2 Using the Fermilab NuMI Beam for NOνA

2.1 The NuMI Beam

The NOνA project will upgrade the existing NuMI neutrino beam [1] to accommodate intensities of 700 kW. The NuMI beamline brings 120 GeV protons extracted from the Main Injector onto a 0.95 meter-long graphite target. Two parabolic magnetic horns focus the resulting secondary beam directing them toward the Soudan mine in northern Minnesota which houses the MINOS far detector. Neutrinos are produced from pion and kaon decay in an evacuated pipe 675 meters in length and 2 meters in diameter.

A unique feature of the NuMI neutrino beam is the ability to reconfigure the target and horn locations to produce neutrino energy spectra ranging in energy from 3 to 15 GeV on-axis. These configurations are illustrated in Figure 2.1, together with the spectra for three possible beam element arrangements, referred to as low, medium, or high energy beam tunes. Our calculations indicate that the medium energy tune will give the best performance for the NOνA experiment.

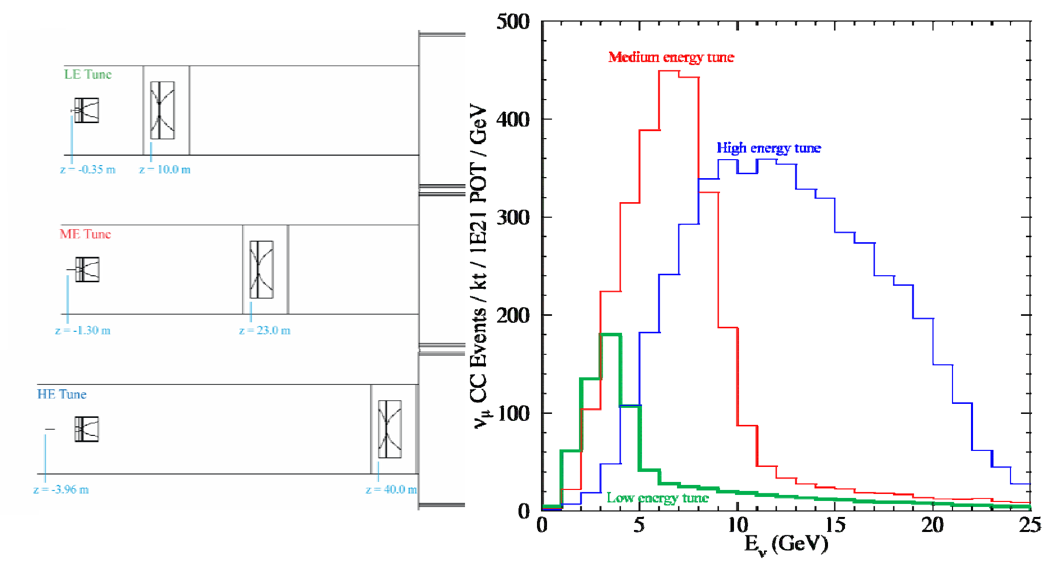

Fig. 2.1: Left: The locations of the target and second horn for the three NuMI beam configurations. Locations along the beam axis are referenced to *z=0* located at the front face of the first horn. The vertical scale is a factor 10 larger than the horizontal scale. Right: The expected neutrino interaction rates at the MINOS far detector site (on-axis at a distance of 735 km) for each of the three beam tunes.

2.2 Off-Axis Concept

The NOνA Far Detector will be sited 14.6 mrad off the NuMI beam axis, in contrast to the MINOS Far Detector which is sited on the center of the NuMI beam. The rationale for this choice is explained below.

In their rest frame, pions and kaons decay isotropically producing mono-energetic neutrinos. When these pions and kaons are boosted, the neutrino energy spectrum seen in the lab frame has a broad distribution, falling off as the angle between the boost direction and neutrino production angle increases. For small angles, the flux and energy of neutrinos produced from the decay $\pi \rightarrow \mu + \nu$ in flight and intercepted by a detector of area A and located at distance *z* are given in the lab frame by:

$$F = \left(\frac{2\gamma}{1+\gamma^2\theta^2} \right)^2 \frac{A}{4\pi z^2} \tag{2.1}$$

$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}, \tag{2.2}$$

where θ is the angle between the pion direction and the neutrino direction, E_π the energy of the parent pion, m_π the mass of the pion and $\gamma = E_\pi/m_\pi$. The expressions for neutrinos from the corresponding charged kaon decays are identical except that 0.43 is replaced by 0.96 resulting in a more energetic and broader distribution for identical meson energies.

The functions in Equations 2.1 and 2.2 are plotted in Fig. 2.2. The right portion of Fig. 2.2 shows that at 14 mrad the energy of the neutrino does not have a strong dependence on the energy of the parent pion. This is further demonstrated in Fig. 2.3, which shows the resulting number of neutrino events as a function of energy and off-axis angle. At 14 mrad, the medium energy beam produces a narrow energy beam with approximately five times more neutrinos at 2 GeV. This peak is well matched to the oscillation maximum which is expected to be 1.6 GeV for Δm_{32}^2=2.4 meV^2.

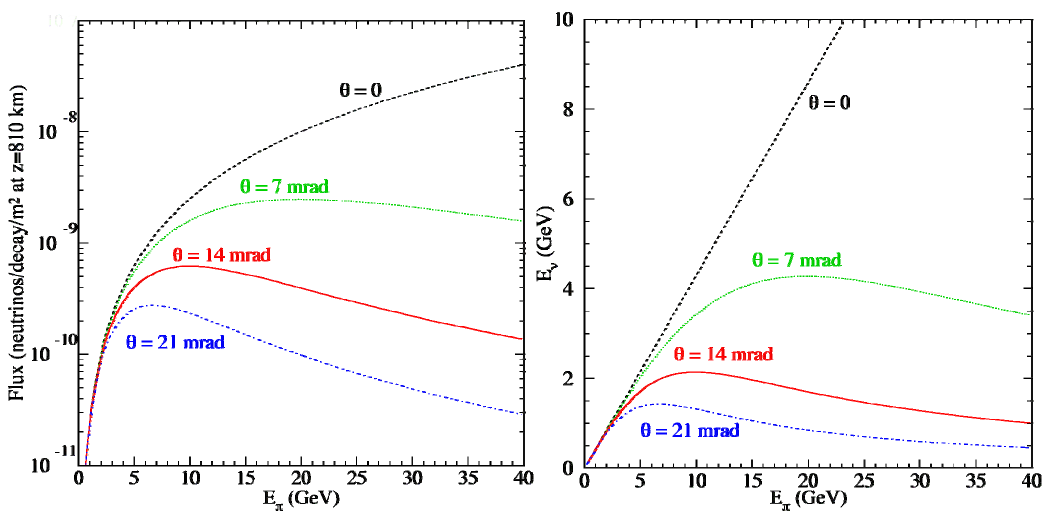

Fig. 2.2: Left: The neutrino flux from a pion of energy E_π as viewed from a site located at an angle θ from the beam axis. The flux has been normalized to a distance of 800 km. Right: The energy of the neutrinos produced at an angle θ relative to the pion direction as a function of the pion energy.

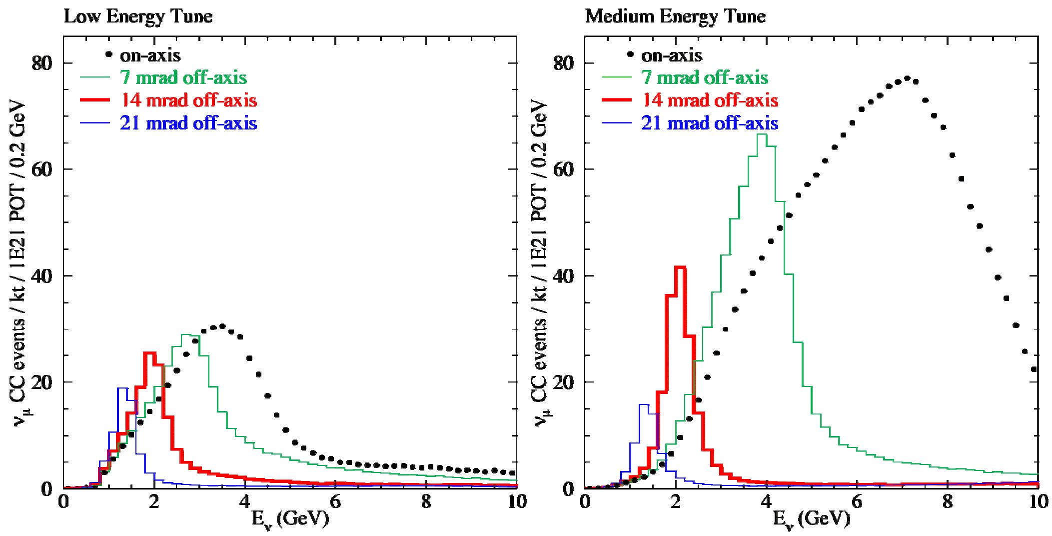

Fig. 2.3: Charged-current ν_μ event rates prior to oscillations calculated for a distance of 810 km from Fermilab and at various off-axis locations in the NuMI beam. The spectra are for the NuMI low-energy (left) and medium-energy (right) configurations.

In addition to the increased flux, the narrowness of the off-axis spectra enhances background rejection. One important source of background events are neutral-current events where the outgoing lepton (the neutrino) is not observed. The topologies of these events can fake the electron showers produced by ν_e charged-current events. As the neutrino carries much of the event energy away, the visible energies of neutral-current events tends to "feed down" to lower energies. In a wide band beam this feed down into the signal region is much larger than it is in a narrow band off-axis beam where the feed down tends to push the neutral-current events outside the signal energy window. Figure 2.4 shows the number of neutral-current events as a function of their visible energy, illustrating this effect.

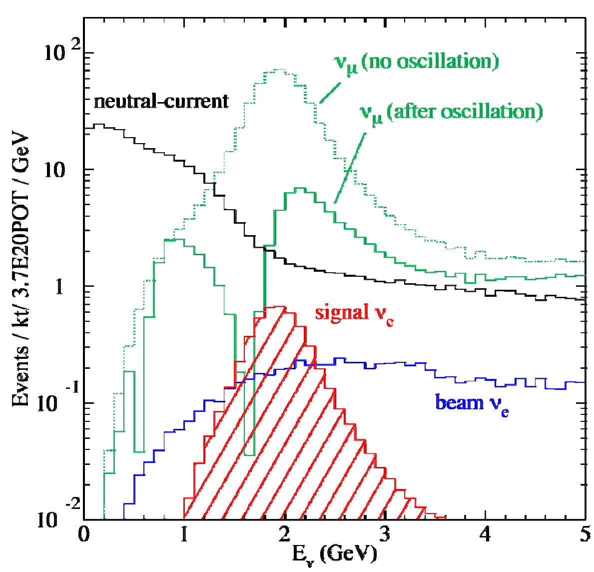

Fig.2.4: Simulated energy distributions for the ν_e oscillation signal, intrinsic beam ν_e events, neutral-current events and ν_μ charged-current events with and without oscillations. The simulation used $\Delta m^2_{32} = 2.5 \times 10^{-3}$ eV^2, $\sin^2(2\theta_{23}) = 1.0$, and $\sin^2(2\theta_{13}) = 0.10$. An off-axis distance of 12 km at 810 km was assumed.

Another important source of backgrounds to the electron-neutrino appearance search is the intrinsic ν_e component of the NuMI beam which arise from muon and kaon decay. As these neutrinos result from three-body decays they are more broadly distributed in energy than the ν_μ's produced by two-body decays. The spectra of the ν_e's in the NuMI beam off-axis are shown in Fig. 2.4. The relative narrowness of the off-axis ν_μ beam compared to the ν_e beam is an additional advantage of the off-axis approach.

2.3 The NuMI Beam in the Post -Tevatron Collider Era

The NuMI beam line is currently in its third year of operation. It has achieved periods of 192 kW average beam power with 2.5 x 10^{13} protons/spill and achieved a peak of 320 kW and 4.0 x 10^{13} protons/spill. As of the spring of 2007, approximately 3.1 x 10^{20} protons have been delivered to the MINOS experiment.

Fermilab is engaged in a staged program to increase the number of protons delivered to the NuMI target (see Table 2.1). The first stage of these upgrades is called the Proton Plan and has the goal of slip-stacking 9 batches in the Main Injector. The second stage of these upgrades is part of the NOνA project and the details are presented in Chapter 8. Once the NOνA work is completed, the Main Injector (MI) is expected to deliver 4.9 x 10^{13} protons every 1.3 seconds to the NuMI target, yielding a total power of 700 kW. Approximately 6 x 10^{20} protons can be delivered to the experiment per year, assuming a reasonable level of accelerator inefficiencies [2].

A possible next stage of accelerator and NuMI upgrades would bring the beam power to 1.2 MW. This design concept is called SNuMI (Super NuMI) and would use the Accumulator (currently part of the anti-proton source) to momentum stack 3 Booster batches prior to transfer to the Recycler. This plan would fill the Main Injector with 8.3E13 protons every cycle. Extraction of these pulses at a repetition rate of 1.333 s would increase the NuMI beam power to 1.2 MW, and deliver 10 x 10^{20} protons to the experiment in one year. Another possible upgrade path under study is the construction of an 8 GeV linear proton accelerator to replace the existing 8 GeV Booster [3]. Construction of this new accelerator, "Project X", would increase the MI power to 2.3 MW, doubling the protons on target available for NOνA.

	Present Operating Conditions (May 2007)	**Proton Plan Multi-batch Slip-stacking in MI**	**NOνA Multi-batch Slip-stacking in Recycler**	**Conceptual SNuMI Accumulator Momentum Stacking**	**Conceptual Project X linear accelerator**
8 GeV Intensity (p/Batch)	4.3 - 4.5x10^{12}	4.3x10^{12}	**4.3x10^{12}**	4.5x10^{12}	5.6x10^{13}
Number of 8 GeV Batches to NuMI	7	11	**12**	18	3
MI Cycle Time (sec)	2.4	2.2	**1.3**	1.3	1.4
MI Intensity (protons per pulse or ppp)	3.3x10^{13}	4.5x10^{13}	**4.9x10^{13}**	8.3x10^{13}	1.6x10^{14}
MI to NuMI (ppp)	2.45x10^{13}	3.7x10^{13}	**4.9x10^{13}**	8.3x10^{13}	1.6x10^{14}
NuMI Beam Power (kW)	192	320	**700**	1169	2314
Protons/year to NuMI	2x10^{20}	3x10^{20}	**6x10^{20}**	10x10^{20}	20x10^{20}
MI Protons/hour	4.95x10^{16}	7.3x10^{16}	**1.3x10^{17}**	2.2x10^{17}	1.0x10^{18}

Table 2.1: Present accelerator operating conditions and future upgrades. The Present Operating Conditions and Proton Plan values are given for mixed mode cycles including Collider running. The SNuMI and Project X columns are shown in lighter gray since they are conceptual and not part of the NOνA Project.

2.4 Integrated Protons on Target Assumed for the NOνA Experiment

The sensitivity of the NOνA experiment depends on the product of three numbers, the number of protons delivered to the experiment per year of operation, the mass of the NOνA detector in kilotons, and the number of years the experiment is operated. The projected sensitivities of the NOνA experiment are shown in Chapter 3 for a 15 kiloton (kt) detector and 36 x 10^{20} protons delivered to the NuMI target. This corresponds to 6 years of running in the 700 kW beam expected following the NOνA Project accelerator upgrades (see Table 2.1).

Chapter 3 also presents the increased sensitivities NOνA would have with 60 x 10^{20} and 120 x 10^{20} protons delivered to the NuMI target, corresponding to 6 years of running 15 kt with 1.2 MW and 2.3 MW beams respectively. These are the projected proton intensities for the conceptual SNuMI and Project X upgrades; they are not, however, part of the NOνA Project. Chapter 3 is intended to demonstrate the increased reach of the NOνA experiment if SNuMI or Project X were accomplished.

2.5 Chapter 2 References

[1] The NuMI Technical Design Handbook, http://www-numi.fnal.gov/numwork/tdh/-tdh_index.html.

[2] R. Zwaska, NOVA-doc-1698.

[3] Fermilab Steering Group Report, http://www.fnal.gov/directorate/ Longrange/ Steering_Public.