International Context

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Given the significant investment future neutrino oscillation experiments represent, international coordination seems to be at least prudent if not mandatory. In this short note, which is derived from a presentation given on October 24$^{\text{th}}$, 2011 at the pre-meeting of the neutrino working group of the Intensity Frontier workshop, we try to summarize the international context in which LBNE and Project X are likely to find themselves.

With the discovery of neutrino oscillation starting in the late 1990s precision studies of neutrino mixing have moved to the forefront of experimental high energy physics and numerous proposals, comparative studies *etc.* have been published to explore the possibilities for an experimental program to pursue this science, see *e.g.* [1]. Neutrino physics is, at this moment, at a transition from discovery to precision science and while some may find that this makes the field less exiting and vibrant, it should not be forgotten, that neutrino oscillation is the first sign of physics beyond the Standard Model whose discovery is not entirely due to astrophysics and cosmology. Therefore, precision studies of neutrino oscillation are the equivalent of precision studies of *e.g.* supersymmetric particles, if they should happen to be discovered at the LHC. In this sense neutrino physics is ahead of the program at the High Energy Frontier – the initial discovery of new physics has been made and now we need to follow up and understand what it is, we have discovered.

The initial discoveries in neutrino physics have largely been made using neutrino sources which already were available, either natural ones like the atmosphere or artificial ones like nuclear power reactors. The obvious advantage of these sources is their easy availability and the associated low cost. The drawback is, that the experimenter has no control over these sources and systematic uncertainties can be substantial. To make further progress, purpose-made neutrino sources will be necessary and this implies a transition to intense accelerator-driven systems with a concomitant increase in complexity and cost, while at the same time very large detectors are still needed to obtain sufficient statistics. These large detectors, if located deep underground, are also ideal tools to study low energy phenomena like supernova neutrinos, proton decay *asf.*. While this presents a true synergy, one cannot fail to notice that none of these non beam-related physics topics would warrant an investment at the required level and it is the beam-related precision oscillation physics which is the physics driver for this program.

In this note, we will limit ourselves to the description of the various alternatives to LBNE and Project X and their ability to study oscillations amongst three active flavors. This limitation is not inherent in the facilities, they all have significant capabilities towards new physics searches, but is due to the fact that this aspect has been studied most, especially in terms of a comparison of facilities. The overarching goal of studying three flavor oscillation with precision it to find out whether in neutrinos, like in the quark sector, all flavor transitions are described by a unitary 3×3 matrix or if there are contributions from new physics. The ultimate hope, the holy grail, is, of course, to solve the flavor puzzle. The precision study of neutrino oscillation can be broken down into the following questions: What is the size of $\sin^2 2\theta_{13}$? Is there leptonic CP violation? What is the ordering of the three mass eigenstates, or the mas hierarchy? Is the atmospheric mixing, as parametrized by θ_{23}, maximal? There is no particularly compelling way to rank these questions by their importance and depending on ones theoretical prejudices many different rankings seem to be equally valid. The magnitude of $\sin^2 2\theta_{13}$ has practical implications because it greatly impacts on the choice of an appropriate technology to pursue the other questions.

The past year has seen quite some excitement with indications that $\sin^2 2\theta_{13}$ maybe finite. Both, T2K [2] and MINOS [3] report signals which point in this direction and while each of these indications is below $3\,\sigma$ significance, global fits seem to already exclude $\sin^2 2\theta_{13} = 0$ at more than $3\,\sigma$ [4]; taken at face value the global fit implies that $\sin^2 2\theta_{13} > 0.02$ at the $3\,\sigma$ level. Fortunately, reactor neutrino experiments [5–7] will soon provide first results and also T2K will resume data taking, therefore we can expect a definitive answer to whether the current indications are correct or not sometime 2012. Since the answer to this question has profound implications for any future long baseline neutrino experiment, as we will demonstrate in the following, no major decision should be taken until the question of whether $\sin^2 2\theta_{13} > 0.02$ or not has been resolved.

In figure 1 we compare the physics sensitivities for the discovery of the mass hierarchy (left hand panel) and for the discovery reach for CP violation (right hand panel). Both panels show the fraction of true δ_{CP} for which the measurement can be performed at the $3\,\sigma$ confidence level as a function of the true value of $\sin^2 2\theta_{13}$. The various lines are for different experimental setups as indicated by the legend and the details of the experiments are given in the caption. The selection of possible experiments has been guided by whether there is a serious effort towards

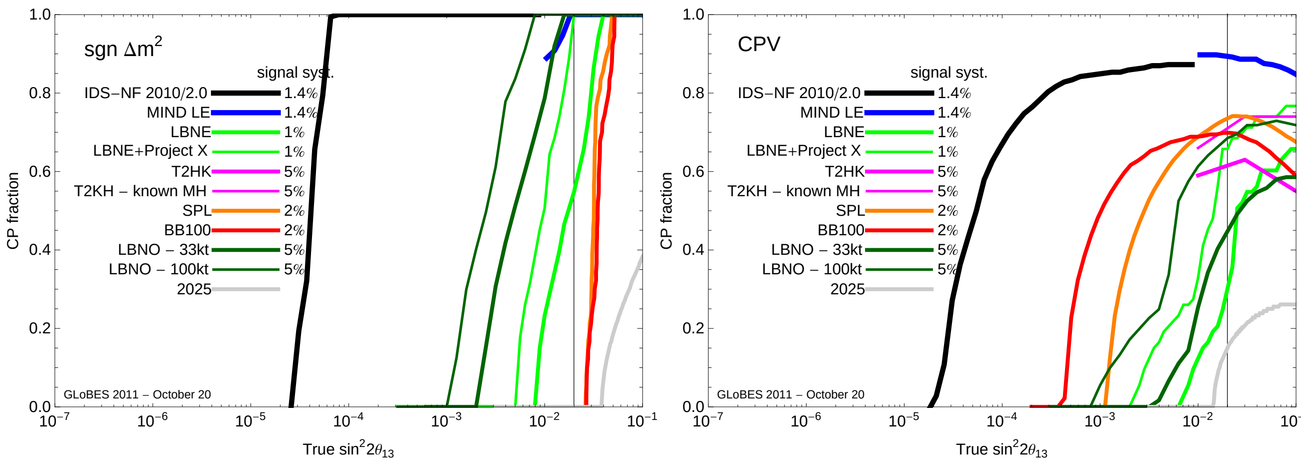

FIG. 1. The three flavor oscillation discovery reaches quantified by the fraction of true δ_{CP} versus the true value of $\sin^2 2\theta_{13}$ at $3\,\sigma$ confidence level (1 dof) for the mass hierarchy (left hand panel) and for CP violation (right hand panel). The various lines are for different experimental setups as labeled in the legend, where also the systematic uncertainty on the signal normalization is given. IDS-NF 2010/2.0 is a two baseline neutrino factory setup with magnetized iron detectors of 100 kt at a baseline of 4 000 km and 50 kt at a baseline of 7 500 km using 10^{21} 25 GeV muons per year (10^7 s) for 10 years. MIND LE is a single baseline neutrino factory with one magnetized iron detector of 100 kt at a baseline of 2 000 km using 10^{21} 10 GeV muons per year (10^7 s) for 10 years; both neutrino factory setups are taken from [8]. LBNE is a 700 kW beam of 120 GeV protons running for 10 years (2×10^7 s, each) directed towards a 200 kt water Cerenkov detector (or a 6 times smaller liquid argon detector) with a baseline of 1 300 km. LBNE + Project X assumes the same setup, however with 2.3 MW beam power; the sensitivity for both setups is taken from [9]. T2HK assumes a 560 kt water Cerenkov detector and 1.66 MW 50 GeV proton beam for 5 years (10^7 s, each) with a baseline of 295 km and the sensitivities are taken from [10], where the curve labeled T2HK – know mass hierarchy, assumes the mass hierarchy to be known. The SPL setups assumes a 8 GeV 4 MW proton beam for 10 years (each 10^7 s) towards a 440 kt water Cerenkov detector over a baseline of 130 km, the sensitivities are taken from [11]. Note, that a re-optimized beam for the SPL has been shown to enhance sensitivities somewhat [12]. The BB100 setup is a $\gamma = 100$ beta beam towards a 440 kt water Cerenkov detector over a baseline of 130 km using 5.8×10^{18} ^{6}He per year (10^7 s) for 5 years and 2.2×10^{18} ^{18}Ne decays per year for 5 years [11]. Note, that within the EURISOL design study it was found that these ion intensities may be very difficult to reach [13]. Both setups BB100 and SPL include the atmospheric neutrino data sample which gives rise to some sensitivity towards the mass hierarchy. LBNO is a liquid argon detector of 33 kt or 100 kt (see legend) using a 1.7 MW 50 GeV proton beam for 10 years (1.7×10^7 s each) over a baseline of 2 300 km and the sensitivities are from [14]. Finally, the curve labeled 2025 summarizes our knowledge in the year 2025 if no facilities are built, but all beams, i.e. NuMI and the T2K beam are upgraded to 2.3 MW and 1.66 MW, respectively and is taken from [15]. All sensitivities, except the T2HK curves, have been computed using GLoBES [16, 17].

a machine and detector design. The two neutrino factory options are taken from the Interim Design report [8] of the International Design Study for the Neutrino Factory (IDS-NF). LBNE and LBNE + Project X are described in detail in the Physics Working Group report of LBNE [18]. The SPL setup is based on a possible low energy superconducting linac which used to be part of CERN's plan to upgrade its proton infrastructure for high luminosity LHC running. The BB100 setups represent a beta beam which could be realized with the existing PS at CERN and therefore, in principle, could be run concurrently with SPL. The machine options for both setups have been studied in the context of the Euro-ν [19] and EURISOL [13] programs. LBNO is developed in the context of the LAGUNA-LBNO study [20, 21], which currently includes three possible detector technologies, water, liquid argon and liquid scintillator and seven potential sites. The accelerator would be based on a possible upgrade/replacement of the PS at CERN. The results presented in figure 1 are valid for all values of $\sin^2 2\theta_{13}$ and for all values and both measurement the two baseline neutrino factory, IDS-NF 2010/2.0, performs best. It is worthwhile to point out that mass hierarchy sensitivities for BB100 and SPL, given their very short baseline of 135 km, is entirely due to the atmospheric neutrino sample collected in the 440 kt water Cerenkov detector. Therefore, it can be expected that T2HK would have a least the same sensitivity to the mass hierarchy for a similar exposure to atmospheric neutrinos. In absence of any knowledge of the true value of $\sin^2 2\theta_{13}$ it seems one would prefer a neutrino factory since it has the deepest reach in the $\sin^2 2\theta_{13}$ direction.

However, as mentioned previously, we have strong hints that $\sin^2 2\theta_{13} > 0.02$. In this case, it has been demonstrated [15] that existing experiments, *i.e.* Double Chooz, Reno, Daya Bay, T2K and NOνA, will not be enough to determine the mass hierarchy or discover CP violation at $3\,\sigma$ in a significant fraction of the parameter

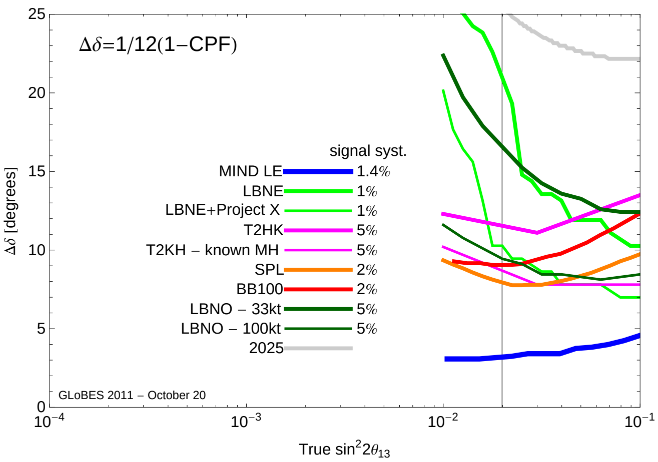

FIG. 2. The experimental setups are the same as defined in the caption of figure 1. Shown is the $1\,\sigma$ error on the CP phase, as defined in the text, as function of the true value of $\sin^2 2\theta_{13}$.

space even if $\sin^2 2\theta_{13} = 0.1$; only if the beams are considerably upgraded some sensitivity results as shown by the curve labeled 2025. In the large θ_{13} case the problem needs to be rephrased since the precise value of θ_{13} will be known in this case. As a result, the mass hierarchy measurement now should be accomplished by any, judiciously chosen, experiment. Thus, only CP violation remains as a distinguishing feature and the focus shifts from discovery to precision measurements. The effect this has on the perception of the relative merit of the various setups is illustrated in figure 2. This figure is obtained from figure 1 by taken the value of CP fraction, CPF and apply $1/12(1 - CPF)$, which yields the average $1\,\sigma$ error on the CP phase where the average is taken between the true values for the phase of 0 and π. Obviously, in this representation the advantage offered by a neutrino factory, in this case the one baseline 10 GeV MIND LE setup, is significant as it improves the accuracy with respect to any other setup by a factor of two.

The real issue with a comparison of precision like the one in figure 2 is of course, that the results depends very strongly on the assumed value for systematics error. In this figure we chose to provide the systematic error on the appearance signal, as it has been shown to be the leading contribution to the overall systematic error budget [22]. At large θ_{13} the appearance signal can be sizable and thus statistical errors may well go down into the per cent range and per cent level systematics is no longer negligible. The values currently used are assumptions which in none of the cases has been substantiated by simulation. Past experience with pion-decay based neutrino beams shows that even reaching a systematic error of 5% can be challenging. This will be even more true for appearance experiments where both neutrino and antineutrino signals have to be compared with per cent level accuracy. Nuclear effects in neutrino interactions are currently not well known and therefore available event generators can not be considered reliable. Thus, the question arises whether these event generators can be used to predict the level of systematical errors in these experiments. To illustrate the problem: an experiment with 400 events and 1% systematics will have the same total error as an experiment with 10 000 events and 5% systematic error, thus even a moderate change in the systematics level can have a profound impact on the overall peformance in terms of precision. With respect to systematics, beams with *a priori* knowledge of the flavor composition and neutrino spectrum, like for instance beams from muon decay, offer enormous advantages. Thus, whatever the correct answer to the systematics question is, it seems fair to assume that neutrino factories will have smaller systematical errors than any of the other facilities. Systematical errors will control the precision of Standard Model parameter determinations and thus, also determine the level to which new physics can be found on top of the large Standard Model background, which is due to the leading $\sin^2 2\theta_{13}$ oscillation.

To summarize, all of the facilities discussed in this note are at relatively early planing stages, where LBNE is probably the most mature project. Most of the superbeam based approaches involve some sort of staging in either beam power or detector size. In this context it should be noted, that also a neutrino factory can be staged in luminosity and in its initial stage can avoid muon cooling and a dedicated proton driver. The time scale of all superbeam setups seems to be comparable, at least assuming a similar funding profile, which in practice may not be the case. Thus competition between superbeams seems likely and strategies to deal with schedule risks in this context should be developed, *e.g.* time lines of T2HK in comparison to Project X. This is even more true for large $\sin^2 2\theta_{13}$, where new results in 2012 could significantly affect the decision processes in all regions. As a result the perception of the US program being ahead may have to be revised. It also should be noted, that an aggressive program to control systematic errors will be required to optimally exploit the large θ_{13} case.

I would like to thank Mary Bishai and Sam Zeller for providing the LBNE sensitivities and Tracey Li for providing the LBNO sensitivities. This work has been supported by the U.S. Department of Energy under award number DE-SC0003915.

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