Modification of LBNF Beam, Concept

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Abstract
This note describes modified proton and pion beam lines for LBNF that will provide usage of a multi megawatt proton beam. Two options are considered:

Option 1) Pion beam bent downward for 5.7 degrees,
Option 2) Pion beam and proton beam each bent downward for 2.88 degrees.
Option 2, allows for off axis running at oscillation secondary maxima.

Introduction

At present LBNF[1] is designed to operate with proton beams up to 2.4 MW. The concept is shown in Figure 1.

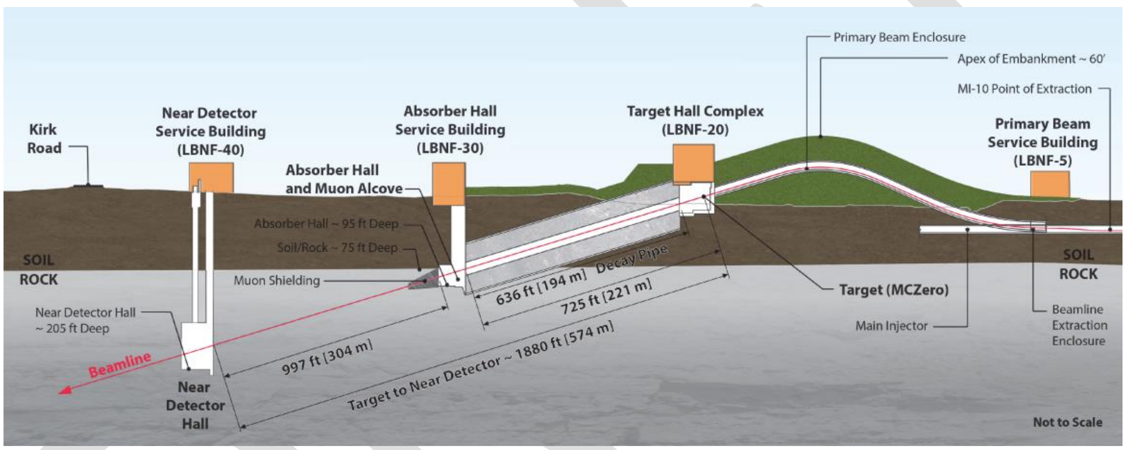


Figure1. present LBNF concept, not to scale.

The assumption is that the multi megawatt proton beam will hit the target aimed downward at 5.7 degrees, pions will be collected with one or more Horns and will enter the ~220 m long decay pipe. The neutrinos from pion decays will travel ~1300 km and hit the DUNE detector located in the Sanford Underground Research Laboratory in South Dakota. From MARS simulations [2] of energy deposition, it is expected that ~40% of the beam power is deposited in the Target Hall Complex, 30% in the Decay Pipe region and 30% by the Absorber complex at the end of the Decay Pipe.
To contain the radiation produced by the decay products of the beam, the Decay Pipe is designed to have a 4 m inside diameter, Helium filled and with a wall made out of 5.6 m of concrete shield, as shown in Figure 2a and Figure 2b.

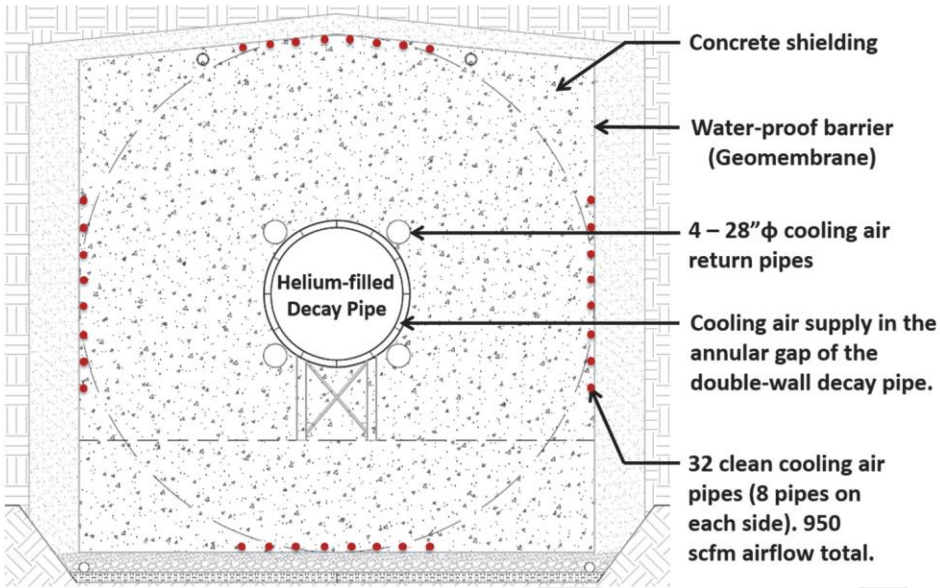


Figure 2a. Cross section of Decay Pipe, Target complex

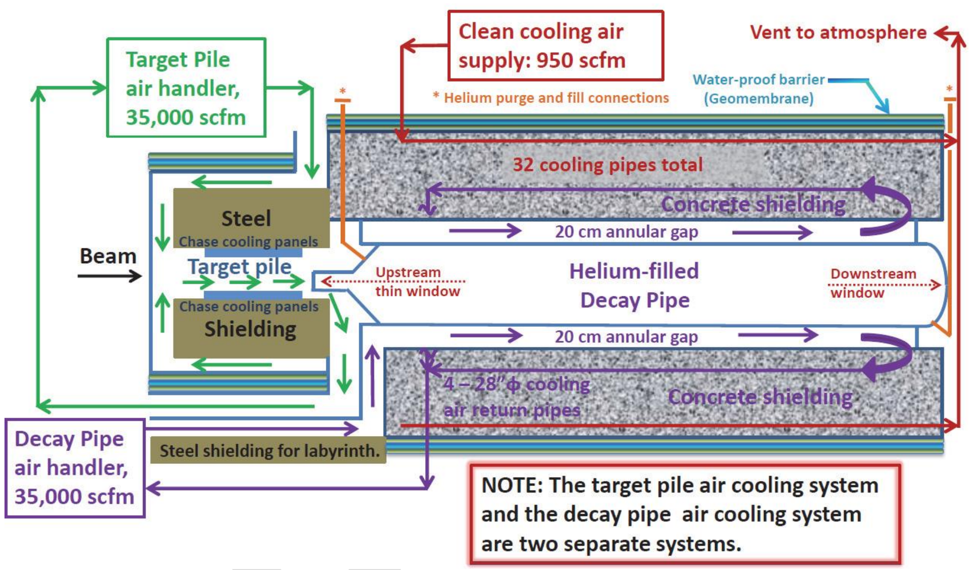


Figure 2b. Target complex and Decay Pipe, not to scale.

The Target Complex is show in Figure 3 and the distance from the target to the entrance of the Decay Pipe is ~25 m.

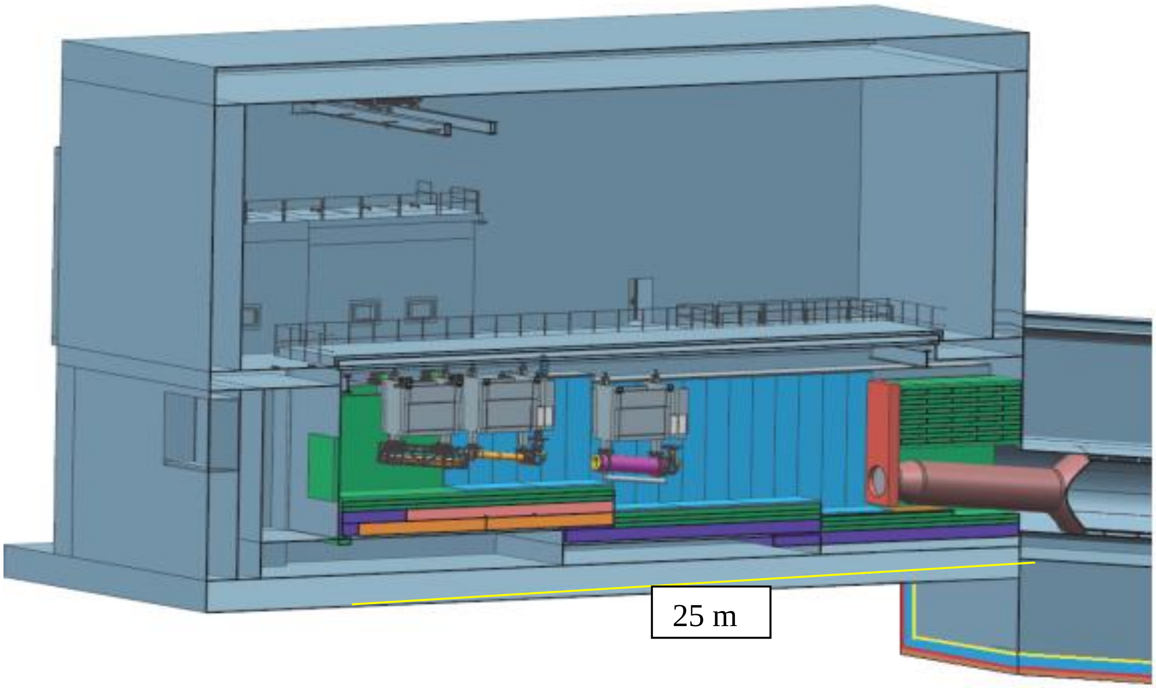


Figure 3. Target Complex. Proton beam enters from the left.

The next two sections will outline two possible modifications of the described concept.

Modified LBNF Beam Lines, 5.7 degree bend of Pions, Option 1

We assume the proton beam hits the target housed in Horn 1 and the main dump is in the forward direction as shown in Figure 4. This option does not require a hill to bring the proton beam onto the target.

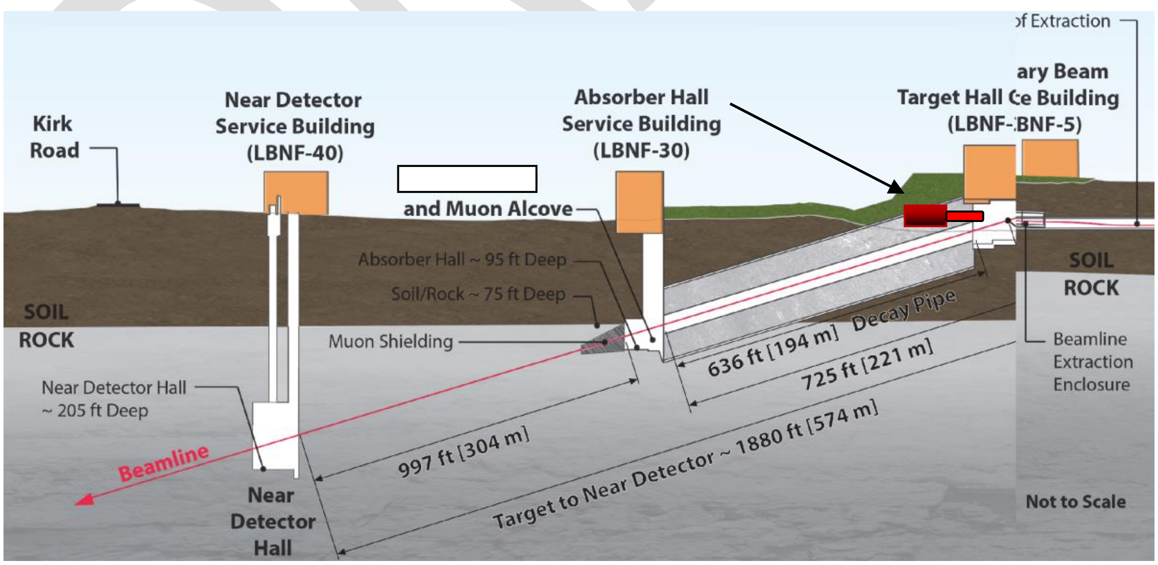


Figure 4. LBNF as described as Option 1 in this note. Main Dump is depicted as red object, not to scale.

As shown in the Figure 5, the beam coming from the exit of Horn 1 is then bent downward at 5.7 degrees toward the DUNE detectors.

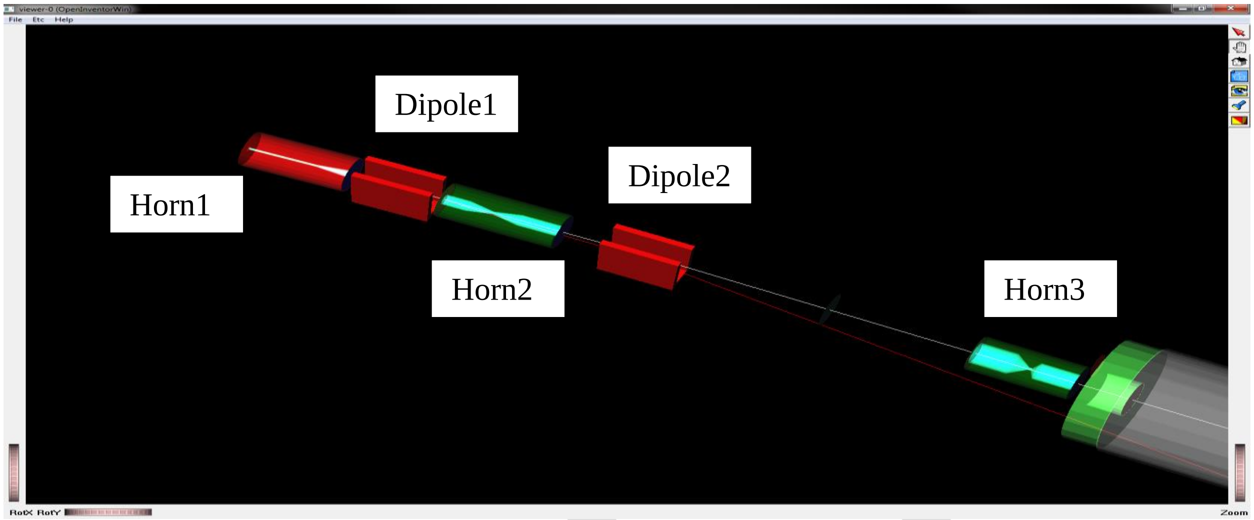


Figure 5. System consists of three horns and two C-type dipole magnets. Target is part of Horn1. The proton beam comes from the left.

Bending is achived with two indentical dipoles and Horn2 is part of the “Double Bend Achromat”. Horn3 is just inside the front of entrance to the Decay Pipe.
To evaluate the efficeincy of the suggested concept, simulations based on G4Beamline[3] are compared with the DUNE simulation described in reference[4]. Figure 6 shows the DUNE configuration with thin red objects indicating the positions of the dipoles in Option 1.

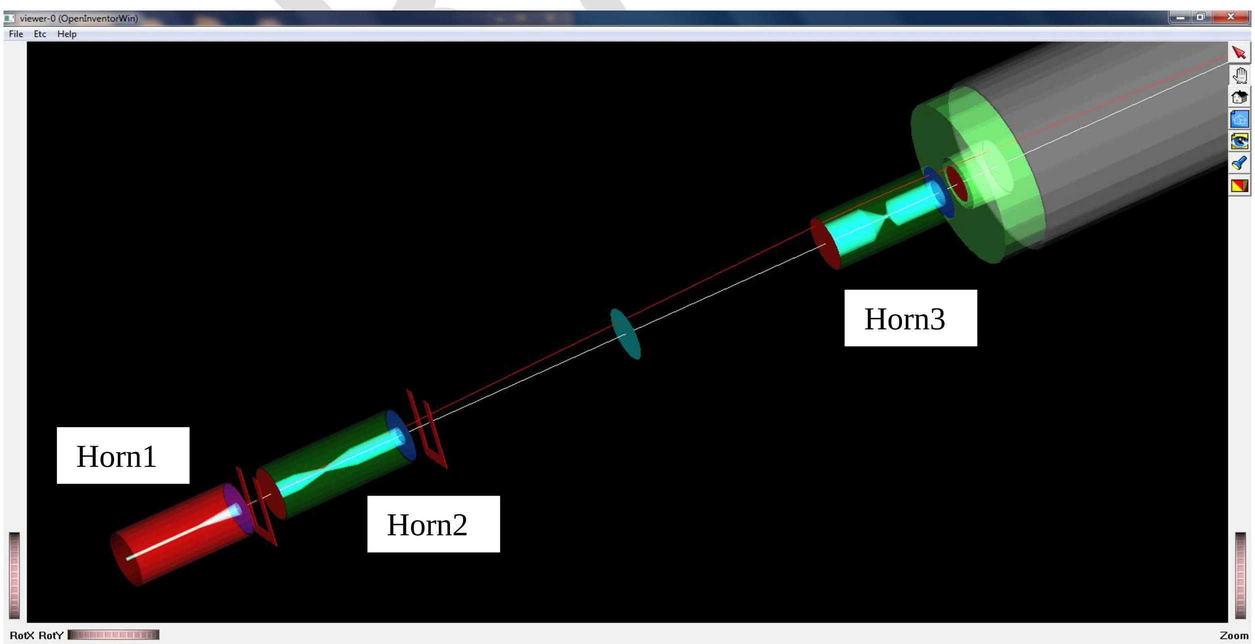


Figure 6. DUNE optimized configuration. Two red C-shape structures are place holders for dipoles with zero bend, and beam goes straight to the Decay Pipe (gray object)

In simulations a 120 GeV proton (10k particles) beam hits a two meter long Carbon target housed in the neck of Horn1. To speed up simulations, the horns are modeled as fields only (there is no horn material in the simulations) and only pions and neutrinos are recorded at the exit of Horn1. This beam is followed though the rest of the system. Because the horn geometry is identical to the DUNE optimized configuration we can compare the number of non-oscillating neutrinos in the far detector with the DUNE results and this gives us the opportunity to fix the normalization and correct for the lack of materials in our simulations. Figure 7 shows the result of the simulation with adjusted normalization factor for our runs. The blue curve is the result of the DUNE simulation for the optimized configuration and the red curve is result of our simulation with normalization factor fixed to adjust scale.

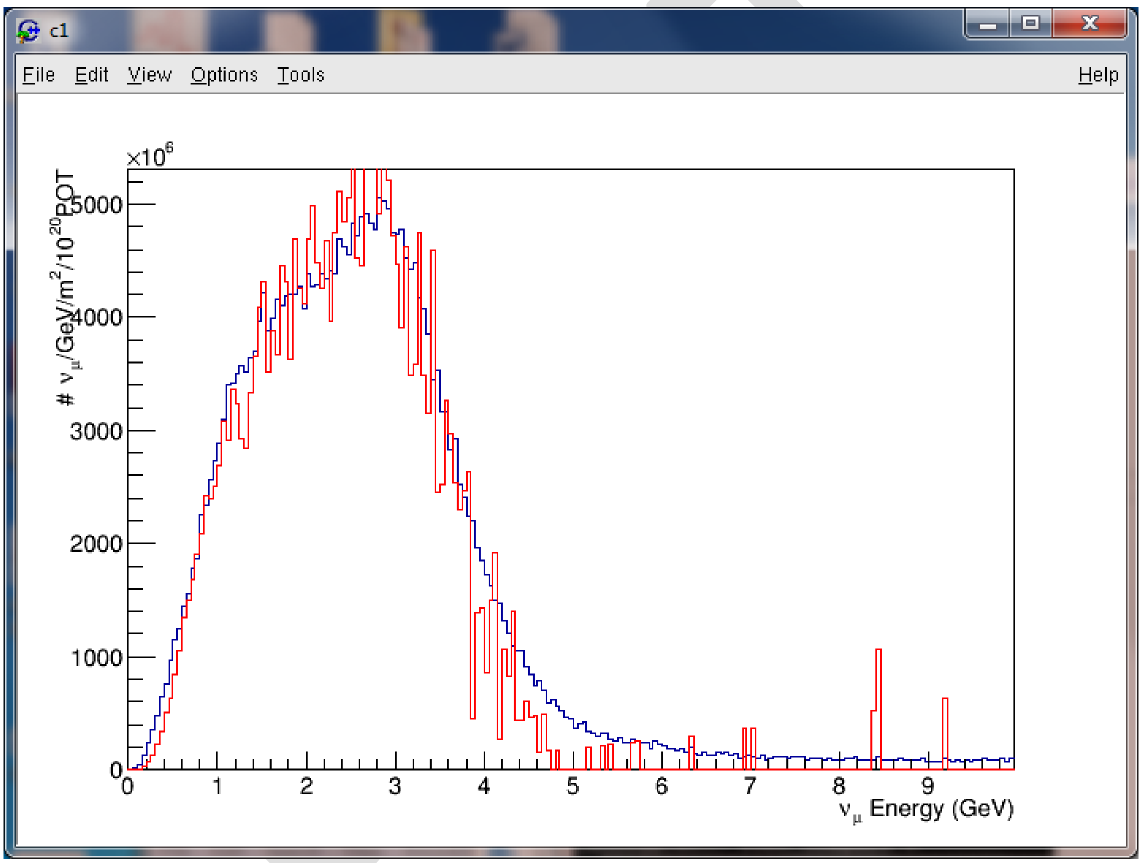


Figure 7. Blue curve is DUNE and red is this simulation with 10k protons on target.

With the normalization fixed we run two cases, selecting pions to have central kinetic energy of 6 GeV and 2 GeV. These two choices give neutrinos in the far detector around two oscillation maxima. As can be seen from figures 8 and 9 the number of non-oscillating neutrinos in the far detector around the two oscillation maxima is about the same as in the original DUNE case. Advantages of this configuration are total sign selection, probably removing of the largest background, removal of the main beam dump far from the water table, and significant reduction of beam power in the Decay Pipe.

- For the DUNE 57% power goes in the Decay Pipe and 12.8 to the dump at the end of the Decay Pipe
- For Option 1 beam, 27% of the power goes to the decay pipe and only 2 % to the Dump at the end of the Decay Pipe

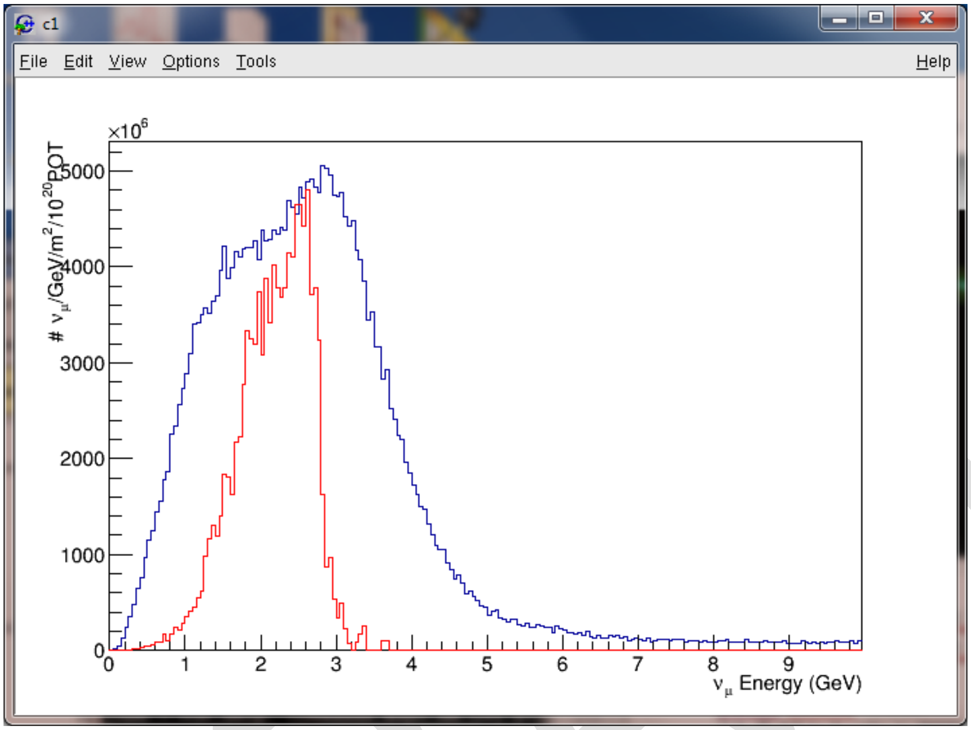


Figure 8. Central kinetic energy of the pion beam is 6 GeV.

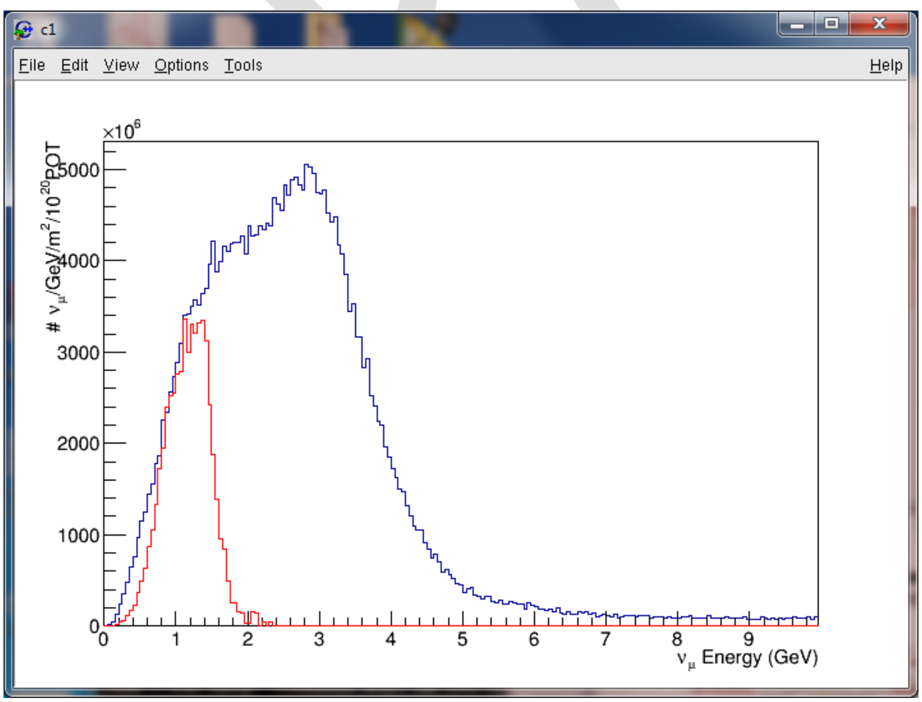


Figure 9. Central kinetic energy of pion beam is 2 GeV

In the concept presented here, the two bending magnets are identical, C-type dipoles, conventional, iron dominated with field ~0.5T, ~2.4m long, gap 0.6 m and 1m field width. The first dipole is separated by 0.2m from both horns. None of the parameters used here have been optimized.

There are two potentially additional benefits in this approach. In the conventional DUNE concept, particles up to 120 GeV energy reach the end of the decay pipe and this is a major problem for the muon monitors, making their use limited.

In the Option 1 approach not only is the beam power deposited at the end of the decay pipe greatly reduced but also the maximum energy of the particles. Only particles up to 12 GeV energy hit the bottom of the decay pipe and this provides the opportunity for the muon monitors to be used not only for monitoring beam stability but also for muon flux monitoring and perhaps muon beam energy distribution.

An additional possible benefit is the opportunity to use wires in the Decay Pipe to additionally tailor the beam seen by the DUNE detectors. One possibility is to remove Horn3 and replace it with a set of wires in the Decay Pipe.

Modified LBNF Beam Lines, Proton on target with 2.8 degree Bend, Option 2

One of the challenges of neutrino oscillation measurements is to get as large as possible a signal at higher oscillation maxima. Accepting the possibility that the pion beam can be bent (and still preserve a wide momentum neutrino beam [5]) just after the production target, we are presented with the opportunity to combine Off and On axis experiments using the same detector and pion production system.

Figure 10 illustrates the suggested changes of the DUNE concept for Option 2.

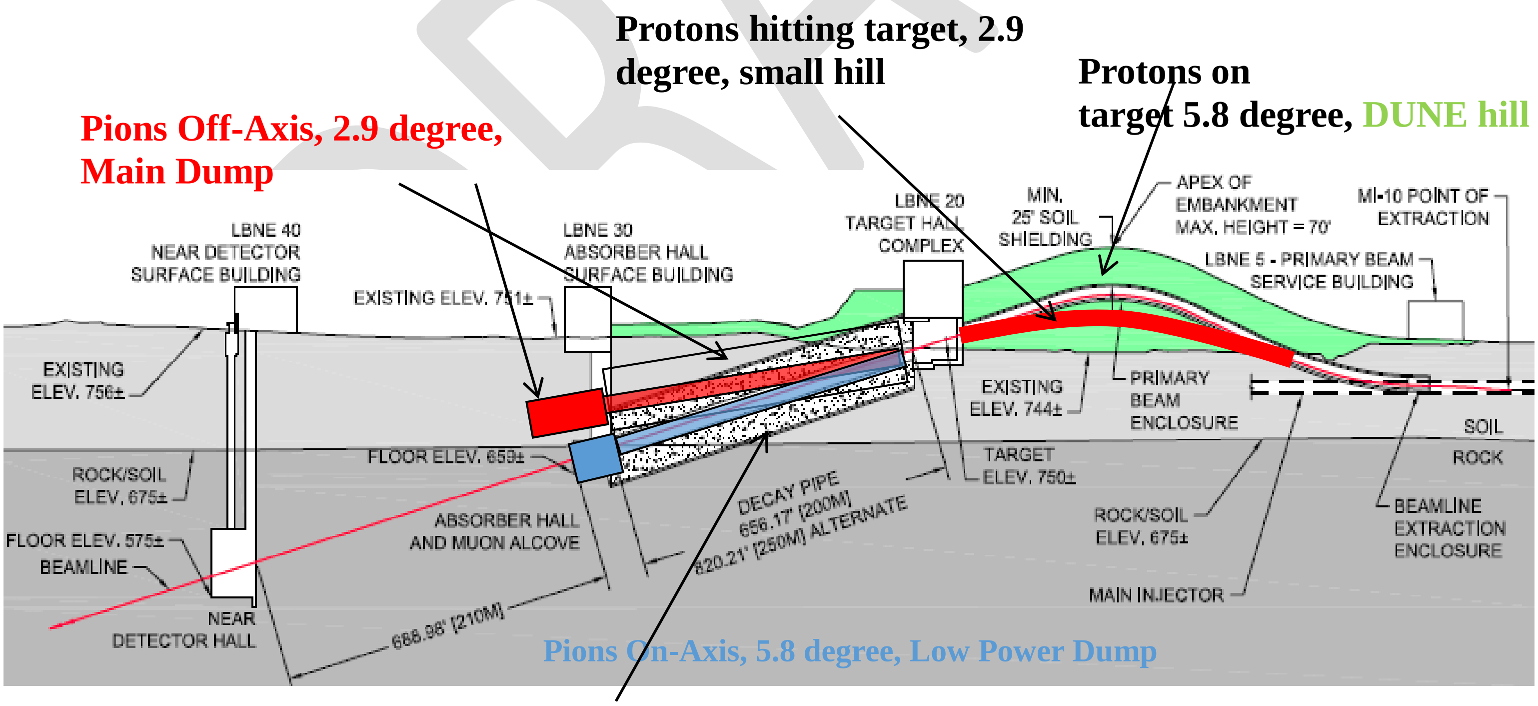


Figure 10. Option 2.

Looking at the plots from [6], as shown in figure 11, it looks like there will be a rate increase of about a factor of three (if not more) at the second maxima using the Option 2 off axis beam compared to DUNE.

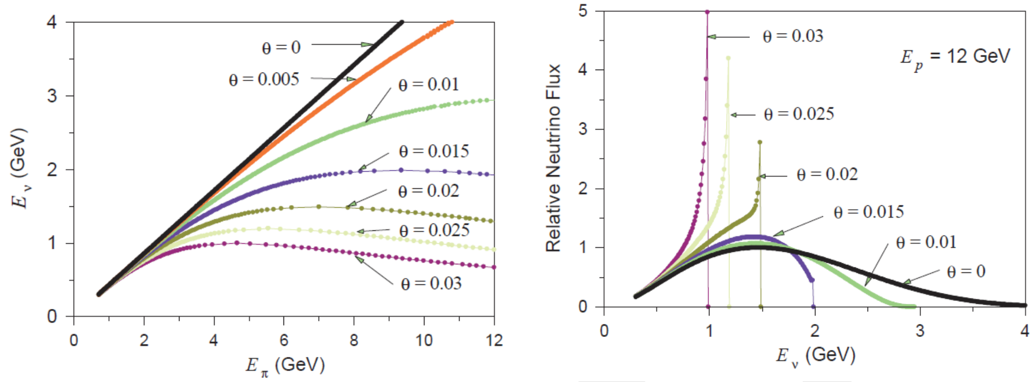


Figure 11. This is from reference [6].

Starting from DUNE we replace its 5.8 degree proton beam on target with our 2.9 degree proton beam. This requires a smaller hill, or maybe just a higher berm. The new decay pipe will not require additional excavation and the only additional cost is for 30% more concrete assuming it has to have a 5.6 m thick wall and is 220 m long. The main dump will be about 11 m above the present location.

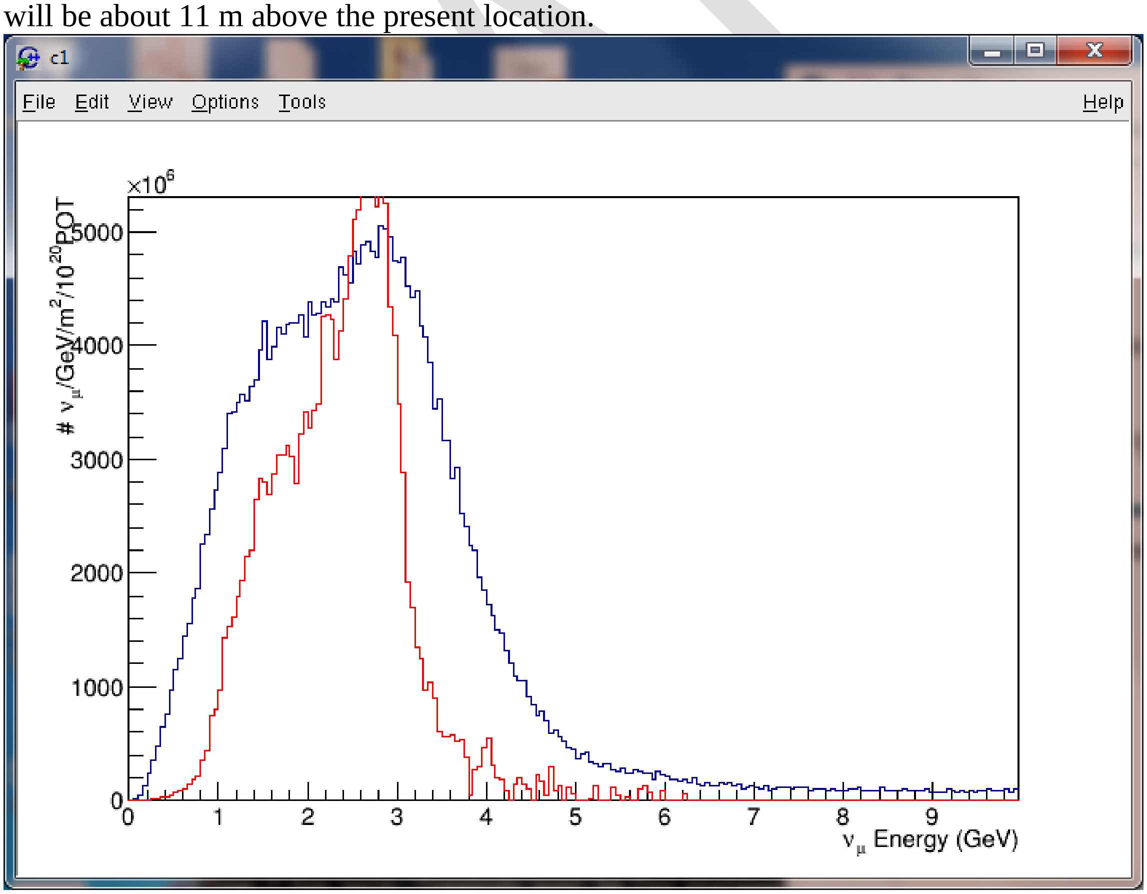


Figure 12 Non-oscillating neutrinos at far detector for 6 GeV pion central kinetic energy.

Option 2 magnets are similar to these for Option 1 except they are half as long. As for Option 1, the horns are as in the DUNE Optimized case and there was no attempt to optimize any of the parameters. As in Option 1 most of the advantages of bending the pion beam are preserved. The smaller bending angle for pions produces a wider neutrino beam at the far detector around first maxima and it seems that optimization of the system can recover most of the neutrinos if not more than in the DUNE original proposal.
Very preliminary simulation Off-Axis runs are shown in Figure 13.

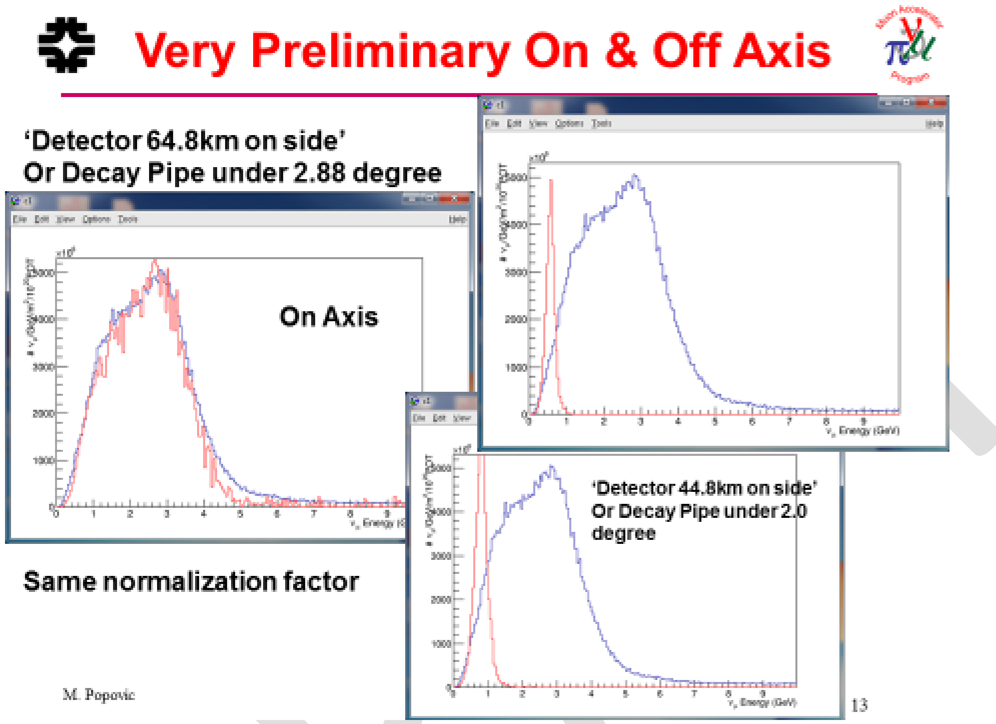
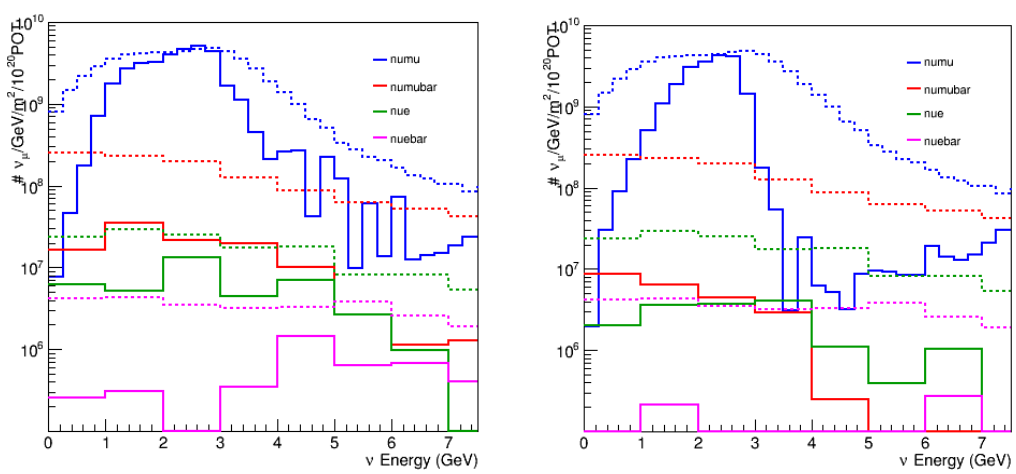
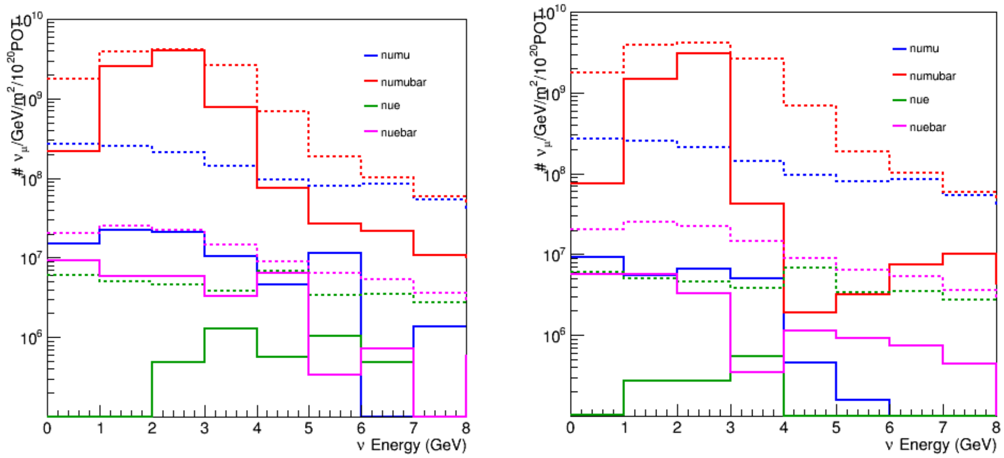


Figure 13. Off-Axis runs, very, very preliminary.

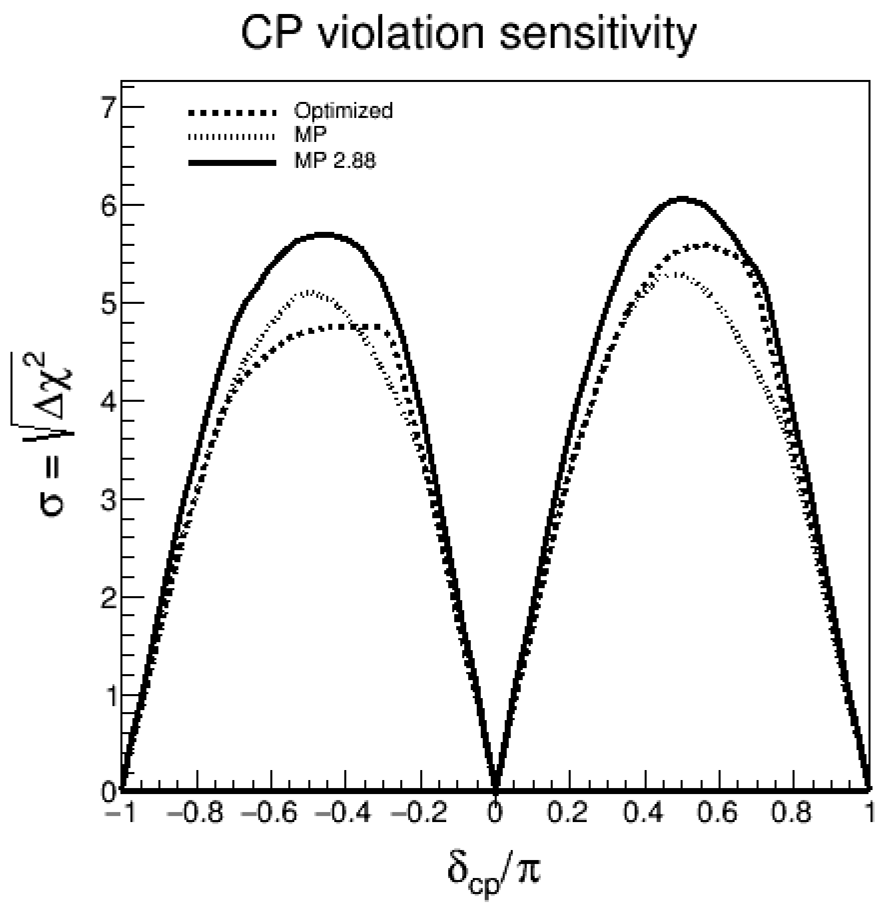
These are very preliminary flux and background plots (from Zarko Pavlovic)



Pi+ collection, 2.88 degree and 5.7 degrees pion bend, dotted lines are Optimized DUNE



Pi- collection, 2.88 and 5.7 bend.



Conclusions

The modification of beams presented for LBNF is minor, requiring the addition of two conventional dipoles and larger separations of Horn1 and Horn2. The neutrino flux at far the detector is similar compared to the Optimized DUNE configuration around two oscillation maxima for just two different settings of the dipoles. Advantages of the presented concept are:

- removal of the proton delivery hill,
- removal of high power beam in the Decay Pipe,
- removal of high power absorber from the proximity of water table,
- full charge separation,
- possibility of muon flux characterization
- possibility of Off Axis run

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