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Reducing sensitivities to systematic uncertainties of the deep neural networks employed in the NOvA experiment

UCL CDT DIS

NOvA

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The NOvA experiment

NOvA = Neutrinos at the Main Injector(N) Off-axis(O) Electron Neutrino(v) Appearance(A) Experiment.

Long baseline neutrino oscillation experiment

- Uses Fermilab's NuMI neutrino beam
- The Near Detector(ND) measures the beam at Fermilab
- The Far Detector observes the possibly oscillated beam at the 1st oscillation peak, 810 km away

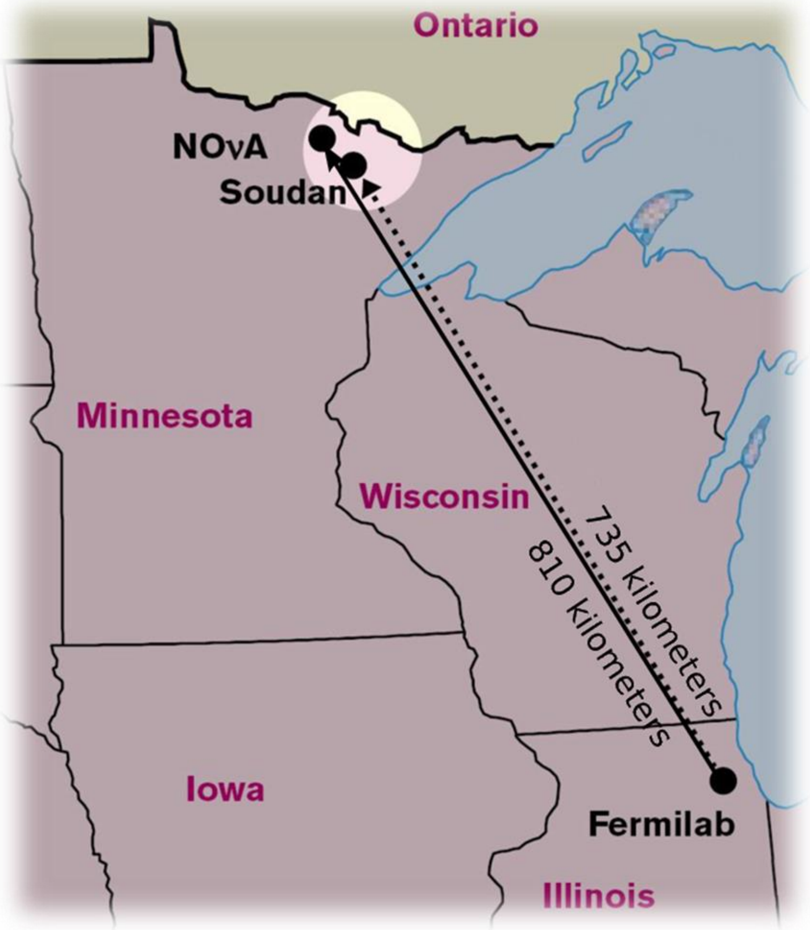
$$\boxed{\begin{array}{l} \nu_\mu \to \nu_e, \quad \nu_\mu \to \nu_\mu \\ \bar{\nu}_\mu \to \bar{\nu}_e, \quad \bar{\nu}_\mu \to \bar{\nu}_\mu \\ \theta_{23}, \quad \delta_{CP} \end{array}}$$

Physics goals

- Observe (dis-) appearance
- Measurement of oscillation parameters
- Constraints on CP violation

Additional searches:

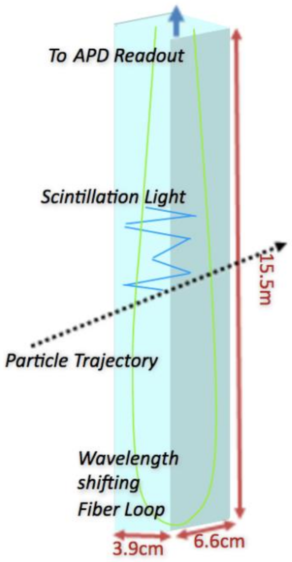
- Sterile neutrinos
- Gravitational wave/Supernova neutrinos
- Magnetic monopoles

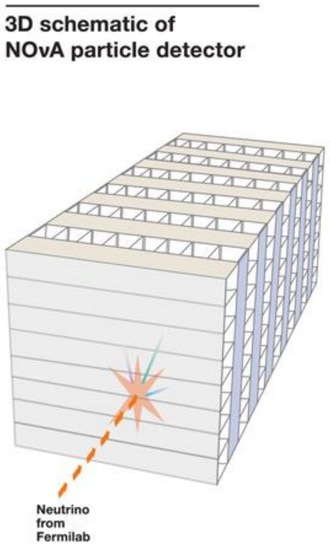


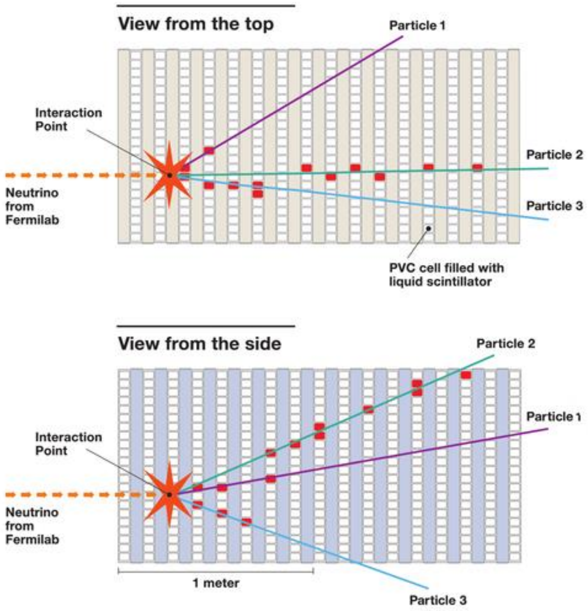
The NOvA Detectors

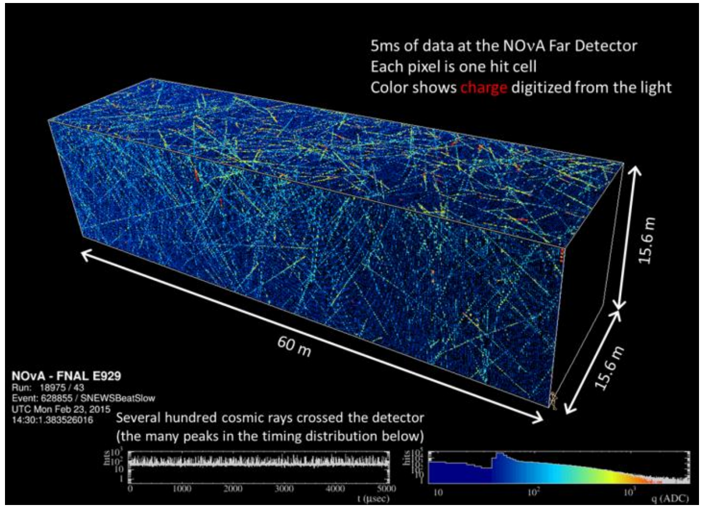
Near detector
- 96 x 96 x 192 cells
- 4 x 4 x 12.7m
- 0.3 kt

Far detector
- 384 x 384 x 896 cells
- 8 x 8 x 60m
- 14 kt

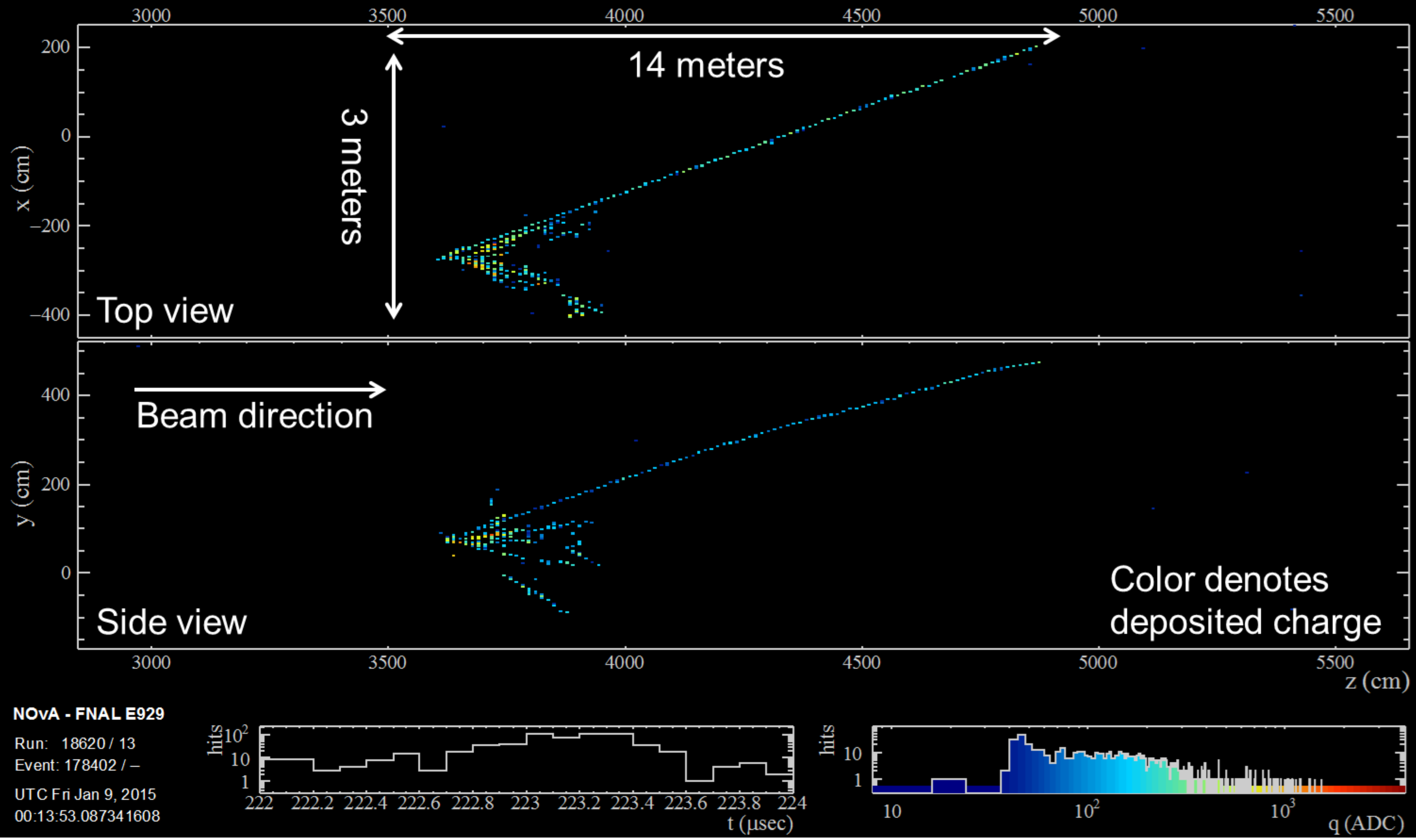




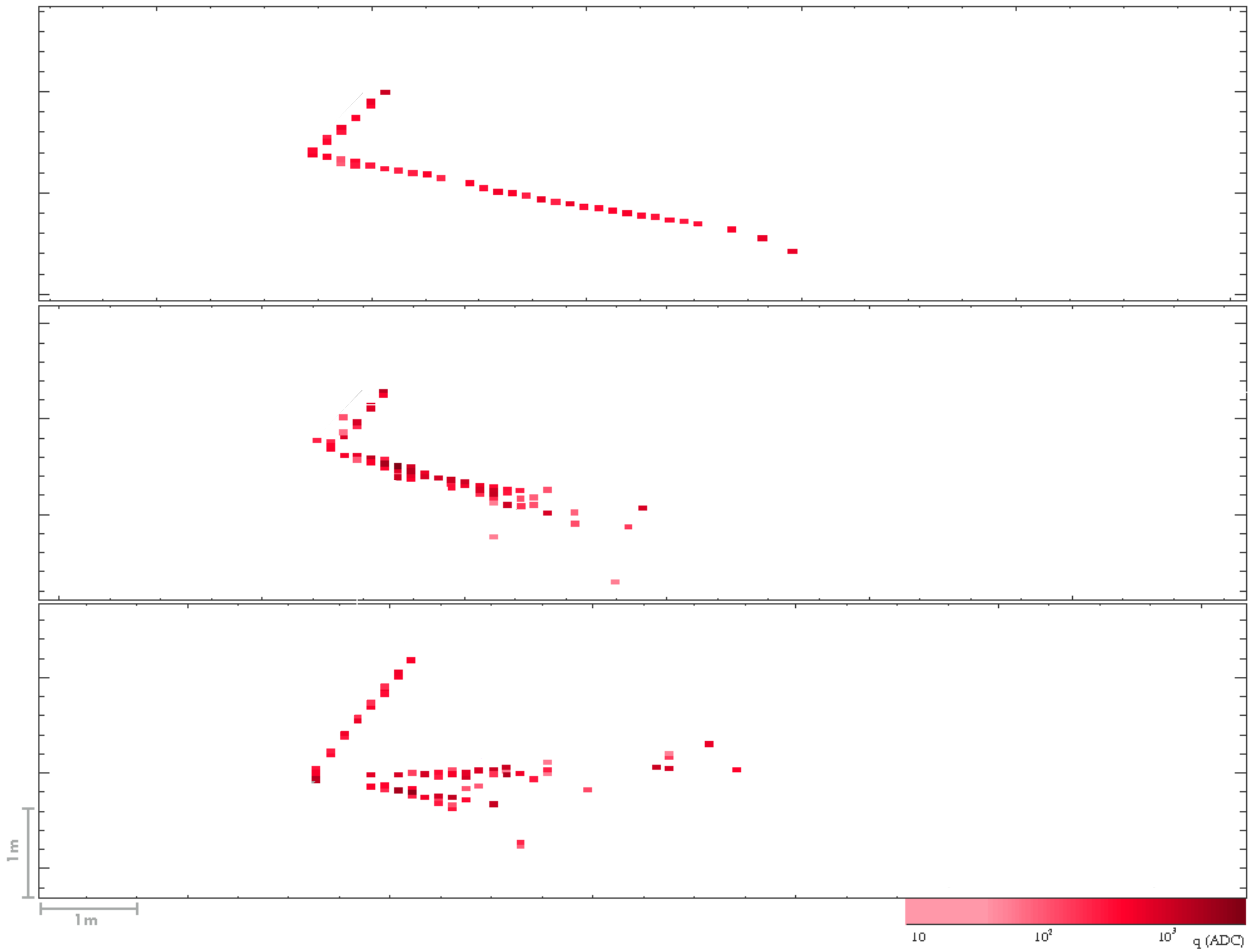




NOvA Event Display



NOvA Event Topologies

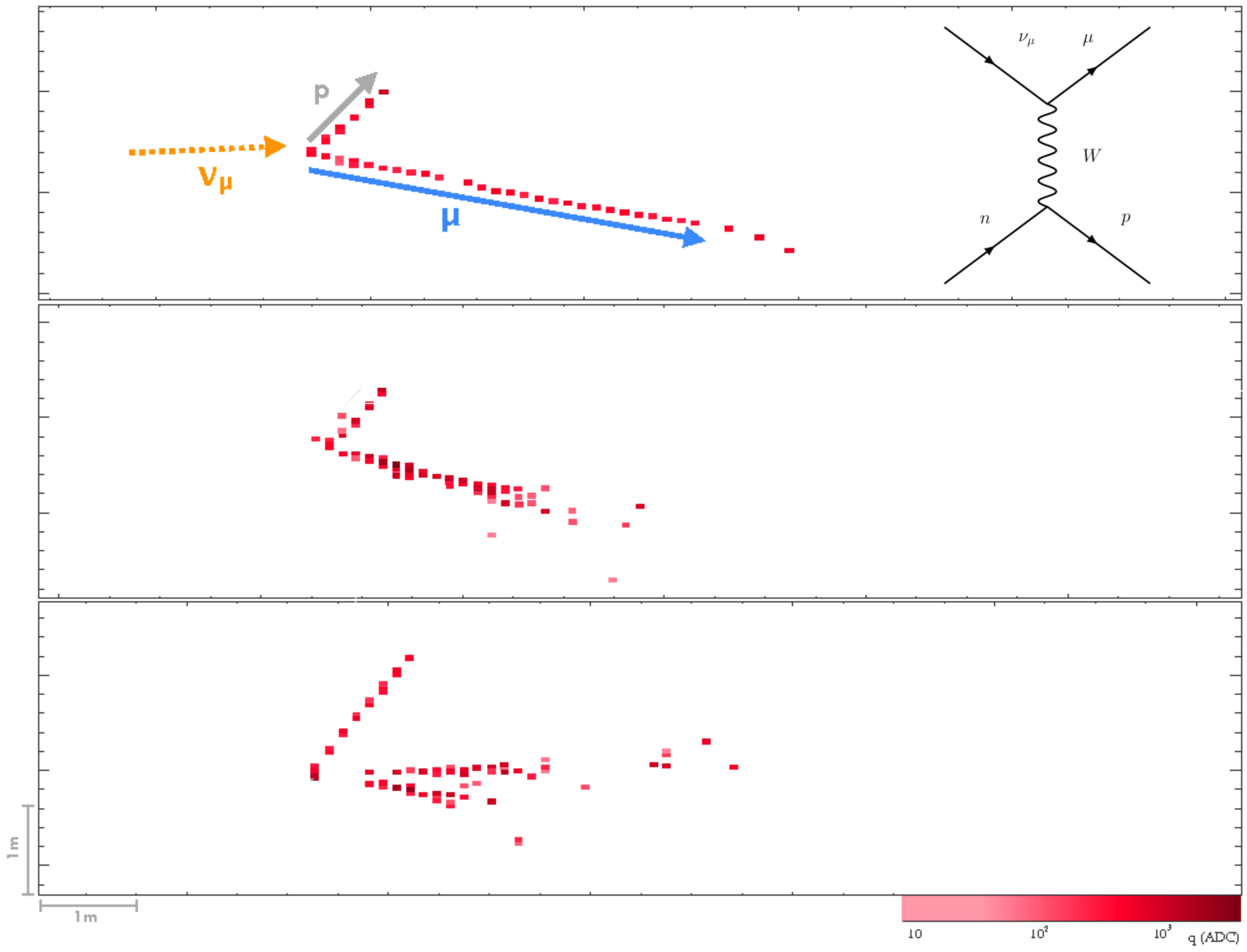


Interaction types and individual particles can be identified.

Let's try it now!

Pixelated nature of the detector allows for computer vision techniques to be employed.

NOvA Event Topologies



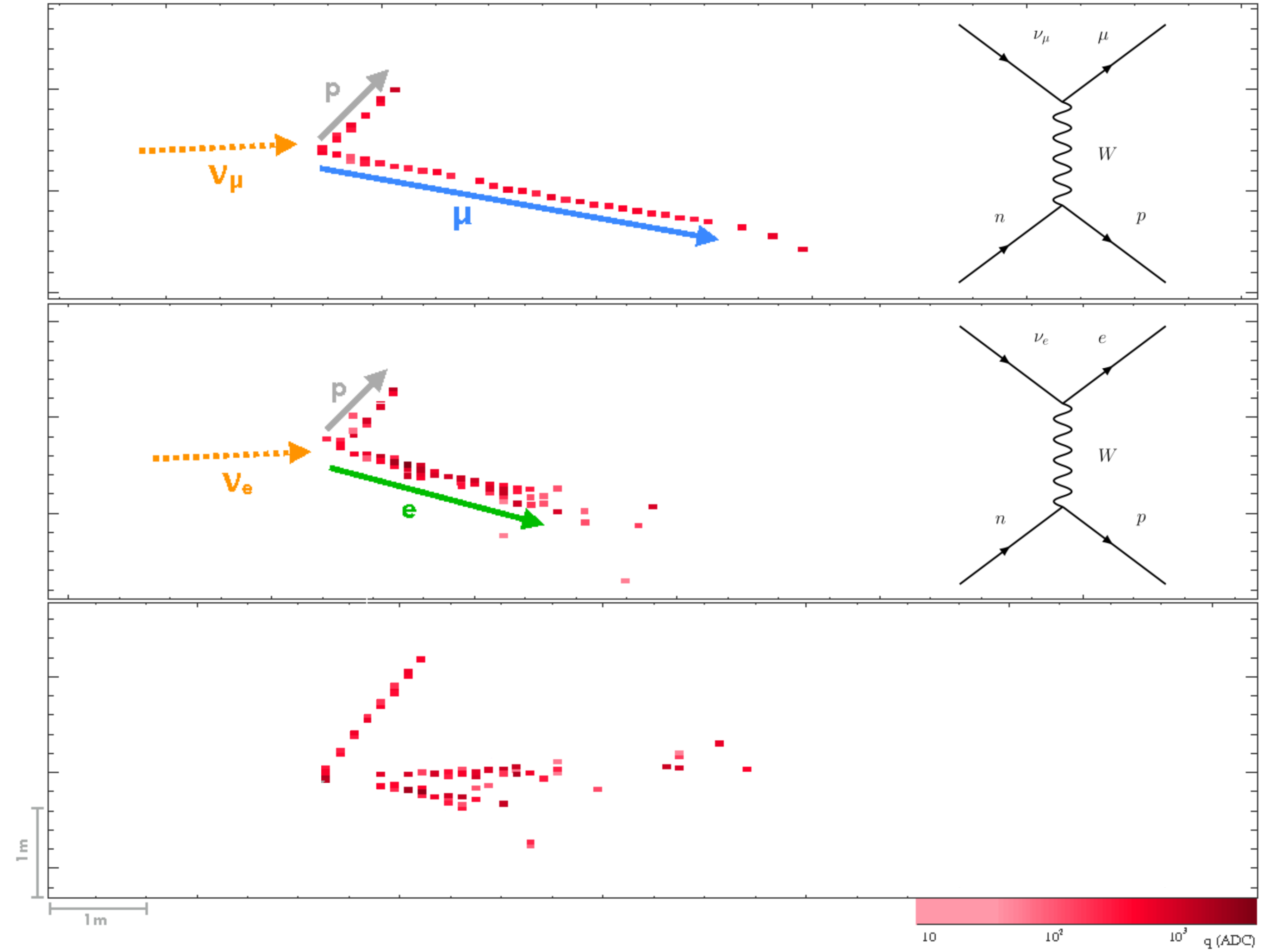
Interaction types and individual particles can be identified.

Let's try it now!

- Top: ν_μ Charged Current

Pixelated nature of the detector allows for computer vision techniques to be employed.

NOvA Event Topologies



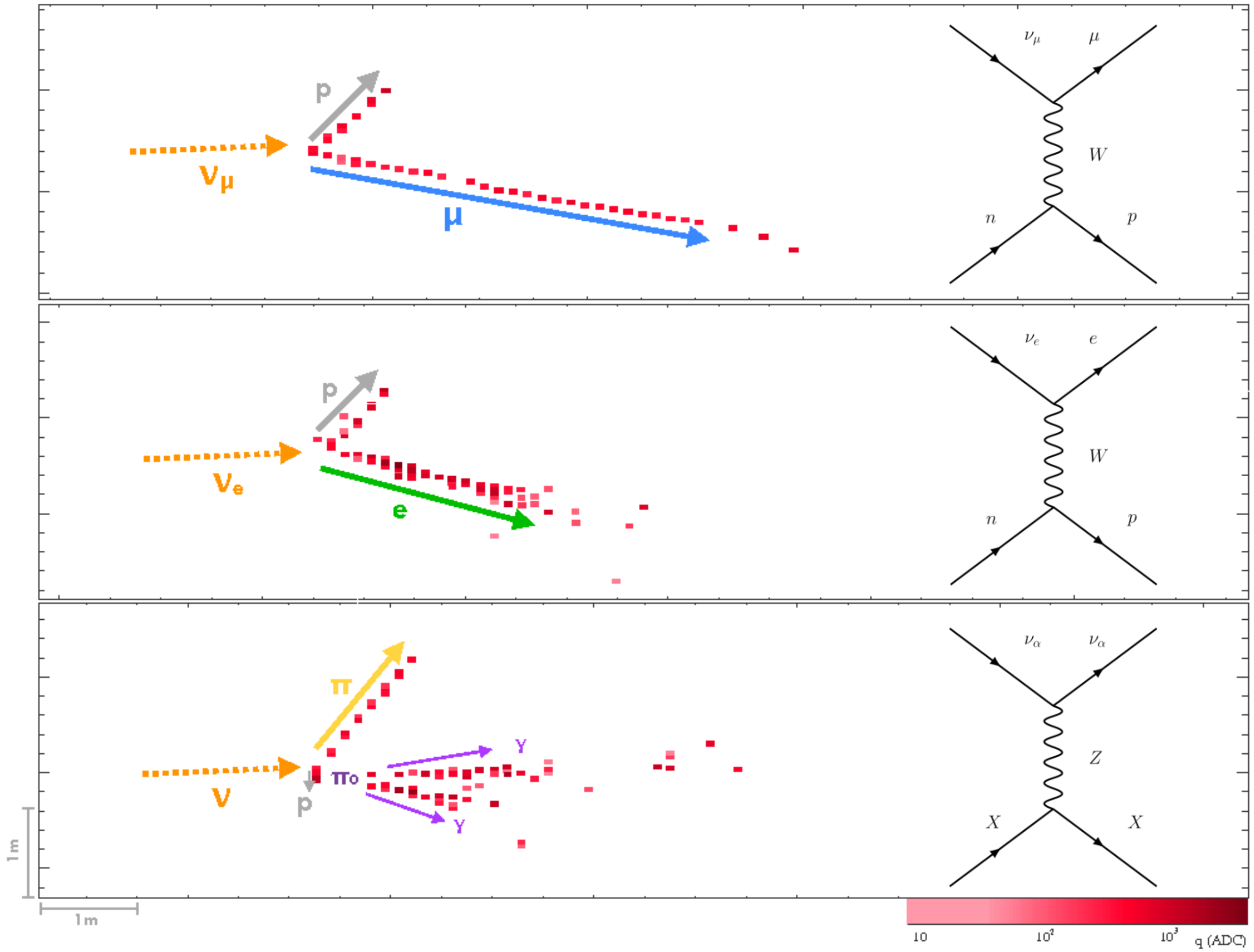
Interaction types and individual particles can be identified.

Let's try it now!

- Top: ν_μ Charged Current
- Middle: ν_e Charged Current

Pixelated nature of the detector allows for computer vision techniques to be employed.

NOvA Event Topologies



Interaction types and individual particles can be identified.

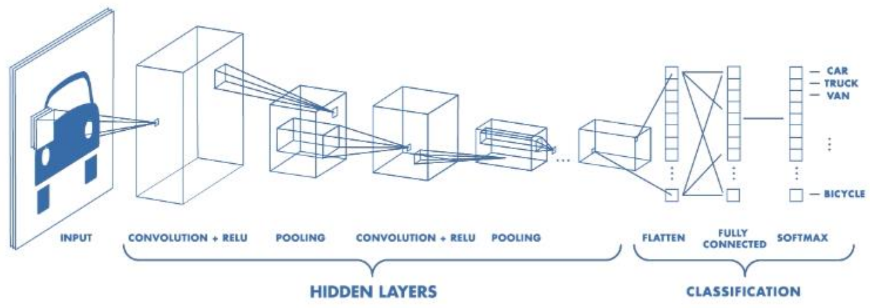
Let's try it now!

- Top: ν_μ Charged Current
- Middle: ν_e Charged Current
- Bottom: Neutral current

Pixelated nature of the detector allows for computer vision techniques to be employed.

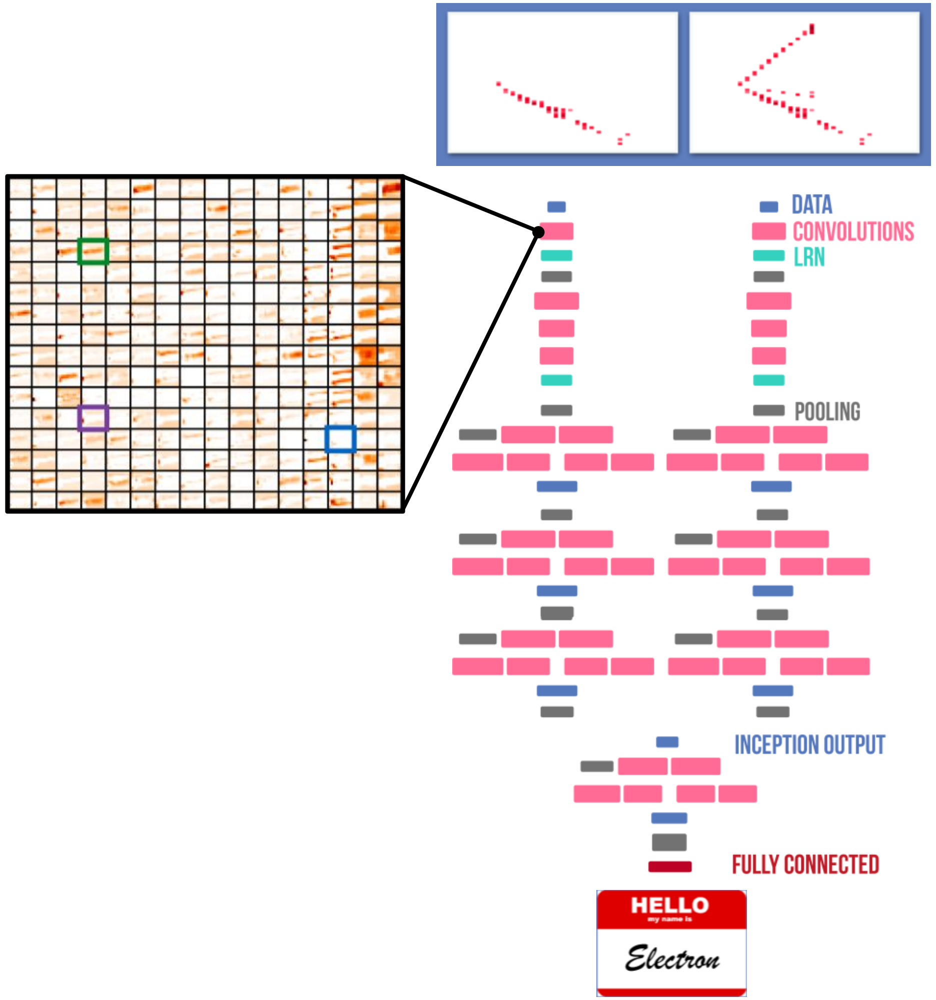
NOvA Convolutional Visual Network (CVN)

Uses 2 separate convolutional neural networks (CNN)



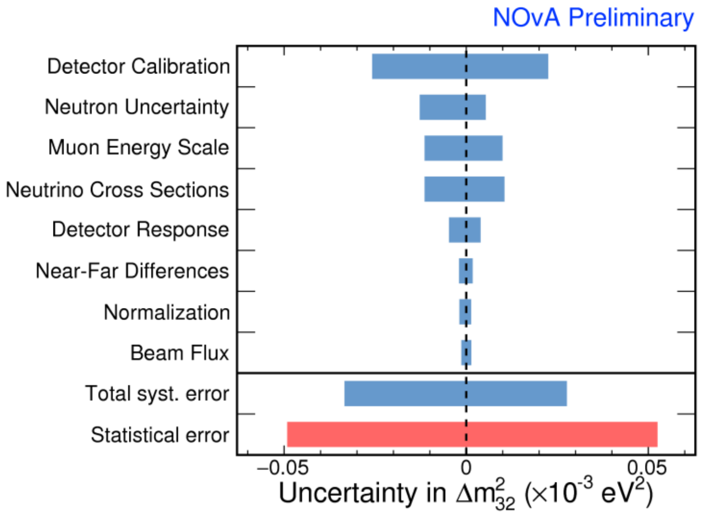
X 2

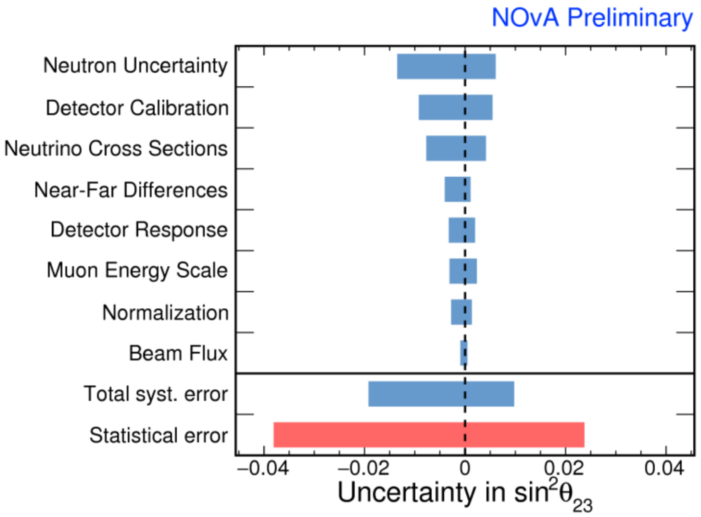
- 30% more exposure
- Included and used in published analysis (since 2016)
- Other architectures also employed.
  (4-Branch, energy estimators)



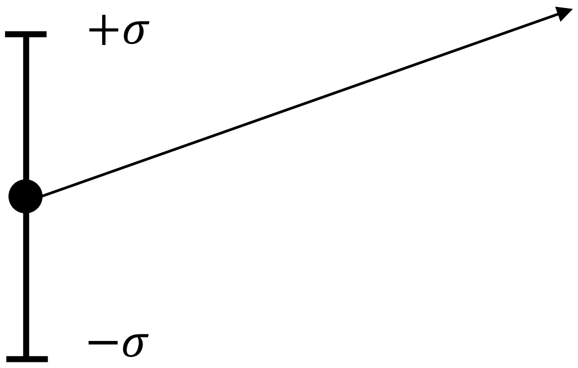
Aurisano et al., “A Convolutional Neural Network Neutrino Event Classifier”, JINST 11, P09001 (2016).

Systematic Uncertainty



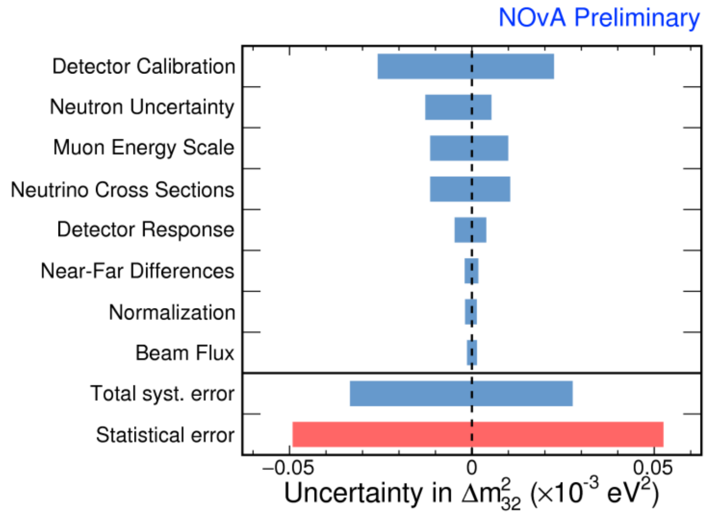


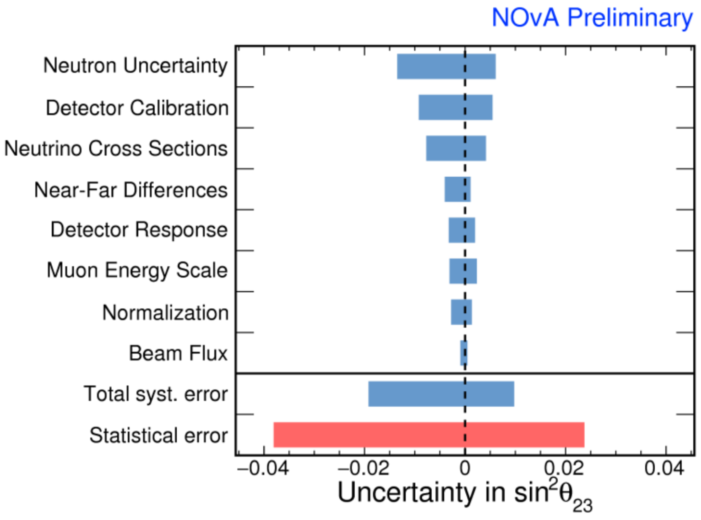
Nuisance parameter



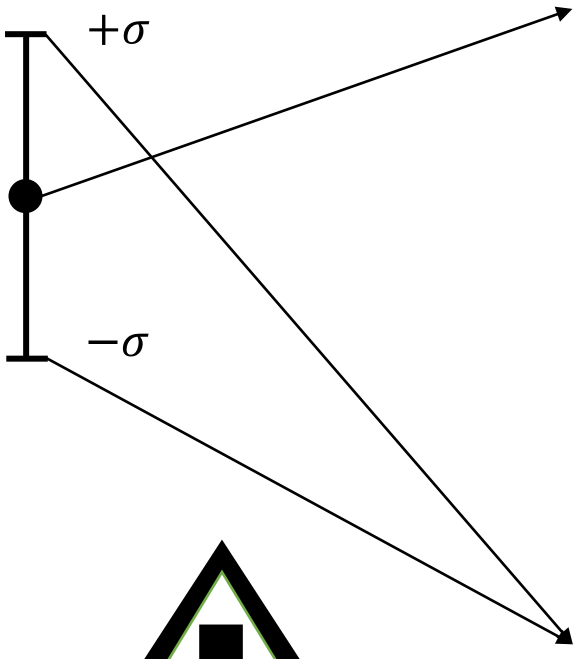
- Produce training data at nominal
- Train neural network
- Validate network
- Apply network on real data

Systematic Uncertainty





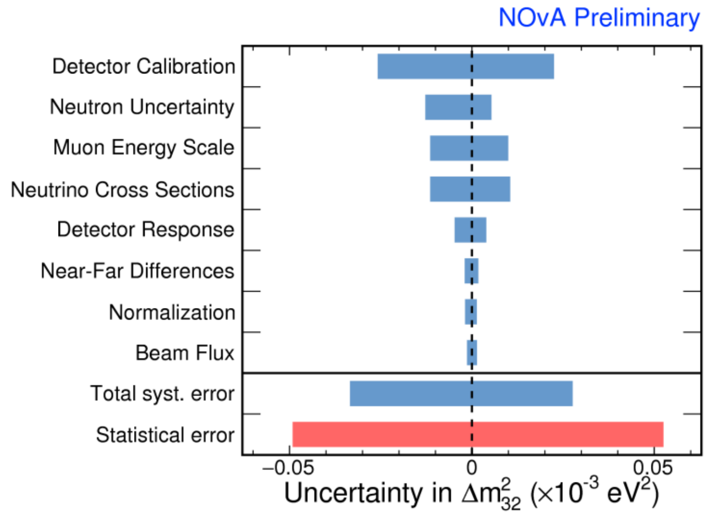
Nuisance parameter

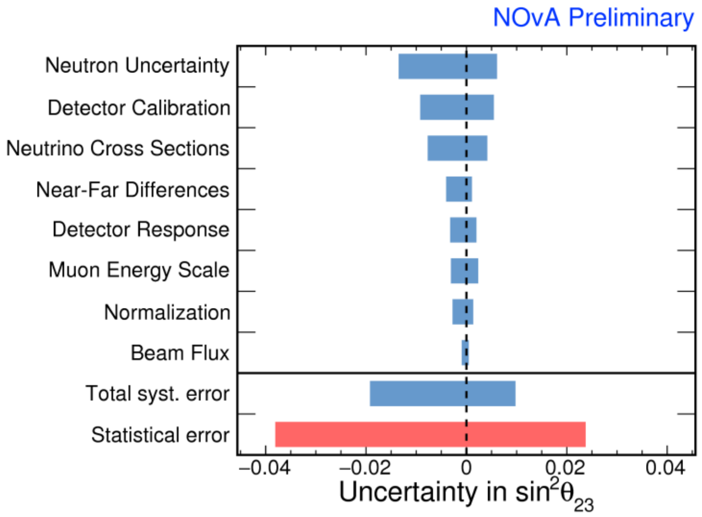


- Produce training data at nominal
- Train neural network
- Validate network
- Apply network on real data

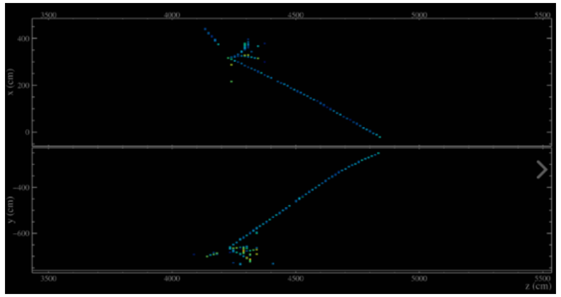
- Nuisance parameter not at nominal in real data
- Domain adaption

Simplified simulated systematic





- Detector calibration contributes significantly
- Affects the training data
- Can be emulated by scaled brightness of pixelmaps



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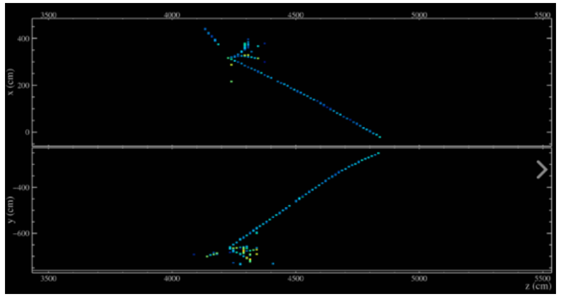

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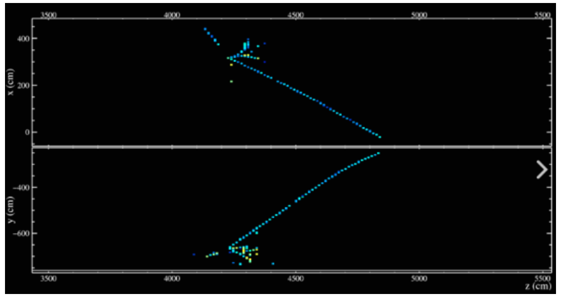

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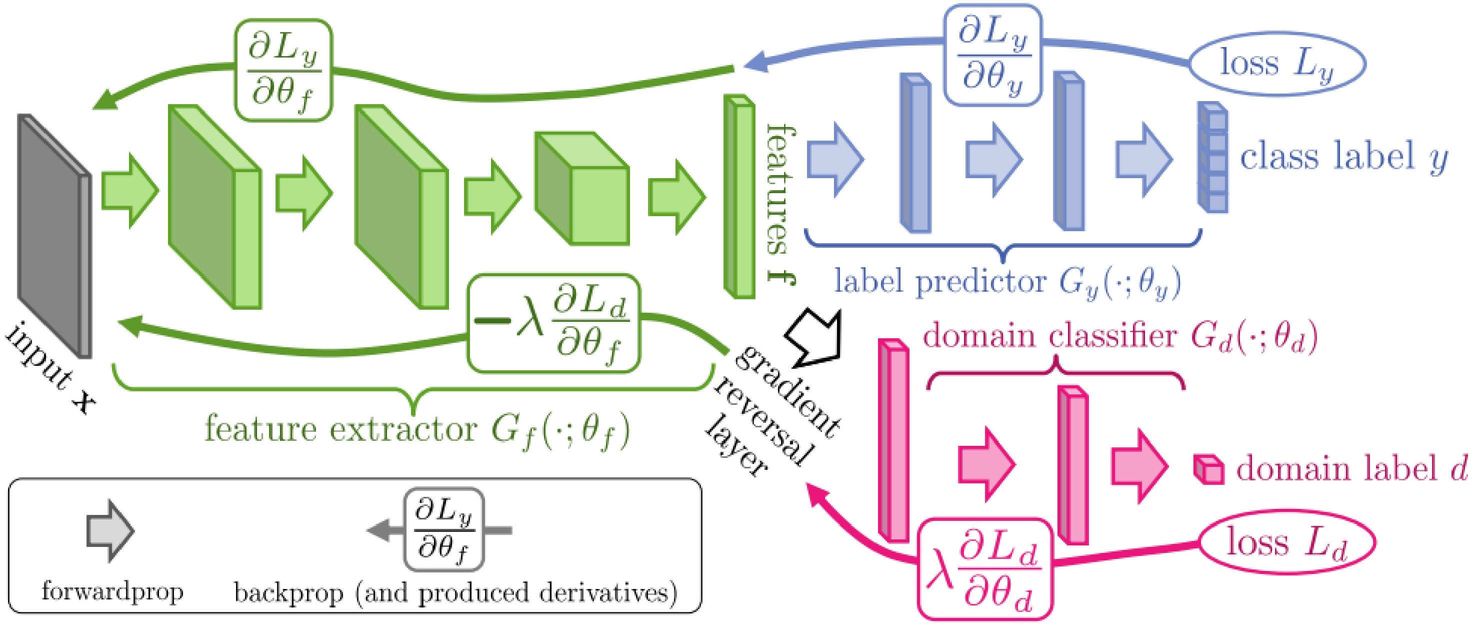


Proposed in "*Domain Adversarial Training of Neural Networks*" (DANN)

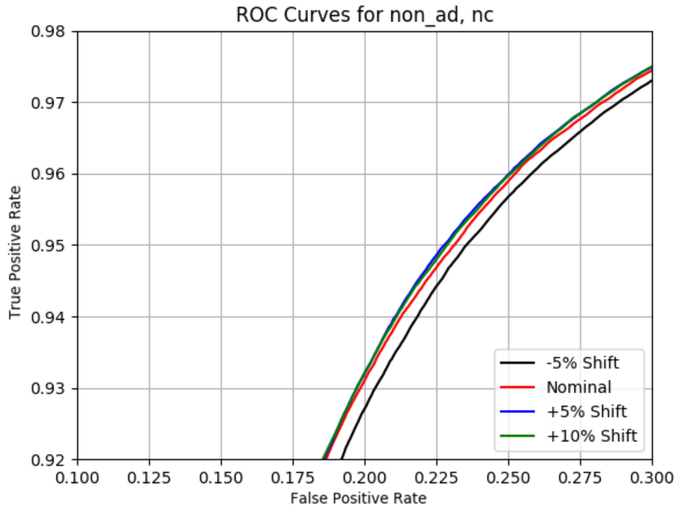
arxiv.org/pdf/1505.07818.pdf

$$Loss = Distance(model\ output\ - truth)$$

$$Loss_{AD} = Loss_{class} - \lambda * Loss_{domain}$$

- Seeks to penalize any systematic dependent features of the network through backpropagation.

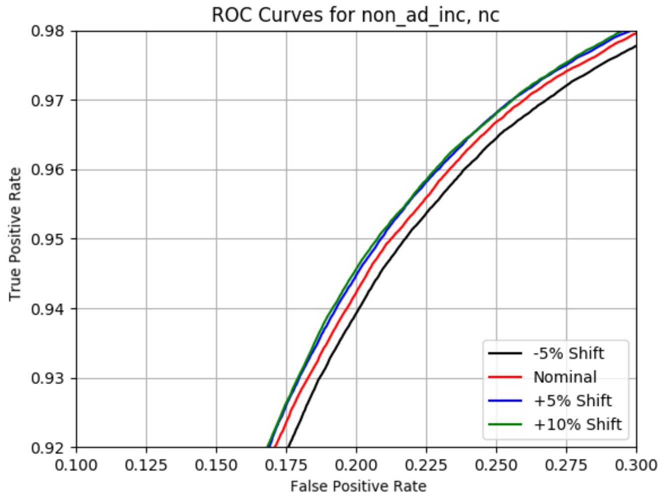
Domain adaption: gradient reversal

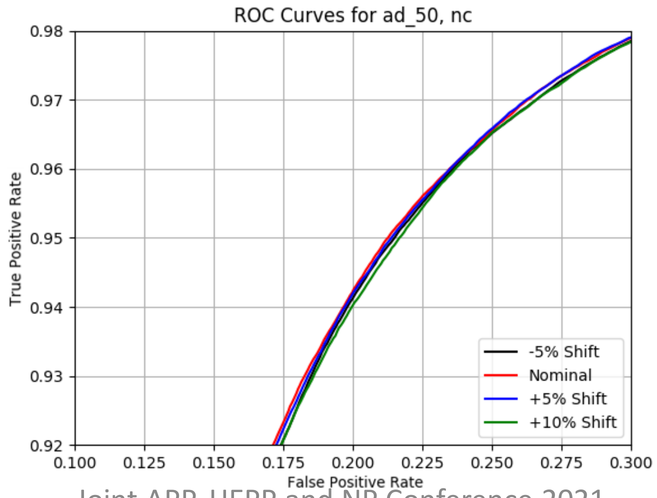


Implemented the gradient reversal layer in the NOvA CVN keras framework. (Tensorflow backend)

Initial stage look promising.

- Inclusive dataset ⟶ increased performance
- Adversarial strength of 50 ⟶ increased performance
  ⟶ lower sensitivity to the systematic





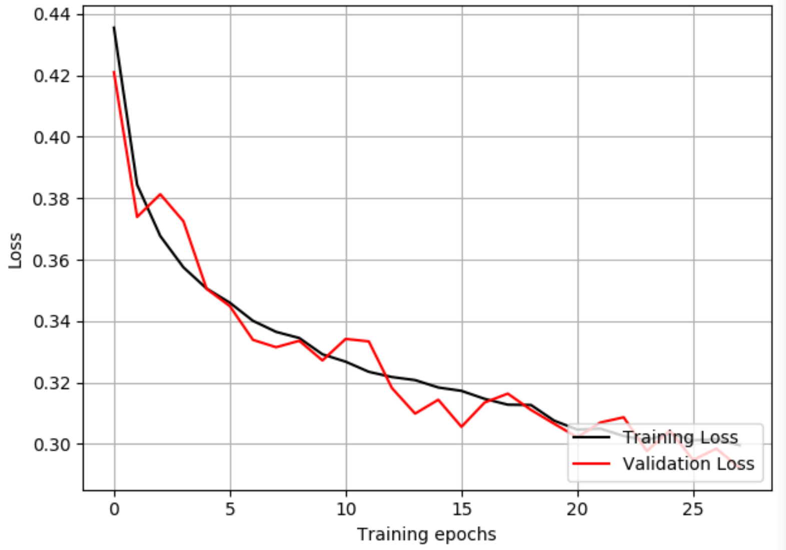
Real systematic uncertainties

Working toward evaluation of the Calibration and Lightlevel systematics

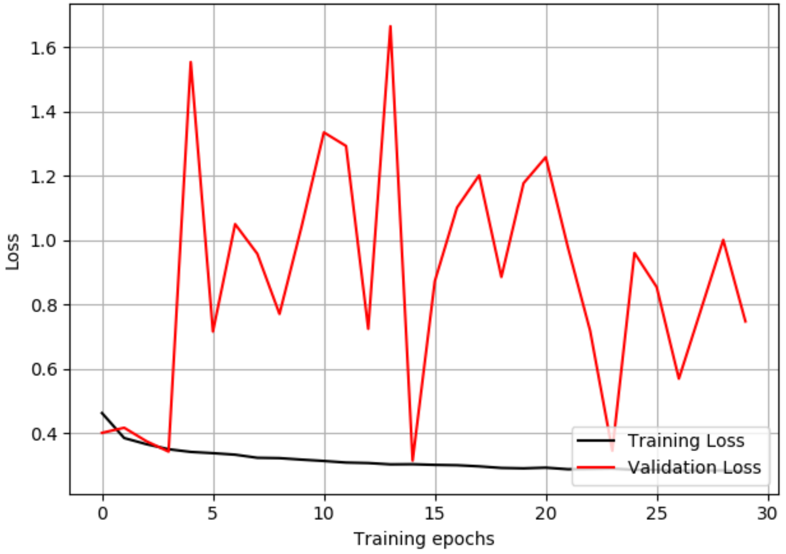
Recent changes to the CVN architecture are problematic

- Switched from ResNet to a custom MobileNet
- Causes instability during training
  (confined to the inclusion of the gradient reversal layer)

Expected loss curve



Observed loss curve



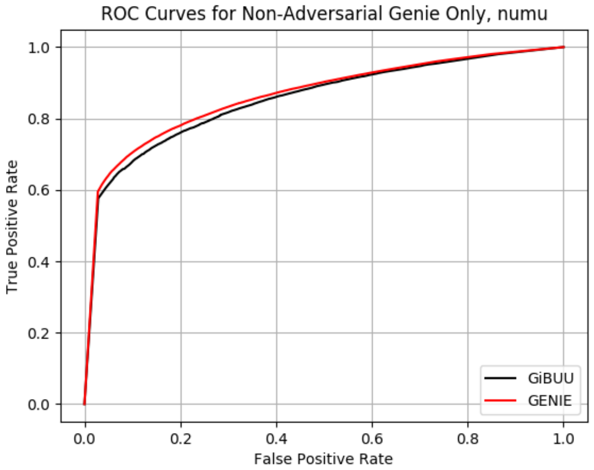
Other domains: Neutrino event generators

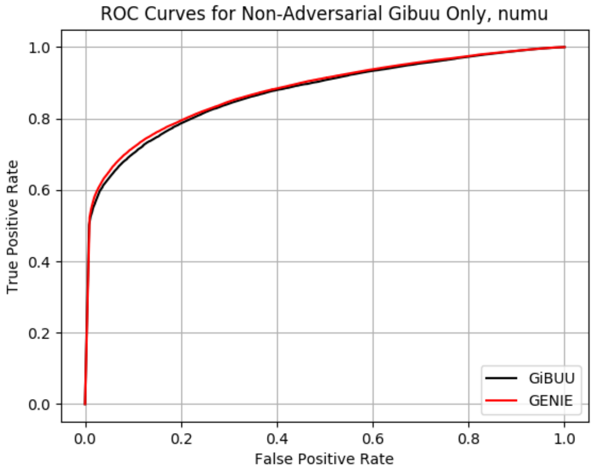
Uses different modeling to simulate the underlying interaction physics.

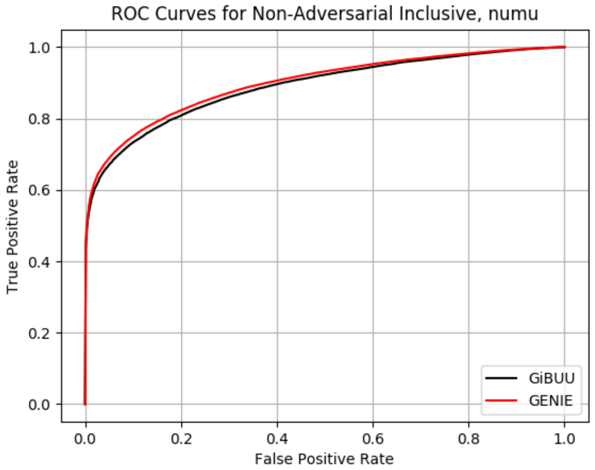
- NOvA employs GENIE
- Some other long baseline experiments employ GiBUU

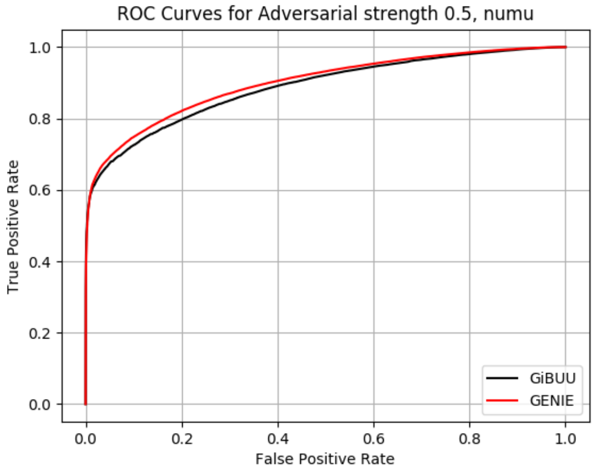
Inclusive data → higher performance and robustness

Adversarial training → no additional improvement or robustness









Summary

- NOvA’s segmented detectors allow for AI reconstruction
  Systematic uncertainties could pose a problem

- Domain adaption techniques can be applied
  Adversarial training through gradient reversal

- Effective on fake systematics

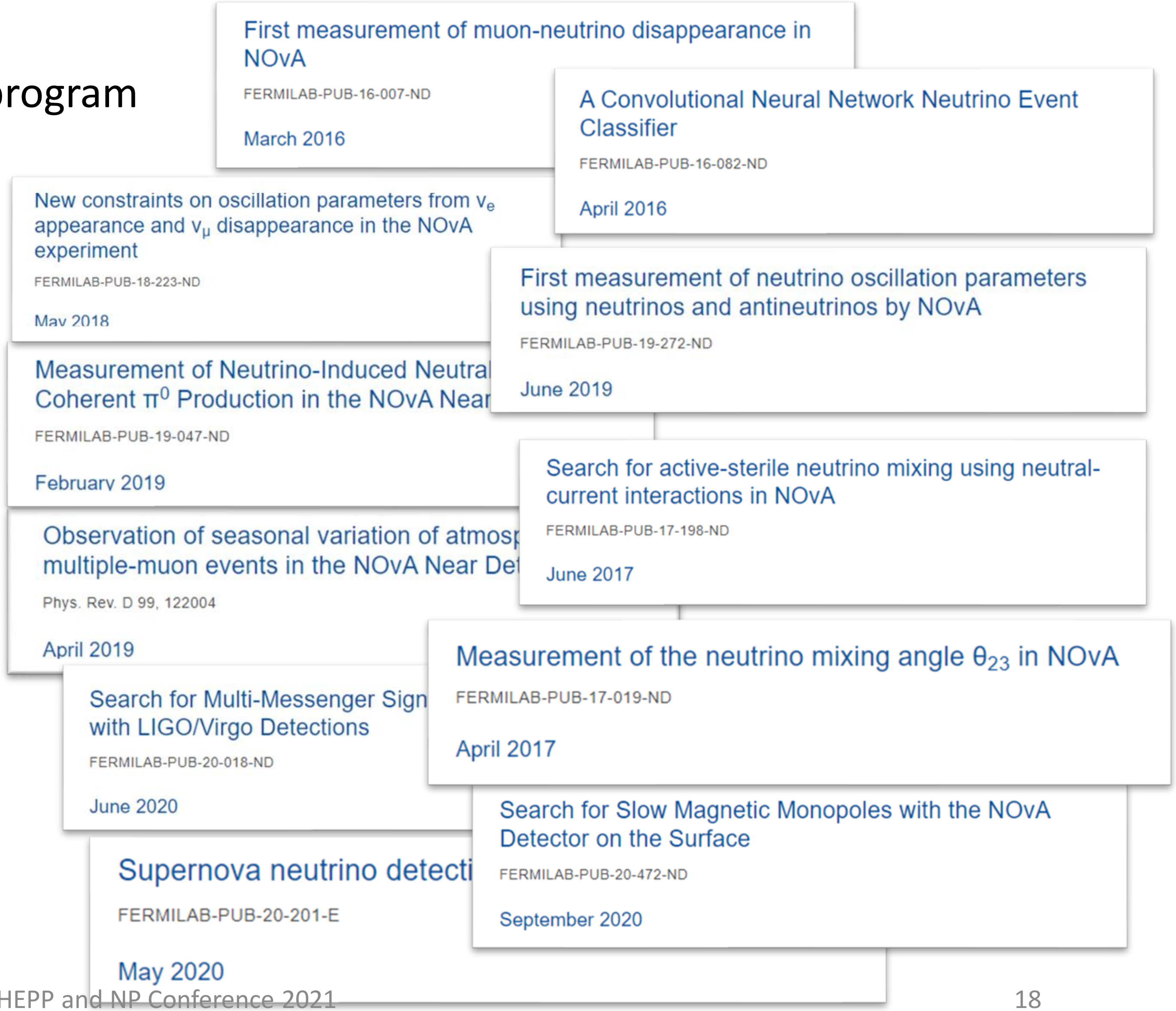
- Currently working towards evaluation of real systematics:
  - Calibration & Lightlevel

- Exploring applications on alternative domains

Physics overview

NOvA supports a large variation in its physics program

- Neutrino oscillation measurements
  - Observe (dis-) appearance
  - Measurement of oscillation parameters
  - Constraints on CP violation
- Sterile Neutrino search
- Supernova/gravitational wave neutrinos
- Magnetic monopoles search

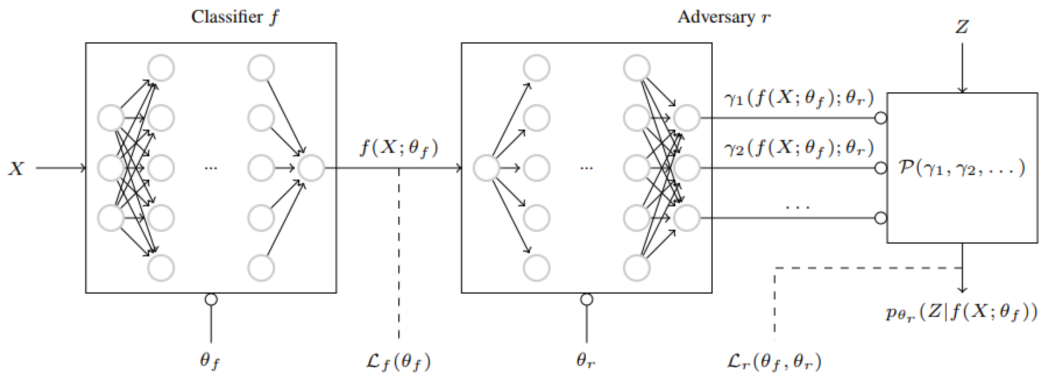


And more can be found here

Domain adaption: Learning to pivot(RW)

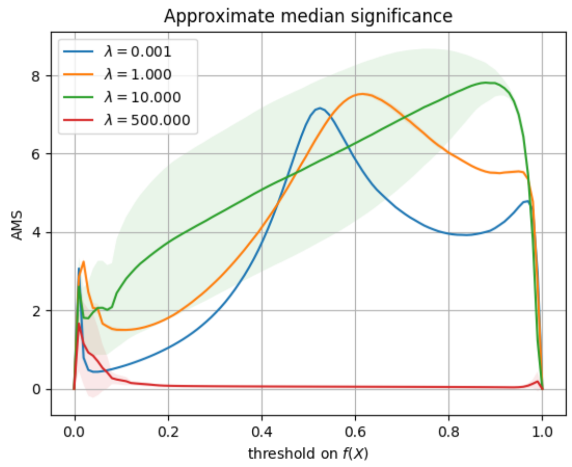
Add an adversarial network to a classifier.

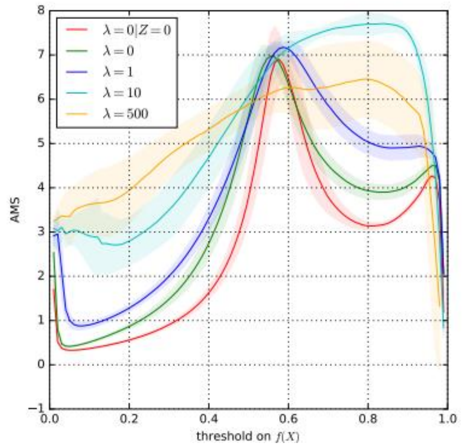
- Throughout training it seeks to identify and penalize any features which have a dependency on a nuisance parameter.
- Will reduce classifier performance, however due to the gained robustness overall significance increases.



Proposed in “Learning to Pivot with Adversarial Networks”

- Recreated the papers results, looked promising.





However implementing on the NOvA CVN lead to repeated mode collapse.

- Could be due to small size of the systematic, or the performance of the CVN itself.

arxiv.org/pdf/1611.01046.pdf