Deep Learning for Liquid Scintillator-Based Double-Beta Decay Searches

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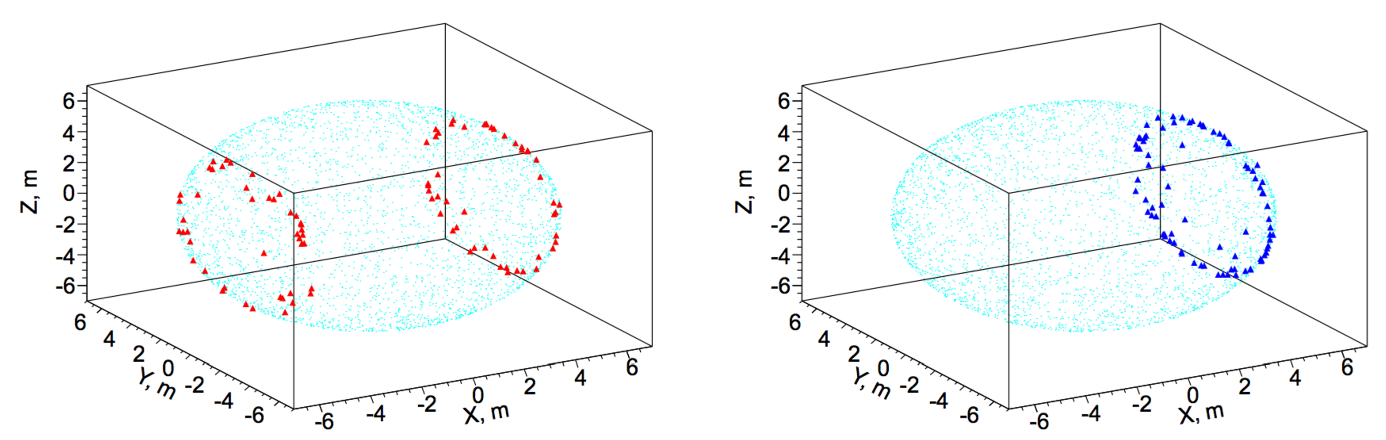
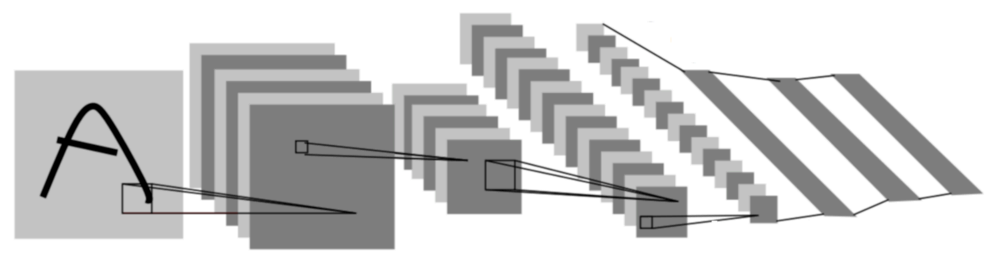
Abstract:
Liquid scintillator-based (LS) detectors are one of the leading detector technologies in the search for neutrinoless double-beta decay. They are currently limited by naturally occurring and spallation induced backgrounds. In the future they will be limited by the neutrino-electron scattering of Boron-8 solar neutrinos. Here we use a convolutional neural network, a common algorithm from computer vision, to attempt to distinguish between events that would have made it through existing cuts. We train our network on Monte Carlo simulated truth data with a range of detector capabilities, and evaluate the training results in these different conditions. The ultimate goal of this project is to apply sophisticated machine learning techniques to reject backgrounds in real detector data.

Introduction:
Observing neutrinoless double-beta ($0\nu\beta\beta$) decay would prove that the neutrino is a Majorana particle, which could explain cosmological baryon number excess in addition to the neutrino mass. LS detectors are leading the historic search for this decay because they are scalable from 1 ton to 1 kiloton with energy resolutions of $\sigma(E)$ =~5%/$\sqrt{E(\text{MeV})}$. Scintillation light in these detectors is isotropic, but beta decay electrons often exceed Cherenkov threshold; with good timing, the characteristic ring pattern from Cherenkov light could be used to recover directional information.



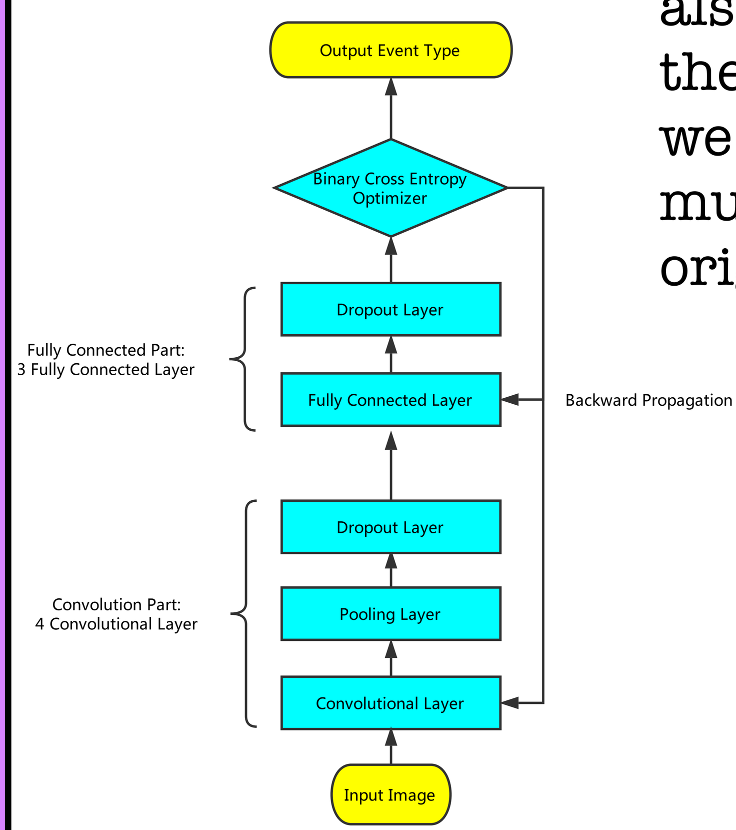
(Nucl.Instrum.Meth. A849 (2017) 102-111)
See also A. Elagin, Wednesday Session Wall #151

Convolutional Neural Networks (CNNs):
Machine learning has recently been extremely effective at many tasks including classifying images and handwritten characters. Cherenkov rings from single- and double-beta decays superficially resemble 0's and 8's, so we start with the specific technique that was good at distinguishing handwritten digits: convolutional neural networks. These use translation-invariant filters to extract features from groups of adjacent pixels.

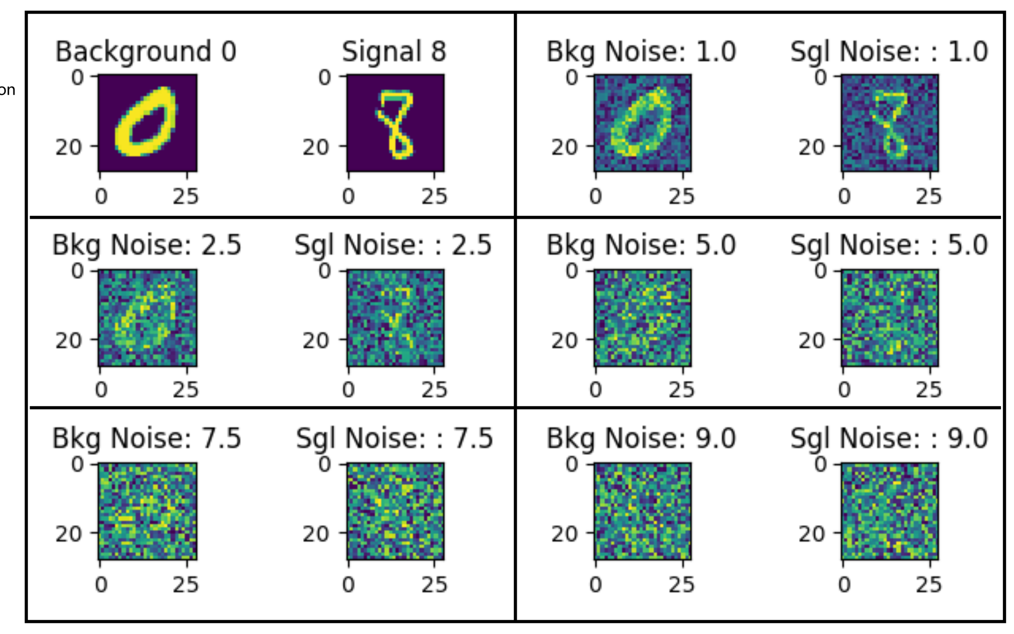


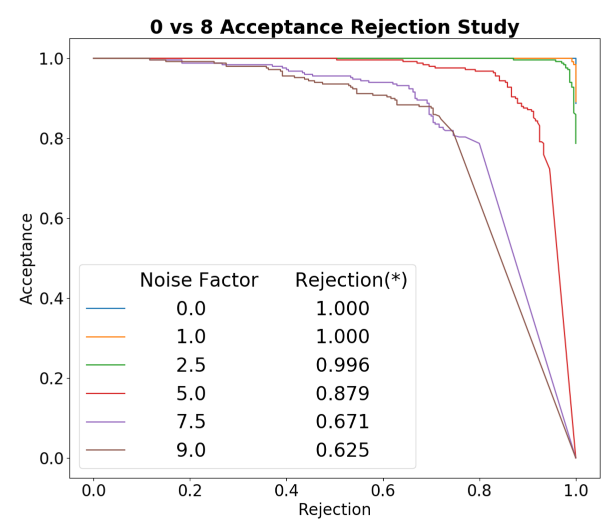
(LeCun et al, 1998)

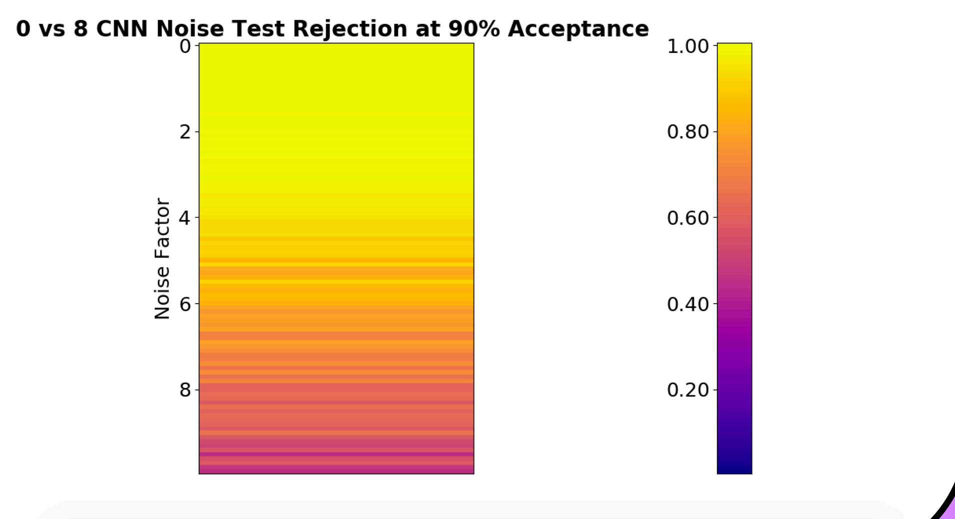
Our network:



A Simple Test: For comparison, we also trained it on 0's and 8's from the iconic MNIST dataset, to which we added noise (noise level is a multiple of the signal strength, i.e. original pixel intensities)

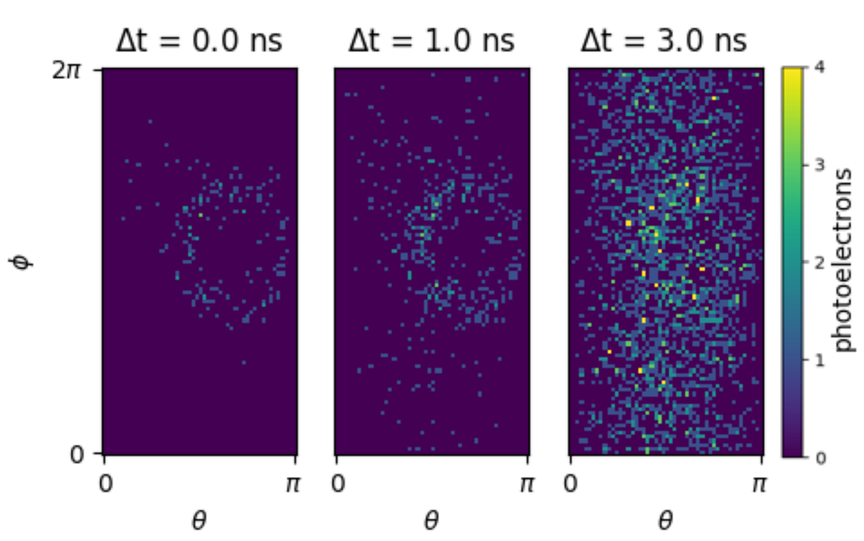




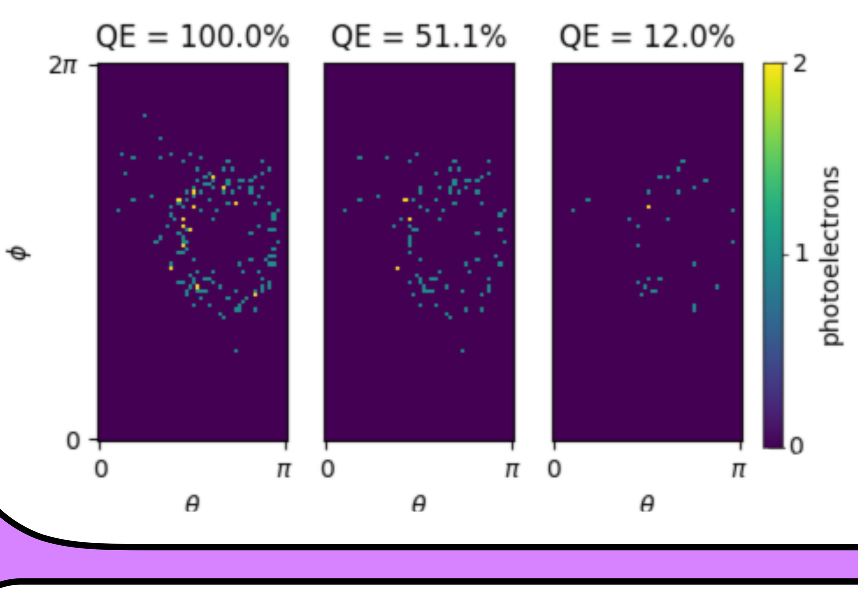


Data:
We use data from a Monte Carlo simulation of a 6.5m-radius spherical detector with arbitrary spatial resolution and timing. We trained on different time cuts.

KamLAND-Zen, the leading LS detector has time resolution ~1.5ns; NuDot [1] will have time resolution < 200 ps.



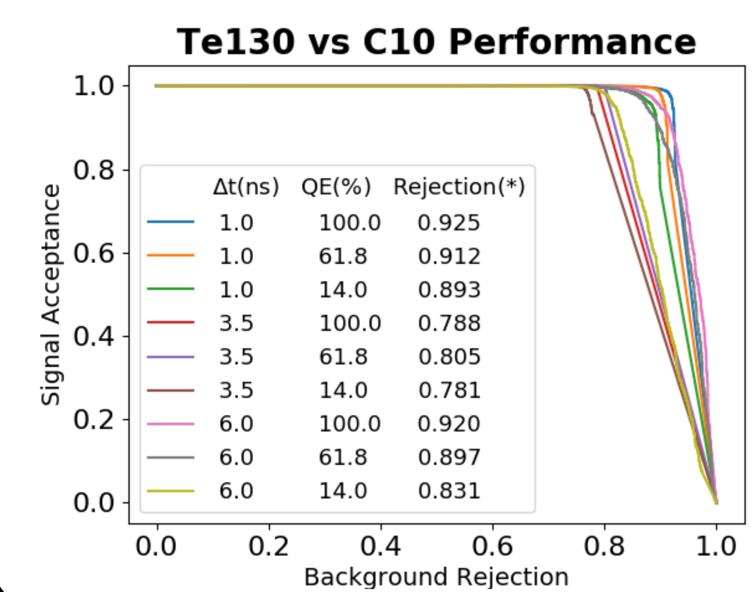
We also tried with artificially increased quantum efficiency (QE) so we could check our events by eye, but it turns out to not be necessary for network discrimination as long as we can get a good time cut.



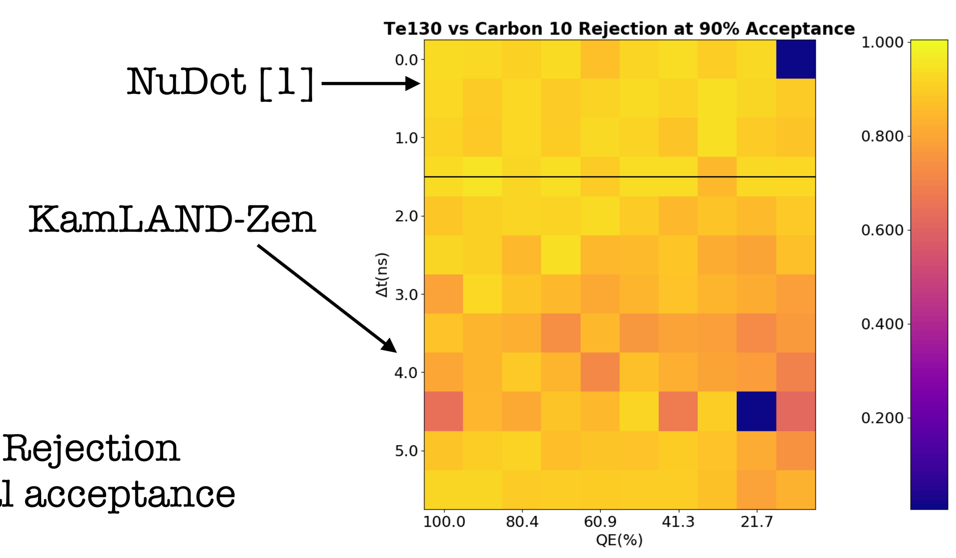
KamLAND-Zen's PMTs have QE ~12% at Cherenkov wavelengths. We are assuming 100% coverage.

Also see: [1] Gruszko for NuDot (Wall #53)

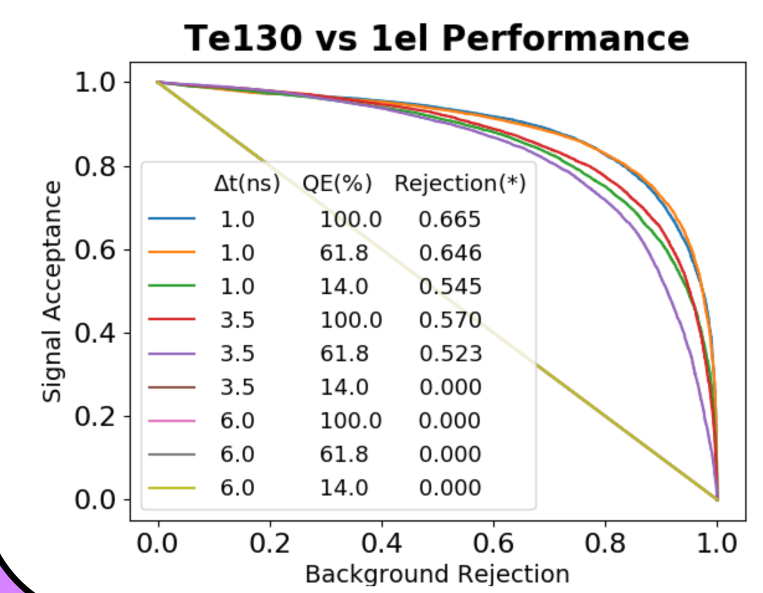
Study 1 - Carbon-10 Background:
Spallation-induced Carbon-10 is currently a dominant background in KamLAND-Zen. We trained our network to distinguish ^{130}Te $0\nu\beta\beta$ events from ^{10}C β^+ decays whose energy distribution spans the $0\nu\beta\beta$ Q-value.



* Background Rejection at 90% signal acceptance



Study 2 - Solar Neutrino Background:
Neutrino-electron scattering of Boron-8 solar neutrinos will be a dominant background in the future. Here we trained our network to distinguish ^{130}Te $0\nu\beta\beta$ events from scattered electrons with the exact $0\nu\beta\beta$ Q-value.



* Background Rejection at 90% signal acceptance