CNN-based event filtering in LAr detectors using PMTs

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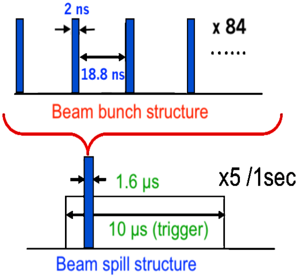
Project overview

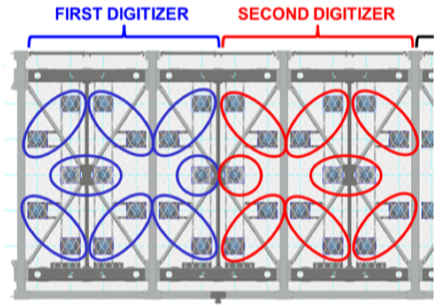
- Within the BNB spill window we expect over three times more cosmic ray backgrounds than neutrino interactions.
- We aim to reduce this background using the information we have available from the PMTs.
- The output is fed into a Convolutional Neural Network (CNN) to discriminate between cosmics and genuine neutrino interactions.



Details

Goal: Reduce the cosmic background in the BNB trigger window using the information we have available from the PMTs.

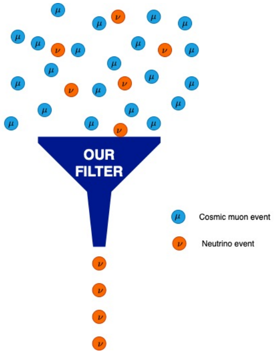
- Following the ICARUS trigger, PMT signals are considered per pair of PMTs.
- As a position, we take a 3D position of each pair as the point halfway between them.
- We also use the time each pair went above the threshold in the trigger.



- And the first opening of the trigger gate after applying the beam gate coincidence (one time per channel), so first time that channel opened.
- These are then converted into 3D images which are used to train our CNN to separate cosmics from neutrino interactions.

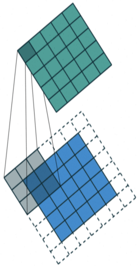
Application

- The primary goal of this tool is to ace as an offline event filtering tool, reducing the cosmic background prior to further processing using PMT multiplicity and timing information.
- We eventually plan to update the tool to also include PMT waveform information and consider each PMT instead of a pair.



Why CNN?

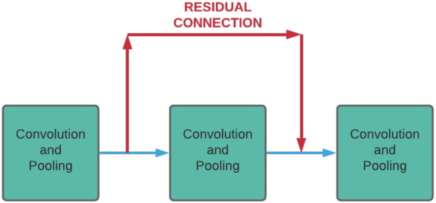
- Separating signal events from background events is a well-studied application of machine learning in HEP.
- ICARUS light detection system - densely packed in PMTs - contains enough detail of interactions and lend itself nicely to image recognition techniques.



- CNNs are designed for image recognition tasks.
- Main concept: apply filters to images to extract features.
- We build images using the information we have available from the PMTs.

Network architecture

- Architecture: **3D ResNet**
- Parameters: **33,185,473**
- 20k neutrinos + 45k cosmics for training
- Optimiser: SGD with learning rate of 0.1 (divided by 10 when error plateaus), momentum of 0.9, and decay of 0.0001



- Weighted loss function, with coefficients: class weights: 1.0 (neutrino), 1.4547077197679608 (cosmic)
- Trained on NVIDIA V100 GPU
- We plan to investigate other architectures to be able to use multiple opening times per channel

Overview

New input data used in this study:

- The MC data (`v09_06_00` *icaruscode*, no overburden, events in two cryostats):

Type	Tot. number of events	Triggered events
CORSIKA	**248600**	50697
GENIE BNB (+**filter**)	50000 (24728 in AV)	24474
GENIE BNB (**no filter**)	59700	44775

  - In the first two samples only two categories of events were considered neutrinos and cosmic background (*binary classification problem*).
  - For the non-filtered neutrino sample and cosmic muon events we distinguish three categories of events (*multi-class classification problem*):
    - two kinds of neutrinos: OAV* and IAV**
    - cosmic background events.

* OAV - neutrinos that are out of Active Volume ** IAV - neutrinos inside Active Volume

Overview

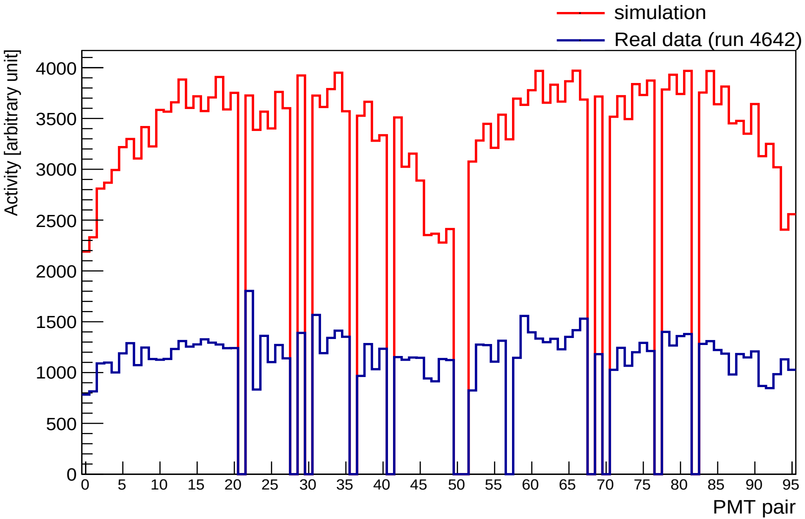
- **Real cosmic + BNB beam data:**

Run number:	**4642**
Number of events:	**156758**
Triggered events:	95984
Data taking time:	14 hours not interrupted
Beam proton intensity:	2.8E12
Beam rep. rate:	3 Hz
Active volume:	**East** (one cryostat)

Expected events:

- For a proton intensity of 1E12 and 5Hz in 24h:
  - 400 beam events + 400 rock muons
  - 6400 cosmics (0.016 cosmics in 1.6 μs spill)
- For run 4642:
  - 360 beam events / 2400 cosmics (156k spills × 0.016 cosmics)

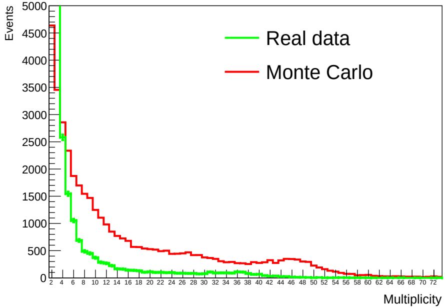
Overview of the PMT pair activity (one cryostat)

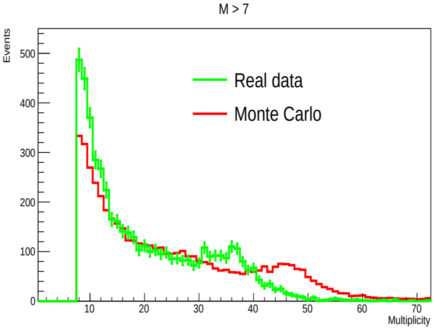


- Better agreement of simulated to real cosmic data - PMTs have been equalised.
- Note: the y-axis is arbitrary in scale (i.e. we don't think the data rate is ~1/2 the MC rate, it's just the shape we want to compare here).

Multiplicity

Multiplicity - is telling us how many PMT pairs surpassed the threshold at least once in one event.

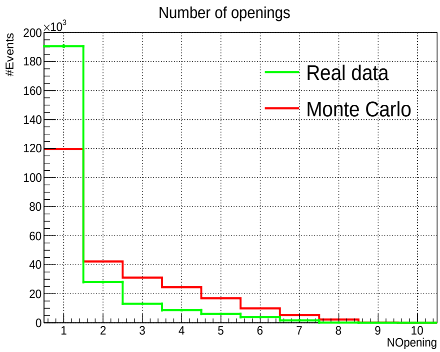




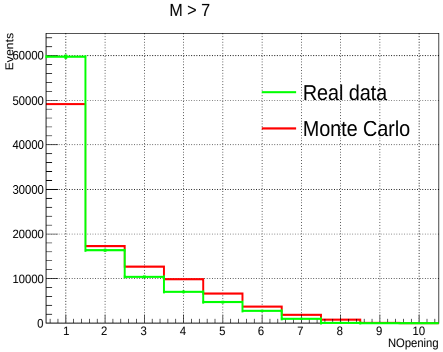
- The excess at low multiplicity for the real cosmic data can indicate the noise contribution or spill over fro light still in the active volume when the trigger window activates.
- After applying a cut on Multiplicity bigger than 7 we observe a better agreement of data to MC samples.

Comparison with the simulated cosmic muon data

- NOpening - the number of times each PMT pair surpasses the trigger threshold per event.*



The number of times each PMT pair *opens*.

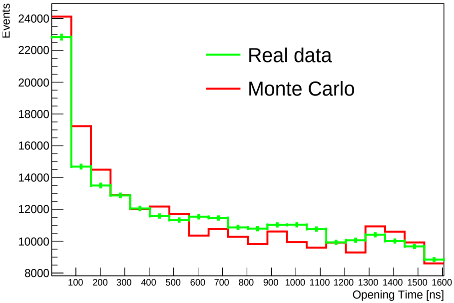


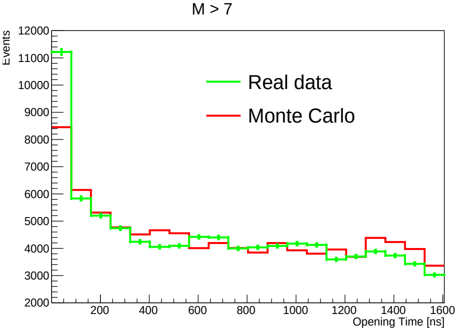
Number of openings after a cut on Multiplicity.

*The time interval we're waiting to check if the new opening happened: 200 ns.

Comparison with the simulated cosmic muon data

- **OpeningTime** - the time each PMT pair went above the trigger threshold per event.**





- For all the variables: Multiplicity, NOpening and OpeningTime is clear that something is going on at low values.

**The larger Opening time, the later PMT pair crossed the threshold.

Results (binary classification)

- For the training data sample* we used the ratio of cosmics to neutrinos as expected in the real data (SBN-doc-14145-v3):
  - $\sim 1\ \nu$ interaction every 180 spills.
  - ~ 1 over 55 spills, is due to cosmic rays inside the beam spill time window.
- Updates to our methodology:
  - weighting of the loss function (allows more neutrinos in training),
  - running a more sophisticated training,
  - removal of empty cosmic events,
  - **training on bigger statistics.**

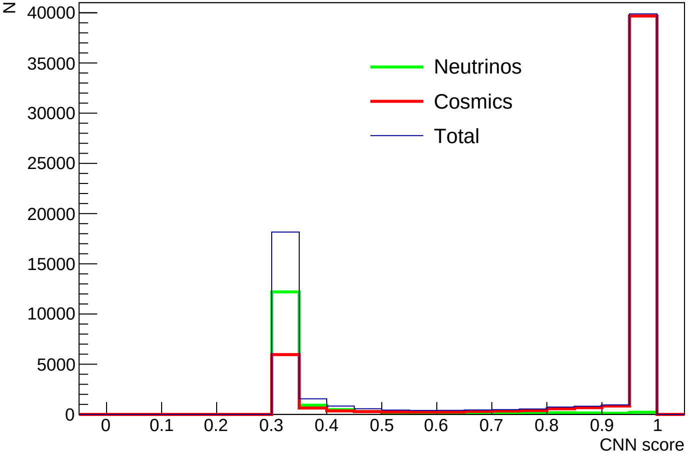
$$\mathscr{E} = \frac{\#\nu\ tagged\ as\ \nu\ in\ test\ sample}{\#\nu\ in\ test\ sample} = 91\%$$

$$\mathscr{P} = \frac{\#\nu\ tagged\ as\ \nu\ in\ test\ sample}{\#events\ in\ test\ sample(\mu+\nu)\ tagged\ as\ \nu} = 66\%$$

$$\mathscr{P}_{before_C NN} = \frac{\#\nu\ in\ training\ sample}{\#events\ in\ training\ sample(\mu+\nu)} = 23\%$$

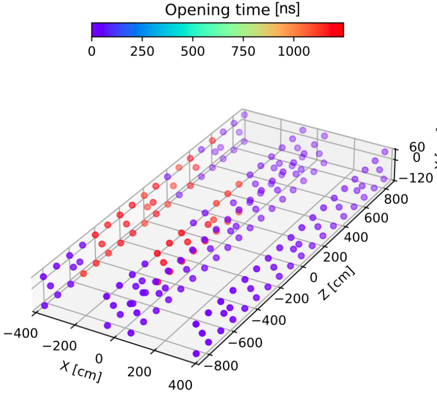
* Training and test sample consider triggered events only

CNN prediction (binary classification problem)



- CNN score = the probability of an event having particular label (ν or cosmic μ).
- ν purity after the CNN increased by a factor of 4.

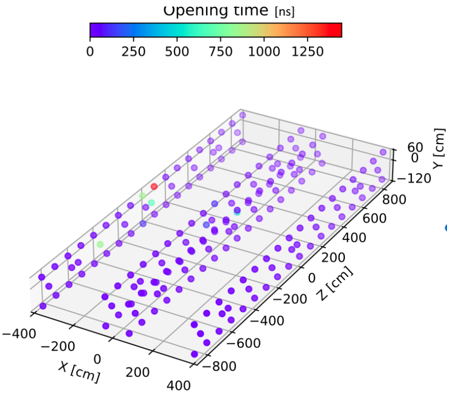
Visualisation of the images used to train our CNN



Predicted as neutrino event

runNo: 4642, subRunNo: 1, eventNo: 305, prediction: 0.263

Looks like long track with a systematic offset in the times on one wall with respect to another (presumably because the track is closer to one wall).



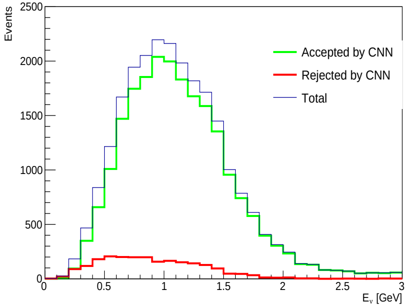
Predicted as cosmic background event

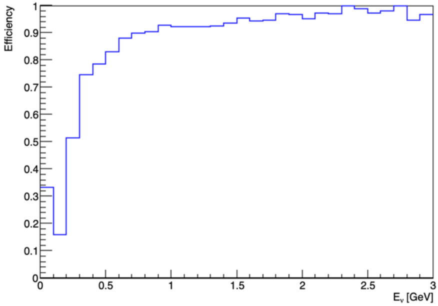
runNo: 4642, subRunNo: 1, eventNo: 63, prediction: 1.000

Looks like it's not through going muon (not so many adjacent PMTs in Z dir. are lit) and that has some hits at totally different times to the others (presumably coming from a second cosmic).

CNN performance w.r.t neutrino energy

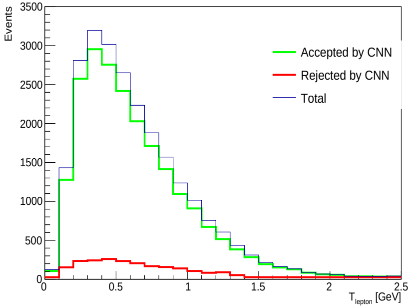
- The classification is not biased by neutrino energy.
- Neutrino selection efficiency with respect to the neutrino energy becomes high and flat for $E_\nu > 0.5$ GeV.

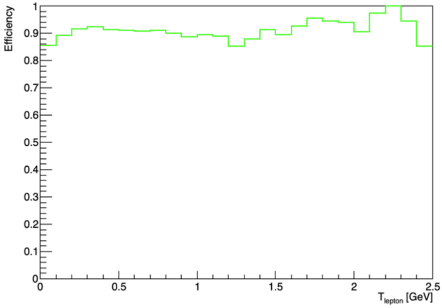




CNN PERFORMANCE W.R.T OUTGOING LEPTON ENERGY

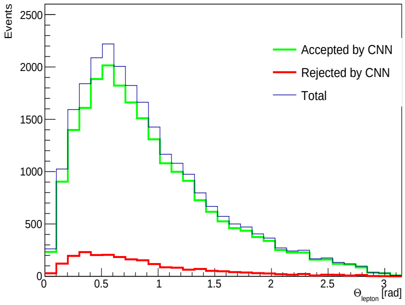
- The classification is not biased by outgoing lepton energy.
- High and flat neutrino selection efficiency with respect to the outgoing lepton energy.

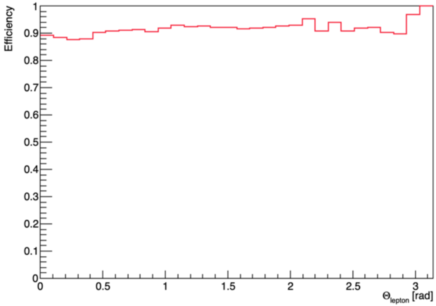




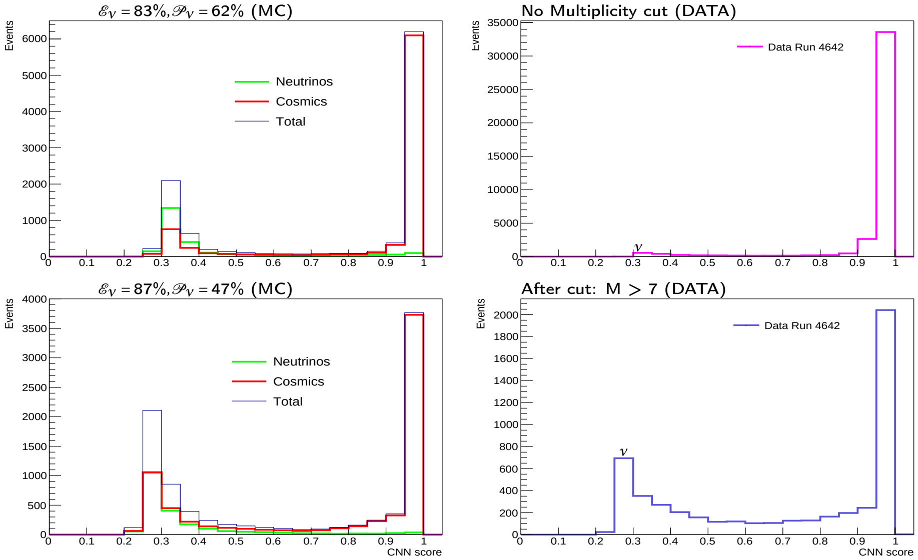
CNN PERFORMANCE W.R.T OUTGOING LEPTON ANGLE

- The classification is not biased by outgoing lepton angle.
- High and flat neutrino selection efficiency with respect to the outgoing lepton angle.





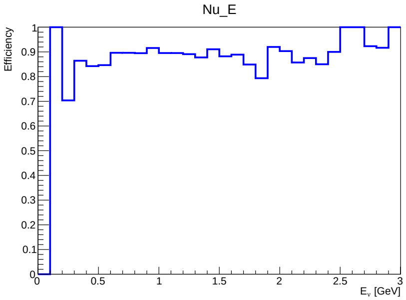
MC vs real data (Multiplicity cut)



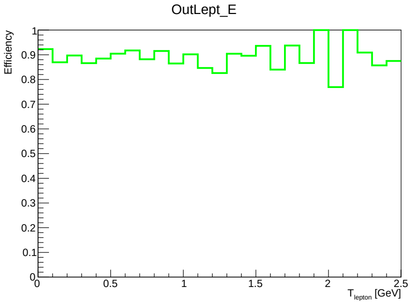
Test on the simulated data with M > 7

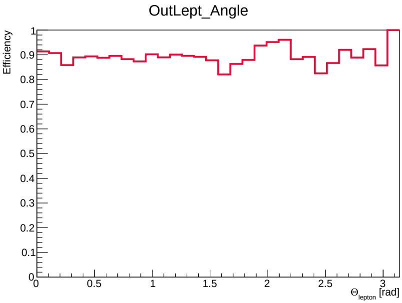
Test on run 4642 with M > 7

ν SELECTION EFFICIENCIES ($M > 7$)

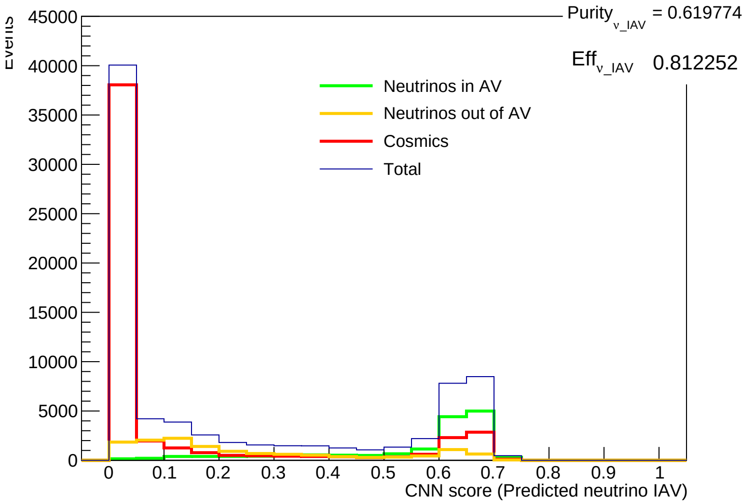


- High and flat neutrino selection efficiency for kinematic variables:
  - Neutrino energy,
  - Outgoing lepton energy,
  - Outgoing lepton angle.





INTRODUCING THREE TYPES OF EVENTS



Considering three types of events: neutrinos out of active volume (OAV), neutrinos in active volume (IAV) and cosmic muons.

Conclusions and next steps

- New results (from the *binary classification*) show that we are able to reduce cosmic background from ~77% to ~34% whilst maintaining a neutrino interaction selection efficiency within the BNB window of ~91%
- Applying multiplicity cut at M>7 shows better agreement between data and simulation and improves the neutrino selection efficiency.
- Introducing the third type of events shows that:
  - we can trust the network selecting cosmic muons ($\mathscr{P}_{cosmic} = 93\%$),
  - we dramatically reduce the cosmic background (from ~77% to ~38%) and keep a high ν selection efficiency (~81%).
- Further separation of the relatively small remaining background can be done in higher level analyses (we can't expect only PMTs to get us to 100% neutrino purity).
- Further steps:
  - Train the network with additional PMT information,
  - add CRT information,
  - add e^- vs μ tag to the neutrino trees,
  - work alongside with relevant experts to implement improved simulations of the PMT responses.