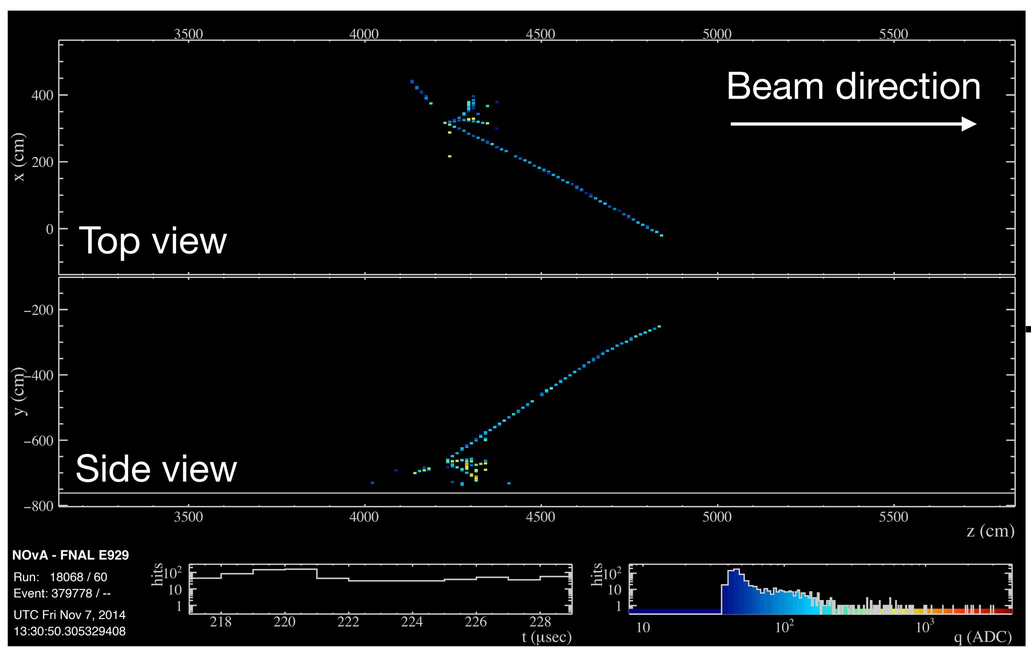
RECENT ADVANCEMENTS IN MACHINE LEARNING TECHNIQUES UTILISED BY NOvA

Ashley Back[1], **Alexander Booth[2]**, Erin Ewart[1], Alexander Shmakov[3], Wenjie Wu[3] & Alejandro Yankelevich[3] *for the NOvA Collaboration*



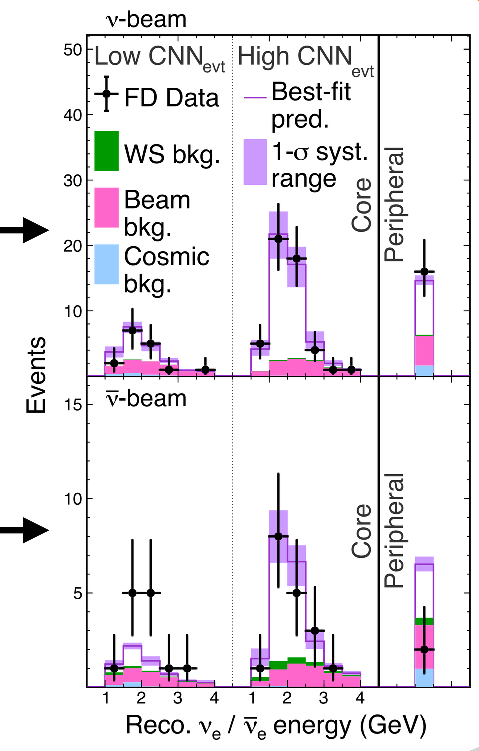
NOvA uses a variety of algorithms to reconstruct physics information - **machine learning contributes significantly**.

Detectors are naturally segmented - **pairs of pixel maps**.

Slicing → Vertex Finding → Particle Clustering → Particle ID & Energy / Event ID & Energy

Using CNNs to do particle ID **since 2017** (Phys.Rev.Lett. 118(2017)).

Focus now on extending to vertex finding and **improving robustness and interpretability** of ML techniques.

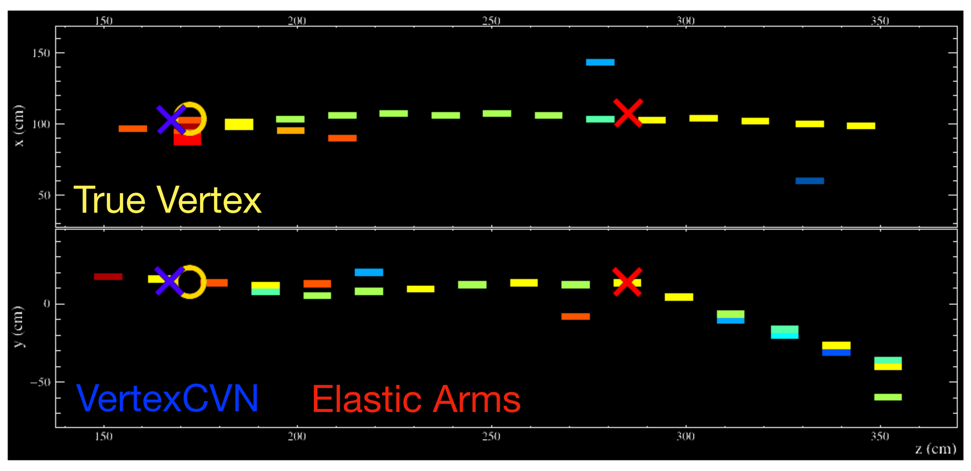


VertexCVN

NOvA's first attempt to apply machine learning to estimate the position that a neutrino interacts with the detector medium.

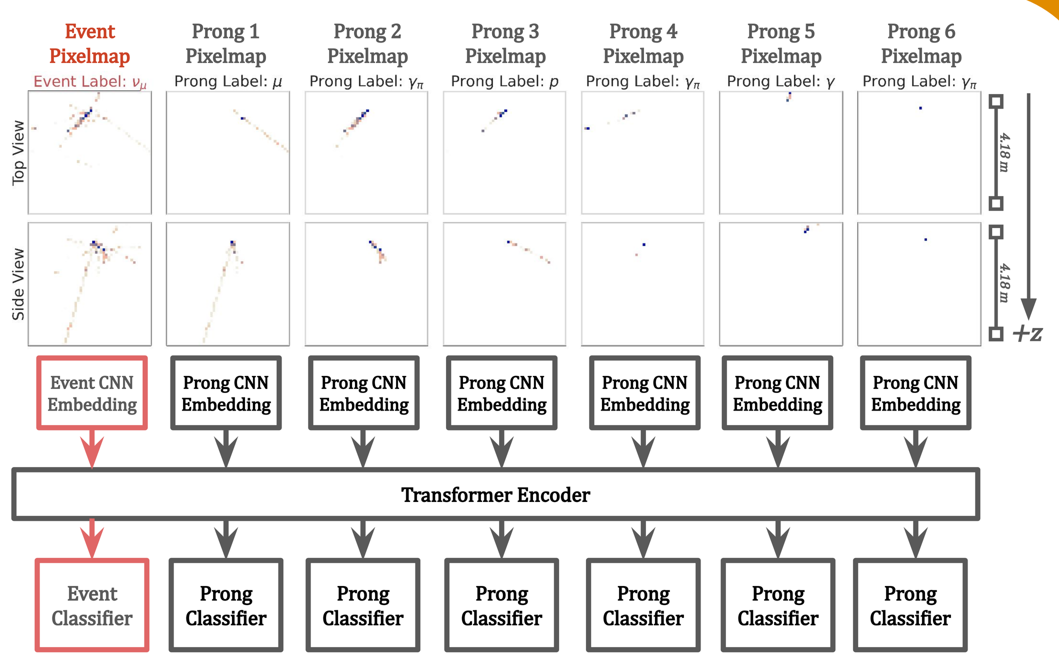
Developed to address several known failure modes of NOvA's existing algorithm "Elastic Arms".

- **Forward failure** - tendency for main prong to be split into two.
- **Backward failure** - tendency for multiple, small prongs to be combined into one.



TransformerCVN

NOvA's events contain **several particles**, each producing **sparse**, high-dimensional spatial observations.



A novel NN combining **spatial learning** enabled by **convolutions** with **contextual learning** enabled by **attention**.

Joint approach **simultaneously classifies** each **event** and reconstructs every **individual particle's** identity.

Architecture & Training

Uses a modified version of the network used by NOvA to do event classification **MobileNetv2** (arXiv:1801.04381):

- proven to do good feature extraction for NOvA.
- can use existing pixel maps as input.
- designed for fast inference on CPU.

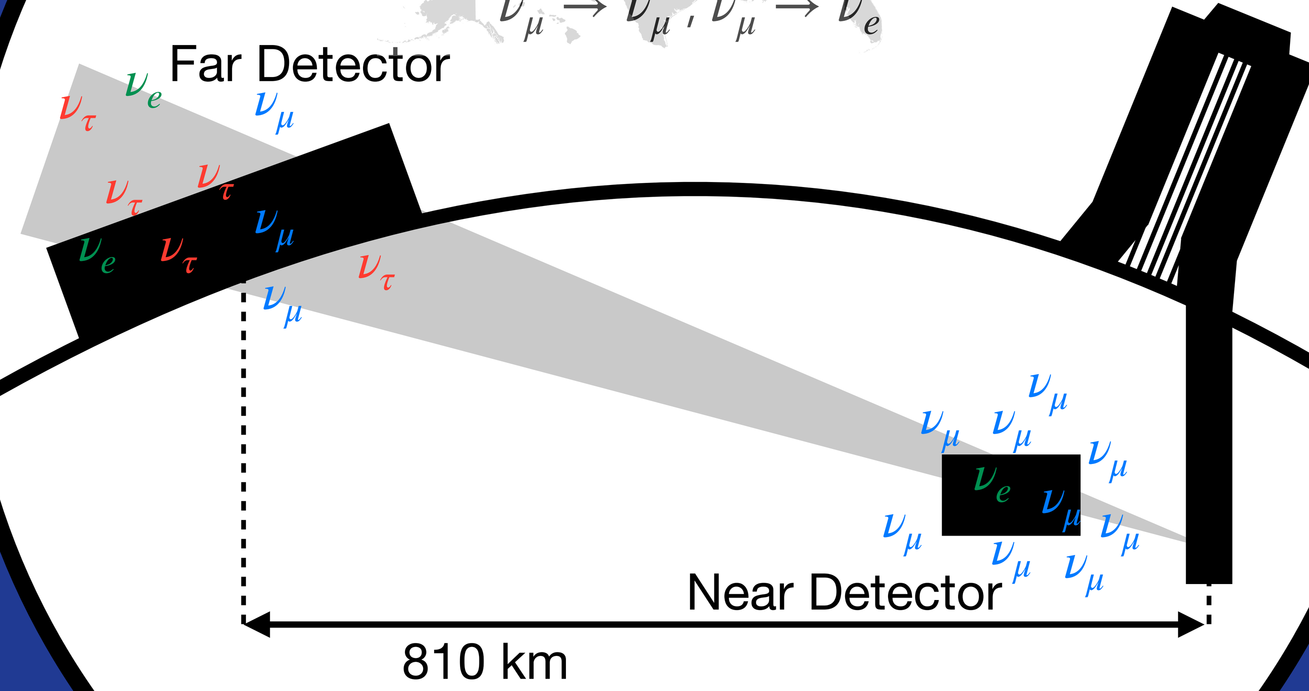
Trained with **beam modes combined** but **separately** for **Near** (~18 million events) and **Far** (~ 26 million events) detectors.

Network converges within **first epoch**.

NOvA's primary goal is to study 3 flavour neutrino oscillations via:

$\nu_\mu \to \nu_\mu$, $\nu_\mu \to \nu_e$

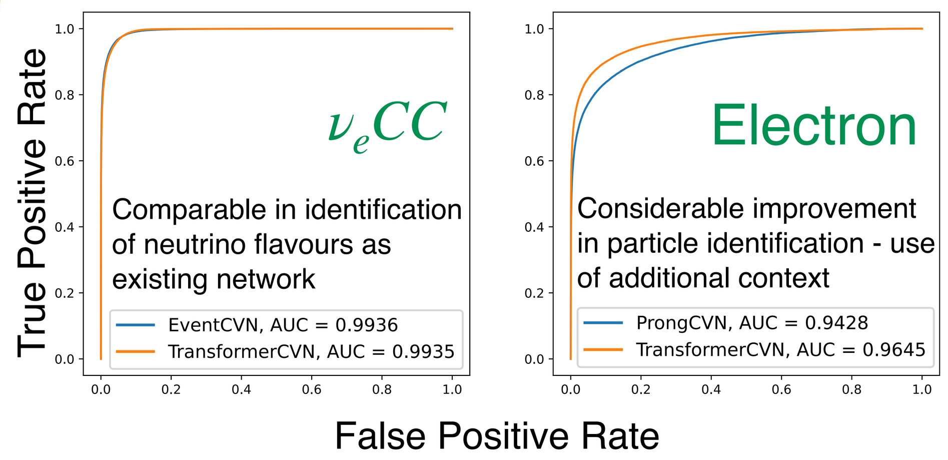
$\bar{\nu}_\mu \to \bar{\nu}_\mu$, $\bar{\nu}_\mu \to \bar{\nu}_e$



Other goals include:

- Search for sterile neutrinos
- Neutrino cross sections
- Supernova neutrinos
- Cosmic ray physics

Performance



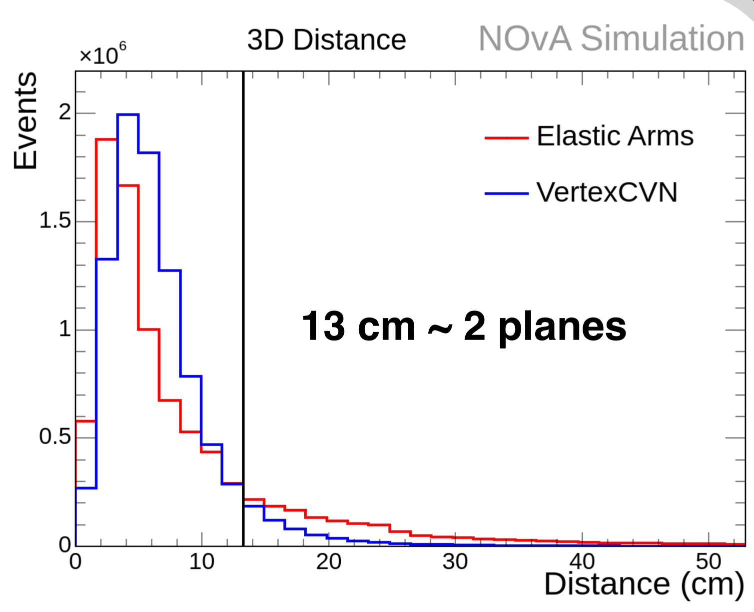
Classifies events with **90% accuracy** and improves identification of individual particles by **6%**.

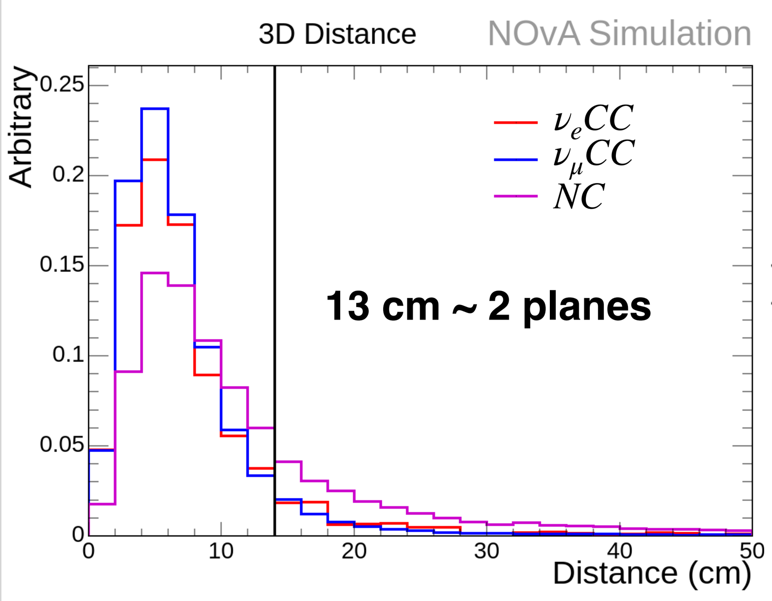
Results

VertexCVN is **more precise** than Elastic Arms but slightly **less accurate**.

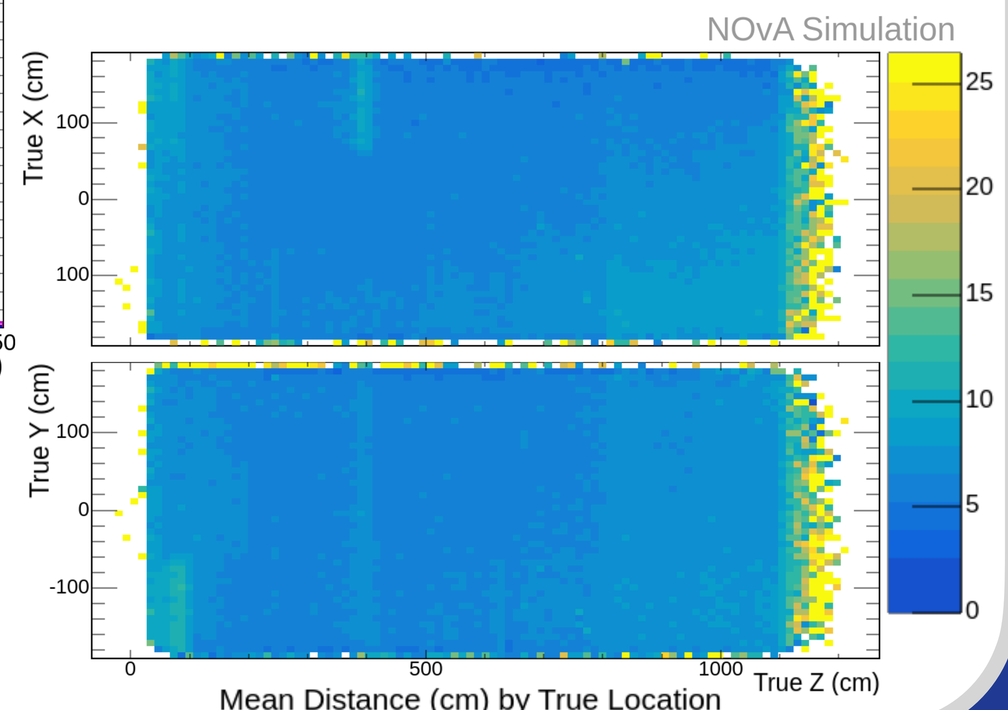
Relative performance has been studied for different types of neutrino interaction:

- more performant on $\nu_e CC$ (even in ND where training sample population is small).
- less performant on NC.





VertexCVN performance is **largely insensitive** to the true position of the vertex.



A manual scanning of events has shown:

- the **targeted failure modes** have been **eliminated**.
- two (minor) failure modes in total.

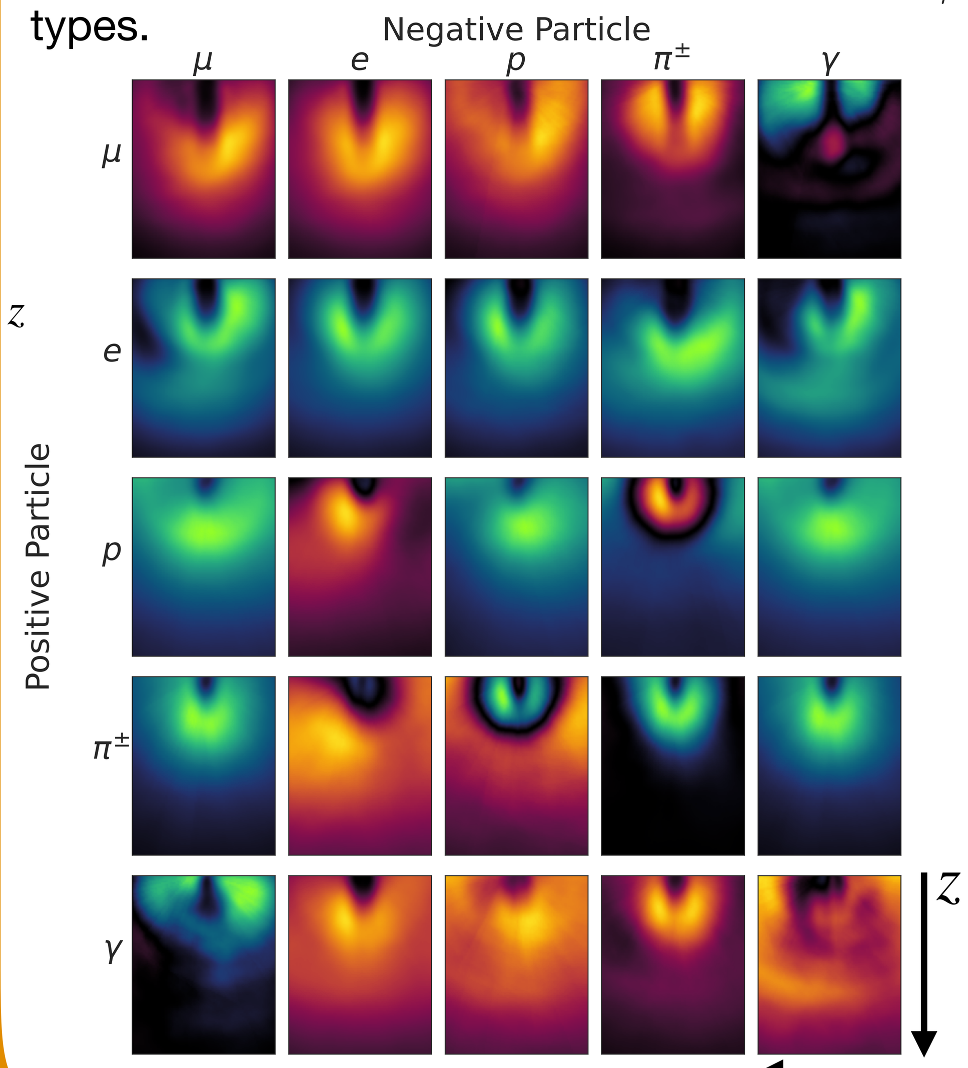
Interpretability

Attention mechanism can be tracked throughout the network.

Build an interpretable understanding of the relationships between different particles and event types.

Attention Map

Event Type \ Prong Type	Event	e	μ	p	γ_n	$\pi^\pm$	γ_π	γ_{other}	Other	Cosmic
ν_μ	0.17	0.07	0.13	0.11	0.07	0.10	0.13	0.09	0.07	0.06
ν_e	0.18	0.12	0.08	0.10	0.06	0.10	0.10	0.11	0.07	0.08
Neutral	0.14	0.08	0.08	0.12	0.07	0.11	0.15	0.10	0.07	0.07
Cosmic	0.13	0.11	0.10	0.08	0.10	0.09	0.10	0.11	0.03	0.15



Saliency & Difference Maps

Elect to **aggregate** interpretation metrics across the full dataset to extract **consistent signals**.

Attention: relative importance of different types of prong for providing context necessary to make event-level prediction.

- Presence of electron prong impactful for $\nu_e CC$.
- NC depends on photons from a neutral pion.

Saliency: the derivative of a network output with respect to the input pixel.

- **Diagonal**: saliency for a particular predicted class.
- **Off-diagonal**: pair-wise difference saliency maps computed as positive particle minus negative particle.

https://**nova**experiment.fnal.gov

Abstract #: 406

Fermilab Report #: FERMILAB-POSTER-24-0096-V

This work was supported by UK Research & Innovation