

# Long-baseline sensitivity studies and comparison (discussion session)

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**Abstract.** In this discussion session, the sensitivity and optimization of future long-baseline experiments is addressed, with a special emphasis on *feasible* projects and the description in terms of the error on the parameters. In addition, a statement on the precision interesting for  $\nu_e \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_\tau$  oscillation measurements is obtained. A special topic is the impact of the recent T2K hint for non-zero  $\theta_{13}$ .

## 1. Introduction and task assignment

The task assignment for this session has been the discussion of the sensitivity and optimization of future long-baseline experiments. One of the objectives has been the focus *feasible* projects (*i.e.*, for beta beams), another the expression of the sensitivities in terms of the error on the parameters. In addition, a statement on the precision interesting for  $\nu_e \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_\tau$  oscillation measurements has been asked for, and a report on studies of such measurements for superbeam and neutrino factory. An important recent topic has been the  $2.5\sigma$  hint from the T2K experiment for large  $\theta_{13}$  [1]. This hint has strengthened the physics case for a new facility, especially since existing equipment will most likely not be sufficient to establish the mass hierarchy and CP violation at a high confidence level [2].

Now first of all, what does “feasible” mean? For the purpose of this session, only setups actively being studied, such as within the Euronu design study or the international design study for the Neutrino Factory (IDS-NF), have been selected. Another interpretation of “feasibility” is to consider setups only for which a cost estimate is in preparation. More specifically, three representatives have been chosen:

- LBNE as superbeam representative.<sup>1</sup>
- A CERN-SPS based beam as beta beam representative, possibly to be combined with the SPL superbeam.
- The IDS-NF baseline for the Neutrino Factory, possibly with a low energy alternative

The expression of the sensitivities in terms of the “error on the parameters” has been interpreted as a the expression in terms of the main impact parameters for the sensitivities, and systematics.

<sup>1</sup> Note that there are also different experimental proposals actively being studied for superbeams, such as J-PARC to Hyper-Kamiokande [3]. However, in terms of the parameters relevant for physics, such as baseline and energy, it is similar to the T2K experiment – although not in terms of performance, of course.

In order to discuss the comparison of facilities, an introductory talk to each kind has been asked for by three champions for the three classes of experiments: Jim Strait (superbeams) [4], Elena Wildner (beta beams) [5], and Ken Long (Neutrino Factory) [6]. The questions asked to the champions where:

- Optimization ( $L$ ,  $E$ , *etc.*) of the setup: Is that the physics-wise optimal setup for that class?
- Under which boundary conditions was that obtained: physics-wise, *e.g.*, where in parameter space, and technology-wise, *e.g.*, constrained to some site?
- Does the optimization change for  $\theta_{13}$ ?
- What is the discovery reach for  $\theta_{13}$ , mass hierarchy, and CP violation? What are the assumptions going into that? What is the performance for large  $\theta_{13}$ ?
- What are the critical systematics and other important impact factors for physics potential (for example, external knowledge on cross sections required, which cannot be obtained with near detectors)?

These talks where followed by a discussion session, the results of which are summarized below.

## 2. Discussion on comparison of facilities

The topics and results of the discussion session have especially lead to a number of re-formulated questions, which need to be addressed in the future.

One of the most relevant topics is the optimization of the setups for large  $\theta_{13}$ . There are different ways to address this optimization, such as identifying the minimal requirements for an experiment to measure the main performance indicators, see, *e.g.*, Ref. [7] for beta beams and Ref. [8] for the Neutrino Factory, or the identification of the experiment parameters ( $L$ ,  $E$ , off-axis angle, *etc.*) with the best performance in the  $\delta_{\text{CP}}$ -direction, see, *e.g.*, Ref. [9] for the Neutrino Factory and Ref. [10, 11] for superbeams. In either case, the optimal experiment configuration for a specific performance indicator can be predicted as a function of  $\theta_{13}$  and detector response. This prediction is quite straightforward for beta beams and the Neutrino Factory, because the beam spectrum can be analytically computed, whereas it depends on the target system and horn geometry for the superbeams. Therefore, the question for the optimal setup is not straightforward to answer for superbeams unless a particular beam configuration is used. In addition, note that if  $\theta_{13}$  is known (within certain errors), the optimization direction in parameter space will change from  $\theta_{13}$  into  $\delta_{\text{CP}}$ . This has peculiar effects: For example, from Ref. [10] (Figs. 6 and 8), it can be read off that the “minimal” wide band superbeam for  $\theta_{13}$  close to the Chooz bound has a baseline  $L \simeq 700$  km similar to MINOS, which is just long enough to measure the mass hierarchy for any  $\delta_{\text{CP}}$  and CP violation for 75% of all  $\delta_{\text{CP}}$ . A longer baseline is mostly preferable for the mass hierarchy measurement if  $\theta_{13}$  turns out to be smaller. Therefore, it is expected that a solid lower bound on  $\theta_{13}$  will have a major impact on the optimization of future experiments. One of the questions to be addressed in the future was therefore: Does the optimization of the individual experiments change of the T2K hint is confirmed? Another one: What is the impact of prior  $\theta_{13}$  (*e.g.*, from Daya Bay) and mass hierarchy (*e.g.*, from atmospheric neutrinos) measurements on sensitivities and optimization? From the conceptual point of view, a point no common agreement was reached on, was: Does a future experiment have to measure all parameters (such as  $\delta_{\text{CP}}$  and mass hierarchy) in a self-consistent way, or is it better to rely on a combination of different strategies (such as a beam experiment for CP violation and atmospheric neutrinos for the mass hierarchy)?

Another important topic, which is especially relevant for large  $\theta_{13}$ , is systematics. For example, the cross sections are an important ingredient to the normalization uncertainty, and may even affect the spectral shape. Let us consider a very simplified picture independent of

nuclear models and other workarounds. Whereas the cross sections at the Neutrino Factory can be obtained in a self-consistent way at the near detectors (only the  $\nu_\mu$  cross sections are needed), the appearance channel cross sections for superbeams and beta beams have to be extracted from other experiments or, possibly, the  $\nu_e$  contamination of the beam (superbeams), since a different flavor is present in the near detector. Here a combination of a superbeam and beta beam may be clearly synergistic, since a near detector in one experiment class can measure the cross sections needed for the appearance analysis of the other experiment class. It has been noted in the discussion that the assumptions for systematics are not transparent in experiment comparison plots, maybe even not comparable; these should be documented and made publically available. In addition, studies of the performance as a function of the exposure have been identified as interesting in that context, since these will illustrate when the systematics limitation becomes relevant and what the systematics-dominated limit will be.

As far as the performance indicators are concerned, the results of future experiments will be shown, among other sections, as fits in the  $\theta_{13}$ - $\delta_{\text{CP}}$ -plane. However, even though recent global fits show already a slight (low confidence level) preference for some value of  $\delta_{\text{CP}}$  [12], the value of  $\delta_{\text{CP}}$  will not be well enough constrained to rely on in terms of the optimization of the experiment. Since the preferred value of  $\delta_{\text{CP}}$  depends on the experiment class, it is therefore an important question how to quantify the precision on  $\theta_{13}$  and  $\delta_{\text{CP}}$ . As possible solutions, the performance of future facilities may either be shown as a function of the true  $\delta_{\text{CP}}$ , see, *e.g.*, Refs. [13, 14] (“CP pattern”), or for certain benchmark sets of parameters in the  $\theta_{13}$ - $\delta_{\text{CP}}$ -plane. The advantage of the first method is a more complete understanding of the parameter space, the advantage of the second method is that the performance indicator looks closer to the actually expected result. Other questions in this direction, to be addressed in the future, were: Can the  $\theta_{13}$  precision from reactor experiments be easily exceeded by long-baseline experiments? What limits the  $\theta_{13}$  precision at reactor experiments? Is  $\theta_{13}$  or  $\sin\theta_{13}$  (as it appears in the mixing matrix) the quantify of interest?

### 3. Precision interesting for oscillation searches with tau neutrinos

As far as the  $\nu_e \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_\tau$  *oscillation* measurements are concerned, the main focus has been on effects present in the neutrino propagation rather than neutrino production or detection. A qualitative statement can be already made from simple statistics considerations: given the relatively low detection efficiency of the  $\nu_\tau$  detectors if the hadronic decay channels of the  $\tau$  cannot be considered, and the relatively small considered detector masses up to about 4 to 10 kt (such as for emulsion cloud chambers), the statistics will be much lower than in the leading  $\nu_e \leftrightarrow \nu_\mu$  and  $\nu_\mu \rightarrow \nu_\mu$  oscillation channels. For example, for the Neutrino Factory, magnetized emulsion cloud chambers with a fiducial mass of up to 5-10 kt have been proposed [15, 16], compared to 100 kt magnetized iron detectors for the leading channels. Given the difference in efficiency, about a factor of 50 to 100 more statistics can be accumulated in the leading channels compared to the  $\nu_\tau$  channels – not even to speak of the  $\tau$  production threshold. Because of this huge difference,  $\nu_\tau$  detection sometimes helps, but is hardly competitive to other options, see, *e.g.*, Ref. [17] for standard oscillation physics and Ref. [18] for non-standard interactions. Therefore, a re-formulated version of the initial question concerning the precision interesting for  $\nu_\tau$  searches could be: what kind of new physics would be present in the  $\nu_\tau$  channels with a factor of 50-100 enhancement compared to the leading channels in spite of almost maximal  $\theta_{23}$ ? A possible answer to this question may be sterile neutrinos, especially if CP phases are present, see Ref. [19]. Another possible answer may be a chirally enhanced effect in  $\epsilon_{\mu\tau}^s$  [20], which is, however, best observed in a near detector. Another potential issue in that context is the fact that there are relatively few studies for  $\nu_\tau$  oscillation searches for superbeams yet. The status of the  $\nu_e \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_\tau$  oscillation measurements has been reviewed by Toshihiko Ota [21]. The remaining question is, of course, if there are other new physics cases requiring

$\nu_\tau$  oscillation searches, and if they affect the baseline optimization. For example, an interesting case may be phases from non-unitarity, for which a  $\nu_\tau$  detector in a distance of 130 km has been discussed [22–24].

#### 4. Summary and conclusions

In this session, the long-baseline sensitivity studies and comparisons have been discussed, and the precision interesting for  $\nu_e \rightarrow \nu_\tau$  and  $\nu_\mu \rightarrow \nu_\tau$  oscillation measurements. For the sensitivity studies, the main outcome has been that the optimization and performance for large  $\theta_{13}$  has to be reviewed. In addition, systematical errors, which are important in that case, have to be identified, tested, and documented in a transparent way. The physics case for  $\nu_\tau$  searches relies on new physics potentially present in the  $\nu_\tau$  channels in spite of the large difference in statistics to the leading channels and the almost maximal value of  $\theta_{23}$  (which typically leads to similar sized signals in the leading channels). So far only extremely few convincing cases have been identified.

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