To CCQE and Beyond: characterising neutrino interactions for next generation oscillation experiments.

Project description

Focus: Neutrino interaction physics
Requirements: Familiarity with ROOT, the neutrino interaction lectures
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In order to determine the neutrino mass hierarchy and the extent of CP-violation generated in the neutrino sector using accelerator-based neutrino oscillation experiments, the systematic uncertainty on future measurements must be constrained to within a few percent. Perhaps the most challenging difficulty in achieving such precision stems from our naivety of few-GeV neutrino-nucleus interactions. In this project you'll design measurements to overcome this challenge.

We will assume someone has invented (and paid for us to build) an almost perfect detector. It's got perfect resolution, no tracking thresholds and a flawless ability to identify particle type. We will put in the T2K off-axis beam and expect our first analyses to have around 500,000 charged-current muon neutrino interactions to work with (and we'll say this is a scintillator detector, so you get a CH target). You will be given a handful of different simulations of what the detector might see.

The simulation files are available at this cernbox link. These include simulations using the NuWro, NEUT and GENIE Monte-Carlo event generators, which each have different interaction models, nuclear ground states and FSI strengths (but I won't tell you which is which!), each formatted as an easy-to-read ROOT tree. There are a lot of variables in each one, but you should only worry about the ones I list below:

1. `Mode`: this gives the interaction mode for each event in NEUT's enumeration scheme (other generators schemes have been converted to match this). The definition of each mode can be found here.
2. `Enu_true`: the incoming neutrino energy for each event. Note the neutrino is always going along the z-axis.
3. `Nleptons/Nprotons/Nneutrons/Npiplus/...`: The number of each particle type in the final state of the interaction.
4. `pmu_4mom`: the outgoing muon's four momentum expressed as a `TLorentzVector`.
5. `hm_*_4mom`: The four momenta of the highest momentum hadron of each type in the final state. Ignore the `hm_*_4mom_vect` variables.
6. `shm_proton_4mom`: The four momenta of the second highest momentum proton in the final state. This might be useful for 2p2h identification.
7. `Erecoil_true`: The energy deposited by all particles in the final state.
8. `flag*`: Alternative ways of flagging particular final state interaction modes or topologies. You can always do the same thing using the other variables I listed, but these may be convenient.

Our “almost-perfect” detector’s data will be able to tell us 3.-7., whilst 1.-2. are just to help you understand how observable quantities correspond to the fundamental interactions. Your aim will be to use these files to design measurements we could make to investigate the sources of systematic uncertainty most important for future oscillation analyses. For example:

- Can you separate 2p2h (Mode==2) from other processes consistently in each simulation? If not, why not?
- Similarly, can you distinguish resonant pion production (Modes 11,12,13) from shallow/deep inelastic scattering (Modes 23 and 26)?
- Can you determine the nuclear structure in each simulation: the Fermi motion shape and removal energy? Bonus points if you can tell which of the simulation uses a nuclear shell model!
- Can you come up with a way of determining when there are final state interactions and how strongly they alter hadron kinematics?

As a simple example we might think of separating 2p2h from other interactions by looking for two protons and no other hadrons in the final state alongside a restriction on the outgoing muon kinematics:

```
FlatTree_VARS->Draw("pmu_4mom.Vect().Mag()>>hall(10,0,2000)", "flagCC0pi==1 && Nprotons==2 && pmu_4mom.Vect().CosTheta()>0.9", "")
FlatTree_VARS->Draw("pmu_4mom.Vect().Mag()>>hqe(10,0,2000)", "flagCC0pi==1 && Nprotons==2 && pmu_4mom.Vect().CosTheta()>0.9 && Mode==1", "same")
FlatTree_VARS->Draw("pmu_4mom.Vect().Mag()>>h2p2h(10,0,2000)", "flagCC0pi==1 && Nprotons==2 && pmu_4mom.Vect().CosTheta()>0.9 && Mode==2", "same")
FlatTree_VARS->Draw("pmu_4mom.Vect().Mag()>>hpiabs(10,0,2000)", "flagCC0pi==1 && Nprotons==2 && pmu_4mom.Vect().CosTheta()>0.9 && Mode>2", "same")
```

The resultant plot is shown in Fig. 1. We do a reasonable job of reducing the QE component and almost totally exclude the pion absorption FSI contribution, but we can certainly still do better (hint: what might we expect the proton momentum and opening angle to be? Can we make use of transverse kinematic imbalances?).

If you manage to gain sensitivity to these key aspects of neutrino interactions, what information are you relying on the detector to give you? Could this be accessible in a realistic detector?

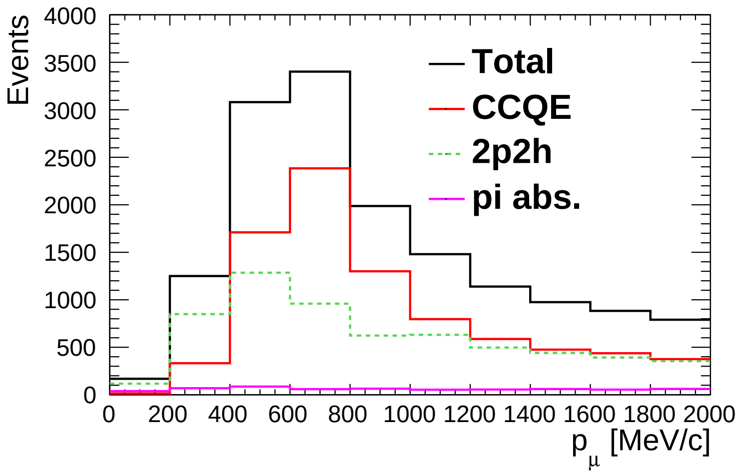

Figure 1: An example attempt at separating 2p2h from other interaction modes.