# Pulse Shape Simulation
# Lab Meeting
# Benard

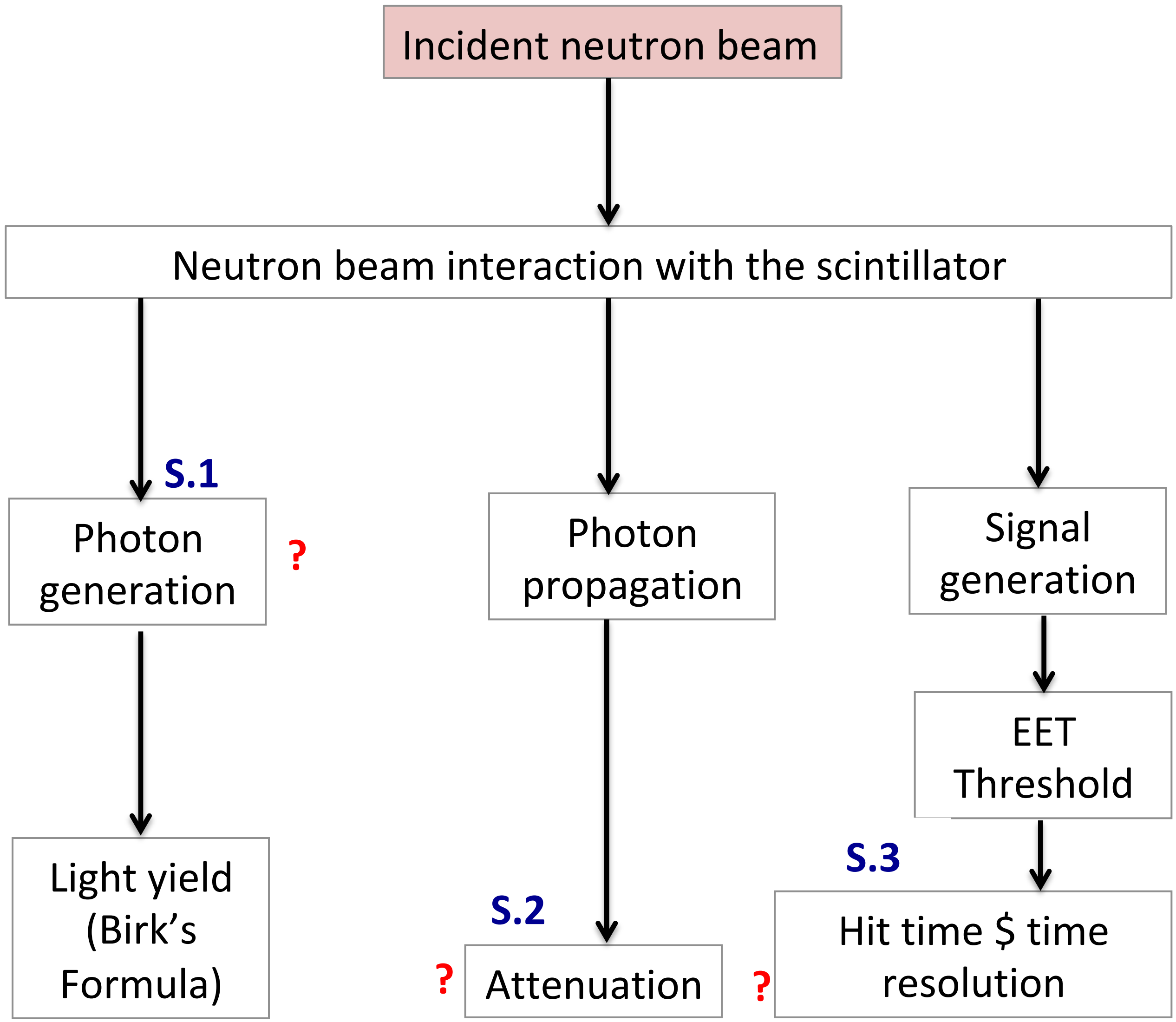
2018-06-22

# Last Lab Meeting

Issues raised:

1) Critical angle issue.
2) Reflection and attenuation.
3) Hit time distribution fluctuations.
   (Distribution not Gaussian)

# Analysis procedure



# Photon Generation in BC-408 Scintillator

- Removed the cut condition that photons reach PMTs when both $\theta$ and $\Phi$ are greater than the critical angle.

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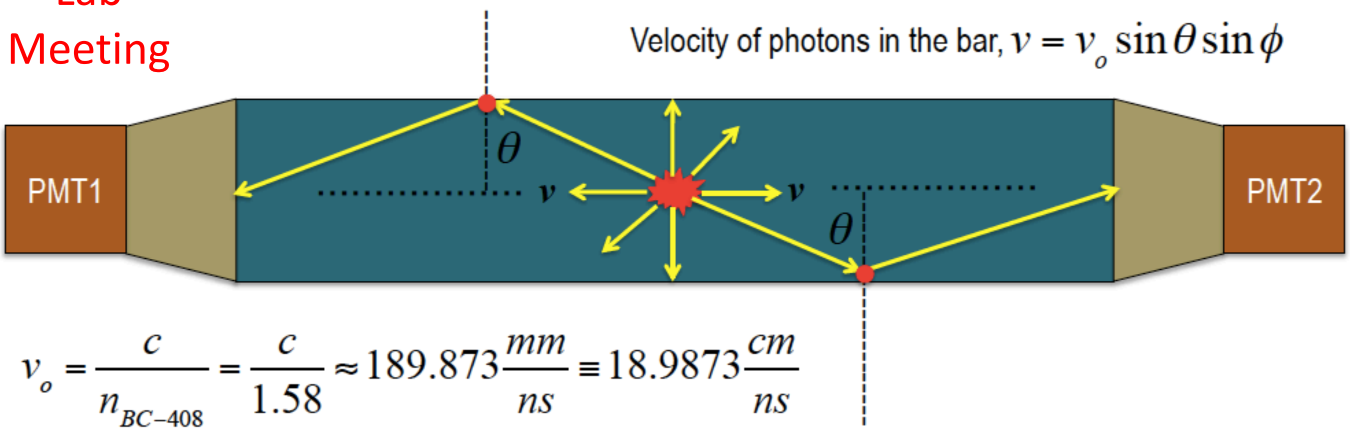
Velocity of photons in the bar, $v = v_o \sin\theta \sin\phi$




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

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

- Photons reach the PMTs when both $\theta$ and $\phi$ are greater than the critical angle: **X**
  $$\theta_c = \arcsin(1/n_c) = \arcsin(1/1.58) \approx 39.265^\circ$$

# Photon propagation

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

**X** $$E_{PMT} = E_{\gamma}\exp\left[\frac{l}{\lambda}\right] = E_{\gamma}\exp\left[\frac{l}{3350}\right]$$ **Last Lab Meeting**

## Attenuation and reflection

- Above case applies to a case where reflection of the pulses is not considered, which was too general case for our data set.

- Since data results showed some reflection, in simulation photons should lose energy depending on the attenuation length according to:

$$E_{PMT} = E_0\left[\underbrace{\exp\left(-\frac{x}{335}\right)}_{\text{Incident component}} + E_2\underbrace{\exp\left(-\frac{2L-x}{335}\right)}_{\text{Reflected component}}\right]$$

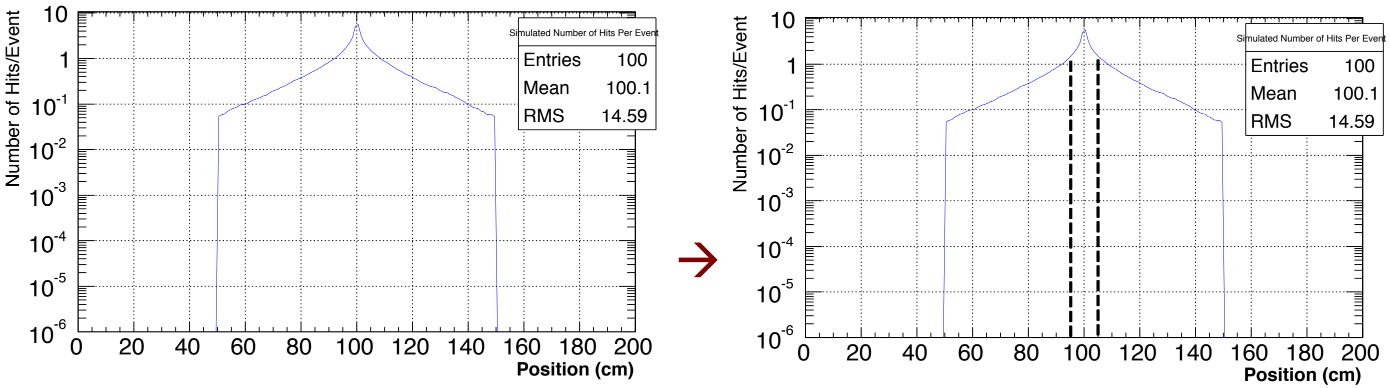
Incident component

Reflected component

# Hit Position and Classification

- High energy neutron beam collimated at the center of the 2 m long scintillator bar.

- Condition for classifying hits: Almost all neutron hits must occur within [100 ± 10] cm.




Result 1: Simulated hit position with most hits within [100±10] cm

Separated two pulses close to each other by requiring two conditions:

- A separation distance of larger than 10 cm.
- A generation time difference larger than 2 ns

# Light Yield Per Unit Length
## [Birks Formula]

- Light yield per unit length for hits within a group was obtained by applying the Birk's formula.

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

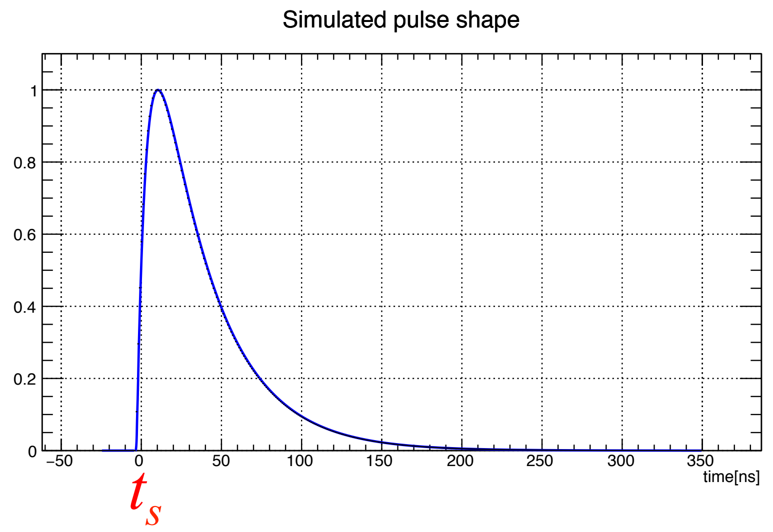
Where;

- $dL/dz$ = Light yield per path length
- $dE/dz$ = Energy loss per path length
- $L$ = Scintillator response.
- $S$ = Electronics response = 1
- $\xi$= 2nd order parameter negligible for neutrons
- $kB$ = $2^{nd}$ order parameter negligible for neutrons

# Signal Generation

Small pulse is produced for each photon arriving at each end of the scintillator.

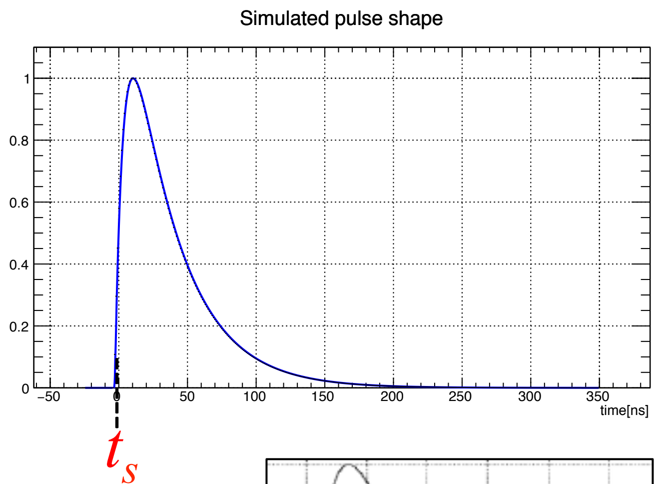
- ◎ Arrival time of photon = start time of small pulse.
- ◎ Area of each small pulse = photon energy

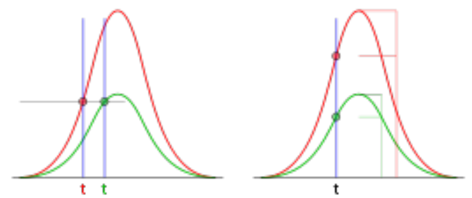



These small pulses merge to form an enhanced signal/waveform.

# Signal and EE Threshold

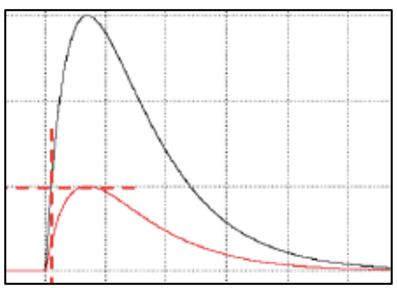
Flash ADC has a pulse processing system similar to leading-edge VTD.




Leading-edge Constant-fraction

- Considered EET signal whose start time is same as signal.



- Time when height of neutron signal is equal to maximum height of EET signal, then;
- Signal hit time (simulation) ≈ signal hit time (real expt.)

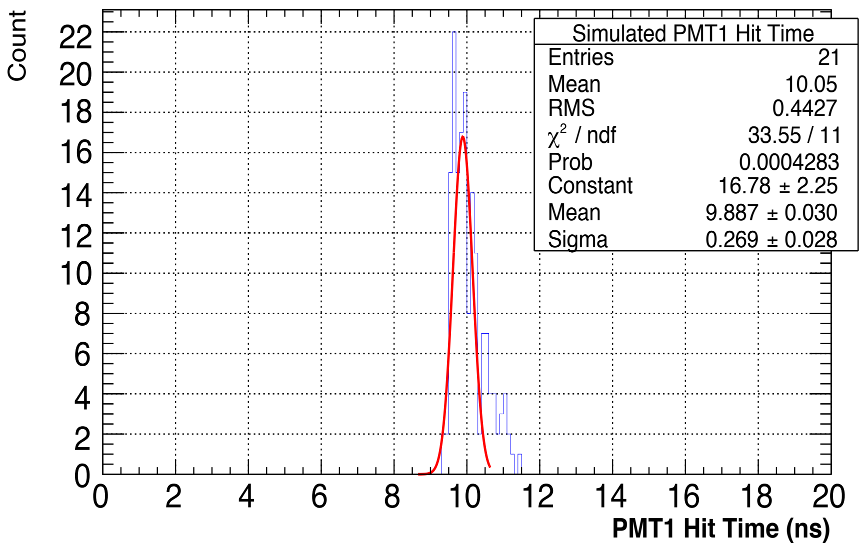
Hit time consideration:
So only when,

- Signal at each PMT has height ≥ height of maximum EET signal, each PMT hit time information is stored.
- Both PMT hit times exist, mean hit time is computed for storage.

# Hit Time and Resolution

## Simulation Result

Hit time for left photomultiplier tube with sigma value = 269.0 *ps*

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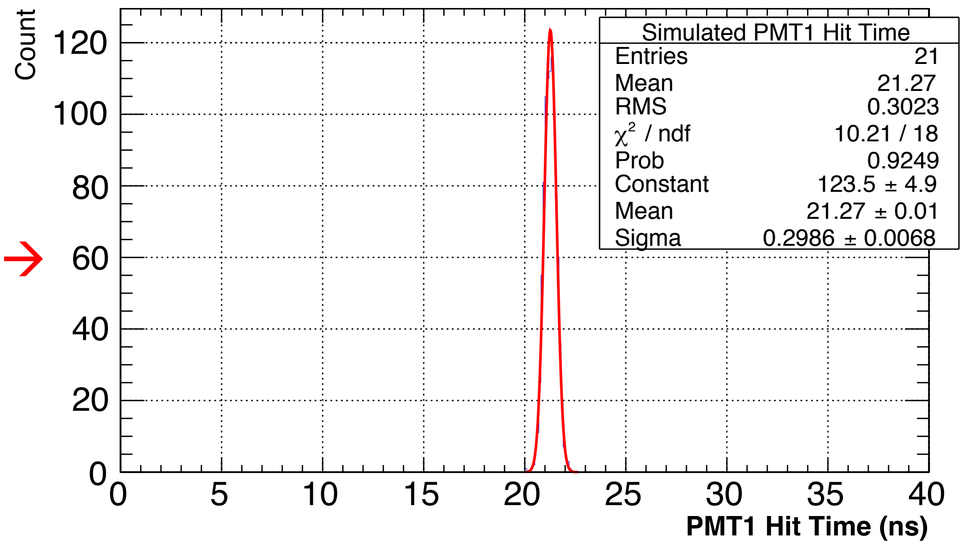
Hit time for left photomultiplier tube with sigma value = 298.6 *ps*

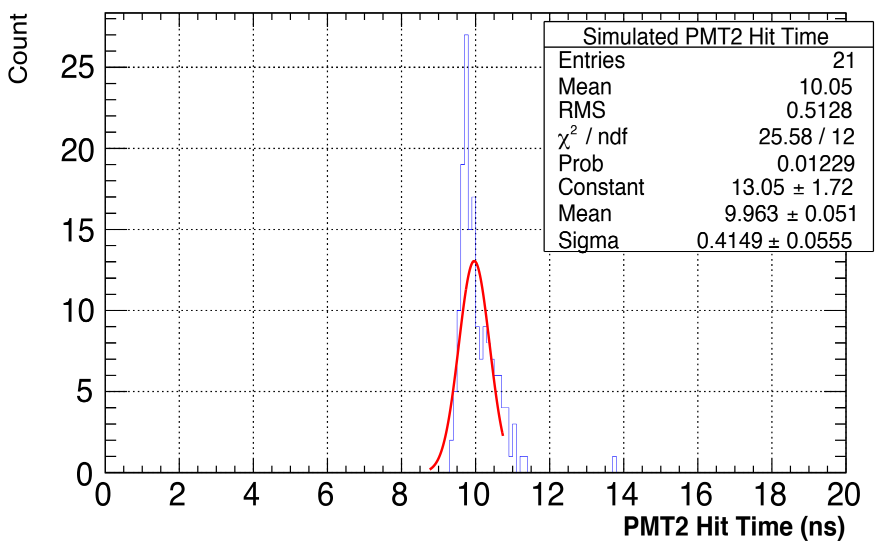



Current Result

# Hit Time and Resolution

## Simulation Result

Hit time for right photomultiplier tube with sigma value = 414.9 *ps*

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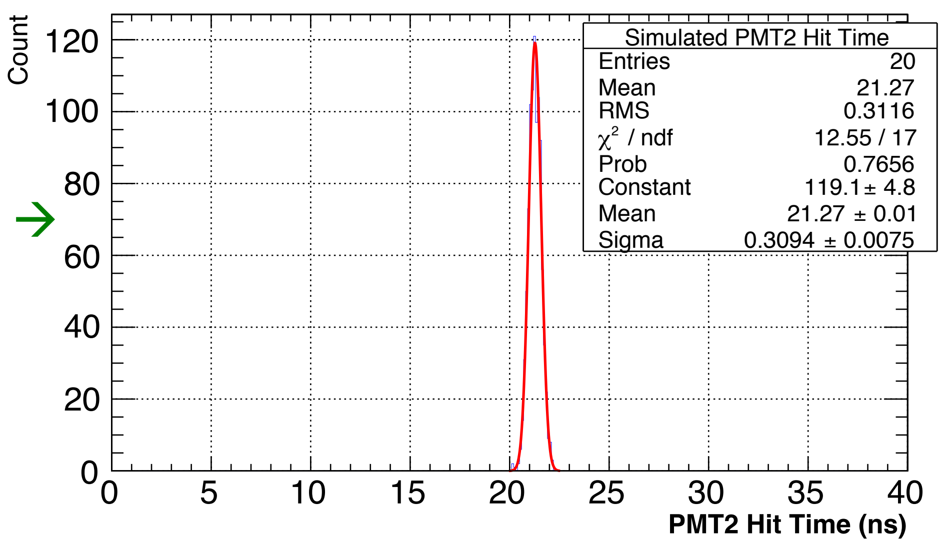
Hit time for right photomultiplier tube with sigma value = 309.4 *ps*

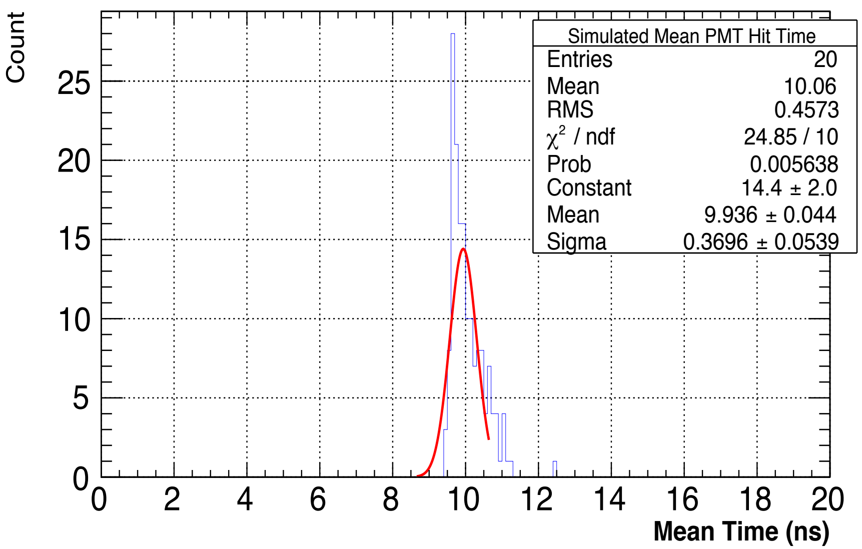



Current Result

# True Hit Time and Resolution

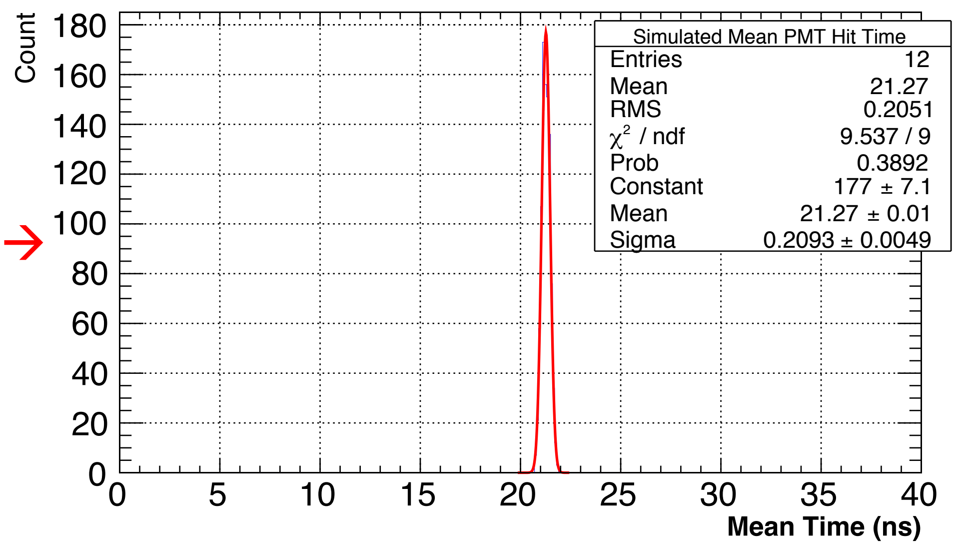
## Simulation Result

True Hit time for right photomultiplier tube with sigma value = 369.6 $ps$




Last Lab Meeting X

Hit time for right photomultiplier tube with sigma value = 209.3 $ps$




Current Result

$$\sigma_{T_{mean}}^2 = 0.5^2 * \sigma_{T_1}^2 + 0.5^2 * \sigma_{T_2}^2 + 2 * 0.5^2 \sigma_{T_1 T_2} \therefore \sigma_{T_{mean}} = 0.5 * \sqrt{\sigma_{T_1}^2 + \sigma_{T_2}^2 + 2 * \sigma_{T_1 T_2}} \approx 304.0 \pm 7.1 ps$$

# Further Study

Causes of the long tail of the pulse shape generated by the Flash ADC electronics.

# Backup 1: Last Lab Meeting

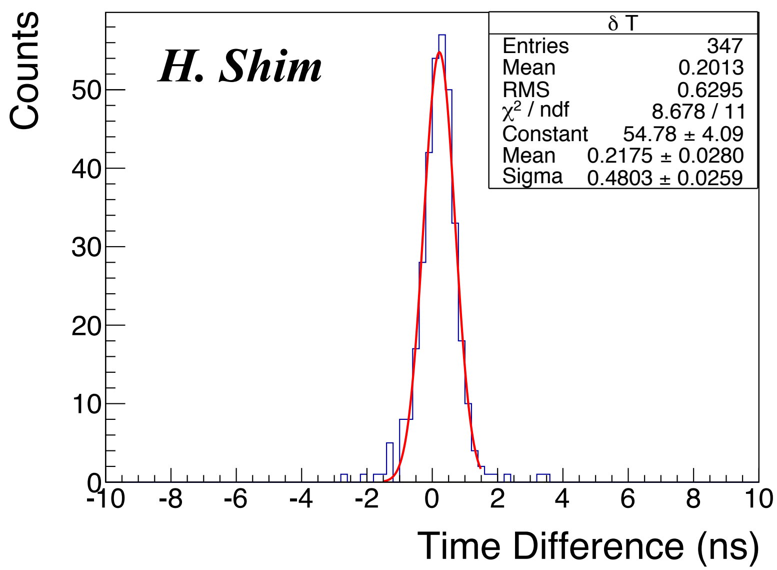
Critical Issues:

1) Critical angle.
2) Reflection and attenuation.
3) Hit time distribution fluctuations.
4) Cause of long tail in pulse shape.

# Backup2: Time Resolution

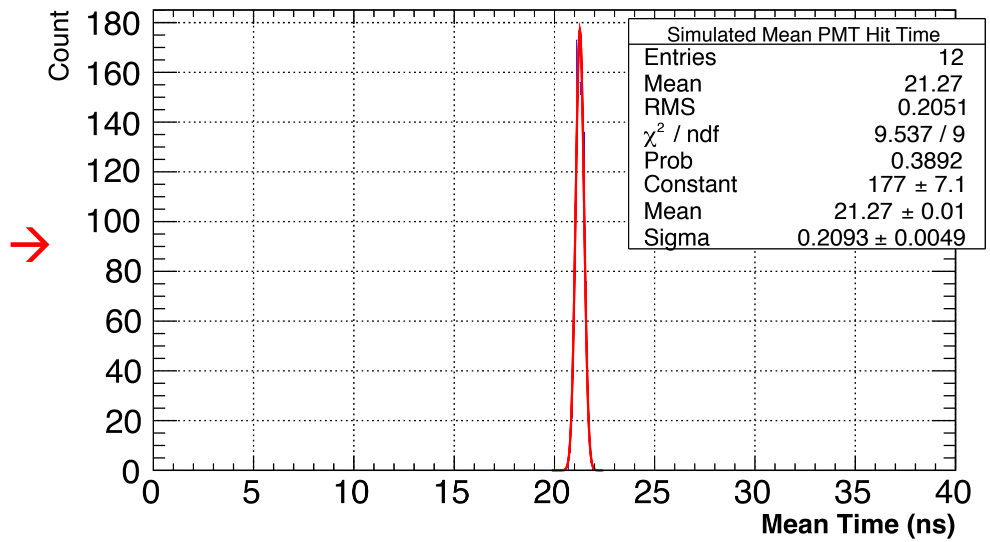
## Data vs. Simulation

True Hit time with sigma value = 369.6 *ps*




Data result

True Hit time with sigma value = 209.3 *ps*




Simulation Result

| ***Time Resolution, $\sigma_t$*** | ***Data (ps)*** | ***Simulation (ps)*** |
|---|---|---|
| | 339.6 | 209.3 |

# Backup3

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.

# Backup4

Useful function:

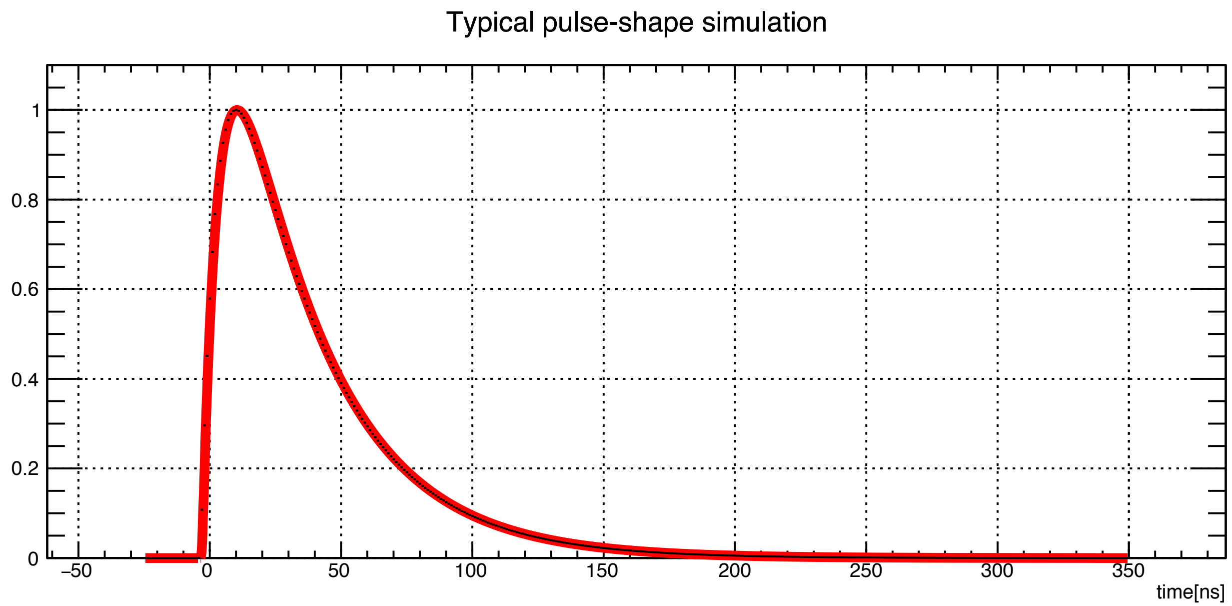
f (x) = [0](exp(-(x[0]-par[1])/[2])-exp(-(x[0]-[1])/[3]))/([2]-par[3])

[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



# Backup5

## Attenuation Length, $\lambda$ For 2 m-Long Prototypes

- Attenuation length, $\lambda$ 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.
- $\lambda$ is the attenuation length and depends on the material and energy.

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

# Backup 6: Last Lab Meeting

This table shows the variances of simple functions of the real variables $A, B$ with standard deviations $\sigma_A, \sigma_B,$ covariance $\sigma_{AB}$ and exactly known real-valued constants $a, b$ (i.e., $\sigma_a = \sigma_b = 0$).

| Function | Variance | Standard Deviation |
|---|---|---|
| $f = aA$ | $\sigma_f^2 = a^2\sigma_A^2$ | $\sigma_f = \|a\|\sigma_A$ |
| $f = aA + bB$ | $\sigma_f^2 = a^2\sigma_A^2 + b^2\sigma_B^2 + 2ab\,\sigma_{AB}$ | $\sigma_f = \sqrt{a^2\sigma_A^2 + b^2\sigma_B^2 + 2ab\,\sigma_{AB}}$ |
| $f = aA - bB$ | $\sigma_f^2 = a^2\sigma_A^2 + b^2\sigma_B^2 - 2ab\,\sigma_{AB}$ | $\sigma_f = \sqrt{a^2\sigma_A^2 + b^2\sigma_B^2 - 2ab\,\sigma_{AB}}$ |
| $f = AB$ | $\sigma_f^2 \approx f^2 \left[\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 + 2\frac{\sigma_{AB}}{AB}\right]$ [11][12] | $\sigma_f \approx \|f\| \sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 + 2\frac{\sigma_{AB}}{AB}}$ |
| $f = \frac{A}{B}$ | $\sigma_f^2 \approx f^2 \left[\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 - 2\frac{\sigma_{AB}}{AB}\right]$ [13] | $\sigma_f \approx \|f\| \sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2 - 2\frac{\sigma_{AB}}{AB}}$ |
| $f = aA^b$ | $\sigma_f^2 \approx \left(abA^{b-1}\sigma_A\right)^2 = \left(\frac{fb\sigma_A}{A}\right)^2$ | $\sigma_f \approx \left\|abA^{b-1}\sigma_A\right\| = \left\|\frac{fb\sigma_A}{A}\right\|$ |
| $f = a\ln(bA)$ | $\sigma_f^2 \approx \left(a\frac{\sigma_A}{A}\right)^2$ [14] | $\sigma_f \approx \left\|a\frac{\sigma_A}{A}\right\|$ |
| $f = a\log_{10}(bA)$ | $\sigma_f^2 \approx \left(a\frac{\sigma_A}{A\ln(10)}\right)^2$ [14] | $\sigma_f \approx \left\|a\frac{\sigma_A}{A\ln(10)}\right\|$ |
| $f = ae^{bA}$ | $\sigma_f^2 \approx f^2(b\sigma_A)^2$ [15] | $\sigma_f \approx \|f(b\sigma_A)\|$ |
| $f = a^{bA}$ | $\sigma_f^2 \approx f^2(b\ln(a)\sigma_A)^2$ | $\sigma_f \approx \|f(b\ln(a)\sigma_A)\|$ |
| $f = a\sin(bA)$ | $\sigma_f^2 \approx [ab\cos(bA)\sigma_A]^2$ | $\sigma_f \approx \|ab\cos(bA)\sigma_A\|$ |
| $f = a\cos(bA)$ | $\sigma_f^2 \approx [ab\sin(bA)\sigma_A]^2$ | $\sigma_f \approx \|ab\sin(bA)\sigma_A\|$ |
| $f = A^B$ | $\sigma_f^2 \approx f^2 \left[\left(\frac{B}{A}\sigma_A\right)^2 + (\ln(A)\sigma_B)^2 + 2\frac{B\ln(A)}{A}\sigma_{AB}\right]$ | $\sigma_f \approx \|f\| \sqrt{\left(\frac{B}{A}\sigma_A\right)^2 + (\ln(A)\sigma_B)^2 + 2\frac{B\ln(A)}{A}\sigma_{AB}}$ |
| $f = \sqrt{aA^2 \pm bB^2}$ | $\sigma_f^2 \approx \left(\frac{A}{f}\right)^2 a^2\sigma_A^2 + \left(\frac{B}{f}\right)^2 b^2\sigma_B^2 \pm 2ab\frac{AB}{f^2}\sigma_{AB}$ | $\sigma_f \approx \sqrt{\left(\frac{A}{f}\right)^2 a^2\sigma_A^2 + \left(\frac{B}{f}\right)^2 b^2\sigma_B^2 \pm 2ab\frac{AB}{f^2}\sigma_{AB}}$ |