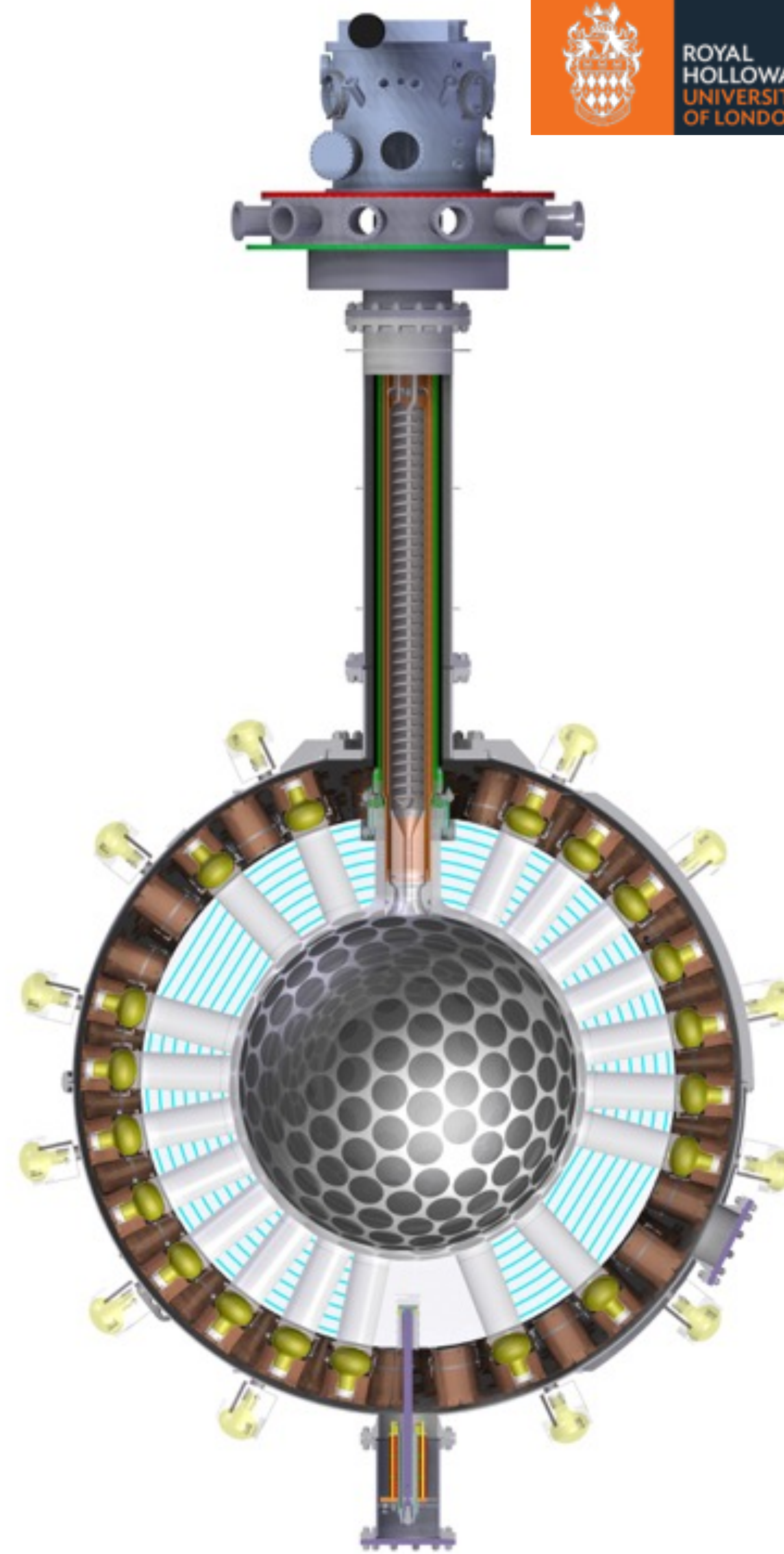
THE DEAP-3600 SEARCH FOR DARK MATTER

Outline:
- Detector overview, backgrounds, PSD
- Low level analysis, after-pulse tagging
- Calibration systems and commissioning data
- Conclusions and Outlook

ALISTAIR BUTCHER
PATRAS 11 - ZARAGOZA



ROYAL HOLLOWAY UNIVERSITY OF LONDON

Who is DEAP-3600?

University of Alberta

Carleton University

Laurentian University / Université Laurentienne

Queen's University

Royal Holloway University of London

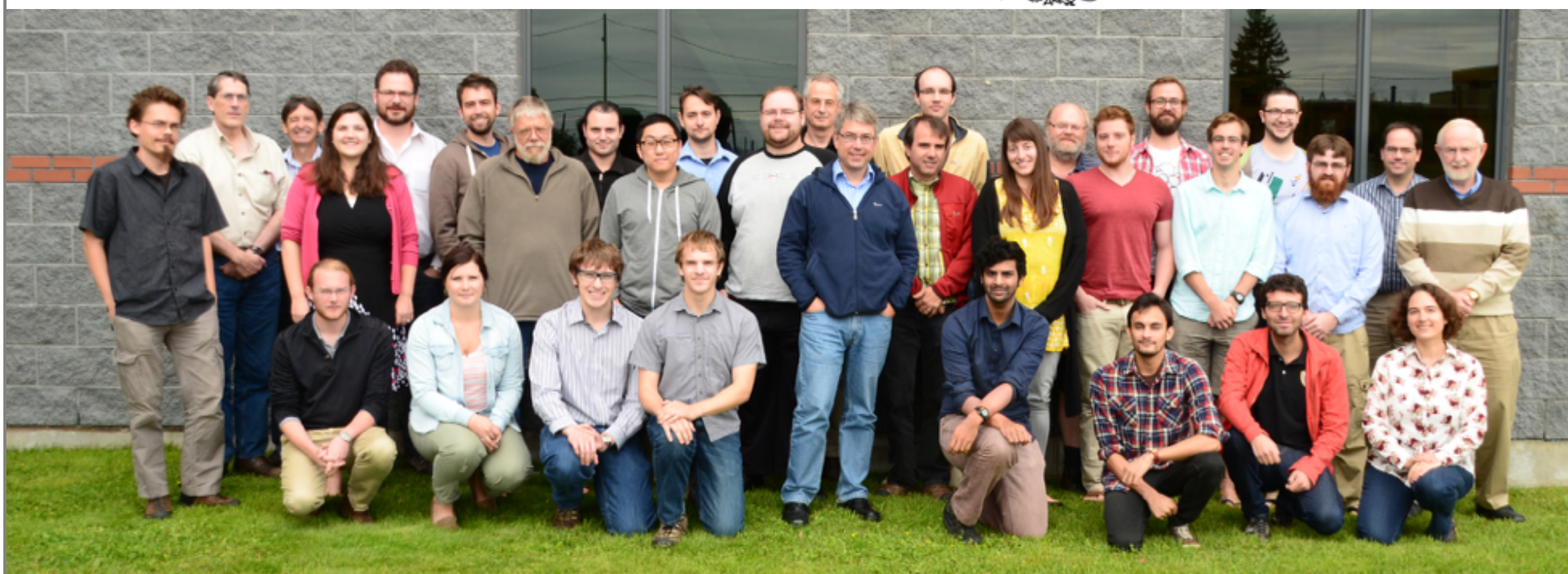
SNOLAB — Mining for knowledge / Creuser pour trouver... l'excellence

Science & Technology Facilities Council

University of Sussex

TRIUMF

IF Instituto de Física

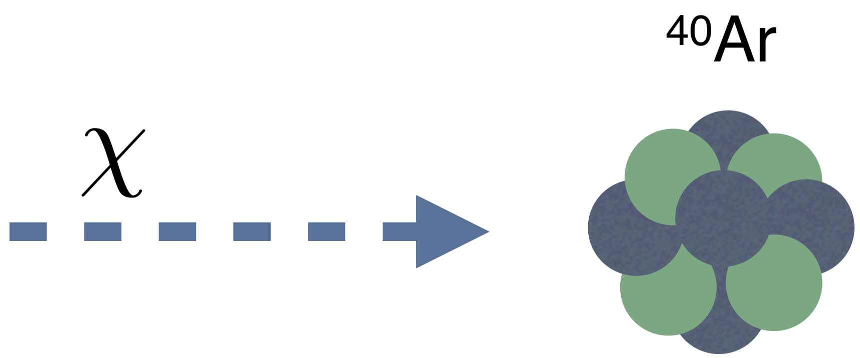


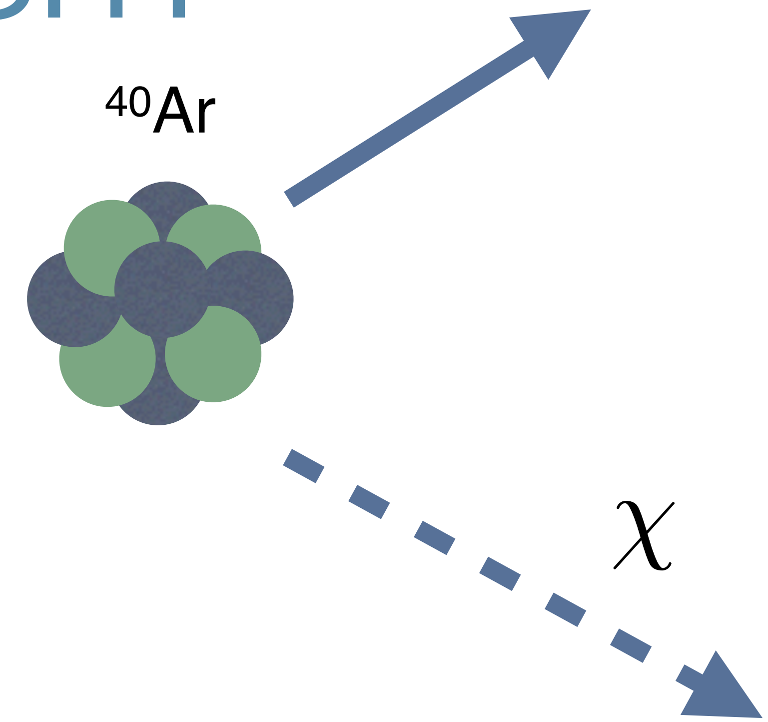
What is DEAP-3600?

Dark matter **E**xperiment using **A**rgon **P**ulse-shape discrimination

- Single phase detector based at SNOLAB
  - 2km overburden - 6010 m water equivalent
  - 0.27 μ/m^2/day
- 3600 kg liquid argon with 1000 kg fiducial mass
  - Argon is transparent to its 128 nm scintillation photons
  - Excellent separation between electronic and nuclear recoils
- Detector measures charge and time of 255 PMTs
- 10^{-46}cm^2 spin independent cross-section sensitivity for 100GeV WIMP after 3 years

Detection Mechanism





We see:

- Scintillation from ionisation and excitation due to a recoiling nucleus
- 128 nm UV scintillation photons are then wavelength shifted, using TPB, to 420 nm blue light for detection by PMTs

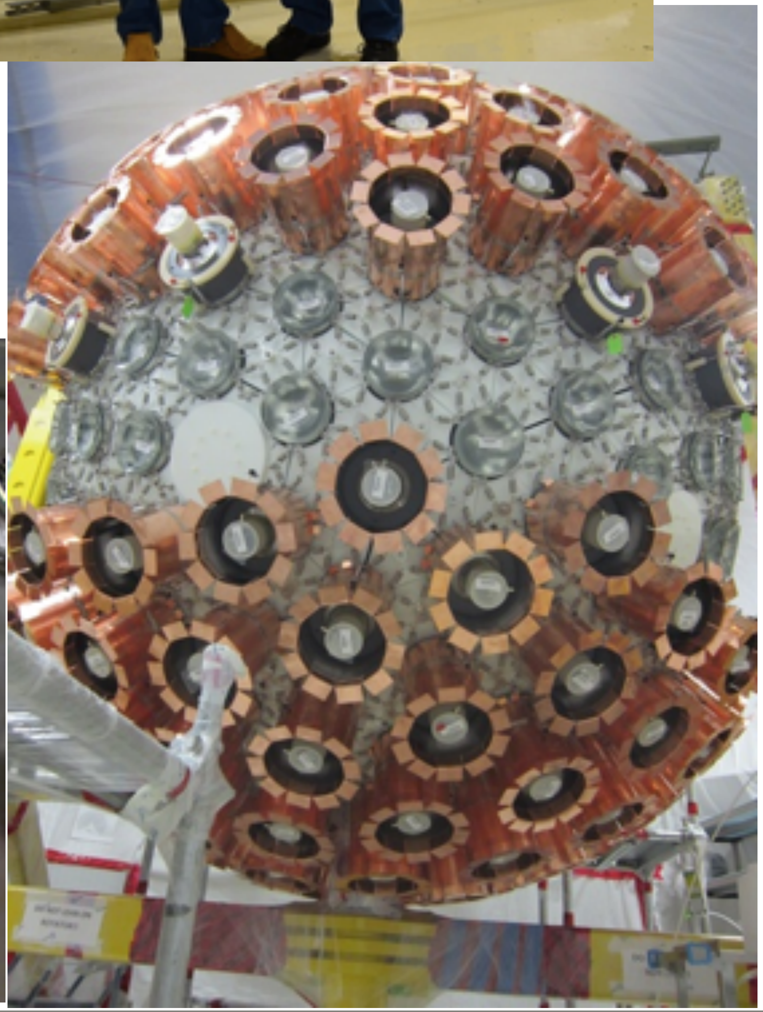
Electronic and nuclear recoils produce different ratios of singlet to triplet states - electrons producing predominantly triplet states, nuclear recoil singlet

Singlet Lifetime (τ_S)	Triplet Lifetime (τ_L)
7 ns	1.5 μs

	Nuclear Recoils	Electronic Recoils
Fraction of photons from singlet state	~0.7	~0.3

The Detector

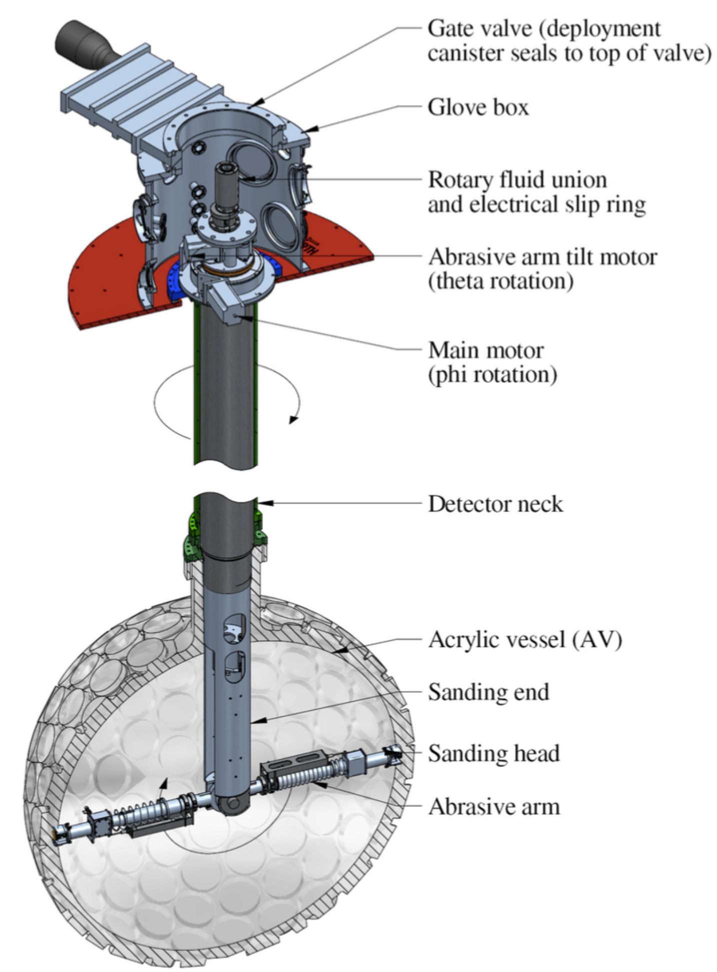
- Liquid argon is housed inside a sealed acrylic vessel AV - 85.5 cm inner radius
- Acrylic light guides are bonded directly to the acrylic vessel - provide shielding from neutrons
- 255 R5912 HQE Hamamatsu 8-inch PMTs coupled to each light guide
    - 32% QE, 75% solid angle coverage
- Steel outer shell sits within an 8m radius water tank - 48 outward facing PMTs act as veto



Backgrounds

Background in fiducial volume	Goal
Ar-39	< 2 pBq/kg
Neutrons (all sources)	< 2 pBq/kg
Radon	< 1.4 nBq/kg
Surface α	< 100 μBq/m^2
Total in 3 years	< 0.6 events

- Beta/Gamma
  - Ar-39 dominant rate 1Bq/kg
  - Removed using PSD
  - In-situ calibration source!
- Neutron recoils:
  - Excellent shielding from AV
  - (α,n) - strict material controls: ex-situ assays
  - Muon induced - 2km overburden and water veto
- Surface alphas:
  - Mainly due to Rn daughters
  - Inner surface of AV was resurfaced in-situ - 1 mm of acrylic removed
  - Fiducial volume cuts in reconstruction



Pulse Shape Discrimination

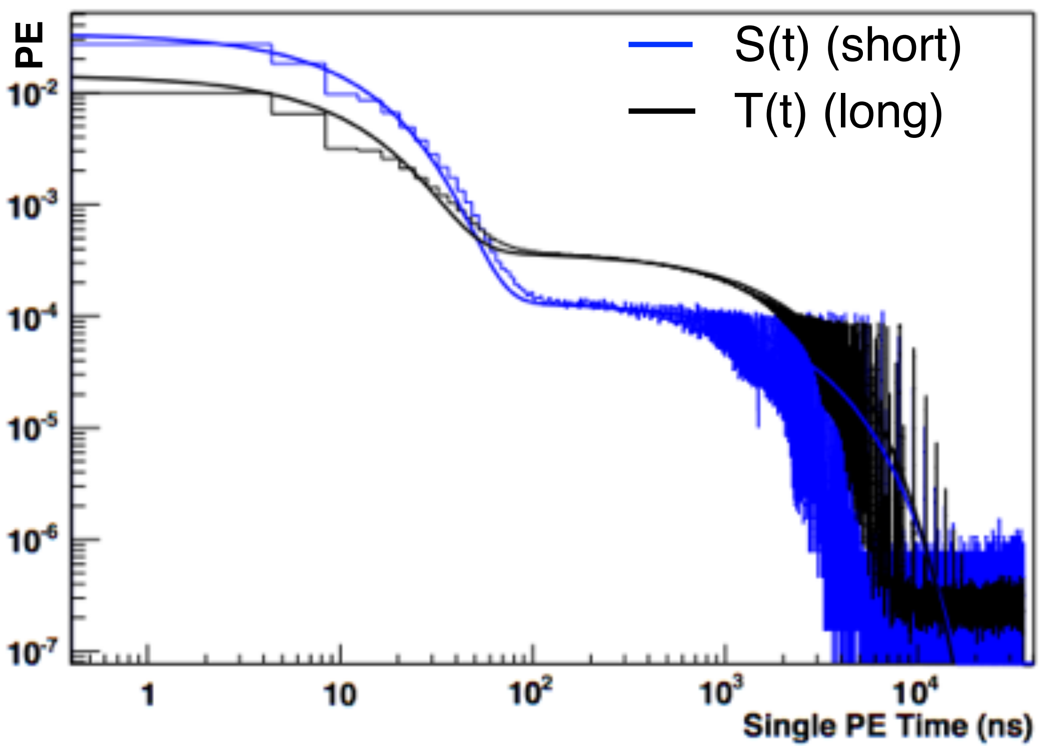
- Knowledge of the singlet and triplet lifetimes in liquid Argon allows us to construct a scintillation timing PDF

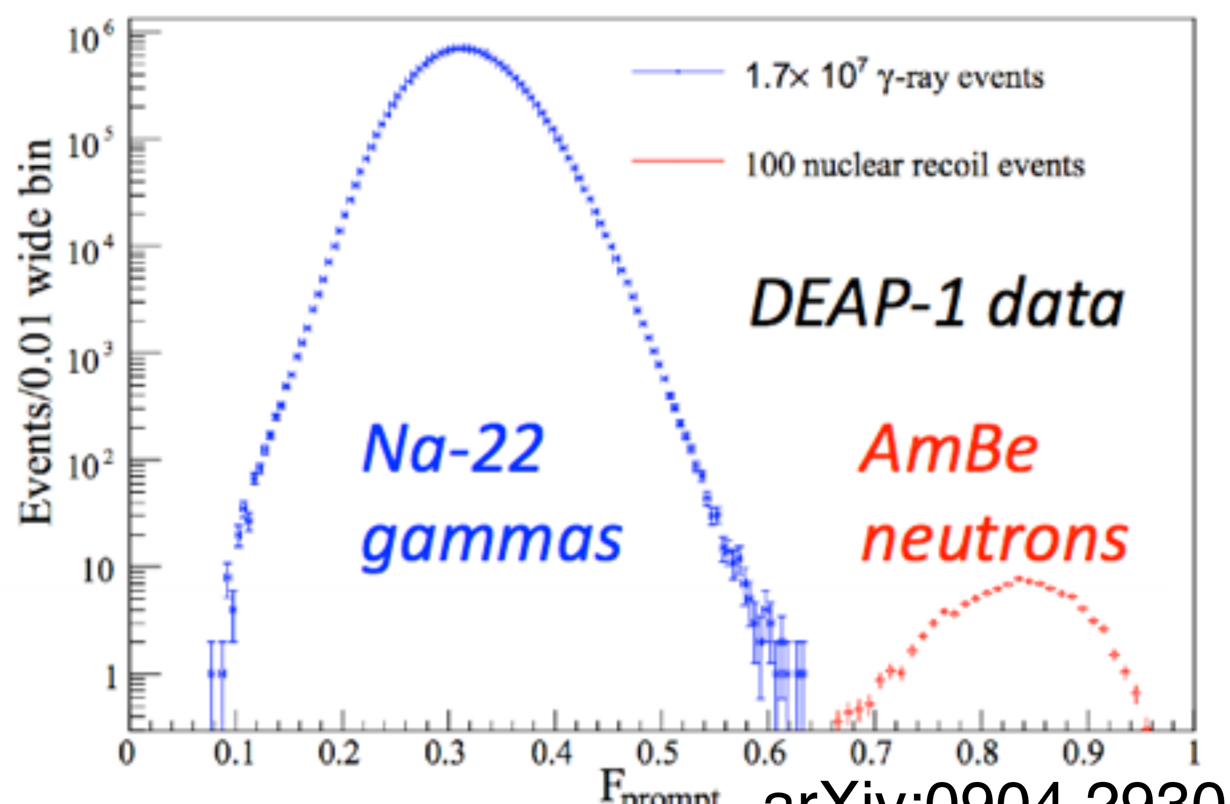
$$P(t) = f \exp\left(-\frac{t}{\tau_S}\right) + (1-f)\exp\left(-\frac{t}{\tau_L}\right)$$

  - 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 RAT, of photons drawn from short, $S(t)$, and long, $T(t)$, time constant distributions.





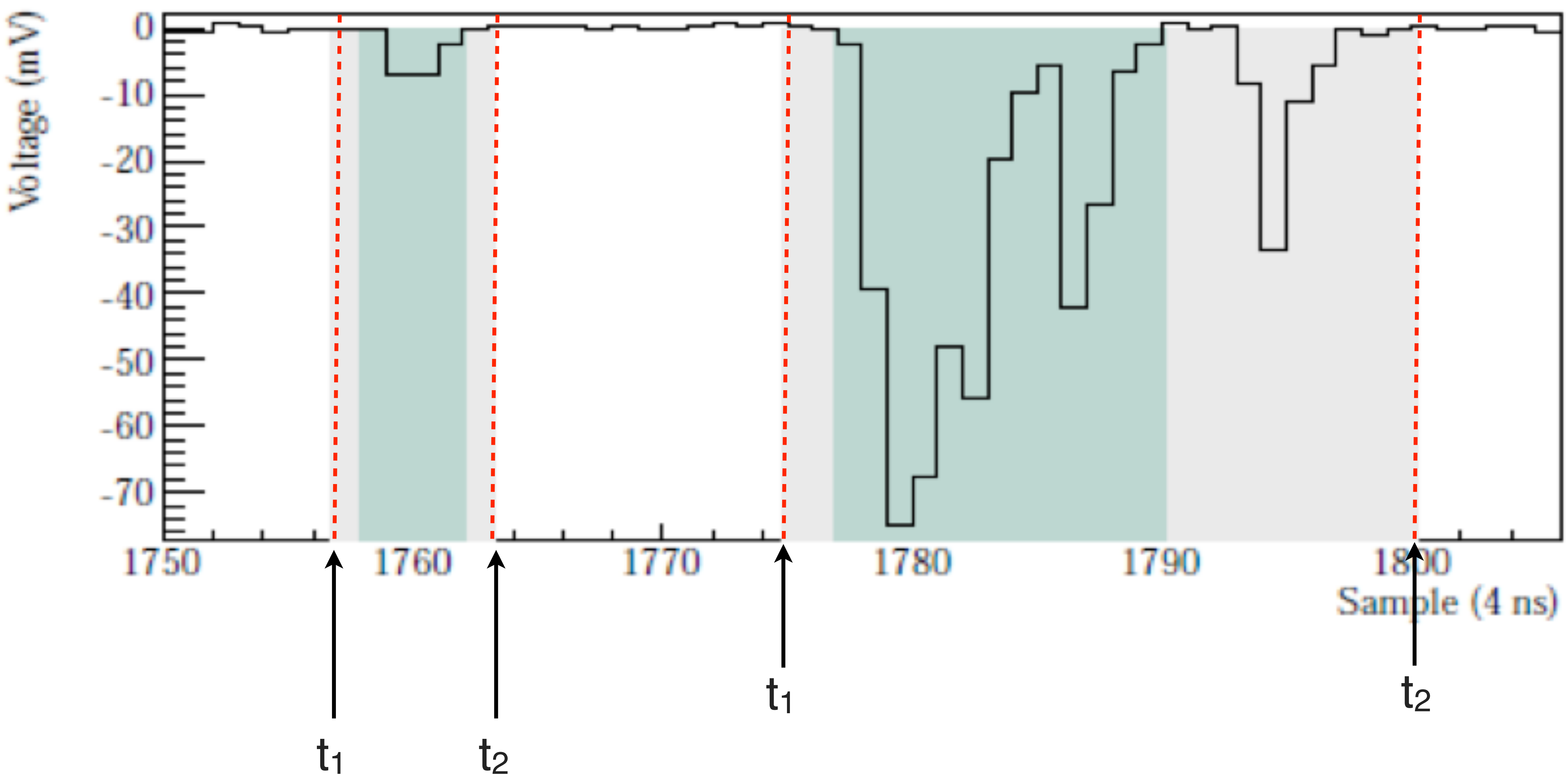
arXiv:0904.2930

Energy reconstruction and higher level PSD variables rely on accurate photoelectron counting.

PE Finding

arXiv:1408.1914v2

Start with pulse finding.



- 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.

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

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

- 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

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

Prior PDF

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

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

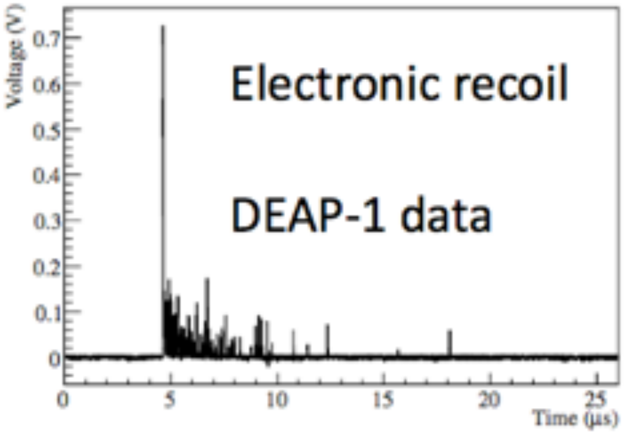
- We have a Poisson probability, since we have low occupancy (<10 PE per PMT), of seeing j photons given an expected number of PE in the PMT, μ, which is calculated from the total charge over the single PE charge.

- 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.

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

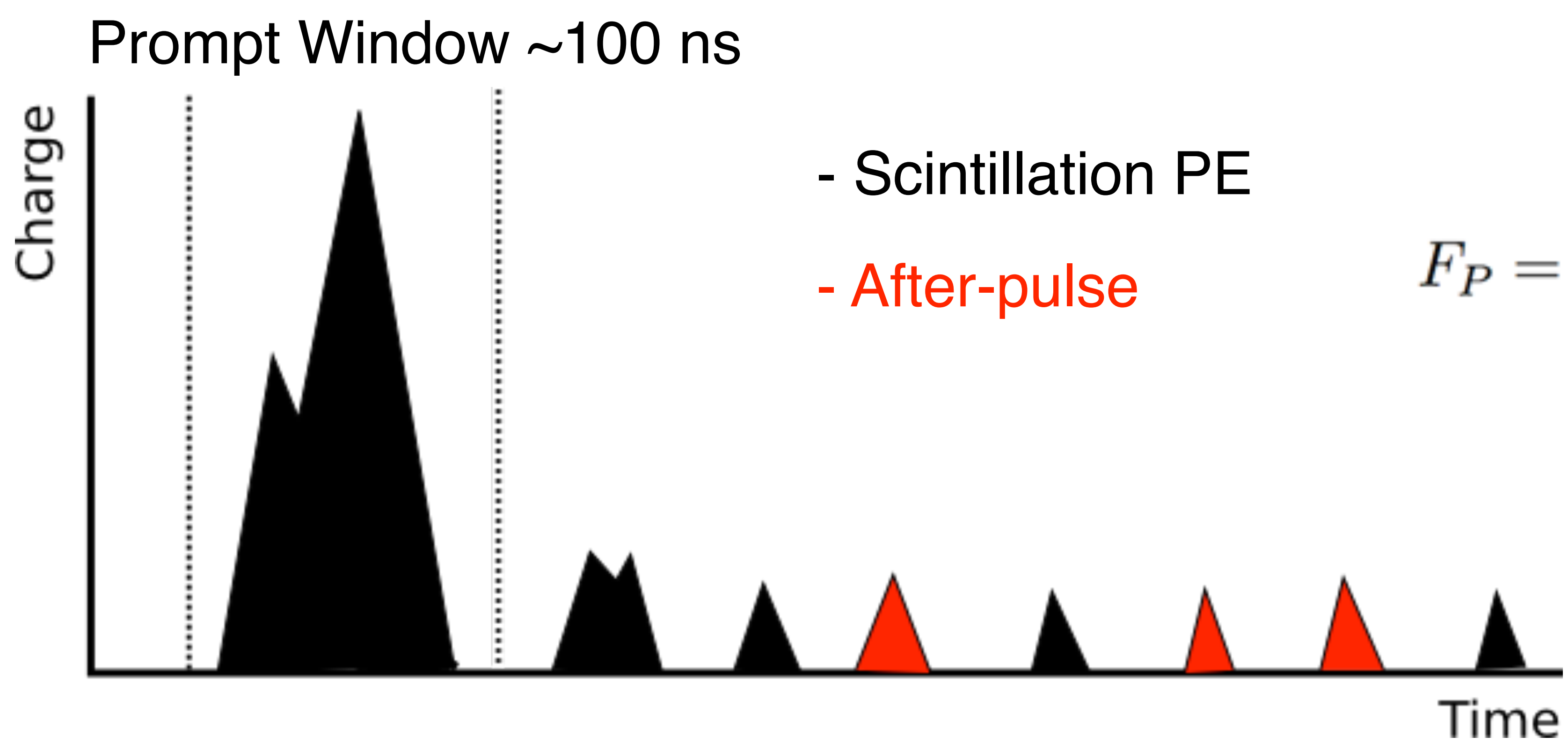
- Here $S(t)$ and $T(t)$ are the singlet and triplet lifetime states respectively with F_p being Fprompt. f_d is the fraction of photons due to the dark rate.

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.



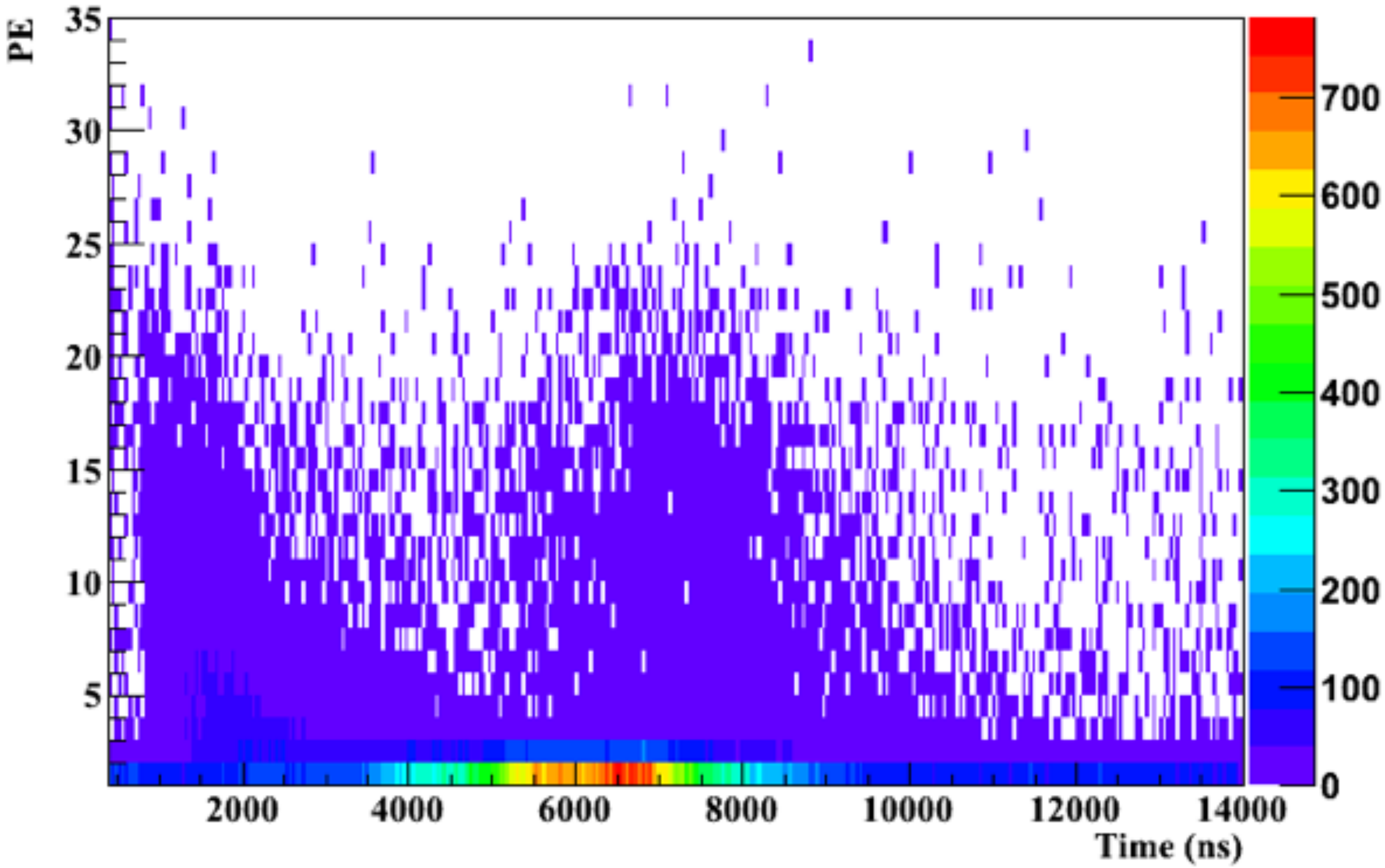
$$F_P = \frac{\int_{t_0}^{t_{100ns}} Q(t)dt}{\int_{t_0}^{t_{end}} Q(t)dt}$$

- 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 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.

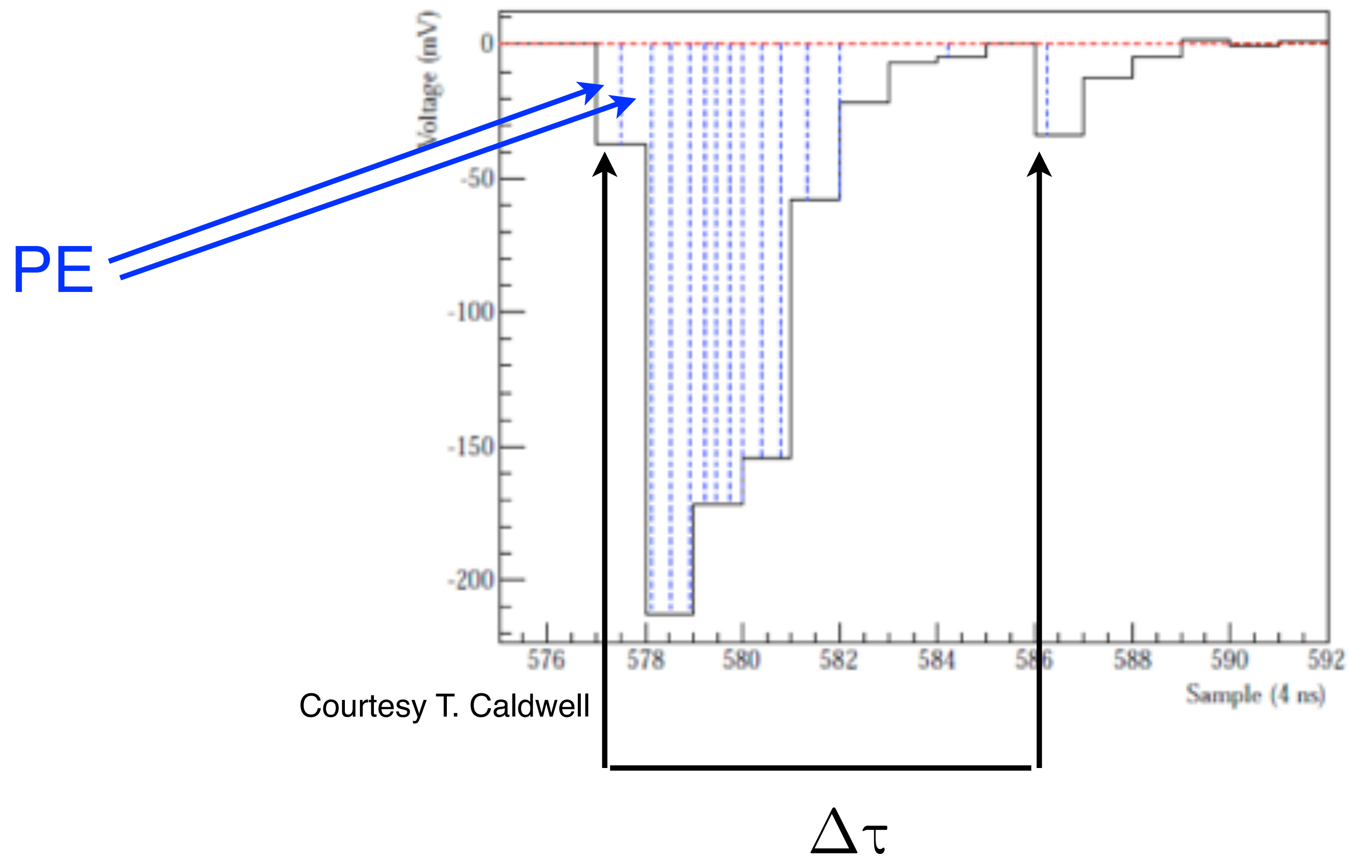
Every point in the plot below is an after-pulse of a certain integral PE and arrival time. The after-pulsing rate is expected to be between 5 and 15%.



After-pulsing will be measured in-situ after TPB deposition over the next few weeks.

After-pulsing Prior

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



- 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 calculate the probability the

After-pulsing PDF

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

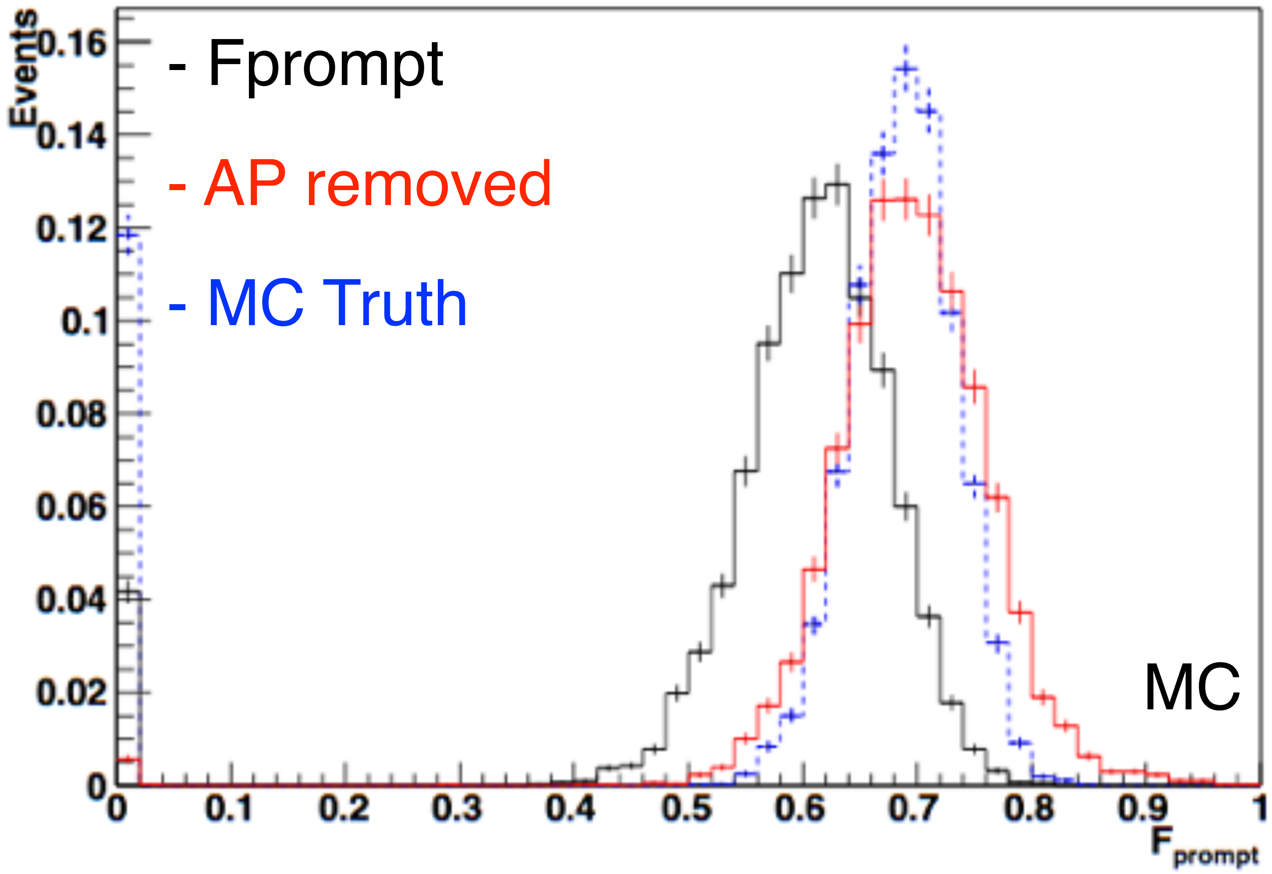
p_{ap} is the probability of an after-pulse occurring, N_{cont} is the number of contributing PE, m is the number of after-pulse PE produced

After-pulsing Prior

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

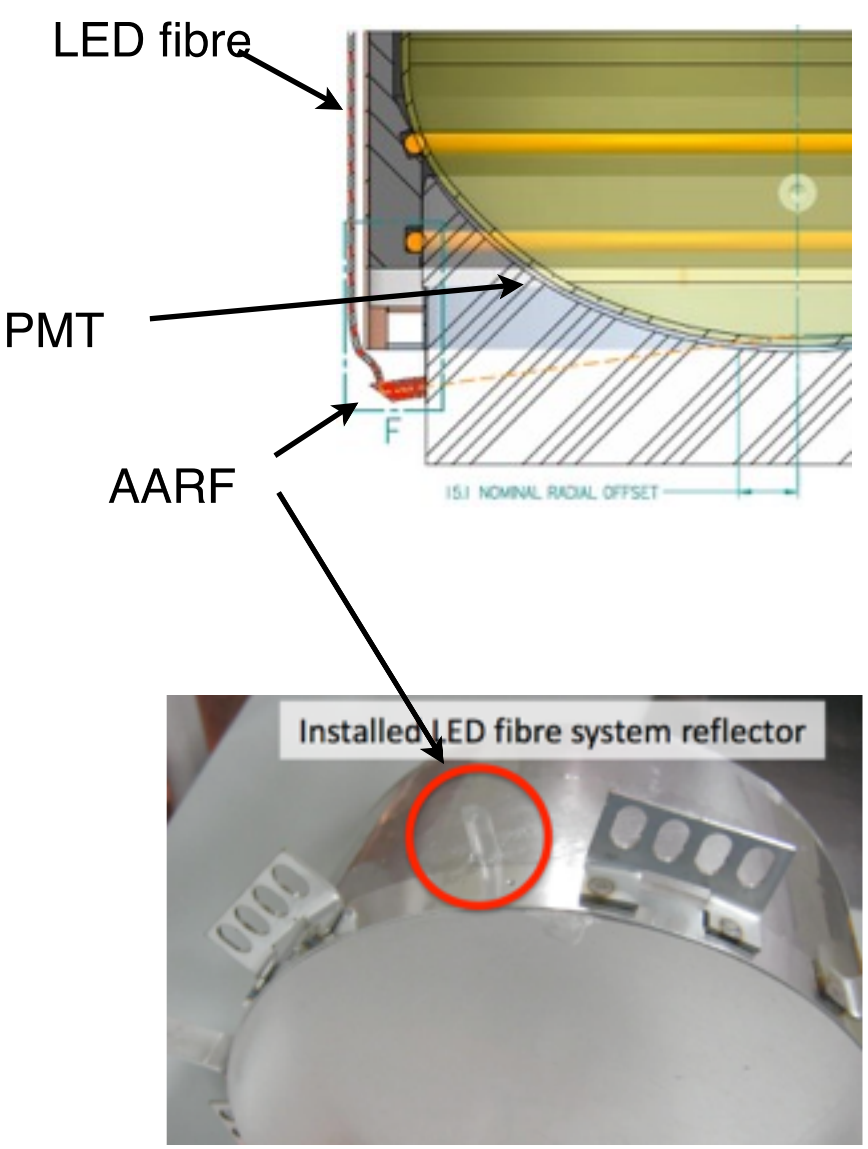
$$P_N(n|t_1, t_2) \rightarrow P_N(l|t_1, t_2) \times P_{NAP}(m|t_1, t_2, N_{cont})$$

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

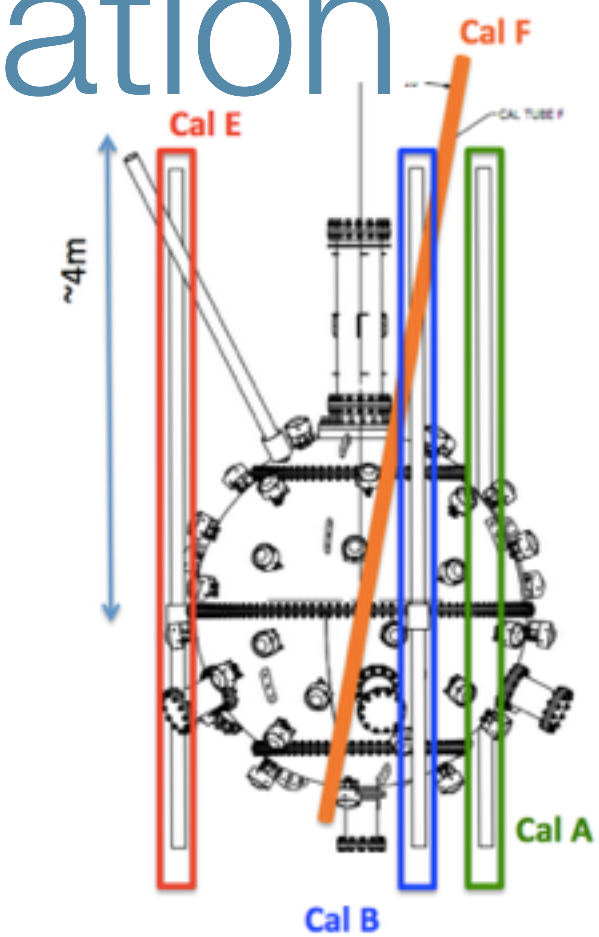


Using the modified single PE finder after-pulse removal shifts the mean back up to 0.7.

Calibration

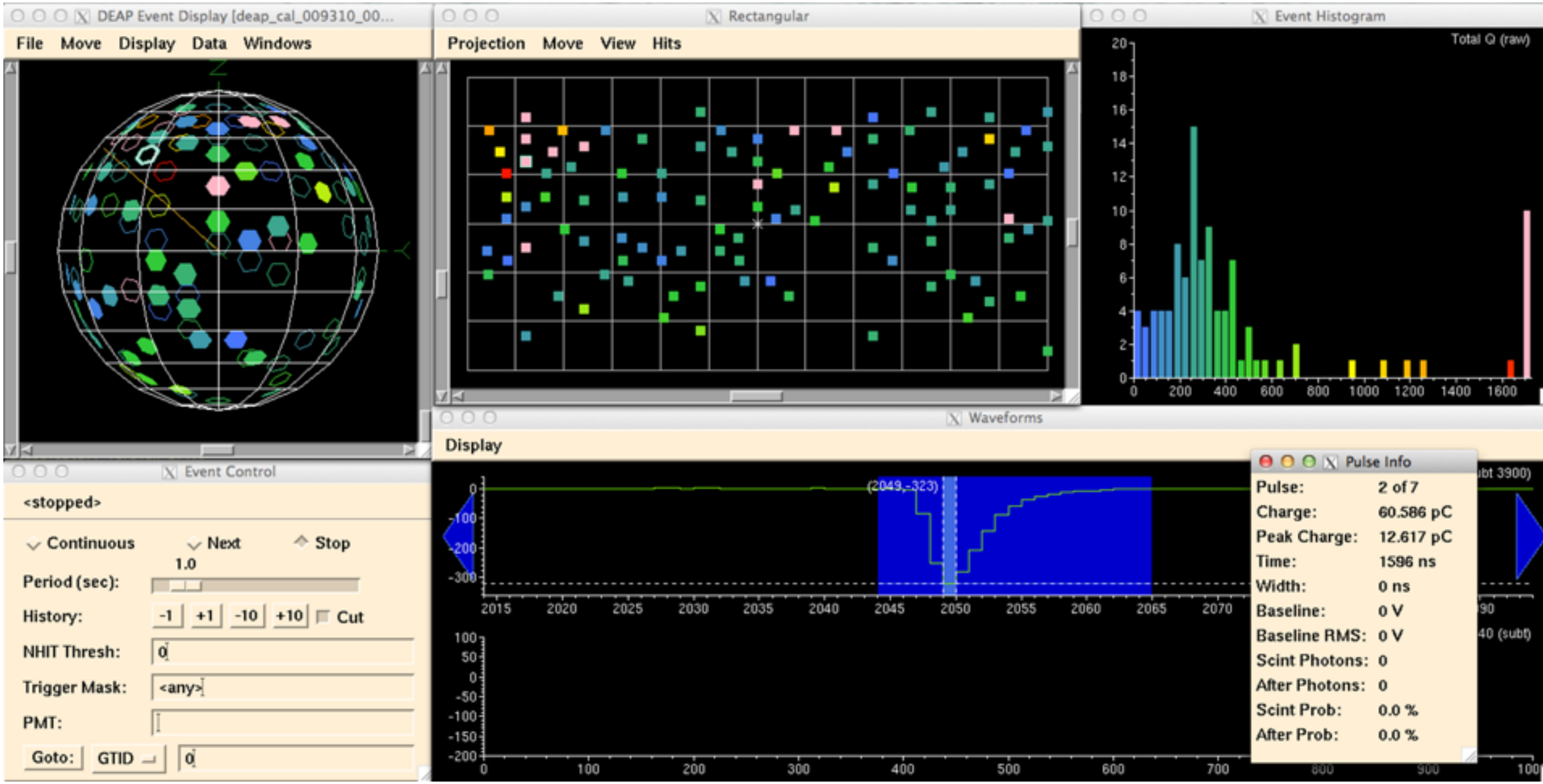


- Optical Calibration
    - Laser Ball - several different wavelengths
    - LED fibre system - AARF
- Used during commissioning and physics runs these provide
    - PMT timing and gain calibration/ monitoring
    - Acrylic Vessel/Light Guide monitoring
- Optical calibration with AARFs has begun
    - The laser ball will be used in the vacuum stage to give an in situ measurement of the after-pulsing PDF and PMT efficiencies



- Tagged Na-22 and AmBe-neutron sources
- Na-22: populate argon volume with well understood gamma spectrum
- AmBe: populate detector with WIMP like nuclear recoil events

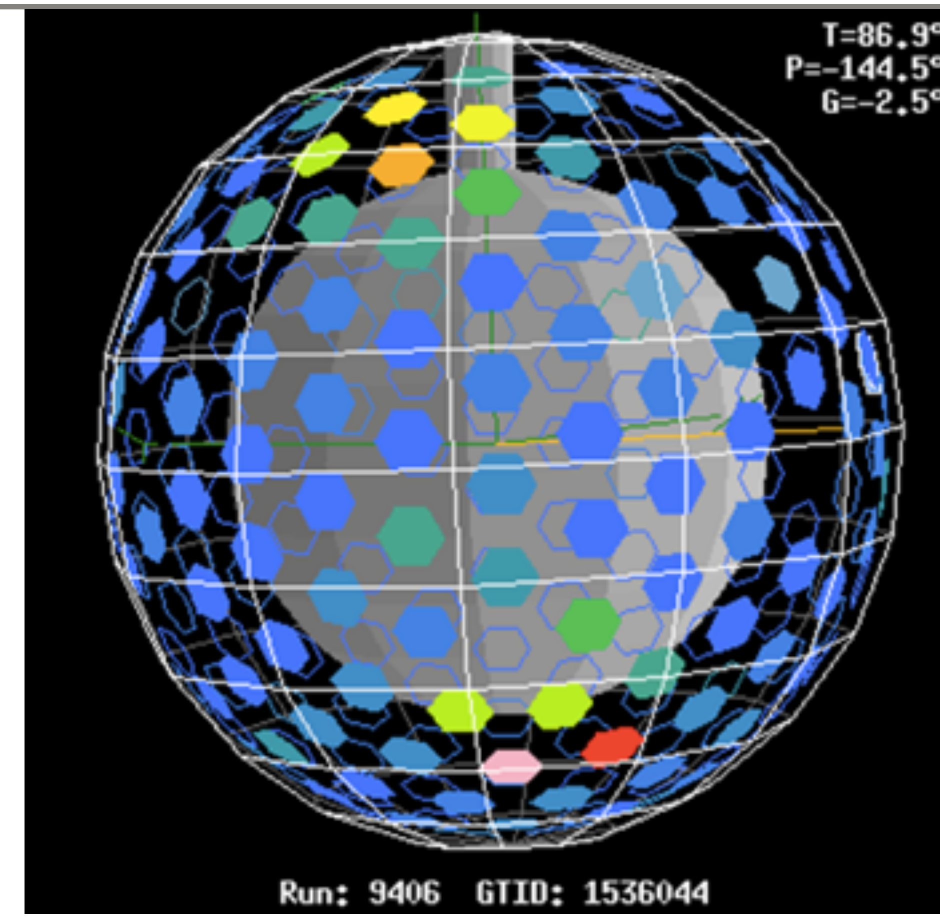
Calibration

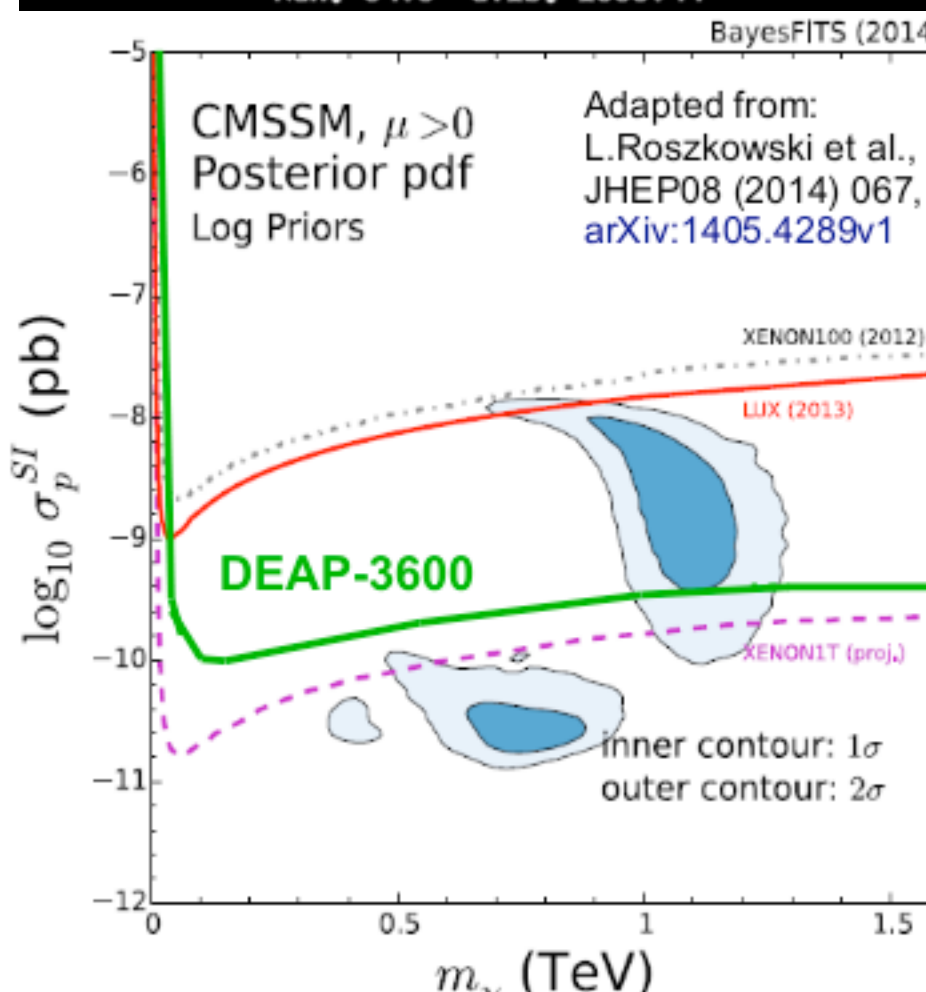


AARF event.

Conclusions and Outlook

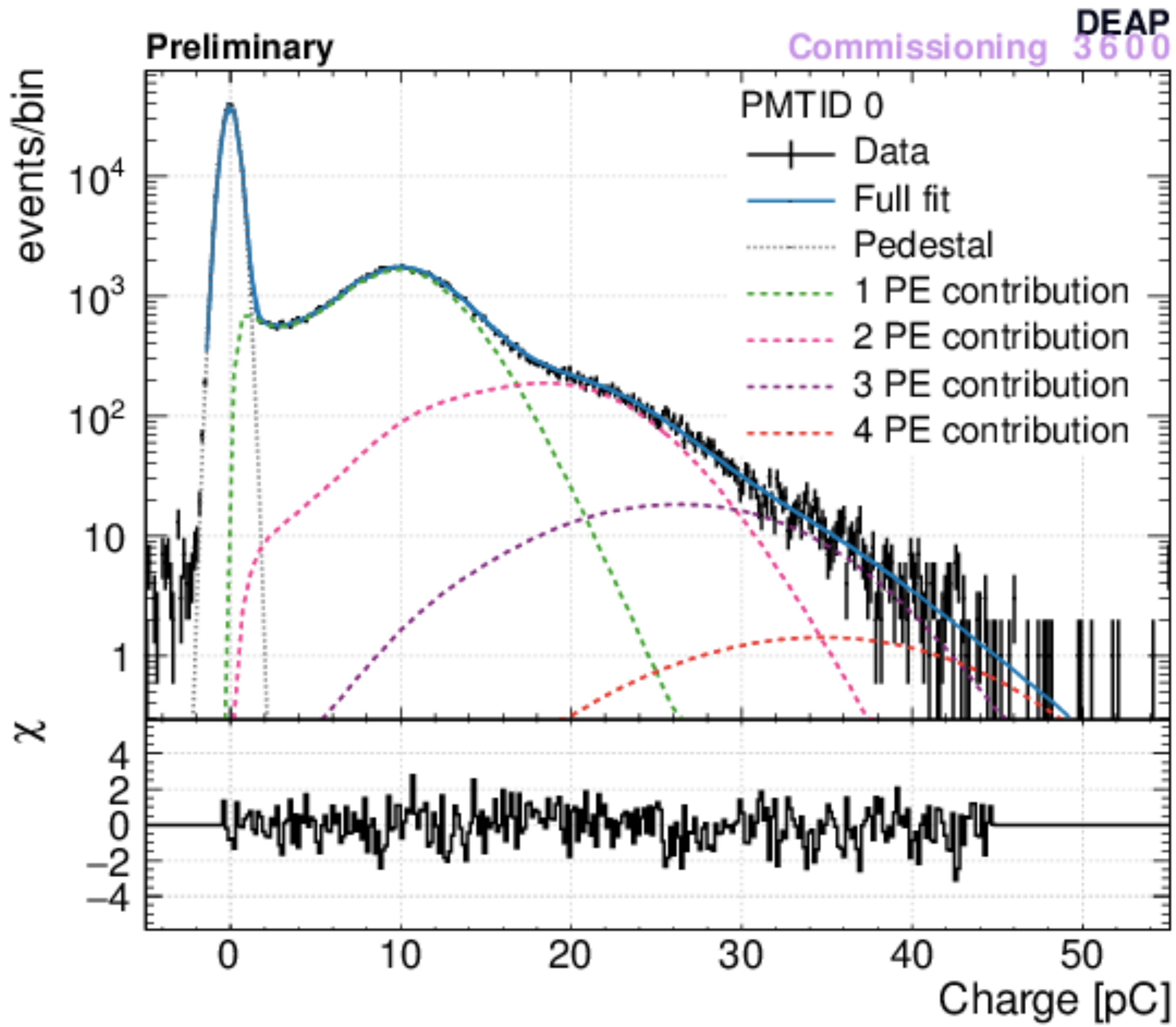
- Commissioning has started - PMTs operating for 6 months
- TPB deposition is imminent
- Optical calibration has started with analysis of AARF system
- Analysis framework is ready for data
- Fill with gaseous Ar in July
- First result late 2015





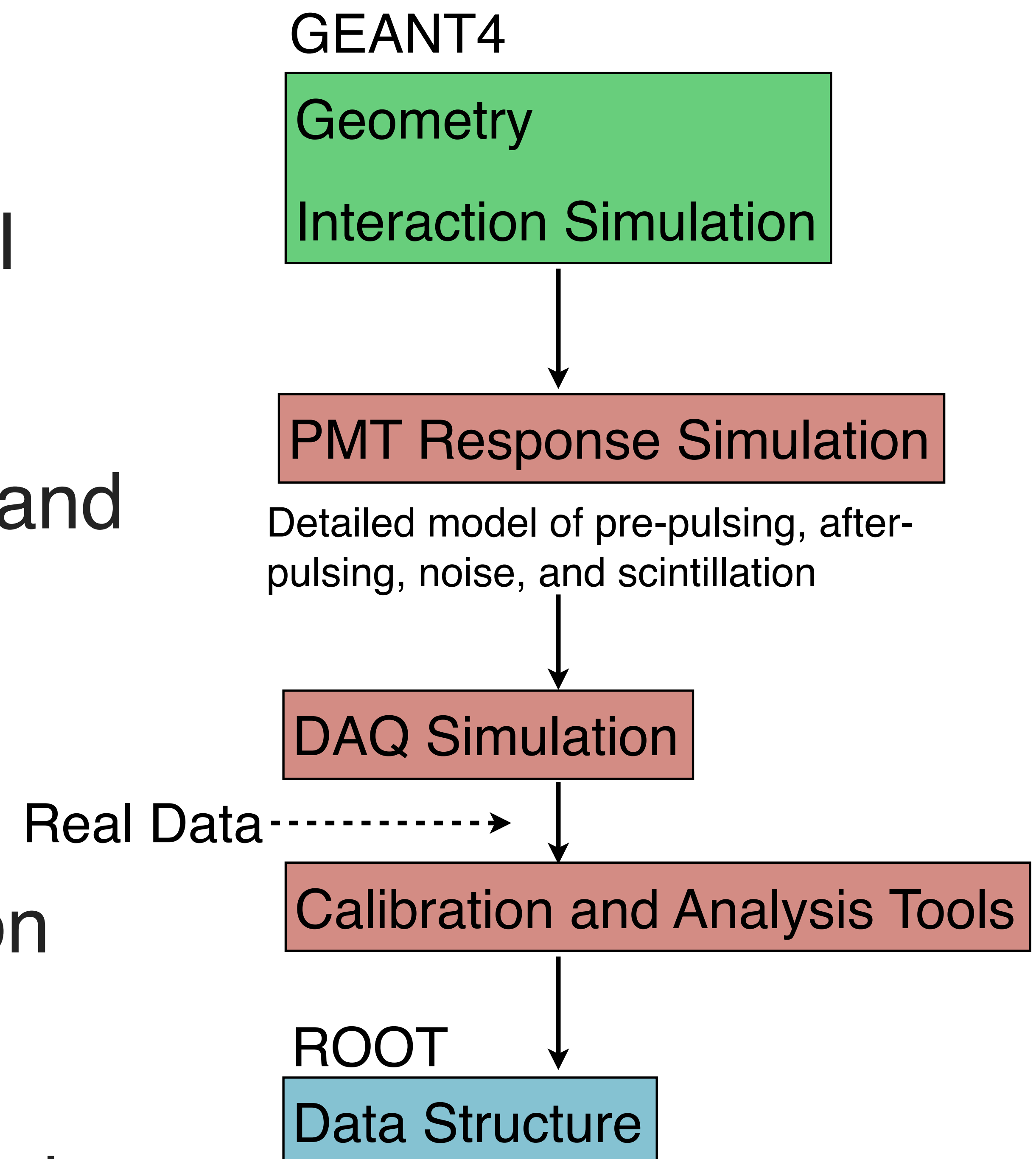
Backup

Single PE Distribution



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



RAT
Reactor Analysis Tool