Measurement of CP violation at a Neutrino Factory

J.J. Gómez-Cadenas [a]

[a]IFIC, Edificio de Institutos de Paterna, Apto Correos 2085, 46071 Valencia, Spain and CERN, CH-1211 Geneve 23, Switzerland

The prospects of measuring CP violation in the leptonic sector using the intense neutrino beams arising from muon decay in the straight sections of a muon accumulator ring (the so-called *neutrino factory*) are discussed.

1. INTRODUCTION

In this paper I discuss the prospects to observe a CP-odd phase in the leptonic sector, using the intense, pure two-flavour neutrino beams produced in a future neutrino facility, the so-called *neutrino factory*.

The organization is as follows. Section 2 summarizes the state-of-the-art concerning neutrino oscillations. Section 3 describes the neutrino factory. The prospects to measure a CP-odd phase are discussed in section 4.

2. NEUTRINO OSCILLATIONS

Perhaps the most exciting physics result of the last two decades in the field of particle physics[1] is the growing evidence that neutrinos have mass and oscillate. There are three independent sets of experimental data that support this hypothesis. They are:

1. The measurements of the rates (both absolute and as a function of the zenith angle) of atmospheric neutrinos by the experiment SuperKamiokande and others[1,2]. The observed ν_μ rate is about 50 % smaller, while the observed ν_e rate is consistent with the predicted rate. In addition, the rate reduction of the observed ν_μ varies with the incoming neutrino zenith angle as expected if oscillations are at play. Recent analysis of the atmospheric data[3,4] favor strongly oscillations of ν_μ's into ν_τ's, while almost completely excluding oscillations into sterile neutrinos. The mass gap[2] between the two oscillating neutrinos, $\Delta m^2_{23} = \Delta m^2_{atm}$ is in the range 10^{-3}–$10^{-2} eV^2$, while the mixing angle $\theta_{23} = \theta_{atm}$ is close to maximal.

2. The measurement of the rates of solar neutrinos, by several experiments[5]. The solar neutrino deficit is interpreted either as MSW (matter enhanced oscillations)[6] or as vacuum oscillations (VO)[7] that deplete the original ν_e's presumably in favor of ν_μ's (oscillation into sterile neutrinos are also disfavored[3,4]). The corresponding squared mass differences are: *(i)* $\Delta m^2_{12} = \Delta m^2_{sun} \sim 10^{-5} - 10^{-4}\ eV^2$ for the large mixing angle MSW solution (LMA-MSW); *(ii)* $\Delta m^2_{12} \sim 10^{-6} eV^2$ for the small mixing angle MSW solution (SMA-MSW) and *(iii)* $\Delta m^2_{12} \sim 10^{-10} eV^2$ for VO. The mixing angle is close to maximal for both the LMA-MSW solution and the VO solution and small ($\sin^2 2\theta_{12} = \sin^2 2\theta_{sun} \sim 10^{-3}$) for the SMA-MSW solution.

3. The evidence of neutrino oscillations claimed by the LSND collaboration[8]. This experiment has operated in an almost-pure ν_μ beam, and observes an excess of ν_e's over their calculated background. They interpret their results in terms of oscillations of ν_μ's into ν_e's, with a squared mass difference $\Delta m^2_{lsnd} \sim 1 eV^2$.

[1]Excluding, of course, the possible discovery of a Higgs particle by the LEP experiments.

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

One obvious fact that follows from the existence of three different mass squared differences, $\Delta m^2_{sun} << \Delta m^2_{atm} << \Delta m^2_{lsnd}$ is that more than three neutrinos are needed in order to explain all data simultaneously. This would require sterile neutrinos, which are disfavored by current experimental data[3]. Alternatively, to explain oscillations with three standard neutrinos one must discard some of the data. This will be, apologetically, my approach in this paper.[3] I will consider only the two strongest evidences for neutrino oscillations, namely, the solar and atmospheric anomalies and I will, for simplicity assume Dirac neutrinos. Under this assumptions the NMS matrix[4] connecting the flavor and mass eigenstates, $(\nu_e, \nu_\mu, \nu_\tau)^T = U_{NMS} \cdot (\nu_1, \nu_2, \nu_3)^T$, contains four physical parameters, i.e., three mixing angles and a CP-odd phase, and can be conveniently parameterized as:

$$U \equiv U_{23} U_{13} U_{12} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1)$$

with $s_{12} \equiv \sin\theta_{12}$, and similarly for the other sines and cosines.

Neutrino oscillations are due to the fact that neutrinos produced in a weak eigenstate can change flavor as they propagate a distance L from the production point.

In Vacuum, defining the product of NMS matrix elements $W^{jk}_{\alpha\beta} \equiv [V_{\alpha j} V^*_{\beta j} V^*_{\alpha k} V_{\beta k}]$, one can write the probability of a neutrino (antineutrino) of flavor α to oscillate into a neutrino (antineutrino) of flavor β as:

$$P(\quad \nu(\bar{\nu})_\alpha \to \nu(\bar{\nu})_\beta) = -4 \sum_{k>j} \mathrm{Re}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin^2\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}} \mathrm{L}}{4\mathrm{E}_\nu}\right) \pm 2 \sum_{k>j} \mathrm{Im}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}} \mathrm{L}}{2\mathrm{E}_\nu}\right) \quad (2)$$

Equation 2 contains a CP-even $(-4 \sum_{k>j} \mathrm{Re}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin^2\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}} \mathrm{L}}{4\mathrm{E}_\nu}\right))$ and a CP-odd $(\sum_{k>j} \mathrm{Im}[\mathrm{W}^{\mathrm{jk}}_{\alpha\beta}] \sin\left(\frac{\Delta \mathrm{m}^2_{\mathrm{jk}} \mathrm{L}}{2\mathrm{E}_\nu}\right))$ term, which is only different from zero if there is at least an imaginary phase in the NMS matrix. This is, of course the case for three families, but not for two families. In this case the oscillation reduces to the familiar formula:

$$P_{\nu_\alpha \nu_\beta} = \sin^2 2\,\theta \, \sin^2\left(\frac{\Delta m^2 \, L}{4E_\nu}\right) \quad (3)$$

On the other hand, the fact that $\Delta m^2_{atm} >> \Delta m^2_{sun}$ permits to describe accurately neutrino oscillation probabilities at terrestrial distances with only three parameters, θ_{23}, $\Delta m^2_{23} = \Delta m^2_{atm}$ and θ_{13}: Equation 2 then simplifies to:

$$\begin{aligned} P_{\nu_e \nu_\mu} &= \sin^2 2\,\theta_{13} \sin^2\theta_{23} \, \sin^2 \frac{\Delta m^2_{23} L}{4E_\nu} \\ P_{\nu_e \nu_\tau} &= \sin^2 2\,\theta_{13} \cos^2\theta_{23} \, \sin^2 \frac{\Delta m^2_{23} L}{4E_\nu} \\ P_{\nu_\mu \nu_\tau} &= \sin^2 2\,\theta_{23} \cos^2\theta_{13} \, \sin^2 \frac{\Delta m^2_{23} L}{4E_\nu} \end{aligned} \quad (4)$$

Notice that all the probabilities depend in the same way of Δm^2_{atm}. The dependence with the angle θ_{13} is such that in the limit $\theta_{13} \to 0$ one recovers the two-family oscillations formulae.

Precisely the fact that θ_{13} is small (the CHOOZ experiment[9] has set a limit $\sin^2\theta_{13} < 0.05$), together with the strong mass hierarchy ($\Delta m^2_{atm} >> \Delta m^2_{sun}$) results in the solar and atmospheric oscillations approximately decoupling in 2-by-2 mixing phenomena. A consequence of this is that future solar experiments[10] will improve the knowledge in the solar parameters $\Delta m^2_{12}, \theta_{12}$ while future atmospheric and long base line accelerator experiments[11] will improve the knowledge of the atmospheric parameters $\Delta m^2_{23}, \theta_{23}$, but they can learn very little about *(i)* θ_{13} which links the solar and atmospheric oscillations, *(ii)* the sign of Δm^2_{23} (which specifies

[3] It is Currently fashionable to disbelieve the LSND results. However, they have not been proved wrong, so far, by an alternative experiment. One such experiment, MiniBoone is approved in FNAL.

[4] The NMS matrix is the equivalent to the CKM matrix in the lepton sector.

the neutrino mass spectrum) and *(iii)* the CP-odd phase δ. These topics are the almost exclusively realm of a neutrino factory.

If the solar solution lies in the LMA-MSW region then $\Delta m^2_{sun} \sim \Delta m^2_{atm}/10 - \Delta m^2_{atm}/100$, and the approximation which leads to formulae 4 is no longer valid for sufficiently small values of θ_{13}. Instead, a good and simple approximation for the $\nu_e \to \nu_\mu$ transition probability is obtained by expanding to second order in the small parameters, $\theta_{13}, \Delta_{12}/\Delta_{13}$ and $\Delta_{12}L$[12]:

$$\begin{aligned} P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} &= s^2_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta_{13}\,L}{2}\right) \\ &+ c^2_{23}\,\sin^2 2\theta_{12}\,\sin^2\left(\frac{\Delta_{12}\,L}{2}\right) \\ &+ \tilde J\,\cos\left(\pm\delta - \frac{\Delta_{13}\,L}{2}\right) \\ &\quad \frac{\Delta_{12}\,L}{2}\sin\left(\frac{\Delta_{13}\,L}{2}\right), \end{aligned} \tag{5}$$

where

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij}}{2E_\nu}\,. \tag{6}$$

and

$$\tilde J \equiv c_{13}\,\sin 2\theta_{12}\sin 2\theta_{23}\sin 2\theta_{13} \tag{7}$$

is the combination of mixing angles appearing in the Jarlskog determinant.

Notice that, according to equation 5, the CP-odd term is proportional to J (and therefore to the product of all the mixing angles), and also to Δm^2_{sum}. Therefore any CP asymmetry will be suppressed by the solar Δm^2 and mixing angle and will become too small to be measurable if those parameters are too small, as would be the case if the solar solution does not lie in the LMA-MSW region. Fortunately, recent data from SuperKamiokande[3,4] favors precisely this region. In the rest of this paper I will assume that nature is kind and the LMA-MSW solution is indeed the true one. This expectations will be confirmed in a few years from now, by forthcoming solar experiments[10].

The above formulae are obtained assuming propagation in vacuum. However, when ν's cross the earth, forward scattering amplitudes are different for the different flavors:

$$\begin{aligned} M^2_\nu &= V_{NMS}\begin{pmatrix} m^2_1 & & \\ & m^2_2 & \\ & & m^2_3 \end{pmatrix} V^\dagger_{NMS} \\ &+ \begin{pmatrix} \pm 2E_\nu A & & \\ & & \\ & & \end{pmatrix} \end{aligned} \tag{8}$$

where $A \equiv \sqrt{2} G_F n_e$ and n_e the ambient electron number density[6]. The presence of matter modifies the transition probabilities which can be written (for example for the $\nu_\mu \to \nu_e$ transitions) as:

$$\begin{aligned} P_{\nu_e\nu_\mu(\bar\nu_e\bar\nu_\mu)} &= \sin^2\theta_{23}\sin^2 2\,\theta_{13} \\ &\left(\frac{\Delta m^2_{23}}{B_\pm}\right)^2\,\sin^2 B_\pm L \end{aligned} \tag{9}$$

which has the same form of the corresponding probability in vacuum (equations 4) substituting the mixing angle θ_{23} by an "effective mixing angle" $\sin^2\theta_{23}\sin^2 2\,\theta_{13}\left(\frac{\Delta m^2_{23}}{B_\pm}\right)$ and the mass difference $\Delta m^2_{atm}/4E_\nu$ by an "effective mass difference":

$$\begin{aligned} B_\pm &\equiv ((\Delta m^2_{23}\cos 2\,\theta_{13} \pm 2E_\nu A)^2 \\ &+ (\Delta m^2_{23}\sin 2\,\theta_{13})^2)^{1/2} \end{aligned} \tag{10}$$

Matter effects on Earth are important if A is comparable to, or bigger than, Δ_{atm} for some neutrino energy, and if the distances traveled through the Earth are large enough for the probabilities to be in the non-linear region of the oscillation.

For the Earth's crust, with density $\rho \sim 2.8 g/cm^3$ and roughly equal numbers of protons, neutrons and electrons, $A \sim 10^{-13} eV$. The typical neutrino energies we are considering are tens of GeVs. For instance, for $E_\nu = 30 GeV$ (the average $\bar\nu_e$ energy in the decay of $E_\mu = 50 GeV$ muons) $A = 1.1 \times 10^{-4}\ eV^2/GeV \sim \Delta_{23}$. This means that matter effects will be important at long distances. Since the "effective mass" $B_\pm$ is CP-odd, the net effect of matter is to induce, at sufficiently large baselines a "fake" CP-asymmetry which hides genuine CP-violation.

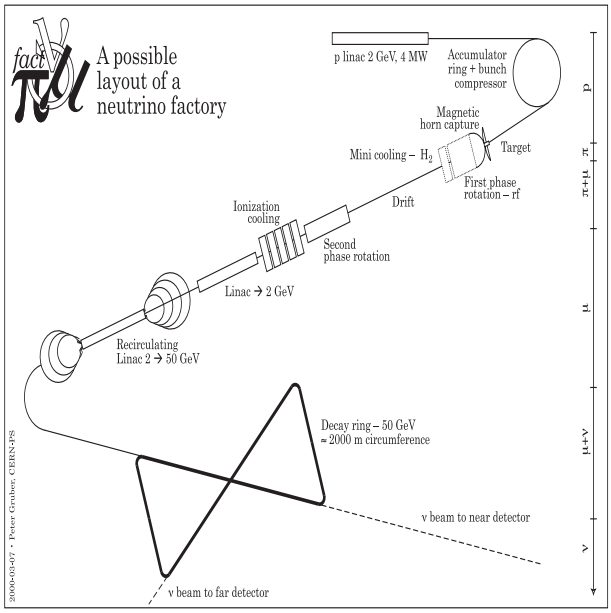

Figure 1. Generic Layout of a Neutrino Factory.

3. THE NEUTRINO FACTORY

3.1. The Machine

The generic layout of a neutrino factory is shown in Fig. 1. A high power (4 MW) proton beam impinges on a target producing pions which are collected and focused with a magnetic device (such as the magnetic horn depicted in the figure) and let decay in a drift space. Next, the muon phase space is reduced (phase rotation, ionization cooling) and the muons are injected into a set of linacs which accelerate them up to an energy of 50 GeV. Finally they are fed into a storage ring. The muons decaying in the straight sections of this ring produce a high intensity, pure neutrino beam that points towards a neutrino detector (a bow-tie design, such as the one shown in the figure allows two different locations). By changing the sign of the charge of the collected pions it is possible to get the two conjugated neutrinos.

The design parameters of the neutrino factory have been extensively discussed in the Lyon and Monterey workshops[13,14]. The results discussed here were obtained assuming an integrated data set of 10^{21} useful μ^+ decays and 10^{21} useful μ^- decays, a muon beam energy of 50 GeV, no polarization and a detector mass of 40 kt.

3.2. Wrong sign muons

As one can see in formula 5, in order to be sensitive to the parameters θ_{13} and δ one must measure the transition probabilities involving ν_e and $\bar{\nu}_e$, in particular $\nu_e(\bar{\nu}_e) \rightarrow \nu_\mu(\bar{\nu}_\mu)$. The neutrino factory is unique in providing high energy and intense $\nu_e(\bar{\nu}_e)$ beams coming from positive (negative) muons. Since these beams contain also $\bar{\nu}_\mu(\nu_\mu)$ (but no $\nu_\mu(\bar{\nu}_\mu)$ as is the case for conventional neutrino beams), the transitions of interest can be measured by searching for "wrong-sign" muons[15,16], e.g., negative (positive) muons appearing in a (massive) detector with good muon charge identification capabilities, provided that the non-beam backgrounds (i.e, backgrounds arising from the bulk of ν_μ and ν_e charged and neutral current events) to this signal can be kept sufficiently small. Notice that there are no other neutrino flavors in the beam, unlike the case of conventional hadron beams which contain an irreducible contamination of other flavors due to the decay of kaons and opposite-sign pions.

3.3. A Large Magnetic Detector for the Neutrino Factory

The detector proposed in[17] is shown in Fig. 2. It is a large cylinder of 10 m radius and 20 m length, made of 6 cm thick iron rods interspersed with 2 cm thick scintillator rods built of 2 cm long segments (light readout on both ends allows the determination of the spatial coordinate along the scintillator rod). Its mass is 40 kt. A super conducting coil generates a solenoidal magnetic field of 1 T inside the iron.

A neutrino traveling through the detector sees a sandwich of iron and scintillator, with the X, Y coordinates being measured from the location of the scintillator rods and the Z coordinate being measured from their longitudinal segmentation.

Neutrino interactions in such a detector have a clear signature. A CC ν_μ event is characterized by a muon, easily seen as a penetrating track

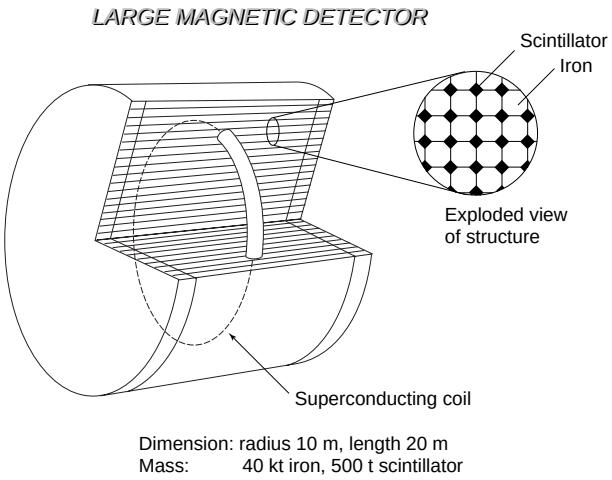

Figure 2. Sketch of the large magnetic detector for the neutrino factory.

of typically several meters length, and a shower resulting from the interactions of the final-state hadrons. A NC event, though, contains no penetrating track and the length of the event is the length of the hadron shower in iron, typically less than one meter. CC ν_e events, on the other hand, cannot be easily recognized since, with a detector of this coarse granularity, it is difficult to disentangle the prompt electron from the hadronic shower on an event-by-event basis. The performance of the detector will be similar to that of MINOS[18]. The main difference lies in the mass which is one order of magnitude larger, and in the smaller surface-to-volume ratio.

The potential backgrounds to the wrong-sign muon signal events are NC events (as well as CC events in which the right-sign lepton is not detected) in which a secondary negative muon arising from the decay of π^-, K^- and D^- hadrons fakes the signal. The discrimination of these backgrounds is based on the fact that the muon produced in a CC *signal* event is harder and more isolated from the hadron shower axis than the one produced from hadron decay in background events. Accordingly, in[17] an analysis is performed based on the momentum of the muon, p_μ, and a variable measuring the isolation of the muon from the hadron shower axis, $q_{\mathrm{t}} = p_\mu \sin\theta$.

An example of the rejection power of this analysis can be seen in Fig. 3 which shows the efficiency for signal detection as well as the fractional backgrounds due to "right" sign charged currents, in which the "right sign muon" is lost. Two independent plots are shown, one as a function of the cut on p_μ and the oter as a function of the cut on q_{t}. Also shown is the ratio $S/N = \varepsilon_{\mathrm{s}}/\sigma_{\mathrm{b}}$, where ε_{s} is the signal selection efficiency and σ_{b} is the error in the number of background events which survive the cuts. Muons from charmed-hadron decays constitute the main background from $\overline{\nu}_\mu$ CC events. Overall, a reduction of the background at the level of 10^{-6} seems achievable. For an extensive discussion I refer to [17].

4. MEASUREMENT OF THE CP VIOLATION PHASE

We are now in position to show how the CP violation phase could be measured in the neutrino factory. As pointed out before, I will assume that the solar solution is in the currently favored range LMA-MSW. Also, to simplify the discussion fixed values of the atmospheric parameters are used in this section, $\Delta m^2_{23} = 2.8 \times 10^{-3} eV^2$ and maximal mixing, $\theta_{23} = 45^\circ$.

Let us start discussing the measurement of the CP phase δ versus θ_{13}. Consider first the upper solar mass range allowed by the LMA-MSW solution: $\Delta m^2_{12} = 10^{-4}$ eV^2. Fig. 4 shows the confidence level contours for a simultaneous fit of θ_{13} and δ, for Montecarlo generated data (including detector response) corresponding to $\theta_{13} = 8^\circ$, $\delta = 54^\circ$. The results include statistical errors as well as those due to background subtraction. Detection efficiencies are also taken into account. Genuine CP violation is separated from the fake CP violation induced by matter effects taking advantage of the different dependency on energy and base line (see[12] for a detailed discussion).

Notice that at "short" distances (i.e., 700 Km) the correlation between δ and θ_{13} is very large. The phase δ is not measurable and this indetermination induces a rather large error on the an-

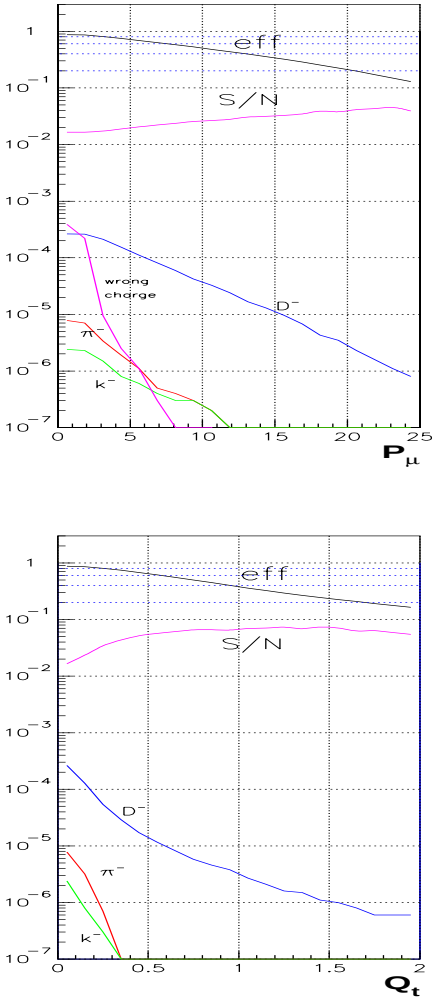

Figure 3. Wrong-sign muon efficiency and fractional backgrounds for $\overline{\nu}_\mu$ CC events, as a function of p_μ or $q_{\rm t}$, for a neutrino beam originating from 50 GeV/c μ^+ decays.

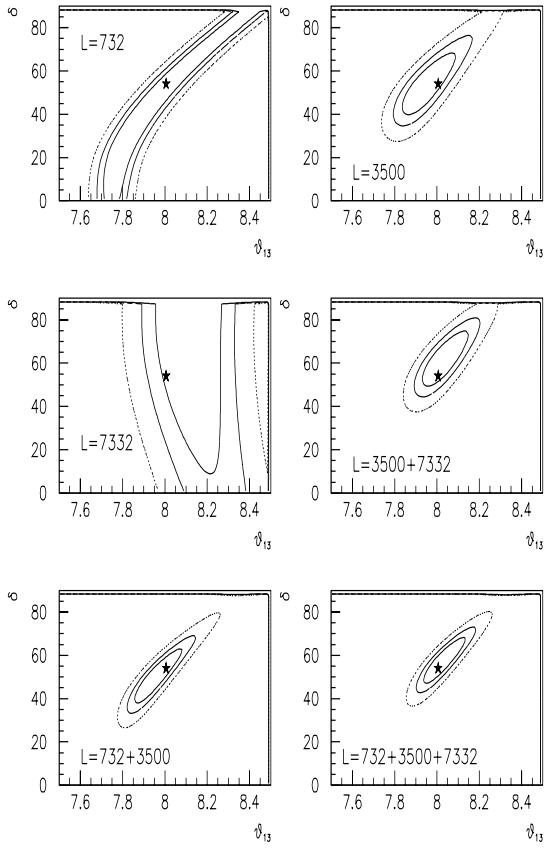

Figure 4. 68.5, 90, 99 % CL contours resulting from a χ^2 fit of θ_{13} and δ. The parameters used to generate the "data" are depicted by a star and the baseline(s) which is used for the fit indicated in each plot. Statistical errors, backgrounds and efficiencies are included.

gle θ_{13}. However, at the intermediate baseline of 3500 km the two parameters can be disentangled and measured. At the largest baseline, the sensitivity to δ is lost and the precision in θ_{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, although not in a dramatic way. However, also from the point of view of understanding systematics I believe that two base lines are preferred. Notice that a CERN-based neutrino factory could choose a "short base line" experiment located in the Gran Sasso laboratory in Italy, at a distance of about 700 Km[5]. The "long base line" experiment must be located, as discussed at about 3000 Km. Possible locations, with good potential underground sites[6] exist in Spain (in La Palma, one of the Canary islands) if the second beam shoots south or in Norway and/or Finland if shooting north.

The sensitivity to CP-violation decreases linearly with Δm^2_{12}. At the central value allowed by the LMA-MSW solution, $\Delta m^2_{12} = 5 \times 10^{-5} eV^2$, CP-violation can still be discovered, while for $\Delta m^2_{12} = 1 \times 10^{-5} eV^2$, the sensitivity to CP-violation is lost with the experimental set-up used. We have quantified what is the minimum value of Δm^2_{12} for which a maximal CP-odd phase, $\delta = 90°$, can be distinguished at 99% CL from $\delta = 0°$. The result is shown in Fig. 5: $\Delta m^2_{12} > 2 \times 10^{-5} eV^2$, with very small dependence on θ_{13}, in the range considered.

For an extensive discussion I refer to [12,19,20].

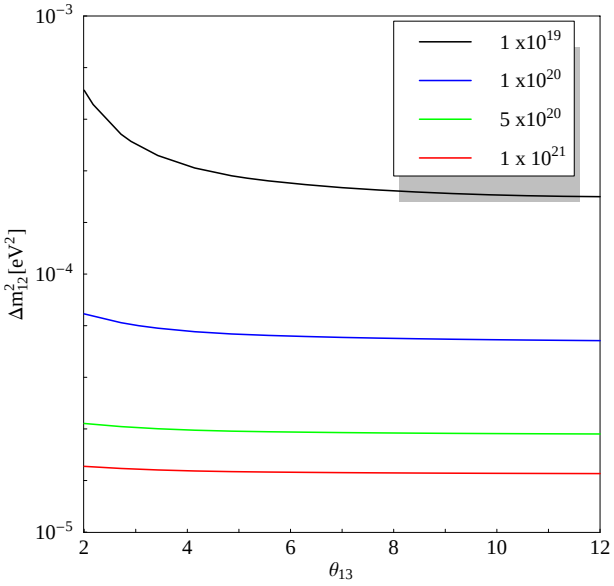

Figure 5. Lower limit in Δm^2_{12} at which a maximal CP phase (90°) can be distinguished from a vanishing phase at 99% CL, as a function of θ_{13} at $L = 3500$km and for different numbers of useful muons. Background errors and efficiencies are included.

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In spite of the fact that the birth of my daugther Irene in the same week of CP2000 restricted my participation in this wonderful confer-

[5]This is an ideal location for one experiment since the current generation of neutrino experiments will start to take data there in a few years from now.

[6]The detector(s) discussed must be deep underground to reduce the huge flux of cosmic rays.

ence I was nonetheless able to contribute thanks to the kindness, patience and understanding of the organizers to which I would like to express my most sincere acknowledgments.

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