Neutrino event classification in DUNE

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(for the DUNE Collaboration)

PHYSTAT-nu

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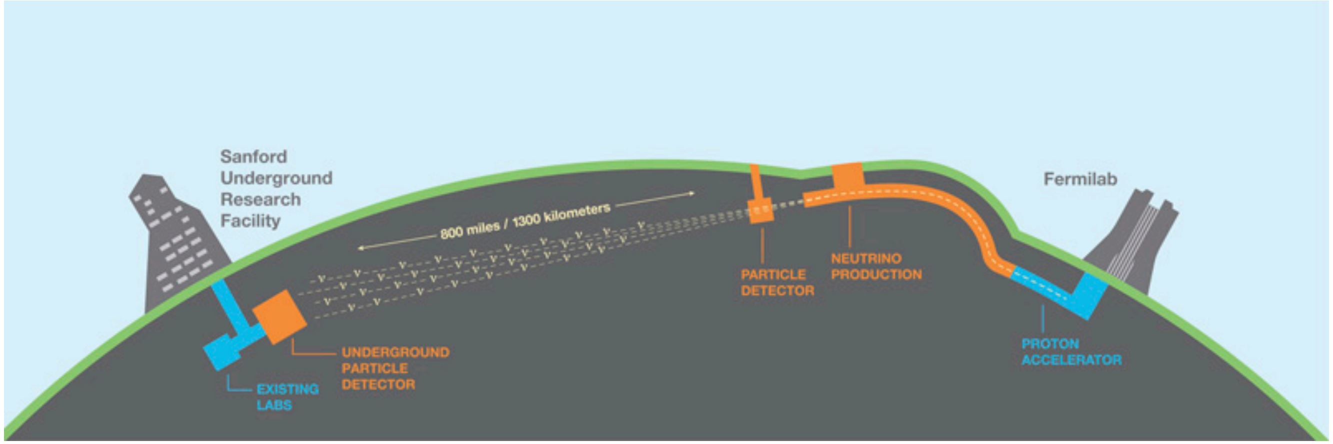
The DUNE Experiment

- DUNE is a next-generation neutrino oscillation experiment.



- Far Detectors (FD) are 800 miles from the neutrino beam source.
  - Four modules, each with 10,000 ton of liquid argon.
- High power muon neutrino beam produced at Fermilab.
  - Can switch polarity to produce a muon antineutrino beam.
- Look for the appearance of electron (anti)neutrinos at the FD.
  - Measure *CP*-violation.

NB: I will only write neutrino from now on, but the same is applicable for antineutrinos

Ingredients for the CP-violation analysis

- We need to consider two signal channels and their backgrounds.
  - Charged current $\overset{(-)}{\nu}_\mu$ disappearance – main background is NC $1\pi^{\pm}$.
  - Charged current $\overset{(-)}{\nu}_e$ appearance – main background is NC $1\pi^{0}$.

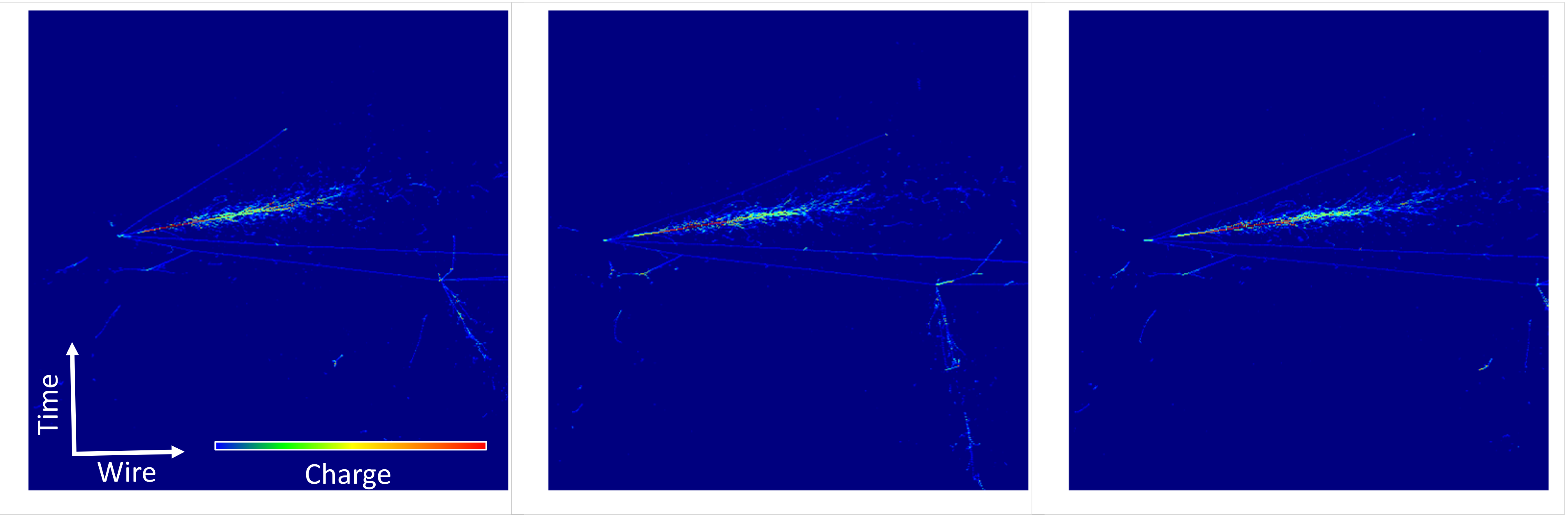
- Primary goal:
  - Classify the neutrino flavour as ν_e ,ν_μ , ν_τ or NC.

- Secondary goal:
  - Can we go beyond flavour classification to individual interaction mode classification?
    - Different event classes will have different energy resolutions and systematic uncertainties, so separation can provide increased sensitivity.

Far Detector Data

- The Far Detectors contain three wire readout planes.
  - This provides three "images" of each neutrino interaction.

- Simulated electron neutrino interaction (signal).



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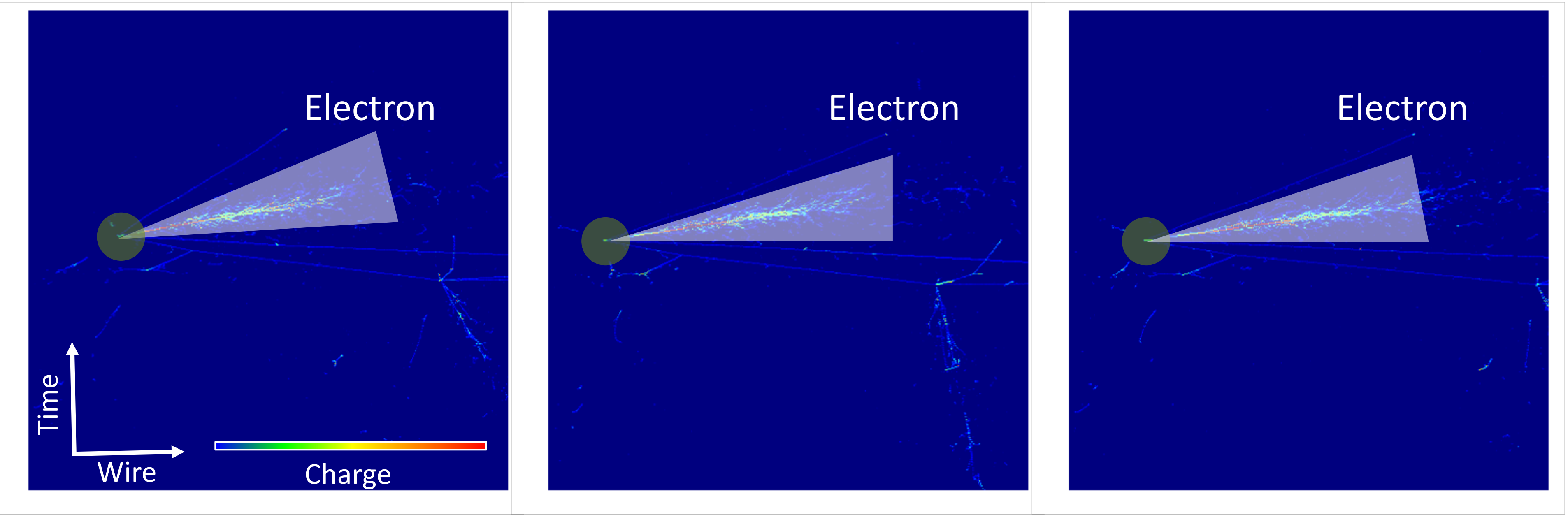

- Electron produces the highlighted shower, beginning at the vertex.

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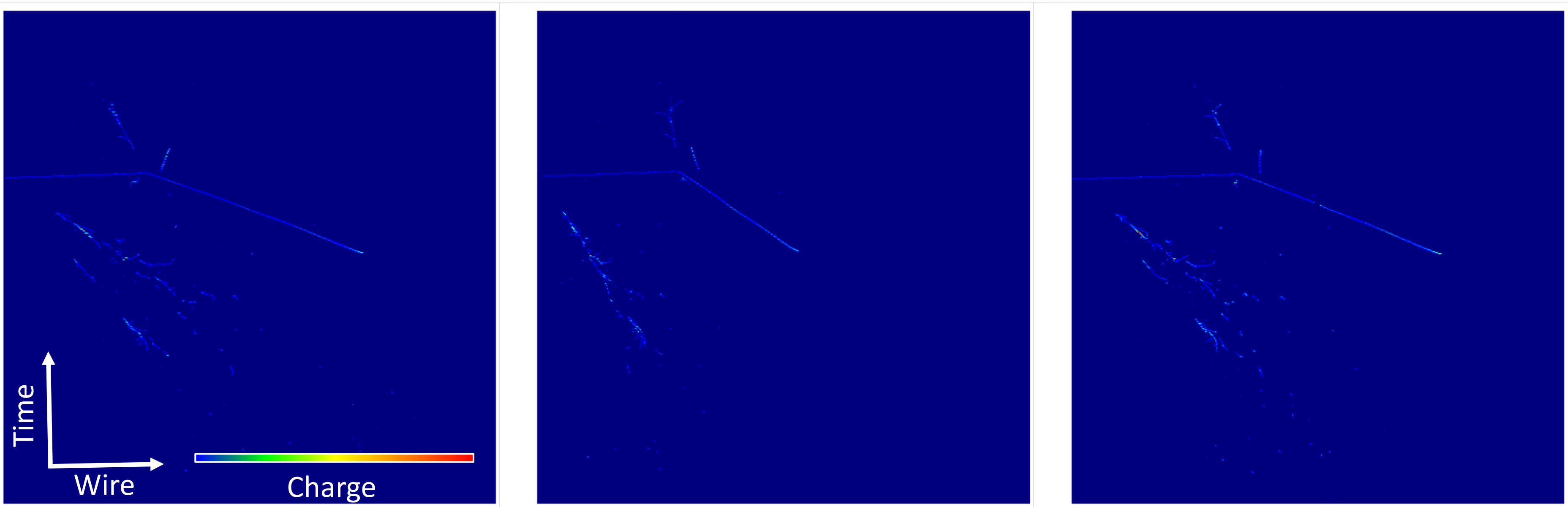

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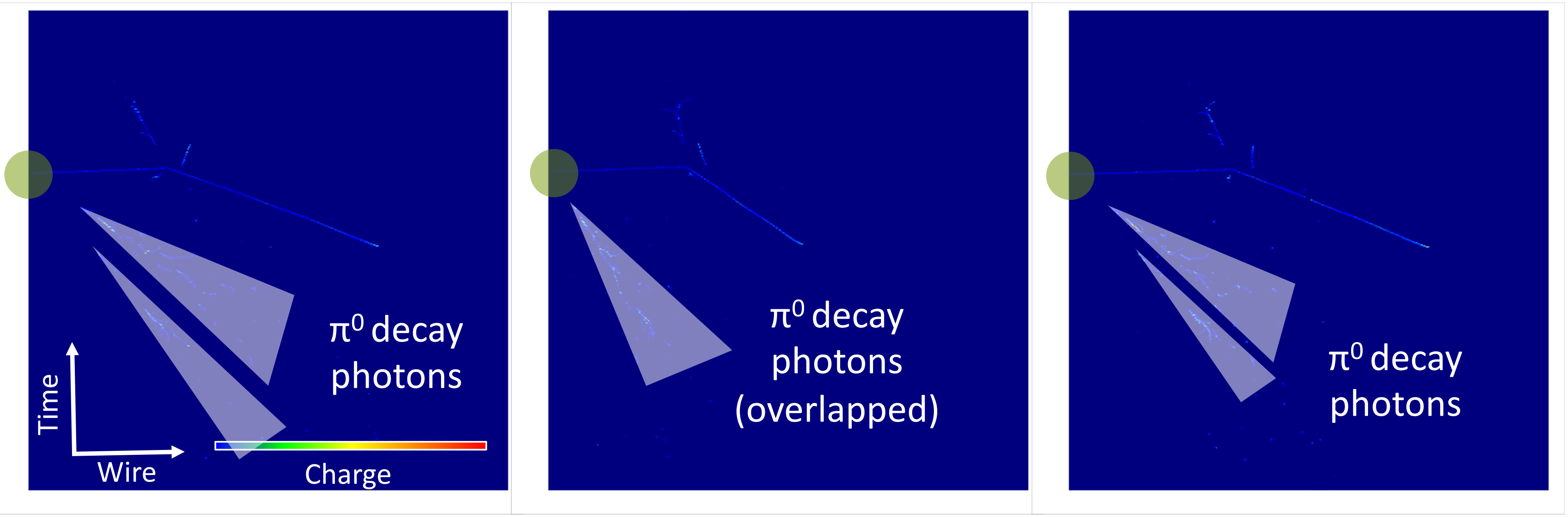


- π^0 decay photon showers are displaced from vertex.

Image Recognition

- Fine-grained detail of LArTPCs lends itself to image recognition.

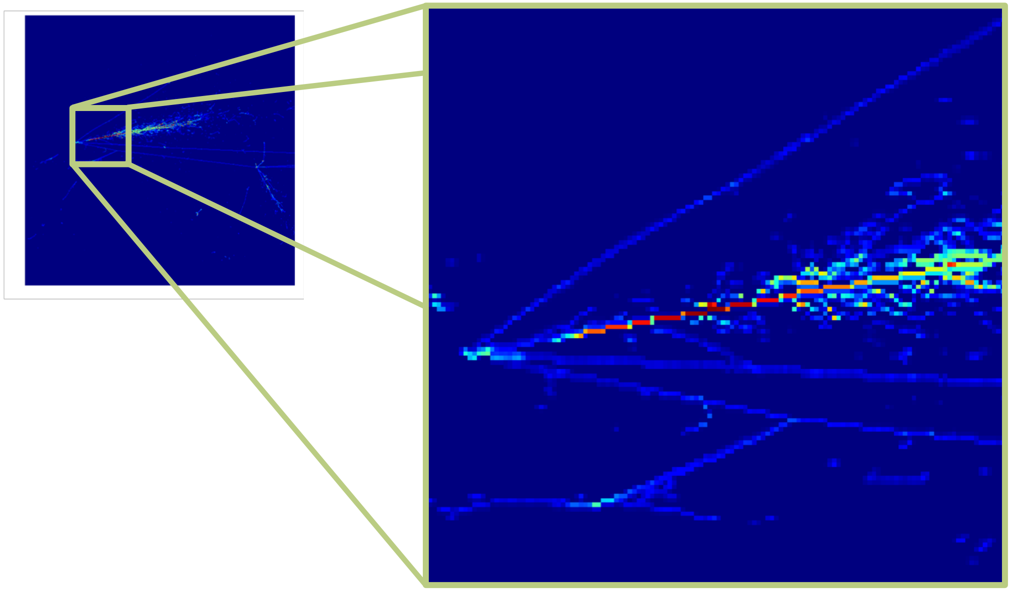
- The human eye is a remarkably good image recognition tool.
  - Once you know what to look for, it is fairly easy to find distinguishing features of different types of interactions.

- Realistically, the experiment will produce too much data for scanning the interactions by eye.

- We need to be able to train a computer to do this task.
  - Recent years have shown rapid development of automated image recognition. One of the most promising approaches is the Convolutional Neural Network (CNN).

Convolutional Neural Networks

- CNNs are used to classify images by applying filters to small patches of the image (using a convolution).
- Scans over the image with a number of N x N pixel filters.



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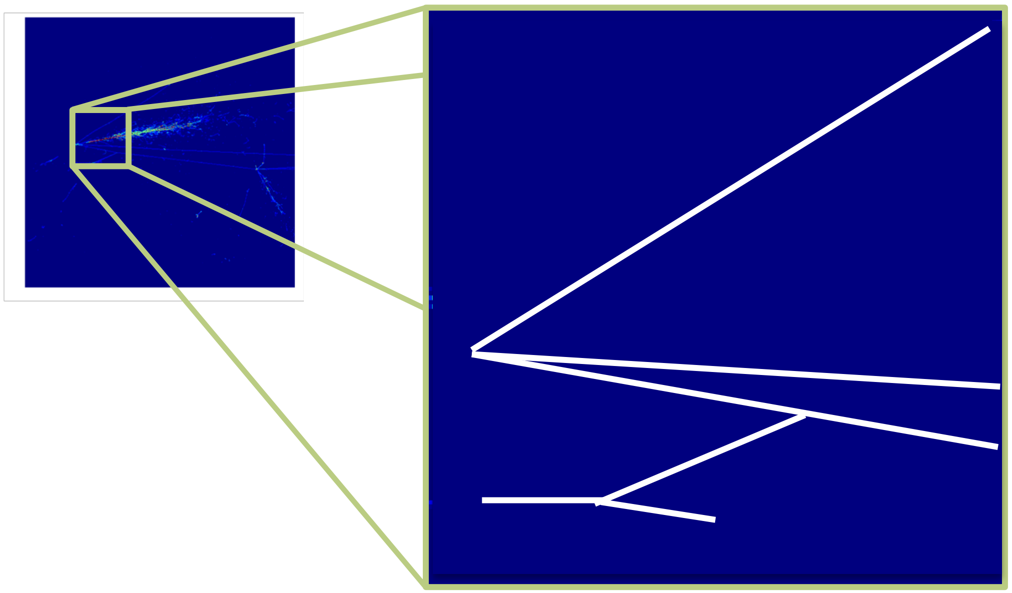

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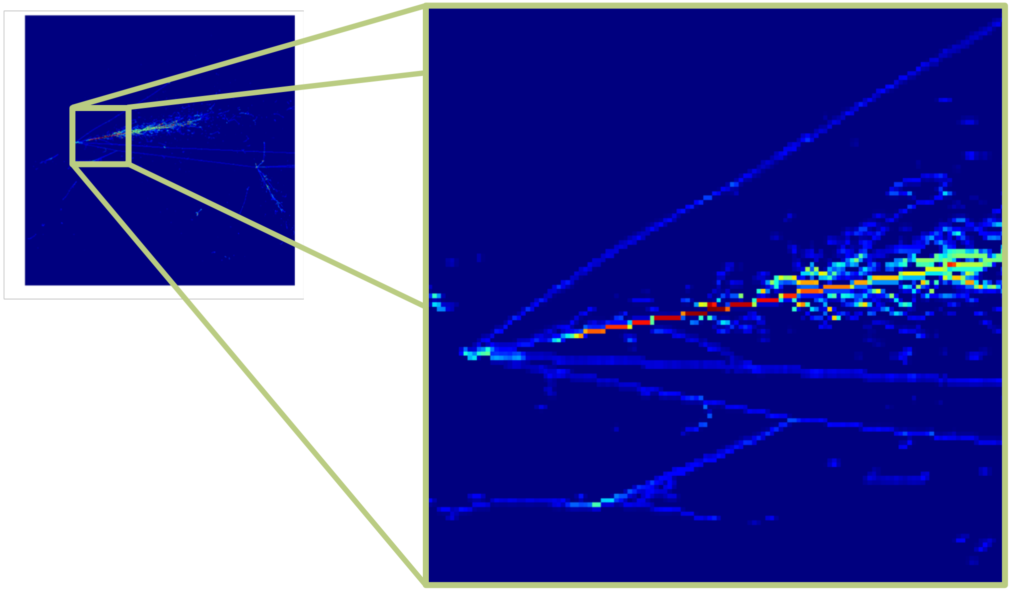

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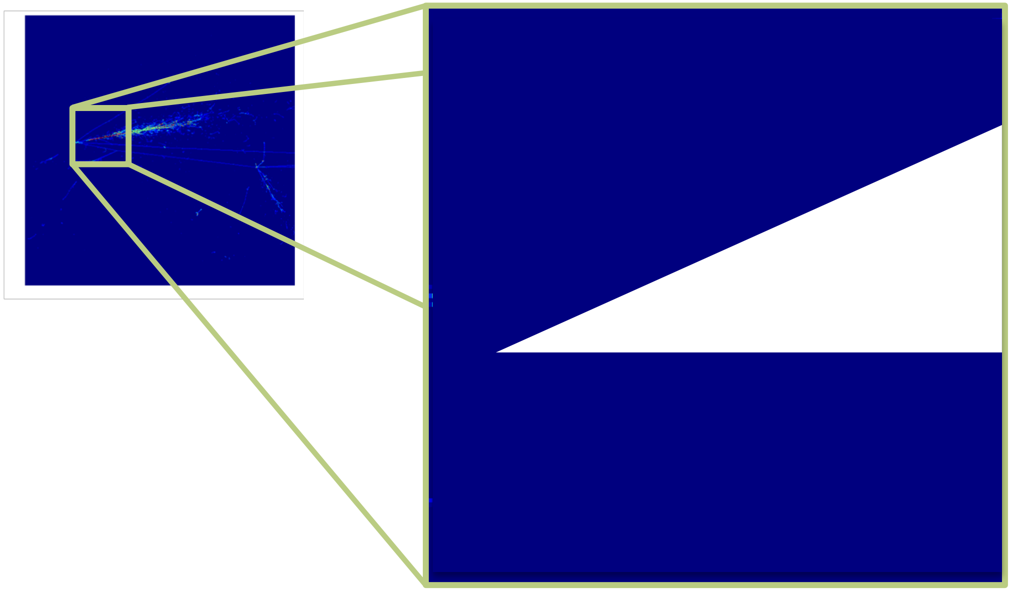

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- For example, filter 1 may look for tracks.
- Filter 2 might look for showers.

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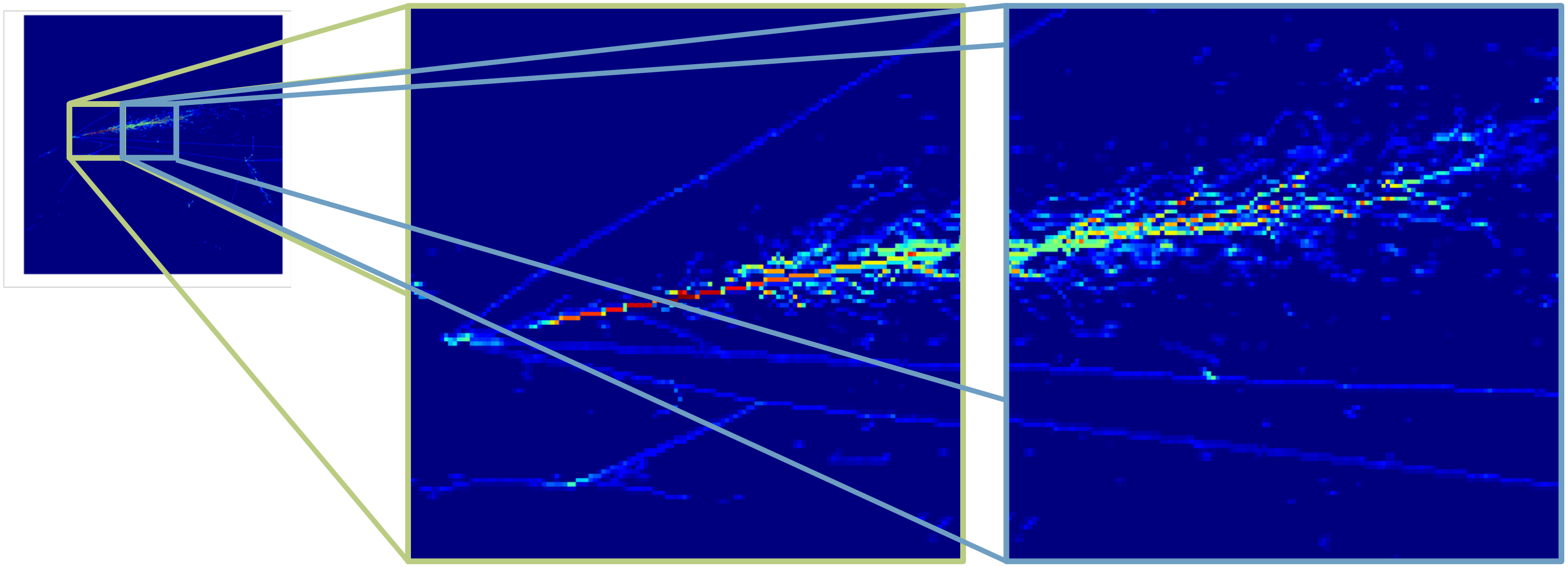
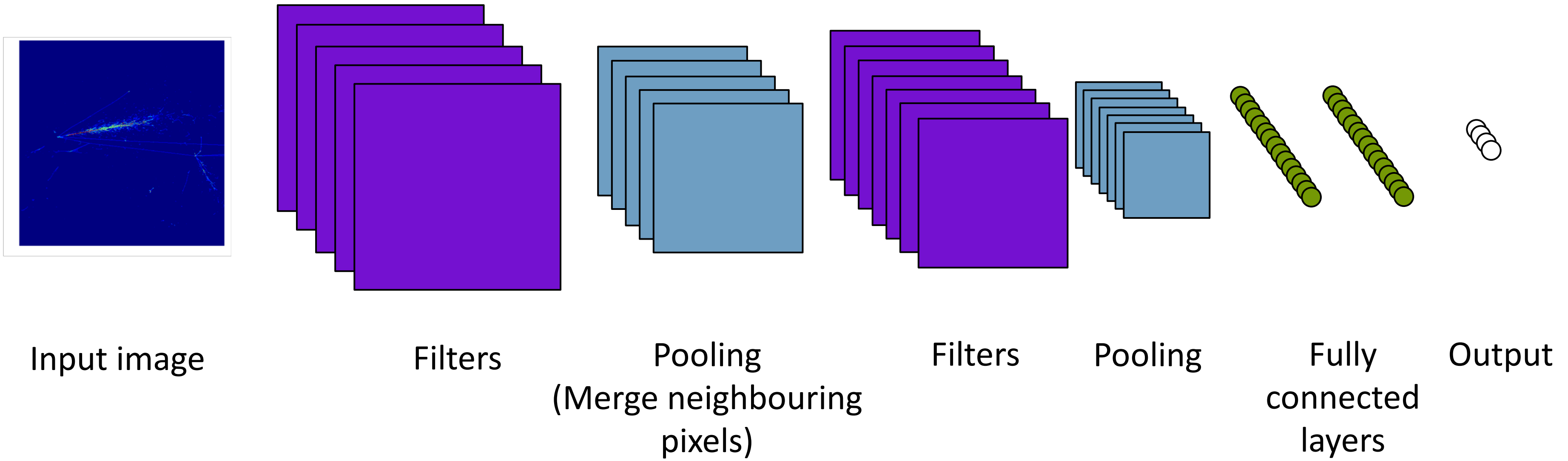


- Then move onto the next patch of the image and repeat the process.

Convolutional Neural Networks

- The output from each filter then forms the basis of the next layer which can include further filters.

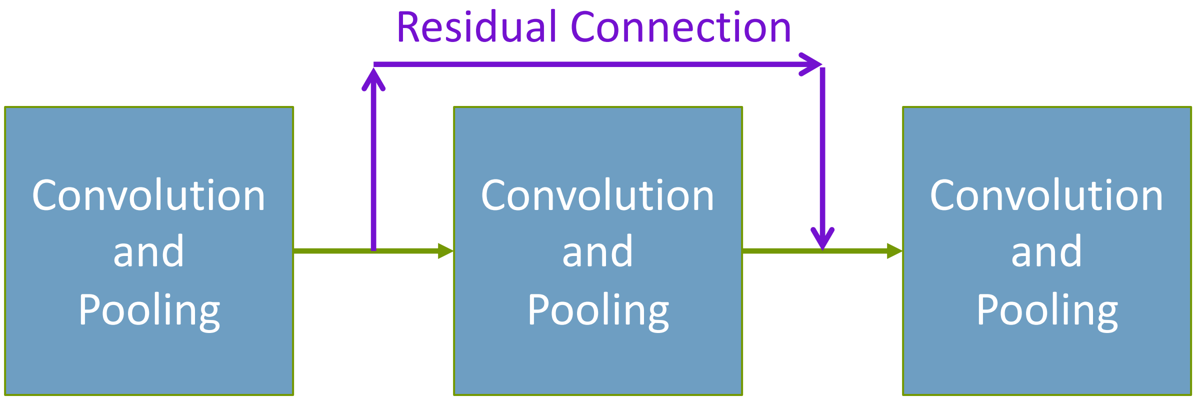


- Different architectures can be considerably more complex than the above toy example.

DUNE CNN introduction

- The initial DUNE CNN was based on the NOvA implementation.

- In the last year we have moved to a completely new architecture and framework.
  - We now use a SE-ResNet[1,2] based architecture.

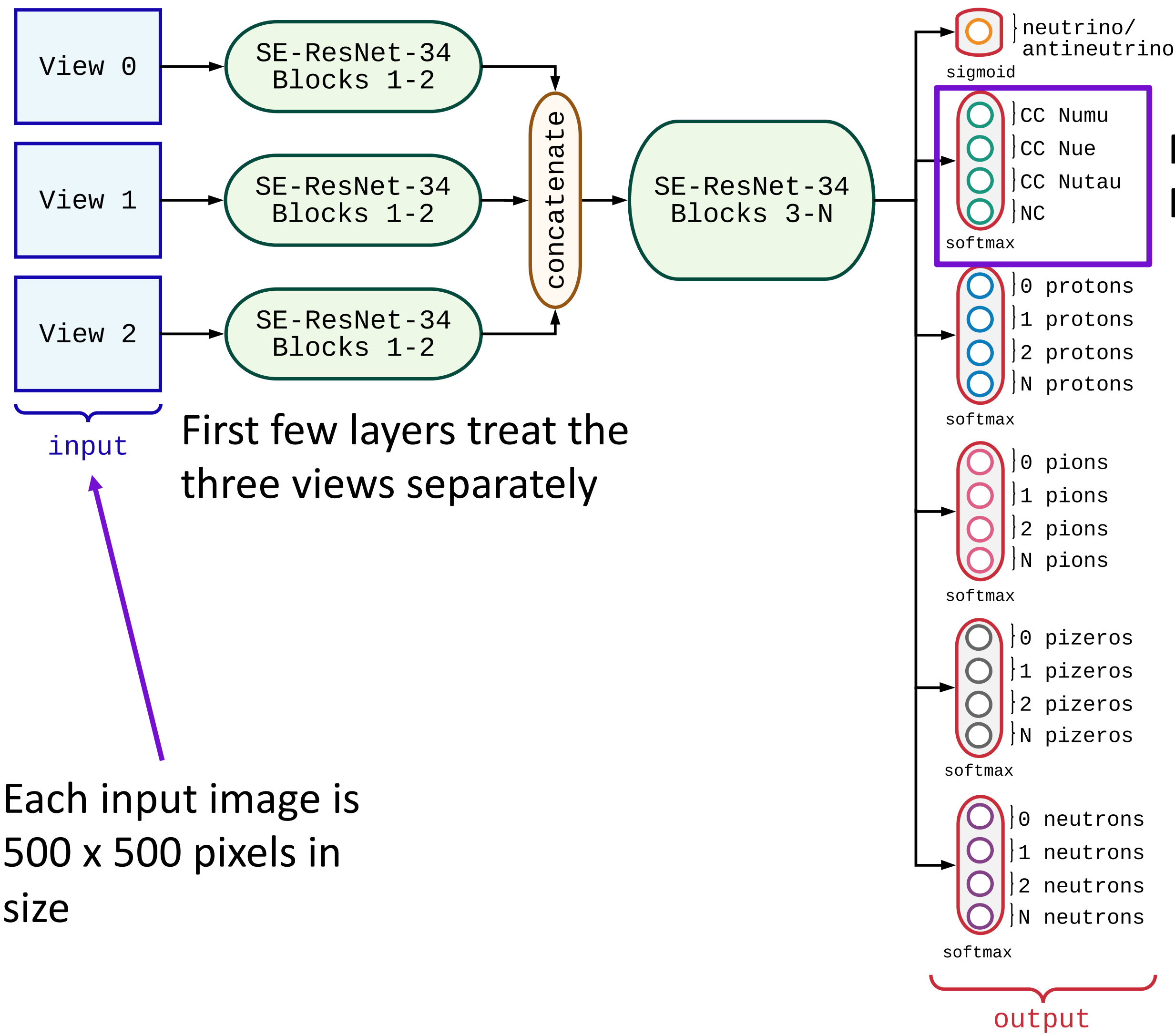


  - Helps preserve the fine-grained detail deeper into the network.

[1] H. Kaiming et al., Deep residual learning for image recognition, CoRR, arXiv 1512.03385, 2015

[2] J. Hu et al., Squeeze-and-Excitation Networks, arXiv 1709.01507, 2017

Architecture Overview



Primary output: Flavour identification

First few layers treat the three views separately

Each input image is 500 x 500 pixels in size

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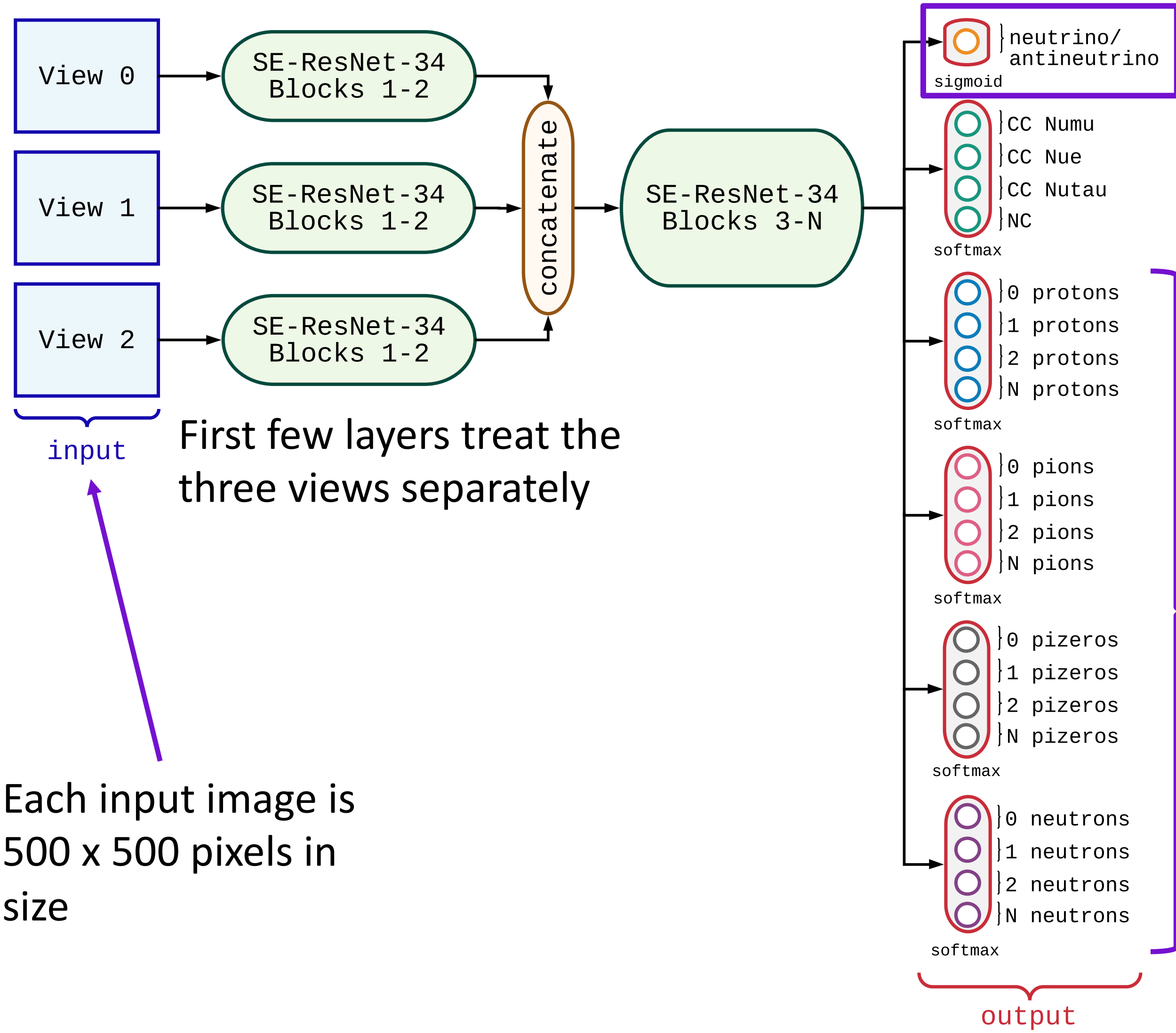

Neutrino / antineutrino

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Secondary outputs: Particle counting for exclusive final states

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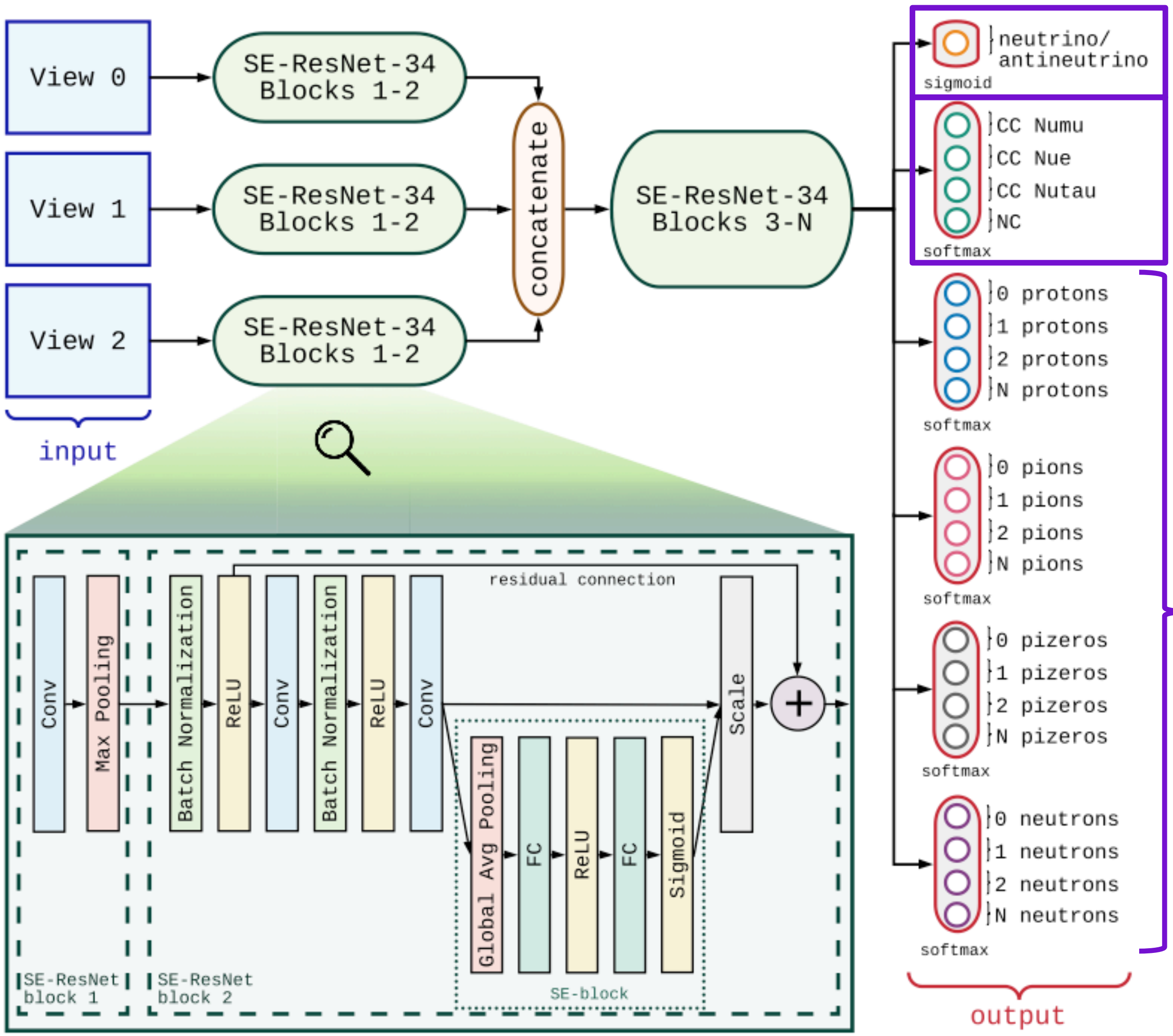


Neutrino / antineutrino

Primary output:
Flavour identification

Secondary outputs:
Particle counting for
exclusive final states

Training and using the CNN

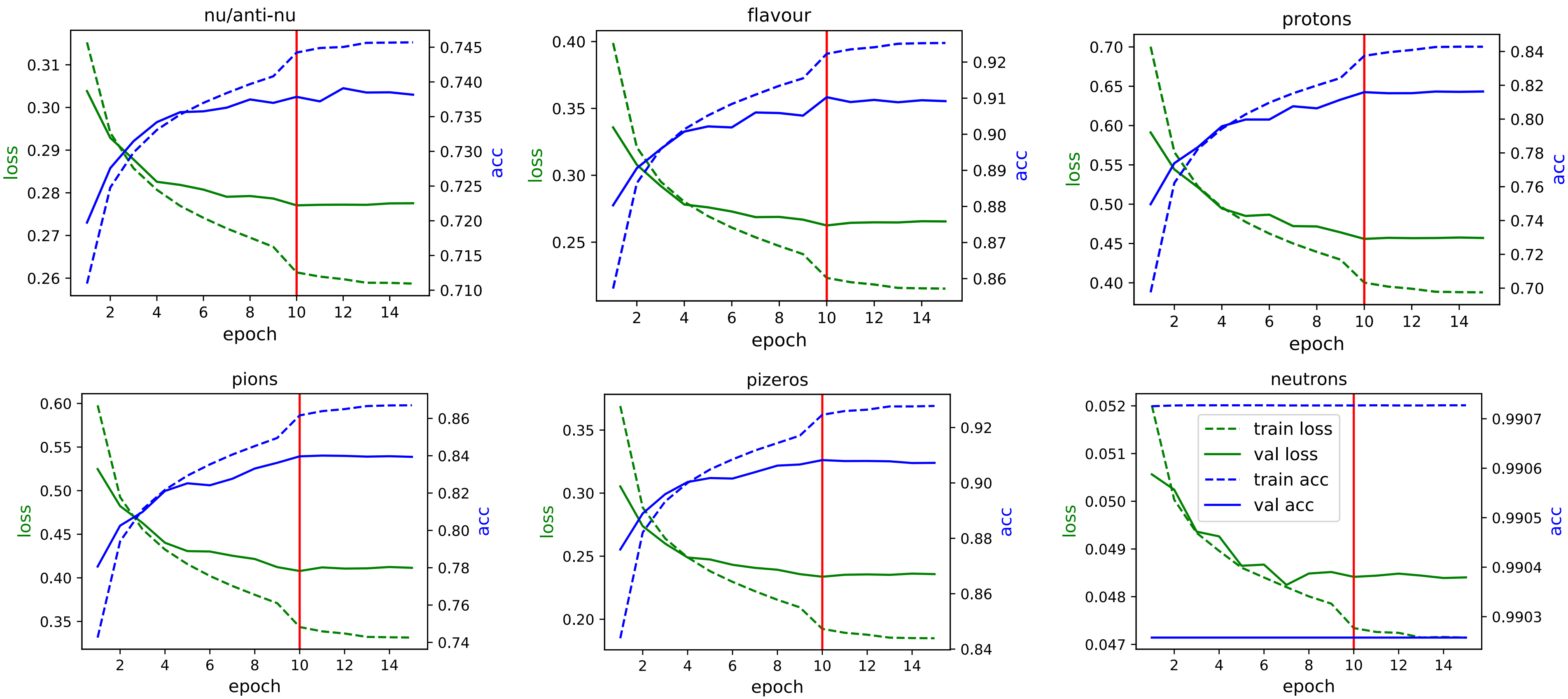
- Use millions of images (~10M images) of simulated neutrino interactions with the true neutrino flavour known.
  - Allows the CNN to learn the features of each type of neutrino interaction.
  - The CNN filters are not predefined – it needs to learn which filters to use to extract the information required to classify events.
  - Tested on a fully independent sample.

- Once the CNN is trained it is applied to images with no truth information attached – eventually the experimental data.

- The CNN gives probabilities for each event to be the following:
  - Charged-current ν_e, ν_μ, ν_τ and neutral-current (all flavours).
  - Outputs sum to one.
  - Use these probabilities for the event selection.

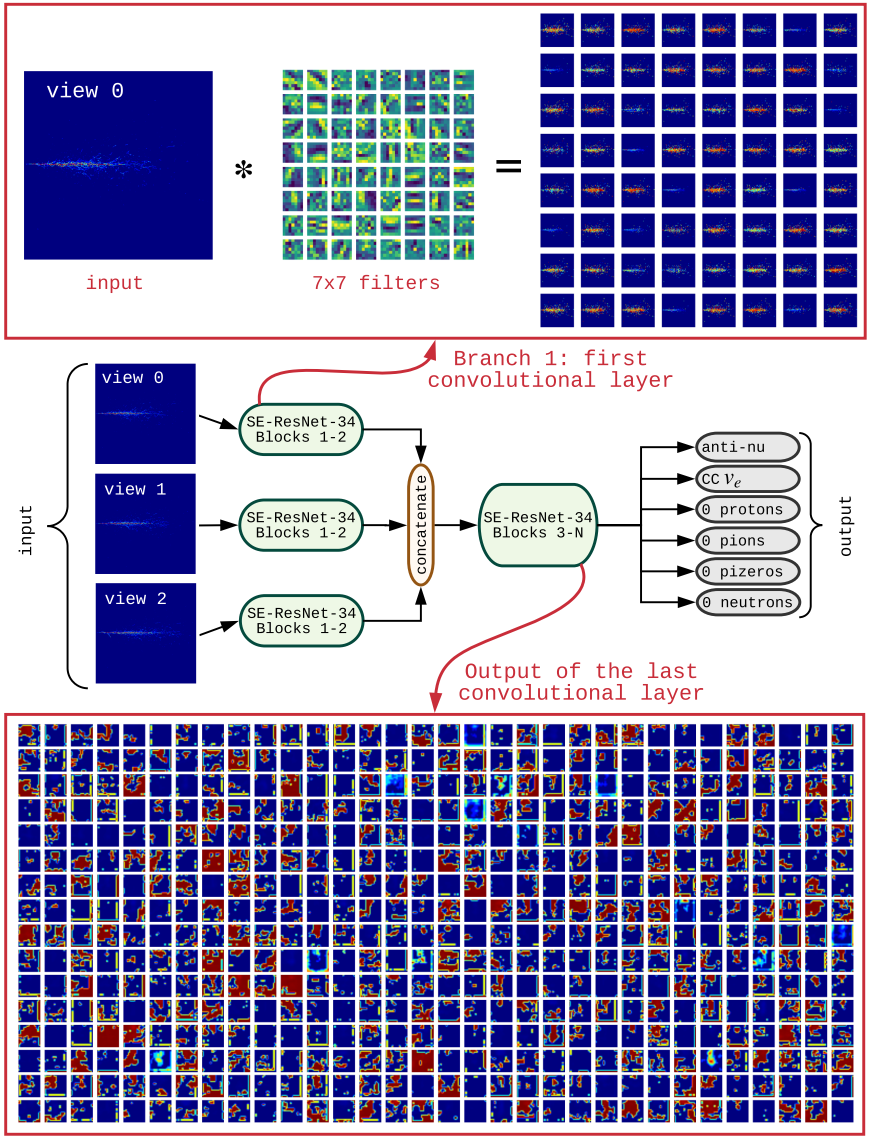
Training and using the CNN

- We have trained and tested the network on a very powerful machine (x8 NVIDIA Tesla V100 GPUs).
- Loss and accuracy:



Visualisations of the feature extraction

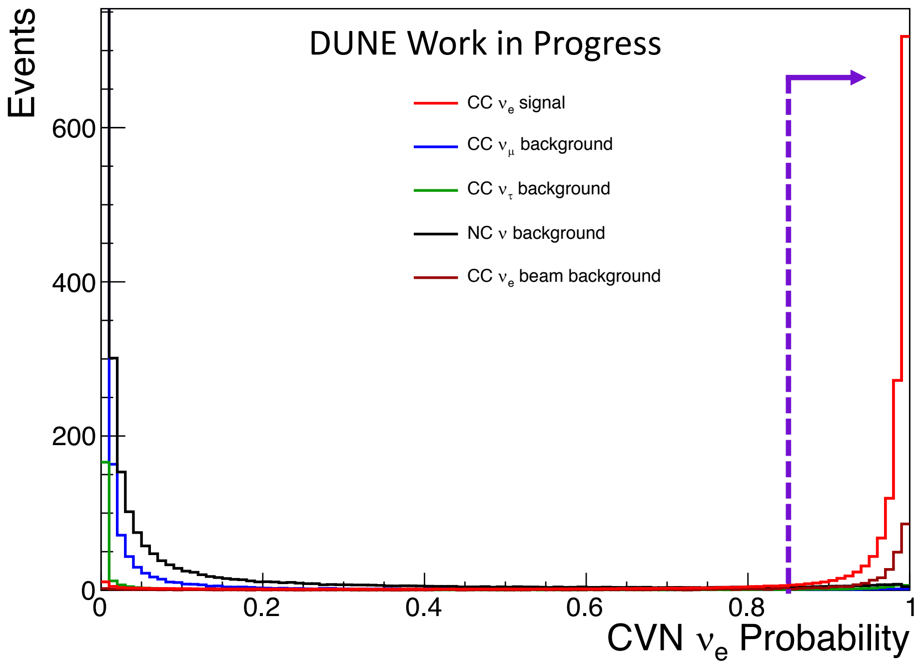
- Example: 12.2 GeV CC ν_e interaction.
- Top box demonstrates the output from the first convolutional layer of the first branch of the network.
- The bottom box shows the 512 feature maps produced by the network's final convolutional layer.



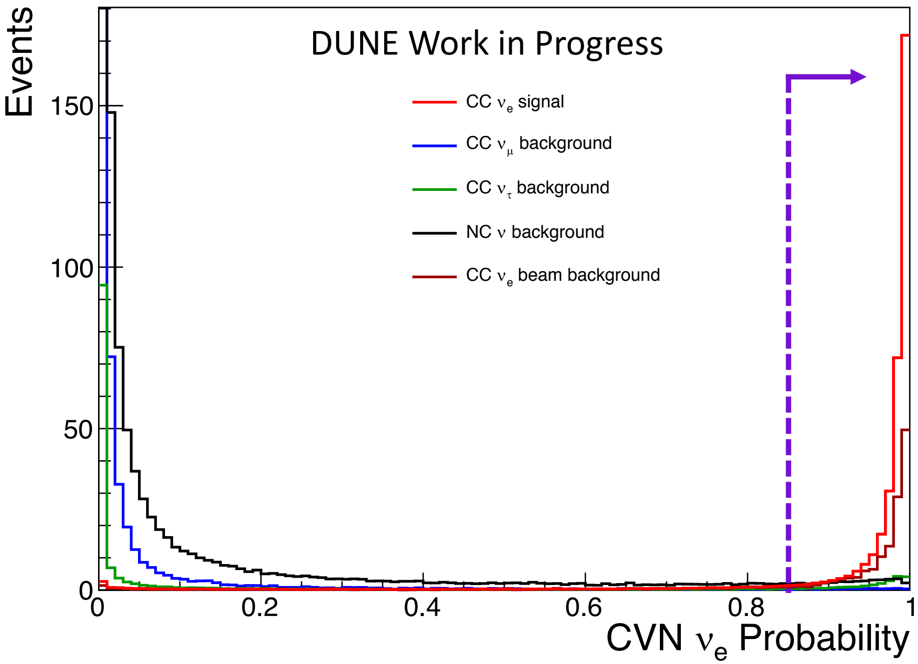
Selecting Electron Neutrinos

- Electron neutrino probability spectra from the DUNE CVN.
  - Curves combine neutrinos and antineutrinos.

Neutrino beam



Antineutrino beam



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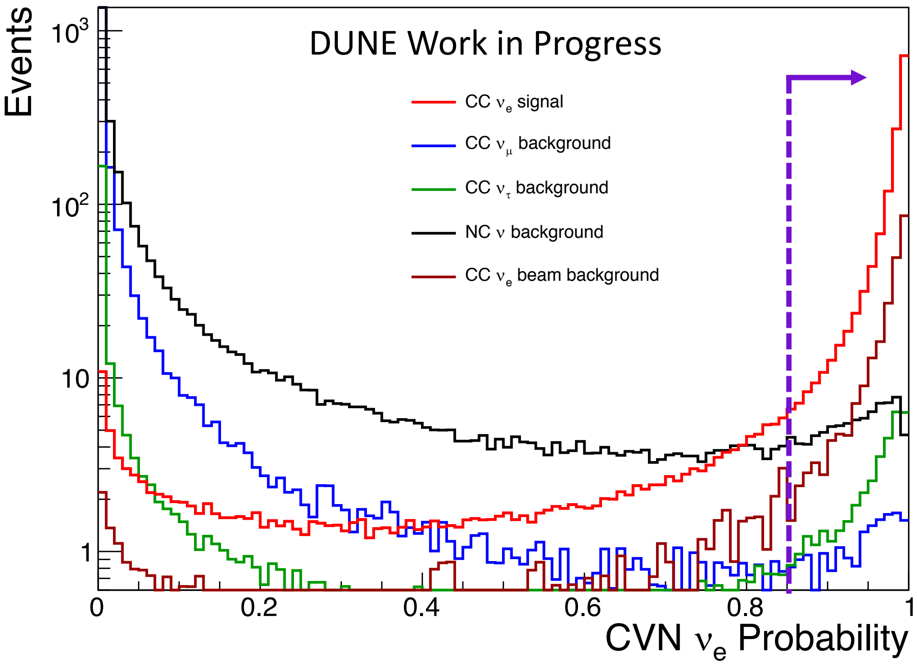

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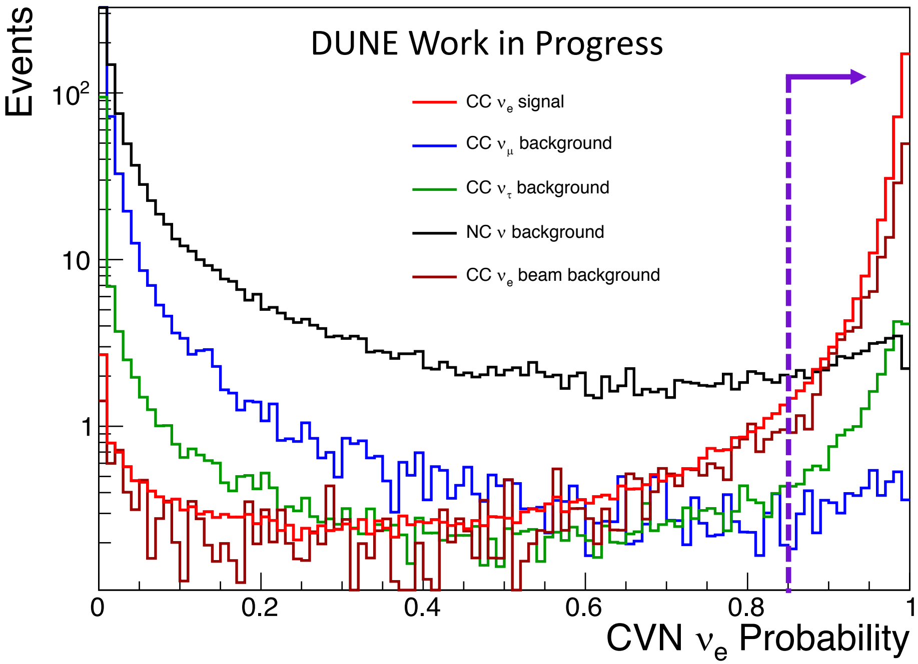
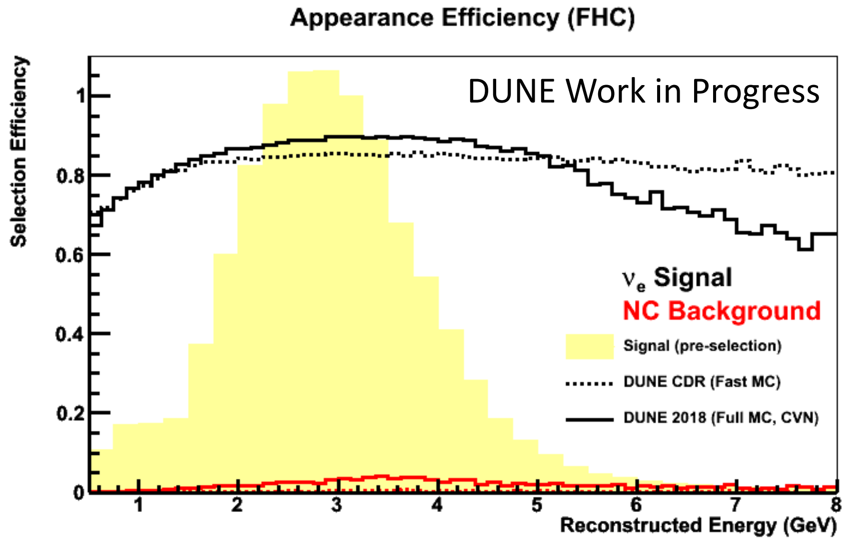
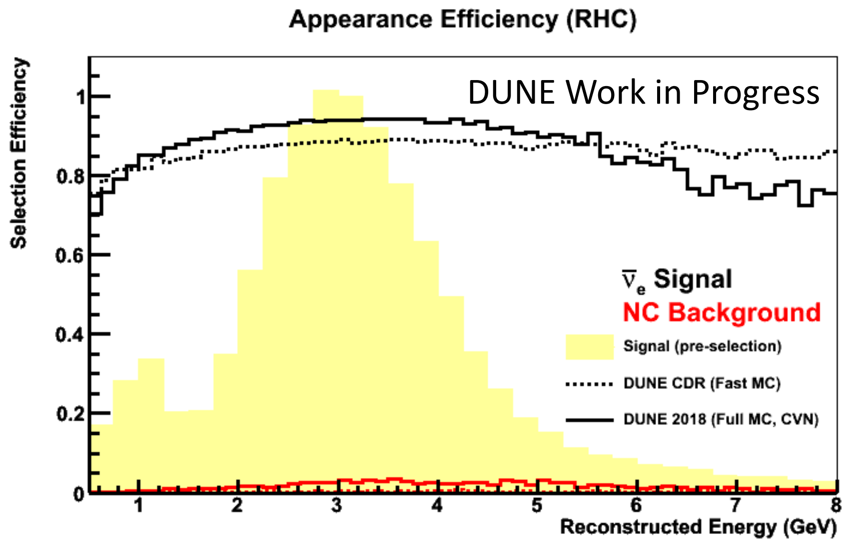


Electron Neutrino Efficiency

- Select all events that are more than 85% likely to be electron neutrinos.
- Over 90% selection efficiency in the flux peak.
- Efficiency better for antineutrinos due to typically cleaner final state (neutron instead of proton).

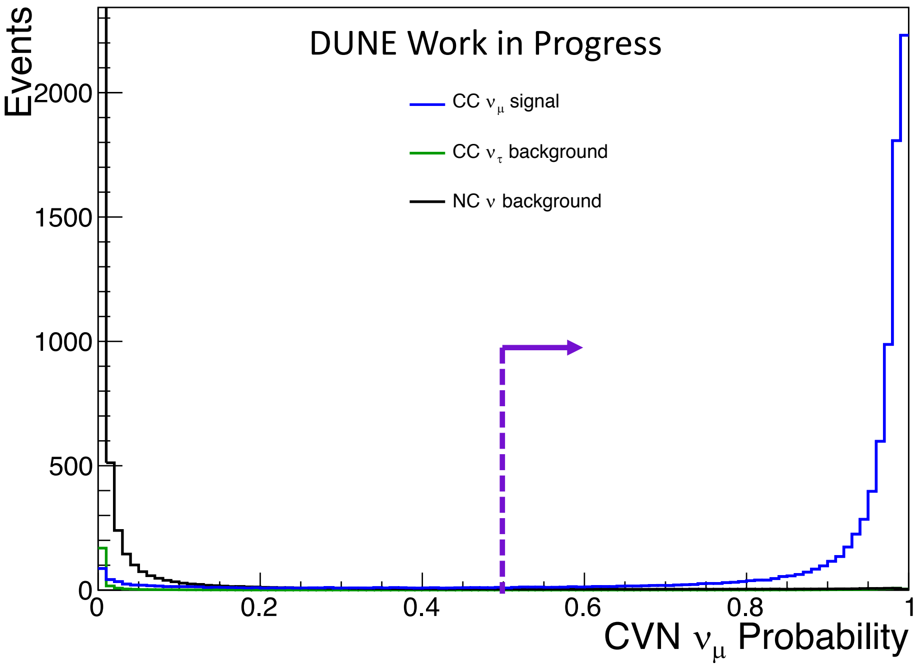




Selecting Muon Neutrinos

- Muon neutrino probability spectra from the new CVN.
  - Curves combine neutrinos and antineutrinos.

Neutrino beam



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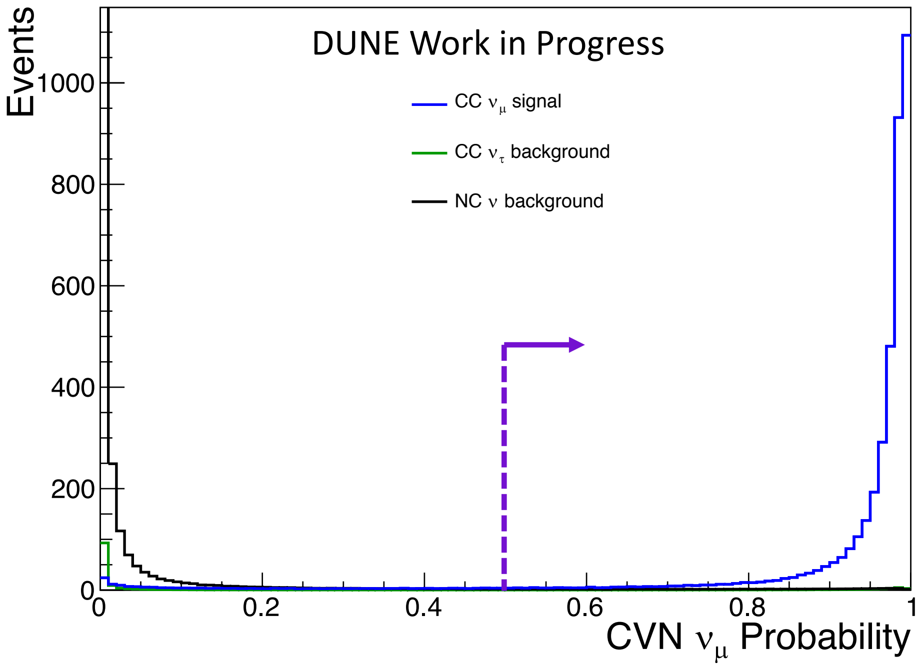

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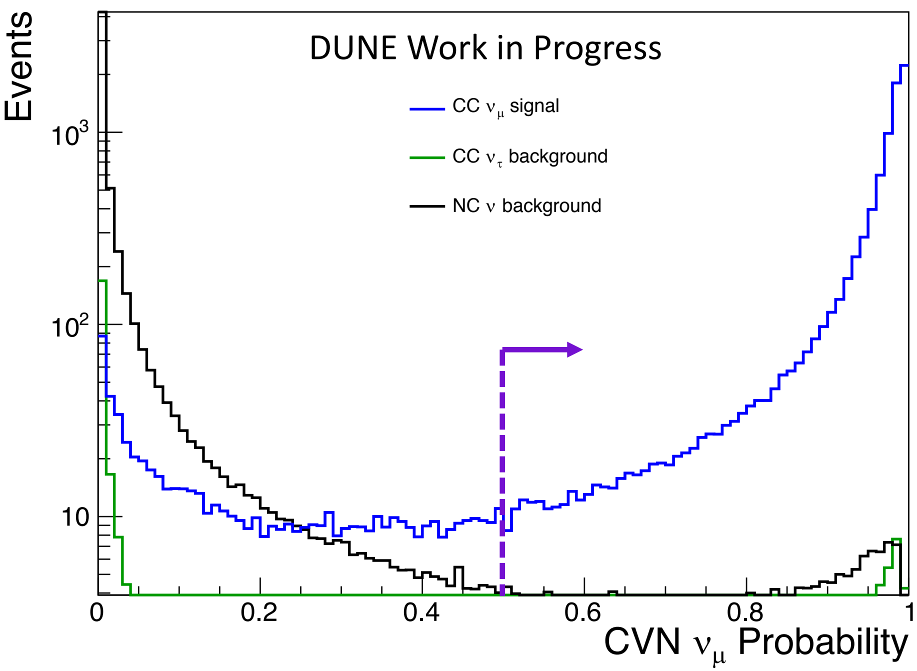
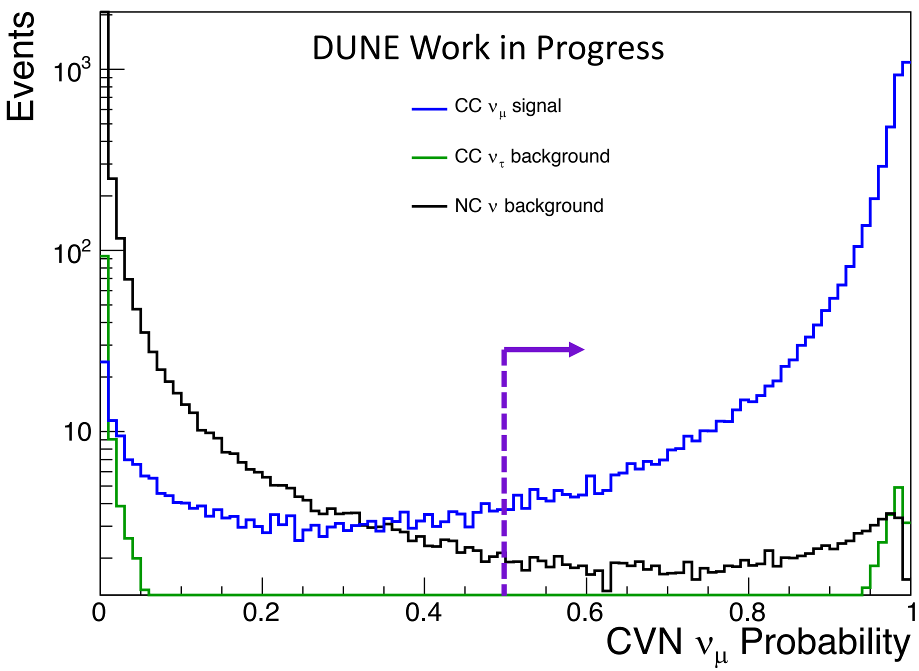


Antineutrino beam



Muon Neutrino Efficiency

- Select all events that are more than 50% likely to be muon neutrinos.
- Over 90% selection efficiency in the flux peak.
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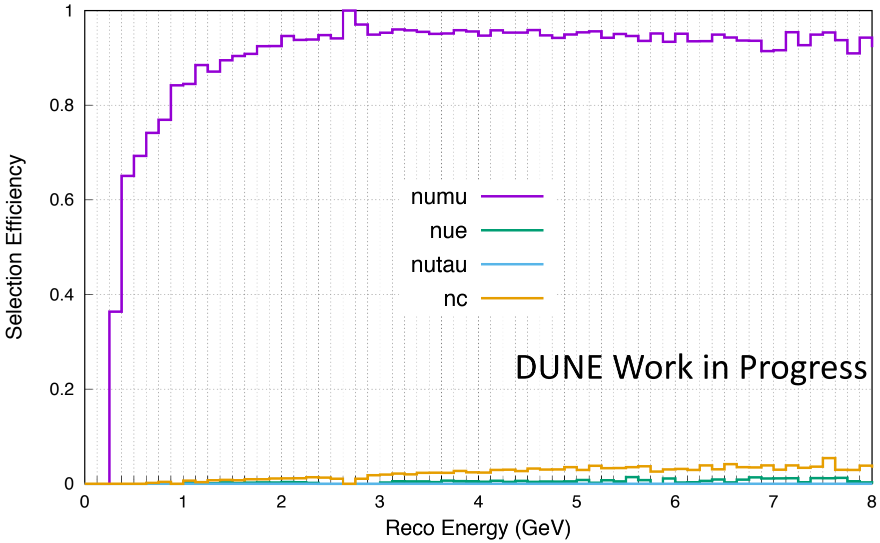
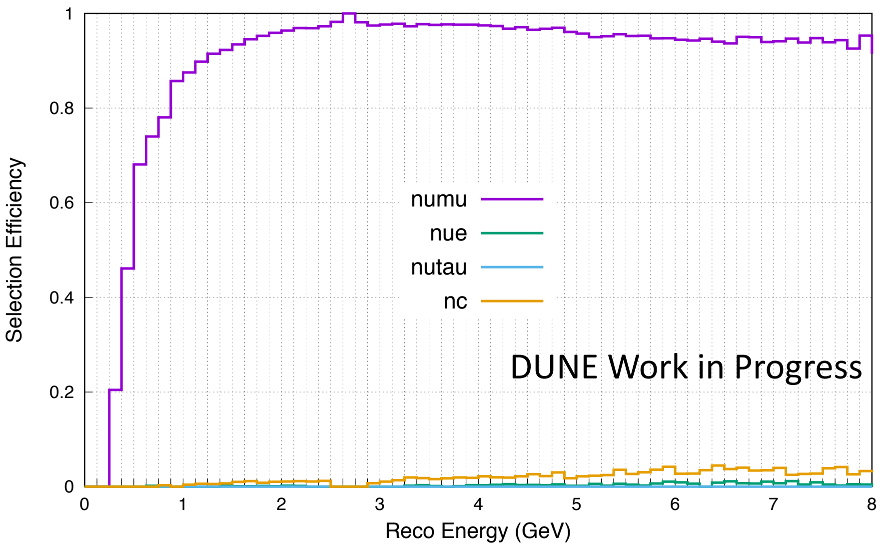
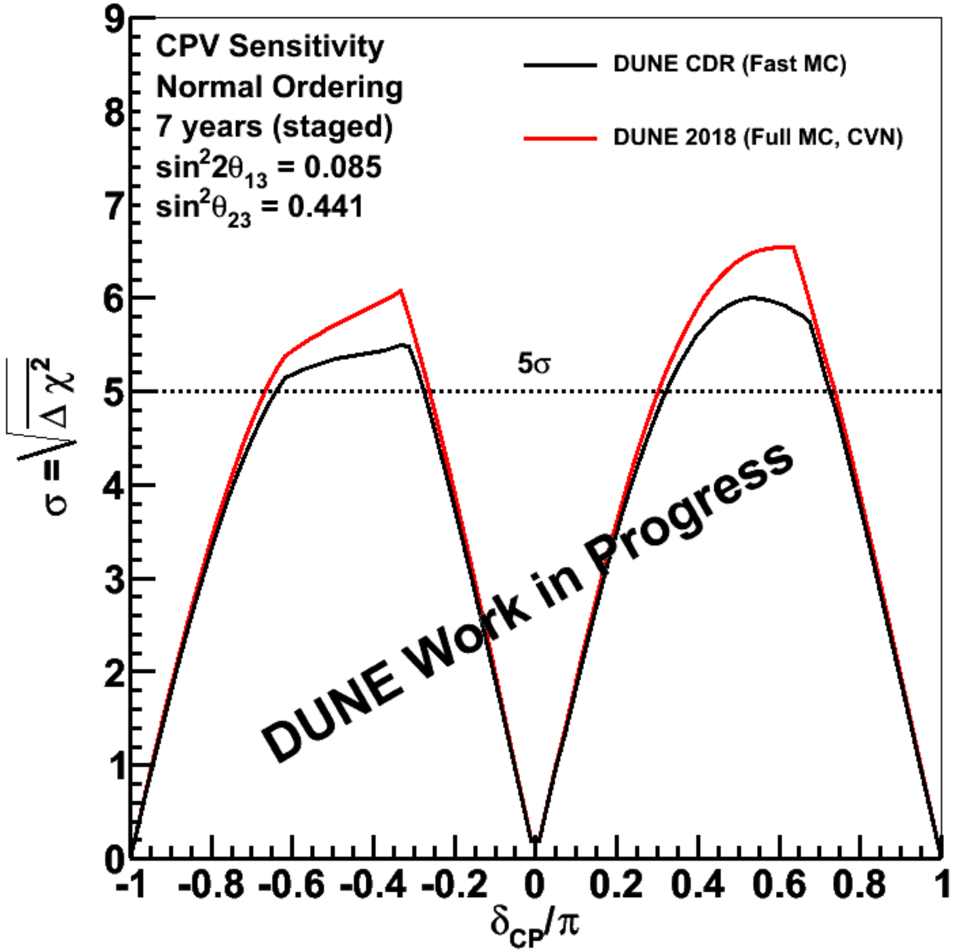




CP-Violation Sensitivity – Dec 2018

- Same selection criteria:
  - ν_e selection: $P(\nu_e) > 85\%$.
  - ν_μ selection: $P(\nu_\mu) > 50\%$.
- Very large improvement over the previous CVN.
- Exceeded the DUNE conceptual design report sensitivity.
  - Very big milestone for DUNE!



Robustness

- We will use protoDUNE to test the CVN on real data.
  - There are no neutrinos at protoDUNE, but we can use single particle. extracted from events to approximate simple neutrino interactions.

- Select individual reconstructed objects and pass into the CVN.
  - Cosmic muon tracks mimic CCQE ν_μ interactions.
  - Beam electron showers mimic CCQE ν_e events.
  - The CVN should return classifications of CC ν_μ and CC ν_e with no hadronic system, respectively.

- We will also use fake data studies to ensure robustness against systematic effects, including those from alternative event generators.

Summary

- The DUNE CVN provides powerful neutrino interaction flavour classification.
  - Hope to demonstrate good performance of exclusive final-states in the coming months.

- ProtoDUNE provides an excellent opportunity to test the CVN on data using single particles to mimic simple neutrino interactions.

- Further improvements will provide diminishing returns on the experimental sensitivity.
  - The focus now shifts to ensuring robustness and equal performance when applied to data and simulation.