2. OVERVIEW OF THE NuMI BEAMLINE

The purpose of this section is to give an integrated conceptual overview and scope of the major elements of the baseline NuMI beamline. This section describes how the physics goals of the MINOS experiment impose certain requirements upon the design of the NuMI neutrino beam. Also described are general properties of neutrino beam systems and how these can be tailored to the physics needs. In particular, a quite flexible design has been adopted for NuMI, which allows a versatile future program.

2.1 Neutrino Beam Fundamentals

Most neutrino beams used in high energy physics are designed to be nearly pure beams of muon type neutrinos; ν_μ. The components to produce such a beam are illustrated in **Figure 2-1.** High energy protons interact in a target to produce a high flux of pions (π) and kaons (K), which then decay after some distance into muons and muon neutrinos (i.e. $\pi^+ \rightarrow \mu^+\nu_\mu$). Quadrupole magnets or, in the case of NuMI, focusing horns or are used to guide a large fraction of the desired π/K flux along the neutrino beam direction. The neutrinos are created by π/K decays along the length of a large diameter decay pipe. The pipe is followed by steel and earth to absorb the undecayed hadrons and the muons. A typical neutrino beamline is hundreds of meters in length from the primary target to the experimental detector, where neutrino interactions can be observed.

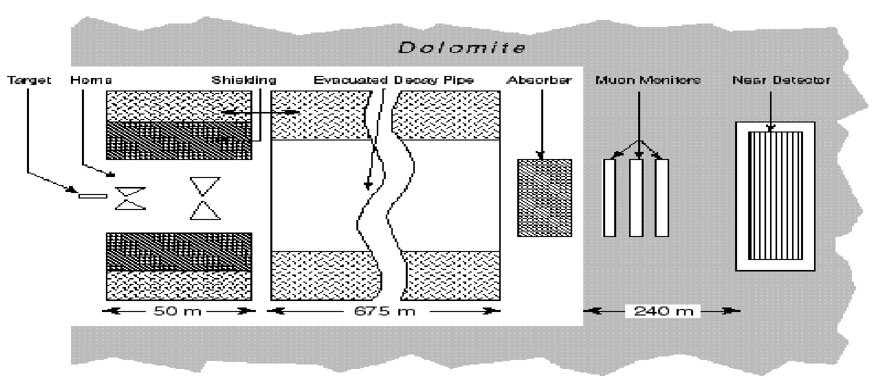

Figure 2-1 Schematic drawing of the NuMI neutrino beam-line

The energy spectrum of a neutrino beam created in this manner is calculated from measured π/K production data and simulation of focusing elements and decay kinematics. In general, secondary particles, such as π's from proton-nucleus interactions, are produced with transverse momenta of order 0.3 GeV/c. The longitudinal momenta cover a wide range, with 1 to 50 GeV/c being relevant for NuMI.

Pion decay kinematics leads to the following approximate relationships for the neutrino energy and a quantity proportional to flux

$$E_\nu = \frac{0.427 E_\pi}{(1+\gamma^2\theta^2)}$$

$$Flux = \left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi r^2}$$

where γ is the Lorentz boost of the pion, θ is the angle between the pion and neutrino flight directions, A is the cross-sectional area of the detector, and r is the distance to it. The energy and flux of the neutrinos peak along the pion flight direction, $\theta = 0$.

The typical production angle of a pion is $p_t/p_l \sim 0.3/(m_\pi\gamma) \sim 2/\gamma$; for zero degree targeting this is the same as the angle θ above. Thus there is a factor of order 25 to be gained in the flux by focusing the pions towards the detector, the $\theta = 0$ case. This factor, and the desire to keep the radius of the decay pipe reasonably small, are the motivations for a horn focusing system. Note that for well focused pions and a detector near the axis of the pion beam, the $\theta = 0$ situation, the neutrino's energy is 43% of that of the pion. The Lorentz boost favors neutrinos from high energy pions, thus high energy neutrinos, in the flux by a factor γ^2. A further implication, since one cannot simultaneously focus pions of all energies, is that one must choose a certain neutrino energy range to emphasize.

The optimization of the focusing system is guided by the desired shape of the energy spectrum of the neutrinos which will result from the π and K decays. For the NuMI beam the shape of this spectrum is chosen to maximize the ability to search for neutrino oscillations in a particular region of parameter space, as is described in the following sections.

2.2 Neutrino Oscillation Experiments

Neutrino oscillation searches can be characterized as either "appearance" or "disappearance" experiments. In an appearance experiment, the flavor composition of the initial neutrino source should be well known, and ideally limited to a single flavor. Then if the experiment detects the interactions of neutrinos of a different flavor, it can be concluded that the original neutrinos have indeed oscillated. Alternatively, an experiment which is capable of identifying a single flavor of neutrinos, in particular that of the initial source, can measure the flux of those neutrinos at a distance from the source and determine whether or not the number of neutrinos expected (in the absence of oscillations) has arrived. If the expected number is not observed the conclusion can be drawn that the neutrinos have "disappeared" or oscillated into a different flavor. There are also a number of "pseudo-appearance" measurements that experiments can make which can provide convincing signatures of neutrino oscillations.

Beam design goals include achieving the highest possible ν_μ intensity, low backgrounds of other neutrino flavors, well understood spectra so that systematic errors are small, and the selection of a neutrino energy spectrum matched to the oscillation physics. The rest of this section describes how the energy spectrum goals drive the NuMI design.

Given the fixed distance between Fermilab and Soudan, the energy spectrum of oscillations depends only on the parameter Δm^2, with the strength characterized by the parameter θ (neutrino oscillation θ) . Several examples of oscillation probability as a function of energy, chosen to cover the Δm^2 region indicated by the atmospheric neutrino anomaly, are shown in **Figure 2-2**. At very low energy, oscillations are so rapid that the detector resolution washes out individual wiggles, although one can still look for average signals. With a beam which covers a fairly broad energy spectrum (called a wide band beam), including the highest oscillation energy, one can detect the oscillation shape, as is illustrated in **Figure 2-2** for ν_μ charged current interactions. Further, measuring the energy at which neutrinos disappear and what fraction are lost, as in **Figure 2-3**, yields precision measurements of Δm^2 and $\sin^2(2\theta)$. Producing neutrinos at even higher energies is not very useful, since the oscillation probability falls off as E^{-2}. To address the atmospheric neutrino anomaly and to provide opportunity for future neutrino studies, NuMI requires neutrinos in the energy range of order 1 to 16 GeV.

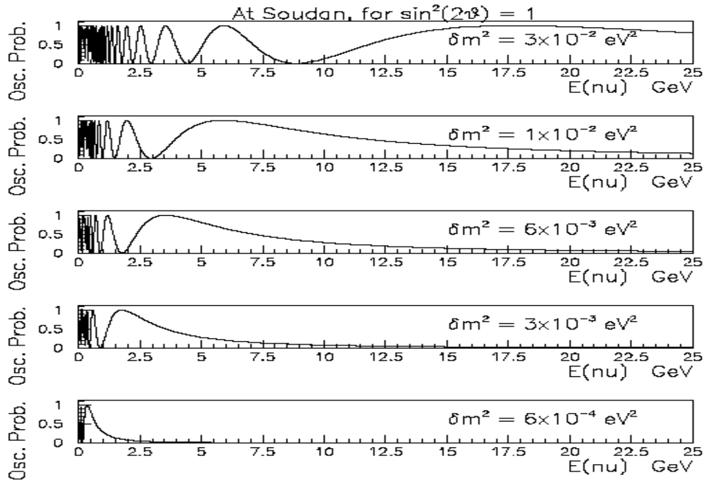

Figure 2-2 Neutrino oscillation probability as a function of energy for values of Δm^2 covering the region appropriate to the atmospheric anomaly.

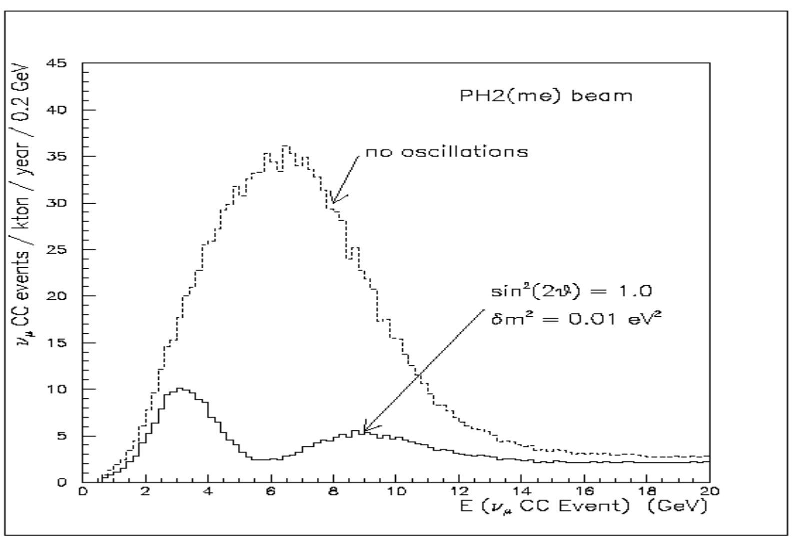

Figure 2-3 CC event total energy in the MINOS far detector distorted by oscillations.

In the case of ν_τ appearance experiments that detect events from the oscillation of $\nu_\mu \rightarrow \nu_\tau$, the energy threshold for production of a τ lepton also comes into play. Because of the energy turn-on of the ν_τ charged current cross section, as shown in **Figure 2-4**, the region from 5 GeV to 15 GeV remains the interesting one, even at low Δm^2.

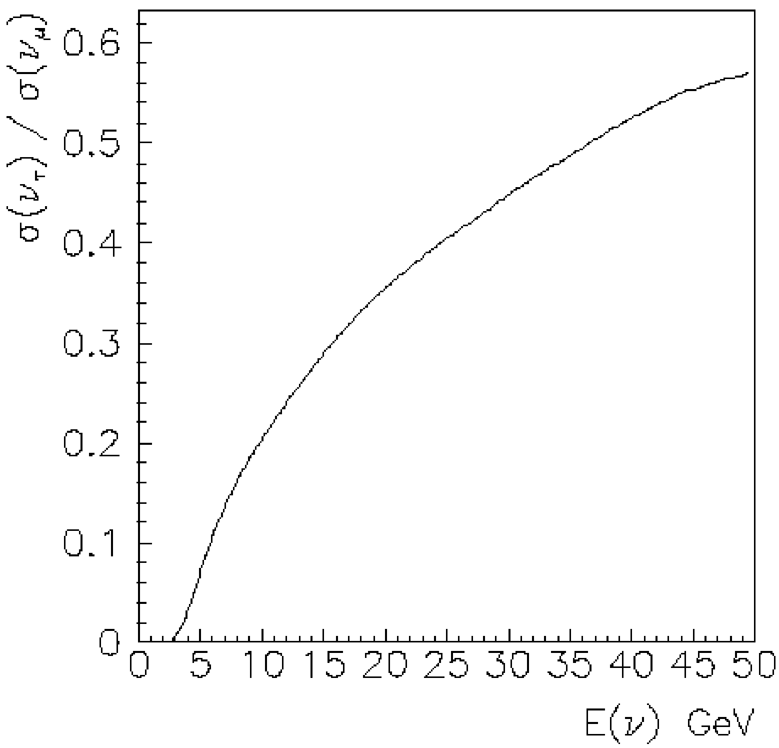

Figure 2-4 The ratio of the of ν_τ charged current interaction cross section to the ν_μ charged current interaction cross section, plotted as a function of neutrino energy.

2.3 Neutrino Beam Conceptual Design

As explained in the previous section, a neutrino beam energy spectrum that covers from 1 to 16 GeV is desired for NuMI. However, magnetic-horn beam devices typically deliver maximum focusing over a momentum bite of only about a factor of three. To address this, we have designed a horn system that can cover the energy region in three steps, using the same horns set in different positions and with different targets. The coverage for three different horn-target configurations is shown in **Figure 2-5**. The resulting event rates for the three configurations are compared in this plot with the idealized case of all pions perfectly focused down the beamline without loss. In each configuration the focusing achieves, at its optimal energy, about half the event rate of the perfect focusing case, which is typical of horn systems.

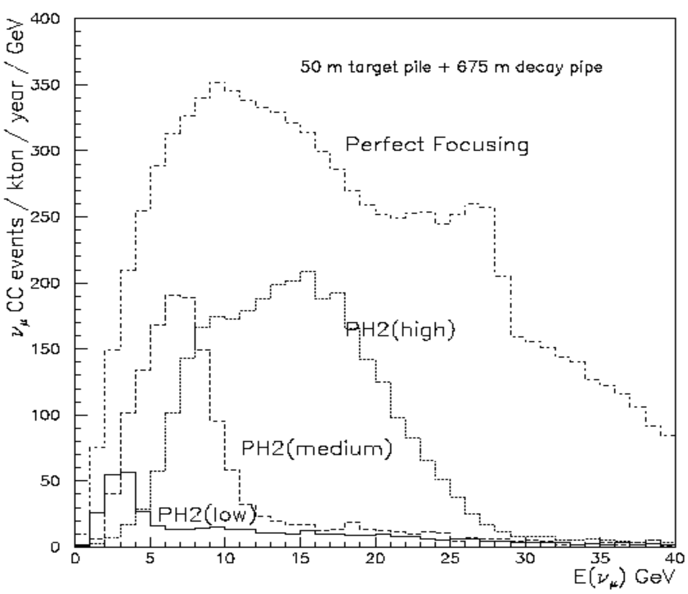

Figure 2-5 Comparison of event rates at Soudan in the case of ideal perfect focusing, and rates achieved with three configurations of the PH2 beam design.

Parabolic shaped horns were found to be better than conical ones in allowing for such reconfiguration. The NuMI beamline uses a two such horns. Thus the beams are labeled PH2(he), PH2(me) and PH2(le) for the two parabolic horn high energy, medium energy, and low energy configurations. The same set of horns could also produce an anti-neutrino beam to study possible CP violation.

2.3.1 Primary Beam System

The primary beam system for the NuMI facility encompasses the extraction and transport of 120 GeV primary protons from the Main Injector to the NuMI target. As the targeting is at zero degrees, the proton beam at the target must be aimed precisely at the MINOS far detector. The NuMI Beam design has been guided by the goals of minimizing beam losses and ensuring long term reliability and stability.

2.3.1.1 Extraction

The 120 GeV primary beam is extracted from the Main Injector ring and transferred through the Main Injector MI-60 extraction enclosure, a region known as the NuMI stub, and a steeply inclined carrier pipe to the pretarget and target regions located deep underground in newly excavated caverns. See **Figure 2-6.**

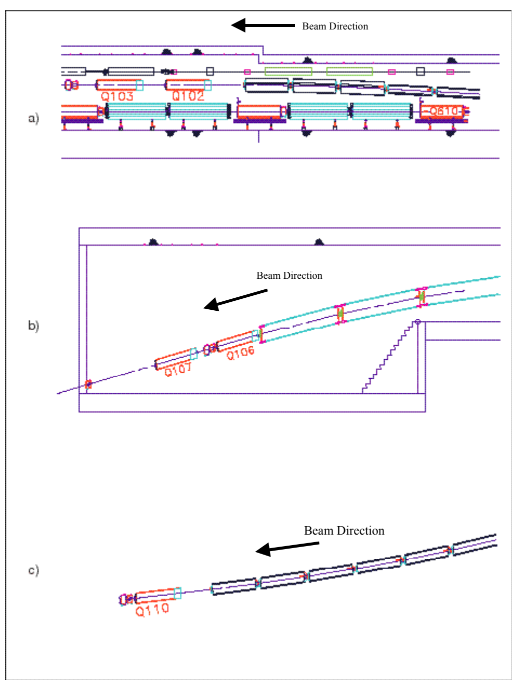

Figure 2-6 Schematic elevation view of the NuMI primary beam in a) Main Injector enclosure, b) NuMI stub, and c) pretarget hall.

The original NuMI proposal assumed a resonant extraction with a 1 msec spill. However, due to radioactivity from beam losses on the septa, this option was discarded in favor of a kicker-induced single turn mode. The 120 GeV protons are taken out of the Main Injector accelerator using a standard single turn extraction technique. The extraction mechanism is a horizontal kick, leading to Lambertson magnets that deflect primarily in the vertical. At the Lambertson magnets, the extracted beam lies outside of the circulating beam. Three Lambertsons and one C-magnet complete the extraction. The machine repetition cycle for this mode of extraction can be as low as 1.9 seconds. To produce the intensities required to achieve the MINOS experimental goals, the NuMI beam requires extraction of at least 2.5×10^{13} protons per pulse.

2.3.1.2 Transport of Primary Protons

The extracted protons are focused and bent strongly downward by a string of quadrupoles and bending magnets so that they enter the pre-target hall located 400 feet downstream of the NuMI Stub, a specially constructed appendage to the MI enclosure. For conventional construction reasons the pre-target and target halls are located in the dolomite rock formation, requiring that the initial trajectory be bent down more than is actually required to aim the neutrino beam to Soudan. Another set of bend magnets brings the protons to the correct pitch of 58 mradians for a zero targeting angle beam directed toward the experiment. The size and angular dispersion of the proton beam are controlled by a final set of quadrupoles and are matched to the diameter of the production target.

2.3.2 Neutrino Beam Devices

The neutrino beam devices transform the primary proton beam from the Main Injector into a beam of neutrinos. This is done in a three-step process. Protons strike a target to produce short lived hadrons, the hadrons are focused towards the neutrino experimental areas, and as the hadrons travel through a long pipe a fraction of them decay to neutrinos and muons. Devices called horns, which produce intense magnetic fields, focus the hadrons. At the end of the pipe the remaining hadrons are absorbed in a beam stop. Neutrinos, which are weakly interacting particles, continue through the hadron absorber and the earth to the experimental areas. To minimize the number of hadrons that are absorbed by air, the long decay pipe is evacuated.

2.3.2.1 Target

The extracted protons interact with nuclei in the target, producing pions and kaons with a broad spectrum in both longitudinal and transverse momentum. The NuMI target and focusing system have been designed as a unit in order to maximize the ν_μ charged current event rate at the MINOS far detector.

The target should be sufficiently long to enable most of the primary protons from the Main Injector to interact, but shaped so that *secondary* interactions of the π's and K's are minimized and energy absorption is low. This is achieved with a target that is long and thin, allowing secondary particles to escape through the sides, as illustrated in **Figure 2-7.** The depth of field of the horn focusing system sets a limit on the length of the target.

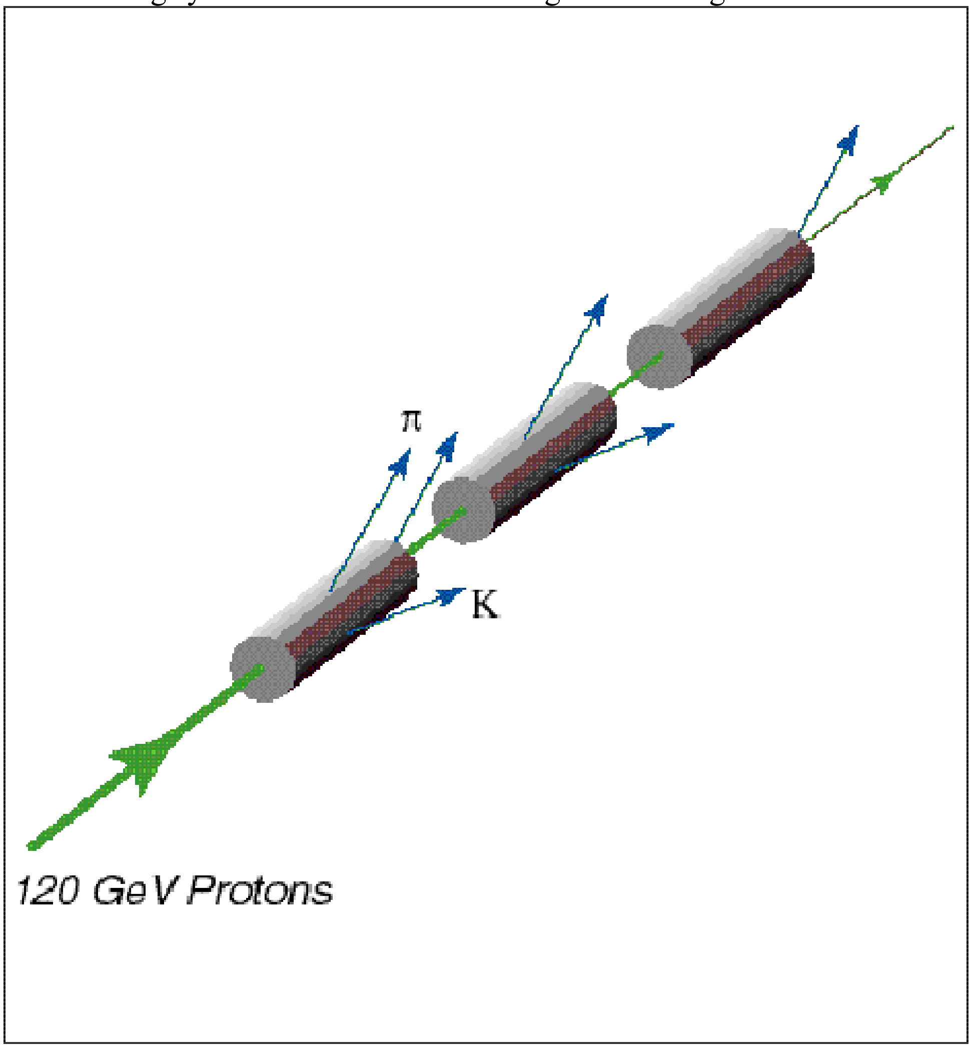

Figure 2-7 Schematic drawing of a long, slim segmented target for optimum production and decay of pions

The optimal choice of target radius is driven by two opposing trends: the *desired* flux of pions and kaons out of the target decreases with increasing radius due to particle re-absorption, but *undesirable* target stress from the heat load of the high intensity proton beam also decreases with increasing target and beam spot radius. Because the target becomes highly radioactive soon after beam start-up, replacement of a failed target is an arduous and time-consuming process. The design of the target is therefore a compromise between obtaining maximum yield and ensuring integrity against mechanical failure due to shock and heat build-up.

2.3.2.2 Horn Focusing System

The target is followed by two focusing horns, which produce toroidal magnetic fields and act as lenses to bend the secondary particles (of one sign) back to the primary proton direction. Of course the neutrinos from the decays of the π's and K's do not all follow the same path, but they are preferentially directed along the decay pipe axis. Thus the optimum design has all secondary particles directed toward the detector so that the resulting neutrino flux is maximized. However, in reality one can focus only some of the pions at all momenta or all of the pions at particular momenta, but not all pions at all momenta for all angles from the target.

NuMI has chosen horns with parabolic shaped inner conductors. These produce magnetic fields that act to first order as lenses, where the focal length is proportional to the pion momentum. Thus a selection of a particular target position causes a certain momentum to be focused by the first horn. Pions that were well focused by the first horn pass unaffected through a central aperture in the second horn. Pions that were somewhat over- or under-focused by the first horn move to larger radius and are focused by the second horn, extending the momentum bite of the system.

The pions actually pass through the current carrying inner wall of a horn to reach the focusing magnetic field. Absorption of pions in the horn walls ranges from 20% to 40% depending on the incidence angle. The design of a horn is a balance between trying to make the inner wall thin (to reduce absorption) and sturdy (since it is subjected to large pulses of electric current – 200 kA in the NuMI design). A water spray is used to keep the aluminum inner conductor below 100 C.

The deployment of the horns and target to achieve the various PH2 beam neutrino event spectra described above are shown in **Figure 2-8**.

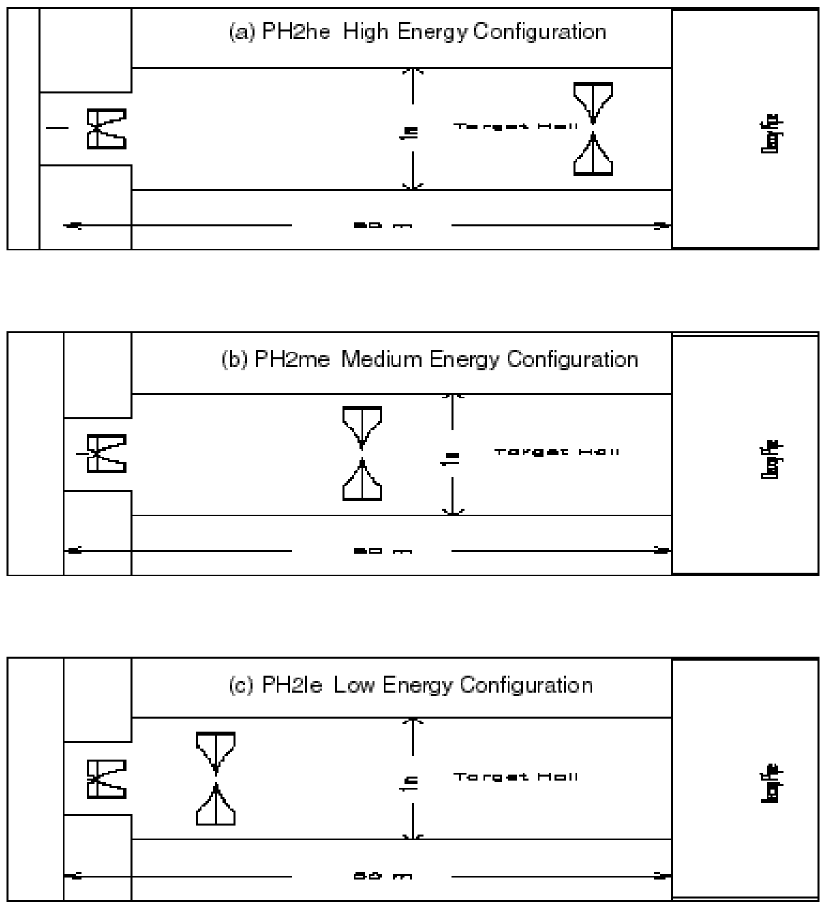

Figure 2-8 Schematic drawing of PH2 beam focusing configurations in the NuMI target hall. To change the tune to lower energy, the target is moved closer (and finally into) the first horn, and the horns are moved closer together

2.3.3 Decay Region and Hadron Absorber

The decay pipe length of 675 meters provides a sufficient flux of muon neutrinos in the wide energy band of the neutrino beam for the MINOS experiment. The decay pipe must aim at the MINOS cavern at Soudan. Misalignment of the decay pipe along its length can not occlude the 1-meter radius aperture by more than 2%. The vacuum level in the decay pipe should be 1 Torr or lower. The Hadron Absorber has to protect groundwater from irradiation under normal running conditions over long periods of time. It has to limit the levels of radiation to acceptable levels in tunnel regions accessible to personnel, for both normal running conditions and abnormal running conditions--such as the proton beam missing the target (in which case the beam is significantly narrowed in size at the hadron absorber). The absorber core and surrounding iron shielding has to maintain its integrity during both normal and abnormal running conditions.

2.3.3.1 Decay Pipe

The decay pipe provides an evacuated space for the secondary π's and K's to decay as they travel towards the MINOS detectors. The choice of length is a compromise between the neutrino flux in the detectors and cost considerations. The neutrino flux is predominantly from the pions with momentum between 2 GeV/c and 60 GeV/c. At the upper end of this range, the mean decay length of a π is several km. The number of high energy neutrinos for the long baseline experiment thus continues to increase significantly with any reasonable decay pipe length. The current baseline design is driven by cost, calling for a decay pipe length of 675 m. Combining the 675 m decay pipe with the 50 m distance from target to start of the decay pipe results in a 725 m long decay region for the NuMI beamline.

The choice of radius for the decay pipe is made by balancing the loss of secondaries that interact with the walls of the pipe against the cost increases associated with larger radius pipes. In general, for the nominal beam pipe length, the gains in neutrino flux are rather dramatic as the radius of the pipe increases to about 1 m, with comparatively modest gains over the next meter of increase.

As shown in **Figure 2-9**, a larger-radius decay pipe would be more optimal for the low energy (PH2le) configuration, while a longer one would be better for the high energy (PH2he) beam. The baseline combination of 1 m radius and 725 m decay length is a reasonable compromise.

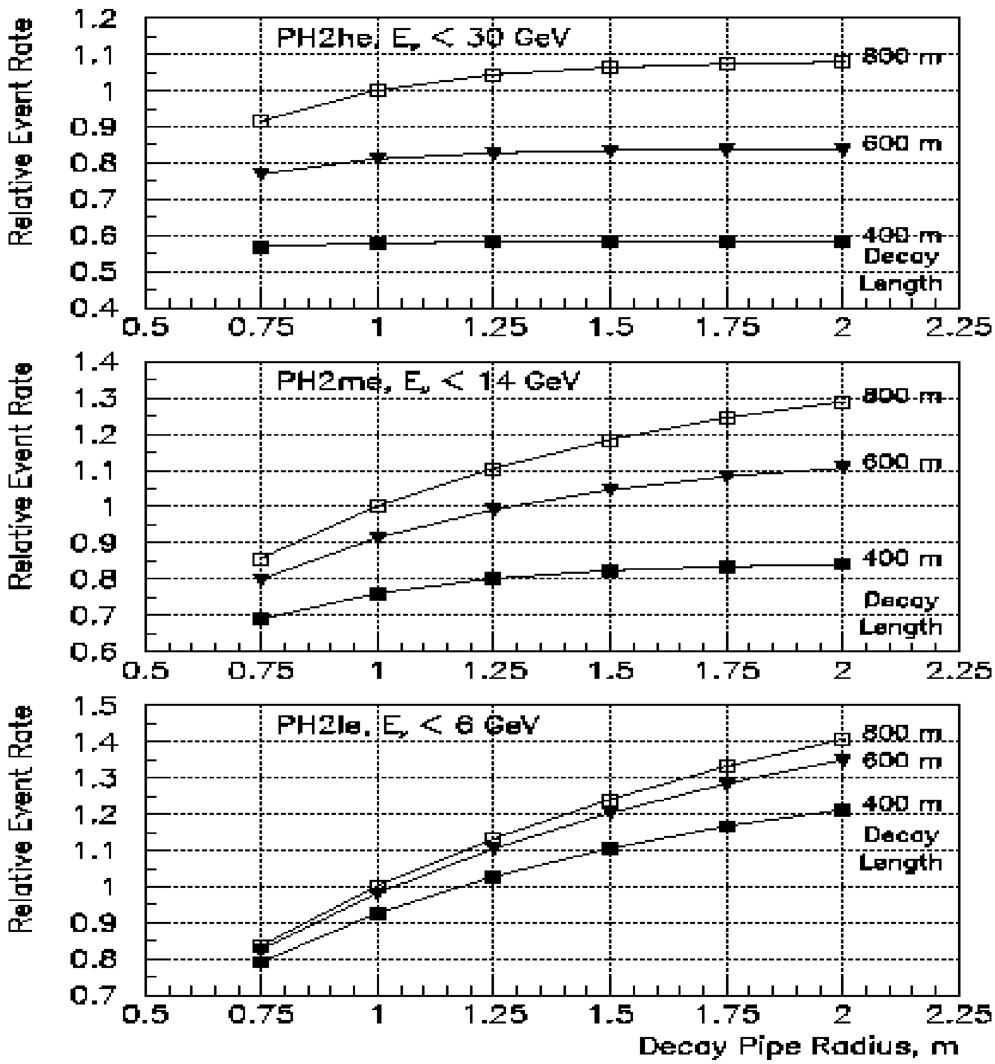

Figure 2-9 Comparison of neutrino event rates as a function of decay pipe length and radius.

2.3.3.2 Hadron Absorber

The experimental detectors are designed to observe the interactions of neutrinos. Other types of particles must be eliminated since their much higher event rates would overload the data acquisition system. All hadrons, including those primary protons that did not interact in the target, are stopped by a hadron absorber at the end of the decay pipe. Because the absorber is far downstream of the target, the natural divergence of the proton beam implies a larger spot size at the absorber, and the absorber does not have to handle nearly so high a deposition energy density as the target does. The absorber consists of a water cooled aluminum central core surrounded by steel.

2.3.3.3 Muon Shield

The hadron absorber alone is too short to eliminate the muon component of the beam, which is produced from pion decays along with neutrinos. These muons must be absorbed before reaching the MINOS near detector. Muons can be eliminated by active shielding using large and expensive magnetic devices or by providing sufficient material to absorb their energy via multiple scattering. The NuMI beamline is located in dolomite, which is a dense rock. The 240 meters of dolomite between the end of the hadron absorber and the near detector is sufficient to stop all muons coming from the decay pipe.

2.3.4 Neutrino Beam Monitoring

The neutrino beam monitoring systems enable the beam users to measure the quality of the neutrino beam being delivered to the experiments. This is accomplished by measuring the flux and spatial distribution of hadrons directly upstream of the absorber and muons at several locations within the dolomite muon shield. Hardware problems with beamline and target components will be deduced from changes in these beams. An alarm signal will be provided when performance is not nominal.

In order to detect variations, the muon intensity measurement will be normalized both to the number of incoming protons and to each other, while the measured profiles are compared to nominal profiles. Since the intensity of the NuMI beam is quite high, the actual neutrino event rate and radial distribution in the on-site neutrino beam monitor (MINOS near detector) can be combined with the normalized measurements of the muons to insure that the systems producing the neutrino beam are functioning correctly.