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Oscillation physics at neutrino factories

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Abstract. I discuss the physics opportunities raised by so called neutrino factories. Specifically the sensitivity to the small mixing angle θ_{13}, to the mass hierarchy and to the CP phase are presented and compared to the ones of other experiments like superbeams and reactors.

PACS. 14.60.Pq Neutrino mass and mixing

1 Introduction

Several years ago the decay of muons in a storage ring was proposed as high intensity source of neutrino beams [1]. In the decay of a muon one ν_μ and one $\bar{\nu}_e$ is produced. Due to the high energy of the muon $\sim 50\,\mathrm{GeV}$ the neutrino emission is peaked in forward direction. The $\bar{\nu}_e$ can oscillate into $\bar{\nu}_\mu$ and the $\bar{\nu}_\mu$ can produce μ^+ via charged current in the detector. These μ^+ are called wrong sign muons. Whereas the surviving ν_μ produce μ^-. Thus a neutrino factory detector has to be able to separate both charges with a very high purity. The wrong sign muon sample is especially interesting since it measures the transition probability $P_{\bar{\nu}_e \to \bar{\nu}_\mu}$, which is particularly sensitive to θ_{13}, the mass hierarchy and the CP phase. This transition on the other hand is also plagued with degeneracies and it is therefore not straightforward to translate the event numbers into physical parameters like θ_{13} or the CP phase δ (see e.g. [2]). The results shown in the following are a compilation and an update of the results presented in [3,4,5,6]. A relatively recent and more general review is given in [7].

2 Sensitivity to $\sin^2 2\theta_{13}$

In Fig. 1 the sensitivity to $\sin^2 2\theta_{13}$ at 90% CL is shown for various experiments. The left edge of the blue (dark grey) bar is the limit for statistical errors only. The left edge of the green (medium grey) bar is the limit including systematics. Once correlations among the oscillation parameters are taken into account the left edge of the yellow (light grey) bar gives the limit. And finally the right edge of the yellow (light grey) bar yields the limit properly including degeneracies. Thus the actual limit on $\sin^2 2\theta_{13}$ is given by the right edge of the yellow (light grey) bar.

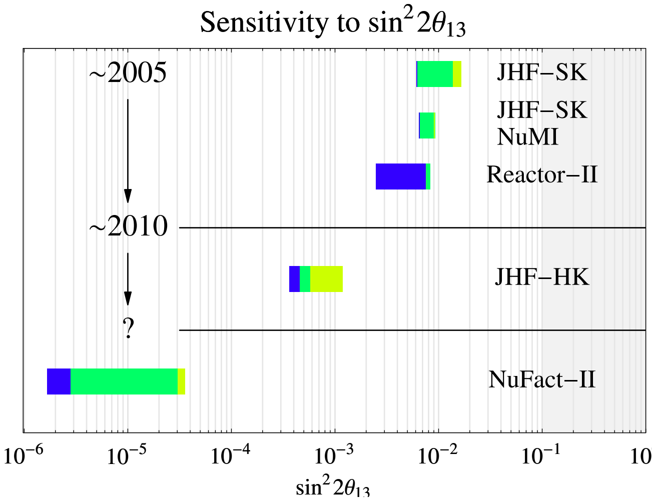

Fig. 1. Sensitivity to $\sin^2 2\theta_{13}$ at 90% CL for various experiments as defined in [3,4,5,6]. The blue (*dark grey*) bar represents the effects of statistics (*left edge*) and systematics (*right edge*). The right edge of the green (*medium grey*) bar shows the effect of including correlations and finally the yellow (*light grey*) bar gives the sensitivity limit by also considering degeneracies. The remaining oscillation parameters are – $\Delta m^2_{31} = 3.0 \cdot 10^{-3}\,\mathrm{eV}^2$, $\theta_{23} = \pi/4$, $\Delta m^2_{21} = 7.0 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\sin^2 2\theta_{12} = 0.8$

The next generation superbeam and reactor experiments can reach sensitivities down to approximately 10^{-2} as it is also found in [4,8,9,10,11]. The relative impact of statistics, systematics, correlations and degeneracies is however rather different for beam experiments and reactor experiments, since reactor experiment use electron disappearance.

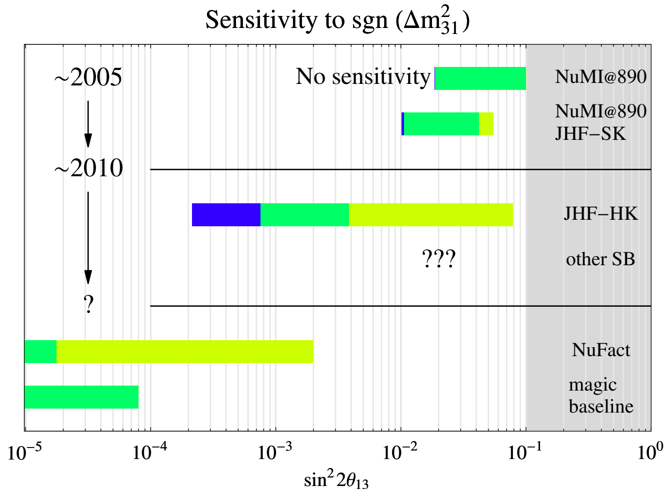

Fig. 2. Sensitivity to normal mass hierarchy as function of the true value of $\sin^2 2\theta_{13}$ at 90% CL for various experiments as defined in [3,4,5,6]. The blue (*dark grey*) bar represents the effects of statistics (*left edge*) and systematics (*right edge*). The right edge of the green (*medium grey*) bar shows the effect of including correlations and finally the yellow (*light grey*) bar gives the sensitivity limit by also considering degeneracies. The remaining oscillation parameters are – $\Delta m^2_{31} = 3.0 \cdot 10^{-3}\,\mathrm{eV}^2$, $\theta_{23} = \pi/4$, $\Delta m^2_{21} = 7.0 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\sin^2 2\theta_{12} = 0.8$

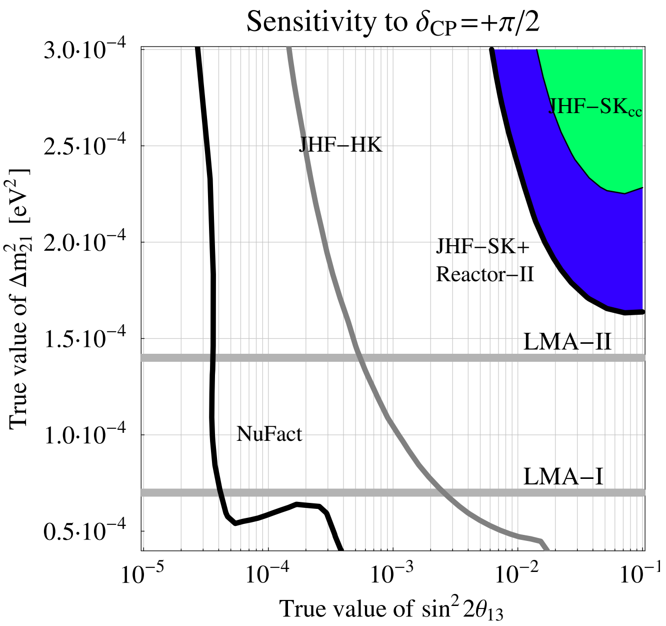

Fig. 3. Sensitivity to maximal CP violation, i.e. $\delta = \pi/2$, at $3\,\sigma$ CL as function of the true values of $\sin^2 2\theta_{13}$ and Δm^2_{21}. Sensitivity is given to the right of each curve. The other oscillations parameters are – $\Delta m^2_{31} = 3.0 \cdot 10^{-3}\,\mathrm{eV}^2$, $\theta_{23} = \pi/4$ and $\sin^2 2\theta_{12} = 0.8$

A further improvement of the sensitivity clearly requires more statistics which is equivalent to having bigger detectors and stronger beams. Moreover in order to reduce the impact of correlations and degeneracies additional information is necessary which is naturally provided by running with anti-neutrinos. A conceivable setup which fulfills these conditions is JHF-HK – a combination of a 4 MW beam and a 1 Mt water Cherenkov detector [8]. This setup can improve the limit by one order of magnitude with respect to initial superbeams or reactors. At the same time it represents the limit for the superbeam technology because the systematical uncertainty on the size of the beam intrinsic background of ν_e becomes the limiting factor. Thus a further increase in statistics will not improve the sensitivity [3].

Finally a neutrino factory will have the best sensitivity to θ_{13} due to its extremely high luminosity and its very clean beam. A neutrino factory using the magic baseline [5] in combination with an intermediate baseline of 3 000 km may reach sensitivities of the order a few times 10^{-5} in units of $\sin^2 2\theta_{13}$.

3 Mass hierarchy

The issue whether the mass eigenstate m_3 is the heaviest (normal hierarchy) or the lightest one (inverted hierarchy) is still unsolved. Future experiments may be able, by exploiting the MSW effect [12,13,14], to distinguish the two mass ordering schemes. The size of matter effects in the $\nu_\mu \leftrightarrow \nu_e$ transition depends on θ_{13}, the matter density and the baseline. The effects are strongest around the MSW resonance which occurs in Earth matter and with the current value of Δm^2_{31} at approximately 10 GeV. An optimal experiment to determine the mass hierarchy should therefore have a very long baseline and a significant number of events in the resonance region [15,16]. This condition is only satisfied by a neutrino factory. This can also be seen in Fig. 2, where the sensitivity to normal mass hierarchy at 90% CL is given for different experiments as a function of the true value of $\sin^2 2\theta_{13}$. The color coding of the bars is the same as in Fig. 1. One observes that the green/yellow (medium/light grey) region is much larger compared to the case of θ_{13} in Fig. 1. The reason for this behavior is that it is possible to fit the data with the opposite mass hierarchy by adjusting the value of θ_{13} and simultaneously the value of the CP phase. In principle it is however possible that in case one of the two is determined independently the sensitivity would strongly improve. For the superbeam experiments sensitivity is only obtained for very large values of θ_{13}. Only a neutrino factory can offer a reliable measurement over a large portion of the parameter space especially once the magic baseline is used [5].

4 CP violation

The ultimate goal of oscillation physics is to solve the question whether there is also CP violation in the leptonic sector. Leptonic CP effects[1] are suppressed by the smallness of θ_{13} and by the mass hierarchy parameter $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$. Therefore the size of CP effects and

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[1] in oscillations

therewith the sensitivity of a given experiment is determined by θ_{13} and Δm^2_{21}. Furthermore the problem arises that θ_{13} and the CP phase δ are strongly correlated [17] which necessitates to use at least two independent measurements, which also in this case are naturally provided using neutrino *and* anti-neutrino data. For large values of θ_{13} the information borne by anti-neutrinos can be replaced by reactor data which yield an uncorrelated determination of θ_{13} [6]. The sensitivity to maximal CP violation, i.e. $\delta = \pi/2$, at $3\,\sigma$ CL is shown in Fig. 3 as function of the true values of $\sin^2 2\theta_{13}$ and Δm^2_{21}. Sensitivity is given to the right of each curve. The discovery potential of the first generation experiments JHF-SK, NuMI and Reactor-II is rather limited which is shown by the colored area. The issue of leptonic CP violation requires much better statistics and therefore an experiment of the size of JHF-HK (grey line) is needed in order to cover the allowed range for Δm^2_{21}. For a precision measurement a neutrino factory (black line) seems necessary and its sensitivity is significantly better than of any other experiment especially for small values of θ_{13}. An important role in the precision determination of the CP phase at a neutrino factory is played by the uncertainty of the matter density. The MSW effect by itself leads to an effective CP violation which has to be entangled from the intrinsic CP violation, therefore a good knowledge on the matter density is required. A nice and detailed discussion of those issues is given in [18]. The final accuracy for the CP phase may reach a level of few degrees.

5 Conclusion

Spurred by the great advance of observational neutrino physics in the last few years many new ideas have been brought forth to improve our knowledge on the oscillation parameters. The focus has been on possibilities to determine θ_{13}, the mass hierarchy and the CP phase, since those three parameters are still unknown. The approaches reach from traditional accelerator-based beams over reactor neutrino experiments to a neutrino factory. The different strategies have a distinct succession of time scales. A reactor experiment can be operational in less than five years from now. The beam experiments can be available in approximately five years in their initial stages and it is envisaged to extend and upgrade those experiments in the years to follow until we finally will have a neutrino factory. Not only the time scales of the different experiments are varying but also the scales of θ_{13} at which the physics program can be achieved. The reactors and initial beams will probe new oscillation physics down to $\sin^2 2\theta_{13} \simeq 10^{-2}$. There potential mainly lies in a better determination of θ_{13}. The second generation beam experiment will improve their physics reach with respect to $\sin^2 2\theta_{13}$ by one further order of magnitude and they will have a good potential to discover leptonic CP violation. The ultimate tool for neutrino precision physics however still is a neutrino factory.

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