NEUTRINO FACTORY: EXPERIMENTAL ASPECTS

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ABSTRACT

The discovery of neutrino oscillations marks a major milestone in the history of neutrino physics, and opens a window to what lies beyond the Standard Model. Many current and forthcoming experiments will answer open questions; however, a major step forward, up to and possibly including CP violation in the neutrino mixing matrix, will be offered by the neutrino beams from a neutrino factory. The neutrino factory is a new concept for producing neutrino beams of unprecedented quality in terms of intensity, flavour composition, and precision of the beam parameters. These beams enable the exploration of otherwise inaccessible domains in neutrino oscillation physics by exploiting baselines of planetary dimensions. Suitable detectors pose formidable challenges but seem within reach with only moderate extrapolations from existing technologies. Although the main physics attraction of the neutrino factory is in the area of neutrino oscillations, an interesting spectrum of further opportunities ranging from high-precision, high-rate neutrino scattering to physics with high-intensity stopped muons comes with it.

1. History and introduction

The neutrino factory is a muon storage ring with long straight sections along which decaying muons produce well-defined neutrino beams. The idea is a natural offspring of the concept of a muon collider, first proposed by Budker [1)] at the 1969 Yerevan Conference, and developed further by Skrinsky [2)]. The first proposal for a genuine neutrino factory was put forward in quite some detail as early as 1974 by Koshkarev [3)].

It was not until the 1990s that the idea of the muon collider was again taken up, this time going well beyond the level of studies on paper. The US-led Muon Collider Collaboration [4)] developed a conceptual layout of a multi-TeV muon collider, including all stages from muon production to the storage of high-energy muons in a circular collider, and launched an ambitious R&D programme. In the context of this work, the idea of a neutrino factory was developed further and highlighted in a comprehensive paper by Geer [5)].

The neutrino fluxes from the neutrino factory are much higher than achieved before and have a well-defined flavour composition, free of background. These characteristics made physicsts think about neutrino oscillation measurements in a new way. Distances between production and detection can now span the planet, and given the flavour composition of the beam, one can map out a plan to measure the neutrino mixing matrix much like physicists now are measuring the CKM quark mixing matrix. Alternatively, one can also think about putting experiments extremely close to the production location, and using these extremely intense neutrino beams to map out nuclear structure much like electron and muon beams have done in the past.

The coincidence between the evidence of oscillations of solar ν_e [6)] and atmospheric ν_μ [7,8)] and the possible oscillation of accelerator-produced ν_μ as claimed by the LSND experiment [9)] on the one hand, and the intriguing potential of the neutrino factory for the study of neutrino oscillations on the other hand, initiated a European study group on the neutrino factory within the context of an ECFA-sponsored 'Prospective Study of Muon Storage Rings in Europe' [10)].

In 1999 and 2000, the studies intensified both in the US and in Europe. At FNAL, the 'six-months' study [11)] was carried out which resulted, on the positive side, in the demonstration that a neutrino factory could be built already today. On the negative side, however, it became clear that building a neutrino factory today would be more costly than thought before, and that the physics potential of the FNAL design would hardly convince the physics community at large to build that machine, as the scope of the machine was considerably reduced.

As a follow-up, 'Study 2', centred at BNL, is currently in progress.

In parallel, and in collaboration with the US, the European study continues, with a focus on a neutrino factory at CERN. A first comprehensive physics report was published in 2000 [12)].

The Japanese efforts concentrate, in a first step, on the construction of a neutrino 'superbeam' at the recently authorized Japanese Hadron Facility, directed to the SuperKamiokande experiment.

2. Neutrino oscillations: status and prospects

The physics case for the neutrino factory is largely — but not solely — driven by neutrino oscillations.

2.1. What do we know?

It is largely accepted that we observe neutrino oscillations with the following characteristics:

- Solar ν_e disappear with $\Delta m^2_{12} \sim 10^{-4}$ to 10^{-5} eV^2, or with $\Delta m^2_{12} \sim 10^{-10}$ eV^2, with either small-angle or large-angle mixing $\sin^2 2\theta_{12}$ (the so-called LMA-MSW, SMA-MSW and VO solutions).

- Atmospheric ν_μ disappear with $\Delta m^2_{23} \sim 10^{-3}$ eV^2 and large-angle mixing $\sin^2 2\theta_{23}$, but do not oscillate into ν_e.

- Therefore, at least all three known neutrino families participate actively in the oscillations. This suggests, as a minimum, a neutrino mixing matrix analogous to the CKM matrix in the quark sector. There would be a minimum of six independent variables: three angles θ_{12}, θ_{13}, θ_{23}, a CP-violating phase δ as well as two mass-squared differences Δm^2_{12} and Δm^2_{23}.
- In the likely limit $\Delta m^2_{23} \gg \Delta m^2_{12}$, the solar and the atmospheric neutrino oscillations nearly decouple and can effectively be described by the two-family oscillation formalism. Taking into account all three families, however, the solar-neutrino oscillation is governed by θ_{12}, Δm^2_{12} and θ_{13}, while the atmospheric-neutrino oscillation is governed by θ_{23}, Δm^2_{23} and θ_{13}. The two oscillation phenomena are linked through the angle θ_{13}.
- If the LSND claim [9] of a transition $\nu_{\mathrm{e}} \leftrightarrow \nu_\mu$ with $\Delta m^2 \sim 1$ eV^2 is correct, a fourth neutrino is needed which must be sterile since it is not seen in Z decay.

2.2. What will be the questions in ten years from now?

Apart from the epic question of Dirac- or Majorana-type neutrinos, there is a strong case for going further in the fundamental quest of the neutrino masses and mixing angles, as a necessary step to unravelling the fundamental new scale(s) behind neutrino oscillations. However, despite of ongoing solar-neutrino experiments and SuperKamiokande, and despite of an impressive number of new experiments coming into operation (BOREXINO, ICARUS-600, KamLAND, K2K, MiniBooNe, MINOS and SNO), in ten years from now no major advances will have been made in the knowledge of:

- The angle θ_{13}, which is the key between the atmospheric and solar neutrino realms, for which the present CHOOZ bound is $\sin^2\theta_{13} \leq 5 \times 10^{-2}$ [13,14].
- The sign of Δm^2_{23}, which determines whether the three-family neutrino spectrum is of the 'hierarchical' or 'degenerate' type (i.e. only one heavy state and two almost degenerate light ones, or the reverse).
- Leptonic CP violation.
- Matter effects in the neutrino propagation through the Earth, in particular a model-independent experimental confirmation of the MSW effect [15].

The neutrino factory is the best machine known today to address these questions. As a consequence, the operating parameters of the neutrino factory should not be driven by today's questions but rather by the questions which will be asked in ten years from now.

3. Neutrinos from muon decay

The decay of the muon is a well-known and precisely calculable process, as there are only leptons involved. In the muon rest frame, the distribution of muon antineutrinos (neutrinos) and electron neutrinos (antineutrinos) in the decay $\mu^\pm \to e^\pm + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$ is given by:

$$\frac{d^2N}{dxd\Omega} = \frac{1}{4\pi}[f_0(x) \mp \mathcal{P}_\mu f_1(x) \cos\theta] ,$$

where E_ν denotes the neutrino energy, $x = 2E_\nu/m_\mu$, and $\mathcal{P}_\mu$ is the average muon polarization along the muon beam direction. θ is the angle between the neutrino momentum vector and the muon spin direction and m_μ is the muon mass. The positron (electron) flux is identical to that for muon neutrinos (antineutrinos), when the electron mass is neglected. The functions f_0 and f_1 are given in Table 1 [16].

Table 1: Flux functions in the muon rest-frame.

	$f_0(x)$	$f_1(x)$
ν_μ, e	$2x^2(3-2x)$	$2x^2(1-2x)$
ν_e	$12x^2(1-x)$	$12x^2(1-x)$

The neutrino energy spectrum in μ^+ decay is shown in Figure 1 for unpolarized muons, together with the monoenergetic line of ν_μ in π^+ decay. While the $\bar{\nu}_\mu$ spectrum (which is the same as the positron spectrum) peaks at the kinematic limit of 53 MeV, the $\nu_{\rm e}$ spectrum is a bit softer and peaks at 2/3 of it.

The neutrinos from muons decaying in the straight sections are Lorentz-boosted in the forward direction towards the detector which is located at some distance L. The neutrino flux in the forward direction is proportional to E_μ^2/L^2, and half of the neutrinos are contained within a cone angle of $1/\beta\gamma = m_\mu/p_\mu$. As the detector will be located at a distance of several hundred kilometres or even more, it will be much smaller than the transverse size of the beam. Taking into account the neutrino cross-section which rises linearly with energy, the event rate in the detector scales with $M \times E_\mu^3/L^2$, where M is the fiducial target mass of the detector.

The energy spectrum of the neutrino flux in the distant detector is the same as shown in Fig. 1, but with the energy scale multiplied by the Lorentz boost factor $2E_\mu/m_\mu$.

The momentum of the circulating muons is in principle a free parameter. Thanks to the E_μ^3 dependence of the neutrino rates in the far detector, one always wins

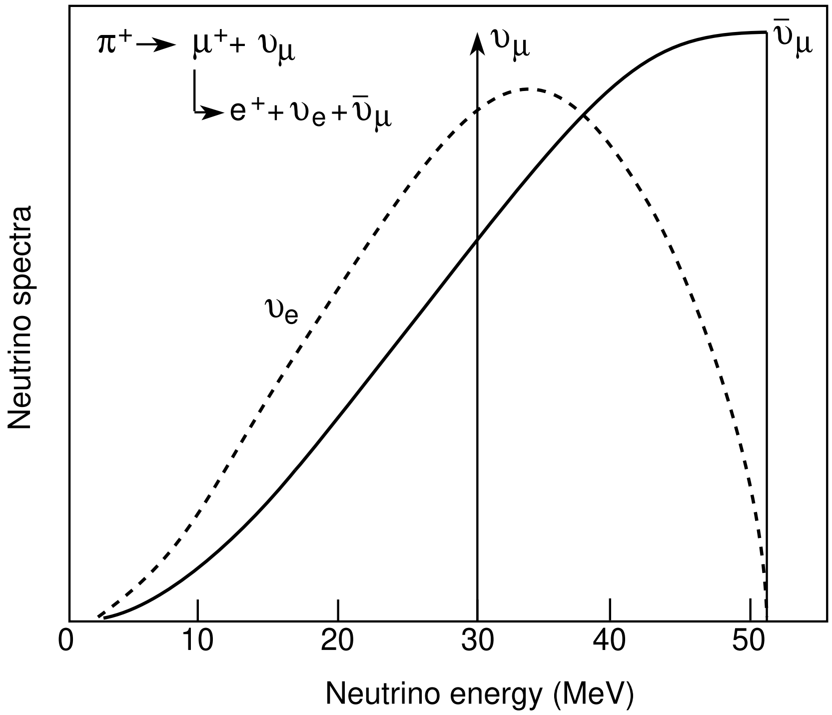

Figure 1: Neutrino energy spectra in π^+ and μ^+ decay.

with higher momentum of the circulating muons, at any neutrino energy. Therefore, there is a strong incentive to run the neutrino factory at the highest possible muon momentum.

In Table 2 a comparison is made between a conventional muon neutrino beam from pion and kaon decay, and a beam from the neutrino factory. The comparison is made specifically for the proposed NGS beam [17)] from CERN to the Laboratorio Nazionale del Gran Sasso (hereafter called Gran Sasso) 732 km away, with a neutrino factory sending a beam over the same distance.

4. Muon-polarization issues

Because of the well-defined helicities of the decay particles in muon decay, there is a strong correlation between the direction of emission and the muon-polarization vector. The ν_e ($\bar{\nu}_e$) plays a special role insofar as its helicity is opposite to that of the other two particles: the positron (electron) and $\bar{\nu}_\mu$ (ν_μ). This means, in the decay $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ for example, that the ν_e's are always emitted in the opposite direction to the muon-polarization vector, so that they can never reach the 'far' detector other than with negligible energy. Table 3 summarizes the situation for both

Table 2: Comparison of a conventional neutrino beam with the neutrino factory.

	Conventional	Neutrino factory
Parents	π^+, K^+ or π^-, K^-	μ^- or μ^+
ν_μ beam Background	ν_μ $\sim$2% of $\bar{\nu}_\mu$, $\sim$1% of ν_e	$\nu_\mu : \bar{\nu}_e = 1 : 1$ none
$\bar{\nu}_\mu$ beam Background	$\bar{\nu}_\mu$ $\sim$6% of ν_μ, $\sim$0.5% of $\bar{\nu}_e$	$\bar{\nu}_\mu : \nu_e = 1 : 1$ none
Variation of <energy>	limited	free within factor of $\sim$3
$\Delta E/E$ of ν energy $\Delta R/R$ of ν radius ν flux uncertainty	$\pm$10% $\pm$10% $\pm$10%	$<$ 1% $<$ 1% $<$ 1%
$\nu_\mu/(\text{cm}^2\text{year})$ at 732 km	3×10^7 (4.5×10^{19} 400 GeV/c pot)	3×10^9 (10^{21} injected 50 GeV/c μ)

muon polarities and both polarization states: other than ν_μ, ν_e can be 'switched off' by 100% polarization with the right sign.

Table 3: Neutrino beam composition for different muon-polarization.

	$\mathcal{P} = +1$	$\mathcal{P} = -1$
μ^+	only $\bar{\nu}_\mu$	$\nu_e + \bar{\nu}_\mu$
μ^-	$\bar{\nu}_e + \nu_\mu$	only ν_μ

Figure 2 shows the event spectra, taken from Ref. [18], in a detector located 732 km away from the neutrino factory for $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ beams of 50 GeV/c. The sensitivity of the spectra to the muon polarization is striking.

Also, since the ν_e ($\bar{\nu}_e$) is always emitted together with a second particle in the same direction, it never attains the maximum energy permitted by the kinematic limit. This opens the way in principle to look near the kinematic limit for the appearance of ν_e ($\bar{\nu}_e$), which could then only be the result of an oscillation of ν_μ ($\bar{\nu}_\mu$) into ν_e ($\bar{\nu}_e$). While this strategy is already possible with unpolarized muons, it improves considerably with muon-polarization. Therefore, having a large degree of polarization is potentially interesting for several reasons:

- certain interesting event rates can be enhanced;
- the ratio of signal to background events can be changed;
- our current inability to build multi-kiloton detectors which can distinguish the interactions of ν_e and $\bar{\nu}_e$ can be circumvented.

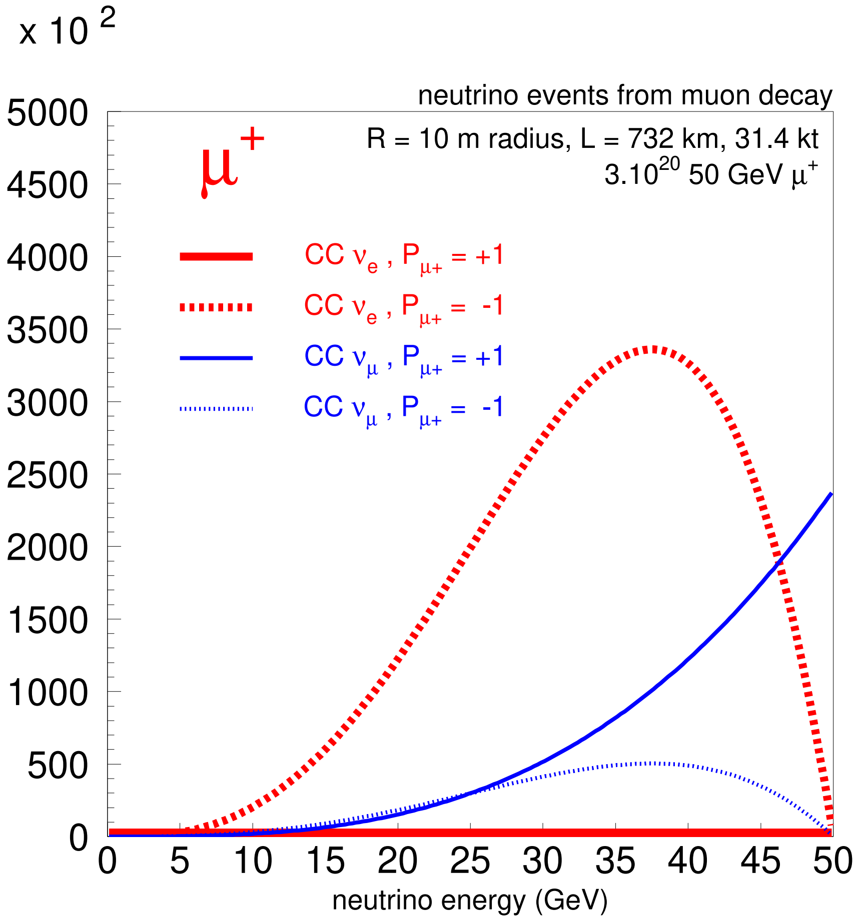

Figure 2: Event spectra in a detector located 732 km away from the neutrino factory for $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ beams of 50 GeV/c. The beam energy spread and the beam divergence are both assumed as zero.

At any rate, whatever the polarization of the circulating muons, it must be known precisely. Fortunately, this measurement is in principle straightforward through the measurement of the energy of the decay electrons at a given angle with respect to the muon momentum. A possible scheme to measure the muon-polarization, together with the muon momentum and the energy spread of the muon beam, has been worked out by Blondel [19)].

5. Physics at the neutrino factory

5.1. Neutrino-oscillation physics

Both atmospheric and planetary experiments have an energy range such that $\Delta m^2\, L/E_\nu \ll 1$ for the smaller (Δm^2_{12}) but not necessarily for the larger (Δm^2_{23}) of these mass gaps. Even then, solar and atmospheric transitions are not (provided $\theta_{13} \neq 0$) two separate two-family oscillations. For $|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$, neutrino oscillation probabilities at planetary distances are well described by only three parameters, θ_{23}, $\Delta m^2_{23} = \Delta m^2_{13}$ and θ_{13}:

$$\begin{aligned}
P_{\rm CP}(\nu_{\rm e} \to \nu_\mu) &= \sin^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}\,L}{4E_\nu}\right)\,,\\
P_{\rm CP}(\nu_{\rm e} \to \nu_\tau) &= \cos^2\theta_{23}\,\sin^2 2\theta_{13}\,\sin^2\left(\frac{\Delta m^2_{23}\,L}{4E_\nu}\right)\,,\\
P_{\rm CP}(\nu_\mu \to \nu_\tau) &= \cos^4\theta_{13}\,\sin^2 2\theta_{23}\,\sin^2\left(\frac{\Delta m^2_{23}\,L}{4E_\nu}\right)\,.
\end{aligned} \tag{1}$$

The present best fit value for θ_{13} is in the range $6°$–$8°$ [20,21], although it is compatible with zero within errors. Among the transitions in Eq. (1) the channels $\nu_{\rm e} \to \nu_\mu$ and $\nu_{\rm e} \to \nu_\tau$ have clearly the best sensitivity to a small θ_{13}. From the experimental point of view, the measurement of $\nu_{\rm e} \to \nu_\mu$ oscillations through the appearance of wrong-sign muons is far superior to that of $\nu_{\rm e} \to \nu_\tau$ oscillations since the latter involves the detection of tau's.

As for CP violation, it is possible to construct a measurable CP-odd asymmetry, which in vacuum is proportional to $\sin\delta$. In Refs. [22] and [23], the authors considered the following integrated asymmetry (see also Ref. [24]):

$$\bar{A}^{\rm CP}_{{\rm e}\mu} = \frac{\{N[\mu^-]/N_o[{\rm e}^-]\}_+ - \{N[\mu^+]/N_o[{\rm e}^+]\}_-}{\{N[\mu^-]/N_o[{\rm e}^-]\}_+ + \{N[\mu^+]/N_o[{\rm e}^+]\}_-}\,.$$

The sign of the decaying muons is indicated by a subindex, $N[\mu^+]$ ($N[\mu^-]$) are the measured number of wrong-sign muons, and $N_o[{\rm e}^+]$ ($N_o[{\rm e}^-]$) are the expected number of $\overline{\nu}_{\rm e}$ ($\nu_{\rm e}$) charged-current interactions in the absence of oscillations. The significance of this asymmetry (i.e. the asymmetry divided by its statistical error) scales with the baseline and neutrino energy in the following way:

$$\frac{\bar{A}^{\rm CP}}{\delta\bar{A}^{\rm CP}} \propto \sqrt{E_\nu}\,\left|\sin\left(\frac{\Delta m^2_{23}\,L}{2}\right)\right|\,.$$

The best sensitivity to a non-zero CP-odd asymmetry is found at the maximum of the atmospheric oscillation. At the corresponding distance, however, matter effects are already important and must be taken into account.

Of all neutrino species, only $\nu_{\rm e}$ and $\overline{\nu}_{\rm e}$ have charged-current elastic scattering amplitudes on electrons. That induces effective 'masses' $\mu = \pm 2\,E_\nu\,A$, where the signs refer to $\nu_{\rm e}$ and $\overline{\nu}_{\rm e}$, and A is the matter parameter

$$A = \sqrt{2}\,G_F\,n_{\rm e}\,,$$

with $n_{\rm e}$ the ambient electron density [15].

Matter effects are important if A is comparable to, or bigger than, the quantity Δ_{ij} for some mass difference and neutrino energy, and if distances are large enough for the probabilities to be in the non-linear region of the oscillation. In the LMA-MSW solar scenario, and only in this scenario, the effects of Δm^2_{12} are not negligible over planetary distances. Matter effects induce an asymmetry between neutrino and antineutrino oscillation probabilities even in the absence of genuine CP violation.

For the Earth's crust and outer mantle, 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 under consideration are tens of GeV. For instance, for $E_\nu = 30$ GeV, $A \sim 1.1 \times 10^{-4}$ eV^2/GeV $\sim \Delta m^2_{23}$. This means that matter effects will be important at long distances. Notice that at $L = 732$ km and 3500 km the neutrino path remains in the Earth crust, whereas for 7000 km the flight path touches the denser mantle and $A \sim 1.5 \times 10^{-4}$ eV^2/GeV.

The method of choice to study these topics is to measure the transition probabilities of $\nu_{\rm e}(\overline{\nu}_{\rm e}) \to \nu_\mu(\overline{\nu}_\mu)$.

The neutrino factory is the best machine known today to address the above questions. When discussing the operation parameters of the neutrino factory, it seems obvious that these should not be driven by today's physics questions but in the first instance by the questions which will be asked in ten years from now.

Ideally, one would like to study all transitions listed in Table 4 together with the transitions of the respective antiparticles.

Table 4: Neutrino flavour transitions.

	$\nu_{\rm e}$ beam	ν_μ beam	ν_τ beam
Appearance	$\nu_{\rm e} \to \nu_\mu$	$\nu_\mu \to \nu_{\rm e}$	$\nu_\tau \to \nu_{\rm e}$
Appearance	$\nu_{\rm e} \to \nu_\tau$	$\nu_\mu \to \nu_\tau$	$\nu_\tau \to \nu_\mu$
Disappearance	$\nu_{\rm e} \to \nu_x$	$\nu_\mu \to \nu_x$	$\nu_\tau \to \nu_x$

The neutrino factory adds significantly to the possibilities through the novel feature of a well-defined $\nu_{\rm e}$ beam. A ν_τ beam is not within reach, however — neglecting possible T-violation effects — all channels accessible with a ν_τ beam are also accessible with the $\nu_{\rm e}$ and ν_μ beams of the neutrino factory.

We note that in principle three types of detector are called for: one for tau detection, one for electron and one for muon detection, always including the separation of the charge of the respective lepton, which distinguishes the interactions of neutrinos from those of antineutrinos.

In practice, tau detection poses stringent requirements on the detector. One established way is to track the decay kink of the charged tau through precise track-coordinate measurement in emulsions. However, $\nu_\mu \leftrightarrow \nu_\tau$ transitions may no longer be in the focus of interest when the neutrino factory comes into operation.

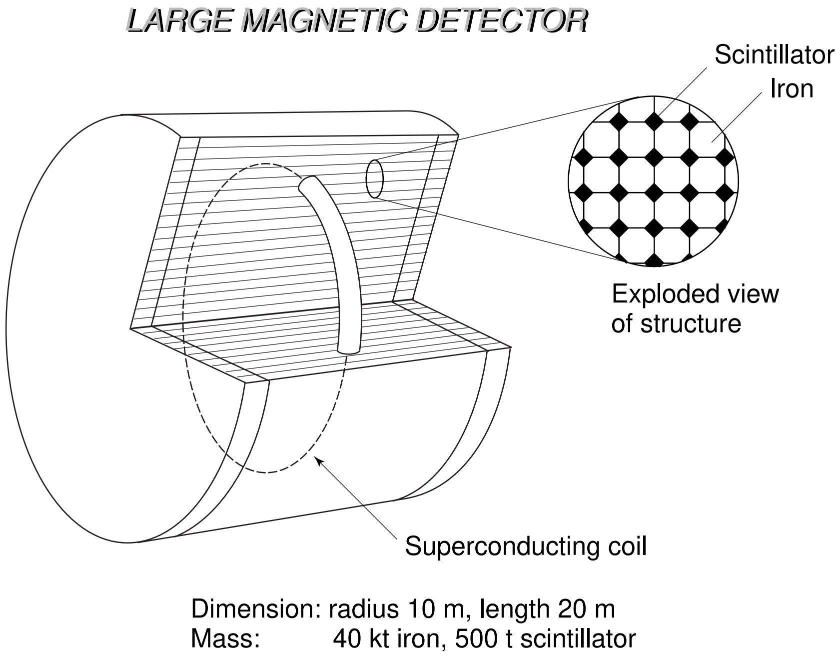

Figure 3: Sketch of the large magnetic detector for the neutrino factory.

The other detector type concerns the identification and measurement of final-state electrons and muons. This is considerably easier for muons than for electrons, yet detectors might be contemplated which can do a good job both for electrons and muons. However, we may again expect that at the time the neutrino factory comes into operation, the standard measurements such as spectral distortions due to disappearance of $\nu_{\rm e}$ or ν_μ, or abnormal ratios of 'short' to 'long' events in calorimetric detectors, will no longer be the focus of interest.

What is likely to be the focus of interest is a measurement of the appearance of 'wrong-sign muons' which would arise from $\nu_{\rm e} \to \nu_\mu$ transitions and would constitute a sensitive measurement of the mixing angle θ_{13}. Figure 4 from Ref. [22] highlights the sensitivity which one might achieve with the neutrino factory, for different momenta of the circulating muons. The gain from choosing a large muon momentum is apparent.

For the measurement of 'wrong-sign muon' appearance, one comes to think of a magnetized steel/scintillator sampling calorimeter. Depending on the geometry of such a detector, it might also prove useful as an atmospheric neutrino detector.

To be quantitative, we consider a large magnetic detector of the type proposed by Cervera et al. [26], shown in Fig. 3. 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 m long segments (light readout on both ends allows the determination of the spatial coordinate along the scintillator rod). Its mass is 40 kt. A superconducting

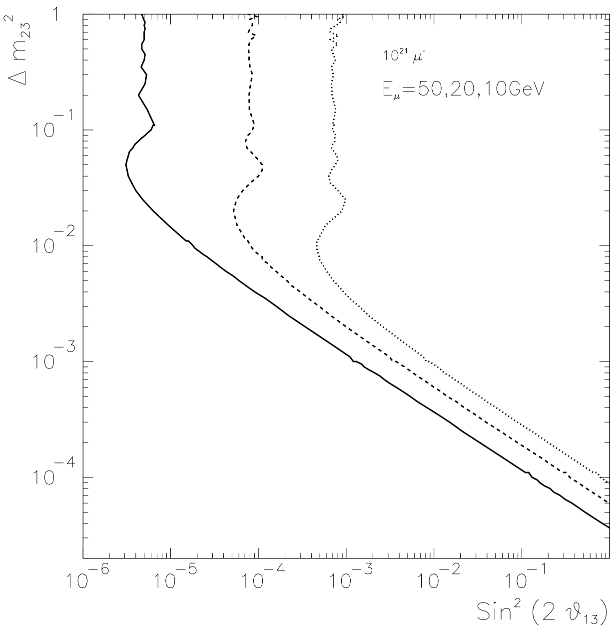

Figure 4: Sensitivity for the mixing angle θ_{13} at the neutrino factory, for 10^{21} useful muon decays, a detector distance of 732 km, and for muon beam momenta of 10, 20 and 50 GeV/c. Detection efficiency and a background estimate are included.

coil generates a solenoidal magnetic field of 1 T inside the iron.

In a $\overline{\nu}_\mu$, ν_e neutrino beam from the decay of μ^+ of 50 GeV/c, the bulk of events in the detector are $\overline{\nu}_\mu$ CC events signalled by the presence of a positive primary muon, $\overline{\nu}_\mu$ and ν_e NC events with no primary charged lepton, and ν_e CC events for which the electron is not identified, though. The signal consists of 'wrong-sign' μ^- arising from the ν_μ produced by the oscillation $\nu_\mathrm{e} \rightarrow \nu_\mu$.

The ultimate quest is for CP violation in the neutrino mixing matrix, for which the neutrino factory is the only known contender. CP violation would be signified in the asymmetry

$$A_{\mathrm{CP}} = \frac{P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)}{P(\nu_\alpha \rightarrow \nu_\beta) + P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)} \ ,$$

which is most easily exploited in the appearance of μ^- and μ^+ in beams of ν_e and $\bar{\nu}_\mathrm{e}$, respectively. Experimentally this seems simple; however, there is one major obstacle.

Our planet is not CP symmetric and produces, through the MSW effect [15)], an apparent CP asymmetry which must be calculated and subtracted from the measured effect. The interplay between the intrinsic CP violation and the MSW effect poses an interesting challenge. Indications are that measurements at different distances together with measurements at different neutrino energies provide sufficient information so as to be able to disentangle the contributions to the measured effect. Again the

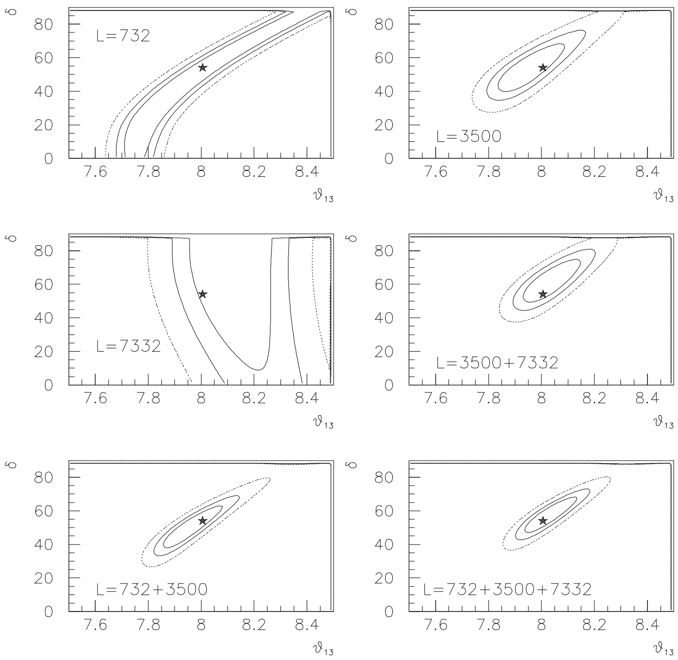

Figure 5: 2-parameter fit for θ_{13} and δ

neutrino factory is vital because by its very construction, it can serve two detectors at different distances simultaneously, and it permits the concurrent exploitation of a large span in neutrino energy.

Measuring CP-violating asymmetries is bound to be difficult if not impossible within a scheme of three neutrino families. For the transition $\nu_{\mathrm{e}} \leftrightarrow \nu_\mu$, the CP-violating asymmetry is proportional to Δm^2_{12} , which makes the so-called LMA-MSW solution of the solar-neutrino deficit the only solution which enables experimentally observable CP-violating asymmetries. Assuming that Nature has chosen that set of oscillation parameters, figure 5 taken from Cervera et al. [27] shows the confidence regios for a simultaneous fit of θ_{13} and the CP violating phase δ (assuming $\theta_{13} = 8°$, $\delta = 54°$ and $\Delta m^2_{12} = 10^{-4}\,\mathrm{eV}^2$). The analysis takes matter effects, the muon–detection efficiency and experimental backgrounds into account.

The conclusion is that two distances are needed to disentangle the measurements of θ_{13} and of the CP violating phase δ: approximately 700 and 3000 km.

5.2. Other interesting physics opportunities

With the neutrino factory, other interesting physics opportunities besides neutrino oscillations arise:

- High-intensity, low-energy muons:

- searches for rare muon decays (e.g. $\mu \to e\gamma$ at a level way below 10^{-14}).

- intense beams of radioactive nuclei which are of growing interest for the non-destructive study of the change of material parameters by 'doping' with nuclei.
- High-precision neutrino physics:
  - in 'near' detector 4×10^8 ν_μ CC events per kg for 10^{21} injected 50 GeV muons;
  - precision measurements of neutrino–nucleon cross-sections;
  - precision measurements of nucleon structure functions in *unpolarized* and *polarized* targets, for various nuclei;
  - measurement of $\sin^2\theta_\mathrm{w}$ to ± 0.0001 in neutrino–electron scattering.
- Prolific *tagged* charm production.

6. Accelerator issues

The schematic layout of the neutrino factory complex which is currently being developed at CERN in the framework of an international collaboration, is shown in Fig. 6.

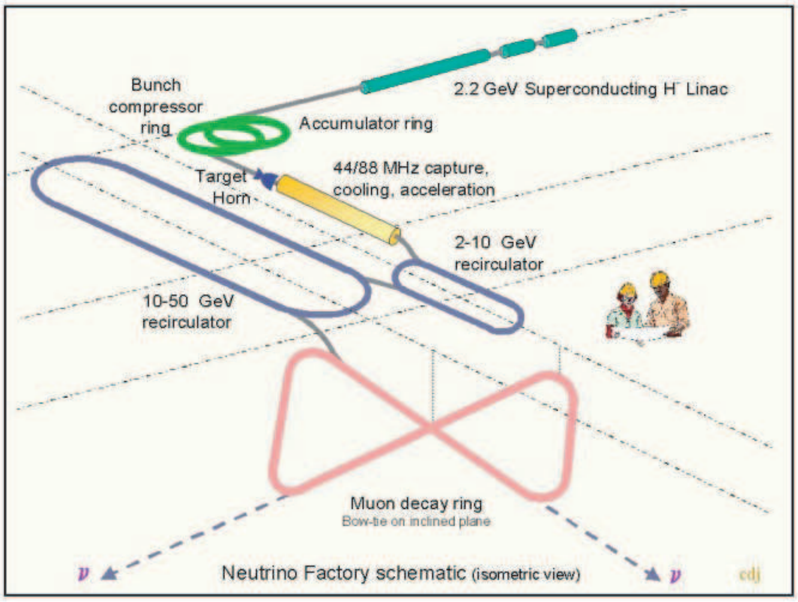

Figure 6: Schematic layout of the CERN neutrino factory complex.

The protons deliver 4 MW onto a high-Z target. The target technology is very difficult, as very strong pressure waves have to be sustained. Also, a high amount of heat must be transported away from the target, as ∼25% of the beam power is dissipated therein. The target is embedded in a strong solenoidal field of some 20 T. The accepted forward-going pions are phase-rotated, i.e. their momentum spread is reduced at the cost of bunch lengthening. After a drift space where the pions decay, the decay muons are 'cooled', with a relatively moderate compression of the phase space by a factor of ∼ 20. Since muons are unstable, all further actions on them must be highly efficient so as to accelerate them as fast as possible to their final momentum.

The cooled muons are first accelerated to an energy of 2 GeV, and then enter a recirculating linac, where they are repeatedly accelerated in a straight section, and returned in recirculating arcs. Each arc is optimized for a certain momentum. For physics reasons, a momentum range up to 50 GeV/c is desired, where 50 GeV/c is a limit imposed by financial considerations rather than by physics objectives.

Finally the muons enter the muon storage ring. It has two straight sections, each pointing to 'far' detectors at different distances (say 700 and 3000 km, implying inclination angles of $\sim 3^o$ and $\sim 13^o$, respectively, with respect to the horizontal plane. The arcs are as short as possible. The two straight sections and the arcs are arranged in a near-planar geometry. At the end of one straight section, a 'near' detector is located.

While the overall design is considered feasible by the experts, it is recognized that a lot of R&D work must be successfully accomplished before a serious engineering design could be made. Particularly critical areas are the target zone and the muon cooling.

7. European R&D efforts

The HARP experiment (Fig. 7) carries out, at the CERN PS, a programme of measurements of secondary hadron production, over the full solid angle, produced on thin and thick nuclear targets by beams of protons and pions with momenta in the range 2 to 15 GeV/c. The experiment comprises a large-acceptance charged-particle magnetic spectrometer of conventional design, located in the East Hall of the CERN PS. It will take data during 2001.

The first aim of this experiment is to acquire adequate knowledge of pion yields for an optimal design of the proton driver of the Neutrino Factory. The second aim is to reduce substantially the existing ∼ 30% uncertainty in the calculation of absolute atmospheric neutrino fluxes and the ∼ 7% uncertainty in the ratio of neutrino flavours, required for a refined interpretation of the evidence for neutrino oscillation from the study of atmospheric neutrinos in present and forthcoming experiments.

Another experimental effort is the MUSCAT experiment which aims at a precise measurement of the multiple scattering of low-momentum muons in liquid hydrogen, as neither existing measurements nor theoretical predictions are precise enough to exclude bad surprises in a muon cooling channel (liquid hydrogen is the planned absorbing material for ionization cooling of muons). The experiment is located at TRIUMF and will take data during 2001.

8. Long-baseline candidate sites

The currently envisaged long-baseline candidate sites for a CERN-based neutrino factory are shown in Fig. 8. Important criteria for the site selection will be

- Distance from and inclination angle at CERN;
- Underground depth;
- Infrastructure (airport, transport of heavy equipment);
- Support (local authorities, national particpel physics community).

The characteristics of the candidate sites are given in Table 5: the straight distance from CERN, and the inclination angle of the straight line with respect to the horizontal plane at CERN.

Table 5: Characteristics of candidate long-baseline sites (distances in km, angles in degrees).

	Distance	Angle
Gran Sasso	733	-3.3°
Santa Cruz de Tenerife	2753	-12.5°
Longyearbyen	3518	-16.0°
Pyhäsalmi	2288	-10.4°

9. Summary

Taking everything together, the physics potential of the neutrino factory looks very good. The specific features of the muon beams originating from muon decay make possible experiments which are not feasible with conventional neutrino beams from pion and kaon decay. The outstanding objective is the transition $\nu_{\mathrm{e}} \rightarrow \nu_\mu$ which brings into reach a precision measurement of θ_{13} and maybe CP violation in the neutrino mixing matrix.

Yet Nature must be kind to have chosen the right set of oscillation parameters to make CP violation experimentally accessible. Ongoing as well as new experiments will tell within the next three years what the situation is, possibly making the case for the neutrino factory irresistibly strong.

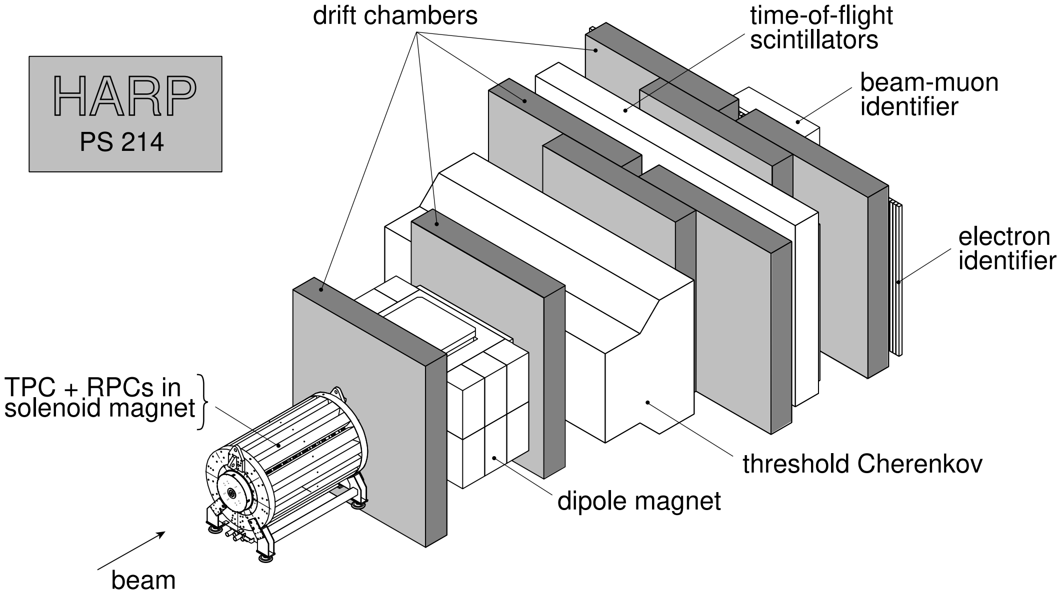

Figure 7: Layout of the HARP experiment

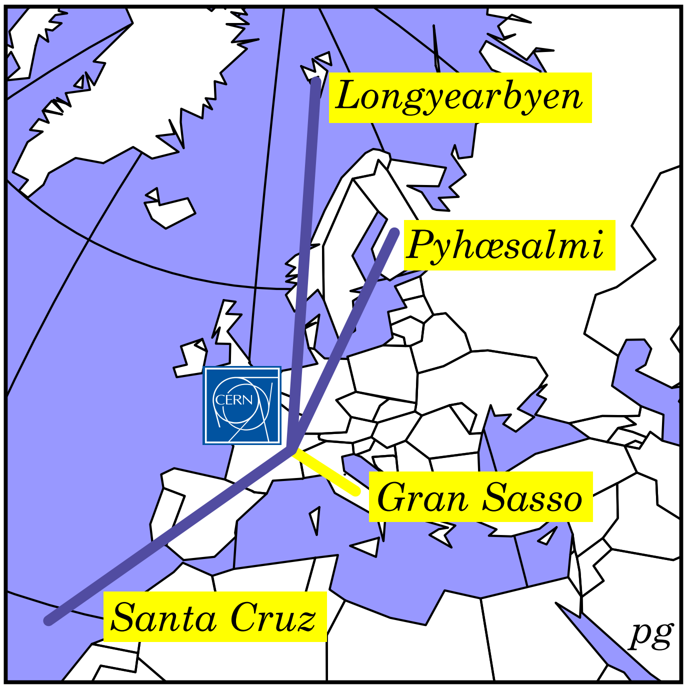

Figure 8: Candidate long-baseline sites for a CERN neutrino factory.

Technically, the neutrino factory could be in operation within ten years. However, in the real world of scarce resources, political and financial considerations are more likely to determine the time schedule than technical factors.

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