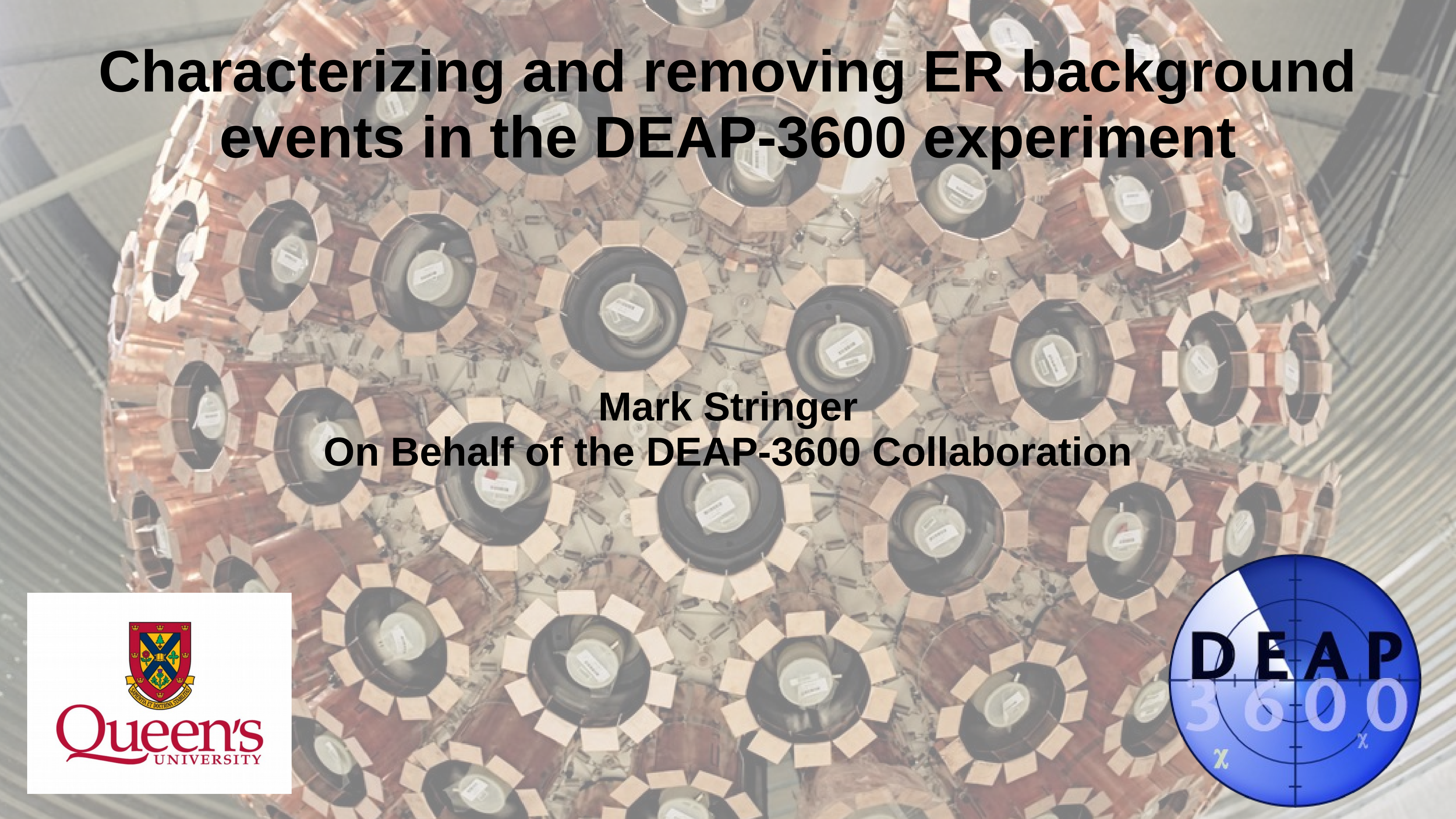
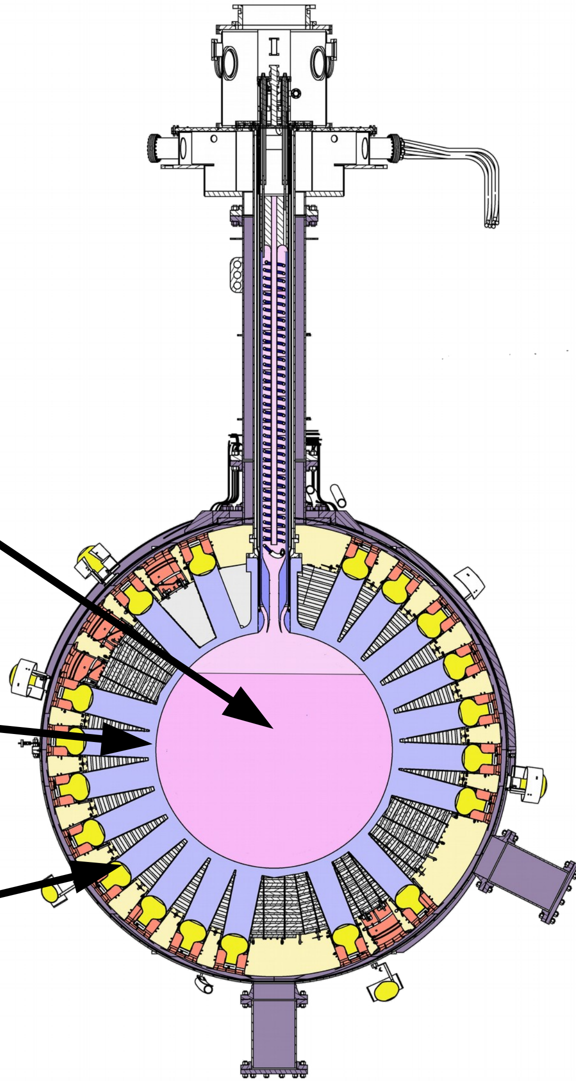
Characterizing and removing ER background events in the DEAP-3600 experiment



Mark Stringer
On Behalf of the DEAP-3600 Collaboration

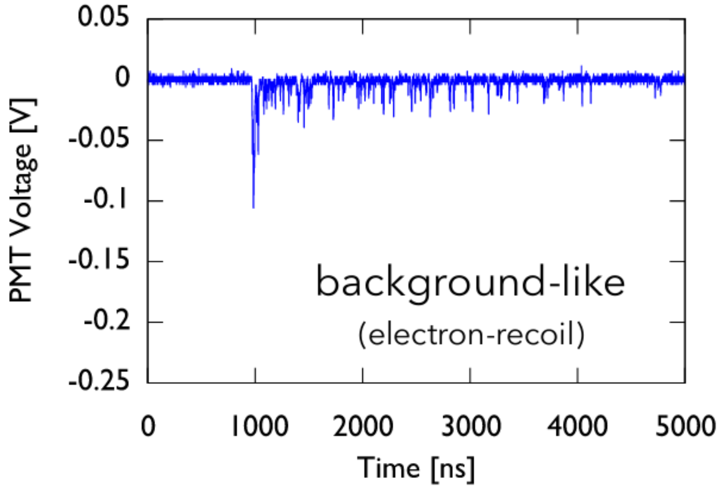
DEAP-3600

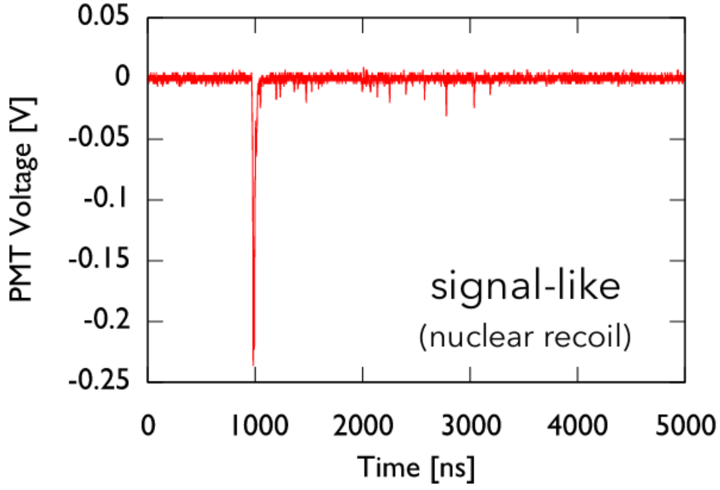
- Direct dark matter search experiment
- Detection method:
  - Argon scintillates
    when excited by interacting particles
    - Good light yield
      - 40,000 photons/MeV
    - Peak emission 128 nm
  - Shifted to 420 nm by TPB
    - Shifted light detected by PMTs



Argon Scintillation

- Argon has two dominant excited states
  - Singlet (6 ns)
  - Triplet (1.4 μs)
- Nuclear Recoils (NR)
  i.e. (WIMP, α, n) → Singlet State
- Electron Recoils (ER)
  i.e. (β, μ, γ) → Triplet State
- NR events have much more light earlier in the pulse



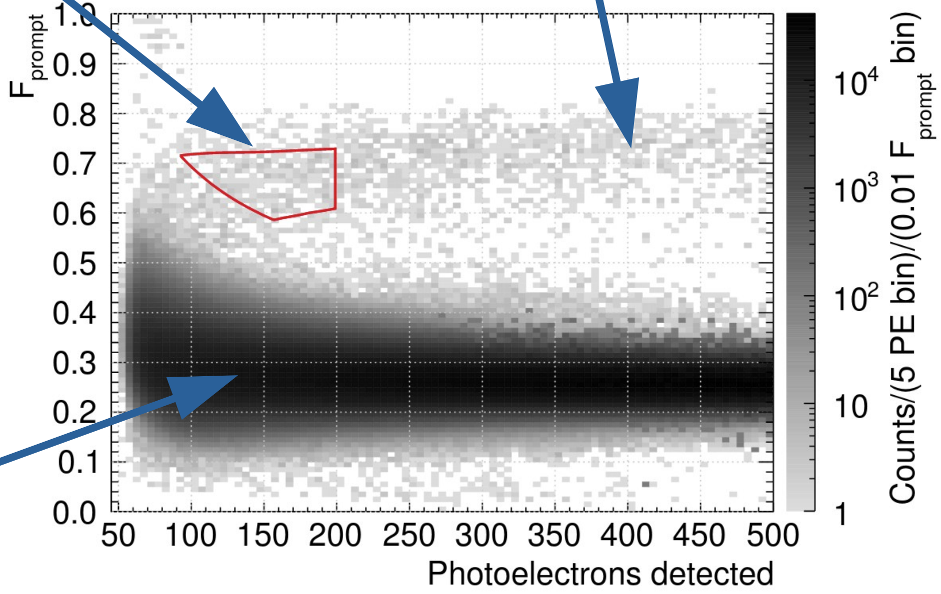


Pulse shape Discrimination

$$F_{\text{prompt}} = \frac{\sum_{t=-28\,\text{ns}}^{60\,\text{ns}} \text{PE}(t)}{\sum_{t=-28\,\text{ns}}^{10\,\mu\text{s}} \text{PE}(t)}.$$

WIMP ROI defined to contain 0.05 ^{39}Ar events for the entire livetime of the dataset

NR band produced by AmBe neutron source



^{39}Ar has activity of 1 Bq/kg of Atmospheric Ar (~3300 Bq in DEAP-3600)

https://arxiv.org/abs/1902.04048

Excluding ^{39}Ar events

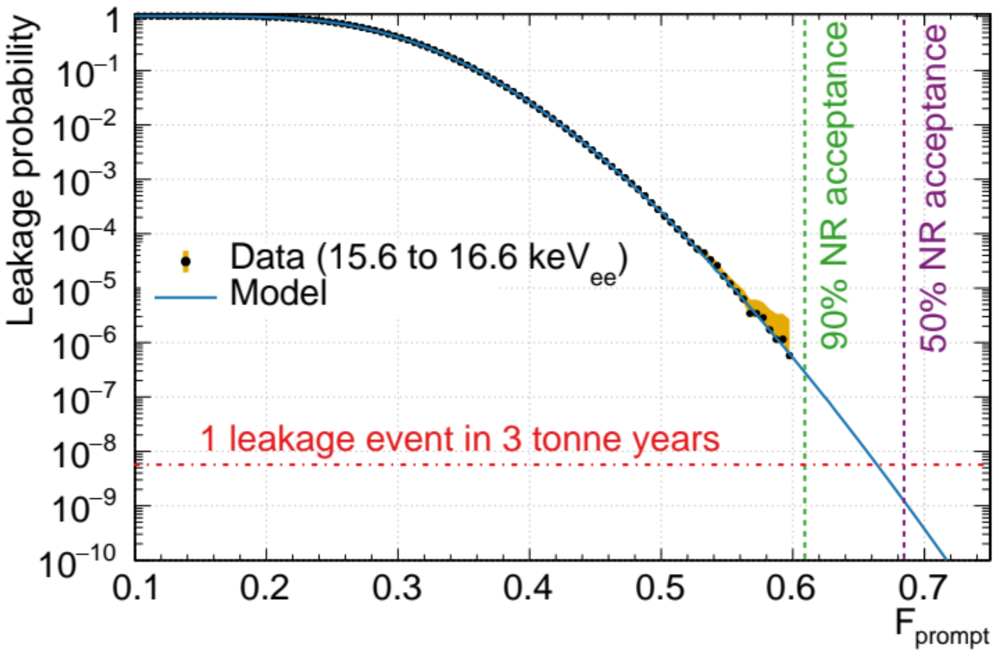
High rate of ^{39}Ar allows effective model for Fprompt distribution of ^{39}Ar

$$F^{\mathrm{ER}}(f,q) = \Gamma(f;\bar{f},b) \otimes \mathrm{Gauss}(f;\sigma),$$
$$\bar{f}(q) = a_0 + \frac{a_1}{q-a_2} + \frac{a_3}{(q-a_4)^2},$$
$$b(q) = a_5 + \frac{a_6}{q} + \frac{a_7}{q^2},$$
$$\sigma(q) = a_8 + \frac{a_9}{q} + \frac{a_{10}}{q^2},$$

q is number of PE

Total leakage can be obtained via:

$$L = T\sum_q R(q) \times P_{\mathrm{Leak}}(f,q)$$

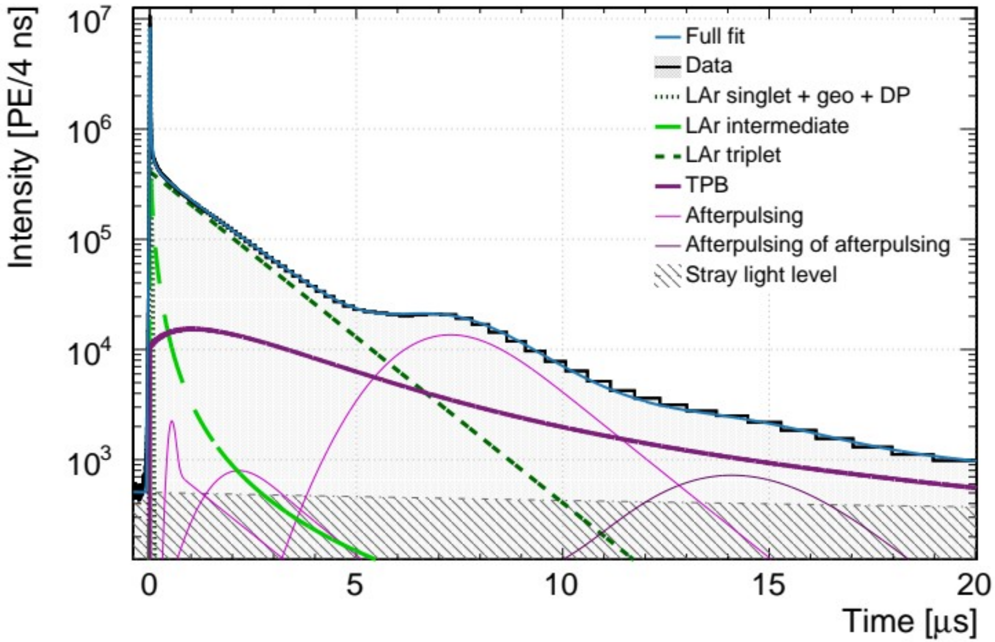


Fprompt distribution in lowest energy bin used in WIMP search

https://arxiv.org/abs/1902.04048

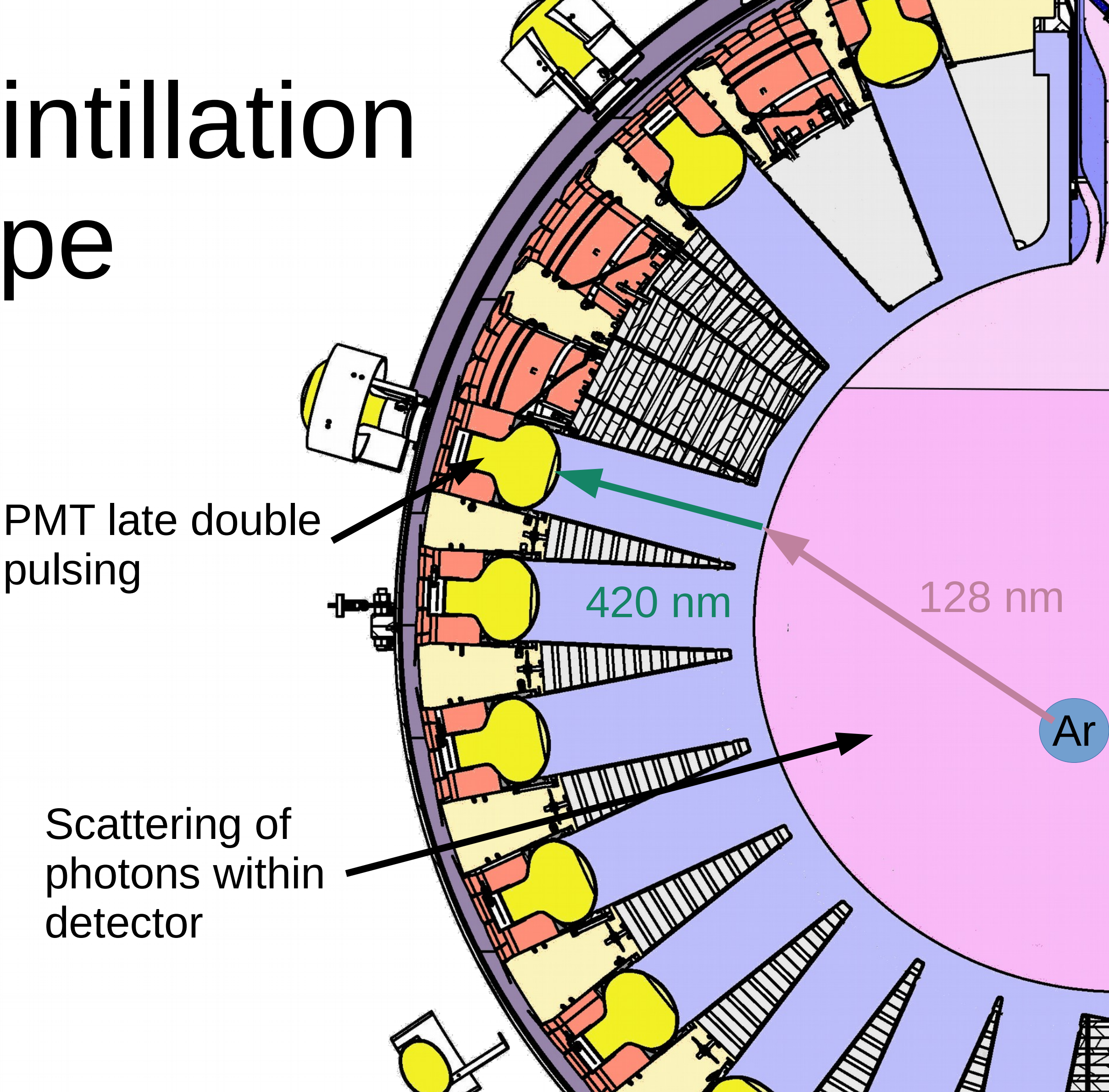
Measuring the Scintillation Pulse Shape

- Fprompt provides power to discriminate ER from NR events
- Constructing a scintillation model
  - Allows ongoing monitoring of the detector
  - Motivates design choices for future detectors

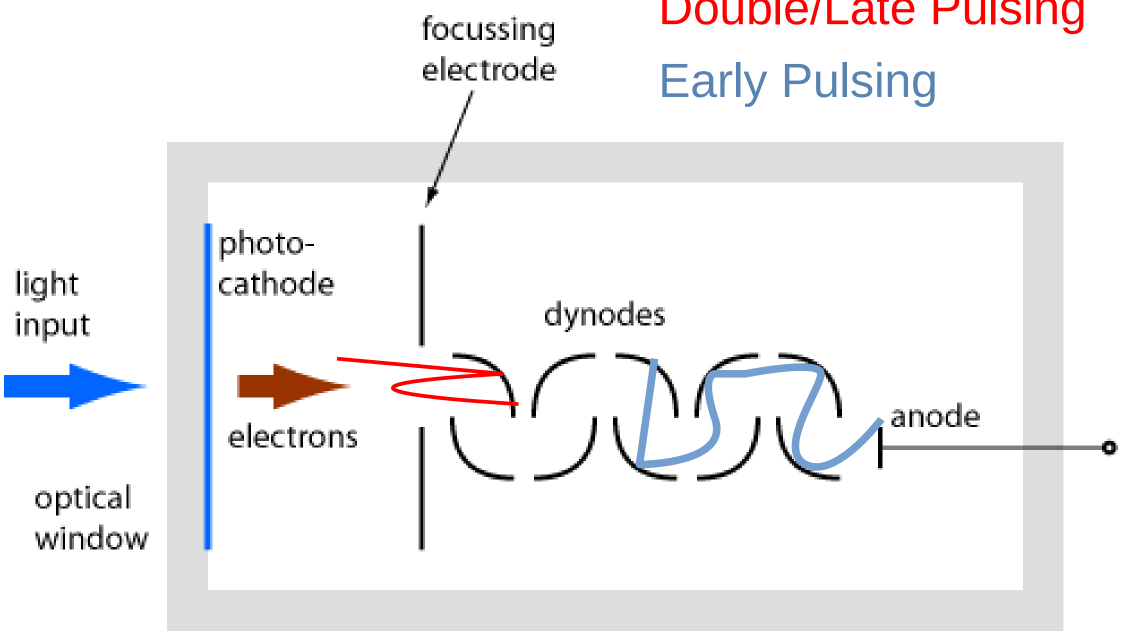


Modelling the Scintillation Pulse Shape

- Double exponential structure of LAr scintillation
- Instrumental Effects:
  - TPB Re-emission
  - PMT effects



Instrumental Effects: PMT/Detector Effects



https://www.rp-photonics.com/photomultipliers.html

Prompt pulsing
15 ns width due to
scattering of light

$$I_{\mathrm{geo}}(t) = \nu_{\mathrm{DET}} \cdot \mathrm{Gaus}(t, \mu_{\mathrm{DET}}, \sigma_{\mathrm{DET}}) + \nu_{\mathrm{DP}} \cdot \mathrm{Gaus}(t, \mu_{\mathrm{DP}}, \sigma_{\mathrm{DP}})$$

Double/Late pulsing
Peak ~58 ns late

$$I_{\mathrm{EP}}(t) = R_{\mathrm{EP}} \cdot (I_{\mathrm{LAr}}(t - t_{\mathrm{EP}}) \otimes I_{\mathrm{TPB}}(t - t_{\mathrm{EP}}) \otimes I'_{\mathrm{geo}}(t - t_{\mathrm{EP}}))$$

Argon Scintillation

$$I_{\mathrm{LAr}}(t) = \frac{R_s}{\tau_p} e^{-t/\tau_p} + \frac{1 - R_s - R_t}{(1 + t/\tau_{rec})^2} \frac{1}{\tau_{rec}} + \frac{R_t}{\tau_t} e^{-t/\tau_t}$$

Triplet emission

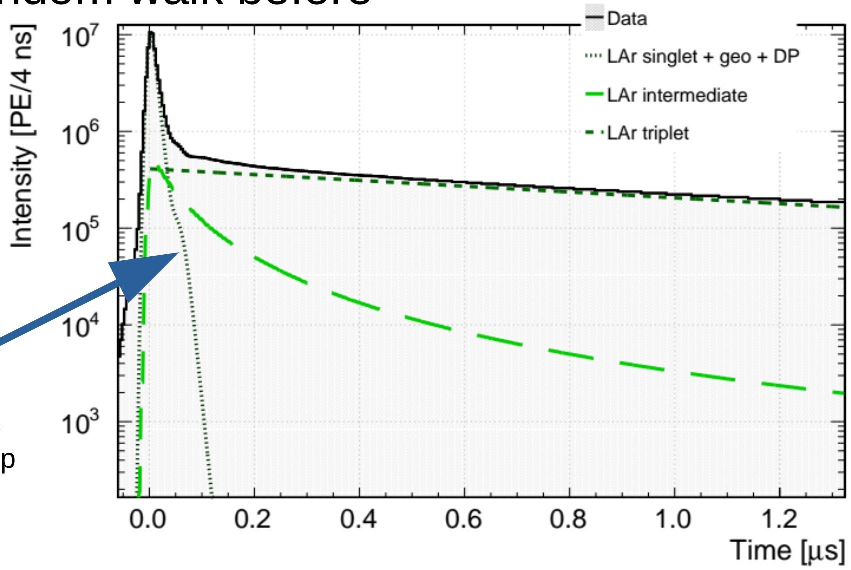
Singlet emission – decay time modifed to reflect TPB response in fit

Intermediate emission – electrons scattered far away from ions → random walk before recombination

$$I_{\mathrm{LAr}}(t) \otimes I_{\mathrm{geo}}(t)$$

Double pulsing produces shoulder in singlet peak

Assumes fast TPB response is absorbed into I_{geo} and τ_p

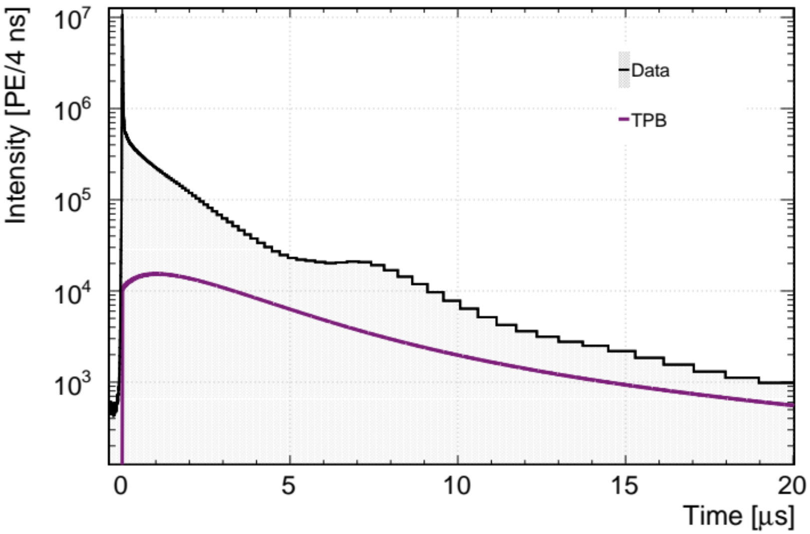


Instrumental Effect: Delayed TPB Re-emission

$$I_{\mathrm{TPB}}(t) = (1 - R_{\mathrm{TPB}})\delta(t) + \frac{R_{\mathrm{TPB}} \cdot N_{\mathrm{TPB}} \cdot e^{-2t/\tau_T}}{1 + A_{\mathrm{TPB}}\left[Ei(-\frac{t+t_a}{\tau_T}) - Ei(-\frac{t_a}{\tau_T})\right]^2 (1 + t/t_a)}$$

Prompt re-emisson
modelled by delta function

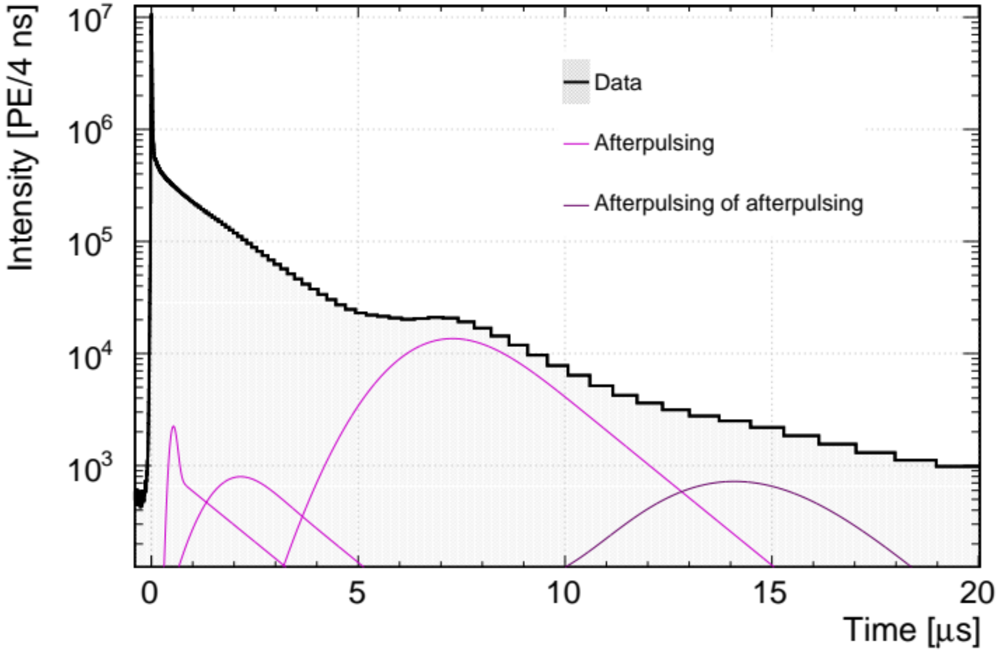
Delayed TPB emission using Voltz and Laustriat model (https://arxiv.org/abs/1804.06895v1)



$$I_{\mathrm{LAr}}(t) \otimes I_{\mathrm{TPB(Late)}}(t)$$

Delayed emission caused by Ar scintillation photons

Instrumental Effect: PMT Afterpulsing



$$I_{\mathrm{AP}}(t) = \sum_{i=1}^{3} \nu_{\mathrm{AP}i} \cdot \mathrm{Gaus}(t, \mu_{\mathrm{AP}i}, \sigma_{\mathrm{AP}i})$$

$$\mu_{\mathrm{AP}i} = 0.5, 1.7, 6.3\ \mu\mathrm{s}$$

$$I_{\mathrm{APofAP}}(t) = I_{\mathrm{AP}}(t) \otimes I_{\mathrm{AP}}(t)$$

Like TPB re-emission, AP is in response to detected LAr photons

$$I_{\mathrm{LAr}}(t) \otimes [I_{\mathrm{AP}}(t) + I_{\mathrm{APofAP}}(t)]$$

Instrumental Effect: Significantly delayed TPB emission from previous events

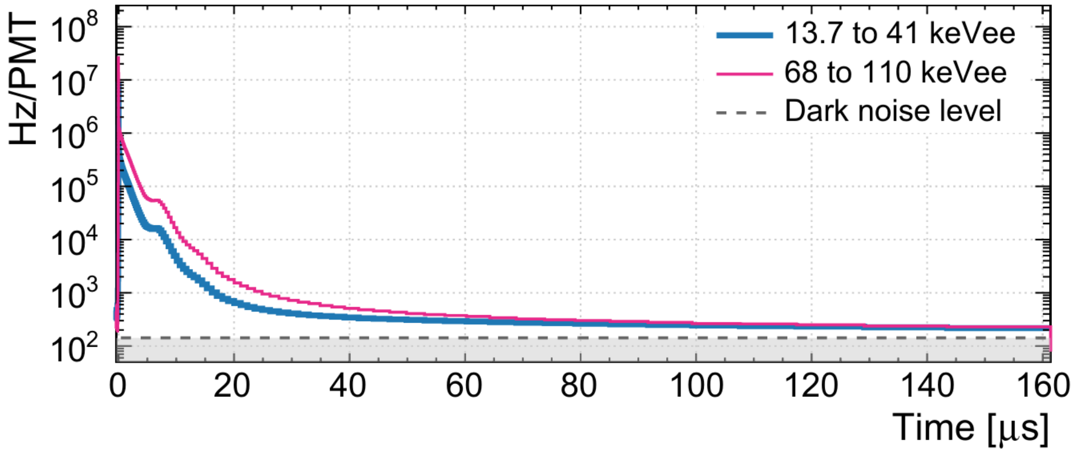
Sum up all contributions of events before Δt'

Number of PE in window due to event Δt' before

$$\bar{I}_{\mathrm{stray}}(\Delta t) = \frac{\int_{\Delta t}^{\infty} N_p(\Delta t')d\Delta t'}{\int_{\Delta t}^{\infty} N_{ev}(\Delta t')d\Delta t'}$$

Total number of events with Δt'

Additional light at late times thought to be caused by very long lived TPB component



$$\eta \cdot \bar{I}_{\mathrm{stray}}(\Delta T_{cut} + 1.6\mu s + t)$$

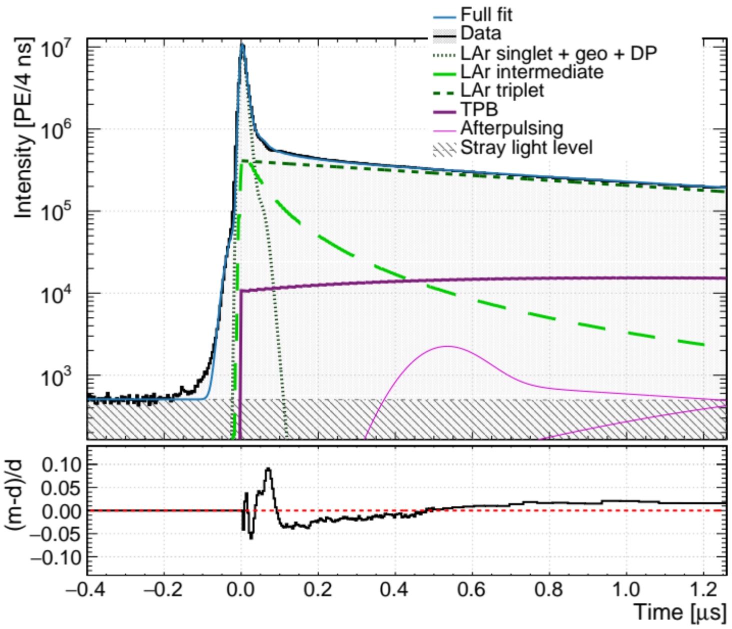
Minimum cut time between events (200 μs)

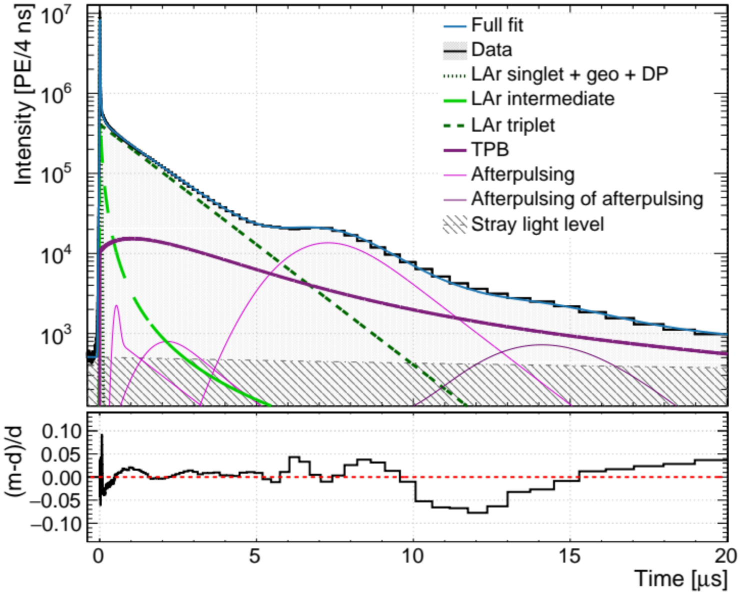
Correction as we evaluate N_p in pre-trigger window

At later times in the event window stray light still significantly higher than dark noise

The Full Model

Model agrees within 10% of data





LAr scintillation + TPB late light

Afterpulsing

$$I_{\mathrm{PS}}(t) = \mathbf{I_0} \cdot \Big(I_{\mathrm{LAr}}(t) \otimes I_{\mathrm{TPB}}(t) \otimes I_{\mathrm{geo}}(t) + I_{\mathrm{LAr}}(t) \otimes [I_{\mathrm{AP}}(t) + I_{\mathrm{APofAP}}(t)] \Big)$$

$$+ \eta \cdot \overline{I}_{\mathrm{stray}}(\Delta T_{cut} + 1.6\mu s + t) + \mathbf{I_0} \cdot R_{\mathrm{EP}} \cdot (I_{\mathrm{LAr}}(t - t_{\mathrm{EP}}) \otimes I_{\mathrm{TPB}}(t - t_{\mathrm{EP}}) \otimes I'_{\mathrm{geo}}(t - t_{\mathrm{EP}}))$$

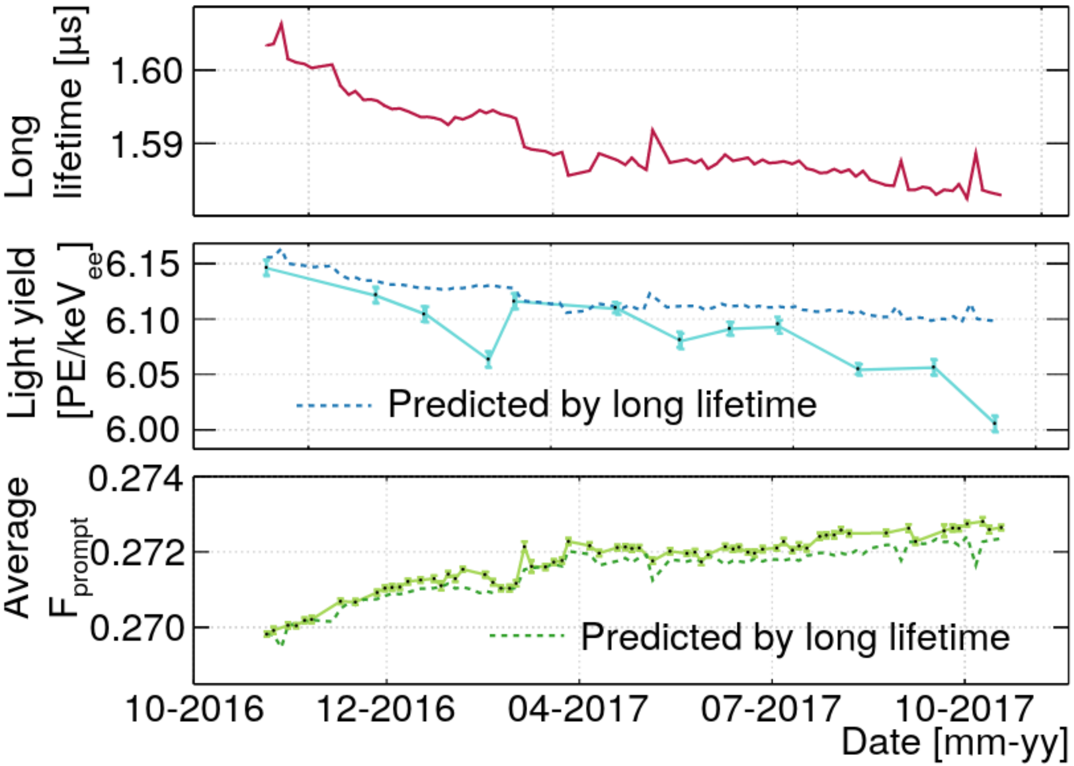
Stray light

Early Pulsing

Monitoring the Pulse Shape

- High rate of ^{39}Ar means stability of detector can be measured in periods < 1 day
- Throughout analysis for 231 days dataset long livetime was stable within 1 %

Long lifetime includes detector effects – not just LAr triplet livetime



Detector response to 2.61 MeV γ-rays in LAr
https://arxiv.org/abs/1902.04048

Conclusions

- ^{39}Ar backgrounds can be effectively removed by evaluating the fraction of light in the start of the event window
- A detailed model including long lived TPB emission has been developed to model the response to ^{39}Ar decays
  - Allows monitoring of the detector during running i.e. variations in the AP rate and Ar purity without dedicated calibration runs
  - Motivates the design choices for a future experiment using LAr and TPB

For more details see: https://arxiv.org/abs/2001.09855