Waveform Feature Extraction Using (Relatively) Slow Digitization

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Motivation & Goals

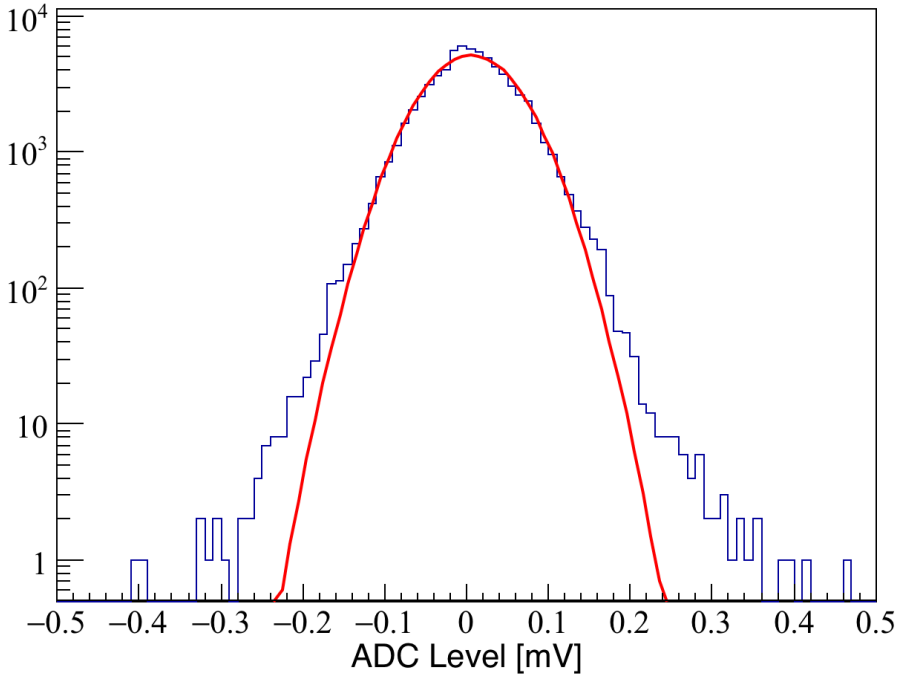
- **Slow digitization (~40 Msps) yields power and cost savings in proposed Gen2 optical module**
- **Single digitization source simplifies hardware, calibration, and downstream software**
- **Question:** Do we impair physics capabilities with slower digitization?
- **Goal:** Evaluate effects of using a single, slow digitizer on feature extraction:
  1. Charge resolution
  2. Timing resolution
  3. Double-pulse separation

Analysis

- **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**

IceCube DOM fADC Noise

- **Create a histogram of the first bin of fADC waveforms with local coincidence**



- **Noise peak is reasonably well-described by a Gaussian of width 54 µV**
  - Use this Gaussian in model

Waveform Unfolding: Wavedeform

- **Waveform is a superposition of SPEs**
- **SPE template waveform represents response to SPE**

  → Unfold the waveform using a vector of time-shifted SPE templates as a basis

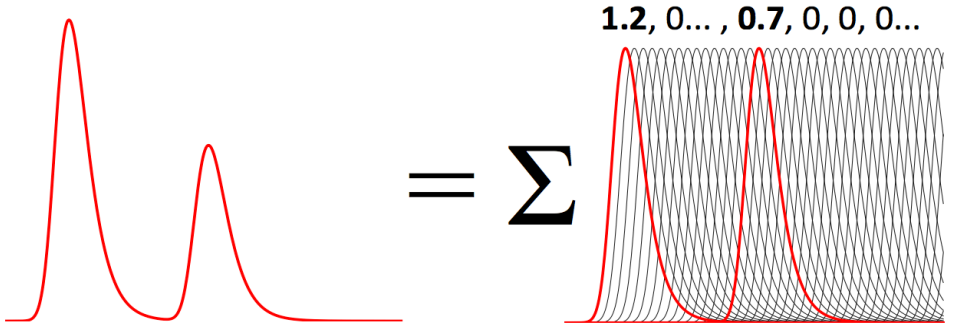
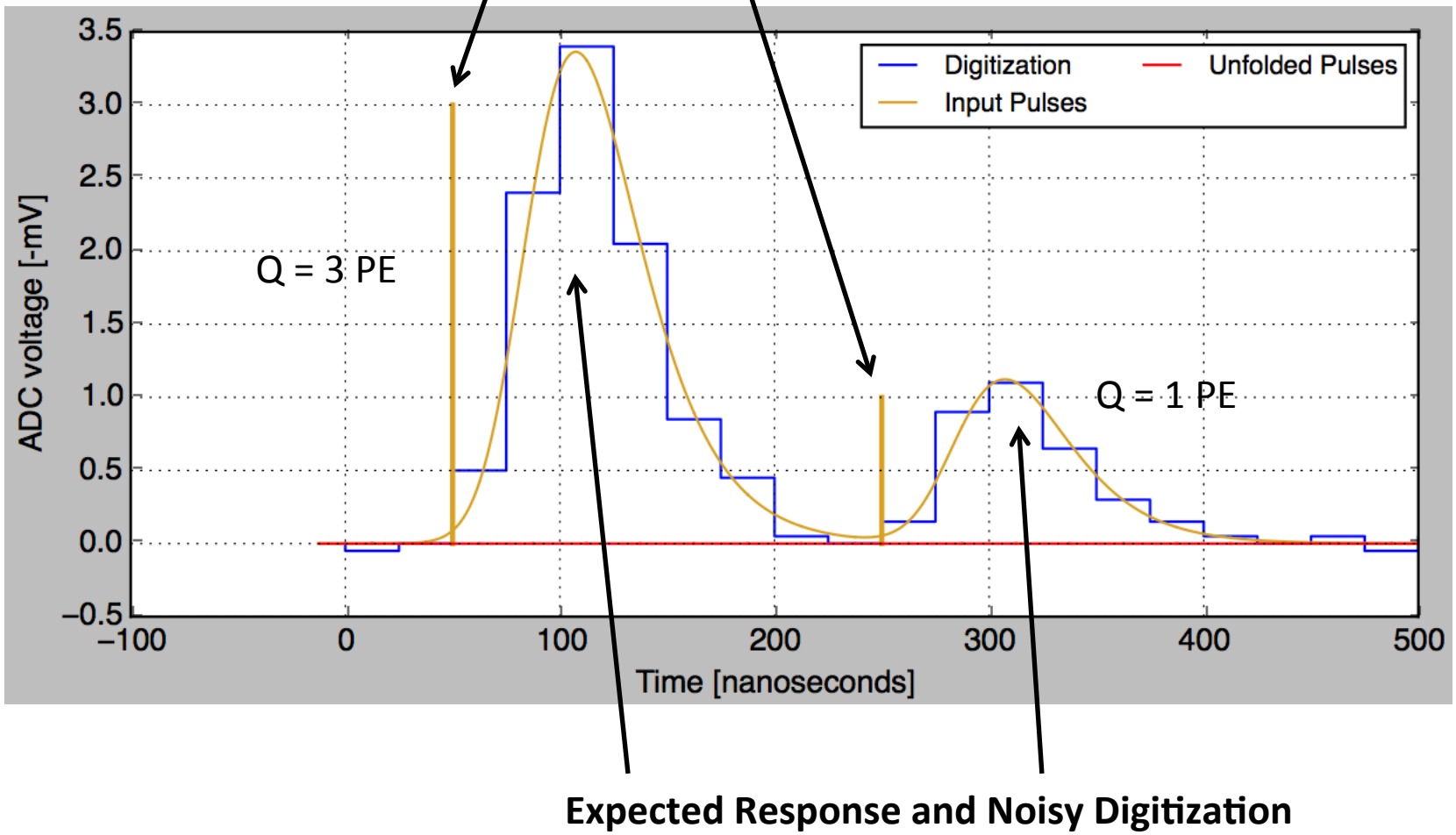


Illustration: J. Kelly

- **Formulate the unfolding as a least-squares problem**
  - Solution is the weighted superposition of basis functions that minimizes the chi-squared (basis weight == charge)
  - Basis weights must be non-negative: we can't simply invert the basis matrix to get the answer
  - Use Lawson-Hanson NNLS: Represent the waveform using the fewest basis functions possible
  - Use relatively dense basis with 1 ns spacing
  - Use IceCube "road-grading": bins within 2σ of noise are set to zero

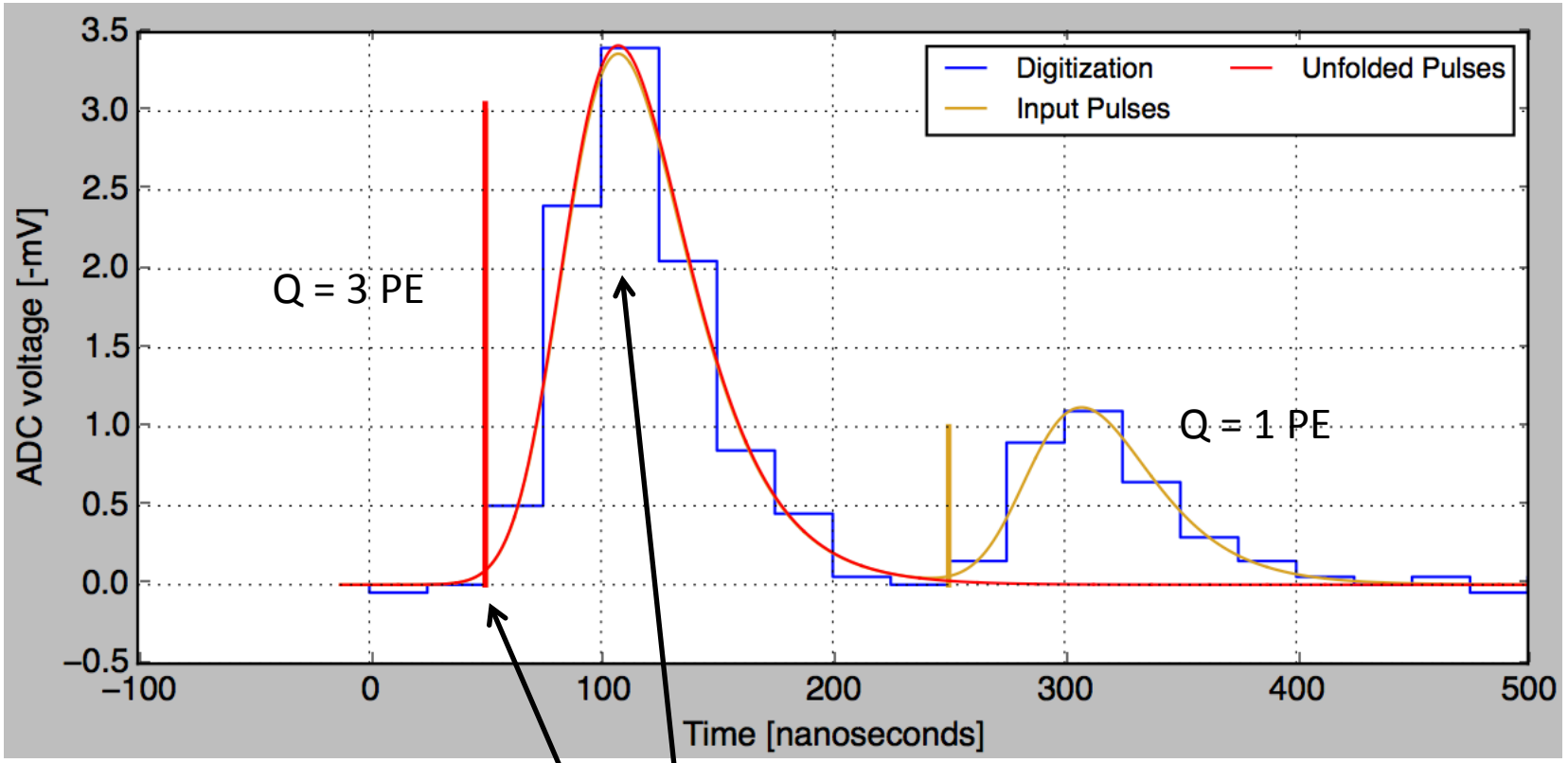
Waveform Unfolding

- **Initial:**



Waveform Unfolding

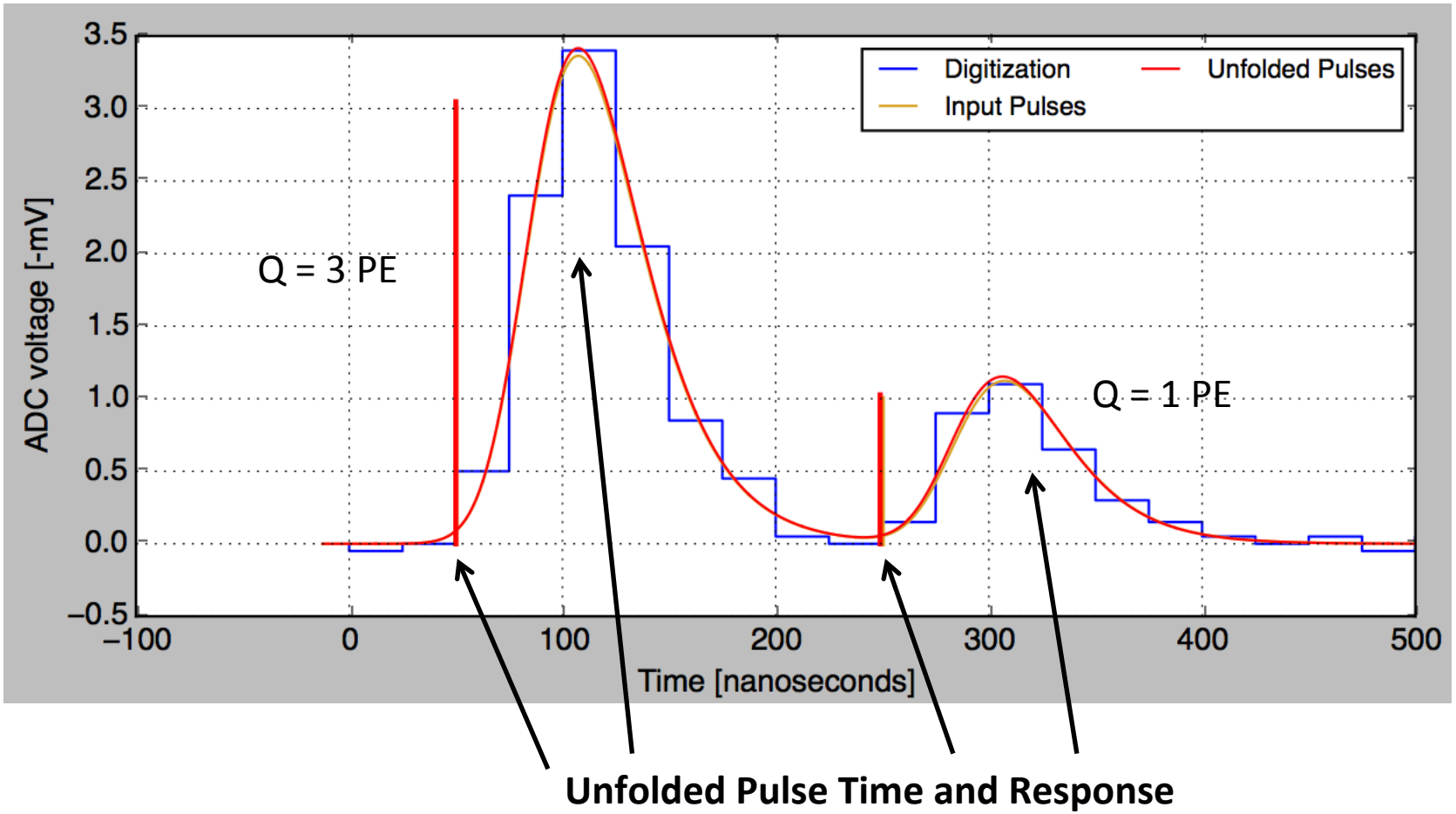
- **Iteration #1:**



Unfolded Pulse Time and Response

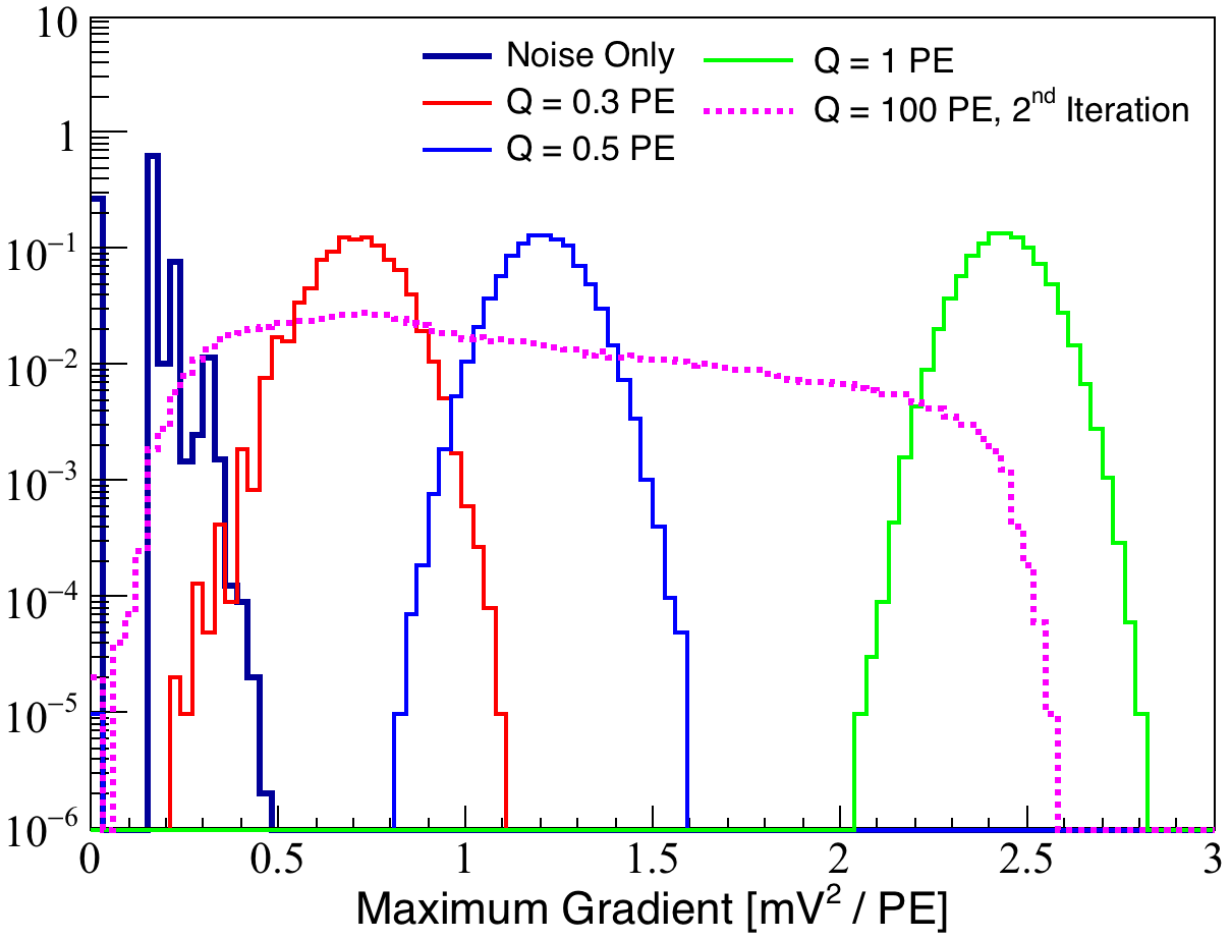
Waveform Unfolding

- **Iteration #2:**



Free Parameter: Stopping Tolerance

- **Add pulses to the waveform in order of max basis gradient**
  - Stop when no member of basis set has a gradient larger than specified tolerance
  - Determine best tolerance by injecting noise only and single pulses

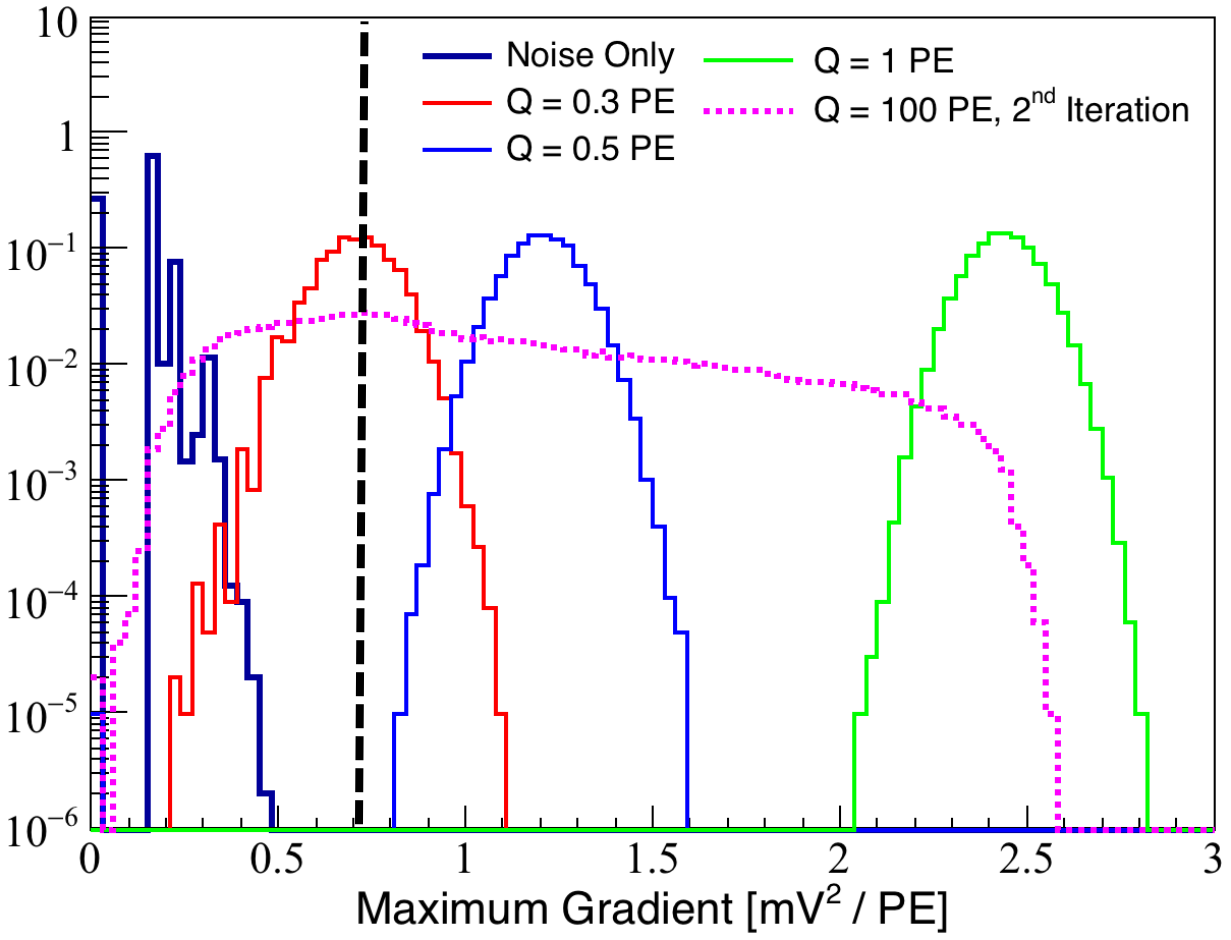


Free Parameter: Stopping Tolerance

- **Add pulses to the waveform in order of max basis gradient**
  - Stop when no member of basis set has a gradient larger than specified tolerance
  - Determine best tolerance by injecting noise only and single pulses

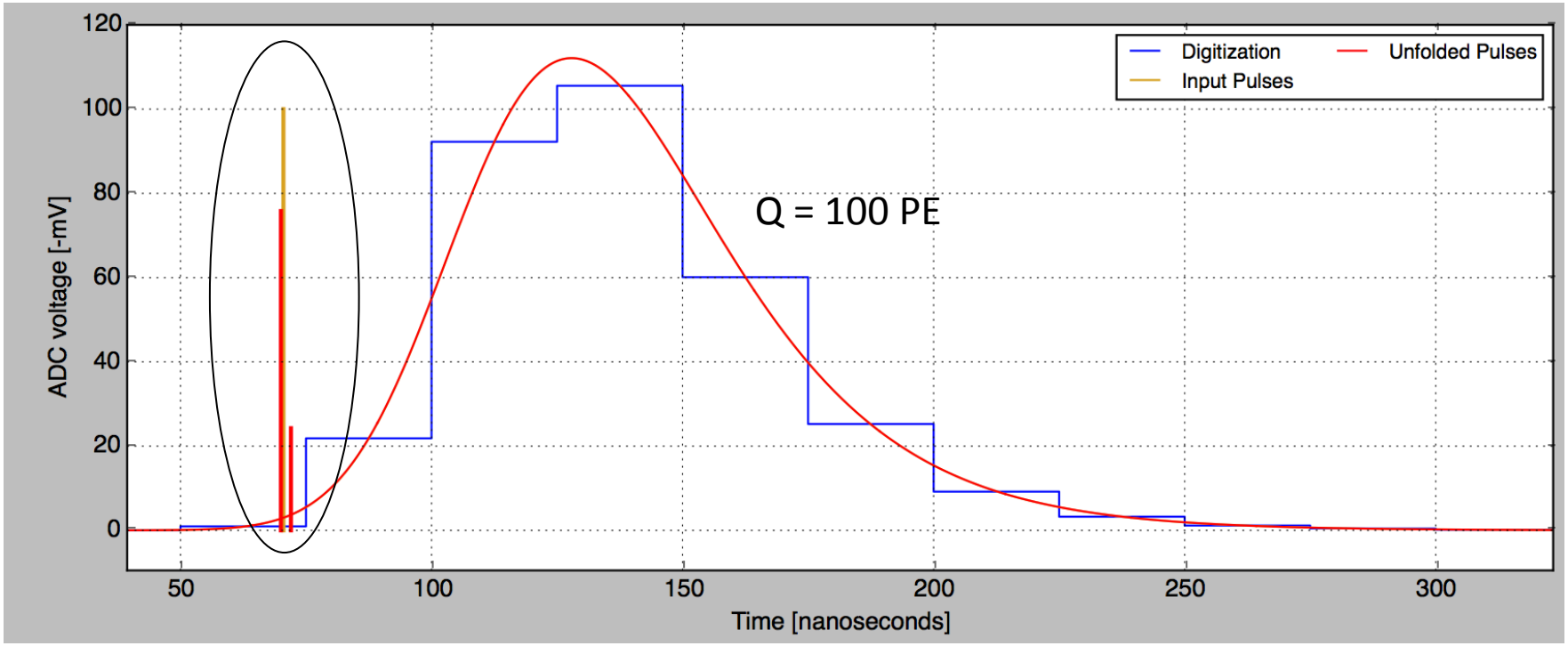
- **0.7 mV^2/PE tolerance avoids noise-only pulses and captures ~50% of 0.3 PE pulses**

- **Produces a 2nd pulse for ~50% of 100 PE pulses**



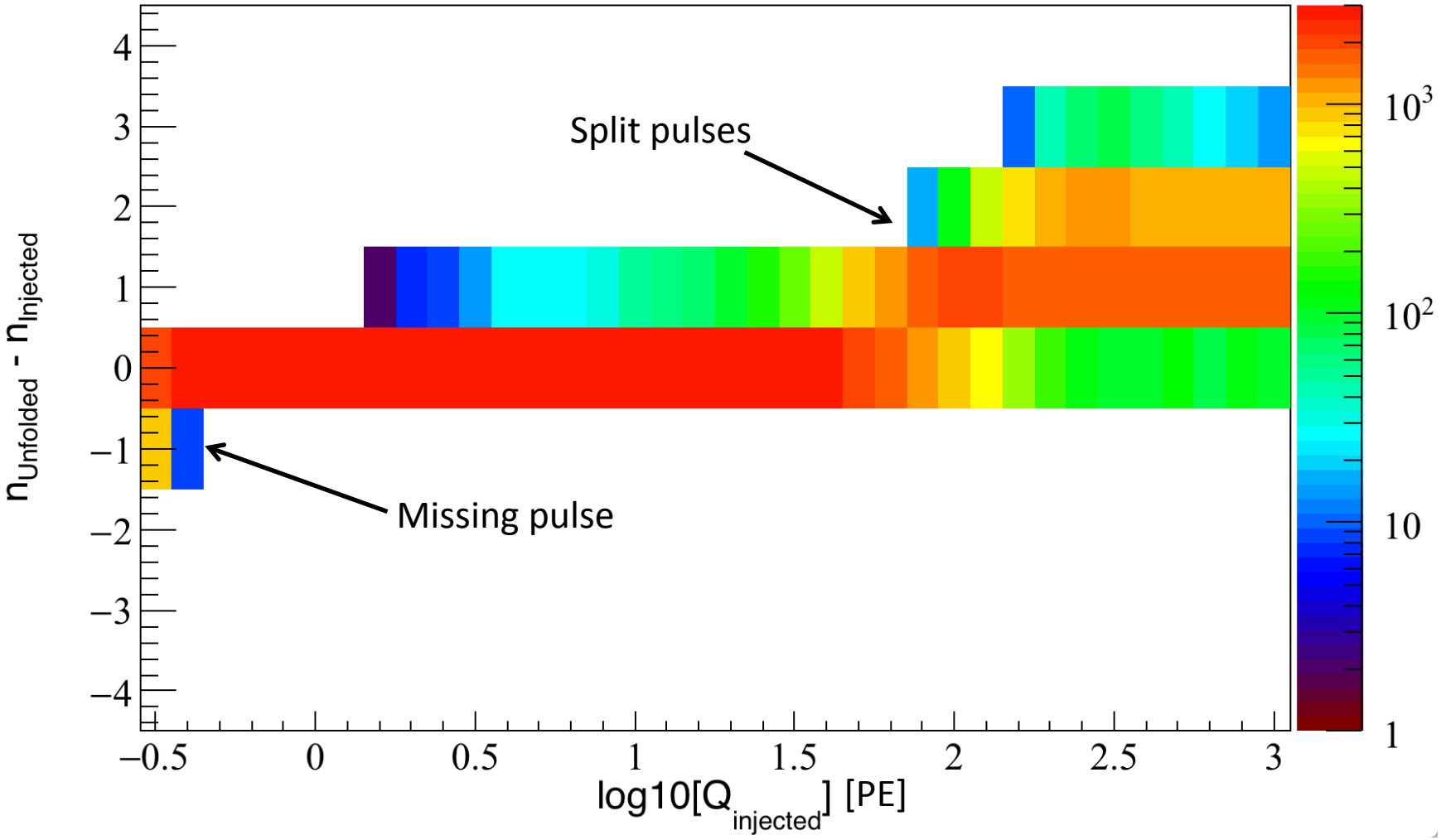
Split Pulses

- **Occurs when pulse is injected in between start times in basis**



- **Data is fit nearly perfectly with unfolded solution**
- **Unfolding problem is extremely underdetermined**
  - Behavior like this is impossible to avoid

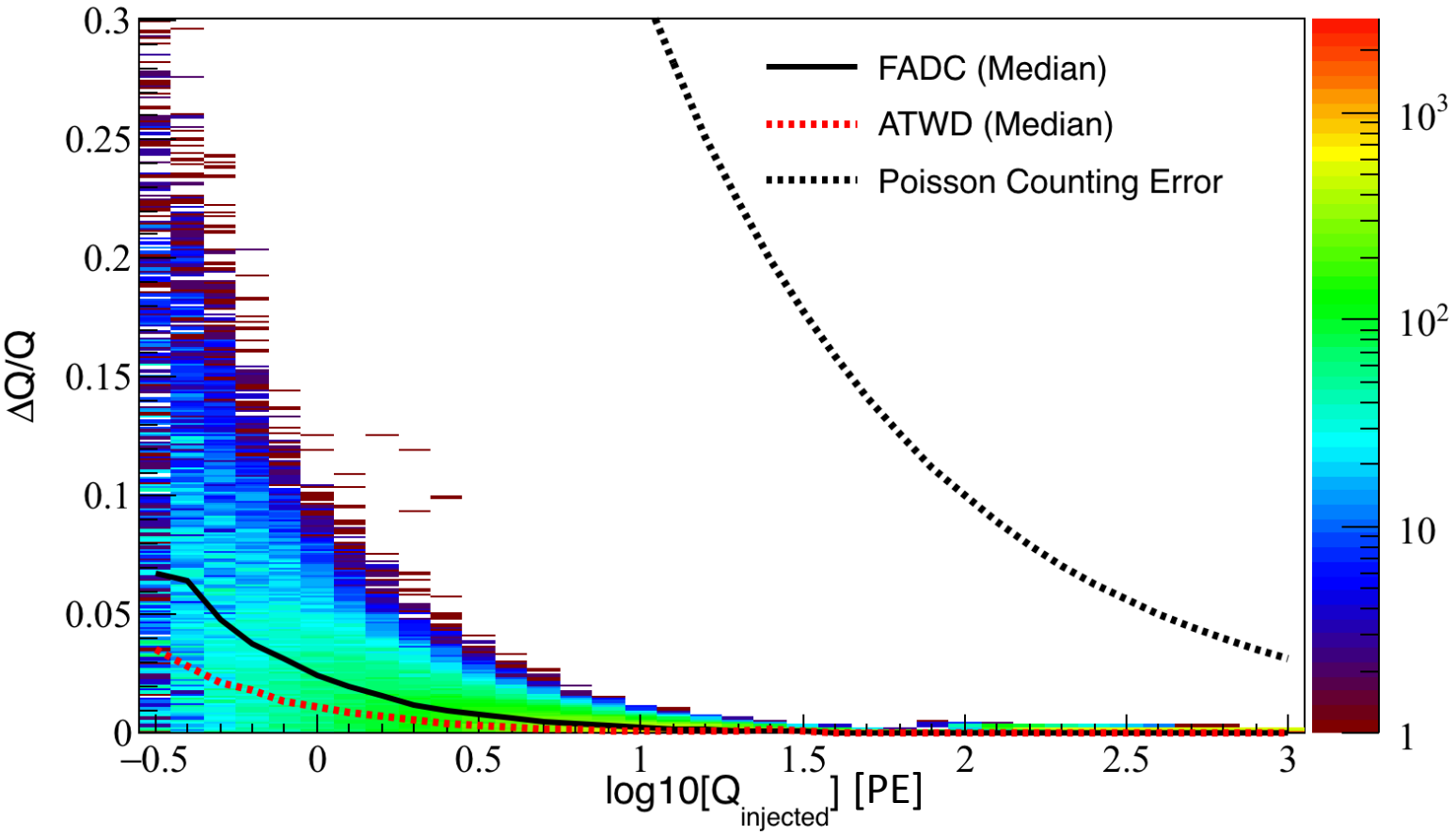
Split Pulses



- **Pulses > ~50 PE tend to be split**
- **Splitting pulses isn't necessarily bad**
  - Photons don't all arrive at the same time in real life

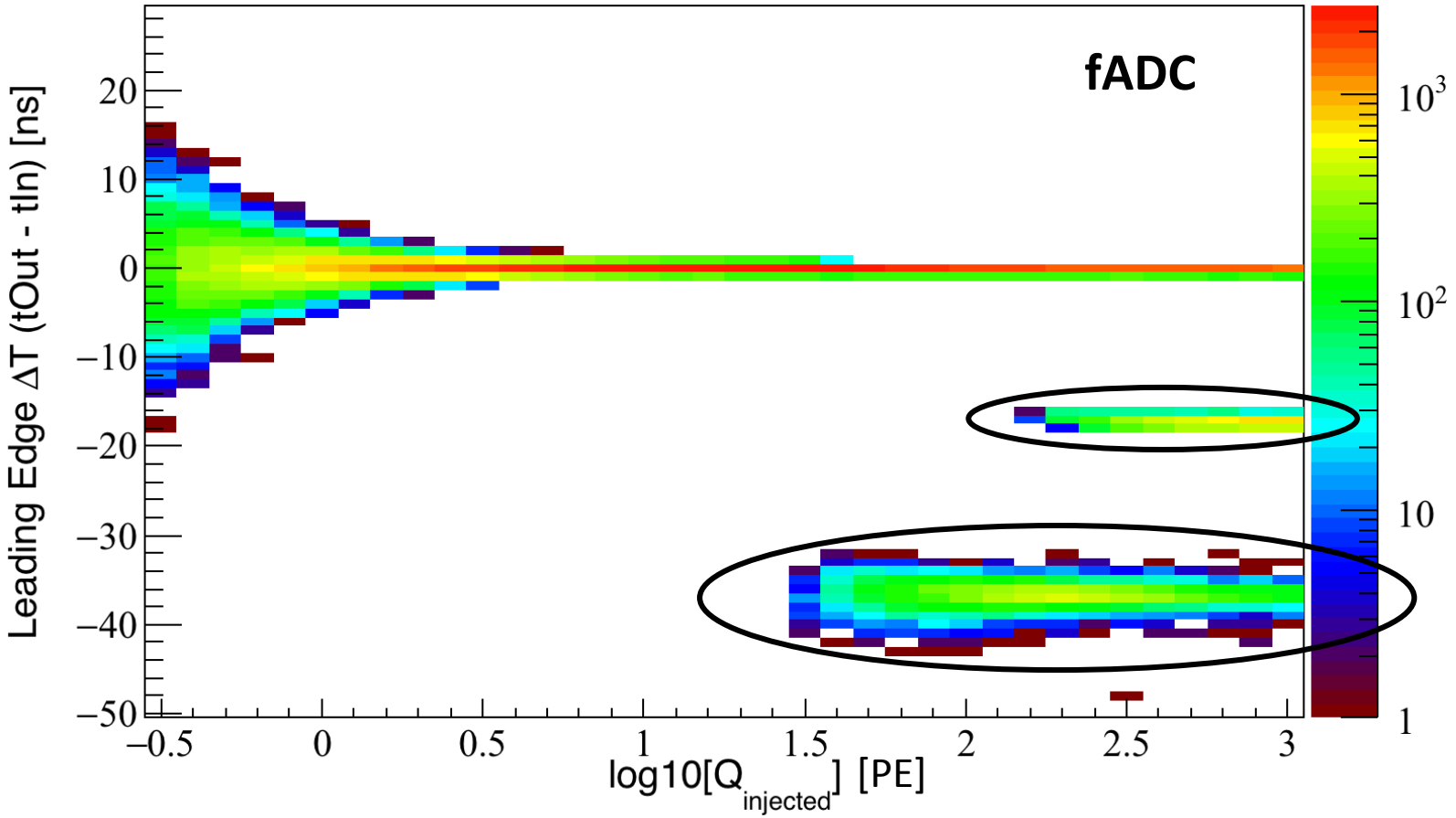
Charge Resolution

- **Inject single pulses with charge 0.3 PE < Q < 1000 PE**



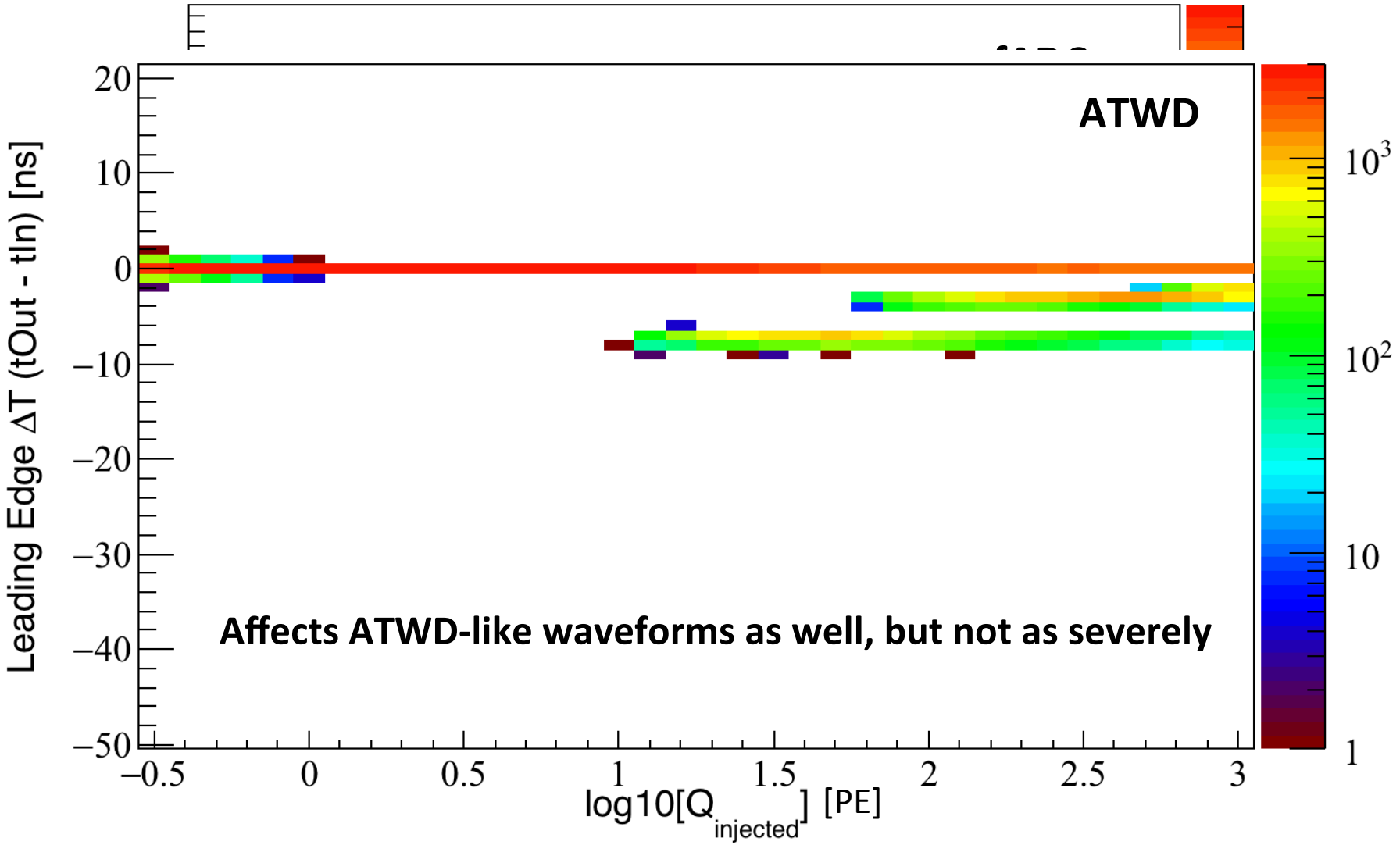
- **Poisson error dominates if using Q_unfolded to measure amplitudes**
- **Resolution better than 1 PE over entire range of Q_injected**
- **Shouldn't be significantly different with more complex waveforms**

Leading-Edge Time Resolution



- **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**

Leading-Edge Time Resolution

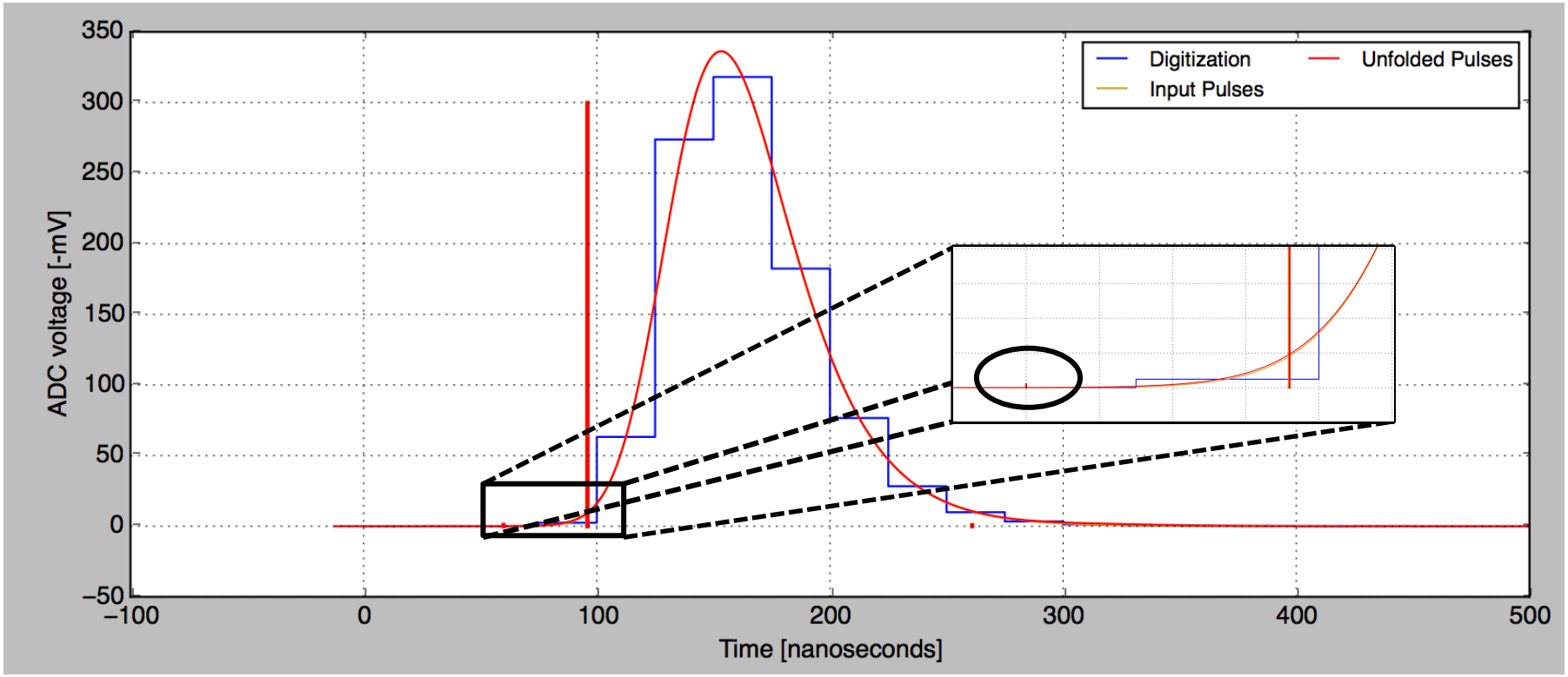


- A single early pulse can significantly affect track reconstruction

- **This is a major problem**

Leading-Edge Time Resolution

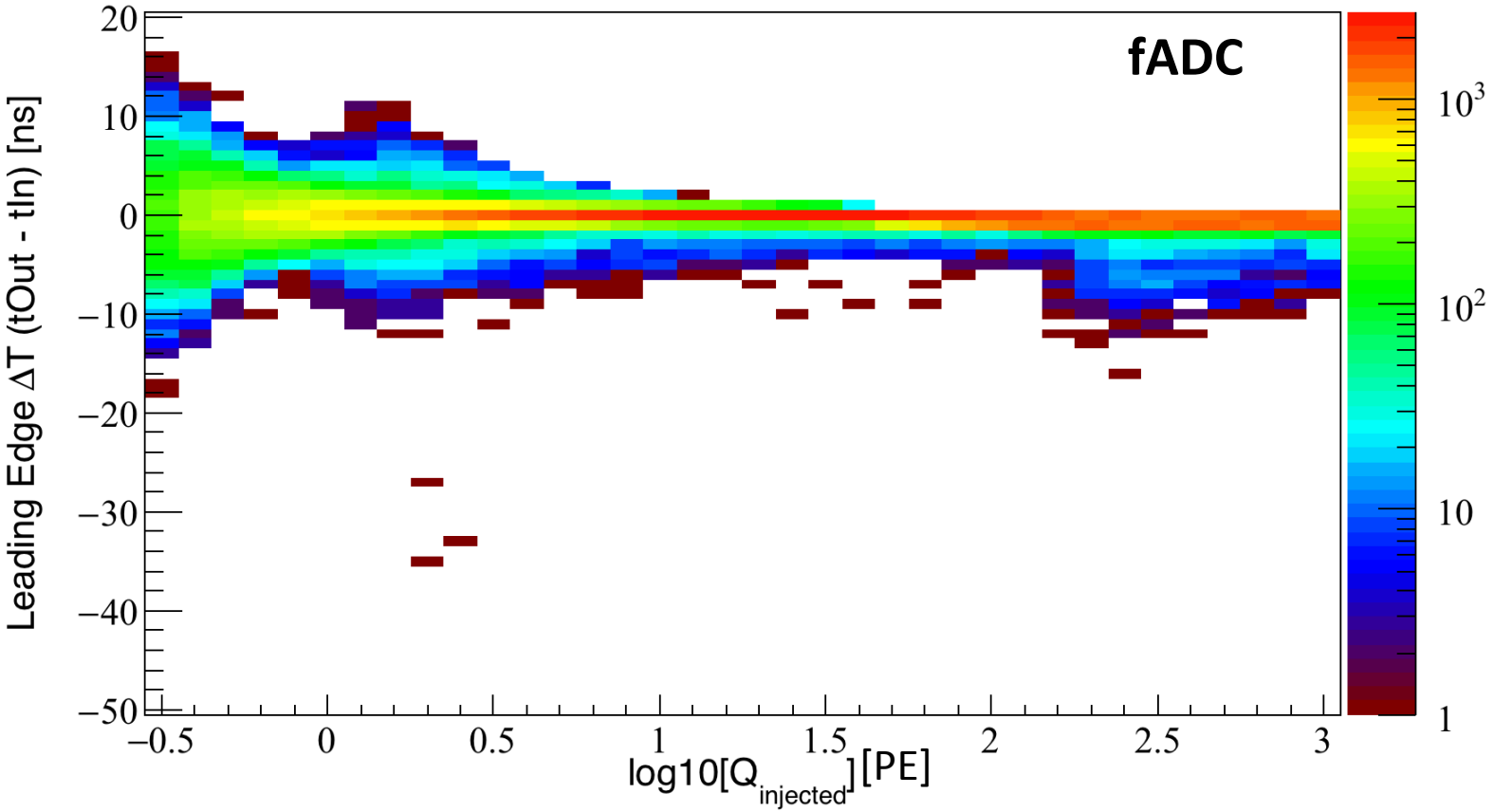
- **Mechanism: Large pulse immediately preceding a start time in basis**
  - Algorithm adds a pulse 1-2 waveform bins earlier to match leading edge



- **Best description of waveform is a superposition of start times on either side of start time of injected pulse**
  - This solution is not considered because tolerance is reached before neighboring basis function is allowed to become nonzero

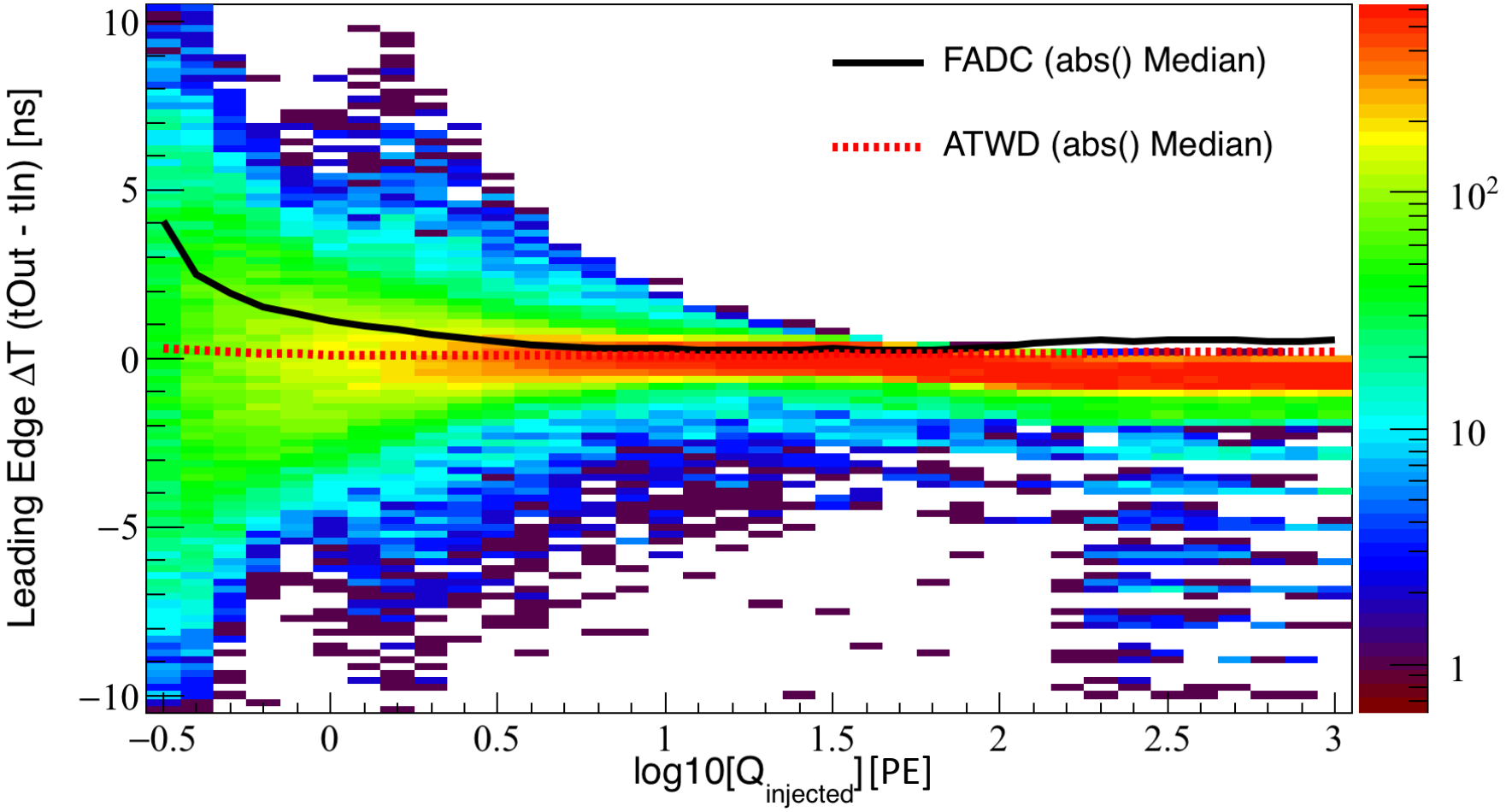
Leading-Edge Time Resolution

- **Ad hoc solution: Run unfolding until no basis has a positive gradient, then add back basis in order of charge until tolerance is reached**



- **Significantly reduces artificial early start times**
- **Work to improve algorithm is needed and is ongoing**
- **This problem indicates that waveform templates must be precise!**

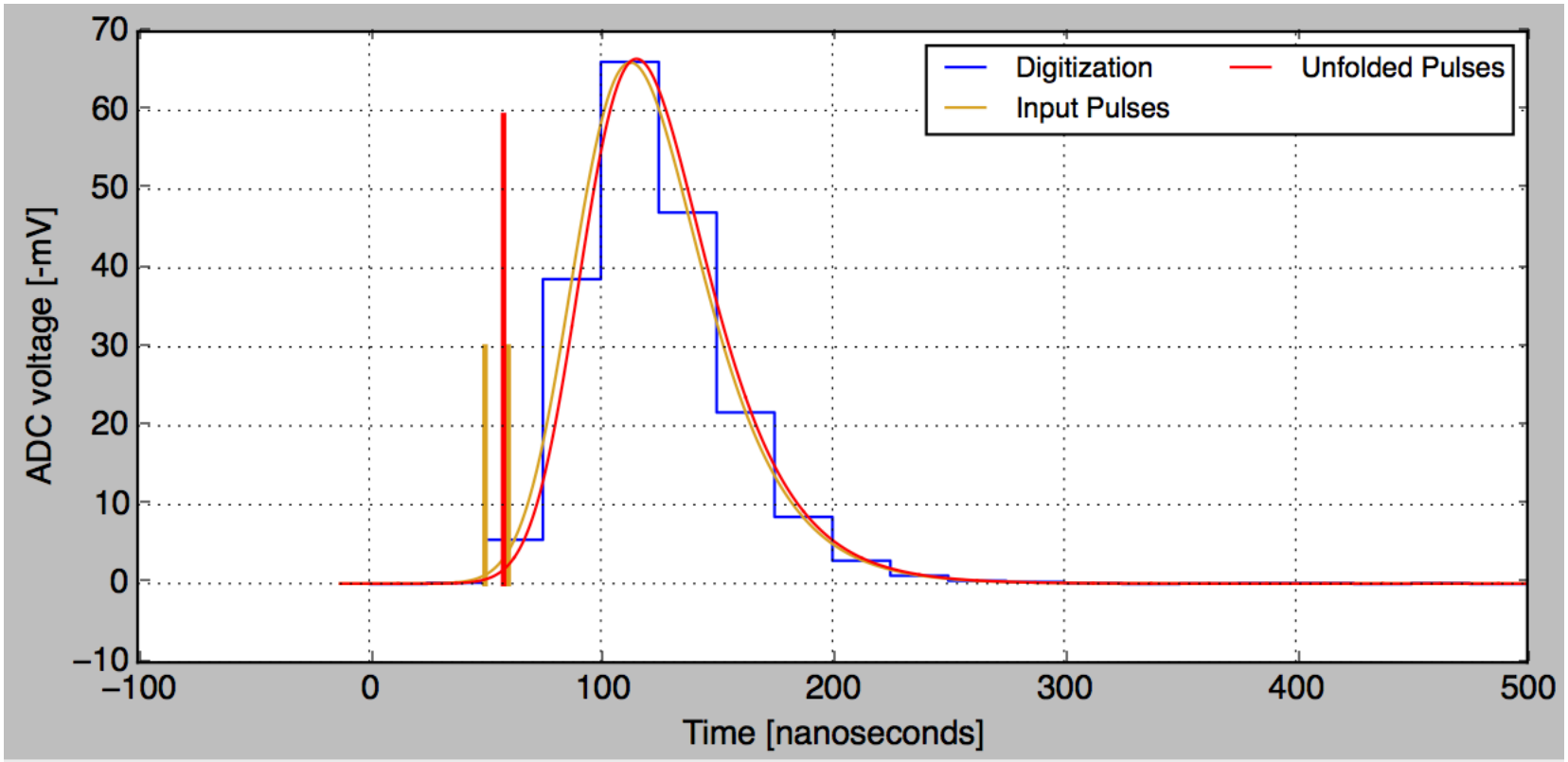
Leading-Edge Time Resolution



- **Median timing uncertainty from unfolding already near 1 ns at 1 PE**

Double Pulse Resolution

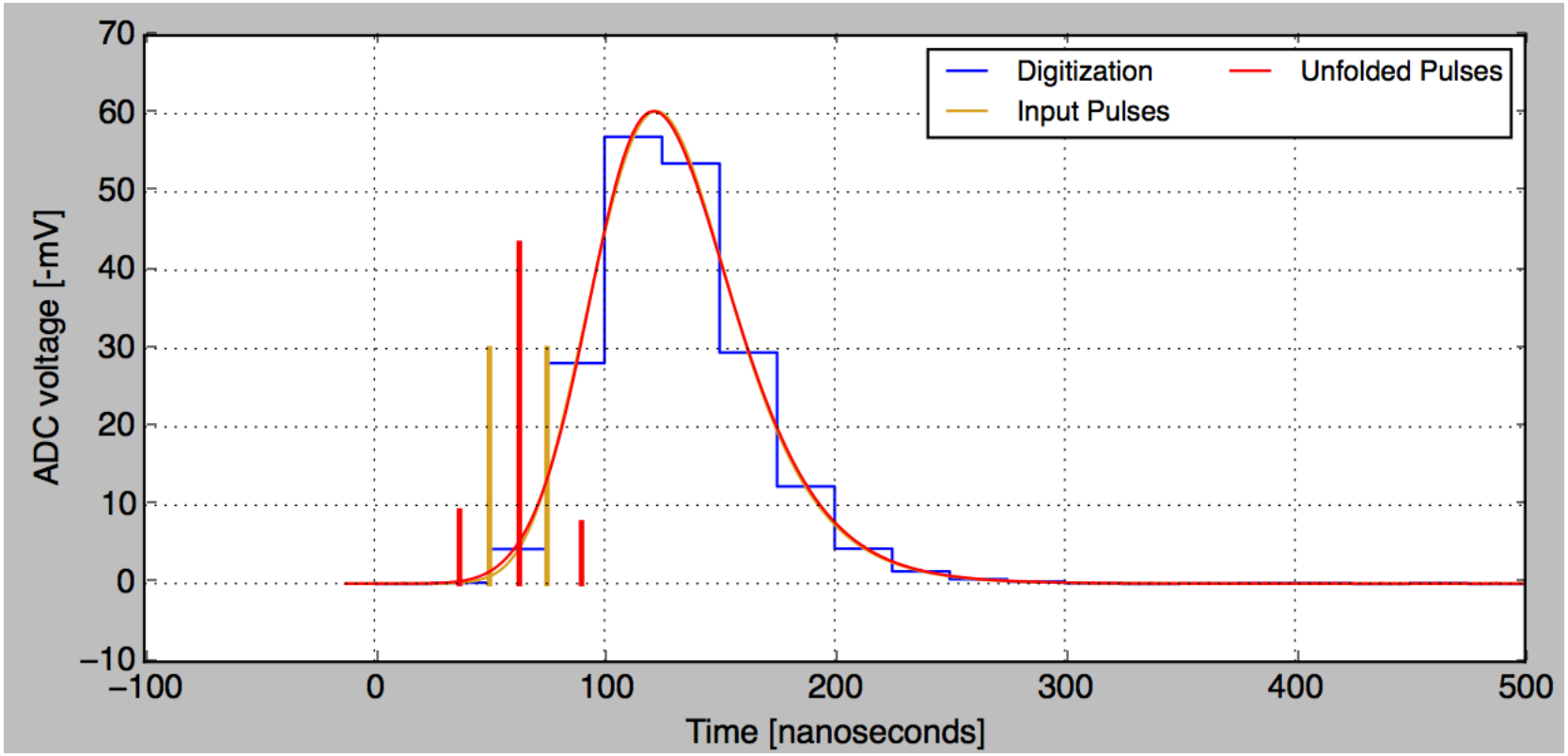
- **Inject two pulses: Q1 = Q2 = 30 PE**
- **ΔT = 10 ns**



- **Double pulse not resolved**
- **Treated as single, large pulse**

Double Pulse Resolution

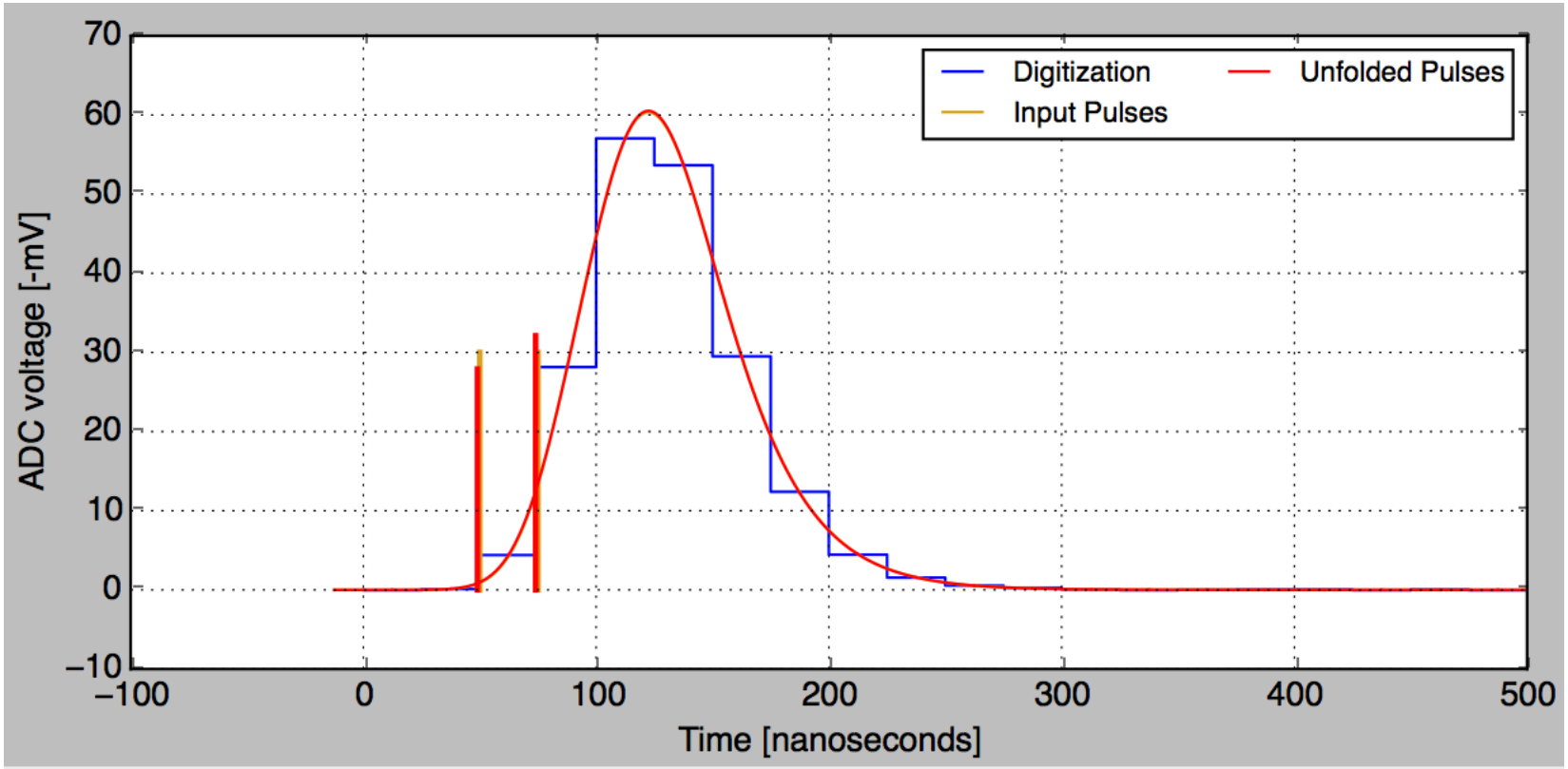
- **Inject two pulses: Q1 = Q2 = 30 PE**
- **ΔT = 25 ns**



- **Waveform unfolded into three pulses, with largest in the middle of the two injected pulses**

Double Pulse Resolution

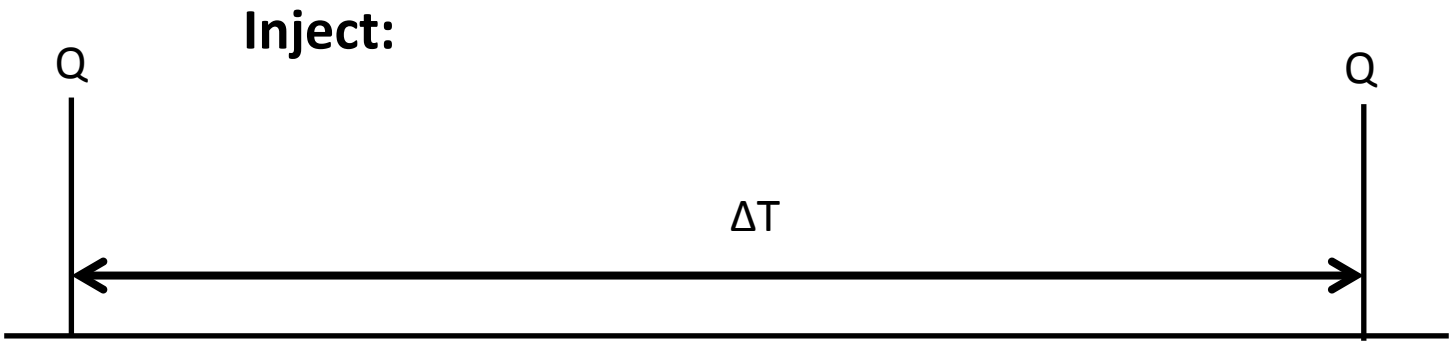
- **Inject two pulses: Q1 = Q2 = 30 PE**
- **ΔT = 25 ns**

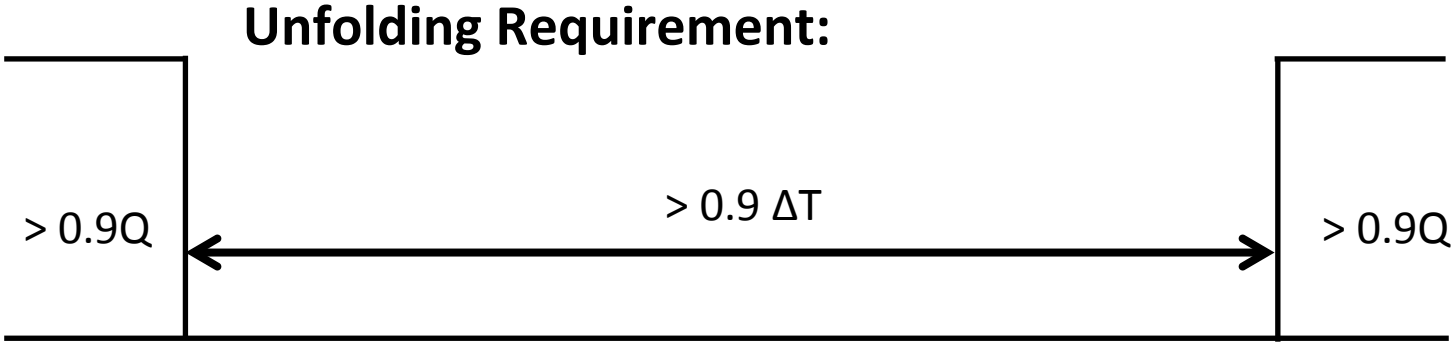


- **Same waveform, but with unfolding modifications from leading edge study**
- **Double pulse resolved even though not obvious from waveform by eye**

Double Pulse Resolution

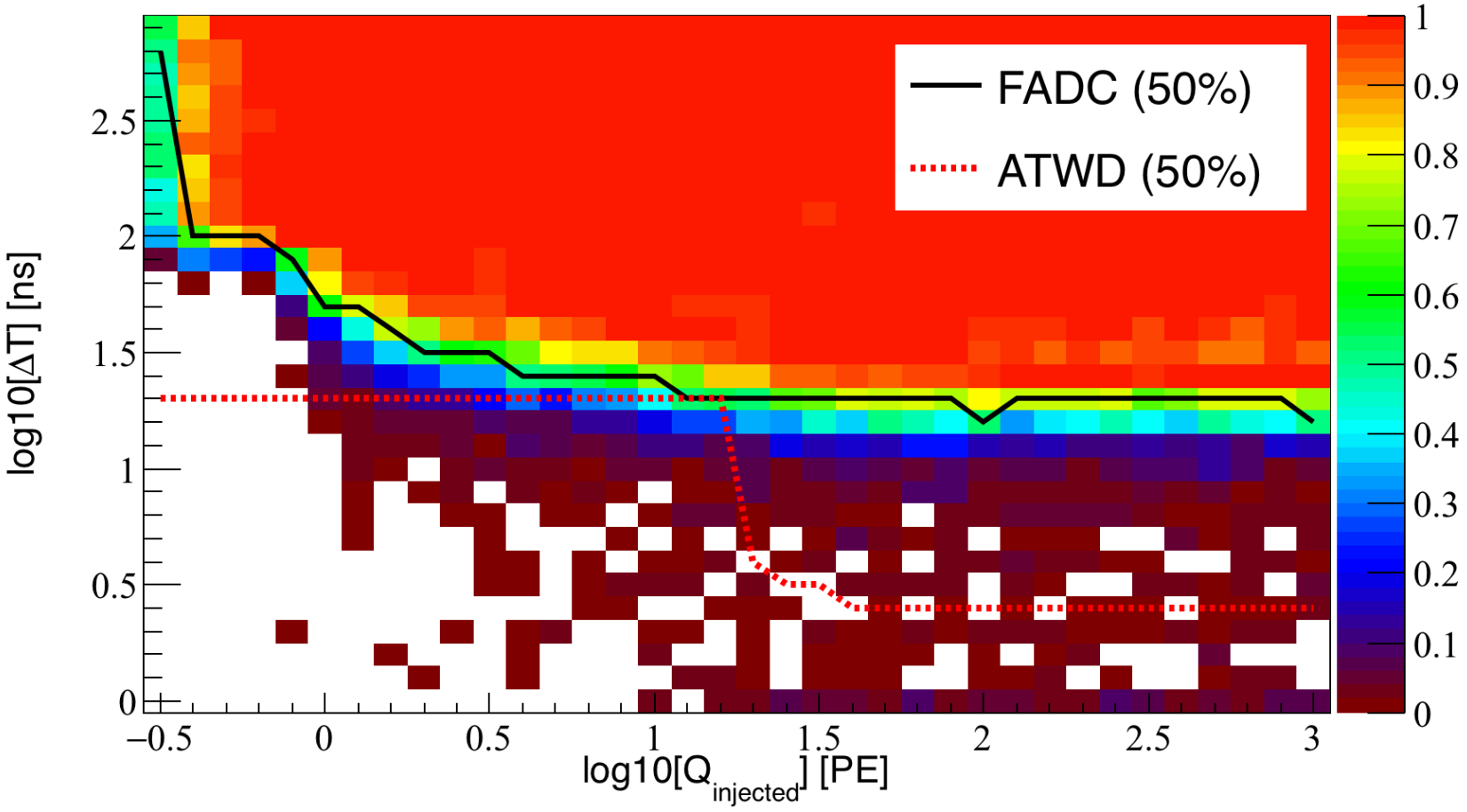
- **Inject two pulses, each with charge Q and separation ΔT**
- **Declare double-pulse resolved if there is a gap of at least 0.9 * ΔT inside the 0.45 – 0.55 quantiles of unfolded charge**





Double Pulse Resolution

- **Fraction of double pulses resolved**



- **Q = 1 PE: ~50 ns**
- **Q > 10 PE: ~20 ns**
- **Not fully optimized!**

Conclusions and Caveats

- **We can extract charge and leading edge time from a 40 Msps waveform with accuracy better than other limitations (i.e. Poisson sampling, time calibration, etc.)**
- **We make the implicit assumption that the SPE template used for unfolding is the same one that we injected**
  - If SPE template used for unfolding is not correct, results could be very different, particularly for large pulses
  - SPE pulse templates probably need to be more accurate than those used in IceCube
- **The performance of wavedeform out-of-the-box is unacceptable for this use case**
  - Modifications to the algorithm yield acceptable performance
  - Additional work likely needed if single 40 Msps digitizer is used in Gen2

Extra Slides