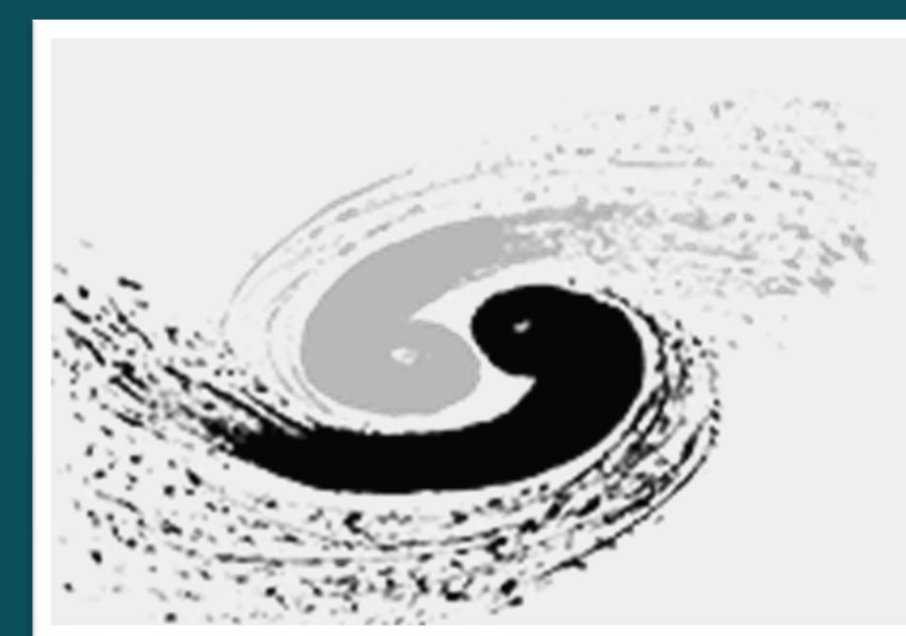


Standalone Measurement of Afterpulses in 20-inch PMTs for the JUNO Experiment

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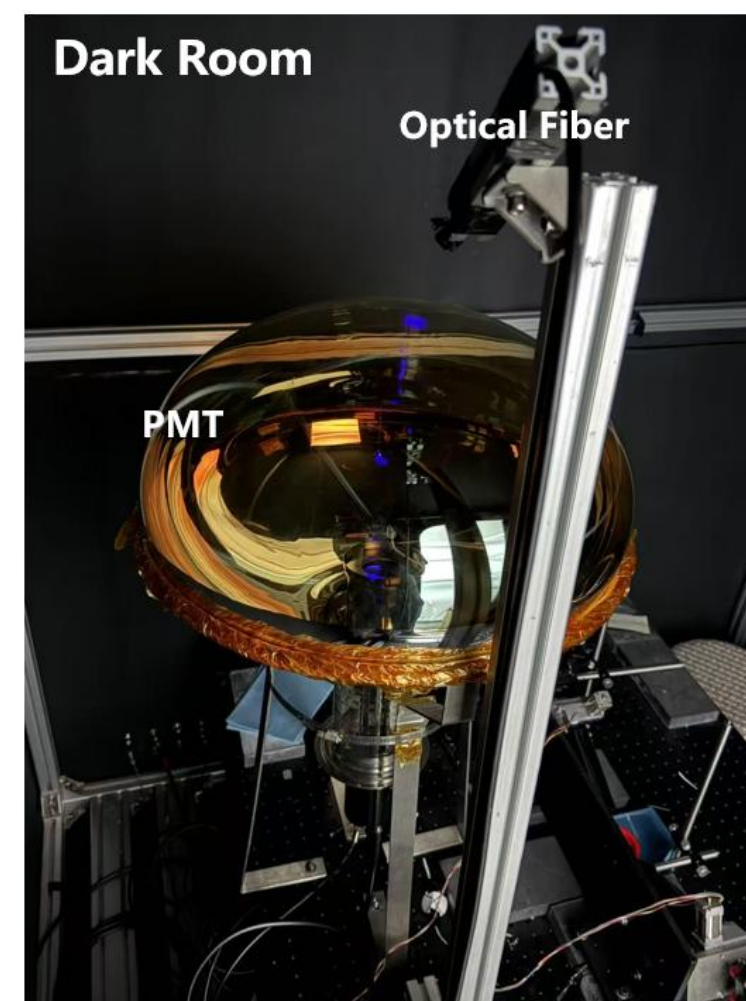
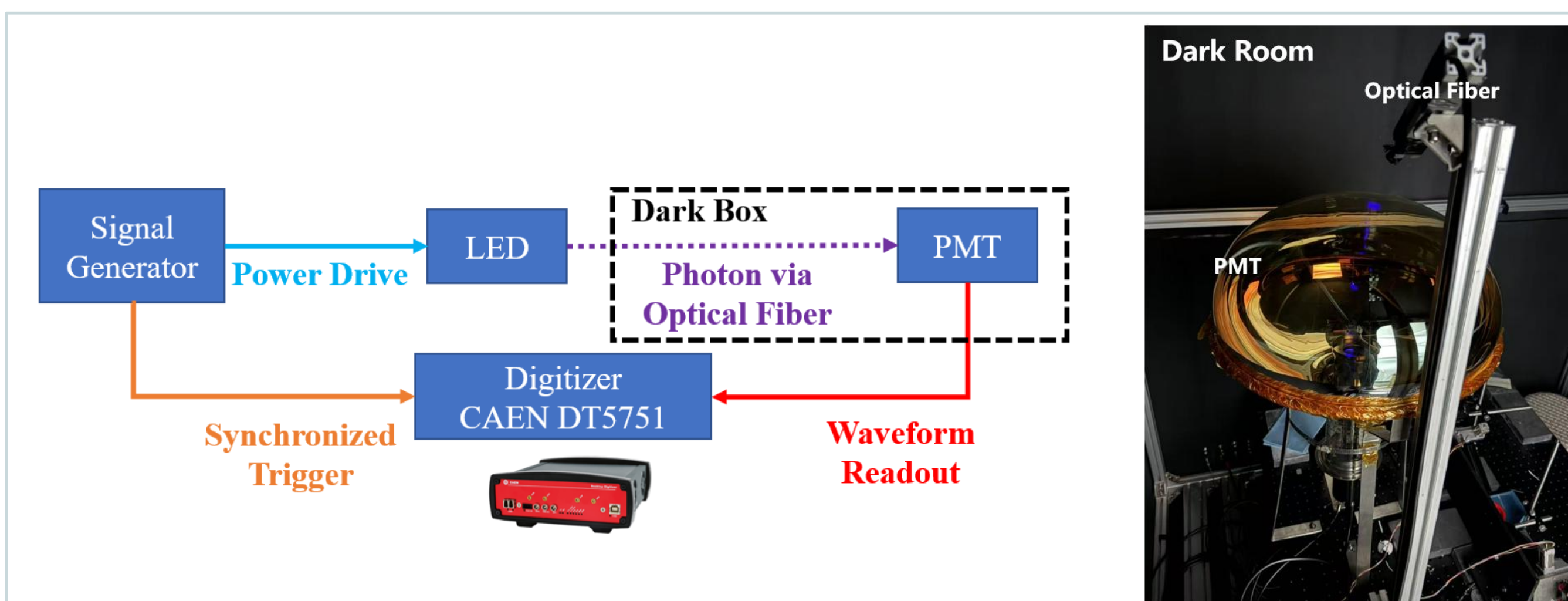
1. INTRODUCTION

Afterpulses are secondary PMT pulses following a primary photoelectron signal, commonly associated with ion feedback, electron scattering, or charge accumulation/release.

In large liquid-scintillator detectors such as JUNO, cosmic muons can produce intense PMT signals. The resulting long-delayed afterpulses may survive in the post-muon region and affect cosmogenic-product measurements and muon-veto strategy.

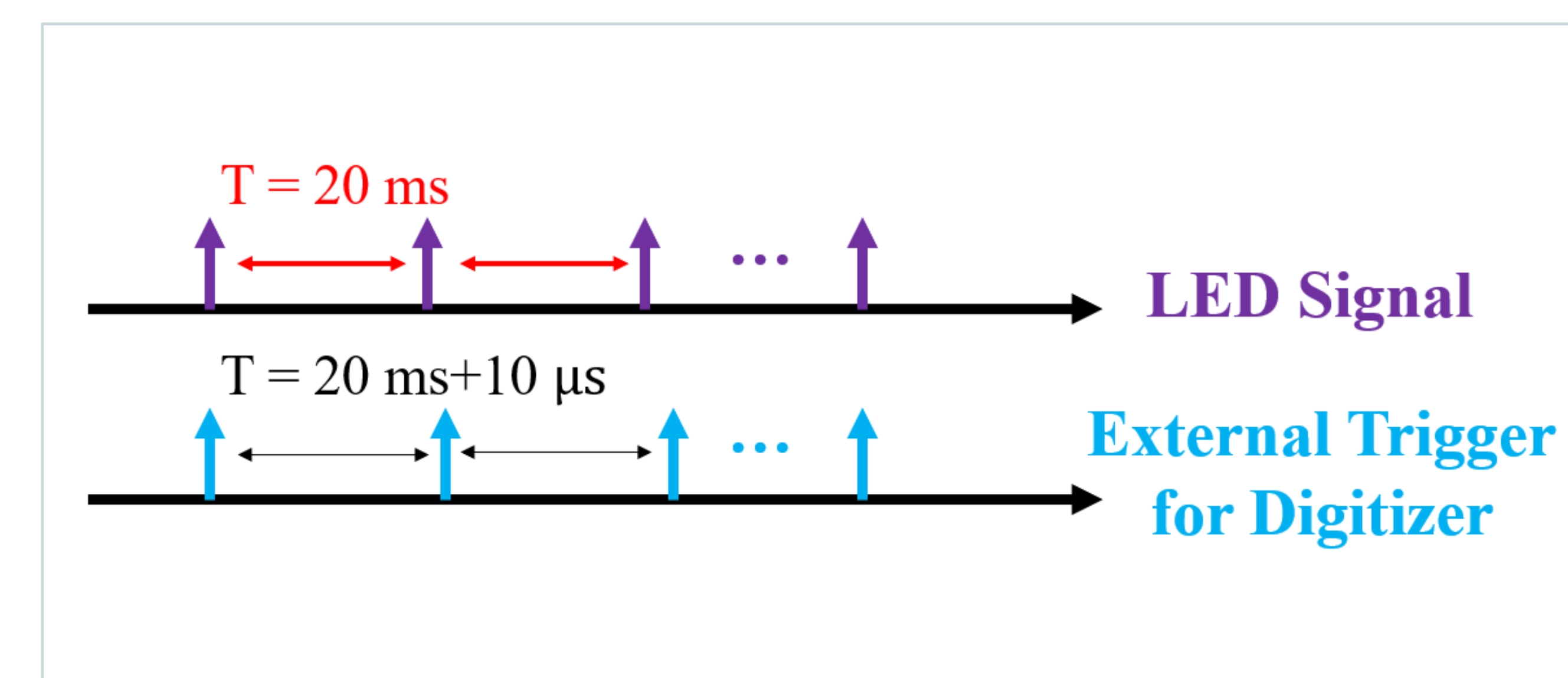
This study: We measure sub-percent long-delayed afterpulses after 20 μ s in JUNO 20-inch dynode and MCP-PMTs, extending the delay range to 20 ms.

2. MEASUREMENT DESIGN



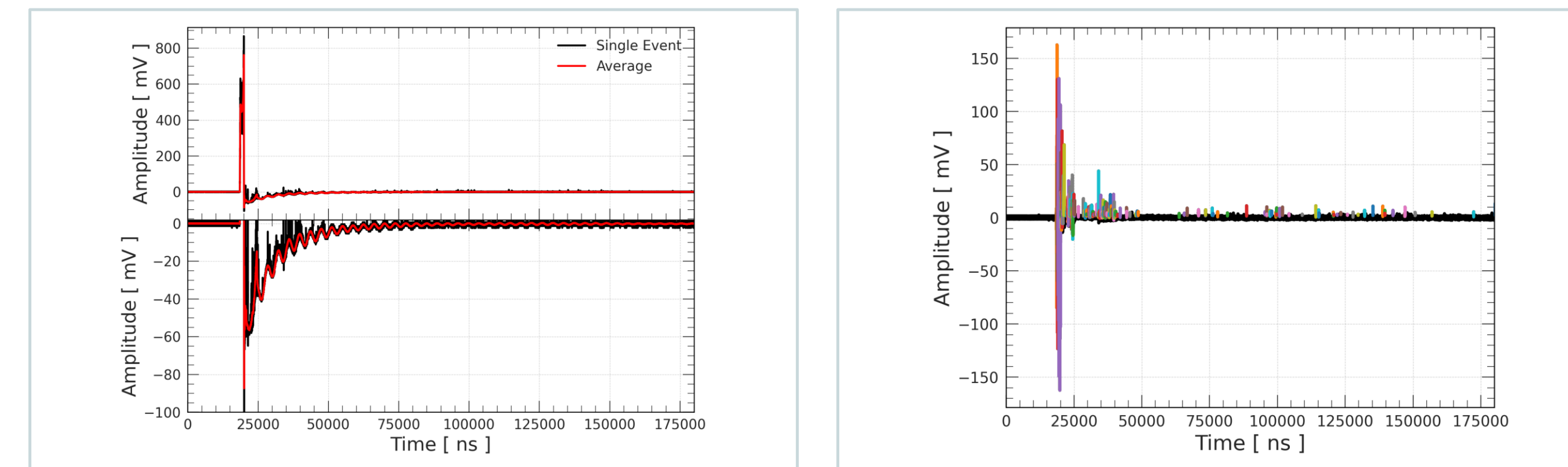
- A pulsed 430 nm LED illuminates the JUNO 20-inch PMT under test inside a dark box.
- Strong primary light pulses of $\sim 10^4$ PE are used to enhance sub-percent afterpulses.
- PMT waveforms are digitized at 1 GS/s in a direct 1.8 ms acquisition window.
- LED-off runs estimate dark-noise/accidental backgrounds.

3. READOUT WINDOW EXTENSION

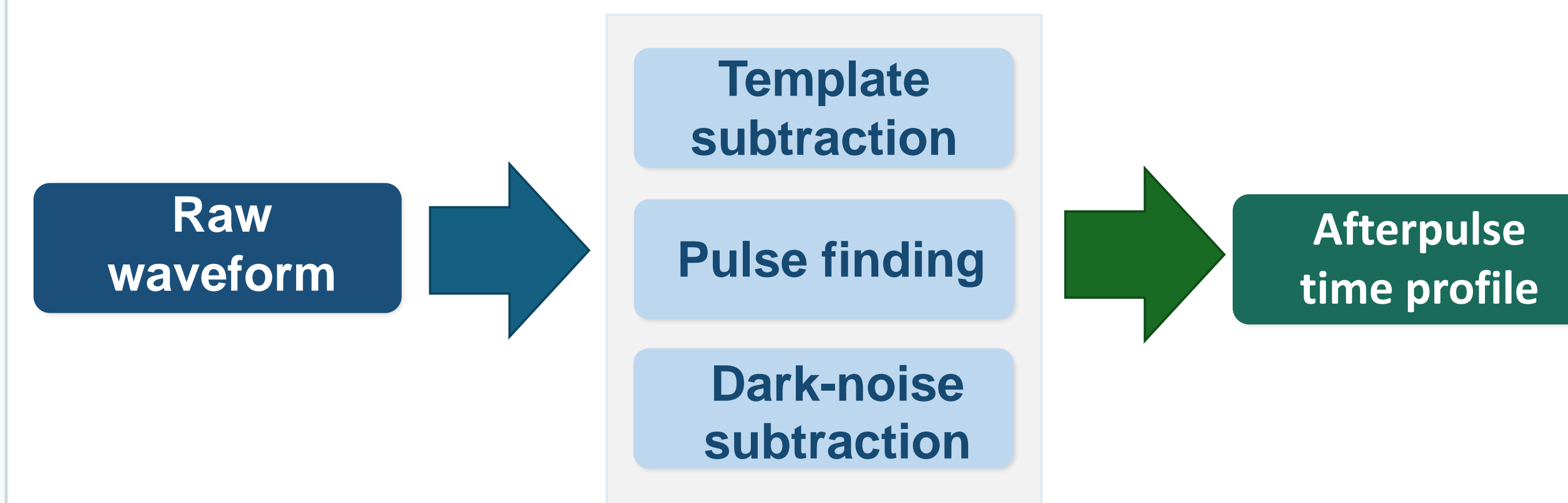


- Motivation: Extend the afterpulse search beyond the 1.8 ms direct DAQ window.
- Strategy: Set the LED period to 20 ms and the trigger period to 20.01 ms.
- Output: The 10 μ s phase drift per trigger allows accumulated short waveforms to reconstruct the full 20 ms delay axis.

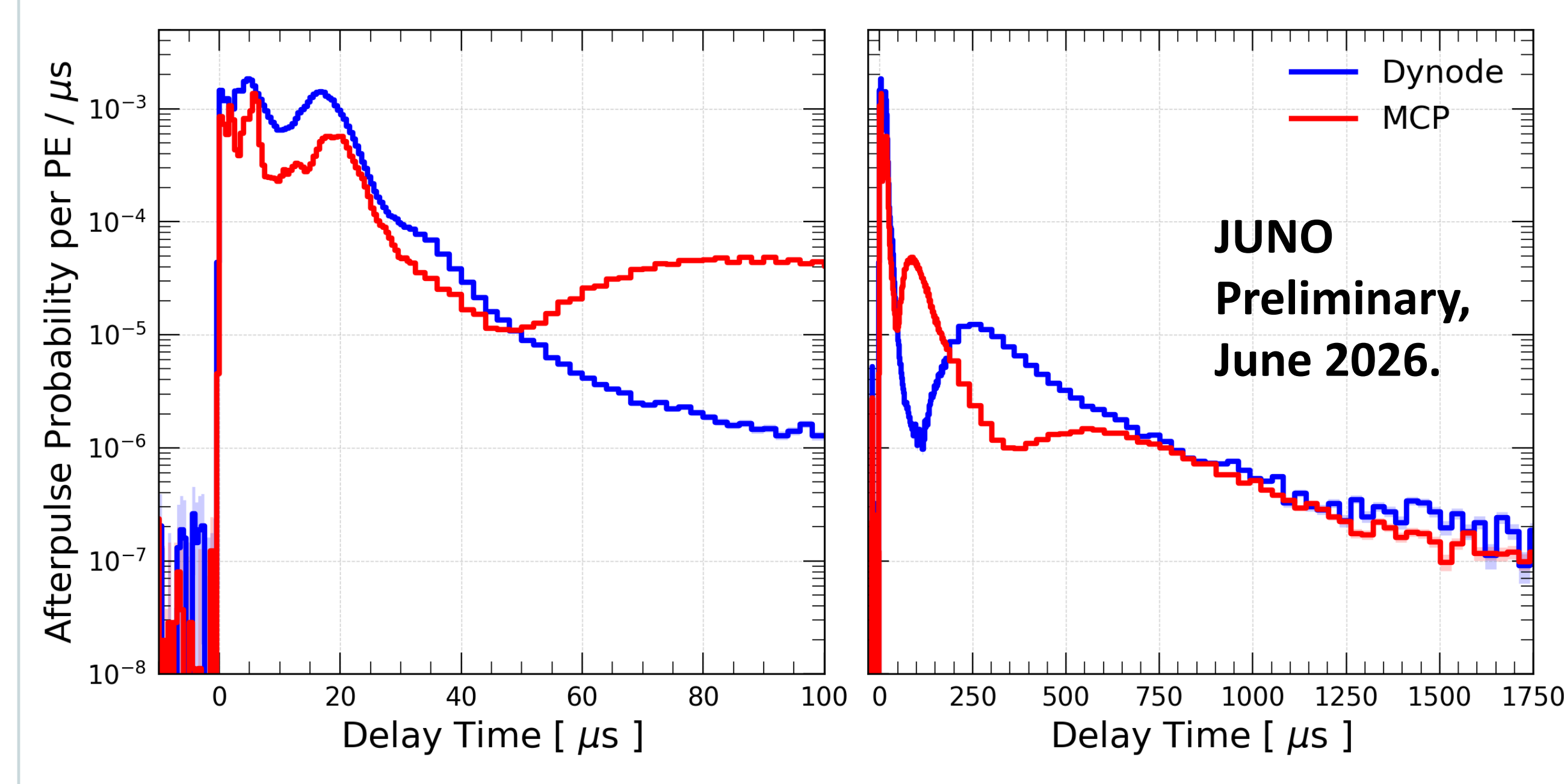
4. WAVEFORM RECONSTRUCTION



- An average waveform template is subtracted to suppress baseline oscillations after the large primary pulse.
- Delayed pulse candidates are identified using a $3\sigma_{\text{baseline}}$ amplitude threshold.
- For each pulse, the delay time and charge are extracted relative to the primary signal.



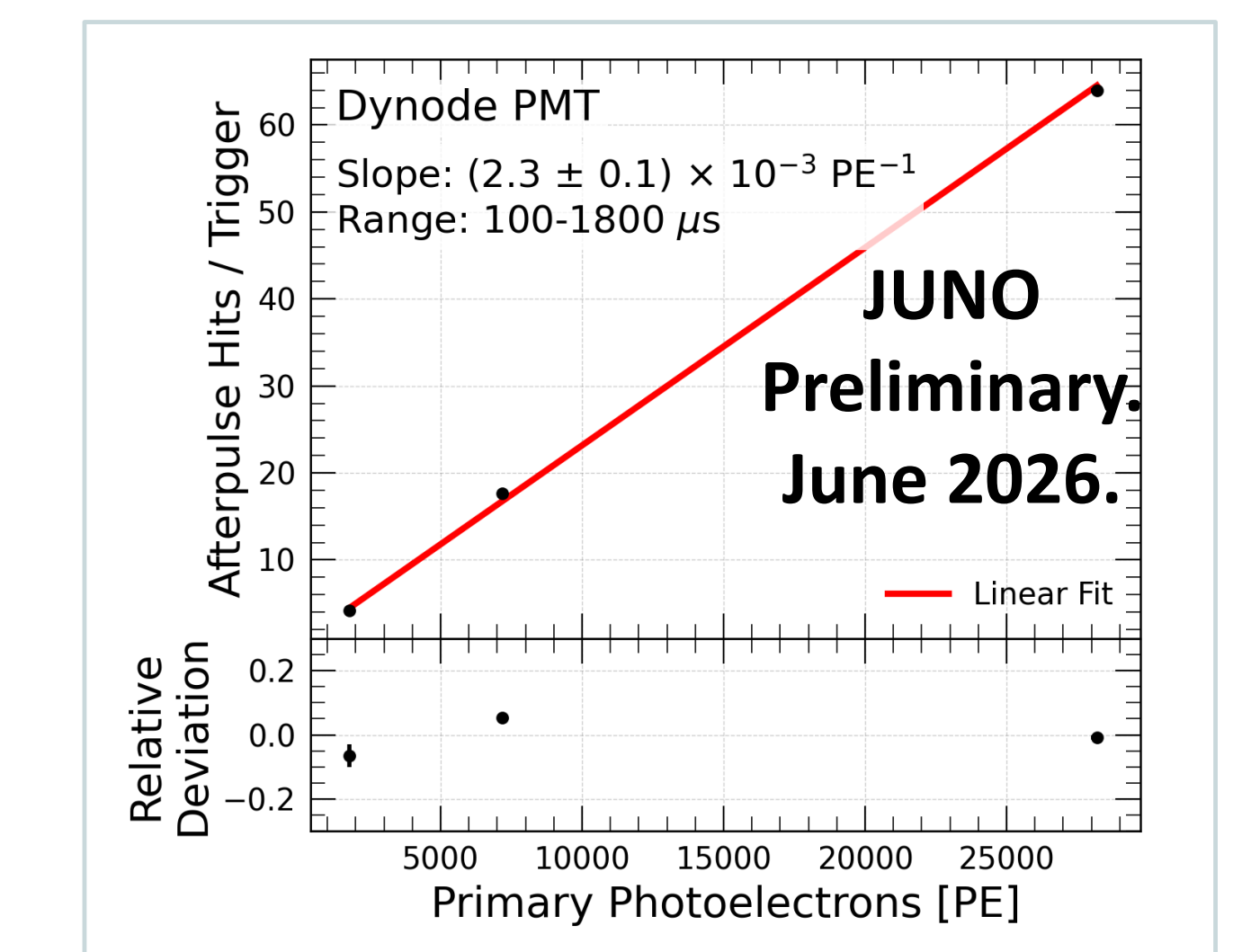
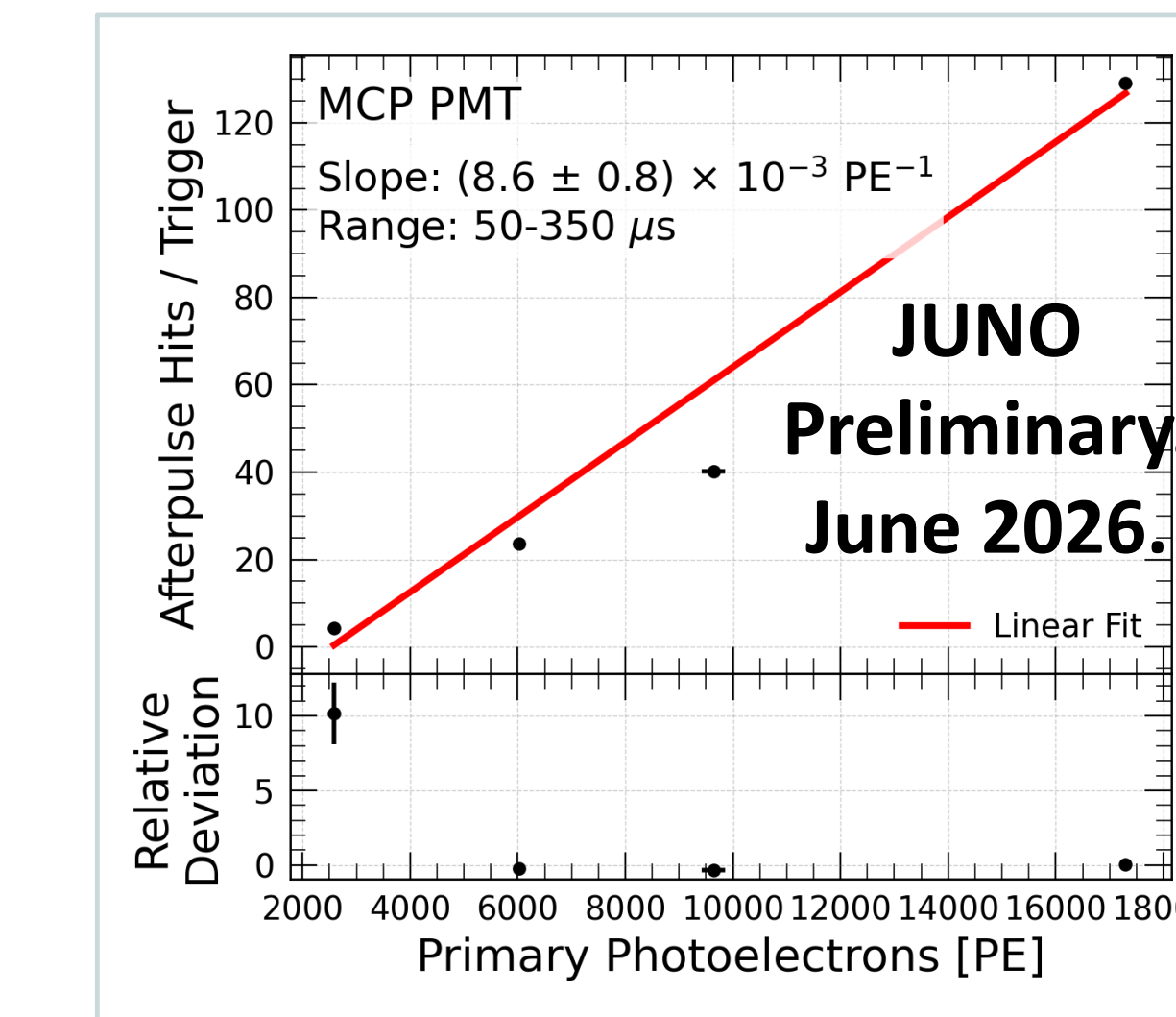
5. DIRECT 1.8 ms TIMING PROFILES



- The <20 μ s region has been measured previously [1,2] and is shown only for continuity; this work focuses on afterpulses after 20 μ s.
- Direct-window data reveal clear long-delayed afterpulse components with slowly decreasing delayed tails.
- PMT-dependent timing structures:** a broad component near 260 μ s for the dynode PMT, and peaks near 90 μ s and 550 μ s for the MCP-PMT.

6. YIELD SCALING WITH PRIMARY SIGNAL

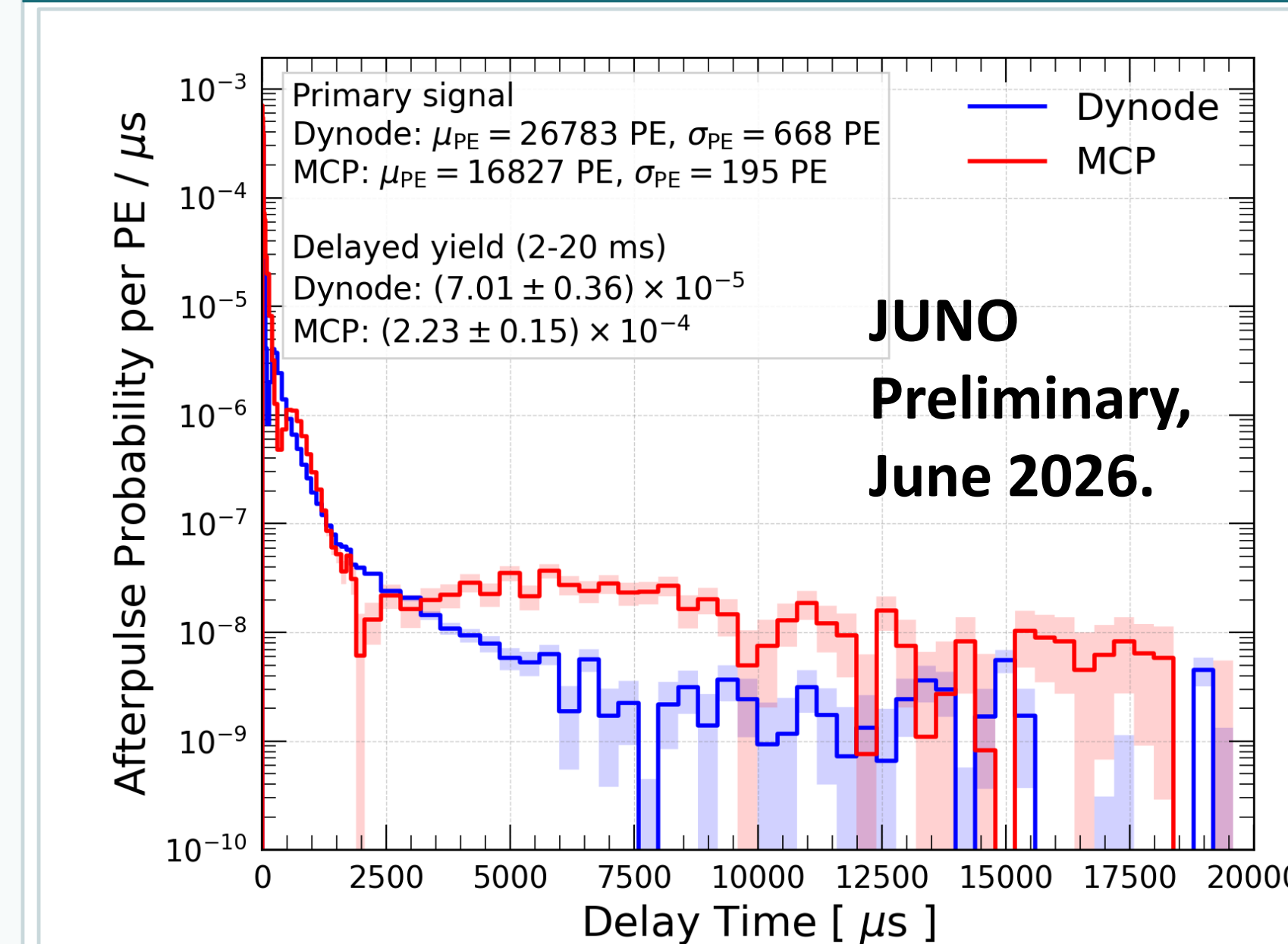
- Reconstructed afterpulse hits integrated in selected delayed windows increase approximately linearly with calibrated primary PE
- The fitted slopes give an effective delayed-pulse yield per primary PE.



PMT	Window	Effective Yield / PE
Dynode	10–100 μ s	$(6.9 \pm 0.7) \times 10^{-3}$
	100–1800 μ s	$(2.3 \pm 0.1) \times 10^{-3}$
MCP	10–50 μ s	$(8.4 \pm 0.5) \times 10^{-3}$
	50–350 μ s	$(8.6 \pm 0.8) \times 10^{-3}$
	350–1800 μ s	$(1.4 \pm 0.2) \times 10^{-3}$

Note: The listed uncertainties include statistical uncertainties only. The first windows start from 10 μ s to avoid truncating components near 20 μ s.

7. EXTENDED TIME PROFILES TO 20 ms



2–20 ms integrated:
 $10^{-5} - 10^{-4}$ / PE

- In the 2–20 ms window, the integrated residual afterpulse probability is small, with a more visible millisecond-scale component in the MCP-PMT.

8. INTERPRETATION AND OUTLOOK

- Possible origins include ion feedback, delayed emission, and light feedback; dedicated studies are needed.
- Absolute yields can be affected by large-signal nonlinearity, MCP gain recovery, threshold effects, and higher-order afterpulses, requiring further dedicated studies.

TAKEAWAY

- This measurement reveals PMT-dependent long-delayed afterpulse structures in JUNO 20-inch PMTs.
- Several-hundred- μ s components are observed near 260 μ s for the dynode PMT and near 90 μ s and 550 μ s for the MCP-PMT.
- The integrated 2–20 ms residual contribution is much weaker, at the $10^{-5} - 10^{-4}$ level per primary PE, indicating limited impact.

References

- [1] R. Zhao et al., Nucl. Sci. Tech. 34, 12 (2023), arXiv:2207.04995.
- [2] Q. Wu et al., Nucl. Instrum. Meth. A 1003, 165351 (2021).