Simulation of a Wide-Band Low-Energy Neutrino Beam for Very Long Baseline Neutrino Oscillation Experiments

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Abstract

We present simulations of a wide band low energy neutrino beam for future very long baseline neutrino oscillation (VLBNO) experiments using the proton beam from the Main Injector at Fermi National Accelerator Laboratory. The target and horn design optimized for the Brookhaven Laboratory's AGS-based program for VLBNO experiments are used without modifications. The neutrino flux distributions for various proton beam energies and new neutrino beamline designs possible at Fermi National Lab. are presented. The beamline siting and design parameters are chosen to match the requirements of an on-axis beam from Fermilab to one of the two possible sites for the future Deep Underground Science and Engineering Laboratory (DUSEL). Our very preliminary conclusions are that a 40-60 GeV 0.5-1 MW beam from the Fermilab Main Injector to a DUSEL site would allow us to reach the desired physics sensitivities for the next generation of neutrino oscillation experiments.

Contents

I. INTRODUCTION

The physics case for very long baseline neutrino oscillation (VLBNO) experiments using an on-axis wide-band neutrino beam has been discussed in [1] and [2]. For baselines greater than 1000Km, it has been previously demonstrated that an on-axis, broad band beam is a powerful probe of the parameters of the neutrino mixing matrix, the mass hierarchy and CP-violation. Up till now, the neutrino beam model used for VLBNO experiments has been based on the Super Neutrino Beam Facility proposed at the Brookhaven National Lab's (BNL) alternating Gradient Synchrotron (BNL-AGS) [3]. The AGS is capable of accelerating protons up to 28 GeV and has achieved the highest proton beam intensities to date. In this study we will focus on modeling the performance of a proposed new neutrino beamline based at Fermi National Laboratory (Fermilab) using the 120 GeV Main Injector (MI) proton accelerator. The longest baseline neutrino oscillation experiment currently in operation is the MINOS (Main Injector Neutrino Oscillation Search) experiment at Fermilab which utilizes the NuMI (Neutrinos at the Main Injector) neutrino beamline [4]. The MINOS experiment has collected neutrino data from 1.4×10^{20} protons-on-target delivered by the NuMI beam. The first neutrino oscillation results from MINOS using neutrinos from the NuMI beamline were recently publicly announced [5]. The GEANT [6] based simulation of the NuMI beamline has now been validated using real data from the MINOS experiment. We will use the same simulation software and the operational experience of the NuMI beamline to model the performance and neutrino beam properties of a new wide-band low-energy (WBLE) beamline based at the Fermilab MI.

The requirements of a new WBLE beam based at the Fermilab MI is driven by the physics of $\nu_\mu \rightarrow \nu_e$ oscillations. In Figure 1, the location of the oscillation maxima as a function of distance from the neutrino source - the baseline - and the neutrino energy is displayed. In principal, the ideal neutrino beam for the next generation of neutrino experiments envisioned in [1] and [2] would be one that has a broad energy band that covers the energy region where the oscillations are maximum and no flux beyond the region of interest to eliminate backgrounds from higher energy neutrinos that are not sensitive to oscillations but feed-down into the low observed-energy regions. The oscillation spectrum looks different at different baselines, therefore, for different baselines, the ideal beam energy spectrum which maximizes the sensitivity to oscillations will have different properties. For the purpose of this study, we will consider the two proposed sites for the Deep Underground Science and Engineering Laboratory (DUSEL) [7] as a possible location for the far neutrino detector for a VLBNO experiment using Fermilab as the neutrino beam source. The two proposed DUSEL sites are Homestake Mine, SD and Henderson Mine, CO. These two sites are located at a baseline of 1300 Km and 1500 Km from Fermilab respectively. In Figure 2, the different components of the $\nu_\mu \rightarrow \nu_e$ oscillation probabilities and their dependence on the CP phase for a to Homestake baseline are plotted. The oscillation probabilities for the

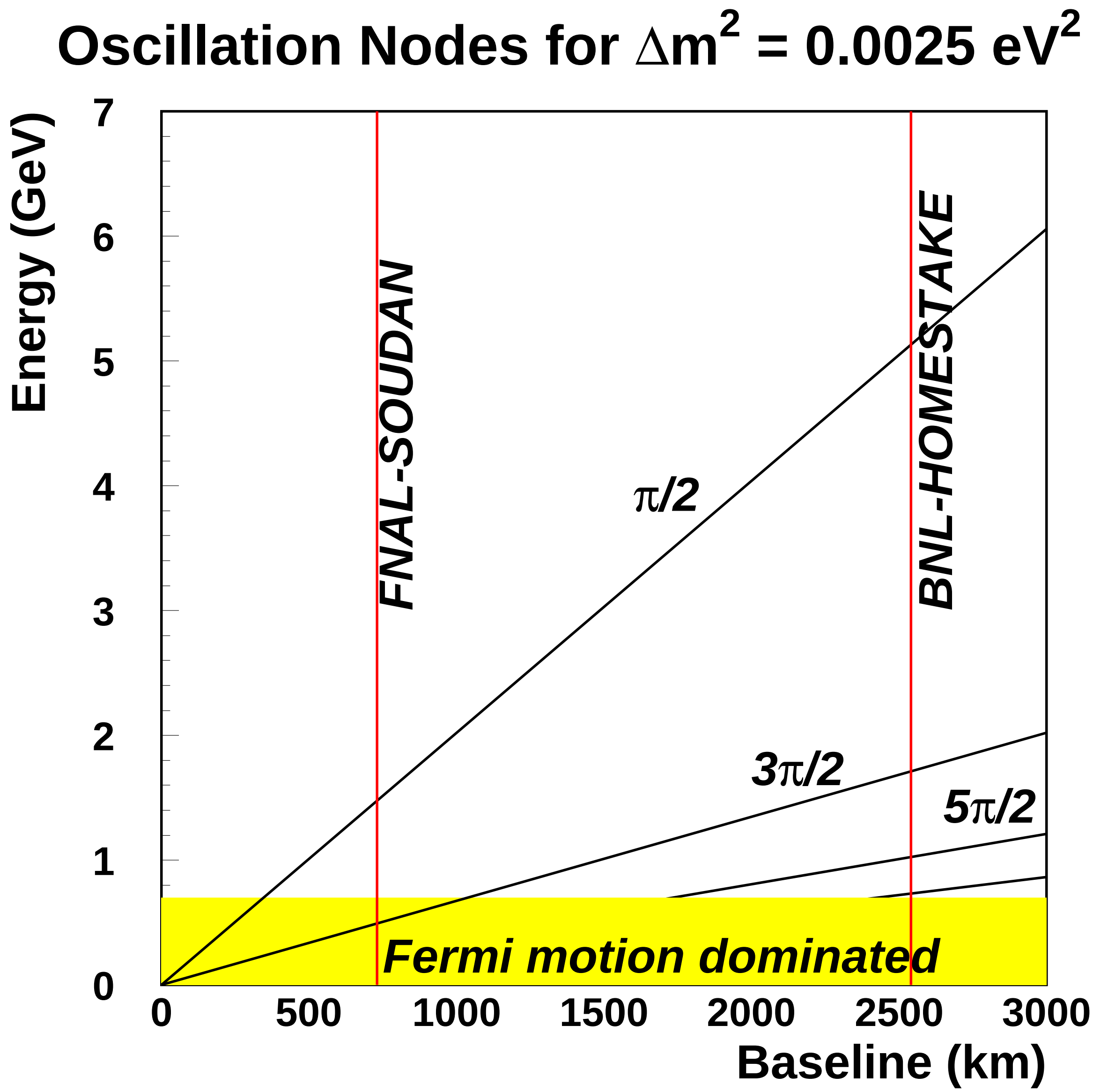

FIG. 1: Location of $\nu_\mu \rightarrow \nu_e$ oscillation nodes in the ν energy spectrum mode as a function of distance from the beam source.

much longer baseline from BNL to Homestake is also shown in Figure 2 to illustrate the change in the different oscillation effects with baseline. In this study we will concentrate on optimizing the neutrino beam for VLBNO experiments from Fermilab to Homestake Mine (FNAL-HS). Since the distances from Fermilab to Homestake and Henderson Mines are not significantly difference, the same beam design will be applicable for both baselines. We can specify the following broad requirements for a FNAL-HS beam based on examination of the oscillation probabilities in Figure 2:

1. We require the maximal possible neutrino fluxes to encompass at least the 1st and 2nd oscillation nodes the maxima of which occur at 2.6 and 0.8 GeV respectively.

2. Since neutrino cross-sections scale with energy, larger fluxes and lower energies are desirable to achieve the physics sensitivities using effects at the 2nd oscillation node and beyond.

3. For $\nu_\mu \rightarrow \nu_e$ it is critical to minimize the neutral-current contamination at lower energy, therefore minimizing the flux of neutrinos with energies greater than 5 GeV where there is no sensitivity to the oscillation parameters is highly desirable.

4. The irreducible background to $\nu_\mu \rightarrow \nu_e$ appearance signal comes from beam generated ν_e events, therefore, a high purity ν_μ beam with negligible ν_e contamination is required.

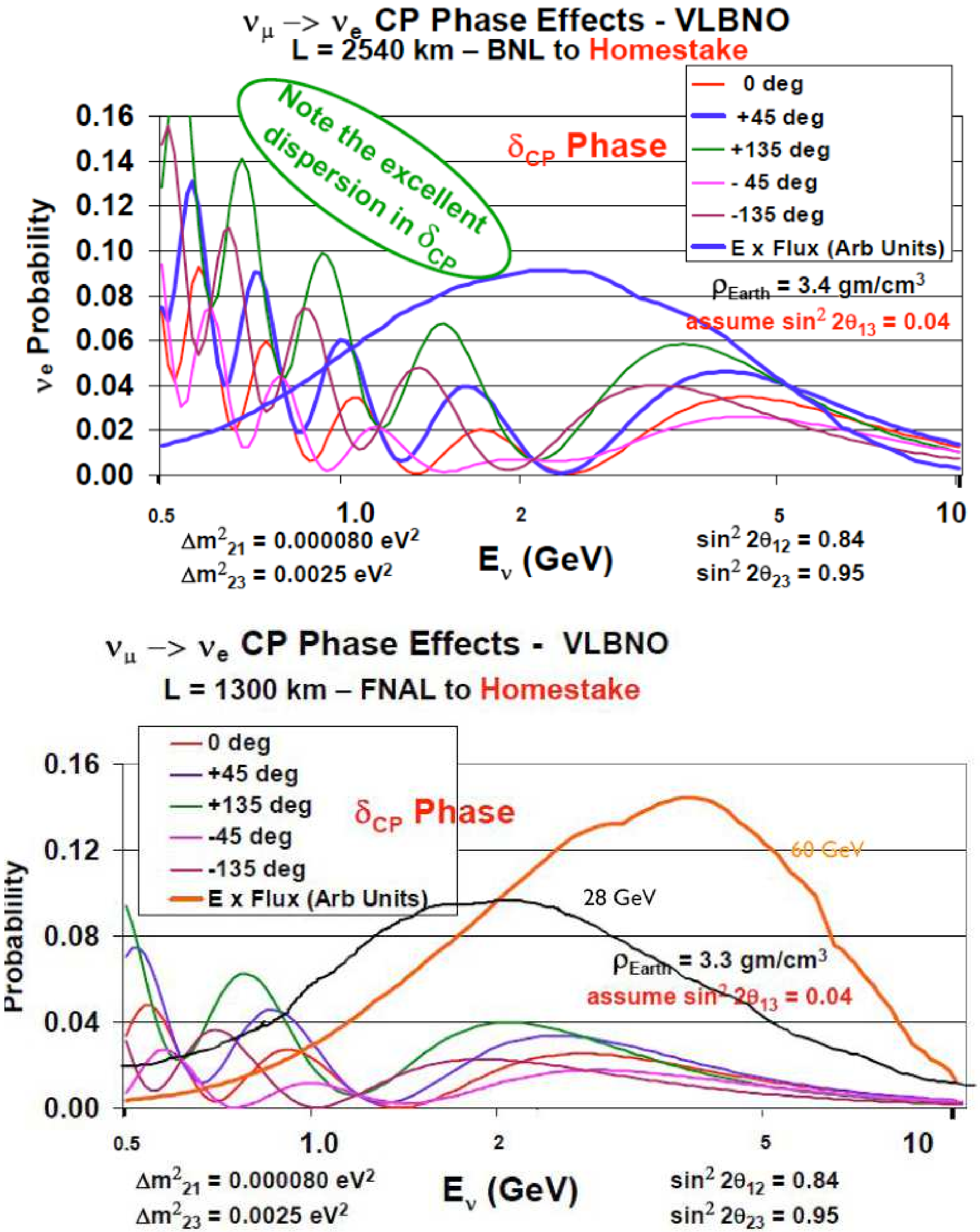

FIG. 2: Probability of $\nu_\mu \rightarrow \nu_e$ appearance as a function of ν energy for beams from BNL (top) and Fermilab (bottom) to a DUSEL site at Homestake Mine, SD

II. PROSPECTS FOR SITING A NEW HIGH-INTENSITY NEUTRINO BEAMLINE AT FERMI NATIONAL LAB

The current conceptual layout for siting a new neutrino beamline from Fermi National Lab to the two proposed DUSEL sites [8] [9] is shown in Figure 3. The siting layout shown

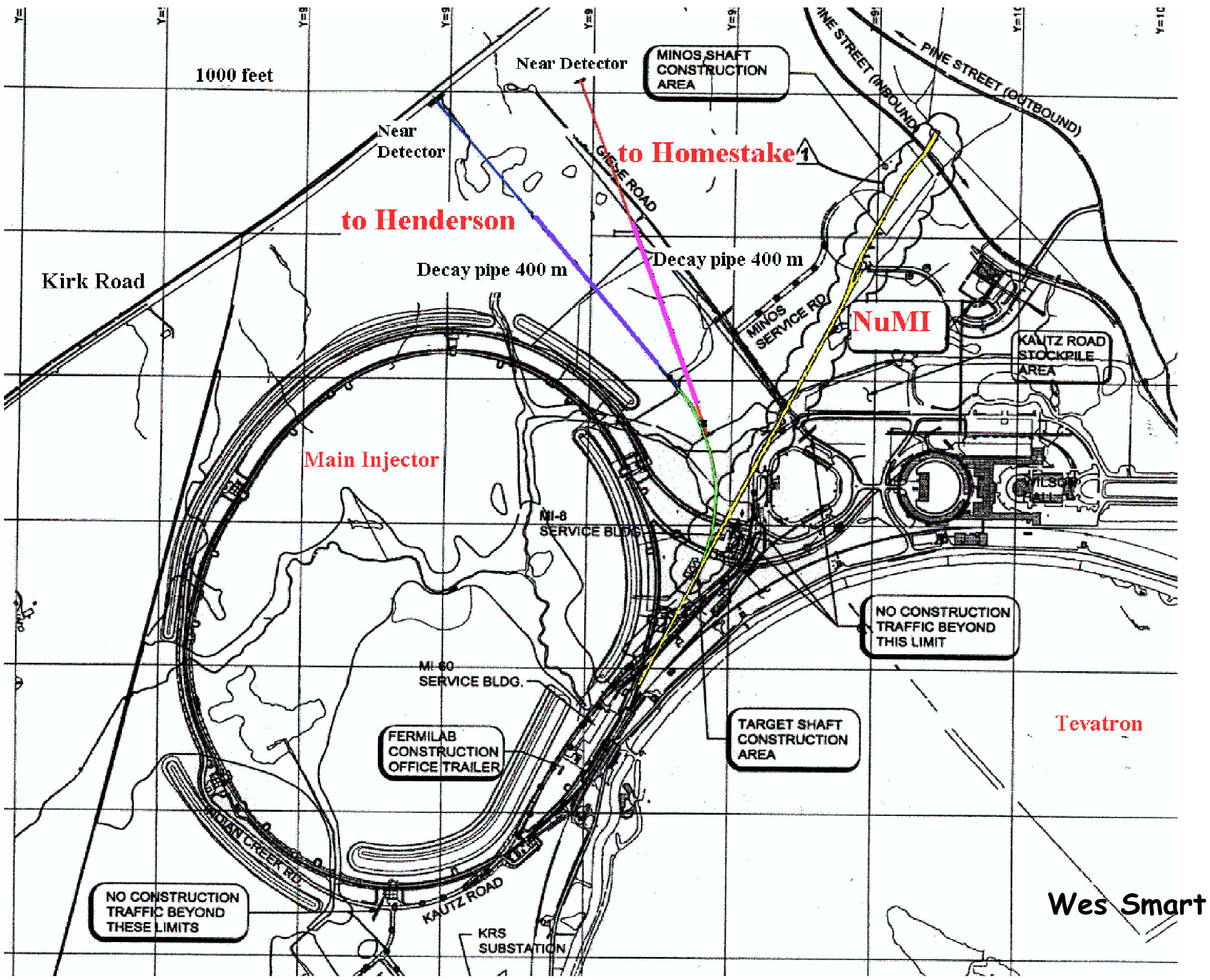

FIG. 3: Possible siting of a long baseline neutrino beamline from the Fermilab site to the two current proposed sites for DUSEL [8].

in Figure 3 has the following conceptual design elements:

- The present extraction of the Main Injector into the NuMI beamline will be used.
- An additional tunnel will be constructed starting from the approximate location of the NuMI lower Hobbit door in order to transport the proton beam to the west.

- The radius of curvature of the tunnel bending to the west will be similar to the Main Injecture curvature which will enable up to 120 GeV protons to be steered along the bend using conventional magnets.

- The target hall length is $\leq$ 45 m.

- A decay tunnel length of up to 400 m can be accomodated on the site assuming the near detector is 300m from the end of the decay pipe as in NuMI. A shorter decay pipe than the NuMI decay pipe (677 m) may be desirable to limit the production of higher energy neutrinos.

- The low energy neutrino flux can be enhanced by increasing the decay pipe radius. The widest span in the NuMI beamline is the MINOS detector hall width at 37 ft wide, which is at the limit possible in the Fermilab rock. For a $\leq$ 2 MW beam the concrete shielding needed around the decay pipe increases from the 4 feet used in the 400kW NuMI beamline to about 8 feet [11]. If we assume an extra 1m of clearance left between the decay pipe and tunnel, we find that decay pipes of up to 2.3m in radius may be accomodated. Larger decay pipes may be possible if more expensive thinner steel shielding is used instead of concrete.

Given the conceptual design parameters of the FNAL-DUSEL neutrino beamline outlined above, we will optimize the neutrino energy spectrum by varying the decay pipe widths up to 2m in radius and 400m in length. The BNL AGS neutrino beam used for the VLBNO experiment proposed at BNL [3] utilized a decay pipe which is 2m in radius and 180 m in length.

The time needed for a VLBNO experiment from Fermilab to a DUSEL site to reach the design sensitivity will depend on the neutrino flux in the oscillation region, the neutrino beam power and the size of the far detector. The conceptual design of a 2 MW High Energy Neutrino Source (HINS) at FNAL using the Proton Driver concept is explored in [13]. Recently, several studies at Fermilab [10] have indicated that the accelerator complex has the ability to increase the beam power up to 1MW (at 120 GeV) without the need for a

Proton Driver. The variation in beam power that could be delivered using by the existing complex as a function of beam energy is driven by the proton beam intensity that can be injected into the Main Injector and the Main Injector cycle time. In Figure 4 the MI ramp times at different proton energies is shown. In addition, the possibility of using both the existing recycler and anti-proton accumulator to store protons from the 8 GeV booster during MI cycles opens up the possibility of increasing the proton beam intensity injected into the MI each cycle. The beam power as a function of beam energy predicted for different upgrade possibilities to the accelerator complex is shown in Figure 5. We find that in the

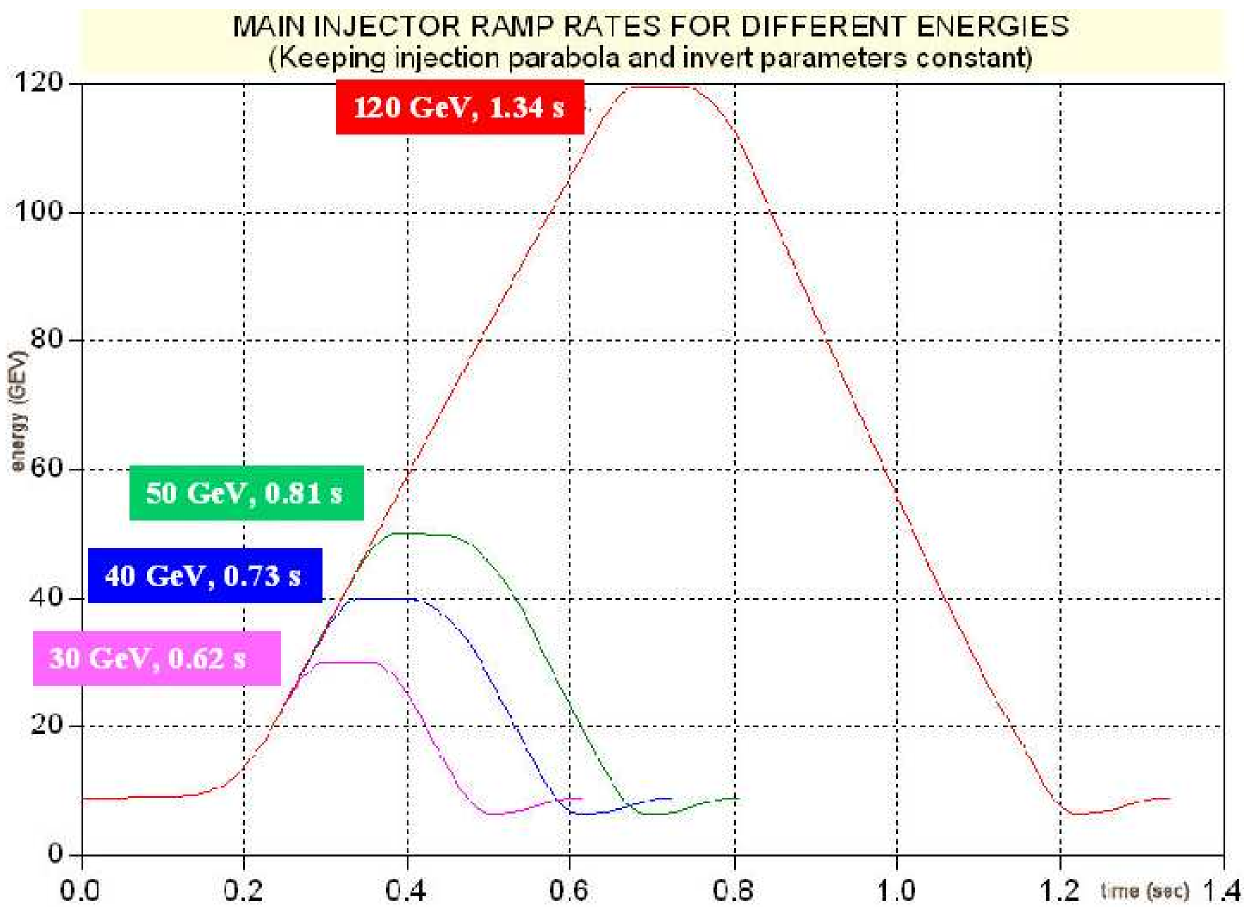

FIG. 4: Main injector ramp times at different proton beam energies [8].

40-60 GeV range, a 0.5 MW beam is possible with the current accelerator complex. Since the neutrino flux will increase with beam energy, it is the goal of these studies to determine whether the the same physics sensitivities previously obtained with the 28 GeV 1MW AGS

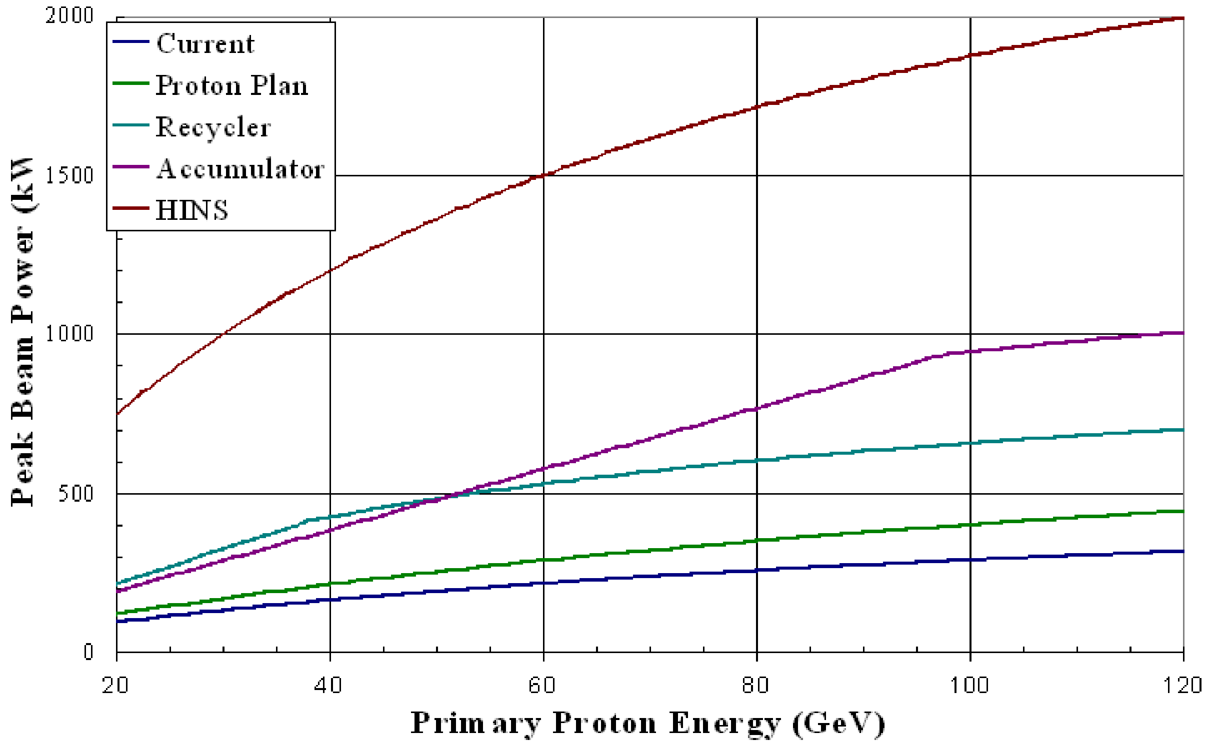

FIG. 5: Projections of main injector proton beam power as a function of beam energy for different upgrade scenarios under consideration at Fermi National Lab [10].

beam using a 180m long decay tunnel with a 2m radius may be achievable with a Fermilab 0.5 MW 60 GeV beam and longer, wider decay tunnel [14].

III. SIMULATION OF A WIDE-BAND LOW-ENERGY BEAM

In Figure 6, the spectrum of reconstructed charged-current (CC) neutrino interactions measured in the MINOS near detector is compared to the Monte Carlo simulation (MC) results. Both data and MC are absolutely normalized to the number of protons delivered to the NuMI beamline. We find that the NuMI/MINOS simulation predicts the absolute neutrino rate observed in the MINOS detector in the 0-7 GeV region to better than 10%. In the high energy region of > 10 GeV, the disagreement between simulation and data is around 30%. The preliminary studies from MINOS [5] indicate that a large fraction of the discrepancy between data and MC at large neutrino energies can be attributed to the uncertainty on the hadro-production models that predict the hadron spectrum produced when the proton beam interacts with the NuMI graphite target. These results from the MINOS experiment provide us with invaluable quantative information on how well the NuMI beam simulation predicts absolute neutrino rates in a working experiment. Using the NuMI simulation framework, we have produced a preliminary simulation of a wide-band low-energy (WBLE) beam. In this section we discuss the implementation of the target and horn design for a WBLE neutrino beam in the NuMI simulation framework.

A. Target simulation

The NuMI beam simulation uses FLUKA '05 [12] to generate the hadron spectrum from the interaction of the NuMI proton beam with a graphite target. The NuMI target design is described in [4]. The NuMI target is composed of 47 20 mm long graphite segments with 0.3 mm spacing. The width of each segment transverse to the proton beam is 6.4mm and each segment is 18mm high. The target is water cooled and is 1.9 proton interaction lengths long. The NuMI target geometry simulated in FLUKA 05 is shown in Figure 7. In Figure 8, the measurements of the proton beam rms in the NuMI pre-target region as a as a function of NuMI beam intensity per batch [15] are plotted. For the data collected from May, 2005 through Feb, 2006, the average NuMI beam intensity was 4-5 E12 protons/batch

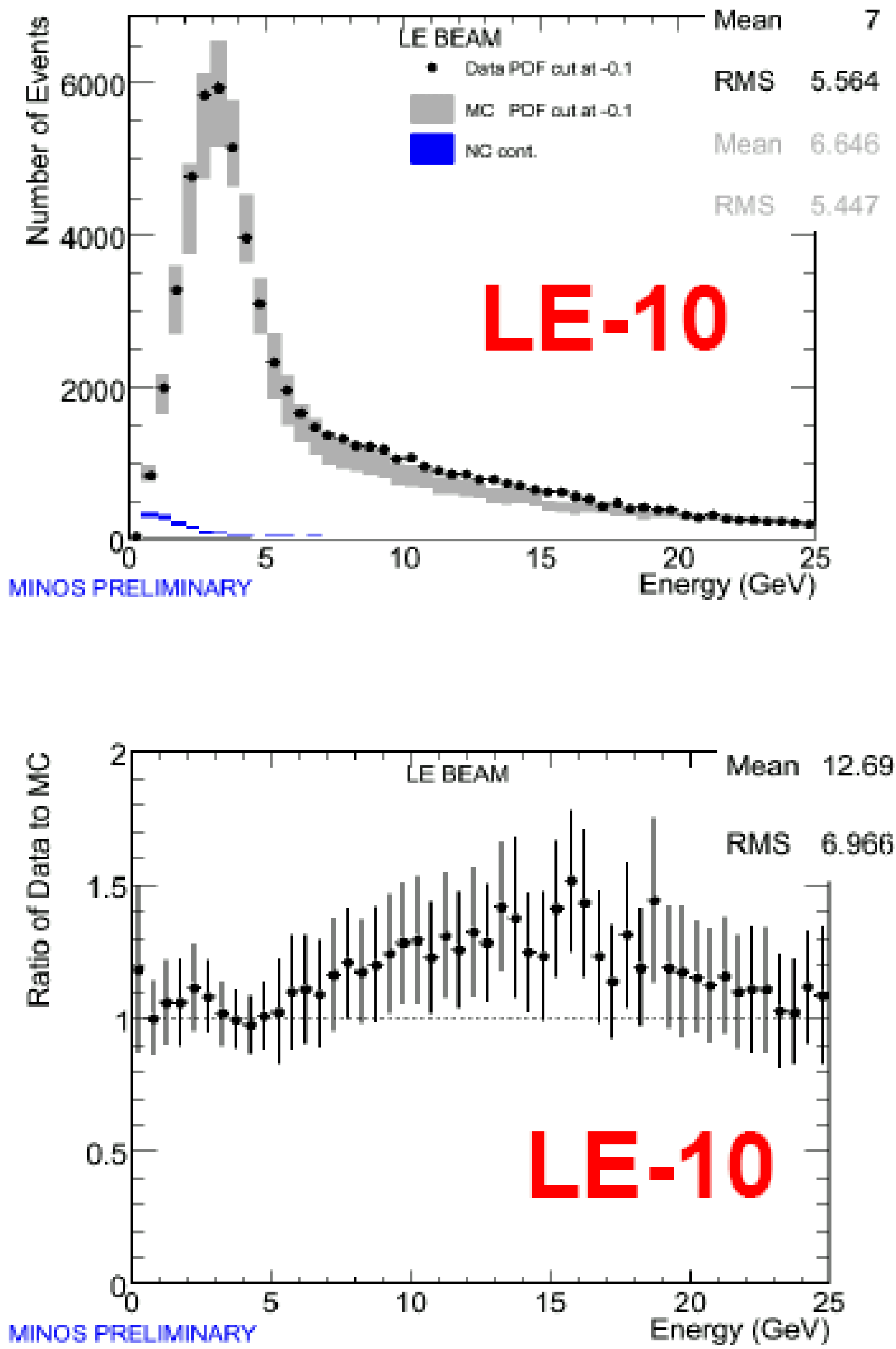

FIG. 6: Comparison between the MINOS near detector measured CC spectrum and the GEANT simulation of the NuMI beam using Fluka, 2005 for hadro-production on the target.

which correspond a proton mean beam rms of 1.1mm in the horizontal and 1.25 mm in the vertical. These measurements are used in the FLUKA '05 simulation of the NuMI proton

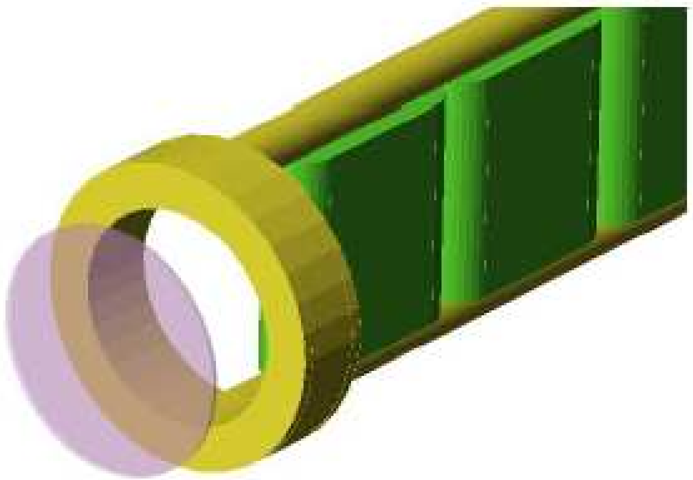

FIG. 7: NuMI target geometry as implemented in Fluka05. The target segments are green, the cooling tubes are shown in yellow and the Be window is shown in magenta.

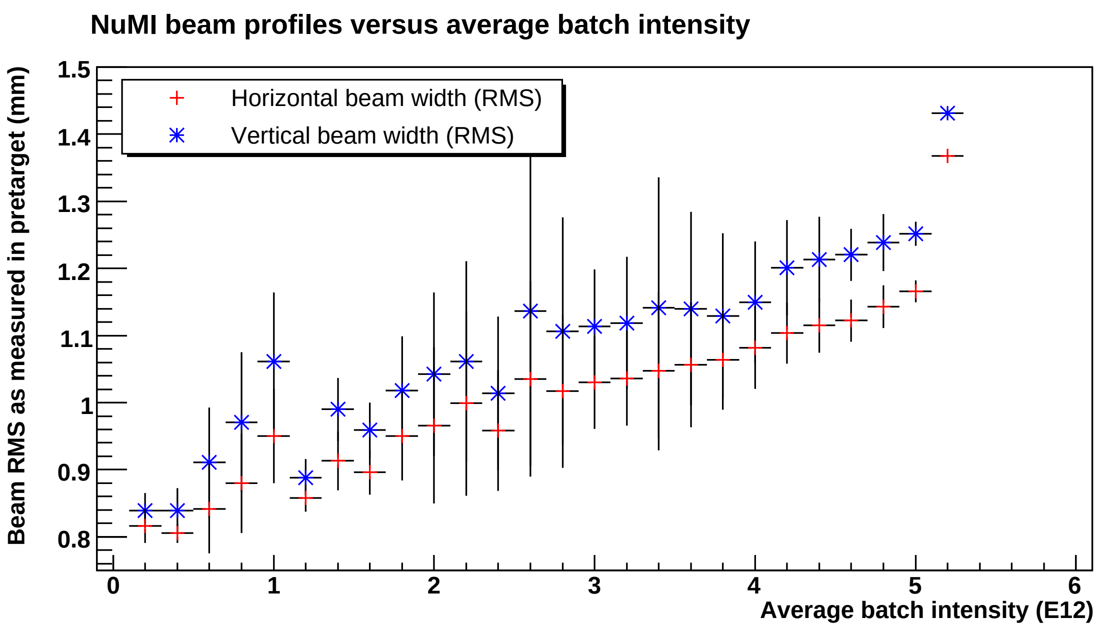

FIG. 8: NuMI beam profile as a function of batch intensity. The points are the mean beam rms and the error bars represent the spread at each batch intensity. The last point is from the first high intensity proton pulse delivered to NuMI using slip-stacked bunches. At this time slip stacking is still in study at NuMI and the beam profile measured for the slip-stacked pulse may not be representative of the beam profiles from well controlled slip-stacked pulses.

beam. The proton beam energy used in the NuMI simulation is 120 GeV.

For the WBLE simulation we use a target geometry based on the BNL AGS study of a WBLE neutrino beam [3]. The target simulation used is a 60 cm long [16] cylindrical rod of graphite with a 12 mm diameter. The AGS target design is cooled by circulating helium. The FLUKA '05 implementation of a simple graphite rod bathed in helium is shown in Figure 9. The maximum proton intensity that the current Fermilab MI can handle is around 60 E12 protons (10 E12/batch) at 120 GeV. Using the NuMI beam as a guideline and extrapolating from Figure 8, we use a proton beam rms of 1.5mm horizontally and vertically in the FLUKA '05 WBLE target simulation. We simulated hadro-production from the WBLE target using different proton beam energies varying from 28 to 120 GeV. The beam rms used was the same at all proton energies simulated.

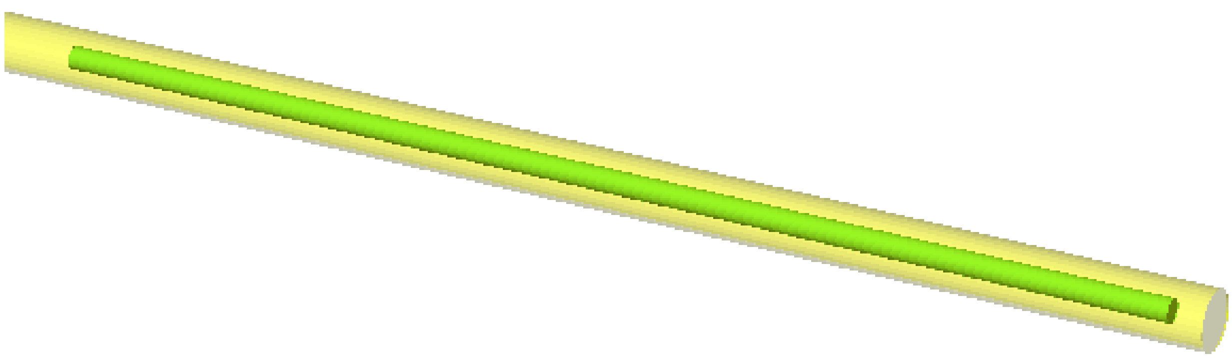

FIG. 9: WBLE target geometry as implemented in Fluka05

Table I summarizes the properties of the NuMI and WBLE target design and beam parameters used in the FLUKA '05 and GEANT simulation.

TABLE I: Target and beam parameters: NuMI and WBLE

Component	NuMI	WBLE
Target		
Shape:	47 rectanglular segments	solid cylindrical rod
	each 6.4mm wide × 18mm high	12mm diameter
	47x20mm = 0.954 m long	0.6 m long
Material:	graphite	graphite
Cooling:	water cooling tubes	Helium flow cooled
Other target area components		
Upstream shielding:	cylindrical graphite baffle	no baffle
	11 mm inner diameter	
	24 mm outer diameter	
	2 m long	
Instrumentation:	budal montor	no budal monitor
	48th segment	
	horizontal upstream	
Proton beam parameters		
Energy:	120 GeV	28, 40, 60, 120 GeV
Rms width:	$\sigma_x = 1.1$mm, $\sigma_y = 1.25$mm	$\sigma_x = 1.5$mm, $\sigma_y = 1.5$mm

B. Horn simulation

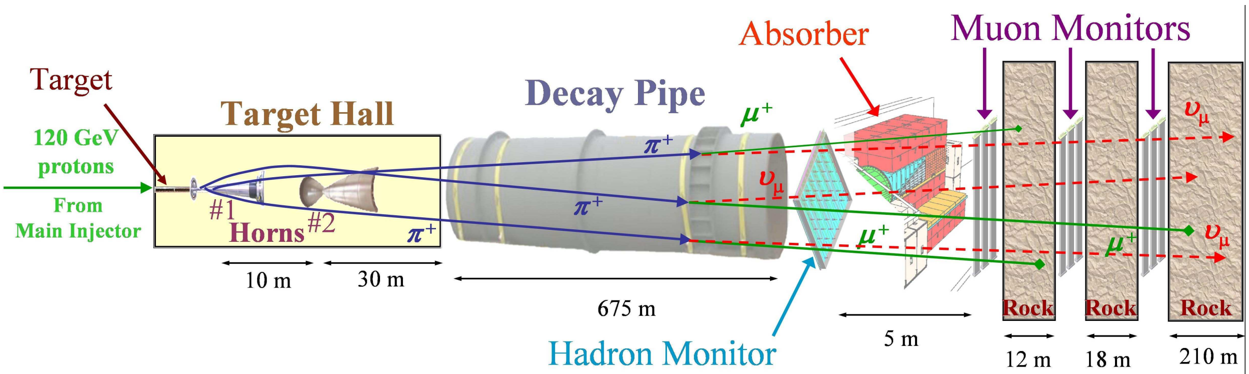

FIG. 10: Layout of the NuMI beamline

The NuMI beam uses two parabolic magnetic focusing horns to focus positively charged hadrons produced in the target in the momentum range of 1-10 GeV/c into a 677m long 1m radius decay pipe as shown in Figure 10. In the NuMI simulation GEANT version 3.21 [6] is used to swim the hadrons produced in the FLUKA '05 simulation through the focusing horns and into the decay region and the final hadron absorber. The NuMI horn shapes are double parabolic, the GEANT implementation of the NuMI horns is shown in Figure 11. The distance between the upper end of Horn 1 and the upstream end of Horn 2 is 10m. Figure 11 shows the path of hadrons produced in the target by several 120 GeV protons incident from the left as they propagate through the NuMI horns. In this simulation the horn current is set at 185 kA [5]. Some of the NuMI horn design parameters are summarized Table II.

In the current implementation of the GEANT simulation of the WBLE horns, we have used the horn geometry from the BNL AGS study [3] without further optimization. The WBLE horn parameters used in this study are summarized in Table II. This horn geometry was optimized for use with the 28 GeV AGS beam and may not be optimal for use with the higher beam energies available from the Fermilab MI. Studies are currently underway to further optimize the AGS horn design to better match the MI beam energies. We have used the NuMI GEANT implementation and replaced the NuMI horns with the AGS horns.

The AGS horn geomtery as it has been implemented in the NuMI GEANT framework is shown in Figure 12. The distance between the upper end of Horn 1 and the upstream end of Horn 2 is 10m. Figure 11 shows the path of hadrons produced in the target by several 120 GeV protons incident from the left as they propagate through the WBLE horns. In this simulation the horn current is set at 185 kA [5] for easy comparison to NuMI. The WBLE horns are designed to be run at currents up to 250 kA.

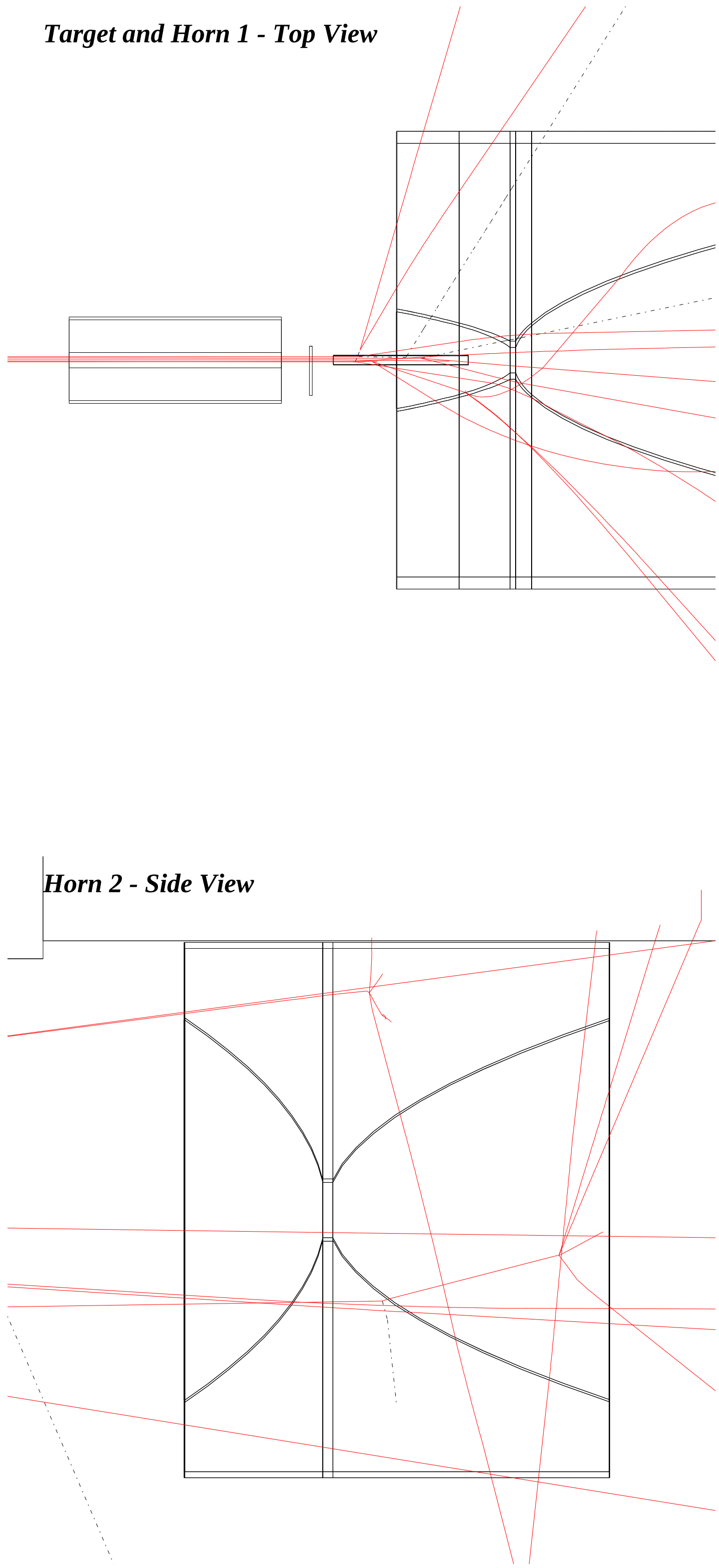

FIG. 11: GEANT simulation of the NuMI target and horns with 120 GeV p+. The vertical and horizontal scales are in the ratio of 1 to 10 (top) and 1 to 5 (bottom). The beam is incident from the left. The current used in this simulation is 185 kA.

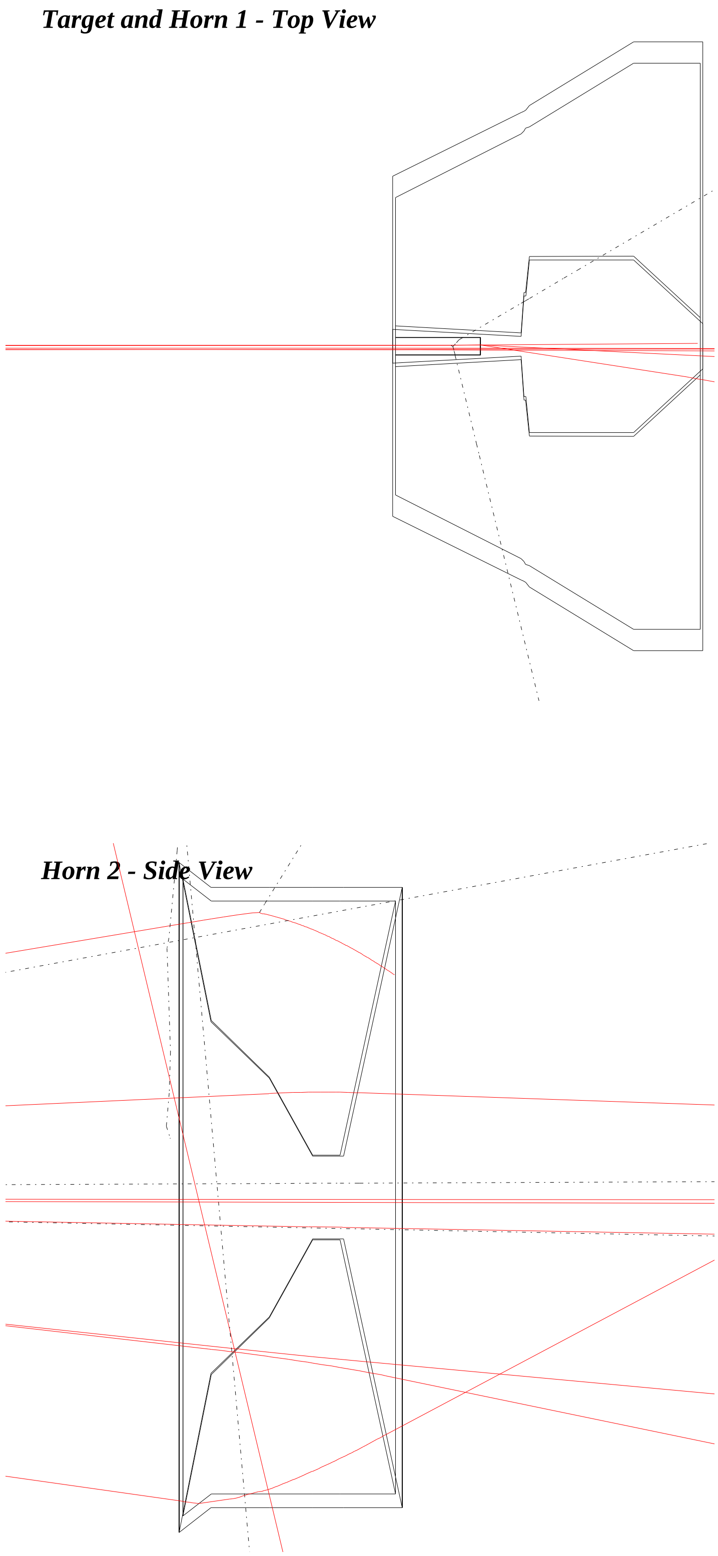

FIG. 12: GEANT simulatinon of the WBLE target and horns with 120 GeV p+. The vertical and horizontal scales are in the ratio of 1 to 10 (top) and 1 to 5 (bottom). The beam is incident from the left. The current used in this simulation is 185 kA.

TABLE II: Horn parameters: NuMI and WBLE

Component	NuMI	WBLE
Focusing magnetic horn 1		
Shape:	Double parabolic	AGS geometry
Conductor:	Al	Al
Inner conductor thickness:	2mm min	2.5 mm
	4.5mm (max at neck)	
Outer conductor :	11.75 inch ID 13.75 inch OD	-
Minimum aperture		
field-free neck:	9mm radius	7mm radius
Length:	3.3 m	2.19m
Current:	200 kA	250 kA
Cooling:	Water spray	Water spray
Focusing magnetic horn 2		
Shape:	Double parabolic	AGS geometry
Conductor:	Al	Al
Inner conductor thickness:	3mm min	1.5 mm
	5mm max	
Outer conductor :	29.1234 inch ID 31.134 inch OD	-
Minimum aperture		
field-free neck:	3.9cm radius	5.8cm radius
Length:	3.58m	1.57m
Current:	200 kA	250 kA
Distance from H1 upstream end	10m	10m
Cooling:	Water spray	Water spray

C. Target region layout and geometry

For the NuMI beam the target region which is shown with a yellow background in Figure 10, is 53m long, 6m wide, and 6m in height. The NuMI GEANT simulation includes concrete blocks used for shielding in the target and horn region, the concrete shielding used for the decay pipe, and the concrete blocks used as the hadron absorber at the end of the decay pipe. The target protection baffle is also simulated using GEANT. The GEANT simulation of the full target region, including shielding, is shown in Figure 13. The red lines indicate the path of charged hadrons (including the proton beam) through the simulation for a 120 GeV proton beam.

For the preliminary implementation of the WBLE target region simulation we have used a 6m wide and 6m high region. We varied the length of the target region depending on the length of the decay volume simulated. For a decay volume of 677m long (like NuMI) we use 50m long target region, for decay volumes of 180 and 380m, we used a shorter target region of 19m long, effectively moving the end of WBLE horn 2 as close as possible to the decay pipe window. We have not yet included any concrete shielding in the target area. The GEANT simulation of particles from a 120 GeV beam incident on the WBLE target and horns in the target region is shown in Figure 14

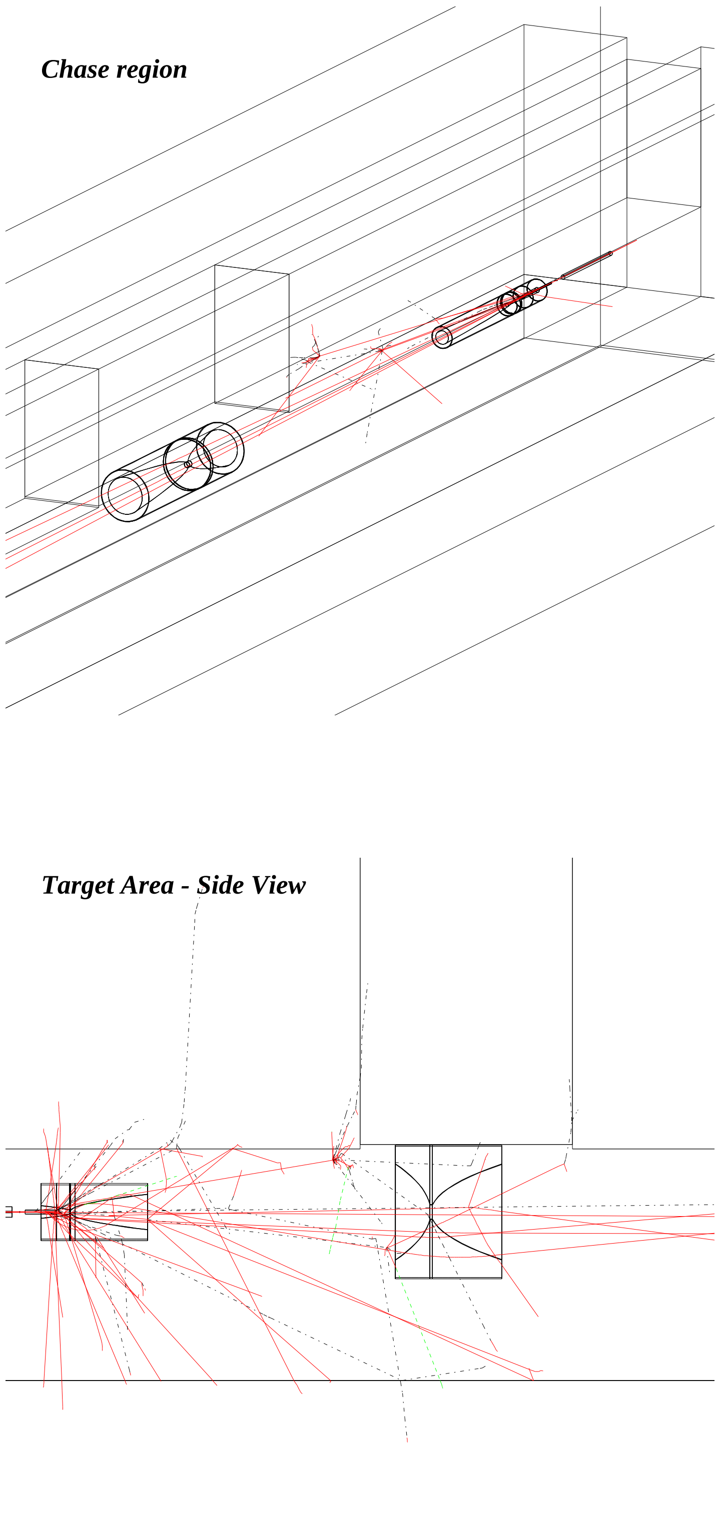

FIG. 13: GEANT simulation of the NuMI target and chase region with 120 GeV p+

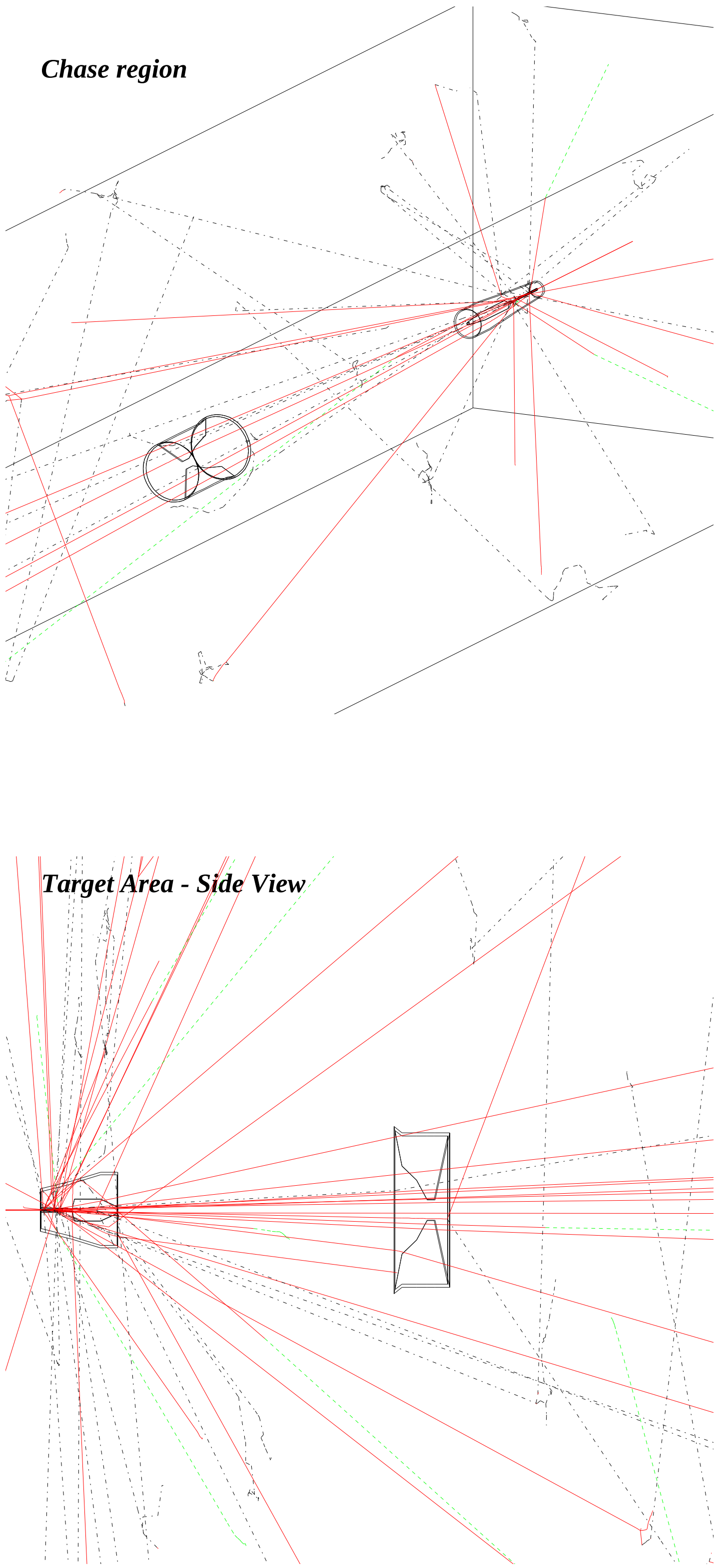

FIG. 14: GEANT simulation of the WBLE target and chase region with 120 GeV p+. The shielding blocks present in the NuMI simulation have been removed for this study.

D. Comparative studies with NuMI and AGS simulations

The WBLE target and horn design in the current FLUKA '05/GEANT simulation was optimized for the 28 GeV AGS beam. To determine how well the design functions at the highest energies we compare the neutrino flux at 1km from the target produced by the NuMI target and horn design to that produced from the WBLE target and horns. In this simulation we have kept the decay tunnel and target region geomtries identical for the NuMI and WBLE simulation - only the targets and horns have been changed. The proton beam energy is set at 120 GeV. We used two settings for the horn currents for each beamline: 0kA and 185 kA. The results of the comparative study of the NuMI beamline in its standard operating mode to that of the WBLE beamline design is shown in Figure 15. We observe

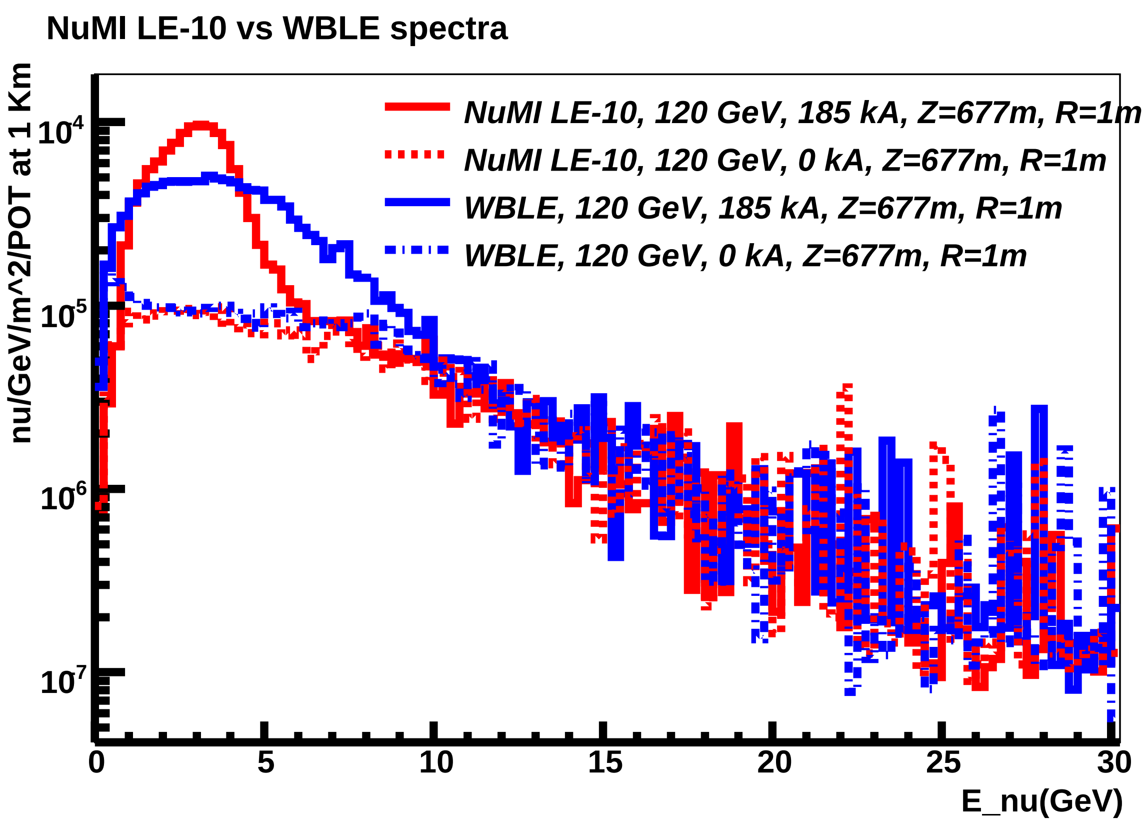

FIG. 15: The neutrino flux from the WBLE horn and target design as compared to the NuMI neutrino flux. The beam energy of 120 GeV and the target area and decay tunnel geometries are identical in both simulations. The results are shown for the horn currents set to 0 and 185 kA.

the following:

- The high energy tails from unfocused hadrons in both the NuMI and WBLE simulations are almost identical in magnitude for energies $> 10GeV$. This gives us confidence that the normalization of the absolute neutrino rates obtained from this new WBLE simulation is reliable based on the measurements done with the MINOS near detector.

- The shape of the spectrum in the region 0 to 10 GeV is much broader in the WBLE simulation as compared to NuMI with more neutrinos produced in the sub GeV range. This validates that the AGS horn and target design does indeed produce a wide-band beam with enhanced flux in the very low energy region as expected.

- The integrated neutrino flux at 1km from the target in the region 0-10 GeV from the WBLE and the NuMI simulation is $3.075\times10^{-4}\nu/m^2$/POT and $2.98\times10^{-4}\nu/m^2$/POT respectively. This indicates that even though the WBLE horn and target designs have not been optimized for the higher energy beam, the integrated neutrino flux is only a few % different from that produced by the NuMI beamline even though the shapes of the neutrino energy spectra are very different.

- When the horns are turned off the absolute neutrino flux from the WBLE and NuMI in the 1-10 GeV range is almost identical. This is a validation that the hadron-production from the WBLE target simulation implemented in FLUKA'05 is in good agreement with the expectations from NuMI. There is an enhancement of the WBLE flux in the sub-GeV range compared to NuMI that needs further investigation, but could be a result the much shorter target geometry.

- The ratio of the WBLE flux at $<$ 5 GeV to that at $>$ 5 GeV for this beam energy and decay tunnel design is only 1.7:1.0. This implies that the NuMI beam energy and decay tunnel design is far from optimal for the VLBNO experiments envisioned in [1] and [2].

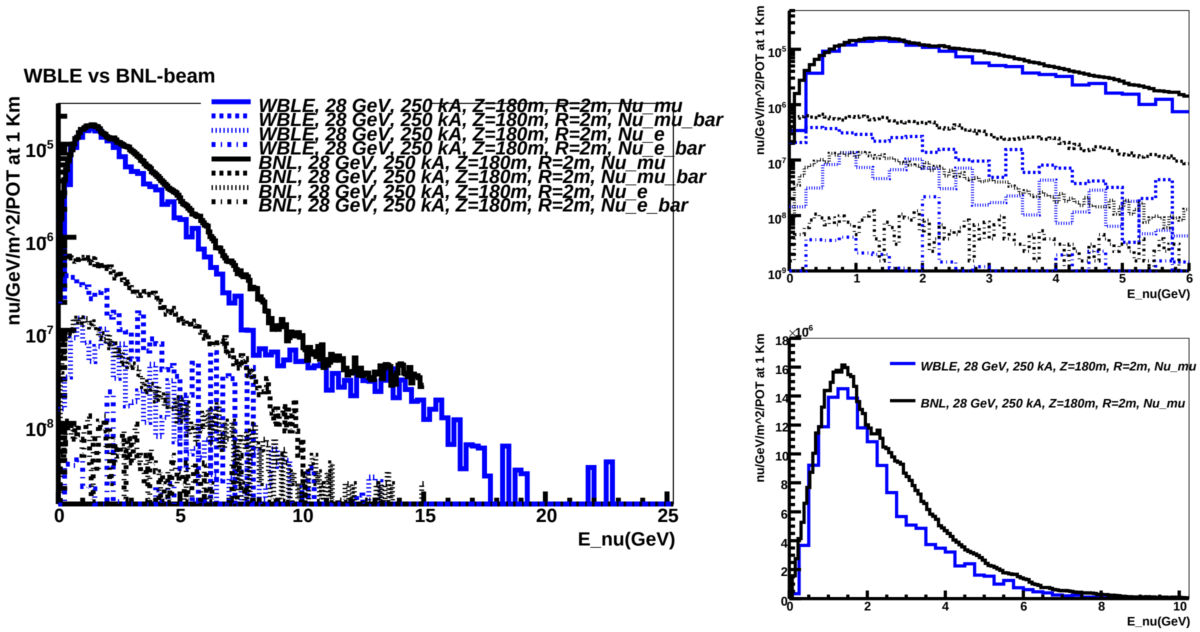

FIG. 16: Comparison of the WBLE simulation for a 28 GeV beam with the previous results obtained in the BNL study

The current estimates of the physics sensitivities of a wide band on-axis long baseline experiment [1] [2] used a simulation of 28 GeV beam from the BNL AGS with the same horn design as described previously. We compare the neutrino flux from these recent simulations with the previous results in Figure 16. The decay pipe geometry in the new WBLE simulation is set to be 2m in radius and 180m long to match the AGS study and the horn currents are set to 250 kA. It is to be noted that the target simulation used in the AGS study was based on an older version of GEANT (what version and what hadro-production model ??) and the current WBLE target simulation uses FLUKA '05. Both these simulations are therefore expected to have very different hadro-production spectra. There are some other minor discrepancies between the two simulations that have not yet been corrected: the target is 0.8m long in the AGS study and the distance between horn 1 and horn 2 is 8.3m whereas the target length is taken to be 0.6 m in the WBLE simulation and the distance between the two horns is 10m. There also some minor residual discrepancies in the horn conductor thicknesses between the two studies and the details of the target region geometry. The results shown in Figure 16 demonstrate that the peak energy and the flux at the peak are in good agreement in both simulations. The integrated flux in the region of 0-3 GeV for the AGS and WBLE simulations is also in good agreement being $3.35 \times 10^{-5} \nu/m^2$/POT and $2.93 \times 10^{-5} \nu/m^2$/POT respectively. The spectrum from the two simulations at energies > 3 GeV is very different, with the WBLE simulation predicting much lower fluxes at high energy. In addition the anti-neutrino rate is almost an order of magnitude lower in the WBLE simulation. This indicates that if the WBLE simulation is indeed more representative of the real neutrino flux, then previous studies could have overestimated the feed-down background in the low observed energy regions.

IV. OPTIMIZATION OF THE FERMILAB WBLE BEAM SPECTRUM

In the previous section we demonstrated that the energy of the NuMI beam and the NuMI decay tunnel are not optimal for the next generation VLBNO experiments using a WBLE horn and target design. Siting restrictions at Fermilab for a beamline to DUSEL limit the decay pipe length to $<$ 400m and the radius to $<$ 2m. In Figure 17, we compare the WBLE neutrino flux from a 60 GeV MI beam with the NuMI decay volume geometry (1m radius 677 m length) and a decay volume that is 380 m long and 2m in radius. We find that the wider-shorter decay volume geometry produces a larger flux in the desired region of 0-5 GeV, a small flux in the region 5-15 GeV and similar flux at $>$ 15 GeV. We use a horn current of 200 kA in this study. The different neutrino fluxes from the WBLE beamline design using

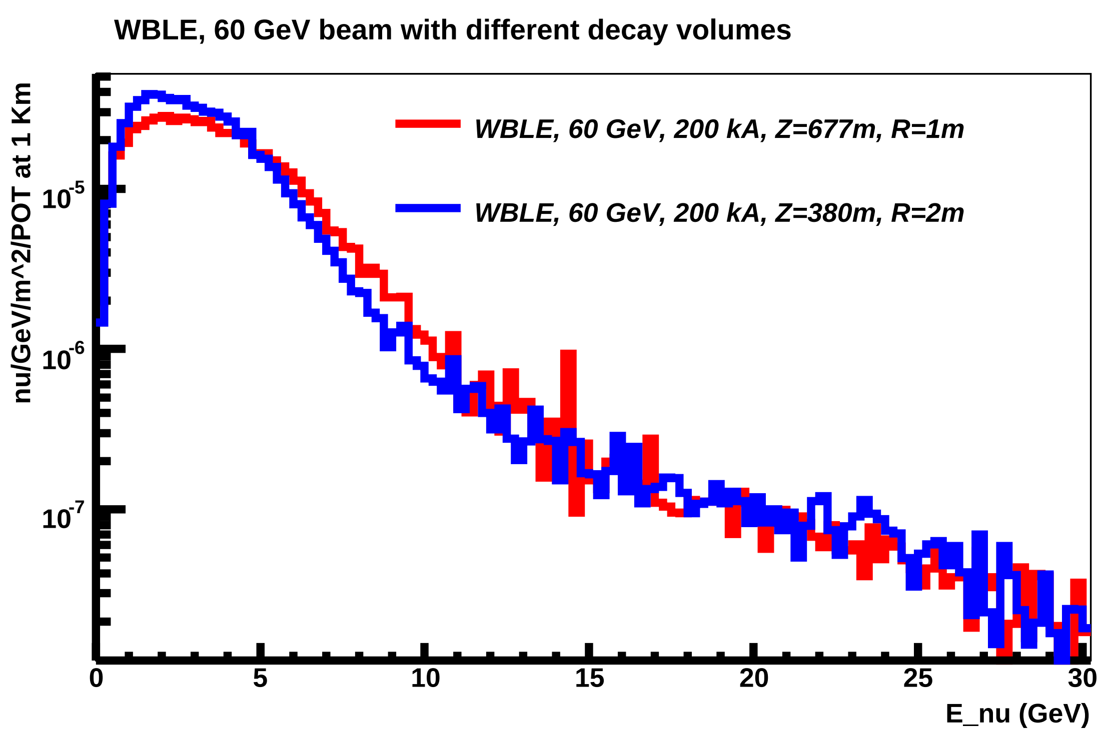

FIG. 17: WBLE neutrino fluxes at 1km using 60 GeV and different decay volume geometries. The decay volume is cylindrical where R is the decay volume radius and Z indicates the decay volume length.

different beam energies and decay tunnel geometries are shown in Figure 18. The BNL

AGS neutrino spectrum is also shown for comparison. The properties of the neutrino flux

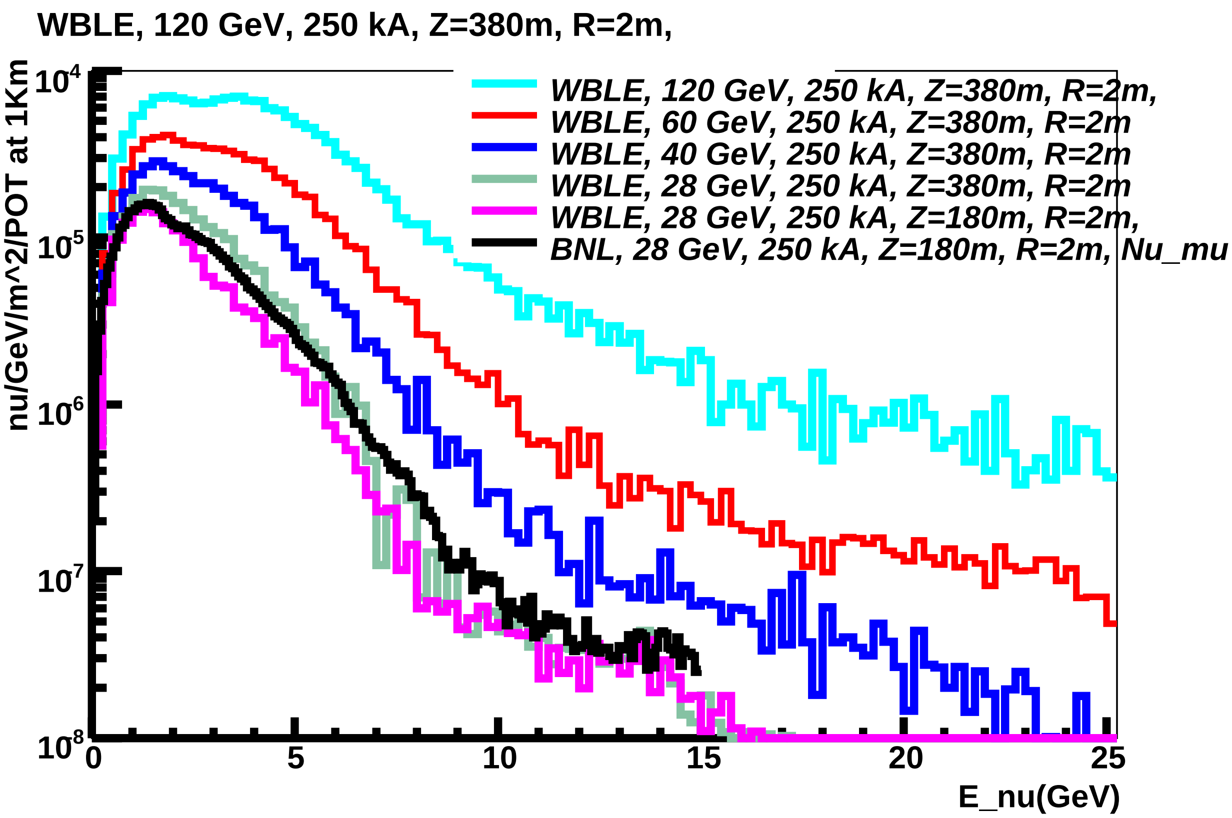

FIG. 18: WBLE neutrino fluxes at 1km using different energies and decay volume configurations. R is the decay tunnel radius and Z indicates the decay tunnel length.

spectrum from some of the different WBLE beam configurations studied are summarized in Table IV. To better assess the VLBNO physics potential of different beam spectra, the CC event rate as a function of POT and detector size expected from each beam scenario is summarized in Table IV. The CC rate is calculated at a distance of 1297 km from the near detector, which corresponds to the distance from Fermilab to Homestake Mine, SD. We find that the 40 GeV MI WBLE beam is a close match in the ratio of low energy relative to high energy neutrino flux to the AGS beam, but with 50 % larger integrated CC rate at the far detector. The 60 GeV MI WBLE beam has a factor of 2 higher ratio of the neutrino flux at > 5 GeV to < 5 GeV as compared to the AGS beam but we gain a factor of 3 increase in integrated CC rate at the far detector. This indicates that it might be possible to achieve the same sensitivity estimated for the 1MW 28 GeV AGS beam coupled with a 500 kT far detector using a 0.5 MW 60 GeV MI beam coupled with a 300 kT far detector if the neutral current backgrounds from the high energy tails can be kept under control. The possibility of using a beam plug between the two WBLE horns to eliminate the high energy tail with minimal effect on the low energy region is currently under study.

TABLE III: Properties of different WBLE designs as compared to the NuMI and BNL beams,

Beam Scenario	Peak E (Flux at 1km) $\nu/(\text{GeV.m}^2\text{.pot})$	E, 50% max flux GeV	E, 10 % max flux GeV	Flux ratio $\frac{<5\text{ GeV}}{>5\text{ GeV}}$	Purity Total
NuMI LE-10	3.1 ± 0.13 GeV	4.1 ± 0.13	6.1 ± 0.13	4.1	89% ν_μ
Z=677, R=1m	(9.7×10^{-5})				1% ν_e
WBLE 60 GeV	1.6	4.4	7.1	5.0	94% ν_μ
Z=380, R=2m	(3.9×10^{-5})				0.9% ν_e
WBLE 40 GeV	1.6	3.9	6.4	8.3	95% ν_μ
Z=380, R=2m	(2.6×10^{-5})				0.9% ν_e
WBLE 28 GeV*	1.4	3.4	5.6	15	96% ν_μ
Z=380, R=2m	(1.9×10^{-5})				0.8% ν_e
WBLE 28 GeV*	1.4	2.6	5.1	17	97% ν_μ
Z=180, R=2m	(1.5×10^{-5})				0.6% ν_e
BNL 28 GeV*	1.39 ± 0.04	3.11	5.81	11	95% ν_μ
Z=180, R=2m	(1.6×10^{-5})				0.7% ν_e

We have also studied the effect of running the WBLE horns at 200 kA instead of the 250 kA design current. This should increase the lifetime of the horns, and matches the experience gained from the NuMI horns which have been shown to run reliably at 200 kA. The results are shown in Figure 19. We find no significant gain in going to the higher horn current of 250 kA for beam energies of 40 and 60 GeV.

Based on these preliminary results of the simulation of a WBLE beam spectrum and event rates from the Fermilab MI beam, we recommend further consideration of the physics sensitivities using the 40 and 60 GeV beam configurations shown Figure 20.

TABLE IV: Charged-current rates for Fermilab-HOMESTAKE using different WBLE designs. For comparison the numbers for NuMI and the BNL design are also noted.

Beam Scenario	Peak E (CC rate) /(GeV.10^{20} pot.kT)	CC rate 1st osc max /(GeV.10^{20} pot.kT)	CC rate 2nd osc max /(GeV.10^{20} pot.kT)	Total CC rate /(10^{20} pot.kT) (distance)
NuMI LE-10 Z=677, R=1m	3.6 GeV (18)	6.1	0.13	82 (735 km)
WBLE 60 GeV Z=380, R=2m	3.9 (2.3)	2.1	0.55	13 (1297 km)
WBLE 40 GeV Z=380, R=2m	2.4 (1.2)	1.2	0.40	6 (1297 km)
WBLE 28 GeV Z=380, R=2m	1.9 (0.85)	0.78	0.30	3.4 (1297 km)
WBLE 28 GeV Z=180, R=2m	2.1 (0.67)	0.56	0.30	2.4 (1297 km)
BNL 28 GeV Z=180, R=2m				~ 4 (1297 km)

V. SUMMARY

We have implemented a simulation of a Wide-Band Low-Energy (WBLE) neutrino beam using a new beamline sited at Fermi National Lab and directed towards a possible DUSEL site. We use the FLUKA '05 particle transport code to model the hadron production spectra obtained from a proton beam on a graphite target. We have used the NuMI GEANT (v3.21) based simulation framework to simulate the hadron transport from the FLUKA '05 target simulation through the BNL AGS horn geometries and decay pipe. We have a preliminary determination of the possible decay volume geometries based on the conceptual layout of a Fermilab to DUSEL neutrino beamline utilizing the NuMI extraction region. We have studied the neutrino flux at 1 Km and CC event rates at the far detector for different

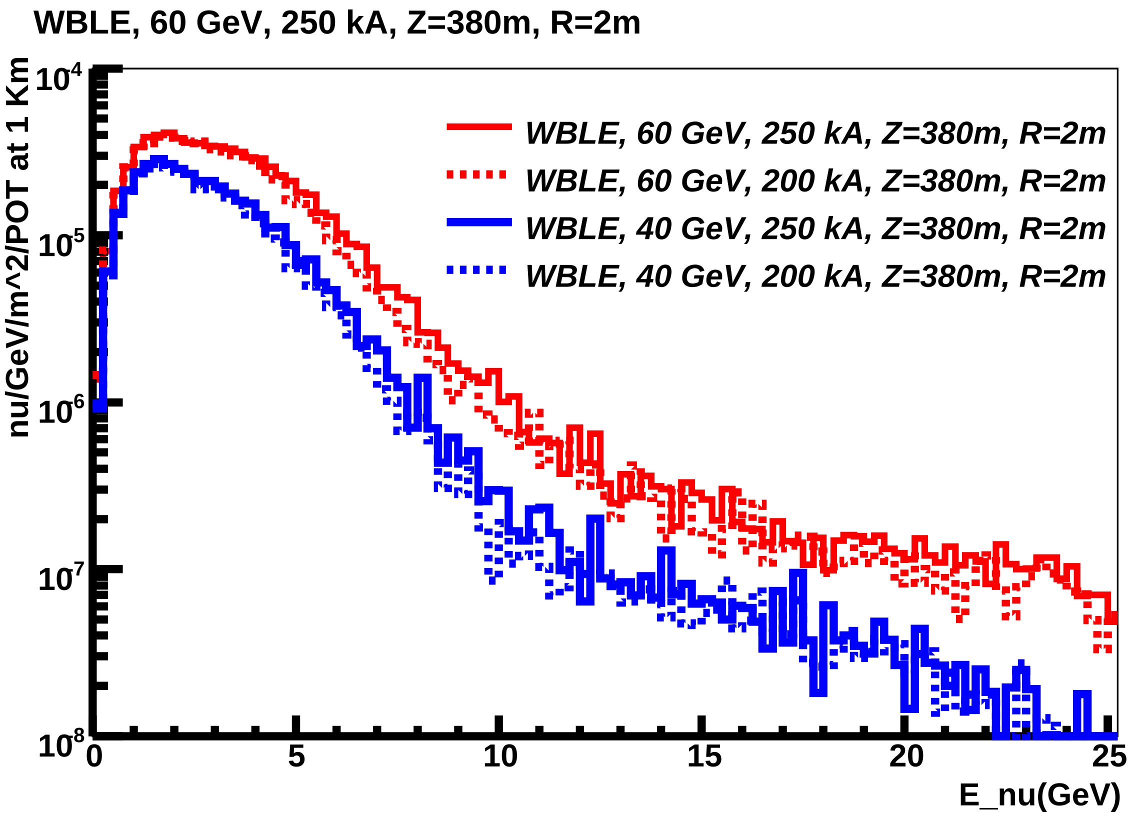

FIG. 19: WBLE 40 and 60 GeV beam neutrino fluxes using different horn currents

MI beam energies, horn currents and decay volume geometries. The simulation has been validated by comparing to the NuMI beamline results and to the previous AGS design. The real-life performance of the NuMI beamline simulation and flux prediction is now well understood from the analysis of 1 year of data collected by the MINOS experiment's near detector. We find that the it may be possible to reach the design sensitivities of a VLBNO experiment using a 40-60 GeV WBLE beam from Fermilab to DUSEL with lower power ($<=$ 1 MW) and smaller far detector than previously thought, provided the NC background from the larger high energy neutrino tails is kept under control. The advantage of being able to run with only 500 KW beam power at 40-60 GeV is that such power levels can be achieved with minor upgrades to the current Fermilab accelerator complex and without the need of an expensive Proton Driver.

The estimation of the physics sensitivies using the Fermilab WBLE on-axis neutrino

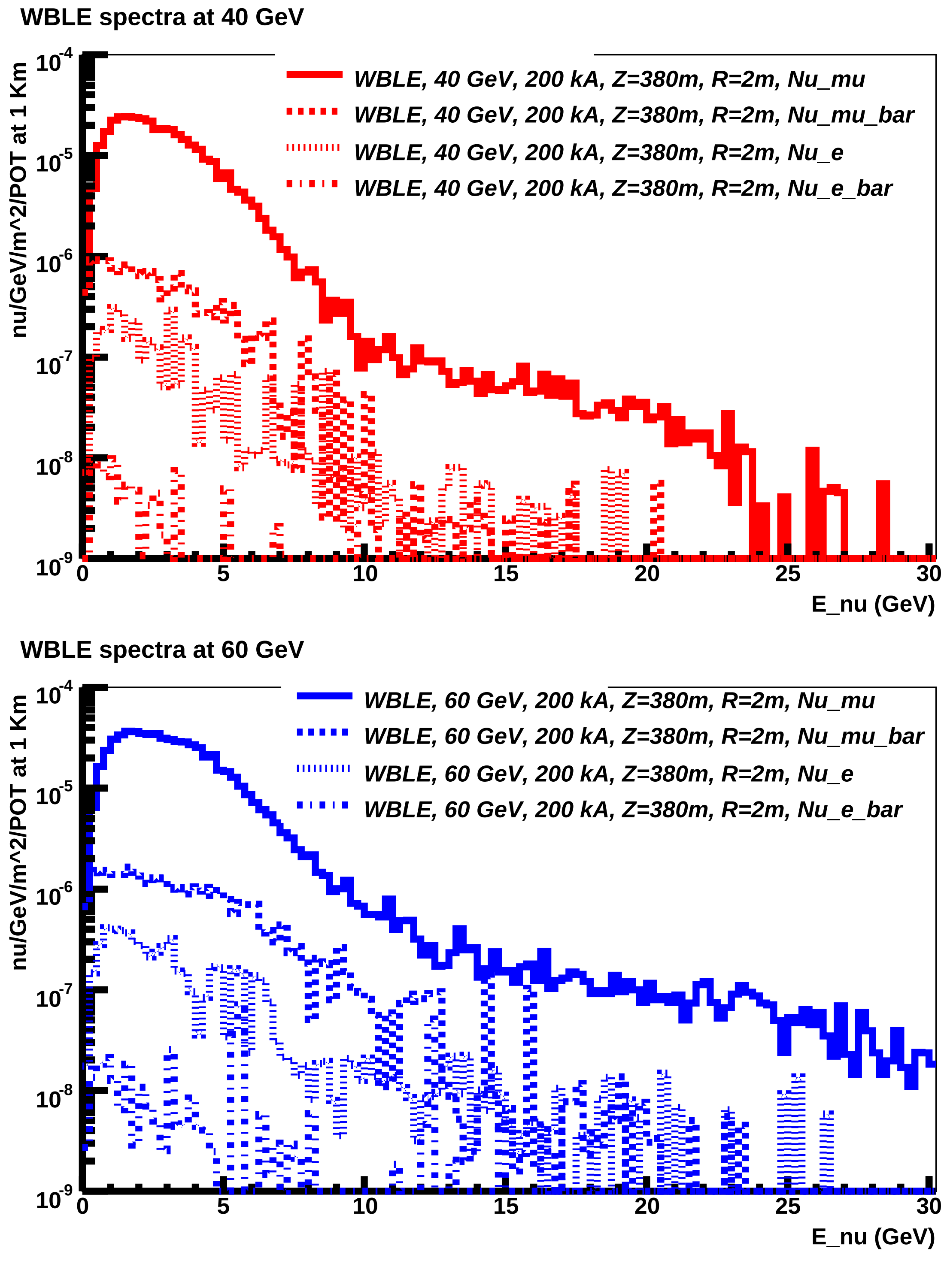

FIG. 20: WBLE 40 and 60 GeV beam spectra and flux components

spectra produced from our preliminary beamline simulation is currently underway.

Acknowledgments

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[14] Since the beam power at 60 GeV from the existing complex will be ≤ 0.5 kW the thickness of the decay pipe shield will be greatly reduced from the 2MW requirement and an a decay pipe > 2m in radius may be accomodated

[15] The NuMI proton pulse is divided into 6 batches, each batch corresponds to a single extraction from the Fermilab booster to the Main Injector

[16] The AGS study recommended an 80 m long cylindrical rod made of a carbon-composite material with a beam rms of 2mm for intensities of 100 E12 28 GeV protons per pulse.