arXiv:2212.09524v1 [hep-ex] 16 Dec 2022

Version 2.02
December 20, 2022

Adding Stroboscopic Muon Information For Reduction of Systematic Uncertainties in DUNE

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Abstract

Muons have a similar latency/energy correlation from pion decay as do the neutrinos, and hence in each time-slice in a stroboscopic analysis measurements of their momentum spectra can reduce systematic uncertainties due to flux. There are, however, unique issues for muons: 1) during standard neutrino data-taking muon measurements in the forward direction must be in formidable high-flux high-radiation environments; 2) because of the very high incident hadron flux in the Absorber Hall, muons must be detected after a thick absorber, imposing a range cutoff at a momentum much above the minimum neutrino momentum of interest; 3) the muon velocity, unlike that of neutrinos, differs from c, and so the muon detected time will require correction for the muon flight path, requiring measurement of the muon momentum; 4) multiple scattering is significant for low-momentum muons, and so a 'good geometry' is essential for precision muon flux measurements; and 5) developments in psec timing allow muon momenta in the momentum region of interest to be measured precisely by time-of-flight over short distances with photodetectors of a few-psec resolution.

However, after trying to design arcane methods to deal with the high rates during routine operation, I conclude that due to the conflict between incident rate and absorber range cutoff, it is probably not possible to measure the stroboscopic muons other than in dedicated data-taking with the same target/horn/decay geometry, a modified absorber configuration with a lower range cutoff, and *much* lower proton beam intensity, itself a problem to be solved. The low-momentum muon spectra taken in this experiment would be cross-normalized to the high-intensity neutrino data through the currently planned muon monitors which can operate in both the low and high intensity geometries. Ideally the low-intensity muon momentum spectrum measurements would be carried out early in the LBNF program before the Absorber Hall becomes too hot.

While beyond the scope of uniquely muon-related issues, the note includes a proposal for an oscillation analysis strategy that exploits stroboscopic information for both neutrinos and muons to reduce systematic uncertainties on the neutrino fluxes and event selection in Far and Near detectors.

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1 The Use of Precision Timing in Neutrino Physics

The further determination of parameters governing the Standard Model neutrino sector will require much-improved control of systematic uncertainties [1, 2, 3, 4, 5]. In response, we have proposed time-slicing the arrival of neutrinos relative to the interaction of the proton bunch that produced them at the target, and rebunching the Main Injector (MI) beam at a higher-frequency such as the 10th harmonic of the current 53.1 MHz to make shorter proton bunches [6]. This technique complements prismatic techniques that probe the dependence on production angle of the neutrinos [7]. Figure 1 shows the neutrino energy spectra in successive time bins relative to the nominal arrival time of the proton bunch at the target.

Here we suggest that additional constraints on the systematics may be obtained from timing measurements of the muons produced at the target in order to associate the muons with the time bin slices corresponding to the muon and neutrino production[1].

Muon momenta from pion decays will be comparable to the neutrino momenta, and for neutrinos with momenta of a few GeV, will in general be too soft to penetrate a thick absorber [8, 9]. Psec time-of-flight measurements over lengths of 6-10 feet with small area telescopes can provide adequate momentum resolution as well as the information needed for a complete stroboscopic analysis that includes the muons.

However, these measurements will almost certainly require a dedicated effort with special runs at much reduced beam intensities but with the same target/horn/decay configuration), very-small area radiators for a TOF telescope if used, and reduced absorber to lower the range cutoff. Planning for precision muon monitoring in this momentum range may affect the design and

[1]Unlike the neutrinos, the muons are slow, and so their detection time needs to be corrected for their transit time to the detector.

required flexibility of the absorber layout inside the Absorber Hall. Ideally these measurements could be made early in the LBNF program.

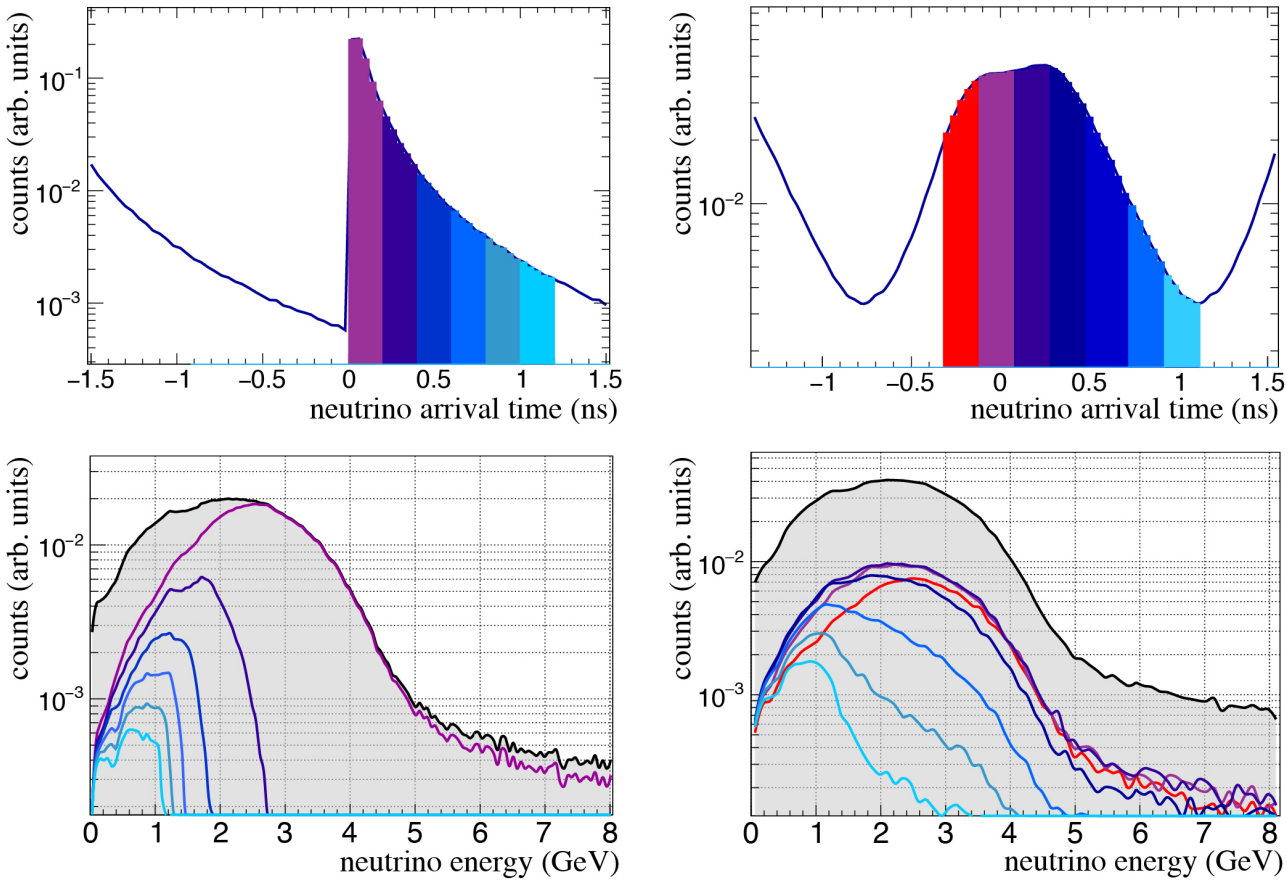

Figure 1: Neutrino energy spectra in time bins relative to the proton bunch, for a delta-function proton bunch (left) and for a 531MHz bunch with 100 psec detector resolution (right). (from Ref [6]. Each time bin can be treated as an independent experiment with its own characteristic neutrino spectrum using the Near and Far detectors, so that five (for example) experiments are run simultaneously, with uncertainties on detector selection efficiencies in common. Here we propose to measure the momentum spectra of the muons associated with that time bin to reduce systematic uncertainties in the neutrino flux.

This proto-note is very rough and largely an aide-memoire for future discussions. I came to the (tentative) conclusion that due to the enormous fluxes even after a thick absorber, the high threshold set by the absorber and the daunting constrains caused by the high-radiation environment, that only by special runs with a much reduced proton intensity would it be possible to make time-sliced precision measurements of muons in the momentum range of interest.

2 Role of Muons in an Over-all Strategy to Reduce Systematics

The addition of neutrino timing information as described in Ref. [6] has the capability to change the overall strategy for reducing systematics in the long-base-line measurement. The systematics

seem [1, 2, 3, 4, 5] to depend most on 3 parameters: 1) the neutrino energy spectrum, in particular the shape; 2) the detection efficiency for specific signatures, such as visible energy; and 3) the K/pi ratio, particularly for electron appearance.

A possible strategy for isolating these systematics:

1. Treat the time bins in Figure 1 as separate experiments, each with its own energy spectrum and backgrounds, so that the five experiments are run in parallel, with common sources of systematics but different neutrino spectra.
2. During normal data-taking, use the currently planned LBNF muon monitors to bin the muons in the same time bins as the neutrinos, making a muon sample that is the normalization for the neutrino flux in that time bin. These high intensity measurements would be cross-calibrated to the low momentum region directly related to the neutrino flux of interest by a separate dedicated experimental run with *much* lower beam intensity and with a much lower absorber range cutoff.
3. In each experiment, bin the events by signature or characteristic parameter, for example electron appearance, or in visible energy, so that the detector efficiencies are the same[2] in a given bin of the parameter across the five simultaneous experiments defined by the time bins. This leaves the spectrum and backgrounds as varying across the time bins, but with (approximately) the same detection efficiencies.
4. For example, the ratio of Far/Near in the ith time bin $(\text{Far/Near})_i$ to that in the jth time bin, $(\text{Far/Near})_j$, for a given visible energy, will primarily depend on the neutrino energy spectrum rather than on the selection and detector efficiencies. In the example binning of Ref. [6] there are 10 such double ratios taken contemporaneously for each bin of a given signature parameter.

3 Some Specifically Muonic Thoughts

Muon arrival times were already measured to a precision of 5 psec using Cherenkov light and MCP-PMTs in 2006 [10]; since then ALD-coated MCP's with higher gain and longer life have been developed for improved time resolution. Muons will also have an energy-time correlation like that of neutrinos, but muons differ in that unlike neutrinos the arrival time depends on the time the lepton travels as well as that of the parent hadron. However, unlike neutrinos, muon momentum can be measured locally by time-of-flight; a 630 MeV muon ($\gamma = 6$) loses 14 psec per foot of travel, allowing compact time-of-flight telescopes. Not every Main Injector spill needs to be rebunched at 531 MHz; one in N can be left at 53.1 MHz, providing access to longer travel times for muon monitors and eliminating the pile-up due to the higher RF frequency ('mixed-mode running). The prescale factor N need not be constant.

3.1 The Planned LBNF Facility

Muon measurement is very local, and monitoring will depend on the details of the existing construction, radiation levels, and availability of access. Figure 2 shows a plan view of the facility [11]. Time-of-flight at momenta of interest, however, will require dedicated running at much lower intensities, if possible at all.

[2]It would be very useful to identify sources that are not the same across the time bins for several signatures.

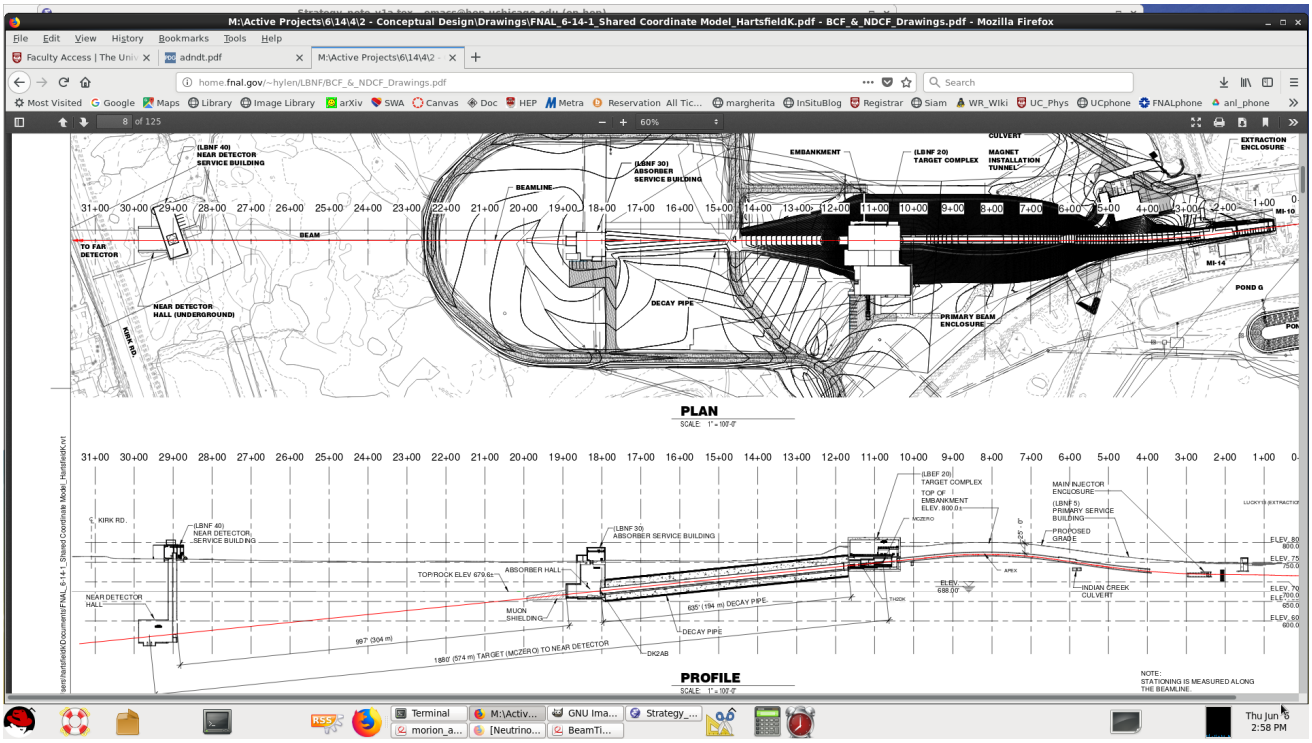

Figure 2: Plan and Elevation of the LBNF target and decay region. From Jim Hylen's web page [11]: LBNF Final Configuration, Drawing 6-14-1 CDF-7 (page 8)

A typical simple muon system consists of a small area (typically a few mm-square) multi-counter telescope, with Cherenkov light read out by PMT's or MCP-PMT's. The active element would be fused silica, for example; the light would be read out locally or be transported to a lower radiation environment by mirrors or phase-stabilized fibers in the case of high radiation. Time of arrival can be measured with the same clock distribution systems as for the neutrinos, for example White Rabbit [12, 13].

3.2 Optical TOF Muon Momentum Measurement

The design of a muon detection system will depend on the expected rate, momentum range, latency (flight time relative to proton bunch), angle to target, and background/radiation levels. The goal of accessing muons in the kinematic ranges corresponding to the neutrinos of interest is a really difficult one, as in the forward direction the fluxes are enormous and require absorber that sets a momentum threshold at much higher momentum than 1-2 GeV. New detector techniques, including using optical time-of-flight with very small optical elements, may allow first steps towards new monitoring designs that provide momentum information as well as flux, and reach to lower thresholds than before. However it seems almost certain that measurements of the flux at momenta corresponding to that of the neutrinos of interest will require dedicated running at much lower intensity and lower range cutoffs, i.e. a dedicated experiment. This need may impact the design of the placement and flexibility of the absorber in the Absorber Hall to allow this mode. Ideally this measurement could be carried out early in the LBNF program before the Absorber Hall becomes too hot.

3.3 The E100 90-Degree Monitor and the Shrinking Target

The E100 Experiment in Proton East (PE) was a single-arm ∼100m-long spectrometer designed to explore the hither-to-unexplored region of high-P_T [14]. The spectrometer viewed targets impinged on by the primary proton beam, with intensities up to $2E13$/spill. Much of the high-intensity running was done with a scintered W target.

Normalization of the measured particle production was done with a simple "90-degree muon monitor" proposed and designed by Jim Cronin. The monitor consisted of a small simple 3-counter scintillator/PMT telescope sealed in a copper pipe and inserted into a bored/lined hole in the ground directly above the PE target inside its heavily shielded target box, nothing fancy. The steel shielding of the target box and the overburden at Proton East provided a range cutoff for what presumably were soft muons to begin with.

We noticed that the particle production rate fell with integrated luminosity; however the rate in the 90-degree monitor fell in synch, with the ratio deviating from being constant to at most a few percent (this is from memory), i.e. the high-P_T measurements tracked the monitor precisely. We believed that the monitor was seeing muons from the target, although any details of the momentum spectrum, scattering along paths, or parent source were completely unknown. Stability and proportionality of whatever it was, however, was excellent.

When the run with metal targets was over, we opened up the target box. Under the W target, which was only a few inches long if that, there was a small conical pile of yellow dust, and the tail end of the target had been ablated away. The 90-degree monitor, however, tracked the shrinking target.

For a longer target such as the LBNF carbon target, multiple 90-degree monitors with geometrically well-defined angular acceptances viewing different sections of the target could provide similar proportionality and stability. More-over, the new capability of measuring TOF over short distances using fast timing detectors adds measurement of the momentum spectrum to the monitoring.

4 Ideas On a Linearized Oscillation Stroboscopic Analysis

4.1 Following Up the Stroboscopic Higher-Frequency RF Proposal for Physics

The stroboscopic proposal of Ref [6] focused on the accelerator physics of rebunching the 53 MHz of the Main Injector on the 10th harmonic and the resulting neutrino energy spectra from a time-sliced event selection. Missing was any estimate of the effect on the limiting systematic uncertainties on the neutrino oscillation parameters.

While beyond the scope of uniquely muon-related issues, this section presents the bones of a proposal for an oscillation analysis that exploits stroboscopic information for both neutrinos and muons. The addition of fast timing at the Near and Far detectors relative to the timing of a narrow proton bunch on target should reduce systematic uncertainties on the neutrino fluxes and detection parameters.

4.2 Exploiting Ratios of Time Bins in Signature Parameter Bins

The following strategy, expanded on the presentation in Section 2, is intended to exploit the sculpted energy spectra in the different time bins illustrated in Figure 1:

1. Treat the time bins in Figure 1 as separate experiments, each with its own energy spectrum and backgrounds, so that the five time bins correspond to five oscillation experiments run simultaneously, with many common sources of systematics but with different neutrino spectra.
2. Using the muon monitors, bin the muons in the same time bins as the neutrinos, and use the low-intensity/high-intensity cross-calibration to make a muon normalization flux sample that corresponds to each experiment.
3. In each experiment, bin the events by signature or characteristic parameter, for example electron appearance or visible energy, so that the detector efficiencies are the same to first-order in a given selection bin across the five experiments defined by the time bins. This leaves the spectrum and backgrounds as varying across the time bins, but with (approximately) the same detection efficiencies.
4. For example, the ratio of Far/Near in the ith time bin $(\text{Far/Near})_i$ to that in the jth time bin, $(\text{Far/Near})_j$, for a given visible energy, will primarily depend on the neutrino energy spectrum rather than on the selection and detector efficiencies. In the example binning of Ref. [6] there are 10 such double ratios taken contemporaneously for a given signature.
5. While the example above is for one bin in a simple selection parameter, visible energy, the above double ratios can be calculated for each bin in each of the selection criteria, forming a matrix[3] of double-ratios with the ijth time bin being one dimension and the bin of the selection parameter being the other.
6. Lastly, find the best-fit physics parameters and systematic uncertainties by comparing the complete set of measured double-ratios to the corresponding set of simulated predictions as a function of: 1) the physics parameters; 2) the flux parameterizations; and 3) the detector/selection efficiencies, starting with a simple minimization, and (inevitably) something more sophisticated and opaque.

5 Summary

This draft has some ideas on strategies to reduce systematics to the percent level by incorporating timing into the muon monitor information. A first step toward a solid proposal would be to analyze the muon information in the DUNE flux simulations in a stroboscopic framework, and to summarize expected muon rates and spectra from existing LBNF studies.

The strategy to include muons includes:

1. Treating each of the five 100-psec time bins (to take the example in the PRD draft [6]) as a separate contemporaneous oscillation analysis with its own neutrino spectrum and muon normalization.
2. Muon flux measurements that include a dedicated running period early in the LBNF program to measure muon momentum spectra and arrival times in the momentum region that corresponds to that of the neutrinos of interest, using small aperture range-TOF telescopes of a simple design running at much lower intensity but with the same beamline/target/horn/decay settings and with an absorber with a range cutoff of at most a few GeV.

[3] Each ratio will usually have more than two indices, i.e. is a tensor. But...

3. Measurements of muon production in each time bin, including angular distributions, momentum spectra, and (possibly) sign information to substantially constrain the flux/cross-section systematics.
4. Multiple 90-degree monitors with geometrically well-defined angular acceptances viewing different sections of the target can provide long-term target monitoring with proportionality and stability. Psec time-of-flight can measure the momentum spectrum for slow muons.

Lastly, Section 4 of the note presents an outline of a ratio-based analysis strategy that relies on stroboscopic information for both neutrinos and muons to reduce systematic uncertainties on the neutrino fluxes and detection parameters.

6 Acknowledgements

I thank Sacha Kopp, Jim Hylen, and Zarko Pavlovic for taking the time to deal with my ignorance, and Jim and Zarko for drawings. I thank Evan Angelico and Andrey Elagin for helpful comments on an earlier draft, and Ed Blucher for a comment on monitoring target stability. All mistakes and stupidities are my own.

7 Appendix A: Site Physical Layout Drawings

The area comprising the target, decay pipe, and the enclosure at the end of the decay pipe, the Absorber Hall, is shown in Figure 3 [11].

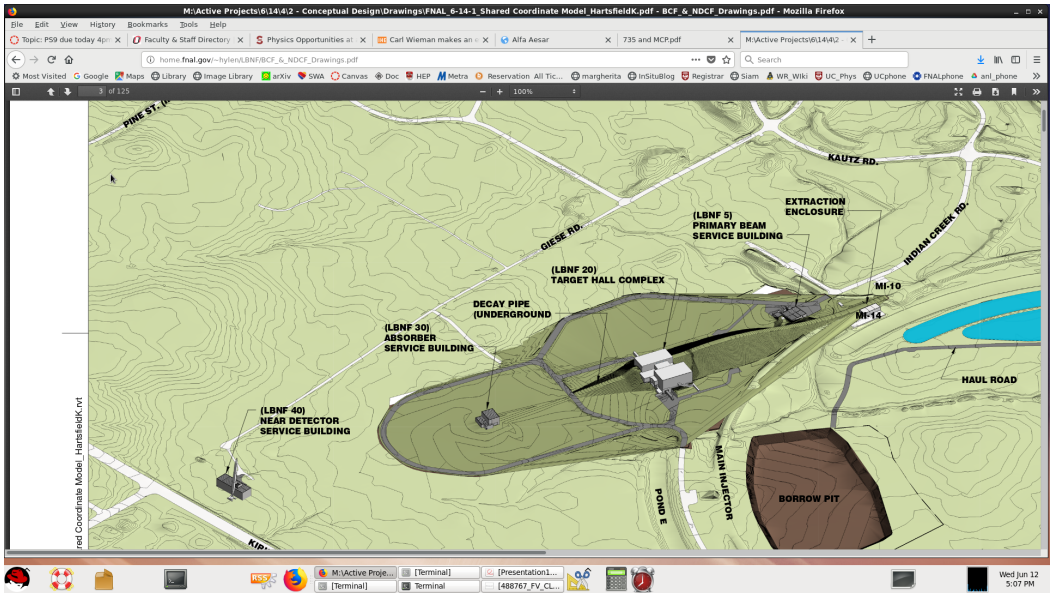

Figure 3: The layout of the Fermilab site encompassing the Primary Beam Service Building (LBNF 5), the Target Hall Complex (LBNF20), the Decay Pipe, and the Absorber Service Building (LBNF30). See Ref [11].

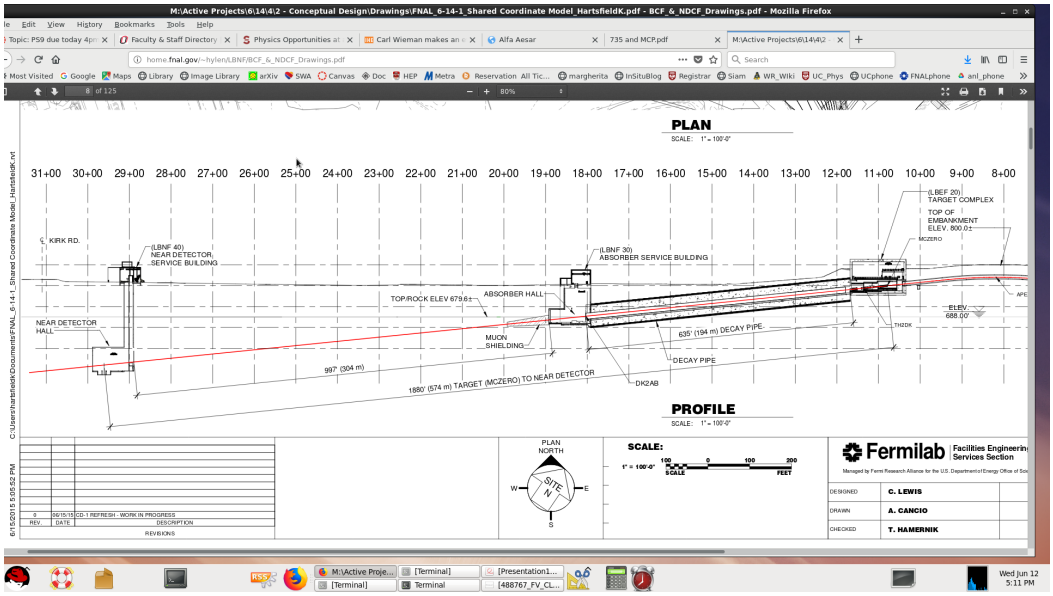

Figure 4: A profile of the LBNF beamline showing the elevations of the highly sloped beamline, service buildings (Target complex, Absorber Service Building, Near Detector Hall), and muon shielding. See Ref [11].

7.0.1 Target Hall

We are interested in neutrinos with momenta of order 1-2 GeV, with some emphasis on the 2nd maximum at 800 MeV. The associated muons are consequently also at low momentum,. Figures 5 and 6 show profiles of the Target Hall.

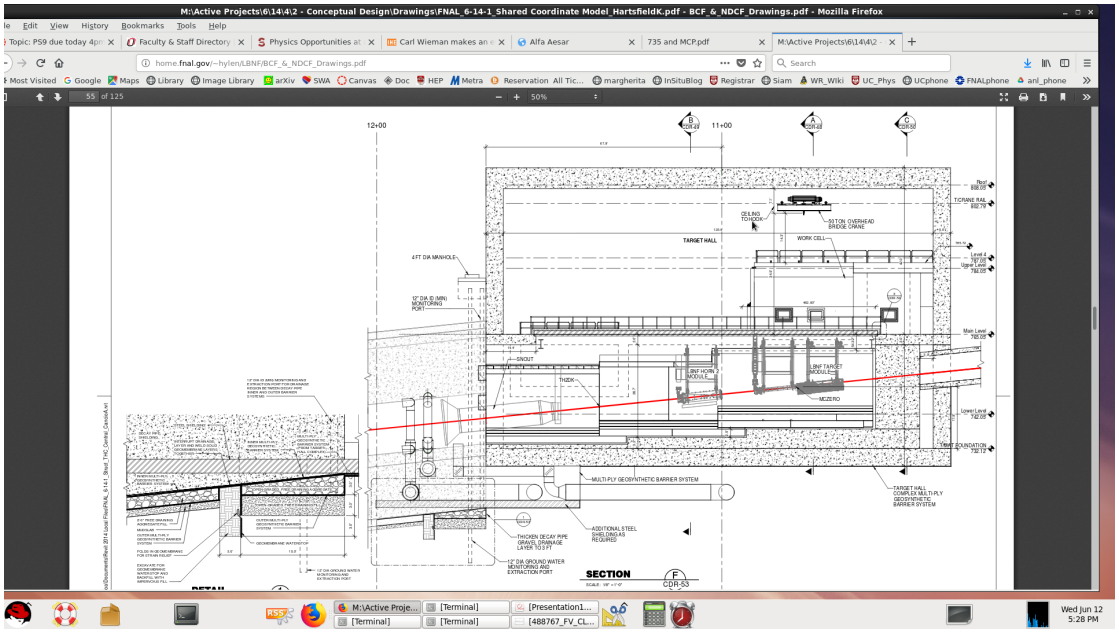

Figure 5: Profile of the Target Hall.

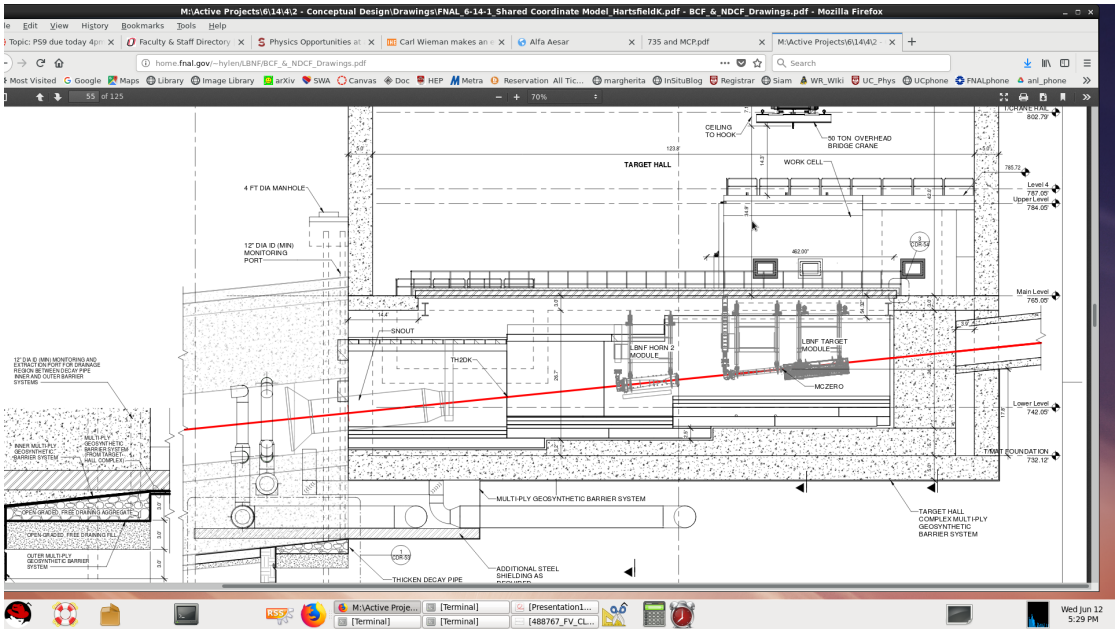

Figure 6: Enlarged profile of the Target Hall.

7.0.2 Absorber Hall

Figures 7 –9 show the Absorber Hall. Low-intensity muon flux measurements may require the ability to put detectors in front of some fraction of the absorber and possibly more space before the absorber.

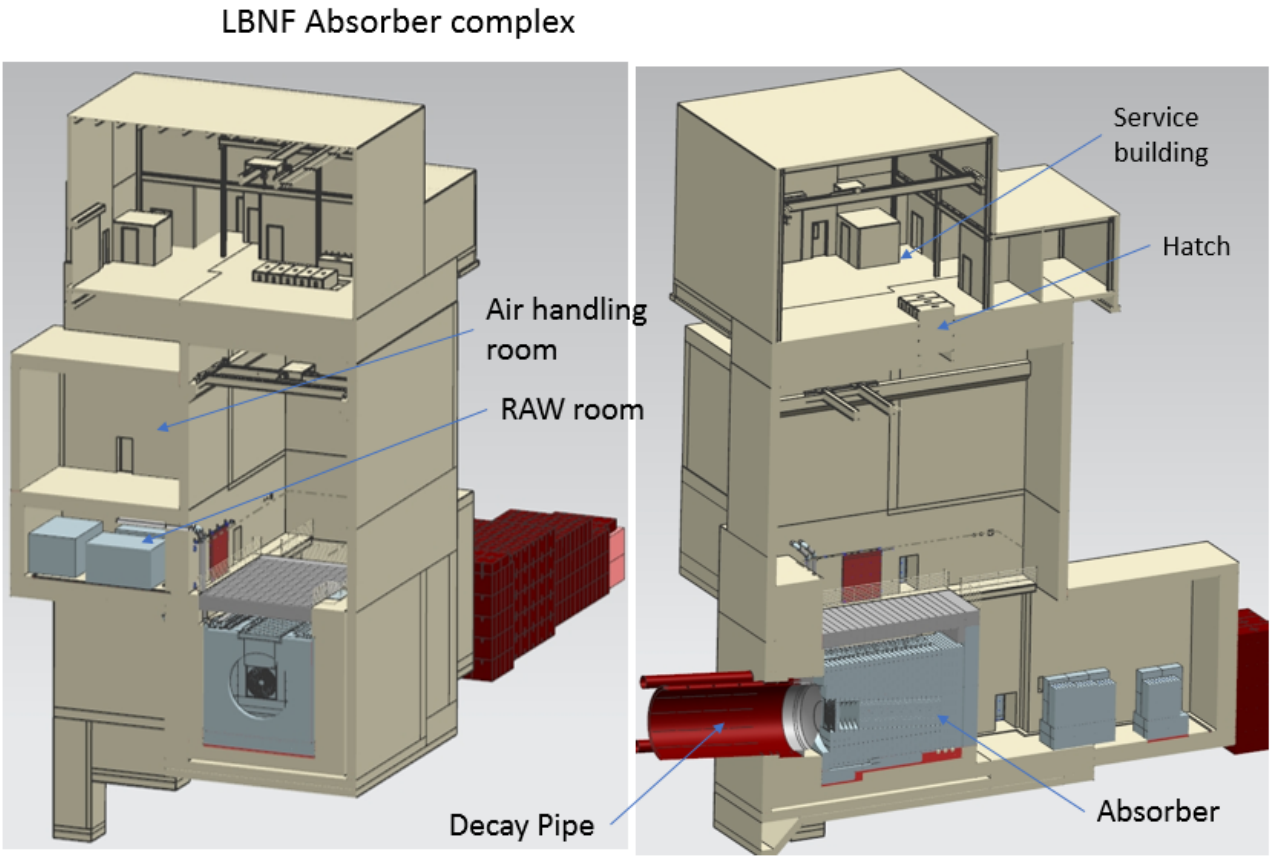

Figure 7: The Absorber Hall

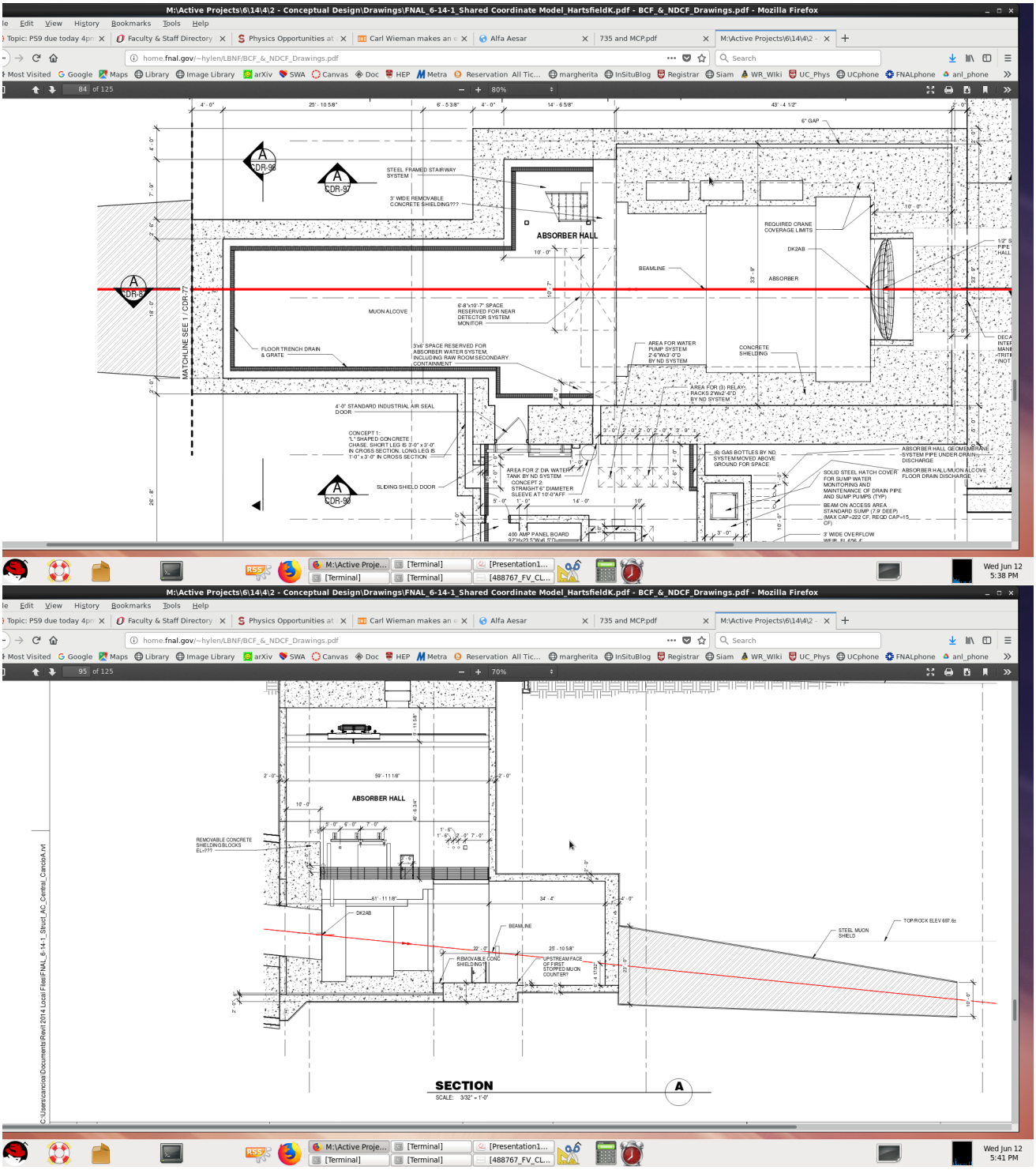

Figure 8: Sections of the Absorber Hall

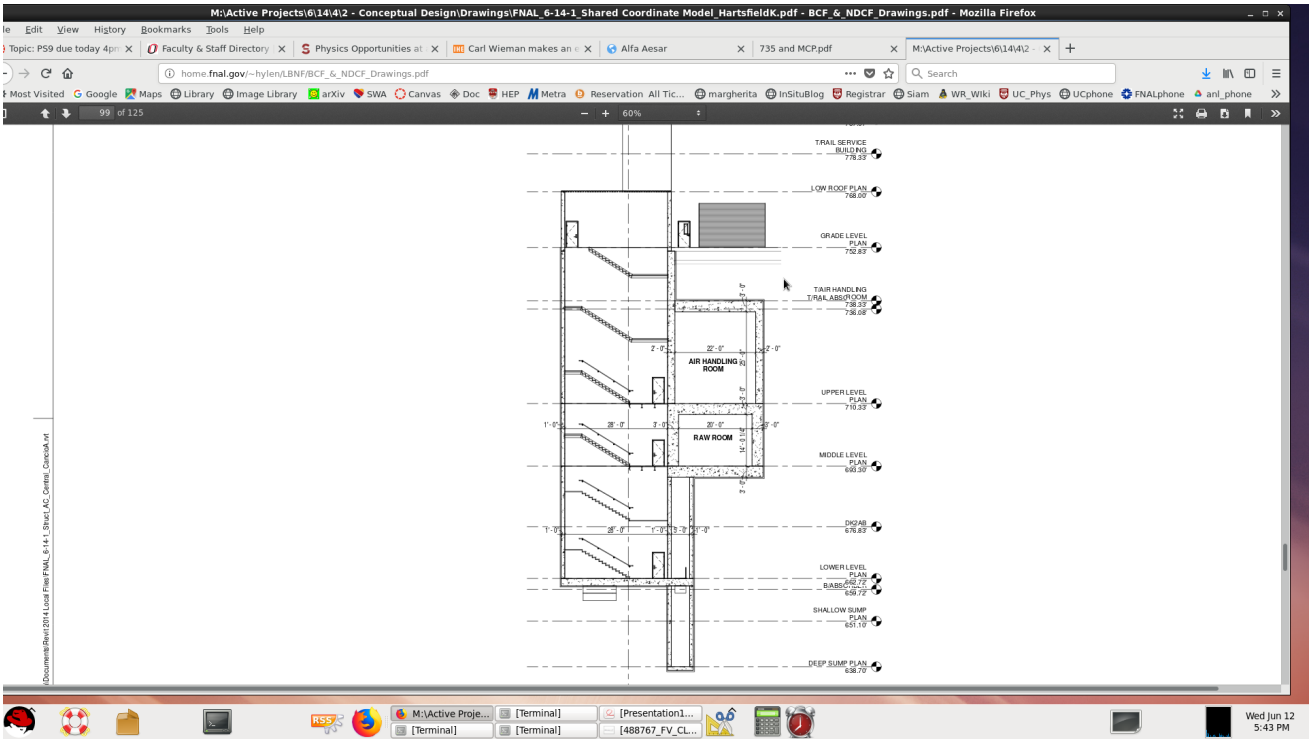

Figure 9: A section view of the multi-level structure adjacent to the Absorber Hall

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