Summary of Machine Learning Applications for the COHERENT Collaboration

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Overview

1. COHERENT

Intro, research interests, some results

2. ML applications on individual detectors

- Neutrino Cubes (Dr. J. Daughhetee: jdaughhe@utk.edu)
- CENNS-10 (Dr. J. Daughhetee)
- NaI$\boldsymbol{\nu}$**E** 185 (Peibo An: pa77@duke.edu)

3. Conclusion

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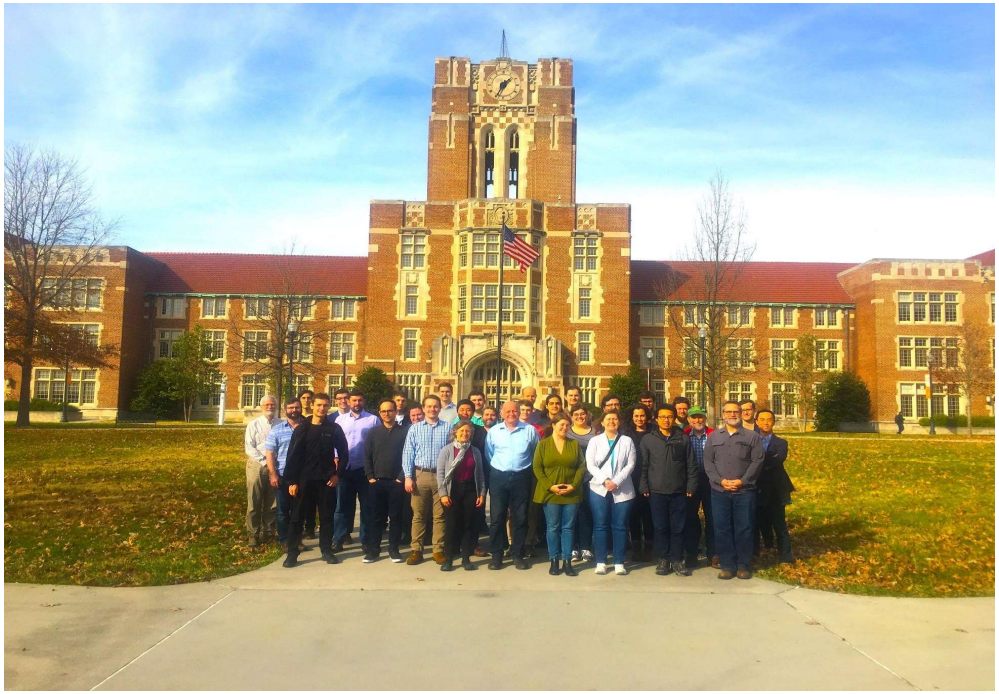
The COHERENT Collaboration



- 21 institutions from 4 countries
- Uses SNS at ORNL as neutrino source
- Studies coherent elastic ν–nucleus scattering (CEvNS) and inelastic neutrino interactions

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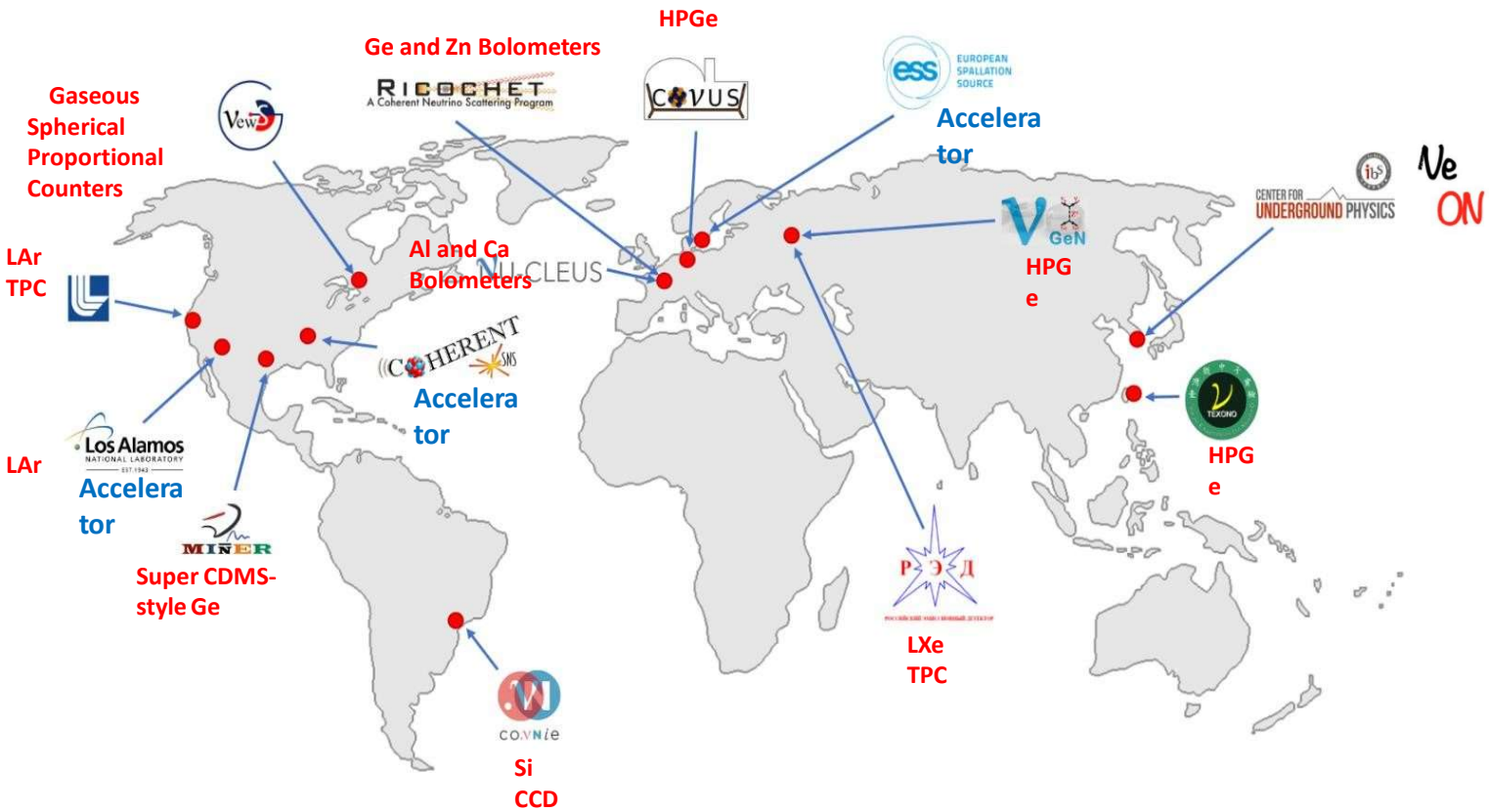
CEvNS Efforts around the world



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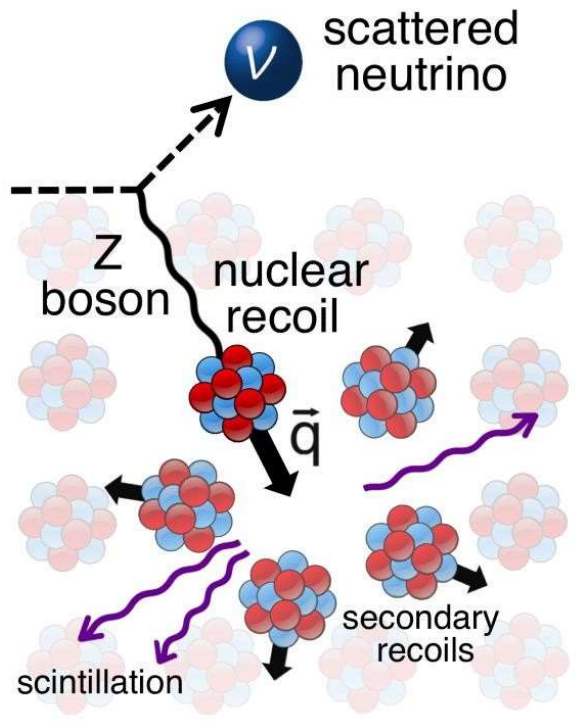
Coherent Elastic ν–Nucleus Scattering

$$\sigma_{tot} = \frac{G_F^2 E_\nu^2}{4\pi}\left[Z\left(1-4\sin^2\theta_W\right)-N\right]^2 F^2(Q^2)$$

- Predicted by D. Freedman in 1974 [1]
- Largest of all SM neutrino cross-sections at 1-100 MeV scale
- Low energy nuclear recoils
- Sensitive Standard Model Probe
- Applications: Dark Matter Experiments, Supernovae, Monitoring



[1] Coherent effect of a weak neutral current, D. Freedman, PRD v.9, n.5 (1974)

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ν_e charged-current interactions on $^{127}\mathrm{I}$

$$\nu_e + {}^{127}\mathrm{I} \rightarrow {}^{127}\mathrm{Xe}^{*} + e^{-}$$

- * indicates that $^{127}\mathrm{Xe}$ can be in excited states. Deexcitations could produce protons, neutrons, gamma rays and alpha particles.
- The cross section[2]:

$$\sigma = \frac{g_A^2}{\pi c^3 h^4} \int_0^{E_\nu - Q} P_e E_e F(Z, E_e)\, S_\beta(E')\, dE'$$

- g_A is the axial vector coupling constant, whose quenching affects the rate of $\beta\beta 0\nu$ decay.

[2] Strength Function of ^{127}Xe and Iodine-Xenon Neutrino Detector, Yu. S. Lutostansky and N. B. Shul'gina, PRLVol. 67 No. 4, July 1991

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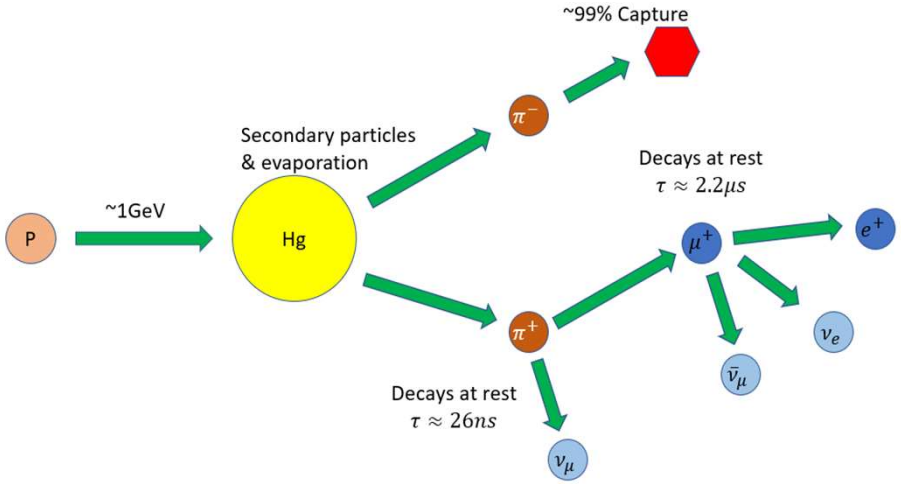
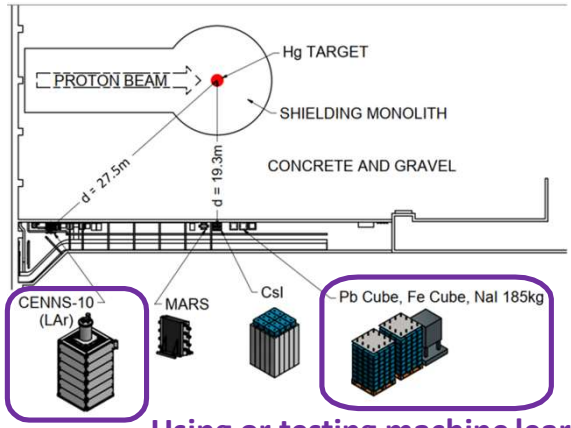
COHERENT at the SNS

- Made a successful observation of CEνNS for the first time using a 14.6 kg CsI[Tl] scintillator and published this result in the journal Science in 2017[2].



- Observation to precision.

- Multiple detectors deployed.



Using or testing machine learning

[2] Observation of Coherent Elastic Neutrino-Nucleus Scattering, D. Akimov et al. (COHERENT), Science (2017). 1708.01294.

The bottom right figure from: [3] COHERENT Proposal 2018

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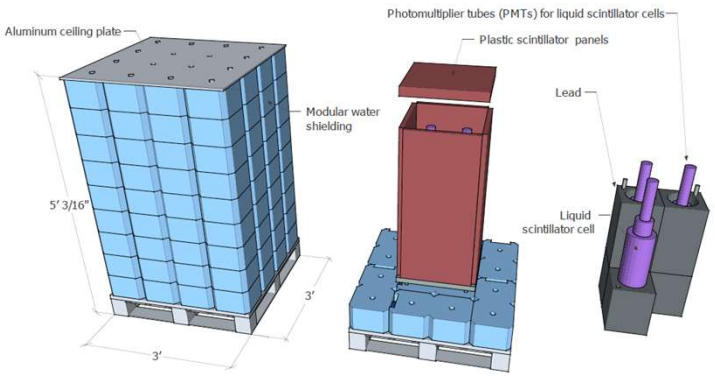
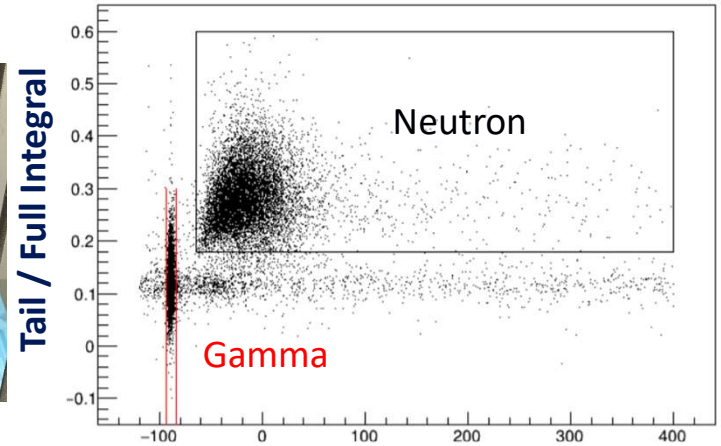
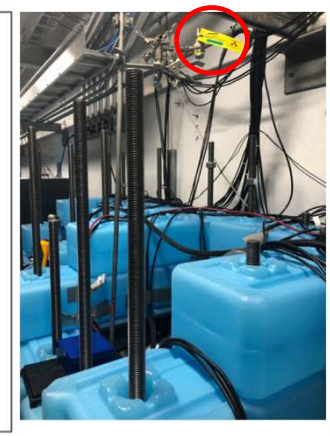
Neutrino Cubes



Time-Tagged ^{252}Cf



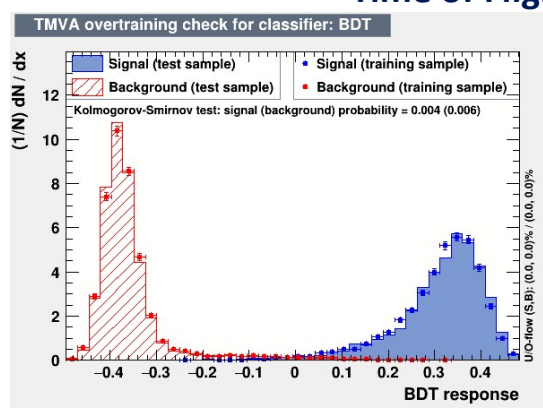


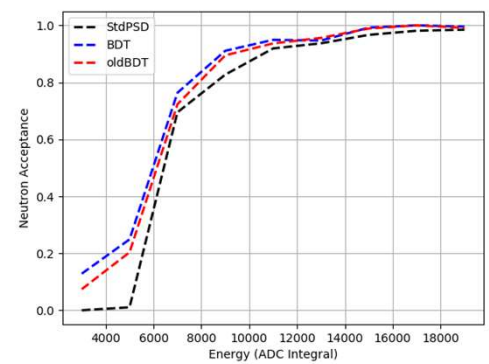
(CC) $\nu_e + {}^{208}Pb \rightarrow {}^{208}Bi^* + e^-$

$${}^{208-y}Bi + x\gamma + yn$$

(NC) $\nu_x + {}^{208}Pb \rightarrow {}^{208}Pb^* + \nu'_x$

$${}^{208-y}Pb + x\gamma + yn$$





Boosted Decision Trees for Event Discrimination

- Detectors searching for neutrino-induced neutrons; a potential CEvNS background.
- Excited nuclei in target material (Fe, Pb) can emit neutrons which can produce nuclear recoil events in embedded detectors.
- NIN process yet to be observed; relevant to SNe nucleosynthesis and as SNe detection channel (HALO).

BDT for ER/NR classification shows some improvement at lower energies for some detector cells. Necessary for lowering recoil energy threshold.

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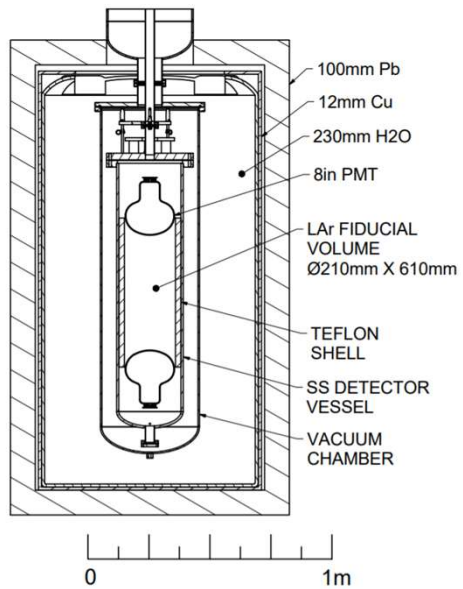
CENNS-10

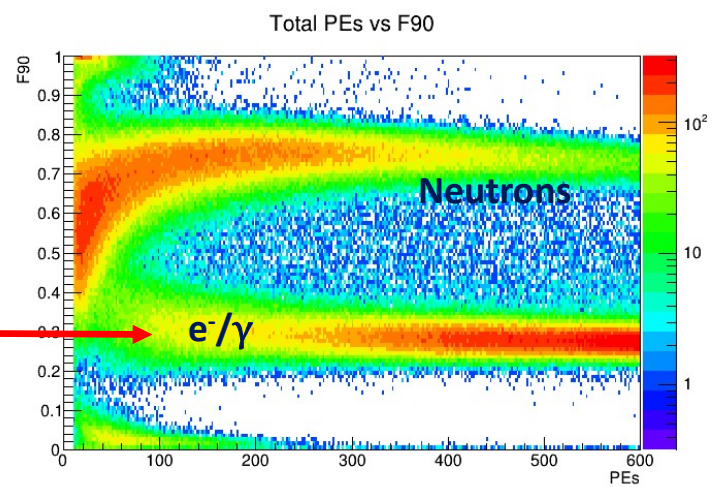
- Loaned from J. Yoo *et al* from Fermilab.
- Single-phase liquid Ar scintillation detector located 28 m from SNS target (~2 x 10^7 ν / s)
- **First Production Run:** July 2017 -> December 2018
  - Dramatically improved light yield results in lower threshold (20 keVnr)
  - 2x 8" Hamamatsu PMTs with 18% eff @ 400 nm
  - Tetraphenyl butadiene (TPB) wavelength shifter coating Teflon walls and PMT glass.
  - 24 kg fiducial volume.

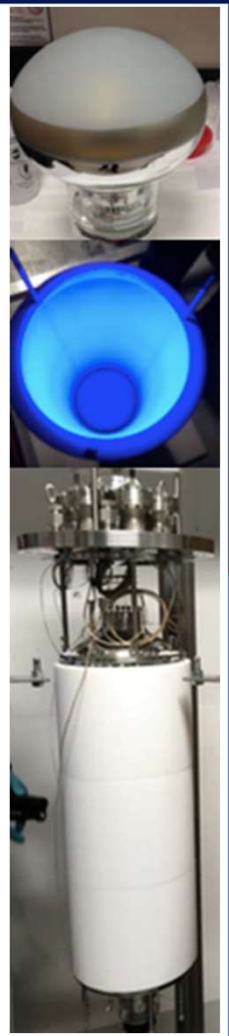
arXiv:*2003.10630*

- Use of PoT signal from SNS greatly reduces steady-state backgrounds, BUT 1 Hz/kg of ^{39}Ar events still a large background:

Data Events	3752
Fit CEvNS	159 ± 43 (stat.) ± 14 (syst.)
Fit Beam Related Neutrons	553 ± 34
Fit Beam Unrelated Background	3131 ± 23
Fit Late Beam Related Neutrons	10 ± 11
2Δ(-lnL)	15.0
Null Rejection Significance	3.5σ (stat. + syst.)







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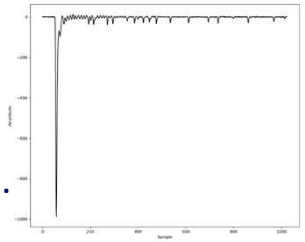
Training 2D (1D) CNN

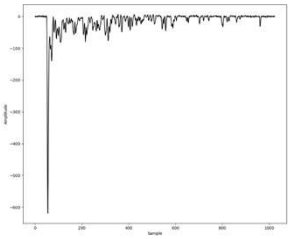
- Time-tagged DT data makes for an excellent source of NR waveforms with little accidentally contamination form ER band.
- Training samples defined via cuts in energy, time, PSD.
- Initial results look promising for maintaining discrimination at low energies (can lead to **lower threshold -> better sensitivity**).

Waveforms

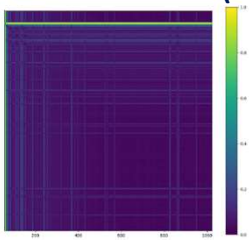
NR



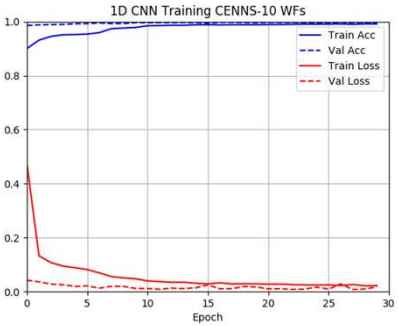
ER

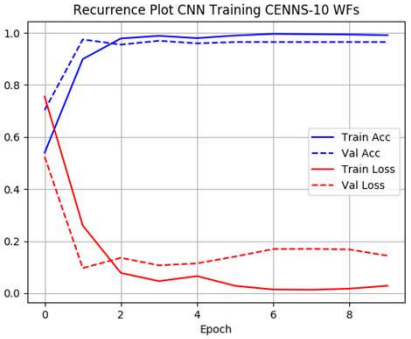


Recurrence Plot (2D)

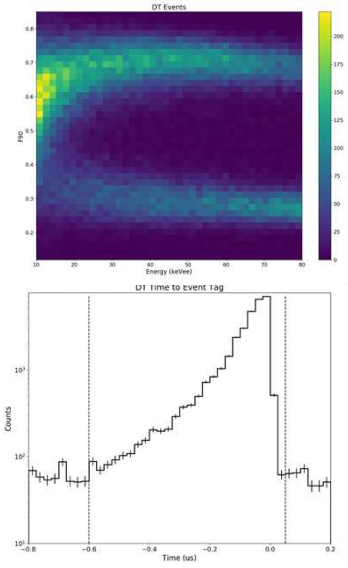


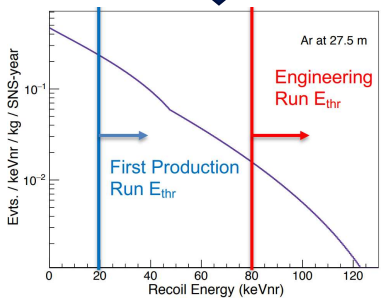
Training History (1D, 2D)





DT Generator Data





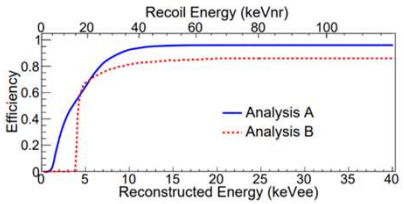
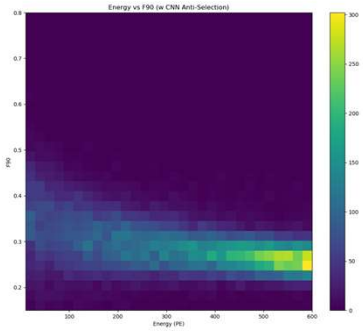
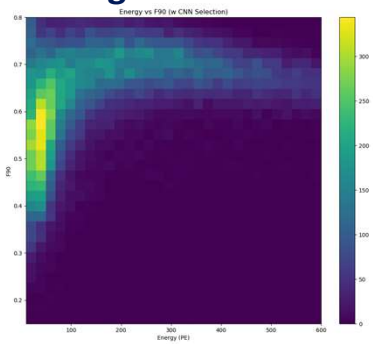


FIG. 3. Energy-dependent reconstruction efficiency estimated for CEvNS events to pass the data selection criteria for each of the two analyses.

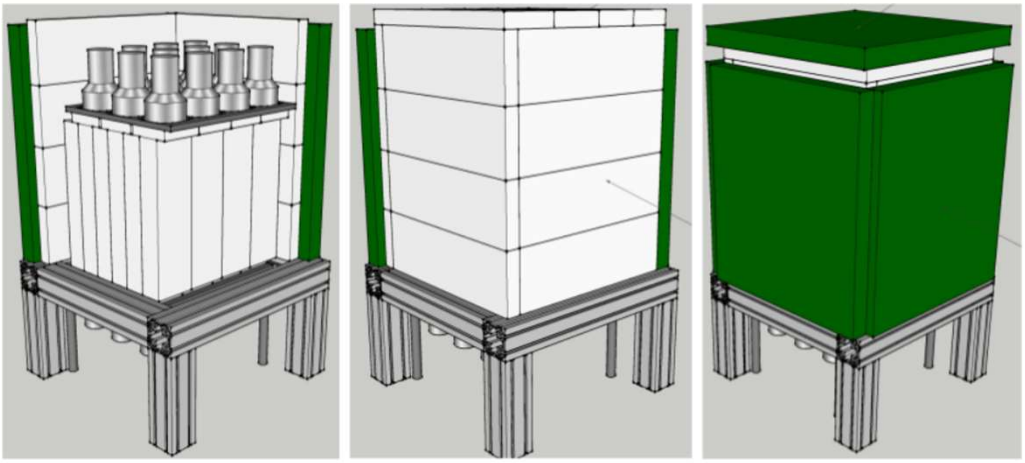
Bkg Classified



Sig Classified



NaI$\boldsymbol{\nu}$E 185



- Consists of twenty-four 7.7 kg NaI[Tl] scintillating detectors, 1.5-inch thick steel shields (white) and 2-inch thick muon vetoes (green).
- Deployed at the SNS, about 20~21 m from the target.
- Goal: measure inclusive ν_e $^{127}\mathrm{I}\ (\mathbf{p},\mathbf{n})\,^{127}\mathbf{Xe}$ cross-section
- Dominant Bgs: steady-state muons

The figure from [4]: Preliminary Examination Report: A NaI[Tl] Neutrino Detector for the SpallationNeutron Source, S. Hedges (2017)

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Simulation production

Add: Chosen targets, B(GT), etc

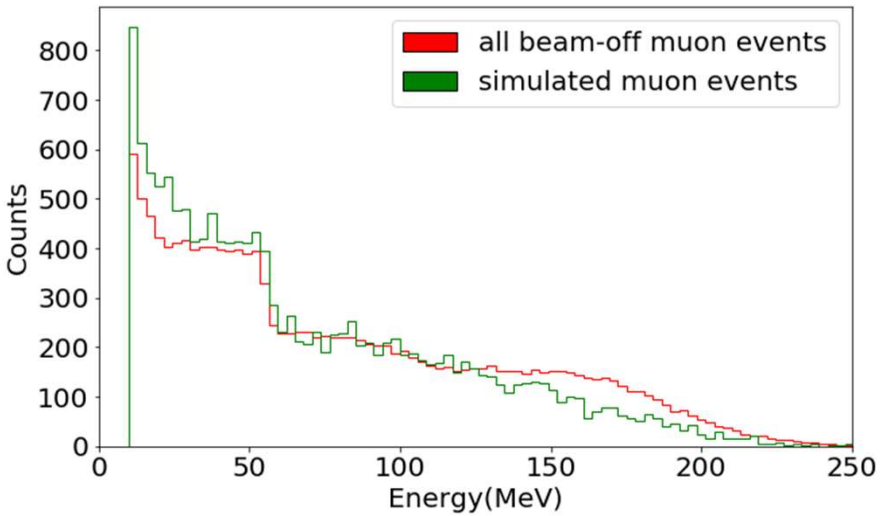
MARLEY →

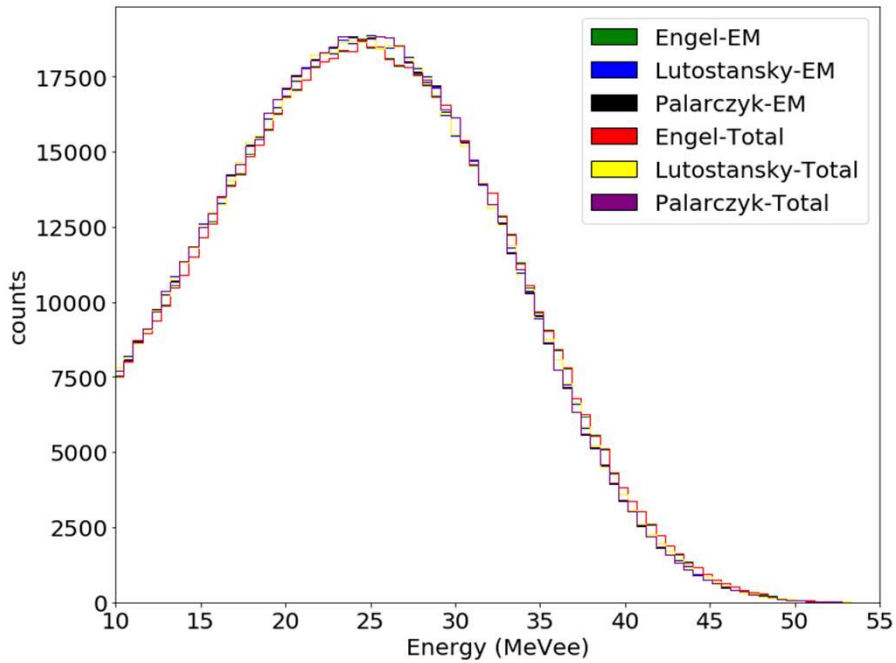
Output events
Add: geometries

Geant4 →

G4 events
Add:post-processing

B(GT) values used:
Jon Engel, et al. PhysRevC.50.1702
Yu. S. Lutostansky, et al. PhysRevLett.67.430
M. Palarczyk, et al. PhysRevC.59.500





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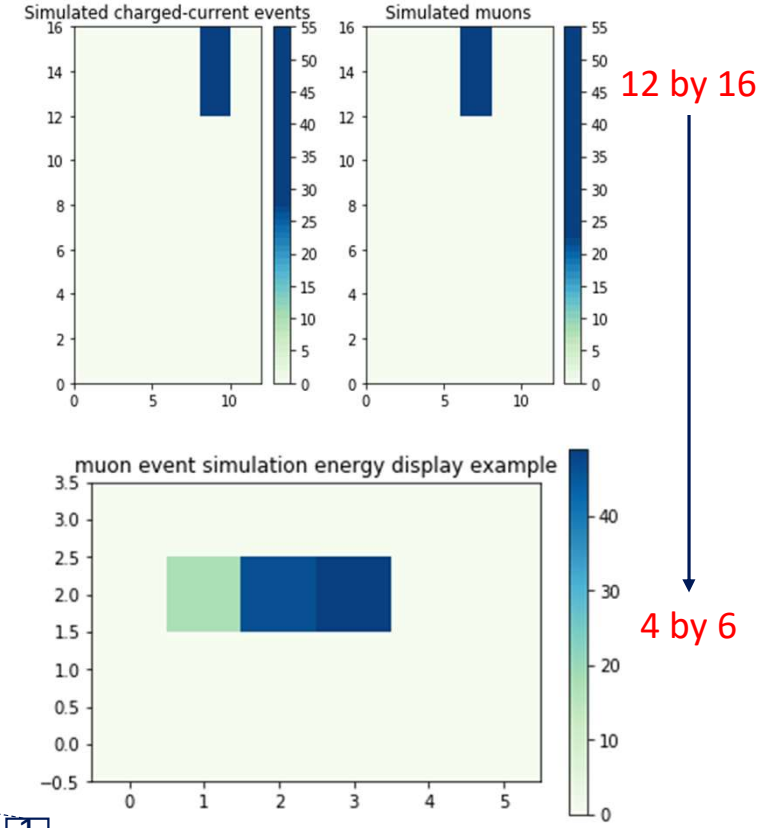
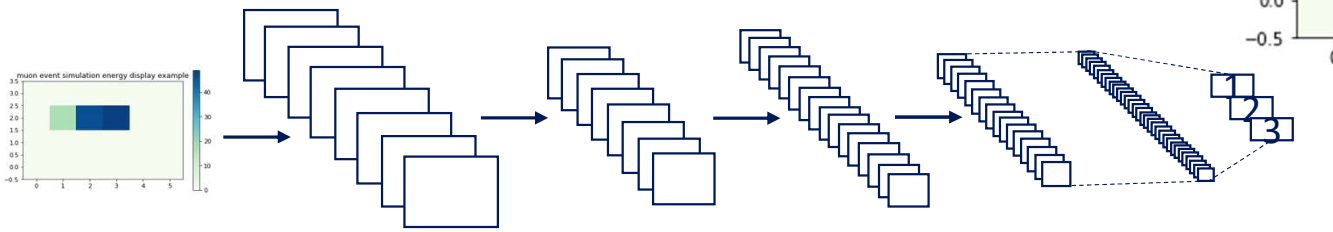
Convolutional Neural Network

- A convolutional neural network (CNN) takes in images with categorical labels and outputs labels

- Input: event energy displays of simulated events

- Output: labels of particles





Input 4 by 6 Conv2D Pooling Conv2D Pooling Dense Out

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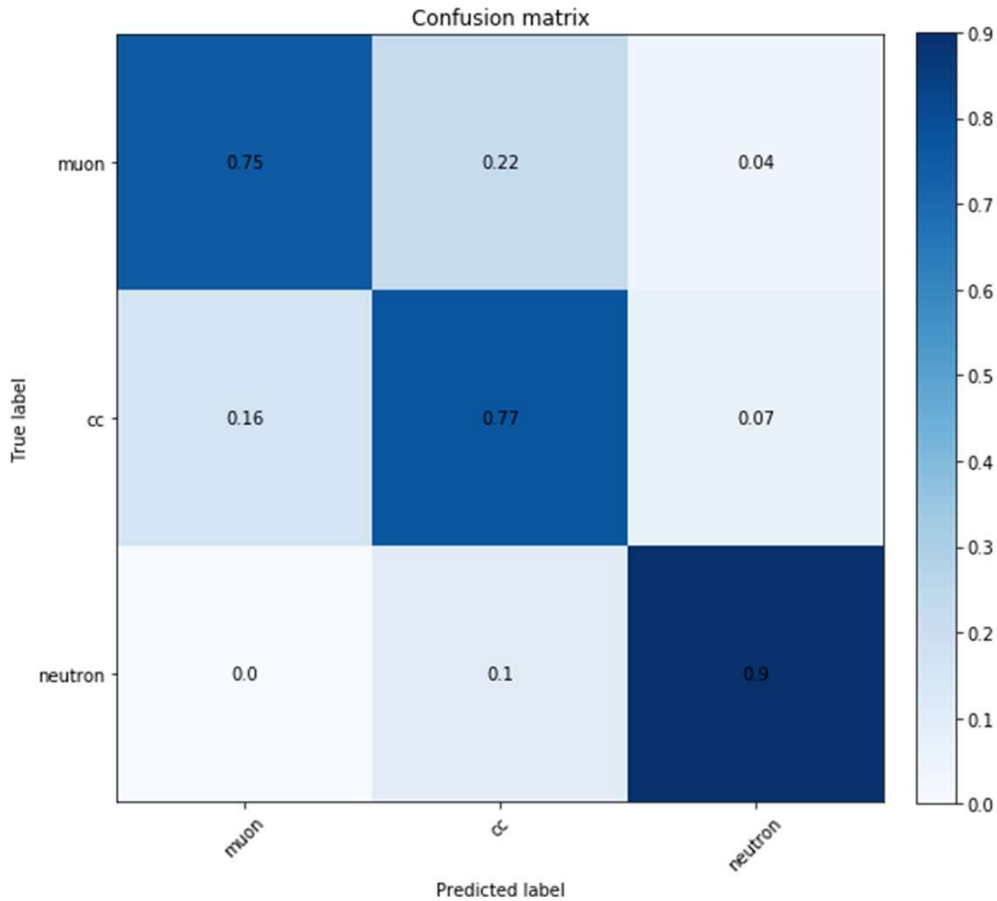
Understanding the performance

- Testset made of 200 cc sim, 1950 muon sim and 50 neutron sim
- About 77% of cc sim are labeled as cc correctly
- About 22% of muon sim are labeled as cc incorrectly

	Signal sim left	Bg sim left
CNN	77%	22%
Cut1 (mul >3)	33.56%	5.28%



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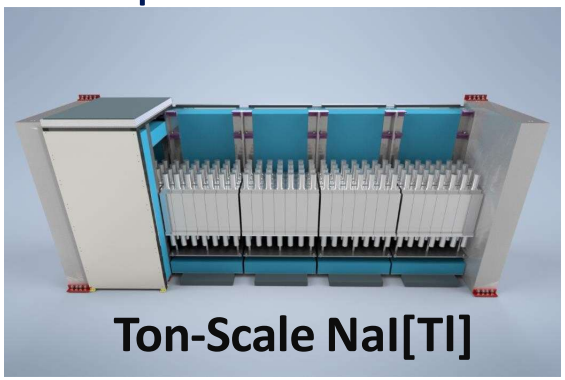
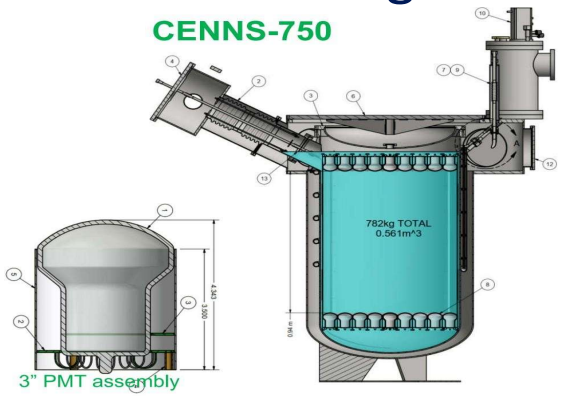
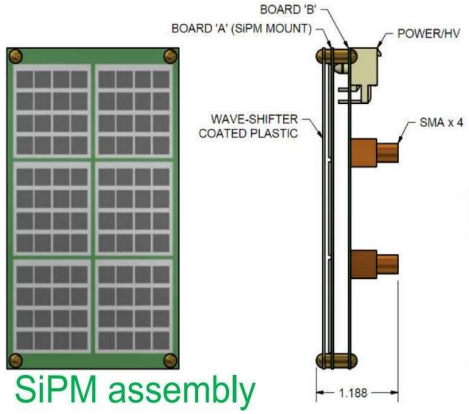
Conclusion

- The COHERENT Collaboration has tested/used ML on multiple detectors.
- The results are preliminary, but very promising.
- The developed ML approaches can be generalized to other detector setups.







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