The Science and Strategy for Phasing of the Long-Baseline Neutrino Experiment

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Abstract

This note is about the principles behind a phased plan for realizing a Long-Baseline Neutrino Experiment (LBNE) in the U.S.. The most important issue that must be resolved is the direction of the first phase of the experiment. Based on both scientific and programmatic considerations, the U.S. should pursue the best option for accelerator neutrino physics, which is the longer baseline towards Homestake with an optimized broadband intense beam.

With the discovery of non-zero θ_{13}, the longer baseline towards Homestake offers the possibility of obtaining a statistically robust spectrum of muon and electron neutrinos and anti-neutrinos with large oscillation effects. Such a measurement is scientifically extremely well-motivated and well-appreciated as a unique capability in the U.S. by the international scientific community and by the funding agencies. This science should remain the key objective in any phasing or reconfiguration plan that aims for U.S. leadership at the Intensity Frontier.

The defining characteristic for the Long-Baseline Neutrino Experiment is the length of the baseline. All other issues: the depth of the detector, the type of the detector, the size and technique for the near detector, although important, do not define the nature of the project since they can be enhanced or changed later. It is important for our field that we use the opportunity provided to us by the wonderfully rich physics of neutrinos, and invest in a new facility with a long baseline that will lead to a comprehensive measurement of the oscillation phenomena.

I. INTRODUCTION

The U.S. high energy community took a very bold step in 2008 when the P5 panel recommended that we pursue a "a world class neutrino program as a core component of the U.S. program" with the long term vision of a large detector and a high intensity beam. This bold action was necessary to allow investment in the key technologies: large detectors, intense beams, and the design of associated infrastructure, underground as well as at FNAL. The actual construction of the experimental program was predicated on the discovery of the final mixing angle, θ_{13}, to be non-zero. This decision has served us well as we have found θ_{13} to be not only non-zero, but rather sizable. We are now in possession of all the needed ingredients for a scientifically well motivated, comprehensive, world class, and stunningly beautiful program of measurements of the phenomena of neutrino oscillations and fundamental symmetries using leptons.

It is important to be reminded of the above as we deal with the financial issues. Of course, the costs for the full desired plan have come out to be too high, and we have been asked for a phased approach. It is important that in the process of optimizing the phased approach and bringing it under the cost-cap we do not lose our original vision for physics and unique world class capability, and are ultimately left with a mediocre program that will be difficult to defend on the world stage.

As we consider the phased program, it is important to consider what parameter defines the Long-Baseline Neutrinos Experiment: it is the length of the baseline. It is, in turn, defined by the sites chosen for the neutrino source and the far detector. The baseline determines the physics you can do, and once it is chosen, it cannot be changed without establishing an entire new facility. All other choices: the size and type of the far detector, the depth of the far detector, the size and technology of the near detector, do not define the project. They are important, but the fundamental capabilities are set by the baseline. If we choose the correct baseline we can exploit it for a long time; if we do not then we will be limited by it forever.

In the following, I will describe what is gained or lost by changing the length of the baseline (from the well-established 1000 to 1500 km discussed in the CD0 mission need and the two national academy reports [1, 2]), the beam configuration, and the size and location of the far detector for the long baseline physics. It is not my intention to repeat the numerical detail which can be found in the April 25-26, 2012 steering panel workshop presentations and also the physics working group report, but my comments will be based on those details.

II. THE PHYSICS

The broad scientific justification for the Long-Baseline Neutrino Experiment is stated eloquently by Engelhardt, Nelson, and Walsh in ArXiv:1002.4452[3]. They state: *Non-collider experiments and astronomical observations have given us our first hints of physics beyond the Standard Model, via the discoveries of neutrino oscillations, dark energy, and dark matter. The implication of these discoveries for fundamental physics is still unknown. The energy scale of the new degrees of freedom giving rise to neutrino oscillations could be as high as* 10^{16} *GeV, as in Grand Unified theories, or as low as* 0.05 *eV, as in Dirac neutrino mass models. Even more mysterious is the nature of dark energy and dark matter, and the associated energy scale or scales. If the new physics is light, it must be very weakly coupled to the Standard Model, or it would already have been discovered. Neutrino oscillation measurements offer an unmatched portal into any new nonstandard sectors containing light fermions, because neutrinos can mix with neutral spin 1/2 particles, and because oscillations over long baselines are extraordinarily sensitive to extremely tiny effects.*

The leading effect is, of course, the mixing of the three neutrinos amongst each other with extremely tiny mass differences and large mixing. This phenomenology must be thoroughly tested before sensitivity to any new interactions can be obtained. The neutrino oscillation data so far can be adequately explained by pair-wise mixing, and there is so far no single experiment that tests the 3-generation phenomenology with adequate redundancy.

The key observable that will allow a quantitative and thorough test of 3-generation neutrino mixing is CP violation. This is because CP violation must exist at some level in any mixing scenario with more than two generations [4, 5]. CP violation results from quantum mechanical interference between multiple pathways from one neutrino flavor to another. The additional fact that the observation of leptonic CP violation would be the first outside the quark system adds great importance to this effort.

However, explicit observation of CP violation must be distinguished from simply extracting the CP phase from the available data. To claim observation of CP violation the following conditions must be met:

- We must have sufficient statistics in the appearance modes $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ to observe an asymmetry.
- The length of the baseline must be adequate to have good separation of the asymmetry due to the matter effect - and the mass hierarchy measurement - from the CP asymmetry to break the parameter degeneracies. Recall that the matter effect has never been demonstrated in a laboratory experiment before.
- A broad spectrum of events with adequate energy resolution must be collected to demonstrate that the energy distribution follows the expectation from 3-generation mixing.

If any of these conditions is not met, we are forced to use multiple constraints from other experiments to extract the CP phase. For example, the shortness of the baseline to Soudan creates ambiguities between the CP violation and the matter effect asymmetries forcing us to use other data (such as T2K). Similarly, the lack of sufficient spectral information in an off-axis NuMI beam experiment leads us to require measurement of θ_{13} from the reactor experiments to extract the CP phase. Since the 3-generation oscillation model must be used in combining the data, this procedure does not adequately test the model.

Given the above scientific requirements, we designed LBNE to have sufficiently long baseline, a broad band beam, and a detector with high energy resolution and particle identification capability so that:

- The disappearance of muons has an unmistakable oscillatory signature which allows us to know how many muon neutrinos disappeared at each energy bin.
- For each energy bin over a considerable range of the oscillation period we can measure how many muon neutrinos turned into electron neutrinos.
- Neutrino energy is adequately high so that the event energy resolution is good, and the rate of anti-neutrino events is sufficiently high.

After accounting for the matter effect which has an energy dependence that is approximately linear ($\sim E$) and is sufficiently large that it can be easily distinguished, the CP asymmetry between neutrino and anti-neutrino data can be measured and demonstrated to have the expected dependence ($\sim 1/E$). This technique requires us to have a sufficiently long baseline and a broadband beam.

A. Numerical Precision on Parameters

The good experimental design of LBNE on the basis of a definitive observation of oscillations and a spectrum of electron and muon events spanning the interesting dynamic range obviously results in improved performance on parameter measurements. The complete set of calculations and plots are in the detailed report from the physics working group, and I will not repeat it here. I have summarized some of the numbers in Table I.

For this table (I) I have chosen a configuration for LBNE with the currently designed beam directed towards Homestake with 1300 km length and a 10 kTon fiducial mass liquid argon TPC detector. The comparison is made with a 20 kTon fiducial mass liquid argon TPC detector at the Soudan location in the existing NuMI beam which has the baseline of 735 km. Both setups are assumed to get 700 kW of beam for 10 years. I have simply extracted the numbers from the physics working group.

These configurations were chosen because the current costing exercise appears to indicate that these configurations will fit the maximum cost guidance from the DOE for phase I of the program. The detector mass may change as the costs become better understood, but it is unlikely to change the scientific conclusions dramatically.

Measurement	LBNE to Homestake 10 kTon LAr	NuMI beam with 20 kTon LAr
Mass Hierarchy (without T2k)	$> 2.5\sigma$ all phase space	$> 2\sigma$ half phase space
Mass Hierarchy (with T2K)	$> 4\sigma$ all phase space	$> 2\sigma$ all phase space
δ_{CP} resolution (no θ_{13} constraint)	20^o at $\delta_{CP} = 0$ 30^o at $\delta_{CP} = 90^o$	25^o at $\delta_{CP} = 0$ 50^o at $\delta_{CP} = 90^o$
δ_{CP} resolution (with θ_{13} constraint)	20^o at $\delta_{CP} = 0$ 30^o at $\delta_{CP} = 90^o$	25^o at $\delta_{CP} = 0$ 30^o at $\delta_{CP} = 90^o$
$\sin^2 2\theta_{13}$ resolution	± 0.008 at $\delta_{CP} = 0$ ± 0.008 at $\delta_{CP} = 90^o$	± 0.008 at $\delta_{CP} = 0$ ± 0.012 at $\delta_{CP} = 90^o$
Oscillations	Sees Oscillations	No oscillations
Δm^2_{31} resolution $\sin^2 2\theta_{23}$ resolution	$0.016 \times 10^{-3}\mathrm{eV}^2$ 0.007	$0.022 \times 10^{-3}\mathrm{eV}^2$ 0.009
Future Upgrade	See second oscillation for large CP effects	No possibility of second oscillation

TABLE I: Summary of performance on parameter measurements. The resolutions stated in this table are at 1σ. For the resolutions on the CP phase and $\sin^2 2\theta_{13}$, there is an assumption that the mass hierarchy is resolved. For the NuMI option, the parameter sensitivity is similar at either the Ash River off-axis site or the Soudan on-axis site with the appropriate tune selected for the NuMI beam.

Table I clearly shows that with a smaller detector at the longer baseline one is able to achieve better performance for all of the parameters. An important assumption made for the table is that the mass hierarchy has been resolved for the resolution on the CP phase and $\sin^2 2\theta_{13}$. This assumption is weak for the case of the NuMI options in half of the parameter range, and should be used with care. The detailed calculations clearly show that one needs 2 to 3 times more detector mass at the NuMI based (Soudan or Ash River) sites for similar parameter sensitivity. For the NuMI choice there are inherent ambiguities due to the shortness of the baseline and the lack of sufficient dynamic range in L/E. These ambiguities can be seen in the mass hierarchy resolution which becomes extremely difficult in some regions of the parameter space where the effect of mass ordering is completely degenerate with the effect of the CP phase for both neutrinos and anti-neutrinos. This cannot be resolved by increasing the detector size. The second limitation due to the lack of dynamic range is in the strong correlation between θ_{13} and the CP phase measurement. For the NuMI options the CP phase measurement requires the use of the external θ_{13} constraint from reactor experiments.

It is entirely possible that as neutrino data accumulates, a global fit of the data will start yielding a value for the the mass hierarchy or the CP phase at some confidence level. However, it is the tradition in the field of physics that a new phenomena such as CP violation cannot be said to exist until a single definitive experiment is performed to establish it. If neutrino physics is to be the corner stone of the U.S. Intensity Frontier HEP program, then it cannot be a peripheral program: it must lead to a definitive experiment for the phenomena of CP violation, and must be able to stand on its own as a complete measurement.

III. COMMENTS ON ALTERNATIVES

In the following I have chosen to respond to a few important commonly asked questions. The reader may choose to read the conclusions first and come back to these comments later.

With a large θ_{13} why is a long baseline and a large detector still needed ?

The value of θ_{13} does not define the length of the baseline or the size of the detector. These parameters cannot be fine tuned based on the size of θ_{13}. This proposed tuning is simply incorrect from the point of view of both science and strategy.

The non-zero value of θ_{13} has made LBNE scientifically very important. The value of θ_{13} assures that there will be an observable signal for $\nu_\mu \to \nu_e$ oscillations with the atmospheric oscillation frequency. However, we are no longer trying to simply observe this signal, but want to measure the asymmetry and the spectral distortion in the signal between neutrinos and anti-neutrinos due to the effect of the CP phase. The CP asymmetry is expected to decrease as $1/\sin\theta_{13}$[6] and therefore the statistical merit obtained for the measurement of the CP phase is independent of θ_{13} for a given the detector size. For a given required error on the CP phase, the size of the detector cannot be tuned for the value of θ_{13}[7, 8] for any configuration of the beam or baseline. And furthermore, as demonstrated in great detail the shorter baseline has significant disadvantages with regards to making the proposed measurements regardless of the value of θ_{13}.

What are the key advantages of a new beam and a longer baseline compared to NuMI ? Is it advantageous to build an even longer baseline beam than 1300 km ?

There are two key advantages to a baseline longer than the NuMI baseline of 735 km:

1) The oscillation nodes for the relevant neutrino oscillations are given by $\frac{1.27\times\Delta m^2/(eV^2)\times L/(km)}{E/(GeV)} = \pi/2, 3\pi/2, 5\pi/2....$ The FNAL Main Injector accelerator (with proton beams of 120 GeV) is best suited for making neutrinos in the few GeV range[8], and furthermore it is very difficult with any accelerator to obtain sufficient statistics (because of the loss of flux due to the boost in pion decay as well as cross section) and resolution with neutrinos below $<$ 1 GeV. The event rate at high energies increases as E^3 due to both the boost and the increase in cross section. Therefore for a rich program of neutrino oscillations in which an explicit oscillatory signature can be measured in the spectrum, it is necessary to be at a baseline of over 1000 km[1].

2) As has been amply demonstrated, the longer baseline allows a measurement of the spectrum of electron neutrinos from appearance over a large dynamic range and an unambiguous terrestrial measurement of the matter effect (in the $\nu_\mu \to \nu_e$ channel), and consequently the mass hierarchy of neutrinos. The matter effect has not been demonstrated in a laboratory experiment yet. The spectral measurement of electron neutrinos and the matter effect are important parts of the neutrino phenomenology and indispensable in understanding CP violation.

Lastly, there are advantages as well as disadvantages to a baseline longer than 1300 km [9]. The most significant advantage is that both the matter and CP effects grow with distance, and therefore a longer baseline experiment could be performed with relaxed requirements on the beam and background systematics. Second advantage is that it is easier to make and detect high energy neutrinos, and because of the increase in the event rate at high energy the detector size need not be increased. The main disadvantage at longer baselines is the large suppression of neutrino or anti-neutrino electron events (due to the matter effect) which makes it difficult to observe the CP asymmetry explicitly as an asymmetry between the two polarities. There are also technical difficulties and added cost associated with making a much steeper beam-line with a longer decay pipe.

It has been concluded over several years of study that for most of the accelerator neutrino physics goals, the baseline of 1500 ± 200 km is close to optimum given the beam energy and power performance expected from the FNAL Main Injector[8].

Why cannot we go to a much shorter baseline that will provide much more flux because of the distance ?

To observe neutrino oscillations the energy of the spectrum must be adjusted to match the length of the baseline as L/E. For an on-axis beam the energy of the neutrino is proportional to the energy of the π-mesons that must be focused in the forward direction. For lower energy pions the intensity of the flux in the forward direction (solid angle) decreases as γ^2 where γ is the boost factor of the pion. Therefore any increase in the flux due to $1/L^2$ is lost due to the loss of solid angle in the decay. Furthermore, the cross section of neutrinos is proportional to energy leading to further loss of event rate at shorter baseline. The loss of anti-neutrino events is particularly severe at baselines shorter than 500 km because the anti-neutrino cross section falls rapidly below ~ 1 GeV. The performance for the CP phase measurement appears to be optimum in the baseline range of 1500 ± 200 km.

Could the NuMI beam-line be made lower in energy to achieve the same performance as the LBNE beam?

It has been stated that since the oscillations are a function of L/E, lowering the energy of the NuMI spectrum should achieve the same scientific performance as LBNE with a longer baseline. This is incorrect for two reasons:

1) The effect of the matter potential is proportional to energy, and consequently requires a longer baseline for a definitive measurement. Without the longer baseline, the effect of matter and CP can be confused with each other as we have seen in the detailed calculations by the physics working group.

2) The second reason is the technical feasibility of lowering the beam energy. There are fundamental kinematic limitations to increasing the flux of low energy neutrinos. At first order the same number of low energy pions can be produced for the same power of the proton beam regardless of the proton energy. Lowering the proton beam energy does not increase the yield of low energy neutrinos. Furthermore, the potential increase by changing target/horn configuration is limited to a few tens of percents.

To get more events at higher L/E, it is better to increase L than lower E.

Is there an advantage in an off-axis location for LBNE ?

An off-axis location reduces the total number of signal events by a factor of two to five depending on the off-axis angle, but it also allows much reduced backgrounds because of the narrow band nature of the beam and the energy resolution of the detector. When the value of θ_{13} was unknown, it was a good strategy to reduce the backgrounds to allow higher sensitivity to $\nu_\mu \to \nu_e$ appearance. Now that we know the value to be non-zero and well above the expected backgrounds, there is no advantage to an off-axis location for LBNE. The narrow band nature of the beam does not allow measurement of the spectrum of electron neutrinos. As the energy is determined mostly by the chosen off-axis angle, the limitation of the off-axis beam is permanent and cannot be fixed by any manipulation of the proton energy or the horn/target geometry. The energy spectrum is expected to be affected by a number of important effects such as the matter effect and the CP phase. It is vital that in any future experiment, the spectrum be measured across the largest possible dynamic range.

What is the role of a near detector for this physics ? Should the decision on the NuMI versus Homestake decision be based on the near detector ?

The near detector is needed for high precision determination of neutrino oscillation parameters. The near detector needs to have minimum requirements such as muon charge determination, good particle identification, and the ability to cancel cross section uncertainties due to nuclear corrections on the argon nucleus. Past experience indicates that systematic errors of the order of $\sim 10\%$ can be achieved for electron appearance measurements without the use of a near detector, but to achieve $< 5\%$ systematic error will most likely require a near detector[10]. Both NuMI and Homestake options will require a near detector when the far detector achieves the statistics that will allow a $< 5\%$ determination of neutrino/anti-neutrino asymmetries.

It has been suggested that since the NuMI beam-line has the needed halls and near detectors, these might be sufficient for the first phase of the experiment. It is important to separate the decision on the future direction of the LBNE program from the need or existence of the near detector in the first phase. The defining parameter for LBNE is the length of the baseline. The placement of the far detector and the performance of the beam-line defines the physics program; the near detector improves it. The decision on the configuration of LBNE should be based on the parameter that cannot be changed later: the length of the baseline, not the near detector.

What is the priority of underground physics for LBNE ?

The best motivation for the Long-Baseline Neutrino Experiment has always been neutrino oscillations and the measurement of CP violation. As remarked above, despite the data collected so far, no single experiment has the comprehensive capability to test our understanding of the phenomena of neutrino oscillations as LBNE. The critical design parameter for this capability is the length of the baseline which has been repeatedly stressed in many reports (and the CD0 mission statement) to be in the range of 1300 to 1500 km. The first performance characteristic for LBNE must remain the length of this baseline and not the depth of the detector.

The choice between having an underground detector in Soudan with a much compromised baseline versus a surface detector at Homestake will be very difficult for many collaboration members.

It should be realized, however, that it is difficult to justify the LBNE detector on the basis of proton decay and supernova alone because, although these are important topics, they have much larger scientific risks. If the accelerator program is compromised by reducing the baseline, the project will become difficult to defend and may ultimately be deemed not sufficiently unique and exciting. Maintaining the baseline as a unique feature is much more likely to attract more funding to enable the deep placement for expansion of the science program. Because of cost considerations the initial design for the Homestake based detector may have to be reduced and on the surface, but even such a design has been shown to have superb reach for the mass hierarchy and CP parameters because of the larger physics effects at the longer baseline. As we learn more about the costs of underground placement and are able to attract other partners, it will become possible to place the detector underground and to enlarge the mass. It is suggested that for CD1, the detector at Homestake be assumed to be on the surface to keep the project under the cost-cap. However, a scope contingency could be added to the project so that if additional resources can be found the detector can be placed underground in phase I.

What is the nature of the international competition ?

The availability of intense beams at Fermilab and the unique geographical conditions in the U.S. have allowed us to define a bold and efficient LBNE design with a 1300 km baseline with a well-optimized beam. A 34 kTon liquid argon detector on the 1300 km baseline from FNAL will outperform the proposed configurations in Japan, T2HK with a 560 kTon detector and a 1.66 MW beam (295km baseline), and in Europe, CERN to Physalmi (2300 km) or CERN to Gran Sasso (732 km). Both the Japanese and European versions of long-baseline experiments are very large projects and are also subject to financial and schedule pressures. In terms of engineering and project planning the U.S. LBNE project is currently ahead.

LBNE with a 1300 km baseline is considered a unique project in the world, and is very likely to attract international partners. If phase I of LBNE is launched in a timely way, it is quite likely that international contributions will allow us to assemble enough resources to rapidly build the full LBNE program. This will require international agreements, but the most important element is the decision on the length of the baseline and the far detector site.

IV. CONCLUSION

For any experiment or facility, there are a few key parameters that define the scientific capability. In this note I have argued that for the Long-Baseline Neutrino Experiment the defining parameter is the baseline. It is, in turn, defined by the sites chosen for the neutrino source and the far detector. The baseline determines the physics you can do, and once it is chosen, it cannot be changed without establishing an entirely new facility. We should use the opportunity provided to us by the new physics of neutrinos, and invest in a new facility at Homestake and a new much more capable beam with a long baseline of 1300 km from FNAL that will lead to a robust and comprehensive program of measurements of the oscillation phenomena. The size of the far detector and some of the infrastructure at the near and far sites can be adjusted to be commensurate with optimum use of resources and the near detector complex can evolve with the project in phases.

The design for LBNE with a broadband beam aimed over 1300 km to a massive detector at Homestake has been reviewed numerous times. The scientific goals of such a project have been reviewed and have the backing from the National Research Council reports in 2003 and 2011 [1, 2], The NUSAG report in 2007 [12], and the P5 report in 2008[13]. There have been numerous publications on the performance of such a project. With the recent discovery of the value of θ_{13}, the LBNE program is scientifically unquestionable. During these reviews we have repeatedly compared the scientific capability of a NuMI based program versus a program with a new longer baseline, and found the LBNE program with a baseline of 1300 km to be superior for any value of the oscillation parameters, especially θ_{13}. As a result of financial constraints we are being forced to look at the NuMI based options again. It might appear attractive to place a sizable detector on an existing beam-line, however such a strategy is not forward-looking, and any such decision will be hasty.

Since the accelerator neutrino program is of the highest priority for LBNE, we should make the correct and forward-looking choice for a new much more capable beam-line towards Homestake coupled to a new technology detector. The physics reach from such a choice will be easier to defend in future reviews. It should also be remarked that the selection of the far detector technology (liquid argon time projection chamber) was on the basis of a longer baseline with higher energy neutrinos. If the baseline becomes shorter such as NuMI then the detector choice may not be well matched. Defending a combination of NuMI with a liquid argon detector with a spectrum that is not well matched to the length of the baseline will be difficult.

Lastly, the LBNE towards Homestake choice is much better matched to the idea of subsequent expansion, phasing, and international partnerships. The nature of our enterprise with a uniquely long baseline towards Homestake, an advanced technology liquid argon TPC detector, and a very capable beam-line makes it very attractive for international partners. It could lead to a growing program as we learn more about the physics of neutrinos and the technology of the liquid argon detector. The program is better placed as motivation for Project-X and future upgrades to Project-X. The LBNE beam will have the ability to take ever increasing beam power from Project-X for improved physics performance including the ability to see larger physics effects at lower energies leading to high precision in neutrino physics [14].

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[1] Neutrinos and Beyond, New Windows on Nature, National Research Council, National Acedemy Press, ISBN:0-309-08716-3, 2003.

[2] An Assessment of the Science Proposed for the Deep Underground Science and Engineering Laboratory (DUSEL), National Research Council, National Academy Press, ISBN-10:0-309-21723-7

[3] Netta Engelhardt et al., Phys. Rev. D81 (2010) 113001, axXiv:1002.4452.

[4] J. L. Hewett, H. Weerts, R. Brock, J. N. Butler, B. C. K. Casey, J. Collar, A. de Govea and R. Essig *et al.*, arXiv:1205.2671 [hep-ex]. See section 4.2: In three or more generation mixing, neutrinos can convert from one flavor to another through multiple pathways, each defined by a complex phase. The total amplitude is then a sum of each of these contributions. Each contribution is a product of two parts: a kinematical part that oscillates with a characteristic energy, $exp(-i \times E_{pth} \times t)$, and a dynamical part that is a product of matrix elements. Only the dynamical part changes to its complex conjugate for anti-neutrinos, and therefore the total amplitude for neutrinos and anti-neutrinos can be different leading to CP violation in the case of more than two generations.

[5] PDG, Review of Particle Physics, Journal of Physics G, Vol. 33, July 2006.

[6] W. J. Marciano, hep-ph/0108181.

[7] M. V. Diwan, D. Beavis, M. -C. Chen, J. Gallardo, S. Kahn, H. Kirk, W. Marciano and W. Morse *et al.*, Phys. Rev. D **68**, 012002 (2003) [hep-ph/0303081].

[8] The study report, all associated documents, presentations, plots, studies, spectra, are at http://www.phy.bnl.gov/∼diwan/fnal-bnl, Fermilab-0801-AD-E, BNL-77973-2007-IR, arxiv:0705.4396.

[9] M. V. Diwan, "The Case for a super neutrino beam," Frascati Phys. Ser. **35**, 89 (2004) [hep-ex/0407047].

[10] Talk at the 2nd International Workshop towards the Giant Liquid Argon Charge Imaging Experiment

(GLA2011), Milind Diwan, https://www.jyu.fi/fysiikka/en/gla2011

[11] A 21st Century Frontier of Discovery: the Physics of the Universe, National Science and Technology Council Committee on Science, February 2004.

[12] "Recommendation to the Department of Energy and the National Science Foundation on the Future U.S. Program in Neutrino Oscillations," Neutrino Scientific Assessment Group, July 13, 2007.

[13] U.S. Particle Physics: Scientific Opportunities. A Strategic Plan for the Next Ten Years, Report of the Particle Physics Projects Prioritization Panel, May 29, 2008.

[14] M. Bishai, M. V. Diwan, S. Kettell, J. Stewart, B. Viren, E. Worchester and L. Whitehead, "Neutrino Oscillations in the Precision Era," arXiv:1203.4090 [hep-ex].