Chapter 9 Summary and Conclusion

The preceding chapters of this document describe the design of the Long-Baseline Neutrino Experiment, its technical capabilities, and the breadth of physics topics at the forefront of particle and astrophysics the experiment can address. This chapter concludes the document with several discussions that look forward in time, specifically:

- a consideration of how the design and construction of the LBNE experiment might unfold from this point on for a general class of staging scenarios,
- a summary of the grand vision for the science of LBNE and its potential for transformative discovery,
- a summary of the compelling reasons — such as LBNE's current advanced state of technical development and planning, and its alignment with the national High Energy Physics (HEP) program — for which *LBNE represents the world's best chance for addressing this science on a reasonable timescale*,
- comments on the broader impacts of LBNE, including the overarching benefits to the field of HEP, both within and beyond the U.S. program.

9.1 LBNE Staging Scenarios and Timeline

> With DOE CD-1 ("Alternate Selection and Cost Range") approval in hand, the LBNE Project is working toward its technical design specifications, including detailed costs and schedule, in preparation for CD-2 ("Performance Baseline"). It should be noted that the Project already has fully developed schedules for both the CD-1 scope (10-kt far detector on the surface at the Sanford Underground Research Facility, no near neutrino detector), and for the full-scope (34-kt far detector located deep underground and near neutrino detector) for the scenario of funding solely from DOE. Partnerships with non-DOE groups are being sought to enable the construction of LBNE with a near neutrino detector and an underground far detector mass greater than 10 kt in the first phase.

Section 1.2.3 described the substantial progress that has been achieved so far toward making LBNE a fully international project. While the specific form and timing of contributions from new partners are not yet known, there are several plausible scenarios in which the Project can be implemented to accommodate non-DOE contributions. A review of the DOE project milestones, indicating where flexibility and potential for incorporating non-DOE contributions exist, provides a starting point.

DOE-funded projects are subject to several *critical decision (CD)* milestones as shown in Figure 9.1 and explained in DOE Order O 413.3B [1]. At CD-2 the first-phase LBNE Project will be baselined. Currently, the timescale for CD-2 is projected to be toward the end of FY 2016, although the DOE has indicated flexibility in the project approval process specifically to allow for incorporation of scope changes enabled by additional partners. For example, it has been suggested that the design and construction approval for different portions of the Project can be approved at different times to facilitate proper integration of international partners. It is also expected that CD-3a approval (start of construction/execution) may take place for some parts of the Project before CD-2, thereby authorizing expenditures for long-leadtime components and construction activities, such as the advanced site preparation at Fermilab for the new beamline. The CD-4 milestone (completion of the construction project and transition to experiment operations) is currently projected for 2025. However, it is expected that commissioning and operations for LBNE will have started approximately a year before CD-4, which is considered the formal termination of the construction project.

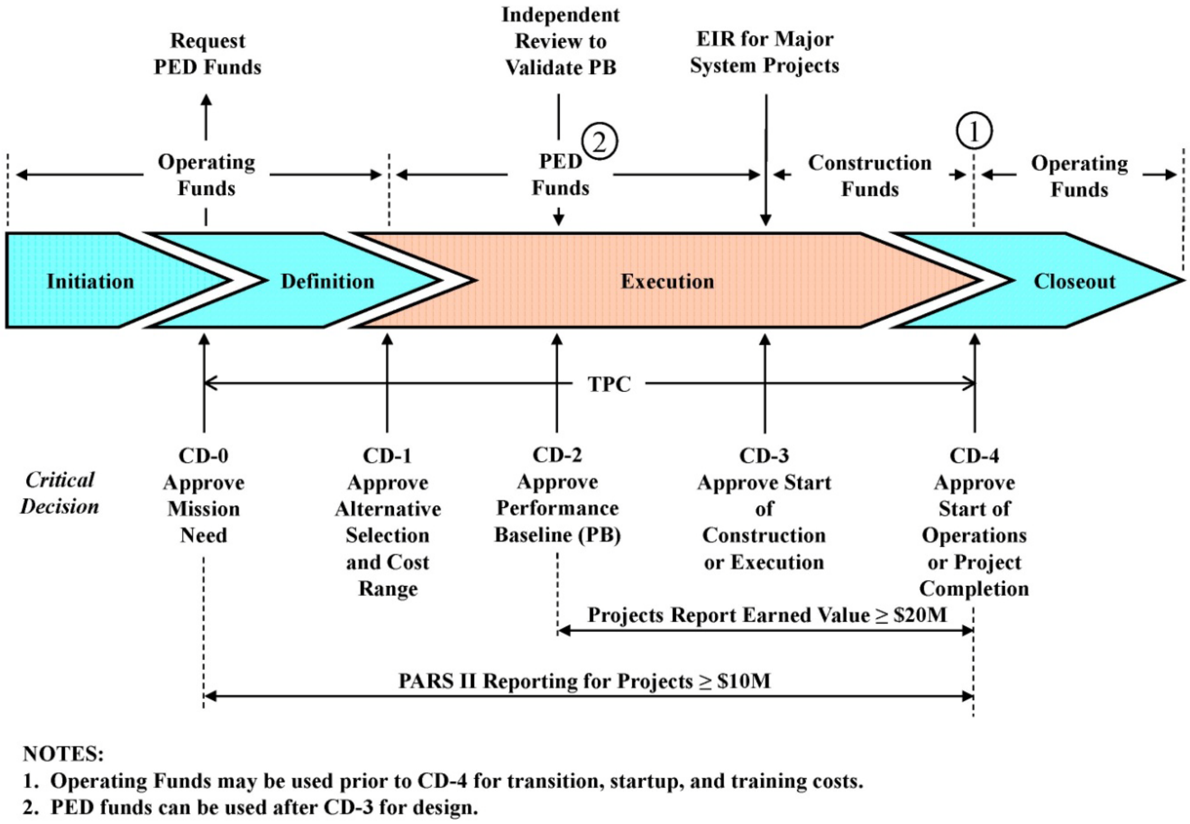

Figure 9.1: Typical DOE Acquisition Management System for line item capital asset projects [1].

The actual timeframe for achieving LBNE science goals will depend on the manner in which a complex sequence of developments takes place, including the actions of partners as well as implementation of the milestones above for the DOE-funded elements of the Project. Various scenarios for incorporating contributions from new partners/sources of funding have been identified [2].

Using the current understanding of DOE funding profiles, we outline one plausible long-term timeline that integrates evolution of LBNE detector mass with development of the Fermilab accelerator complex (i.e., PIP-II) and contributions from non-DOE partners. Implicit in this timeline is an assumption that agreements with new partners be put in place on a timescale of three years (by 2017). In this scenario, the milestones that bear on the physics are as follows:

1. LBNE begins operation in 2025 with a 1.2-MW beam and a 15-kt far detector. (In such a scenario, a significant fraction of the far detector mass might be provided in the form of a standalone LArTPC module developed, funded, and constructed by international partners.)
2. Data are recorded for five years, for a net exposure of $90\,\mathrm{kt}\cdot\mathrm{MW}\cdot\mathrm{year}$.
3. In 2030, the LBNE far detector mass is increased to 34 kt, and proton beam power is increased to 2.3 MW.
4. By 2035, after five years of additional running, a net exposure of $490\,\mathrm{kt}\cdot\mathrm{MW}\cdot\mathrm{year}$ is attained.

Physics considerations will dictate the desired extent of operation of LBNE beyond 2035.

This very coarse timeline is indicative of the degree of flexibility available for the staging of various elements of LBNE. For example, near detector construction (and the corresponding funding) could be undertaken by partners outside the U.S., on a timescale driven by the constraints they face, and could be completed somewhat earlier or later than the far detector or beamline.

With this timeline as a guide, the discussion of LBNE physics milestones can be anchored by plausible construction scenarios.

9.2 Science Impact

While considering the practical challenges implicit in the discussion in Section 9.1 for the realization of LBNE, it is important to reiterate the compelling science motivation in broad terms.

The discovery that neutrinos have mass constitutes the only palpable evidence *within the body of particle physics data* that the Standard Model of electroweak and strong interactions does not describe all observed phenomena. In the Standard Model, the simple Higgs mechanism — now confirmed with the observation of the Higgs boson — is responsible for quark as well as lepton masses, mixing and CP violation. Puzzling features such as the extremely small masses of neutrinos compared to other fermions and the large extent of mixing in the lepton sector relative to the quark sector, suggest that new physics not included in the current Standard Model is needed to connect the two sectors. These discoveries have moved the study of neutrino properties to the forefront of experimental and theoretical particle physics as a crucial tool for understanding the fundamental nature and underlying symmetries of the physical world.

The measurement of the neutrino mass hierarchy and search for CP violation in LBNE will further clarify the pattern of mixing and mass ordering in the lepton sector and its relation to the patterns in the quark sector. The impact of exposures of $90\,\mathrm{kt}\cdot\mathrm{MW}\cdot\mathrm{year}$ (2030) and $490\,\mathrm{kt}\cdot\mathrm{MW}\cdot\mathrm{year}$ (2035) for Mass Hierarchy and CP-violation signatures is easily extracted from Figure 4.16. Should CP be violated through neutrino mixing effects, the typical signal in LBNE establishing this would have a significance of at least three (2030) and five standard deviations (2035), respectively for 50% of $\delta_{\rm CP}$ values (and greater than three standard deviations for nearly 75% of $\delta_{\rm CP}$ by 2035). In such a scenario, the mass hierarchy can be resolved with a sensitivity for a typical experiment of $\sqrt{\Delta\chi^2} \geq 6$ for 50% (100%) of $\delta_{\rm CP}$ by 2030 (2035).

If CP is violated maximally with a CP phase of $\delta_{\rm CP} \sim -\pi/2$ as hinted at by global analyses of recent data [3], the significance would be in excess of 7σ. This opportunity to establish the paradigm of leptonic CP violation is highly compelling, particularly in light of the implications for leptogenesis as an explanation for the Baryon Asymmetry of the Universe (BAU). With tight control of systematic uncertainties, additional data taking beyond 2035 would provide an opportunity to strengthen a marginally significant signal should $\delta_{\rm CP}$ take a less favorable value.

Similarly, the typical LBNE data set will provide evidence for a particular mass ordering by 2030 in the scenario described in Section 9.1, and will exclude the incorrect hypothesis at a high degree of confidence by 2035, over the full range of possible values for $\delta_{\rm CP}$, θ_{23} and the mass ordering itself. In addition to the implications for models of neutrino mass and mixing directly following from this measurement, such a result could take on even greater importance. Should LBNE exclude the normal hierarchy hypothesis, the predicted rate for neutrinoless double-beta decay would then be high enough so as to be accessible to the next generation of experiments [4]. A positive result from these experiments would provide unambiguous — and exciting — evidence that neutrinos are Majorana particles*, and that the empirical law of lepton number conservation — a law lacking deeper theoretical explanation — is not exact. Such a discovery would indicate that there may be heavier sterile right-handed neutrinos that mix with ordinary neutrinos, giving rise to the tiny observed neutrino masses as proposed by the seesaw mechanism [5]. On the other hand, a rejection of the normal neutrino mass hierarchy by LBNE coupled with a null result from the next generation of neutrinoless double-beta decay experiments would lead to the conclusion that neutrinos are purely Dirac particles. This would be a profound and astonishing realization, since it is extremely difficult theoretically to explain the tiny masses of Dirac neutrinos. High-precision neutrino oscillation measurements carried out by LBNE beyond 2035 may provide evidence for Majorana neutrino mass effects that are outside of the ordinary Higgs mechanism or for new interactions that differentiate the various neutrino species.

Within the program of underground physics, LBNE's most exciting milestones would correspond to observations of rare events. By 2035, LBNE will have been live for galactic supernova neutrino bursts for ten years in the above scenario. Such an event would provide a spectacular data set that would likely be studied for years and even decades to follow.

For proton decay, the net exposure obtained by 2035 in the above scenario also provides a compelling opportunity. A partial lifetime for $p \to K^+\overline{\nu}$ of 1×10^{34} years, beyond the current limit from Super-Kamiokande by roughly a factor of two, would correspond to six candidate events in LBNE by 2035, with 0.25 background events expected. Running for seven more years would double this sample. (Similarly, one should not ignore the corresponding value of an LBNE construction scenario that has a larger detector mass operating from the start, in 2025). With careful study of backgrounds, it may also be possible to suppress them further and/or relax fiducial cuts to gain further in sensitivity.

Finally, the proposed high-resolution near detector, operating in the high-intensity LBNE neutrino beam, will not only constrain the systematic errors that affect the oscillation physics but will also conduct precise and comprehensive measurements of neutrino interactions — from cross sections to electroweak constants.

9.3 Uniqueness of Opportunity

Considering the time and overall effort taken to reach the current state of development of LBNE, it will be challenging for alternative programs of similarly ambitious scope to begin operation before 2025, particularly in light of the current constrained budget conditions in HEP. It should be noted that similar-cost alternatives for the first phase of LBNE utilizing the existing NuMI beam

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*A Majorana particle is an elementary particle that is also its own antiparticle were considered during the reconfiguration exercise in 2012 [6]. The panel concluded that none of these alternatives presented a path toward an experiment capable of a CP-violation signal of 5σ. Furthermore, a large water Cherenkov far detector option for LBNE was carefully considered prior to selection of the LArTPC technology [7]. While both detector options are capable of satisfying the scientific requirements, the LArTPC was judged to have a better potential for scientific performance while also presenting the attraction of an advanced technological approach.

In the broader context of planned experimental programs with overlapping aims for portions of the LBNE science scope, it must be recognized that progress will be made toward some of these during the period before LBNE operations commence. For example, indications for a preferred neutrino mass ordering may emerge from currently running experiments and/or from dedicated initiatives that can be realized on a shorter timescale. Global fits will continue to be done to capitalize, to the extent possible, on the rich phenomenology of neutrino oscillation physics where disparate effects are intertwined. At the same time, each experimental arena will be subject to its own set of systematic uncertainties and limitations.

It is in this sense that the power of LBNE is especially compelling. LBNE will on its own be able to measure the full suite of neutrino mixing parameters, and with redundancy in some cases. To use the MH example just given, it is notable that LBNE will have sensitivity both with beam and atmospheric neutrinos. Control of the relative $\nu_\mu/\overline{\nu}_\mu$ content of the beam as well as the neutrino energy spectrum itself, provides additional handles and cross-checks absent in other approaches.

9.4 Broader Impacts

9.4.1 Intensity Frontier Leadership

The U.S. HEP community faces serious challenges to maintain its vibrancy in the coming decades. As is currently the case with the LHC, the next-generation energy frontier facility is likely to be sited outside the U.S. It is critical that the U.S. host facilities aimed at pursuing science at the HEP scientific frontiers (Figure 3.1), the lack of which could result in erosion of expertise in key technical and scientific sectors (such as accelerator and beam physics).

LBNE represents a world-class U.S.-based effort to address the science of neutrinos with technologically advanced experimental techniques. By anchoring the U.S. Intensity Frontier program [8], LBNE provides a platform around which to grow and sustain core infrastructure for the community. Development of the Fermilab accelerator systems, in particular, will not only advance progress toward achieving the science goals of LBNE, it will also greatly expand the capability of Fermilab to host other key experimental programs at the Intensity Frontier.

9.4.2 Inspirational Project for a New Generation

Attracting young scientists to the field demands a future that is rich with ground-breaking scientific opportunities. LBNE provides such a future, both in the technical development efforts required and its physics reach. The unparalleled potential of LBNE to address fundamental questions about the nature of our Universe by making high-precision, unambiguous measurements with the ambitious technologies it incorporates will attract the best and brightest scientists of the next generation to the U.S. HEP effort.

A young scientist excited by these prospects can already participate in current experiments — some of which use medium-scale LArTPCs — and make contributions to leading-edge R&D activities that provide important preparation for LBNE, both scientifically and technically.

9.5 Concluding Remarks

Understanding the fundamental nature of fermion flavor, the existence of CP violation in the lepton sector and how this relates to the Baryon Asymmetry of the Universe; knowing whether proton decay occurs and how; and elucidating the dynamics of supernova explosions all stand among the grand scientific questions of our times. The bold approach adopted for LBNE provides the most rapid and cost-effective means of addressing these questions. With the support of the global HEP community, the vision articulated in this document can be realized in a way that maintains the level of excitement for particle physics and the inspirational impact it has in the U.S. and worldwide.

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