Prospects for Neutron-Antineutron Oscillation Searches with Convolutional Neural Networks in Liquid Argon Time Projection Chambers

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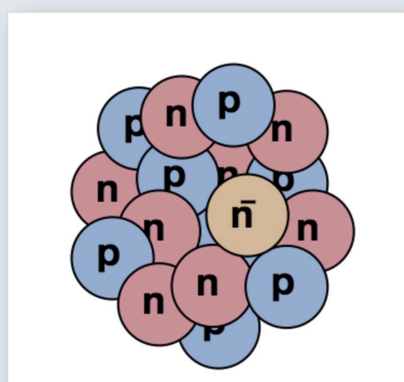
Neutron-Antineutron Oscillation

A rare, Baryon-number violating signature…



Baryon-number violating ($\Delta\mathcal{B}$=2) **process**.

Nucleus-bound neutron **oscillation**, followed by **annihilation** with neighboring nucleon (p or n) inside the parent nucleus.

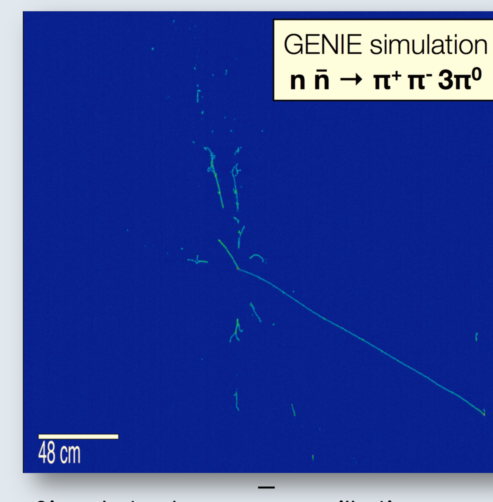
$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1.2%	$\pi^+\pi^-$	2.0%
$\pi^+2\pi^0$	9.5%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	11.9%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	26.2%	$\pi^+\pi^-2\pi^0$	11.0%
$2\pi^+\pi^-2\pi^0$	42.8%	$\pi^+\pi^-3\pi^0$	28.0%
$2\pi^+\pi^-2\omega$	0.003%	$2\pi^+2\pi^-$	7.1%
$3\pi^+2\pi^-\pi^0$	8.4%	$2\pi^+2\pi^-\pi^0$	24.0%
		$\pi^+\pi^-\omega$	10.0%
		$2\pi^+2\pi^-2\pi^0$	10.0%

$n \to \bar{n}$ **annihilation branching ratios** adapted from [arXiv: 1109.4227]

Current best limits on free neutron lifetime:
- Free neutron beam search at **ILL**: $\tau > 0.86 \times 10^8$ s (90%CL) [Z. Phys. C. v63, 409-416]
- **Super-K** oxygen-bound neutron search: $\tau > 2.7 \times 10^8$ s (90%CL) [arXiv:1109.4227]
- **SNO** deuterium-bound neutron search: $\tau > 1.23 \times 10^8$ s (90%CL) [arXiv:1705.00696]

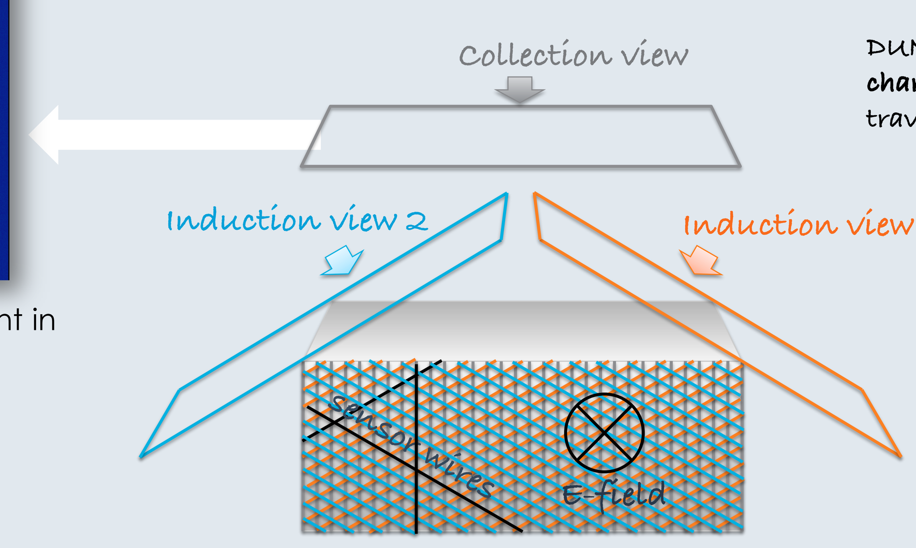
The Deep Underground Neutrino Experiment: DUNE

A high-resolution, 3D-imaging camera



Simulated $n \to \bar{n}$ oscillation event in a LArTPC: **"star event"** topology

DUNE employs a **large-mass** (40 kton) liquid argon time projection chamber (LArTPC) detector, **deep underground** in a low cosmogenic background environment — *ideal for rare physics searches!*



*DUNE works by imaging **ionization charge** created by charged particles traversing the liquid argon.*

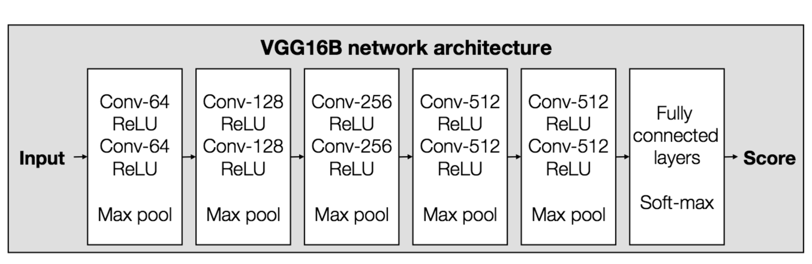
Charge drifts (uniformly) toward a sensor-wire array. Digitized sensor-wire signals vs. time record images of ionization deposition in 3 different views.

Qualitative arguments for DUNE's ability to improve upon existing limits:
- mm-level spatial resolution allows vertex identification.
- dE/dx information provides particle ID and calorimetry.

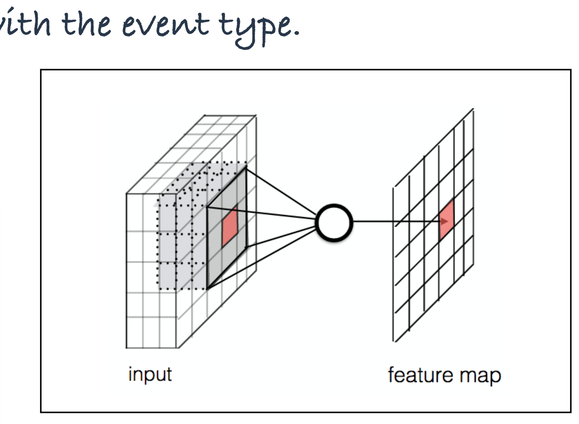
Convolutional Neural Networks

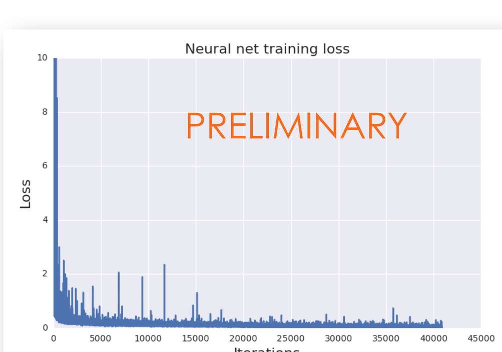
CNN: A class of deep, feed-forward artificial neural network, typically applied in image analysis.

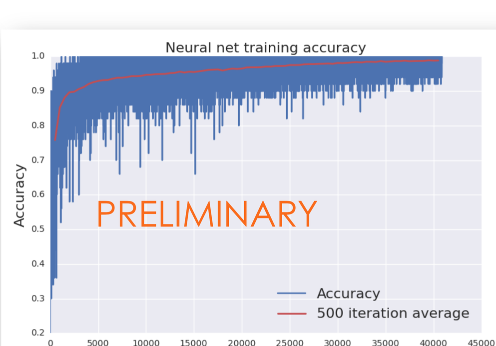
Example: VGG16B network architecture



Network performs convolutions on input images to pick out complex features, and learns to associate these features with the event type.





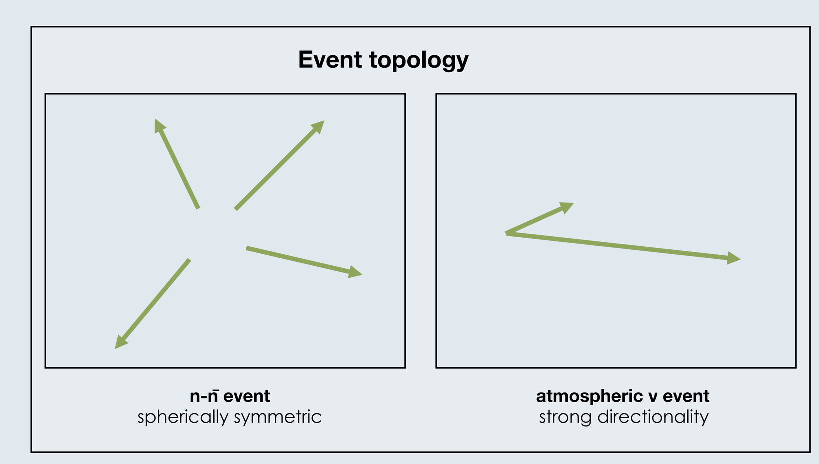


- During training, network learns by minimizing a **loss function**, derived from network weights, which abstracts how many **classification mistakes** the network made.
- Network also monitors **accuracy** — simply, the proportion of images **classified correctly**.
- Reducing learning rate allows network to be fine-tuned after initial training.

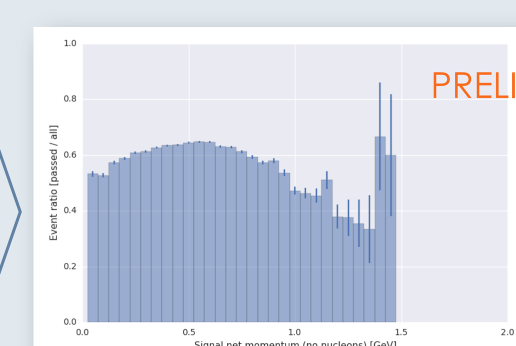
Dominant background expected to be from atmospheric neutrino interactions (NC).

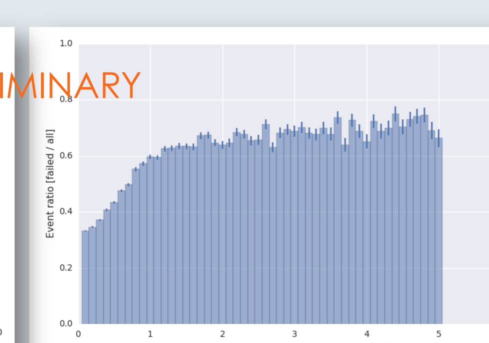
Mitigation with traditional reconstruction exploits topology (spherical symmetry/net momentum) and calorimetric energy reconstruction.

Can a CNN learn to exploit these features?



Signal selection efficiency vs. net momentum





Background rejection efficiency vs. net momentum

High-resolution image of a (strikingly unique) "star-event" topology

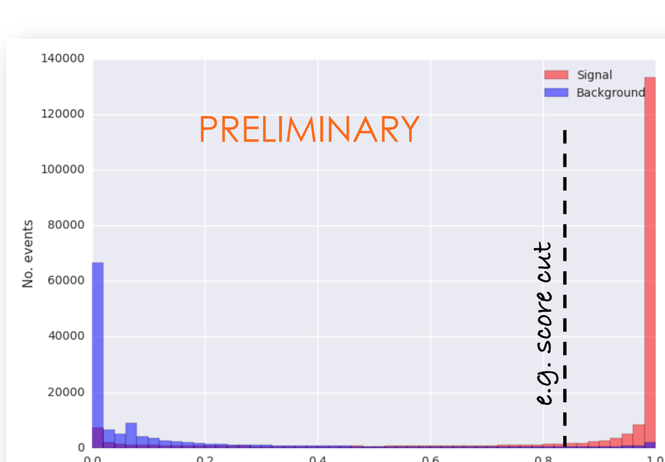
+ powerful technique for image-based classification

= promising high-sensitivity to this rare signature!

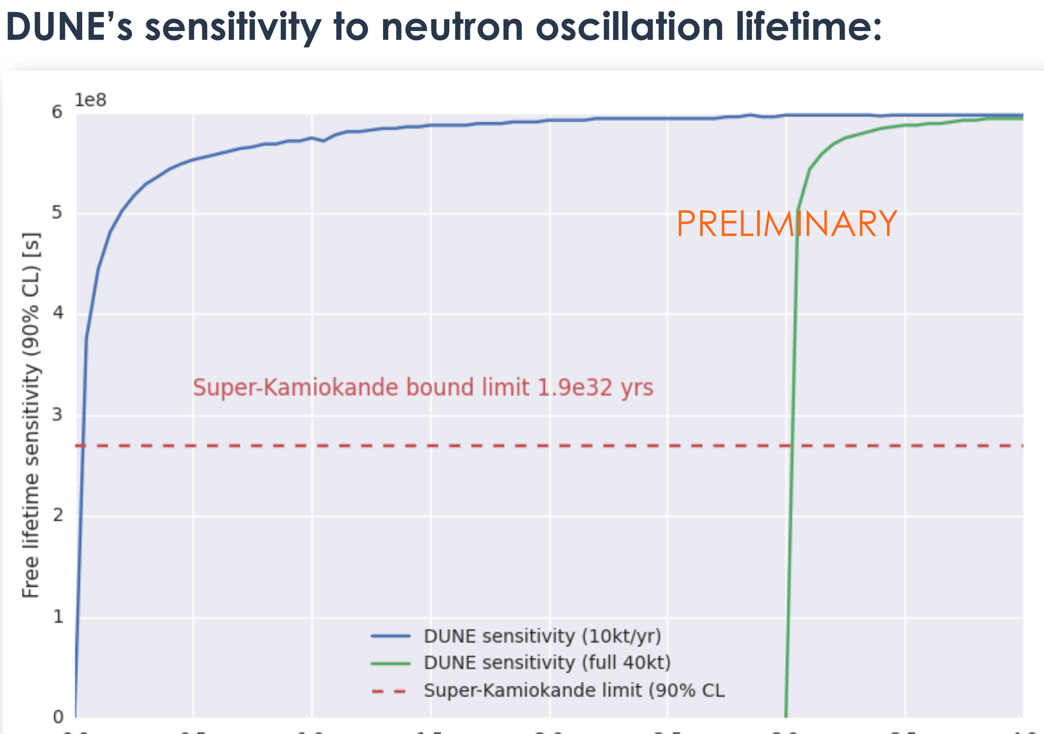
Sensitivity Prospects for DUNE

using CNN analysis…

Benchmarking CNN performance on simulated signal and background event test samples:



DUNE's sensitivity to neutron oscillation lifetime:



- An optimized cut on CNN score of 0.99995 provides a signal selection efficiency of 32% and an atmospheric ν background rejection rate of 99.98%.
- At this efficiency and background rate, DUNE's sensitivity is $\tau > 6.0 \times 10^8$ s (90% CL) after 10 years of running.
- **Factor of ~2 improvement over current best limit from Super-K.**
- Systematic assumptions: $\sigma_\lambda = 3\%$, $\sigma_\epsilon = 25\%$, $\sigma_b = 25\%$

$$P(\Gamma|n_{obs}) = A\int\int\int \frac{e^{-(\Gamma\lambda\epsilon+b)}(\Gamma\lambda\epsilon+b)^{n_{obs}}}{n_{obs}!}P(\lambda)P(\epsilon)P(b)d\lambda d\epsilon db$$

$$\int_0^{\Gamma_{90\%}} P(\Gamma|n_{obs})d\Gamma = 0.9$$

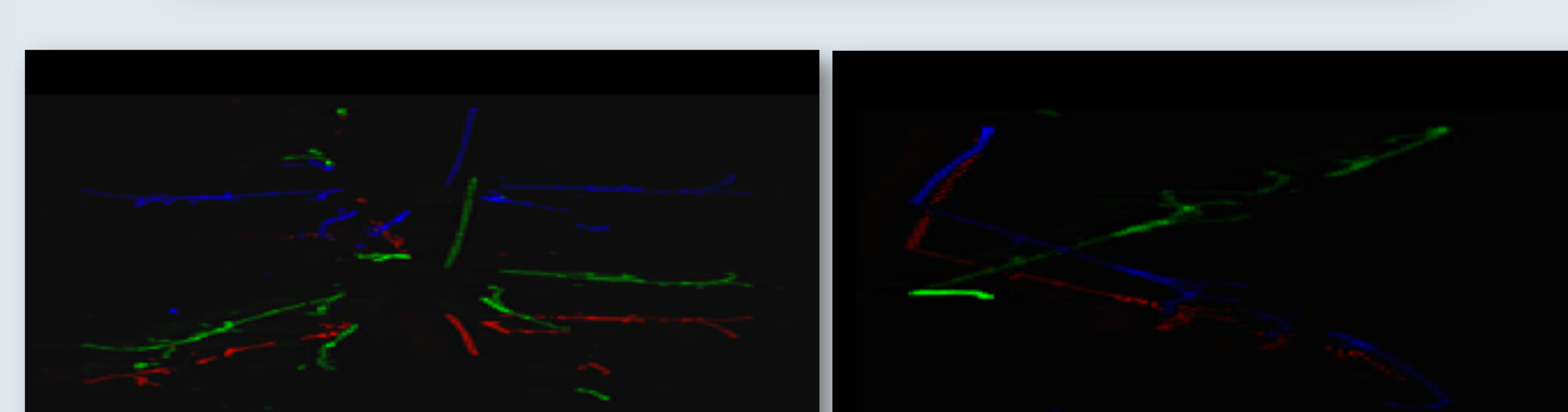
Γ = Oscillation width
n_{obs} = No. events observed
A = Normalisation constant
λ = Exposure
ε = Selection efficiency
b = Background rate

DUNE analysis details:

EVENT GENERATION	GEANT4 SIM	FD SIMULATION	WIRE "RECONSTRUCTION"
Signal and background samples generated in GENIE. Atmospheric flux: Honda @ Homestake (oscillated).	Default G4 simulation in dunetpc.	RawDigit wires with default simulation. Exponential noise simulation with low-frequency cut-off. Channels zero-suppressed and wires with no signal removed.	Wire deconvolution performed on raw waveforms. No further reconstruction stages (hit finding, object reco) performed.

Using version of Caffe CNN framework [arXiv:1408.5093] modified to interface with LArTPC data files [arXiv:1611.05531].

VGG16 network architecture [arXiv:1409.1556] trained with 50,000 signal and 50,000 background events.



Example signal event (left) and background event (right), with three wire plane event displays overlaid using the RGB information of a single image.