + 0.5 MeV γ + 0.6 MeV γ + 2.6 MeV γ	10
	1.0 MeV β + 0.8 MeV γ + 0.6 MeV γ + 2.6 MeV γ	11
	1.0 MeV β + 1.4 MeV γ + 2.6 MeV γ	12

Table 1: Major decay modes for Tl-208.

Table 1 shows the decay modes for ^{208}Tl. Throughout the text the "event Type" number is used to designate what Type of decay is generated, as noted in the table. Table 1 should be compared to the initial model, in the original $\sin^2\theta_w$ memo, which had one 2.6 MeV γ and one β with an endpoint of 3 MeV. In the initial model, it was assumed that all of the energy was observed and attributed to the β. The point of this analysis is to understand the impact of having many photons in an event.

3 The Code

This study uses the same small Monte Carlo developed for the fiducial volume study. Events were generated randomly and uniformly in x,y, and z, with the requirement that the radial position lie within the inner tank. The β energy was deposited as a single point. The initial direction of the photons was generated randomly and isotropically. In carbon, all photons in the energy range of this decay lose energy predominately by Compton scattering. Pair production is an order of magnitude lower probability, even for the 2.6 MeV photon. The standard Compton scattering code package by M. Shaevitz is used to generate the scatters.

Two models for scintillator were chosen. The first is a model of scintillator used by Borexino which consists of PPO and pseudocumene with a decay constant of 5 ns. The second was Butyl PBD which was the scintillator used in the LSND experiment. This has a fast component which was 3 ns and which represented 66% of the light for low energy michel electrons, and a slow component for the remainder of the light which was 15 ns.

Just to be clear, in the discussion below there are two types of photons. Photons produced in the decay are called "decay photons." These Compton scatter to produce electrons. Photons which are produced by electrons in the event, either the β or the Compton scattered electrons, are called "scintillation photons" and these are what are seen by the phototubes.

This analysis relies on the timing of the tube hit. In all events, scintillation light is produced with the time constant of the given model. The elapsed time between when the scintillation photon was produced and when it hit the tube ("time of flight" or tof, below) is added to the scintillation time. For a point-source of scintillation photons, like an ES event, this represents the total contributions to the true time of the scintillation photon.

In events with decay photons, there are two potential additional sources of delay for the scintillation photons. First, it takes time for the Compton photon to scatter around the tank. Thus the production of scintillation light from the electrons from Compton scatters is delayed with respect to the light from the β in a ^{208}Tl decay. The code keeps track of the elapsed time from production of a decay-photon to production of the Compton electron and adds this to the total time of the scintillation photon. A second (much smaller!) delay comes from the fact that Type 1 Tl decays are unusual in that they proceed in two steps. First the 600 keV photon is emitted with a half-life of 0.30 ns followed by the 2.6 MeV photon emission. Thus in this decay mode, both decay photons are delayed by about 0.3ns. This delay was included in the code, using an exponential distribution with half-life of 0.3 ns. The other decay modes for Tl proceed much faster and no timing delay is included in the code for these. In fact, the effect of this second source of delay is completely negligible, but it was interesting to learn about.

If we use the same tubes as those in MiniBooNE, the timing resolution is 1.2 ns for a single p.e. This is not a net time-offset, unlike the other effects just discussed – instead it smears the ES and TL events. This turns out to be a small effect in the analysis.

As in MiniBooNE, this code assumes that only the time of the first hit in the tube is recorded. This is a function of the electronics and multi-hit timing would be a nice improvement over MiniBooNE. But it is not necessary for this analysis.

To study Tl decays, we take Type 1 and Type 12 as representative. Most events are like Type 1 in that there are two charge centers. The cloud of low energy photons in Types 2-11 do not wander far from the β. Thus the only potentially long track is the 2.6 MeV γ. Type 12 is distinct in that it has two high energy photons which can form "streamers." It should be noted that Type 12 has a small probability compared to Type 1 events. Thus, it is considered separately. For this proof-of-principle study, these two event types are representative, but when the analysis is converted for use of ReactorFSIM, all event types should be studied.

To get a sense of what events look like, see Figure 1. This shows Type 1 events. For each case, the xy, yz and xz views are shown as a row. The size of the box indicates the amount of charge deposited at that point. The large single box in the center of the charge distributions is the β. These are actually the first three events which were produced in the file. The top and bottom show relatively unusual ($\sim$10% of cases, from a by-eye-scan) event types, while the middle is very common. In the case of the top, the photon actually exited the tank, but did not take away enough energy to move the event out of the energy window.

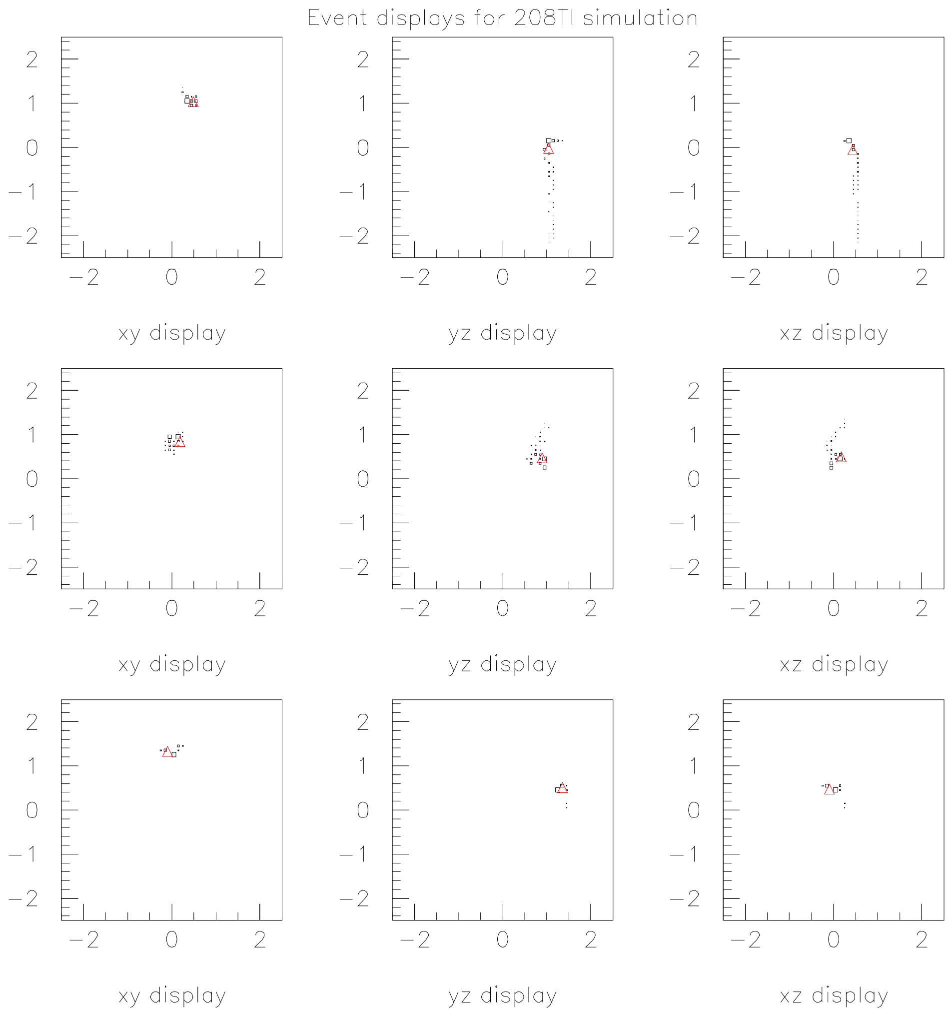

Figure 1: Event displays of 5 MeV ^{208}Tl Type 1 decays.

4 Timing Distributions

Because the photons can travel some distance before they convert, ^{208}Tl events have a measurably different hit time distribution than an ES event. This section examines the possibility of identifying events in this way, assuming the speed of light in the oil is 0.2 m/ns. This section cross the compares the hit timing distribution for: PPO vs Butyl PBD; Type 1 vs 12; and 5 MeV vs 3 MeV.

4.1 General Idea

In a point-source event, if the vertex is found perfectly, then the hit time distribution will form an exponential decay with the time constant(s) of the scintillator after correction for time-of-flight. In reality, the peak of the exponential is smeared due to time resolution. The 1.2 ns timing resolution for each tube is a small effect because it is a Gaussian, which can go either way, and there are $\sim$1000 hits per event. The most important effect comes from the imprecision of the charge-weighted vertex finding algorithm which represents a single, correlated pull in some direction away from the true vertex. The reconstruction program based on charge (see fiducial volume memo for description) results in a resolution on the ES vertex of about 5 cm.

Next, consider the case of Compton scattering of the Tl events, which contain a β, a 2.6 MeV and at least one lower energy photon. The 2.6 MeV photon will scatter far from the β because the Compton length is 23 cm. Thus, this event will have widely distributed charge and the vertex will be reconstructed in the middle. The photon pathlength will be reconstructed with respect to this vertex. Subtracting the timing associated with the tof based on this incorrect vertex will yield a timing distribution that will be smeared compared to the exponential distribution for an ES event. Figure 2 provides an exaggerated sketch to illustrate the idea.

Figure 3 shows this effect. The left plot is 500 ES events and right plot is 500 Tl events. The distribution for PPO is shown on top and Butyl PBD is on the bottom. The black histogram is the timing distribution which was simulated. The red distribution is the reconstructed time based on the vertex-found-from-charge. The bins are 4 ns. The ES distributions are in such good agreement with what was thrown, that the black histogram is barely visible behind the red. However, the Tl events are in disagreement.

The following is a simple method for distinguishing ES events from Tl

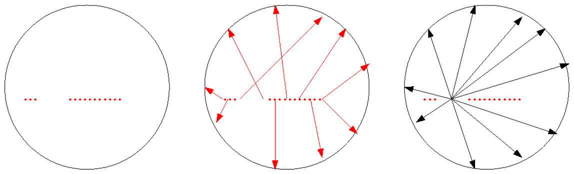

Figure 2: An illustration of why the reconstructed pathlength for each hit is incorrect in extended events such as ^{208}Tl decays. Left: a set of point sources which represent an event in the tank (dots do not indicate strength of the source, just the position). Middle: where the photons from the sources may hit the tank tubes. Right: where the charge-weighted reconstruction might place the vertex, and the relative pathlengths for the photons derived from this vertex.

events. Define 20 bins from -10 ns to 10 ns (notice this is a smaller range than the was shown in Figure 3 – it zooms in on the interesting region). Define the "expectation" for ES scatters from a distribution for 500 events, unit normalized. This "expected" distribution is used as a probability distribution function (PDF) for forming a negative log likelihood ("*logl*") for the timing of the observed hits in a given event: $logl = \Sigma_{bins} - 1. * log(Prob_{bin})$. For bins with less than 20 hits, a Poisson distribution is used to determine $Prob_{bin}$. For bins with 20 or more hits, $Prob_{bin}$ is determined using the CERNLIB erf function. ES events should be in good agreement with the PDF, so the probability should be close to one and *logl* should be small. The probability for Tl events is expected to be lower, leading to larger values of *logl*.

4.2 Separation at 5 MeV

This method gives a clear separation between ES and TL events. Figure 4 (top) shows the separation between ES (black) and Type 1 TL (red) events which can be achieved using the log likelihood variable ("logl"). The line at logl=20 cuts only ∼10% of the ES signal. 4% of the TL Type 1 events are retained in PPO. In butyl PBD, 2% of events are retained. Figure 5 shows the same for Type 12 events. In this case 1% of the background is retained

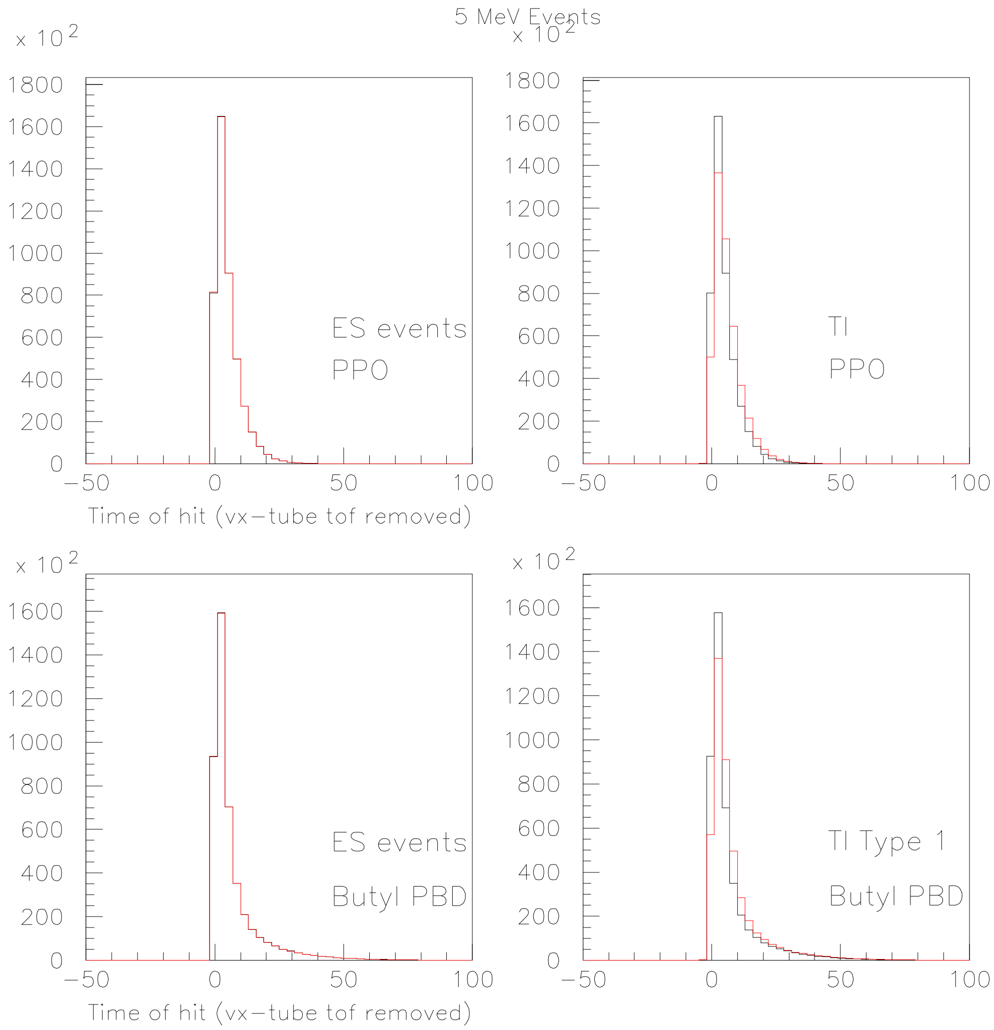

Figure 3: Comparison of reconstructed timing distribution, after correction for time-of-flight, for ES (left) and Type 1 Tl events (right), 500 events of each Type. Black: the true scintillation distribution; Red: the reconstructed distribution. Top: PPO (Borexino Type); Bottom: Butyl PBD (LSND Type)

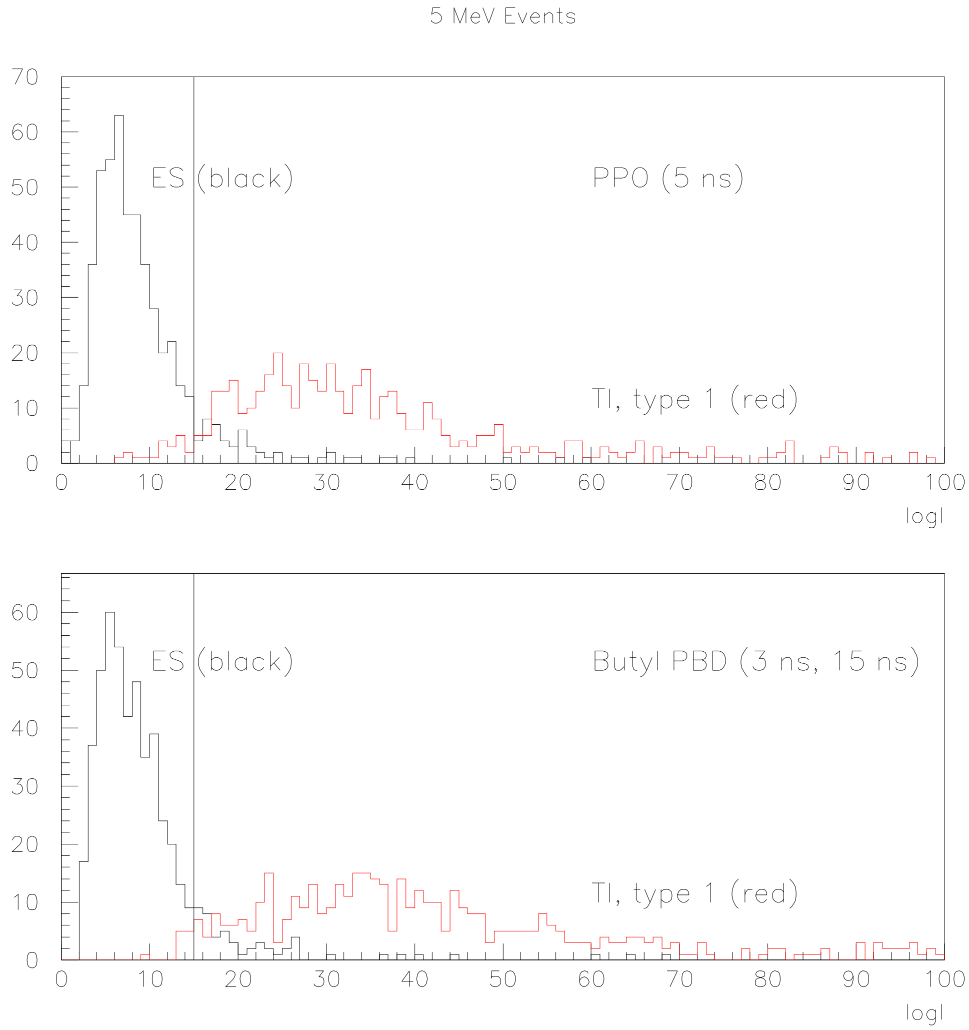

Figure 4: Comparison of the log likelihood of the reconstructed timing distribution for 500 ES (black) and TL Type 1 (red) events. The proposed cut at is at logl=20 (line). Top: PPO. Bottom: Butyl PBD.

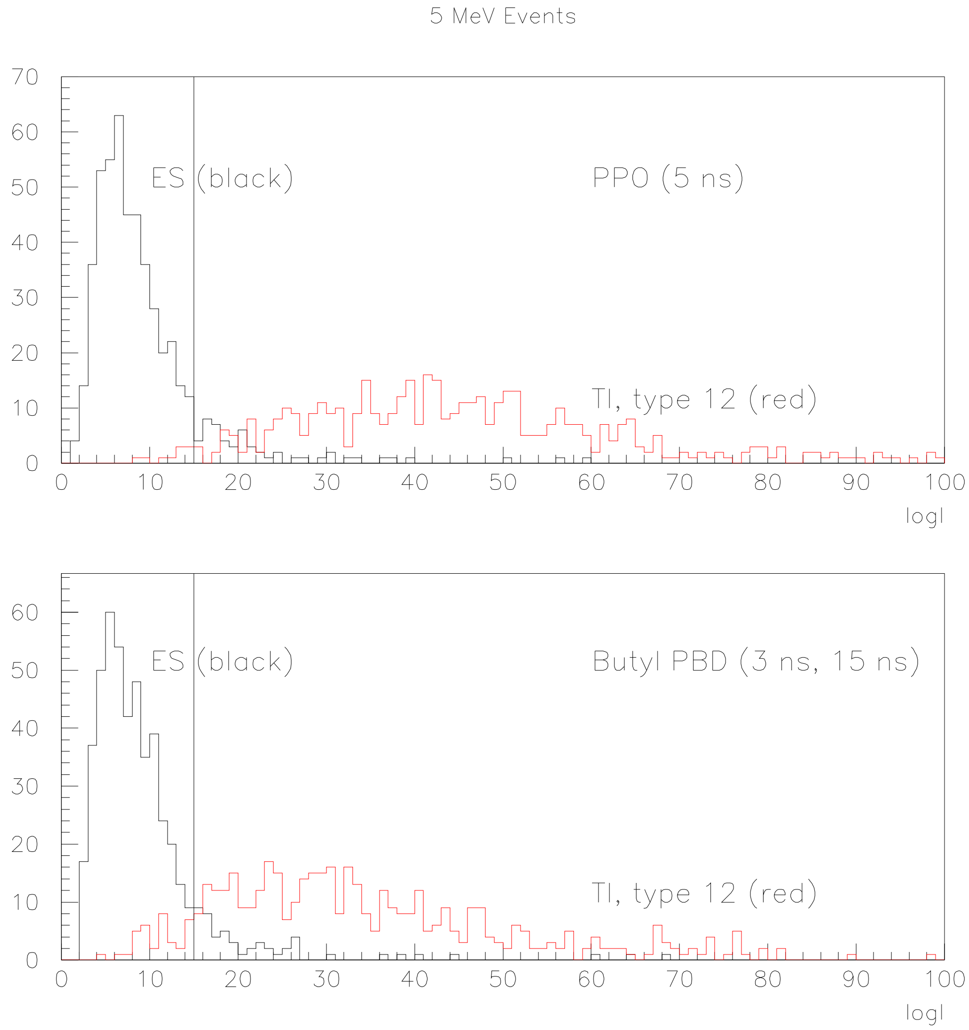

Figure 5: Comparison of the log likelihood of the reconstructed timing distribution for 500 ES (black) and TL Type 12 (red) events. The proposed cut at is at logl=20 (line). Top: PPO. Bottom: Butyl PBD.

in the PPO and 5% is retained by the butyl PBD. Within statistics, these are all the same number, about 3%

4.3 Separation at 3 MeV

The separation at 3 MeV is much better. This is because the photon, which has the large time-spread, is even more dominant in these events. Figure 6 shows the PPO case (which was the worst case in the previous section) for 3 MeV total event energies. The separation at 3 MeV is 0.2% (1 event out of 500!). This is also true for Butyl PBD, for which the rejection was 0.3%. For Type 12 events the rejection was 0.2% and 0.4% for PPO and Butyl PPD.

Thus, at 3 MeV, the rejection is much better than a factor of 100. An average between 3 and 5 MeV can be expected to yield better than a factor of 100 reduction.

5 Using Look-back as a Cross Check & Another Way to Cut ^{208}Tl

The ^{208}Tl can be tagged by its decay chain. This allows an in-situ check that the likelihood PDF looks as expected using events in the far detectors. This method can tag ~95% of the ^{208}Tl decays. This look-back also provides a method of veto in the near detectors. It can reduce the rate of ^{208}Tl by a factor of 20.

^{208}Tl is produced by $^{212}\mathrm{Bi} \rightarrow ^{208}\mathrm{Tl} + \alpha$. The lifetime of ^{208}Tl is 3 min. So, if an event is observed in the 3 to 5 MeV window, one can look backward for 9 min to search for an α, which would tag the event as a ^{208}Tl.

A 9 min search window sounds like it would introduce a very large rate of spurious coincidences. But this section shows that this is not true for three reasons. First, the α will be required to be within a radius of 25 cm (since the RMS on the vertex is about 5 cm). Thus, only 0.1% of the fiducial vulume is being considered for this look-back. Second, we are only interested in events below an MeV. The α from the Bi decay has much higher energy, but it quenches in the detector yielding $\sim$ 0.25 MeV. Third, as discussed below, α's can be identified. For this look-back to work: 1) α's must be distinguishable from other particles, 2) α's from decays have to be at a sufficiently low rate to not produce fake coincidences, and 3) α's from cosmic rays have to be removed.

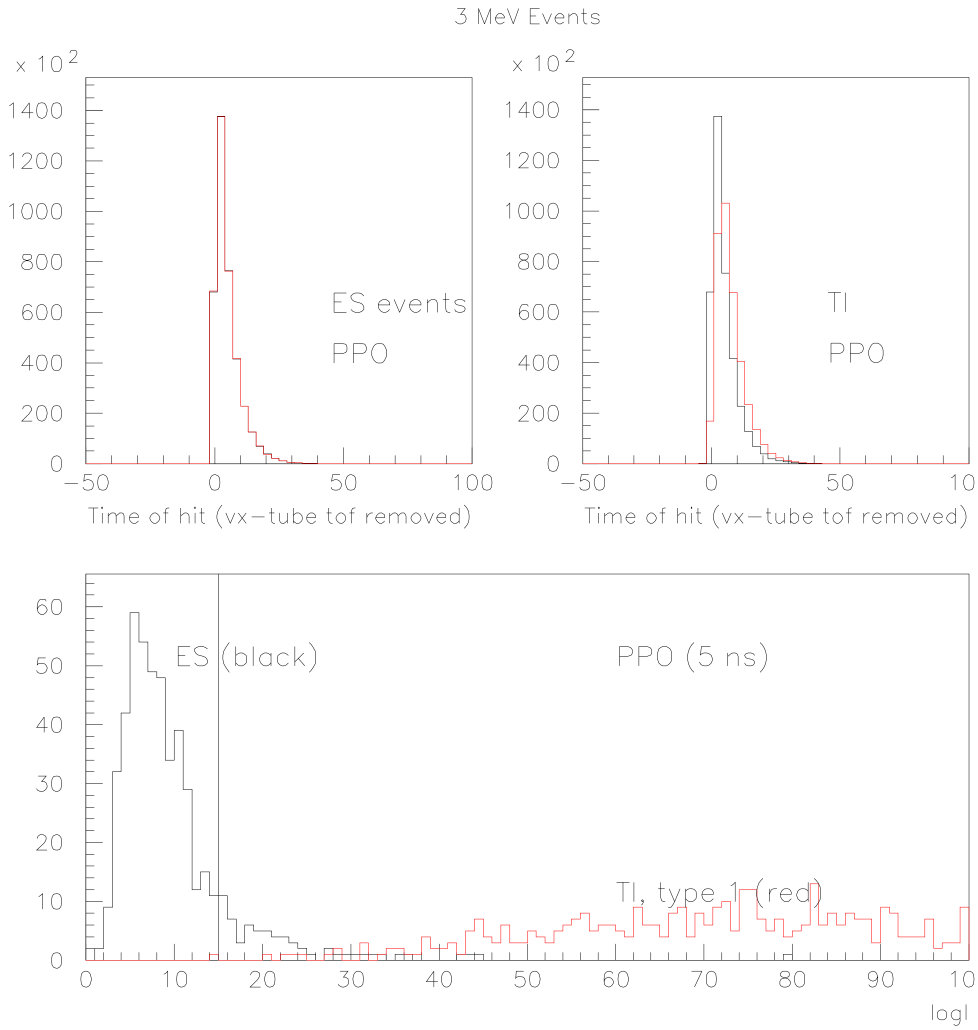

Figure 6: Top: Black: Scintillation light timing distribution. Red: reconstructed timing, with time of flight from vertex to tube removed. Left: ES, Right: TL Type 1. Comparison of the log likelihood of the reconstructed timing distribution for 500 ES (black) and TL Type 1 (red) events in PPO.

CTF has shown that, using the PPO mixture described above, α's can be distinguished from β's. The method for the test was described in the $2-\alpha$ memo. In short, the fraction of photocurrent collected from 32 to 500 ns is compared to the total. They report 97% efficiency for identifying α's, with a background of 2.5% from the ~ 3 MeV β's from a ^{214}Bi source.

The α's can be distinguished from photons and neutrons by timing and energy. A sense of the timing associated with photons has been given in the previous chapters of this memo. The time-delay from Compton scattering of photons is not so large as to extend the signal to many 100's of ns. Also, the charge drops off quickly with time. So the rate of confusion of photons with an α should be small. The neutrons capture to produce 2.2 MeV or 5-8 MeV of energy in the detector. This energy is far too high to fake an α since the α's quench.

Next consider 3 types of particles from cosmics that can fake the parent α: β's (2.5% of which are mis-identified according to CTF), protons and α's. Keep in mind that for these events to fake a parent α, they must be located within 25 cm of the Tl candidate. In addition, These events can be tagged because they are largely produced by cosmic rays. If the 25 cm search radius is within proximity of a through-going muon, then a time window of $\sim$3 s can be applied. Without a detailed MC, it is difficult to know the efficiency and deadtime for this aspect of the look-back. Clearly this needs further MC study and in-situ tests. However, in principle this should be quite effective.

Lastly, one must consider real α's which are not produced by cosmics. Given the 25 cm radial search region, the probability of an accidental coincidence with a real α from a decay other than Bi is very small. From Jon's and Hannah's code, the rate of α production from the full Th chain is 0.1/ton/day (this includes the signal α from the Bi decay) and from the full U chain is 0.03/ton/day. Thus for the full 70 tons of the detector, this represents only 9.1 events per day in the entire detector.

Aside from identifying a clean sample of ^{208}Tl in the far detector for the PDF cross-check, the look-back can be applied to the near detectors as a veto. A 3-lifetime lookback will reduce ^{208}Tl events by another factor of ~ 20. The systematics associated with this veto can be well-studied using the far-detectors.

6 Conclusions (and Future)

This study presents the following:

- ES and ^{208}Tl events, generated across the full Gd region, can be successfully separated using a hit-timing algorithm. At 3 MeV, the separation is $\sim$99.7% rejection for 10% retention. At 5 MeV, $\sim$97% rejection of 10% retention is observed. On average, across 3 to 5 MeV, a rejection factor of > 100 costs 10% of the ES events.

  In the future, the algorithm could be improved. The PDF can be generated as a function radius. The pull in the vertex-finding algorithm as a function of radius can be corrected. The time-range over which the likelihood is formed (presently -10 ns to 10 ns) can be tuned. We may have multi-hit timing information from our electronics. And so forth... One can imagine eking out additional factors.

- A look-back to tag the parent ^{214}Bi decay, which produces an α is feasible. To achieve a 95% reduction in the ^{208}Tl, a look-back of 9 min is needed. Because the α will be required to be within a 25 cm radius of the candidate event, there should a low rate of fake-coincidences in this window.

The net reduction is a factor of > 1000. If the level of 10^{-13} g/g purity (scaling from the experience of refining Yb) is achieved, and the factor from the above methods is higher than 1000, then the ^{208}Tl background will not have a large impact on the analysis. With that said, using the philosophy of "belt and suspenders," better purification techniques and other methods for cutting this background should continue to be pursued.