Attenuation Length and the Speed of Light in a BCAL Prototype Module Measured Using Pre-production SiPMs and Cosmics

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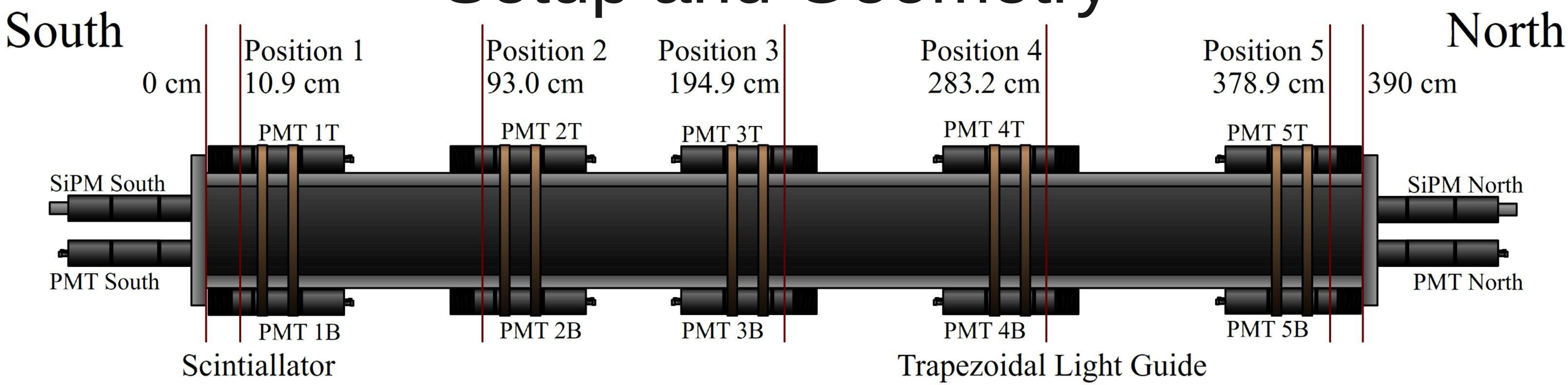
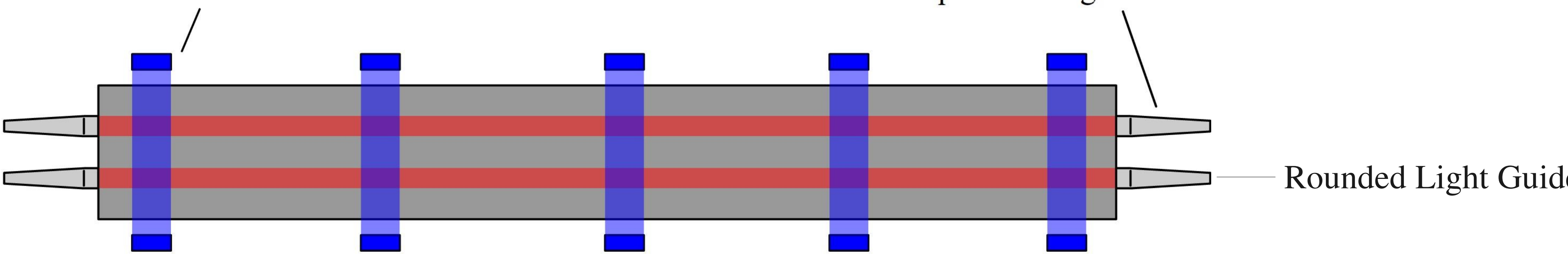
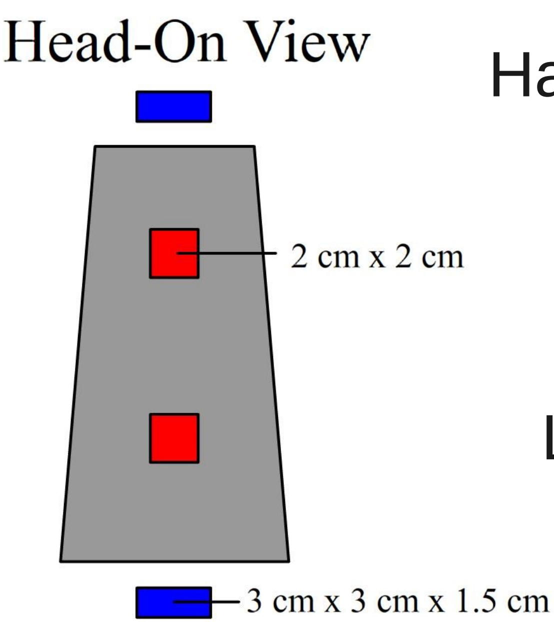
September 11, 2012

Setup and Geometry





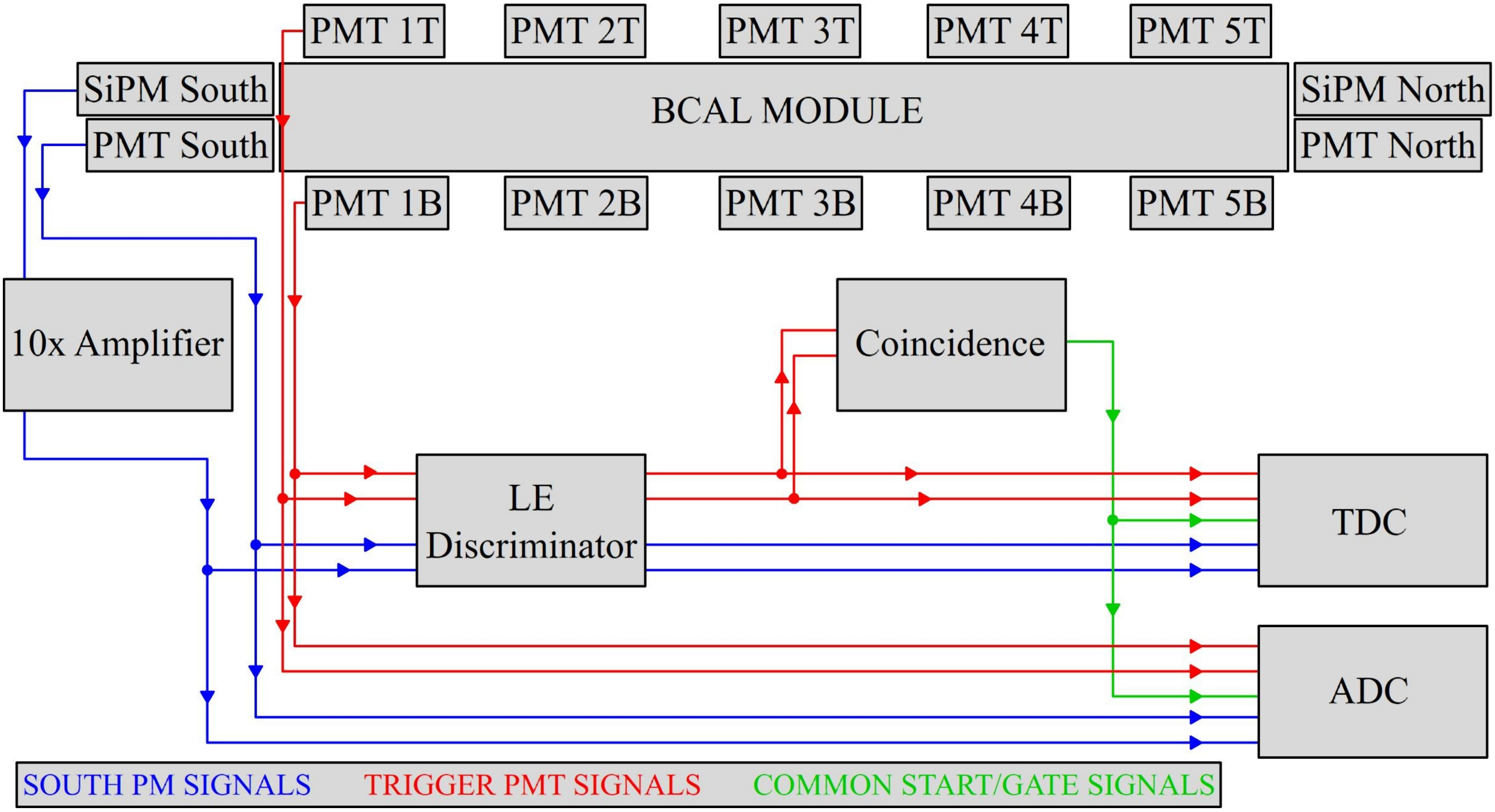


Hamamatsu R329-02 PMTs in wet contact with rounded light guides

Pre-production 2010 SiPMs in dry contact with trapezoidal light guides

Light guides held to module face with Silicone optical Grease

Circuit Logic

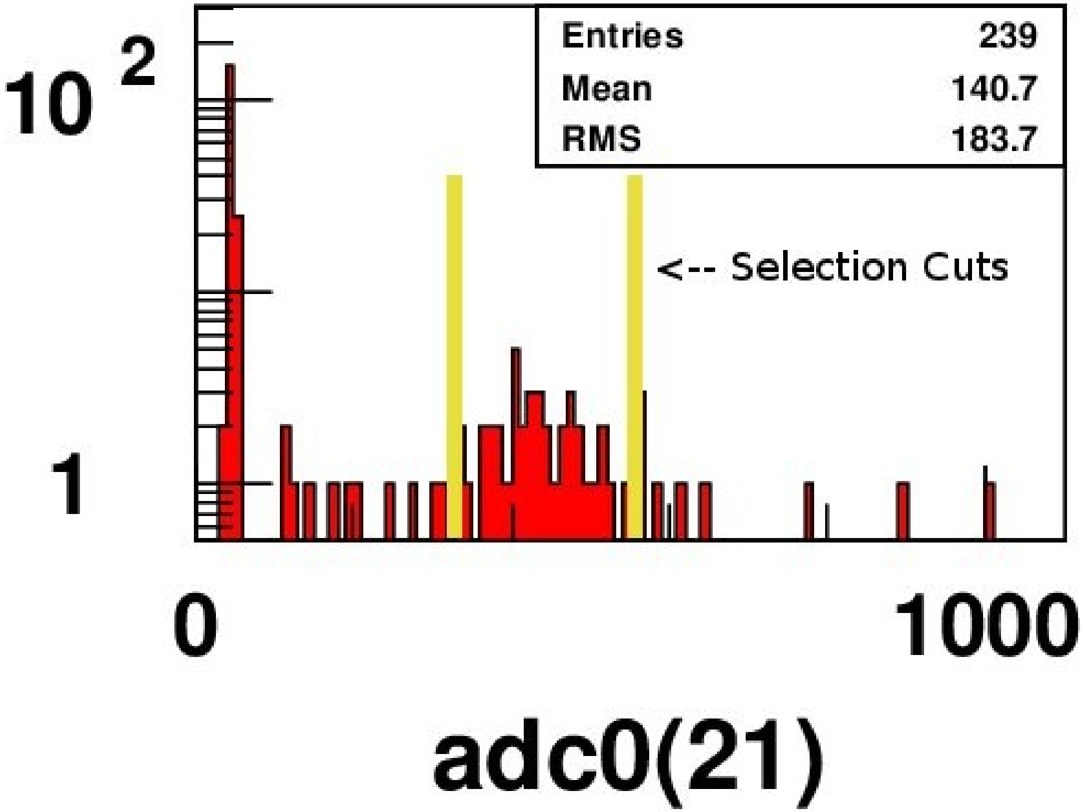


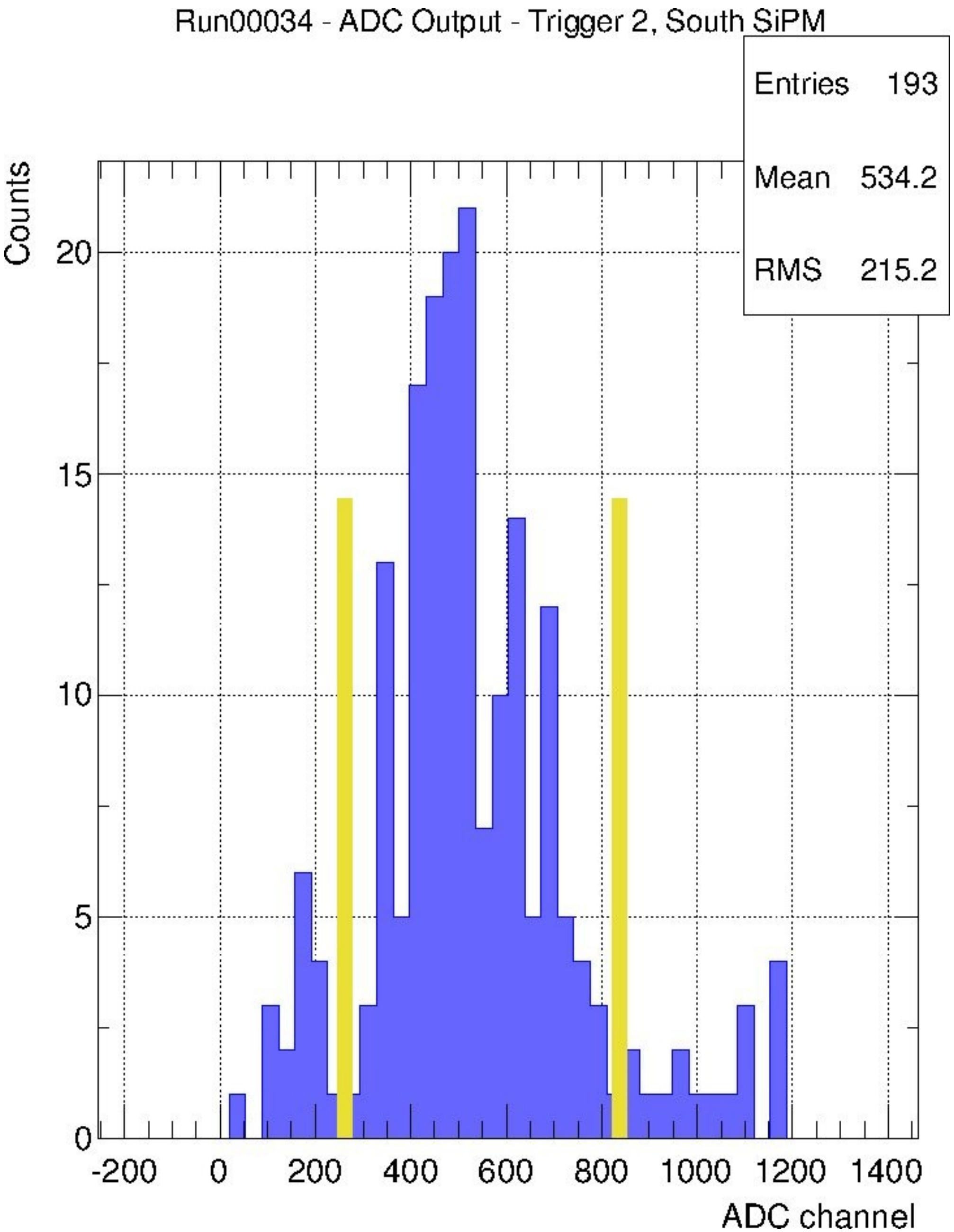
Shown for one trigger pair and the south photomultipliers. The other four trigger pairs and the north photomultipliers have identical setups

Selection Cuts

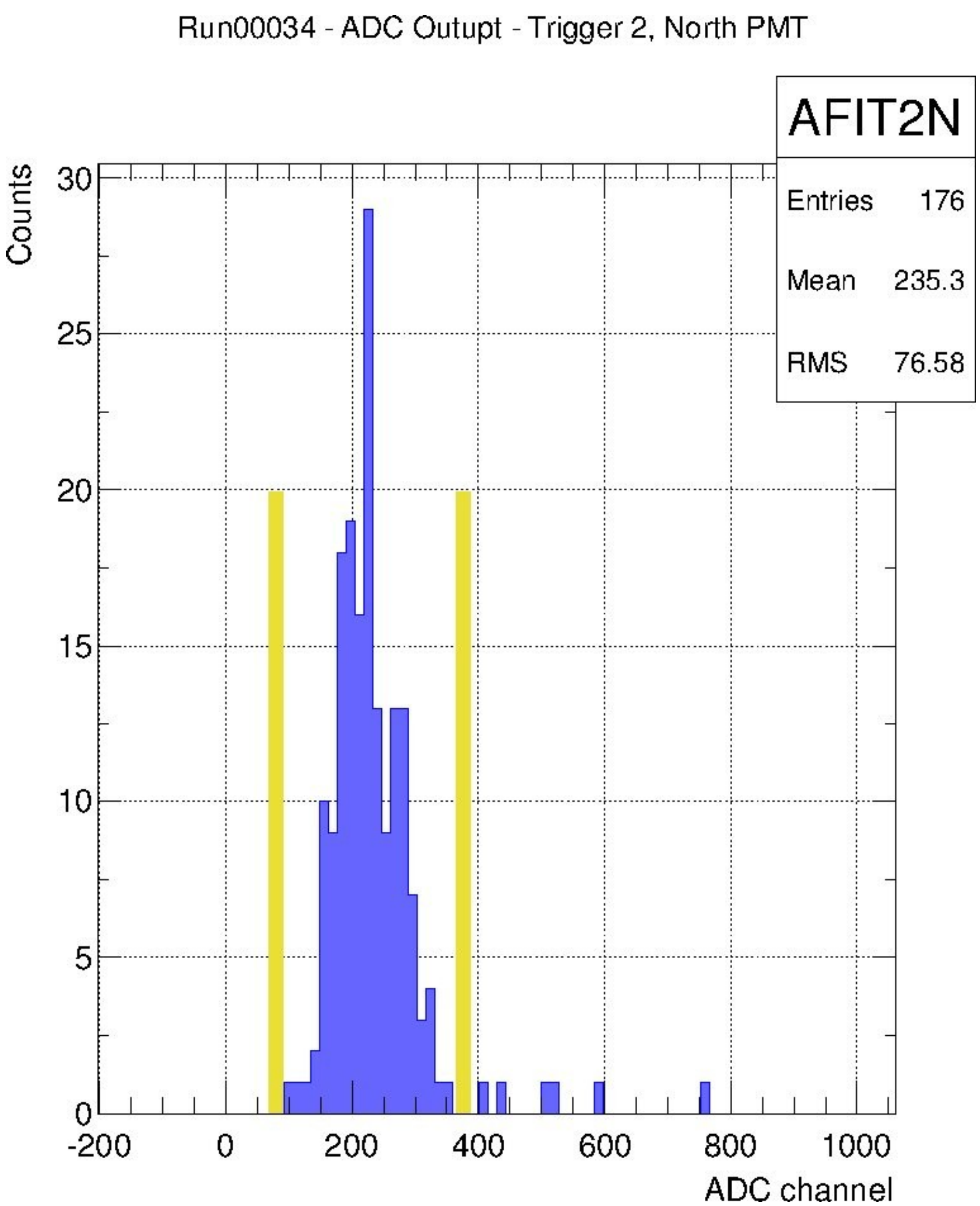
Left: Trigger ADC Example

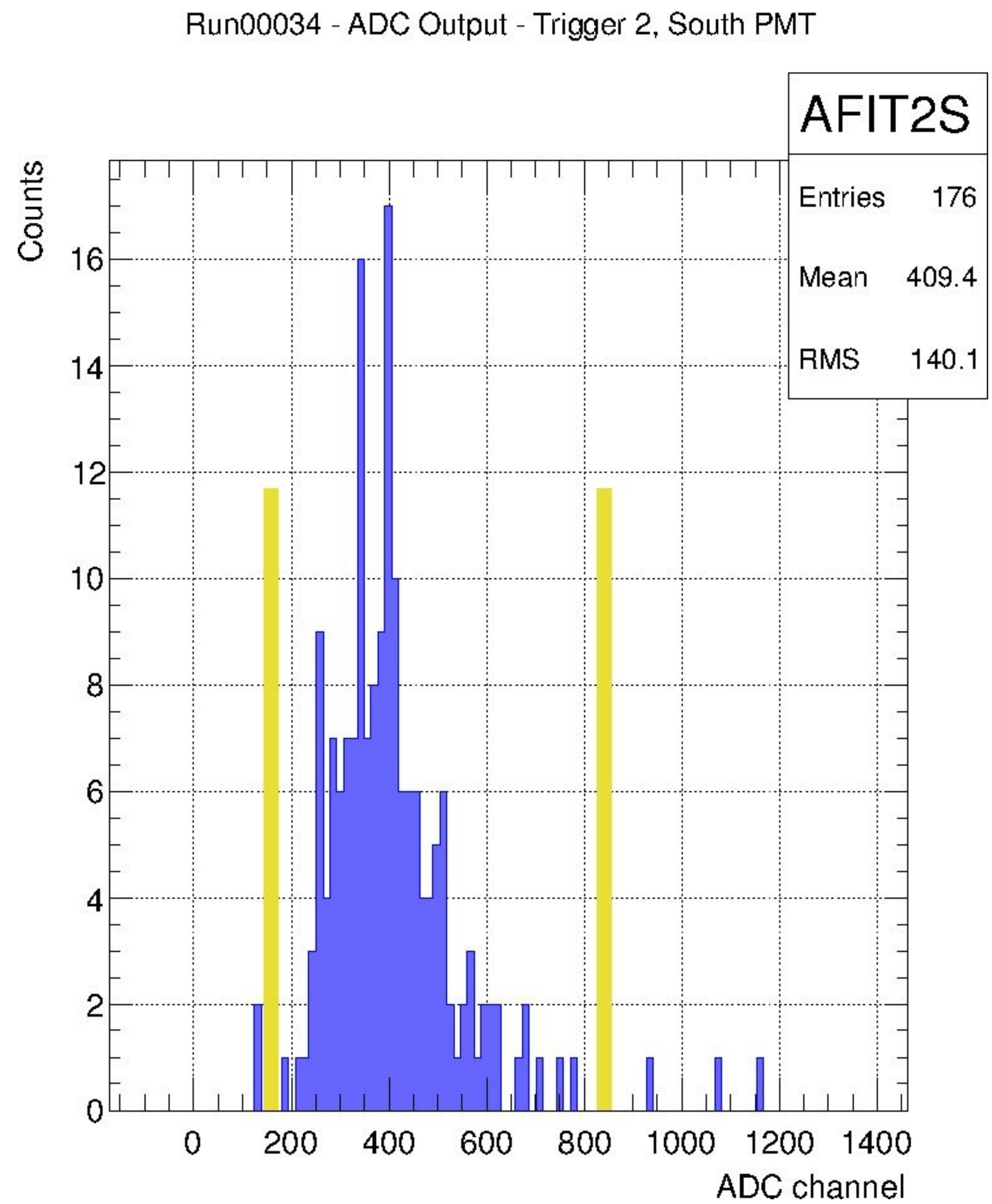
Right: SiPM ADC Example



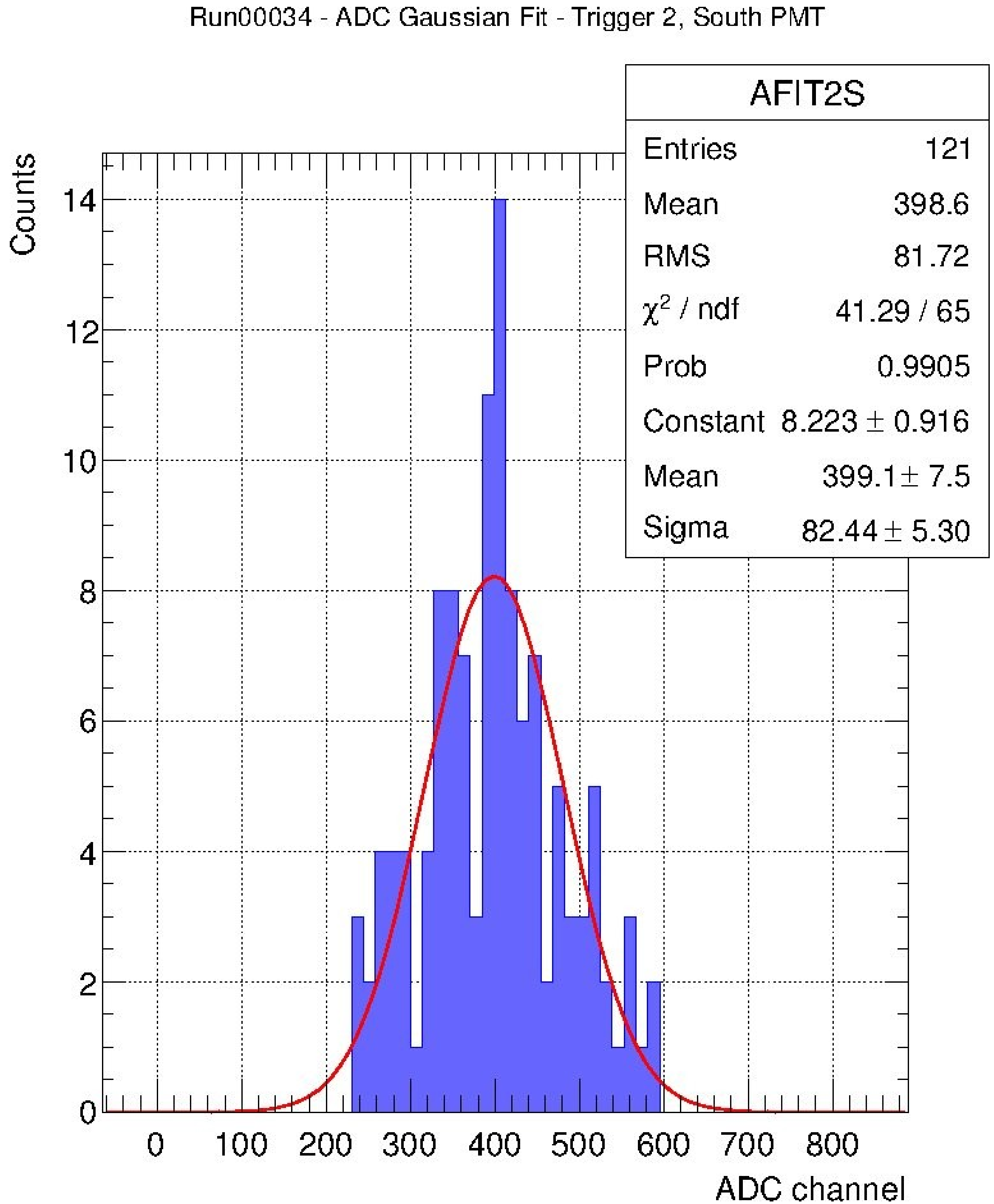


Left: North PMT Example   Right: South PMT Example

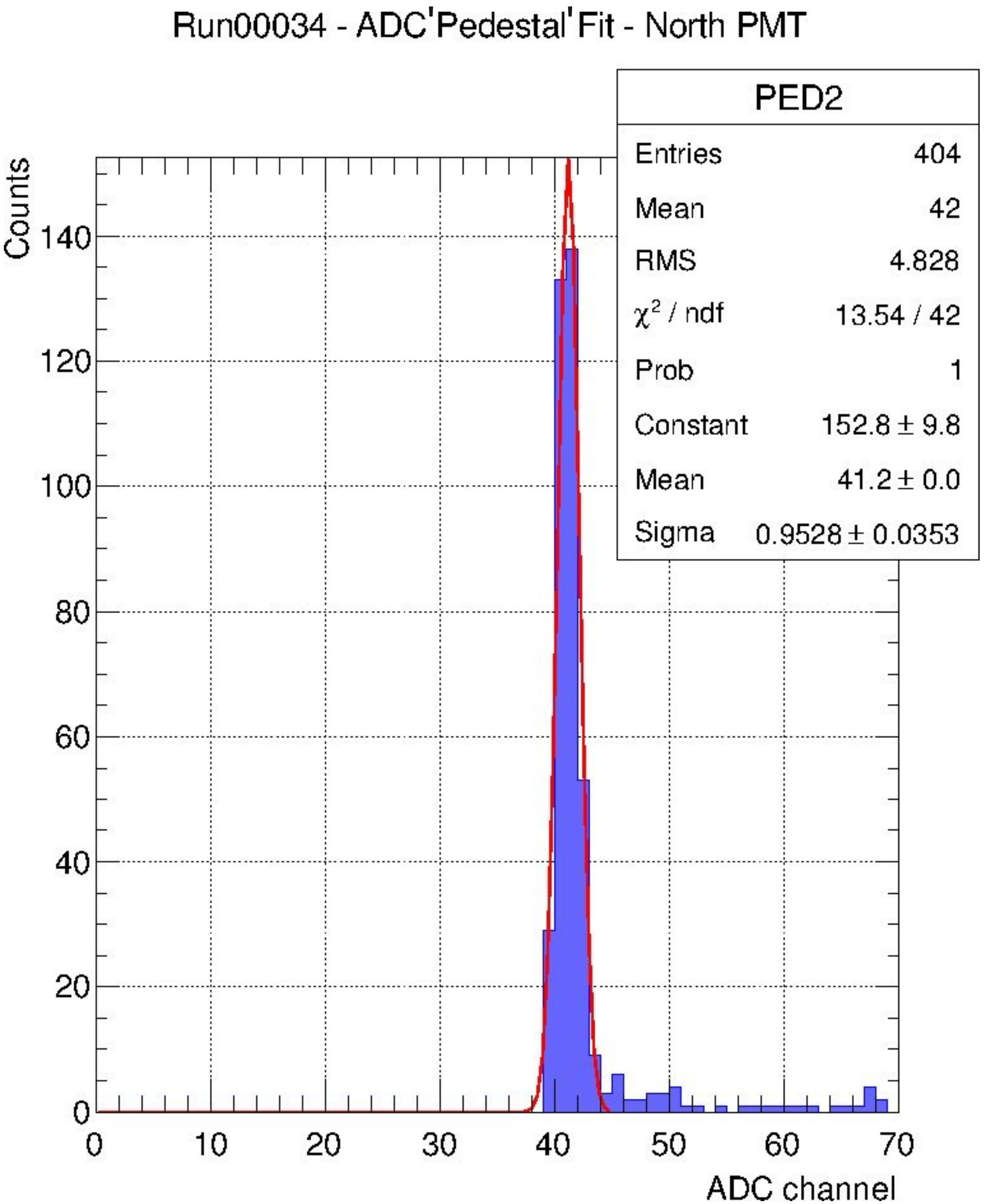


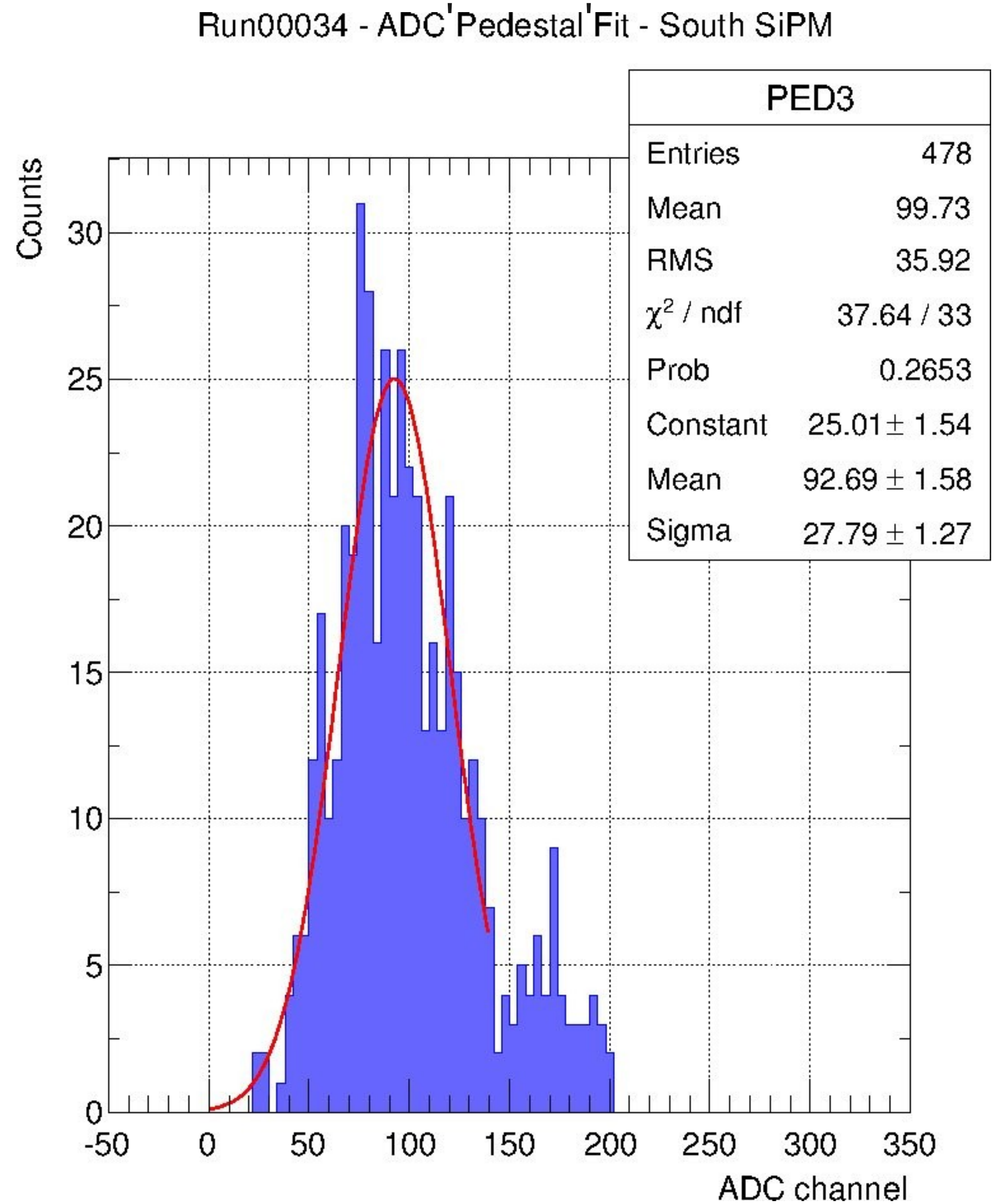


ADC Spectrum After Cuts and Gaussian Fit



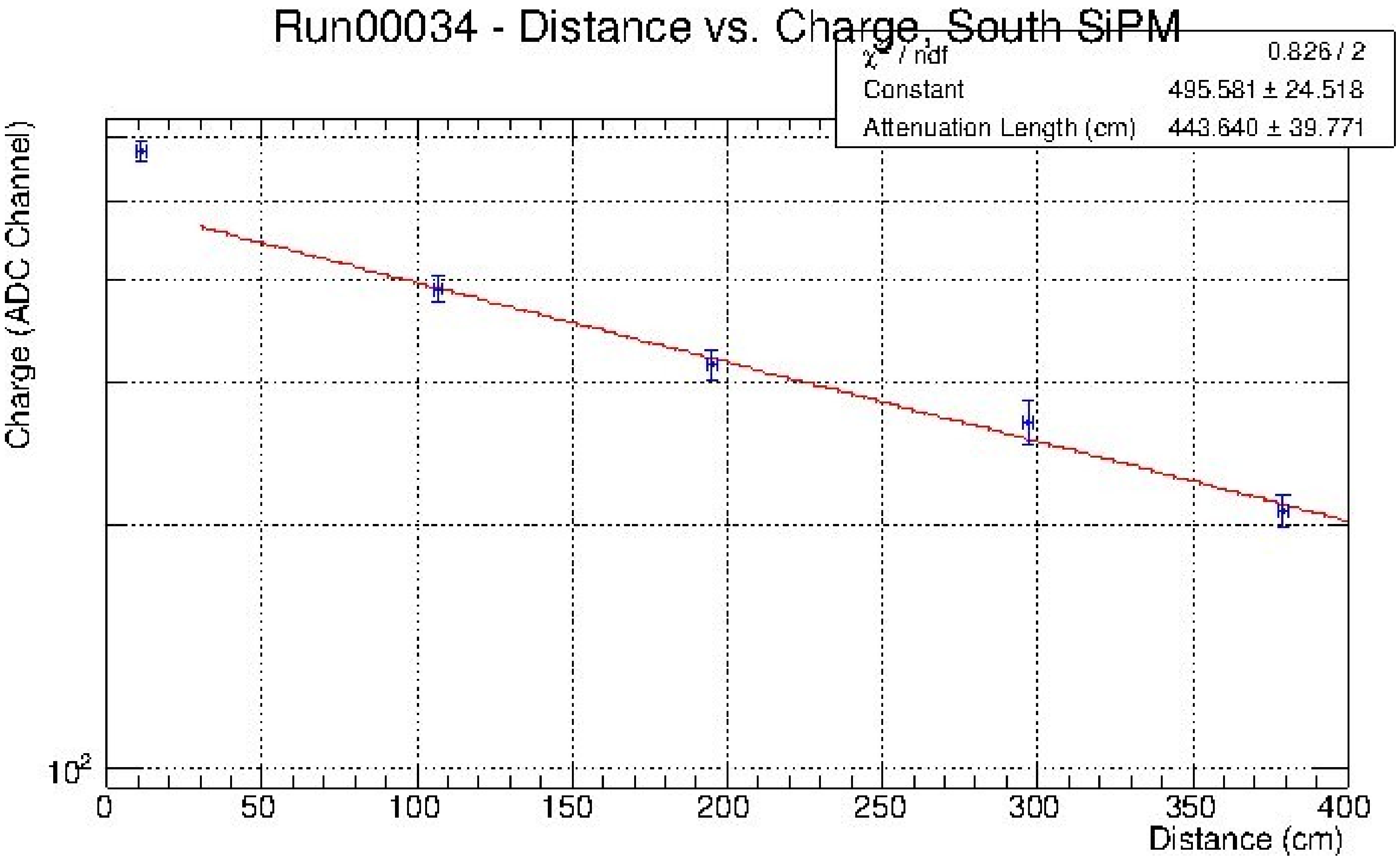
Typical Noise Spectrum Fits for a PMT and a SiPM





ADC Spectrum Mean – Noise Spectrum Mean $\propto$ Mean Charge

Fit Distance vs. Charge to an Exponential to find Attenuation Length



ADC Setting: 0.25 pC per Channel

Attenuation Lengths for PMTs

Run Number	Overbias	Amplifier	South PMT	North PMT
34	0.5 V	None	316 $\pm$ 12 cm	353 $\pm$ 14 cm
35	0.8 V	None	337 $\pm$ 13 cm	328 $\pm$ 11 cm
36	0.2 V	None	330 $\pm$ 18 cm	323 $\pm$ 17 cm
27	0.5 V	None	310 $\pm$ 13 cm	314 $\pm$ 12 cm

Attenuation Lengths for SiPMs

Run Number	Overbias	Amplifier	South SiPM	North SiPM
34	0.5 V	x 10	444 $\pm$ 40 cm	421 $\pm$ 30 cm
35	0.8 V	x 10	438 $\pm$ 29 cm	Overflow
36	0.2 V	x 10	487 $\pm$ 34 cm	396 $\pm$ 26 cm
27	0.5 V	None	448 $\pm$ 44 cm	469 $\pm$ 46 cm

Weighted Averages:

Attenuation Length – PMT = 325 $\pm$ 5 cm

This is in good agreement with the value obtained from tests done in 2010, which reported an attenuation length, measured with Hamamatsu R329-02 PMTs, of 318 $\pm$ 6 cm*

Attenuation Length – SiPM = 436 $\pm$ 13 cm

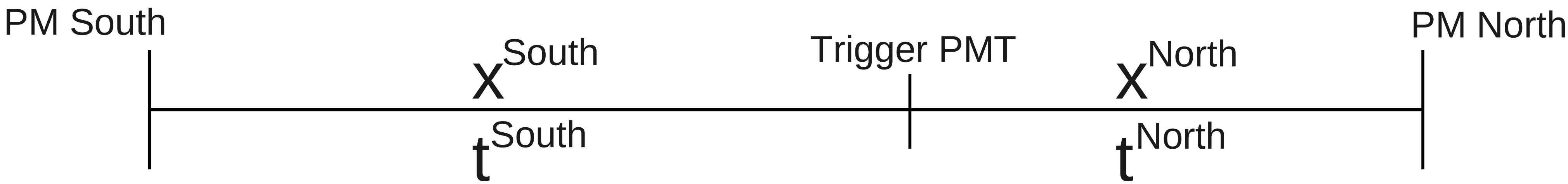
*GlueX-doc-1582 (*Cosmic Ray Tests and Light Output from Bcal*)

When these fibers were tested with a photo-diode, which has a flat spectral response, an attenuation length of 385 cm $\pm$ 7 % was found

This is accurate, since the photo-diode is not biased toward any particular wavelengths of light, so it reads out exactly what the fiber sends to it. However, PMTs and SiPMs do not have flat spectral responses, so in that respect, this is not the most accurate estimation of the attenuation length

The Kuraray SCSF-78MJ fibers transmit much more green light than other wavelengths, so it is not surprising that the more green-sensitive SiPMs would report a larger attenuation length than their blue-sensitive PMT counterparts

Timing Information



Eliminating Trigger Dependence

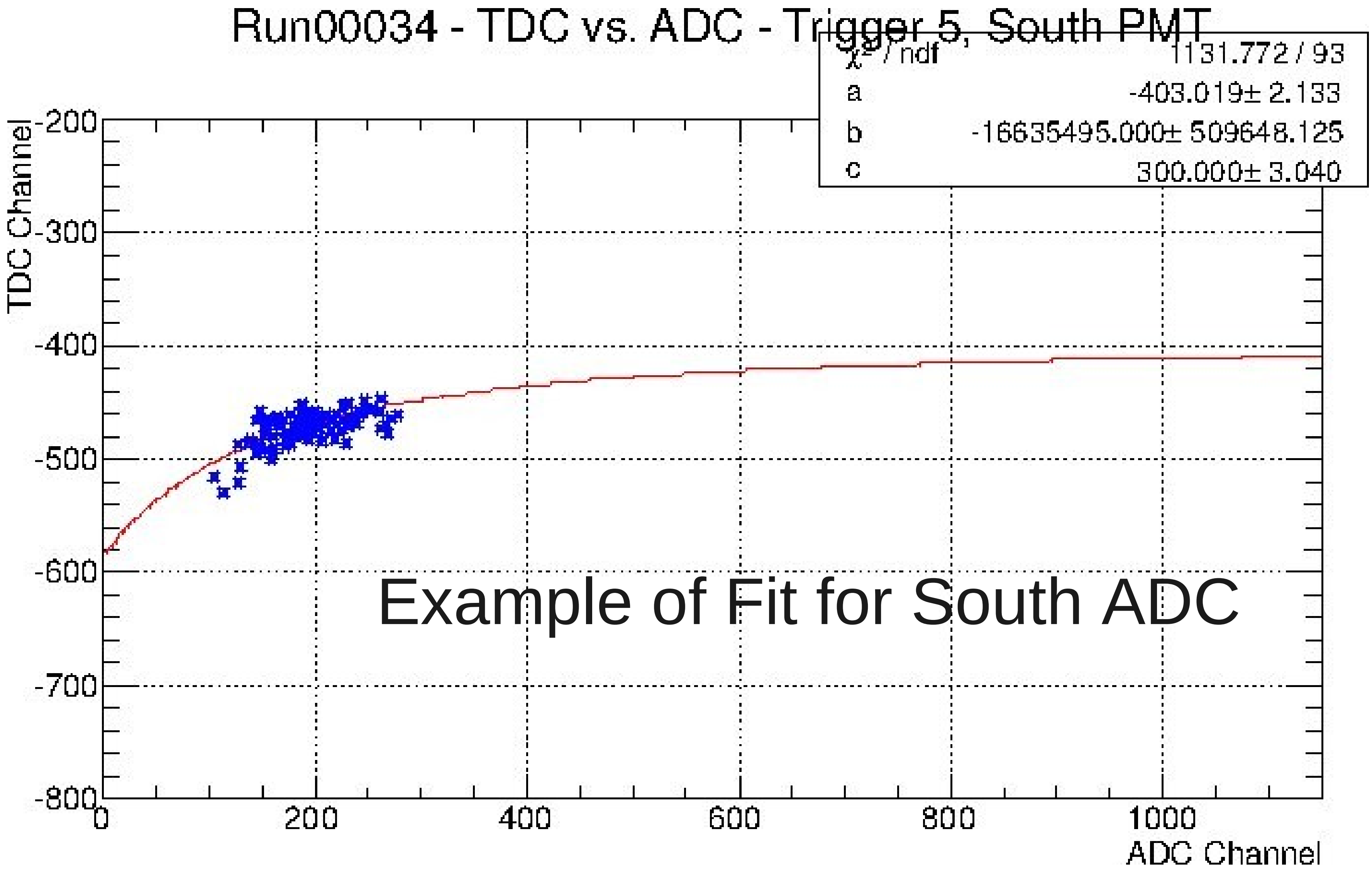
$$TDC_i^{North} = t_i^{North} + t_{trigger}$$

$$TDC_i^{South} = t_i^{South} + t_{trigger}$$

$$TDC_i^{North} - TDC_i^{South} = t_i^{North} - t_i^{South}$$

(Event-by-event subtraction)

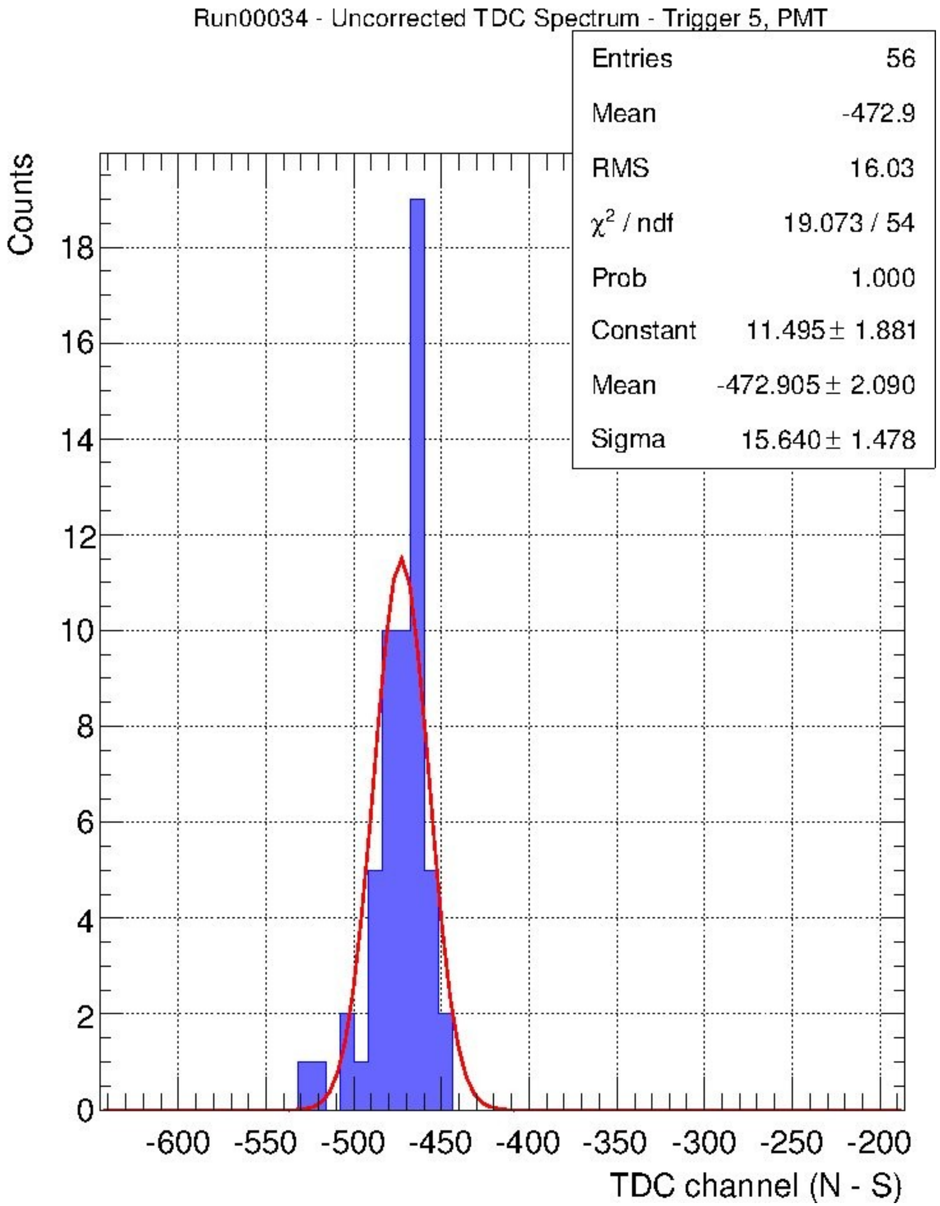
Time-Walk Fits for North and South ADCs



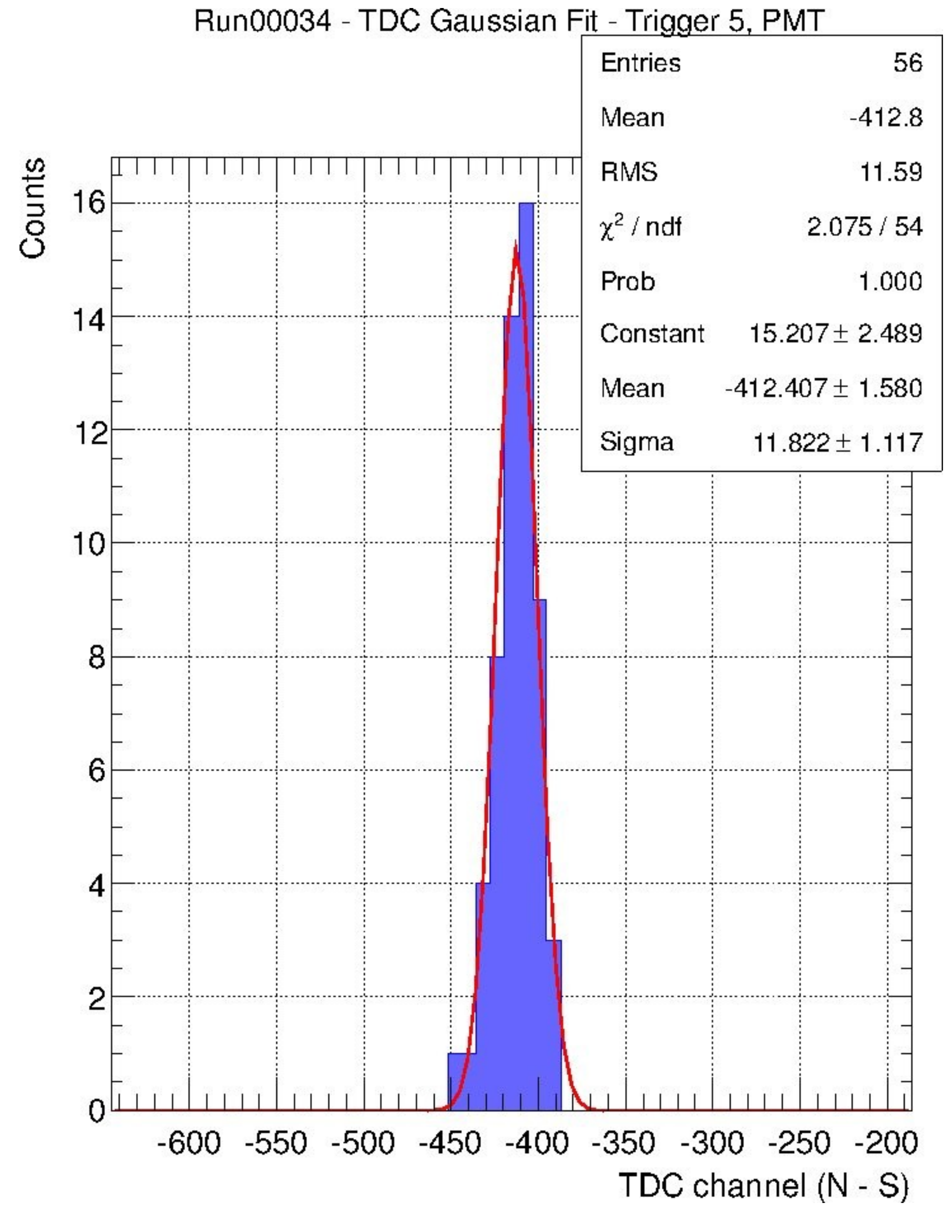
Example of Fit for South ADC

$$TDC^{North} - TDC^{South} = a + \frac{b_1}{(ADC_{North} + c_1)^2} + \frac{b_2}{(ADC_{South} + c_2)^2}$$

Gaussian Fit of Corrected TDC (N - S) Spectrum



Uncorrected Spectrum



Corrected Spectrum

TDC Setting: 48.82 ps per Channel

Distance vs. Corrected TDC Spectrum Mean

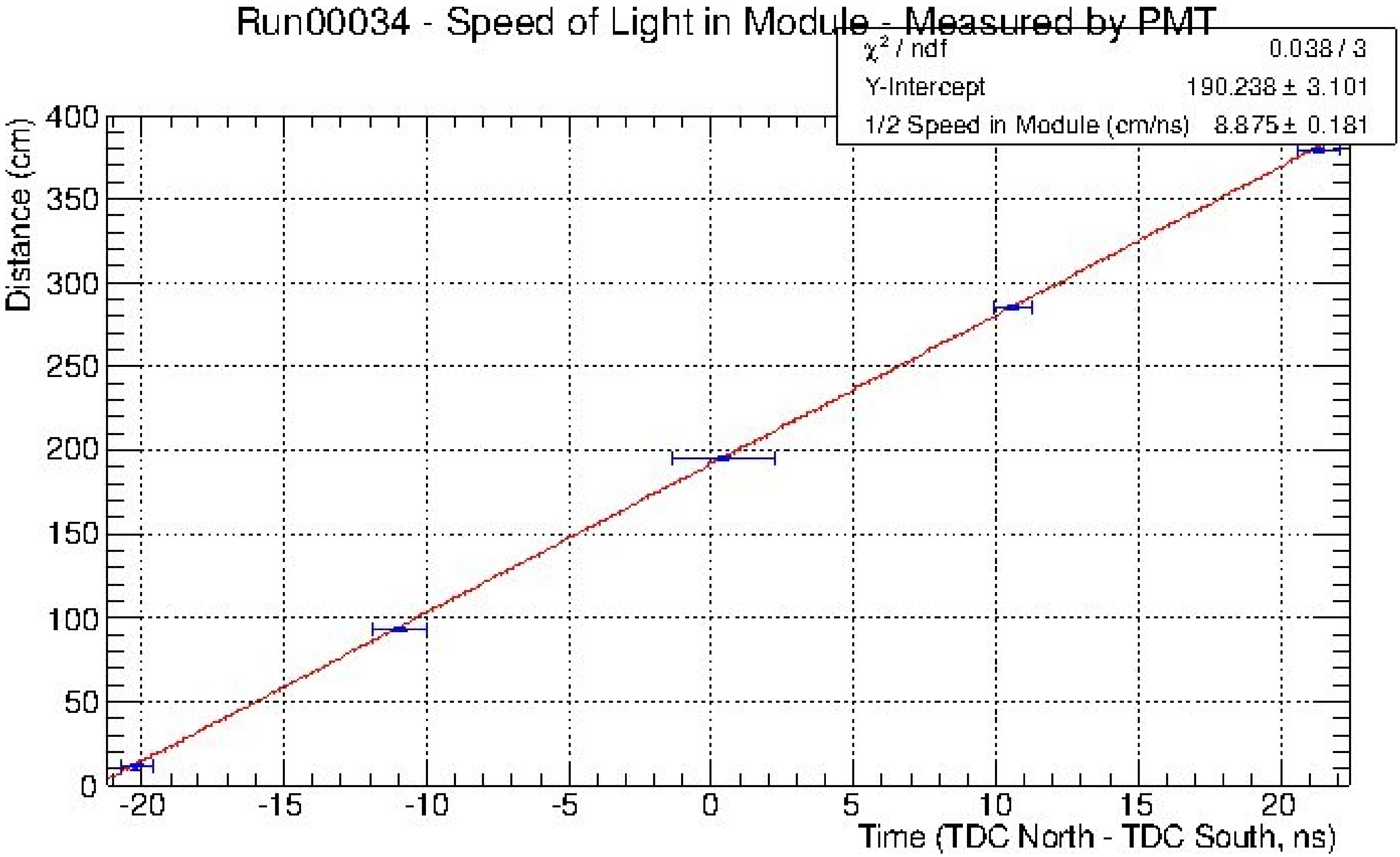
$$t_i^{North} - t_i^{South} = \frac{x^{North}}{v} - \frac{x^{South}}{v}$$

$$= \frac{x^{North} - (L - x^{North})}{v}$$

$$= \frac{2x^{North} - L}{v}$$

$$\Longrightarrow \quad x^{North} = \frac{v}{2}(t_i^{North} - t_i^{South}) - \frac{L}{2}$$

Plot of Distance vs. Corrected TDC Spectrum Mean



1/2 Speed of Light, Measured by PMTs

Run Number	Overbias	Amplifier	Measured by PMT
34	0.5 V	None	8.88 $\pm$ 0.18 cm/ns
35	0.8 V	None	8.82 $\pm$ 0.14 cm/ns
36	0.2 V	None	8.27 $\pm$ 0.26 cm/ns
27	0.5 V	None	8.76 $\pm$ 0.32 cm/ns

1/2 Speed of Light, Measured by SiPMs

Run Number	Overbias	Amplifier	Measured by SiPM
34	0.5 V	x 10	8.61 $\pm$ 0.11 cm/ns
35	0.8 V	x 10	Overflow
36	0.2 V	x 10	8.43 $\pm$ 0.19 cm/ns
27	0.5 V	None	No TDC Info

Averages for Speed:

Errors found by (t)(RMS) / $\sqrt{n}$

where t is the Student's coefficient for a 1 Sigma confidence level for a data set with n - 1 degrees of freedom

n = 3 for speeds measured by PMTs
n = 1 for speeds measured by SiPMs

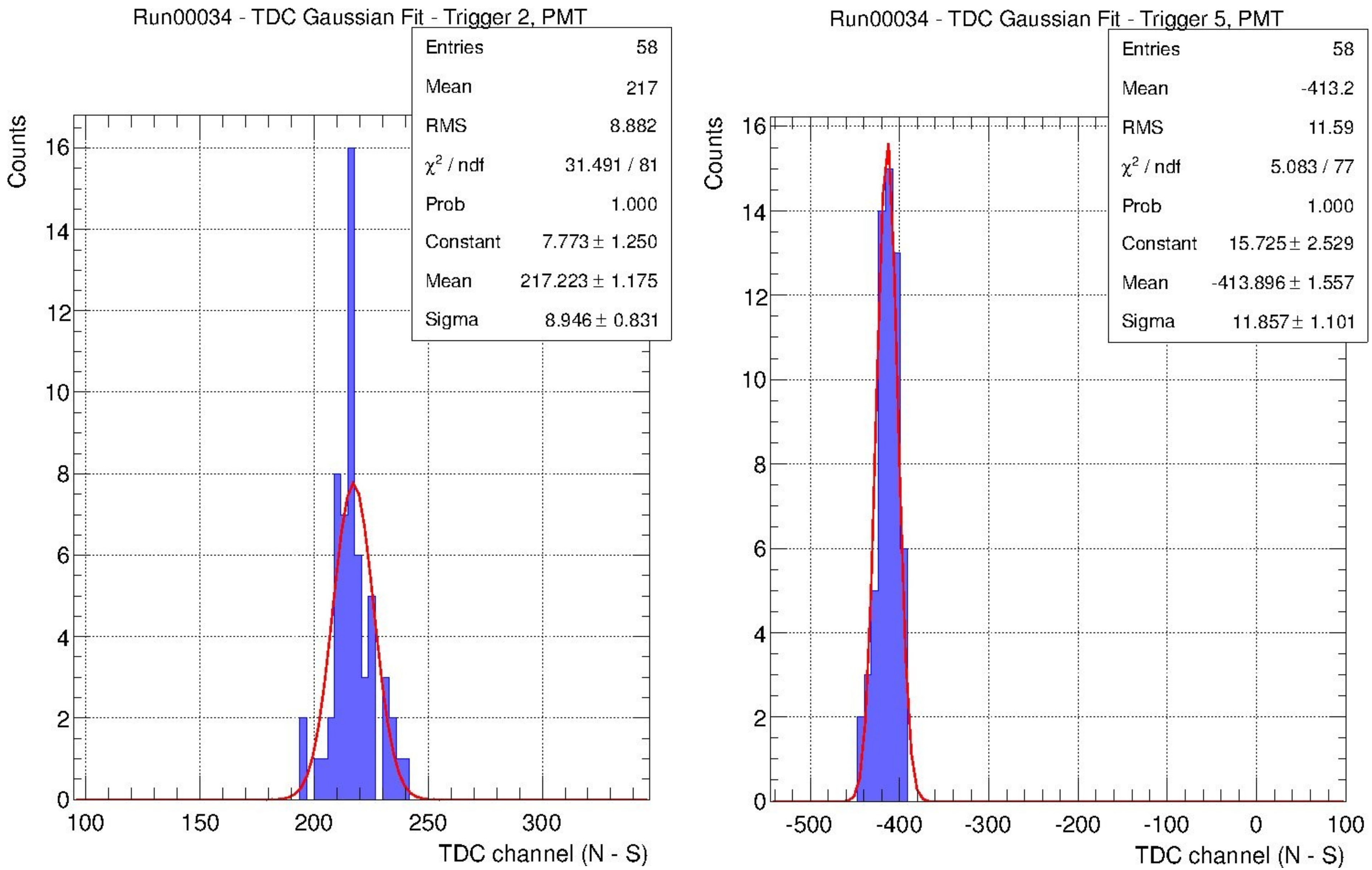
Speed of Light in Module (PMT) = 17.37 $\pm$ 0.30 cm/ns

Speed of Light in Module (SiPM) = 17.04 $\pm$ 0.26 cm/ns

Analysis of the 2005 TRIUMF beam tests using a prototype module employing blue fibers yielded a value of v = 16.2 $\pm$ 0.4 cm/ns*. 2001 cosmics tests showed v = 18.8 $\pm$ 0.6 cm/ns**. Test results from KLOE show v ~ 17.2 cm/ns*.

*GlueX-doc-824 (*Beam Tests for the GlueX Barrel Calorimeter Prototype*)
**GlueX-doc-50 (*Attenuation length and timing resolution of scintillating fibers for Hall D*)

PMT Timing Resolution



Sigma Ranges from 8 to 12 Channels

Approximate Resolution for MIP:

Time Difference Resolution of PMTs ~ 12 Channels

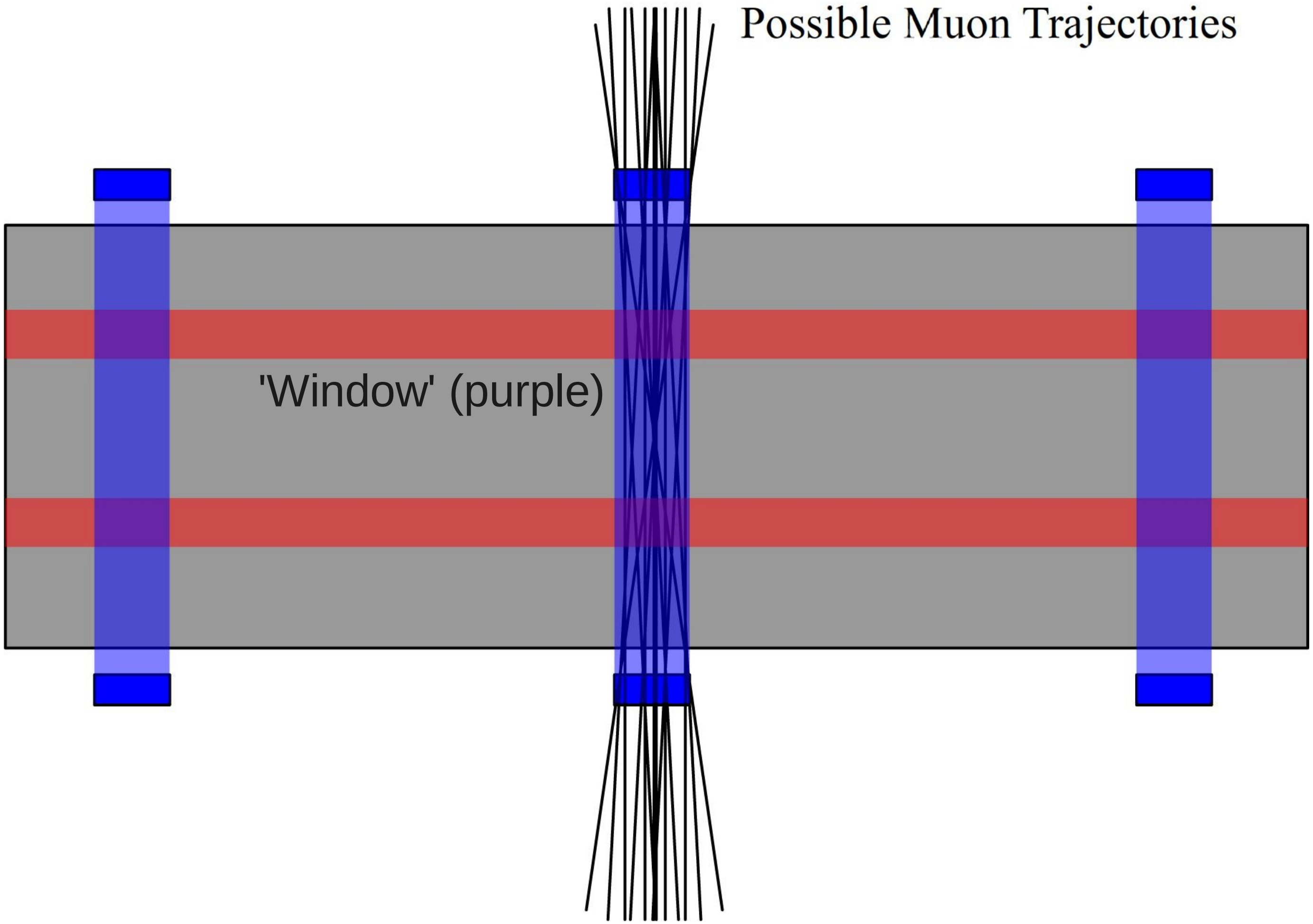
TDC Setting: 48.82 ps per Channel

Time Difference Resolution of PMTs ~ 590 ps

During the 2006 Hall B cosmics tests, again using a prototype module employing PolHiTech 044 (blue) fibers, the timing resolution for a pair of PMTs was found to average around 600 ps*

*GlueX-doc-1221 (*Analysis of Time Information from 2006 BCAL Cosmics Runs*)

$(590 \text{ ps})^2 = \text{Resolution(Trigger)}^2 + 2\ \text{Resolution(PMT)}^2$



There is a (3 cm)/(v) time difference between events occurring at each end of the event window

However, hits are more likely to occur in the middle of the window

We use 1 Sigma of the events, found in approximately 1/3 of the length of the window, for the trigger resolution

If an event happens at one end of the window, both PMTs are effected

The effective window size, then, doubles (3 cm closer to one PMT means 3 cm further from the other as well)

Using v ~ 17 cm/ns, we have a (1/3)(2)(3 cm)/(0.017 cm/ps) ~ 120 ps Trigger resolution

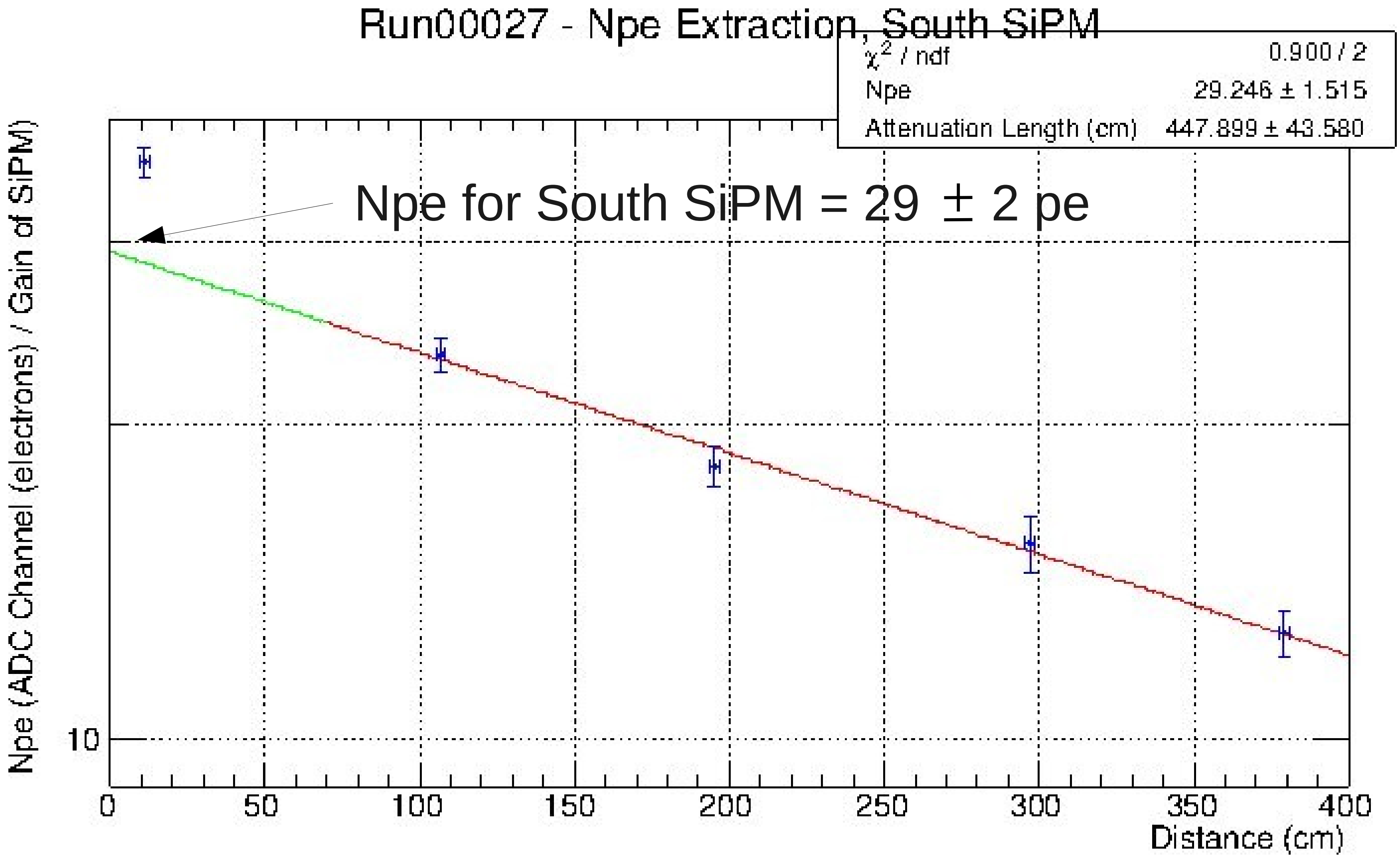
$$(590\text{ ps})^2 = (120\text{ ps})^2 + 2\,\text{Resolution(PMT)}^2$$

$$\text{Resolution(PMT)} = \sqrt{\frac{(590\text{ ps})^2 - (120\text{ ps})^2}{2}}$$

$\longrightarrow$ Resolution (PMT) ~ 410 ps

The resolution of the SiPMs could not be resolved at this point in time. The runs for which we have timing information for the SiPMs are those which we used the x10 amplifier on the signals. Right now, we don't have an accurate grasp on how much the amplifier contributes to the timing resolution of the SiPM pair. It is not a particularly 'fast' amplifier, so we suspect the contribution is significant. We plan to continue analysis to try to extract an accurate value for the resolution of an individual SiPM if possible.

Npe Extraction for SiPMs (No x10 Amplifier)



Assuming a single-exponential behaviour, the number of pixels fired in the SiPM (Npe for ease of explanation) for a MIP which occurs very near the edge of the module (at distance ~ 0 cm) is the y-intercept in the plot of Npe vs. Distance

Npe for North SiPM (Graph Not Shown) = 34 ± 2 pe

Conclusions:

Attenuation Length – PMT = 325 $\pm$ 5 cm

Attenuation Length – SiPM = 436 $\pm$ 13 cm

Speed of Light in Module (PMT) = 17.37 $\pm$ 0.30 cm/ns

Speed of Light in Module (SiPM) = 17.04 $\pm$ 0.26 cm/ns

Resolution(PMT) for MIP ~ 410 ps

Resolution(SiPM) could not be determined

Npe for MIP Close to Edge of Module = 32 $\pm$ 2 pe