Calibration of the Preshower Calorimeter

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Abstract

The CLAS12 Pre-Shower Calorimeter (PCAL) has been described geometrically. This information is used to correct for the light attenuation curve seen by the scintillators. The ADC readout plotted as a function of distance away from the PMT, gives the form of the light attenuation. This form is fit and the parameters are recorded to the CLAS12 database. The process used to obtain these parameters is described in this note.

Contents

1 Design

The Preshower Calorimeter (PCAL) is triangular in shape. The triangular form is isosceles in nature (not equilateral). This is done to better match the EC design and space limitations. A diagram of the side view of the PCAL with respect to the EC can be seen in Fig. 1.1.

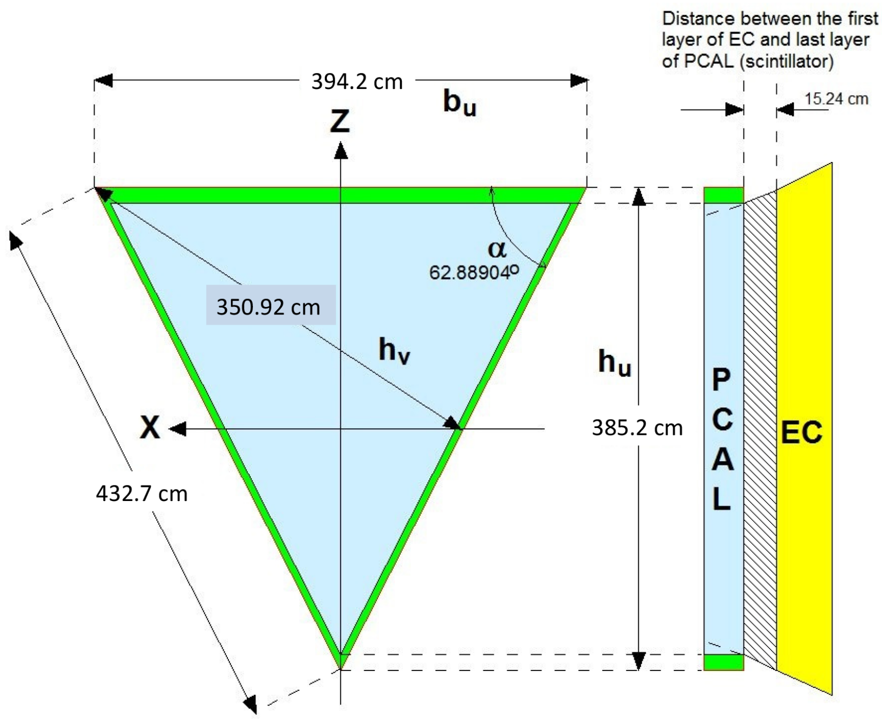


Figure 1.1: This diagram demonstrates the dimensions of the PCAL unit. This figure has been taken directly from the PCAL geometry note[1].

The PCAL box encapsulates layers of scintillator strips and lead sheets. Between each lead sheet there are three different orientations of scintillating strips. These orientations are described as the U, V, and V layers. Each layer is parallel with one side of the PCAL box. The sequencing of the lead sheet, U layer, V layer, and W layer is repeated five times within each sector of the PCAL unit. This results in fifteen layers of scintillator strips. Each repeating layer signal is coupled to the same PMT, and is not able to separate five different signals. A UVW view of the PCAL can be seen in Fig. 1.2.

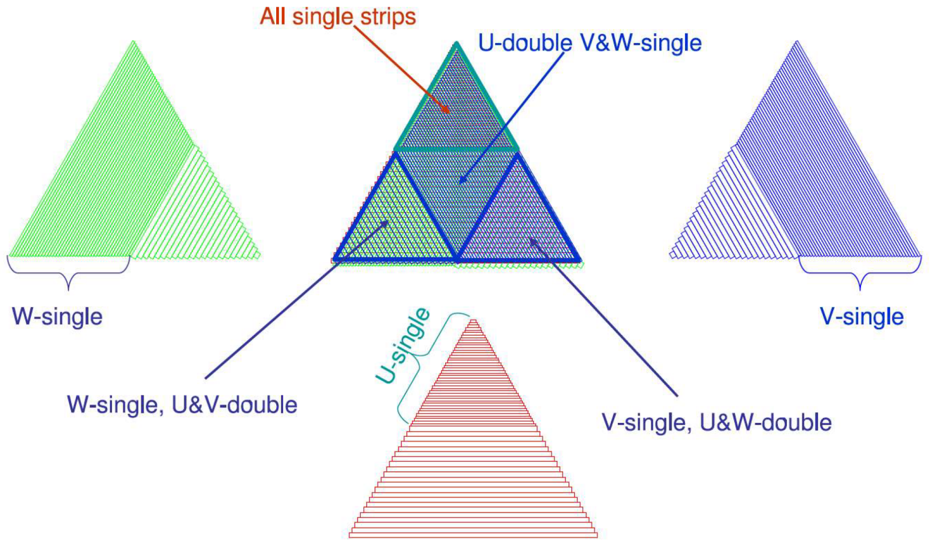


Figure 1.2: This is a schematic of how each orientation of scintillator is laid out. This figure is also taken directly from the PCAL geometry note[1].

There are 84 U strips, 77 V strips, and 77 W strips in each corresponding layer. The last 32 U strips are grouped into one PMT per pair. The first 30 V and W strips are also grouped in pairs within their respective layer. As a consequence there is better spatial resolution at low strip numbers in the U layer and at high numbers in the V and W layers. This pattern of scintillators can be seen in Fig. 1.2.

Strips in each view can be numbered for ease. Lower numbered strips are the smaller strips while higher numbered strips are longer. For example, V1 is the shortest and V62 is the longest strip in the V view. This strip convention is used throughout this document and is taken from the PCAL geometry note[1]. Using this convention, the layout of the PMT readout can easily be understood from Fig. 1.3 which shows PMT readout of a strip in each view. The current analysis extracts calibration information based on 2-strip pixels only.

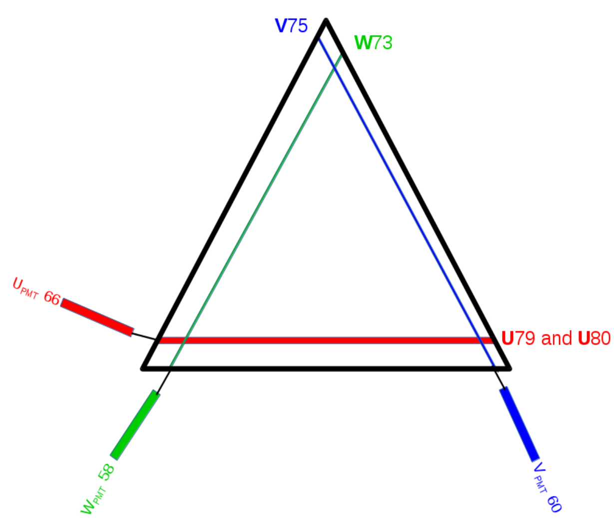
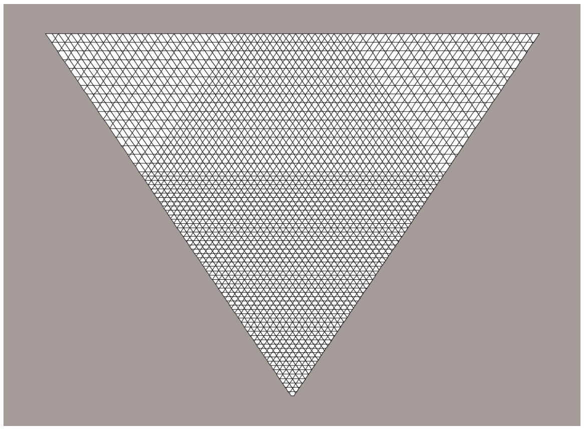


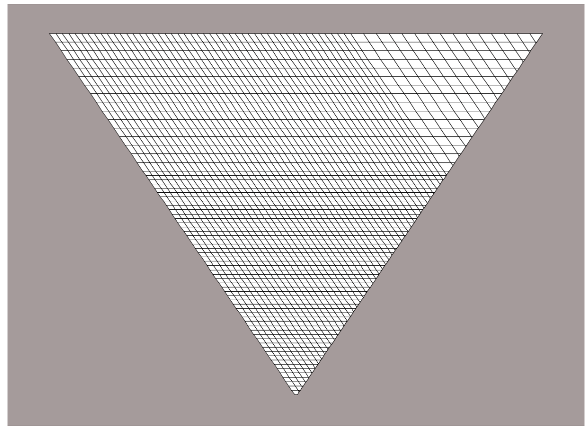
Figure 1.3: This is a cartoon showing the layout of the PMT readout for different views.

1.1 Overlapping Shapes

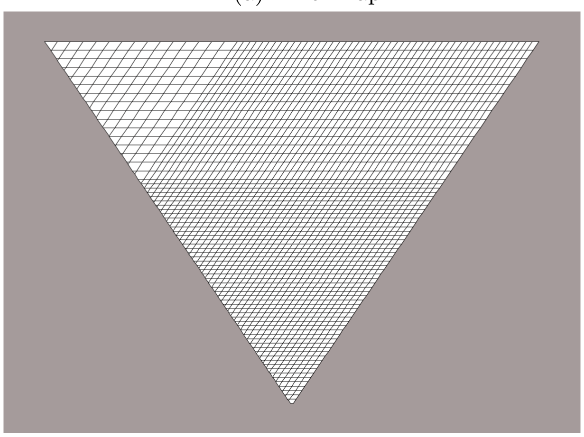
In order to calibrate the PCAL unit of the CLAS12 detector, one can think of dividing each PCAL module into bins based on the overlapping shapes. The overlap shapes/pixels are of two types: a 3-strip pixel, shape formed when all all the views are superimposed together, and a 2-strip pixel formed from the overlap of two strips where the strips are part of different views. Maps of different overlap conditions are shown in Fig. 1.4.



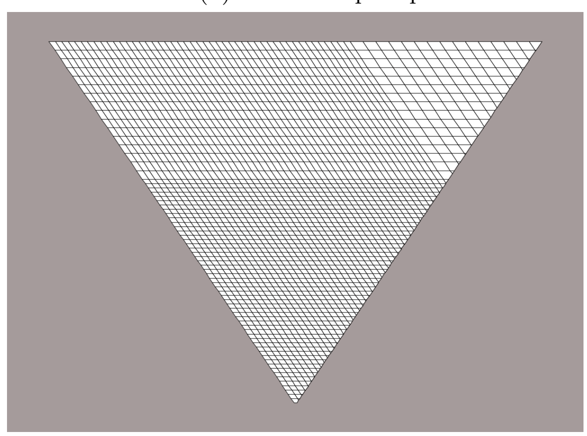
(a) Pixel map.



(b) UW overlap map.



(c) UV overlap map.



(d) WU overlap map.

Figure 1.4: Shown are the different ways overlaps can be considered in a single PCAL module.

2 Data and Simulation

The data used for the calibration was collected for the cosmic ray events before the PCAL unit was installed as a part of the CLAS12 detector subsystem. The collection required a trigger on the W-view meaning that information of cosmic ray tracks that created a PMT pulse of certain height were only stored. As the W-view is the last of the views, this trigger would also ensure to a reasonable level that the tracks were perpendicular to the unit.

The calibration constants are extracted from simulated events as well to check the consistency of calibration code (based on `C++`) and the method used for the data. A `JAVA` framework is used for simulation and eventually the data. Details about the generation of simulated events and attenuation coefficients' extraction can be found in Section 7.

3 Various Cuts

The data used for calibration is from cosmic ray muons. These cosmic rays hit randomly throughout the PCAL unit. The distribution of these events although expected to be uniform, don't guarantee a good hit or detected signal in all three layers. Moreover due to the strange pixel shapes and varying sizes different pixels have very different number of counts. An intitial skim was used to cut out events that would prevent a clean signal for calibration purposes. Events were removed based on a multiplicity cut and a Dalitz condition.

3.1 Multiplicity Cut

To ensure a more accurate calibration, a multiplicity cut was applied to the collected data. The multiplicity cut removed any event that contained more than three PMT readouts (one in each layer). This reduces the number of cosmic ray events that are not relatively perpendicular to the face of the PCAL unit. This is due to the fact that if a cosmic ray trajectory is not perpendicular to the PCAL face, it could clip multiple strips in one orientation (i.e. strip U30 and U31 both recieve a signal). Therefore, by restricting the calibration to one perpendicular hit, more well defined calibration constants could be determined. The accepted range of angles (different from perpendicular to the PCAL face) varies as a function of strip number and is not uniform in all directions. This multiplicity cut also helps in removing events where multiple cosmic rays hit the detector within the same time interval, due to possible firing of more PMTs.

3.2 Dalitz Cut

The Dalitz condition implies that if a point inside a triangle is chosen, no matter the location, the sum of the distances to each edge will be unchanged. Rather than calculating each x and y point for every hit, distance as a function of strip width can be used to test this condition. The relatively simple strip calculation can be computed by knowing the corresponding strip number to the triggered PMT combined with equations 1-4. This distance is empirically found to be two. Preskimmed data demonstrating this distribution can be found at `https://clasweb.jlab.org/wiki/index.php/PCAL_Cosmic_Ray_Tests`. If this condition is not satisfied, then the hit recorded is most likely electronic noise, an indirect hit, or multiple cosmic ray hits recorded at once.

$$dist(u) = \begin{cases} u/84.0 & \text{if } u < 52 \\ (52.0 + (u - 52.0) \times 2.0)/84.0 & \text{if } u \geq 52 \end{cases} \tag{1}$$

$$dist(v) = \begin{cases} 2.0 \times v/77.0; & \text{if } v < 15 \\ (30.0 + (v - 15.0))/77.0 & \text{if } v \geq 15 \end{cases} \tag{2}$$

$$dist(w) = \begin{cases} 2.0 \times w/77.0; & \text{if } w < 15 \\ (30.0 + (w - 15.0))/77.0 & \text{if } w \geq 15 \end{cases} \tag{3}$$

$$uvw = dist(u) + dist(v) + dist(w) \tag{4}$$

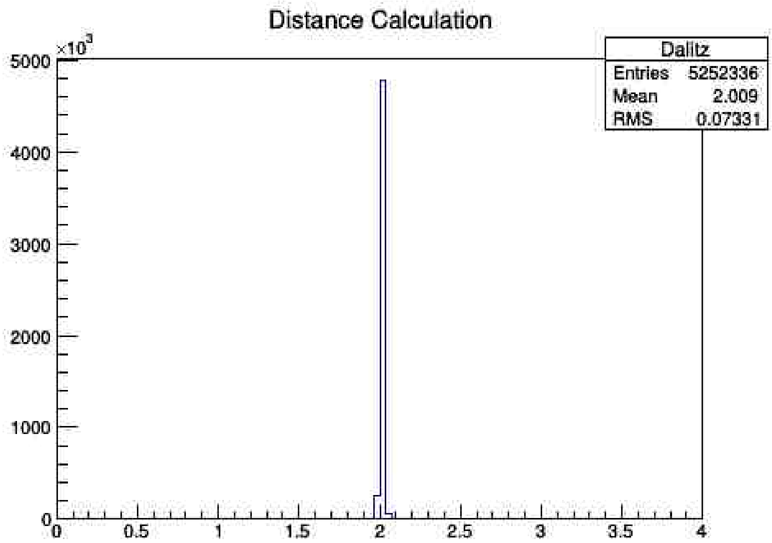
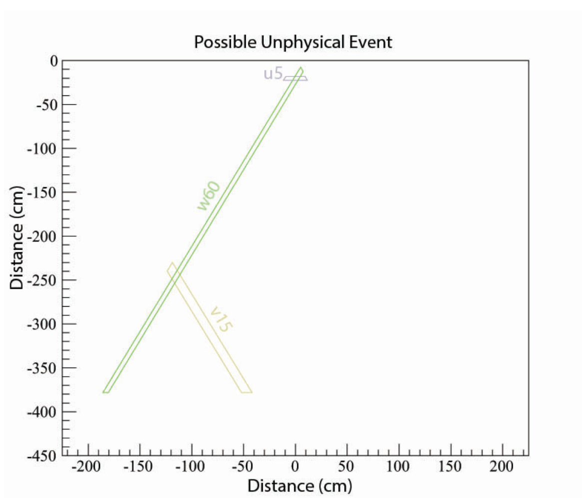


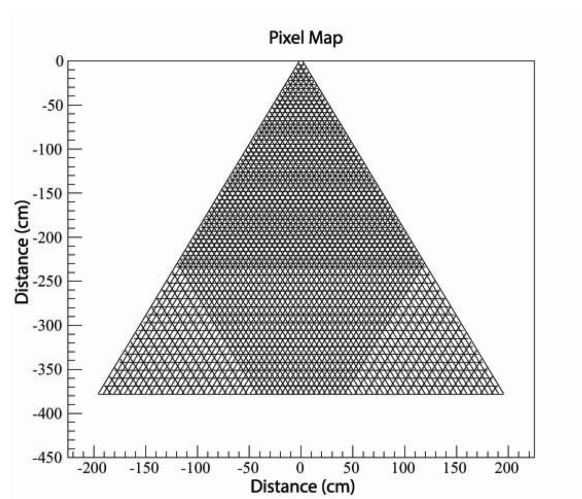
Figure 3.1: Plotted is the resulting number (uvw) obtained from equation 4 after the initial skim.

3.3 Unphysical Events

An investigation into the types background was performed. Looking at an occupation number (events within a pixel), some recorded hits were unphysical if only one cosmic ray was considered to prompt the signal. Examples can be seen by Figures 3.2a and 3.3.



(a) Shown is one example of an event that would pass a multiplicity cut, but is clearly from either multiple rays or other noise.



(b) Shown is a rough outline of the scintillator mapping created with minimal input.

Figure 3.2: Rough outline of the PCAL system.

Some of the unphysical events can be spotted easily because low u and low v strip numbers should never correlate to just one incident cosmic ray. To investigate in more detail, a program outlining the PCAL detector by strip number was generated. This was generated using α, β, number of strips, and strip width (w) as defined by Figure 4.1. This outline or pixel mapping can be seen in Figure 3.2b. This ideal outline of the system was then used in combination with a random number generator to verify which strip numbers could correlate to a physical perpendicular trajectory through the system. These correlation numbers were then stored in tables and recalled in the analysis. Neighboring pixels in all directions were also marked as valid to account for uncertainty in the calculations and given numbers. Removing any event that did not end up in correlated PMTs results in no obvious

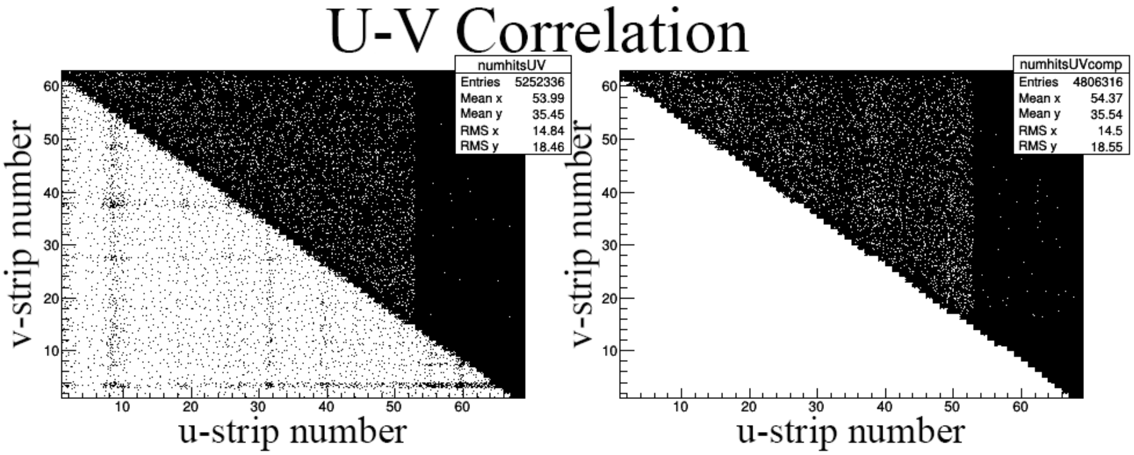


Figure 3.3: The left histogram shows the U and V strip correlation after both the multiplicity and dalitz cuts were applied. The right histogram shows the U and V strip correlation after rejecting all known unphysical background.

unphysical signals as seen in figure 3.3. However, looking at the signal distribution an exponential background still appears. This demonstrates that either different cuts and/or a very good fitting routine needs to be put in place.

4 Fit to ADC Output

Although in general a 3-strip pixel can be odd shaped, a 2-strip pixel can be straightforward. This two layer correlation creates trapezoidal bins formed by the overlap of two different strip orientations*. An example of one of these trapezoids outlined in black can be seen in Fig. 4.1. Each one of these trapezoids should have a ADC readout value. The width of this physical bin can be found by

$$s = \frac{w}{\sin \alpha} \tag{5}$$

or

$$s = \frac{w}{\cos \beta}, \tag{6}$$

where w is a single scintillator strip width (≈ 4.5cm). Statistically one might expect some sort of peak describing the distribution of values. The centroid of this distribution is used as a data point at that center of that physical bin.

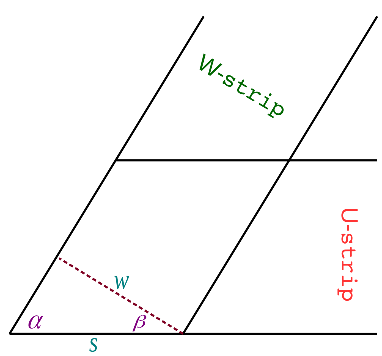


Figure 4.1: Shown is an outline of a generic intersection of a u and w strip. The distance between the trapezoidal area and the PCAL edge can be represented by a linear function of s.

*All of the studies in this section were primarily focused on the u strip attenuations, rather than the v/w strips.

4.1 Signal Shape

The desired outcome is to approximate the signal by a simple function, for instance a Gaussian function. Upon investigation the integrated ADC values appear to be a combination of a Gaussian and exponential fits.

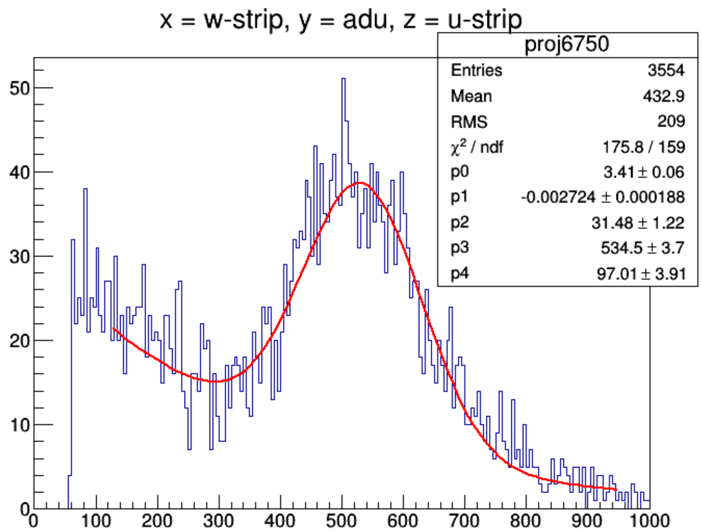


Figure 4.2: Shown is an example of the distribution of the ADC readout from one u/w trapezoidal bin (specifically the logical numbers u =67, w=50). The red line is a fit to an exponential combined with a Gaussian distribution.

This type of background can be seen for every physical two layered bin along any strip.

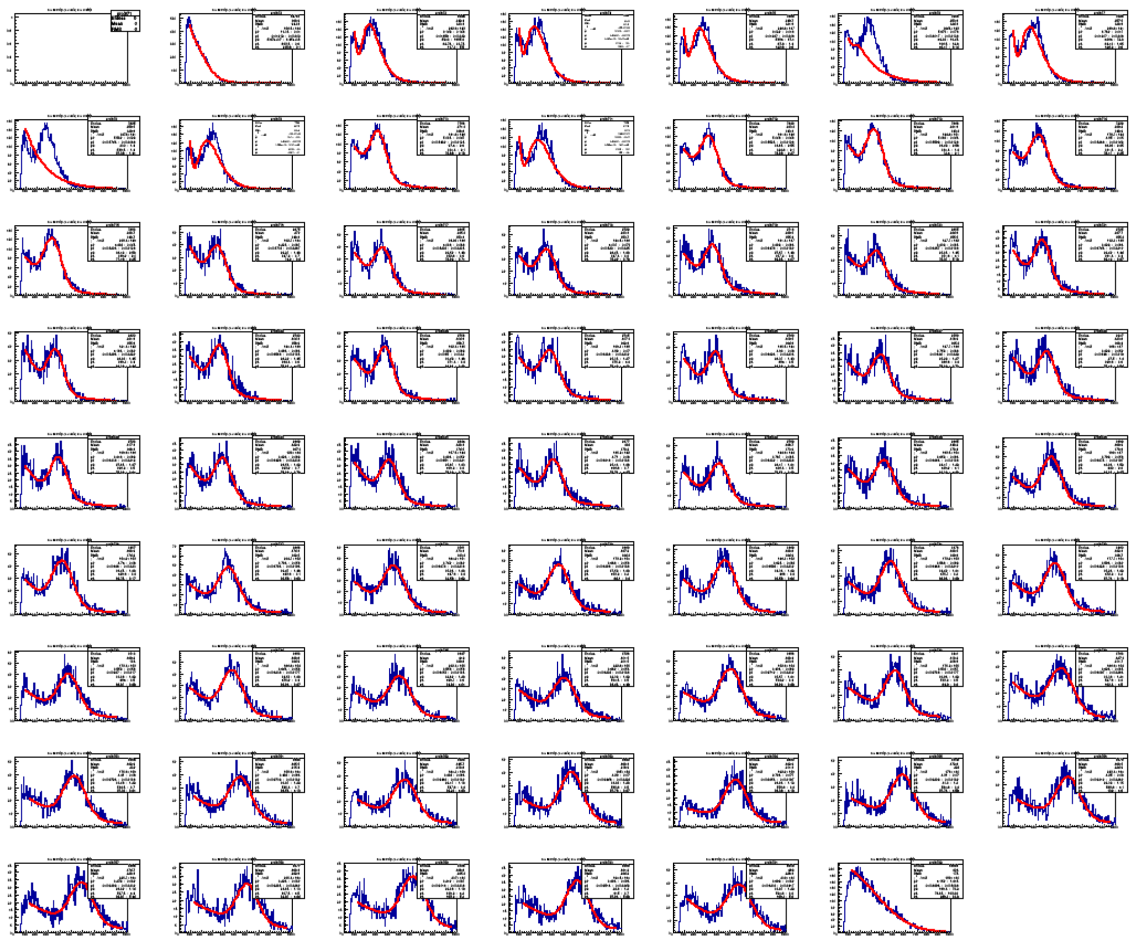


Figure 4.3: Shown is an example of all the distributions of the ADC readout from the 67th logical u strip.

4.1.1 Fit function

Upon initial inspection the distribution is fit to an exponential and a Gaussian. The exponential is background/noise in most cases, whereas the Gaussian represents near perpendicular cosmic ray hits. The centroid of the Gaussian is extracted and determined to be the primary light intensity in that trapezoidal bin.

This plan works well for most interior physical bins. However, after looking at the strips corresponding to the edges of the PCAL unit, it is realized this can't be all that is done. Two possible improvements are utilized to better extend the calibration to the outer edges.

1. Cut on each fit Gaussian signal.
   Using the fact that each bin in one scintillating strip corresponds to the other two, a cut on one affects the others. By making an iteration over all events a three sigma cut can be placed on each signal. This reduces the exponential background. This improves the fits to some of the edges.

2. Cut on the overall energy deposited.
   Assuming that the signal is from the same cosmic ray and if that event doesn't participate in corner clipping, then the event should deposit the same amount of energy into each layer. After cutting on the original signal and fitting attenuation curves, individual gains can be approximated. Using the emperically found gains, a cut on the sum of ADC signals can be performed. This also helps the extend good fits to the edges of the pcal unit. This is the case due to the fact that two intersecting medium range strips (other layers) set limits on the possible events on the outer most strips. By improveing the outer most strips, they can be used to set limits on the overlapping shorter strips.

4.2 Iteration Process

An iteration process was employed to improve the signal extraction. This process cuts events on ADC values determined by either the signal fits or by attenuation fits and then repeats. This allows for a converging result because each cut on one layer affects the other two. Therefore the raw signal fit keeps improving as the attenuation fit and gains improve. To illustrate how the process works, each iteration described in this section will describe cuts used when plotting the raw signal. After the cuts are described an illustration of the fit to the signals will be shown with a diverse sampling (as diverse as six options gets). Next an attenuation fit over six of the strips will be shown. This shows how the multiple cuts affect each attenuation fit as a function of strip number.

4.2.1 Pass 0

- Multiplicity Cut: Only events where one PMT fired for each strip were allowed.
- Dalitz Cut: An empircal distance sum was used to remove events that don't fall into this range determined by Equation 4.
- Valid hit or near neighbor hit: Using generated events on a calculated skeleton of the pcal, each pixel was determined to be valid or not. Extra uncertainty was allowed by also marking nearest neighboring pixels.

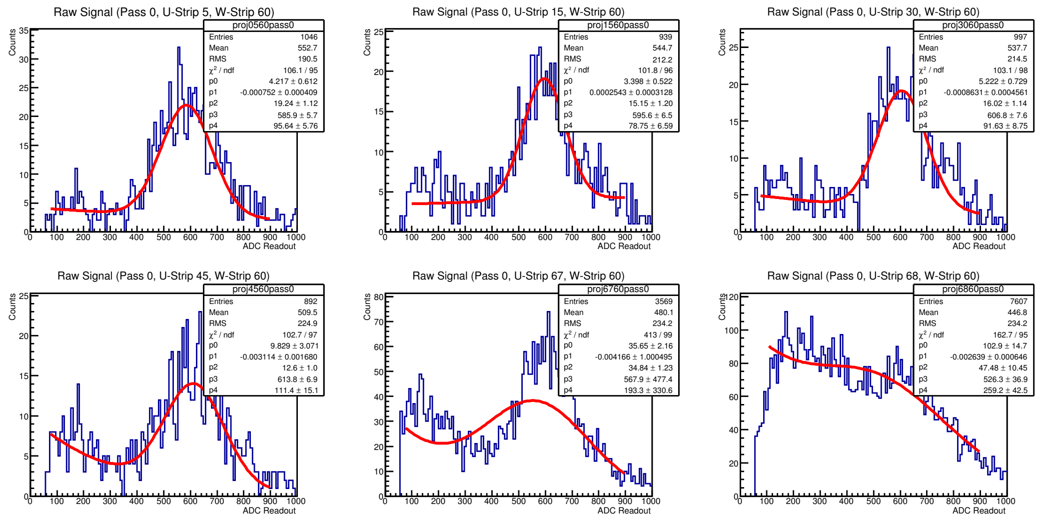


Figure 4.4: Shown is the ADC signal corresponding to signals from multiple u-strips (5, 15, 30, 45, 67, and 68) and a projection of the w60 strip.

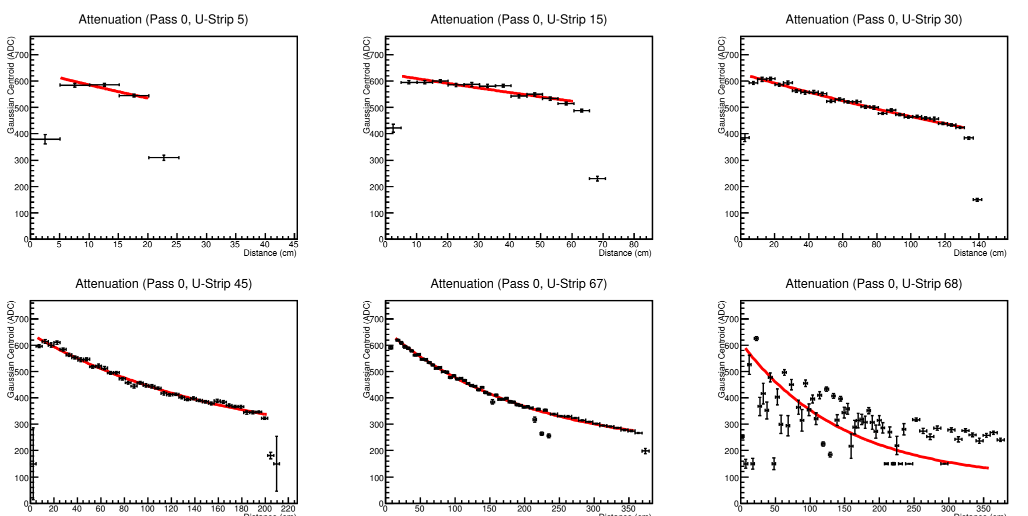


Figure 4.5: Shown is the overall attenuation fits to the selected u-strips (5, 15, 30, 45, 67, and 68).

4.2.2 Pass 1

- Multiplicity Cut: Only events where one PMT fired for each strip were allowed.
- Dalitz Cut: An empircal distance sum was used to remove events that don't fall into this range determined by Equation 4.
- Valid hit or near neighbor hit: Using generated events on a calculated skeleton of the pcal, each pixel was determined to be valid or not. Extra uncertainty was allowed by also marking nearest neighboring pixels.
- 3σ Cut on Signal: Each signal was fit to a Gaussian and exponential in pass 0. The parameter σ from the Gaussian fit was used to cut out the events that did not lie within this function.

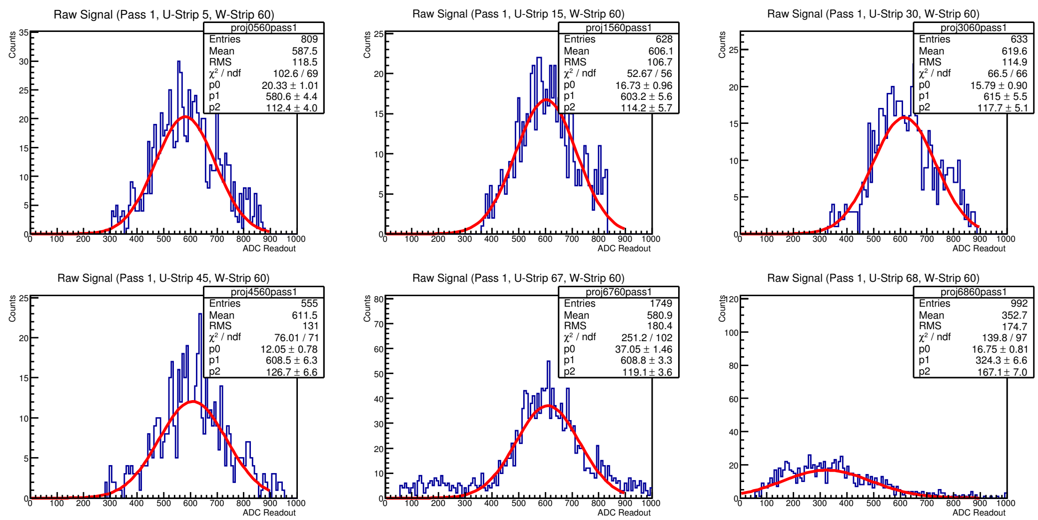


Figure 4.6: Shown is the ADC signal corresponding to signals from multiple u-strips (5, 15, 30, 45, 67, and 68) and a projection of the w60 strip.

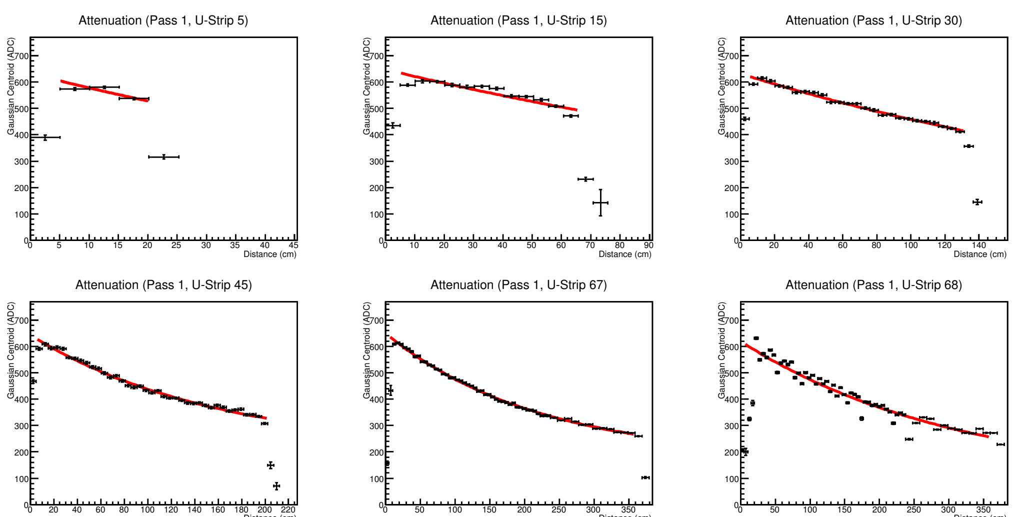


Figure 4.7: Shown is the overall attenuation fits to the selected u-strips (5, 15, 30, 45, 67, and 68).

4.2.3 Pass 2

- Multiplicity Cut: Only events where one PMT fired for each strip were allowed.
- Dalitz Cut: An empircal distance sum was used to remove events that don't fall into this range determined by Equation 4.
- Valid hit or near neighbor hit: Using generated events on a calculated skeleton of the pcal, each pixel was determined to be valid or not. Extra uncertainty was allowed by also marking nearest neighboring pixels.
- Cut on Attenuation Fits: When the signals where the Gaussian centroid from pass 1 were outside an ADC value of ± 50 from the attenuation fit, the obtained σ was ignored and a new cut about the attenuation fit was employed. If the centroid was close to ADC value from the attenuation fit a 2σ cut was used to remove extra background.

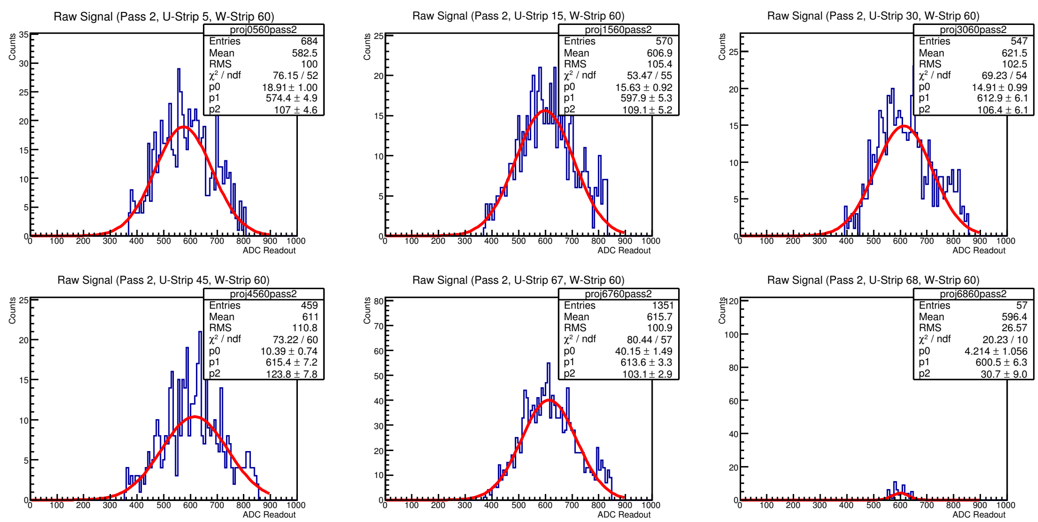


Figure 4.8: Shown is the ADC signal corresponding to signals from multiple u-strips (5, 15, 30, 45, 67, and 68) and a projection of the w60 strip.

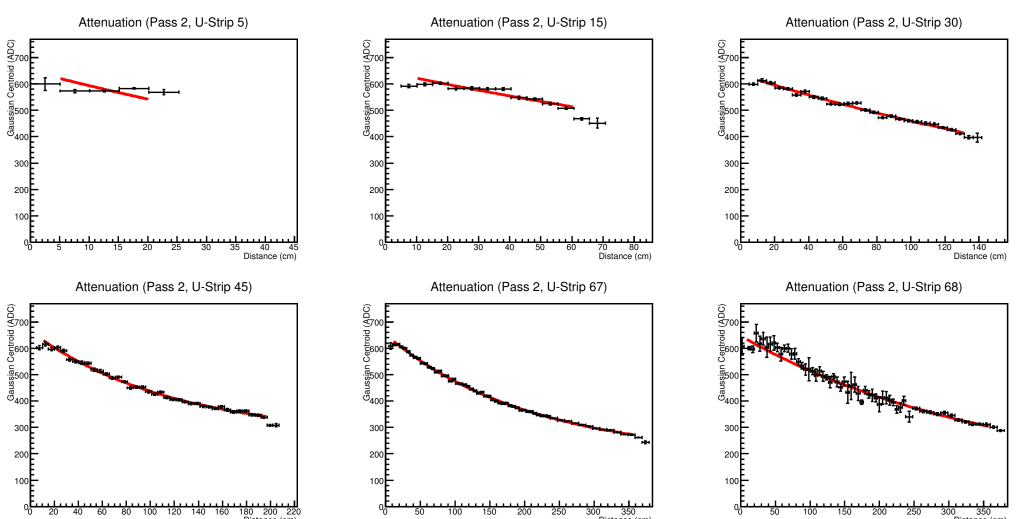


Figure 4.9: Shown is the overall attenuation fits to the selected u-strips (5, 15, 30, 45, 67, and 68).

4.2.4 Pass 3

- Multiplicity Cut: Only events where one PMT fired for each strip were allowed.
- Dalitz Cut: An empircal distance sum was used to remove events that don't fall into this range determined by Equation 4.
- Valid hit: Using generated events on a calculated skeleton of the pcal, each pixel was determined to be valid or not.
- 3σ Cut on Signal: Each signal was fit to a Gaussian in pass 2. The parameter σ from the Gaussian fit was used to cut out the events that did not lie within this function.
- Attenuation Corrected Intensity Cut: The ADC value measured was corrected with the attenuation curves obtained from pass 2. The corrected value was summed over each layer. A cut on this intensity was placed generously from 1300 to 2700

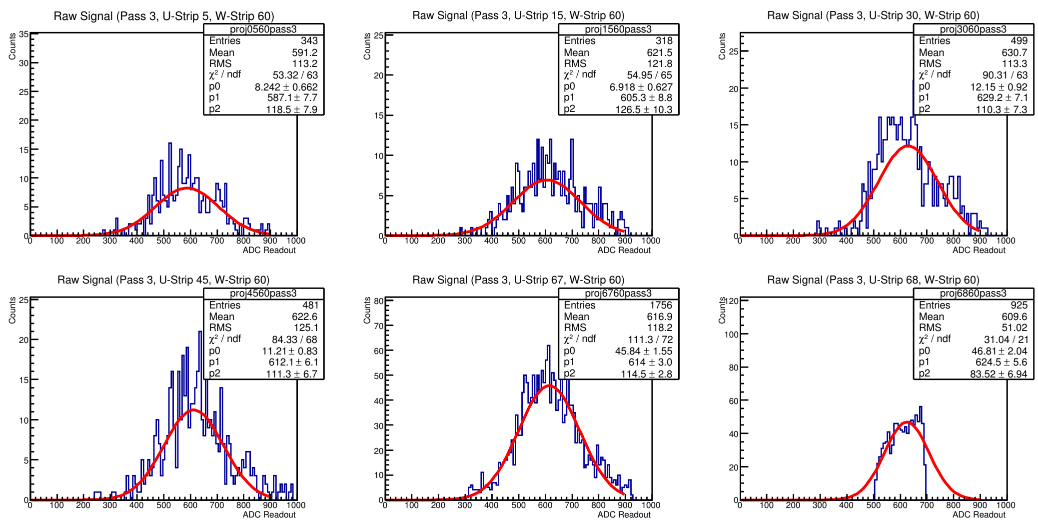


Figure 4.10: Shown is the ADC signal corresponding to signals from multiple u-strips (5, 15, 30, 45, 67, and 68) and a projection of the w60 strip.

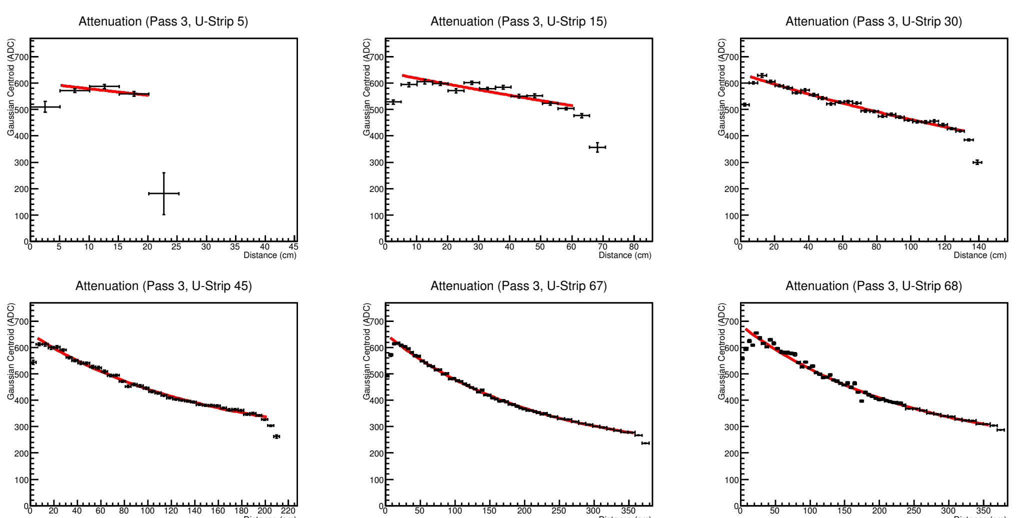


Figure 4.11: Shown is the overall attenuation fits to the selected u-strips (5, 15, 30, 45, 67, and 68).

4.2.5 Pass 4

- Multiplicity Cut: Only events where one PMT fired for each strip were allowed.
- Dalitz Cut: An empircal distance sum was used to remove events that don't fall into this range determined by Equation 4.
- Valid hit: Using generated events on a calculated skeleton of the pcal, each pixel was determined to be valid or not.
- 3σ Cut on Signal: Each signal was fit to a Gaussian in pass 2. The parameter σ from the Gaussian fit was used to cut out the events that did not lie within this function.
- Attenuation Corrected Intensity Cut: The ADC value measured was corrected with the attenuation curves obtained from pass 2. The corrected value was summed over each layer. A cut on this intensity was placed generously from 1300 to 2700

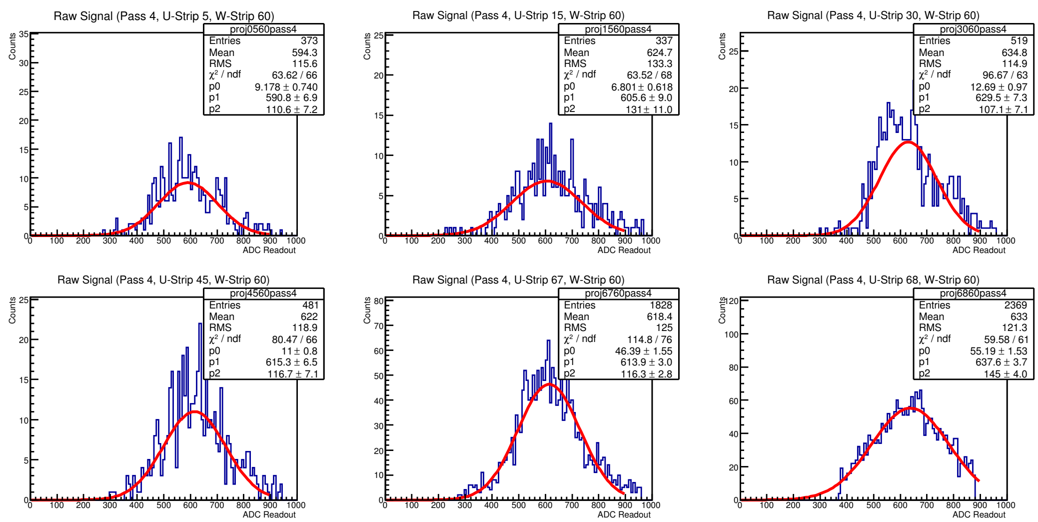


Figure 4.12: Shown is the ADC signal corresponding to signals from multiple u-strips (5, 15, 30, 45, 67, and 68) and a projection of the w60 strip.

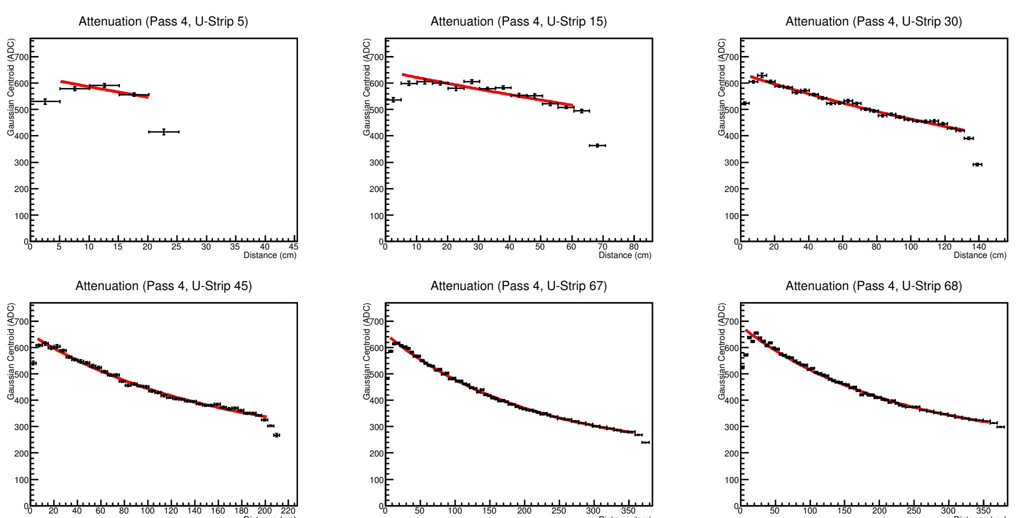


Figure 4.13: Shown is the overall attenuation fits to the selected u-strips (5, 15, 30, 45, 67, and 68).

4.2.6 Pass 5

- Multiplicity Cut: Only events where one PMT fired for each strip were allowed.
- Dalitz Cut: An empircal distance sum was used to remove events that don't fall into this range determined by Equation 4.
- Valid hit: Using generated events on a calculated skeleton of the pcal, each pixel was determined to be valid or not.
- 3σ Cut on Signal: Each signal was fit to a Gaussian in pass 2. The parameter σ from the Gaussian fit was used to cut out the events that did not lie within this function.
- Attenuation Corrected Intensity Cut: The ADC value measured was corrected with the attenuation curves obtained from pass 2. The corrected value was summed over each layer. A cut on this intensity was placed generously from 1300 to 2700

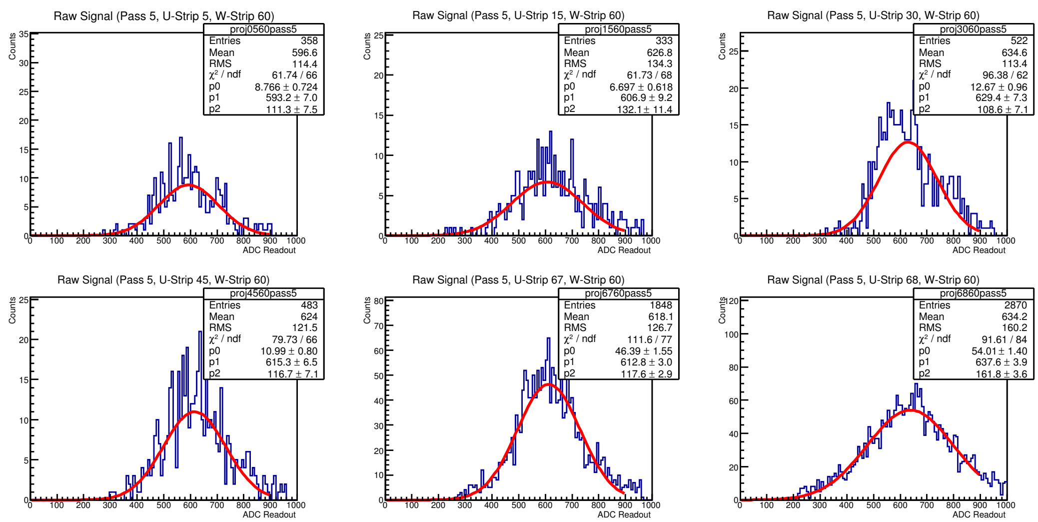


Figure 4.14: Shown is the ADC signal corresponding to signals from multiple u-strips (5, 15, 30, 45, 67, and 68) and a projection of the w60 strip.

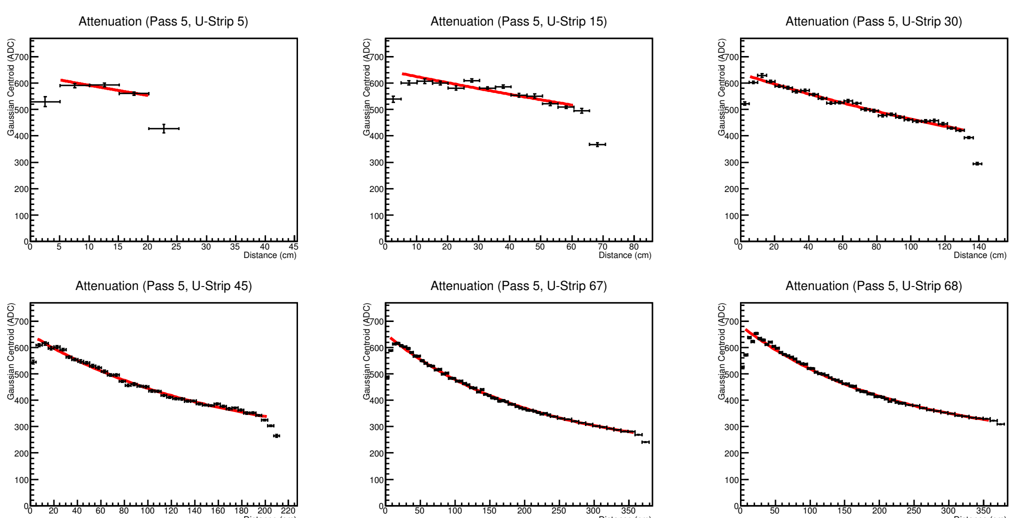
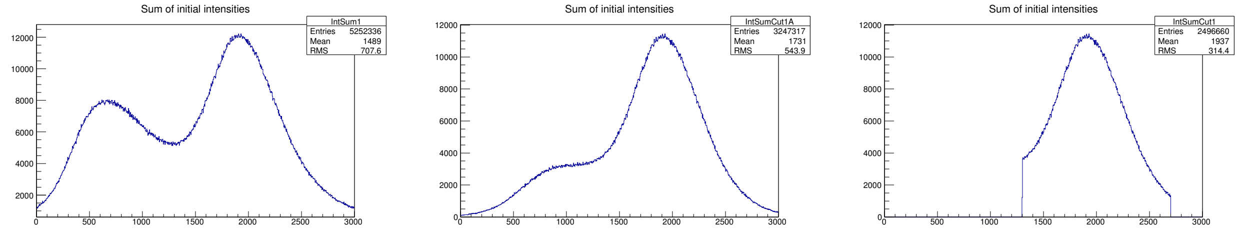


Figure 4.15: Shown is the overall attenuation fits to the selected u-strips (5, 15, 30, 45, 67, and 68).



(a) Sum of all initial intensities. No cuts.

(b) Sum of all initial intensities. Three sigma Cut.

(c) Sum of all initial intensities. Three sigma and sum Cut.

Figure 4.16: Sum of initial intensities should be near $650 \times 3 = 1950$ (after gain corrections).

4.3 Comparison of Fits

Possibly the best evidence for needed cuts about each signal in an iterative process is seen by looking at the raw signal fits for a w strip with the possible u projections. These comparisons can be seen from pass 0 to pass 5 in Figures 4.17 and 4.18. The difference between these signal tends to be cleaned up to a more Gaussian signal. By itself it is difficult to remove the backgound, but due to the correlating cuts on the u and v layers a reasonable output is produced.

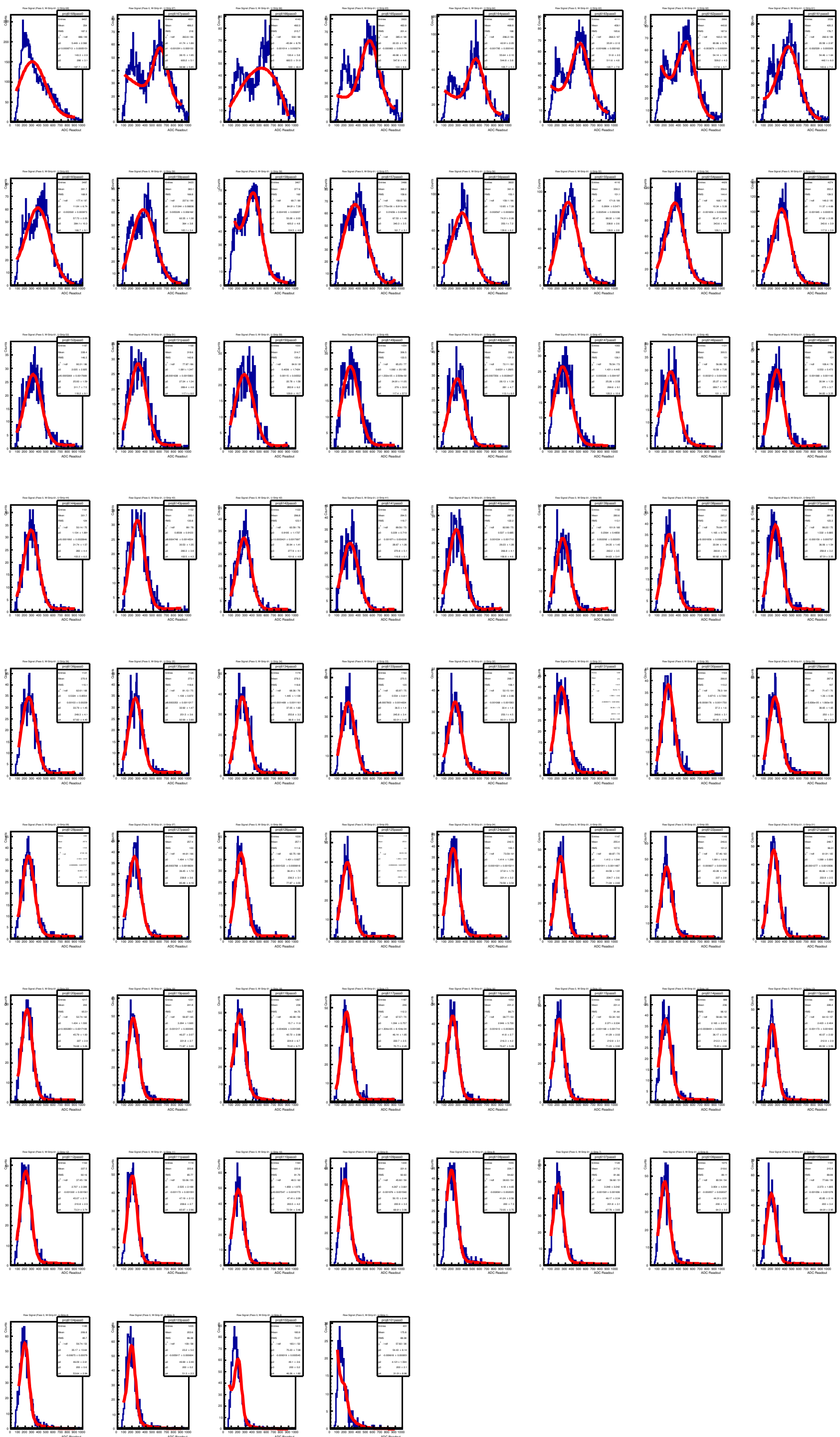


Figure 4.17: Shown is the ADC signal corresponding to signals from multiple u-strip projections of the w61 strip (pass0).

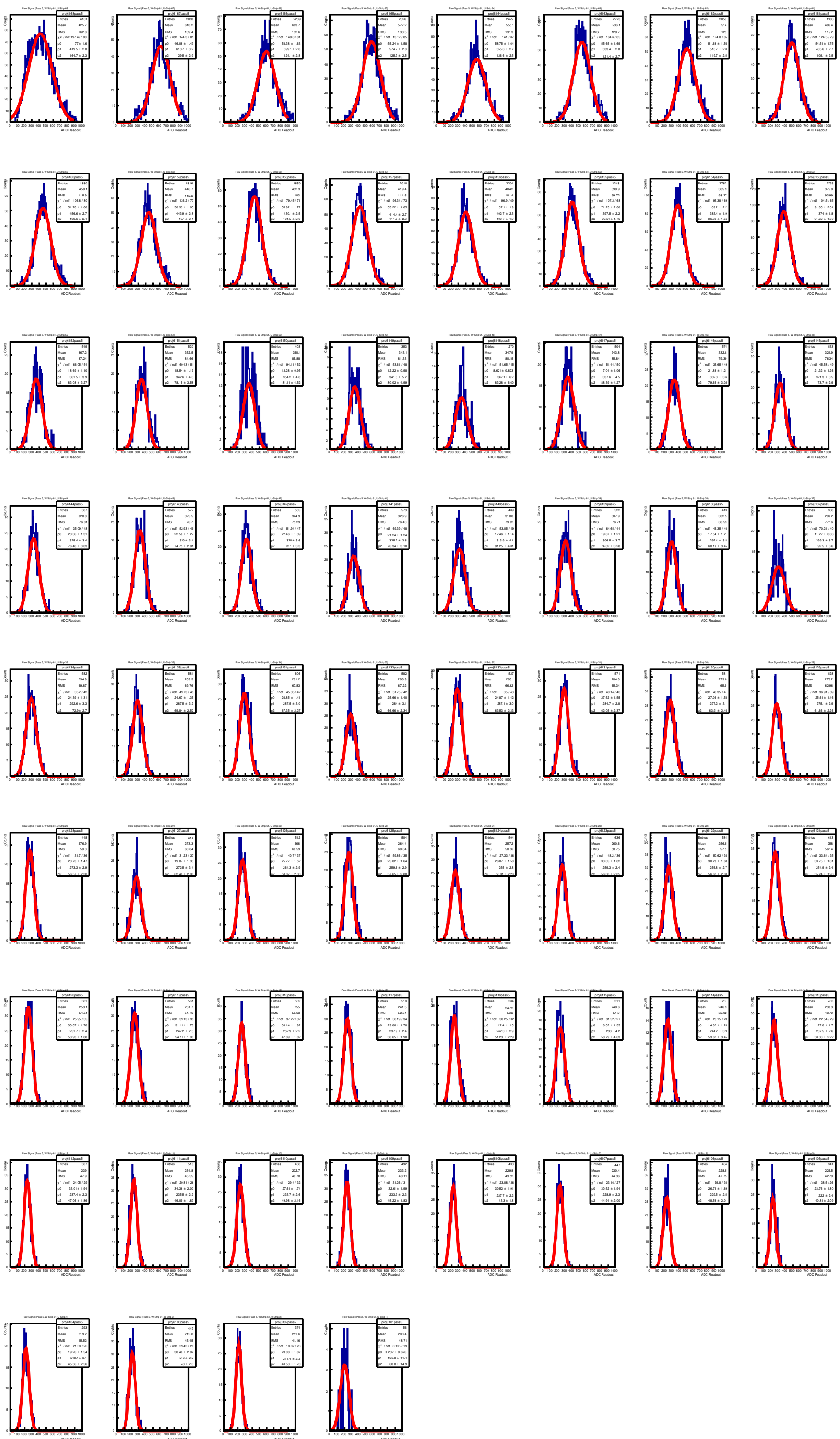


Figure 4.18: Shown is the ADC signal corresponding to signals from multiple u-strip projections of the w61 strip (pass5).

5 Light Attenuation

Fits are done based on 2-strip pixels corresponding to strip number. The strip number is converted into distance by a process using equations 1-3, equation 5, and an offset to have the distance quoted to the center of the physical bin. The exccess fiber lengths in theory could be added into the distance, but will only cause a shift in the fit. The fiber lengths are taken from the PCAL geometry note [1]. The Gaussian centroids can be found as a function of total distance from the edge of the PCAL unit. This total distance is fit to an exponential form.

5.1 Strip Number vs Distance

The overlaid strip numbers convert directly into distance as seen by Figure 5.1

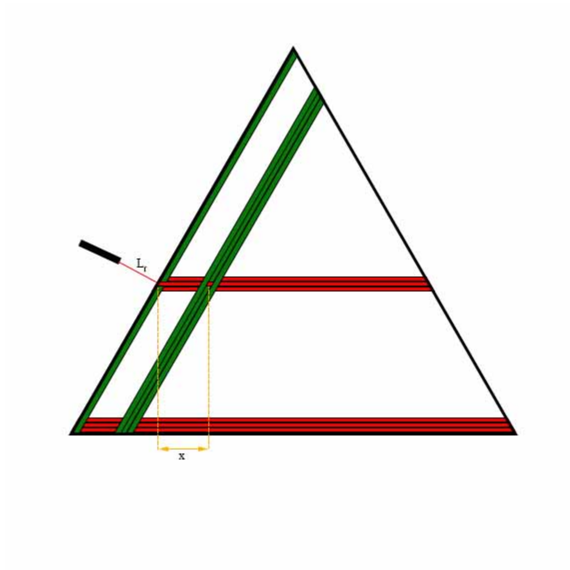


Figure 5.1: A cartoon schematic of the pcal unit demonstrates the method to correct for the light attenuation.

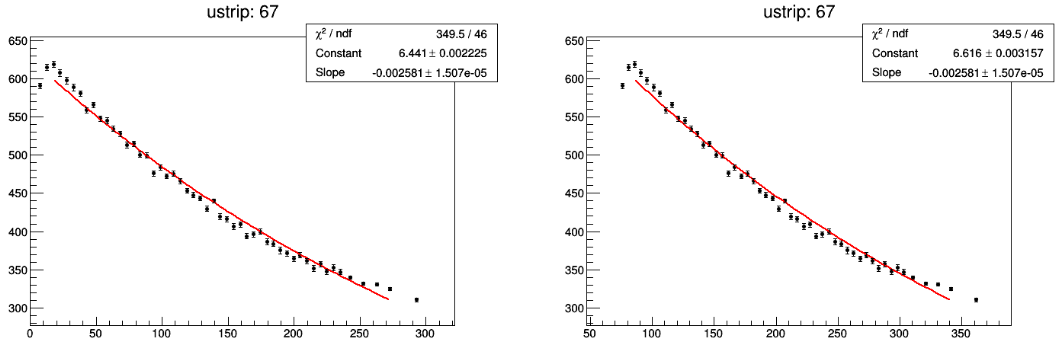
5.2 Fit Function

The fit function suggested in the geometry note is an exponential (equation 7). It is also suggested that here the distance, L, should include the distance from the end of the strip to the cosmic ray track, L_s, as well as the extra fiber length, L_f. In other words $L = L_s + L_f$. However to analyze the quality of fit L_f can be treated as a constant and absorbed into the parameter a in equation 7.

$$I = e^{a+bL} \tag{7}$$

As seen by figure 5.2, a single exponential may not be the best fit for the data. One might suggest a fitting function similar to equation 8, in order to separate the fiber attenuation from the scintillator attenuation. However this function again can reduce to equation 7 because L_f is a constant for each scintillator strip and is seen not to be a good fit.

$$\begin{aligned} I &= a_1 e^{b_1(L_s+L_f)} e^{b_2 L_s} \\ &= a_1 e^{b_1(L_s+L_f)+b_2 L_s} \\ &= a_1 e^{(b_1+b_2)L_s + b_1 L_f} \\ &= a_1 e^{b_1 L_f} e^{(b_1+b_2)L_s} \\ &= e^a e^{(b_1+b_2)L_s} \\ &= e^a e^{bL_s} \\ &= e^{a+bL_s} \end{aligned} \tag{8}$$



(a) Shown is a fit with equation 7, where the y axis is the ADC value and the x axis is L_s.

(b) Shown is a fit with equation 7, where the y axis is the ADC value and the x axis is $L_s + L_f$.

Figure 5.2: Plotted is the fit of equation 7, where $L = L_s$ (a) and $L = L_s + L_f$ (b).

Other functional forms that could represent the data should be similar to that of an exponential. A couple of these forms include an exponential plus a constant or a sum of exponentials. In both cases, some considerations have to be made on the domain of the function. The sum of two exponentials was considered to have some portion of the attenuation in the fibers to be different than inside the scintillator. This does not get a better fit, and does not allow any more information to be extracted. Therefore the function used in fitting the attenuation was chosen to be an exponential with an added constant as seen by Equation 9.

$$I(L_s) = ae^{bL_s} + c \tag{9}$$

5.3 Calibration Constants

A table of constants can be uploaded to the clas12 database once the fitting procedure is complete. On strips where less than five points were available for fitting, either a single exponential or a constant term was used for the fitting function. This was done to avoid situations with more parameters than points available. In general the less points available for the fit, the shorter the strip is, allowing for less of a need for a correction. All the fits shown are for Sector One of the PCAL.

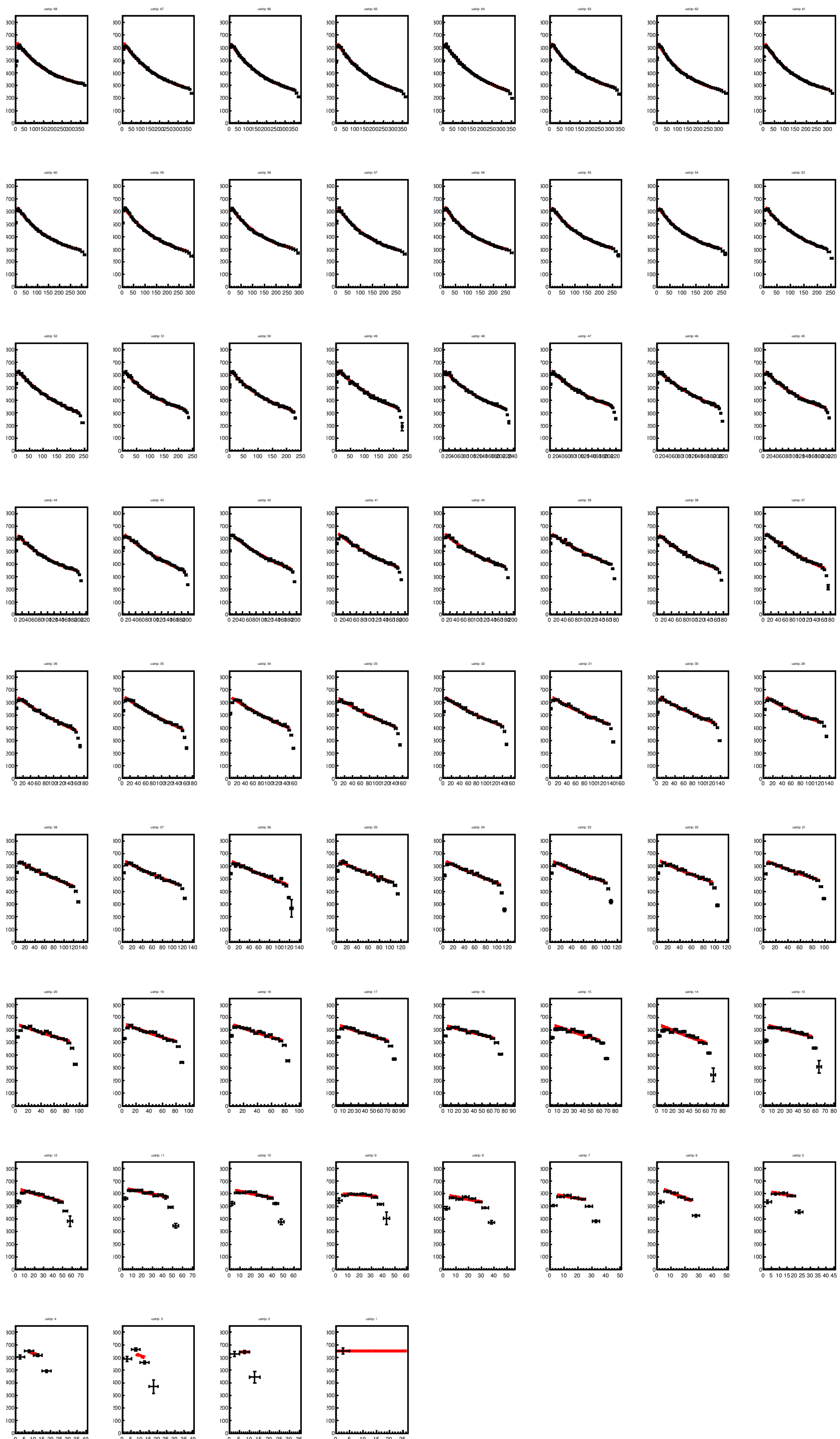


Figure 5.3: Plotted are all of the u strip attenuation plots starting at 68 in the upper left hand corner. These plots are all plotted on a linear scale. The y-axis is set from 0 to 850 and the x-axis varies depending on the number of points in the plot.

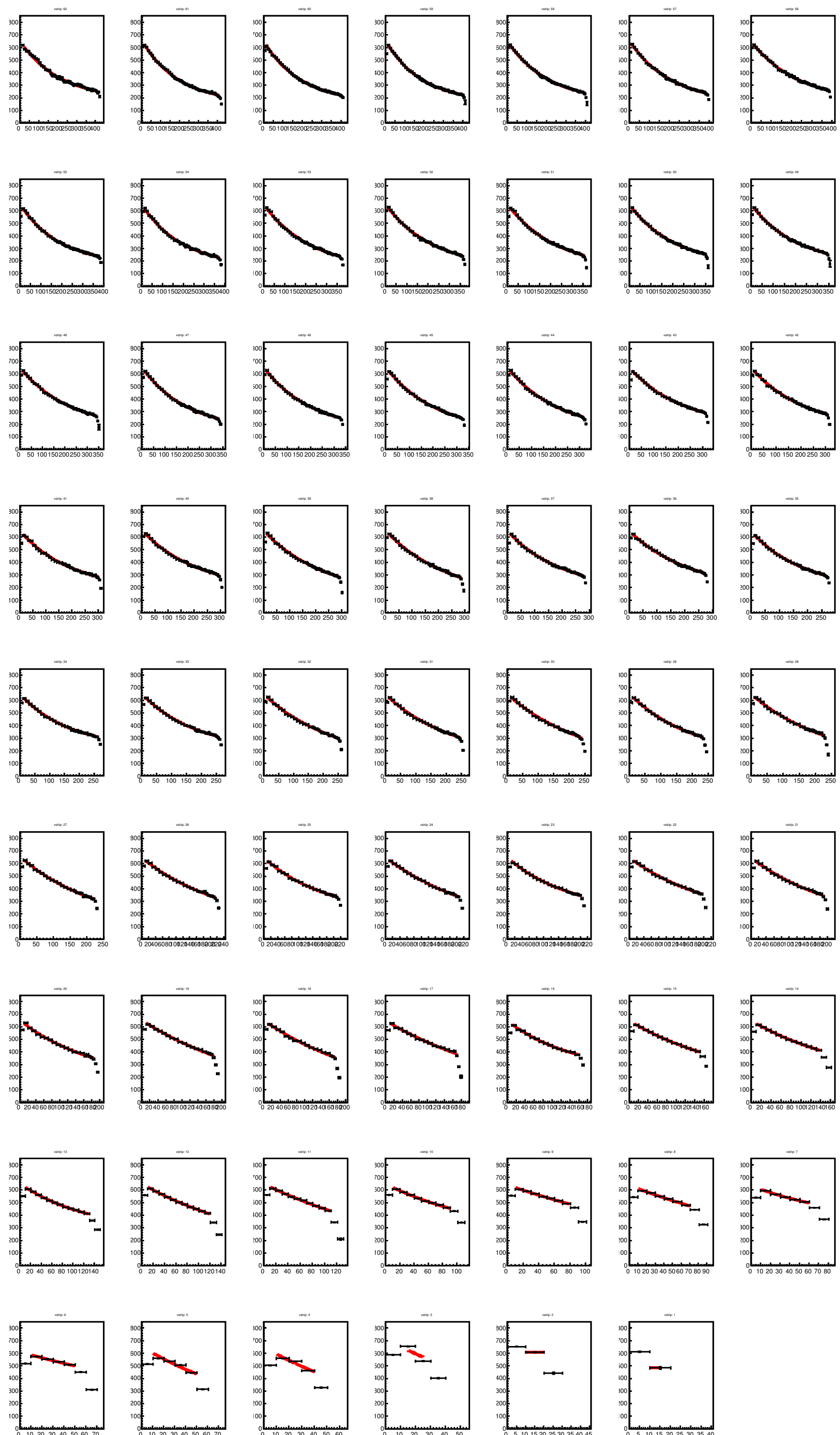


Figure 5.4: Plotted are all of the v strip attenuation plots starting at 62 in the upper left hand corner. These plots are all plotted on a linear scale. The y-axis is set from 0 to 850 and the x-axis varies depending on the number of points in the plot.

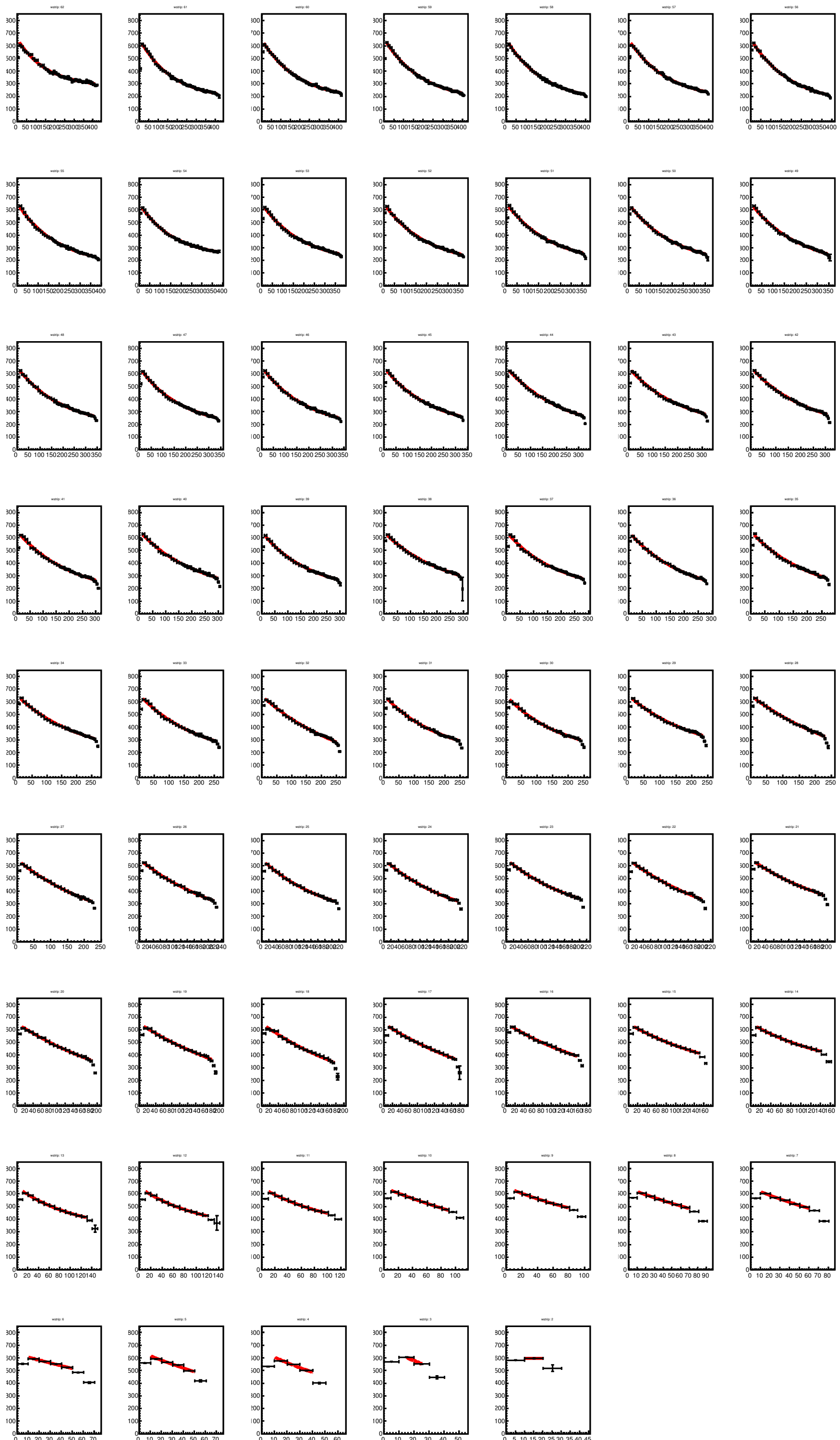


Figure 5.5: Plotted are all of the w strip attenuation plots starting at 62 in the upper left hand corner. These plots are all plotted on a linear scale. The y-axis is set from 0 to 850 and the x-axis varies depending on the number of points in the plot.

U-Strip	Parameter a	Parameter b	Parameter c
1	650	0	0
2	650	0	0
3	650	-0.009	0
4	650	-0.009	0
5	616.113	-0.00639717	33.8858
6	649.996	-0.00717551	0.0046356
7	649.968	-0.00318808	0.0319326
8	649.972	-0.00232476	0.0273016
9	649.146	-0.00112904	0.854413
10	649.999	-0.00281005	0.000286188
11	649.993	-0.00286292	0.00718601
12	650	-0.0041656	0.000445736
13	650	-0.003283	0.000103724
14	649.997	-0.00376077	5.37227e-06
15	650.001	-0.00339912	6.96689e-06
16	649.997	-0.00305411	8.14649e-06
17	649.999	-0.00345134	9.95183e-09
18	649.998	-0.00310718	4.19396e-07
19	650	-0.00311517	5.01049e-06
20	650	-0.00281725	6.09084e-06
21	650	-0.00315783	3.38135e-05
22	650	-0.00328681	2.55834e-08
23	650	-0.00316776	2.15877e-05
24	649.999	-0.00317021	4.66803e-05
25	650	-0.00327065	5.9556e-06
26	650.001	-0.00309179	1.40689e-08
27	551.087	-0.00385902	98.9141
28	649.997	-0.00307714	7.49416e-05
29	419.522	-0.00552754	230.477
30	650	-0.00316014	0.000130702
31	650.001	-0.00312815	2.25921e-06
32	585.658	-0.00373922	64.3455
33	581.001	-0.00374214	68.997
34	650.002	-0.00328878	0.000131253
35	650	-0.00332314	1.43305e-05
36	649.998	-0.00340294	1.07435e-07
37	556.399	-0.00428136	93.5991
38	483.854	-0.00534903	166.146
39	482.458	-0.00431684	167.541
40	392.765	-0.00669036	257.235
41	499.22	-0.00443664	150.78
42	513.839	-0.00445738	136.164
43	581.507	-0.00388427	68.4914
44	391.463	-0.00757633	258.536
45	434.393	-0.00632194	215.608
46	463.813	-0.00513914	186.187
47	413.809	-0.00605594	236.189
48	442.234	-0.00592955	207.766
49	509.976	-0.00449146	140.024
50	443.895	-0.00614484	206.105
51	425.765	-0.00641114	224.233
52	504.812	-0.00511618	145.188
53	454.838	-0.0061679	195.162
54	406.411	-0.00766326	243.589
55	415.976	-0.00690821	234.026
56	421.326	-0.00710769	228.675
57	435.635	-0.00660386	214.362
58	411.518	-0.00663318	238.483
59	438.882	-0.00625669	211.118
60	423.763	-0.00618908	226.238
61	444.671	-0.0063621	205.328
62	438.481	-0.00674885	211.519
63	437.138	-0.00564978	212.862
64	482.525	-0.00495599	167.473
65	473.388	-0.00516614	176.613
66	465.633	-0.00500512	184.367
67	455.941	-0.00479029	194.059
68	410.201	-0.00506009	239.798

Table 1: Calibration Constants for the U layer.

V-Strip	Parameter a	Parameter b	Parameter c
1	650.002	0	0
2	649.999	0	0
3	650.001	-0.009	0
4	650.001	-0.009	8.41036e-07
5	650	-0.00794645	5.04738e-06
6	649.225	-0.00402729	0.773706
7	341.165	-0.009	308.835
8	649.999	-0.0043402	0.000921065
9	650	-0.00346629	0.00030414
10	409.661	-0.0073313	240.338
11	650	-0.0036951	0.000157707
12	543.255	-0.00487653	106.745
13	385.429	-0.00755387	264.571
14	462.536	-0.00523798	187.463
15	490.318	-0.00478212	159.682
16	409.407	-0.00682511	240.592
17	644.496	-0.00311038	5.50402
18	649.997	-0.00345834	1.60129e-06
19	650	-0.00314254	4.40293e-06
20	476.84	-0.00525174	173.161
21	504.696	-0.00482932	145.304
22	501.641	-0.00447931	148.359
23	427.011	-0.00618067	222.989
24	532.597	-0.00429752	117.404
25	452.731	-0.00555935	197.267
26	514.63	-0.00444436	135.371
27	562.158	-0.00411837	87.8438
28	552.525	-0.00397784	97.4754
29	505.009	-0.00490977	144.992
30	545.684	-0.00417772	104.316
31	520.37	-0.00441109	129.628
32	545.125	-0.00412529	104.875
33	454.001	-0.00531295	195.999
34	430.052	-0.00591867	219.949
35	472.603	-0.00523221	177.394
36	479.173	-0.0044464	170.826
37	472.073	-0.00500161	177.926
38	521.65	-0.00433543	128.35
39	523.67	-0.00413843	126.33
40	475.448	-0.00450584	174.551
41	463.401	-0.0051012	186.6
42	486.03	-0.0046867	163.97
43	474.905	-0.00454652	175.094
44	512.336	-0.00460079	137.664
45	518.211	-0.00460405	131.79
46	503.032	-0.00487218	146.968
47	501.666	-0.00500745	148.335
48	488.139	-0.00450074	161.861
49	479.791	-0.00489837	170.209
50	487.47	-0.00479649	162.531
51	516.592	-0.0043148	133.409
52	504.835	-0.0045441	145.166
53	516.386	-0.00442848	133.615
54	493.162	-0.0051403	156.838
55	475.544	-0.00530062	174.455
56	483.85	-0.00428974	166.15
57	493.428	-0.00469419	156.572
58	485.197	-0.00470872	164.802
59	484.814	-0.00529538	165.185
60	492.715	-0.00499336	157.285
61	496.221	-0.00497787	153.779
62	472.264	-0.00469273	177.736

Table 2: Calibration Constants for the V layer.

W-Strip	Parameter a	Parameter b	Parameter c
1	650	0	0
0	650	0	0
0	650	-0.009	0
0	649.996	-0.00691378	0.00571745
0	650	-0.00558302	0.000738429
0	649.98	-0.00407219	0.0177906
0	422.924	-0.0082021	227.077
0	505.741	-0.00555023	144.259
0	372.286	-0.00737429	277.714
0	649.979	-0.00366028	0.0192191
0	650.001	-0.00372954	0.00118075
0	342.164	-0.009	307.836
0	355.773	-0.00855197	294.227
0	363.361	-0.00666561	286.64
0	434.311	-0.00525056	215.689
0	556.671	-0.00394053	93.3294
0	649.998	-0.00335208	7.53184e-06
0	650.001	-0.00360869	0.000280125
0	650	-0.00315057	1.4947e-05
0	650	-0.00319373	1.11969e-05
0	527.95	-0.00400632	122.05
0	618.622	-0.00362112	31.3758
0	500.057	-0.00478853	149.941
0	548.15	-0.00446747	101.85
0	479.19	-0.00563269	170.81
0	577.911	-0.00381978	72.0904
0	571.915	-0.00386651	78.0872
0	650	-0.00301759	6.97793e-06
0	476.296	-0.00466684	173.704
0	469.596	-0.0056956	180.406
0	483.094	-0.00545448	166.906
0	648.632	-0.0033354	1.3664
0	496.17	-0.00515118	153.83
0	487.383	-0.00461829	162.617
0	506.497	-0.00489625	143.503
0	517.17	-0.00494086	132.832
0	464.957	-0.00562927	185.046
0	481.521	-0.00435674	168.479
0	461.989	-0.00582562	188.011
0	499.489	-0.00442904	150.51
0	506.749	-0.00475107	143.248
0	502.841	-0.00434983	147.157
0	469.808	-0.00484038	180.192
0	527.099	-0.00412014	122.901
0	486.457	-0.00490661	163.543
0	489.691	-0.00510504	160.309
0	471.254	-0.00553953	178.746
0	472.808	-0.0050091	177.192
0	509.753	-0.00440386	140.247
0	487.851	-0.00484449	162.148
0	484.151	-0.0047396	165.851
0	479.294	-0.00498712	170.706
0	468.169	-0.00519666	181.83
0	427.693	-0.00598915	222.306
0	491.659	-0.00526729	158.341
0	514.732	-0.0050567	135.269
0	475.716	-0.00527028	174.285
0	500.373	-0.00518313	149.628
0	496.167	-0.00495883	153.833
0	475.153	-0.00531751	174.847
0	476.541	-0.00557183	173.458
0	371.958	-0.00688108	278.043

Table 3: Calibration Constants for the W layer.

U-Strip	Gain
68	0.919826
67	0.994387
66	0.996668
65	1.13365
64	1.0289
63	0.988108
62	1.05729
61	1.00024
60	0.918702
59	0.937388
58	0.971579
57	0.968278
56	0.9886
55	1.01584
54	0.972431
53	0.985789
52	1.06724
51	1.06537
50	1.15373
49	1.05132
48	1.05095
47	0.990354
46	1.05387
45	1.00345
44	0.90308
43	1.05416
42	1.03789
41	1.08503
40	0.964149
39	0.984689
38	1.07509
37	1.02063
36	0.973037
35	0.960093
34	0.999216
33	1.01442
32	0.966014
31	1.01264
30	1.01884
29	0.99361
28	1.12513
27	1.11908
26	1.14991
25	0.99626
24	1.01688
23	1.04101
22	0.993246
21	1.00052
20	0.927249
19	0.943803
18	0.975746
17	1.0319
16	1.05238
15	1.03268
14	0.999323
13	1.07013
12	0.974823
11	1.02237
10	1.0473
9	1.00103
8	1.13001
7	0.979758
6	0.945828
5	1.06426
4	1.08689
3	1.00753
2	1.03341
1	2.38937

(a) Gains for the U layer.

V-Strip	Gain
62	0.856903
61	0.975891
60	0.957263
59	0.984709
58	0.945978
57	0.94414
56	0.929243
55	0.981845
54	1.00783
53	0.970635
52	0.99664
51	0.984337
50	0.9841
49	1.02766
48	0.972439
47	1.05155
46	1.03861
45	0.98368
44	1.00809
43	0.991325
42	0.989896
41	0.965113
40	0.939102
39	1.05284
38	1.04087
37	0.972662
36	0.980653
35	0.993551
34	0.961802
33	1.01387
32	1.03706
31	1.04414
30	1.00396
29	0.994342
28	0.993199
27	1.00151
26	1.04742
25	1.05564
24	1.08135
23	0.971184
22	0.916638
21	1.026
20	0.978999
19	1.0785
18	1.03334
17	1.00605
16	1.02326
15	0.947529
14	0.943325
13	0.978369
12	0.965212
11	0.94848
10	1.05385
9	0.960673
8	1.04593
7	0.965207
6	0.930664
5	0.924364
4	0.906707
3	0.994952
2	1.11947
1	1.16553

(b) Gains for the V layer.

W-Strip	Gain
62	0.984625
61	1.04515
60	0.984452
59	1.05211
58	1.01464
57	1.01152
56	1.12032
55	1.08628
54	1.04743
53	1.03443
52	0.973068
51	0.986971
50	1.0584
49	1.02468
48	1.00968
47	1.03928
46	1.1033
45	1.00978
44	1.01194
43	0.991657
42	1.04533
41	1.07685
40	1.0462
39	1.01952
38	1.04494
37	0.940542
36	1.07141
35	1.02338
34	1.01296
33	0.977284
32	1.11503
31	0.955289
30	1.00997
29	0.980596
28	0.999784
27	1.0662
26	1.01917
25	0.998049
24	1.07542
23	1.01097
22	1.00608
21	0.995989
20	1.00445
19	1.04812
18	1.05886
17	1.00316
16	1.00583
15	0.920611
14	0.95728
13	0.928774
12	0.932801
11	0.975309
10	1.02923
9	0.969189
8	0.978204
7	0.927413
6	1.01355
5	1.00309
4	0.965665
3	0.959464
2	1.1257
1	1

(c) Gains for the W layer.

Table 4: Preliminary Gains

6 Calibration Studies

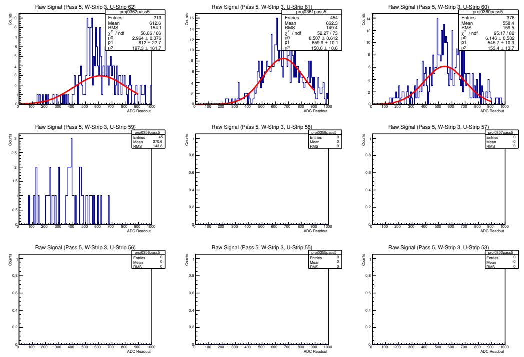
6.1 Optimal ADC Bin Size

A study was performed to view an optimal binning of the ADC readout. The ADC readout was plotted from zero to one thousand. This study looked at the effect from variation of the number of bins. The final Gaussian fit was used on each signal pixel when finding differences. It is clear that the optimal binsize is limited by the small pixel readouts, or the portion of the detector nearest the beam line. Therefore a reasonable limit on the smallest bin size (for these statistics) was estimated to be around $\frac{1000}{200} = 5$ on the ADC readout. To get more trustworthy fits a choice was made of bin size to be $\frac{1000}{125} = 8$ on the ADC readout.

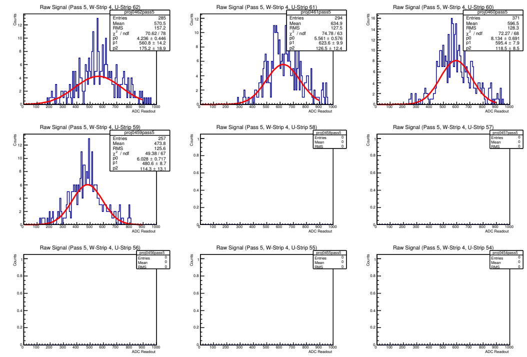
6.2 Minimum Statistics

A minor study was conducted to determine the minimum statistics needed for calibration of the PCAL unit. However, this is tangled into multiple different components. Adjusting the bin size might affect the total statistics needed. This study only focuses on the optimal bin size determined by section 6.1. Another factor for the amount of statistics needed is the physical bin size. This limits the overall statisics to the lowest number needed to calibrate the shortest strips (i.e. low u strip number, high w/v strip number). Figure 6.1 shows the first few u-strips (strips 3 through 8), that are physically binned by the w-strips.

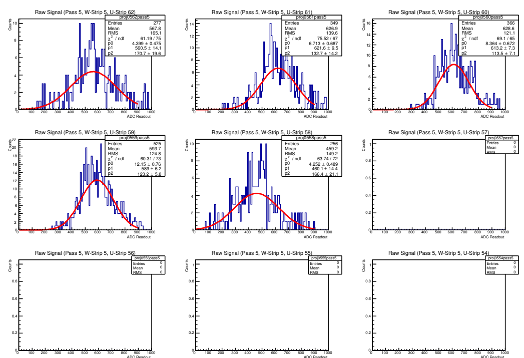
If these strips are to be calibrated and the ADC bin size is to stay the same, then based on these plots the minimum statistics needed is roughly equal to the data obtained currently. This analysis contains 5.2 billion post-skimmed events. This equilavates to a days worth of data with the PCAL unit laid out horizontally. Due to the decrease of the cosmic ray flux when the unit is vertically aligned, a larger time scale will be needed.



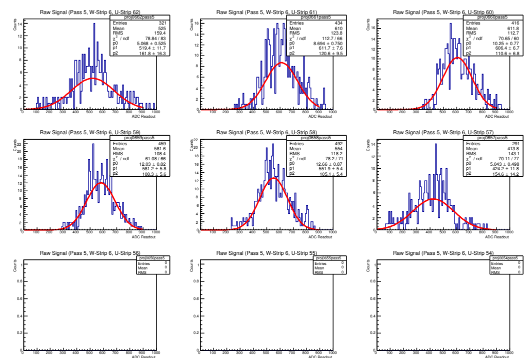
(a) Shown are all of the w projections onto u-strip 3. The distribution shown peaks around 15 counts.



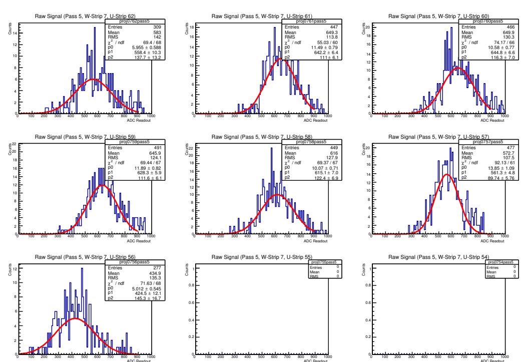
(b) Shown are all of the w projections onto u-strip 4. The distribution shown peaks around 15 counts.



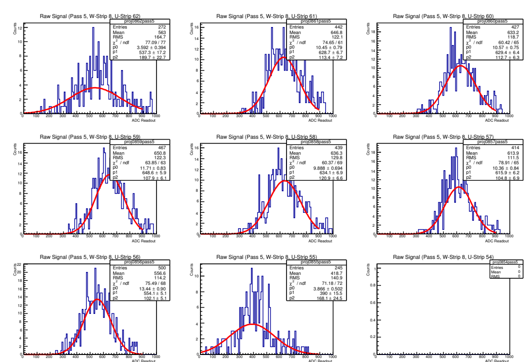
(c) Shown are all of the w projections onto u-strip 5. The distribution shown peaks around 15 counts.



(d) Shown are all of the w projections onto u-strip 6. The distribution shown peaks around 15 counts.



(e) Shown are all of the w projections onto u-strip 7. The distribution shown peaks around 15 counts.



(f) Shown are all of the w projections onto u-strip 8. The distribution shown peaks around 15 counts.

Figure 6.1: Plotted are a six of the short scintillator strips. Each subfigure shows projections of the last 9 w-strips. Therefore these plot axises are counts versus ADC value detected by the u layer PMT.

7 Simulation

This section deals with extraction of the attenuation coefficients in the JAVA framework. Generation of simulated events is discussed, followed by a brief description of the cuts that are applied. Then the ADC signals are fit for each overlap shape at a specific distance from the PMT ends to extract the coefficients.

7.1 GEMC: Event Generation

Events are generated using the GEMC software which uses a *gcard*:

```
gemc gcard/fc-ecpcsc-s2.gcard -RUNNO=12 -N=5000000 -USE_GUI=0
```

The attenuation constants extracted from the data are saved in the database as CCDB constants. These constants (with gains normalized) are picked up by the *gcard* with RUNNO=12. When executed with the above command, 5,000,000 events are produced. A snapshot of the code snippet is shown in Fig. 7.1. A total of 3 million events are generated in module 2 of the PCAL unit in order to do the simulation studies.

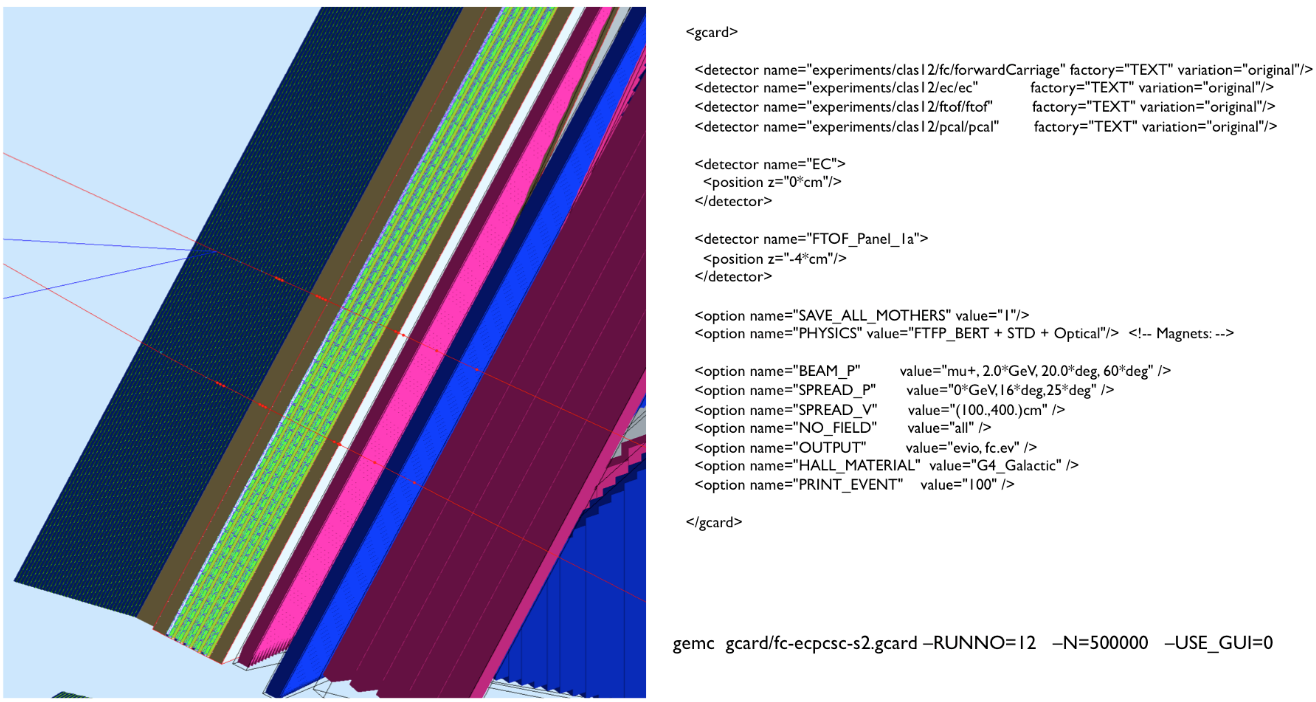


Figure 7.1: Snippet of the code to produce simulated events using GEMC. The graphic shows two muon tracks passing from right to left.

7.2 Input: Generation coefficient

The attenuation coefficients given in Tables 1, 2 and 3 are used as the generation coefficients. In the attenuation equation,

$$y = Ae^{Bx} + C \tag{10}$$

A, B and C are the attenuation coefficients and $A + C$ is defined as the gain. The gain was normalized to an *ad hoc* MeV muon. The normalized values are fed as the generation input, which, as previously mentioned, are picked up by the *gcard*. Here distance is the variable x.

7.3 Cuts Applied

Different cuts wherever relevant should be applied to ensure a more accurate calibration. The ADC distributions of the generated events are much cleaner as they contain no background. However, they do contain corner clippers.

Therefore, to be consistent with the method used for the calibration of the data, two cuts are made so far: the multiplicity cut and the valid pixel cut. These cuts are discussed below:

7.3.1 Multiplicity Cut

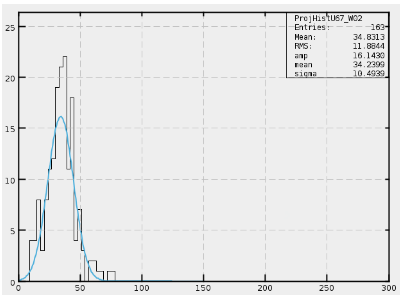
Only events with exactly one U-hit, one V-hit and one W-hit are selected. This will also help to reduce/remove events which are not relatively perpendicular to the surface of the PCAL module. Events which do not pass this cut are removed from the analysis.

7.3.2 Valid Pixel Cut

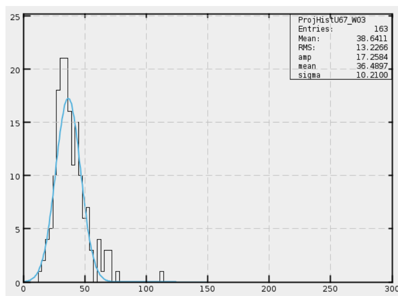
Another condition required for the events to be selected is that they are within the physical shape made by the overlap. The database geometry provides with the coordinates of the vertices of the PCAL module which can be used to construct pixel and overlap shapes. Events with only one hit in these shapes in each view is only taken into account. The shapes which pass this cut are termed as the valid pixel/overlap shapes. Events that do not fall within these shapes are removed from the analysis. In other words, this cut ensures the signal track was physically valid and relatively perpendicular with respect to the face of the PCAL module.

7.4 ADC signals and fits

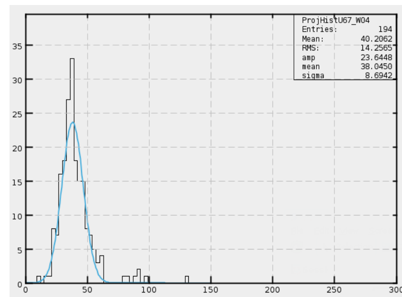
The events that passed the cuts are binned according to which strip is being calibrated. For example, to calibrate U-strips, bins of W cross-strips are used. In most of these bins a Gaussian function describes the ADC distribution reasonably well. The centroids for such bins are approximated from the Gaussian fits. However, it is also found that some bins have very small number of counts and the Gaussian funtion can not define the distribution accurately. To account for that a fit condition is employed. If the number of events is less than 20, the statitical mean is used as the centroid. The process is repeated for every strip in each view. The ADC distributions and the Gaussian fits for U67 are shown in Figures 7.2-7.6.



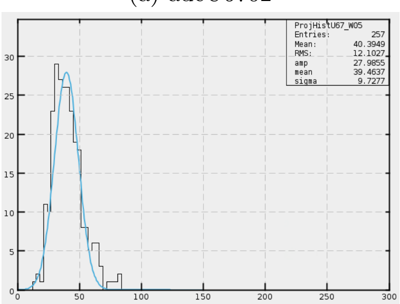
(a) adcU6702



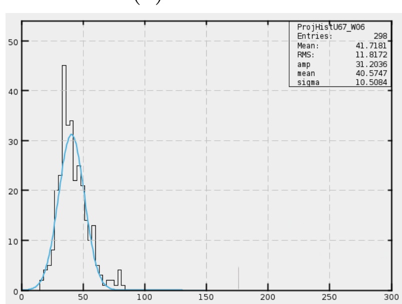
(b) adcU6703



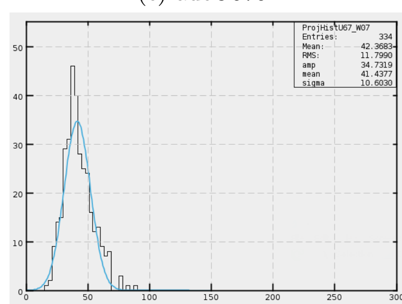
(c) adcU6704



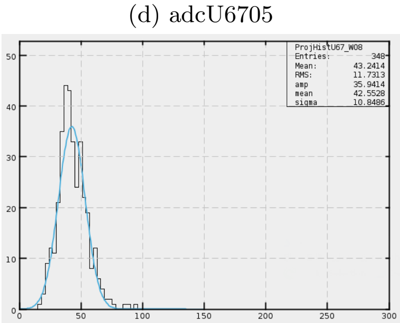
(d) adcU6705



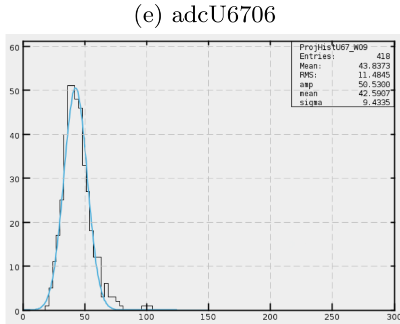
(e) adcU6706



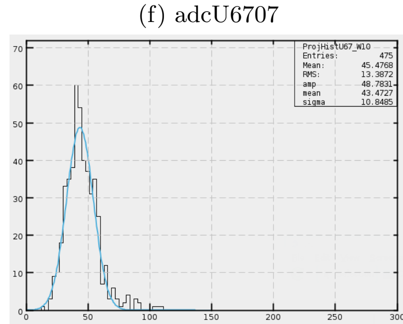
(f) adcU6707



(g) adcU6708

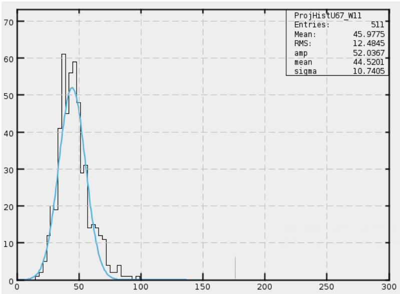


(h) adcU6709

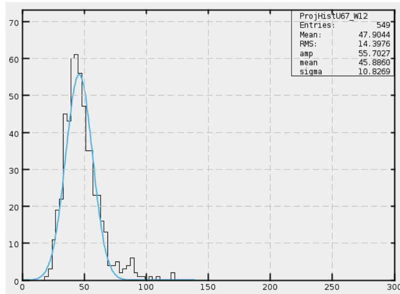


(i) adcU6710

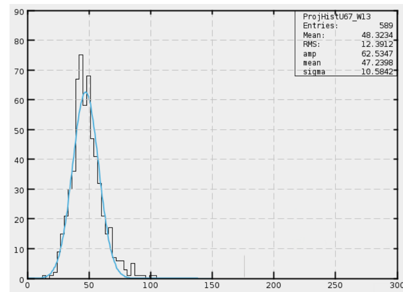
Figure 7.2: ADC distribution for U67. The last two digits in the caption of each figure represent the bin number based on the W strip. Blue curve is the Gaussian fit.



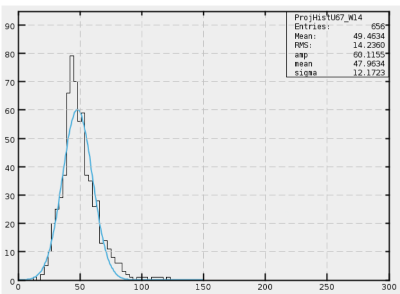
(a) adcU6711



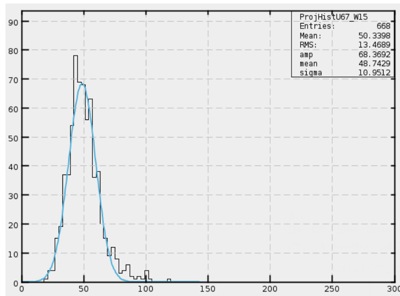
(b) adcU6712



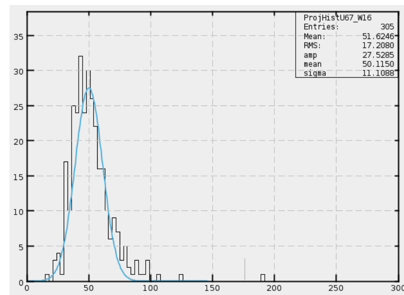
(c) adcU6713



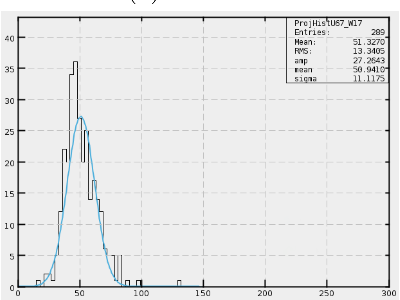
(d) adcU6714



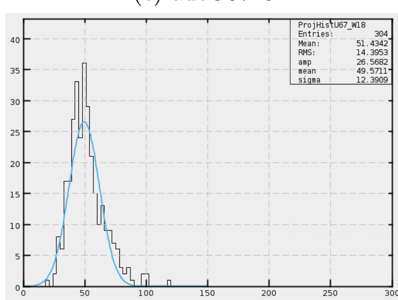
(e) adcU6715



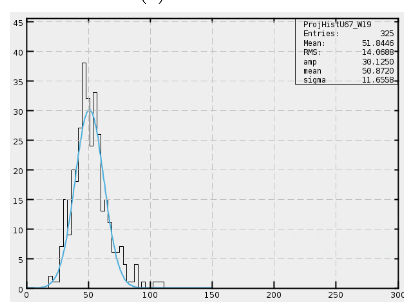
(f) adcU6716



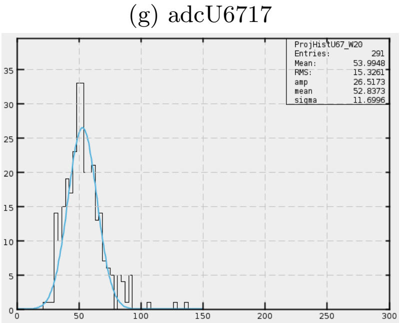
(g) adcU6717



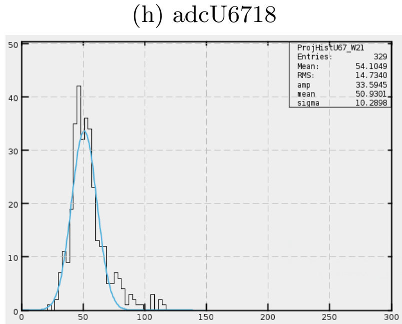
(h) adcU6718



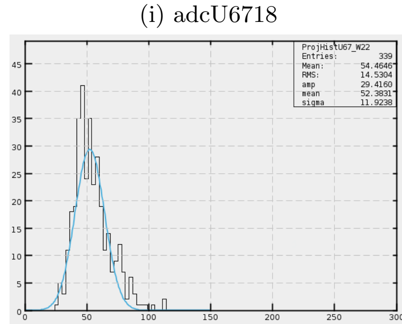
(i) adcU6718



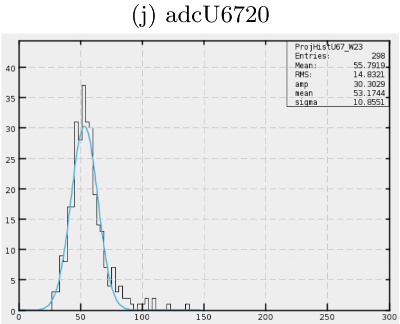
(j) adcU6720



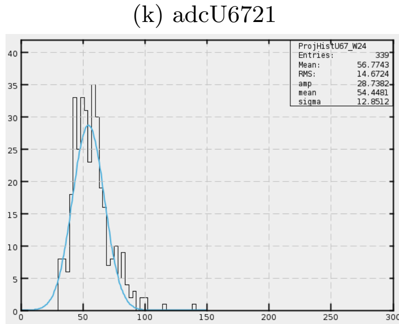
(k) adcU6721



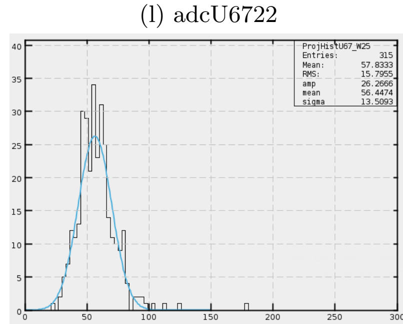
(l) adcU6722



(m) adcU6723

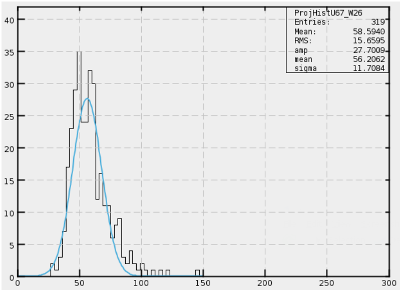


(n) adcU6724

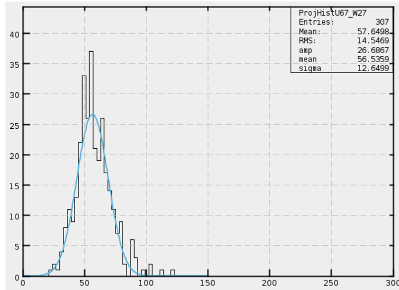


(o) adcU6725

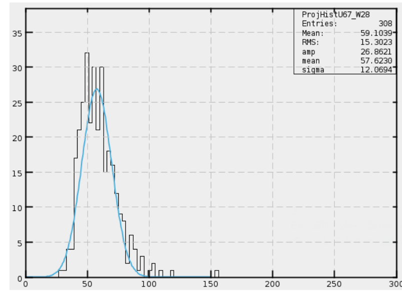
Figure 7.3: ADC distribution for U67. The last two digits in the caption of each figure represent the bin number based on the W strip. Blue curve is the Gaussian fit.



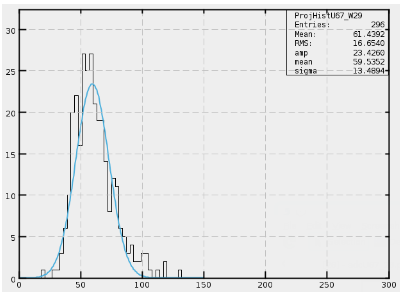
(a) adcU6726



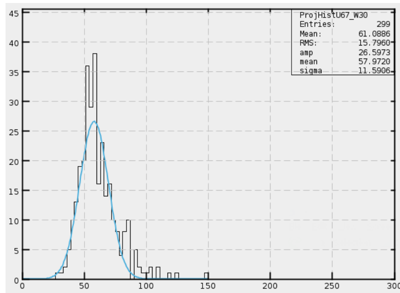
(b) adcU6727



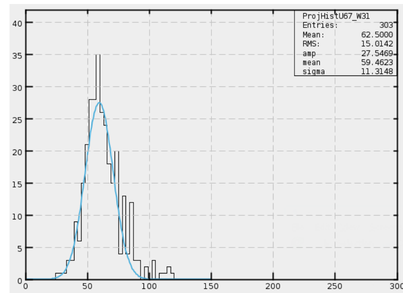
(c) adcU6728



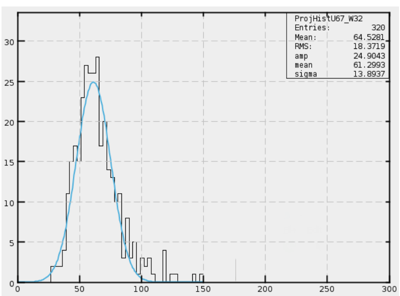
(d) adcU6729



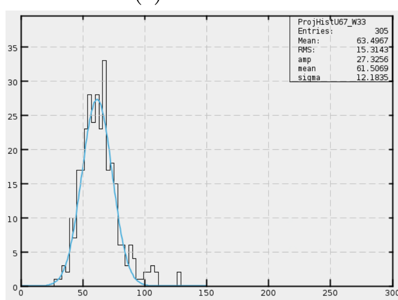
(e) adcU6730



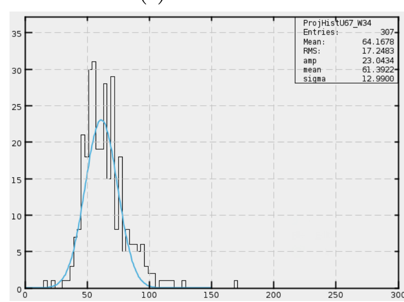
(f) adcU6731



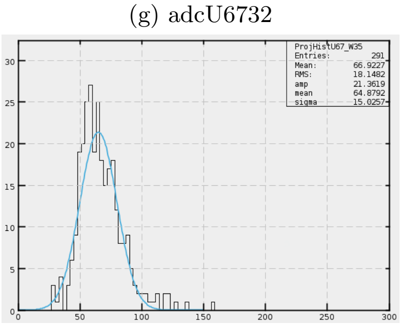
(g) adcU6732



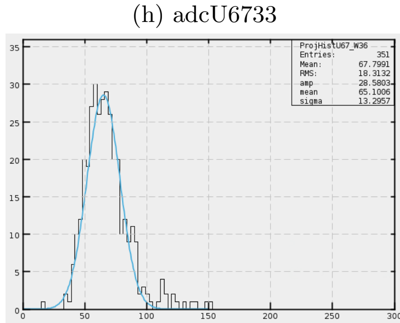
(h) adcU6733



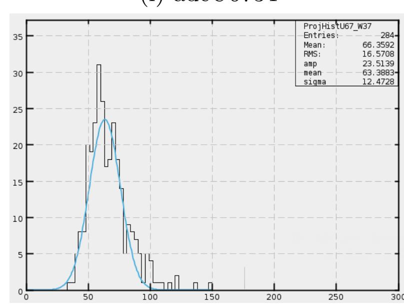
(i) adcU6734



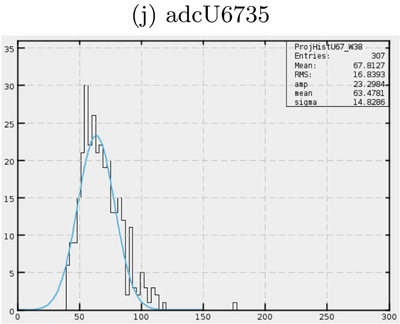
(j) adcU6735



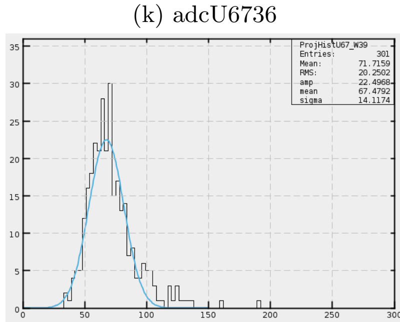
(k) adcU6736



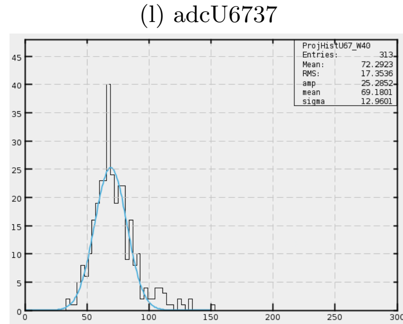
(l) adcU6737



(m) adcU6738

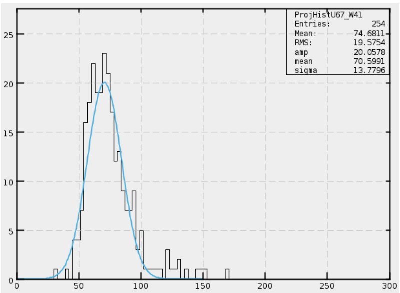


(n) adcU6739

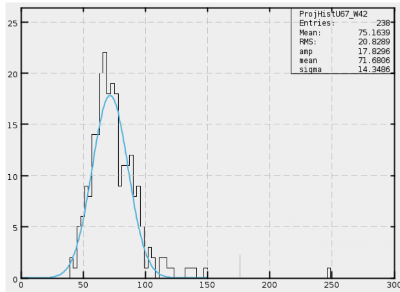


(o) adcU6740

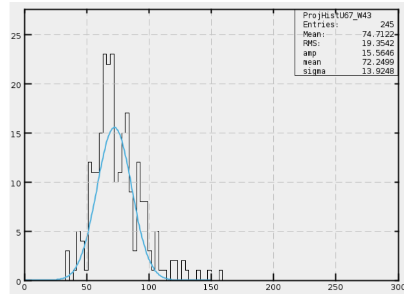
Figure 7.4: ADC distribution for U67. The last two digits in the caption of each figure represent the bin number based on the W strip. Blue curve is the Gaussian fit.



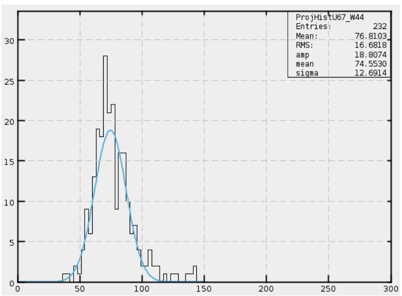
(a) adcU6741



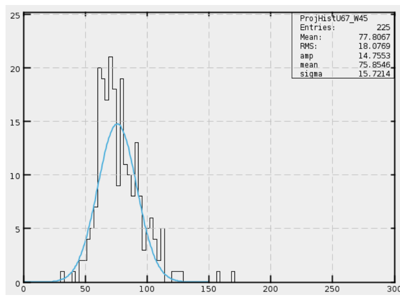
(b) adcU6742



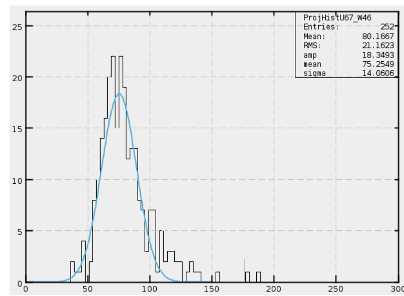
(c) adcU6743



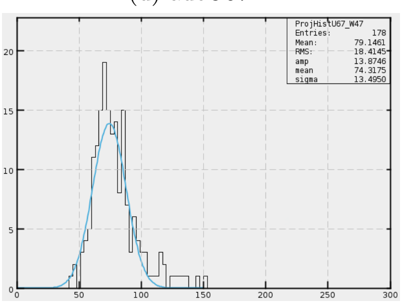
(d) adcU6744



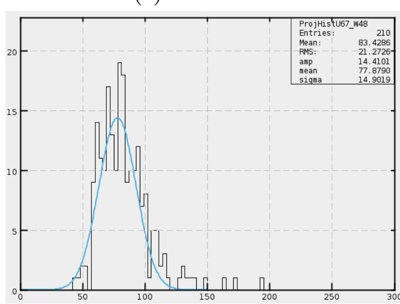
(e) adcU6745



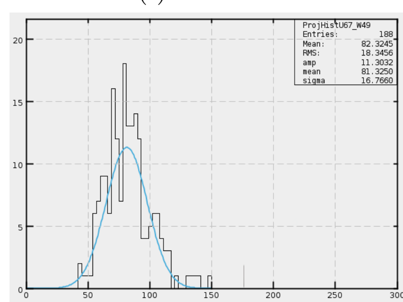
(f) adcU6746



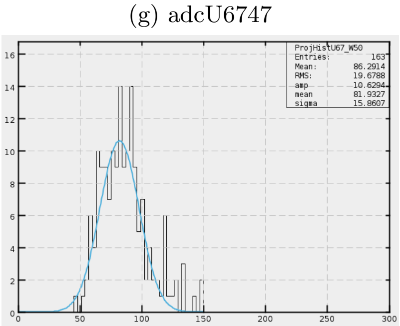
(g) adcU6747



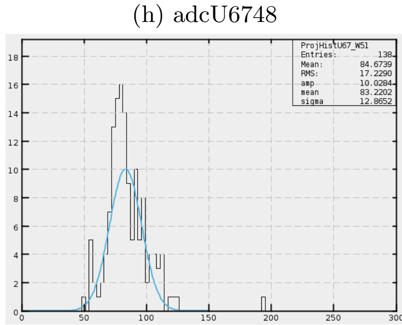
(h) adcU6748



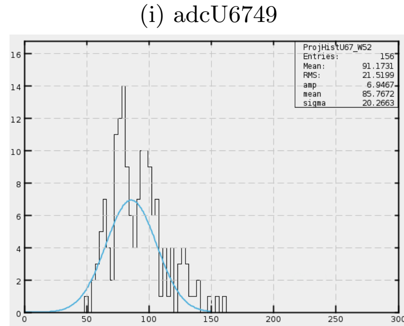
(i) adcU6749



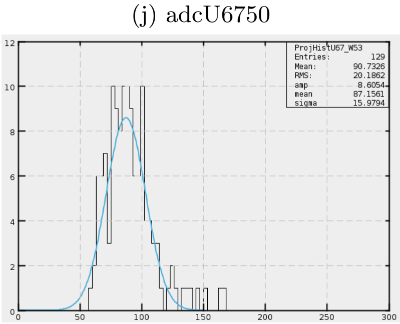
(j) adcU6750



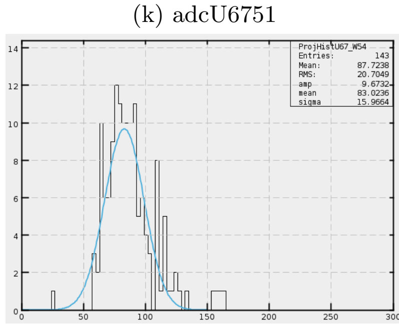
(k) adcU6751



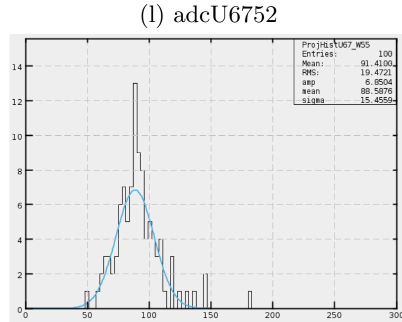
(l) adcU6752



(m) adcU6753

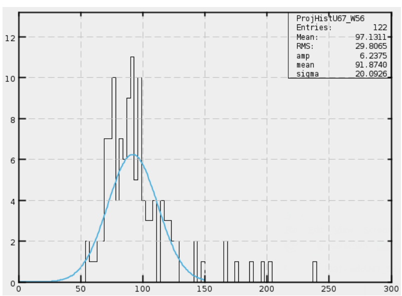


(n) adcU6754

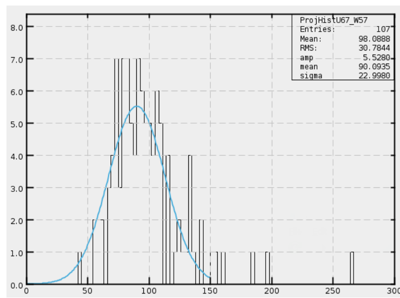


(o) adcU6755

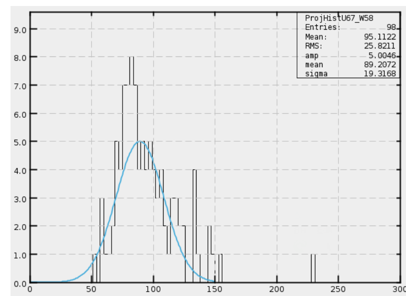
Figure 7.5: ADC distribution for U67. The last two digits in the caption of each figure represent the bin number based on the W strip. Blue curve is the Gaussian fit.



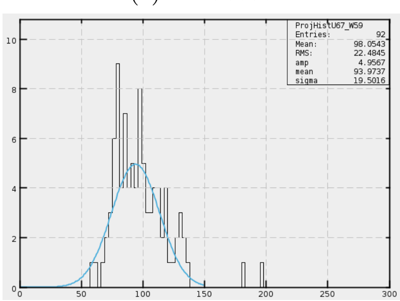
(a) adcU6756



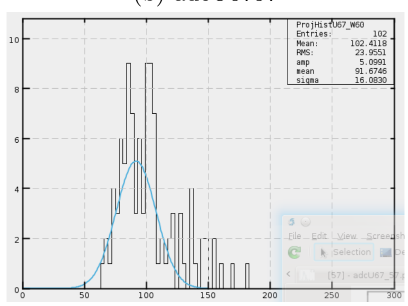
(b) adcU6757



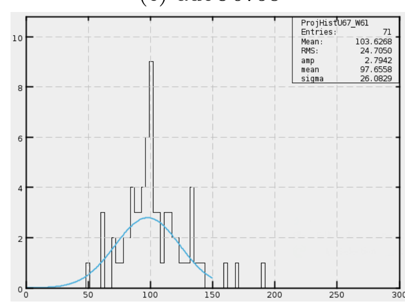
(c) adcU6758



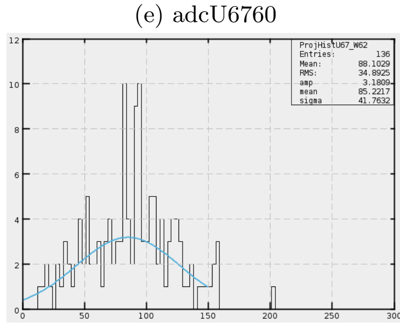
(d) adcU6759



(e) adcU6760



(f) adcU6761



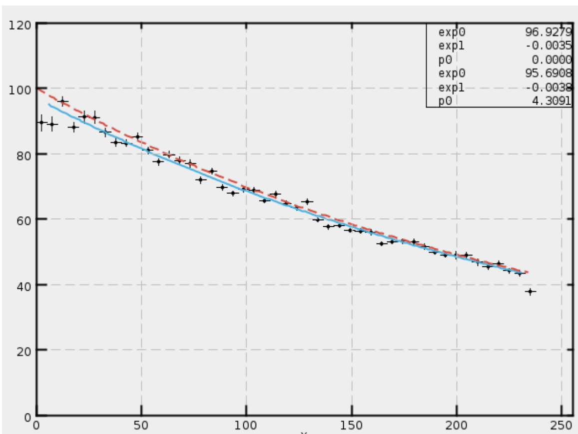
(g) adcU6762

Figure 7.6: ADC distribution for U67. The last two digits in the caption of each figure represent the bin number based on the W strip. Blue curve is the Gaussian fit.

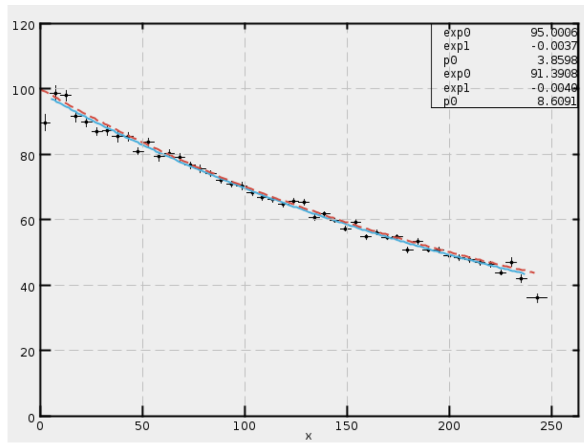
In the similar way centroids for other U-strips are extracted and stored. The correspoding distances from the center of these bins are also evaluated. The next section deals with the exponential fits using these values to extract the calibration constants.

7.5 Exponential fits

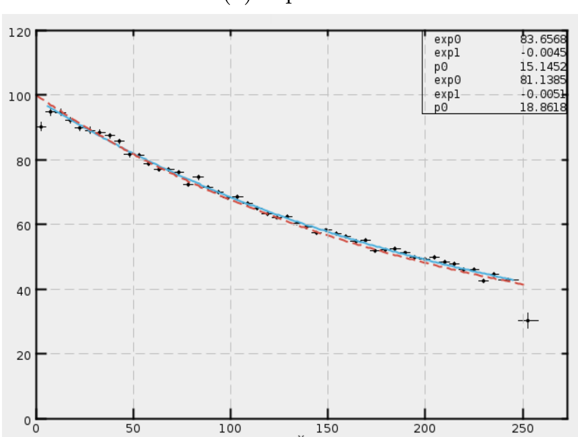
The centroid of each bin is plotted as a function of distance between the bin center to the PMT ends. An exponential funtion of the form given in Eq. 10 is used to fit these points. The fit parameters are then extracted which are the required attenuation coefficients (A, B and C). This process is repeated for each strip in each view so that a set of 68 U, 62 V and W coefficients are recorded. To illustrate the process, the fits for ten U-strips (U51- U59 and U67) are shown in Figures 7.7- 7.8. As a comparison, the CCDB constants are also drawn (red curves).



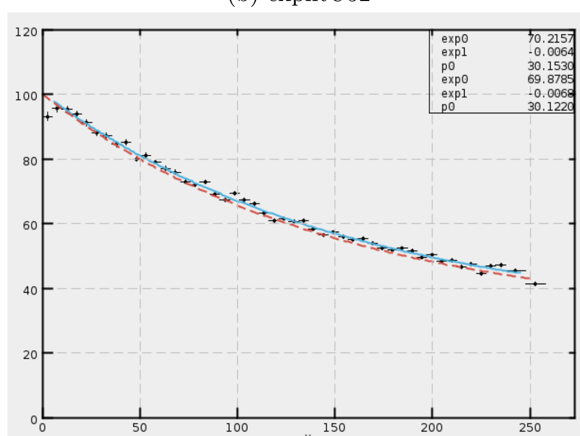
(a) expfitU51



(b) expfitU52

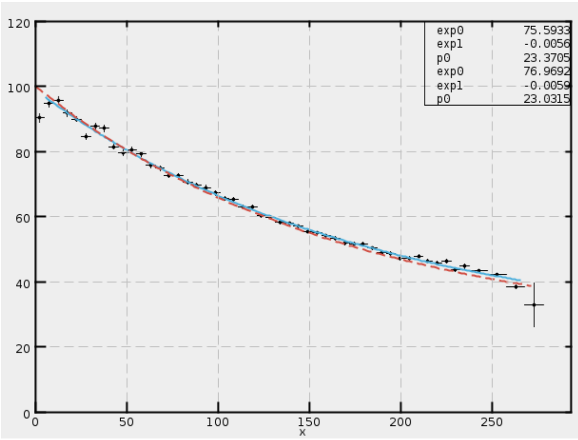


(c) expfitU53

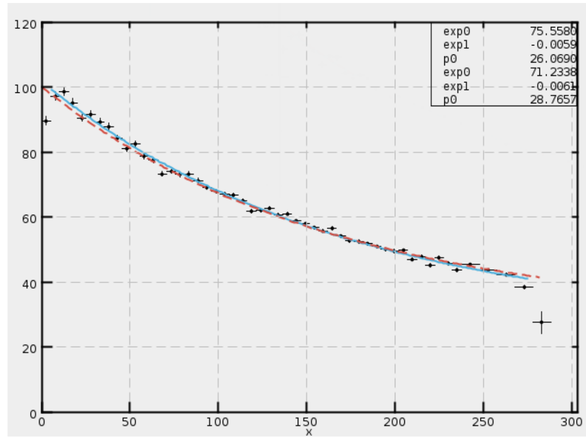


(d) expfitU54

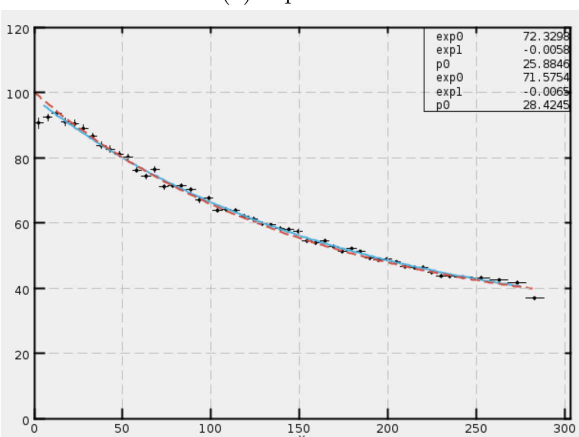
Figure 7.7: Exponential fits for strips U51-U54. The first set of three coeffcients are from the fit and the next set of three are the coefficients used in the event generation.



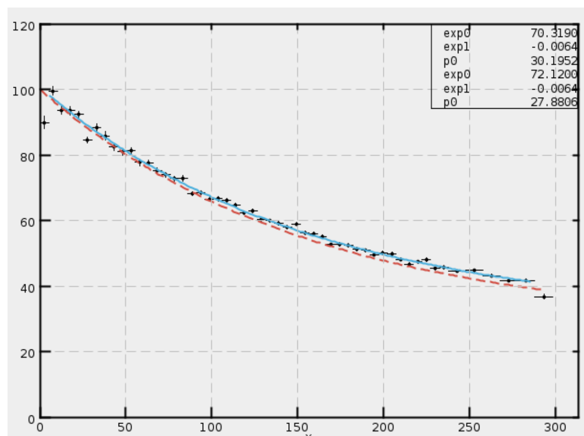
(a) expfitU55



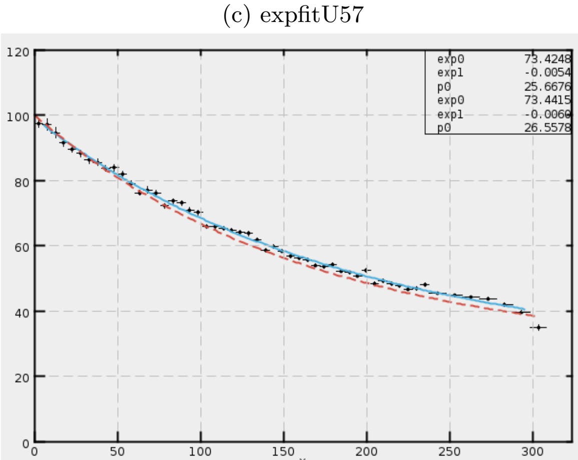
(b) expfitU56



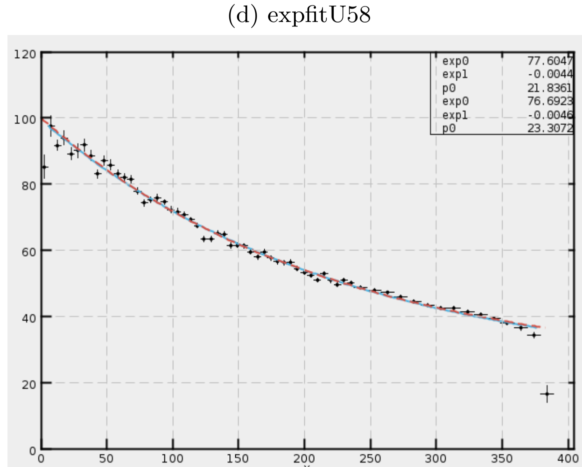
(c) expfitU57



(d) expfitU58



(e) expfitU59



(f) expfitU67

Figure 7.8: Exponential fits for strips U55-U59 and U67. The first set of three coeffcients are from the fit and the next set of three are the coefficients used in the event generation.

7.6 Attenuation Coeffiecients

The attenuation coefficients for all the strips extracted using overlap shapes are listed in Tables 5, 6 and 7 respectively for the U, V and W views.

U-Strip	Parameter A	Parameter B	Parameter C
1	51.6222	0	0
2	87.6722	0	0
3	75.2066	0	0
4	0	0	0
5	115.642	-0.0227617	1.31895e-05
6	25.9129	0.0573538	1.84741e-11
7	92.8515	-0.0111834	8.87529
8	99.9122	-0.0071888	0.000272534
9	98.7009	-0.00673623	5.30282e-05
10	95.7012	-0.00501738	3.87816e-06
11	99.5796	-0.00600944	5.70812e-05
12	101.893	-0.0068082	7.35174e-05
13	98.5639	-0.00536148	4.98004e-05
14	100.276	-0.00639663	5.58738e-05
15	99.7085	-0.00501107	5.66326e-05
16	100.059	-0.00515426	5.60184e-05
17	98.1727	-0.00350673	4.48953e-05
18	95.789	-0.00272249	7.85182e-06
19	99.1342	-0.00377288	5.03733e-05
20	100.051	-0.00427194	5.98579e-05
21	99.1343	-0.00399251	4.8361e-05
22	99.2099	-0.00426886	4.78836e-05
23	99.6019	-0.00407383	3.86109e-05
24	99.9645	-0.00461704	5.33197e-05
25	98.7092	-0.00440979	3.91902e-05
26	100.775	-0.00416001	6.2126e-05
27	99.3643	-0.00397178	4.43273e-05
28	99.8181	-0.00397622	5.15282e-05
29	97.8789	-0.00332809	2.01511e-05
30	99.9657	-0.00359143	5.95054e-05
31	99.7239	-0.00366359	4.3584e-05
32	98.0351	-0.00356509	4.60719e-07
33	99.4801	-0.00364831	4.0398e-05
34	99.3881	-0.00371637	2.09242e-05
35	101.015	-0.00372339	5.36132e-05
36	98.1016	-0.00366948	0.766677
37	100.265	-0.00380836	5.16826e-05
38	84.1899	-0.00488329	15.3043
39	98.6384	-0.00380455	4.01091e-07
40	97.8206	-0.00349042	0.0308864
41	96.808	-0.00352197	2.07162e-06
42	86.4983	-0.00420312	11.2017
43	99.1538	-0.00374538	1.95099e-06
44	98.6514	-0.00371103	1.79772e-07
45	96.0939	-0.00402188	2.2359
46	87.9136	-0.00497247	12.1946
47	86.9237	-0.00479709	12.3982
48	97.3443	-0.00364544	2.5916e-07
49	92.823	-0.00404197	6.66571
50	72.8505	-0.00625032	24.4329
51	96.9279	-0.00346737	7.73055e-08
52	95.0006	-0.00369719	3.85976
53	83.6568	-0.00451389	15.1452
54	70.2157	-0.0064378	30.153
55	75.5933	-0.00561765	23.3705
56	75.558	-0.00589872	26.069
57	72.3298	-0.00582056	25.8846
58	70.319	-0.00644272	30.1952
59	73.4248	-0.00540184	25.6676
60	75.9223	-0.00532469	22.5712
61	90.9427	-0.00271026	1.37682e-07
62	75.5486	-0.00468108	23.8171
63	77.8982	-0.00465535	22.7054
64	78.8414	-0.00434455	20.5445
65	82.9688	-0.0039061	18.0106
66	89.8554	-0.00247545	2.51534e-08
67	77.6047	-0.00440715	21.8361
68	75.2323	-0.00463455	25.3975

Table 5: Calibration Constants for the U layer.

V-Strip	Parameter A	Parameter B	Parameter C
1	81.3251	0	0
2	93.8447	0	0
3	89.258	0	0
4	0	0	0
5	112.714	-0.0116148	0.000140092
6	108.147	-0.00753567	8.66376e-09
7	104.461	-0.00518872	2.50789e-06
8	45.7132	-0.0283992	67.1725
9	99.9987	-0.00409683	0.654341
10	103.367	-0.00490372	2.64129e-07
11	101.999	-0.00448106	8.5592e-06
12	101.161	-0.00434226	5.51421e-06
13	89.4121	-0.00480225	12.9398
14	98.3878	-0.00325741	0.624151
15	72.3921	-0.00538143	27.9022
16	98.7883	-0.00352409	6.08974e-08
17	99.6729	-0.00356374	3.38963e-07
18	100.02	-0.0036647	1.82501e-07
19	101.396	-0.00337965	3.62534e-08
20	89.5551	-0.00406814	10.8602
21	100.24	-0.00320595	3.83976e-07
22	79.997	-0.00447596	21.0638
23	79.5925	-0.00469138	21.4686
24	84.2625	-0.00430666	16.033
25	87.2411	-0.00406931	12.8588
26	99.4143	-0.00322608	2.38418e-06
27	99.0414	-0.00328074	2.68513e-08
28	90.6274	-0.00369328	9.22529
29	90.2512	-0.00396402	9.83799
30	81.0107	-0.00490791	20.333
31	80.4556	-0.00436419	18.046
32	95.7675	-0.0036954	5.01714
33	86.3945	-0.00415465	14.1529
34	81.9767	-0.00475111	18.6153
35	86.444	-0.00400936	13.1011
36	98.1088	-0.00321114	1.63514
37	91.1958	-0.00427169	8.74885
38	87.556	-0.00374749	10.6152
39	84.6679	-0.00480555	16.3922
40	86.1274	-0.00410958	13.1448
41	79.803	-0.00479862	21.4568
42	82.7876	-0.00421391	17.9667
43	77.6727	-0.00477563	24.3102
44	82.7088	-0.00433188	17.2481
45	81.0337	-0.00505961	20.0948
46	83.7595	-0.00407532	14.8532
47	81.9191	-0.00453048	18.6102
48	86.6122	-0.00409001	14.6335
49	84.7559	-0.00461439	16.8
50	84.9907	-0.00415237	16.3736
51	82.6795	-0.00486204	18.6174
52	85.7642	-0.00455222	15.118
53	85.23	-0.00445134	15.377
54	84.2234	-0.00451731	17.081
55	83.6998	-0.00428485	16.7591
56	84.6766	-0.00440632	14.549
57	84.574	-0.00386128	15.0527
58	86.9262	-0.00392846	12.2401
59	82.764	-0.00404404	15.0655
60	85.8456	-0.00382857	12.7791
61	84.1674	-0.00396819	15.3756
62	77.0637	-0.00309805	8.36148

Table 6: Calibration Constants for the V layer.

W-Strip	Parameter A	Parameter B	Parameter C
1	76.5834	0	0
2	94.6674	0	0
3	0	0	0
4	109.142	-0.0130086	0.00015922
5	107.035	-0.00894442	8.24225e-07
6	105.492	-0.00708408	1.33493e-05
7	96.1992	-0.00724769	11.9308
8	98.279	-0.00491833	1.82152
9	49.0971	-0.0127096	55.5526
10	94.9267	-0.00399965	5.86104
11	102.166	-0.00463505	7.03285e-06
12	102.1	-0.00427262	1.17733e-06
13	88.889	-0.00478508	12.4618
14	95.8496	-0.00374209	5.45295
15	77.3844	-0.00529214	25.067
16	100.583	-0.00404282	2.15117e-07
17	96.9804	-0.0038156	1.44707e-05
18	99.9379	-0.00396405	2.17298e-05
19	75.9695	-0.00514872	21.2028
20	71.233	-0.00617771	28.0456
21	77.7536	-0.00547851	23.1228
22	99.7207	-0.00369463	1.71972e-05
23	98.6427	-0.00343161	1.23854e-06
24	100.039	-0.00387015	3.2979e-06
25	82.408	-0.00501709	16.3269
26	99.6441	-0.00372218	1.05835e-07
27	93.5772	-0.00365972	5.49534
28	91.8945	-0.00409323	8.37447
29	86.8697	-0.00452968	14.2807
30	84.8415	-0.00458064	15.0535
31	79.2046	-0.00520979	22.875
32	77.2896	-0.00508816	23.2359
33	82.1087	-0.00533502	19.7361
34	89.4605	-0.00406	10.7605
35	88.6131	-0.00375663	10.4811
36	97.2606	-0.0033744	2.02937
37	86.0419	-0.00461505	14.1821
38	83.2823	-0.00477393	18.1849
39	80.9365	-0.00487184	19.3808
40	86.8735	-0.00415256	13.2762
41	86.8237	-0.00428351	14.3152
42	87.9619	-0.00388999	11.4198
43	83.4599	-0.00446605	16.7767
44	84.7084	-0.00409597	14.6483
45	85.7983	-0.00418715	14.7523
46	78.5469	-0.0046913	22.0838
47	80.8861	-0.00455342	19.7712
48	85.9249	-0.00390414	14.0986
49	84.238	-0.00427813	14.5056
50	80.7529	-0.00426804	18.3437
51	81.6971	-0.00434176	16.7262
52	73.9153	-0.00529965	27.8944
53	83.048	-0.00254593	7.55929e-09
54	81.2306	-0.00447303	18.2888
55	85.9745	-0.00421353	12.3989
56	80.6208	-0.00523589	22.6337
57	87.486	-0.00368434	9.59789
58	81.3392	-0.00504944	21.1264
59	86.0705	-0.00417194	12.3202
60	84.3917	-0.00441815	14.8435
61	77.2549	-0.0049831	23.2266
62	78.4089	-0.00232346	8.83974e-07

Table 7: Calibration Constants for the W layer.

8 Reproducibility

The attenuation coefficients found in the previous section is from the simulated events with given CCDB constants as input. One way to test the result is to compare the input and the output coefficients. However, the coefficents cannot be directly compared to one another as different coefficients can define the same exponential form (Eq. 10) reasonably. Therefore, the better way of comparison is to compare the exponential forms they define as a function of distance.

8.1 Without Iteration

Figure 8.1 shows the difference of the y values calculated from the generated and calculated coefficients for a given distance for the U-view. Similar plot for the V- and W-views are shown in Figures 8.2 and 8.3 respectively. It can be seen that the coefficients are reproduced within 5% for longer strips in each views. The shorter strips are not reproduced that well. One reason is very low number of events in each bin for short strips.

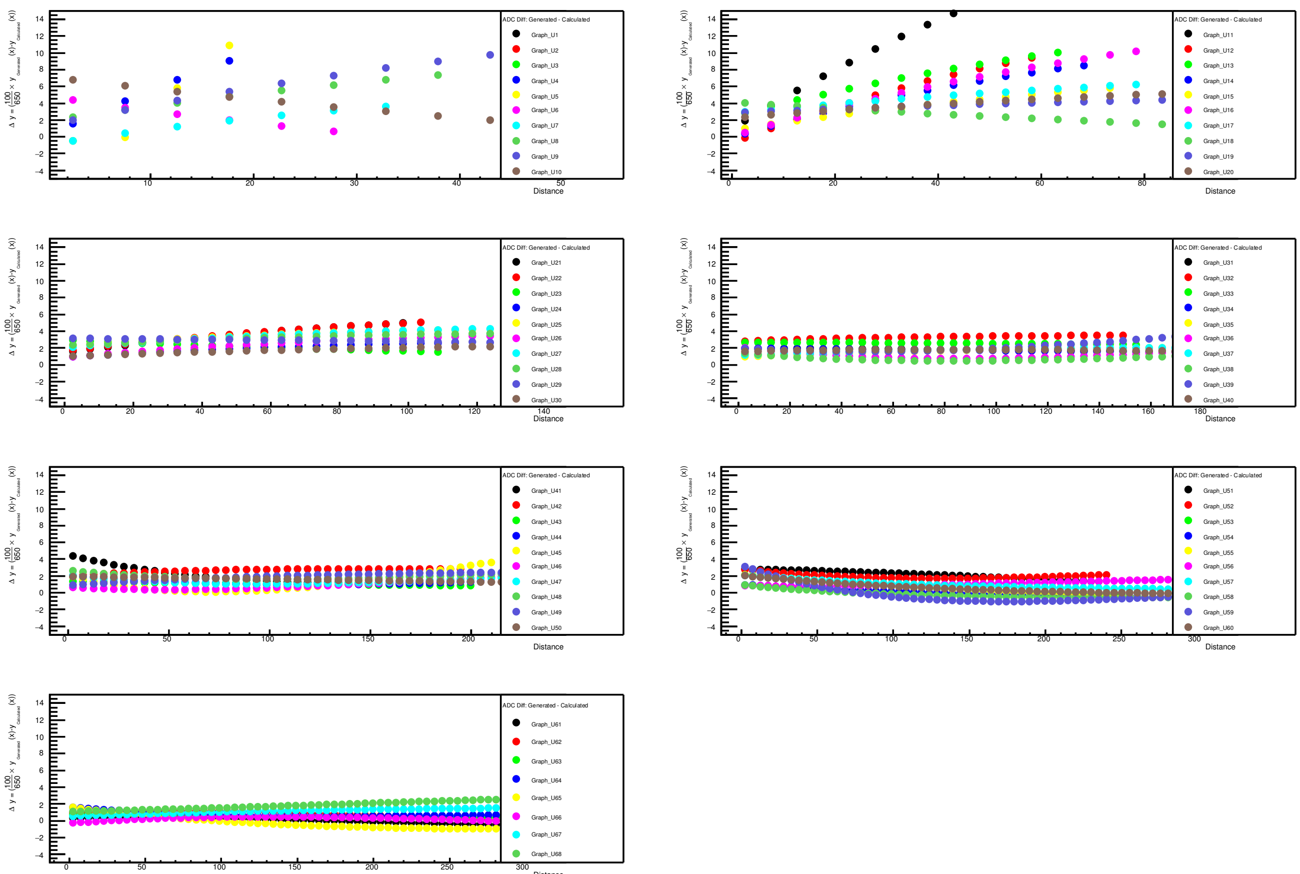


Figure 8.1: Shown is the difference of the generated and calculated attenuation curves as a function of distance for all U-strips

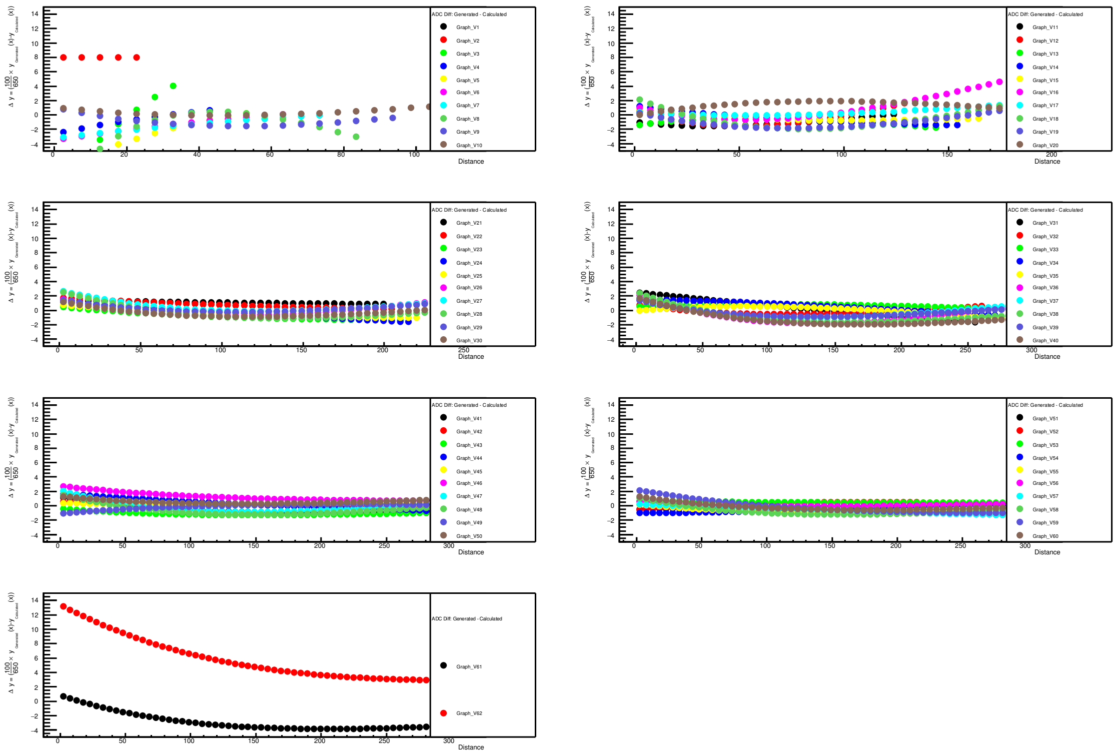


Figure 8.2: Shown is the difference of the generated and calculated attenuation curves as a function of distance for all V-strips

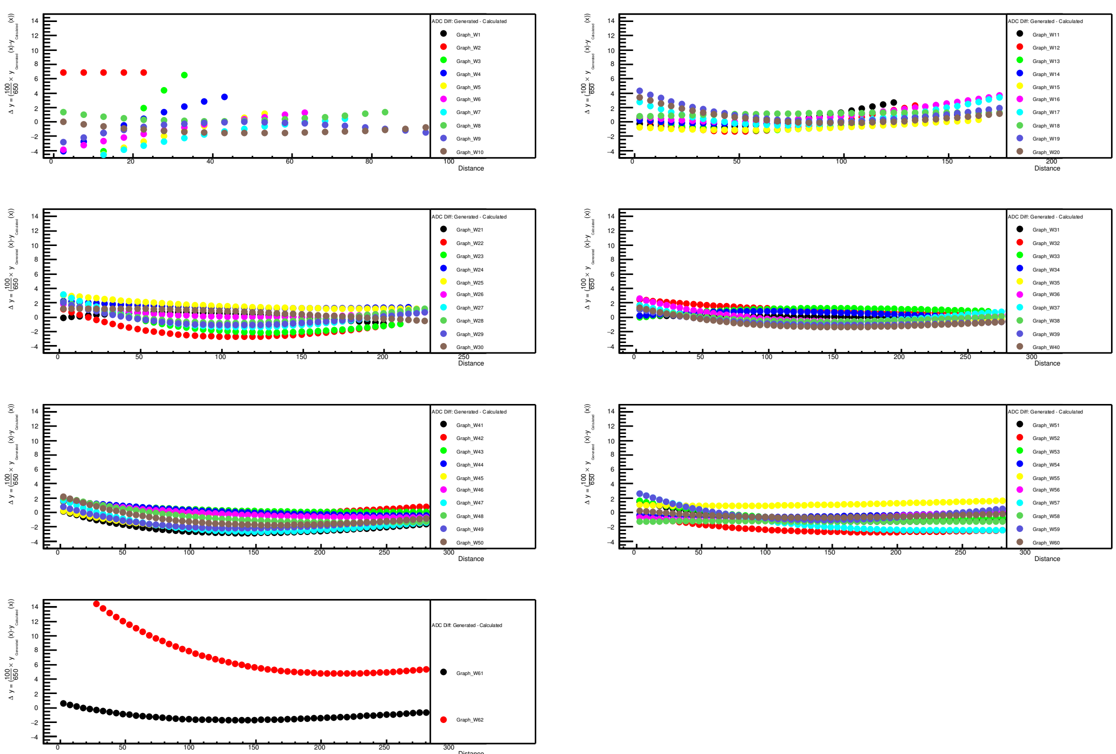
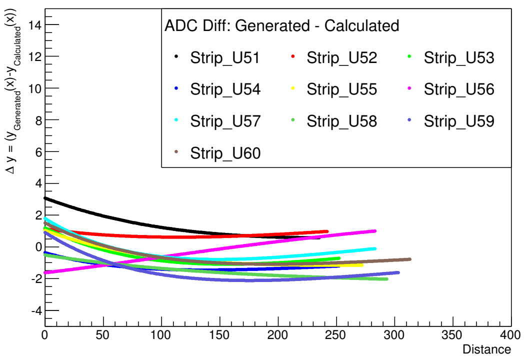


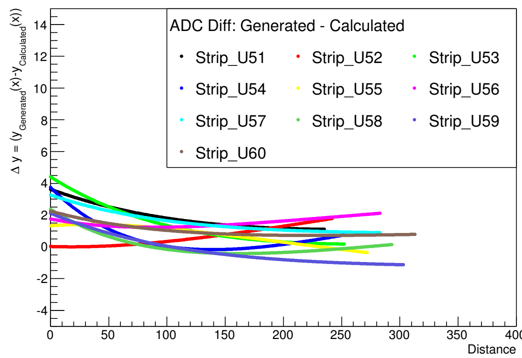
Figure 8.3: Shown is the difference of the generated and calculated attenuation curves as a function of distance for all W-strips

8.2 With Iteration

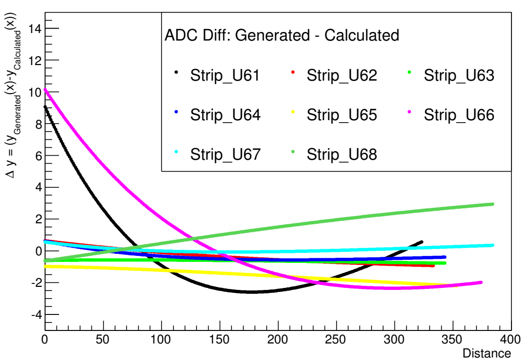
Another way to test the extracted calibration constants with respect to the generated coefficients is to compare results with and without iterations. The iterations are explained in Section 4. Figures 8.4-8.6 show the comparison. The plots on the left are without iterations while those on the right correspond to the coefficients produced from iterations. Comparisons of few longer strips for each view are only shown. The iterations are capable of reclaiming bad initial fits.



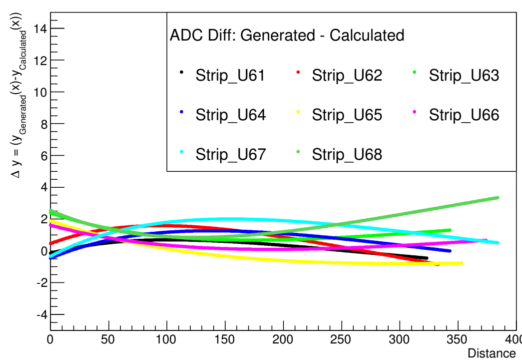
(a) diffU6mean



(b) diffU6root

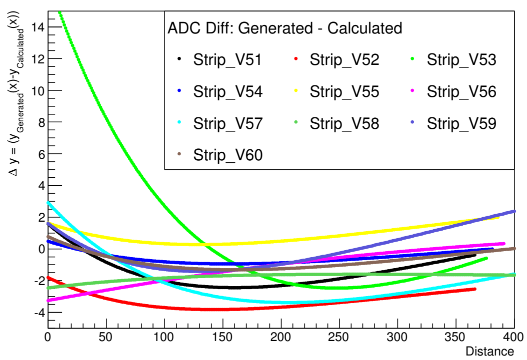


(c) diffU7mean

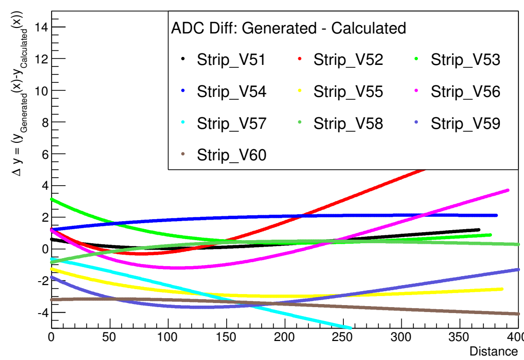


(d) diffU7root

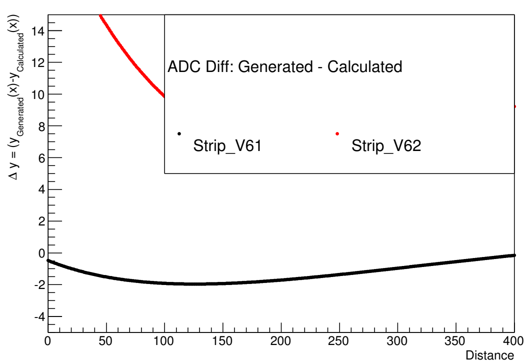
Figure 8.4: The plots on the left are based on coefficients extracted without any iteration while those on the right correspond to with iterations. U-strips 51-68 are compared.



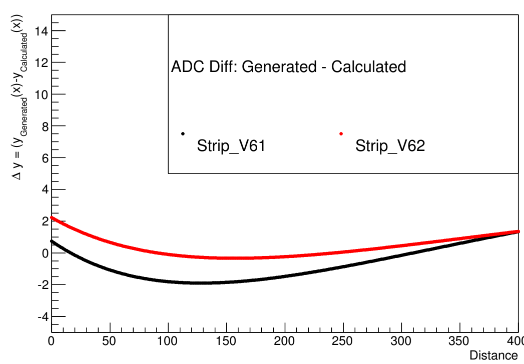
(a) diffV6mean



(b) diffV6root

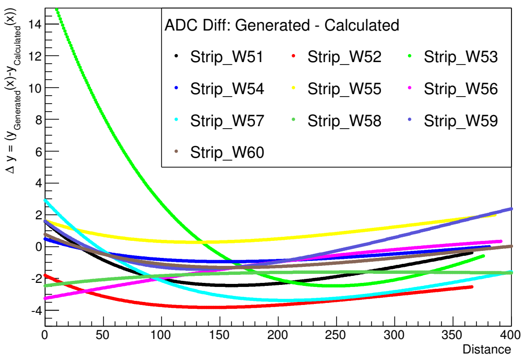


(c) diffV7mean

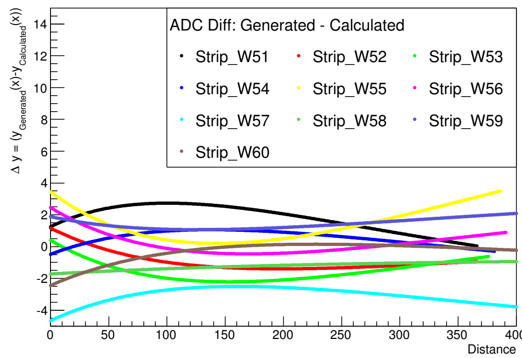


(d) diffV7root

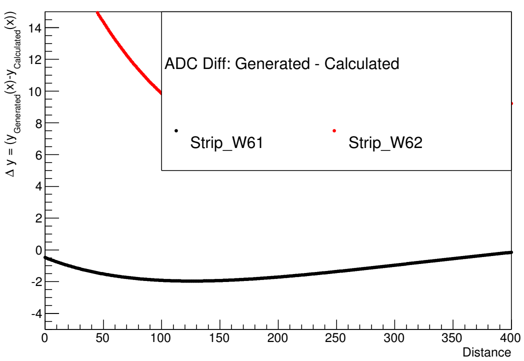
Figure 8.5: The plots on the left are based on coefficients extracted without any iteration while those on the right correspond to with iterations. V-strips 51-62 are compared.



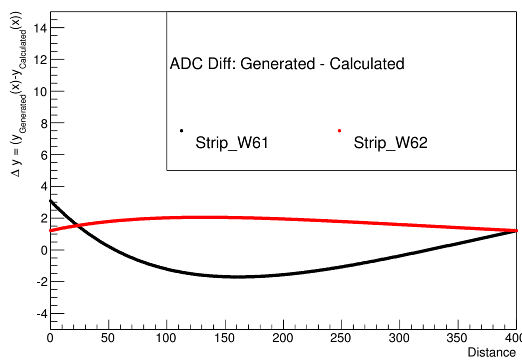
(a) diffW6mean



(b) diffW6root



(c) diffW7mean



(d) diffW7root

Figure 8.6: The plots on the left are based on coefficients extracted without any iteration while those on the right correspond to with iterations. W-strips 51-62 are compared.

9 Systematic Studies

Systematic uncertainties are discussed in thie section. Variation in specific cuts may affect the result. Due to a large variation of statistical uncertainty involved in this analysis, a point to point systematic approach is not realistic. Therefore, an estimation on the systematic errors is made varying each cut and taking the average relative difference in the final result. The systematic uncertainty is quoted based as the shift of the average of the relative differences from zero. The average values are "Mean" values shown in the statistical box of each relative difference plot. The relative difference is given by

$$Relative\ Difference = \frac{R_{Nominal} - R_{variation}}{R_{Nominal}} \tag{11}$$

where $R_{Nominal}$ is the differential cross section quoted and $R_{variation}$ is the differential cross section (unless mentioned otherwise in the text) calculated by varying any specific cut. The systematic uncertainties are discussed in the following sections.

9.1 Sector Dependence

This includes the systematic effect based on different modules/sectors of the PCAL. Words.

9.2 Fitting ADC signal

When the signal function used nominally was replaced by a Landau function, the result had a systematic effect of about 10%.

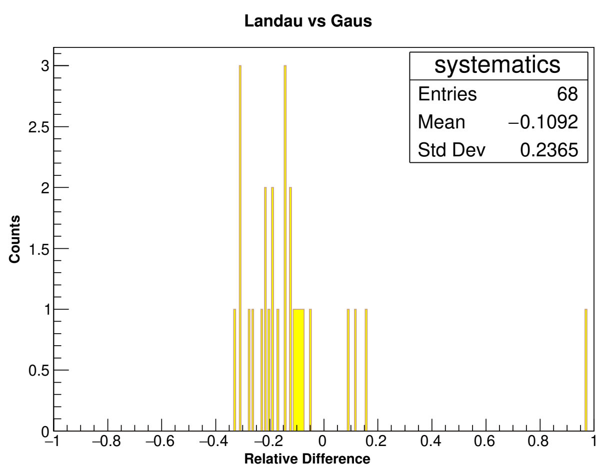


Figure 9.1: Shown in the systematic effect in the differential cross section when using a Landau function over all passes relative to when using a Gaussian function.

Words Words.

References

[1] G. Asryan et al., *https://clasweb.jlab.org/wiki/images/d/d0/Pcal_geometry_note.pdf*

[2] *https://clasweb.jlab.org/wiki/index.php/PCAL_Cosmic_Ray_Tests*