

## Summary of Golden Measurements at a $\nu$ -Factory

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### Abstract

The precision and discovery potential of a neutrino factory based on muon storage rings is summarized. For three-family neutrino oscillations, we analyze how to measure or severely constraint the angle  $\theta_{13}$ , CP violation, MSW effects and the sign of the atmospheric mass difference  $\Delta m_{23}^2$ . The appearance of “wrong-sign muons” at three reference baselines is considered: 732 km, 3500 km and 7332 km. We exploit the dependence of the signal on the neutrino energy, and include as well realistic background estimations and detection efficiencies. The optimal baseline turns out to be  $O(3000 \text{ km})$ .

*Key words:* NUFACT00, neutrino, oscillations, CP violation, nufactory.

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The atmospheric [1,2] plus solar [3] neutrino data point to neutrino oscillations and can be easily accommodated in a three-family mixing scenario. The new SuperK data seem to indicate a slight preference for the solar LMA-MSW solution and disfavor oscillations into sterile neutrinos both in the solar and atmospheric sectors [4]. These facts improve the prospectives for a neutrino factory. In ten years from now, the planned experiments will possibly improve the precision in the solar and atmospheric sector and definitively exclude (or confirm) LSND signal. Nevertheless, there is a strong case for going further in the fundamental quest of the neutrino masses and mixing angles<sup>2</sup>. In fact no significant improvement is expected in the knowledge of: 1) the sign of the atmospheric mass difference,  $\Delta m_{23}^2$ , 2) the angle relating the solar and the atmospheric sectors,  $\theta_{13}$ , and 3) the CP-violating phase,  $\delta$ .

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<sup>2</sup> For a four-family analysis at a neutrino factory see for example [5].

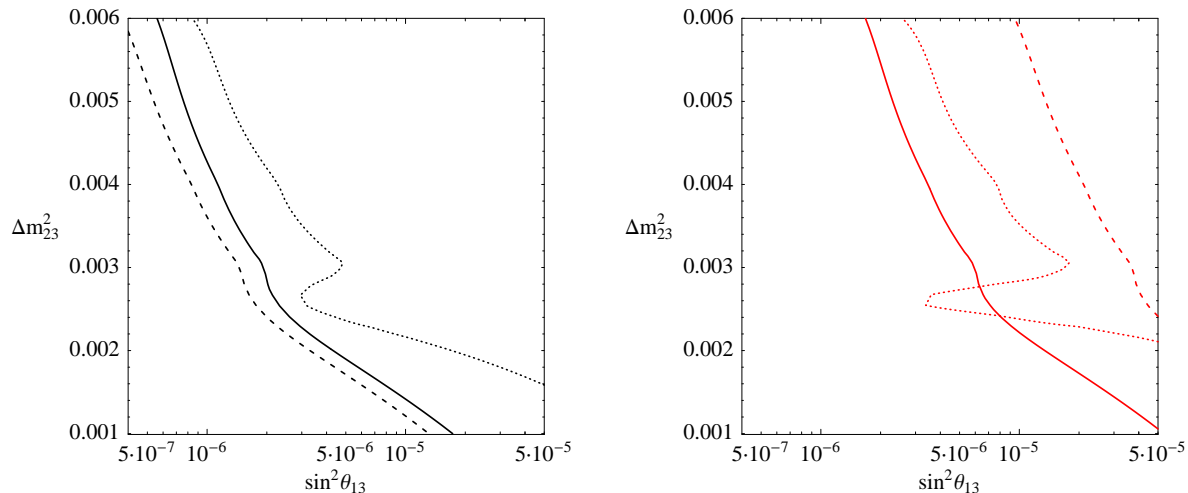


Fig. 1. Asymptotic sensitivity to  $\sin^2 \theta_{13}$  as a function of  $\Delta m_{23}^2$  at 90% CL for  $L = 732$  km (dashed lines), 3500 km (solid lines) and 7332 km (dotted lines), in the SMA-MSW solution. Only statistical errors are included in the left plot while the right one include as well background errors and detection efficiencies.

The most sensitive method to study these topics is to measure the transition probabilities involving  $\nu_e$  and  $\bar{\nu}_e$ , in particular  $\nu_e(\bar{\nu}_e) \rightarrow \nu_\mu(\bar{\nu}_\mu)$ . This is precisely the golden measurement at the *neutrino factory* [6]. Such a facility is unique in providing high energy and intense  $\nu_e(\bar{\nu}_e)$  beams coming from positive (negative) muons which decay in the straight sections of a muon storage ring [7]. Since these beams contain also  $\bar{\nu}_\mu(\nu_\mu)$  (but no  $\nu_\mu(\bar{\nu}_\mu)$ !), the transitions of interest can be measured by searching for “wrong-sign” muons [8].

We will analyze in turn scenarios in which the solar oscillation lies in the SMA-MSW or VO range and in the LMA-MSW range [9,10]. In the latter, the dependence of the oscillation probabilities on the solar parameters  $\theta_{12}$ ,  $\Delta m_{12}^2$ , and on the CP-odd phase,  $\delta$ , is sizeable at terrestrial distances and complicates the measurement of  $\theta_{13}$  due to the presence of other unknowns (mainly  $\delta$ ). The choice of the correct baseline is essential to disentangle  $\theta_{13}$  and  $\delta$ . We shall consider the following “reference setup”: neutrino beams resulting from the decay of  $2 \times 10^{20} \mu^+$ ’s and/or  $\mu^-$ ’s per year in a straight section of an  $E_\mu = 50$  GeV muon accumulator. A long baseline (LBL) experiment with a 40 kT detector and five years of data taking for each polarity is considered. Alternatively, the same results could be obtained in one year of running for the higher intensity option of the machine, providing  $10^{21}$  useful  $\mu^+$ ’s and  $\mu^-$ ’s per year. A realistic detector of magnetized iron [11] will be considered and detailed estimates of the expected backgrounds and efficiencies included in the analysis. Three reference detector distances are discussed: 732 km, 3500 km and 7332 km.

**SMA-MSW or Vacuum solar deficit.** For the SMA-MSW or VO scenarios, the influence of solar parameters on the neutrino factory signals will be negli-

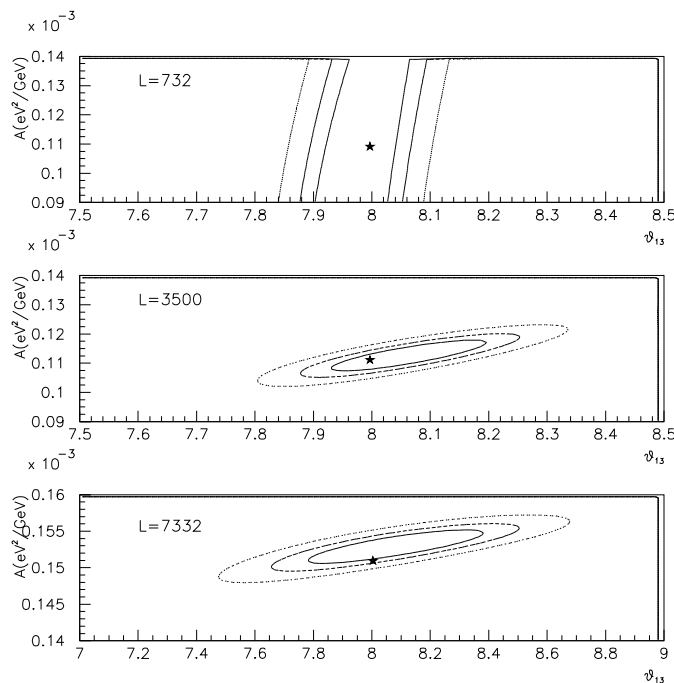


Fig. 2. 68.5, 90, 99 % CL contours resulting from a  $\chi^2$  fit of  $\theta_{13}$  and  $A$ . The parameters used to generate the “data” are denoted by a star, while the baseline(s) used in the fit is indicated in each plot. Statistical errors, backgrounds and efficiencies are included.

ble<sup>3</sup> and CP-violation out of reach. Besides its capability to reduce the errors on  $\theta_{23}$  and  $|\Delta m_{23}^2|$  to  $\sim 1\%$  [12] the factory would still be a unique machine to constrain/measure  $\theta_{13}$  [8] and the sign of  $\Delta m_{23}^2$ . Consider first  $\theta_{13}$ . In Fig. 1 (left), we show the exclusion plot at 90% CL, on the  $\Delta m_{23}^2$  (in the range allowed by SuperK) versus  $\sin^2 \theta_{13}$  plane, obtained with the full unbinned statistics and the two polarities. The same results, but including as well background errors and detection efficiencies are shown in Fig. 1 (right). Notice that the sensitivity is better at  $L = 3500$  km than at 732 km when efficiencies and backgrounds are included. The latter are responsible for it. The sensitivity at 7332 km is also worse than at 3500 km, due to the loss in statistics. In conclusion, the sensitivity to  $\theta_{13}$  can be improved by three-four orders of magnitude with respect to the present limits.

The second major topic would be of perform the first precise measurements related to matter effects, in order to determine the sign of  $\Delta m_{23}^2$ . We have studied the determination of the sign of  $\Delta m_{23}^2$ , assuming that the absolute value has by then been measured with a precision of 10%. We have explored the region around the best fit values of SuperK:  $|\Delta m_{23}^2| = 2.8 \times 10^{-3}$  eV<sup>2</sup> and  $\theta_{23} = 45^\circ$ . We performed a  $\chi^2$  analysis on the  $\Delta m_{23}^2, \theta_{13}$  plane, as described in [9]. The conclusion is that, for “data” generated within the range  $\theta_{13} = 1-10^\circ$  and  $|\Delta m_{23}^2|$  in the range allowed by SuperK, a misidentification of the sign of  $\Delta m_{23}^2$  can be excluded at 99% CL at 3500 km and

<sup>3</sup> In practice, for the numerical results of this section, the central values in the SMA-MSW range are taken:  $\Delta m_{12}^2 = 6 \times 10^{-6}$  eV<sup>2</sup> and  $\sin^2 2\theta_{12} = 0.006$ .

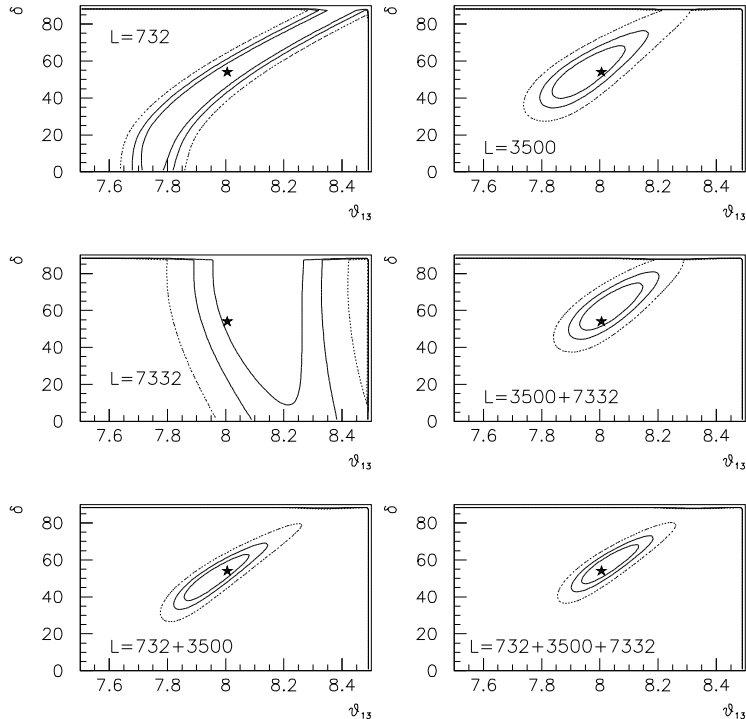


Fig. 3. 68.5, 90, 99 % CL contours resulting from a  $\chi^2$  fit of  $\theta_{13}$  and  $\delta$ . The parameters used to generate the “data” are depicted by a star and the baseline(s) which is used for the fit indicated in each plot. Statistical errors, backgrounds and efficiencies are included.

7332 km, but not at the shortest distance, 732 km. This conclusion agrees with the analysis of ref. [12], which did not include the energy dependence information. We have further studied how the matter parameter  $A = \sqrt{2} G_F n_e$  and the angle  $\theta_{13}$  can be measured simultaneously. Fig. 2 shows the result of a  $\chi^2$  fit as described in [9]. Statistical errors as well as backgrounds and detection efficiencies have been included. At 732 km there is no sensitivity to the matter term, as expected. However, already at 3500 km,  $A$  can be measured with a 10% precision. At the largest baseline, the precision in  $A$  improves although at the expense of loosing precision in  $\theta_{13}$  due to the loss in statistics.

**LMA-MSW.** Fixed values of the atmospheric parameters<sup>4</sup> are used in this section,  $\Delta m_{23}^2 = 2.8 \times 10^{-3} \text{ eV}^2$  and maximal mixing,  $\theta_{23} = 45^\circ$ . Let us start discussing the measurement of the CP phase  $\delta$  versus  $\theta_{13}$ . We have studied numerically how to disentangle them in the range  $1-10^\circ$  and  $0 \leq \delta \leq 180^\circ$ . Consider first the upper solar mass range allowed by the LMA-MSW solution:  $\Delta m_{12}^2 = 10^{-4} \text{ eV}^2$ . Fig. 3 shows the confidence level contours for a simultaneous fit of  $\theta_{13}$  and  $\delta$ , for “data” corresponding to  $\theta_{13} = 8^\circ$ ,  $\delta = 54^\circ$ , including in the analysis statistical errors as well

<sup>4</sup> A precision of 1% in these parameters is achievable through muon disappearance measurements at the neutrino factory [12]. This level of uncertainty is not expected to affect significantly the results presented in this section.

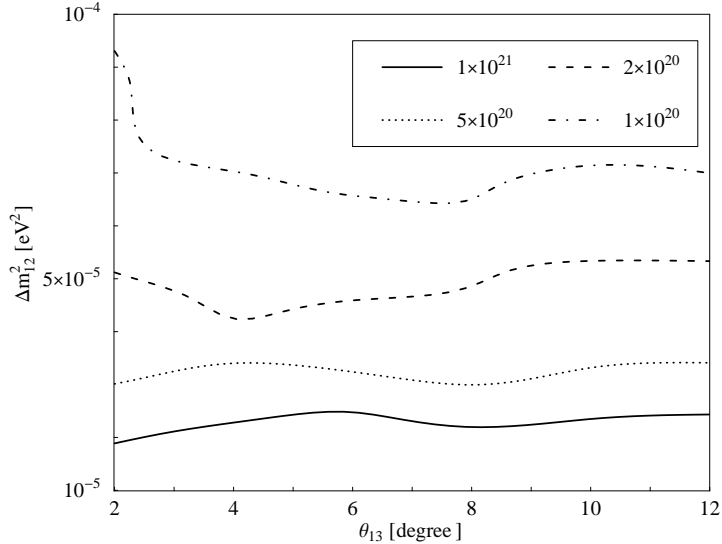


Fig. 4. Lower limit in  $\Delta m_{12}^2$  at which a maximal CP phase ( $90^\circ$ ) can be distinguished from a vanishing phase at 99% CL, as a function of  $\theta_{13}$  at  $L = 3500\text{km}$  and for different numbers of useful muons per year. Background errors and efficiencies are included.

as backgrounds and detection efficiencies. The correlation between  $\delta$  and  $\theta_{13}$  is very large. The phase  $\delta$  is not measurable and this indetermination induces a rather large error on the angle  $\theta_{13}$ . However, at the intermediate baseline of 3500 km the two parameters can be disentangled and measured. At the largest baseline, the sensitivity to  $\delta$  is lost and the precision in  $\theta_{13}$  becomes worse due to the smaller statistics. The combination of the results for 3500 km with that for any one of the other distances improves the fit, but not in a dramatic way. Just one detector located at  $O$  (3000 km) may be sufficient: a precision of few tenths of degree is attained for  $\theta_{13}$  and of a few tens of degrees for  $\delta$ . The sensitivity to CP-violation decreases linearly with  $\Delta m_{12}^2$ . At the central value allowed by the LMA-MSW solution,  $\Delta m_{12}^2 = 5 \times 10^{-5} \text{ eV}^2$ , CP-violation can still be discovered, while for  $\Delta m_{12}^2 = 1 \times 10^{-5} \text{ eV}^2$ , the sensitivity to CP-violation is lost with the experimental set-up used. We have quantified what is the minimum value of  $\Delta m_{12}^2$  for which a maximal CP-odd phase,  $\delta = 90^\circ$ , can be distinguished at 99% CL from  $\delta = 0^\circ$ . The result is shown in Fig. 4:  $\Delta m_{12}^2 > 2 \times 10^{-5} \text{ eV}^2$ , with very small dependence on  $\theta_{13}$ , in the range considered.

One word of caution is pertinent: up to now we assumed  $|\Delta m_{12}^2|$  and  $\sin 2\theta_{12}$  known by the time the neutrino factory will be operational. Otherwise, the correlation of these parameters with  $\theta_{13}$  would be even more problematic than that between  $\delta$  and  $\theta_{13}$ . The error induced on  $\theta_{13}$  by the present uncertainty in  $|\Delta m_{12}^2|$  is much larger than that stemming from the uncertainty on  $\delta$ . Fortunately, LBL reactor experiments will measure  $|\Delta m_{12}^2|$  and  $\sin 2\theta_{12}$ , if in the LMA-MSW range. Even if the error in these measurements is as large as 50%, the problem would be much less serious. We have checked that such uncertainty does not affect our results concerning the sensitivity to  $\delta$ , and only induces an error in  $\theta_{13}$  of the order 20%-30%.

**Conclusions.** We have shown that an analysis in neutrino energy bins, combined with a comparison of the signals obtained with the two polarities, allows to disentangle the unknown parameters, in particular  $\theta_{13}$  and  $\delta$ , at long enough baselines. Once one takes into account realistic backgrounds and detection efficiencies, the intermediate baseline of  $O(3000 \text{ km})$  is optimal for the physics goals considered.

Our two parameter fits at 3500 km indicate that the angle  $\theta_{13}$  can be measured with a precision of tenths of degrees, down to values of  $\theta_{13} = 1^\circ$ . The asymptotic sensitivity to  $\sin^2 \theta_{13}$  can be improved by three orders of magnitude (or more) with respect to the present upper bound.

In the LMA-MSW range, CP-violation may be tackled. The phase  $\delta$  can be determined with a precision of tens of degrees, for the central values allowed for  $|\Delta m_{12}^2|$ . Maximal CP-violation can be disentangled from no CP-violation at 99% CL for values of  $|\Delta m_{12}^2| > 2 \times 10^{-5} \text{ eV}^2$ .

Finally, a model independent confirmation of the MSW effect will be feasible, and the matter parameter  $A$  measured within a 10% precision (or better if combined with the longest baseline: 7332 km). The sign of  $\Delta m_{23}^2$ , can be determined at 99% CL, for  $\theta_{13}$  within the range  $\theta_{13} = 1-10^\circ$  and  $|\Delta m_{23}^2|$  in the range allowed by SuperK.

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