Update on Waveform Feature Extraction

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Motivation & Goals

- **Question:** Do we impair physics capabilities with slower digitization?

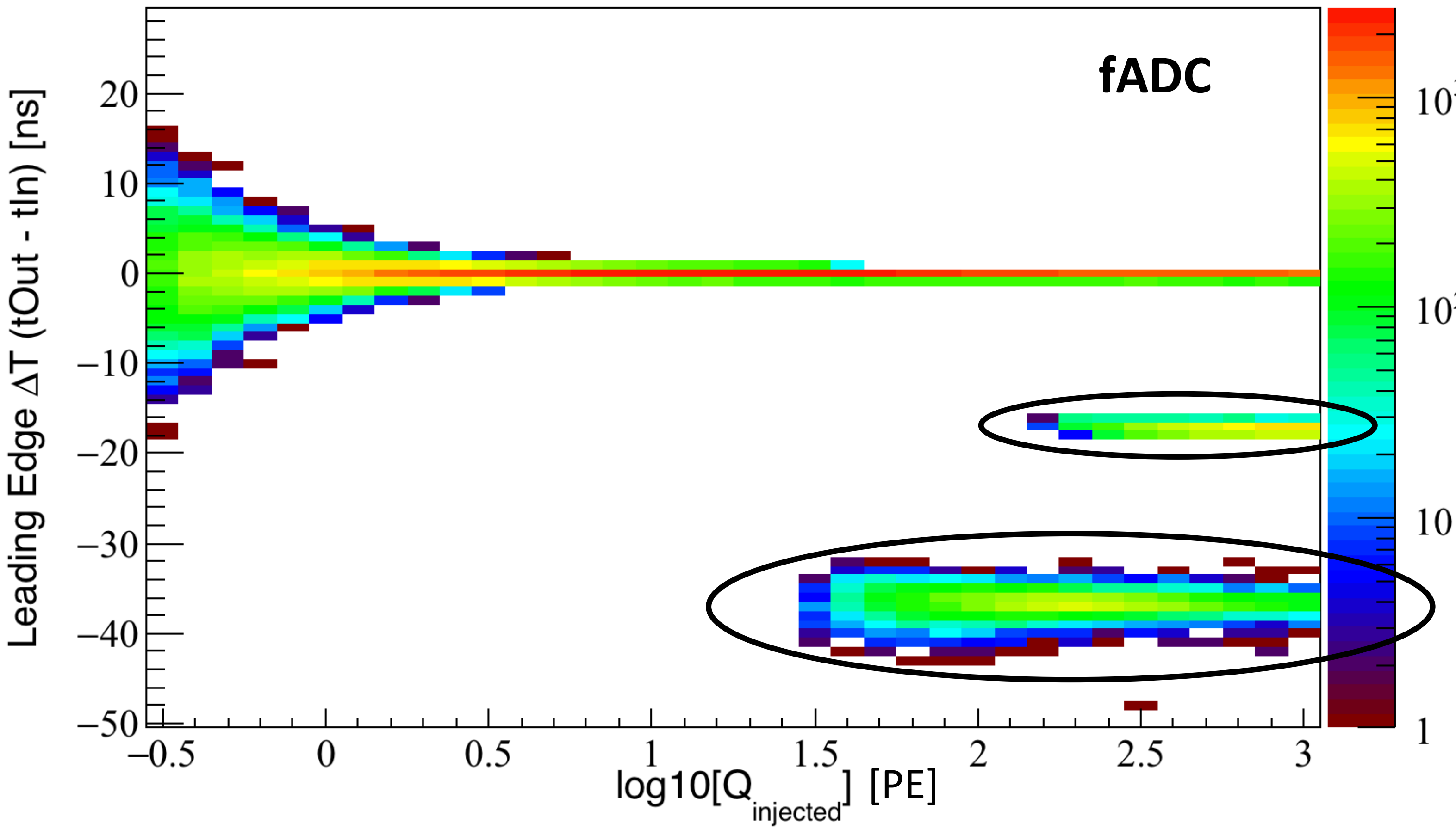
- **Goal:** Evaluate effects of using a single, slow digitizer on feature extraction:
    1. Charge resolution
    2. Time resolution
    3. Double-pulse separation

- **Previous slides:**
    - https://drive.google.com/file/d/1yhqfo6Oq8vFh5WdOGdB0vRpsEQqglJtQ/view
    - Charge resolution much better than Poisson sampling error
    - Significant problems with time resolution

Review

- **Simulate a 40 Msps device with identical low-pass pulse shaping to the IceCube fADC**
  - Create 40 Msps waveforms by injecting pulses assuming the standard IceCube fADC SPE pulse template
  - Add random noise to each bin (128 total bins)
  - Make bin value discrete assuming SPE peak → 20 counts
- **Unfold waveforms using wavedeform**
  - Modified to handle waveforms from single digitizer
- **Compare unfolded pulses to true injected pulses**
- **Do the same for ATWD-like device, for comparison**

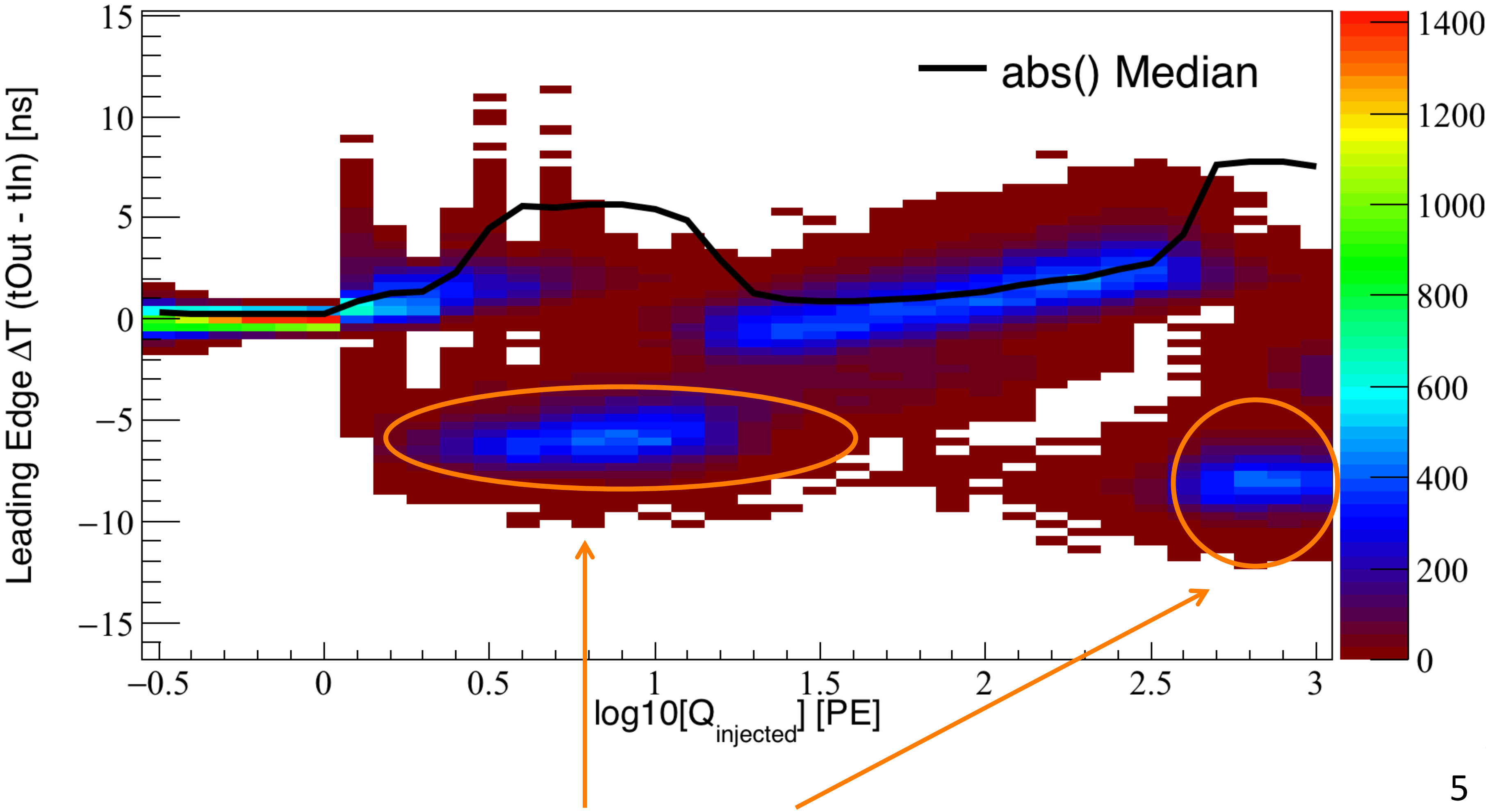
Problem: Early Pulses



- **Unfolding produces early pulses for Q > 30 PE**
- **Early pulses are problematic for reconstruction**
  - **A single early pulse can significantly affect track reconstruction**
- **This is a major problem, mitigated by ad-hoc unfolding modifications**

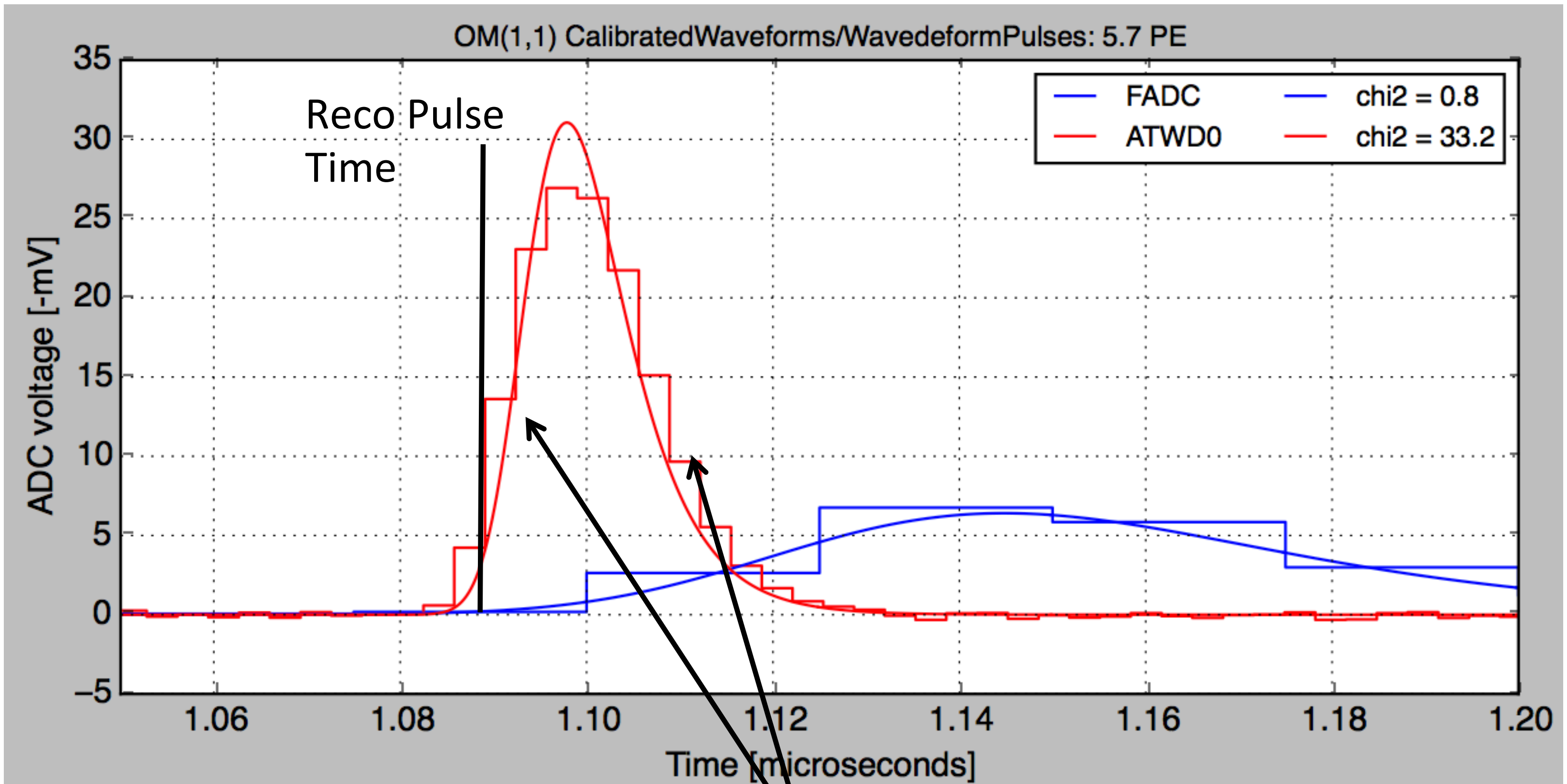
IceCube

- **If we break pulse into individual photons with 3 ns TTS, the problem becomes significant even for IceCube**
  - https://drive.google.com/open?id=1yX0GINukMt1aTJbHMxUQ8roNjh_2GG3p



Example

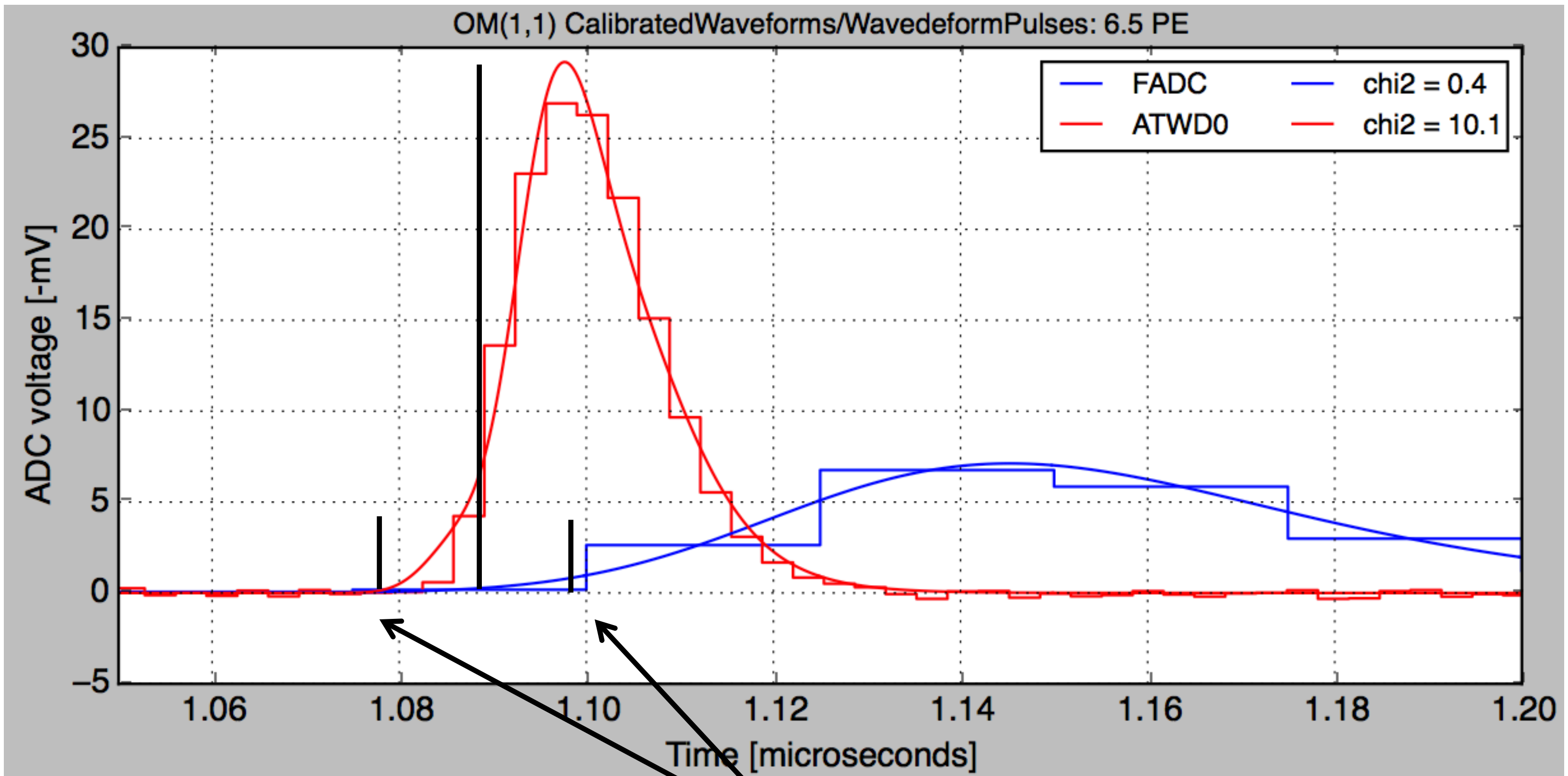
- **Iteration #1**



Mismatching Leading/Trailing ATWD Edges

Example

- **Iteration #3 (Final Iteration)**

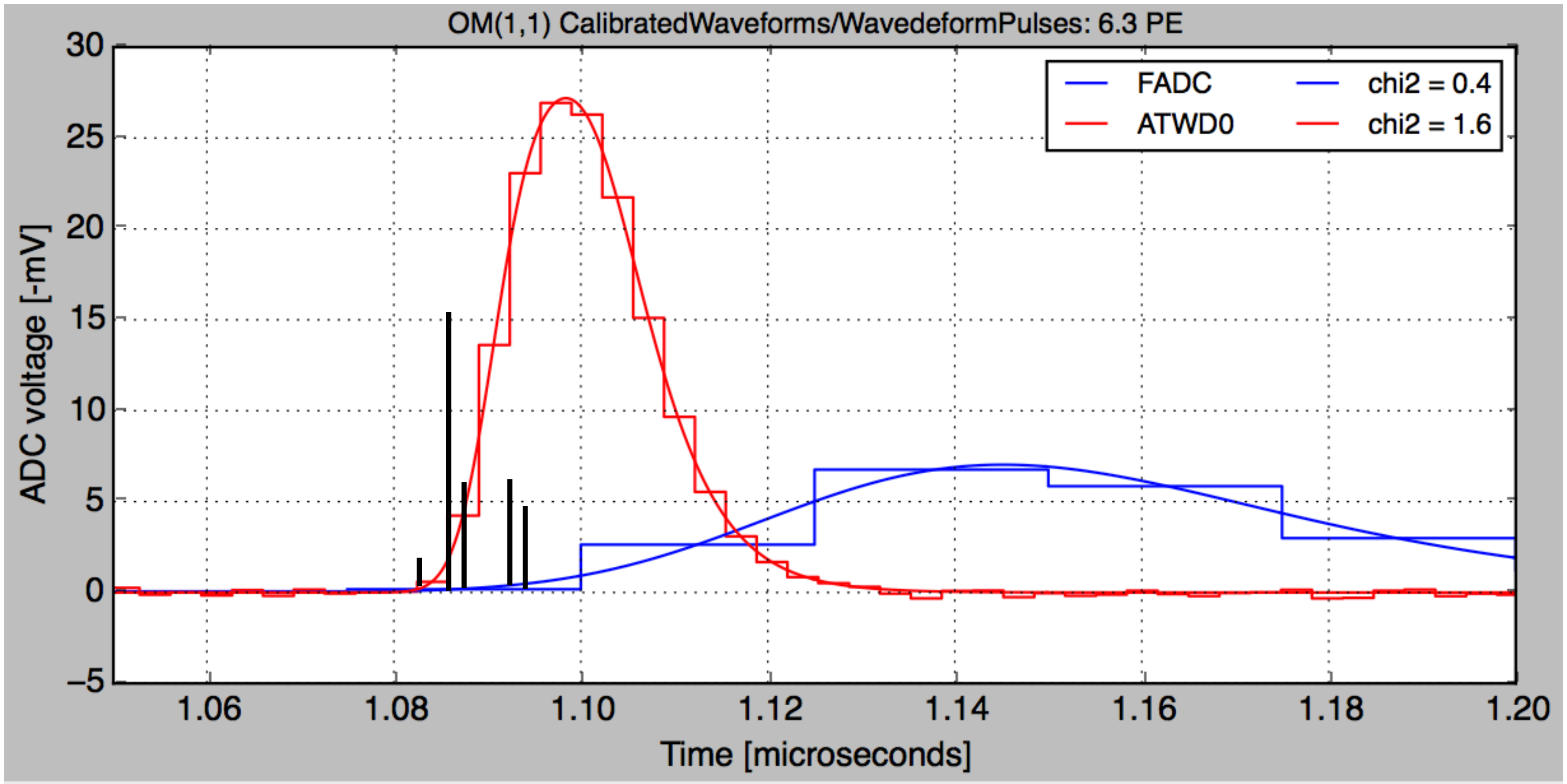


Pulses Added to Match ATWD Edges

First unfolded pulse is ~6 ns earlier than first injected pulse

What If We Remove Stopping Tolerance?

- **Iteration N (Let fit converge to optimal NNLS solution):**



6 ns early pulse is removed from solution set

First non-negligible pulse <2 ns early

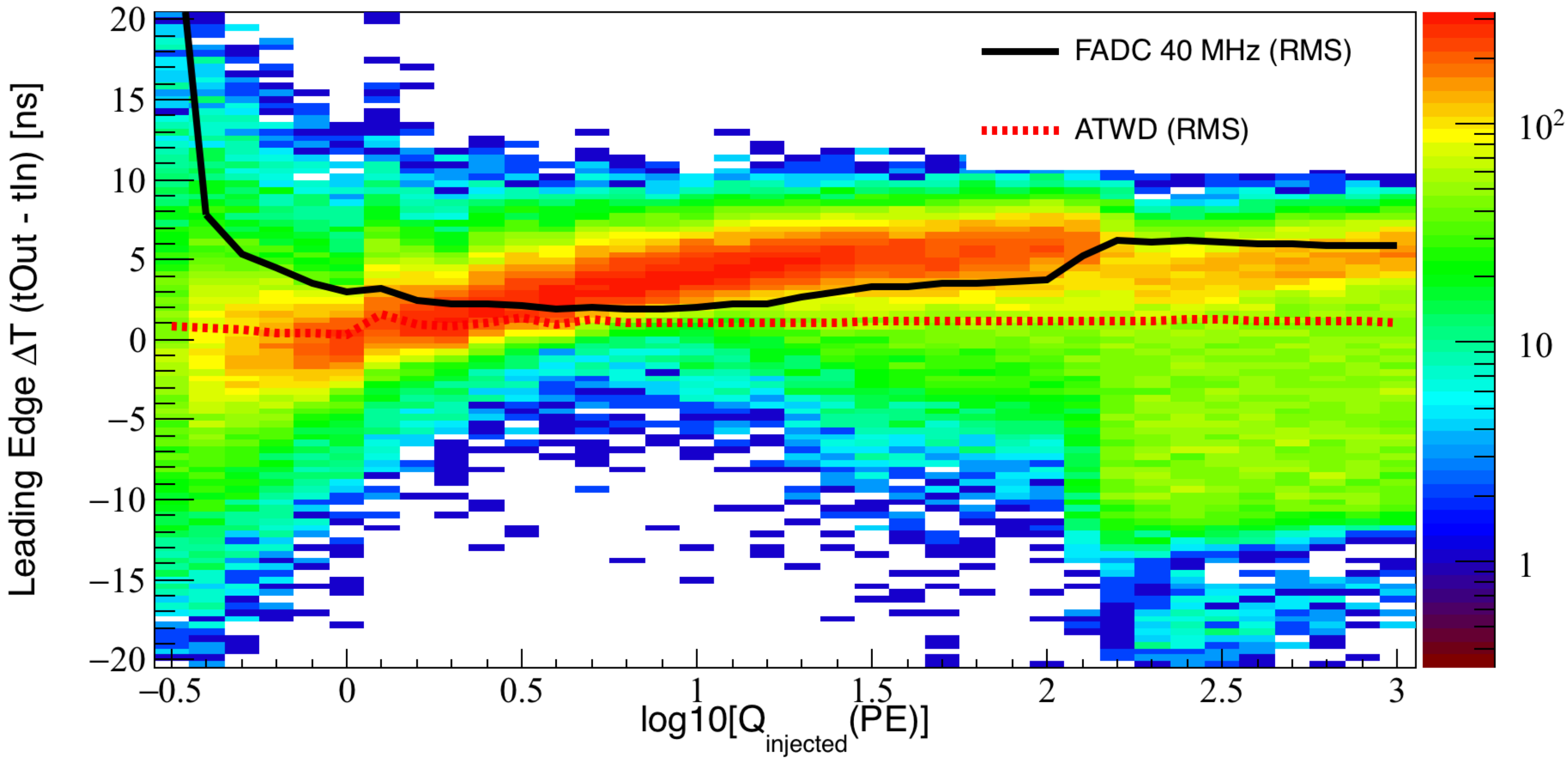
First pulse > 0.3 PE is right on time with leading edge

How Do We Fix This?

- **Optimal NNLS solution is a good, but noisy, starting point**
  - Need to remove pulses with small amplitudes
- **Proposed solution:**
  - Iteratively remove the smallest pulse and re-solve the system of remaining pulses
  - Stop when original tolerance is reached. The final pulse series is the unconstrained set from the previous iteration
- **Proposed solution is an adaptation of existing work:**
  - Peharz & Pernkopf, Neurocomputing. 2012 Mar 15; 80(1): 38–46
- **Algorithm is 15x slower than standard wavedeform, but I've found improvements bring this down to less than 2x**

Leading-Pulse Time Resolution

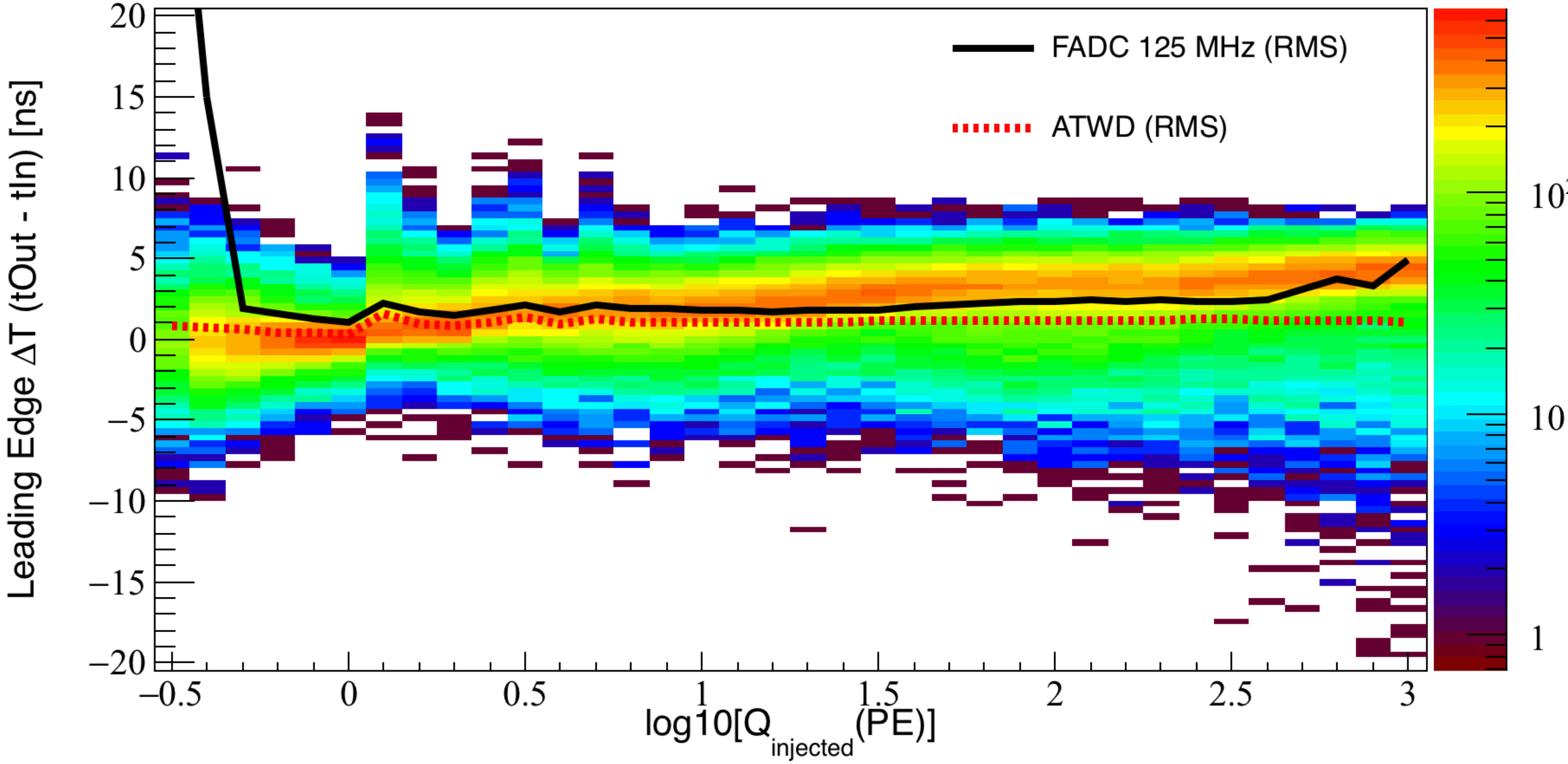
- **Break pulses into individual photons with 3 ns TTS**



- **Substantial fraction of early pulses unavoidable for Q > 100 PE**
- **Physics goals unlikely to be attainable without TDC**

Leading-Pulse Time Resolution

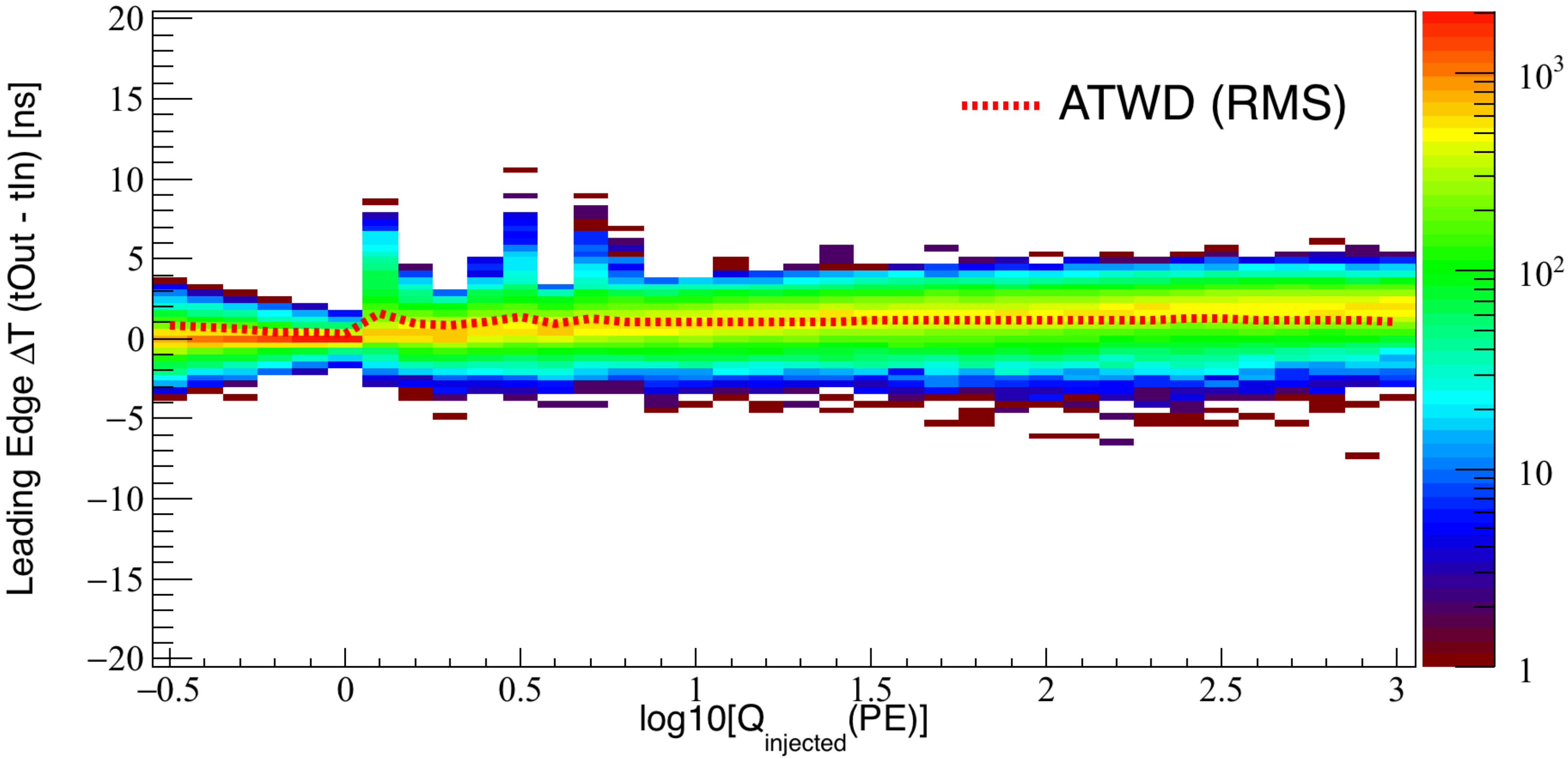
- **Simulate Chris Wendt's 125 MHz digitization, including faster pulse shaping**



- **Significant improvement**
- **Tendency toward positive ΔT as charge increases**

Leading-Pulse Time Resolution

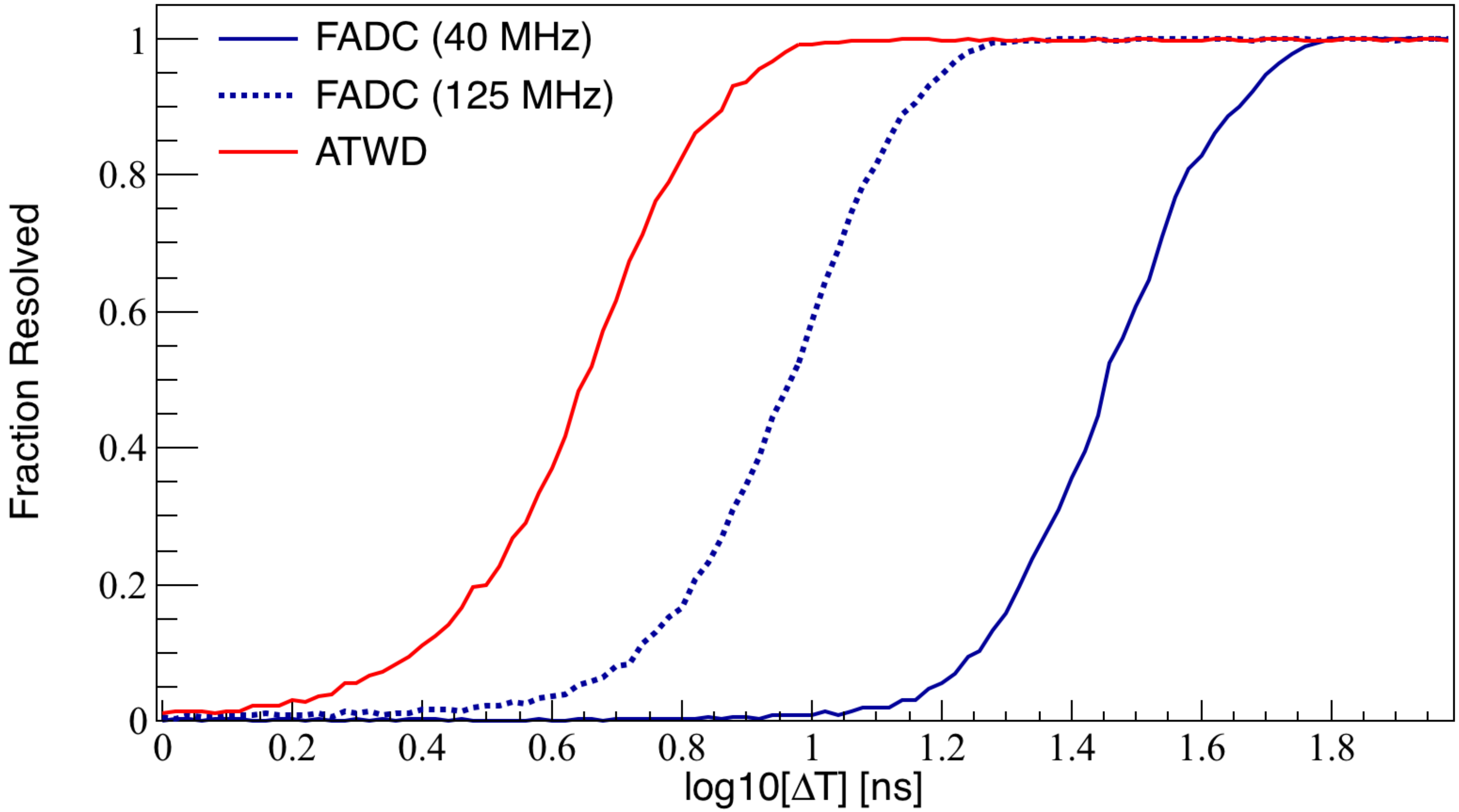
- **ATWD, for comparison**



Double-Pulse Resolution

- **Simplify method from previous study: Focus on single photoelectrons**
- **Inject two single-PE pulses with separation ΔT**
- **Consider the pulses separated if:**
  - Unfolded solution is exactly two pulses
  - Amplitude of each pulse is at least 0.75 PE

Double-Pulse Resolution



- **ΔT @ 50% resolution:**
  - fADC (40 MHz): **28 ns**
  - fADC (125 MHz): **9 ns**
  - ATWD: **4 ns**

Conclusions and Summary

- **Charge resolution is not a problem for slow digitization**
- **Major problems with leading-pulse timing resolution fixed by changes in the waveform unfolding**
- **Leading-Pulse Resolution RMS (100 PE):**
  - 40 MHz fADC: **5.2 ns**
  - 125 MHz fADC: **2.4 ns**
  - ATWD: **1.2 ns**
- **40 MHz digitization would likely need to be supplemented by a TDC to avoid a significant loss with respect to IceCube**
- **Double-pulse resolution (ΔT, 50% resolved):**
  - fADC (40 MHz): **28 ns**
  - fADC (125 MHz): **9 ns**
  - ATWD: **4 ns**