FAQ for PHAS0056 Neutrino Event Classification mini-project

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1 Physics background

1.1 What are neutrinos?

Neutrinos are electrically-neutral particles, which are almost massless. Like electrons, they fall into the lepton family of particles. As far as we know, there are three 'flavours' of neutrino (ν_e, ν_μ and ν_τ), each paired with a charged lepton: the electron (e^-), or one of its heavier siblings, the muon (μ^-) and tau (τ^-). As neutrinos are neutral, they are invisible to particle detectors. Instead, we detect them when they interact with the material in the detector. Neutrinos interact only extremely rarely, by so-called *weak* processes. These fall into two categories: *charged-current (CC)* processes, where the neutrino is turned into its charged partner (for example, a muon-neutrino ν_μ turns into a muon μ^-), or *neutral-current (NC)*, where the neutrino scatters but remains as a neutrino (and does not change flavour). In a charged-current interaction, to balance charge, a neutron in the nucleus will also be converted to a proton.

1.2 What is the NOvA experiment?

This project is looking at simulated data similar to that produced by the NOvA detector (https://novaexperiment.fnal.gov). NOvA, based at Fermilab in the USA, studies a phenomenon called neutrino oscillations (neutrinos changing flavour in flight). This is exciting because it is the only process that's been observed to break the Standard Model of particle physics, the complicated differential equation that explains how all matter and forces in the universe behave and interact at a fundamental scale.

NOvA uses a beam mainly of muon neutrinos, with energies of a few gigaelectronvolts (GeV). However, the complex multi-step process involved in creating a neutrino beam means that the beam has a broad spectrum of energies, and that as well as ν_μ particles, the beam will include some ν_e component, as well as some antineutrinos, $\bar{\nu}_\mu$ and $\bar{\nu}_e$. In the images you see, the beam is travelling in the z direction. That means that in both images, the neutrino beam is coming from the left of the image. One of the pictures shows what you would see if you looked at the detector from above, and the other shows what it would look like from the side.

The NOvA detector is filled with instrumented tubes filled with liquid scintillator. This is an organic molecule, mainly consisting of carbon atoms. Thus you'll mostly be studying what happens when neutrinos interacting with carbon nuclei.

2 Metadata

2.1 What are QE, RES and DIS interactions?

Nucleons (protons and neutrons) and not fundamental particles - they are composed of quarks and gluons. Because of this, neutrinos can interact with nucleons in different ways. Thus something like a charged-current interaction actually refers to a set of different interaction types: quasi-elastic (the simplest interaction, at lowest energies: $\nu_\mu + n \to \mu^- + p$), resonant (where the nucleon is excited to an unstable 'resonant' state, which then decays) or deep inelastic scattering (where the nucleon is broken up, and the neutrino scatters from a quark inside it). For task 1, your signal will correspond to all the types of CC ν_μ interactions, so you will need to include multiple options from this list. In task 2, you'll be able to investigate how well your classifier can identify these individual states.

2.1.1 What is the simple way to think about QE, RES, and DIS?

It isn't completely correct but a reasonable way to think about the interaction modes is:

- QE: Clean event, normally just two tracks
- RES: Something in the middle
- DIS: Messy event potentially many tracks and showers

2.2 What do the final states mean?

The final state refers to what is left after the neutrino interaction takes place. When charged particles move through the NOvA detector, they leave distinctive patterns of energy deposits or 'hits'. These can be used (with varying levels of accuracy) to identify the particles produced by the interaction. Different types of particles tend to produce different patterns of hits: for example, muons often make long, straight *tracks*; protons and charged pions make shorter tracks, while electrons, photons, and neutral pions can (through their decay processes) generate electromagnetic *showers*, wider cone-like patterns of energy deposits. We use these tracks and showers to 'reconstruct' the particles in the final state - in other words, to identify their flavours and measure their energies.

2.3 What do neutrino energy and lepton energy refer to?

The neutrino energy refers to the true energy of the simulated incoming neutrino. When that neutrino interacts it will always produce a final-state lepton. In the case of a neutral-current interaction, that lepton will be the scattered neutrino. In the case of a charged-current interaction, it will be the neutrino's charged-lepton partner. Note that if the incoming particle is an antineutrino, the outgoing lepton will also be an antiparticle. So an electron antineutrino $\bar{\nu}_e$ undergoing a charged-current interaction will produce a positron e^+.

3 Task wording questions

3.1 What do you mean by "ν_μ charged-current events"?

The easiest way to think about this is to look at the interaction variable. If the interaction variable is 0, 1, 2 or 3 then it is a ν_μ charged-current events. For Task 1 you could define a Boolean (True or False) variable and make a binary classifier that takes in a pair of images and returns 1 if the image is a ν_μ charged-current events and 0 if it is not.

3.2 What does "Test your machine learning classifier and investigate how the efficiency of the classifier depends on the meta data variables shown above" mean?

In Task 1 you should have made a binary event classifier that classifies images as being ν_μ charged-current or not. In Task 2 we want you to investigate how well your classifier works. The dataset is an ensemble of different energies, different interaction types, different final state types, different vertex positions, etc. The types of question that you might want to address in this task are:

- How should I define the performance of my classifier? (think false-positives vs false-negatives)
- Does my classifier perform as well on DIS (i.e. messy) events as it does on QE (i.e. clean) events?
- Does my classifier perform as well on low energy neutrinos as it does on high energy neutrinos
- Does my classifier perform well on low energy muons as it does on high energy muons
- Which variables in the metadata does my classifier performance depend on, and what does that mean?

4 Miscellaneous Questions

4.1 Do I have to use all 200 data files?

No, you do not. But probably the 7000 events in the single file won't provide sufficient images to fully train a network to optimal performance. Also when you start investigating the multidimensional metadata, you might find that you quickly run out of statistics in certain regions of phase space.