Outrigger Calibration
&
Use in Reconstruction

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I. Purpose

In this memo I summarize the work I have done to date in trying to calibrate and understand the raw data collected by the outrigger array so that it can be fully utilized in reconstruction of the event angles, core positions and primary energies. In addition the collected data should be useful in gamma-hadron separation although that is not addressed here.

In the process of putting the outriggers into the angle fitting procedure, I have also incorporated muon layer hits as well. I have shown this work at previous collaboration meetings.

I have performed the following tasks:

1. Determined timing calibration constants from laser calibration data
   a) TPeds
   b) electronic slewing
2. Determined parameterizations of the effects of shower-front shape (curvature) and shower thickness (sampling) on the timing distributions of event hits.
3. Re-optimized the angle fitting methods. Specifically the cut sets, such as PE cuts and timing T_χ cuts.
4. Made several code modifications to implement these changes
5. Checked for improvements in event angle reconstruction directly from Monte Carlo events (via space angle difference between the true angle and the fitted angle (delangle)), from real events (via deleo), and from reconstructing the crab event data set which had the majority of outriggers operational.

I give the details of each of these in the following sections. I then summarize with follow-up work to be done in the future.

II. Calibrations

As with the pond pmts, the outriggers need to have timing pedestals and electronic slewing curves determined for each detector. Pulse height calibrations are also needed. Fortunately Andy Smith has made a first attempt at this using his patented spectrum calibration (see his memo).

I determined the timing calibrations using the laser data collected by Matt Wilson, Xianwu Xu, and Scott DeLay. (MUCH THANKS!) This data was collected during July and August of 2003. The data can be divided into to sets. The first set was acquired to determine timing pedestals for each detector and the second was acquired to determine electronic slewing curves. These two sets were taken concurrently.

Matt used outrigger 116 as a reference detector for timing pedestals. He used a single spooled fiber taken to each tank. The light level was set fairly high (high TOT of about 500-600) to insure good timing resolution. A couple thousand pulses laser pulses were fired per outrigger. Periodically throughout the data set pulses were sent to outrigger 116 to insure systematic stability of the relative measurements.

To collect data suitable for determination of slewing curves, Matt used the installed fiber array which supplies light to patches of tanks. The light path is through the new computer-controlled optical switch and a network of optical fiber and splitters. The number of outriggers per patch varies from 1 up to about 10. Matt collected this data patch by patch. The light level was varied from below the one PE level up to about 1000 PE. About 1000 shots were fired per light level. Some tanks didn't receive optimal light level ranges due either to poor transmission efficiency in the optical light path or less than full utilization of the filter wheel range of the laser calibration system.

I have spun through this outrigger calibration data set to determine timing pedestals for each detector relative to outrigger 116. I have also plotted electronic slewing curves for each tank and a parameterization for each curve. The functional form of the parameterization is identical to that used on the pond, with the addition of one parameter which sets the maximum TOT level above which the timing is flat (constant versus TOT). However, there is one major change I have made which is to always use the low leading edge timing and slewing correction. What I have found is that the timing resolution of the lower leading edge is much better than the high edge, even beyond 400 or 500 high TOT. Above this level the timing resolution of both low and high leading edges is about the same. This is shown in figure 1. Figure 2 shows a couple example slewing curves and tped distributions. Outrigger 761 has a nice, full range of TOT, while outrigger 787 does not.   I have full calibration constants for 141 of the 175 outriggers so far. Most of the 34 detectors without calibrations either have no/poor tped data or no/poor slewing data; a few have both.

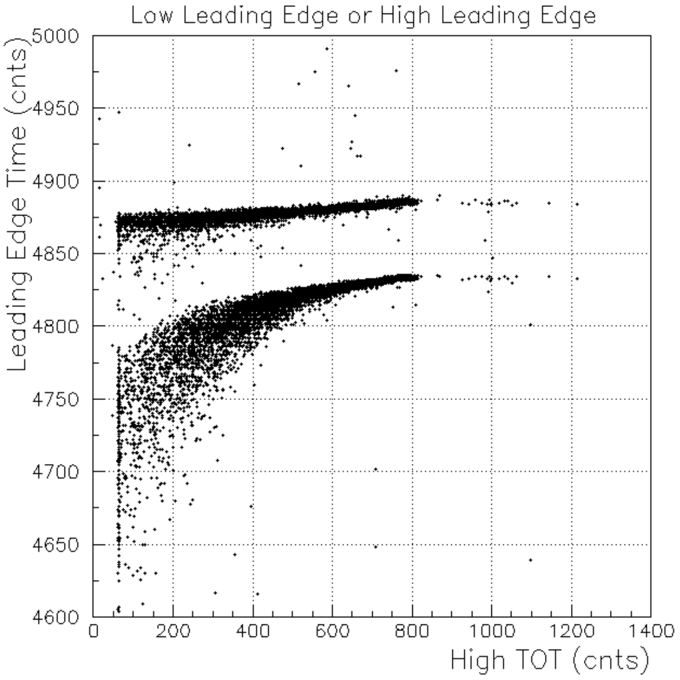


Figure 1: Leading edge time distributions for low and high threshold

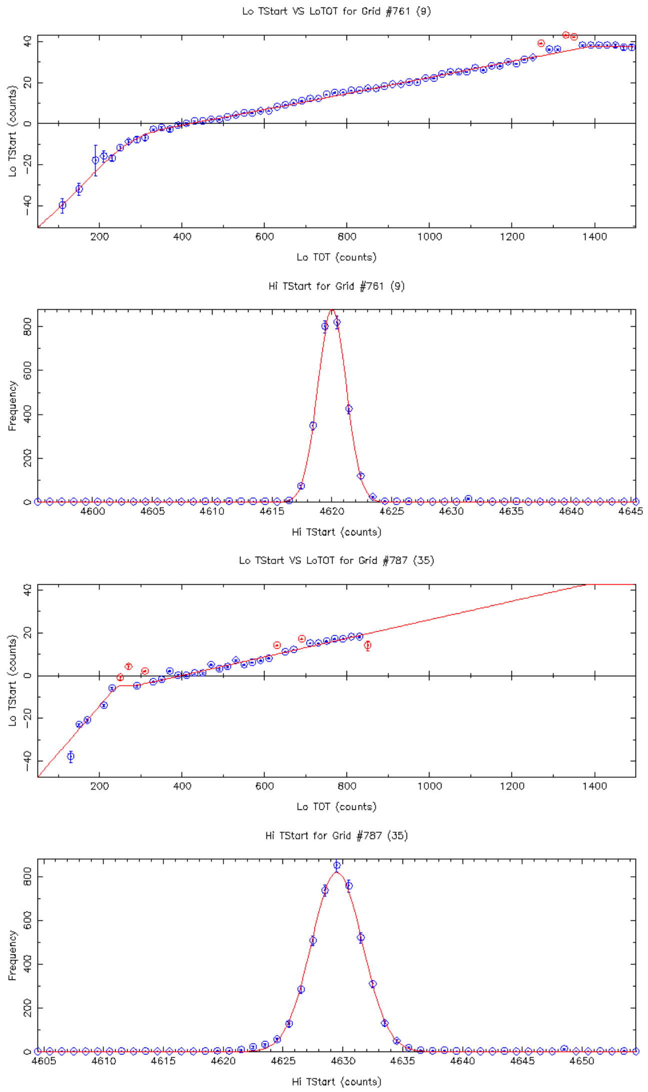


Figure 2: Sample slewing curves and tped timing distributions

The above timing calibrations correct the outrigger timings relative to each other, but not to the pond pmts. To determine the global outrigger – pond timing offset I used shower data and only the inner ring of outriggers (#1 through #32 (channels 753-784)). I selected only events with zenith angle $< 10^\circ$ and cores fitted on the pond. Looking at Monte Carlo events with these parameters indicates that the T_χ's from hits in these outriggers should be centered on zero. So these should be free of any shower front shape/width effects. Indeed, the values of the peaks of the T_χ distributions for these outriggers in real data is distributed roughly Gaussian with a width of about 1.5 ns.

I have timing calibrations for 141 out of 175 outriggers and a global timing offset between the outrigger array and the pond.

III.Shower Parameterizations

Another important aspect of angle fitting Milagro showers is the parameterization of the shower front shape, typically called shower curvature, and shower width, called sampling. These shower properties effect both the pmt hit times and the width of the hit time distributions. Initially in the Cygnus experiment the collaboration parameterized these as two one-dimensional quantities: hit timing versus distance between shower core and counter (curvature), and hit timing versus hit pulse height (sampling). Cygnus also had hit time distribution widths versus pulse height. However, late in Cygnus's running the group determined that improvements in event angular resolution could be achieved by parameterizing both the timing offsets and timing distribution widths as two-dimensional functions of counter-core distance and pulse height. With this in mind I have computed parameterizations of the shower front shape and shower width as seen through shifts in pmt T_χ peaks and changes in T_χ widths versus counter-core distances and pulse heights. In our current angle fitting method we have one sampling correction (T_χ peak shift versus pulse height) and one curvature correction (T_χ peak shift versus core-counter distance).

The basic method I used was to generate T_χ distributions for event hits for various values of counter-core distances and pulse heights. I fit the peaks and width of these distributions and then parameterized their dependence on counter-core distance and pulse height. Seems pretty straight forward.

However, I had (at least) two sources of events I could use, either real data or MC gammas. If I choose the MC gammas, then I am assuming that the MC gets these dependences correct. If I choose real data, which is mainly protons, then I am assuming that these dependences are the same for protons and gammas. If protons and gammas are different in this aspect, and I choose MC gammas, I probably won't see an improvement in real data angle fits which are protons, except perhaps in the Crab data.

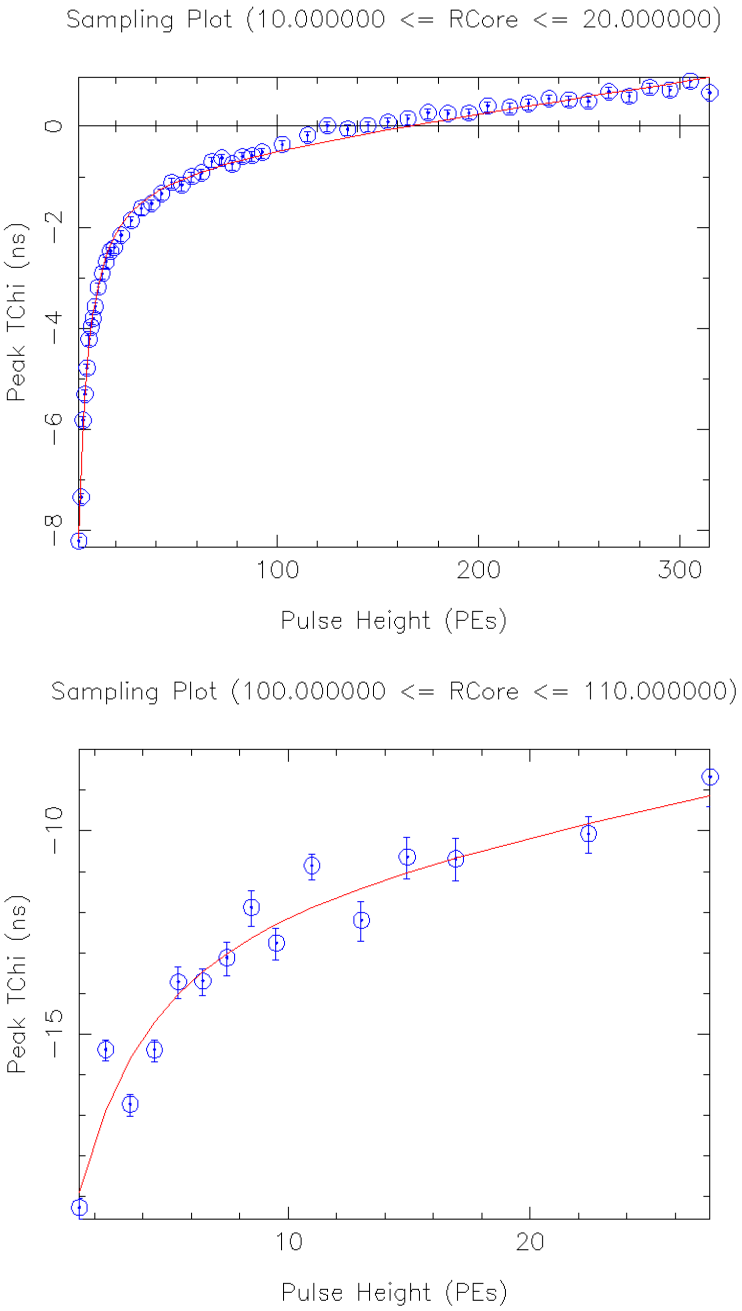
So I used the MC gammas from the standard version 3.2 event set. I chose events with nfit greater than 50. I divided the hits into thirteen 10 m wide counter-core distance bins and each of these into 69 pulse height bins with widths of:

1. For 1- 10 PE - single PE bins
2. For 10-20 PE – 2 PE bins

3. For 20-100 PE – 5 PE bins
4. For 100-500 PE – 10 PE bins

I did this for the air shower layer, muon layer, and the outrigger hits, each group separately. The T_χ's were relative to the true MC angle. I fit each T_χ distribution to a Gaussian near the peak to determine the peak. For hits above 10 PE I used the fitted Gaussian sigma for the distribution width. For hits below 10 PE, I computed the distribution's full-width-at-half-maximum (FWHM) and divided this by 2.38 which is the ratio of FWHM to sigma for a Gaussian.

I plotted and fit the T_χ peaks versus pulse height for each counter-core distance bin. I also fit the T_χ widths versus pulse height. Example plots of this are shown in figures 3, 4, and 5 for the AS, MUON and outrigger layers respectively for the peak shifts and in figures 6, 7, 8 for the widths.



Sampling Plot (10.000000 <= RCore <= 20.000000)

Sampling Plot (100.000000 <= RCore <= 110.000000)

Figure 3: AirShower layer example sampling curves.

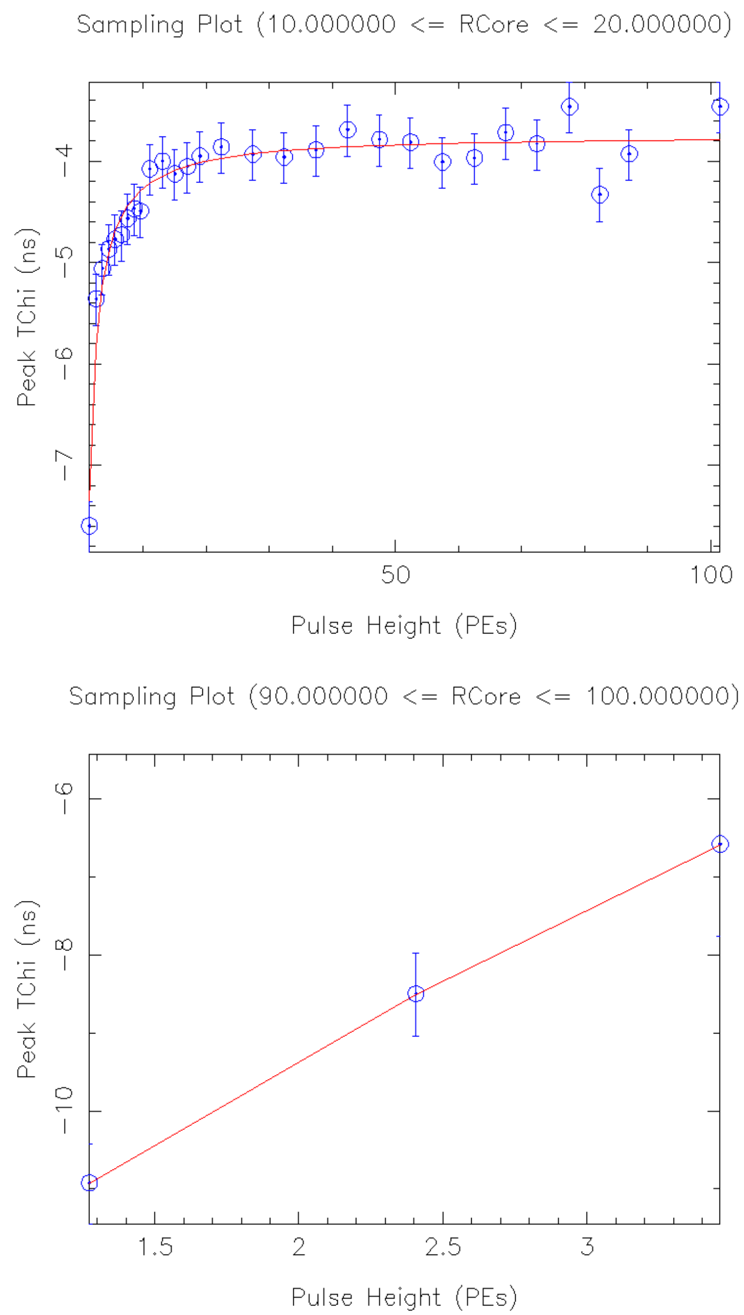


Figure 4: Muon layer example sampling curves.

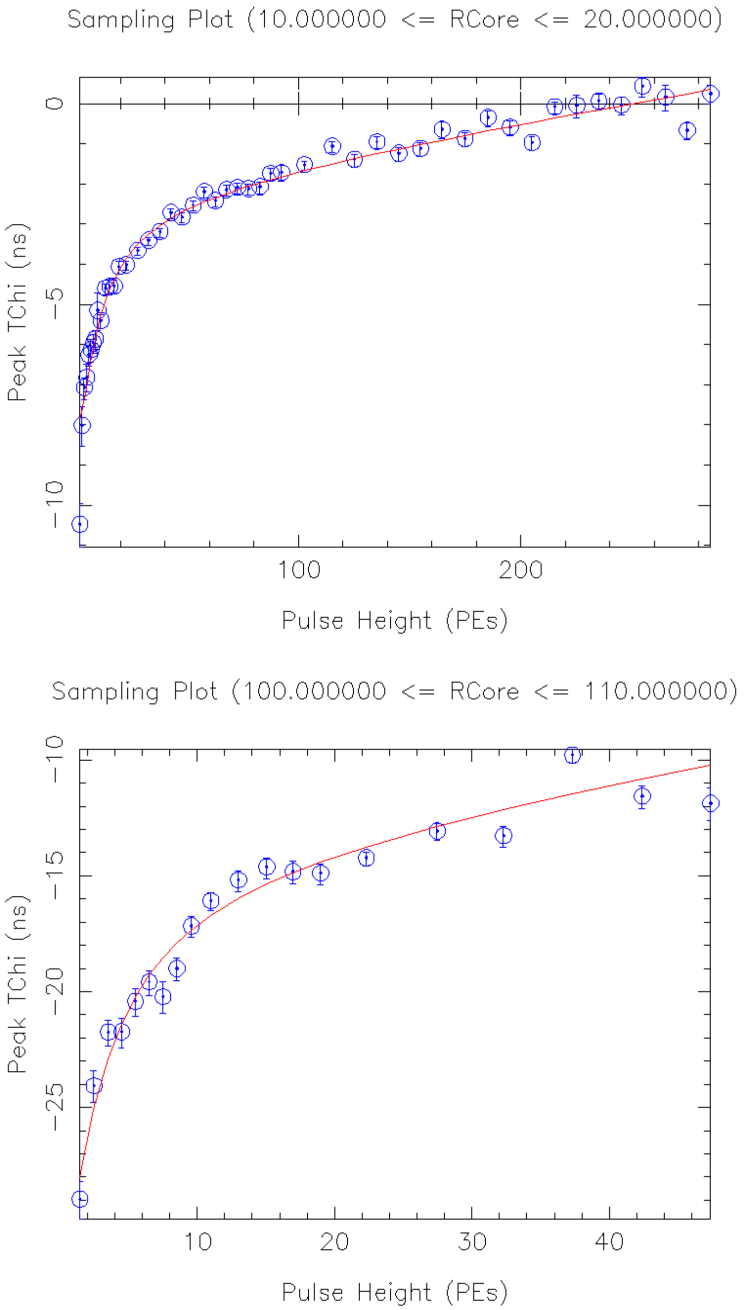


Figure 5: Outrigger example sampling curves.

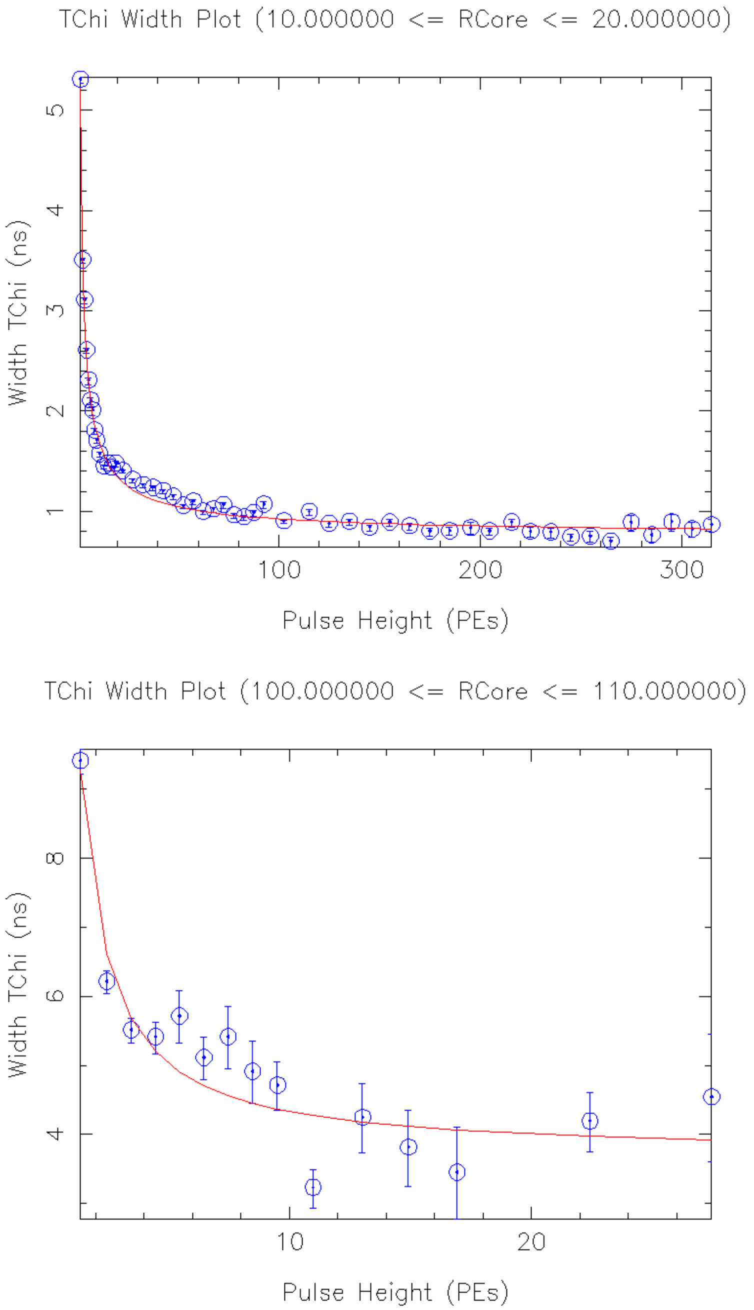


Figure 6: Airshower layer example width versus pulse height curves.

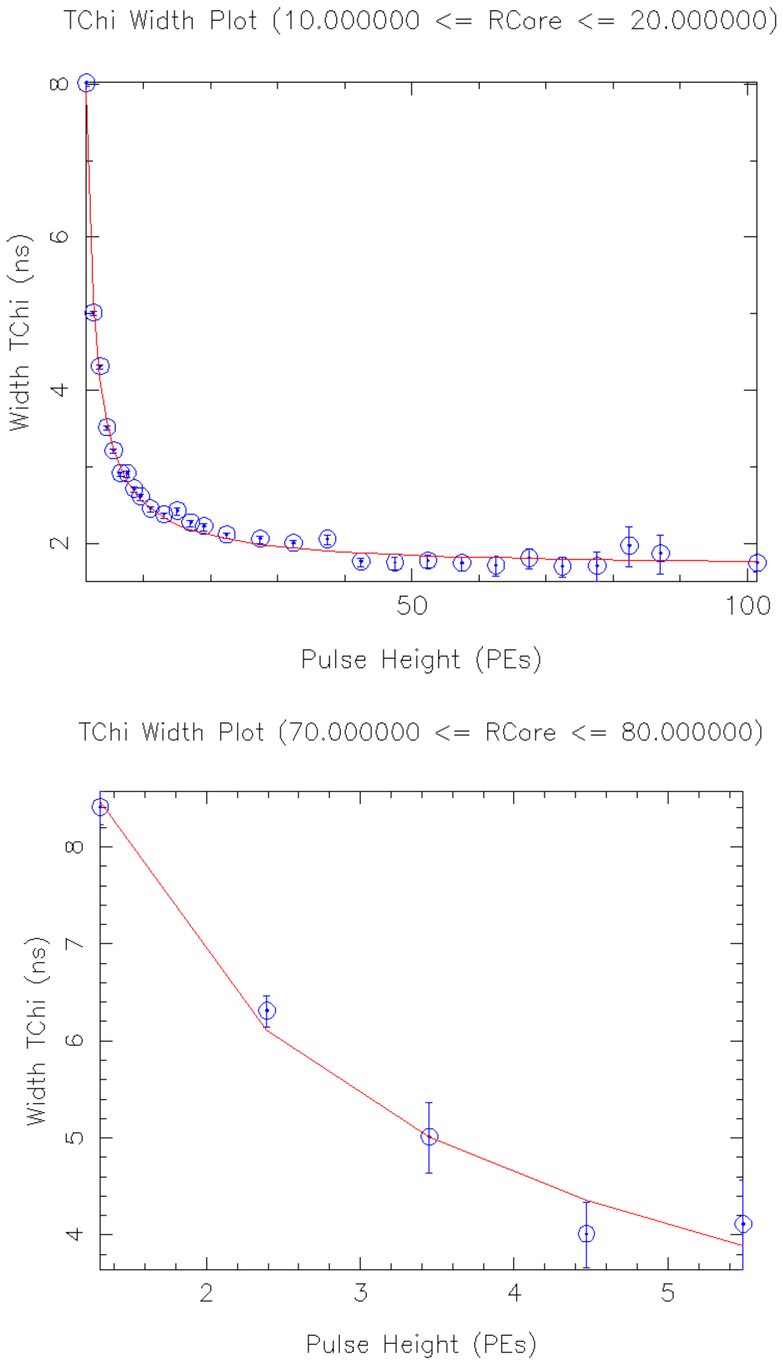


Figure 7: Muon layer example width versus pulse height curves.

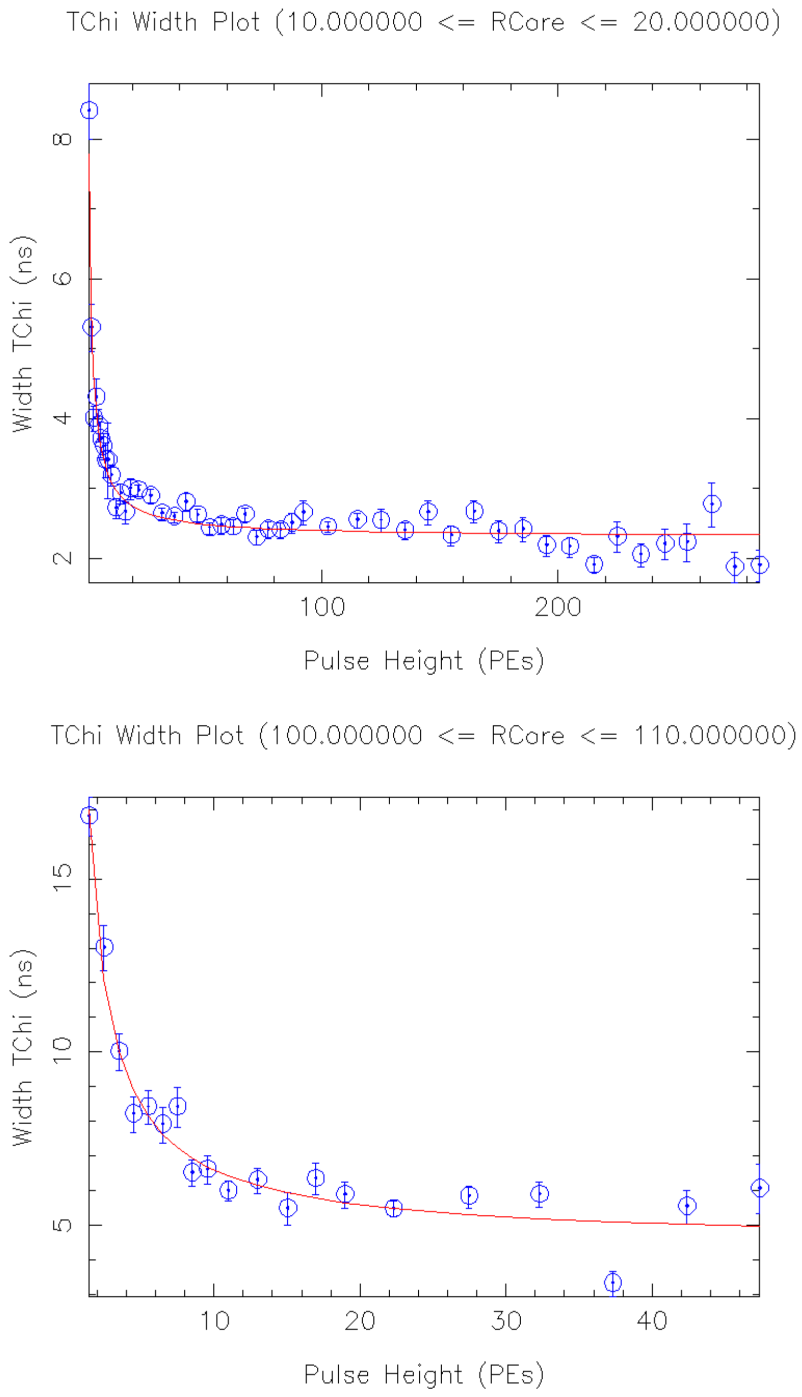


Figure 8: Outrigger example width versus pulse height curves.

IV.Optimize Angle Fitting Method

With the above changes to shower timing parameters and the addition of two sets of calibrated counters to use in the angle fits, I needed to re-optimize our angle fitting method. In appendix A, I very briefly describe our current angle fitting method. Please refer to it to refresh yourself.

The organization of our angle fitting routines seems to assume that one should perform separate fits to AS, MUON and outriggers. However, my approach is to use all hits in one global angle fit.

Fitting parameters which I changed are:

1. T_χ Cuts for each fit pass – Since I have different (actually smaller) T_χ widths, the current cuts were not optimal.
   a) They were:
      - 2.75, 1.75, 1.00, 0.50 sigma
   b) Changed to:
      - 5.00, 3.00, 2.50, 1.00 sigma
2. PE Cuts for each fit pass – We have more hits to work with, so can be a bit more selective, at least in the initial passes.
   a) They were:
      - 2.25, 1.75, 1.25, 0.75, 0.50 PE
   b) Changed to:
      - 3.00, 2.50, 2.00, 1.50, 0.50 PE
3. Introduce relative hit weights between AS, MUON and outrigger counters.
   a) Changed to:
      - 1.00 for AS, 0.50 for MUON, 1.0 for outriggers
4. RELAX parameter – If nfit is below this value relax the PE cut
   a) It was:
      - 450
   b) Changed to:
      - 1000

In addition to these angle fitting changes I have also determined a useful way to reject MC gamma events that have cores landing outside the outrigger array. This method was produced out of talks with Gus Sinnis and Gaurang Yodh. It involves using the timing information of hits in the array. From the above shower shape and thickness studies I have a pretty good prediction of the T widths as a function of counter-core distance and pulse height. If the core is truly outside the array and the fitter puts in inside the array, then the T_χ widths should be underestimated and there should be a large fraction of pmt hits with large T_χ's compared to their expected widths. So a useful parameter is the fraction (F_{big}) of pmt hits with $T_\chi > 3\ \sigma$. The value of 3 is ad hoc, but seems to work. Figure 9 shows a scatter plot of F_{big} versus distance of shower core from pond center. It shows a strong correlation. Figure 10 shows a plot of Fbig for showers inside the array (Rcore < 100.0 m) and outside. I have not optimized this parameter yet, but studying it a bit has shown that one can cut out about 80% of the gamma showers landing outside the array and only loose ~ 5% of showers inside the array, as one example. Figure 11 shows some example showers and their values of F_{big}.

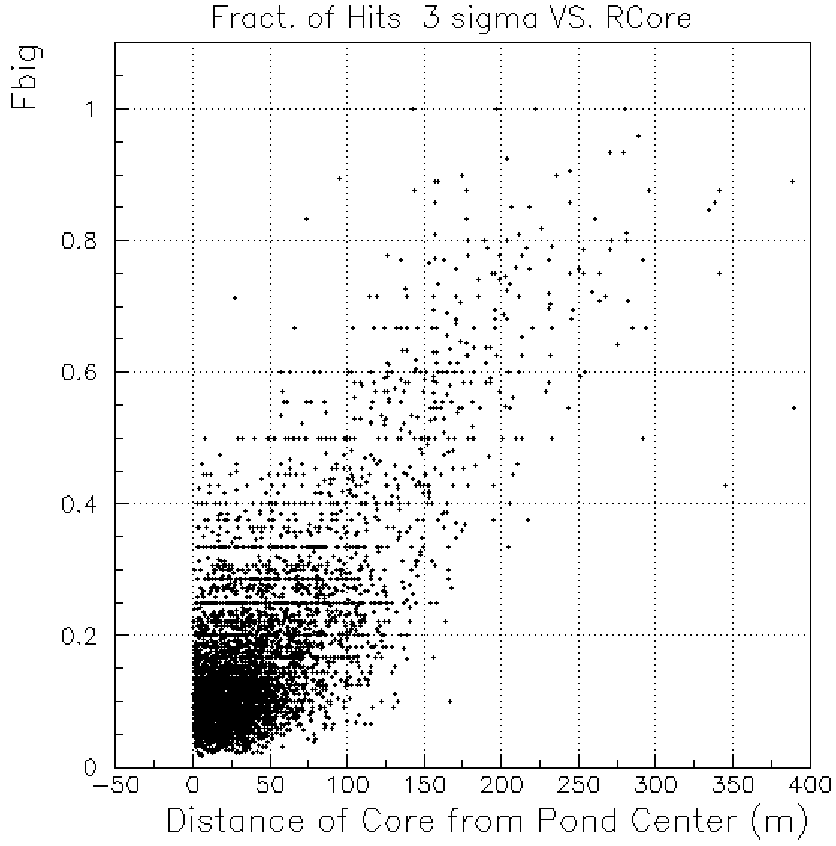


Figure 9: Scatter plot of F_{big} vs. Rcore. Cores outside array have large F_{big}.

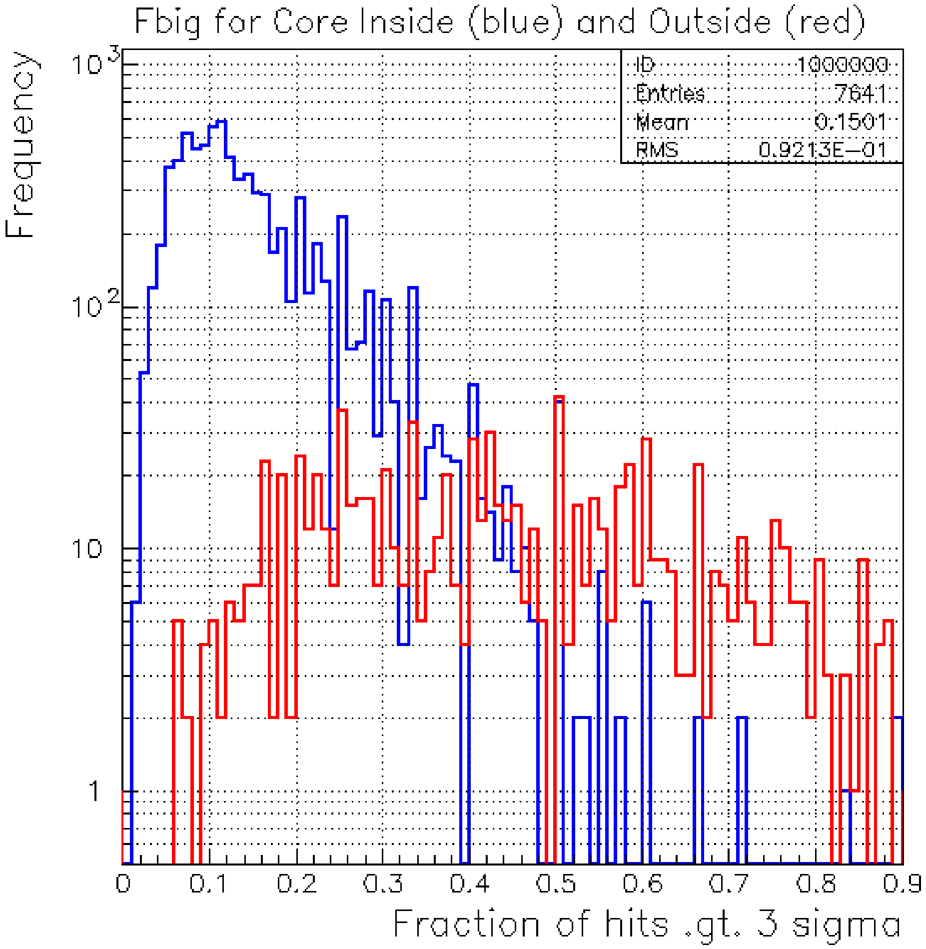


Figure 10: Plot of F_{big} for showers with cores inside (blue) and outside (red) of the outrigger array.

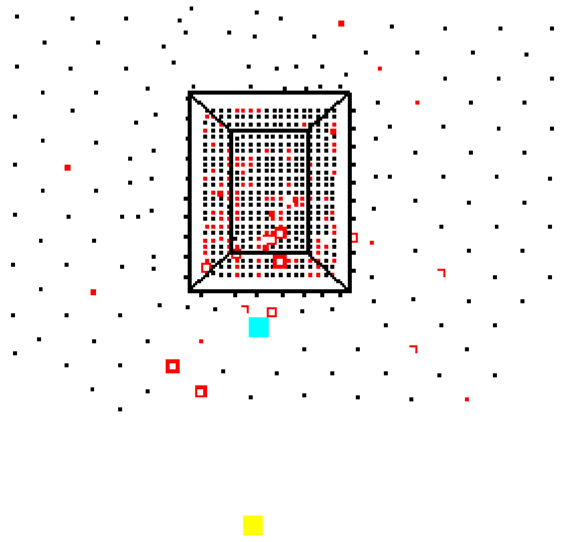


Figure 11a: Sample Event with F_{big} = 0.727.

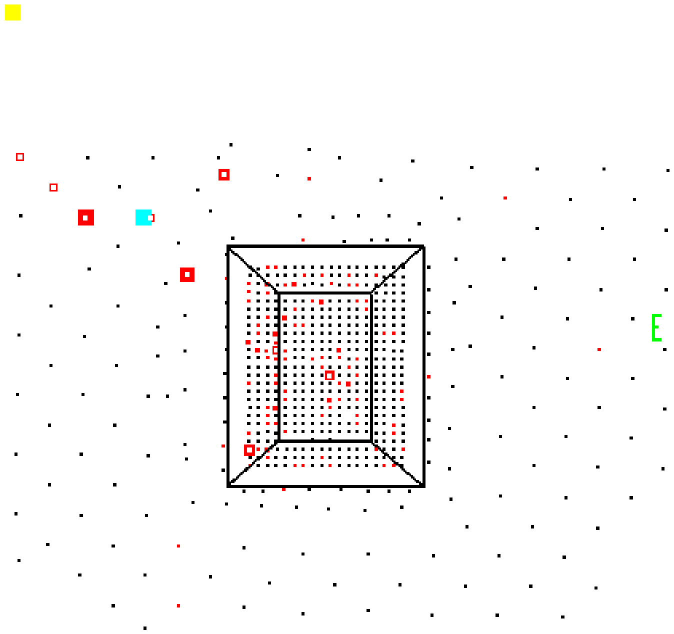


Figure 11b: Sample Event with F_{big} = 0.556.

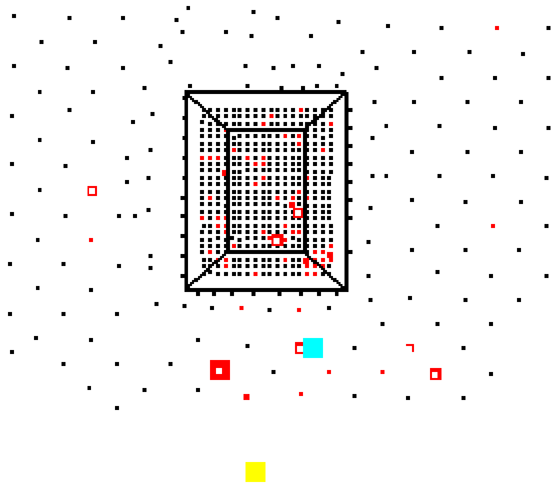
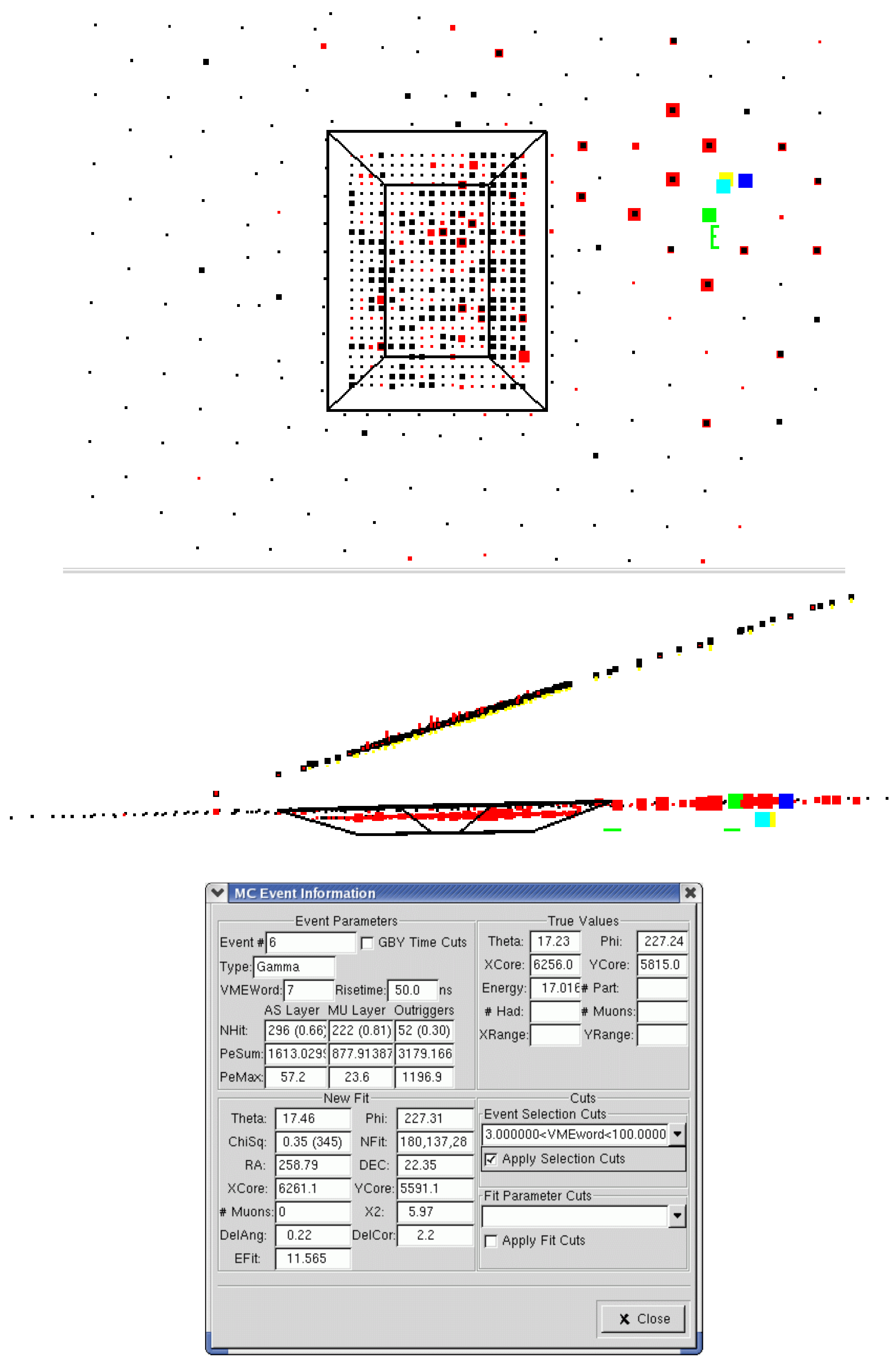


Figure 11c: Sample Event with F_{big} = 0.091.

V. Predictions from MC Gammas

I used the above shower front shape and width parameterizations, inclusion of muon layer and outrigger hits and changes to the angle fitting method to reconstruct event angles of MC gammas. A sample fitted event is shown in figure 12. Figures 13, 14, and 15 show the delangle distributions for bit 1 set, bit 2 only set, bit 3 only set respectively. Clearly there is a significant improvement in each of these data sets. Figure 16 shows the Nfit distributions. There is at least a factor of 2 increase in Nfit using the new method.



Event Parameters

Event # 6
☐ GBY Time Cuts
Type: Gamma
VMEWord: 7
Risetime: 50.0 ns

	AS Layer	MU Layer	Outriggers
NHit:	296 (0.66)	222 (0.81)	52 (0.30)
PeSum:	1613.029	877.91387	3179.166
PeMax:	57.2	23.6	1196.9

True Values

Theta: 17.23
Phi: 227.24
XCore: 6256.0
YCore: 5815.0
Energy: 17.016
Part:
Had:
Muons:
XRange:
YRange:

New Fit

Theta: 17.46
Phi: 227.31
ChiSq: 0.35 (345)
NFit: 180,137,28
RA: 258.79
DEC: 22.35
XCore: 6261.1
YCore: 5591.1
Muons: 0
X2: 5.97
DelAng: 0.22
DelCor: 2.2
EFit: 11.565

Cuts

Event Selection Cuts
3.000000<VMEword<100.0000
☑ Apply Selection Cuts

Fit Parameter Cuts
☐ Apply Fit Cuts

Figure 12: Sample MC gamma event fitted with outriggers and muon layer hits. (Top view, 3-D view, event info)

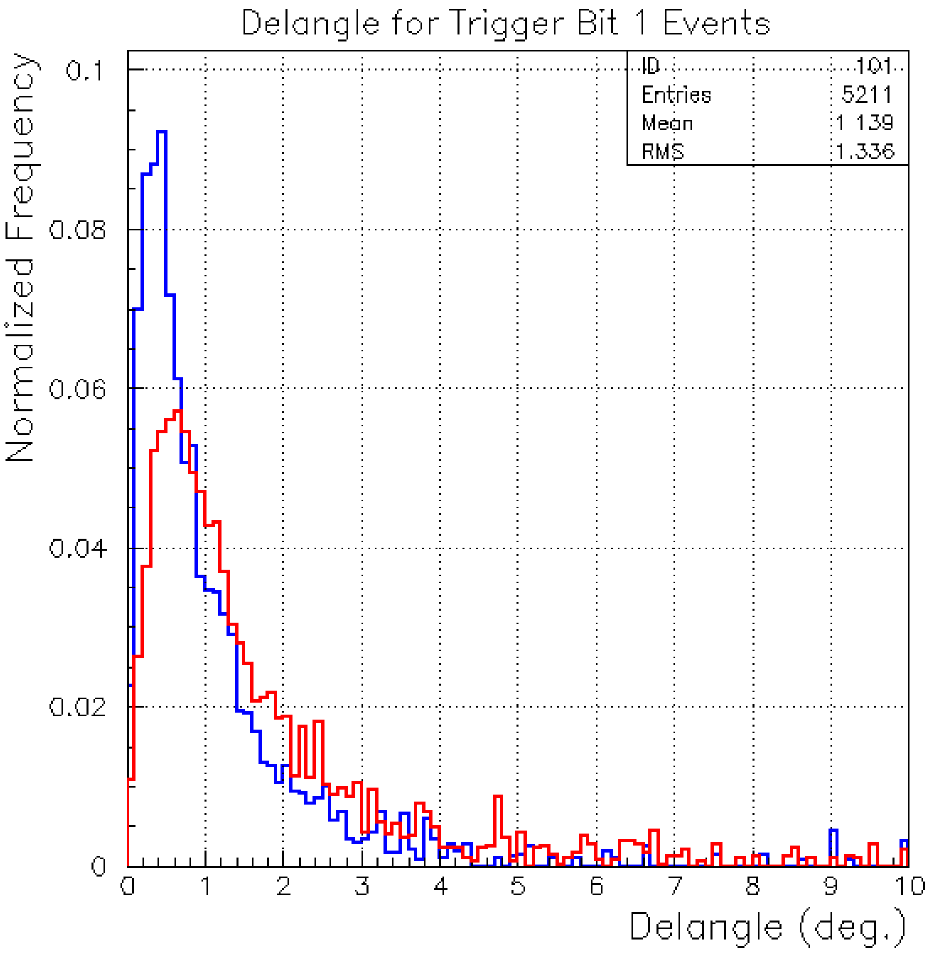


Figure 13: Delangle distributions for events with trigger bit 1 set. Blue is the new fitting method, red is old. Medians are: 0.56°! for new and 1.13° for old.

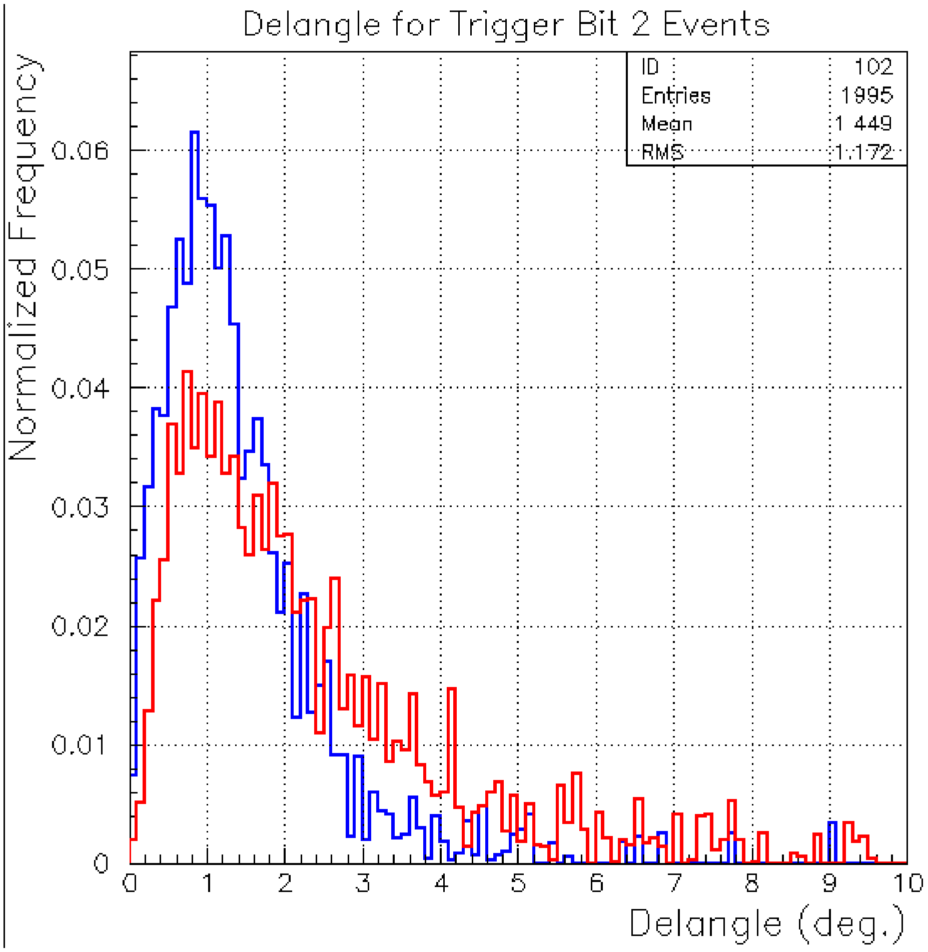


Figure 14: Delangle distributions for events with trigger bit 2 set & not bit 1. Blue is the new fitting method, red is old. Medians are 1.05° for new and 1.78° for old.

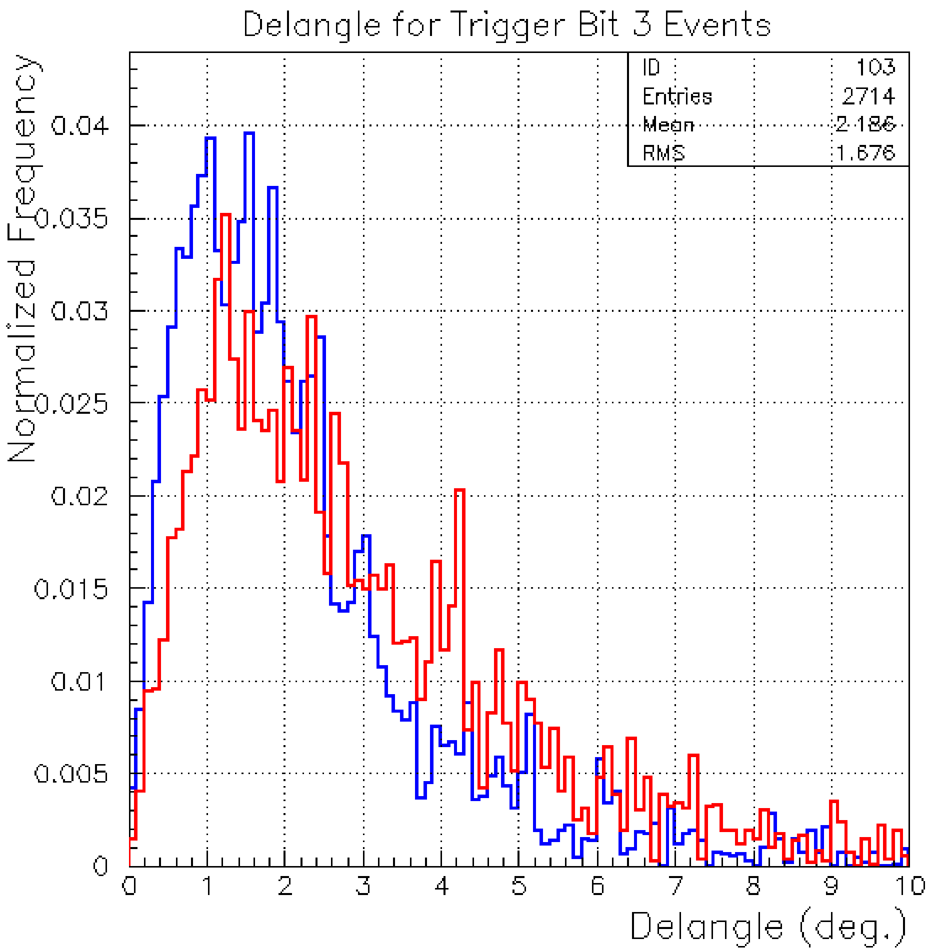


Figure 15: Delangle distributions for events with trigger bit 3 set & not bit 1 or 2. Blue is the new fitting method, red is old. Medians are 1.67° for new and 2.37° for old.

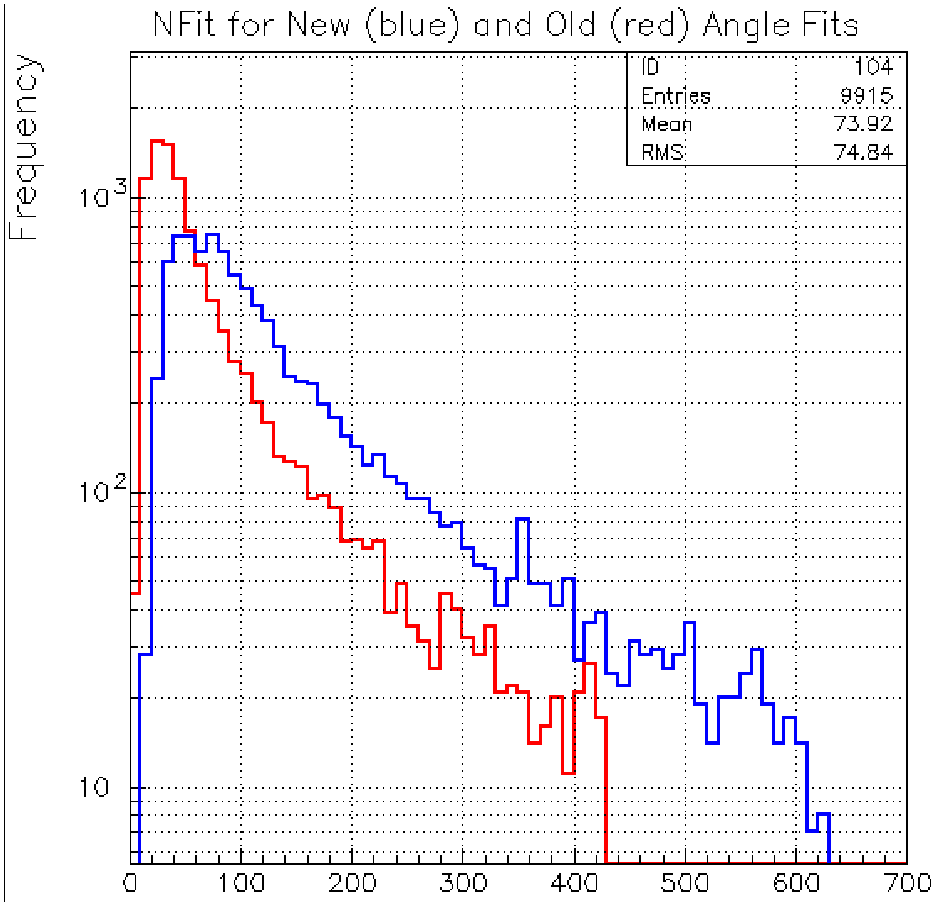
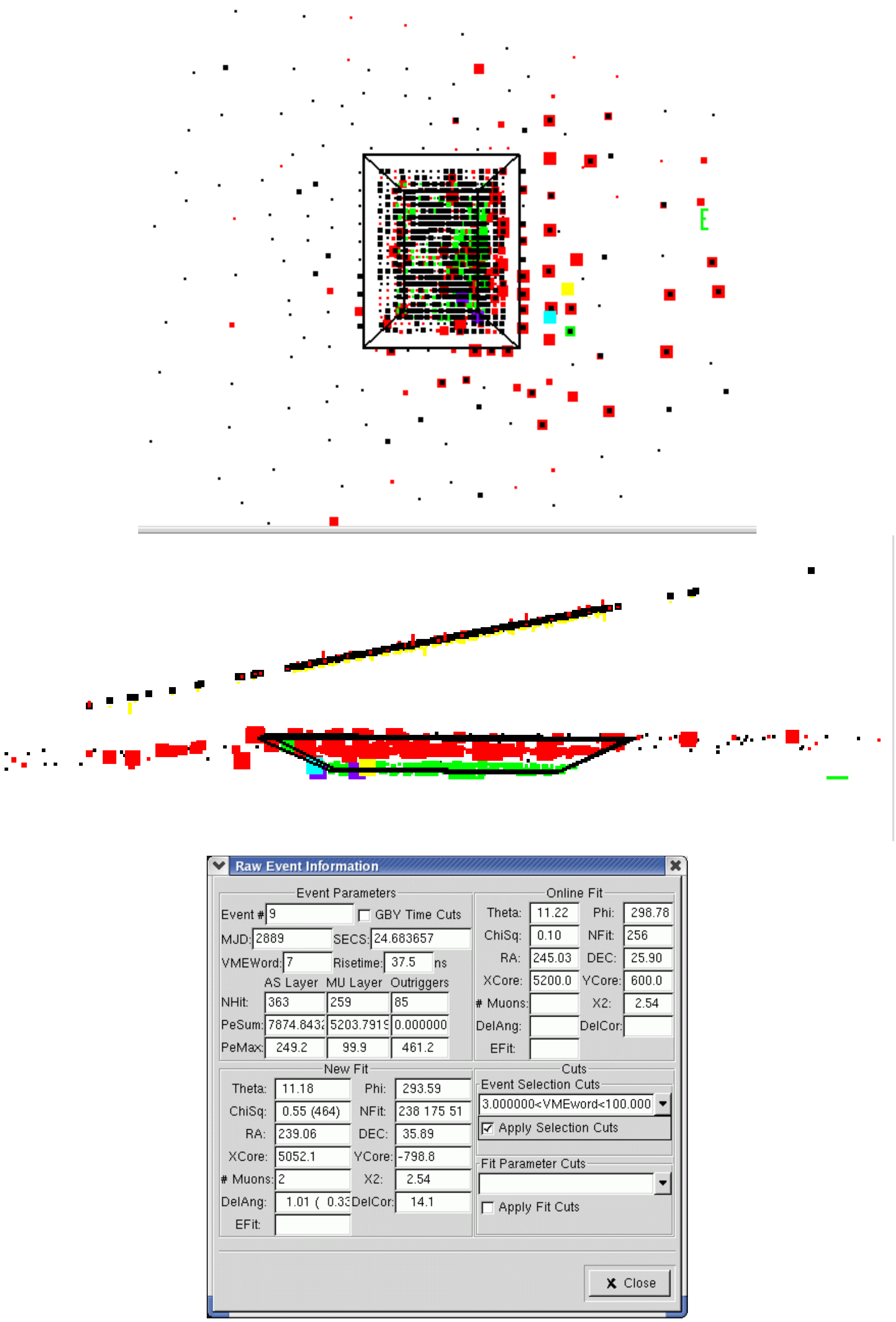


Figure 16: Nfit distributions for new (blue) and old (red) angle fitting methods. Medians are: 100 (blue) and 46 (red).

VI.Results from Real Data

I have also used the above angle fit changes, with the calibrations of the outriggers to fit real events. Figure 17 shows an example event fit with the new method. Shown in figures 18, 19, an 20 are the distributions of DELEO for events with trigger bit 1, 2, or 3 set. Again there is clearly an improvement in this estimate of angular resolution.



Event Parameters

Event # 9 ☐ GBY Time Cuts
MJD: 2889 SECS: 24.683657
VMEWord: 7 Risetime: 37.5 ns

	AS Layer	MU Layer	Outriggers
NHit:	363	259	85
PeSum:	7874.843	5203.791	0.000000
PeMax:	249.2	99.9	461.2

Online Fit

Theta: 11.22 Phi: 298.78
ChiSq: 0.10 NFit: 256
RA: 245.03 DEC: 25.90
XCore: 5200.0 YCore: 600.0
Muons: X2: 2.54
DelAng: DelCor:
EFit:

New Fit

Theta: 11.18 Phi: 293.59
ChiSq: 0.55 (464) NFit: 238 175 51
RA: 239.06 DEC: 35.89
XCore: 5052.1 YCore: -798.8
Muons: 2 X2: 2.54
DelAng: 1.01 (0.3 DelCor: 14.1
EFit:

Cuts

Event Selection Cuts
3.000000<VMEword<100.000
☑ Apply Selection Cuts

Fit Parameter Cuts
☐ Apply Fit Cuts

Figure 17: Sample Real event fitted with outriggers and muon layer hits. (Top view, 3-D view, event info)

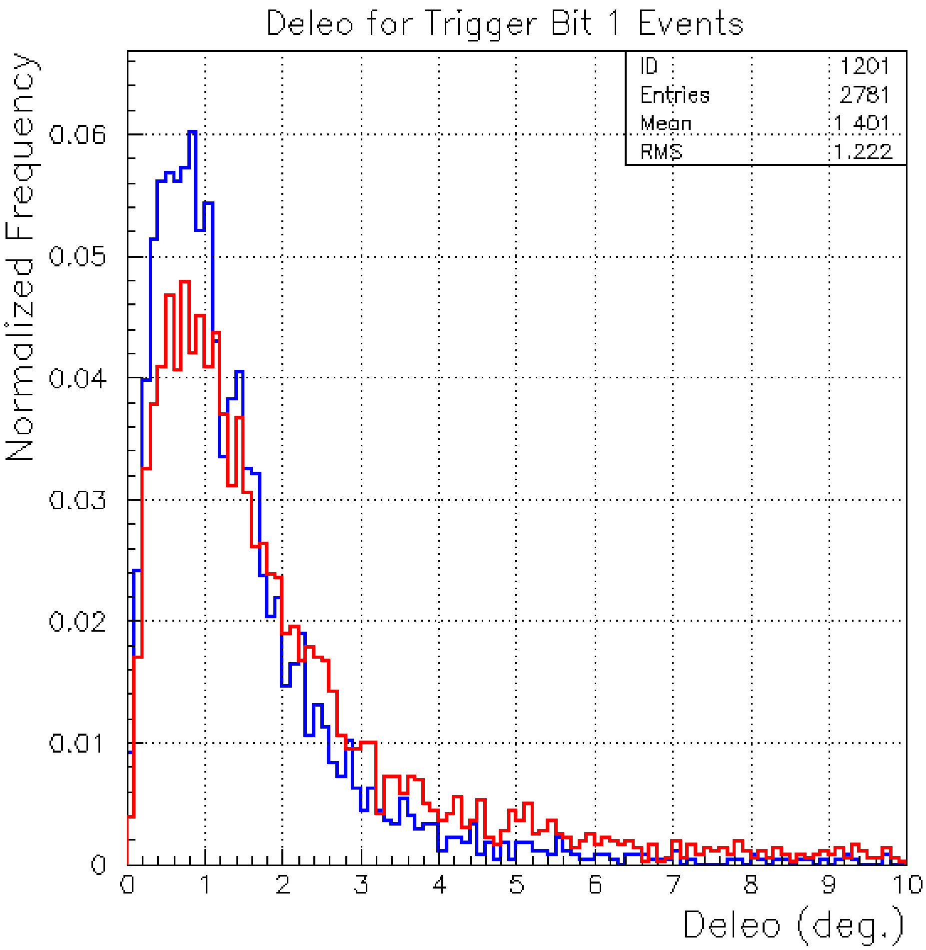


Figure 18: Deleo distributions for events with trigger bit 1 set. Blue is the new fitting method, red is old. Medians are 1.07° for new and 1.38° for old.

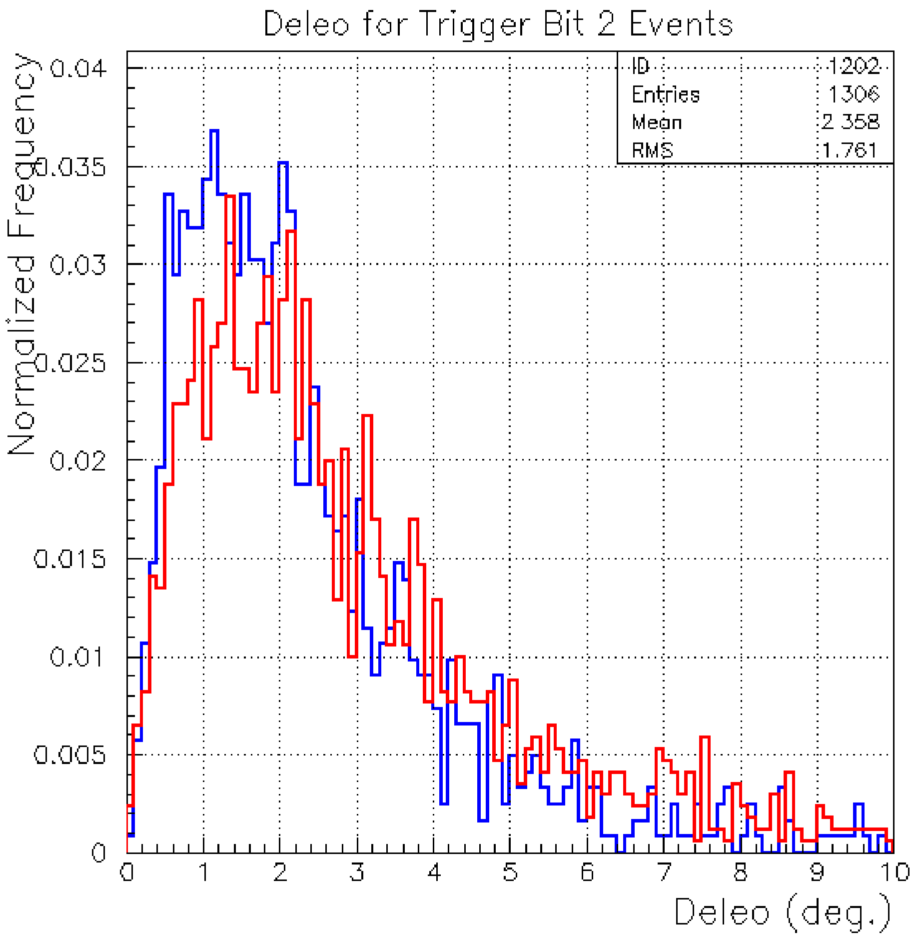


Figure 19: Deleo distributions for events with trigger bit 2 set & not bit 1. Blue is the new fitting method, red is old. Medians are 1.91° for new and 2.29° for old.

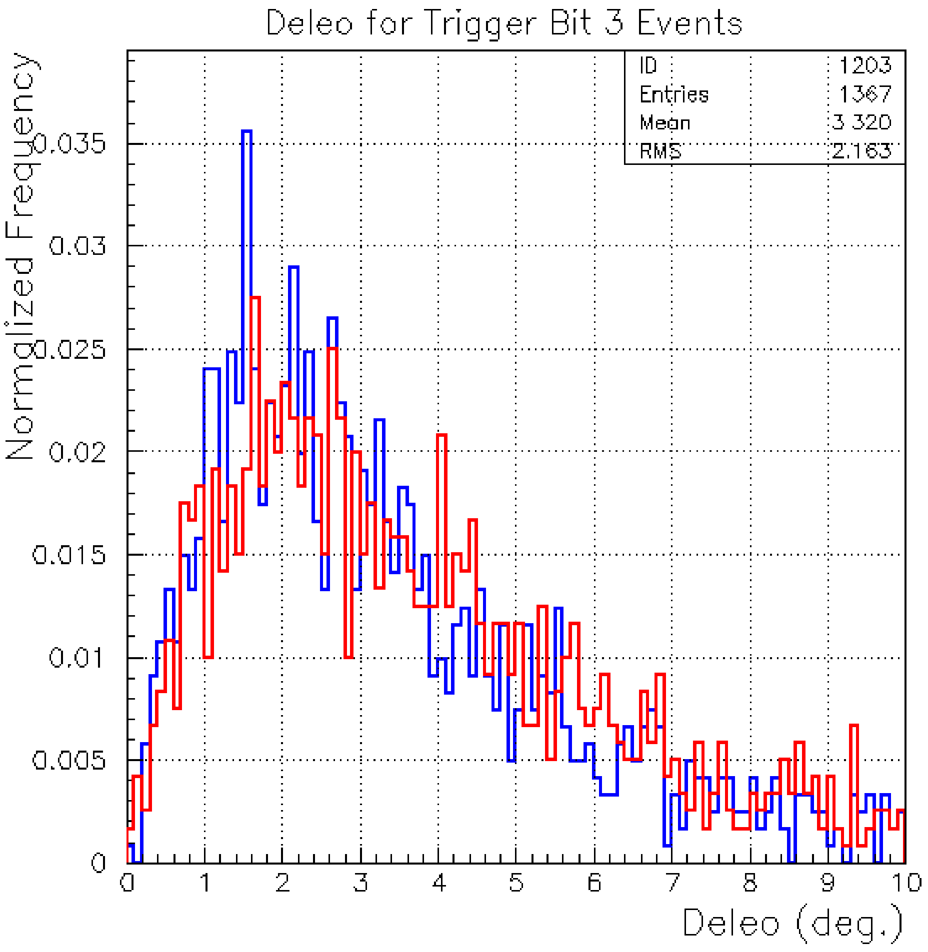


Figure 20: Deleo distributions for events with trigger bit 3 set & not bit 1 or 2. Blue is the new fitting method, red is old. Medians are 2.80° for new and 3.16° for old.

VII.Results from the Crab Data Set

Finally, I have used the above changes to reconstruct event angles in the crab data subset which has the majority of outriggers operational. Figure 21 shows the background subtracted event density versus angular distance away from the crab position.

VIII.Summary

Considering the length of this memo, this summary will be brief. I have made a first pass at calibrating the timings of the outriggers. I have made improvements to our shower parameterizations (curvature and sampling) for all three layers of Milagro. I have made changes to our angle fitting methods in include muon layer and outrigger hits. Fitting the standard 3.2 MC gamma data set predicts that Milagro's angular resolution should improve by about $\frac{1.29}{0.69}=1.89$ for events with trigger bit 1 or 2 set (i.e. NAS > 53). Deleo from real events doesn't show as much improvement, but then again deleo is not very sensitive to systematics such as curvature. The real proof will be in the Crab data. Currently I haven't run through enough data yet. The effort continues...

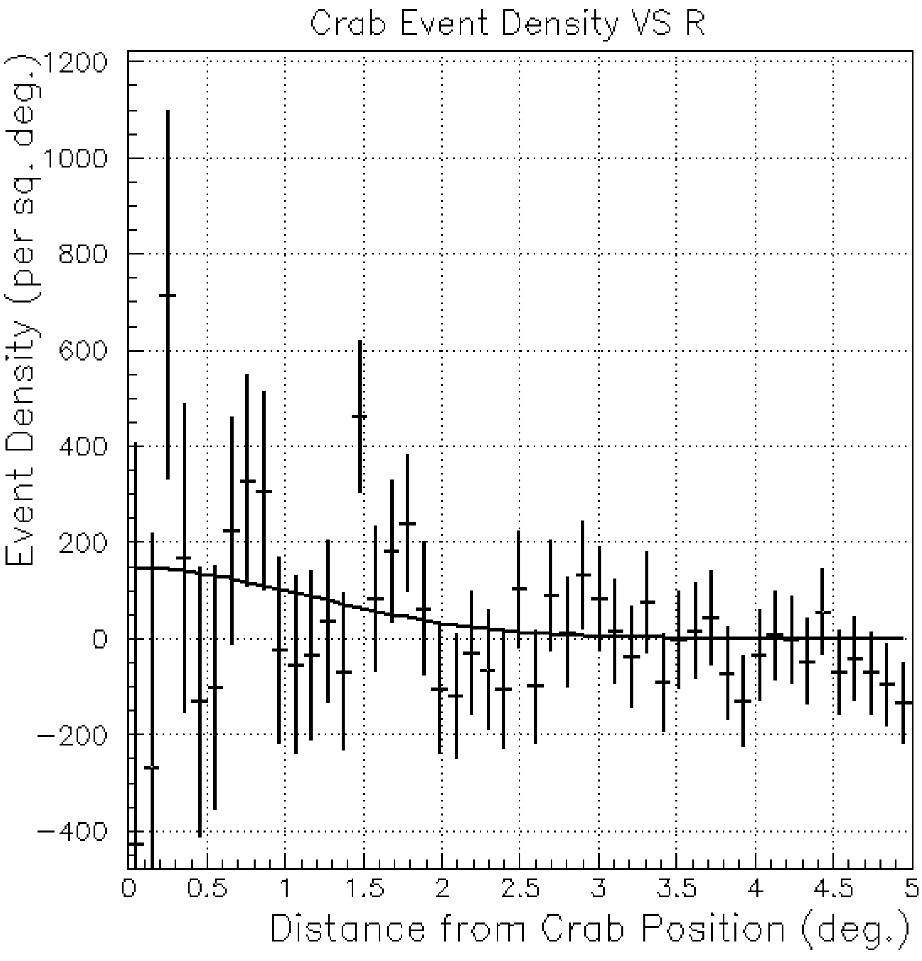


Figure 20: Event Density vs. angular distance from Crab position. Fit was 1.29 +/- 0.45°. Nsigma = 2.1, ~ 95 days