Neutrino Oscillation Physics at a ν Factory

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The potential of a neutrino factory based on muon storage rings at determining the neutrino mass matrix is summarized.

1. Introduction

The SuperKamiokande data on atmospheric neutrinos are interpreted as oscillations of muon neutrinos, with a mixing angle which is close to maximal and a $|\Delta m^2|$ in the range 10^{-3}–10^{-2} eV^2. The results of the updated analysis corresponding to a exposure of 992 days or 61 Kton·yr are available [1]. Interestingly, the experiment is now able to discriminate between the ν_μ oscillation into an active or a sterile neutrino! The latter hypothesis is disfavoured at 99%CL in a two–family mixing scenario. The K2K experiment on the other hand observes a 2σ deficit of μ-like events compatible with an atmospheric $|\Delta m^2| \sim 3 \cdot 10^{-3}$eV^2 [2].

The solar neutrino deficit is interpreted either as MSW (matter enhanced) oscillations or as vacuum oscillations (VO) that deplete the original ν_e's. The analysis of all solar data is currently discussed extended to what has been named the dark-side of parameter space, corresponding to a mixing angle larger than 45^o [3]. Due to matter effects, this region is physically distinct from the usual one. Fig. 1 shows the three famous regions allowed by data: the large and small mixing angle MSW solutions (LMA-MSW and SMA-MSW), and the vacuum oscillation solution (VO). The new data from SuperKamiokande on solar neutrinos have been presented at Neutrino 2000 [4]. The absence of a spectral distortion combined with the size of the Day-Night asymmetry disfavours the SMA-MSW and VO solutions in favour of the LMA-MSW one. As we will see this is very good news for the neutrino factory, since only if the solar parameters lie in the LMA-MSW range, are they expected to affect sizeably the oscillation probabilities at terrestrial distances.

Finally, the signal of $\nu_\mu \to \nu_e$ oscillations at LSND [5] with a mass gap of $0.3 - 1$ eV^2 has neither been confirmed nor disproved yet by a different experiment. The explanation of these data in terms of neutrino oscillations[1] requires the existence of more than three light neutrino species. Since only three can be active, one or more must be sterile. Alternatively, one should unjustifiedly assume that one of the experimental results is wrong in order to accommodate the remaining data by the mixing of the three standard neutrinos. Most often the LSND data is sacrificed, in view of the fact that both the atmospheric and solar anomalies have been confirmed by different experimental techniques, in contrast with the LSND signal.

In spite of the large amount of data available, there remain many unknowns in the neutrino mass matrices in both scenarios, with and without a sterile neutrino. In order to illustrate the potential of the ν factory, I will limit this talk to the conservative scenario of just three light active neutrino species. Several works have explored the potential of the ν factory if additional light sterile neutrinos are at work [28], with results even more tantalizing than those described in what follows.

The exploration of the lepton flavour sector of the Standard Model might well lead us into the physics beyond in a cleaner way than the quark

[1]Alternative interpretations of the data have been considered [6,7], but the agreement is very poor.

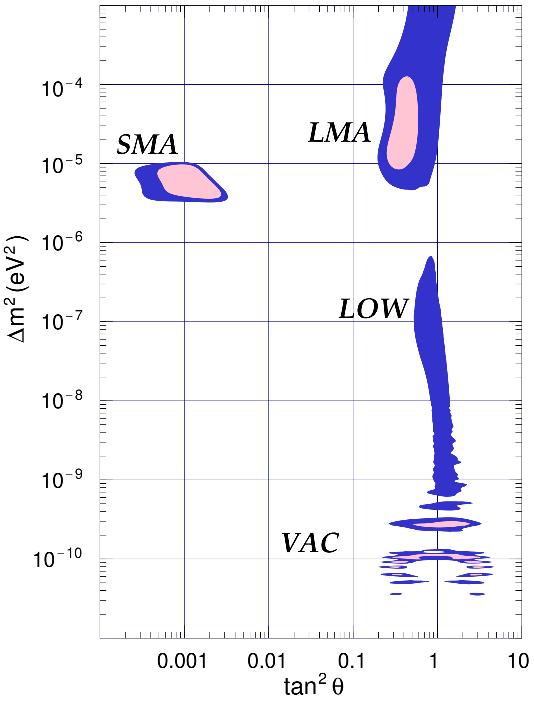


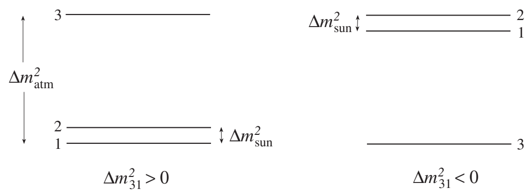
Figure 1. From ref. [3]: global fit to the solar neutrino event rates. The regions are shown at 2 σ (light shade) and 3 σ (dark shade) levels.

sector, where theoretical predictions are often obscured by non-perturbative strong effects. Together with the future Higgs and B-physics programs, a neutrino physics program is a must.

2. Three-active neutrino mixing

The atmospheric plus solar neutrino data can be easily accommodated in a three-family neutrino mixing scenario. The corresponding MNS matrix describing the neutrino mixing relevant for oscillation experiments depends generically on four physical parameters: three angles (θ_{12}, θ_{13} and θ_{23}) and a CP-odd phase (δ). We use the standard parametrization of ref. [8]. Oscillation experiments are sensitive to two neutrino mass differences and the parameters of the MNS matrix. The challenge of a future ν-physics program is of course to determine all these quantities.

For convenience, we identify[2] the solar mass difference with Δm^2_{12} in this parametrization and the atmospheric one with Δm^2_{23}. The experimental results indicate that $|\Delta m^2_{23}| \gg |\Delta m^2_{12}|$ in most of the allowed parameter space. This hierarchical pattern implies a high degree of decoupling between the solar and atmospheric oscillations: while the oscillation probabilities at atmospheric distances are controlled mainly by three parameters: $\Delta m^2_{23}, \theta_{23}$ and θ_{13}, the oscillations at solar distances are controlled by $\Delta m^2_{12}, \theta_{12}$ and θ_{13}. Note that the angle θ_{13} is the connection between the two. If this angle is zero, the decoupling is complete and the solar and atmospheric anomalies are described by two independent two-by-two family mixing processes, with parameters $(\theta_{12}, \Delta m^2_{12})$ and $(\theta_{23}, \Delta m^2_{23})$ respectively. At present, the most valuable information on the angle θ_{13} comes from the Chooz reactor experiment [9]. This experiment has set the upper limit $\sin^2\theta_{13} < 0.05$, which implies that the above mentioned decoupling indeed occurs to a good accuracy.



In this situation, planned solar experiments (SNO, KamLAND and Borexino) will mainly confirm the solar anomaly and give us further information on $(\theta_{12}, \Delta m^2_{12})$. Hopefully, they will clarify the present situation by selecting the true solution among the three regions presently allowed: LMA-MSW, SMA-MSW or VO. The analysis of the potential of the SNO experiment [10] after one year of data taking is available [11]. In combination with SuperKamiokande, this experiment will be able to confirm the solar anomaly,

[2] $\Delta m^2_{ij} \equiv m^2_j - m^2_i$ throughout the paper.

independent of the normalization of the flux of ^{8}B neutrinos, if the ν_e oscillate into an active species. Some discrimination is also possible among the different solar solutions but might not be definite. More definite information will come from the long baseline reactor experiment KamLAND [12], which is expected to start taking data in April 2001. The asymptotic sensitivity to the solar oscillation parameters safely covers the LMA-MSW range, so that in a few years from now we will know whether the solution lies in this range.

Several accelerator experiments have been proposed to confirm and further explore the atmospheric anomaly. If the present positive signal of ν_μ disappearance from K2K survives at higher statistics, the atmospheric anomaly will be confirmed and the corresponding $|\Delta m^2_{23}|$ constrained to be $\geq 3 \cdot 10^{-3}$ eV^2. The next generation of experiments: Minos [13] and Opera [14] will definitely resolve whether the atmospheric oscillation is an active-active one, or if a sterile species is involved. They will also determine the atmospheric parameters $(\theta_{23}, |\Delta m^2_{23}|)$ with a precision of $\sim 10\%$ [15]. On the other hand, their sensitivity to the angle θ_{13} will not improve significantly the present upper bound imposed by Chooz.

Summarizing, in 5-10 years from now no significant improvement is expected in the knowledge of:

- The angle θ_{13}, which is the key between the atmospheric and solar neutrino realms.
- The sign of Δm^2_{23}, which determines whether the three-family neutrino spectrum is of the "hierarchical" or "degenerate" type as depicted in Fig. 2.
- Leptonic CP-violation.
- A model-independent experimental confirmation of the MSW effect will not be available.

The most sensitive method to study these topics is to measure the transition probabilities involving $\nu_e(\bar\nu_e)$, in particular $\nu_e(\bar\nu_e) \to \nu_\mu(\bar\nu_\mu)$. This is precisely the golden measurement at the ν factory [16]. 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 [17]. 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: negative (positive) muons appearing in a massive detector with good muon charge identification capabilities. Possible detection techniques to measure this signal and to quantify the corresponding detection backgrounds have been recently discussed in detail [18–21].

Since the prospects to measure the unknown parameters will strongly depend on whether the solution of the solar anomaly lies in the SMA-MSW or VO range, or in the LMA-MSW range, we consider these two possibilities in turn.

2.1. SMA-MSW or VO solar solutions

Solar oscillation parameters in these ranges do not affect oscillations at terrestrial distances and CP-violation is unfortunately out of reach.[3] However, besides improving the precision in the determination of the atmospheric parameters (θ_{23} and $|\Delta m^2_{23}|$), the ν factory can measure θ_{13} and the sign of Δm^2_{23} through the measurement of the subleading transition $\nu_e(\bar\nu_e) \to \nu_\mu(\bar\nu_\mu)$. The relevant oscillation probabilities are,

$$\begin{aligned} P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} &\simeq s^2_{23}\,\sin^2 2\theta_{13}\left(\frac{\Delta_{13}}{B_\mp}\right)^2 \\ &\times \sin^2\left(B_\mp L\right)\ , \end{aligned} \qquad (1)$$

where $\Delta_{ij} \equiv \Delta m^2_{ij}/4E_\nu$ and

$$B_\mp \equiv \sqrt{\left[\Delta_{13}\,\cos 2\theta_{13} \mp A/2\right]^2 + \left[\Delta_{13}\,\sin 2\theta_{13}\right]^2}\ ,$$

$A = \sqrt{2}\,G_F\,n_e$, and n_e is the electron number density in the Earth.

The asymptotic sensitivity to θ_{13} has been studied including realistic backgrounds to the wrong–sign muon signal and efficiencies by two groups [23,24]. In Fig. 2.1 we show the results for a 40KTon magnetized iron calorimeter [23] at three different baselines: 732, 3500 and

[3] In the case of SMA-MSW there have been works [22] which discussed T-violation in very long baseline experiments with very low energy neutrinos, but such experiments would be very difficult in practice.

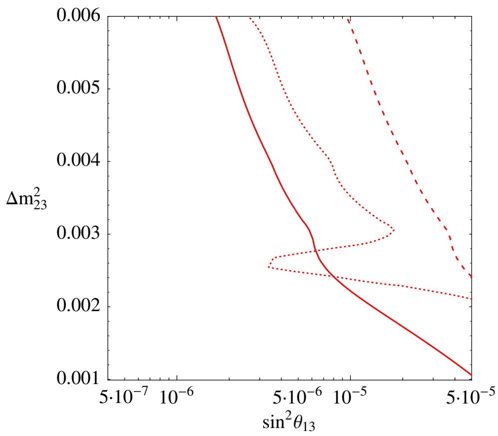


Figure 2. From ref. [23]: asymptotic sensitivity to $\sin^2\theta_{13}$ as a function of Δm^2_{23} at 90% CL for $L = 732$ km (dashed lines), 3500 km (solid lines) and 7332 km (dotted lines).

7332 Km and for 10^{21} useful muon decays and a muon energy of 50 GeV. The optimal sensitivity is reached at the intermediate baseline. Although the asymptotic sensitivity to the angle is expected to improve at shorter baselines when only statistical errors are considered, background contamination is responsible for the poorer sensitivity observed at 732 Km. Similar results have been obtained using a liquid argon detector [24]. The summary is that with 10^{21} muon decays, the sensitivity to $\sin^2 2\theta_{13}$ is more than 3 orders of magnitude better than the present bound.

It has been pointed out [26] that if this angle turns out to be relatively large, $\sin^2 2\theta_{13} \geq 0.01$, the use of the total number of muons without charge identification leads to a precision in the determination of the angle similar to that obtained using the wrong–sign muon signal.

The oscillation probability in eq. (1) is sensitive to the sign(Δm^2_{23}), because neutrinos propagate in matter. Actually, the sensitivity to the sign is equivalent to the sensitivity to the CP-odd asymmetry induced by matter effects: changing the sign is equivalent to exchanging the probability of neutrinos and antineutrinos. This fact suggests that, in order to measure the sign, one needs to compare the wrong–sign muon signals for the two possible polarities of the machine (i.e. with μ^+ and μ^- decaying). This has to be done at long enough baselines, because if $B_\pm L \ll 1$, the sensitivity to the sign is lost. Several groups have discussed the determination of the sign of Δm^2_{23} [25,26,23,24]. The first two studies used only total rates of wrong-sign muons for both polarities, and did not include systematic errors. The last two include realistic background and efficiencies as well as the spectral information for a magnetized iron calorimeter and a liquid argon detector respectively. The conclusion is that the sign can be easily measured for baselines above ~ 2000 Km, although the significance of the measurement improves at longer baselines.

Finally, the determination of the atmospheric parameters can be done by measuring the disappearance of right–sign muons. The achievable precision for $2\cdot10^{20}$ muon decays is expected to be one order of magnitude better [25,24] than that expected at Minos and Opera. In Fig. 2.1 we show the result of a fit of ref. [25] at intermediate baselines of 2800Km, $E_\mu = 30 GeV$ and $2\cdot 10^{20}$ muon decays. The statistical error in these parameters improves at longer baselines, as expected from any disappearance measurement.

2.2. LMA-MSW solar solution

In this case, the solar parameters do affect the oscillation probabilities at terrestial distances and in particular the measurement of CP-violation in the lepton sector is within reach. Indeed, the leading corrections in Δm^2_{12} to eq. (1) depend on the CP-odd phase, δ:

$$\begin{aligned}
P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} &= \sin^2\theta_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{23}}{B_\pm}\right)^2 \sin^2 B_\pm L \\
&+ J\ \cos\delta\ \frac{\Delta_{12}}{A}\ \frac{\Delta_{13}}{B_\pm}\ \sin(\frac{AL}{2}) \\
&\times \sin B_\pm L\ \cos\Delta_{13}L \\
&\pm J\ \sin\delta\ \frac{\Delta_{12}}{A}\ \frac{\Delta_{13}}{B_\pm}\ \sin(\frac{AL}{2}) \\
&\times \sin B_\pm L\ \sin\Delta_{13}L \qquad (2)
\end{aligned}$$

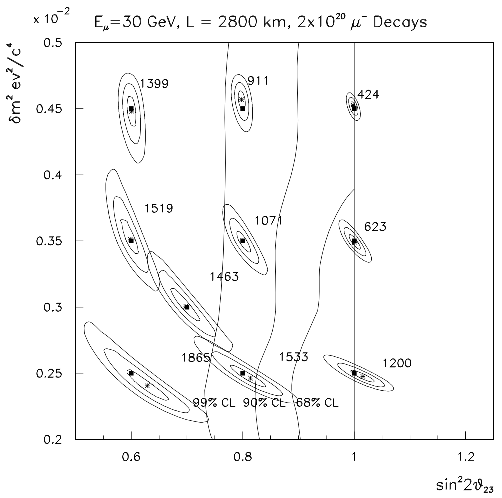


Figure 3. From ref. [25]. Fit of the atmospheric parameters.

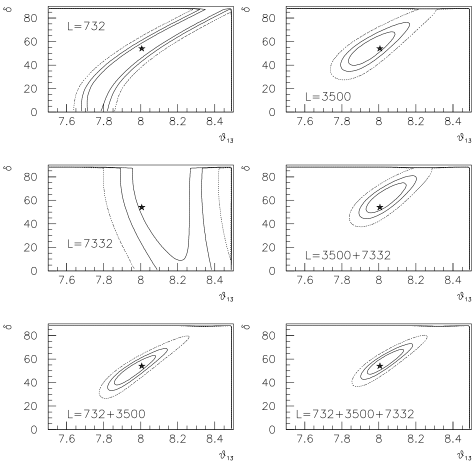


Figure 4. From ref. [23]: 68.5, 90, 99 % CL contours resulting from a χ^2 fit of θ_{13} and δ for different baselines.

The oscillation probabilities for neutrinos and antineutrinos in matter differ even for $\delta = 0$. For this reason, the CP-odd asymmetry is not a good observable to signal CP violation. The strategy to extract the δ phase is to use the spectral information on the wrong-sign muon signal for both polarities of the beam, since all the terms in eq. (2) have a different dependence on the neutrino energy. Particularly important is to understand if the two unknowns θ_{13} and δ can be determined simultaneously from these measurements [27]. It turns out that at short baselines, i.e. $\Delta_{13} L \ll 1$, the sensitivity to δ is lost because of the large correlation between θ_{13} and δ, which forbids the extraction of the phase when θ_{13} is not known [23]. On the other hand, at very long baselines the large matter effects hide the dependence on the phase. The only hope to measure δ is at intermediate baselines in the range 2000–4000 Km, as shown in Fig. 4 from ref. [23]. It shows the expected results of a simultaneous fit of θ_{13} and δ with a 40KTon magnetized iron calorimeter at different baselines and combinations of baselines. These results include realistic background and efficiencies. Including other data samples in the fit besides the number of wrong–sign muons does not seem to improve appreciably the sensitivity to δ [24].

The sensitivity to the CP phase is of course very dependent on the value of $|\Delta m^2_{12}|$ within the LMA-MSW range. Fig. 5 shows the minimum value of this quantity which permits the 99% C.L. separation of a maximal δ phase from a vanishing one, as a function of the number of muon decays. Interestingly, this value depends very little on the angle θ_{13}. However a full exploration of the range presently allowed by the LMA-MSW solution requires a very intense ν factory, providing at least 10^{21} useful decays.

2.3. Muon beams versus conventional beams

An interesting question is to what extent muon beams are preferable over conventional beams in studying the subleading $\nu_e \leftrightarrow \nu_\mu$ transitions. There are mainly three reasons for this.

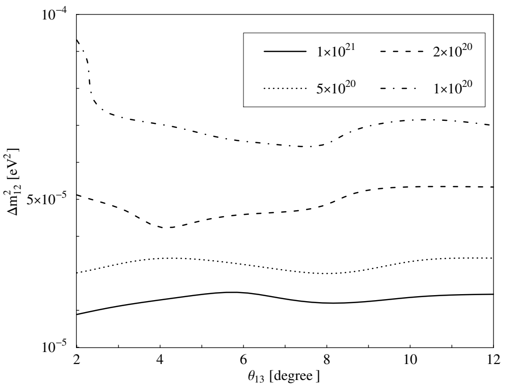


Figure 5. From ref. [23]: lower limit in Δm^2_{12} at which a maximal CP phase (90°) can be distinguished from a vanishing phase at 99% CL, as a function of θ_{13} at $L = 3500$km.

- Beam background. Muon beams are free of beam-related background. Provided the charge of the outcoming muon can be measured, the measurement of $P_{\nu_e\nu_\mu}(P_{\bar{\nu}_e\bar{\nu}_\mu})$ for decaying $\mu^+(\mu^-)$ through the wrong–sign muon signal is free of beam background since there are no $\nu_\mu(\bar{\nu}_\mu)$ in the beam. In contrast, conventional beams are composed mainly of $\nu_\mu(\bar{\nu}_\mu)$ with a per cent contamination of $\nu_e(\bar{\nu}_e)$. Thus the measurement $P_{\nu_\mu\nu_e}(P_{\bar{\nu}_\mu\bar{\nu}_e})$ through the apperance of electrons (positrons) has an irreducible beam background. As a result, while probabilities $P_{\nu_e\nu_\mu}$ as small as $O(1)/N_{CC}$ can be measured in a muon beam, where N_{CC} is the number of charge current events in the absence of oscillations, in the case of a conventional beam the probability $P_{\nu_\mu\nu_e}$ can only be detected up to values of $O(0.1)/\sqrt{N_{CC}}$.

- Intensity. The number of charged currents produced by a beam of neutrinos emanating from a source of decaying muon or pions (and kaons) is

$$N_{CC} \sim n_{\rm parent}\gamma^2_{\rm parent}\frac{E_\nu}{L^2} \qquad (3)$$

where $n_{\rm parent}$ is the number of decaying parents and $\gamma_{\rm parent}$ is their Lorentz γ. In a conventional beam the energies of the decaying pions and kaons are widely distributed and the average $\gamma^2_{\pi,K}$ is rather small. In contrast, in a muon beam, the muons are accelerated to some high energy before they decay, thus the average γ^2_μ is much higher. This explains why, for a fixed power of the initial proton source, the intensity of the neutrino beam emanating from muons is higher than that of a conventional beam, in spite of the fact that the number of decaying muons is smaller than that of pions and kaons [29].

- Beam systematics. The uncertainty in the flux is reduced to a minimum in a muon beam. A preliminary study of the effect of the beam divergence in the flux [30] shows that this uncertainty can be easily controlled at the level below 1%, while in the case of a conventional beam it is typically of $O(10\%)$.

In spite of these advantages, it is a very interesting question to understand what is the physics potential of a high intensity conventional beam, since such a beam is anyway a byproduct of the first stage of a ν factory, and thus constitutes a natural stage in the progress towards an ultimate facility. Some preliminary studies of the prospects of such beams have been developed [31,32] inspired by the JHF neutrino beam, which has been proposed as an upgrade of the K2K beam. Assuming a large detector volume such as O(100kt − 1Mt), experiments with low energy neutrinos of O(100MeV − 500MeV) were considered, so that the baselines that maximize the signal of CP violation are much shorter, of O(100Km). At these energies matter effects are negligible, which improves the extraction of δ. A purely statistical analysis, including no detection nor beam backgrounds, shows that if the angle θ_{13} is of the same order of magnitude as its present upper limit, CP violation could be measured in such a beam if the solution to the solar problem is the LMA-MSW one. Although this is promising, a more detailed analysis including systematics is needed before drawing conclusions. Other questions like the sensitivity to θ_{13} and the sign of Δm^2_{23} should also be addressed in the future.

3. Conclusions

I have discussed a physics scenario with three neutrino-family mixing accommodating the solar and atmospheric anomalies. A ν-factory can measure or severely constrain the unknown angle θ_{13} and the sign of the atmospheric Δm^2_{23}. If furthermore the solution to the solar anomaly lies within the LMA-MSW range, CP-violation in the lepton sector may also be measured.

During the last year the prospective studies have been much refined: they include now spectral information, as well as realistic background and efficiencies [4]. These studies clarify what are the optimal machine parameters resulting from physics considerations alone. Concerning the muon beam energy and intensity one would like to go as high as possible. The measurement of the CP-odd phase in most of the LMA-MSW range requires $O(10^{21})$ useful μ decays. Although a 50 GeV beam energy is preferable, lower energies of 20–30 GeV do not reduce in any dramatic way the physics potential of the ν–factory [25]. Of great importance is to have the possibility of circulating muons with both signs. Finally, the optimal baseline seems to be in the intermediate range 2000–4000 Km, although having two long baselines would be much more prefered. This requires a triangle or bow-tie configuration for the storage ring.

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