Pulse-shape Simulation Using Geant4

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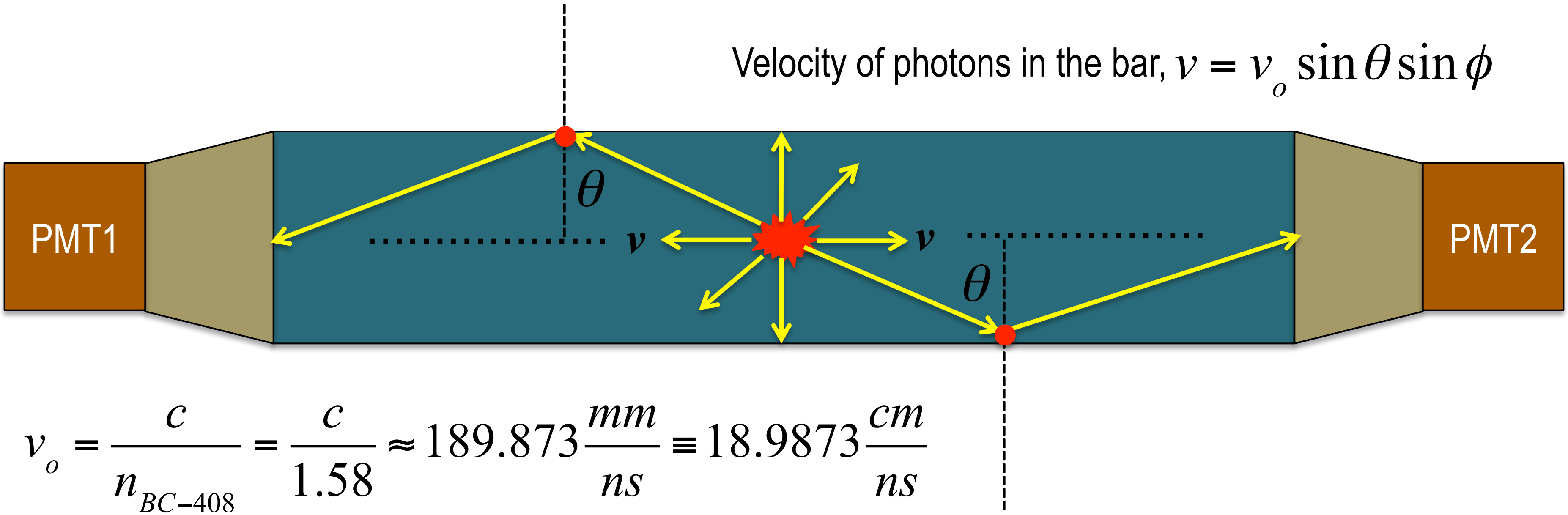
BC-408 Scintillator Photon Generation

- Photons are randomly spread from the energy deposition point in the bar in a spherically symmetric way.

Velocity of photons in the bar, $v = v_o \sin\theta \sin\phi$



$$v_o = \frac{c}{n_{BC-408}} = \frac{c}{1.58} \approx 189.873 \frac{mm}{ns} \equiv 18.9873 \frac{cm}{ns}$$

- Photon velocity component parallel to the bar scintillator is v in spherical coordinates with the critical angle, $\theta_c = \arcsin\left(1/n_c\right) = \arcsin\left(1/1.58\right) \approx 39.265^\circ$

- Photons reach the PMTs when both θ and ϕ are greater than the critical angle:

$$\theta_c = \arcsin\left(1/n_c\right) = \arcsin\left(1/1.58\right) \approx 39.265^\circ$$

Photon Propagation and Signal Generation

- Photons do lose energy whenever they propagate along the scintillating material depending on the attenuation length of the bar according to:

$$E_{PMT} = E_{\gamma} \exp\left[\frac{l}{\lambda}\right] = E_{\gamma} \exp\left[\frac{l}{3350}\right]$$

- A small pulse results from each photon arriving at the photocathode of the photomultiplier tube.

  Two essential parameters can be extracted from the pulse:

- Arrive time of photon = start time of a small pulse and;

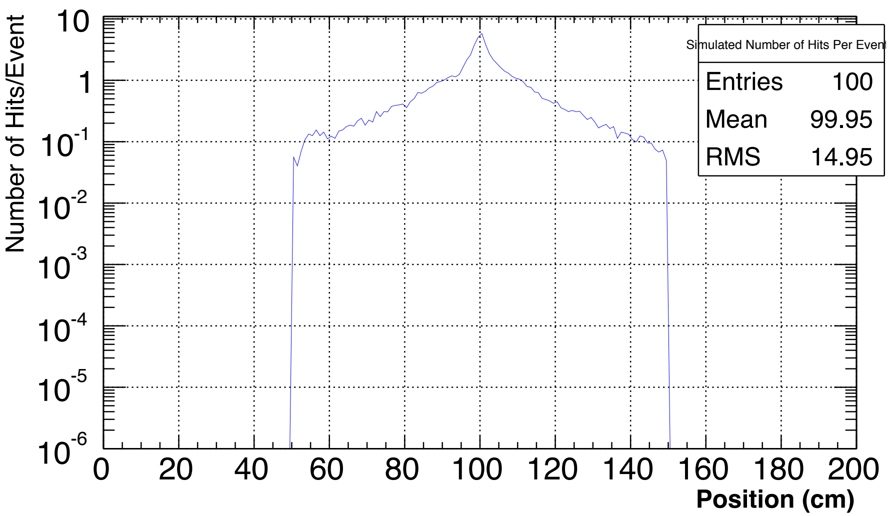
- Photon energy = area of the small pulse.

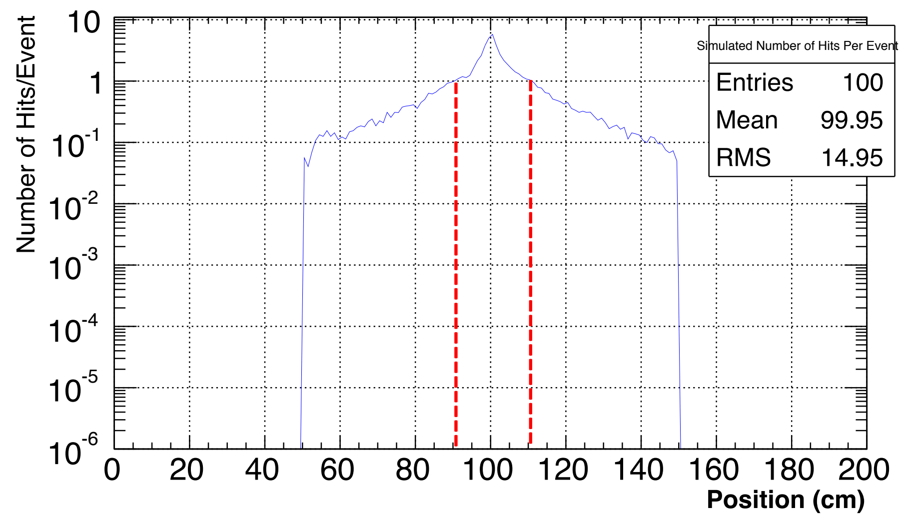
All these small pulses superimpose and emerge as an enhanced pulse or waveform.

Simulated Position and Time Resolutions

Simulated Hit Position

- 392 MeV neutron energy shot at the center of the 2 m-long scintillator so that close to 98 % of the neutron hits occur within 10 cm ± from the center of the bar **[100 cm]**





Result 1: Simulated hit position of the ~ 392 MeV neutrons directed at the center

3. Simulated Position and Time Resolutions

Hit Classification

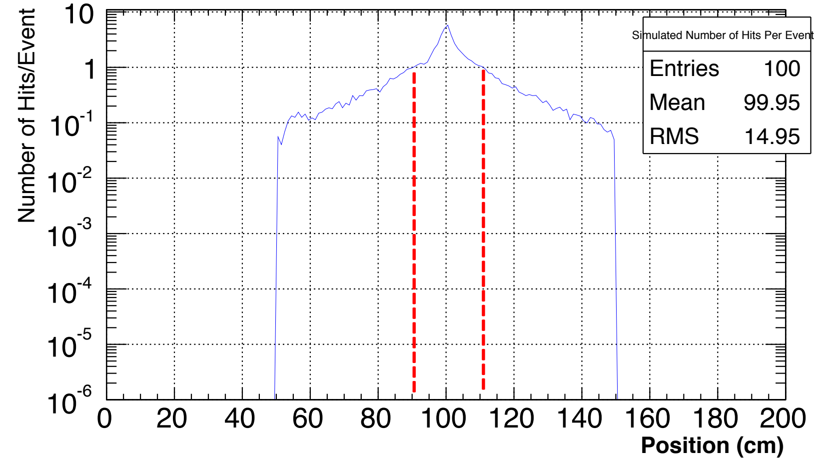
Distinguished two signals close to each other by requiring:

- Separation distance larger than 10 cm.
- Generation time difference larger than 2 ns.

- Collected all hits made in the bar within a gate time interval of 0 ns and 150 ns.
- Light yield per unit length for all hits within a group was obtained by applying Birks formula:

$$\frac{dL}{dz} = \frac{S\,dE/dz}{1 + kB\,dE/dz + \xi\left(dE/dz\right)^2}$$

Light yield per path length as a function of energy loss per path length

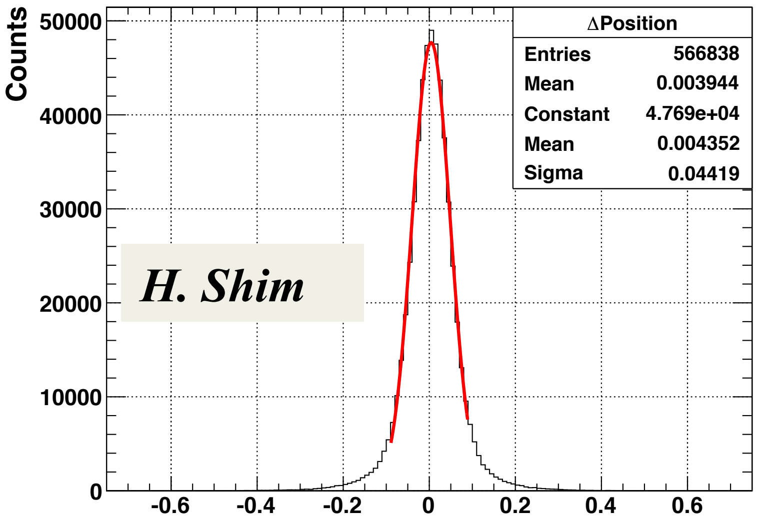


Hit position at the center of the bar

- L = Ecorr (scintillator response)
- S = 1 (Electronics response)
- kB = 0.977 x 10^{-2} $g.cm^{-2}.MeV^{-1}$ (1^{st} order)
- ξ = 2^{nd} order parameter (negligible) for n
- dE/dz = Energy loss per path length
- dL/dz = Light yield per path length

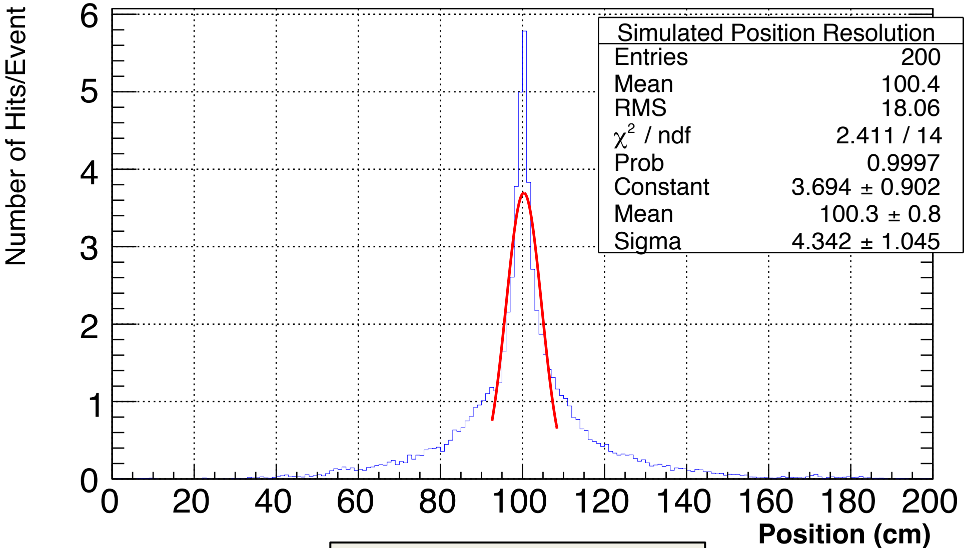
Position Resolution from Data and Simulation

DATA



$$\sigma_{z,\exp} = \frac{4.419}{\sqrt{2}} \approx 3.12cm$$

SIMULATION

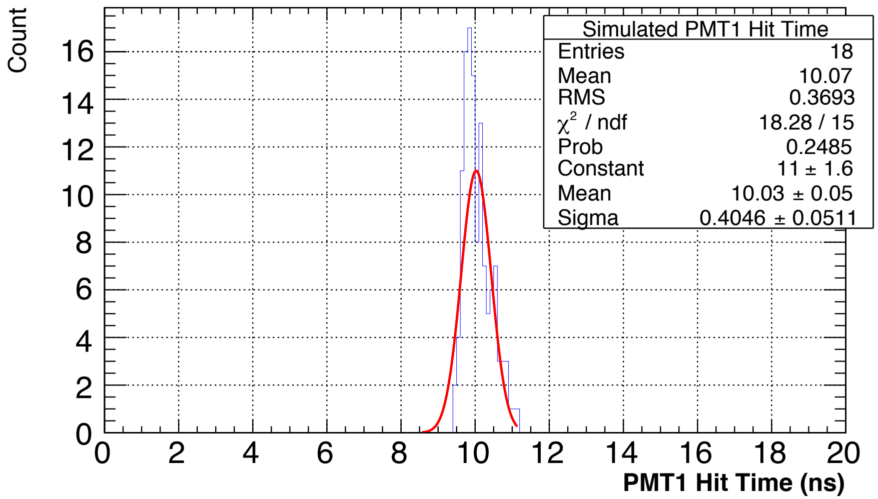


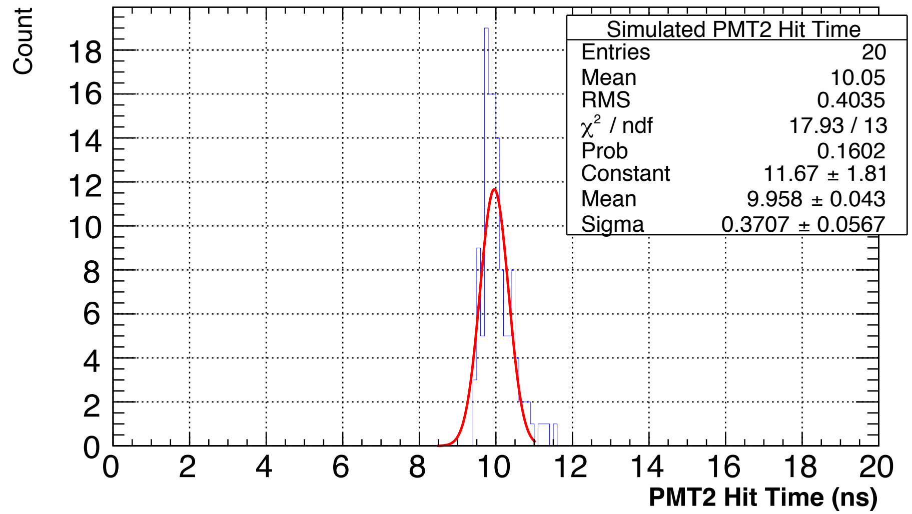
$$\sigma_{z,sim} = \frac{4.342}{\sqrt{2}} \approx 3.07cm$$

Position Resolution, σ_z	*Experiment (cm)*	*Simulation (cm)*	$\%diff = \frac{\lvert E-S \rvert}{\left(\frac{E+S}{2}\right)} * 100\%$
	3.12	3.07	~ 1.62

Time Resolution from Data and Simulation

SIMULATION





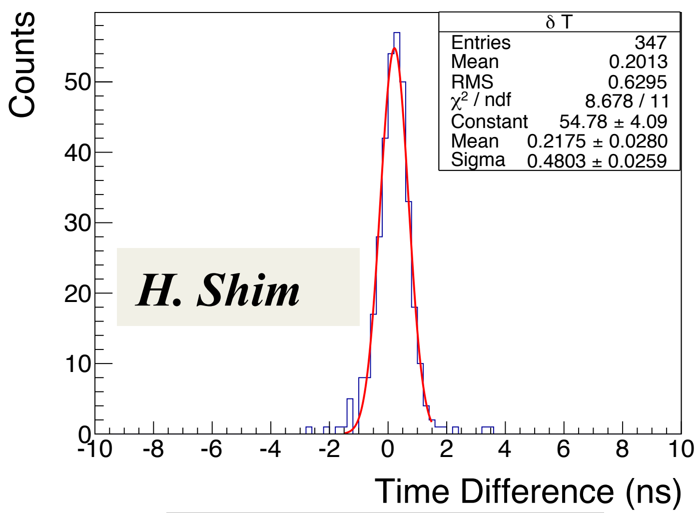
True hit time is the average of the hit times of the two photomultiplier tubes

$$T_{mean} = \frac{(T_1 + T_2)}{2} \approx 10.06ns$$

$$\sigma^2_{T_{mean}} = 0.5^2 * \sigma^2_{T_1} + 0.5^2 * \sigma^2_{T_2} + 2 * 0.5^2 \sigma_{T_1 T_2} \therefore \sigma_{T_{mean}} = 0.5 * \sqrt{\sigma^2_{T_1} + \sigma^2_{T_2} + 2 * \sigma_{T_1 T_2}} \approx 306.0 \pm 0.043 ps$$

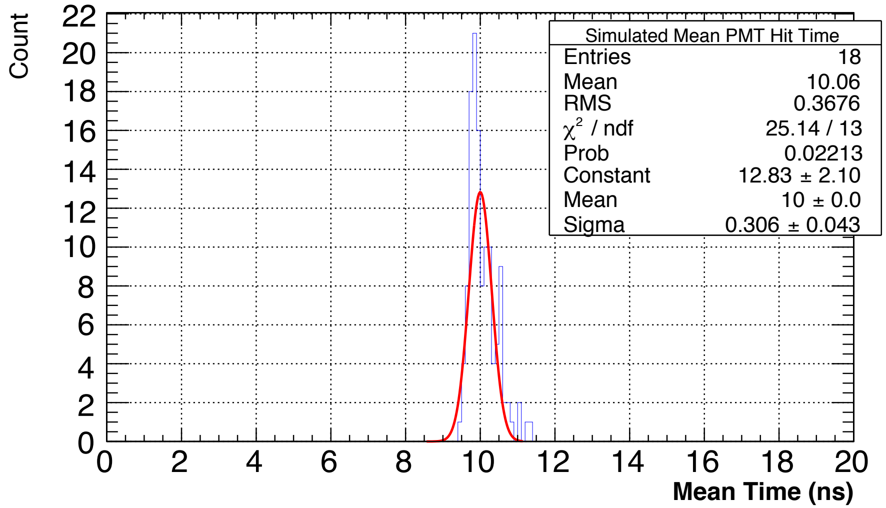
Time Resolution from Data and Simulation

DATA



$$\sigma_{\exp} = \frac{\sigma_{total}}{\sqrt{2}} = 339.6\,ps$$

SIMULATION



$$\sigma_{T_{mean}} = 0.5 * \sqrt{\sigma_{T_1}^2 + \sigma_{T_2}^2 + 2 * \sigma_{T_1 T_2}} \approx 306.0 \pm 0.043\,ps$$

Time Resolution, σ_t	***Experiment (ps)***	***Simulation (ps)***	$\%diff = \frac{\lvert E - S \rvert}{\left(\frac{E+S}{2}\right)} * 100\%$
	339.6	306.0	~ 10.4

Backup

Useful Method:

f (x) = [0](exp(-(x[0]-par[1])/[2])-exp(-(x[0]-[1])/[3]))/([2]-par[3])

Where the four fundamental explicit function parameters are:

[0] = Pulse start time [ns]
[1] = Amplitude
[2] = Rise time [ns]
[3] = Decay time [ns]

Found that the pulse width is different based on the rise and decay times set to generate the pulse. For example, BC-408 plastic scintillators have short rise and decay times of 0.9 ns and 2.1 ns, respectively. The pulse generated using these parameters has a very narrow pulse width compared to the pulse width generated from data. This is because the rise and decay times of 0.9 ns and 21 ns conform only to processes confined within the scintillator. After the pulse is fully processed, processes in the PMT and signal cables come into play resulting in a broadened pulse width and longer rise and decay times.

Backup

Useful function:

f (x) = [0](exp(-(x[0]-par[1])/[2])-exp(-(x[0]-[1])/[3]))/([2]-par[3])

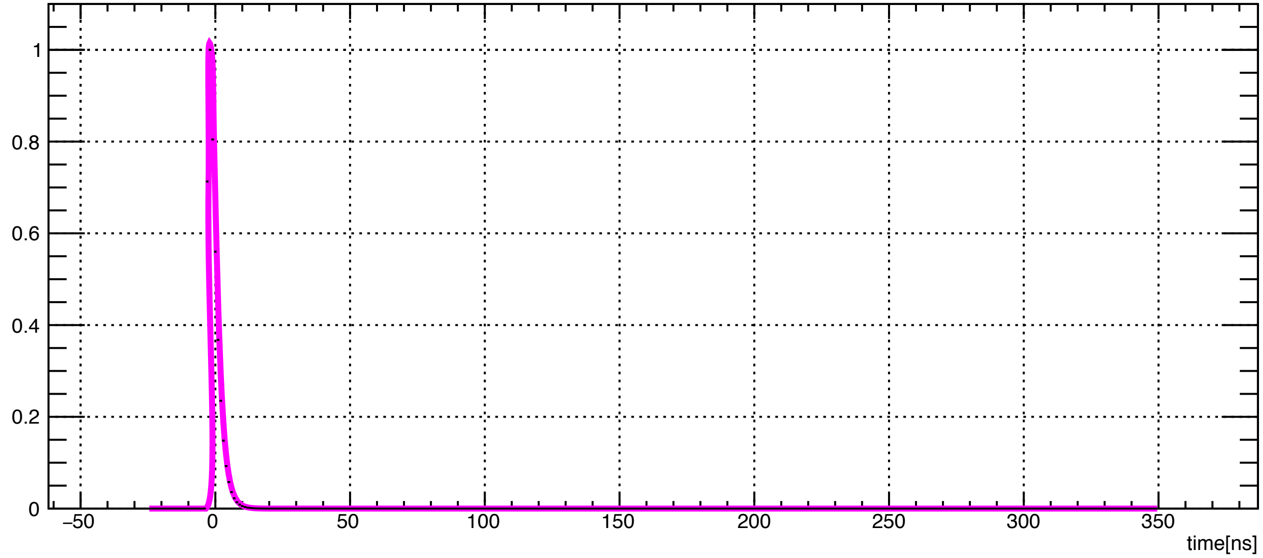
[0] = Pulse start time [ns] = -15 ns

[1] = Amplitude = normalized to 1 to compare with experimental data

[2] = Rise time [ns] = 0.9 ns for BC-408 scintintillator

[3] = Decay time [ns] = 2.1 ns for BC-408 scintillator

Pulse-shape simulation with rise and decay times for BC-408 scintillator



Backup

Useful function:

f (x) = [0](exp(-(x[0]-par[1])/[2])-exp(-(x[0]-[1])/[3]))/([2]-par[3])

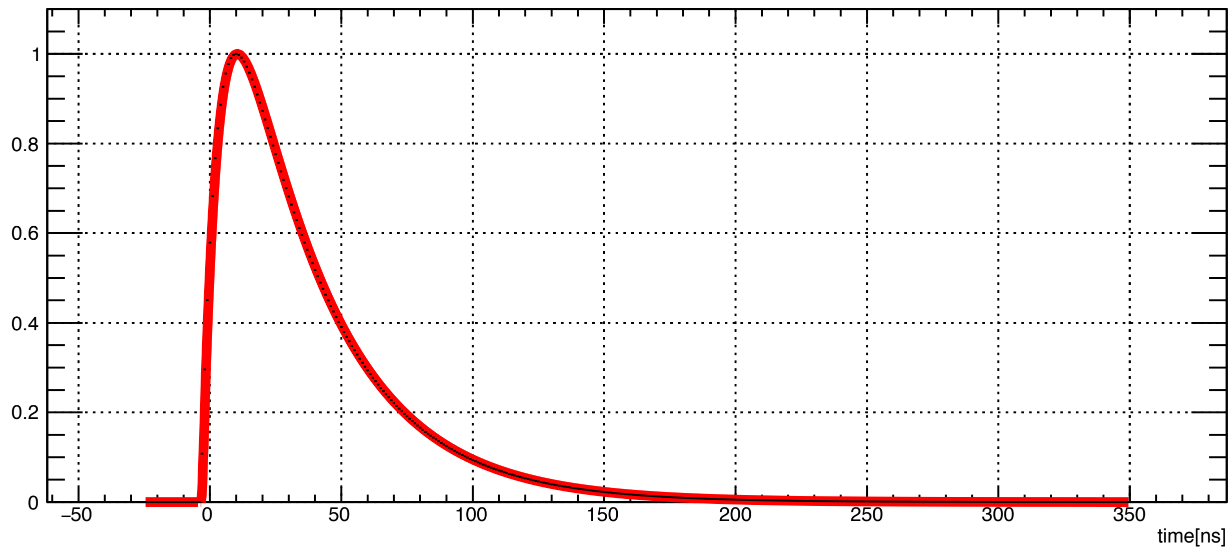
[0] = Pulse start time [ns] = -15 ns

[1] = Amplitude = normalized to 1 to compare with experimental data

[2] = Rise time [ns] = 0.9 ns : Rise time of BC-408 scintintillator

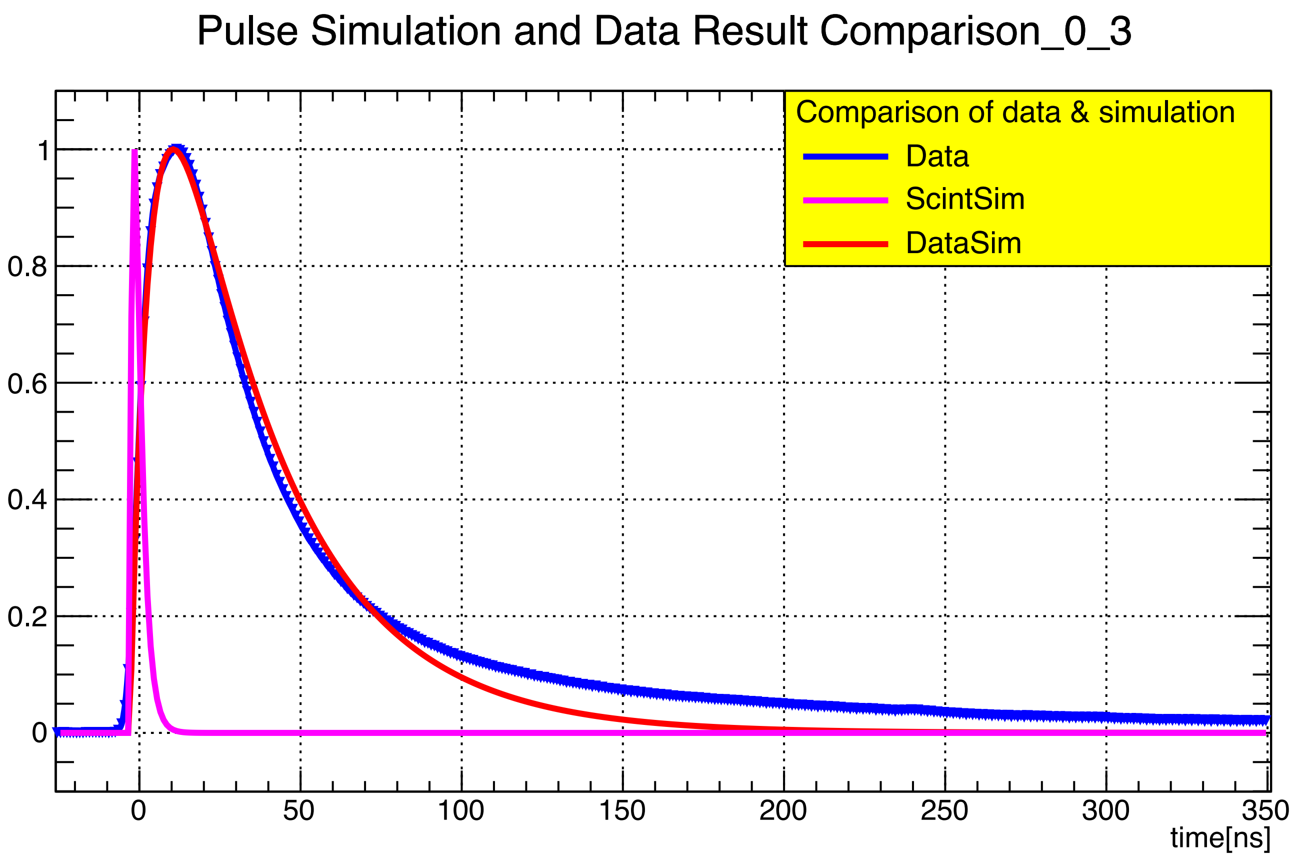
[3] = Decay time [ns] = 2.1 ns : Decay time of BC-408 scintillators

Typical pulse-shape simulation



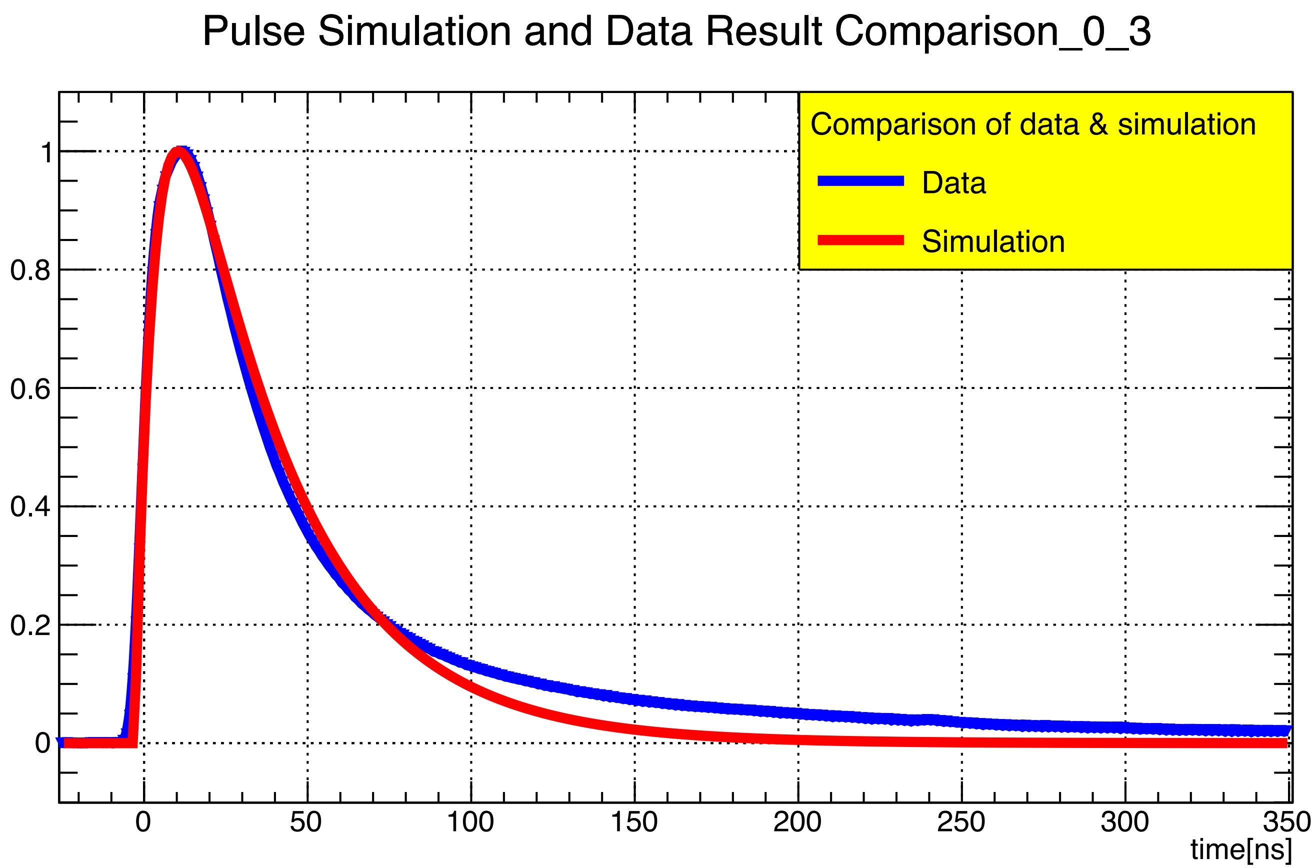
Backup

Useful function:



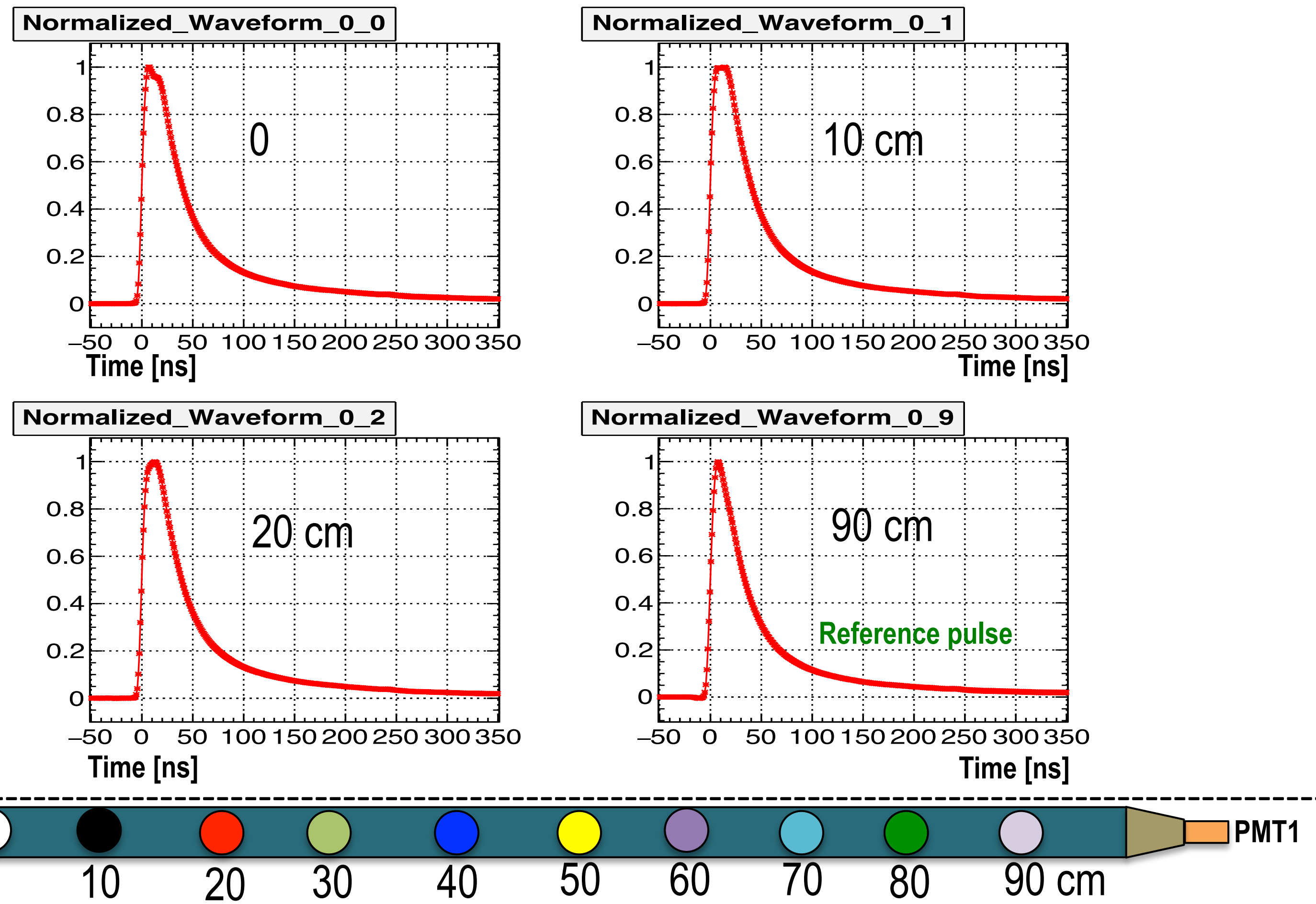
Backup

Useful function:



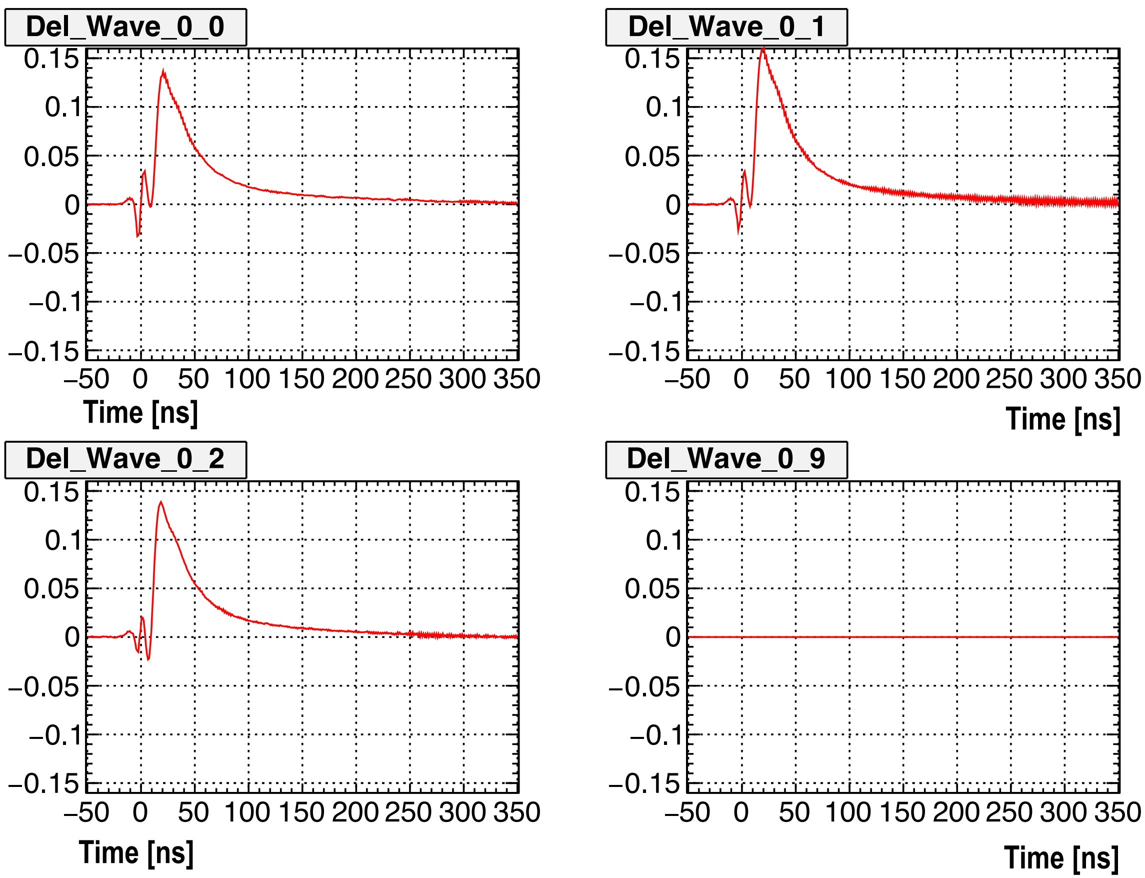
Backup

Study of Waveform by Position along the 1 m-Long Scintillator's Length



Backup

Waveform Delta between two pulses along 1 m-Long Scintillator's Length



Del_Wave_0_0:
is the difference between the pulse at 0 position and the reference pulse at 90 cm.

Del_Wave_0_9:
is the reference pulse. Therefore, delta is zero, that is a flat distribution.

Distortion from reflections[2]
in interconnecting cables is one of the causes of wave delta.

William R. Leo, Techniques for Nuclear and Particle Physics Experiments, p244 (1987)[2]

Attenuation Length, λ For 2 m-Long Prototypes

- Attenuation length, λ is understood as the distance (cm) in the material where the intensity of the beam has dropped to 1/e, or about 63% of the particles have been stopped.

- This is the Beer-Lambert's law:

$$P(x) = P_o e^{-x/\lambda}$$

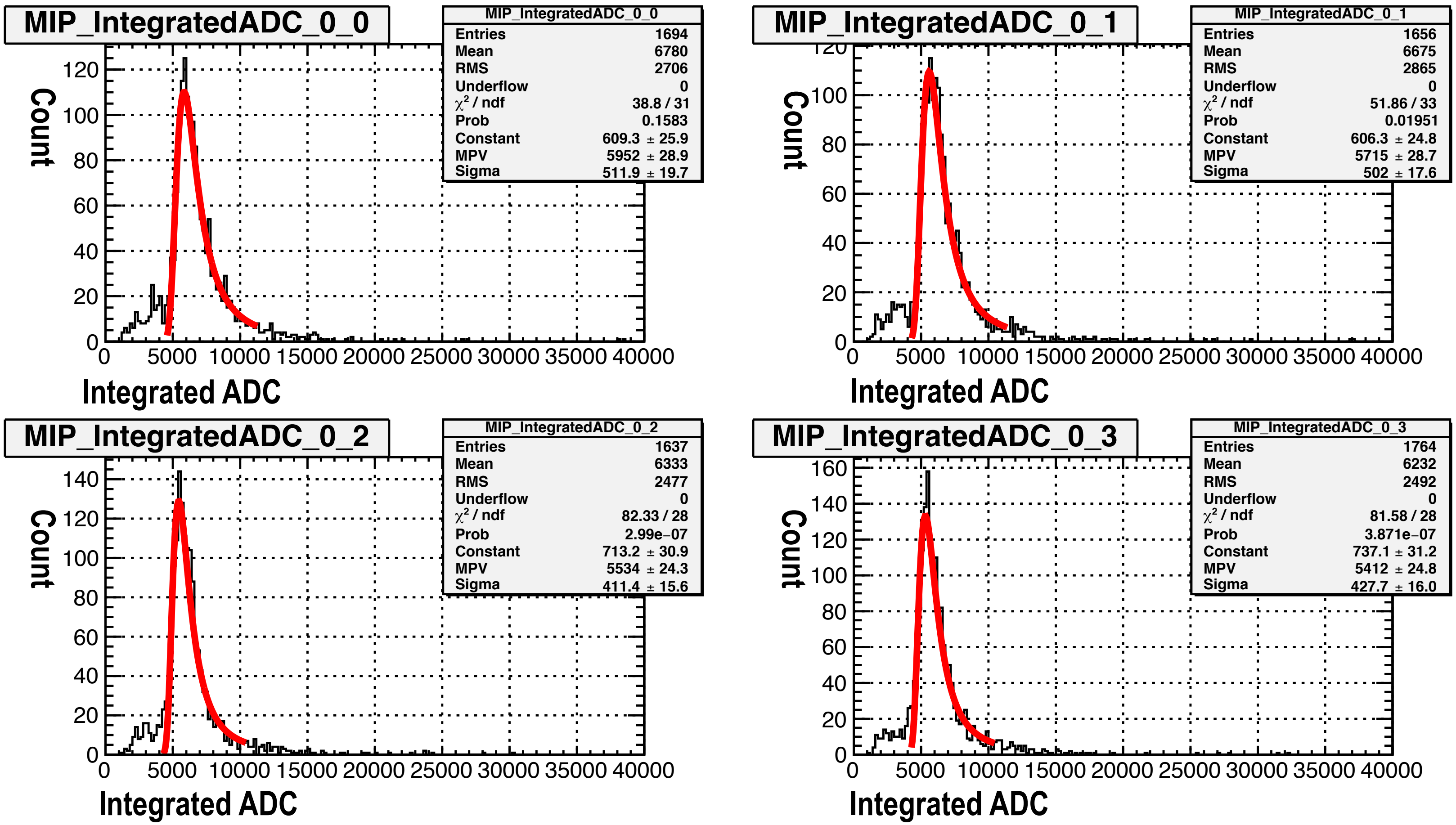
Where;

- $P(x)$ is the number of incident radiation.
- P_o is the number of photons reaching the PMT (ADC value)
- x is the path length of the scintillating material.
- λ is the attenuation length and depends on the material and energy.

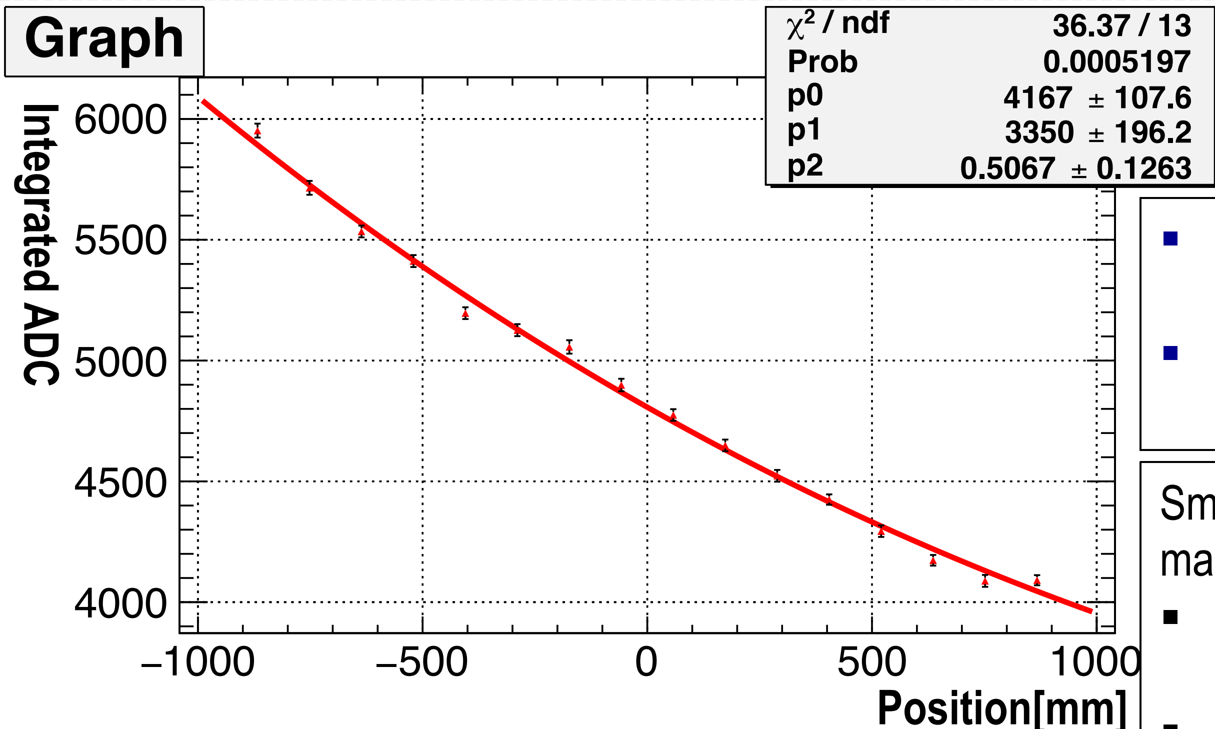
- The integrated ADC method was applied in understanding the attenuation length, λ of the current 2 m-long prototypes.

Backup

Integrated ADC From Cosmic Muons For 2 m – Long Prototypes



Attenuation (λ) From Integrated ADC Using Cosmic Data – 2 m Prototype



Comparison of λ to the BC-408 Manufacturer's value

- Expt. Value = 335 cm
  Dim. [10 x 10 x 200] cm^3
- Th. Value = 210 cm
  Dim. [1 x 20 x 200] cm^3

Smaller attenuation length by manufacturer is due to:

- The smaller dimension of the detector.
- The detector's polished edges.
- The limit in the signal cable interconnections.

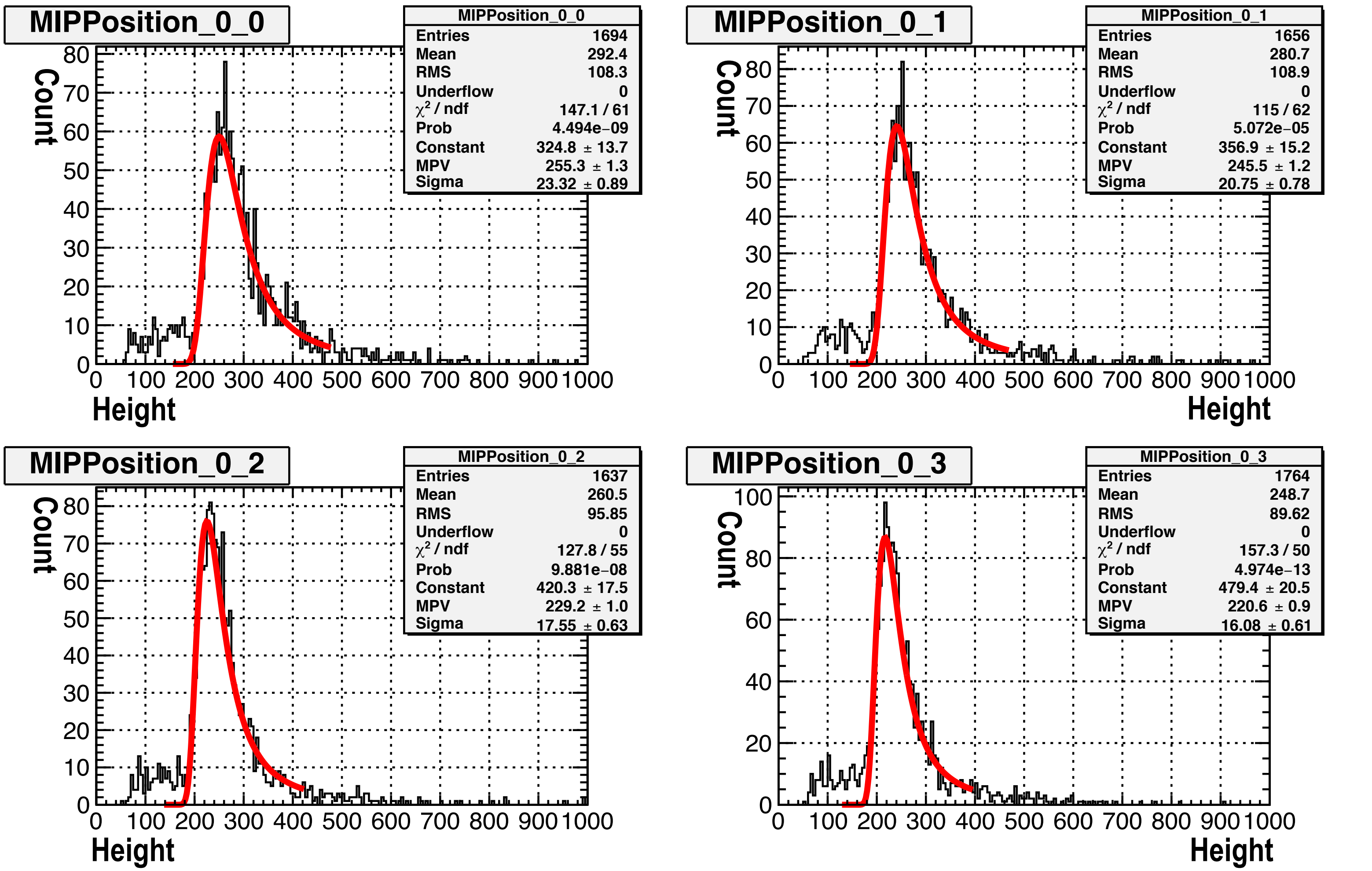
$$P = P_0\left[e^{-\frac{x}{P_1}} + P_2 e^{-\left(\frac{2L-x}{P_1}\right)}\right]$$

Fitting function for integrated ADC

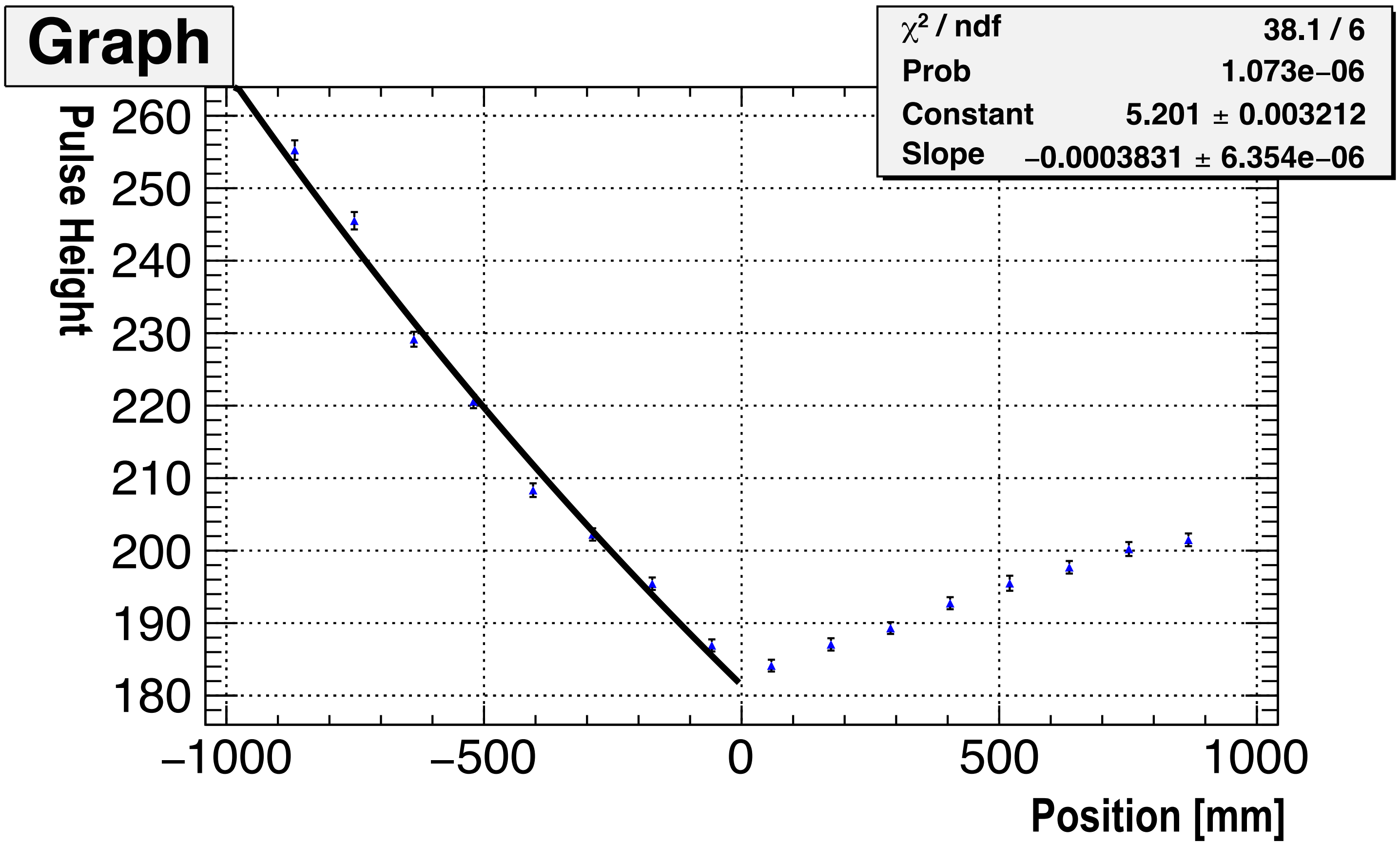
- Po = PMT photons
- P1 = Attenuation Length
- P2 = Reflectivity

Backup

Pulse Height From Cosmic Muons



Backup



Exponential fit function with λ = 1/slope = 1/0.0003831 = 261 cm = attenuation length