Particle Discrimination from Scintillation Detector Signal Using Matched Filtering and Regression Classifier

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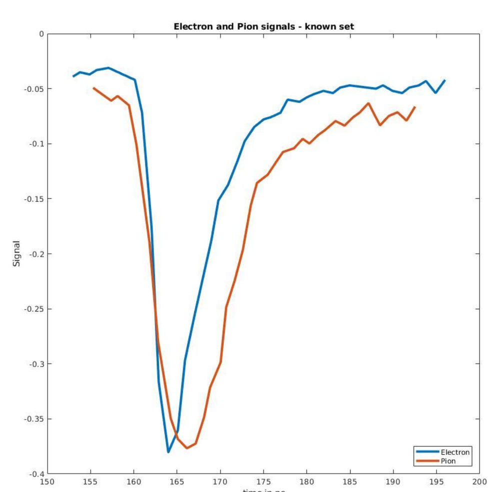
EE-338 Application Assignment

Overview

- Detectors commonly used in modern particle physics experiments are sensitive to one type of particle - i.e. the detector material sensitive to an electron will not be able to detect protons or other hadrons. Similarly, a detector designed for alpha particles (fast moving Helium nucleus) is not suitable for detecting heavy ions and vice versa.
- However, an important class of detectors, the Scintillation detectors can be sensitive to both electrons and pions. Pions are unstable particles with a lifetime of 26 nanoseconds and may be neutral, positive or negatively charged. However, the interaction of pions with many scintillation materials is very similar to that of electrons. Consequently, the output waveform of the detector when an electron or pion falls on it is similar.

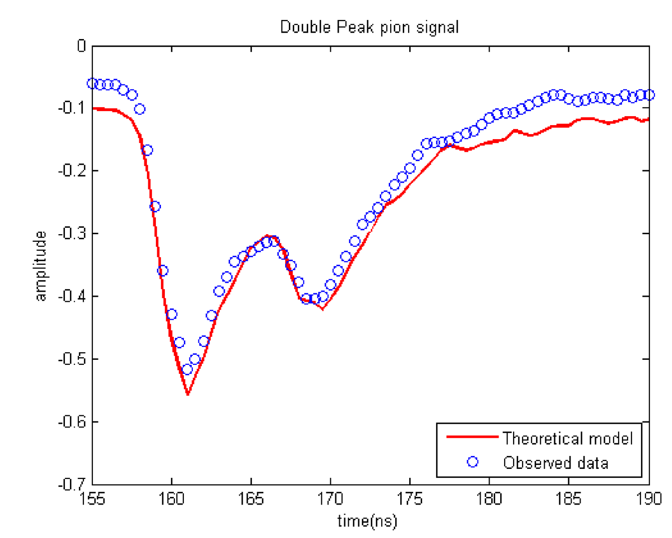


- The subtle differences in the voltage waveform at the electronic readout of the detector may be used to differentiate if the exciting particle was a pion or an electron.
- We compare the results obtained by distinguishing these waveforms by two methods – Logistic Regression (Machine Learning) and Matched Filtering.

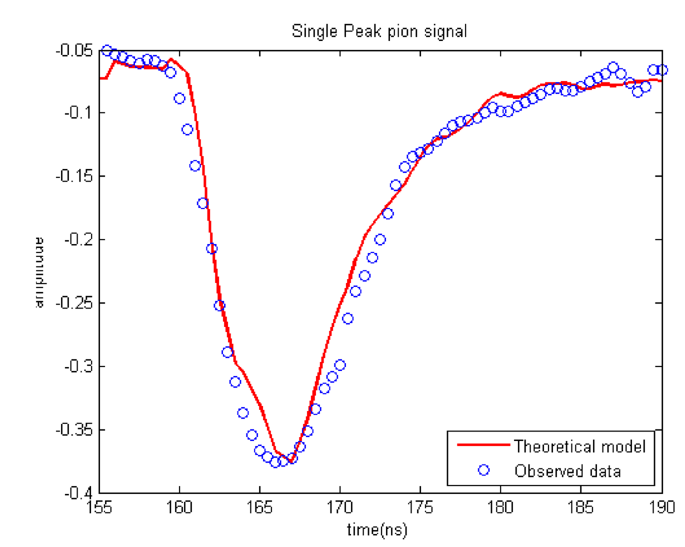
Theoretical Models

- To generate samples for training the ML Classifier and testing the matched filter, we made a theoretical model for the pions.
- The scintillation detector is coated with a reflective surface on the source side to maximize light incident on the detector.
- The pions interact after penetrating a certain length into the detector mass. The primary peak due to pion is reflected by the coating to create a secondary peak, time delayed and diminished in amplitude.
- The pion signals are hence a superposition of a primary peak and a reflected signal. The model is assumed to be $a\{s(t)+e^{-k\tau}s(t-\tau)\}$
- We estimated $s(t)$ and k such that the model best fits the known samples.
- The electrons interact immediately with the scintillator material, so effectively only a single peak is observed (*bremsstrahlung radiation)*.
- The electron samples are hence merely amplitude adjusted variants of a standard signal.

Model Performance



Pion Double Peak Theoretical Model v/s Observed Data



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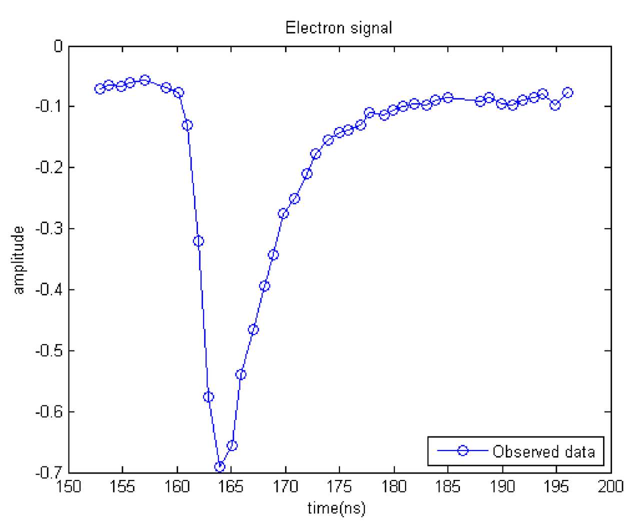

Electron Observed Data

Machine Learning Classifier

- A 1000 sample training set was used to train a logistic regression classifier.
- The signal is suitably sampled into n discrete points in time. Each sample is assumed to be a point in a n-dimensional hyperspace. The classifier attempts to find a hyperplane that divides the electron samples and pion samples into exclusive regions of the space with minimal overlap.
- The machine learning classifier has been tested both against the assumption of a high and low precision hardware trigger for the scintillation detector. The trigger is raised when the signal crosses a preset threshold.
- In the presence of a precise hardware trigger, it can be assumed that the start of the signal is at the same region in the sampling window; else a software trigger is used to pre-process the sample.
- The software trigger is found to be effective at high SNR.

Matched Filter Classifier

- Matched filtering: Matched filtering is a signal classification technique which leverages differences in the inner products of a signal with itself, and all other signals. In the simplest scenario a signal is classified as that one which has the largest inner product with it. However, this picture is complicated by the fact that we do not have a consistently greater inner product for Pions with a Pion sample, for all peak time values (ref. Fig.1).
- We therefore adopted an approach wherein we perform matched filtering with an array of Pion-matched filters, with varying peak-times, and use the maximum of these. Electron detection is greatly simplified by the fact that Electron-Electron inner product is consistently 1, always larger than that with any Pion-Matched filter. (ref Fig.2)

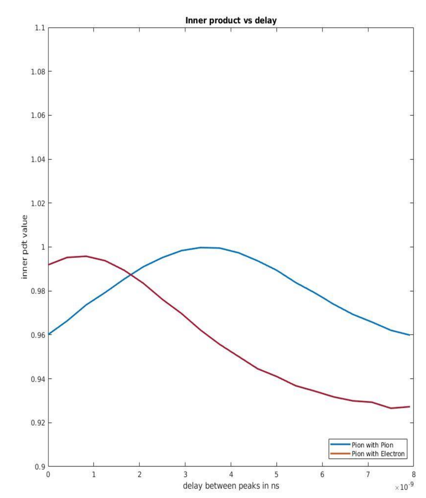

Fig.1

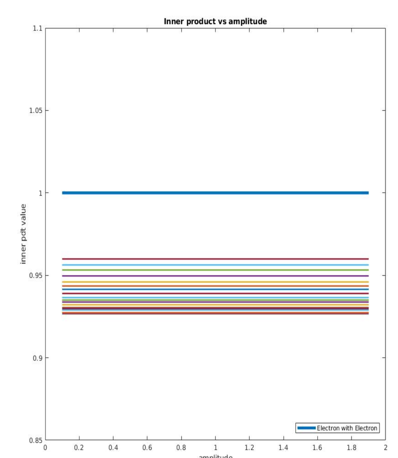

Fig.2

- Performance under noisy conditions: Our simulations show that matched filtering performs excellently under noisy conditions. Filtering out the so called out-of-band noise, by projecting the incoming signal along the Electron and Pion basis vectors proved very effective (ref Fig.3)

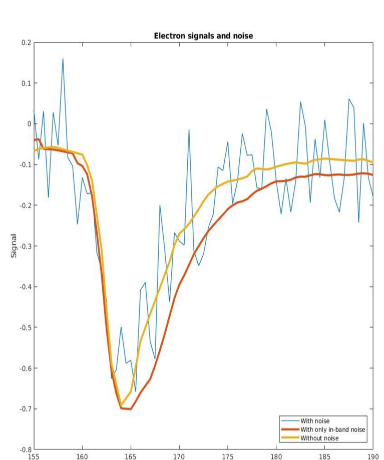

Fig.3

Results

- Matched filtering: Accuracies stood at 98.18% for Electrons and 99.8% for Pions with 2.5 SNR (Additive White Gaussian Noise)
- Logistic Regression Classifier (ML):
  - In presence of a precise hardware trigger,
  1. 99.5% precise at 4.5 SNR and,
  2. 93.6% precise at 3 SNR
  - With a relatively low precision trigger,
  1. 88.4% precise at 4.5 SNR and,
  2. 78.4% precise at 3 SNR

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