Intelligent Low-level Signal Detection and Zero-Suppression in Raw LArTPC Waveforms through Deep Learning Techniques

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Final report

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DUNE

Deep Underground Neutrino Experiment is a LArTPC detector that aims to study:

- Neutrinos from accelerator
- Rare events neutrinos (Supernovae burst, proton decay)

The latter have intrinsic problems:

- lower energy, close to the limit of the detector
- to have higher chances to be detected need 100% live time

Solutions:

- Save all data and analyse offline (throughput ~ TB/s)
- Online data discrimination

Classical approach

For low energy events:

- Too much data from DAQ
- Signal and noise are almost indistinguishable

↓

- Zero suppression method
- Events with charge collection below a fixed threshold are discarded

↓

Very hard to detect low energy neutrinos (e.g.: from supernova burst)

New approach

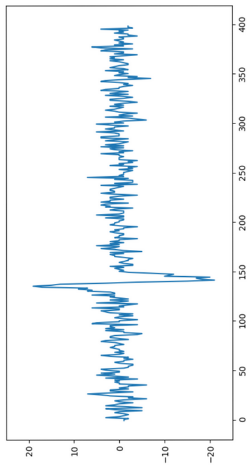
Use machine learning. Benefits:

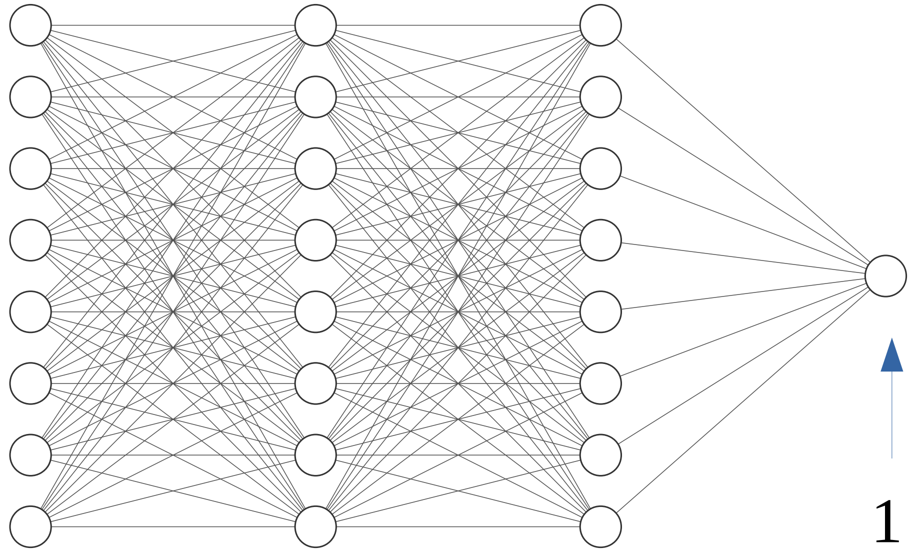
- We don’t have to study and develop a method to discrimante signal
- The machine will learn itself what a signal is and what is not
- Sometimes the machine is able to undestand underlying features and correlations that we are not

Cons:

- We need labelled data (Monte Carlo must be accurate)

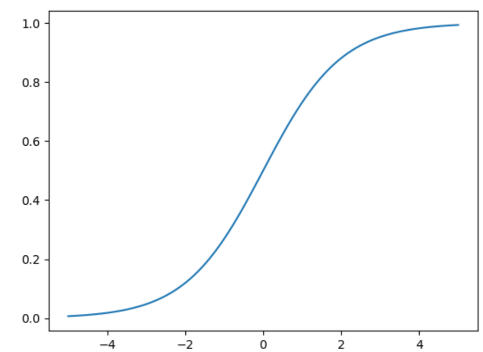
What is a “classical” neural network?





$y \in [0, 1]$

$$\frac{1}{1+e^{-w_i x_i}}$$

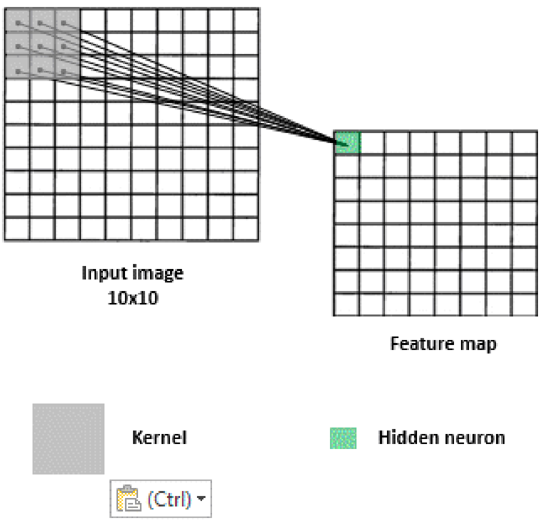


Input vector
to each neuron X

$$max(0, w_i X_i)$$

Advanced NN: Convolutional Neural Networks

- Convolutional NNs use convolution to take advantage of the space invariance and to extract features from data.
- Neurons are replaced by filters that are fitted to find features
- Each layer is made of many filters

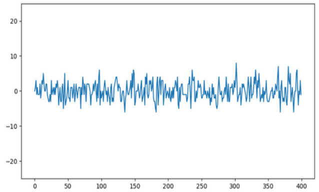
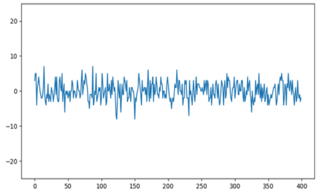
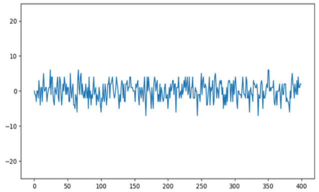


2-dimensional CNN is the cutting edge technology for image recognition, object detection, self-driving cars, ecc...

Waveforms are one dimensional → We use 1D Deep Convolutional Neural Network

Learning process

Supervised learning is the process where labelled data is given to a neural network and its weights are fitted to give the most accurate predictions as possible

Data	Labels		Predictions
	0		0.02
	0	→ Fit and adjust weights →	0.36
	1		0.94

The training process requires *a lot of data* to be sensitive.
I used ~400000 waveforms for training.

Inference

For testing a model the labelled data is split:

- 80% for training;
- 20% for testing predictions performances

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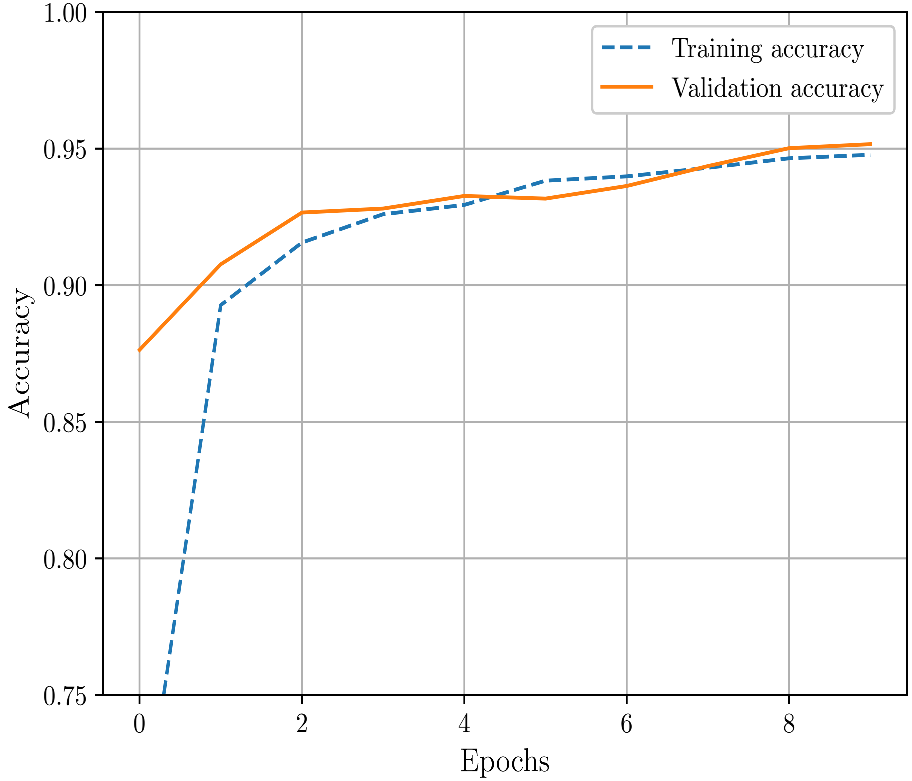
Results for monoenergetic 5 MeV neutrinos

Fast, light and robust CNN has been developed

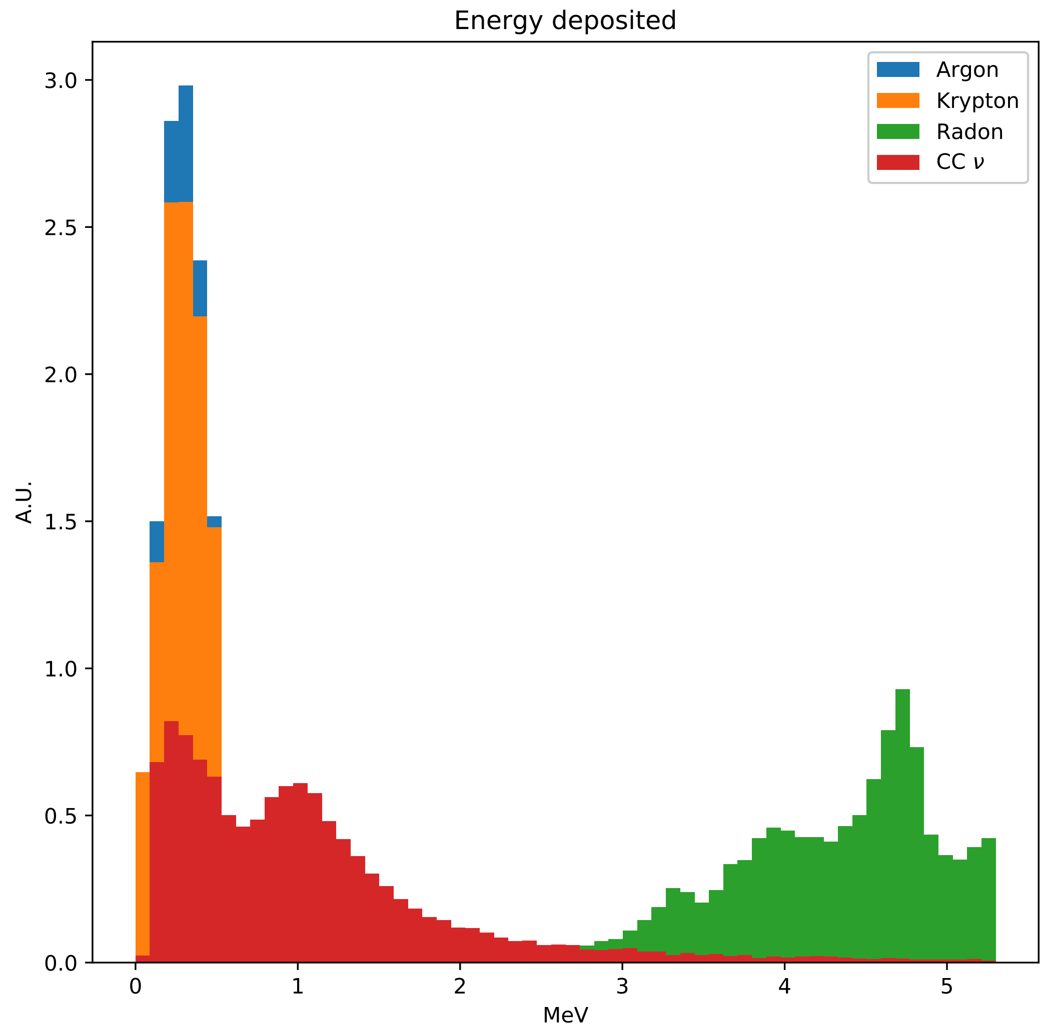


Test set Accuracy	
U Plane	0.955
V Plane	0.976
Z Plane	0.974

Simulated waveforms have a minimum of 2000 electrons productions:
Lower than actual zero suppression threshold

Next step: realistic dataset

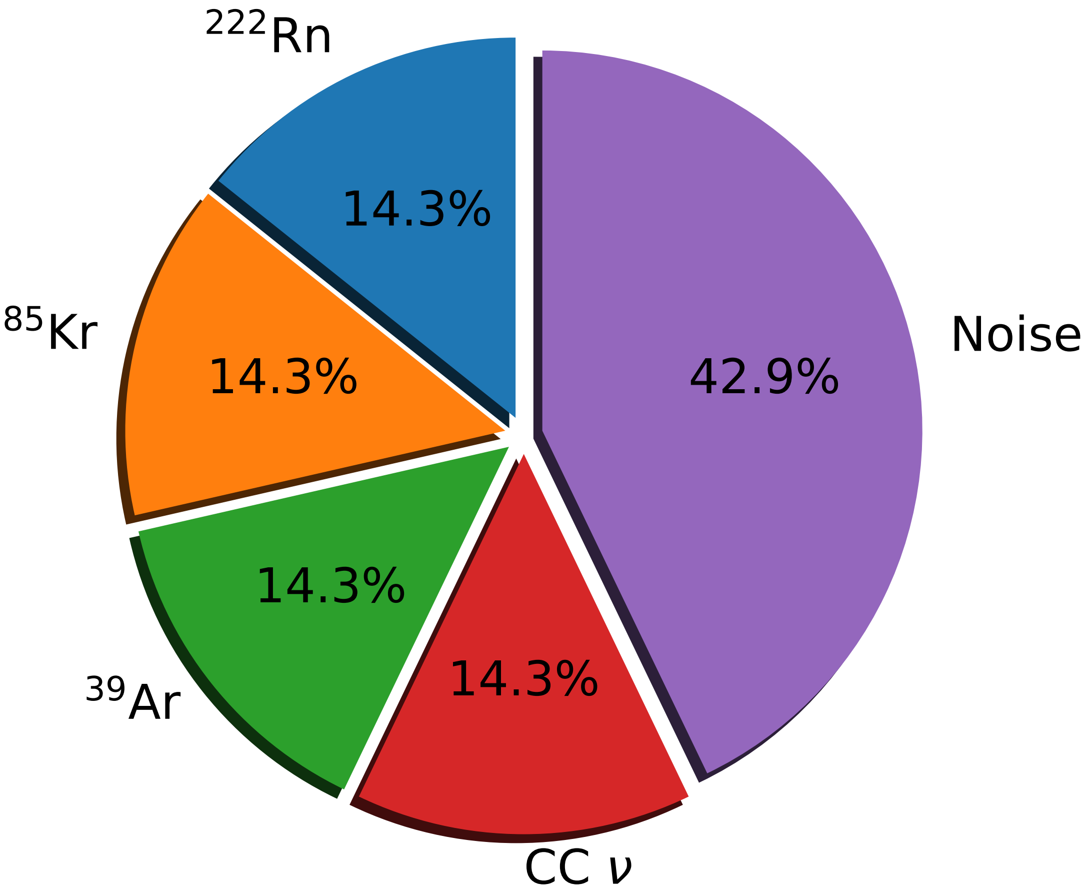
- Data generated from 10,000 events
- Minimum collection of 2000 electrons
- Neutrinos from the Supernova “marley” generator (Charge Current Neutrino)
- Radiological background is a mixture of Radon 222, Argon 39 and Krypton 85



Dataset

778979 waveforms picked randomly from 10000 events:

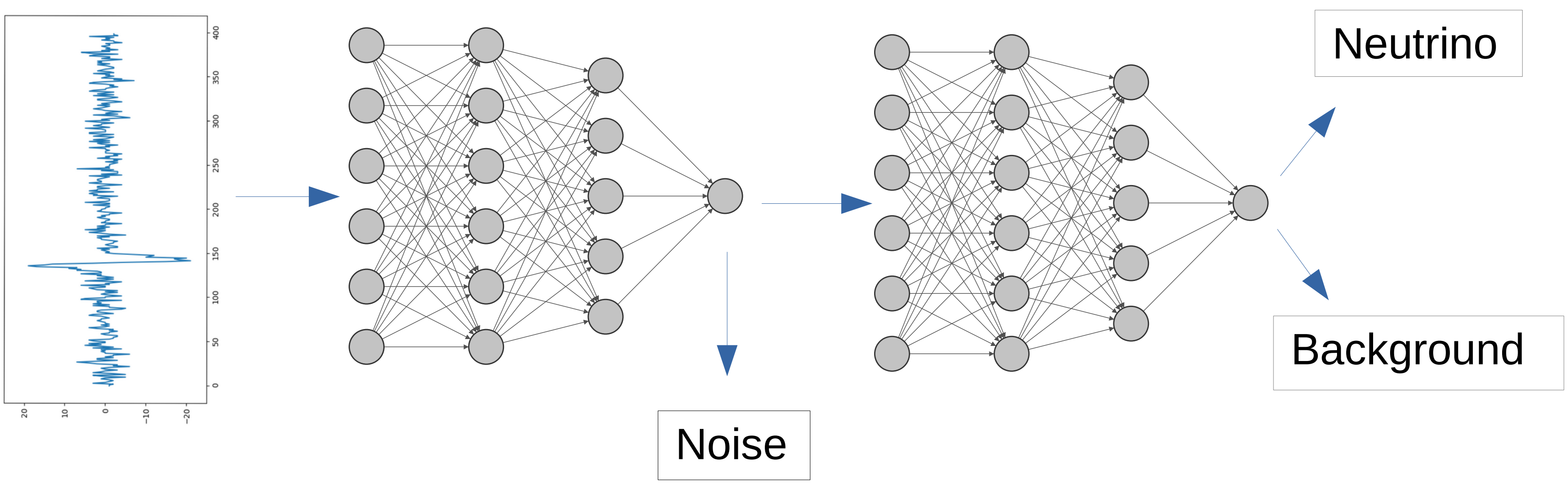
- 80% used for training and validation
- 20% for testing



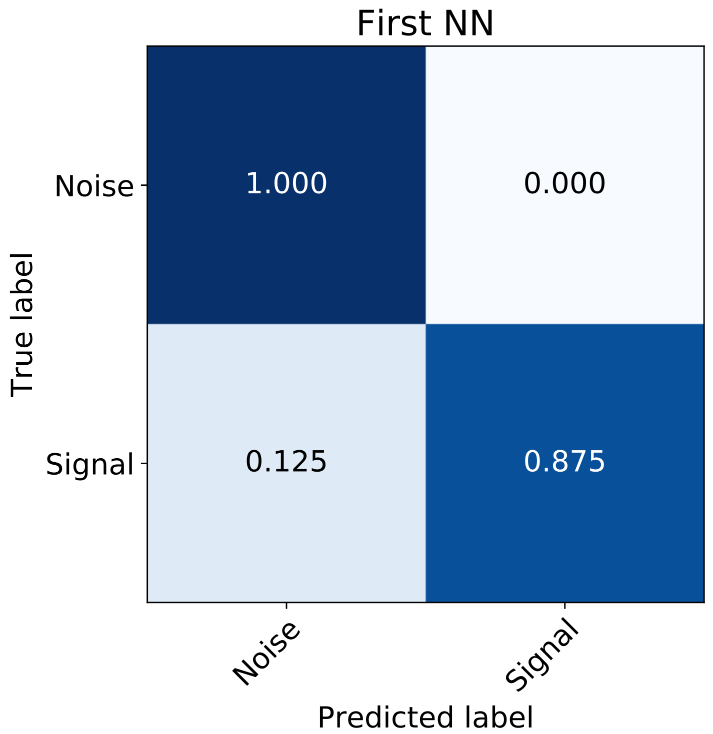
Strategy

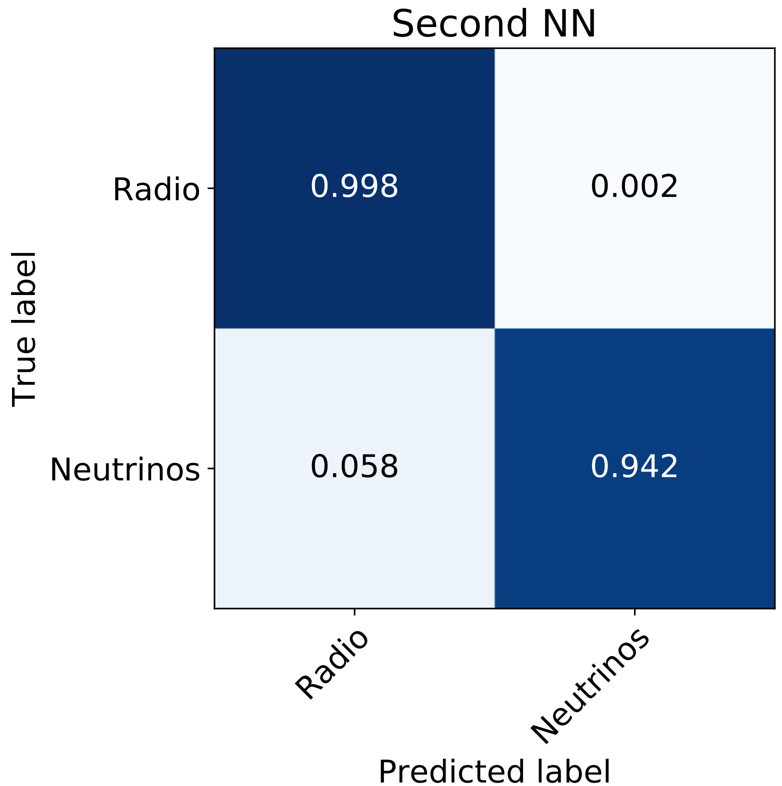
- First neural network → To discriminate any signal from noise
- Second neural network → To discriminate neutrinos from background

Each NN has six convolutional layers developed to exploit the spatial invariance of the peak



Results





False negative:

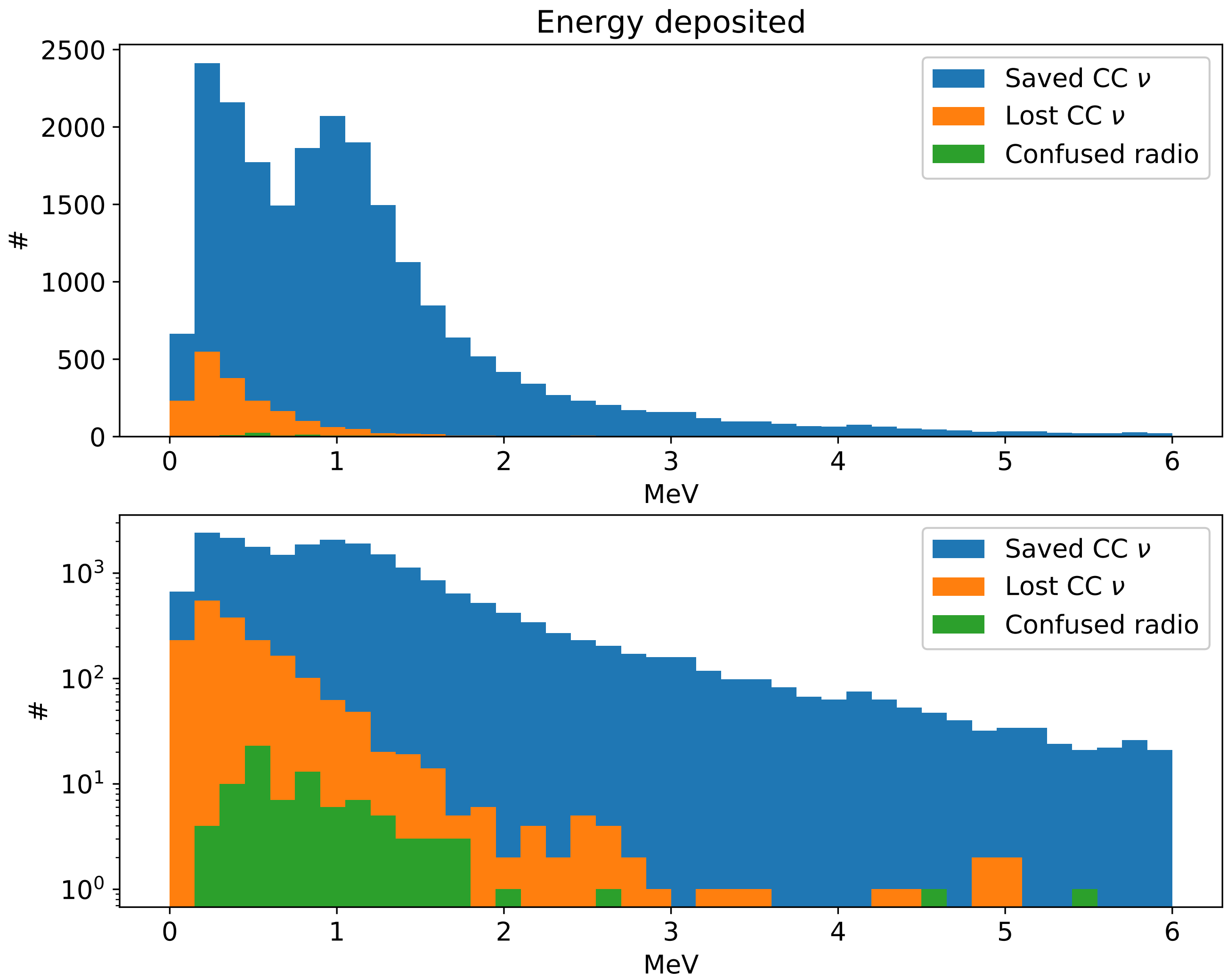
- Radiological = 95.6 %
- Neutrinos = 0.4 %

False positive:

- Radon = 26.1 %
- Argon = 17.0 %
- Krypton = 56.8 %

At the end 92.21 % of the neutrinos are saved

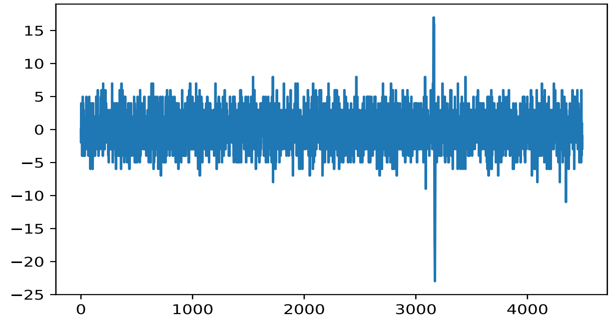
Results

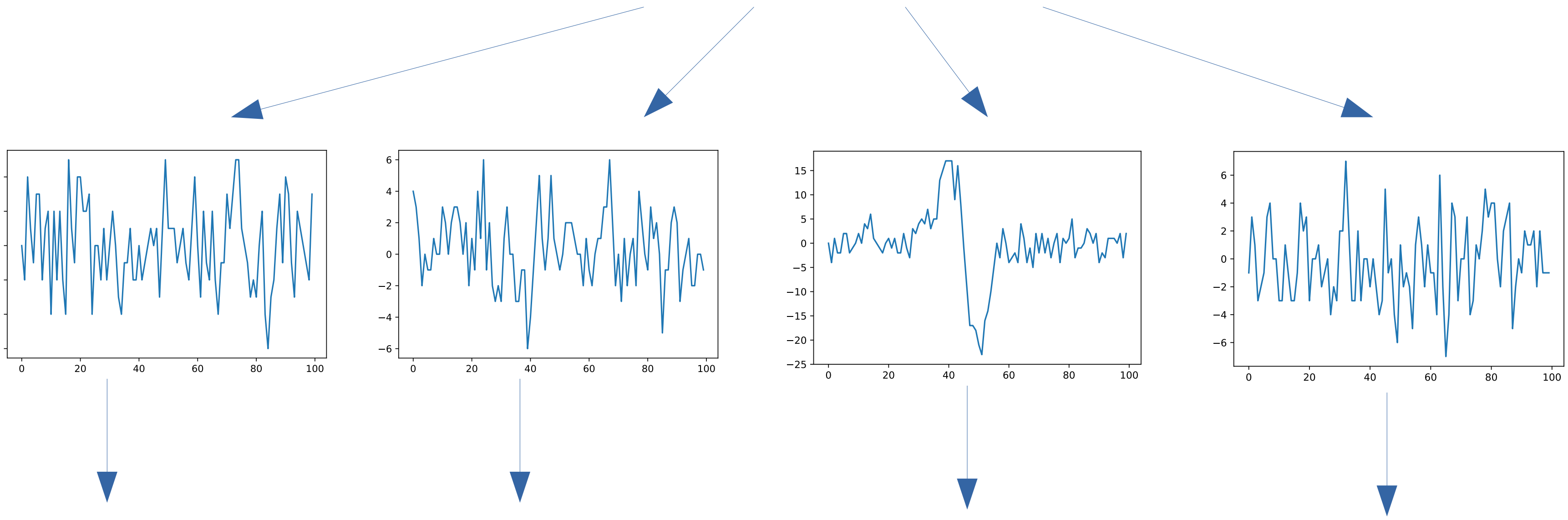


Energy deposited
Saved CC ν
Lost CC ν
Confused radio
#
2500
2000
1500
1000
500
0
0
1
2
3
4
5
6
MeV
Saved CC ν
Lost CC ν
Confused radio
#
10^3
10^2
10^1
10^0
0
1
2
3
4
5
6
MeV

Peak finding, data preparation

440 windows large
100 bins, moving 10
bins at time





Out = 0

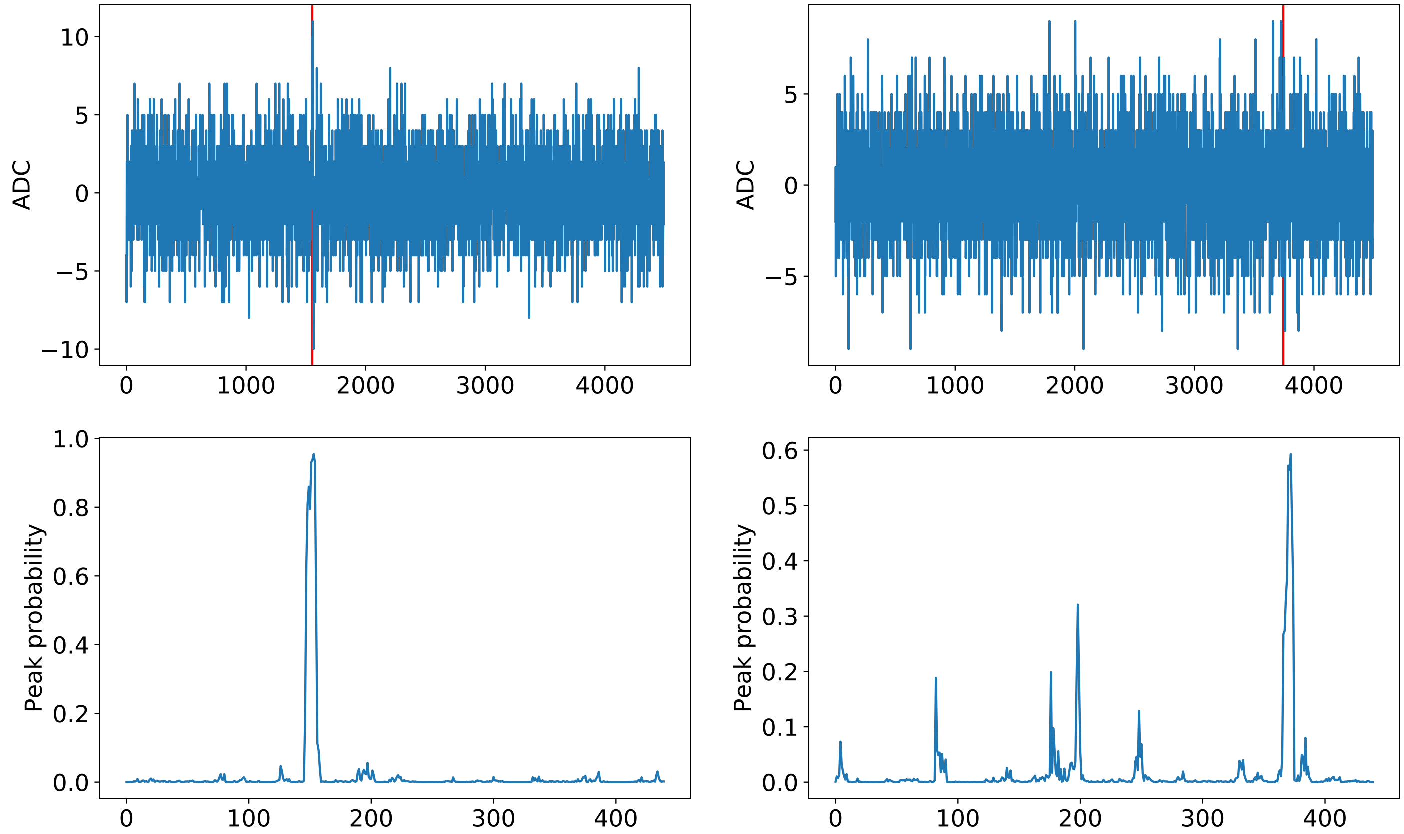
Out = 0

Inside = 1

Out = 0

Results

Another CNN was trained on labelled “windows” data
Accuracy of more than 99%

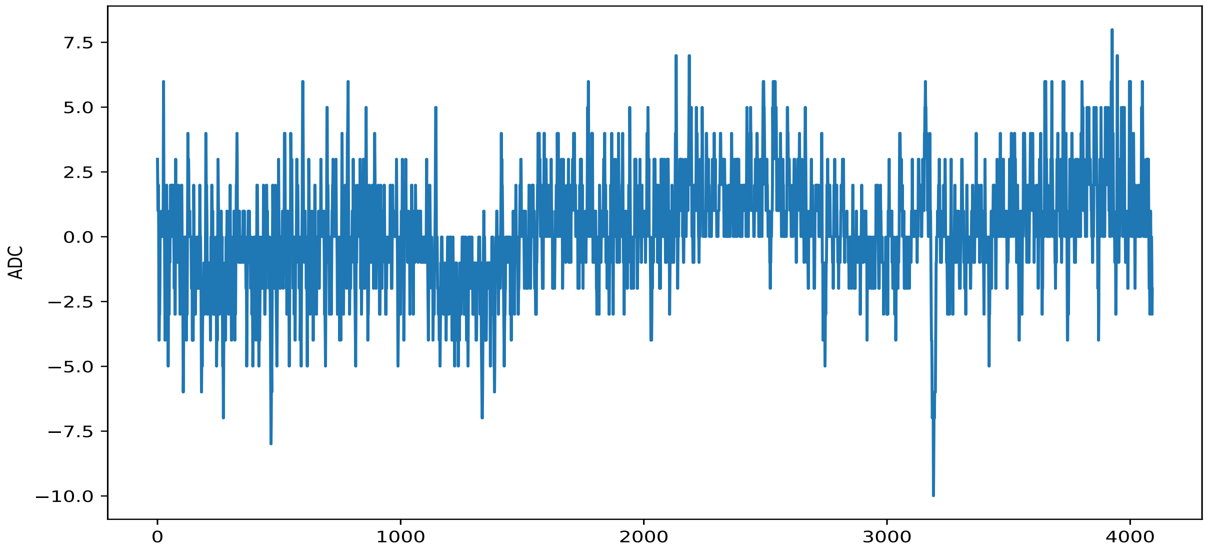


Red line is the position of the peak given by the Monte Carlo

Last step: ICARUS data

ICARUS is a LArTPC detector part of SBN at Fermilab. It aims to study neutrino oscillations, sterile neutrino, ecc...

Problem: due to “hot” electronic the noise is very high, in particular middle induction panel has a really poor signal-noise ratio



Since ICARUS is a LArTPC detector as DUNE will be, why not to apply the developed method to it?

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CNN method applied to ICARUS

- Actual algorithm stores all waveforms and performs a heavy computing de-convolution to extract signal from noise. Must run offline and needs huge storage space and a lot of time.

- Performance for events with less than 15000 collected electrons drops below 75% of accuracy

- The CNN trained on ICARUS data keeps an accuracy between 99.2% and 99.8% for events with collected electrons as low as 2000

- The NN for peak finding has an accuracy of 98%: the overall accuracy is higher than 97%!

- The inference speed is so high that there is no need to make it offline: a Nvidia Tesla K80 is actually faster than the detector throughput

Further Developement

For DUNE:

- Use a training set derived from a much bigger number of events in order to generalize better and being able to avoid sensitivity on statistical fluctuations

- Improve accuracy

- Design a specific hardware (FPGA or ASIC) for our CNN able to handle a huge throughput of data for live application (EdgeTPU by Google has been tested with no satisfying results)

For ICARUS:

- Include our method in LarSoft and perform more accurate tests and comparisons

- If it turns out to be robust and stable, include hardware and software in the DAQ for the CNNs predictions