A DEAPer Search for Dark Matter

Getting Ready for Data

IOP 2014

Outline:

- Physics of DEAP-3600
- Analysis with RAT
- Reconstructing Energy and Timing
- Conclusion and Outlook

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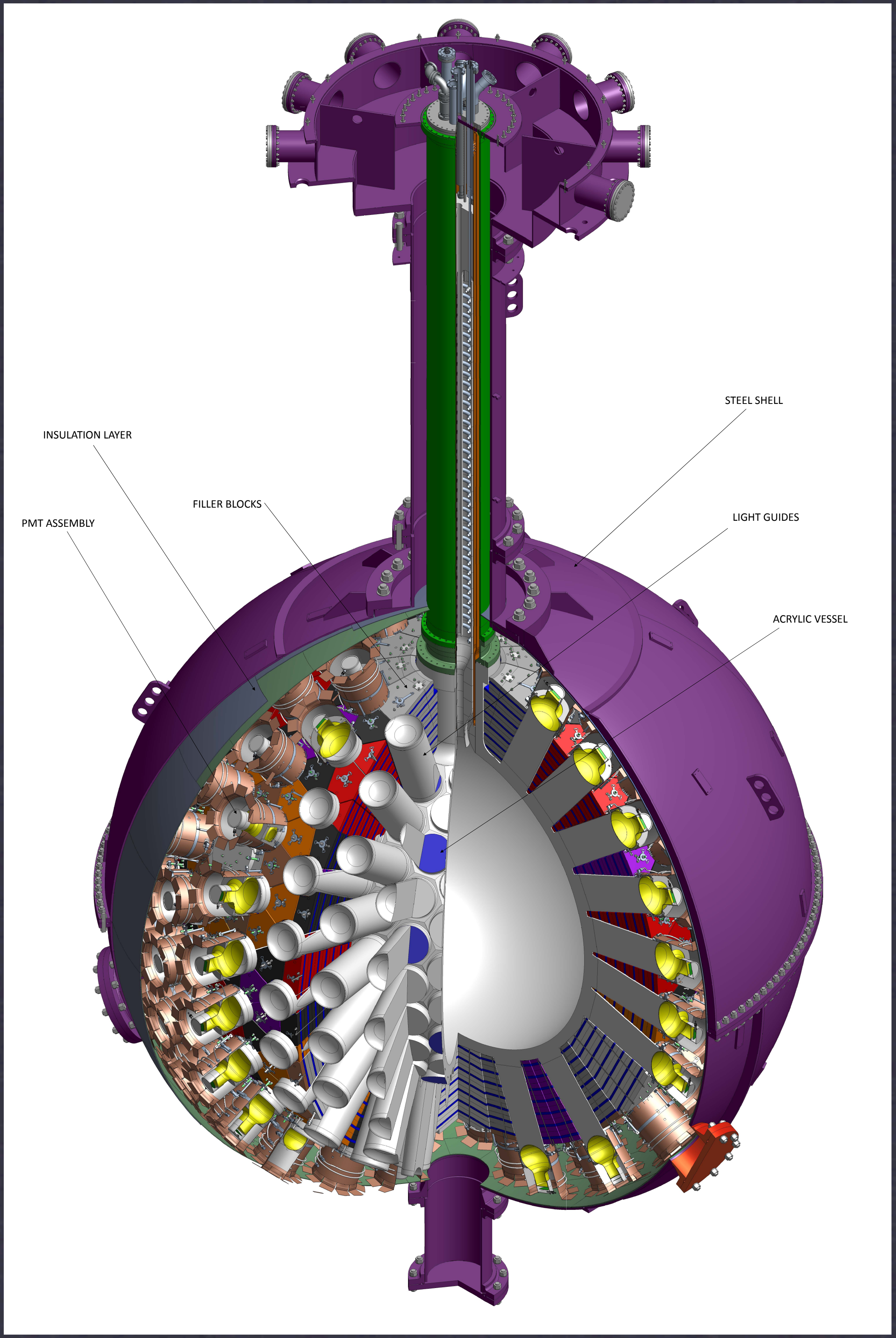


DEAP-3600

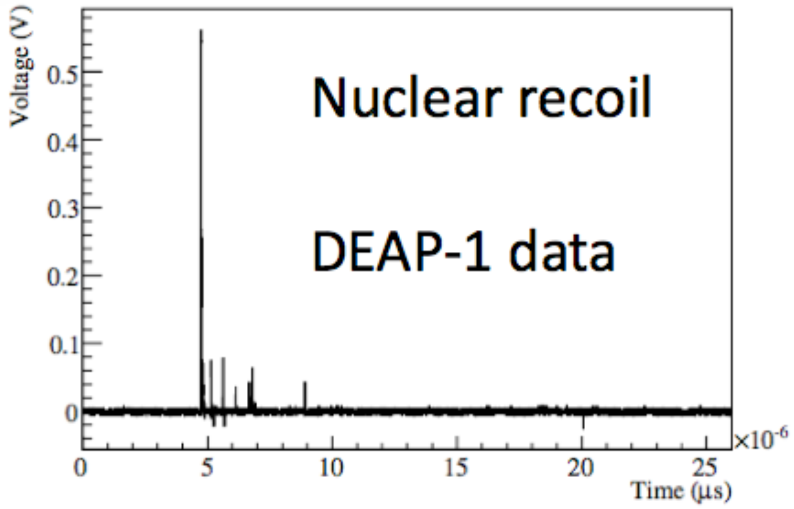
Target: 3600 kg of liquid Argon 1000 kg fiducial mass

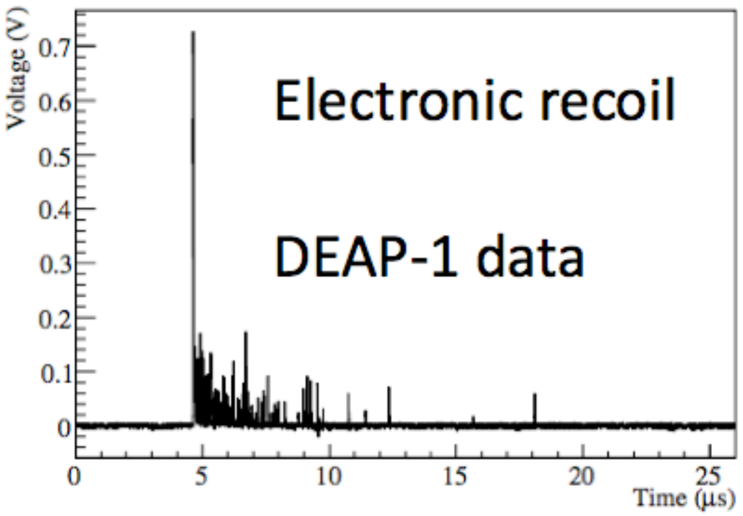
Single phase detector being built at SNOLab

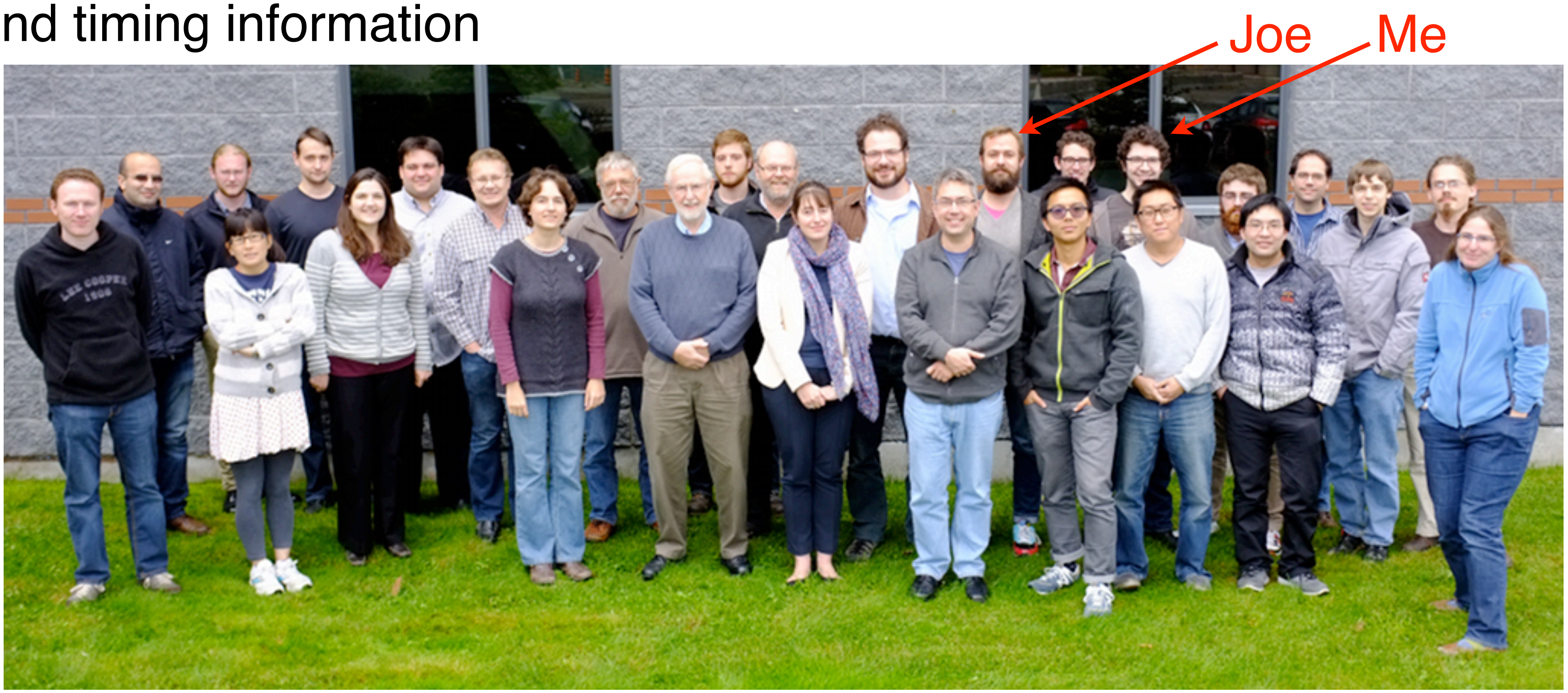
Detector measures charge and time for 255 PMTs - 4π coverage

Liquid Argon scintillation signal has two excited states: ~7 ns lifetime singlet state mainly from nuclear recoils, ~1.5 μs lifetime triplet state mainly from electronic recoils. W. H. Lippincott, et al. Phys. Rev. C 78 (2008)

Particle ID relies on accurate single photoelectron (PE) counting and timing information







Scintillation & Particle ID

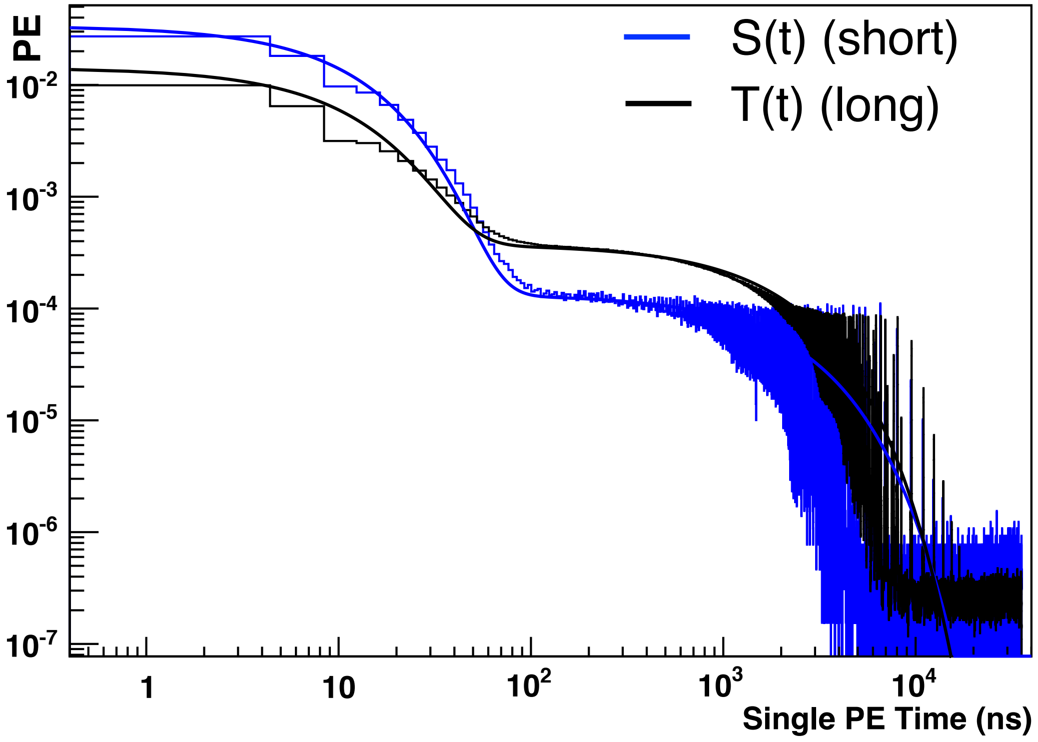
- We want to be able to separate nuclear recoils from electronic recoils
- Knowledge of the singlet and triplet lifetimes in liquid Argon allows us to construct a scintillation timing PDF

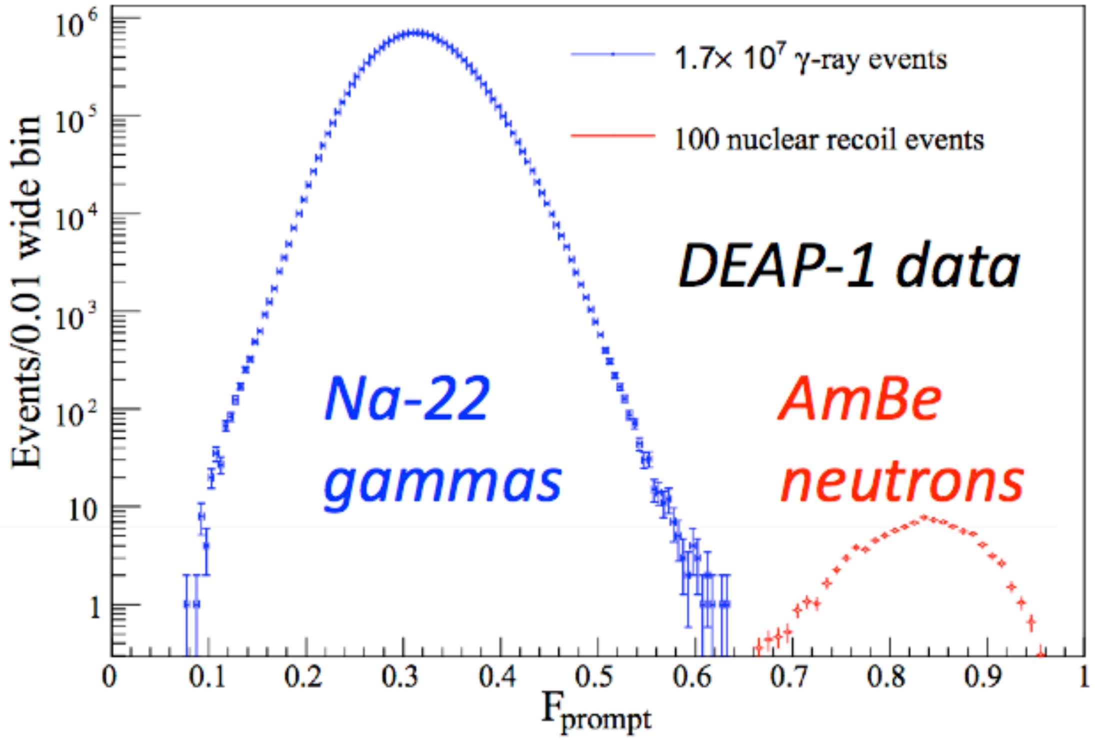
$$P(t) = f\exp\left(-\frac{t}{\tau_S}\right) + (1-f)\exp\left(-\frac{t}{\tau_L}\right)$$

    - where f is the fraction of photons emitted in the singlet state (nuclear recoil like)
    - Pulse shape discrimination (PSD) is used for particle identification - Fprompt, F_P, for example will give an indication of how nuclear recoil like an interaction is - a measure of how much of the waveform occurs in some ~100ns “prompt” window

$$f \rightarrow F_P = \frac{\int_{t_0}^{t_{100ns}} Q(t)dt}{\int_{t_0}^{t_{end}} Q(t)dt}$$

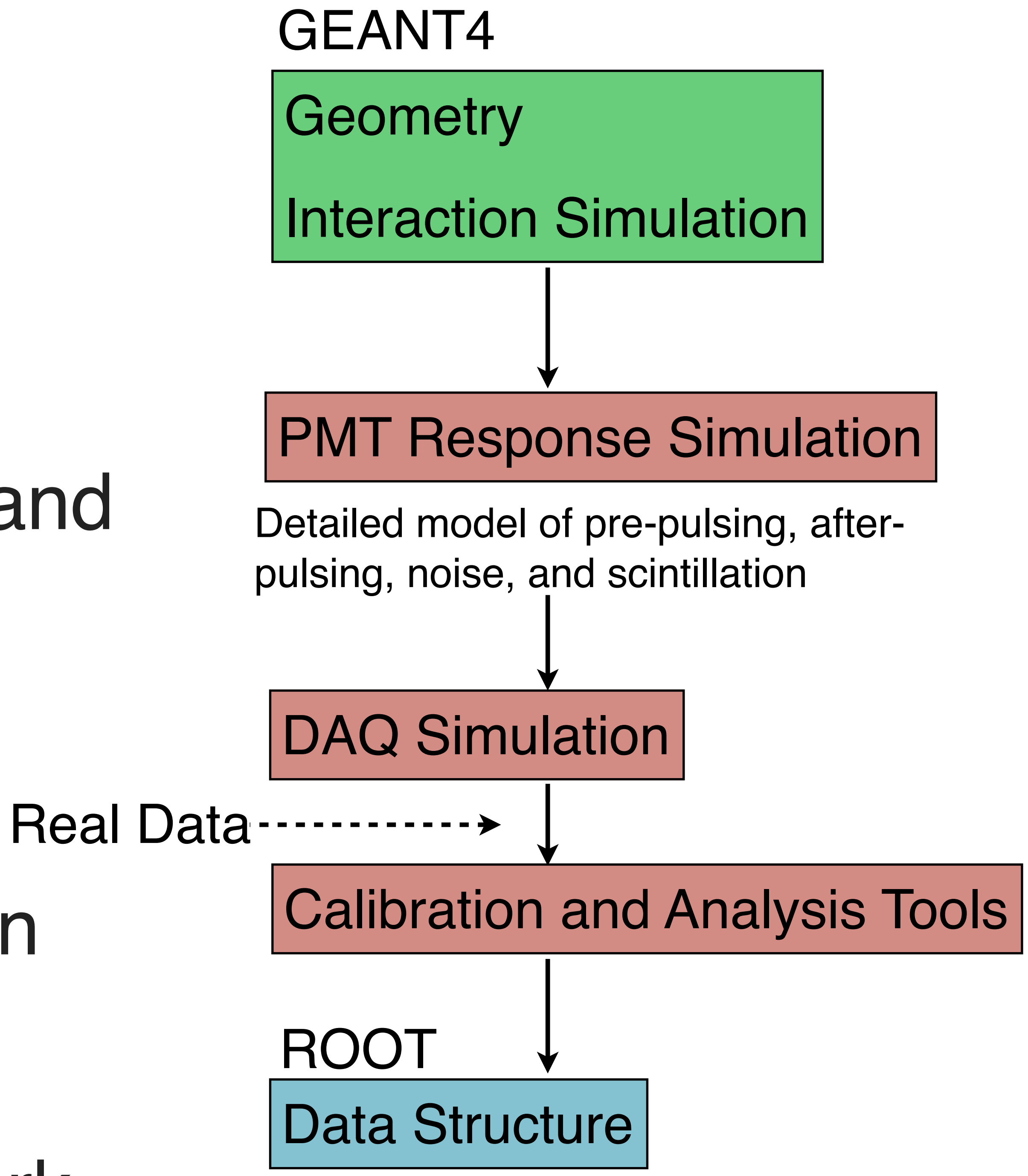
- PDFs are built from simulations, using our tool RAT, of photons drawn from short, $S(t)$, and long, $T(t)$, time constant distributions.





Simulation and Analysis Tool

- RAT - Reactor Analysis Tool (RAT is an Analysis Tool)
- GEANT4 based simulation and analysis tool
- ROOT data structure
- CouchDB server - calibration constants
  - e.g. Single PE charge, dark rate



GEANT4

Geometry

Interaction Simulation

PMT Response Simulation

Detailed model of pre-pulsing, after-pulsing, noise, and scintillation

DAQ Simulation

Real Data

Calibration and Analysis Tools

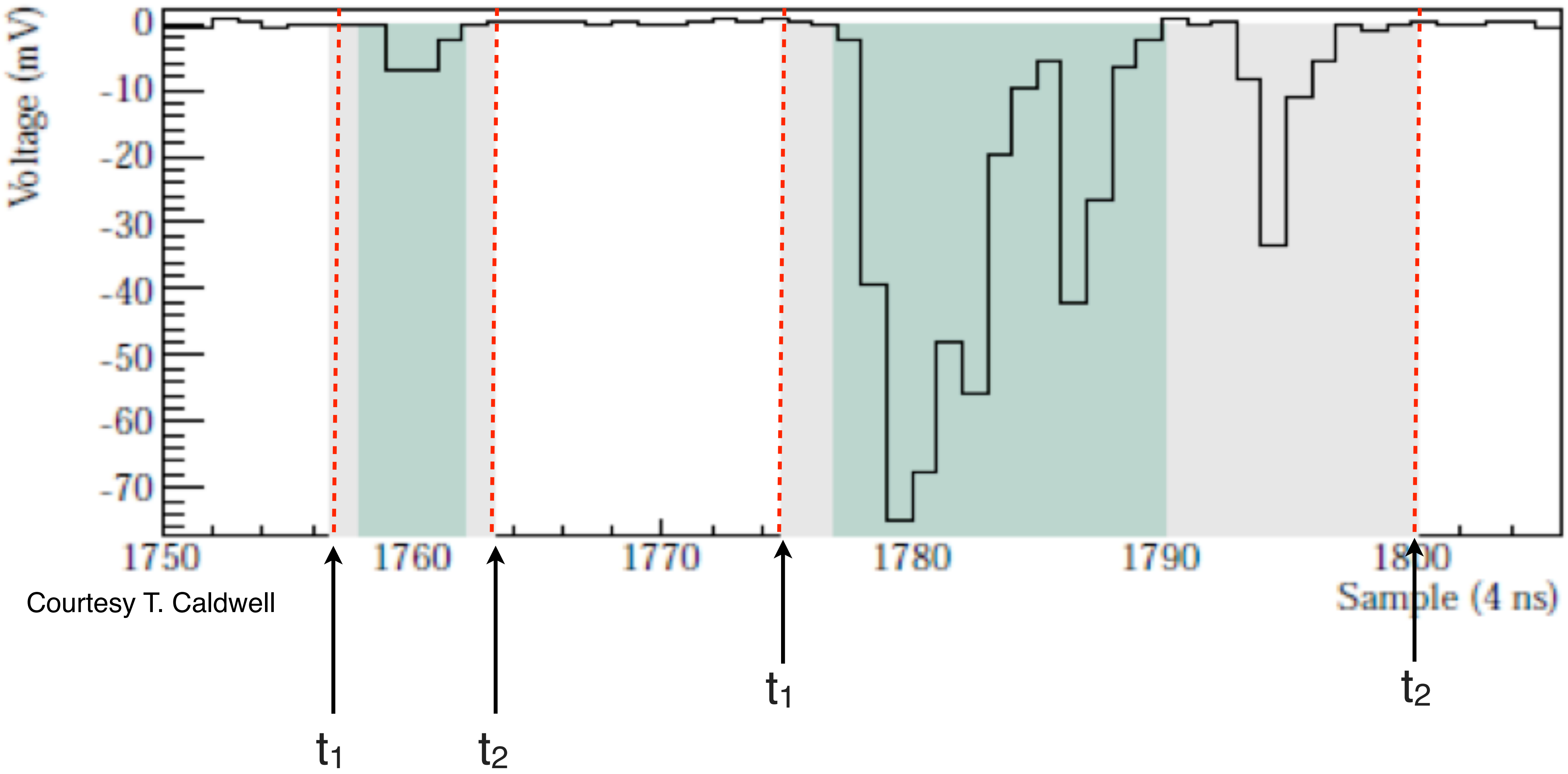
ROOT

Data Structure

RAT

Reactor Analysis Tool

Single PE Finding



Courtesy T. Caldwell

- Pulses are identified by when the integral of 3 samples exceeds 5 times the expected integral due to noise
- We need to identify the number of PE in each pulse given some charge integral, q, and some time interval, t_1 and t_2.

Single PE Finding

- Single PE finding uses a Bayesian calculation, making use of the scintillation timing PDF, applied to pulses fed to it by the pulse finding algorithm

$$\begin{aligned} P_N(n \mid q, t_1, t_2) &= \frac{P_Q(q \mid n) P_N(n \mid t_1, t_2)}{P_Q(q \mid t_1, t_2)} \\ &= \frac{P_Q(q \mid n) P_N(n \mid t_1, t_2)}{\sum_{i=0}^{\infty} P_Q(q \mid i) P_N(i \mid t_1, t_2)} \end{aligned}$$

- Here $P_N(n \mid q, t_1, t_2)$ is the probability that a pulse contains n PE given an integral charge q in a pulse arriving between time t_1 and t_2 in the waveform

- $P_Q(q \mid n)$ is the probability of seeing a charge q given a number of PE n - simply found using the single PE charge PDF convolved with itself n times

- $P_N(n \mid t_1, t_2)$ is the prior probability of finding n PE given the pulse arrived between time t_1 and t_2

Single PE Prior

$$F_P = \frac{\int_{t_0}^{t_{100ns}} Q(t)dt}{\int_{t_0}^{t_{end}} Q(t)dt}$$

- Calculating prior probability $P_N(n \mid t_1, t_2)$ involves some assumptions

$$P_N(n \mid t_1, t_2) = \sum_{j=0}^{\infty} \mathrm{Pois}(j \mid \mu) \times \mathrm{Bin}(n \mid j, I)$$

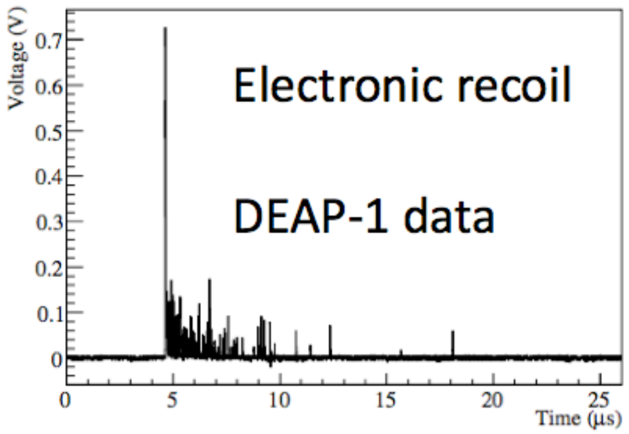
- We have a Poisson probability, since we have low occupancy (<10 PE per PMT), of seeing j photons given an expected number of PE in the PMT, μ, which is calculated from the total charge over the single PE charge.

- This is multiplied by the binomial probability of seeing n photons out of j given the timing based probability, I, of seeing a photon in that time interval.

$$I(t_1, t_2) = \int_{t_1}^{t_2} \left[F_p(1 - f_d)S(t) + (1 - F_p)(1 - f_d)T(t)\right] dt + f_d$$

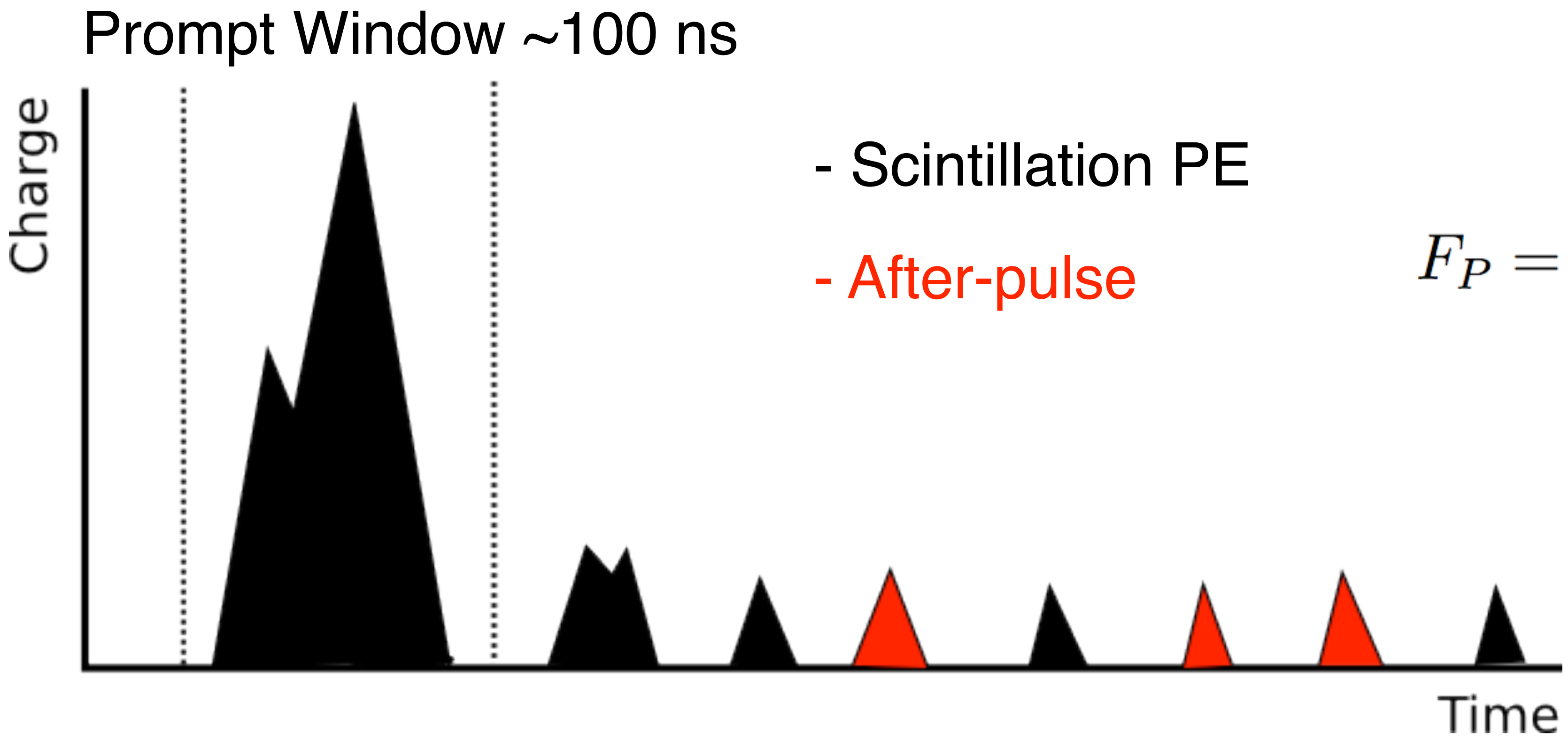
- Here $S(t)$ and $T(t)$ are the singlet and triplet lifetime states respectively with F_p being Fprompt. f_d is the fraction of photons due to the dark rate.

After-pulsing



- Caused by gases in the PMT being ionised by passing photo-electrons. Ions then strike the photo-cathode freeing up more electrons causing later pulses.

- PSD is affected - later pulses cause all events to look more electron like.

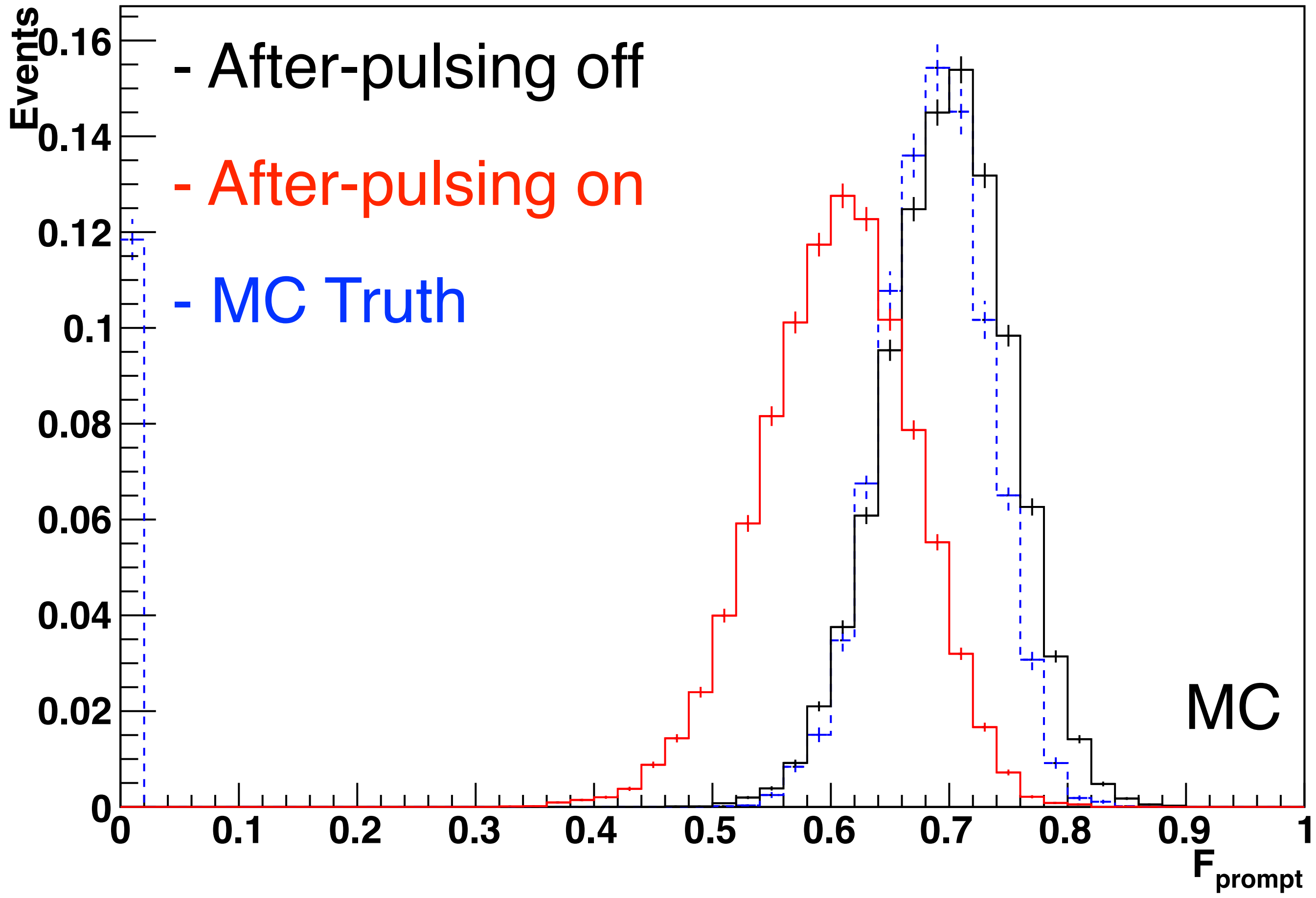


$$F_P = \frac{\int_{t_0}^{t_{100ns}} Q(t)dt}{\int_{t_0}^{t_{end}} Q(t)dt}$$

- After-pulsing causes more pulses to occur outside of the prompt window pushing Fprompt down. We need to be able to count true scintillation PE and correct for after-pulsing.

After-pulsing

$$F_P = \frac{\int_{t_0}^{t_{100ns}} Q(t)dt}{\int_{t_0}^{t_{end}} Q(t)dt}$$

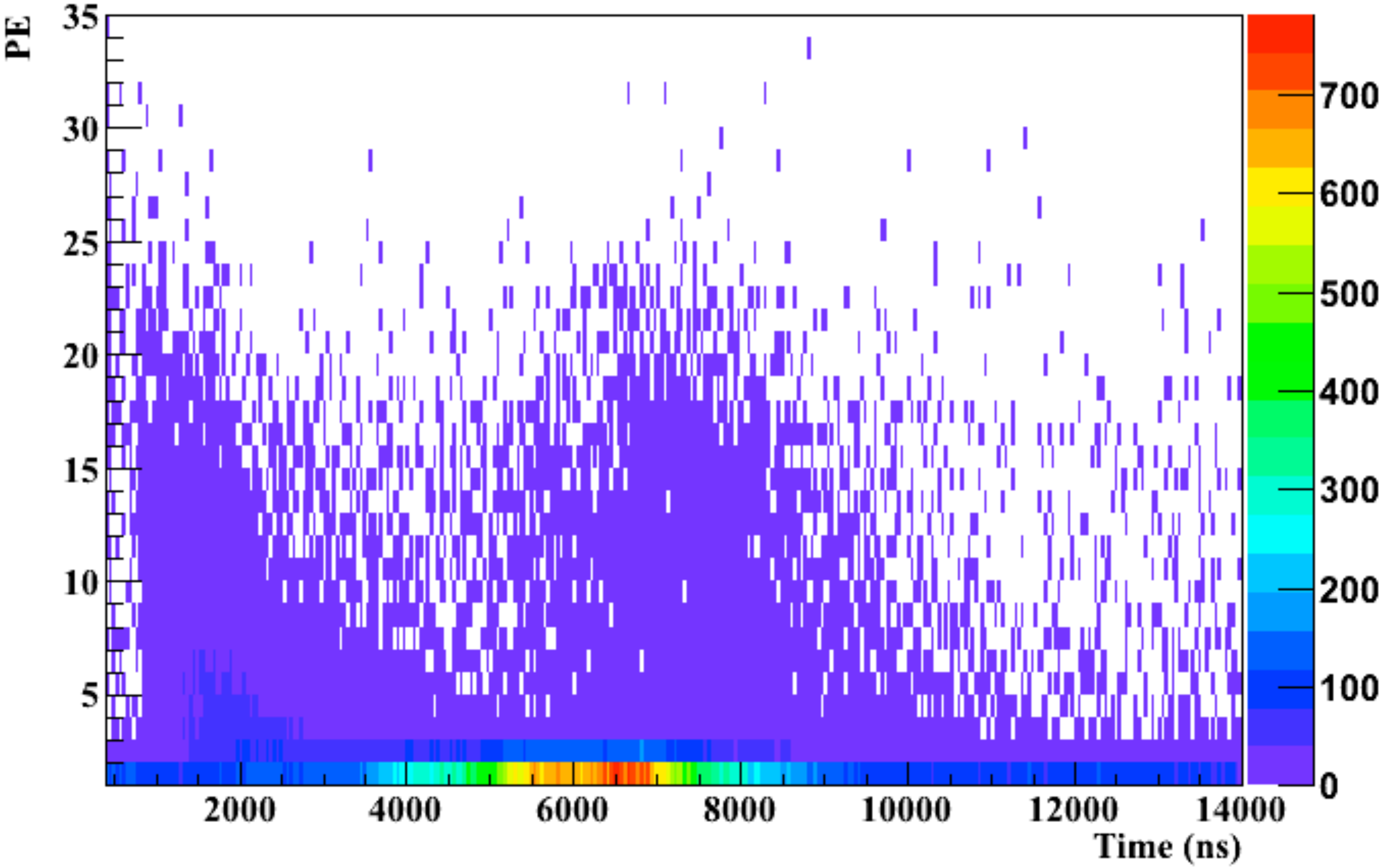


Fprompt for simulated nuclear recoil events with after-pulsing turned on and off. Nuclear recoils should have an Fprompt mean around 0.7, after-pulsing pushes this down to 0.6.

After-pulsing PDF

An ex-situ measurement of after-pulsing was done by flashing a laser and looking at the PMT output after the initial PE spike.

Every point in the plot below is an after-pulse of a certain integral PE and arrival time. The after-pulsing rate is expected to be between 5 and 15%.



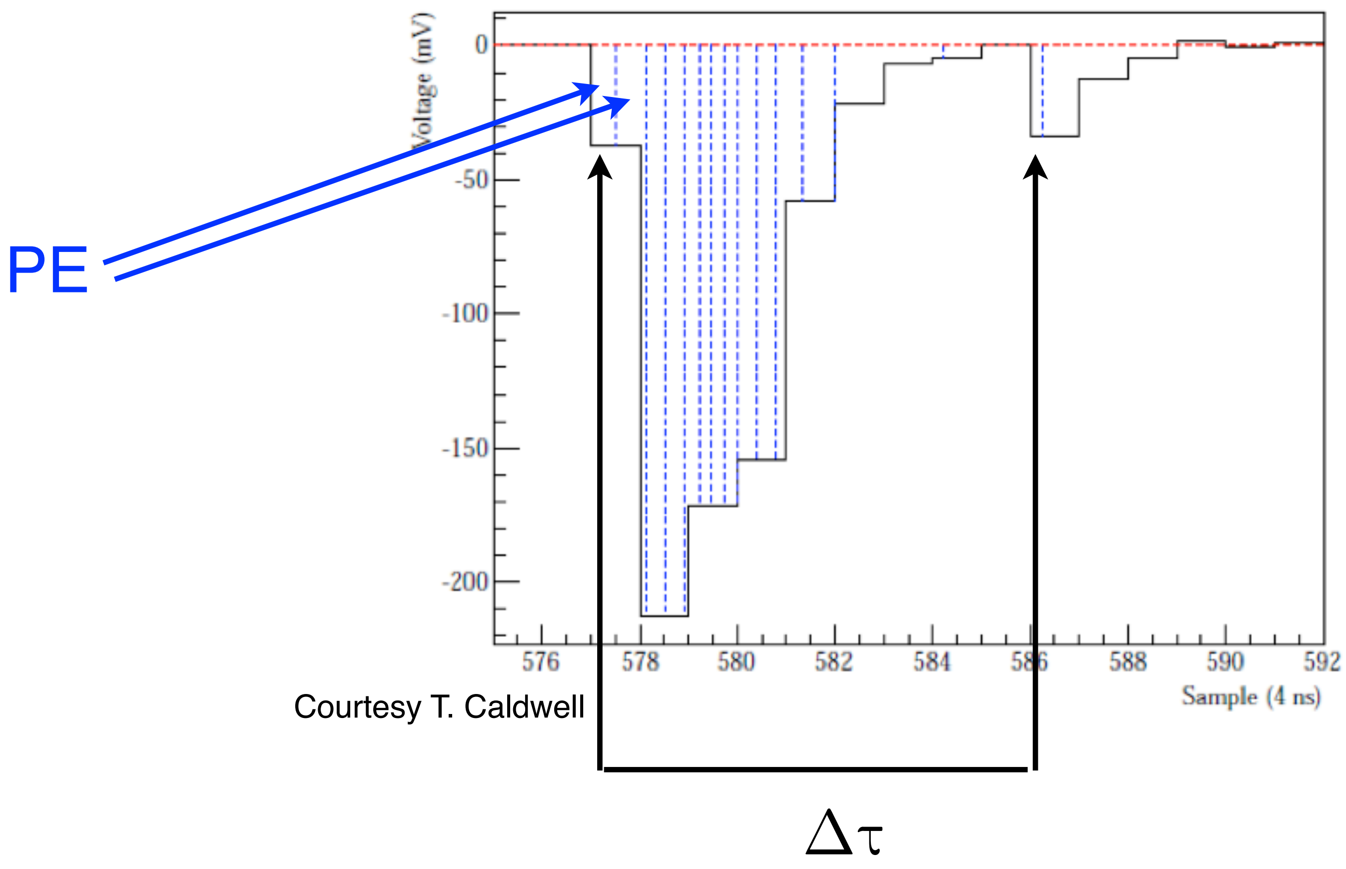
After-pulsing will be measured in-situ during calibration commissioning next month.

Dealing with After-pulsing

- After-pulsing has been measured ex-situ for every PMT in DEAP-3600 and will be measured in-situ during commissioning.
- I have developed an algorithm which attempts to identify which pulses in the waveform are after-pulses. This is a modification of the prior in the single PE finder using the measured after-pulsing PDF data.

After-pulsing Prior

- Every PE in an event has the potential to cause an after-pulse.



Courtesy T. Caldwell

- Every PE in the waveform is looped through and an after-pulse probability is assigned to later pulses from the after-pulsing PDF based on the time difference $\Delta\tau$. This list of contributing pulses can then be used to calculated the probability

After-pulsing PDF

$$P_{NAP}(m|t_1, t_2, N_{cont}) = \sum_{i=1}^{N_{cont}} Bin\left(1; N_{cont}, p_{ap}\right).P(m|\Delta\tau_i)$$

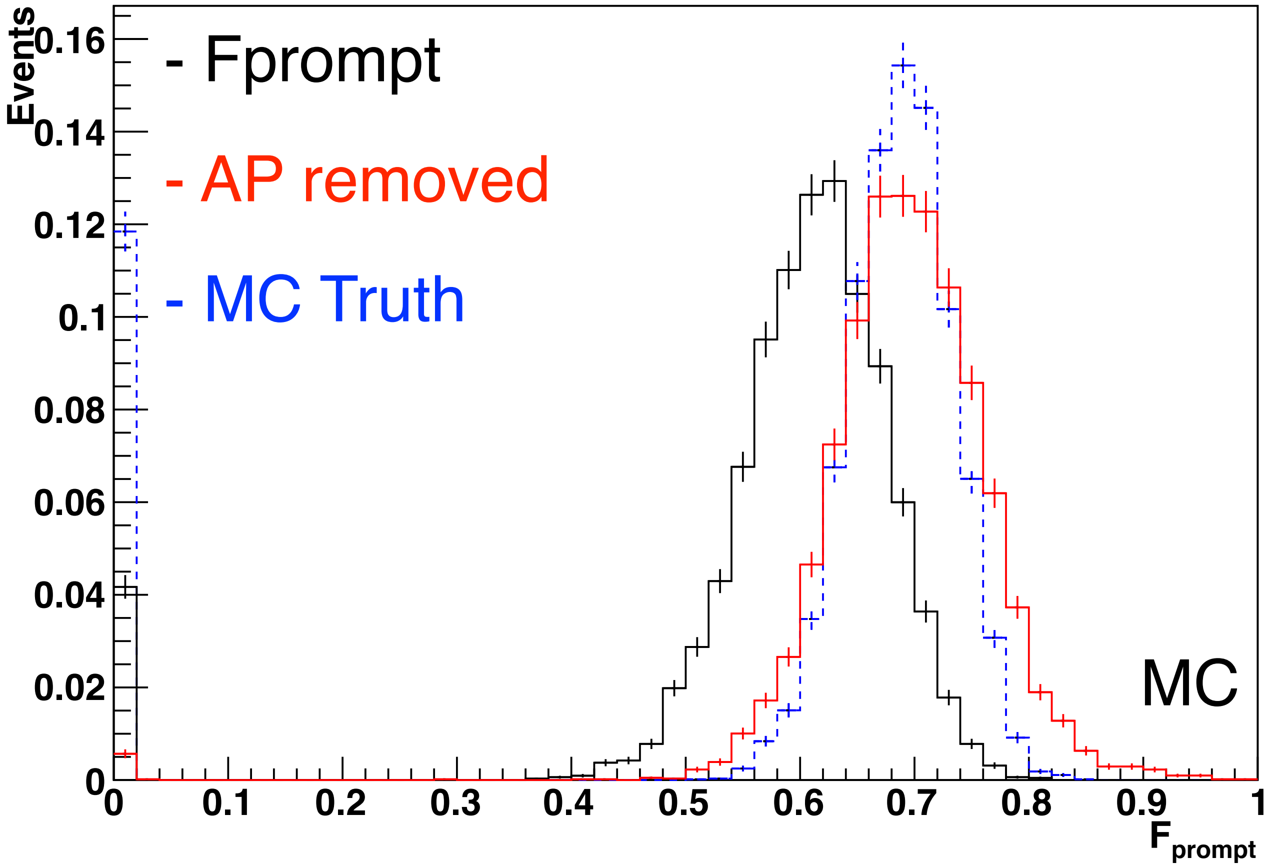
p_{ap} is the probability of an after-pulse occuring, N_{cont} is the number of contributing PE

After-pulsing Prior

The prior in the single PE finder now becomes $P_N(n \mid q, t_1, t_2) = \frac{P_Q(q \mid n) P_N(n \mid t_1, t_2)}{P_Q(q \mid t_1, t_2)}$

$$P_N(n|t_1, t_2) \rightarrow P_N(l|t_1, t_2) \times P_{NAP}(m|t_1, t_2, N_{cont})$$

where l is the number of scintillation photons, m is the number of after-pulse photons, and $n = l + m$ is the total number of PE in the pulse

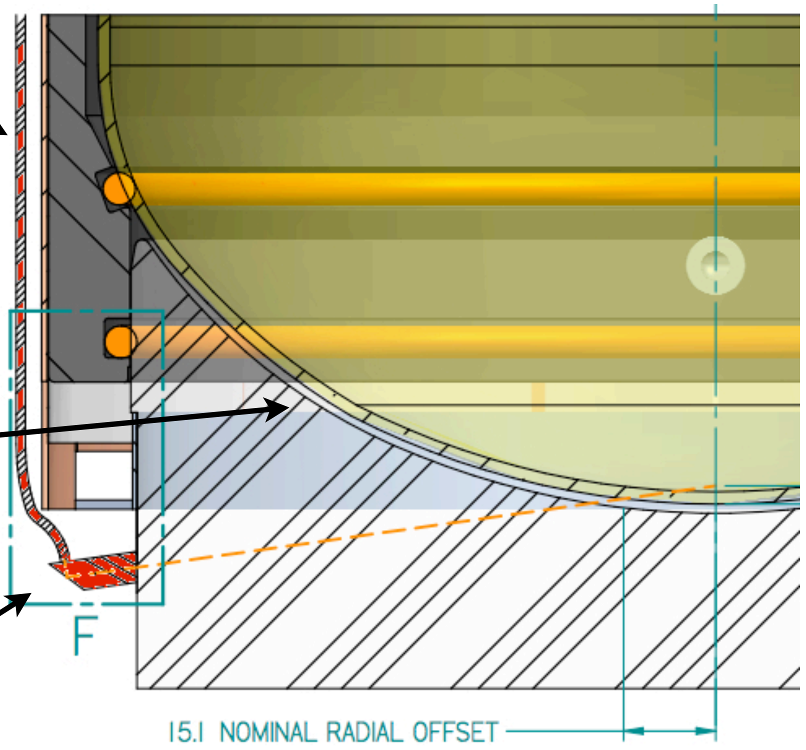


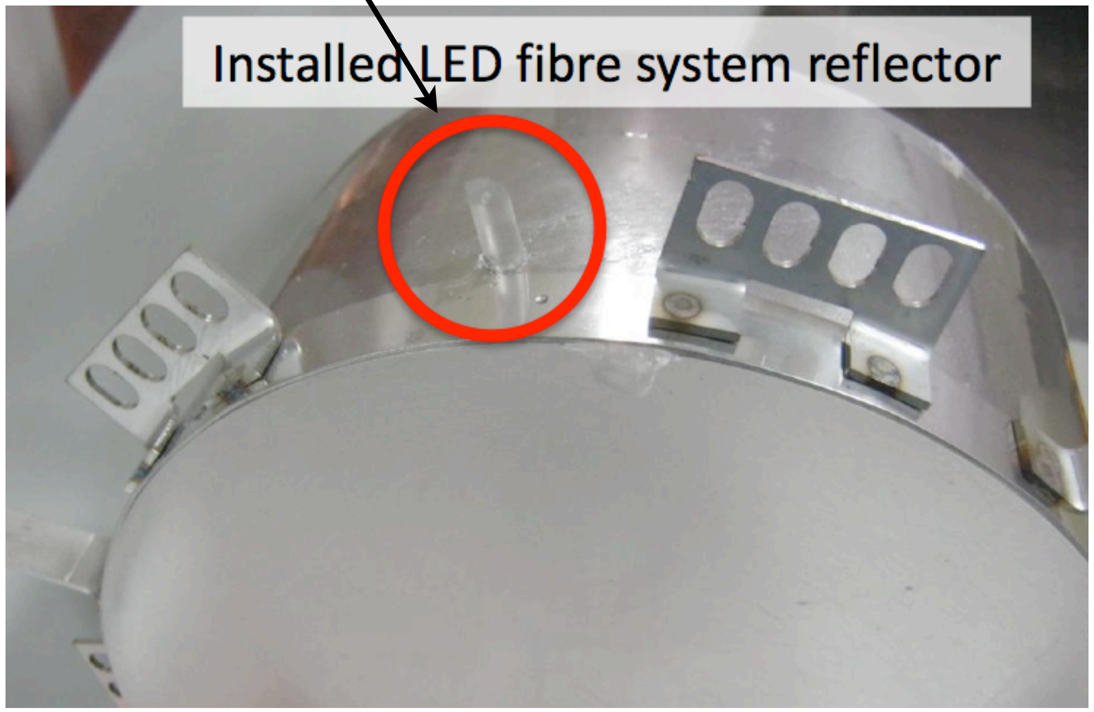
Using the modified single PE finder after-pulse removal shifts the mean back up to 0.7.

Before continuing to develop the algorithm more data driven electronics effects are being added - signal conditioning board response, saturation, etc.

Optical Calibration

- 4 Optical Calibration systems
  - Laser Ball
  - LED Ball (DISCO Ball)
  - LED fibre system
  - Neck Laser
- Used during commissioning and physics runs these provide
  - PMT timing and gain calibration/monitoring
  - Acrylic Vessel/Light Guide monitoring
- Optical calibration starts in May
  - The laser ball will be used in the vacuum stage to give an in situ measurement of the after-pulsing PDF




Installed LED fibre system reflector

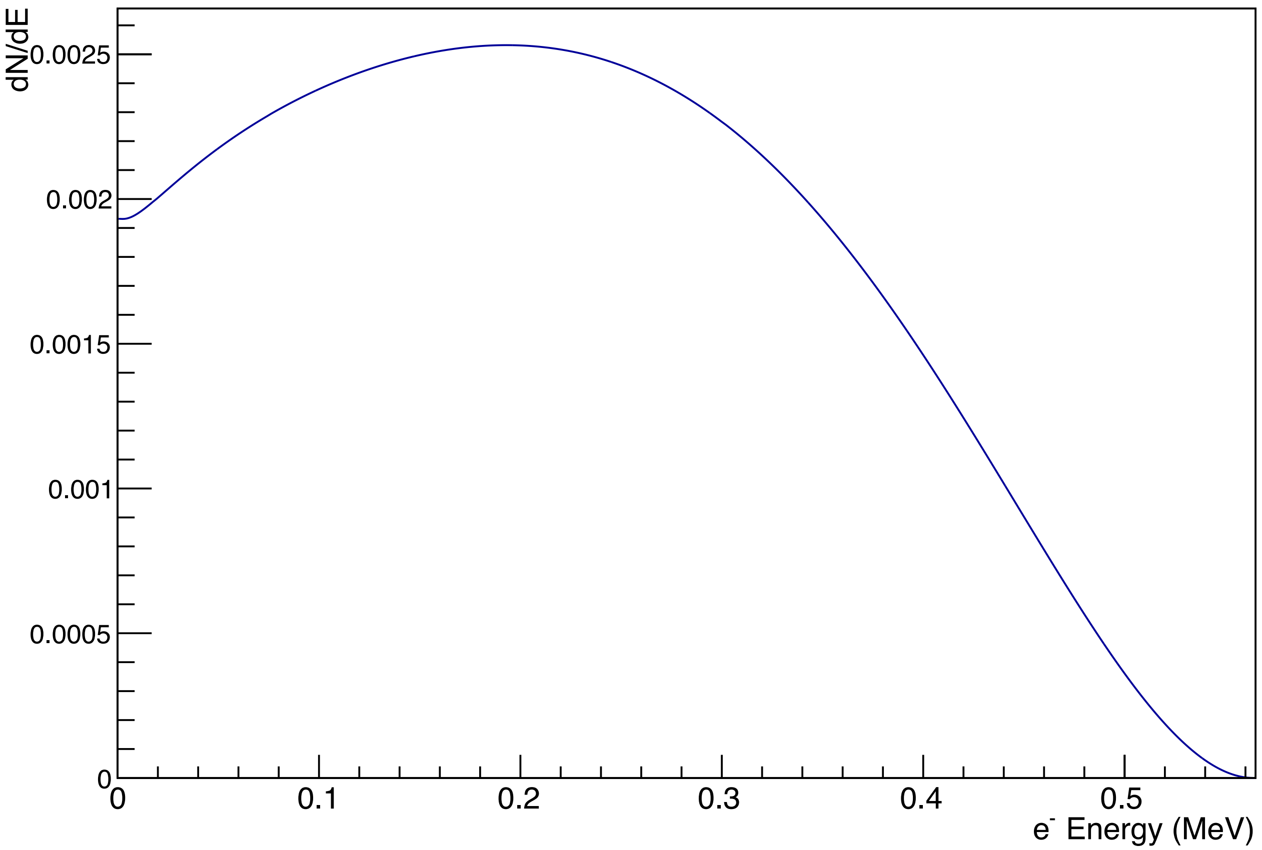
Conclusion & Outlook

- Particle ID in DEAP-3600 relies on correctly identifying the number of PE vs time. After-pulsing may affect particle ID
    - Tools have been developed to combat this
- DEAP-3600 is getting ready to take first in situ PMT data in May.
- Optical calibration systems being installed now - will be ready to take after-pulsing data.
- Analysis is ramping up for data - data challenge in May
- Dark Matter search will begin in Autumn.

Backup

Argon 39

- Argon 39 can be used as a useful calibration tool
  - It has a known spectrum which can be used for energy scale calibration
  - Provides a beta source uniformly distributed throughout the target volume - useful in characterising position reconstruction
- Also helpfully provides 10^{11} electronic background events per year
  - Primary background particle PSD is tested against



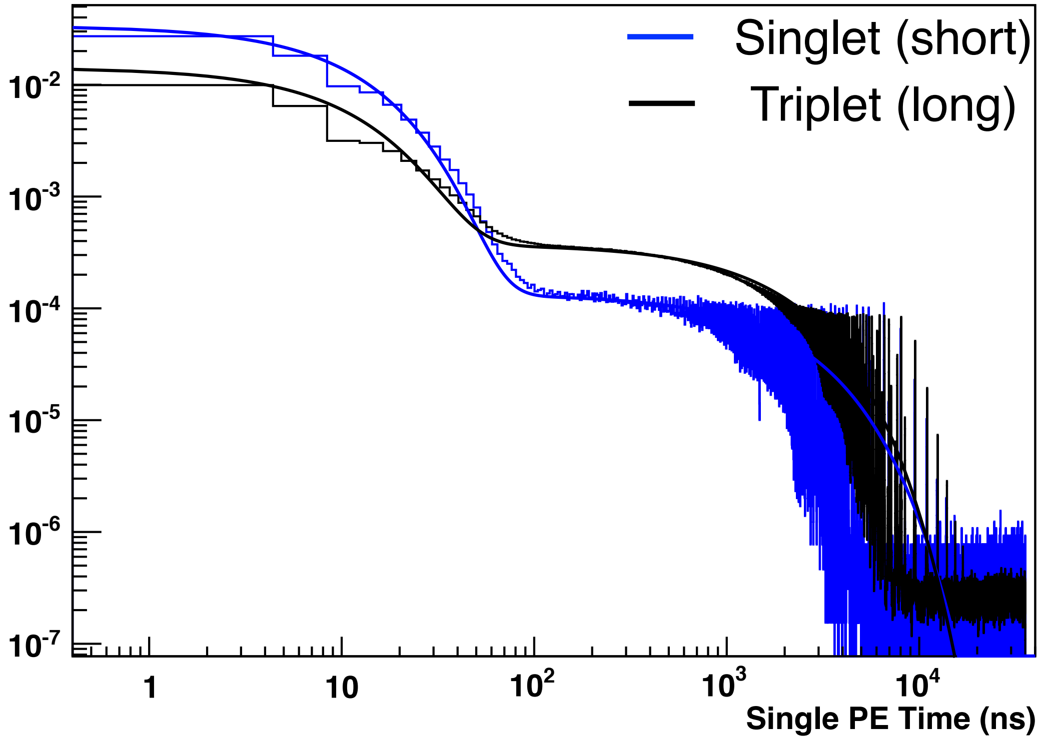
Argon 39 beta decay spectrum

L - recoil

- A more sophisticated PSD variable is Lrecoil.
- Lrecoil is the normalised log likelihood ratio between nuclear recoil and electron recoil timing PDFs

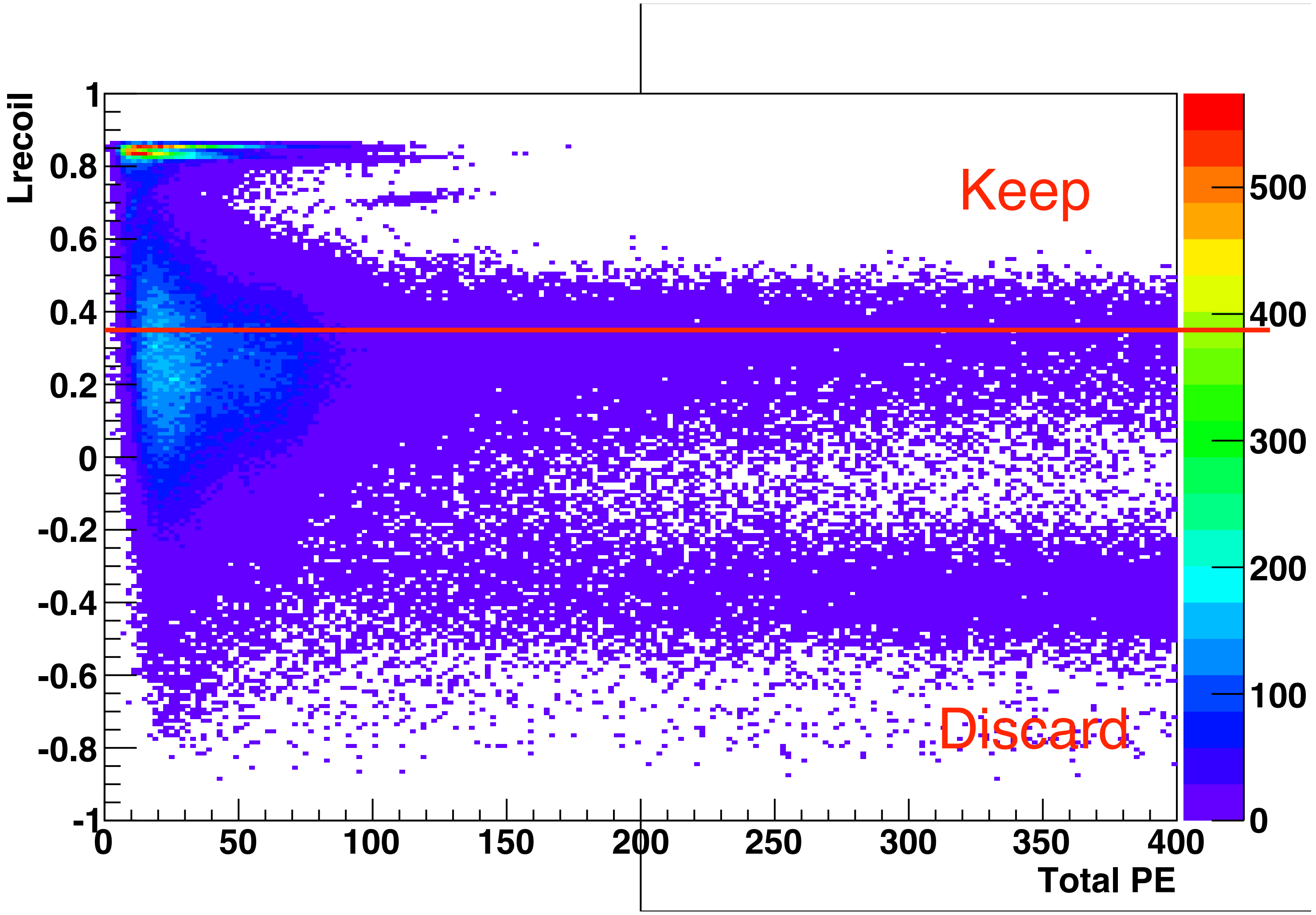
$$L_{\text{recoil}} = \frac{1}{n}\sum_{i=1}^{n} \log P_{\text{recoil}}(t_i) - \log P_{\text{electron}}(t_i)$$

where n runs over all time bins and all pmts



L - recoil

$$L_{\mathrm{recoil}} = \frac{1}{n}\sum_{i=1}^{n} \log P_{\mathrm{recoil}}(t_i) - \log P_{\mathrm{electron}}(t_i)$$



Lrecoil value for neutron events between 0 and 400 PE (0 and ~67 keV), no cuts were applied.