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Machine Learning Applications in PMT Waveform Analysis

Wu Qi, Peng Shuo, QIAN Sen, Chen LingYue
Institute of High Energy Physics, Chinese Academy of Sciences

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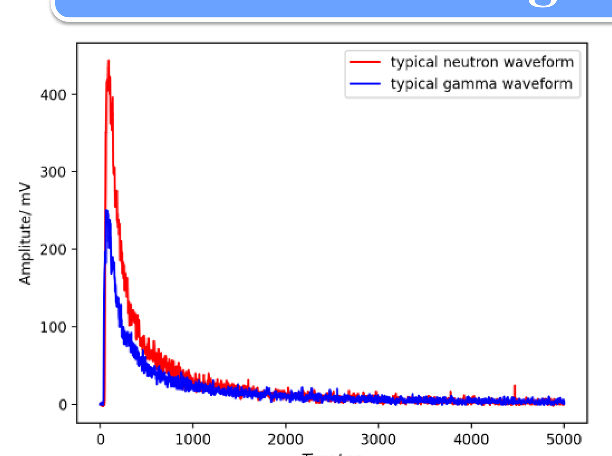
Introduction

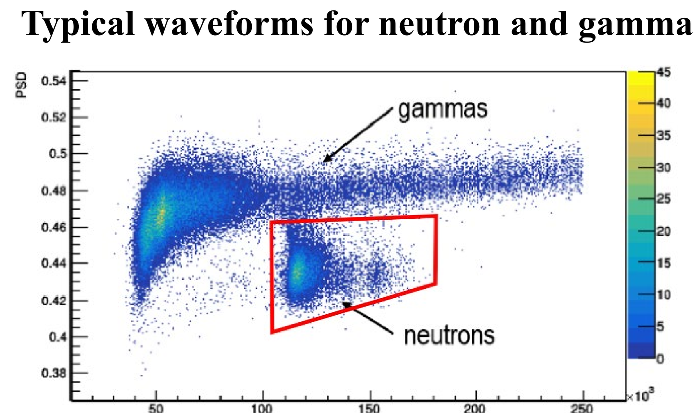
In high energy physics experiments, the radiators are widely used which emit light pulses at certain wavelength when interacting with the incident particles. Since the light directly emitted is always weak, the photomultiplier tube (PMT) is used to realize the photoelectric conversion and the electron multiplication. The time to digital convertor (TDC) and charge to digital convertor (QDC) are two kinds of signal analysis plug-in which can record the time and charge information of the input signal. In recent years, the development of the fast analog-to-digital converters (FADC) which can record the whole waveform makes it possible to offline analyze the information carried by the waveform with different methods and obtain more information.

Pulse shape discrimination is a waveform-based method to discriminate between different kinds radiations. The traditional used PSD method is the charge comparison method whose performance strongly depends on the energy range of the incident particle. Inspired from literatures, a model based on convolutional neural network (CNN) was developed and the accuracy of the piled-up n/γ discrimination for CLLB crystal can reach 97%. Besides the energy information carried by the pulse, the time information is also important when reconstructing the particle trajectory especially in the application of time-of-flight detectors. The traditionally used timing methods, including the leading edge discrimination (LED) and the constant fraction discrimination (CFD), are easily realized in the circuit but obviously the time information of the pulse has not been precisely obtained since only part of the signal is used in the timing analysis. A CNN-based model has been built and the timing results show a 50% improvement compared with the CFD method.

1. PSD using charge comparison method



Typical waveforms for neutron and gamma

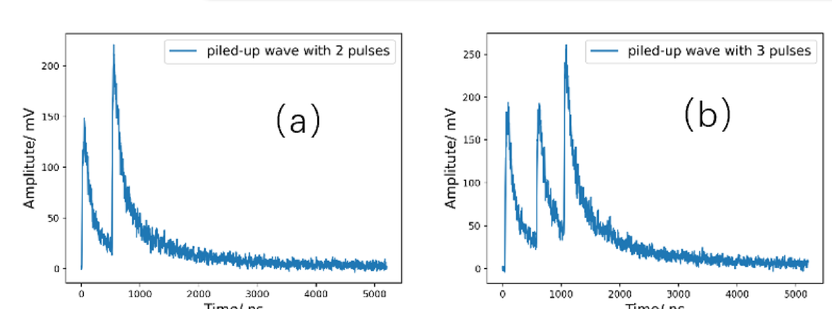


PSD vs long integral expressed in ADC

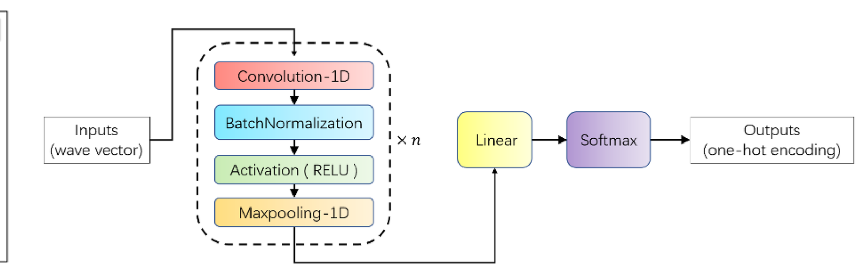
	Typical gamma waveform	Typical neutron waveform
Height [mV]	250	443
Rise time [ps]	22	36
Fall time [ps]	135	112
FWHM [ps]	157	148
Decay time [ps]	129.7, 1015	127.4, 991.5

- For the CLLB crystal, due to the difference in decay time, the n/γ discrimination is always achieved using the charge comparison method.
- The figure-of-merit (FOM) value for this traditional method is 1.10, which indicates that the accuracy is about 99.8%.
- It is hard to realize the PSD for piled-up waveforms with the traditional method. Therefore, the CNN-based piled up PSD method is developed.

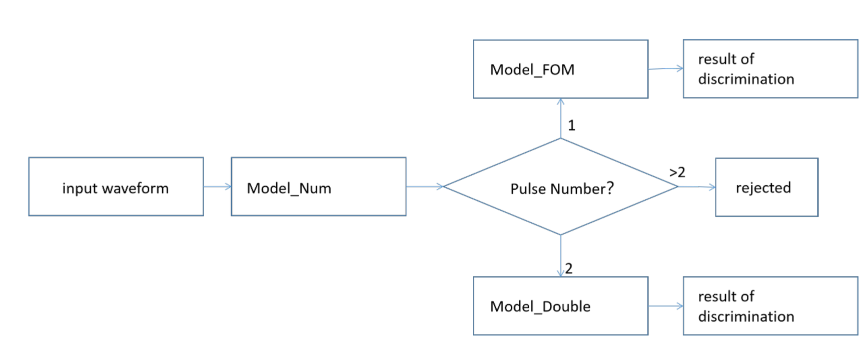
2. CNN based piled-up PSD method



Typical pile-up waveforms containing 2 and 3 pulses



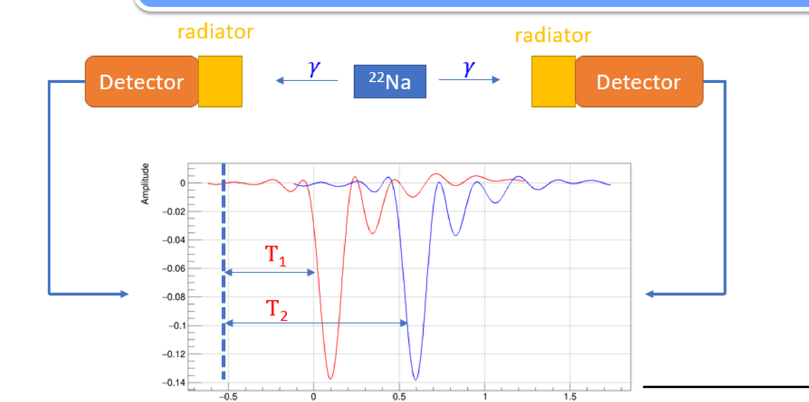
The structure of Model_PulseNum



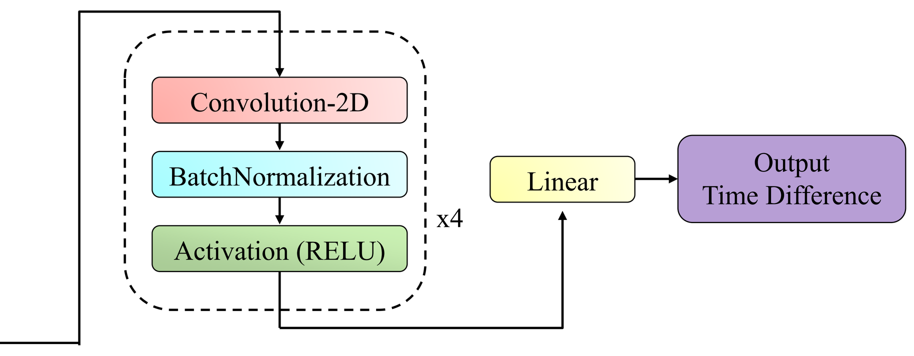
The structure of the PSD system with CNN method

- The piled-up n-γ discrimination system using CNN consists of two units: a pulse number identification unit and a particle identification unit. Both units are well trained and tested.
- This system can realize the n/γ discrimination accuracy of 99.5% for single-pulse and 98.6% for double-pulses.
- Considering the flux of the particle, the system can be modified with more units to deal with more complexed data.

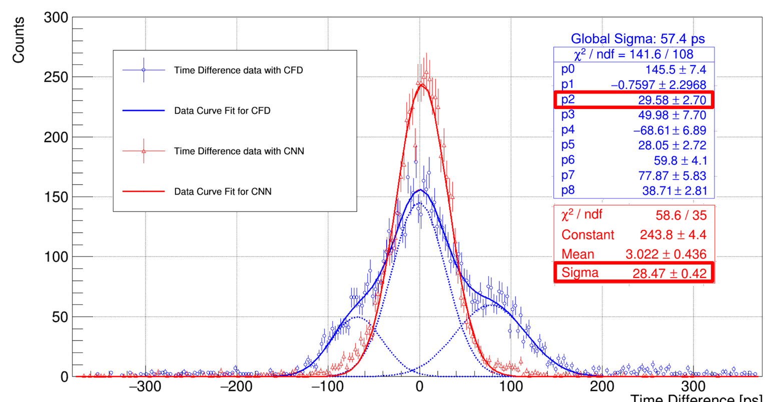
3. CNN based timing method



Schematic diagram of the data acquisition system



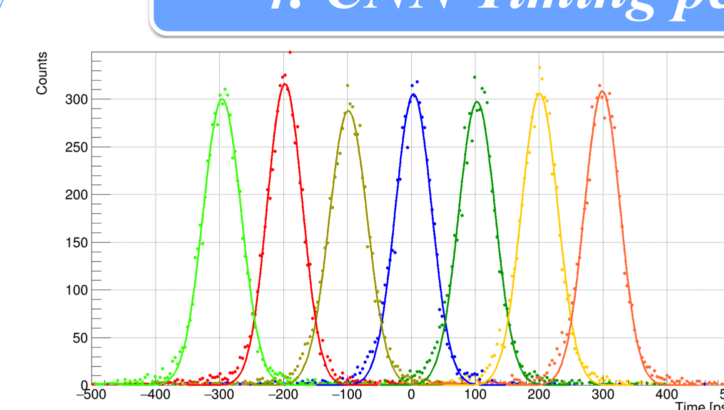
The structure of timing CNN-based model



Comparison between the CFD and CNN timing results

- The data was obtained with paired Cherenkov MCP-Based detectors. Because the γ from the ^{22}Na radioactive source directly interacts with the MCP, two side-peaks are found in the time difference distribution.
- The CNN based model successfully identify the features of the events in side-peaks and correct their time difference. The global standard deviation has an 50% improvement compared with CFD.

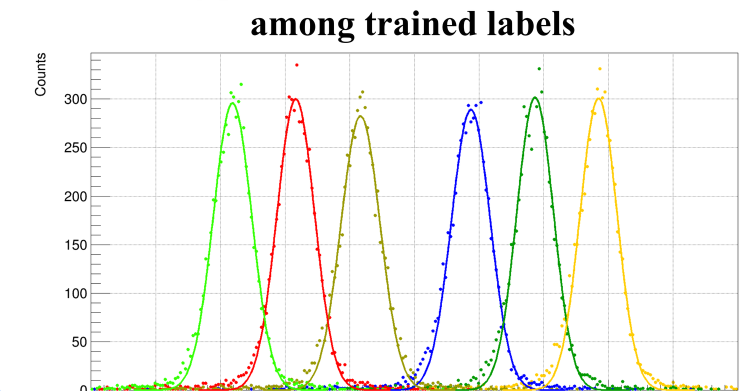
4. CNN Timing performance at different position



Timing performance for time differences among trained labels

Real time difference	-300	-200	-100	0	100	200	300
CNN-Mean	-296	-198	-99	4	103	201	299
CNN-Sigma	30	27	30	29	29	29	30

- The reconstructed mean value of the time difference with CNN is in consistent with the real value with the error of ±4 ps. The sigma are all less than 30 ps.



Timing performance for time differences beyond trained labels

Real time difference	-285	-185	-85	85	185	285
Mean	-281	-183	-83	87	187	285
CNN-Sigma	30	29	30	30	29	29

- The time differences beyond trained labels are also well reconstructed, which means there is almost no overfitting.

5. Conclusions

- **A piled-up n/γ discrimination system with the CLLB crystal based on CNN has been developed and the accuracy can reach 98.6% for double pulses.**
- **The CNN method has been proved to well identify the different time properties in the PMT waveforms and realized the correction. The time improvement can reach 50% compared with CFD with the Cherenkov data.**
- **More features are expected to be well extracted and corrected with the machine learning method from the PMT waveforms, such as the energy, the nonlinearity and the energy resolution of the PMT-based detection system.**

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Corresponding author : qians@ihep.ac.cn