Superbeams plus Neutrino Factories

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Abstract. We show that the combination of the expected physics results from a SuperBeam facility (SB) and those from a Neutrino Factory (NF) resolves fake degenerate solutions which appear in the simultaneous measurement of θ_{13} and leptonic CP violation. Intrinsic, sign(Δm^2_{13}) and θ_{23} degeneracies are largely eliminated because of the different average neutrino energy and baseline of both facilities. A short NF baseline, $L = 732$ km, becomes, after such a combination, a very interesting distance.

1. Introduction

The development of a neutrino factory from muon storage rings [1] requires, by design, the essentials of a superbeam facility [2, 3, 4] as an intermediate step. In this perspective, the correct analysis strategy is to contemplate the combination of their expected physics results. In this talk, based on the work [5], we show the important impact of such a combination, in particular on the disappearance of fake solutions in the simultaneous measurement of θ_{13} and δ.

2. Degenerate solutions

It was shown in ref. [6] that there exists generically, at a given (anti)neutrino energy and fixed baseline, a second value of the set $(\theta^{'}_{13}, \delta^{'})$ that gives the same oscillation probabilities for neutrinos and antineutrinos as the true value chosen by nature. In what follows, these fake solutions will be dubbed *intrinsic degeneracies*. More recently, it has been pointed out [7, 8] that other fake solutions might appear from unresolved degeneracies in two other oscillation parameters: the sign of Δm^2_{13}, and the exchange $\theta_{23} \leftrightarrow \pi/2 - \theta_{23}$ ambiguity for $\theta_{23} \neq \pi/4$ [9].

Strategies to eliminate some of the fake solutions have previously been discussed, advocating the combination of different baselines [6], an improved experimental technique allowing the measurement of the neutrino energy with good precision[10], the supplementary detection of $\nu_e \to \nu_\tau$ channels [11] and a cluster of detectors at a superbeam facility located at different off-axis angles, so as to have different $\langle E \rangle$ [12], or different superbeam experiments [13].

We consider the measurement of the subleading probabilities $P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)}$ in the NF complex(for more details see [15]), through the detection of "wrong-sign" muons, and $P_{\nu_\mu \nu_e (\bar{\nu}_\mu \bar{\nu}_e)}$ in the SB facility, through the detection of electrons/positrons.

We have performed both analytical and numerical studies of the three types of degenerate solutions. From the analytical perspective, the vacuum approximation is excellent as regards the SB scenario with a baseline of hundreds of kilometers, while in practice it also gives a good indication for the results at the short (732 km) and intermediate (2000–3000km) baselines of a NF. Of course, in our numerical treatment, all the fits include the exact formulae for the probabilities, including matter effects.

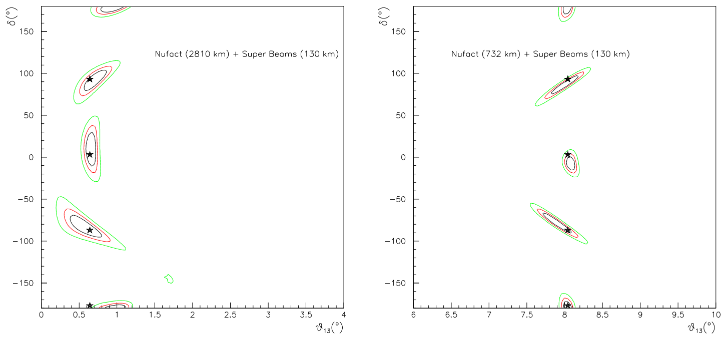

Figure 1. *Fits combining the results from the SPL-SB facility and a NF baseline at $L = 2810$ km and $\theta_{13} = 0.6°$ (left) or $L = 732$ km and $\theta_{13} = 8°$ (right). The true values illustrated correspond to $\delta = -90°, 0°, 90°, 180°$ and $\theta_{13} = 8°$ (top) or $\theta_{13} = 0.6°$ (bottom). Notice that the fake intrinsic solutions have completely disappeared in the combinations.*

For the NF we consider the experimental setup presented in [6, 14, 15]. As the SB facility we consider the design proposed for the CERN SPL [16]. Whenever it is not specified otherwise, we take the following central values for the oscillation parameters: $\sin 2\theta_{12} \cdot \Delta m^2_{12} = 10^{-4}\text{eV}^2$ with $\Delta m^2_{12} > 0$, $|\Delta m^2_{13}| = 3 \times 10^{-3}$ eV^2 and $\sin 2\theta_{23} = 1$. The small expected uncertainties in these parameters have not been included yet, but in a previous work [6], we did not find dramatic effects when one considers them.

2.1. Intrinsic degeneracies

In the vacuum approximation, apart from the true solution, $\delta' = \delta$ and $\theta'_{13} = \theta_{13}$, there is a fake one. Our results for the NF can be found in ref. [6], where it was shown that these intrinsic degeneracies were eliminated when two NF baselines (intermediate and long) were combined. The degenerate solutions for the SPL-SB are presented in ref. [5]. A comparison of the NF and SPL-SB fits shows that the displacement of the fake solution with respect to the true one is opposite for the two facilities. In fact, the position (measured in $\theta'_{13} - \theta_{13}$ or δ') of the degenerate solution depends strongly on the baseline and the neutrino energy through the ratio L/E, so it is very different in the NF, the SPL-SB and also JHF setups, as can be clearly seen in Figs.2 of ref. [5] . As a result, we expect that any combination of the results of two of these three facilities could in principle exclude the fake solutions. As it is shown in Fig. 1 (left), the combination of the optimal NF baseline $L = 2810$ km results with those obtained from the SPL-SB facility is sufficient to get rid of all the fake solutions, even for very small values of θ_{13}! (*solar regime* [6]). It is specially important to remark what happens when one considers the combination of the SPL-SB results and those from the NF baseline of $L = 732$ km (see Fig. 1 (right)) . As explained in refs. [6, 15], when this NF baseline is considered alone there exists a continuum of almost degenerate solutions. After the combination of the results from this NF baseline with those from SPL-SB not only the fake solutions corresponding to the intrinsic degeneracies in the superbeam disappear, but the accuracy in the determination of the true solution becomes competitive with that obtained in the combination with the optimal baseline for large values of θ_{13} (*atmospheric regime* [6]). At small values of θ_{13} the latter still gives better results, as expected.

2.2. Sign(Δm^2_{13}) *degeneracy*

Assume that nature has chosen a given sign for Δm^2_{13}, while the data analysis is performed assuming the opposite sign. It is very easy to find the fake sign solutions in the vacuum approximation, as they mirror the two solutions (true and fake) obtained in the analysis of the intrinsic degeneracies [5], upon the substitution $\delta' \to \pi - \delta'$.

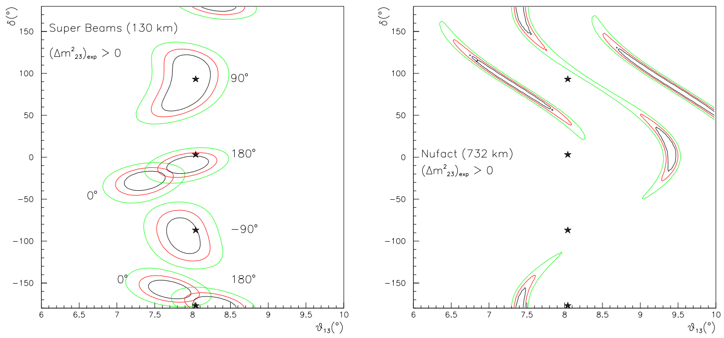

Figure 2. *Fits for central values $\theta_{13} = 8°$ and $\delta = -90°, 0°, 90°, 180°$ for the SPL-SB (left) and NF at $L = 732$ km (right). Nature's sign for Δm^2_{23} is assumed to be positive, while the fits have been performed with the opposite sign. All fake solutions disappear when the two sets of data are combined.*

One of them mirrors the true (nature) solution and will be called below solution I. Since it is approximately E- and L-independent, it will be hard to overcome this degenerate solution. Fortunately, this fake solution does not interfere significantly with the determination of θ_{13} or CP-violation (i.e. $\sin\delta$) ‡. The second fake sign solution, which we will call solution II, is strongly L- and E-dependent. Both solutions I and II can be nicely seen in the numerical analysis for the SPL-SB in Fig. 2 (left), for $\theta_{13} = 8°$ and positive sign(Δm^2_{13}). Of course matter effects are very important in resolving fake sign solutions[21]: the task should thus be easier at large θ_{13} and large enough NF baselines, where matter effects are largest.

At $L = 732$ km some fake sign solutions remain close to the present experimental limit for θ_{13}, as shown in Figs. 2 (right). It should be noticed that, again, in the combination of these latter data with those from the SPL-SB facility, all fake sign solutions disappear for large $\theta_{13} \geq 4°$, and the sign of Δm^2_{13} could thus be determined from it.

The solutions that survive in the combinations for small θ_{13} are indeed of type I, as shown in ref. [5], which do not interfere significantly with the determination of θ_{13} and δ.

2.3. $\theta_{23} \to \pi/2 - \theta_{23}$ degeneracy

The present atmospheric data indicate that θ_{23} is close to maximal, although not necessarily 45°. Superkamiokande results give 90%CL-allowed parameter regions for $\sin^2 2\theta_{23} > 0.92$ [22], translating into the allowed range $35° < \theta_{23} < 55°$.

As in the sign(Δm^2_{13}) degeneracy case, there exist one solution I which mirrors nature's choice and a second solution, solution II, that mirrors the intrinsic degeneracy, as illustrated by the analytical formulae, see Ref. [5]. Because of this parenthood, solution I is *a priori* expected to present generically less L and E dependence than solution II, and be thus more difficult to eliminate in the combination.

We have performed fits with the wrong choice of octant for θ_{23} and central values of θ_{23} at the limit of the currently allowed domains. The results confirm the expectations above and indicate a situation close to that for the fake sign degeneracies, albeit slightly more difficult. For instance, at the $L = 2810$ km baseline of the NF alone, still some fake θ_{23} solutions remain down to $\theta_{13} > 2°$, but again they all disappear when combined with the SPL-SB data. As an illustration, in Figs. 3 we show the results for $\theta_{23} = 35°$ and $\theta_{13} = 4°$, at the SPL-SB facility (left) and the $L = 2810$ km NF baseline (right). The same exercise, but for an $L = 732$ km baseline of the NF, results in the elimination of the θ_{23} degeneracies only for $\theta_{13} \geq 8°$.

‡ $\sin\delta' = \sin\delta$.

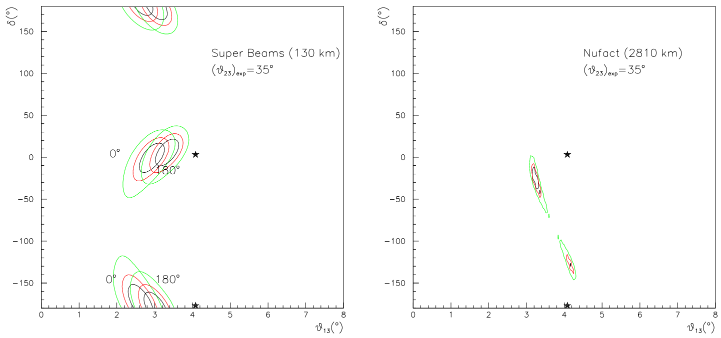

Figure 3. *Fake solutions due to θ_{23} degeneracies for SPL-SB results (left) and a $L = 2810$ km NF baseline (right), for $\theta_{23} = 35°$, $\theta_{13} = 4°$ and $\delta = -90°, 0°, 90°, 180°$. The combination of the results from both experiments resolves the degeneracies.*

In the solar regime both fake θ_{23} solutions have a sizable L, E dependence, when θ_{23} is far from maximal.

In ref. [5] the fits for $\theta_{13} = 0.6°$, for a NF at $L = 2810$ km as well as the same combined with the results from the SPL-SB facility are shown: only one annoying fake solution remains in the latter, which results from the merging of solution I for SB and solution II for the NF, owing to the finite resolution.

In general, our conclusions are rather parallel to those for the fake sign(Δm^2_{13}) solutions, with the caveat that for the θ_{23} ambiguities, solution I, which is harder to resolve, is not that close to satisfying $\sin\delta^{'} = \sin\delta$, and it is thus potentially more harmful to the measurement of CP violation.

3. The silver channels

One possibility that can help very much to remove degeneracies further is to measure also the $\nu_e \to \nu_\tau$ and $\bar\nu_e \to \bar\nu_\tau$ transition probabilities. The relevance of these *silver* channels in reducing intrinsic degeneracies was studied in ref. [11], in the atmospheric regime: the sign of $\theta^{'}_{13} - \theta_{13}$ will be opposite to that for the golden $\nu_e \leftrightarrow \nu_\mu$ ($\bar\nu_e \leftrightarrow \bar\nu_\mu$) channel. In the solar regime, the intrinsic solutions in these silver channels will be identical upon exchanging $\delta' = 0$ and π, and the combination of the golden and silver channels remains a promising option.

Let us now turn to the fake θ_{23} solutions. When considering only $\nu_e \to \nu_\tau$ and $\bar\nu_e \to \bar\nu_\tau$ oscillations, the fake solutions related to the θ_{23} ambiguity get different displacements to the ones for the golden channels. A detailed analysis for a realistic experimental setup will be done elsewhere [25], but we expect that the combination of the two appearance measurements: $\nu_e \to \nu_\mu$ and $\nu_e \to \nu_\tau$ for both polarities can help to resolve the dangerous solution I associated with the θ_{23} ambiguity, for θ_{13} in the atmospheric regime.

Finally, we recall that the disappearance measurements (e.g. $\nu_\mu \to \nu_\mu$) should also be helpful in reducing these ambiguities for large θ_{23}. Obviously, if the angle θ_{23} will turn out to be close to maximal (as the best-fit point now indicates), the θ_{23} degeneracies will be of very little relevance.

4. Conclusions

Superbeams and Neutrino Factory are two successive steps in the same path towards the discovery of leptonic CP violation: the combination of the data from these two experiments is particularly useful to eliminate the degenerate solutions. The position of the fake solution depends strongly on the baseline and the neutrino energy, and it is very different for the NF and the SPL-SB setups. We have studied all the degeneracies both analytically and through simulations, including realistic background errors and efficiencies for a magnetized iron detector at a neutrino factory, and a water Cerenkov one at the proposed SPL superbeam facility. The intrinsic degeneracies disappear down to the sensitivity limit even for the neutrino factory with the detector located at short baselines!. The combination of two different super beams with different L/E should also get rid of them.

We have also shown that the fake solutions associated with the sign and θ_{23} ambiguities can be grouped in two sets: those closer to nature's values (solutions of type I) and those related to the intrinsic fake solution (solutions of type II). Generically solutions I show a milder L/E dependence and are thus more difficult to eliminate through this strategy. For θ_{13} near its present limit, the combination of the SPL-SB data and those from a short NF baseline, i.e. $L = 732$ km, is sufficient to resolve all of them and deliver a clean measurement of θ_{13} and leptonic CP violation. With lowering θ_{13} but still in the atmospheric regime, although the same setup often produces interesting results, it is necessary to consider an intermediate NF baseline, i.e. $L = 2810$ km, together with the superbeam. In particular the sign of Δm^2_{13} can be measured from the combination of their data down to $\theta_{13} > 1°$.

For values of $0.5° < \theta_{13} < 1°$ most degeneracies still disappear in the combined data from the SPL-SB facility and the $L = 2810$ km NF baseline, but some fake solutions remain, mainly of type I. While those associated to the sign$(\frac{\Delta m^2_{13} L}{4E})$ ambiguity bias only slightly the extraction of the true θ_{13} and δ values, those related to θ_{23} would remain a problem, if θ_{23} were far from maximal. But, as it has been pointed out [11], a supplementary measurement of the *silver* channels, i.e. $\nu_e \leftrightarrow \nu_\tau$ ($\bar{\nu}_e \leftrightarrow \bar{\nu}_\tau$), could help in removing the intrinsic degeneracy.

5. References

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