CHIPS Neutrino Event Characterisation Using Convolutional Neural Networks

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Outline

1. **The Problem:** Describe the problem we are trying to solve, how it has been solved in the past, and what the new approach entails (with a little bit of theory).

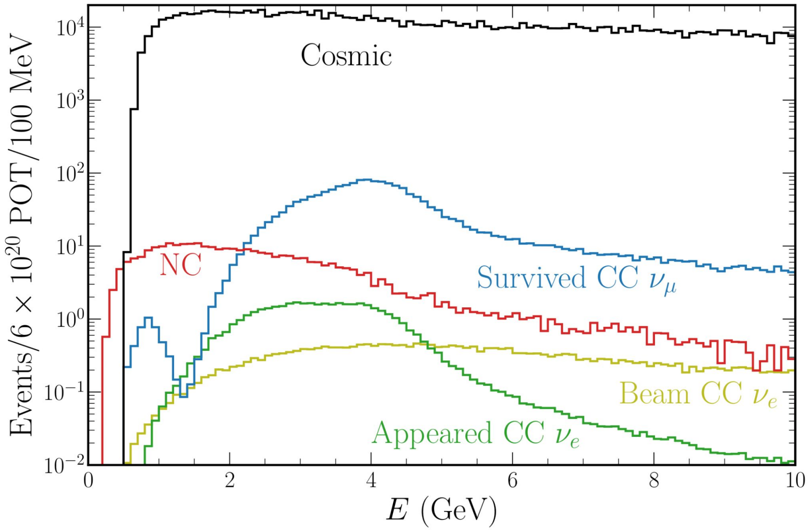
2. **The Solution:** Detail how we implement convolutional neural networks for CHIPS, highlighting essential things for other water Cherenkov detectors.

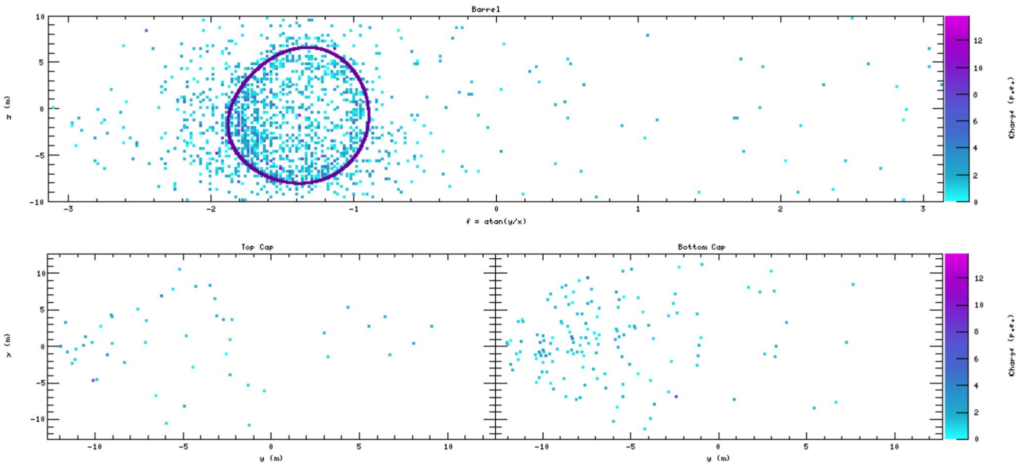
3. **The Results:** How well does it all perform, do we understand what is going on, and is it robust?

The Problem

What problem are we trying to solve?

There are a wide range of neutrino interactions recorded within our detector. How do we determine useful properties about the interactions for use in neutrino oscillation analyses?





What tasks does this entail?

We want to efficiently select a pure beam CC ν_e sample from a sizeable beam CC ν_μ, beam NC, and cosmic muon background whilst accurately estimating the neutrino energy.

Primary Tasks:
(essential for physics)

- Cosmic event rejection
- Beam event classification
- Neutrino energy estimation

Secondary Tasks:
(nice to have)

- Event containment
- Vertex estimation
- Lepton energy estimation

How did we solve this problem?

Recorded Event
Raw hits recorded on the detector PMTs (charge and time)

→

Seeding
Cleaning, slicing and making an initial guess at tracks (Hough transform)

→

Maximum Likelihood Track Fitting
Find the best fit track parameters for a given hypothesis

→

Feature Engineering
Derive useful features from the likelihood fits

→

Classification
Apply BDTs and NNs for cosmic rejection and beam classification respectively

- Dependent on a finite set of inputs that must be implemented in software.
- If a physics process is overlooked then the algorithm has access to a reduced amount of information.
- It can be a large amount of effort to implement and validate.
- Requires a predefined hypothesis, each of which can take a while to run.

Is a different approach possible?

As neutrino experiments tend to effectively record an ‘image’ of each event, modern computer vision algorithms can be used. Such as Convolutional Neural Networks (CNNs).

NOvA

IceCube
South Pole Neutrino Observatory

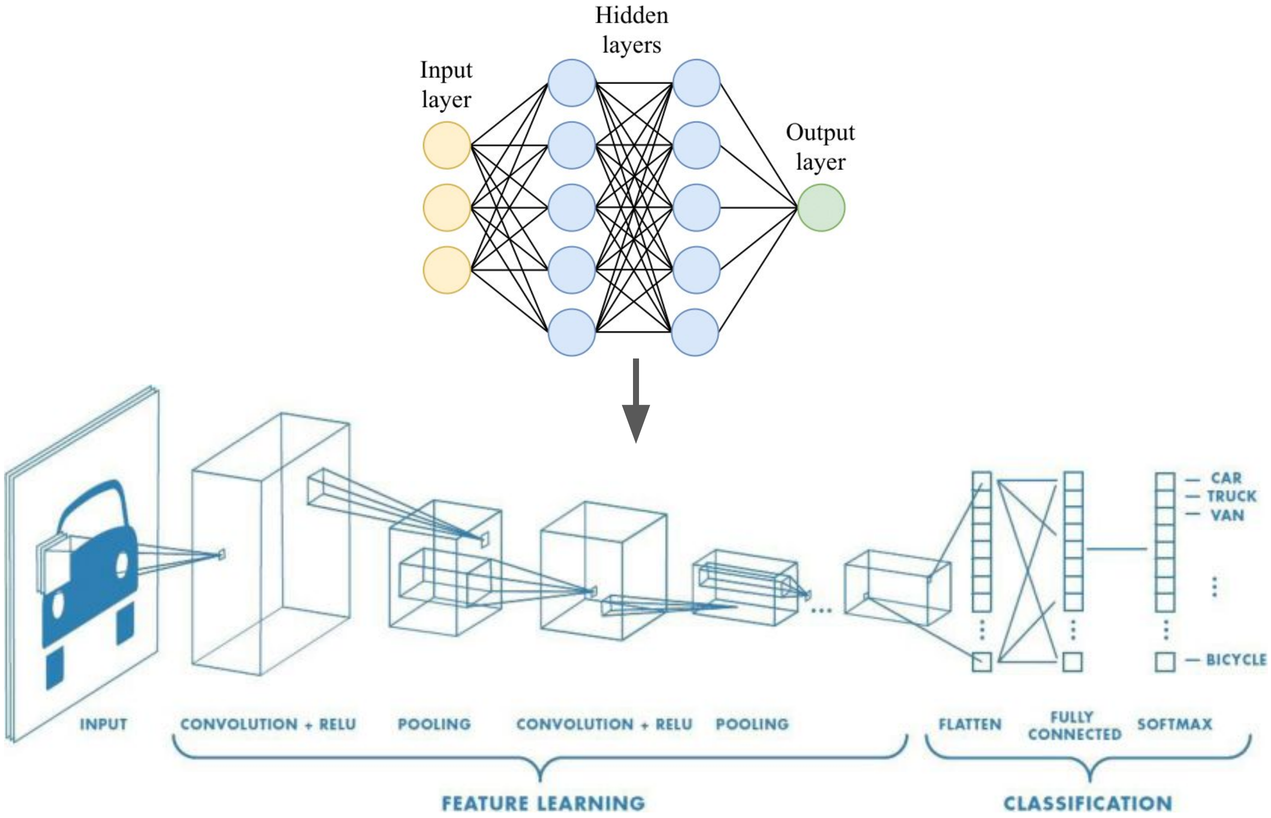
WatChMaL.org

DUNE

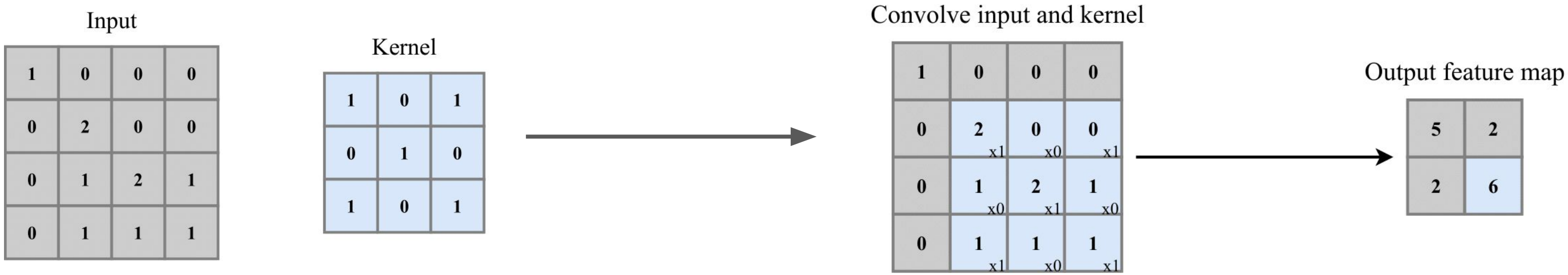
μBooNE

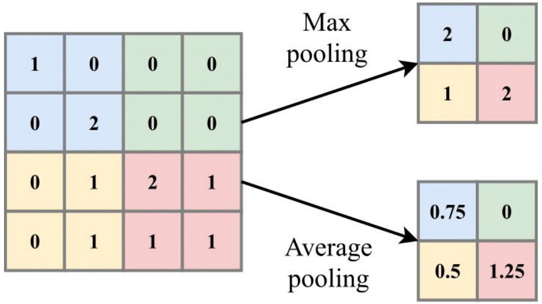
Mainly LArTPC detectors

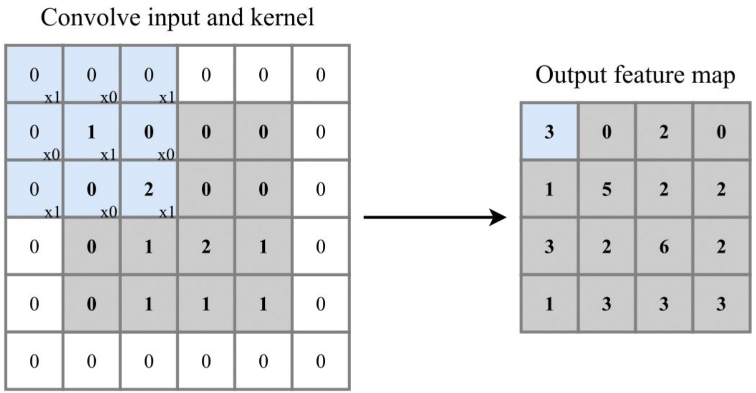
What are convolutional neural networks?



How do they work?

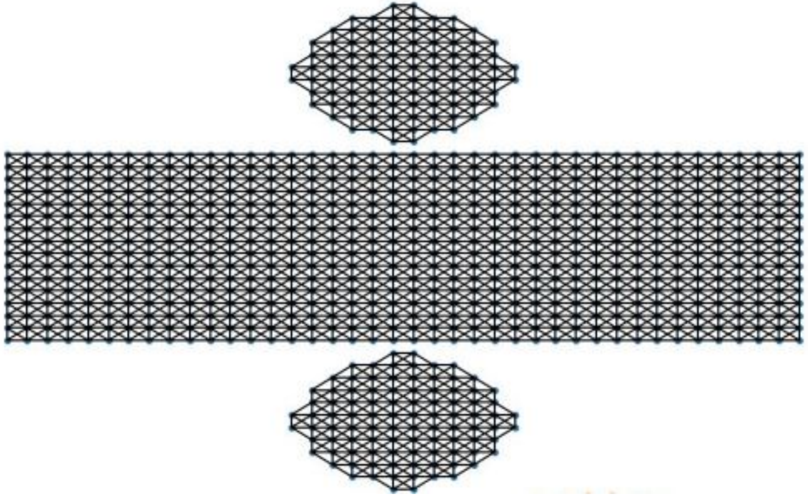


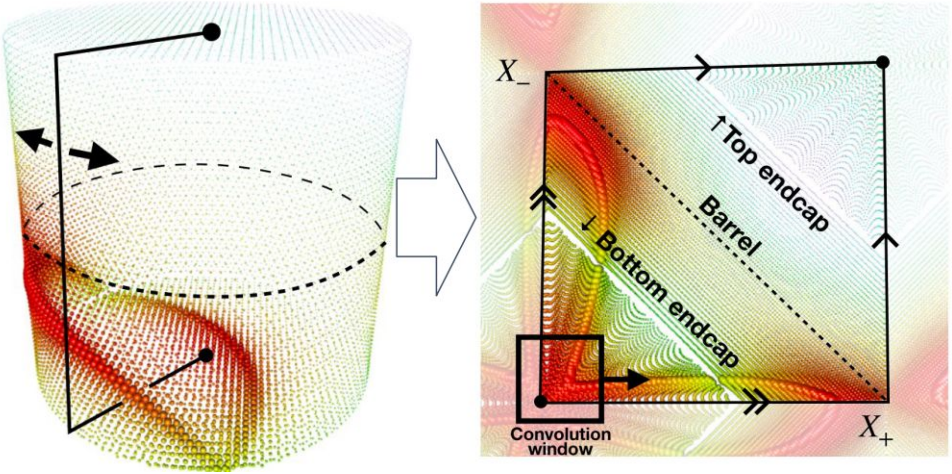




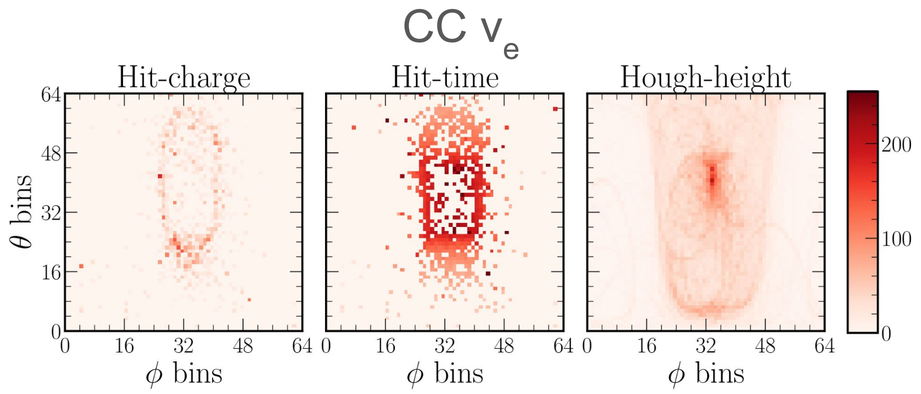
The Solution

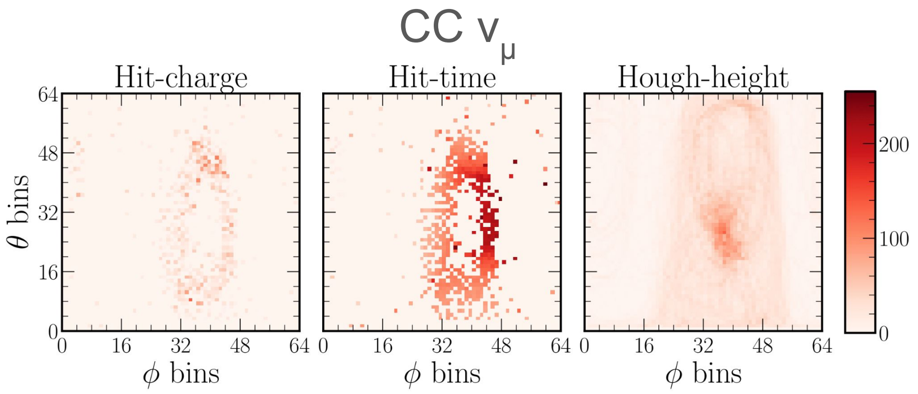
What is the main challenge?

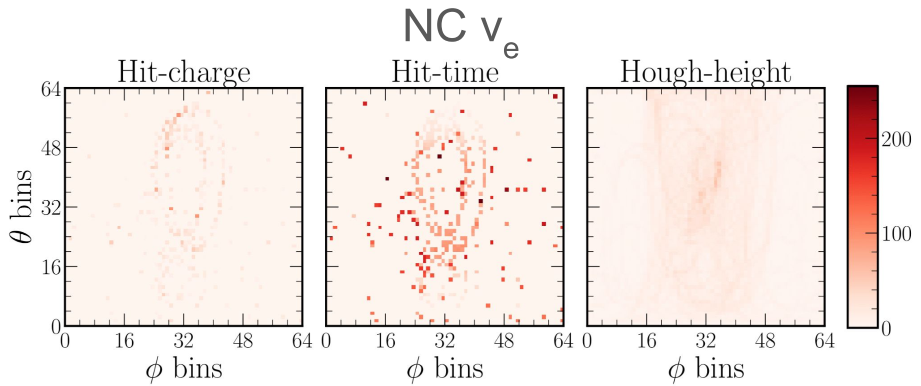


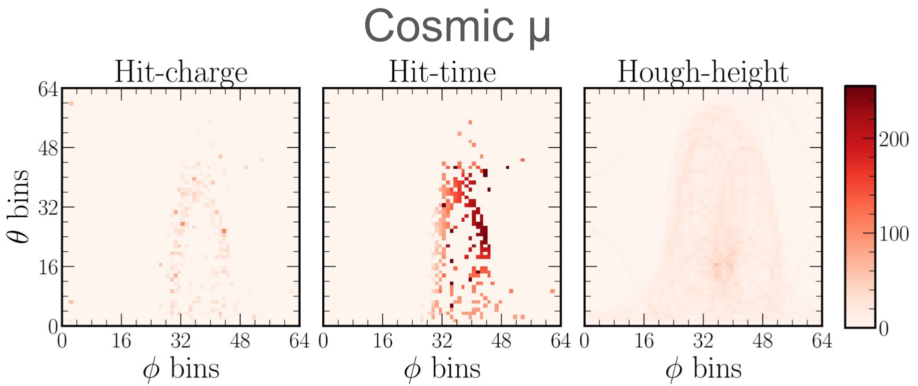


Example inputs

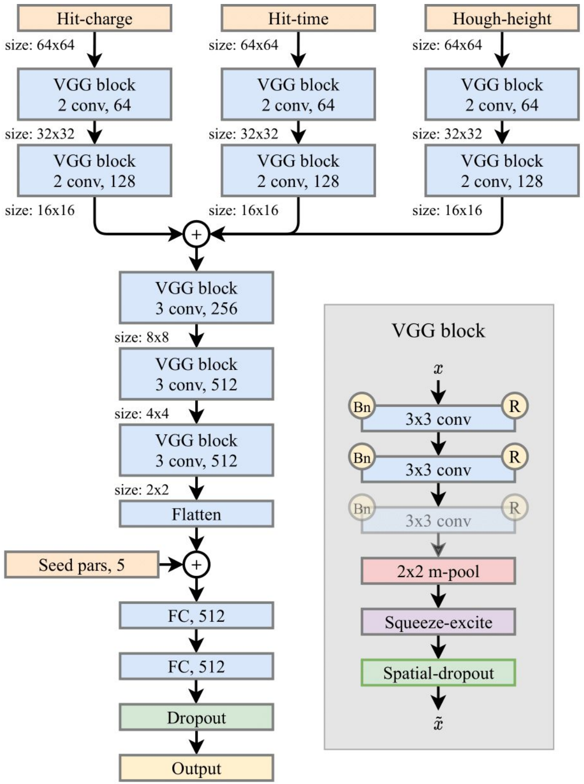






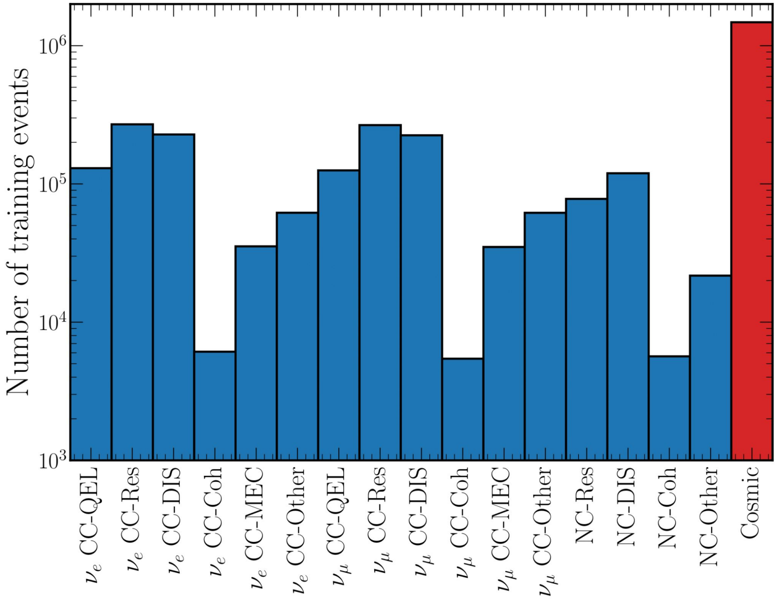


Baseline model architecture



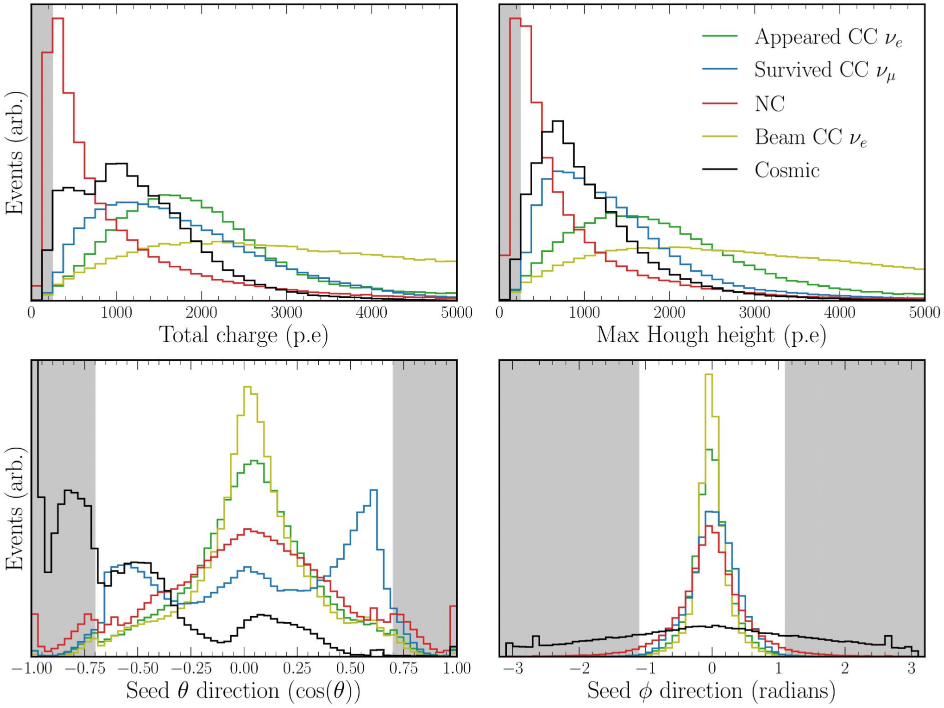
Outputs + Training

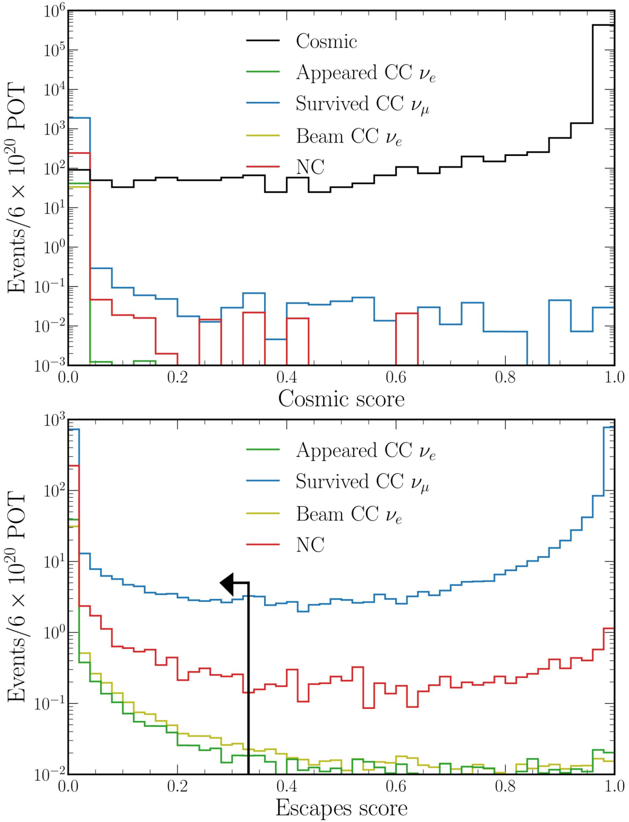
Outputs + Training



The Results

Preselection cuts





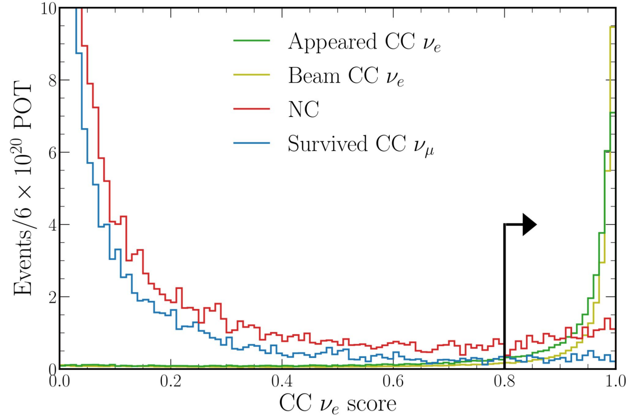
Preselection performance

Selection	App CC ν_e	CC ν_μ	Beam CC ν_e	NC	Cosmic
Total events	44.17 ± 0.15	2045.9 ± 5.8	35.06 ± 0.08	354.7 ± 2.4	2100000 ± 4200
+ Preselection	41.21 ± 0.14	1889.5 ± 5.6	33.52 ± 0.08	243.2 ± 2.0	430000 ± 1900
+ Cosmic cut	41.10 ± 0.14	1874.4 ± 5.5	33.35 ± 0.08	241.6 ± 2.0	< 2
+ Escapes cut	40.68 ± 0.14	795.7 ± 3.5	32.86 ± 0.08	233.0 ± 2.0	< 2
Cuts Eff	$92.1 \pm 0.1\%$	$38.9 \pm 0.1\%$	$93.7 \pm 0.1\%$	$65.7 \pm 0.3\%$	$< 9.5 \times 10^{-7}$

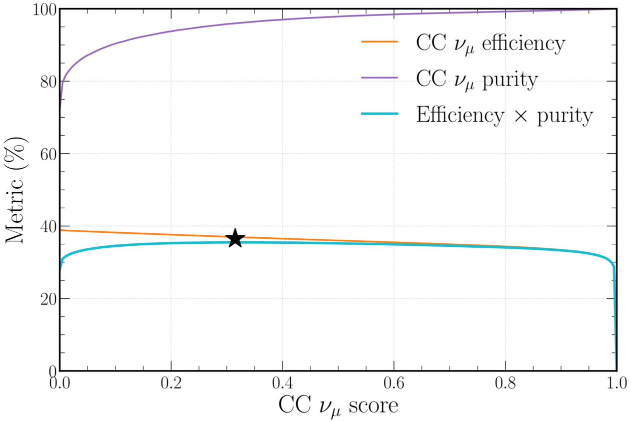
Cosmics are not a problem, even without a veto

Results: CC ν_e selection

Selection	CC ν_e sig	CC ν_μ bkg	CC ν_e bkg	NC bkg	Purity sig	Purity CC ν_e
Total events	44.17 ± 0.15	2045.9 ± 5.8	35.06 ± 0.08	354.7 ± 2.4	$1.78 \pm 0.02\%$	$3.19 \pm 0.03\%$
+ Cuts	40.68 ± 0.14	795.7 ± 3.5	32.86 ± 0.08	233.0 ± 2.0	$3.69 \pm 0.02\%$	$6.67 \pm 0.03\%$
+ FOM-ν_e	31.27 ± 0.12	6.0 ± 0.3	26.69 ± 0.07	17.8 ± 0.6	$38.3 \pm 0.3\%$	$70.9 \pm 0.6\%$
Cuts Eff	$92.1 \pm 0.1\%$	$38.9 \pm 0.1\%$	$93.7 \pm 0.1\%$	$65.7 \pm 0.3\%$	-	-
FOM-ν_e Eff	$70.8 \pm 0.2\%$	$0.29 \pm 0.02\%$	$76.1 \pm 0.1\%$	$5.0 \pm 0.2\%$	-	-

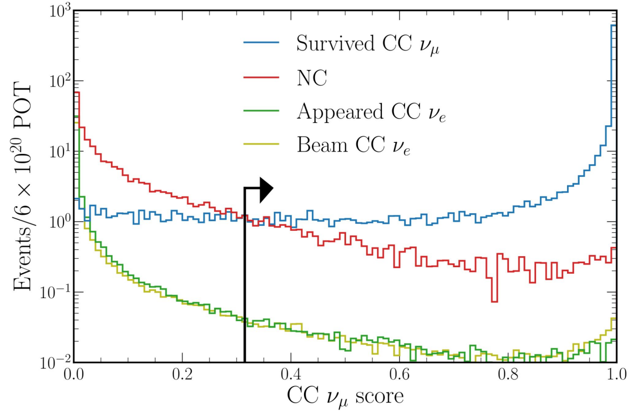


- Old methodology produced a maximum FOM (efficiency*purity) of 0.132 compared to the 0.519 now.
- The 71% signal efficiency compares well to 62% and 64% achieved by NOvA and T2k. But the purity is much lower at 38% compared to 78% and 80% reached by NOvA and T2k.

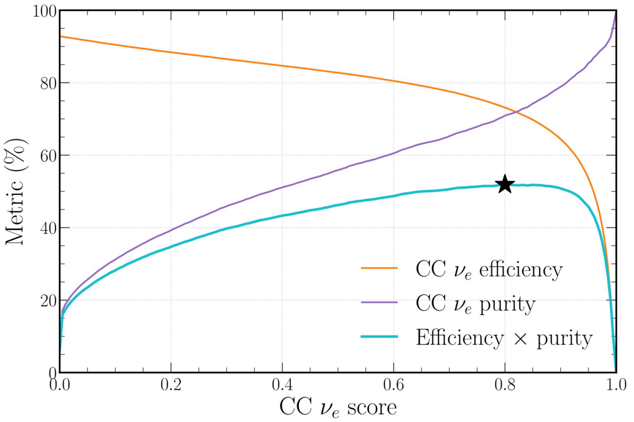


Results: CC ν_μ selection

Selection	CC ν_μ sig	App CC ν_e bkg	Beam CC ν_e bkg	NC bkg	Purity sig
Total events	2045.9 ± 5.8	44.17 ± 0.15	35.06 ± 0.08	354.7 ± 2.4	$82.5 \pm 0.2\%$
+ Cuts	795.7 ± 3.5	40.68 ± 0.14	32.86 ± 0.08	233.0 ± 2.0	$72.2 \pm 0.2\%$
+ FOM-ν_μ	756.4 ± 3.4	1.293 ± 0.03	1.315 ± 0.02	29.0 ± 0.7	$96.0 \pm 0.1\%$
Cuts Eff	$38.9 \pm 0.1\%$	$92.1 \pm 0.1\%$	$93.7 \pm 0.1\%$	$65.7 \pm 0.3\%$	-
FOM-ν_μ Eff	$37.0 \pm 0.1\%$	$2.9 \pm 0.1\%$	$3.8 \pm 0.1\%$	$8.2 \pm 0.2\%$	-

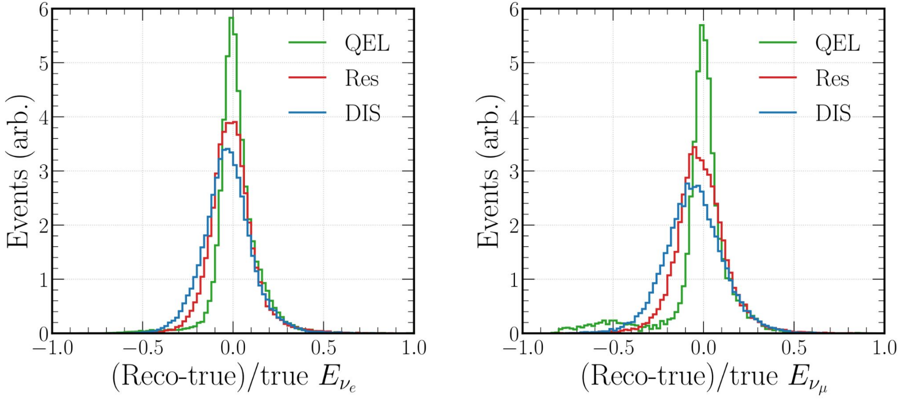


- The signal efficiency of 37% compares well to the 31% and 36% achieved by NOvA and T2K
- This is also the case for the signal purity of 96% compared to the 98.6% and 94% purities of NOvA and T2K.

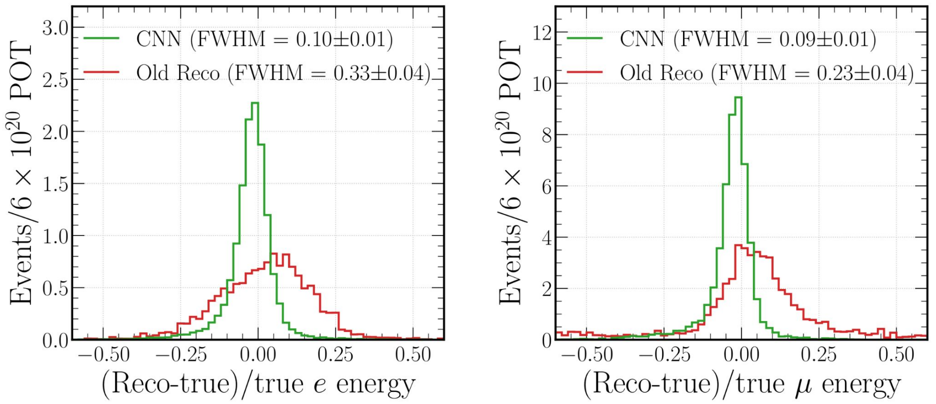


Results: Neutrino energy estimation

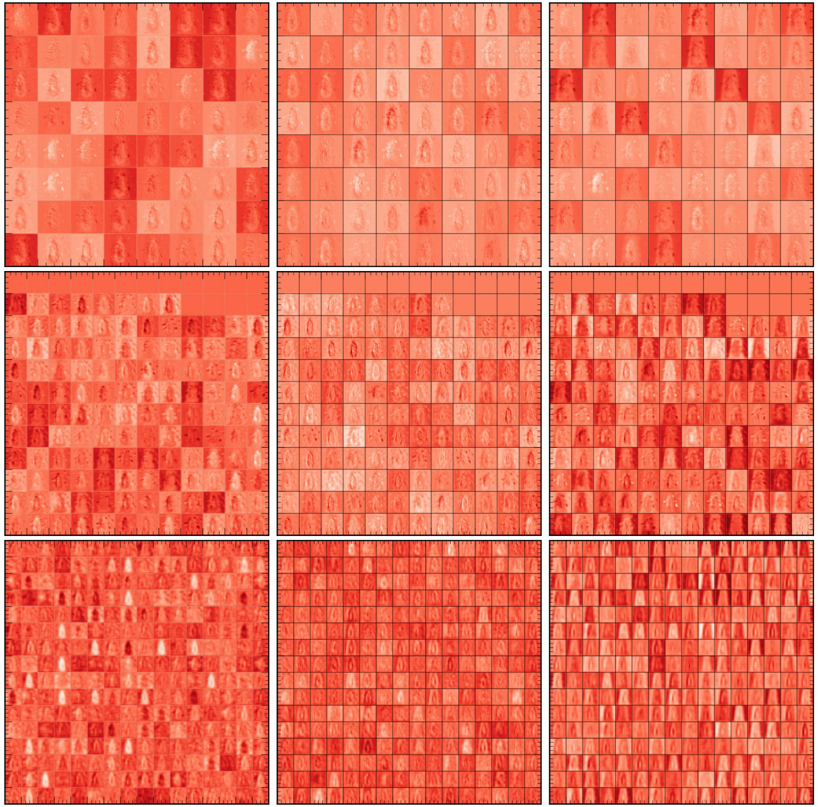
Neutrino energy resolution by component



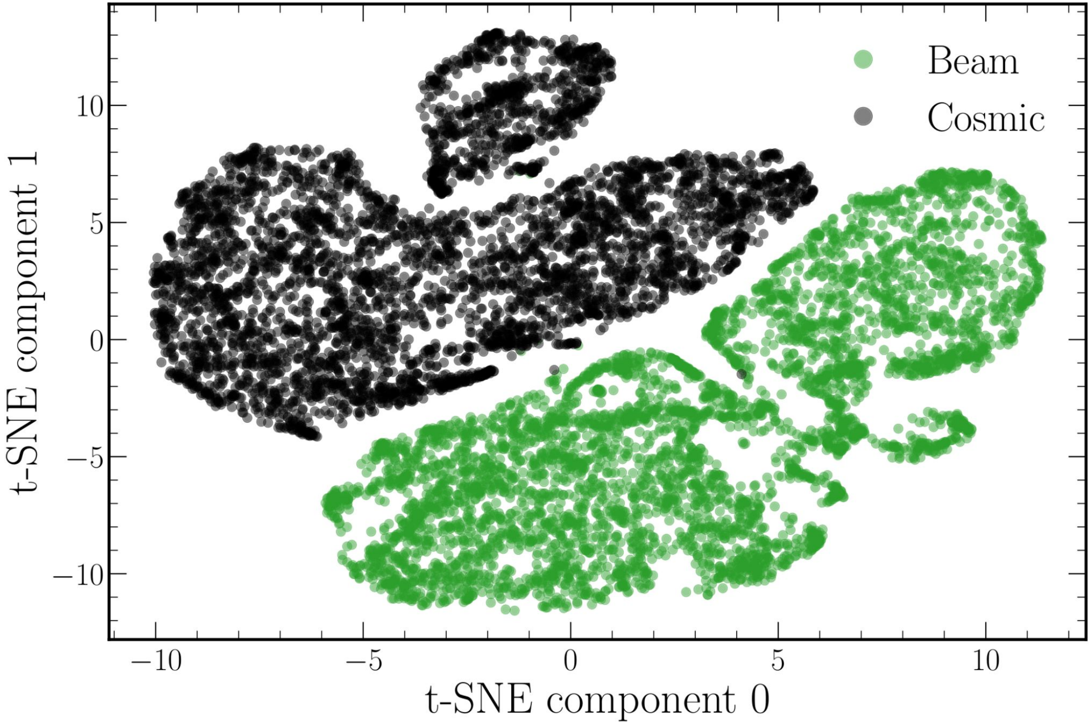
Charged lepton energy resolution comparison



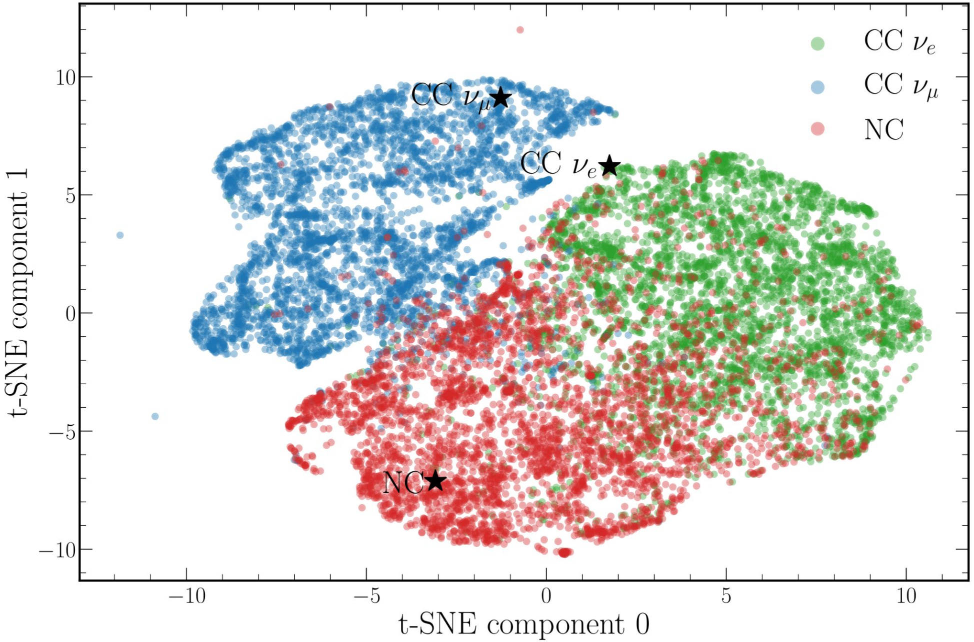
Explainability: The learnt kernels

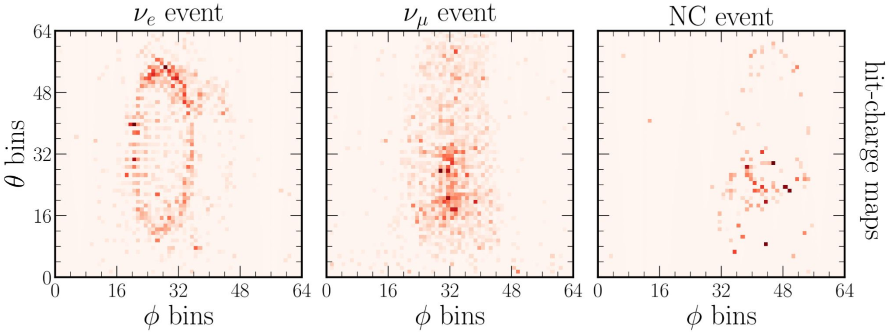


Explainability: Cosmic rejection t-SNE



Explainability: Beam classification t-SNE





Conclusions + Future Work

Conclusions

- Convolutional neural networks can be incredibly effective at solving neutrino event characterisation problems (classification and regression) in water Cherenkov detectors.
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Any Questions?

Future Work

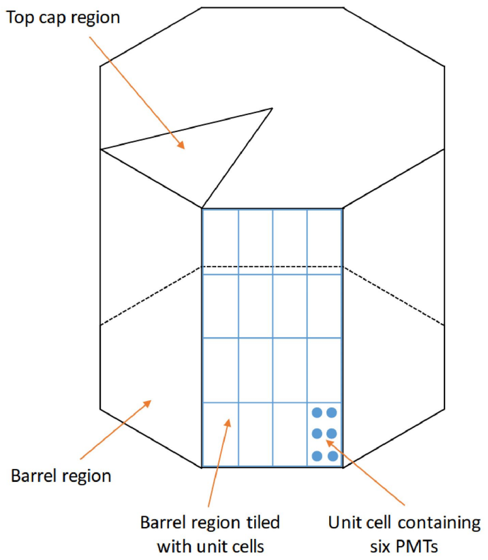
- Blah Blah

Detector simulation

- We use a modified version of **WCSim** (Geant4) for simulating neutrino interactions within our detector.

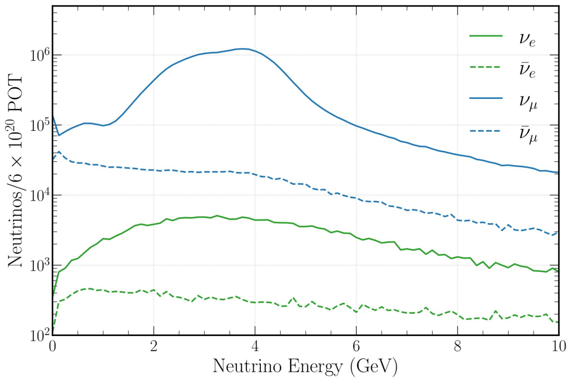
- It builds an n-sided regular polygonal prism consisting of two endcaps and a barrel.

- Individual *unit cells* are used to tile the walls of the detector with PMTs according to the configuration.



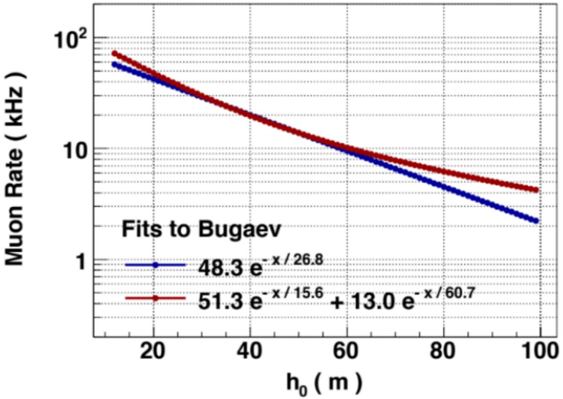
Event generation

- For beam events, we use **GENIE:** The existing NuMI beam simulation is used to generate fluxes. Default cross-sections are used.

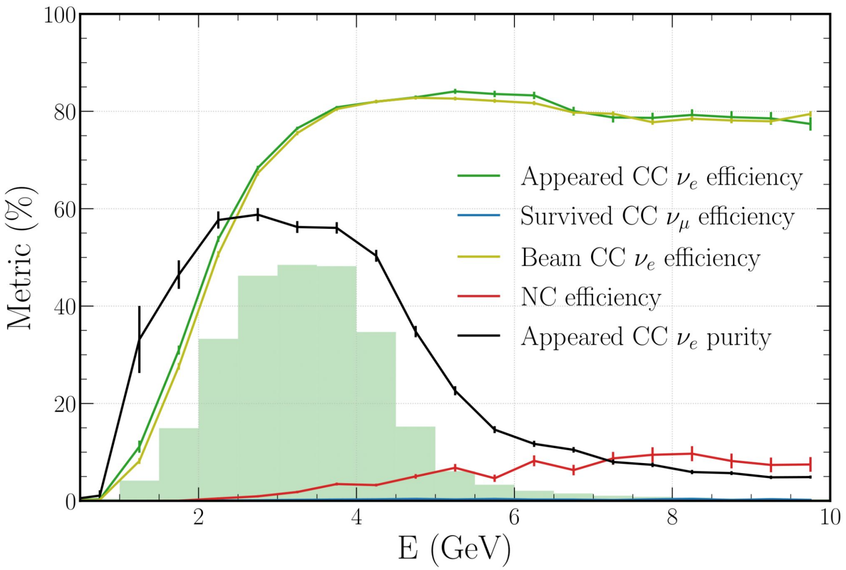


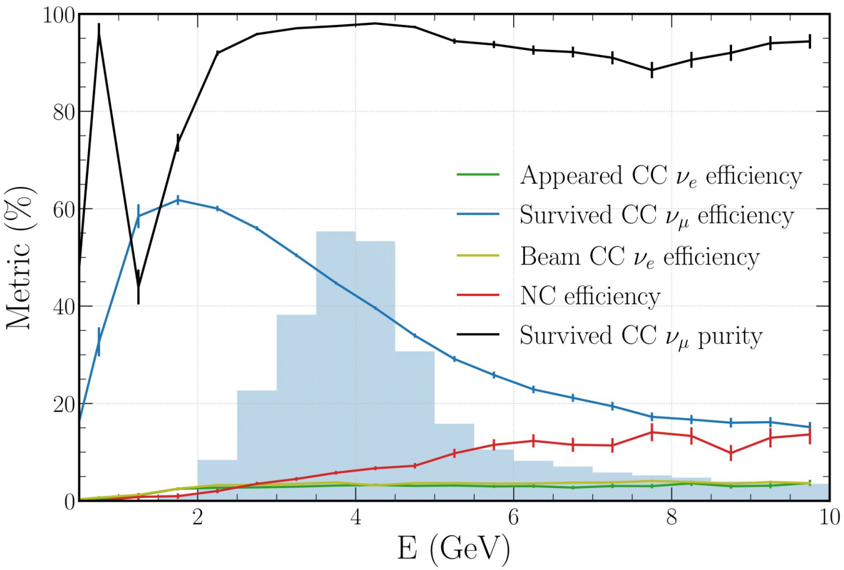
- For cosmic events, we use **CRY:** We assume an overburden of 50m of water and adjust the cosmic muon flux accordingly.

  ~ 11.8 KHz cosmic muon rate ~ 2.1 million/year

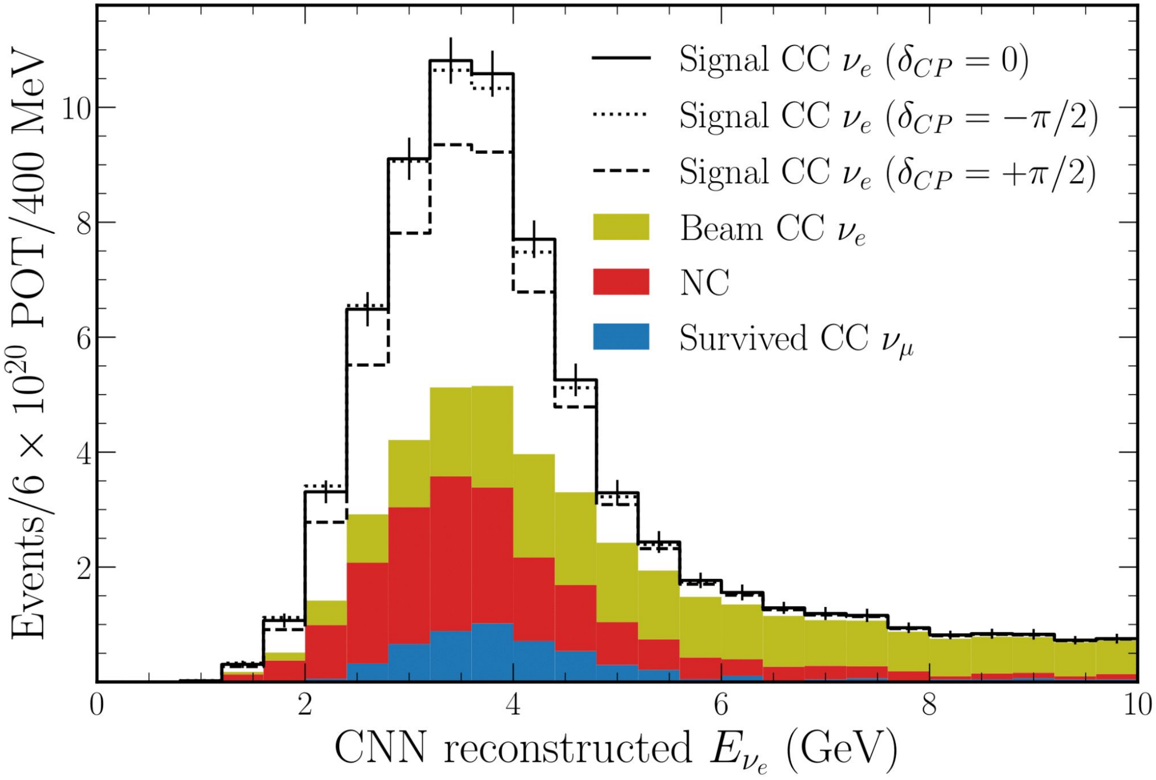


Eff/Pur vs Energy

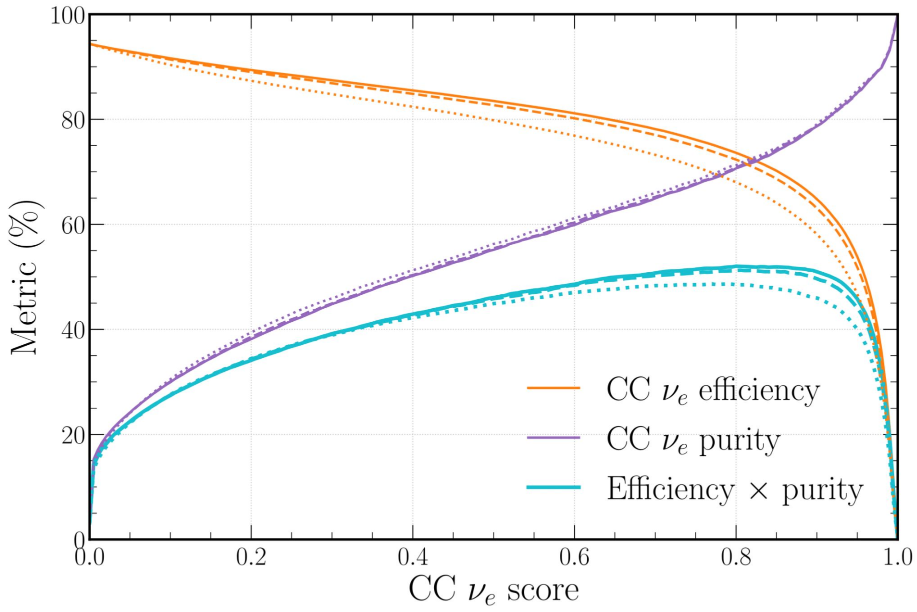




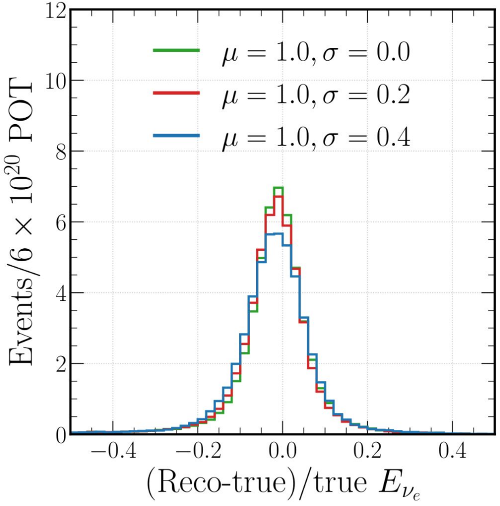
Different values of delta-cp?

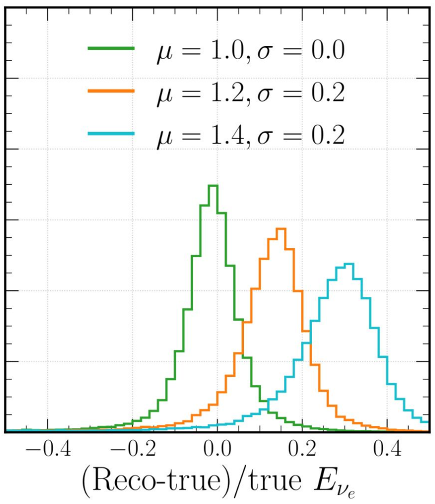


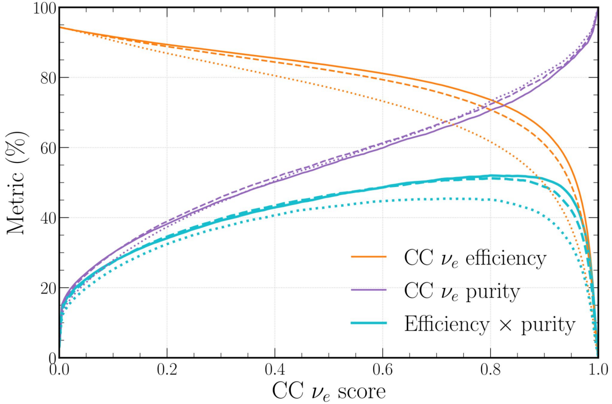
Robustness: Time

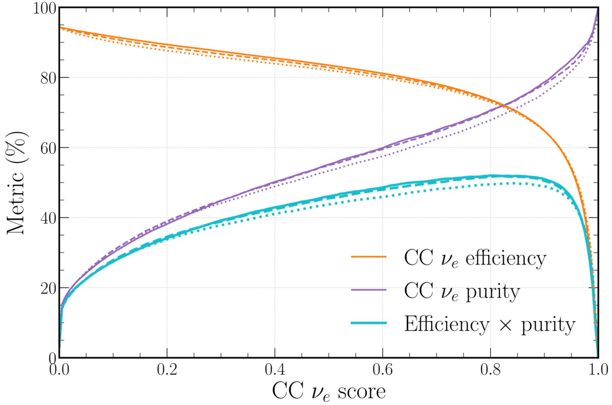


Robustness: Charge









Robustness: Noise