Neutrino Interaction School 2021

Worksheet for Lecture 1: Introduction to Neutrino Interactions
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Welcome to the DUNE Summer School! This worksheet designed to be used as a companion to the "Introduction to Neutrino Interactions" presentation. If you're not able to attend the DUNE school in real time, you can watch a recording of the presentation and download the slides from our indico page, https://indico.fnal.gov/event/48900/. The questions and puzzles in this worksheet will refer to slide numbers in that presentation. Note that, because the presentation is designed to be given in real time, it includes some animated slides. If you are using a PDF copy of the presentation, the slide number (at the bottom of each slide) will not necessarily match the page number in the PDF.

During the live presentation, the **exercises** are designed to be done in small teams, to give a chance for group discussion. The short **questions** will be asked in the class. There's a space here to fill in your answers.

A solution sheet is also available so you can compare your answers with ours.

Exercise 1 (*lecture slide 3*)

This is a warm-up exercise, to remind yourself about some of the particles we'll be talking about in the presentation. *Expected time: 10 minutes.*

Particle		Charge	Spin	Is it a…?						Constituents
				Boson	Fermion	Lepton	Hadron	Meson	Baryon	
Electron	e^-									
Muon	μ^-									
Electron-neutrino	ν_e									
Muon-neutrino	ν_μ									
Positron	e^+									
Proton	p									
Neutron	n									
Photon	γ									
Pion (3 of them)	π									
W (weak force carrier: 2 of them)	W									
Z (weak force carrier)										
Delta-1232 resonances (4 of them)	Δ									

Exercise 2 (*lecture slide 8*)

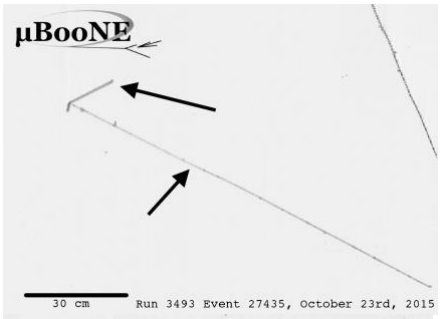
I claim that all DUNE needs to do to search for CP-violation and other neutrino oscillation properties is to:

1. **Plot the energies of all the muon-neutrinos at Fermilab**
2. **Plot the energies of all the electron-neutrinos at SURF**
3. **Take the ratio of those two plots**

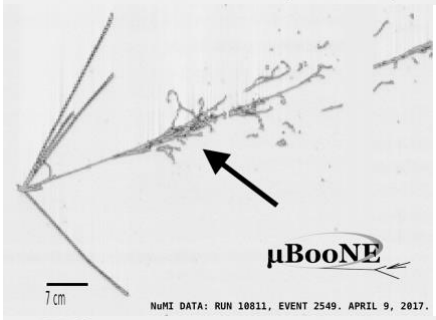
Unfortunately, there are several things that make this rather a challenge! Can you think of any reasons why this approach is too simplistic? *(Expected time: 5-10 minutes)*

Exercise 3 (lecture slide 13)
What particles do you think are in these event displays? *Expected time: 5 minutes.*

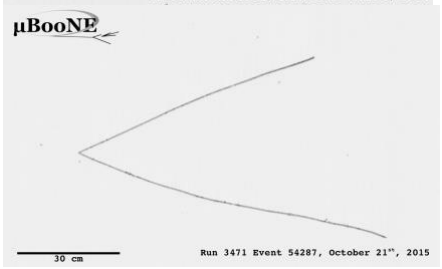
a)



b)



c)

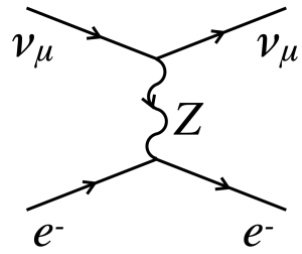


In each of these diagrams, there's also a neutrino. In each diagram, what flavor is the neutrino? Where do you think it is coming from and where does it interact?

Quick Question 1: *(lecture slide 14)*
Draw a charged- and neutral- current vertex for neutrino scattering. Which helps you tell the neutrino flavor?

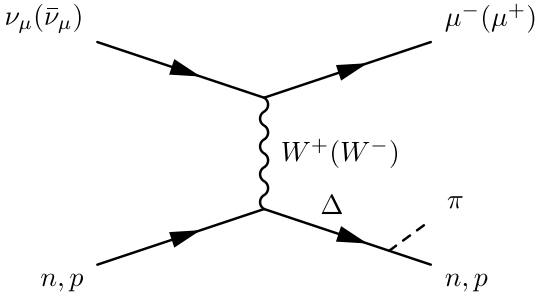
Exercise 4 *(lecture slide 18)*

Here's a diagram for neutral-current ν_μ scattering from an electron. i) Can you draw the ν_e-e^- equivalent? ii) Can you find another ν_e-e^- diagram that gives an identical final state to the one you drew in i)?



Exercise 5 *(lecture slide 31)*

This is the Feynman diagram for pion production through a Δ resonance:



Both neutrinos and antineutrinos can scatter from both neutrons and protons. There are four possible delta resonances. Can you write down the equations for all the allowed neutrino and antineutrino resonant scatters? (Hint, you should find three for each.)
(Expected time: 5 minutes)

Quick Question 2: *(lecture slide 35)*

In deep inelastic neutrinos scatter from an individual quark. In a charged-current interaction, which quarks will neutrinos and antineutrinos interact with?

Quick Question 3: *(lecture slide 41)*

The equations for CCQE neutrino and antineutrino scattering from a single nucleon are:

$$\nu_\mu + n = \mu^- + p \qquad\qquad \bar{\nu}_\mu + p = \mu^+ + n$$

What final states would you expect to see for 2p2h CCQE scattering of ν_μ and $\bar{\nu}_\mu$?

Exercise 6 *(lecture slide 48)*

Match the interaction to the final state *(Estimated time: 5 mins)*

Interaction	**Final state**
ν_μ quasi-elastic scattering	μ^- and 1 proton
$\bar{\nu}_\mu$ quasi-elastic scattering	μ^- and 2 protons
ν_μ 2p2h from an n-p pair	μ^- and hadron shower
ν_μ 2p2h from an n-n pair	μ^+ and 1 neutron
$\bar{\nu}_\mu$ 2p2h from a p-p pair	μ^-, 1 proton, 1 π^0
ν_μ resonant scattering	μ^+, 1 proton, 1 π^-
$\bar{\nu}_\mu$ resonant scattering	μ^-, 1 proton, 1 π^+
ν_μ DIS	μ^-, 1 neutron, 1 proton
	μ^+, 1 neutron, 1 proton

Exercise 7 *(lecture slide 51)*

Match the interaction + FSI options that can produce each final state. Note other final states are also possible. *(Estimated time: 10 mins)*

Interaction	**FSI**	**Final state**
ν_μ quasi-elastic scattering	No FSI	μ^- + 1 proton
$\bar{\nu}_\mu$ quasi-elastic scattering	Elastic scattering	Muon (charge unknown) + 1 proton
ν_μ resonant scattering	Charge exchange	μ^- + 2 protons
$\bar{\nu}_\mu$ resonant scattering	Pion production	μ^- + neutron + 1 π^+
ν_μ MEC	Pion absorption	μ^- + 1 proton + photons
	Nuclear de-excitation	

Quick Question 4: *(lecture slide 59)*

What do neutrino and electron scattering have in common? What are the differences?

Quick Question 5: *(lecture slide 59)*
We asked these questions at the start. Can you think of any answers?

Why are neutrino interactions important?

What do we know about interactions?

What do we still need to understand better?

How are we trying to understand neutrino interactions?