Waveform Feature Extraction in Belle II Time-of-Propagation (TOP) Detector

Shahab Kohani

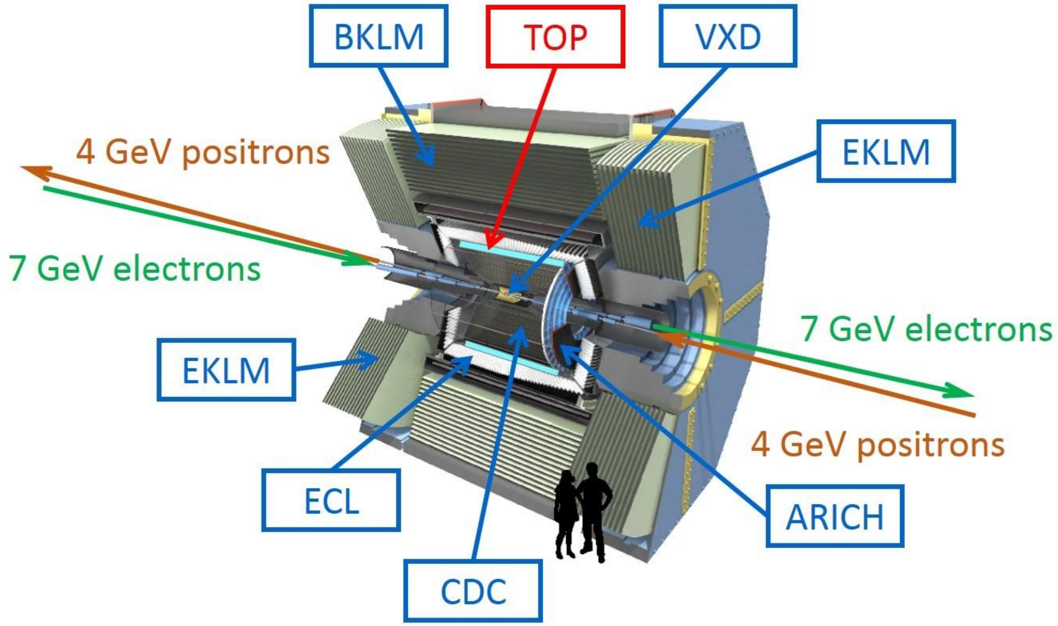
Kurtis Nishimura

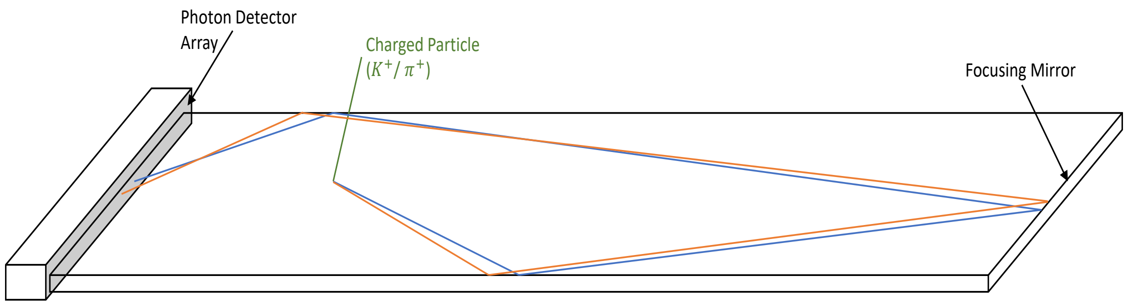
Gary Varner

Tobias Weber

Belle II Time-of-Propagation (TOP) detector

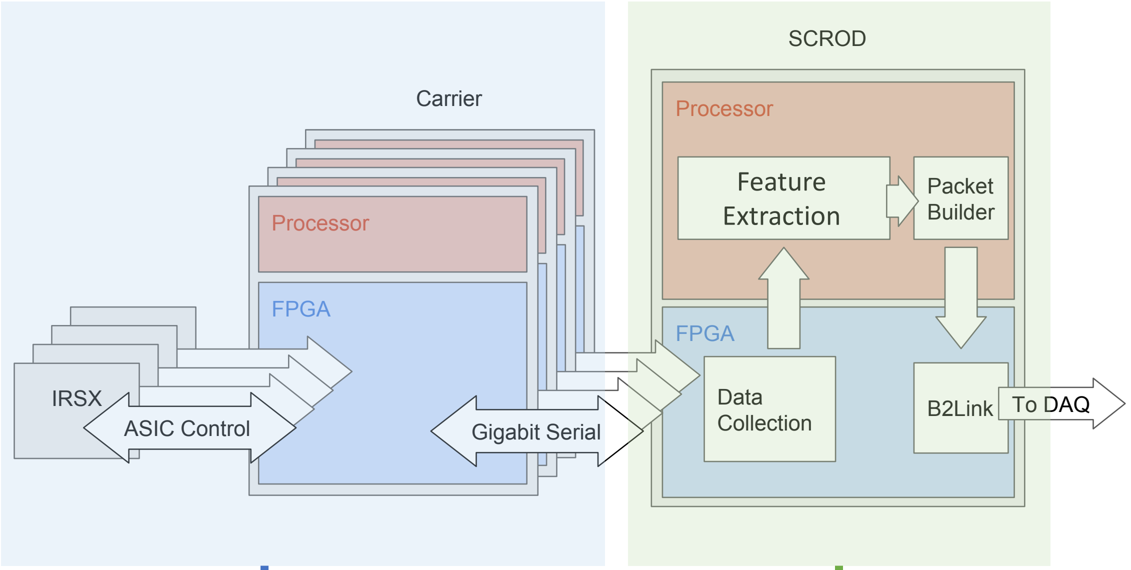
- The Belle II experiment is based at the SuperKEKB electron-positron collider (High Energy Accelerator Research Organization, Japan).
- The Time-of-Propagation (TOP) subdetector is a Cherenkov detector designed to achieve a photon timing resolution of better than 100 ps at a trigger rate of up to 30 kHz.
- When a relativistic charged particle passes through a TOP subdetector module it generates a cone of photons due to the Cherenkov effect.
- These photons are totally internally reflected and propagate through a quartz bar until they are collected by an array of microchannel plate photomultiplier tubes (MCP-PMTs).
- The generated signal is then digitized and processed by the Front-end electronic readout system.

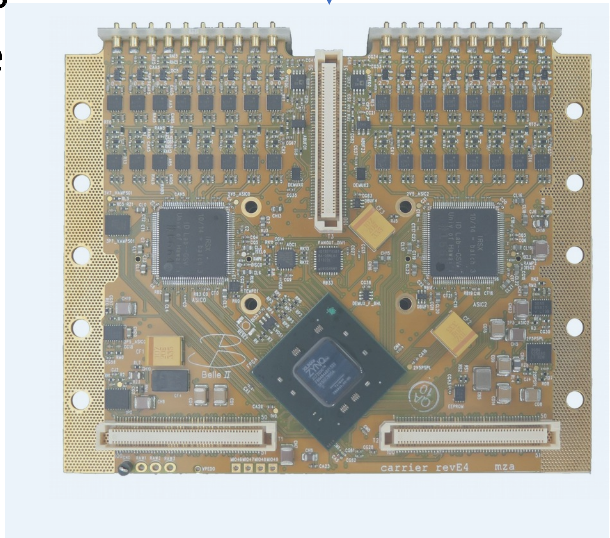


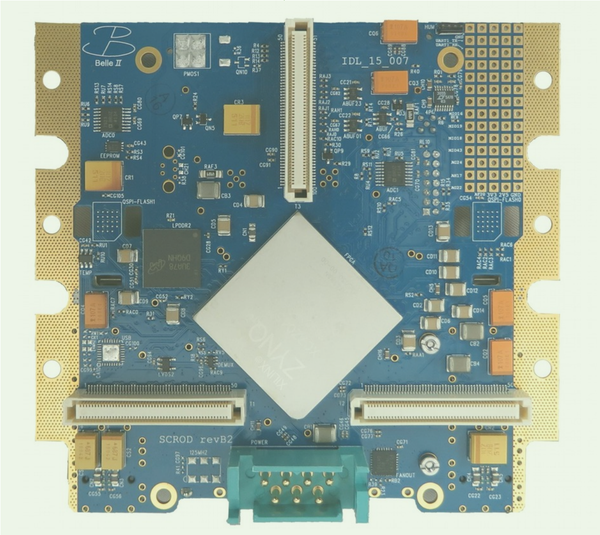


TOP Digital Front-end Readout Electronics

- In a TOP subdetector readout module the IRSX ASICs sample the analog output of the MCP-PMT sensors and convert them into digital waveforms.
- These digitized waveforms are transferred to the SCROD boards for processing. Each SCROD Board is equipped with a Xilinx Zynq Z-7045 SoC consisting of a programmable logic (PL) and a dual core ARM processor (PS).
- The SCROD SoC processes the waveform data and extracts the time at which the photon hit a particular PMT and the charge collected. This is the “feature extraction” process discussed in this presentation.
- The main motivations for implementing the feature extraction procedure in the SCROD is to minimize the bandwidth needed for the data links and to save disk space.







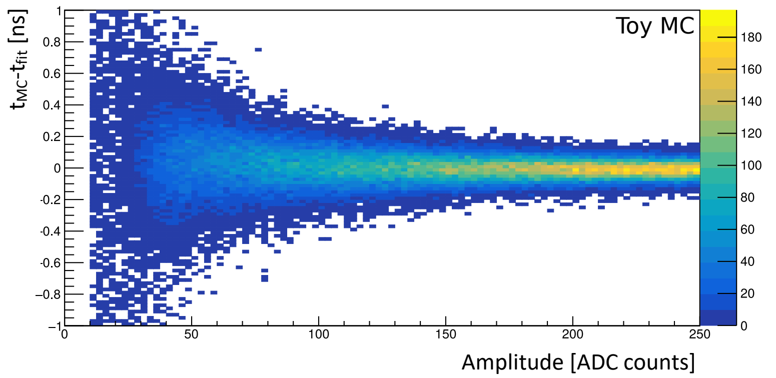
Overview of the Feature Extraction Methods

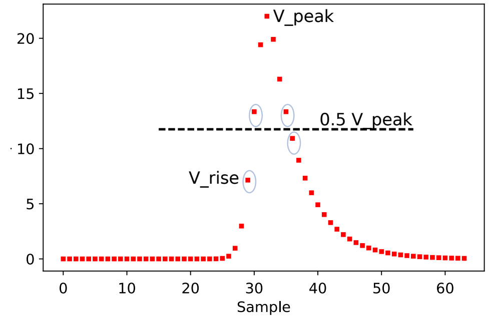
- Constant fraction discrimination (CFD): The base TOP feature extraction method is a software implemented CFD.
  - Search for the highest sample.
  - Find the closest samples to the half peak.
  - The uncalibrated rising edge time is calculated using a linear fit.

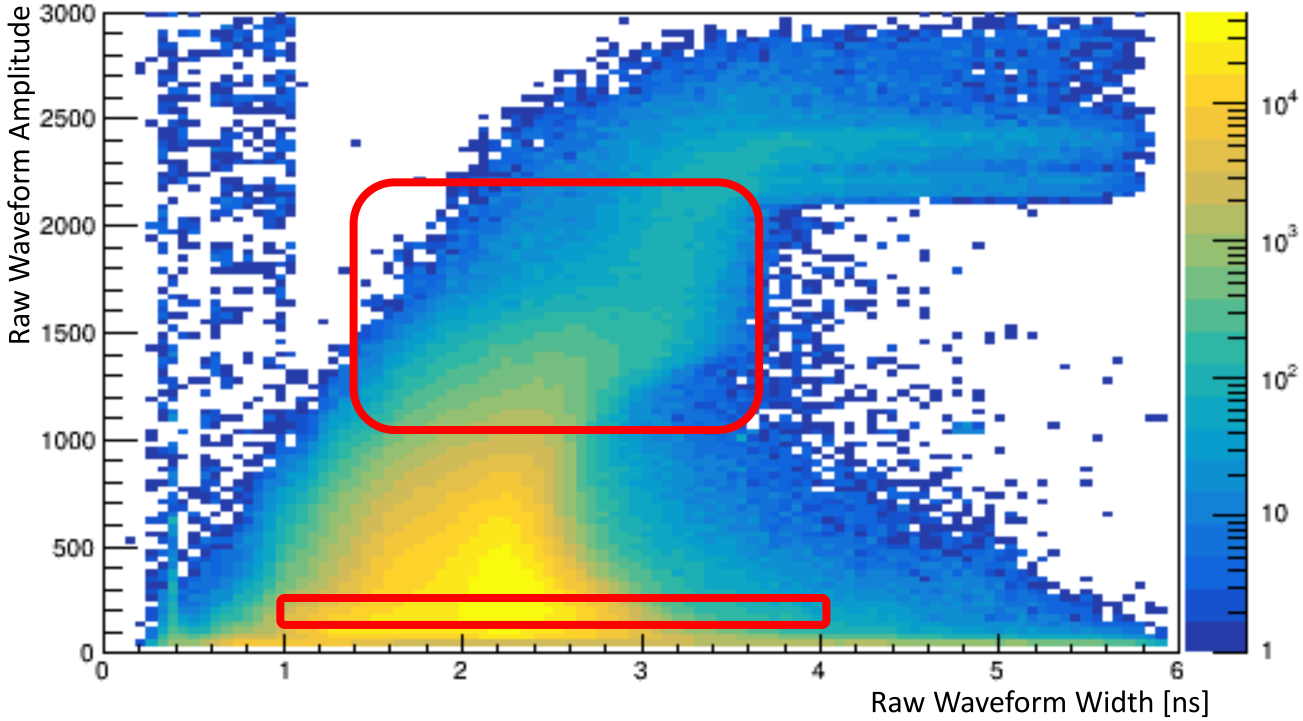
- The advanced feature extraction work based on implementation of template fitting methods.
  - Waveform templates are generated from the experimental waveform data collected form the detector.
  - Template fitting is performed using minimum X^2 method.
  - Time-based calibration should be applied beforehand.

Constant Fraction Discrimination (CFD)

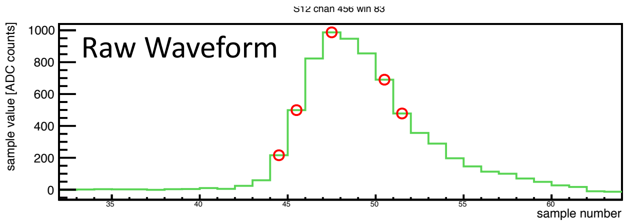
- CFD feature extraction is initially performed on the raw digitized waveform.
- Digitized sample times are not equal. Consequently, a Time-based calibration has to be applied to these results.
- At small amplitudes, the effects of the electronic noise degrade the timing resolution. The high occupancy at this region makes this a significant problem.
- At large amplitudes, due to the change in signal shape (as can be seen by change in signal width here) the CFD method breaks down. Low occupancy in this region makes this problem less urgent.

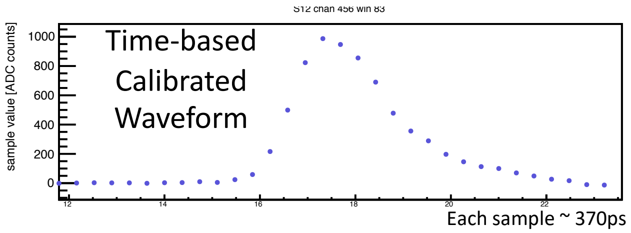






Template Fitting





- Template fitting is used by finding the minimum chi squared value.

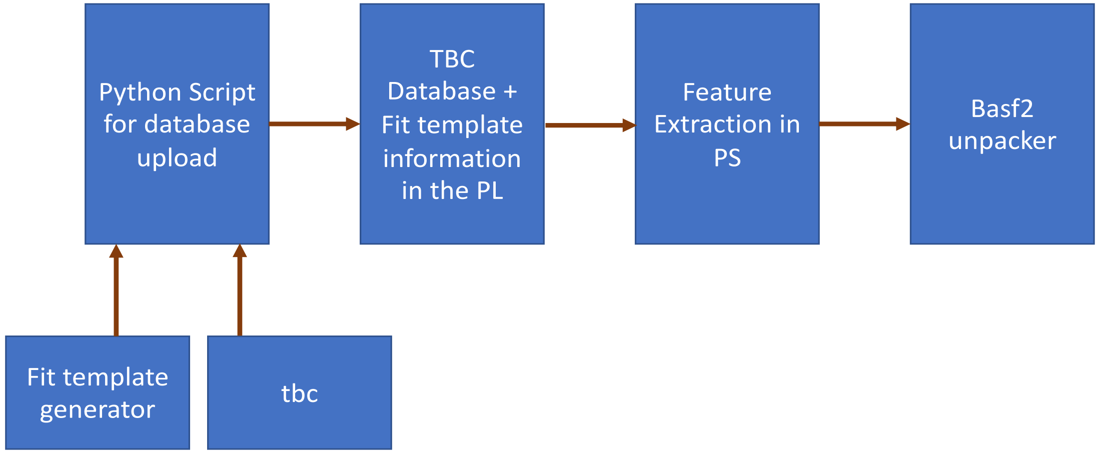
$$\chi^2 = \sum_{n=1}^{N} (S_n - aT(t_n - t_{offset}) + b)^2$$

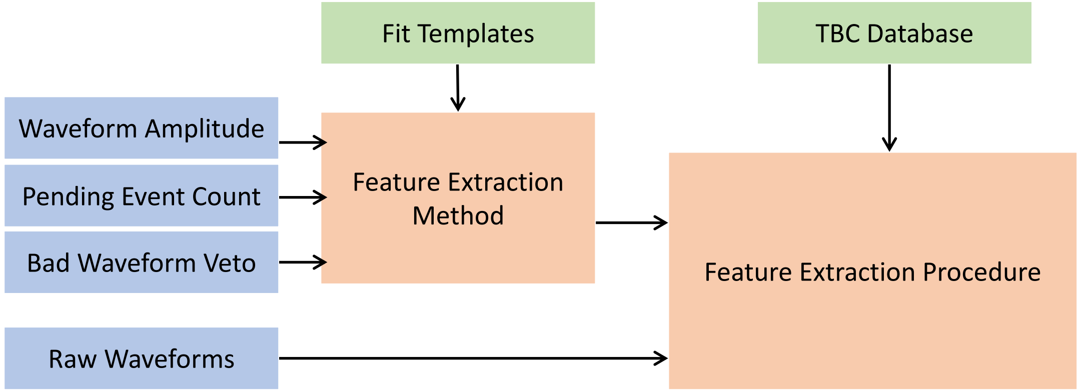
- Minimization on a and b are done analytically.
- Next, t_{offset} is calculated through a gradient descent method. This process is very hard to parallelize.
- The time-based calibrated CFD result is used as the initial ansatz.
- A full grid search was also studied which is easier to parallelize but much slower.
- Currently, $N=32$ to fill the entire raw signal sample range. We know that most of the signal information is in the rise and early fall part of the signal which might allow for using smaller N samples in future.

TOP Feature Extraction Components

The current development path for the feature extraction improvements is made of the following parts:

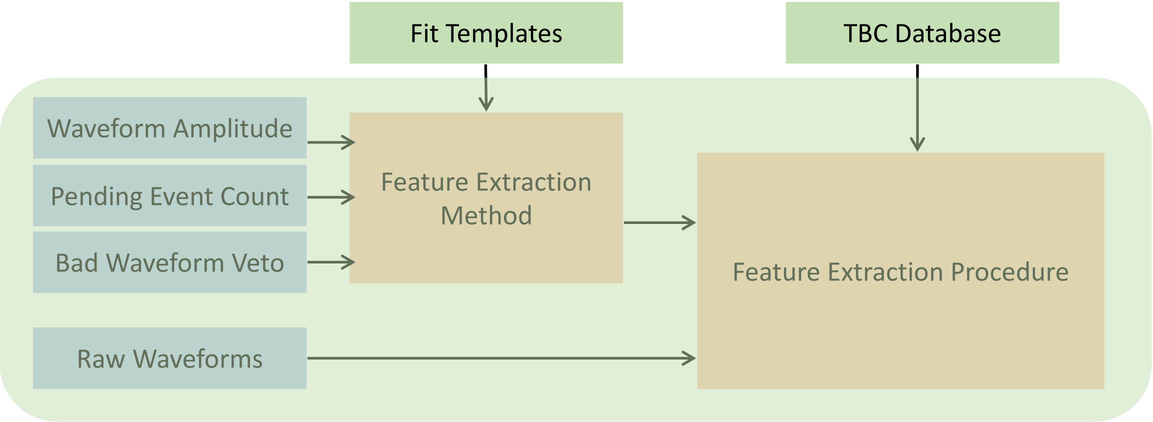
- The main feature extraction routine (both CFD and template fitting) is implemented in the SCROD PS in C language.
- CFD uncalibrated feature extraction is performed on all waveforms and the results are saved in all cases.
- TOP unpacker software based on C++ reads the raw output of the SCROD feature extracted data and can apply time-based calibration offline.
- Template fitting adds template generation and template and TBC DB loader python scripts.
- For feature extraction, the Programmable Logic (PL) is currently used only for TBC database and fit templates.

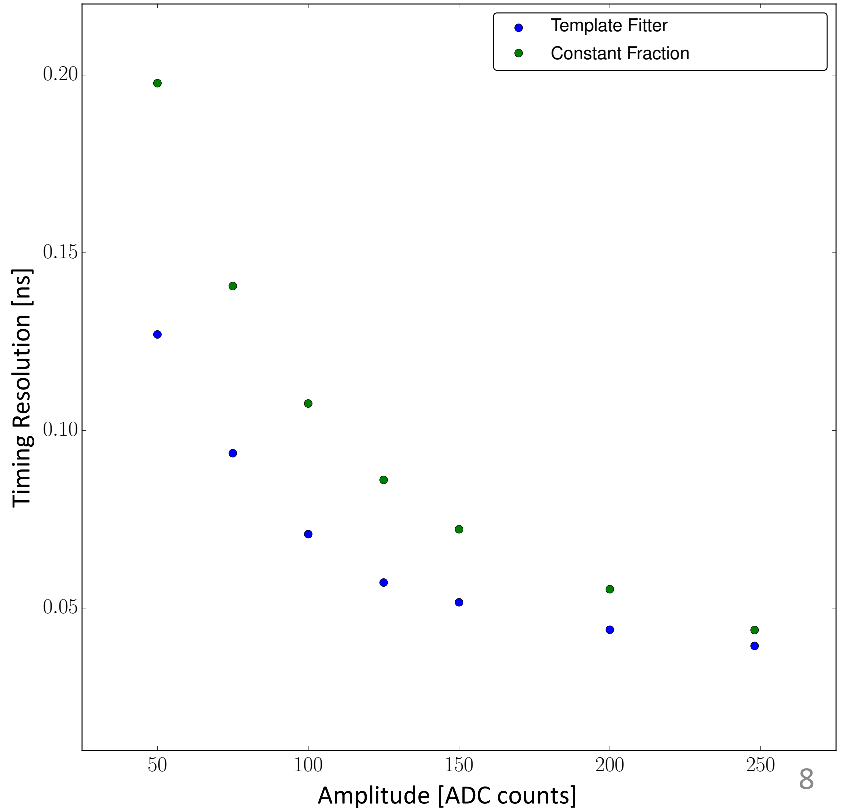




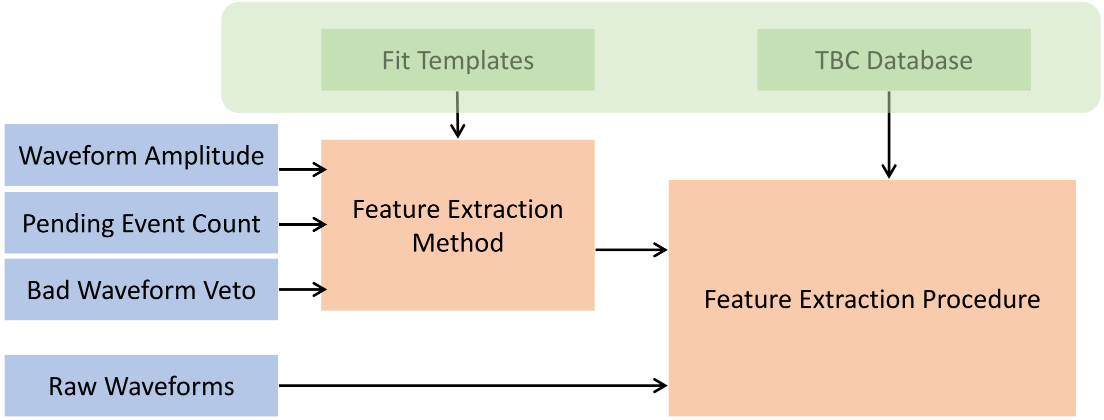
TOP Feature Extraction PS Implementation

- The main feature extraction routine is implemented in the SCROD PS in C language. The PS firmware uses only a single available ARM core.
- Pending event count and waveform amplitude can be used to choose whether the template fitting is performed. This can be expanded to choose different templates or fitting procedures depending on these parameters.
- Template fitting is performed after time-based calibration of the raw waveforms. This is due to usage of common templates across all channels.
- To help with performance template fitting can be limited to only small amplitude good waveforms and low pending event counts.
- Amplitude-dependent templates allow some balance between speed and accuracy of the fit procedure.

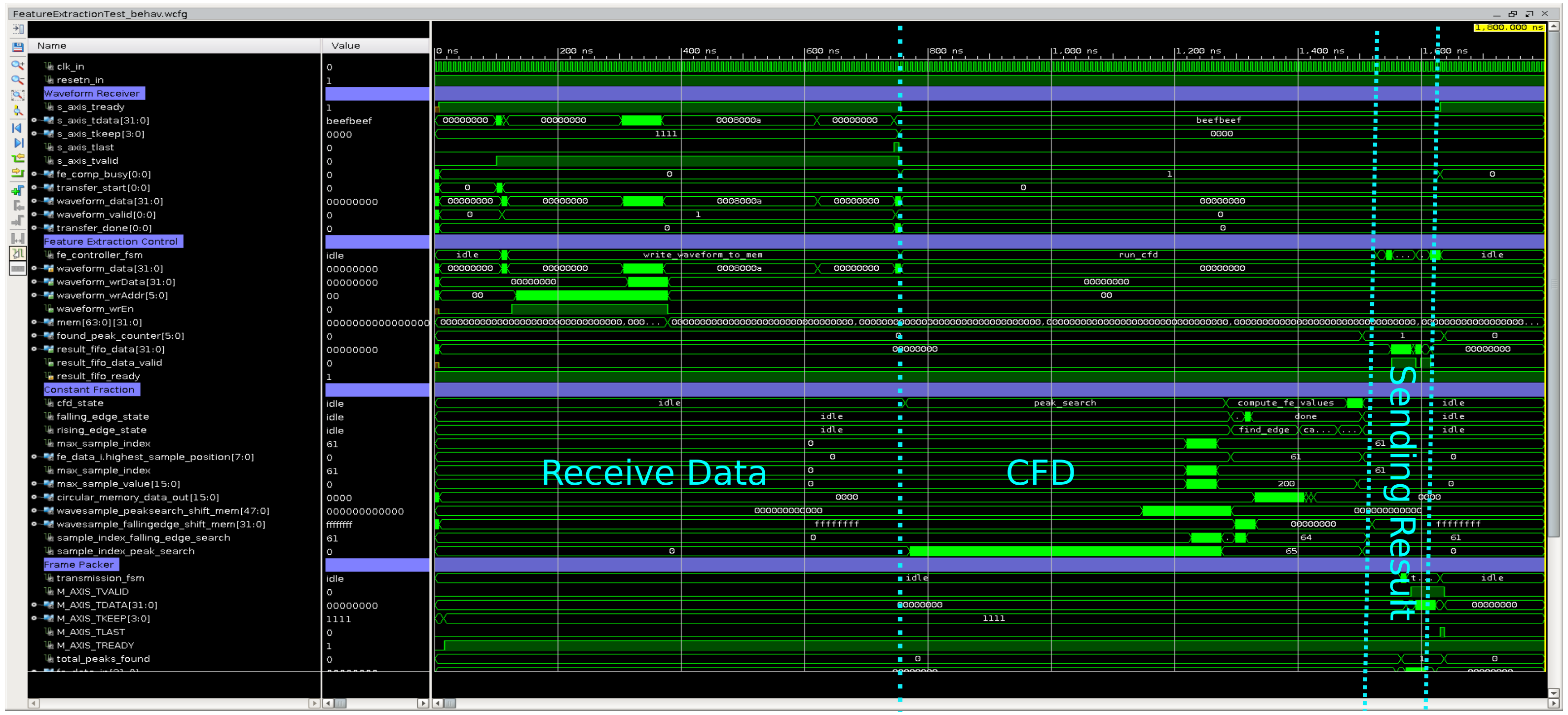




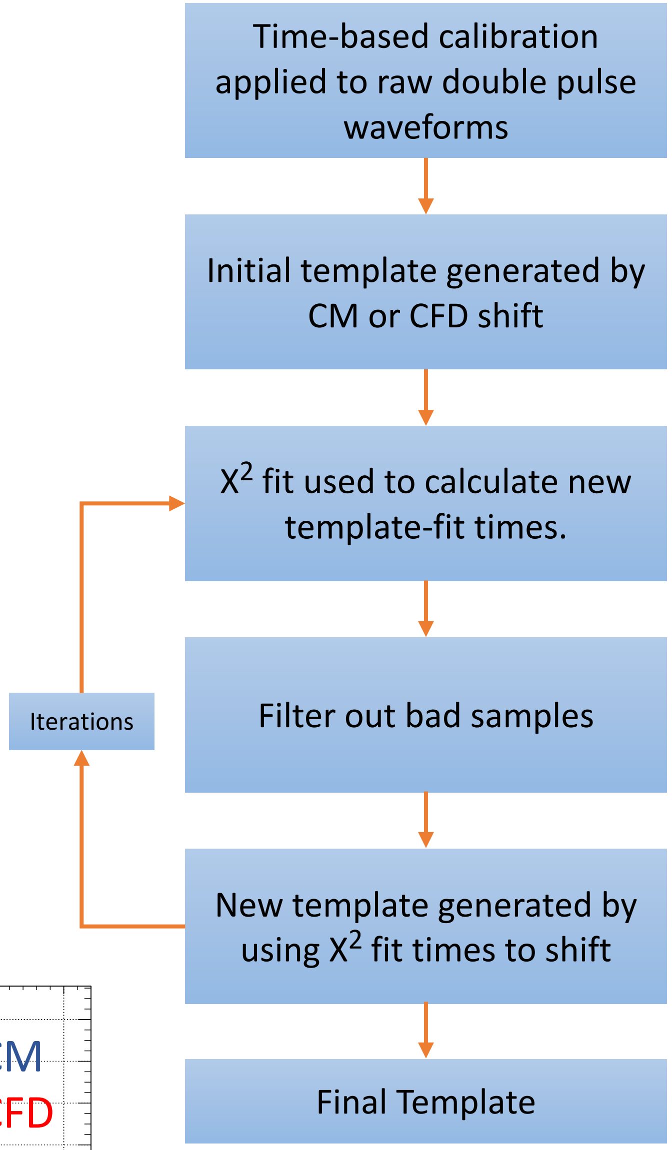
TOP Feature Extraction PL



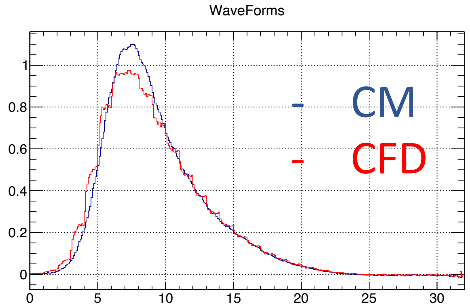
- Initially, programmable logic is only to be used for fit template and time-based calibration databases.
- The current fit procedure is not suitable for parallelization and is not likely to improve by a PL implementation. Simpler search methods to take advantage of parallelization by the PL will be studied in future.
- A preliminary implementation of the CFD procedure in the PL using vhdl to take advantage of the ability to perform search in parallel has been performed and planned for future.



Template Generation

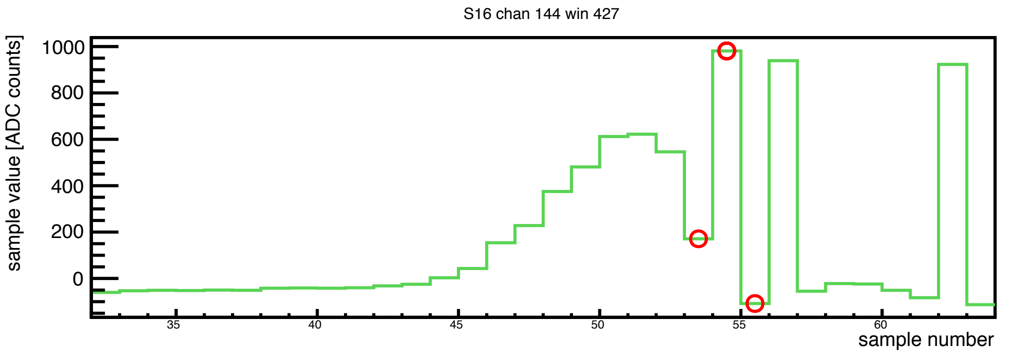


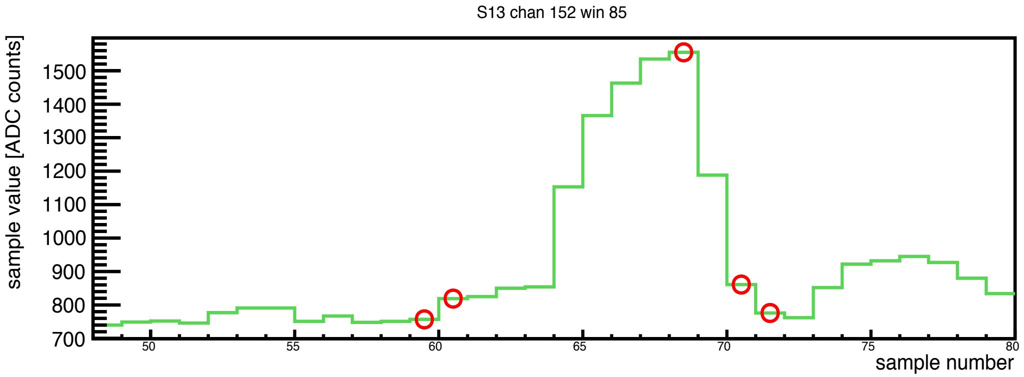
- Currently, initial templates can be generated by using either center of mass or CFD to shift and weight the experimental signals (from laser pulse data) and averaging them.
- The commonality of these templates between all TOP channels necessitates the application of per channel time-based calibration beforehand.
- Using CFD rise time generates some suspicious artifacts in the template. An iterative method using the previous template to fit for new results is ready which also removes the CFD artifacts.
- Due to slight differences between the different channel's analog electronics, signals might be shaped differently which would necessitate a per channel template approach.
- A per channel template approach would increase the memory requirements. Conversely, such an approach can obviate the need for online time-based calibration.

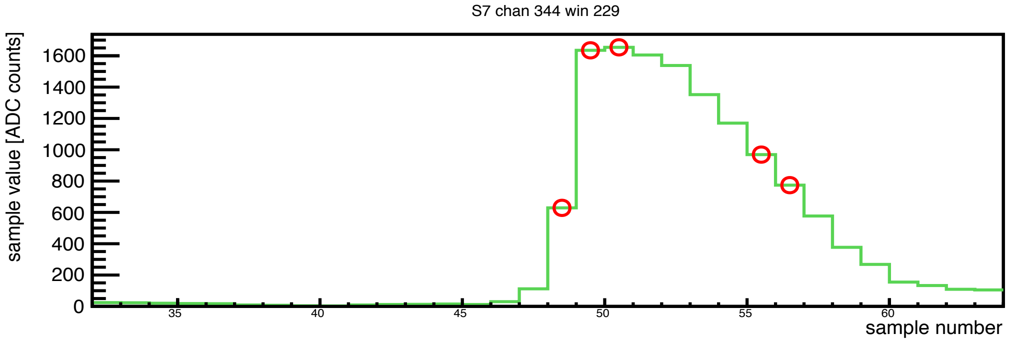


Irregular waveforms

- The CFD procedure is used to determine the width and height of the waveforms. These parameters can be used to classify the signals and identify the irregular double-photon and hardware related bad signals.
- Since the template fitting procedure on irregular signals can be computationally very expensive due to reaching maximum number of allowed iterations, the CFD results can be used to veto the fitting on bad signals.
- In future, we hope to use the fitting procedure better classify waveforms based on the signal shape.







Current status and plan summary

- Currently the CFD feature extraction is in use during TOP detector operations.
- The testing on the template fitting is ongoing.
- The per channel versus universal templates will be studied.
- Using programmable logic to improve performance will be the next step once the PS implementation is finalized.
- In future the error correction methods used for single event upset mitigation in other parts of the TOP firmware should also be deployed in the Feature Extraction module.

Thank you.