Can the NuMI beam-line be further optimized for a lower-neutrino-energy spectrum?

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Jim Hylen[1], Mary Bishai[2], Byron Lundberg[1]

[1]Fermi National Accelerator Laboratory
[2]Brookhaven National Laboratory

By optimizing the horn focusing system, modest increases can be achieved in the low-energy part (1 GeV region) of the neutrino spectrum at NuMI, compared to the existing NuMI LE (low energy) tune. Variations using the existing horn system would be inexpensive. For a new horn design, by looking at the WBS elements for the LBNE old reference design, one could guess that the development, prototyping and construction of new horns, power supply, strip-lines and target, when done under project accounting, would likely increase costs a couple 10's of millions of dollars TPC.

Other ways of trying to increase flux exist and are mentioned below, but seem not attractive.

In order to produce this note while not distracting from other efforts, we only used existing documentation. No new Monte Carlo runs (that could have more sharply focused on this question) were done. Several plots done with Homestake beam-line geometry are presented to give a qualitative feel for possible relative gains for the NuMI beam-line.

Casual readers are invited to skip to the summary at the end.

1. Physics of horn neutrino beams and limitations at low energy

Kinematics: A conventional neutrino beam is obtained by protons producing pions in a target, picking a subset of pions to focus with toroidal magnetic fields produced in horns, and then letting the pions decay in flight. The pion decay kinematics for neutrinos can be approximated by

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

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

where γ is the Lorentz boost of the pion, θ is the angle between the pion flight direction and the detector, and r is the distance to the detector. The energy and flux of the neutrinos peak along the pion flight direction. For well-focused pions and a detector near the axis of the pion beam, $\theta = 0$, resulting in neutrino energy of approximately 43% of the pion energy. For long-baseline beams, the neutrinos spread out to a couple orders of magnitude larger in radius than the detector, and the flux concentration in an on-axis detector is increased for higher energy neutrinos by a factor of γ^2.

Cross-section: Since the neutrino cross-section rises approximately linearly with energy, combining this with the Lorentz boosted flux gives an ~ E^3 advantage for a higher energy neutrino producing an event in the detector.

Hadron production: Figure 1 shows a (modestly out-of-date) spectrum of pions from 120 GeV protons hitting a NUMI-like target. From a few GeV up to 10's of GeV, the spectrum is falling fast enough that it almost compensates the E^3 effect. His is why the NUMI beam can tune through that region with not hugely dis-similar event rates in the detector. However, below that, the pion rate turns over, ***and an on-axis beam rapidly loses neutrino rate at lower energies, even if the focusing were perfect***.

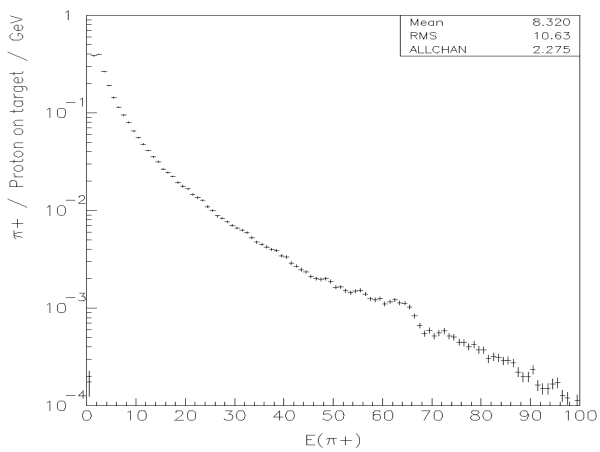

Figure 1. Monte Carlo spectrum of pion production from 120 GeV protons on Carbon (NuMI conceptual design report, FERMILAB-TM-2018).

Decay pipe: Another efficiency factor that is easy to understand analytically is to compare the pion decay lifetime to the 723 m distance between the target and the end of the NUMI decay pipe; this is a 50% hit for 8 GeV neutrinos, but only 0.4% for 1 GeV neutrinos, so not a concern for NUMI. (For the 217 m target-to-absorber distance for the new LBNE beam line, it is a still modest 19% hit at 1 GeV).

The appropriate decay pipe radius depends on details of focusing and degrading of the pions by passage through material, and is addressed by Monte Carlo. Larger radius is needed for lower energy beam. To give a rough feeling of this effect as a function of neutrino energy, a recent study varying the LBNE decay pipe radius by a factor of two is shown in Figure 2a. The LBNE reference design is 2 m radius. The NUMI decay pipe radius of 1 m is undersized for a very low energy neutrino beam, but can't be changed. A feeling for the impact of this can be seen in Figure 2b.

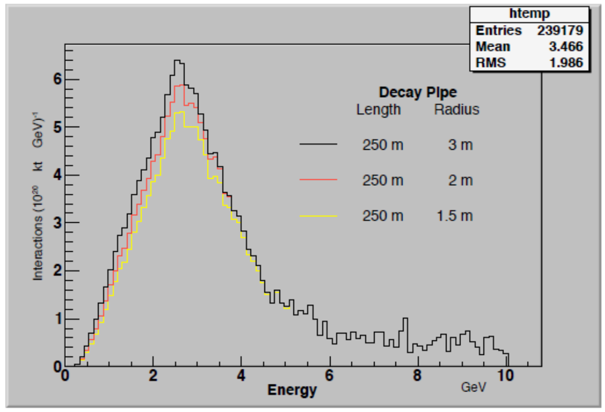

Figure 2a. Neutrino event spectrum as function of LBNE decay pipe radius. (Decay pipe optimization matrix, LBNE-doc-5024).

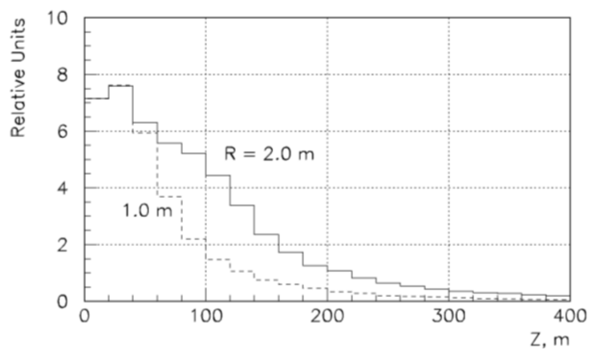

Figure 2b. The distance from the target of the decay point of pions producing neutrinos with energy < 2.5 GeV in the detector, for two different NuMI decay pipe radii. (Optimization Studies of Beam Optics for Low Energy Neutrino Production, September 2001, NuMI-1002).

Horn focusing: Horn focusing tends to be less efficient at low energy. Pions emerge from the target with typically 0.1 to 0.3 GeV of transverse momentum, so low energy pions are coming out at large angles, and a large range of angles. Since the target also tends to be long, it means the production phase space is getting very large. The horn focusing strategy changes, going from an efficient "lens-like" parabolic or conical shape downstream of the target as seen in CNGS, WANF and IHEP horns, to a "get as much field as close as you can" strategy of a straight tube surrounding the target, as seen in the first section of Mini-Boone, T2K and old-reference-design LBNE horns. Horn magnetic fields are proportional to inverse radius, so large angle tracks become problematic, and multiple scattering further spreads the phase space for low energy pions; thus the efficiency of pion collection may drop from 80% at high energy to 40% for low energy. The NUMI parabolic horns allow for 2/3 of the target length to be inserted in the horns, and work well for neutrino energy greater than 2 GeV, but lose some efficiency below that.

A feeling for the possible gain in low energy flux from that change in horn shape and horn current can be gotten from Figure 3. Similar limitations in trying to improve the flux in the 1 GeV region were seen in an IHEP study of alternate shapes for NuMI horns (Optimization Studies of Beam Optics for the Low Energy Neutrino Production).

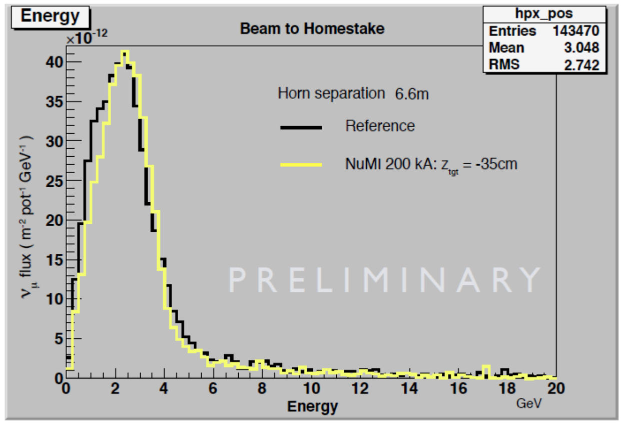

Figure 3. Comparison of neutrino spectrum using NUMI parabolic horn 1 to the previous LBNE reference horn with straight-first-section-and-target-entirely-inserted (NuMI horns for Homestake, LBNE-doc-6005-v3). The reference design used 300 kA horn current.

Decreasing the distance between the first and second horns helps improve the low energy flux. Figure 4 can give some feeling for the size of that effect. We are in the process of changing the NuMI horn separation from 10 m to 19 m now, in preparation for the NOvA run which wants higher on-axis neutrino energy. Going back to the 10 m separation is relatively straightforward, and would take a couple months. Changing to 6.6 m separation would be much more difficult, because of the required reconfiguration of highly radio-activated shielding, but could be possible in a ½ year shutdown.

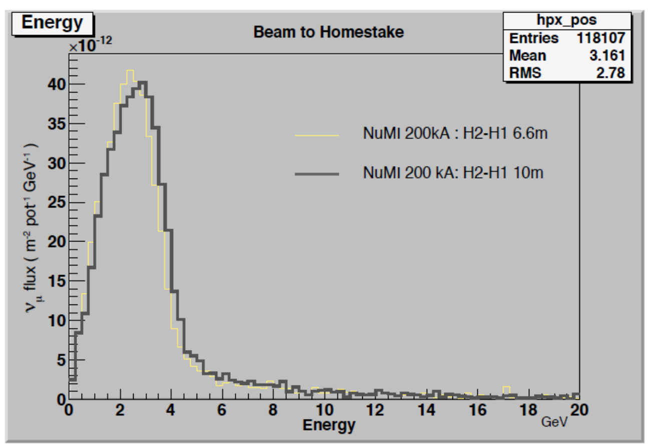

Figure 4. Comparison of neutrino spectrum varying distance between horns for LBNE beam-line (NuMI horns for Homestake, LBNE-doc-6005-v3). NuMI beam-line horns were 10 m apart for the 2005-2012 runs.

Some modest improvement in flux may be available from increasing the horn current. However, detailed engineering studies need to be carried out to assess the risk in pushing NuMI horns to higher current. The beam heating, which depends critically on the target design, plays a significant role in horn stress. At the moment, we should not assume higher current, but this can be investigated.

Since May 2005, NuMI ran with the target starting 10 cm further upstream of the horn (-45 cm instead of -35 cm) and with reduced horn current (185 kA instead of 200 kA) as compared to the original design when running low energy beam. Technical details of the new target that will be used at 700 kW beam make it reasonable to go back to the original position and current. Figure 5 indicates the size of the flux increase from this change.

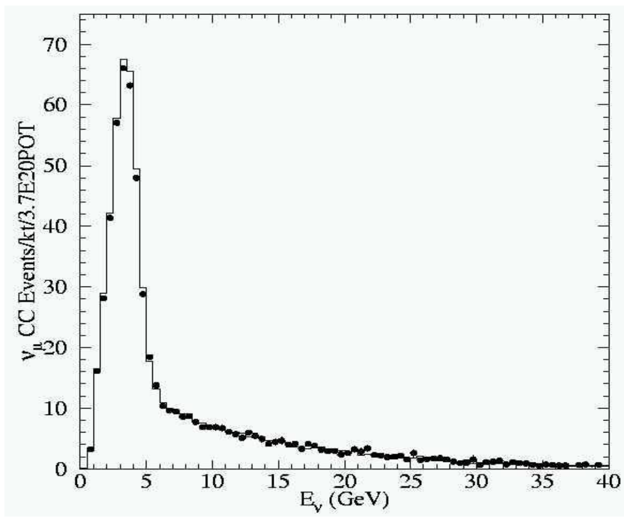

Figure 5. Comparison of NuMI LE-10_185 kA spectrum (dots) with NuMI LE-0_200 kA spectrum (line). (calculated with GNuMI+ Fluka, M. Messier 2005).

2. Target re-optimization

Materials other than carbon can produce more pions per proton-on-target, and having a more point-like source for the horns from increased density can also aid low energy pion focusing. The conflict between the desire for higher density targets and the practical limitations the stress from higher power beams puts on targets has led to R&D on rapidly rotating solid targets, powder-jet targets, water-fall targets, and mercury-jet targets, to mention a few. Implementing any of these in NuMI would require extensive R&D, with improvement of the flux or success of the technology not guaranteed. Another wrinkle is that high density targets tend to generate more beam-heating in the horn, and that heating is a severe limitation with existing horn technology. Even if the technology were in hand, Figure 6 indicates that for the pion energy range desired here, there is not much gain to be had from higher density targets for 120 GeV proton beam.

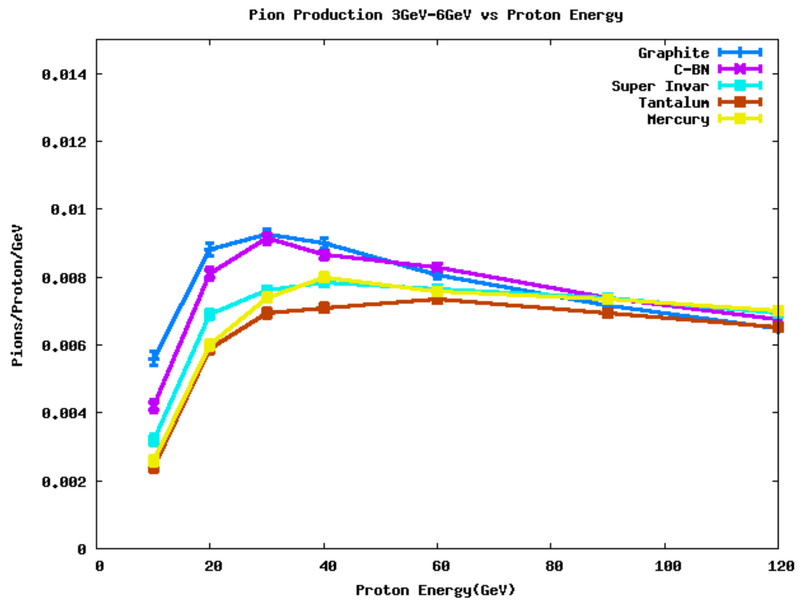

Figure 6. Rate of production of pions with $3 < E_\pi < 6$ GeV from targets of different material as a function of incident proton energy. Rate has been divided by proton energy to illustrate effect at equal beam power. Targets are cylindrical with a radius=0.45cm (3σ beam width) and length=2 nuclear interactions lengths. (Proton beam energy requirements for LBNE, LBNE-doc-3069).

For the current style targets, some optimization studies of target geometry with iterations of detailed engineering work could yield small, but not large, improvements. The engineering studies would also have to include the effect of those variations on the horns.

Proton beam energy: Figure 7 indicates the dependence of the beam spectrum on primary proton beam energy at constant beam power. This is not a promising avenue for NuMI, as until Project X is built, significantly reducing E_p will also reduce the available beam power; further, the entire extraction beam line for NuMI would have to be rebuilt to transport the fatter low energy beams.

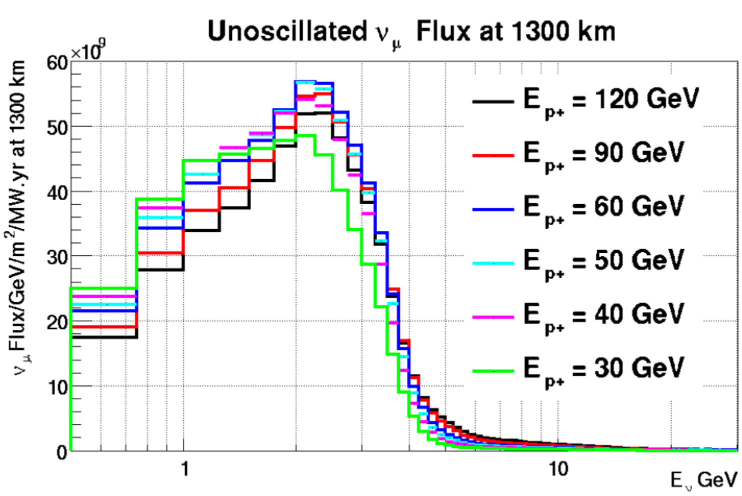

Figure 7. Effect on a sample LBNE spectrum of changing the proton beam energy at constant beam power. (Proton beam energy requirements for LBNE, LBNE-doc-3069).

An envelope for improvement: Figure 8 shows a comparison of the existing NuMI LE-10 beam to a more-optimized-for-low-energy focusing system and with the decay pipe radius increased to 2 m. While modifications to the focusing system may overcome the gap at 3 GeV, the limitation of the 1 m decay pipe radius for NuMI probably limits any gain at the low energy region to half what is shown.

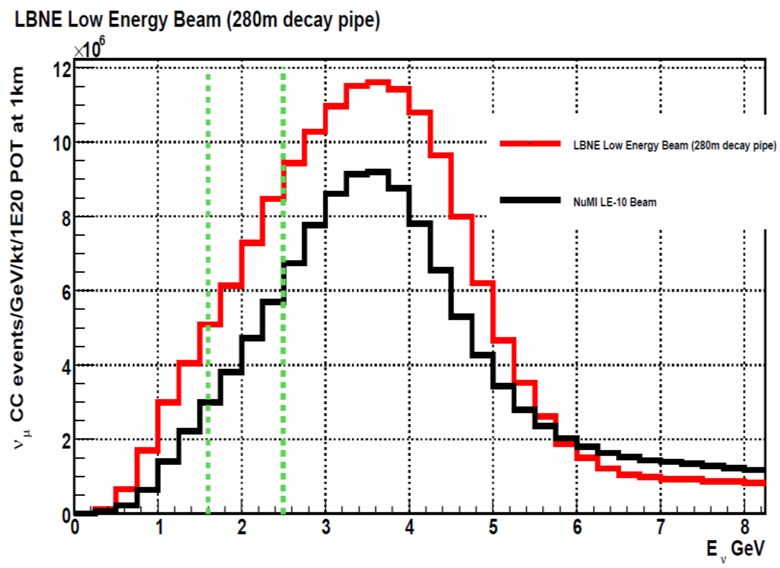

Figure 8. An LBNE low energy beam design (red) that is more optimized to produce lower energy neutrinos, compared to NUMI LE-10_185. The increase in flux was achieved by the combination of increasing the decay pipe radius from 1m to 2m, increasing the horn current to 250 kA, moving the horns closer together (from 10 m to 6 m separation), moving the target 5 cm more into the horn, assuming a more dense graphite target, and changing the decay pipe volume from helium to vacuum. This certainly overestimates any improvement that could be squeezed out of changing the NuMI focusing system. This is for 120 GeV beam. (Mary Bishai, June 2012).

3. Other ways of increasing low energy flux

Moving the detector off-axis is a well-known way to improve low energy flux, but is beyond what we can discuss here.

There are other types of charged particle focusing systems that can achieve significantly higher efficiencies at low momenta than horns. Foremost is solenoid focusing. These are effective point to parallel focusing systems whose total efficiency is limited only by their radial dimension and/or field strength. There are two reasons solenoids are not used for producing high-power neutrino beams. First, unlike horns, they do not selectively focus pions of one sign of charge, but focus positively and negatively charged particles equally. This is a major problem with giant long baseline neutrino detectors, as they are blind to the charge-conjugate state: they cannot efficiently distinguish neutrinos from antineutrinos. Secondly, to be an effective design, the solenoid would need to be 10 to 20 m long with fields of at least 4 T. Such magnets are costly and the challenge of engineering a solution to keep a superconducting coil operating in an environment with such high radiation and beam fluxes is prohibitive.

4. Summary of optimization options

Base option: The change from the 400 kW MINOS target to the 700 kW target design (along with a minor change in carrier design) will allow us to return NuMI horns/target to the original-design LE-0 200 kA focus. Figure 5 shows this produces a modest improvement over the LE-10 185 kA focus that has mostly been used up to now. This is also what is proposed for the Homestake beam-line phase 1 (except for the distance between horns).

Base + raise current: Increasing the NuMI horn current by 10% to 20% is an option that could be looked at, and if found acceptable would be cheap to implement. However, a significant engineering study will be required to assess the risk and look at possible mitigations. This may produce another modest increase in flux.

Base + change separation: Changing the separation between the NuMI horns to the same separation proposed for the Homestake beam-line may be possible. The radiation dose to workers during changing the horn separation in NuMI will be measured this year, after which an extrapolation can be made to understand doses for such a possible future move to 6.6 m separation. Such a move would not be nearly as expensive as a complete horn system redesign, but the expected flux gain is fairly modest (Figure 4).

Alternate Horn System Option: Switching to a horn system such as the old LBNE reference design can increase the flux around 1 GeV (Figure 3). This would be more expensive (~ $20 million more?), and whether it would be worthwhile depends on the importance of that low energy part of the spectrum. It does not help the flux above 2 GeV.

In summary, there are options that could increase the low energy flux at NuMI by perhaps 10% to 30%, but no options for large increases are known.