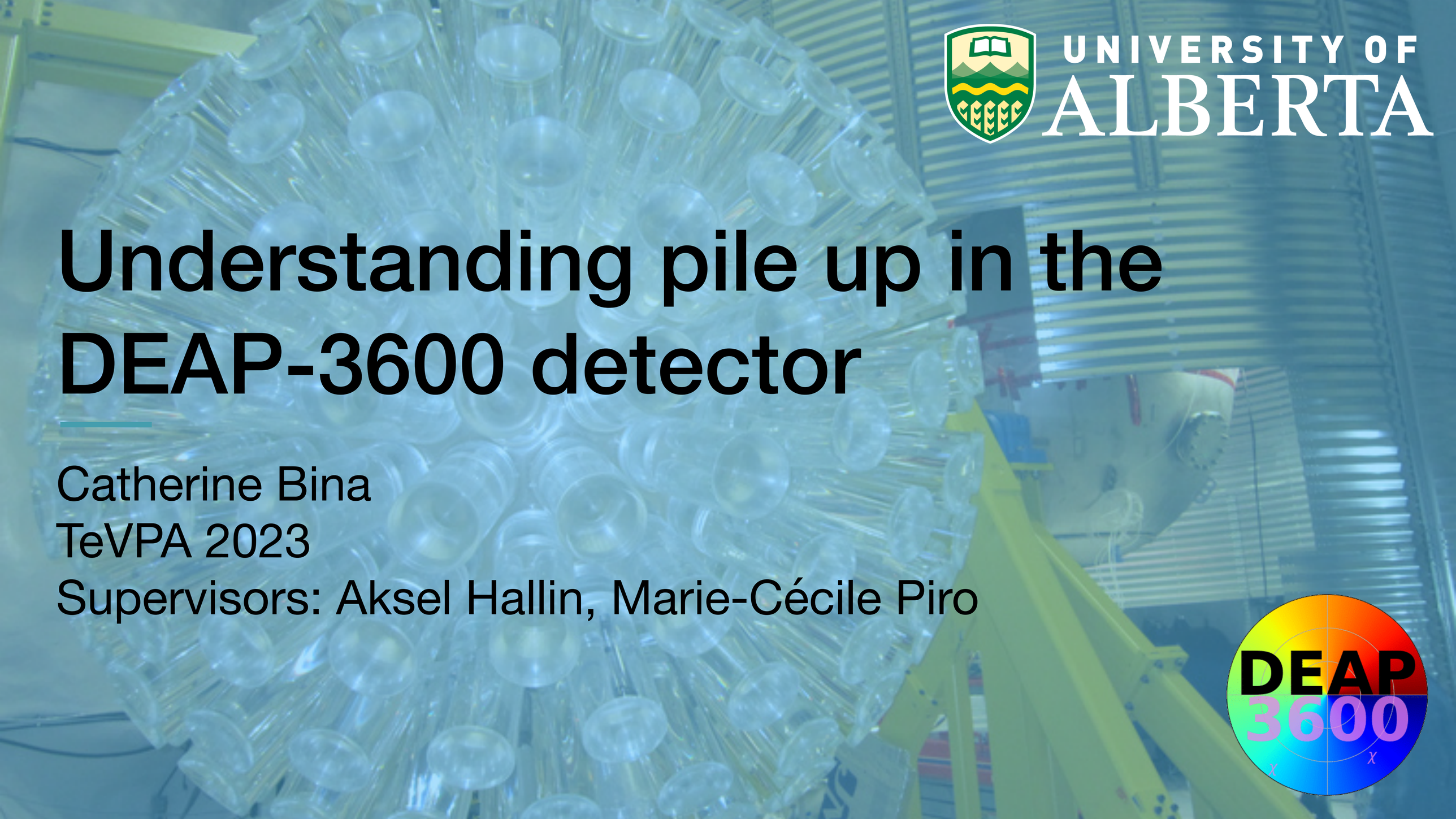
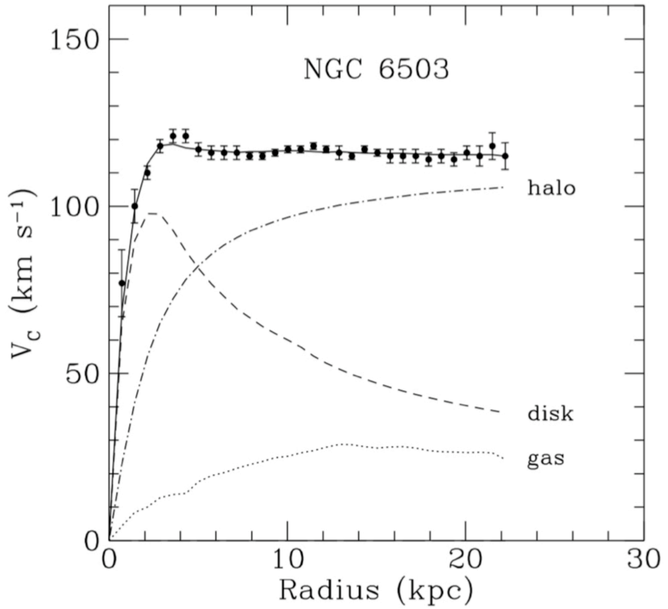
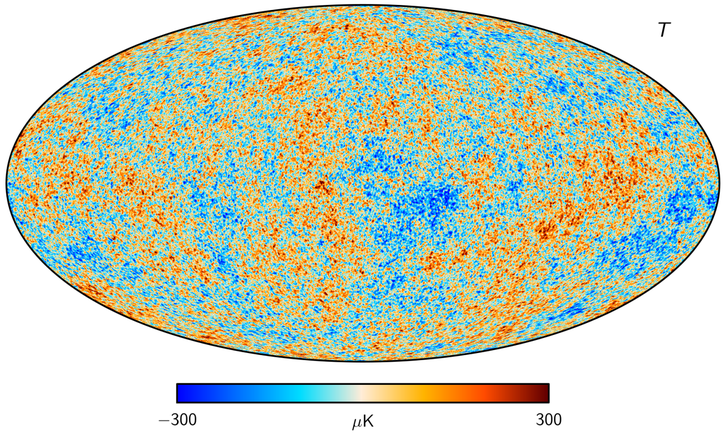


Understanding pile up in the DEAP-3600 detector

Catherine Bina
TeVPA 2023
Supervisors: Aksel Hallin, Marie-Cécile Piro

Strong evidence for the existence of dark matter (DM)





- Predicted to account for 26.4% of the energy density of the universe
- One of the leading candidates are Weakly Interacting Massive Particles (WIMPs)
- Direct detection searches for evidence of dark matter scattering off of target nuclei

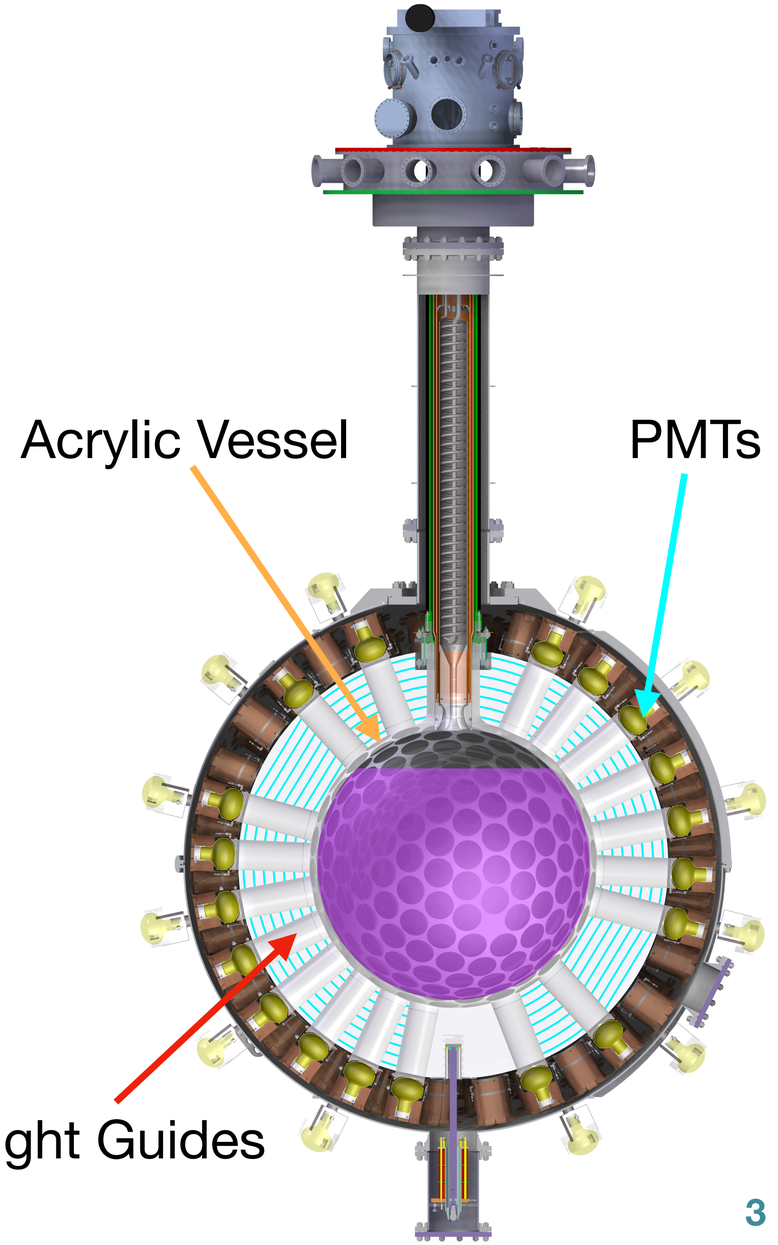
https://www.sciencedirect.com/science/article/pii/S0370157304003515#bib50

https://science.nasa.gov/matter-bullet-cluster

https://wiki.cosmos.esa.int/planck-legacy-archive/index.php/CMB_maps

Dark matter Experiment using Argon Pulse shape discrimination (DEAP)

- Located 2 km underground at SNOLAB in the Cube Hall
- DEAP is a single phase scintillation detector => energy detected as light
- From 2016-2020, the acrylic vessel (AV) was filled with 3,269 kg of liquid argon (LAr)
  - The top 30 cm of the AV contained gaseous Ar
- Signal collected in 255 acrylic light guides (LGs) surrounding the AV and detected via PMTs coupled to the LGs

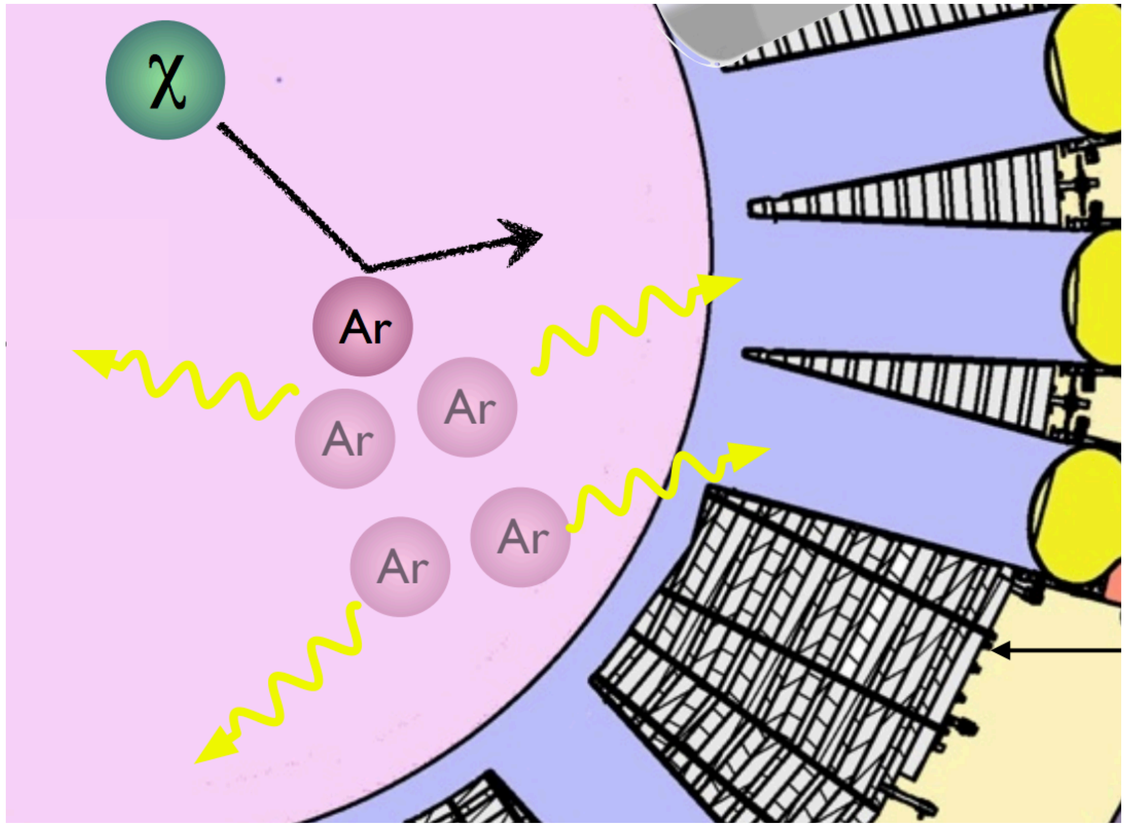


https://doi.org/10.1016/j.astropartphys.2018.09.006

Interactions with the LAr create scintillation light via excimers

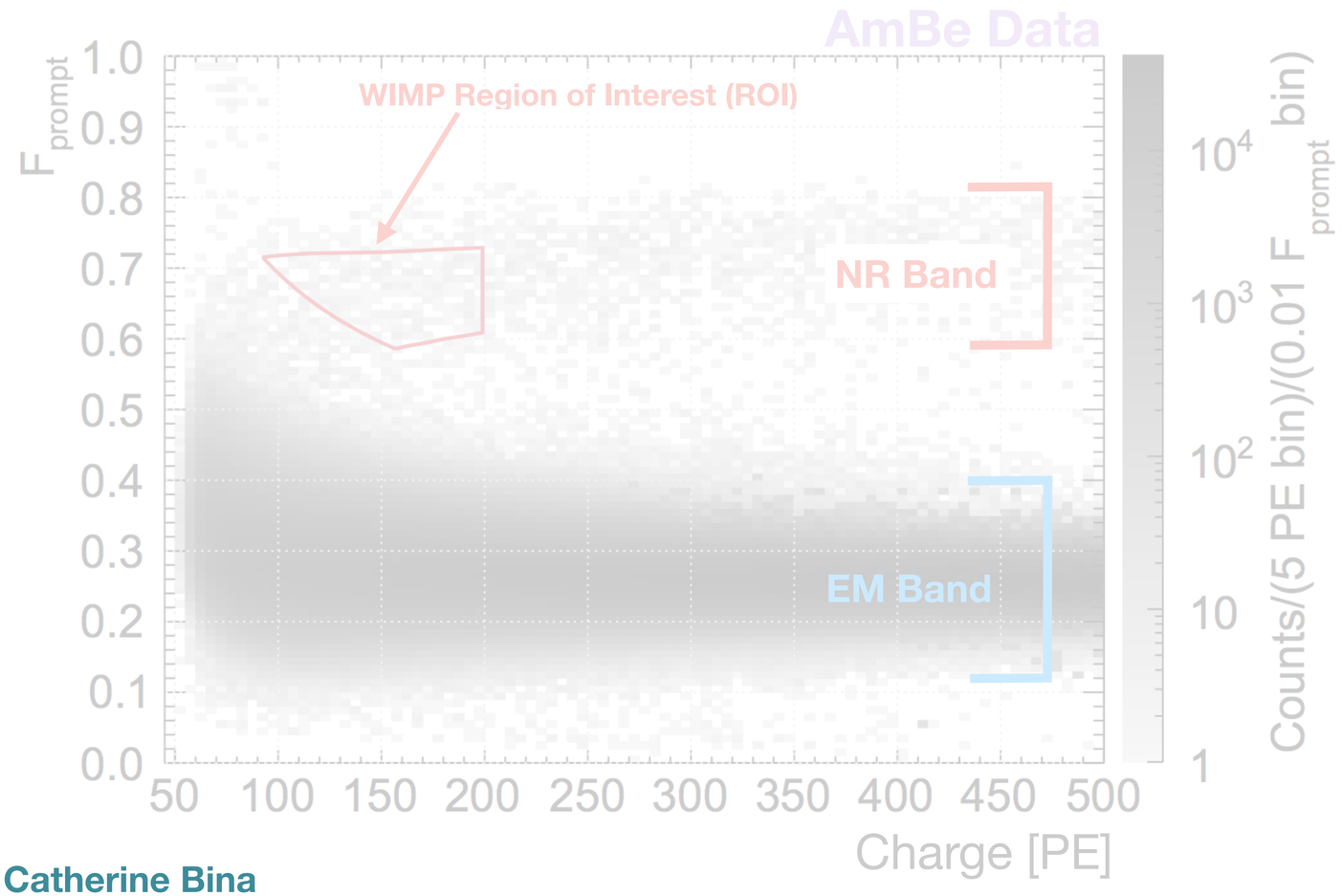
- Excimers can be in either **singlet** or **triplet** states, which have very different lifetimes of **6** and **1400** ns, respectively
  - Decays produce scintillation photons

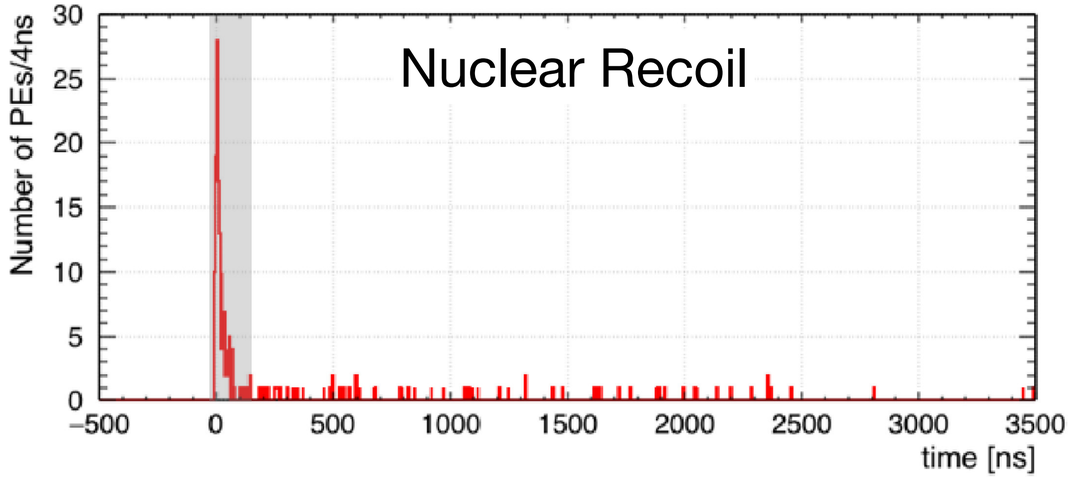
- Used to distinguish between interactions as nuclear recoils (NR) produce mainly singlet state excimers while electromagnetic events (EM) primarily create triplets. This is known as pulse shape discrimination (PSD)

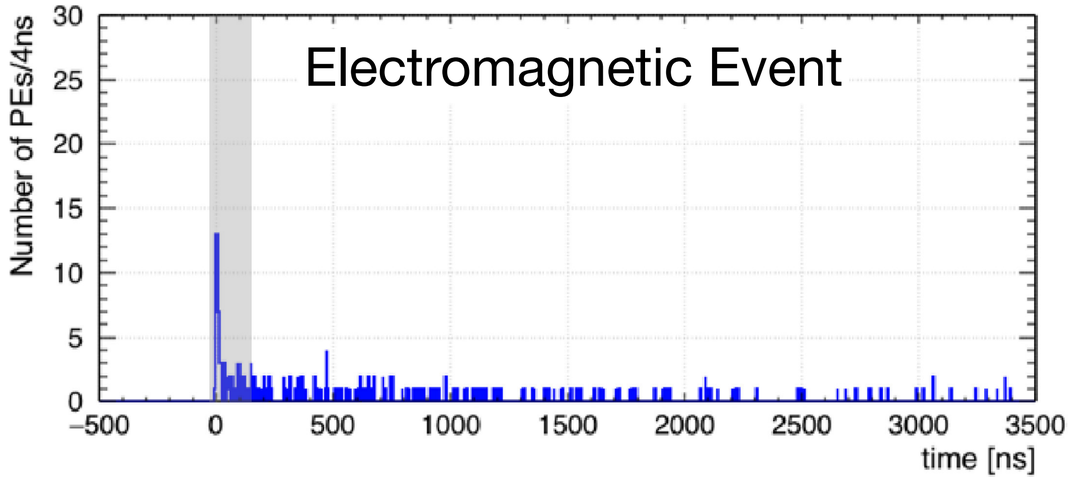


PSD is the primary method of electromagnetic background discrimination for DEAP

$$\text{Fprompt} = \frac{\textit{Early Light}}{\textit{Total Light}}$$







Pulse shape: https://doi.org/10.1140/epjc/s10052-020-7789-x
PSD: https://doi.org/10.1140/epjc/s10052-020-7789-x

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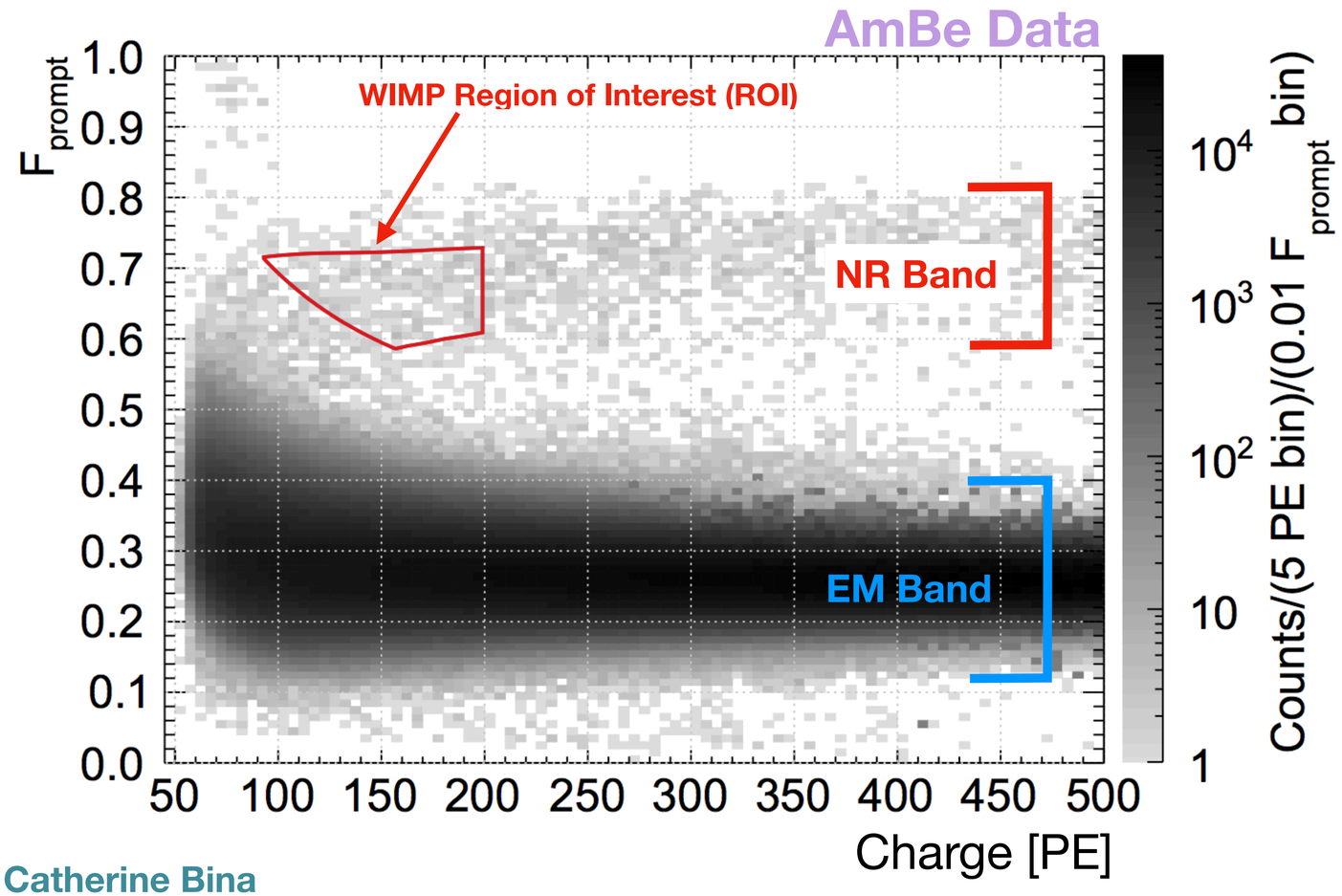
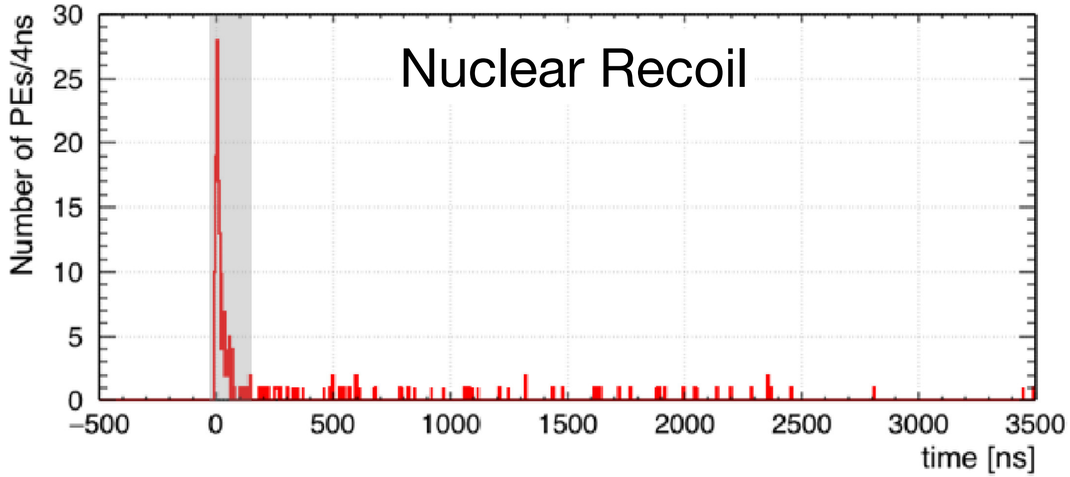
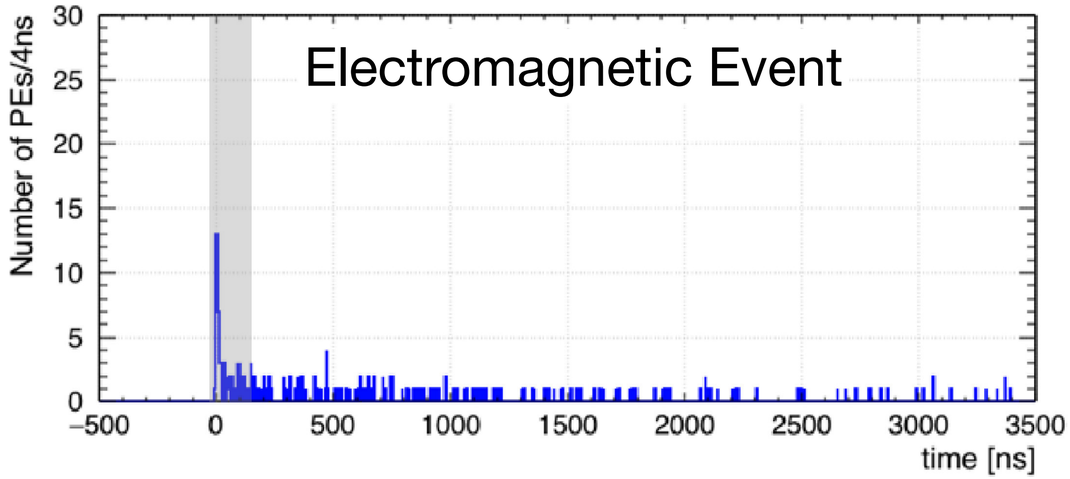
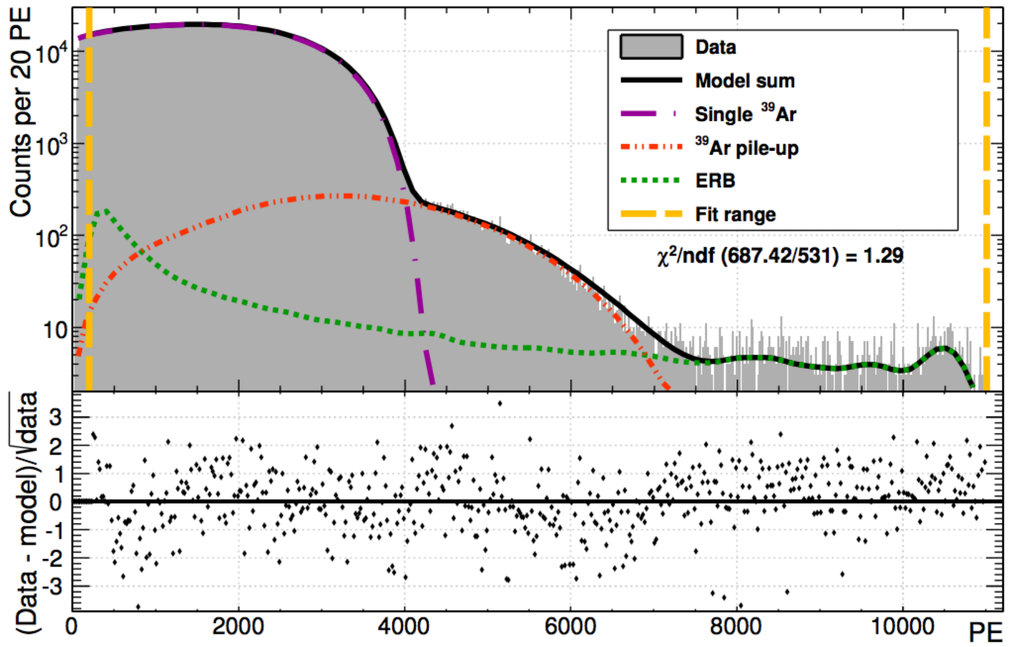


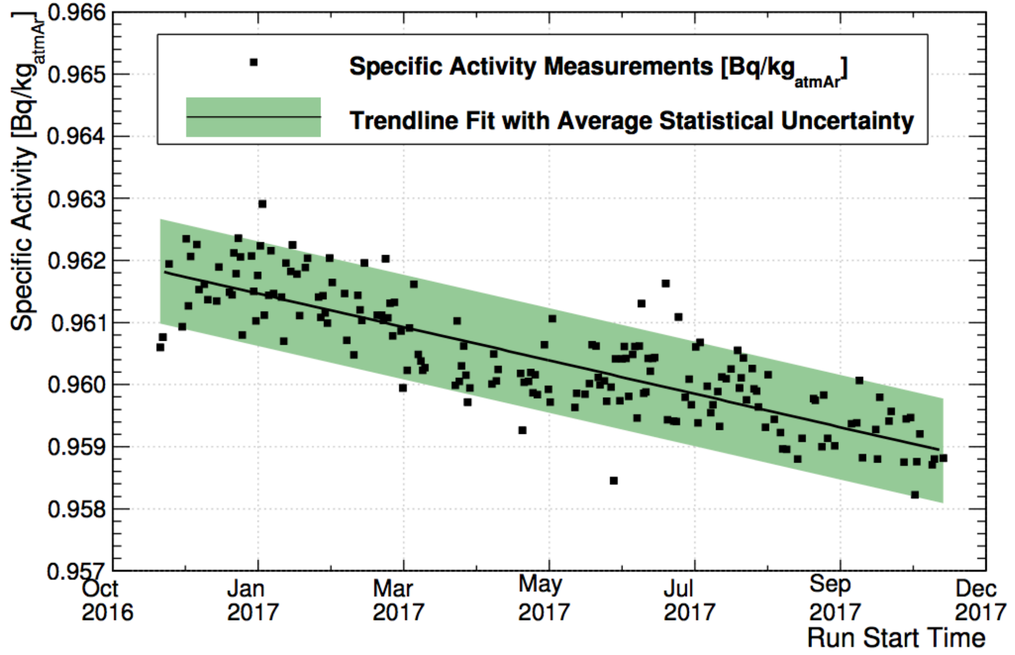




Pulse shape: https://doi.org/10.1140/epjc/s10052-020-7789-x
PSD: https://doi.org/10.1140/epjc/s10052-020-7789-x

Specific activity of ^{39}Ar in atmospheric argon measured to be 0.964 ± 0.024 Bq/kg$_{atmAr}$



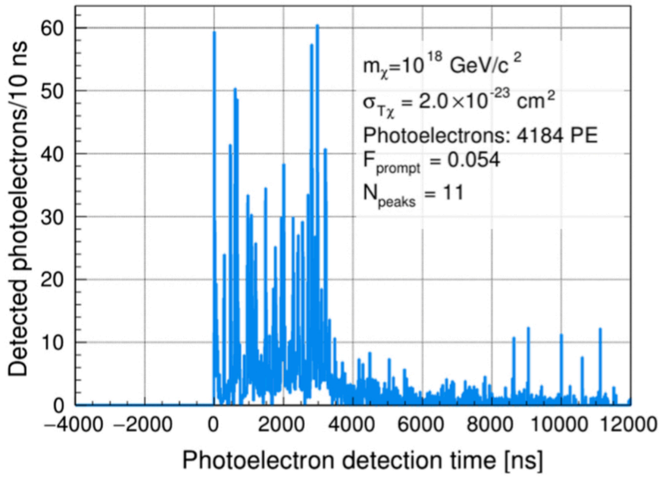


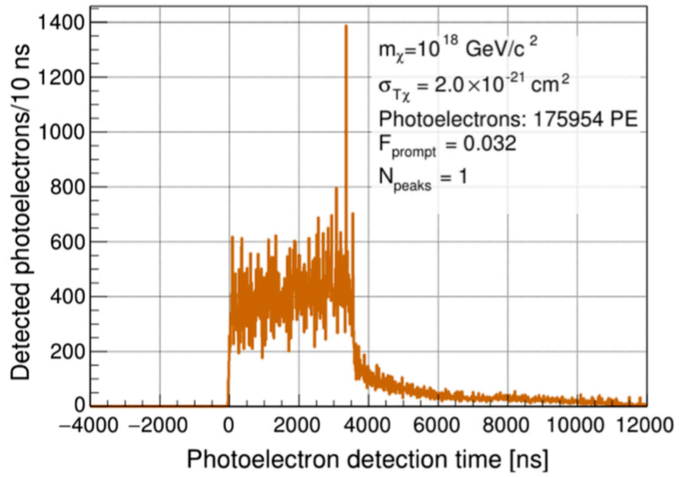
This analysis also resulted in refining the liquid argon mass from 3,279 ± 96 kg to 3,269 ± 24 kg, reducing the uncertainty by a factor of 4

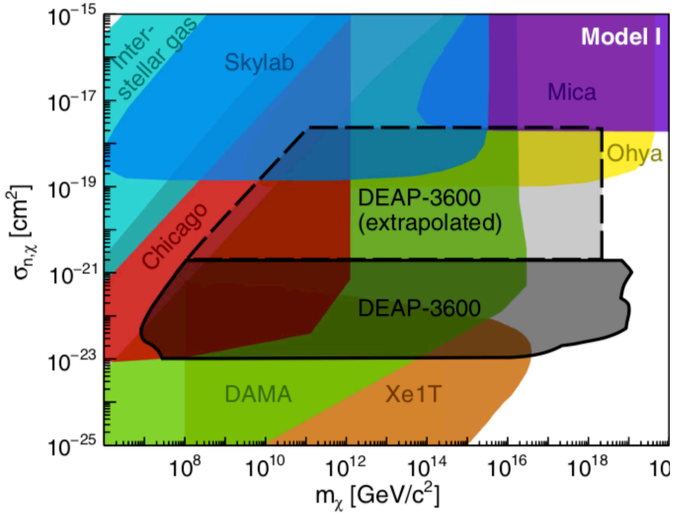
https://doi.org/10.1140/epjc/s10052-023-11678-6

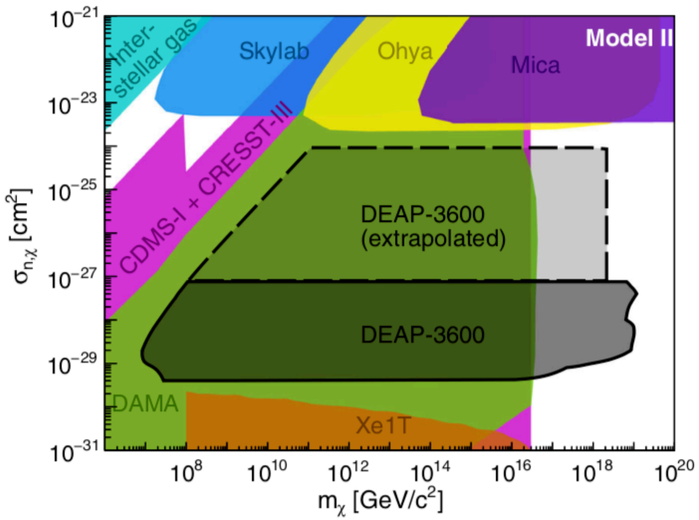
Most recent DM search results put constraints on Planck scale dark matter

- Multiply interacting massive particles
  - Due to heavy mass and low number density
- Detector signature expected to be either **multiple separable peaks in quick succession** or **a single high energy smeared peak**
- No events found in any of the regions of interest



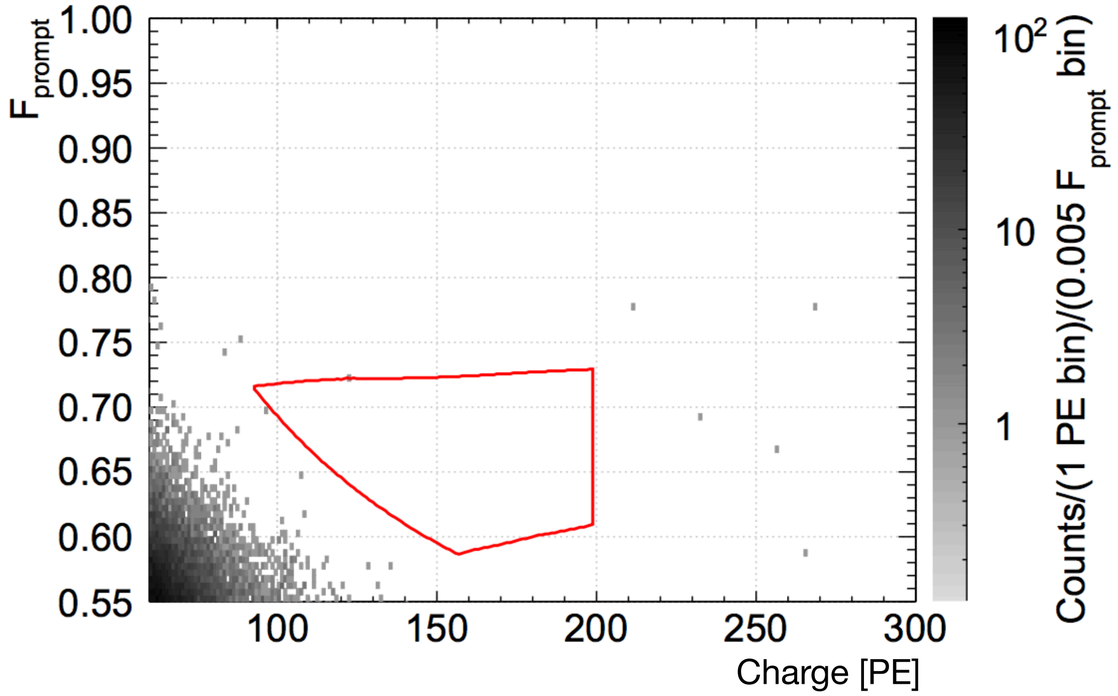


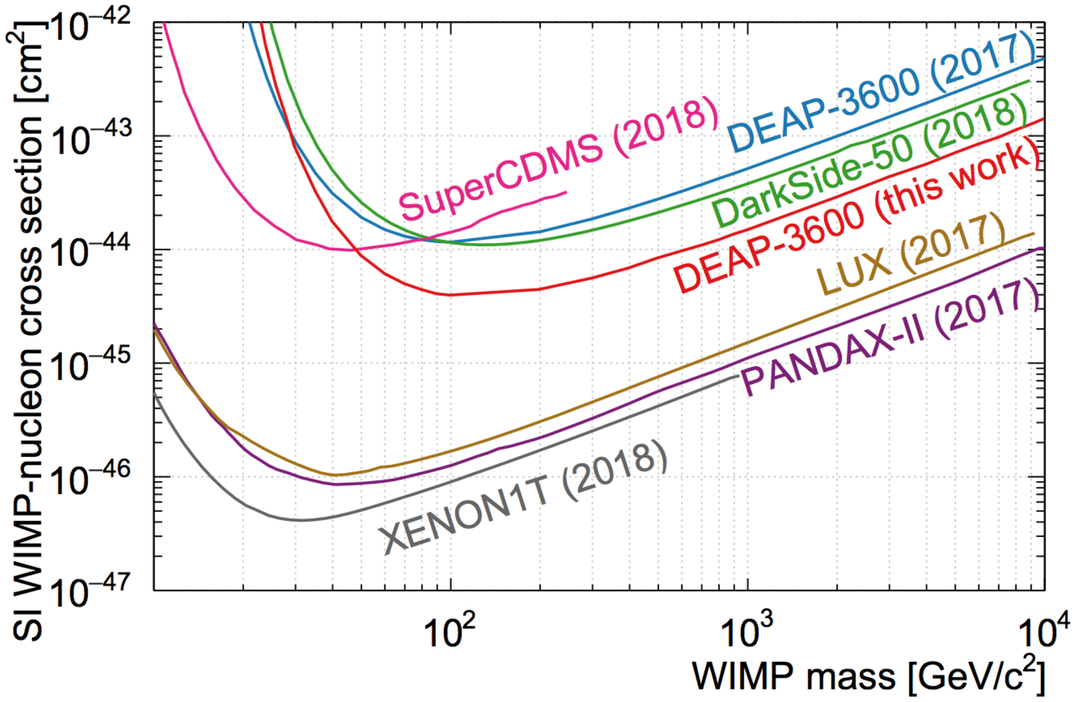




https://doi.org/10.1103/PhysRevLett.128.011801

Most recent WIMP DM results find zero events in the ROI in a 231 live-day exposure

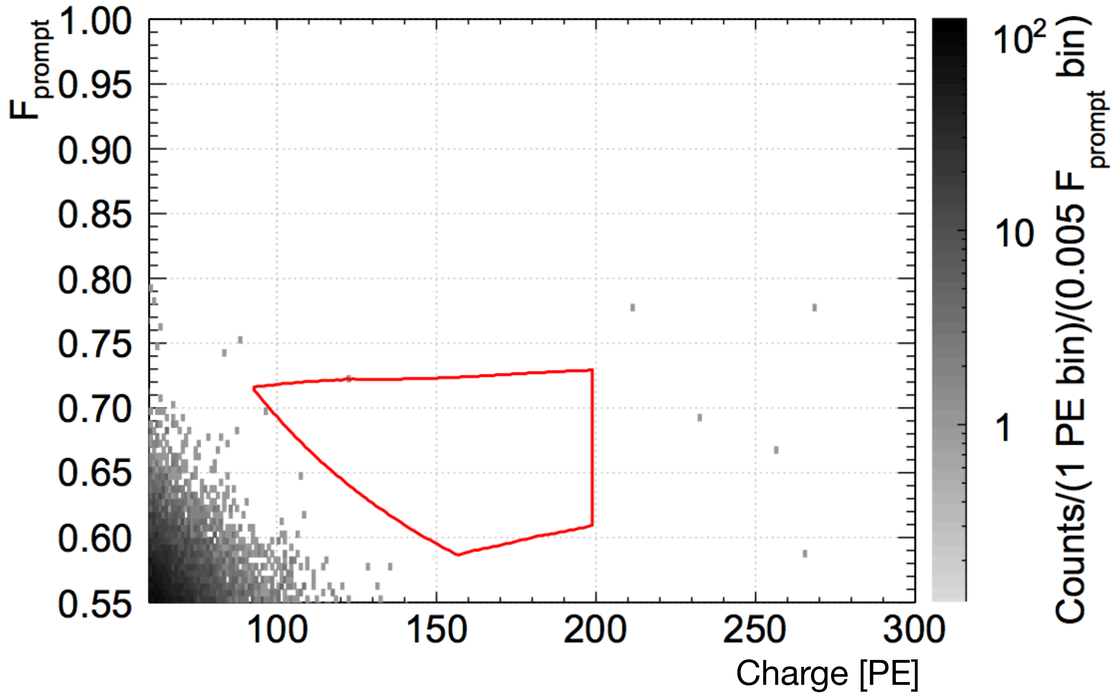


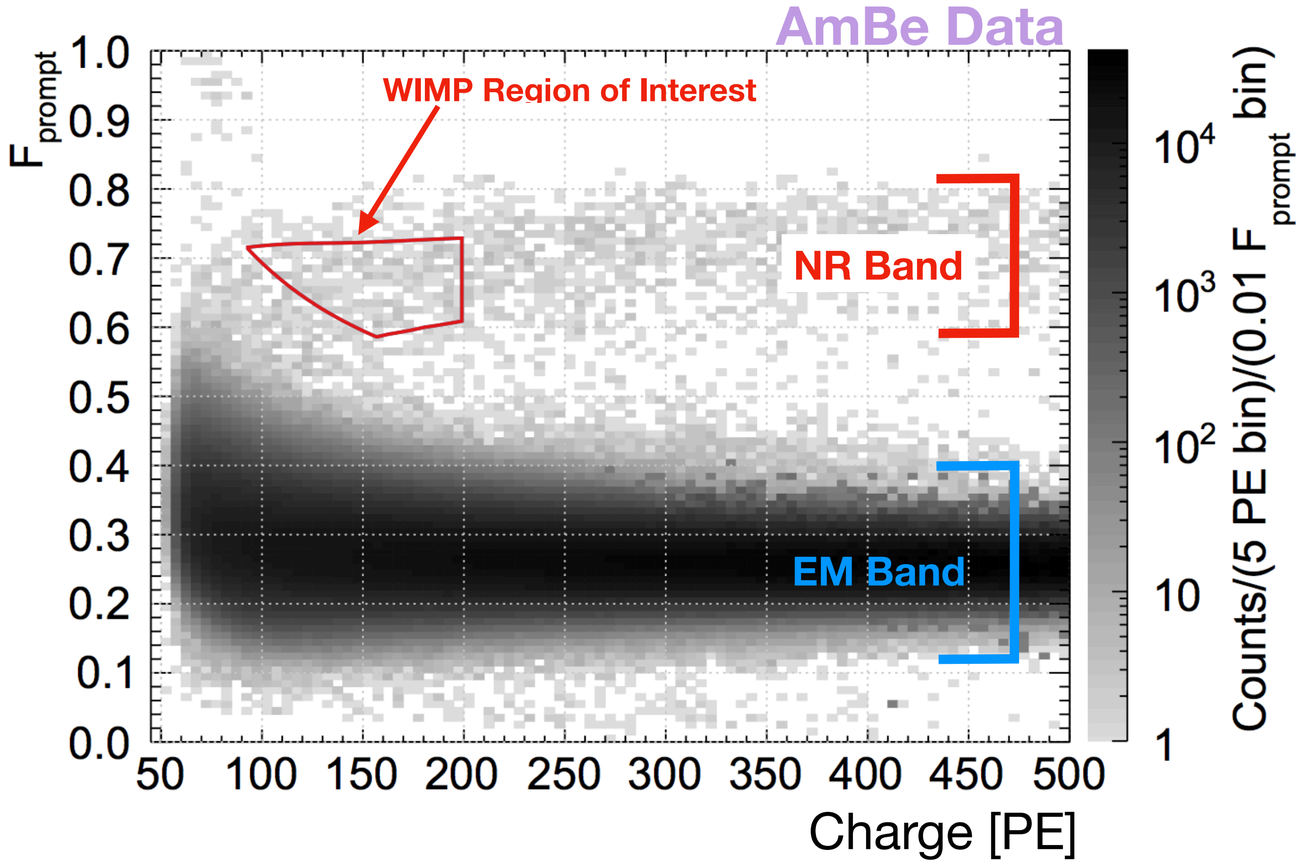


Further analyses using a profile likelihood ratio with our open 388 live-day dataset and 813 live-day open and blind dataset are in the works

https://doi.org/10.1103/PhysRevD.100.022004

Most recent WIMP DM results find zero events in the ROI in a 231 live-day exposure

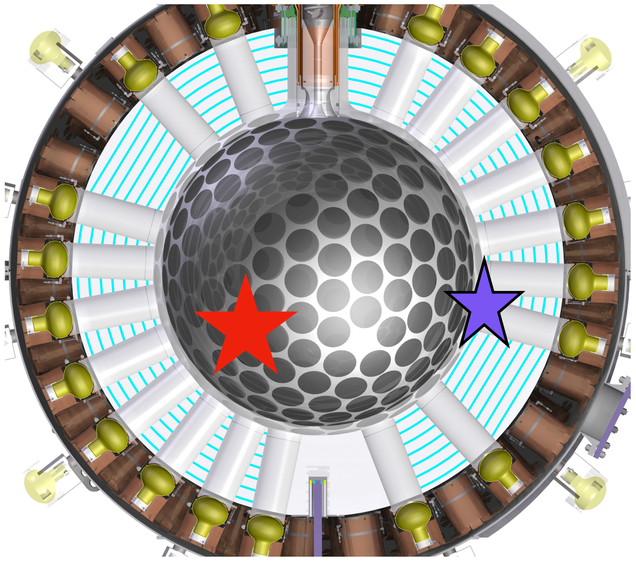




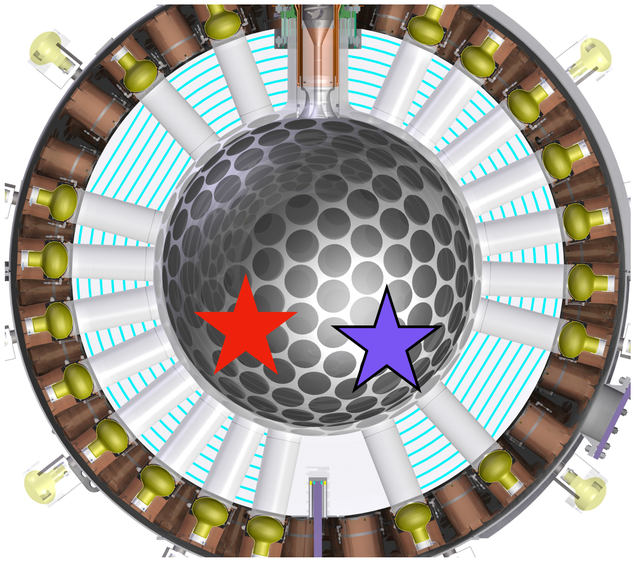
I wanted to investigate what happens when different types of events happened at the same time or when two events occur at the same time and how that would effect where it ends up in the psd space

What constitutes pile up?

- Pile up is any light added to a physics event
- Including, but not limited to:
  - Dark noise
  - Interactions with the detector materials
  - Other liquid argon scintillations
- I wanted a data-driven method to study pile up and so turned to the data collected by our periodic trigger

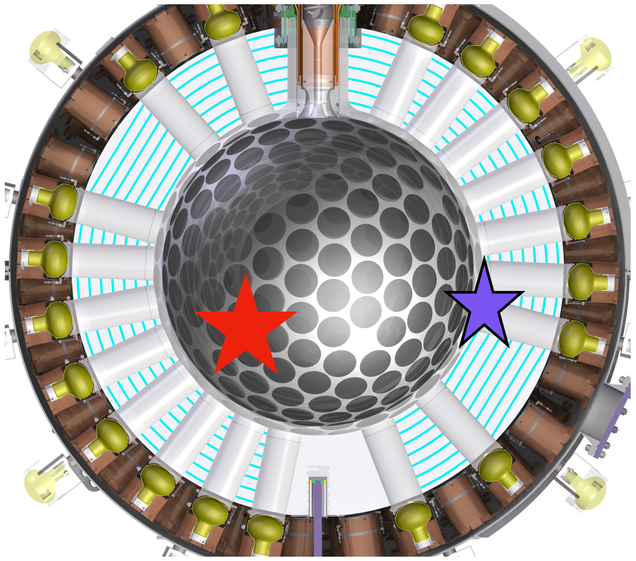


Physics event **Pile up**



Using periodic trigger events as pile up

- The periodic trigger is a thresholdless trigger that reads out data 40 times a second
- This gives us snapshots of what is going on in the detector at any given moment, without any biases from trigger requirements
  - So it shows both interactions with the LAr as well as with the detector materials and noise
- This works to study pile up because it represents the part of an event that “piles up” with a physics event



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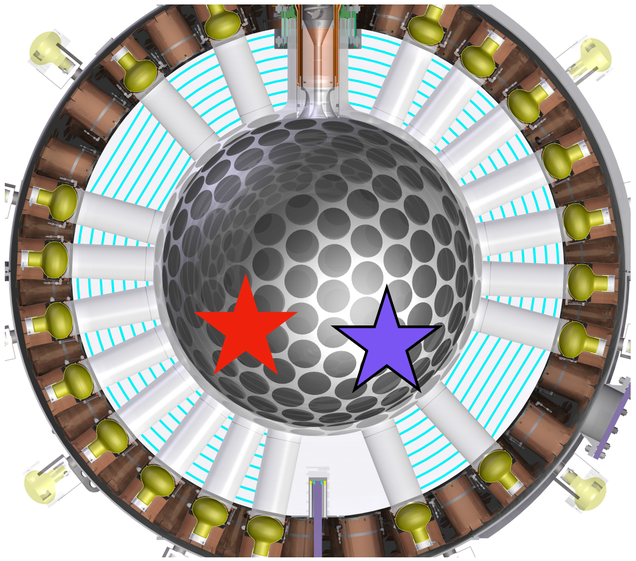
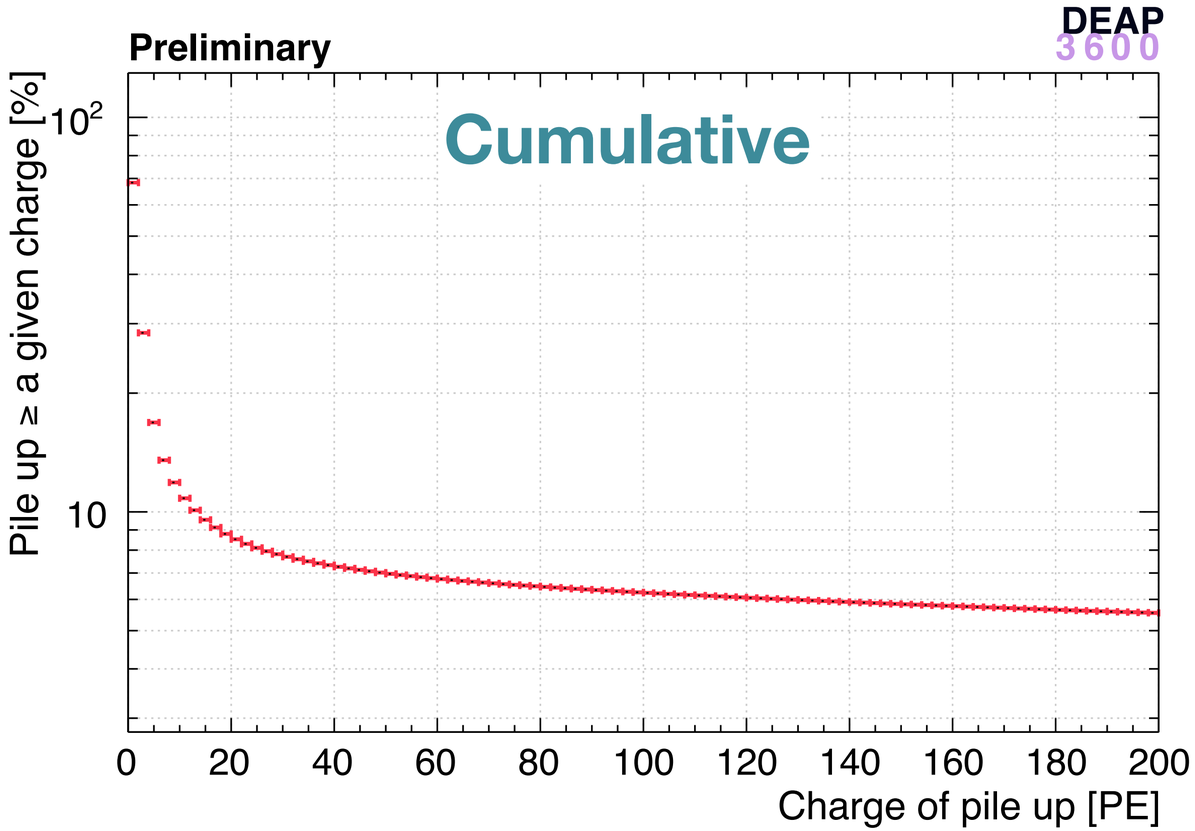
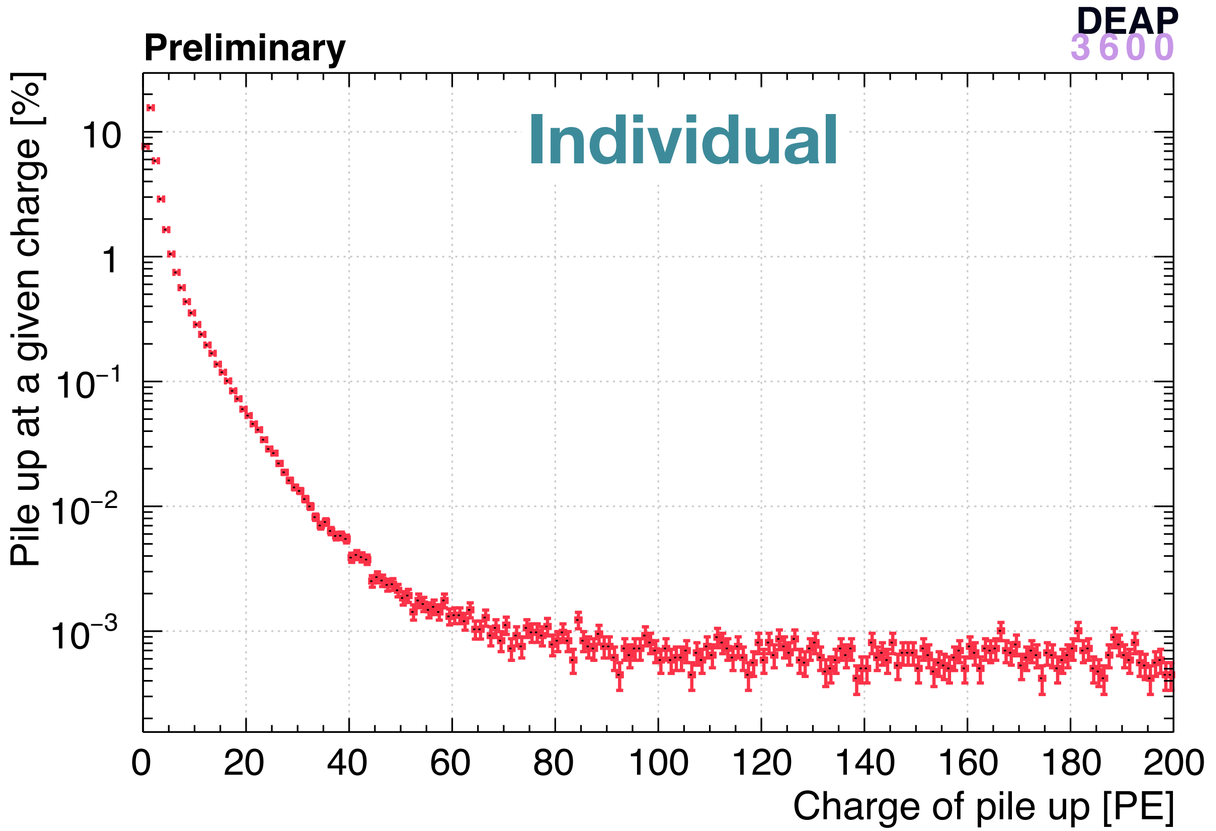


How likely is an event to have pile up?

Periodic trigger events show how often a given amount of charge is seen in the detector, which corresponds to the probability that a given amount of pile up occurs in a physics event

Low charge pile up is most likely and several features can be identified.





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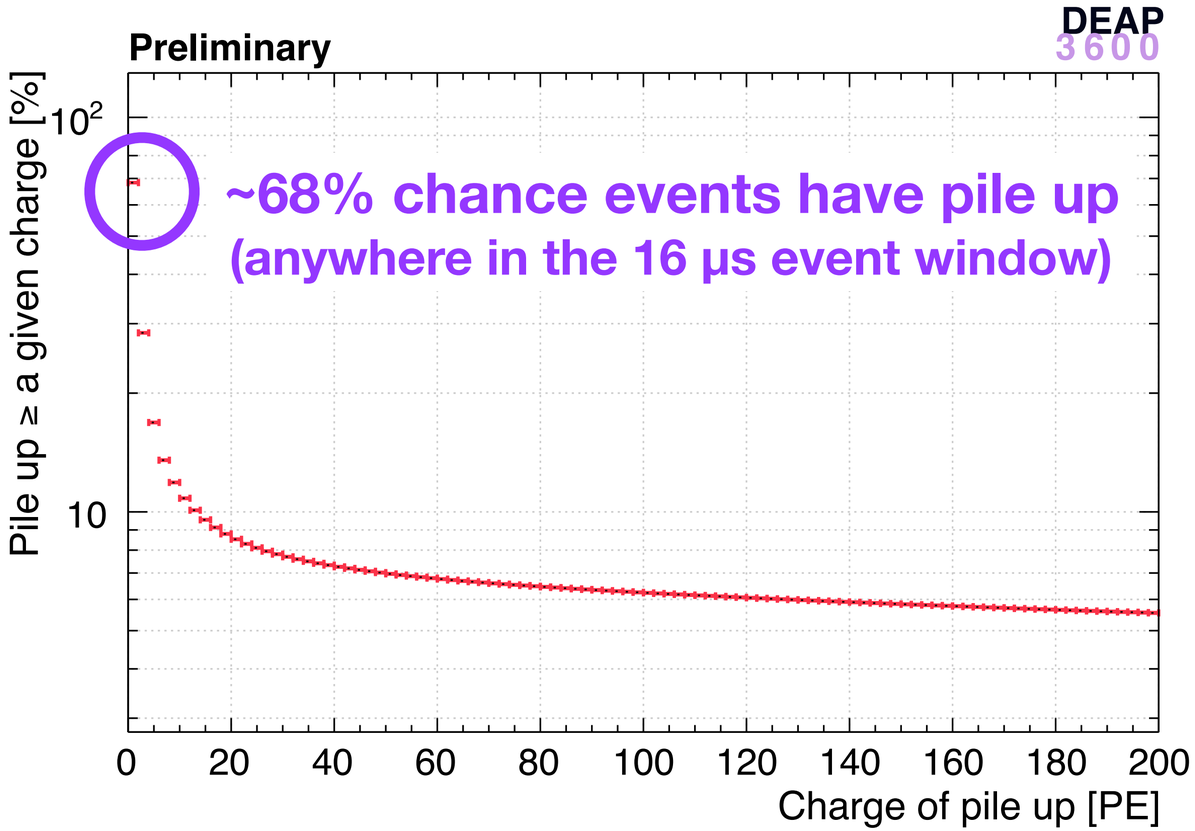

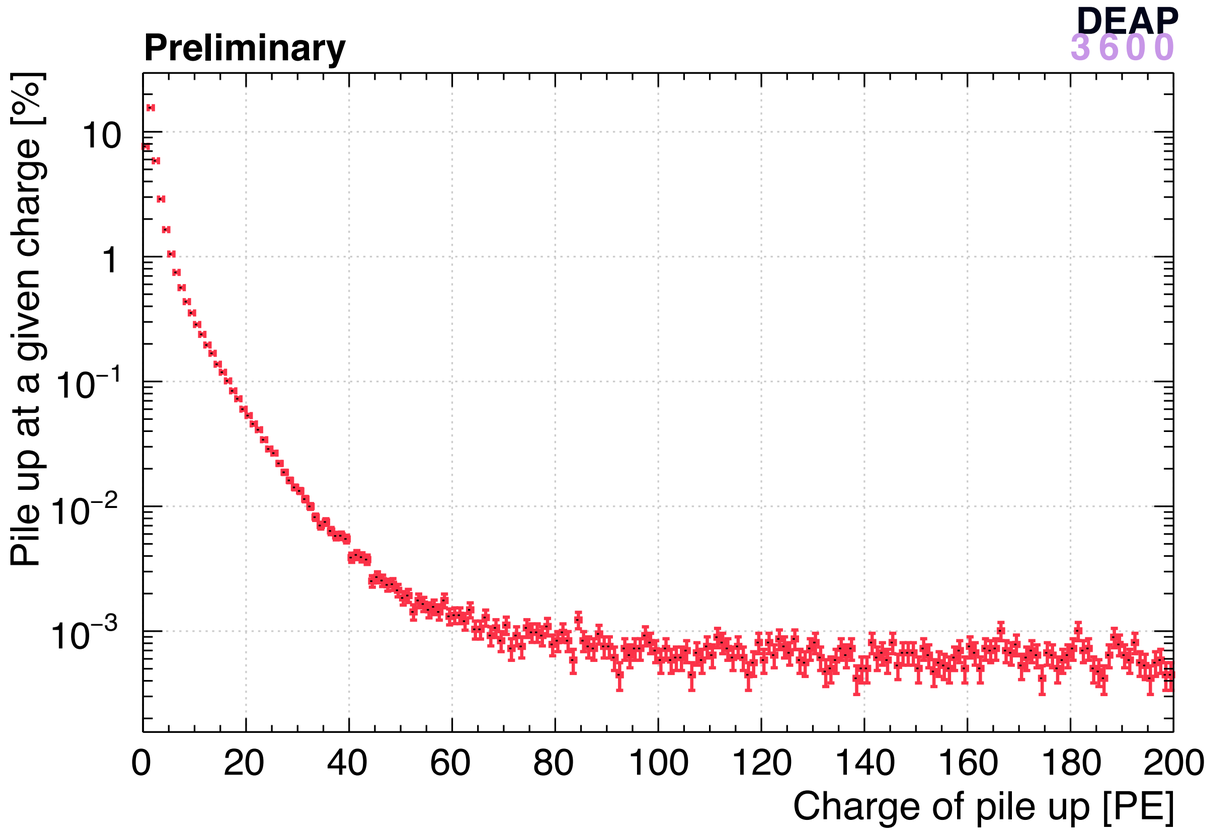

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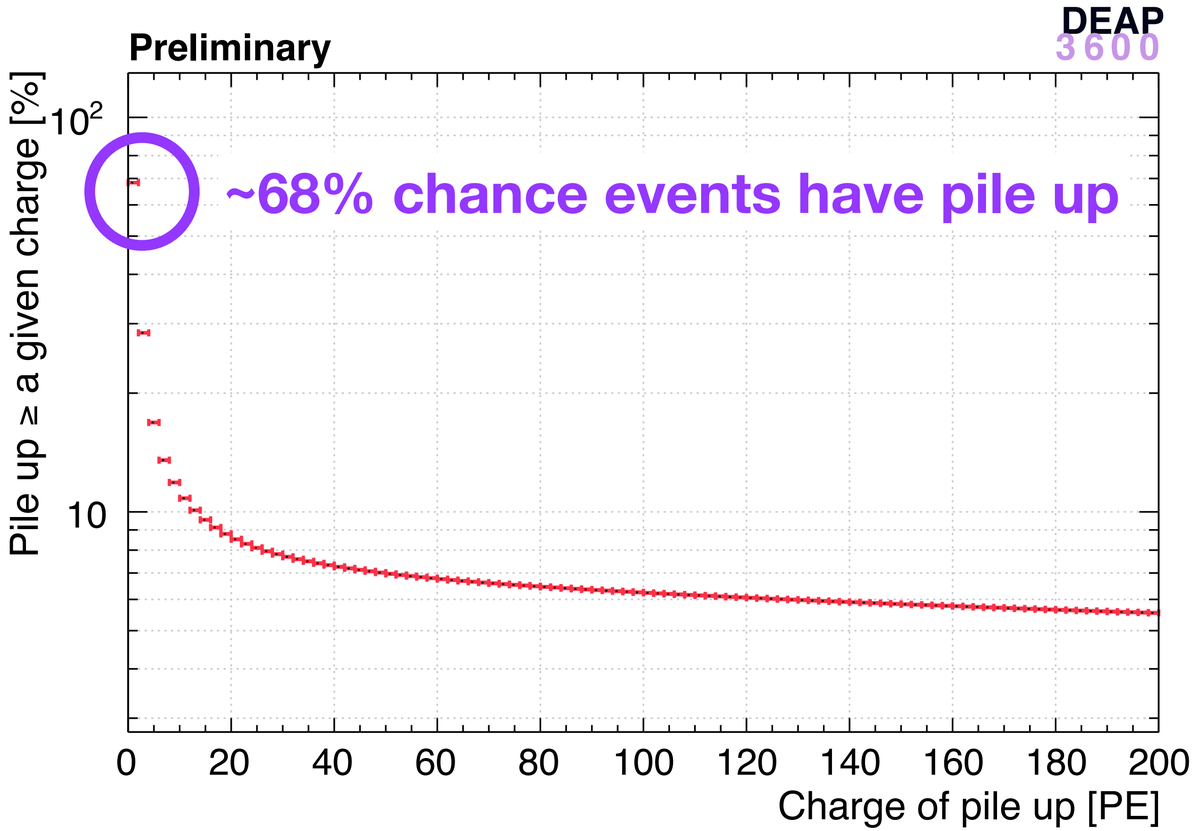
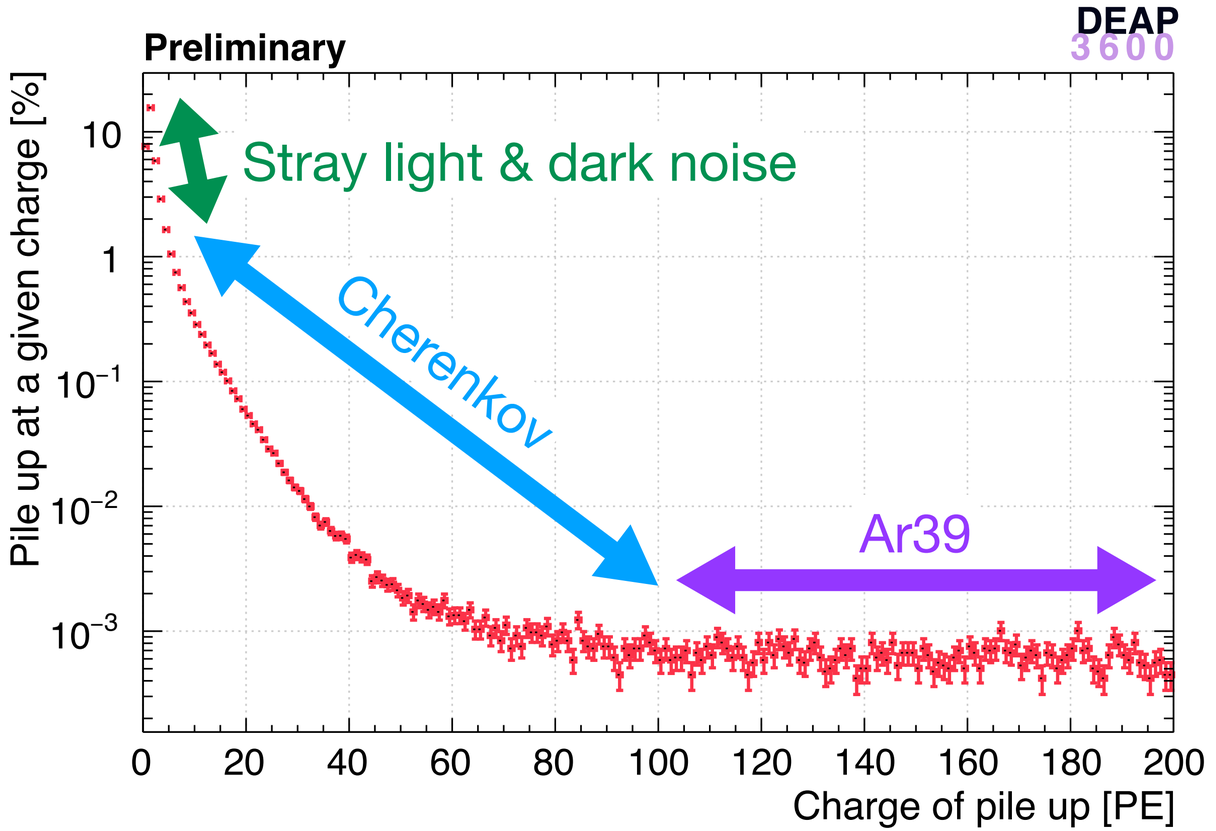
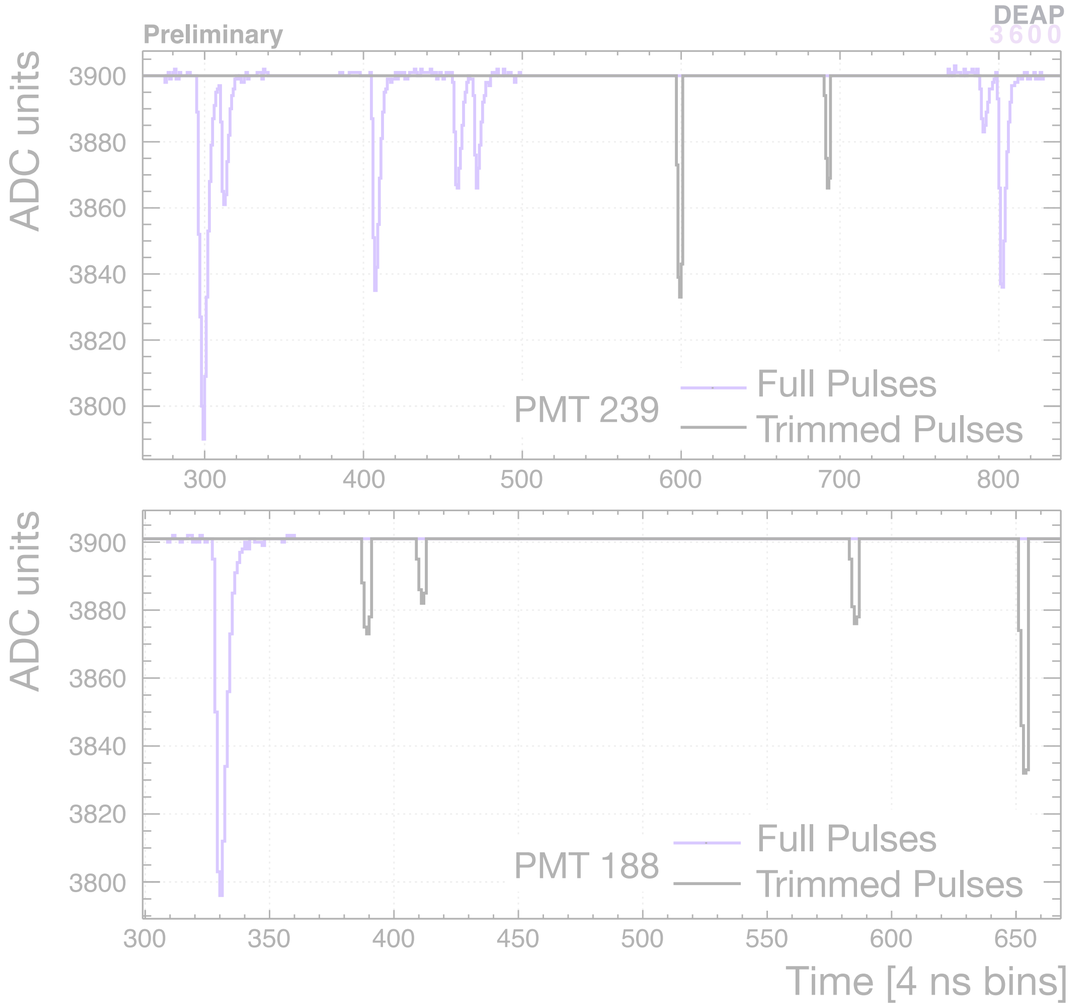




Reconstructing raw data

- The periodic trigger events are added to the physics events to create pile up events at the raw data level
  - This is done so that each pile up event will be processed as a single event by the software
- Raw data waveforms for individual PMTs consist of full pulses and pulses trimmed by the DAQ
- Adding a trimmed pulse to a full pulse would not correctly recreate the waveform of two pulses happening at the same time



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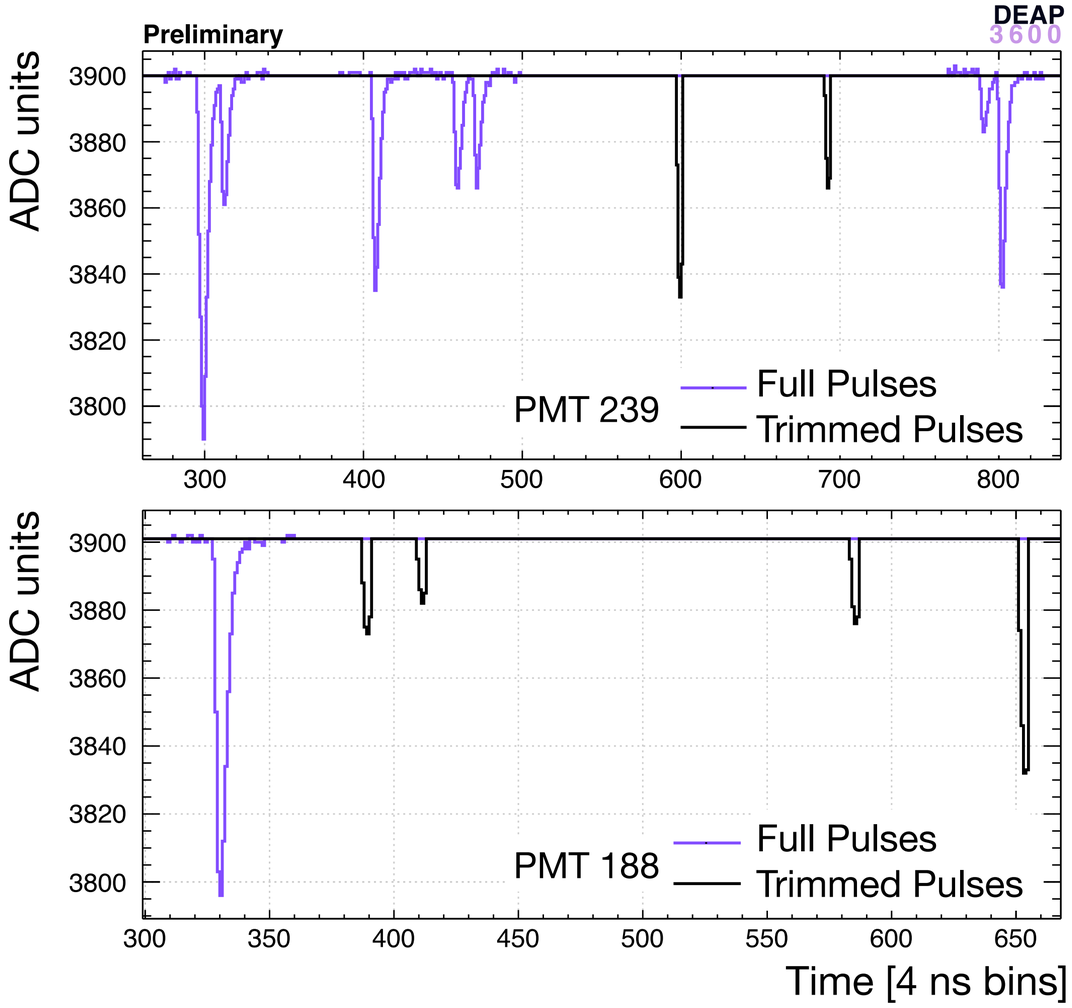

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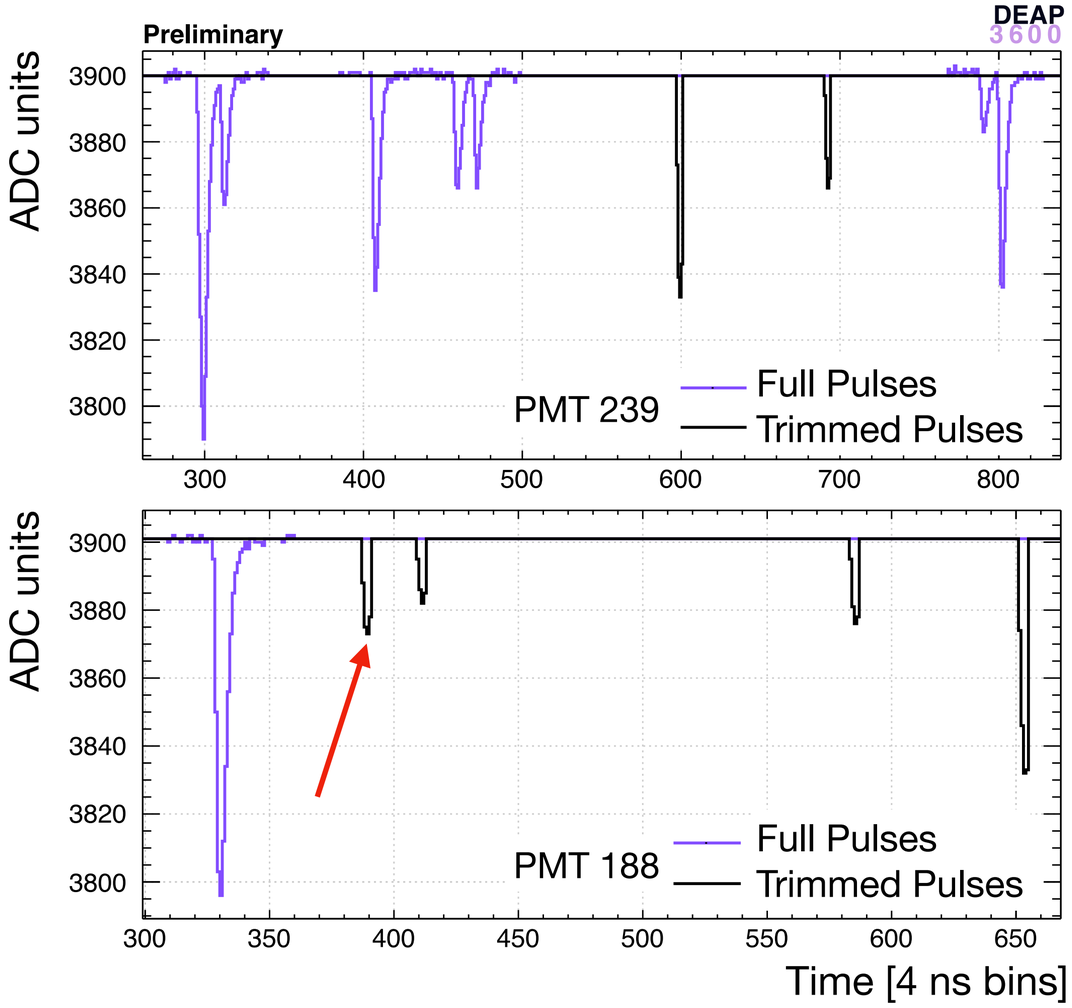

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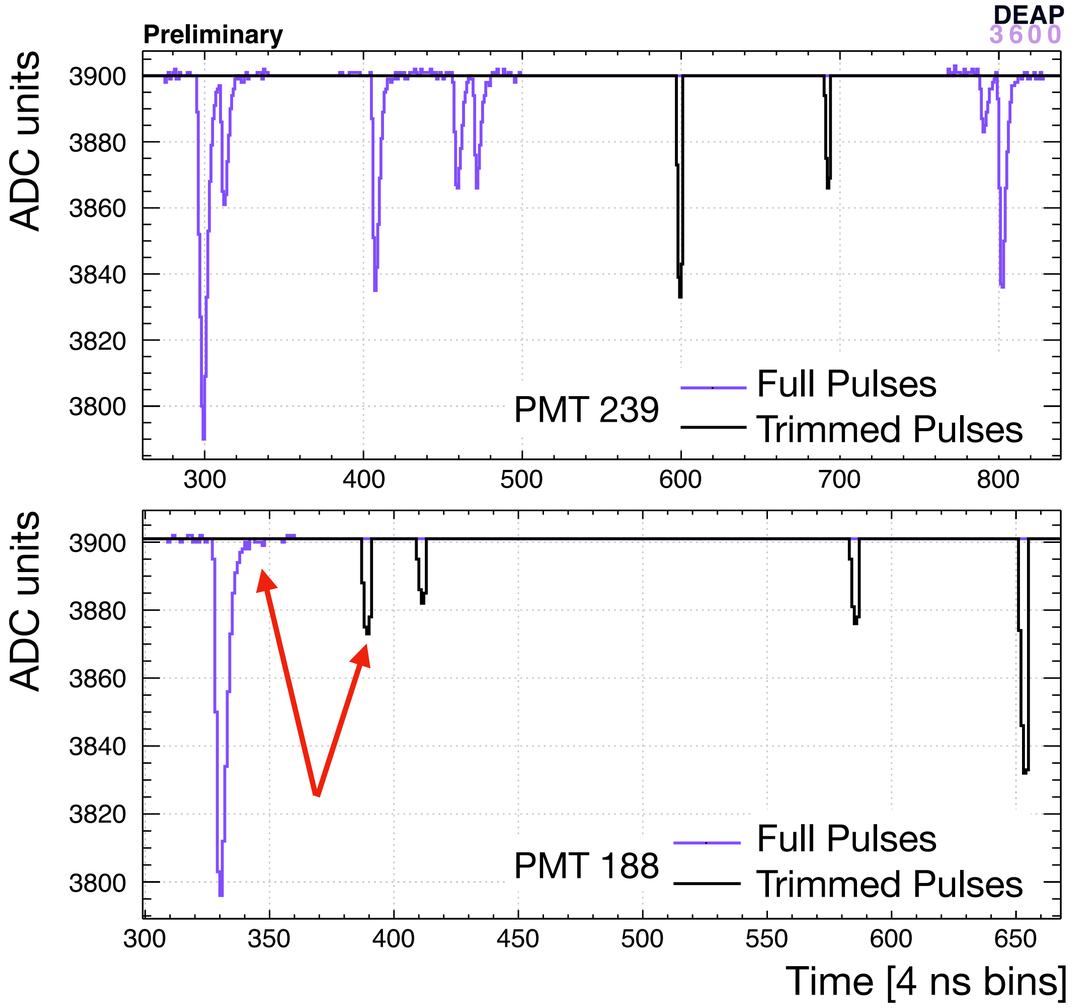

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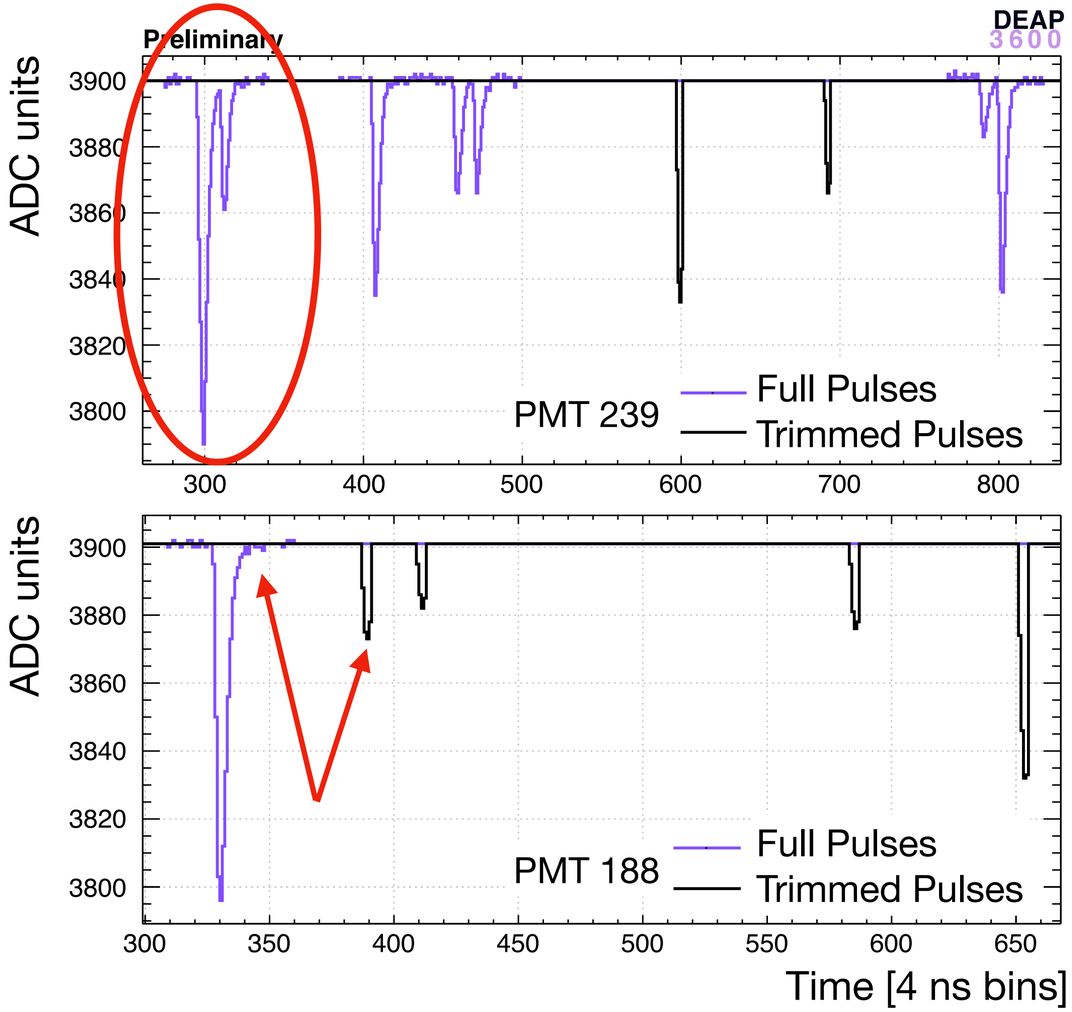
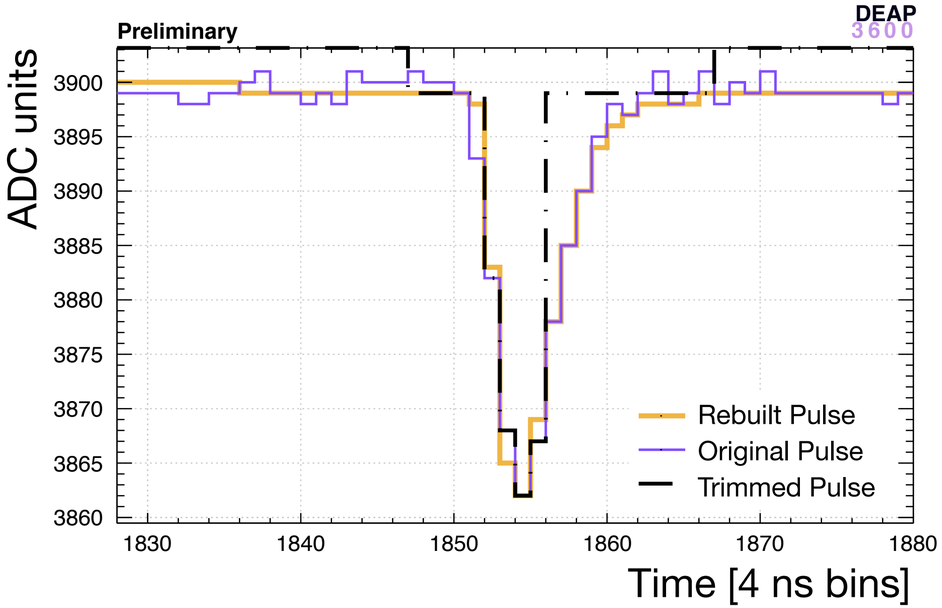
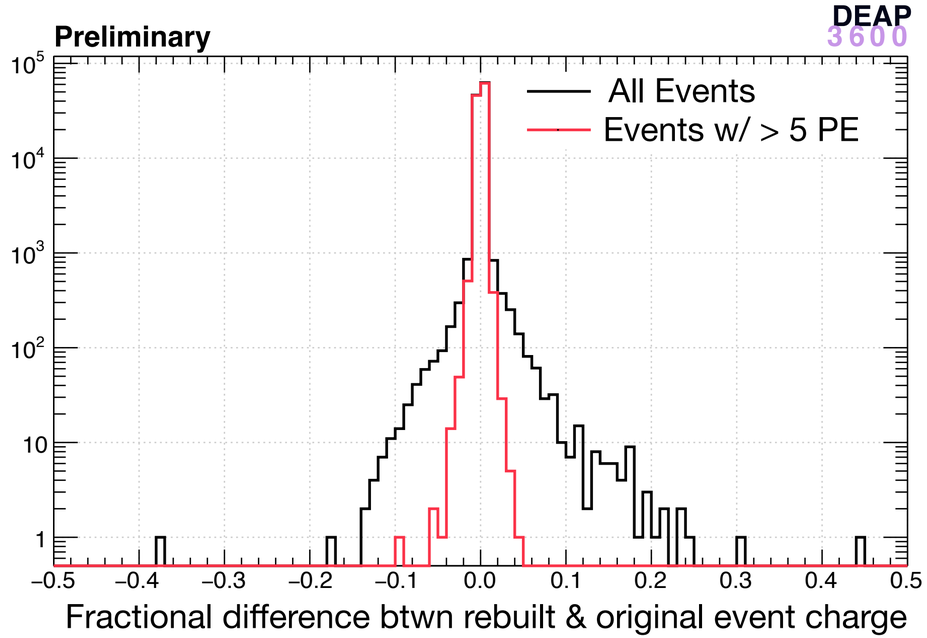


Rebuilding the Trimmed pulses

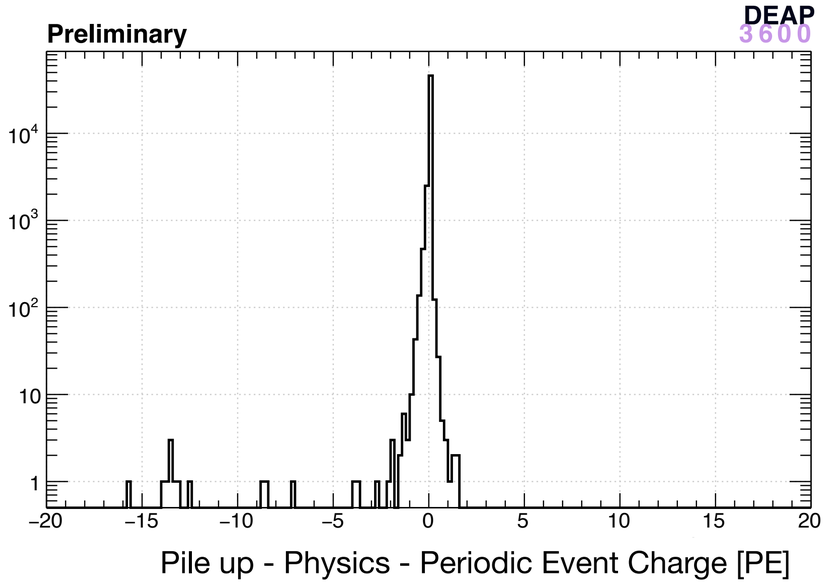
- I fit a generalized pulse shape to the trimmed pulse to rebuild the full pulse
  - Generalized pulse is derived from detailed electronics study
  - It is also fit to the pulses to help determine the calibrated charge and time. I reversed this process
- I confirmed that events processed with the rebuilt pulses reasonably matched those processed with the trimmed pulses

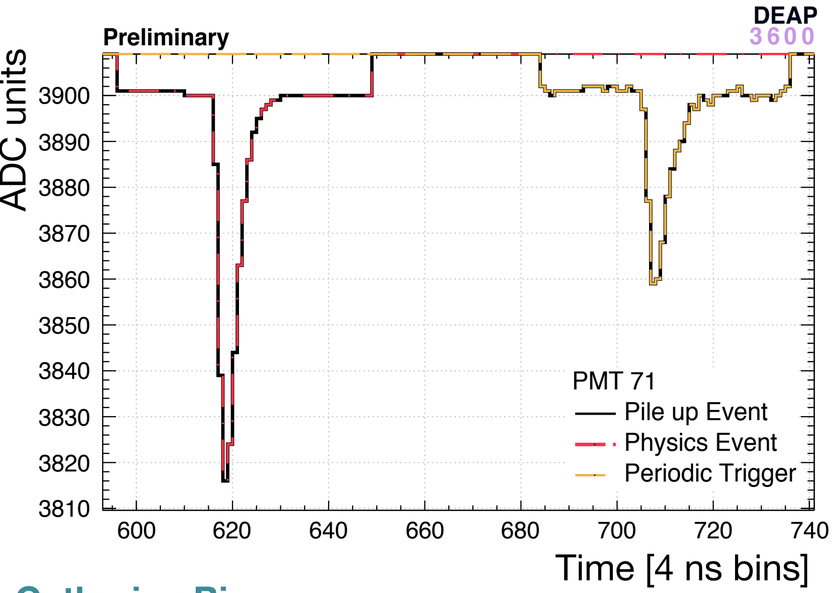


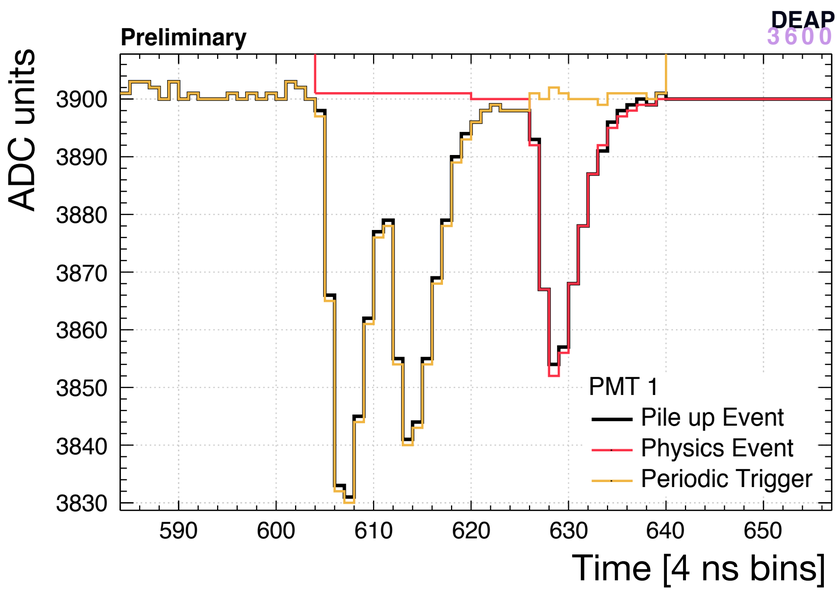


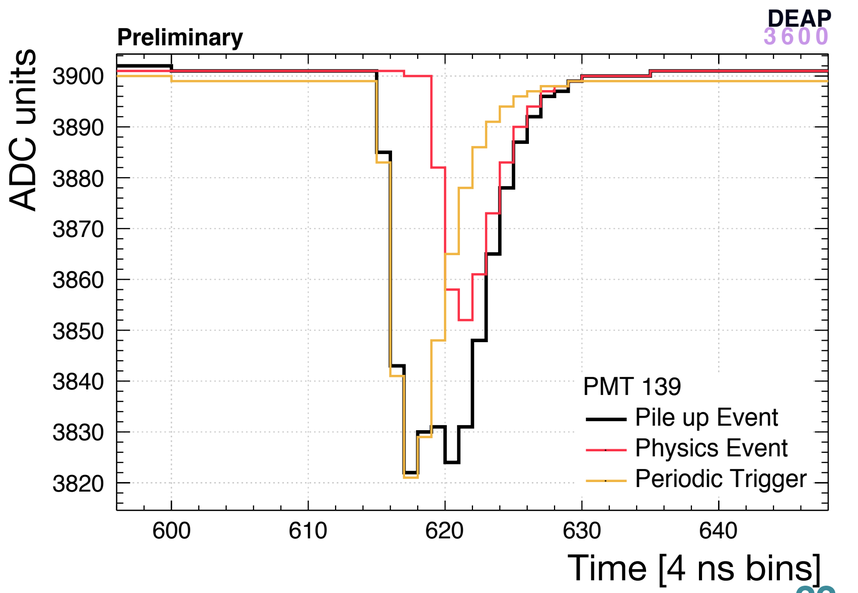
Algorithm for creating artificial pile up events

- The raw waveforms for the periodic trigger event and the physics event are combined for each PMT
- Different scenarios of periodic triggers piled up on a physics event with varying amounts of overlap were tested



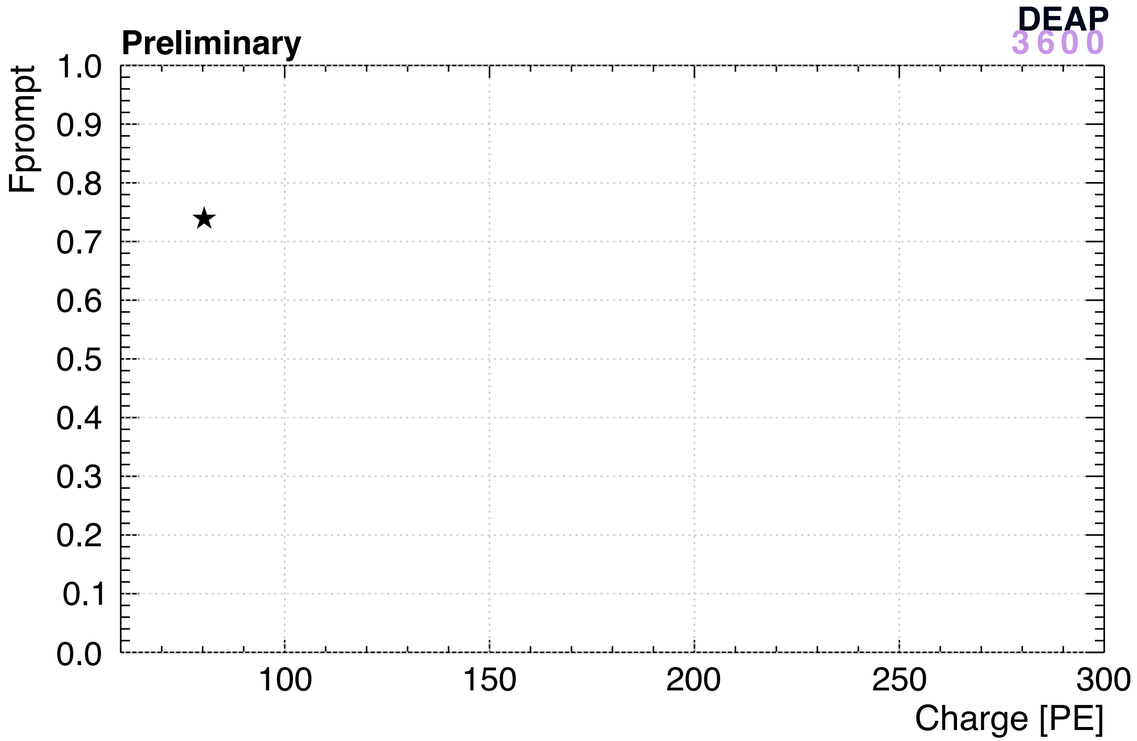




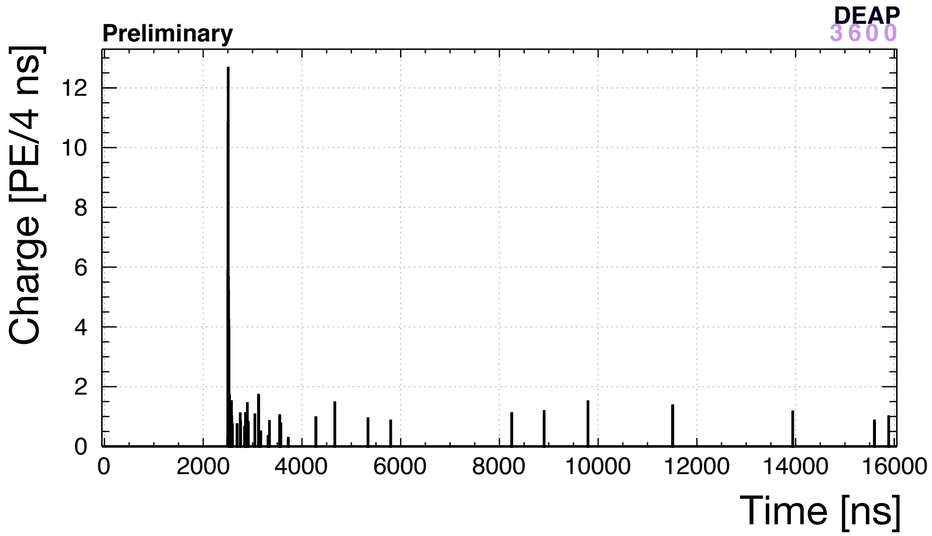


Analyzing artificial pile up events

1. Take an original physics event

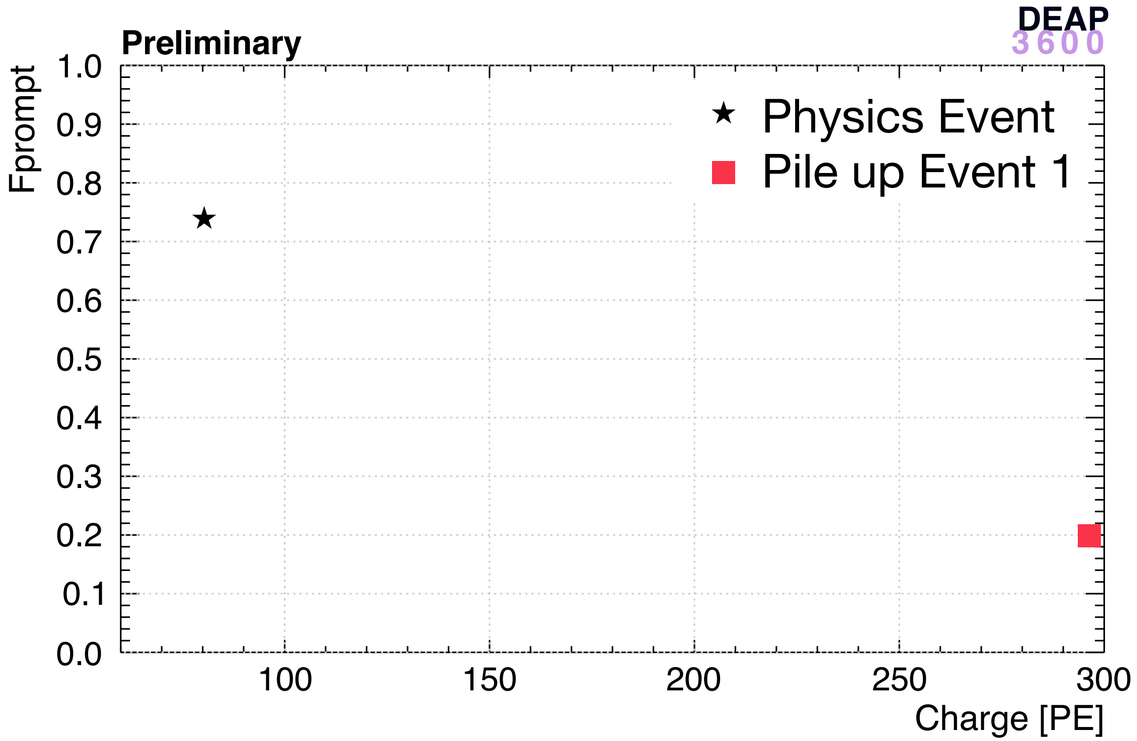


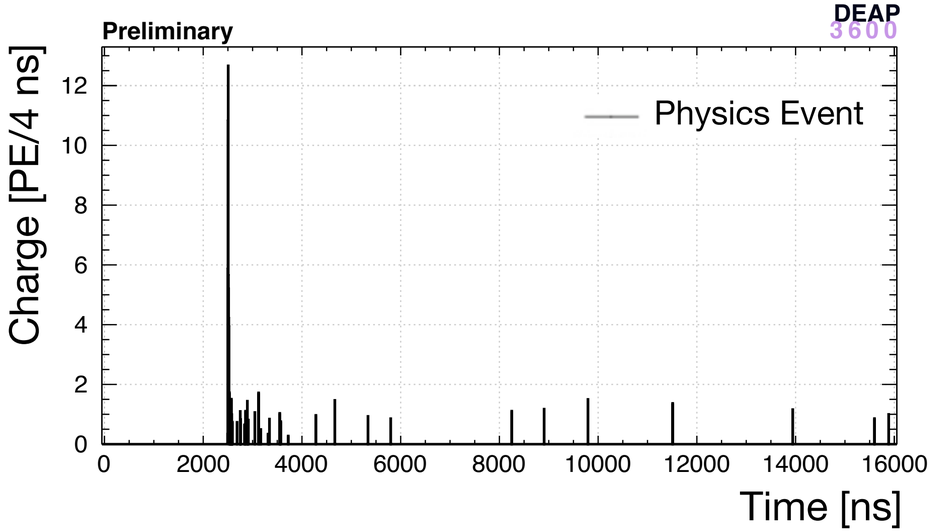
Calibrated Waveform

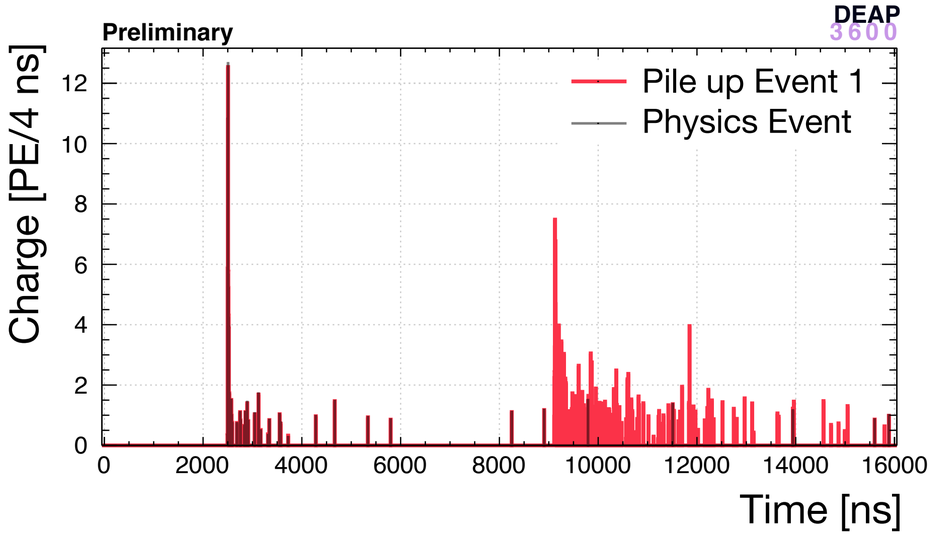


Analyzing artificial pile up events

1. Take an original physics event
2. Pile up a periodic trigger event on the physics event to create a pile up event

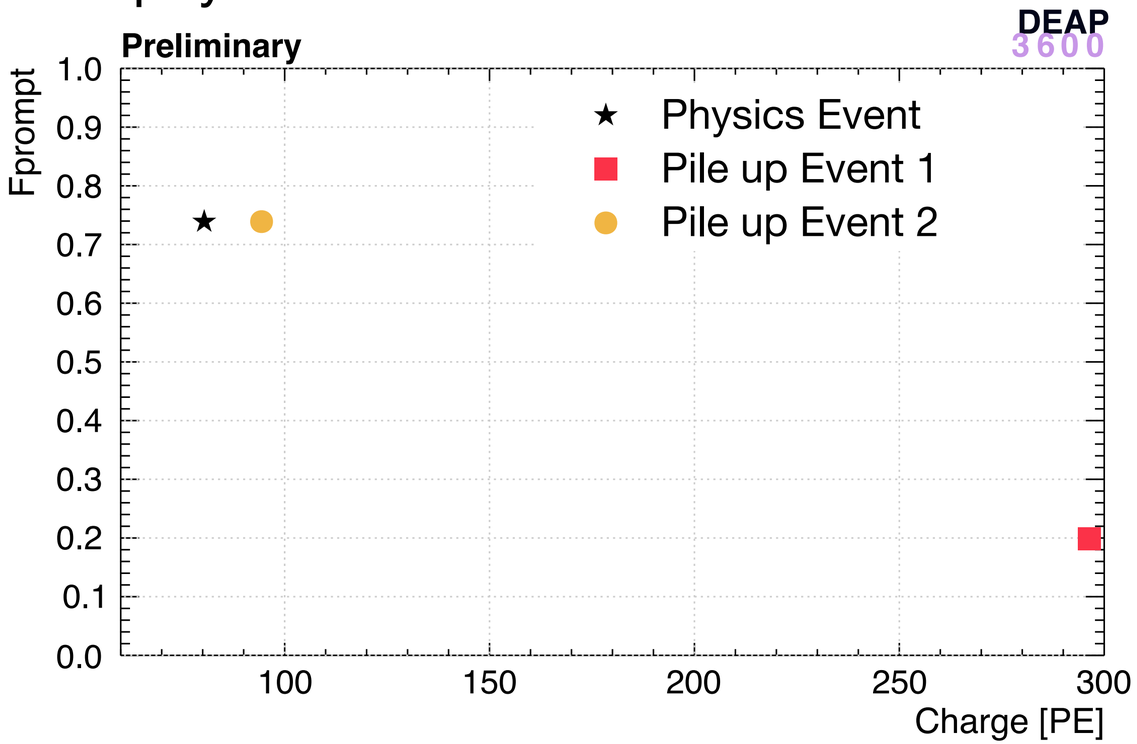


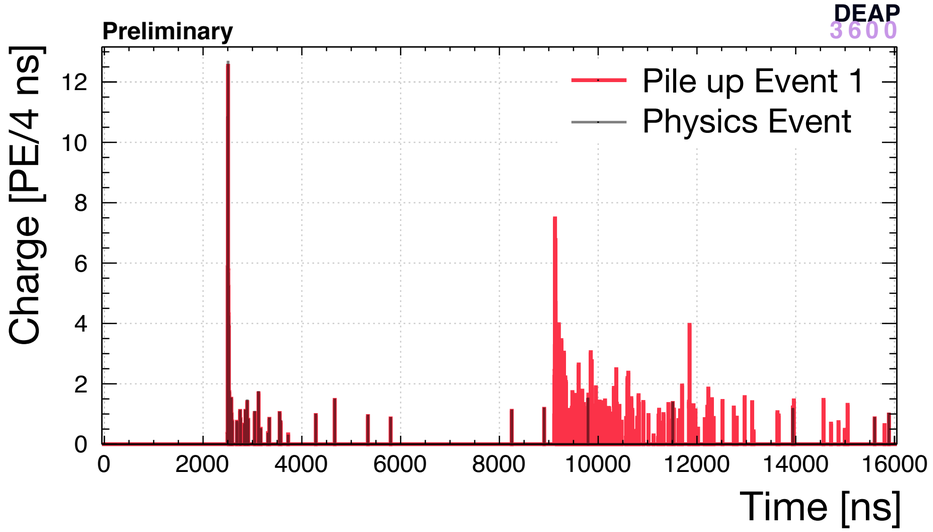


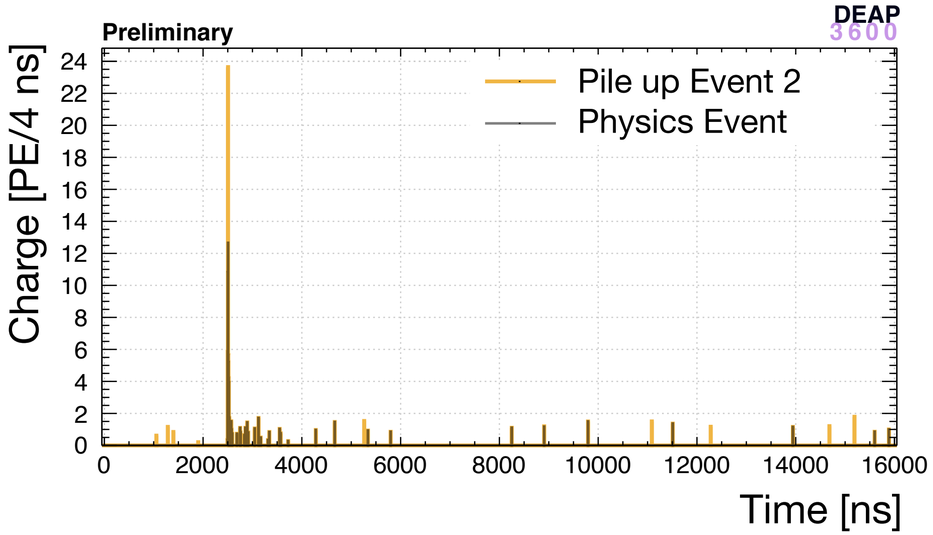


Analyzing artificial pile up events

1. Take an original physics event
2. Pile up a periodic trigger event on the physics event
3. Pile up a different periodic trigger event on the same physics event

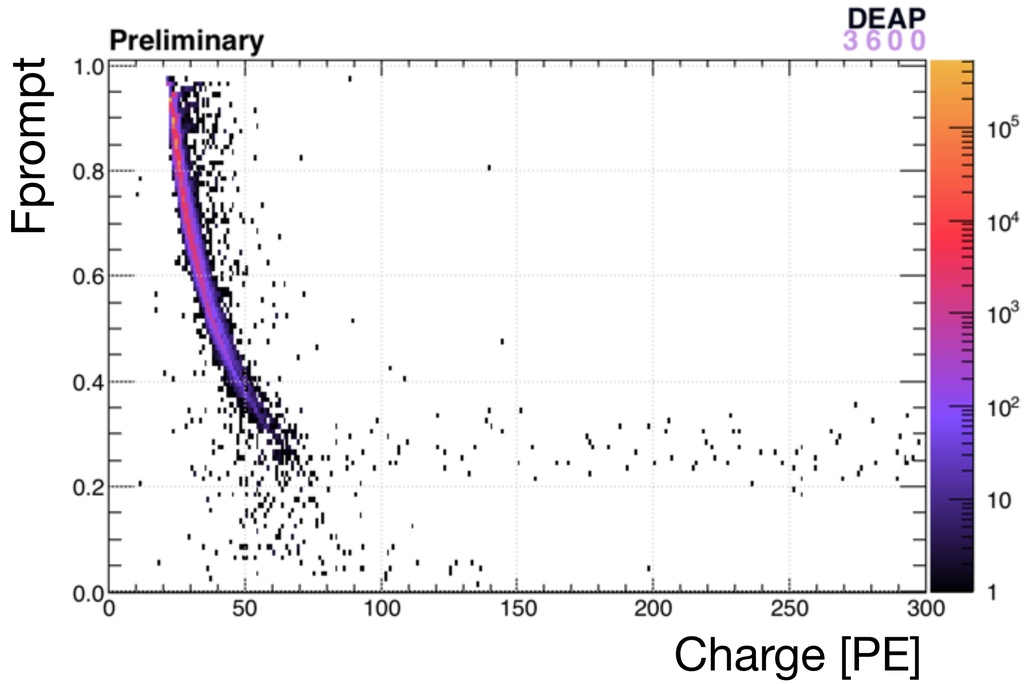


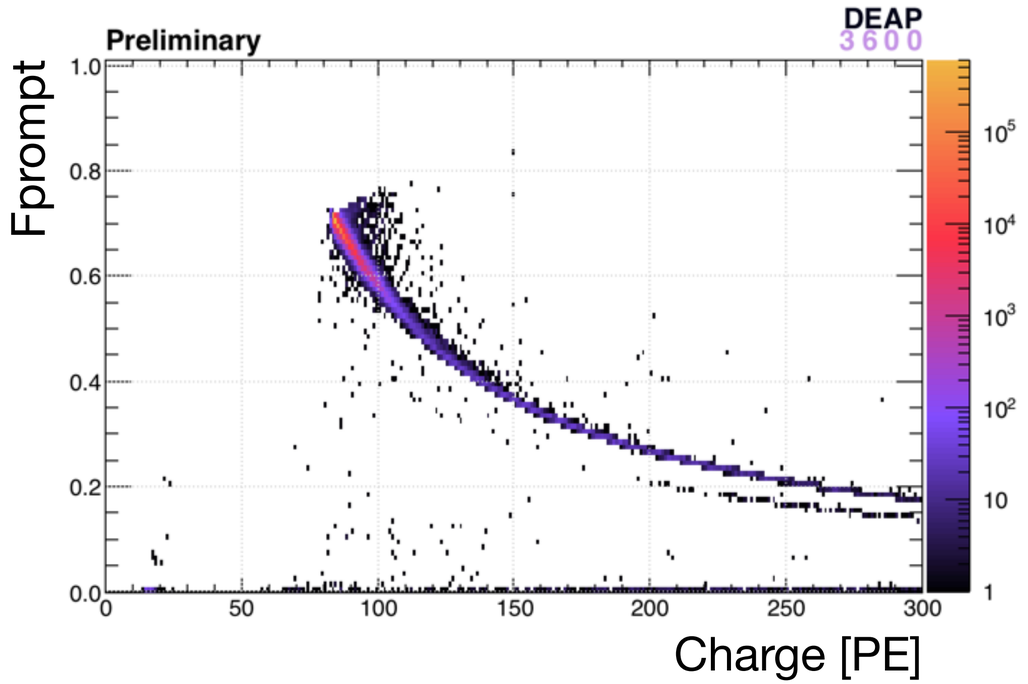




Adding lots of pile up to a single event shows the behavioral trends of pile up

- Most pile up is low charge, so has minimal effect on the original event
  - Though more movement with low charge physics events





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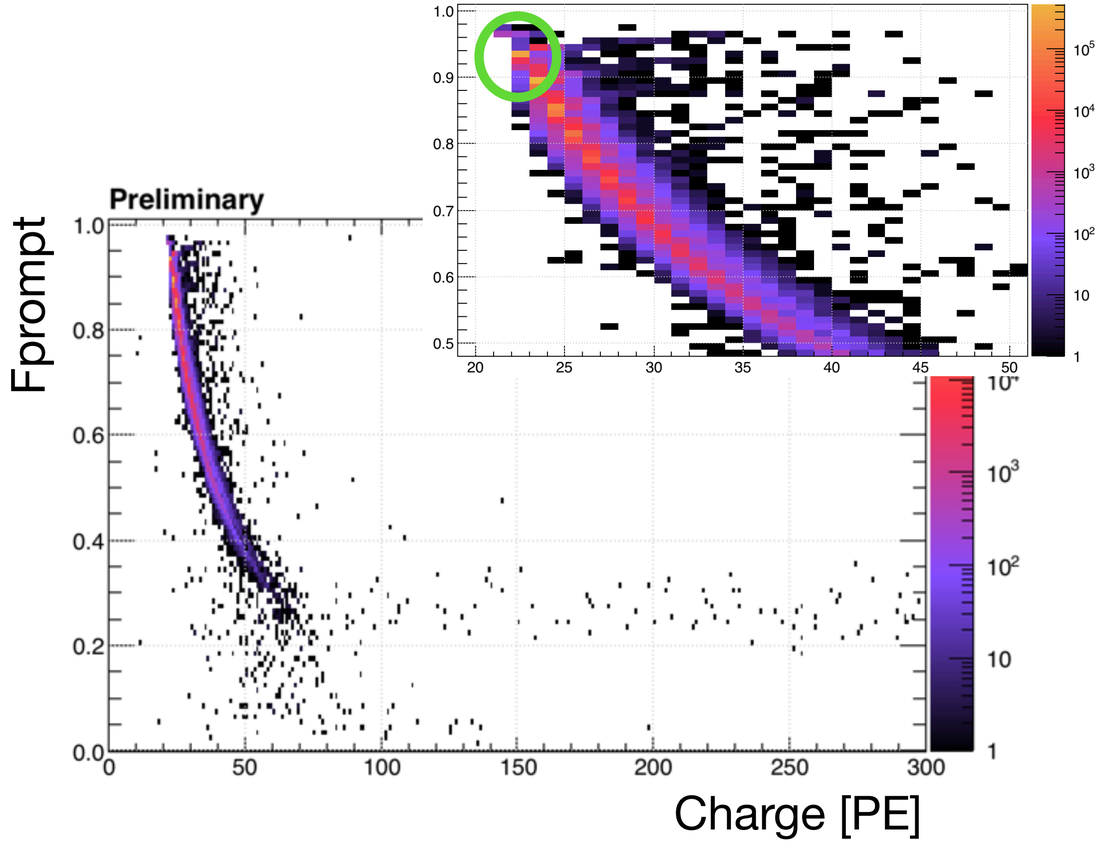
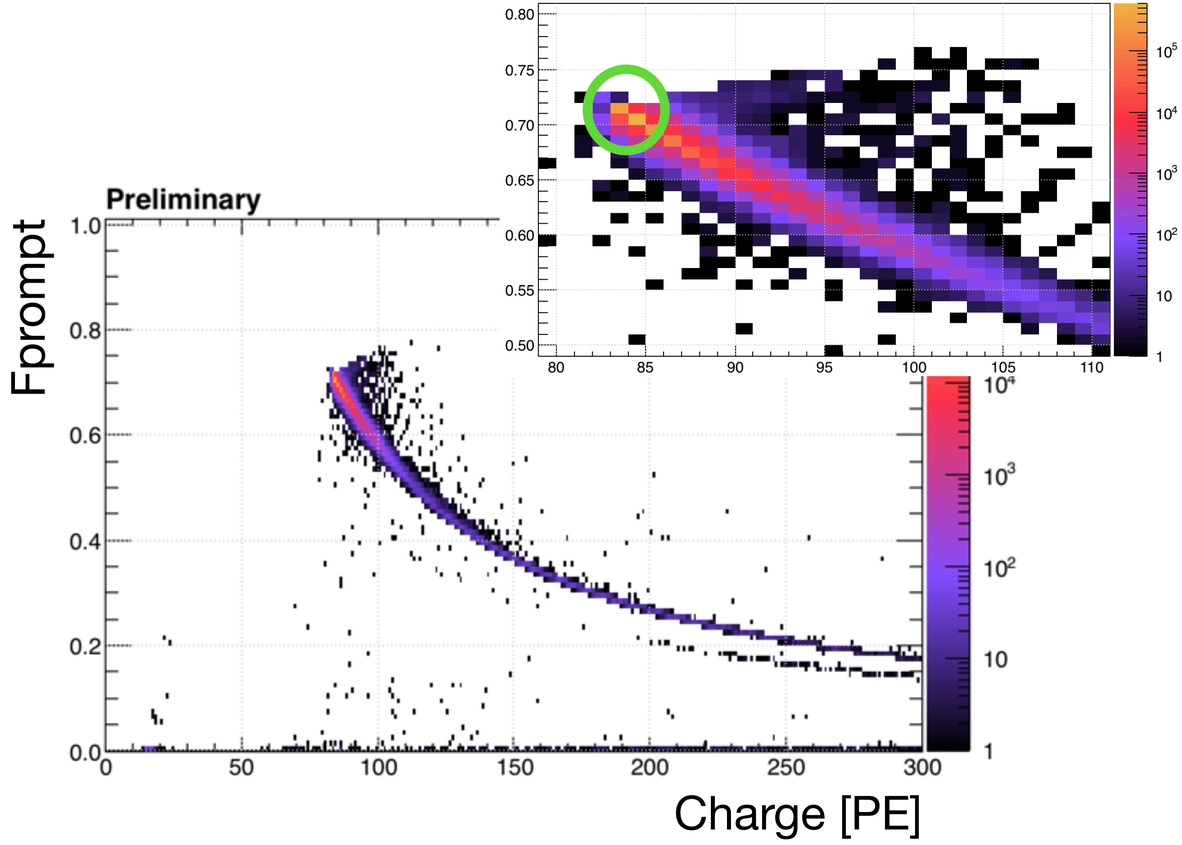
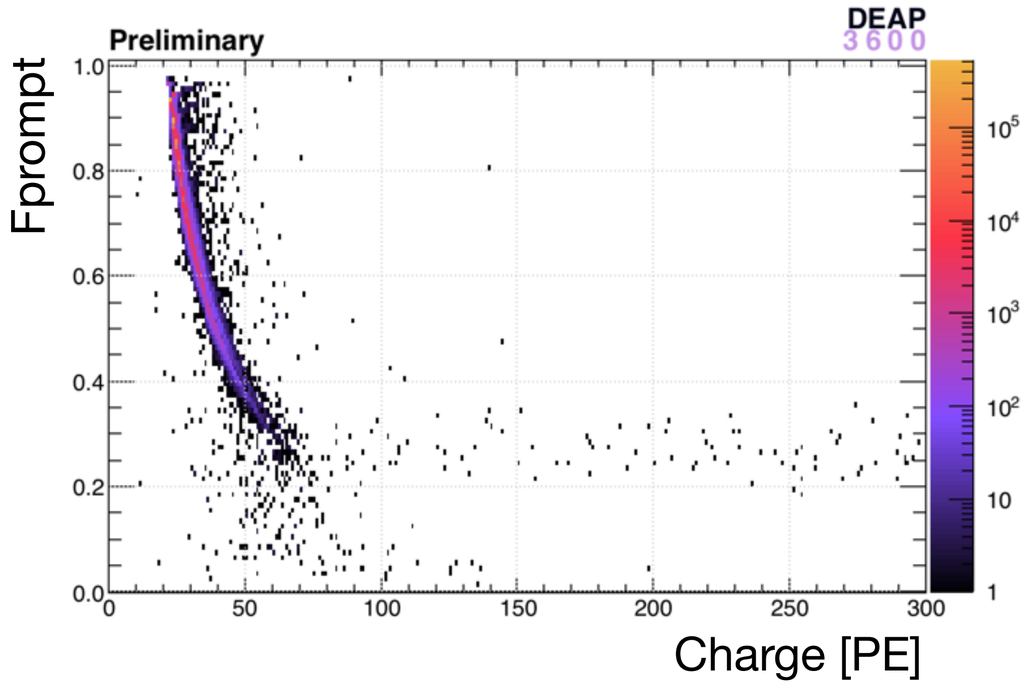
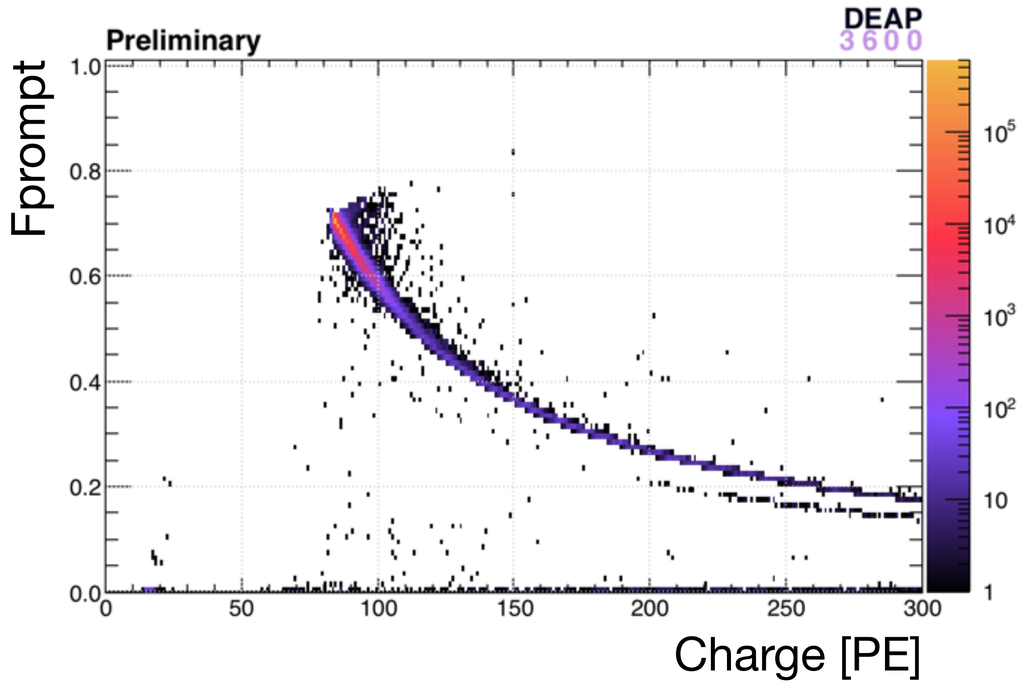




Adding lots of pile up to a single event shows the behavioral trends of pile up

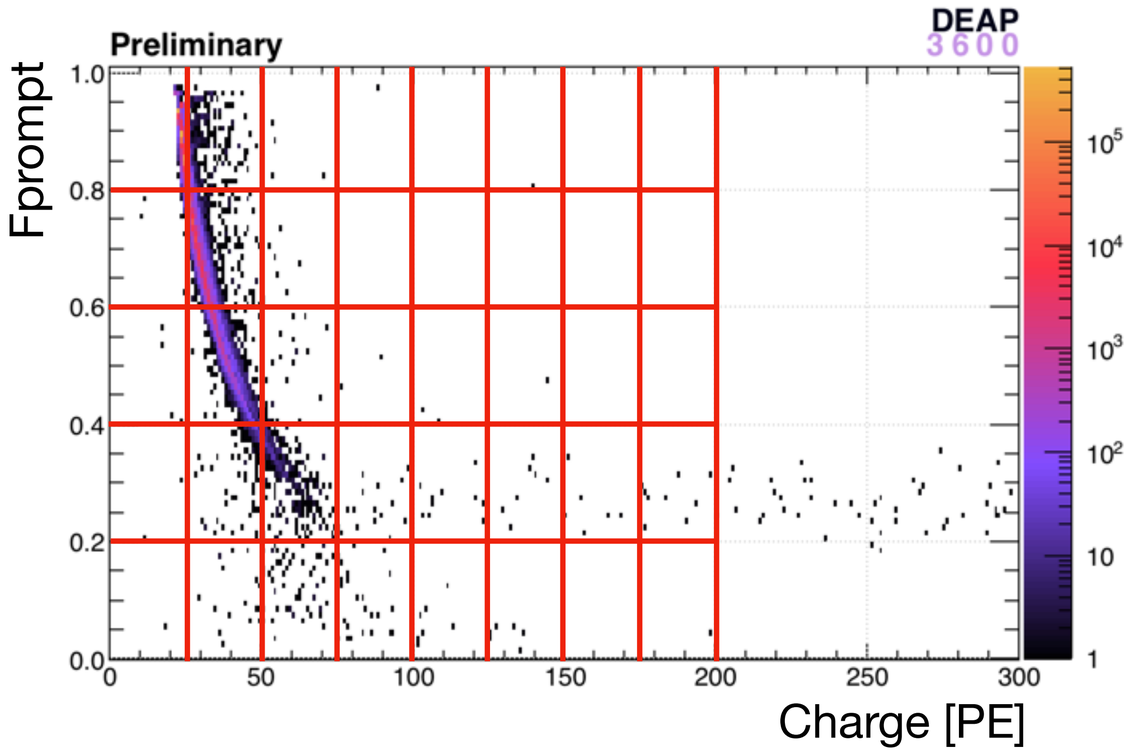
- Of impactful pile up, most adds late light, lowering Fprompt while increasing the charge.
- Much rarer to have prompt light added to the event.





A systematic way to determine if pile up is limiting our dark matter search

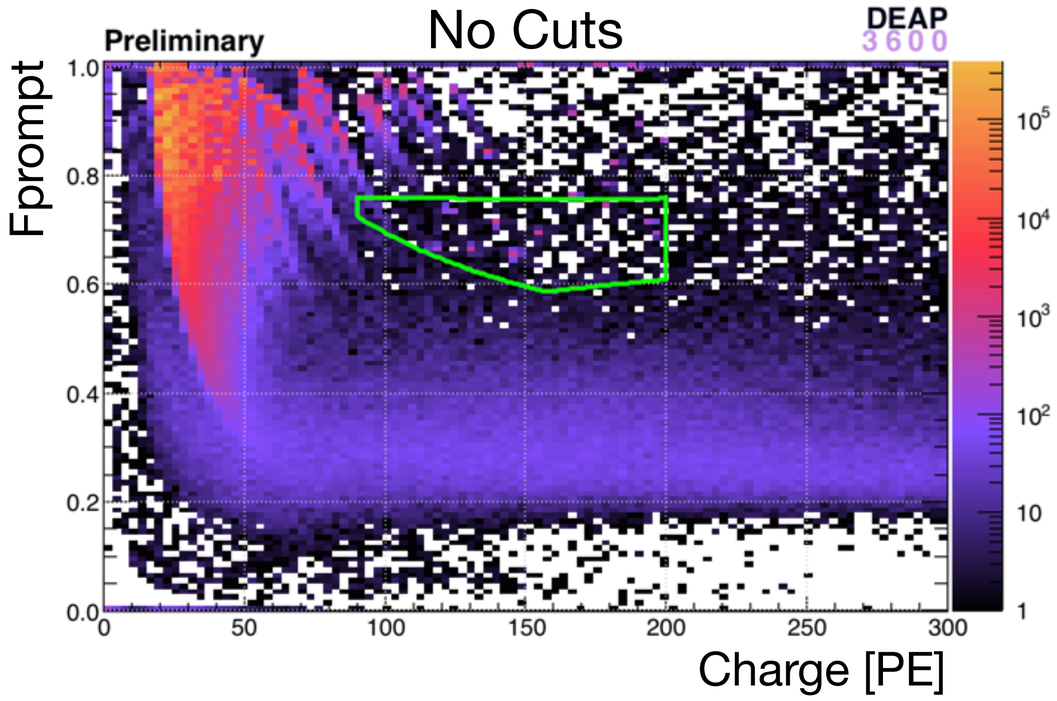
- I created a grid of the PSD space in 0.2 Fprompt and 25 PE increments
- For each region, I randomly selected physics events to add pile up to
  - The number of physics events chosen and the amount of pile up added varied per region depending on the number of physics events expected per day in a given region

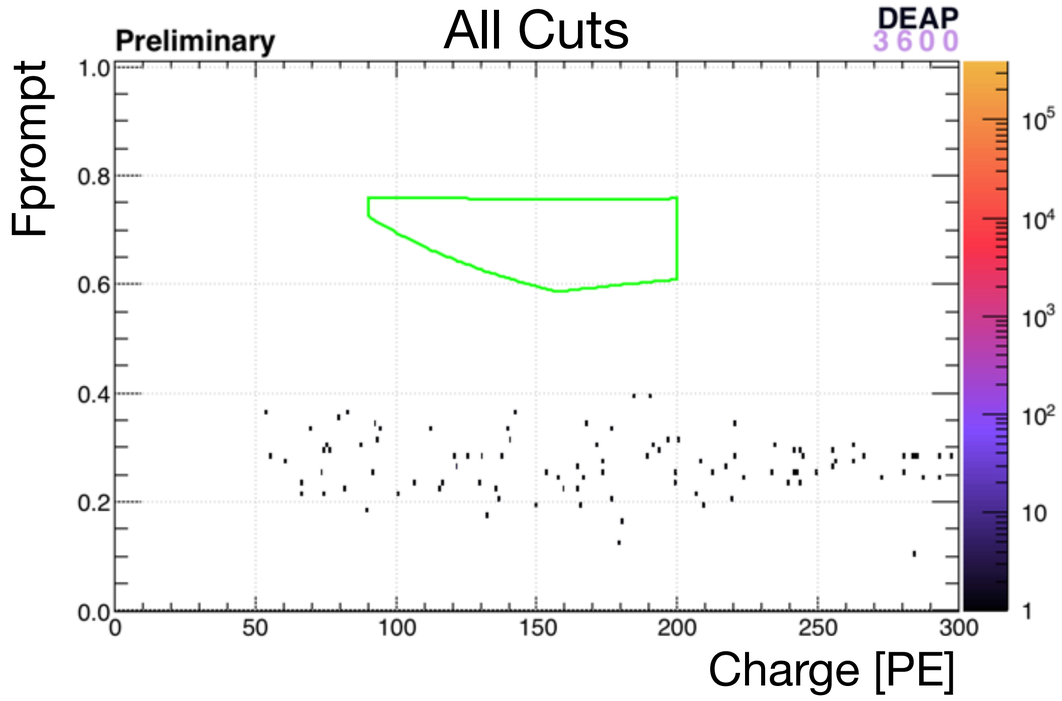


The effect of pile up on high Fprompt events

- These plots represent 33.5 days of data taking for all of the high Fprompt regions up to 200 PE

- **DEAP's cutflow is able to identify and remove all of the pile up events in the region of interest and the nuclear recoil band**





Conclusion

- Preliminary results show that pile up can have a significant effect on physics events, primarily increasing their charge while decreasing their Fprompt
- The advantage of the method that I've developed is that I have the information about the physics event and the periodic trigger event both before and after the periodic trigger is piled up
- The ultimate goal for my project is to determine if our ability to reject pile up is limiting our dark matter search
  - In process of extending my analysis to the other Fprompt regions and for a longer dataset
  - Preliminary results show that our cutflow is sufficient to remove pile up

Thank you

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Back up slides

Pile up percentage

Pile up at or above a given charge (Reverse Cumulative):

$$\text{RC pile up percentage} = \frac{\#\text{ of periodic trigger events with QPE} \geq \text{X}}{\text{total \# of periodic trigger events}} \times 100 \quad *$$

$$\text{RC uncertainty} = \text{RC pile up percentage} \times \sqrt{\frac{1}{\#\text{ of events with QPE} \geq \text{X}} + \frac{1}{\text{total \# of events}}}$$

Pile up at a specific charge (Individual Bin):

$$\text{IB pile up percentage} = \frac{\#\text{ of periodic trigger events with X} \leq \text{QPE} < \text{X} + 1}{\text{total \# of periodic trigger events}} \times 100 \quad *$$

$$\text{IB uncertainty} = \text{IB pile up percentage} \times \sqrt{\frac{1}{\#\text{ of events with X} \leq \text{QPE} < \text{X} + 1} + \frac{1}{\text{total \# of events}}}$$

*The exception to this is the 0th bin, in which case the RC pile up % is calculated with QPE > 0 and the IB pile up % is calculated with 0 < QPE < 1