Neutrino interaction event filtering at liquid argon time projection chambers using neural networks with minimal input model bias

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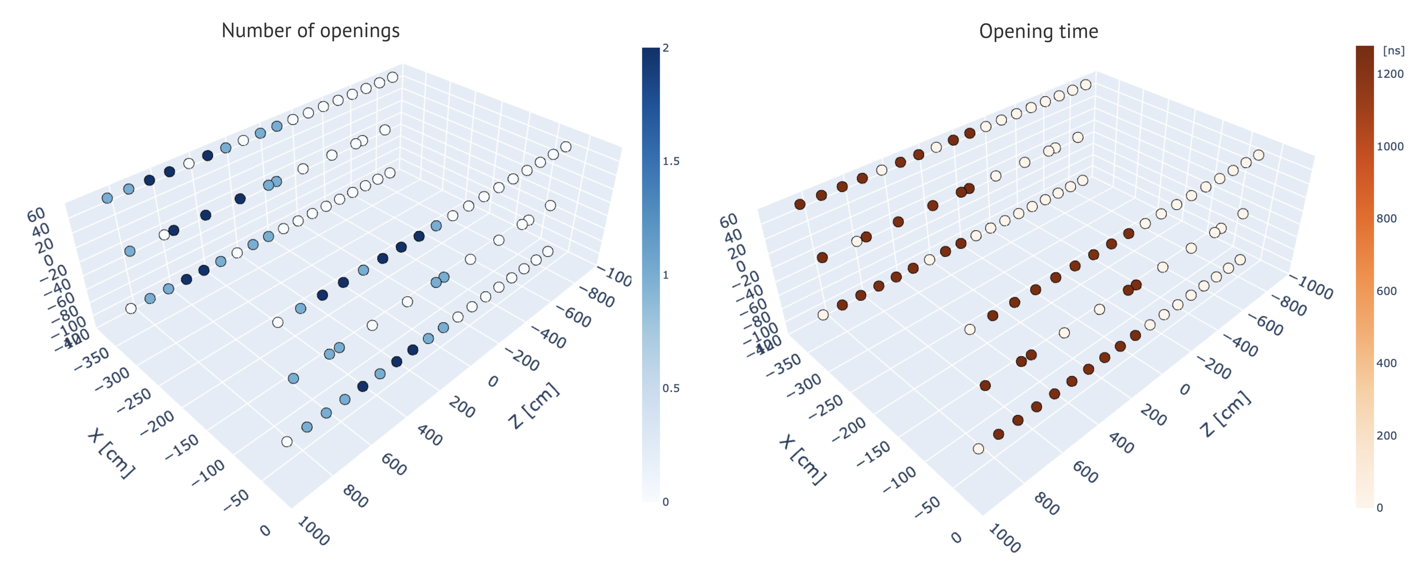
1. Introduction

In current and future neutrino oscillation experiments using liquid argon time projection chambers (LAr-TPCs), a key challenge is identifying neutrino interactions from the pervading cosmic-ray background. Rejection of such background is often possible using traditional cut-based selections, but this typically requires the prior use of computationally expensive reconstruction algorithms. This work demonstrates an alternative approach of using 3D Convolutional Neural Networks (CNNs) trained on low-level timing information from only the scintillation light signal of interactions inside LAr-TPCs. We further present a means of mitigating biases from imperfect simulations by applying Domain Adversarial Neural Networks (DANNs). These techniques are applied to example simulations from the ICARUS detector, the far detector of the Short Baseline Neutrino experiment at Fermilab [1]. The results show that cosmic background is reduced from 77% to 26% while neutrino interaction selection efficiency is over 99%.

2. Input

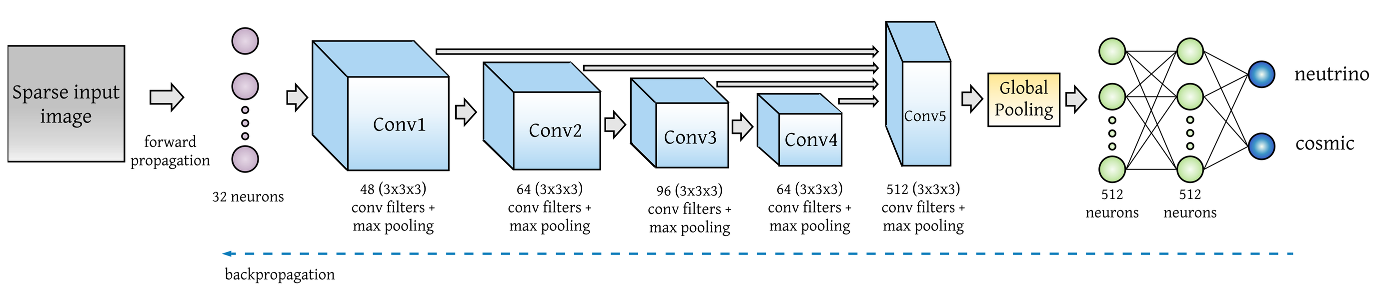
- ICARUS is equipped with 360 8" Hamamatsu PMTs [2] that contain enough detail of interactions and lend to image recognition techniques.
- Following the ICARUS trigger system, the PMTs are paired using OR logic patterns.
- Paired PMT signals are then converted into 3D images using:
  - the 3D position of each pair as the point half way between them.
  - the number of times each pair surpassed the threshold in the trigger.
  - the first opening time of the trigger gate (after beam gate coincidence).
- Simulated 3D images are used to train the CNN to separate neutrino interactions from cosmic background in the beam trigger window based on the PMT information. Example images are shown below:



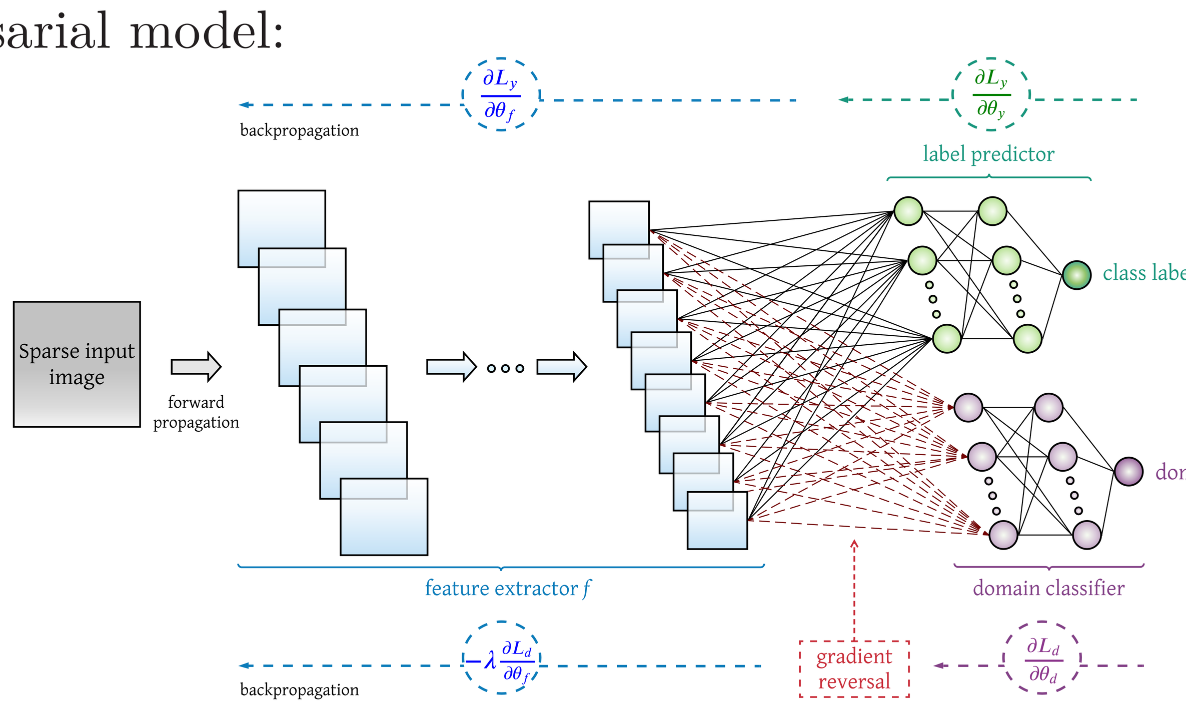
3. Network architectures

The designed CNN architectures use Submanifold Sparse Convolutions [3] to deal with the sparsity of neutrino interactions. They were implemented in PyTorch using the Minkowski Engine [4].

- Original model:

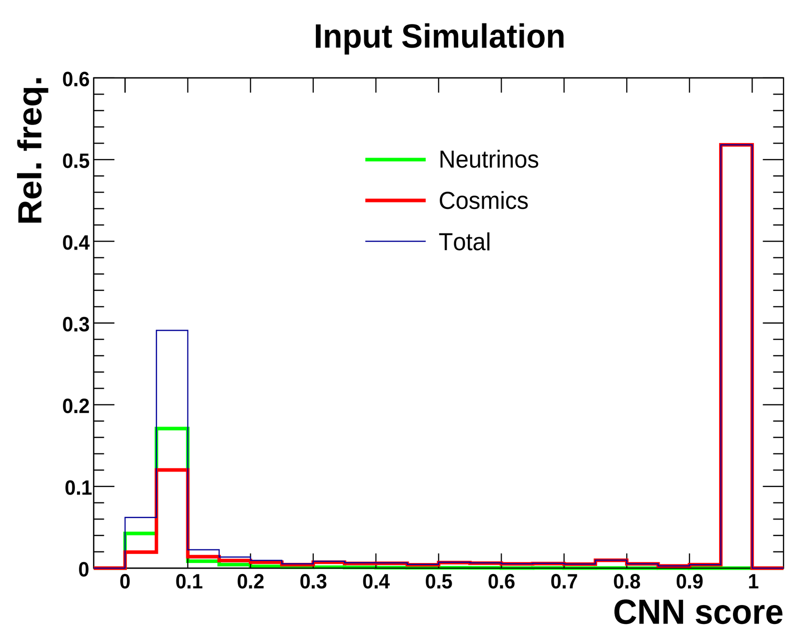


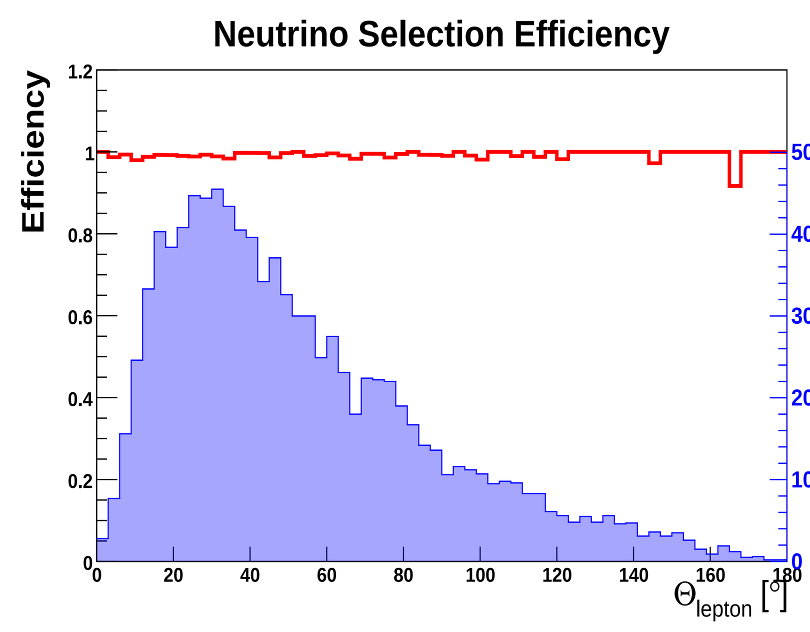
- Adversarial model:



4. CNN-based approach to event filtering

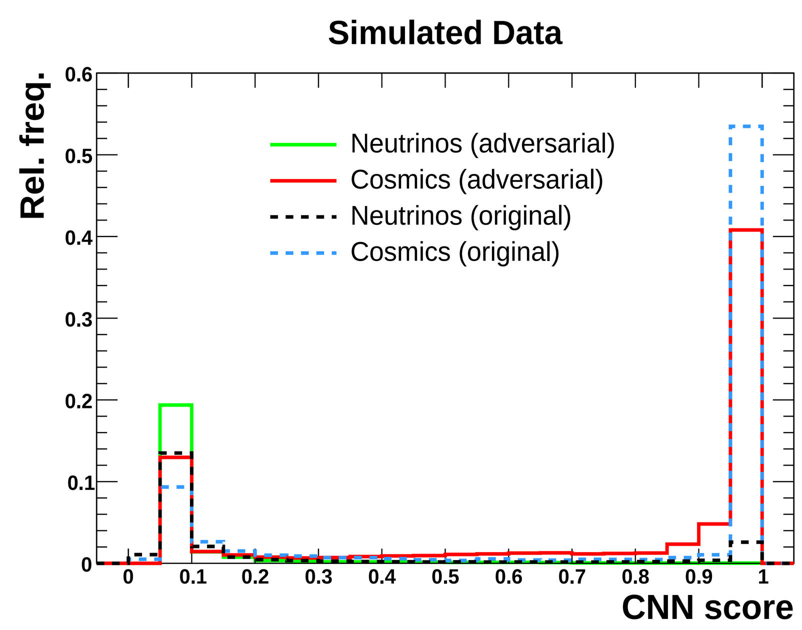
- The output of the CNN is a score for each event between 0 (neutrino-like) and 1 (cosmic-like), as presented by the distribution below.
- If a selection of neutrino events is made by cutting at a CNN score of 0.5 a 99.64% charged-current selection efficiency is maintained whilst 74.22% of cosmic-ray backgrounds are rejected.
- The neutrino selection efficiency was found to be unbiased by kinematics in a variety of tested observables. An example showing the angle of the outgoing lepton with respect to the incoming neutrino is shown in the figure below.





5. Reducing model-dependence with DANNs

- ML algorithms trained on simulation, but applied to physics detector data, face uncertainties due to scientific modelling, e.g. the simulation is based on a physics model that is not identical to nature.
- To control these effects, we optimise the network trained in one domain (e.g. simulation) but applied in another (e.g. detector data) by using **domain-adversarial neural network (DANN)** [5].
- The goal is to ensure the discriminator relies only on domain-invariant features to perform the predictions.



- The DANN's effectiveness in reducing simulation dependence was verified with a series of dedicated *simulated-data* samples (generated by applying distortions to the simulated detector response).
- The figure presents the classification scores for one set of *simulated-data* events. The results obtained from the original CNN are represented by dotted lines and from the DANN by continuous lines. A rise of neutrino selection efficiency from 81.14% to 97.21% is observed.

6. Conclusions

1. A CNN-based event filter to separate neutrino interactions from cosmic backgrounds using the PMT timing information successfully rejects the 74.22% of the cosmic background while being very efficient in selecting neutrino interactions (99.64%).
2. DANN further reduces the reliance on the simulation through adversarial training using simulated data (to be replaced by the detector data in the future). The results show an improvement of neutrino efficiency by 16.07%, allowing us not to miss neutrino events.
3. This has numerous applications in HEP and other problem domains.

7. References

[1] M. Antonello *et al.* (MicroBooNE, LAr1-ND, ICARUS-WA104), arXiv:1503.01520 [physics.ins-det] (2015).

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[4] C. Choy, J. Gwak, and S. Savarese, arXiv:1904.08755 [cs.CV] (2019).

[5] Y. Ganin *et al.*, J. Mach. Learn. Res. **17**, 2096–2030 (2016).