Brainstorming Real-Time/ML-Based Signal Processing for Fiber Cherenkov Readout

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Introduction & Motivation

- Interested in understanding real-time/FPGA(eFPGA) feasibility of fast C pulse resolution
- Existing effort from TTU [eg. 25 June] on LSTM, CNN, etc.
- Our interest: simple/compressed models; how high can we keep performance while getting to very low latency/resources?
    - In parallel, interest from engineers at SLAC on analog vs. digital signal processing

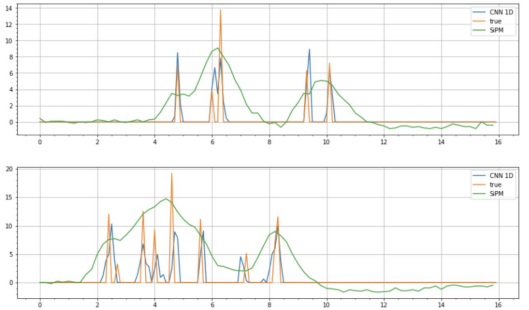
To do:

➔ Harmonize C pulse generation (eg. SiPM photon template, efficiency, noise, …)

➔ Motivate real-time: understand data rate, compare to simple analog processing, etc.

Time separation between pulses ranged 0-2.6 ns

Overall arrival time is varied bv ±0.8 ns

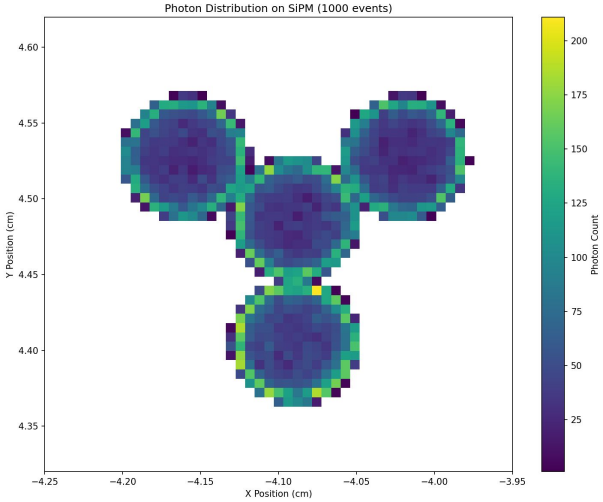


seems possible to deconvolve overlapping SiPM (Cherenkov) pulses to reveal the true distribution of shower components using CNN:

Fiber Calorimeter Waveform Simulation Pipeline

Step 1: Photon Filtering

- Load photon data (x,y,z,t) from ROOT files (HG-DREAM G4 simulation)
- Apply spatial filters (SiPM active area, x[-4.25,-3.95], y[4.32,4.62] cm for now)
- Filter by photon type (Cherenkov core only)

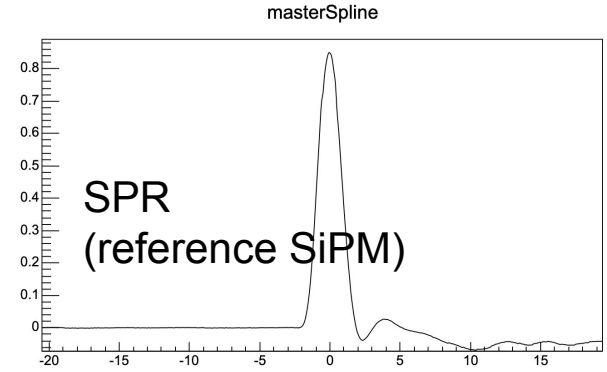


Step 2: Detection Physics

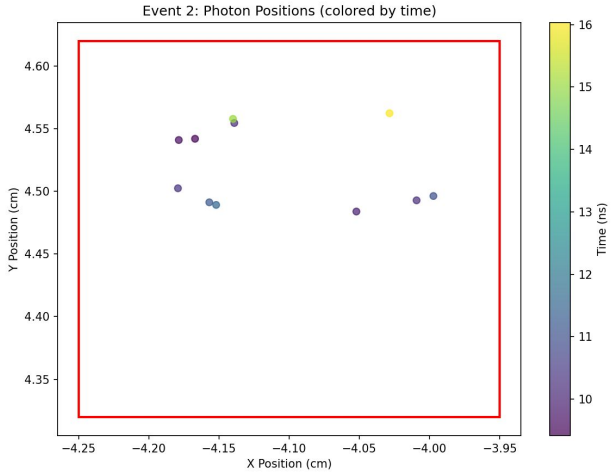
- **Quantum Efficiency**: Random photon detection (default 30%)
- **Timing Jitter**: Gaussian timing uncertainty (default 200 ps)
- **Gaussian Noise**: Scale based on baseline RMS estimation (Need to refine this.)

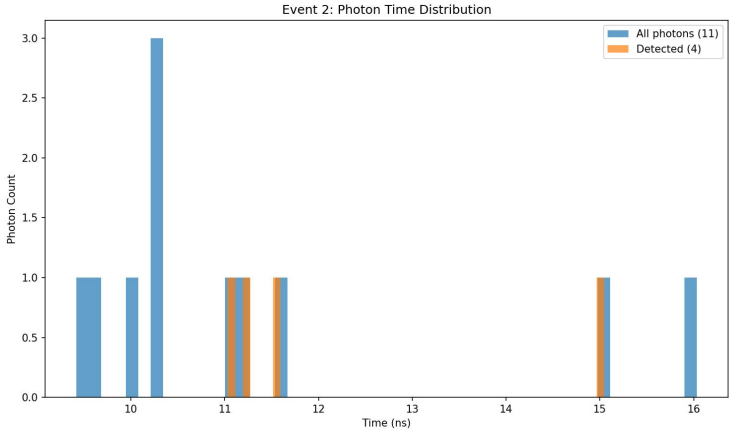
Step 3: Waveform Generation

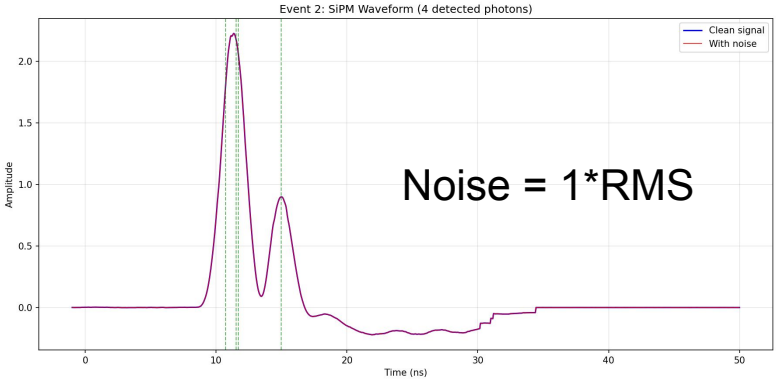
- Convolve detected photons with SiPM pulse shape
- Sum individual pulse responses (apply physical factors)
- Apply time window [-1, 50] ns with 0.05 ns sampling
- Store final waveforms in h5 format. (waveforms, truth time, jittered time, quantum efficiency filtered time)

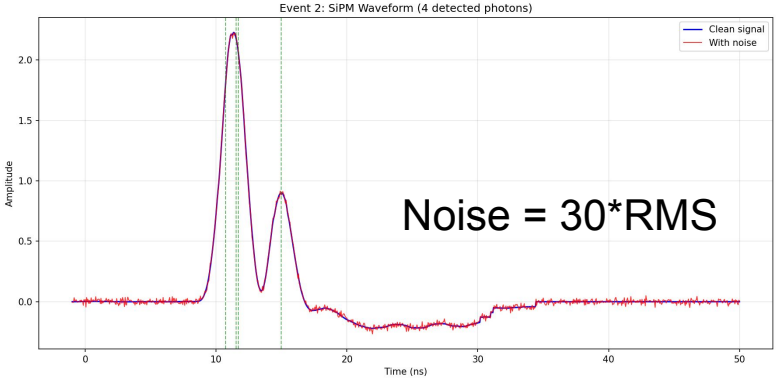


Event Display (Event 2)



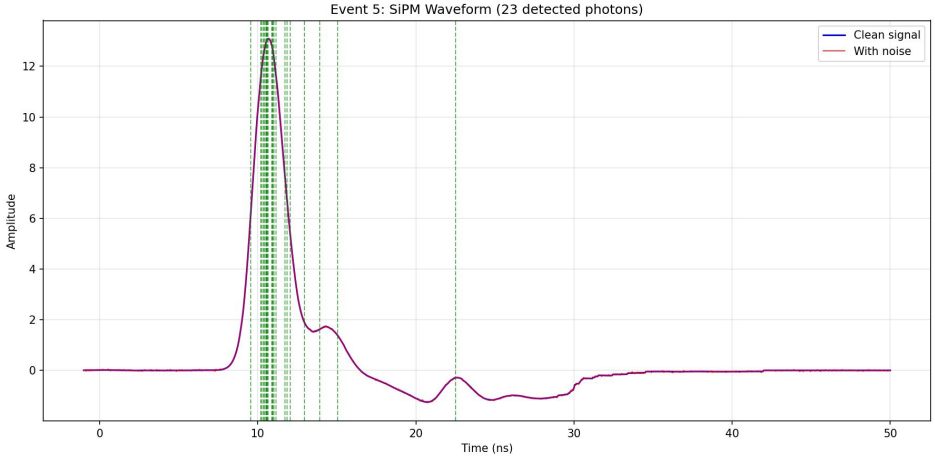


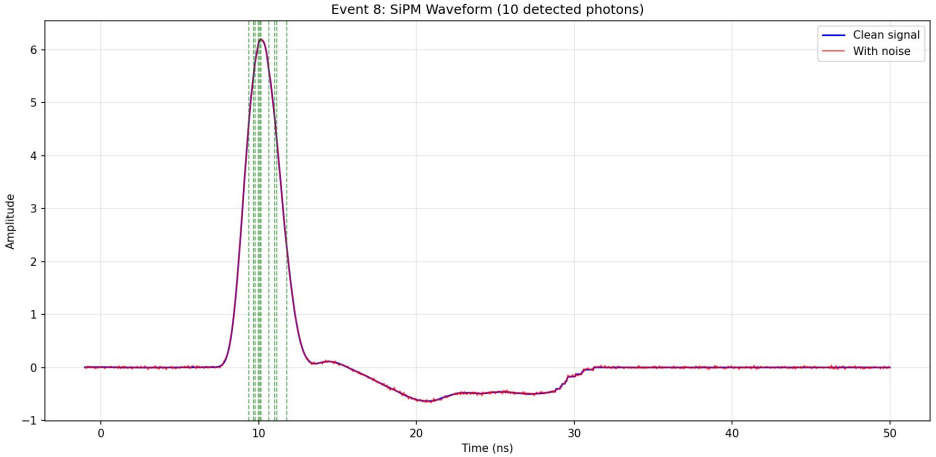


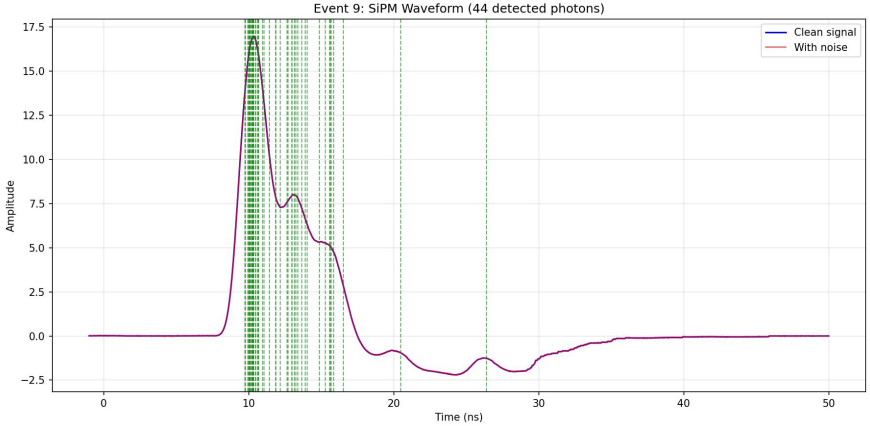


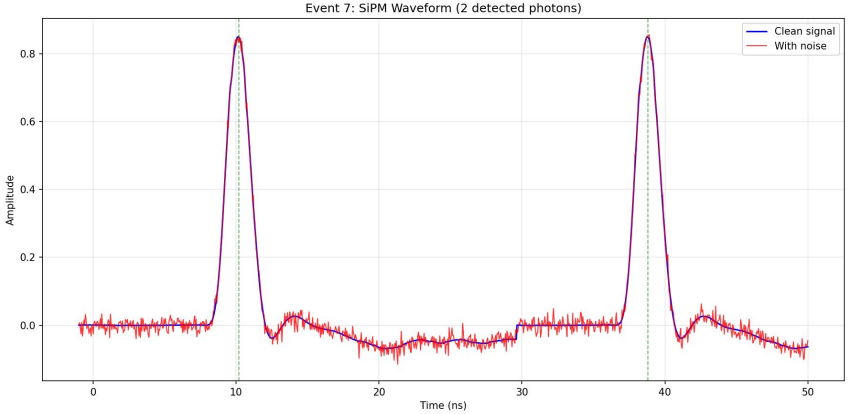
- The noise of g-2 SPR is really low. (need to amplify this)
- Green dashed lines are photon arrival times (after applying timing jitter).

Event Display (More)









Backup

Crystal Calorimeter Waveform SDL-based Synthesis

Step 1: SPR Template Loading

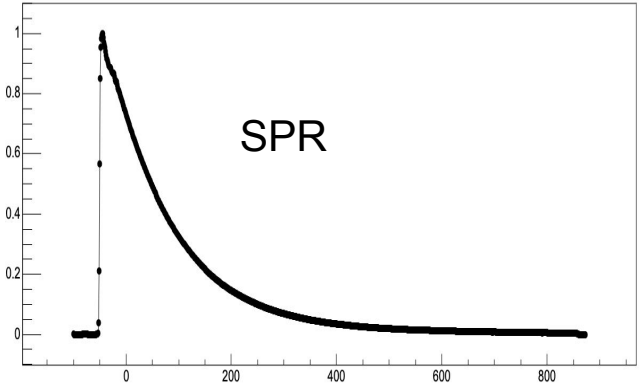
- Load real Cherenkov SPR data (from Broadcom SiPMs?)
- Generate Scintillation response from Cherenkov template
- Apply DSB scintillator physics: 13% @ 100ns + 87% @ 500ns decay

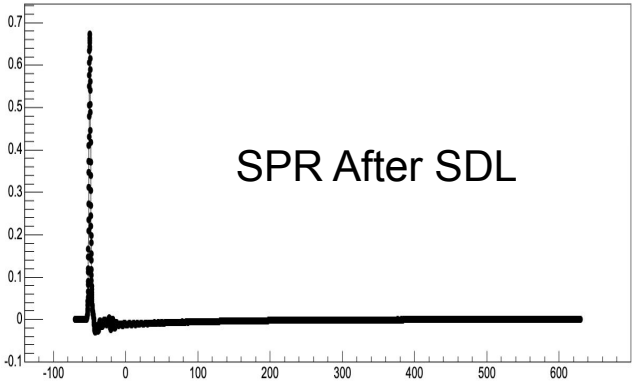
Step 2: Detection Physics

- **C&S Components**: Can be manually configured
- **Timing Jitter**: Gaussian timing uncertainty (default +-600 ps)
- **System Parameters**: Trigger time (145-160ns), baseline (350-430mV)
- **Noise Modeling**: Gaussian noise (0.5-4.0mV std)

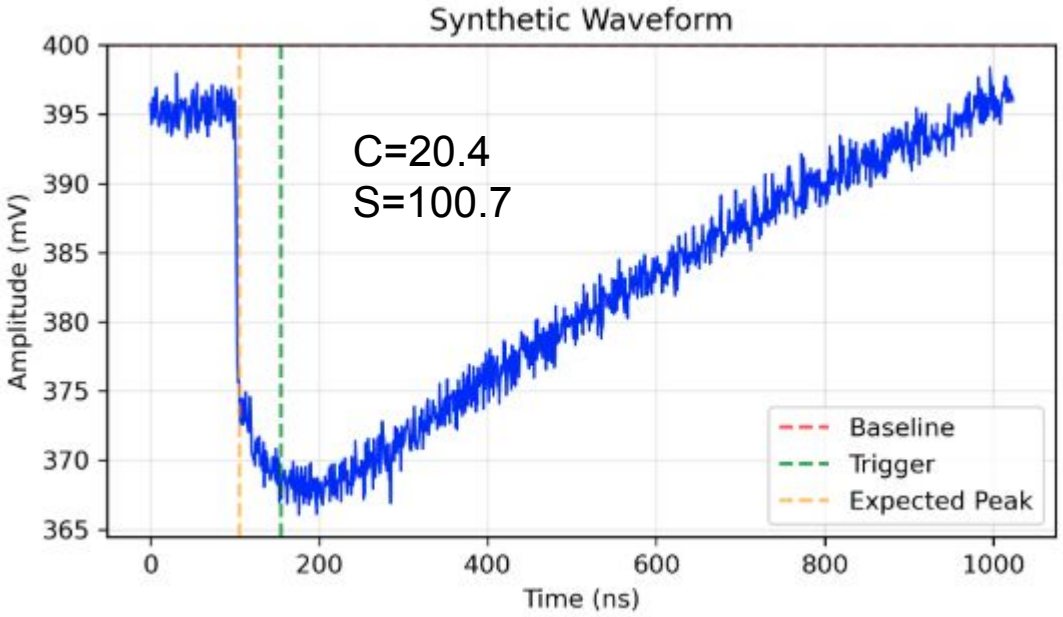
Step 3: Waveform Generation

- Convolve C&S components with respective SPR templates
- Apply time jitter and trigger timing offsets
- Reconstruct analog waveform via inverse SDL method
- Add realistic noise
- SDL Validation (optional)





Crystal Calorimeter Waveform SDL-based Synthesis

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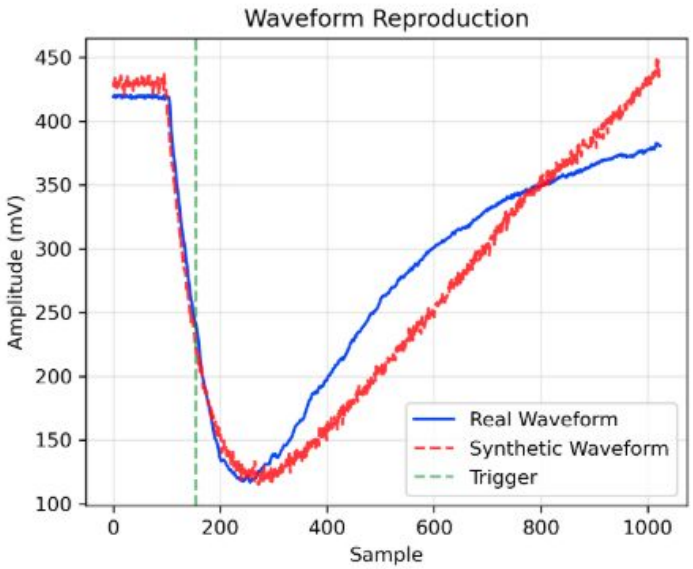
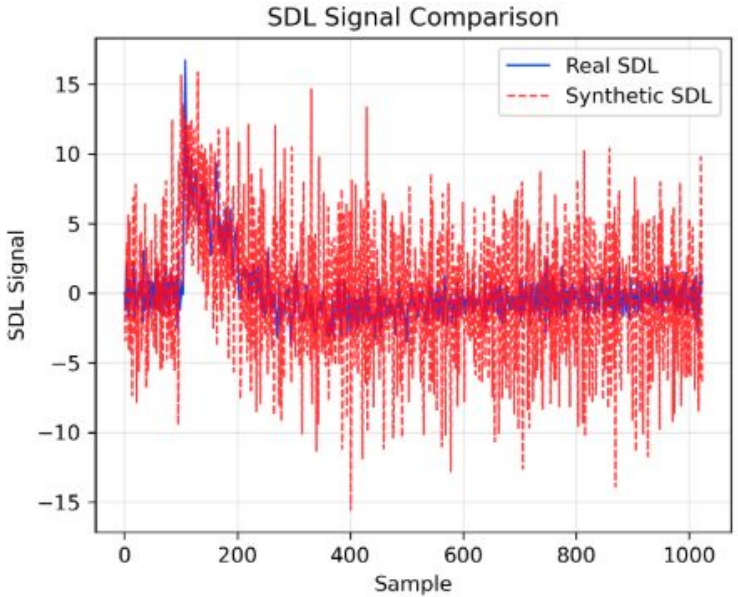
Synthesis Parameters:
Input C: 20.40
Input S: 100.70
Synthesis Time Jitter: -0.078 ns
Synthesis Baseline: 395.5 mV
Trigger Time: 152.6 ns
SPR Peak: -49.65 ns

SDL Validation:
Extracted C: 19.38
Extracted S: 100.84
Extracted Time Jitter: +0.042 ns
C Error: 1.02 (5.0%)
S Error: 0.14 (0.1%)
Time Jitter Error: 0.120 ns
Fit RMS: 1.482
```

Crystal Calorimeter Waveform Reproduction



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Real Waveform:
Index: 40
Target C: 16.76
Target S: 1560.39
```

- Main contribution of SDL signal locates in 0-200ns window.

```
SDL Validation:
Applied to Synthetic Waveform

Target Values:
C Component: 16.76
S Component: 1560.39

SDL Extracted:
C Component: 11.00
S Component: 1575.65
```