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# Expression of Interest for R&D towards A Neutrino Factory Based on a Storage Ring and a Muon Collider

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**The Neutrino Factory and Muon Collider Collaboration**

Edited by K.T. McDonald for the Collaboration

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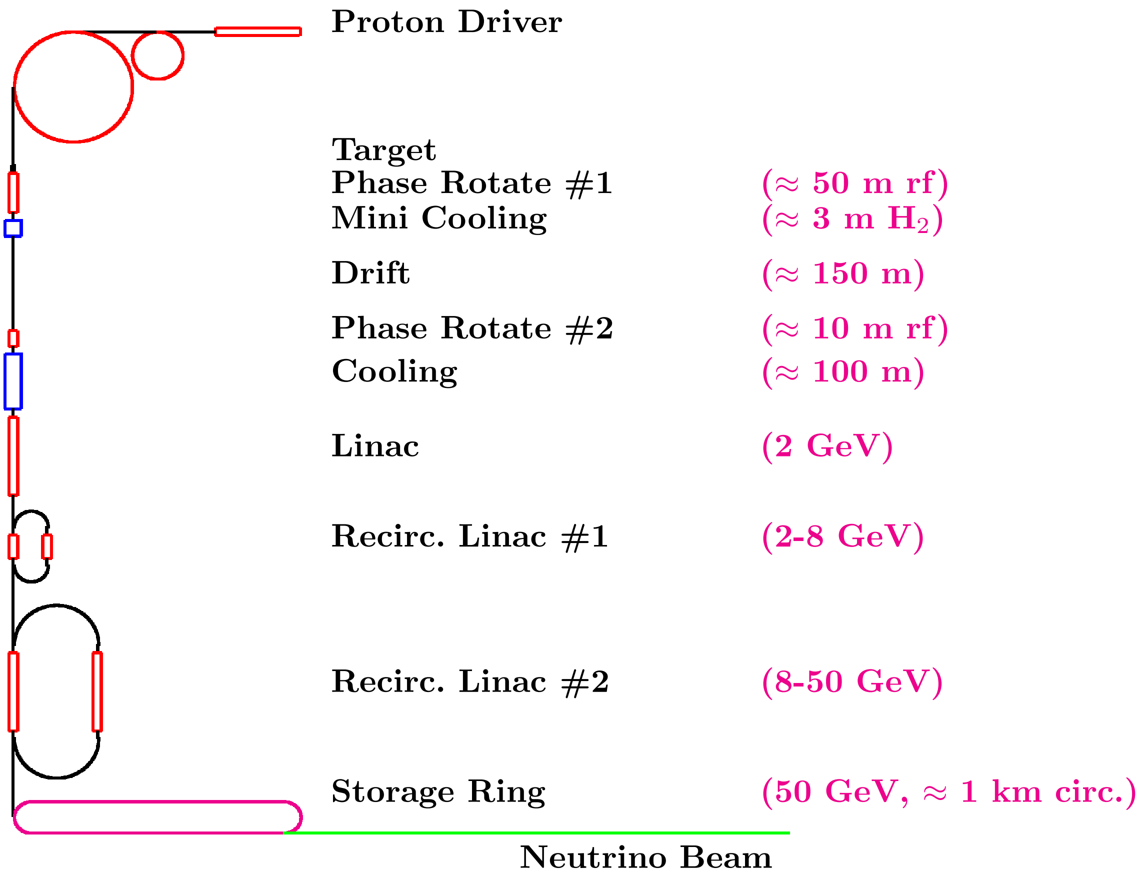

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# Executive Summary

Recent evidence from atmospheric, solar, and accelerator neutrinos suggests that neutrinos have mass, and mix among the flavors $\nu_e$, $\nu_\mu$ and $\nu_\tau$. Neutrino mass is evidence for physics beyond the Standard Model, and has cosmological implications.

Because neutrinos interact so weakly, unusual efforts are required to detect them. Although many of the recent, exciting results in neutrino physics have been obtained by non-accelerator techniques, the neutrino mass and mixing parameters appear to be such that a new generation of accelerator experiments with long baseline distance to the detectors can perform detailed measurements. For this, a new source of well-characterized neutrinos is needed.

We are exploring the feasibility of a neutrino factory based on a muon storage ring. In this, beams of $\nu_\mu$ and $\overline{\nu}_e$ arise from the decay of $\mu^-$ particles (or alternatively, $\overline{\nu}_\mu$ and $\nu_e$ from $\mu^+$). The muons come from the decay of low-energy pions produced by a megawatt proton beam incident on a nuclear target. The muons are captured into a magnetic channel, "cooled" by ionization in liquid hydrogen, accelerated to energy of order 50 GeV, and injected into a storage ring. A nonhorizontal ring can deliver neutrino beams to an on-site detector, as well as to two off-site detectors separated by global distances.

Such a neutrino factory is a challenging extension of present accelerator technology. It is also a natural path to a muon collider, in that both facilities share many common elements upstream of their storage rings. Prior to a formal design study, R&D must be performed in several keys areas, such detailed simulations and actual targetry and cooling experiments. This in an excellent opportunity to advance the field of accelerator physics both at national laboratories and at universities.

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# Contents

# List of Figures

# List of Tables

# 1 Introduction

There is accumulating evidence for massive neutrinos that mix among flavors. The strongest indication is the atmospheric neutrino anomaly first observed by the Kamiokande [1] and IMB [2] detectors, confirmed by the Soudan-2 [3] and MACRO [4] detectors, and recently measured with high statistics by the Super-Kamiokande detector [5]. In addition, the long-standing deficiency of the solar neutrino flux measured by the Homestake chlorine experiment [6] is now supported by data from the Kamiokande [7], Super-Kamiokande [8], GALLEX [9], and SAGE [10] detectors. These data suggest neutrino masses in the range $\lesssim 0.1$ eV for the mass eigenstates $\nu_i$, $i = 1, 2, 3$ whose linear combinations comprise the neutrinos $\nu_e$, $\nu_\mu$, and $\nu_\tau$. Such neutrinos would not be a significant part of the dark matter of the universe,

The LSND experiment at Los Alamos has reported evidence of $\nu_\mu - \nu_e$ oscillations [11], although so far this has not been confirmed by a similar experiment, KARMEN, at Rutherford [12]. If confirmed, this results appears to require the existence of one or more light, sterile neutrinos which could be an important component of hot, dark matter.

The issue of neutrino mass has spawned a new "industry" [13], resulting in about three new preprints per day [14], among other activities. Excitement is high in the accelerator physics community because the physics implied by the atmospheric-neutrino results is accessible to long-baseline accelerator experiments such as K2K [15], Minos [16] and NGS [17]. Of course, the LSND experiment was conducted at a short-baseline accelerator facility, and can be confirmed by future accelerator experiments such as MiniBooNE [18], ORLanD [19], and CERN P311 [20]. Moreover, even the physics associated with many of the interpretations of the solar-neutrino deficit is accessible to study in accelerator-based experiments if neutrino-beam fluxes can be improved by 1-2 orders of magnitude.

To obtain a factor of 100 improvement in neutrino flux in a cost-effect manner, a new approach is called for. The best prospect appears to be neutrino beams derived from a muon storage ring, rather than from pion and kaon decay, although the concept of muon-based neutrino beams needs considerable development before it can be realized in the laboratory.

Muon storage rings have been discussed since at least 1960 [21], and their possible application to neutrino physics was considered as early as 1980 [22]. However, storage rings with enough circulating muons to provide more high-energy neutrinos than from horn beams have been only recently been considered in the context of muon colliders [23]. Enthusiasm for muon-based neutrino beams has been fostered by a series of workshops and studies at Fermilab [24], BNL [25], and CERN [26], resulting in a convergence of international interest at the NuFact'99 Workshop [27, 28].

The neutrino fluxes from these proposed muon-based beams are higher than ever achieved before, with a better-understood flavor composition, and, since the neutrino beams from this source would be secondary beams rather than tertiary beams, they are more collimated than ever previously imaginable. Distances between production and detection can now span the globe, and using the known flavor composition of the beam, one can map out a plan to measure the neutrino oscillation mixing matrix including CP violating effects, much like that now underway to study the CKM quark mixing matrix.

We present a brief review of the physics of neutrino oscillations in sec. 2, also including detector issues most critical for neutrino oscillation measurements. As an example of how diverse a neutrino program at a storage ring could be, highlights of possible nucleon structure and other near-detector measurements are given in sec. 3. The machine itself is discussed in sec. 4, and its possible extension to a muon collider is considered in sec. 5. The active theme of this document, research and development towards the design of a neutrino factory, is discussed in sec. 6.

# 2 Neutrino Oscillations

## 2.1 Interpretations of the Data

The concept of neutrino oscillation was introduced in 1957 [29] and has been extensively discussed in the literature [30] and now on the internet [31]. In the example of only two massive neutrinos, with mass eigenstates $\nu_1$ and $\nu_2$ with mass difference $\Delta m$ and mixing angle $\theta$, the flavor eigenstates are

$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}. \tag{1}$$

The probability that a neutrino of flavor $\nu_a$ and energy $E$ appears as flavor $\nu_b$ after traversing distance $L$ in vacuum is

$$P(\nu_a \to \nu_b) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 [\mathrm{eV}^2]\ L[\mathrm{km}]}{E[\mathrm{GeV}]} \right). \tag{2}$$

As the atmospheric neutrino data involves GeV muon neutrinos with distance scales of the Earth's diameter, this suggests $\Delta m^2$ of order $10^{-3}$ $(\mathrm{eV})^2$ for $\sin^2 2\theta \approx 1$ [32]. The solar neutrino data involves MeV electron neutrinos and distance scales of the radius of the Earth's orbit, suggesting $\Delta m^2$ of order $10^{-10}$ $(\mathrm{eV})^2$ with $\sin^2 2\theta \approx 1$ for vacuum oscillations [33]. The LSND result involves 30-MeV muon antineutrino and a distance scale of 30 m, suggesting $\Delta m^2$ of order 1 $(\mathrm{eV})^2$; large mixing angles are excluded by reactor data [34], so $\sin^2 2\theta$ can only be of order $10^{-2}$ in this case.

Clearly, four different massive neutrinos are required to accommodate all three results, given their disparate scales of $\Delta m^2$. The Standard Model presently includes only three neutrinos with standard electroweak couplings and $m_\nu < m_Z/2$, so a "sterile" neutrino is required if all the data are correct [35]. Even discarding the LSND result, three massive neutrinos are required with a corresponding $3 \times 3$ mixing matrix (MNS matrix) [36], one of whose representations is, where $\mathrm{c}_{12} = \cos\theta_{12}$, *etc.*,

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \mathrm{c}_{12}\mathrm{c}_{13} & \mathrm{s}_{12}\mathrm{c}_{13} & \mathrm{s}_{13} e^{-i\delta} \\ -\mathrm{s}_{12}\mathrm{c}_{23} - \mathrm{c}_{12}\mathrm{s}_{13}\mathrm{s}_{23} e^{i\delta} & \mathrm{c}_{12}\mathrm{c}_{23} - \mathrm{s}_{12}\mathrm{s}_{13}\mathrm{s}_{23} e^{i\delta} & \mathrm{c}_{13}\mathrm{s}_{23} \\ \mathrm{s}_{12}\mathrm{s}_{23} - \mathrm{c}_{12}\mathrm{s}_{13}\mathrm{c}_{23} e^{i\delta} & -\mathrm{c}_{12}\mathrm{s}_{23} - \mathrm{s}_{12}\mathrm{s}_{13}\mathrm{c}_{23} e^{i\delta} & \mathrm{c}_{13}\mathrm{c}_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \tag{3}$$

In the model of three massive neutrinos, the neutrino oscillation probabilities of interest depend on six measurable parameters: three mixing angles ($\theta_{12}$, $\theta_{13}$, $\theta_{23}$), and a phase $\delta$ related to CP violation as indicated in eq. (3); and two differences of the squares of the neutrino masses ($\Delta m^2_{12}$ and $\Delta m^2_{23}$ for instance). The interpretation of the solar and atmospheric neutrino data in terms of the three-neutrino oscillation hypothesis suggests $|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$, with $\Delta m^2_{12}$ and $\Delta m^2_{23}$ being responsible for the transitions and/or oscillations of the solar and atmospheric neutrinos, respectively. Then, $|\Delta m^2_{13}| \approx |\Delta m^2_{23}|$.

The description of the atmospheric neutrino data requires $\Delta m^2_{23} \approx (2-6) \times 10^{-3}$ eV$^2$ and large mixing angle $\theta_{23}$: $\sin^2 2\theta_{23} \approx (0.9 - 1.0)$. For $|\Delta m^2_{12}| \ll |\Delta m^2_{23}|$ and with $\Delta m^2_{23}$ having a value in the above range, the nonobservation of oscillations of the reactor electron antineutrinos in the CHOOZ experiment [38] implies a limit on the angle $\theta_{13}$: $\sin^2\theta_{13} < 0.05$. Given these constraints, the transitions/oscillations of the solar neutrinos in the three-neutrino mixing scheme under discussion depend largely on just two parameters: $\Delta m^2_{12}$ and $\sin^2 2\theta_{12}$.

The presence of matter can strongly modify the oscillations of electron neutrinos due to their charged-current interaction (MSW effect [37]): in particular, the oscillations can be resonantly enhanced by the matter effects even when the oscillation probabilities are small in vacuum. This leads to additional interpretations of the solar neutrino data in which $\Delta m^2_{12}$ can be of order $10^{-5}$ (eV)$^2$ [39]. Indeed, there are four presently viable interpretations of the solar neutrino data:

- Vacuum oscillation (VO) solution with $\Delta m^2_{12} \approx (0.5 - 5.0) \times 10^{-10}$ eV$^2$ and $\sin^2 2\theta_{12} \approx (0.7 - 1.0)$,
- Low MSW solution corresponding to $\Delta m^2_{12} \approx (0.5 - 2.0) \times 10^{-7}$ eV$^2$ and $\sin^2 2\theta_{12} \approx (0.9 - 1.0)$,
- Small mixing angle (SMA) MSW solution with $\Delta m^2_{12} \approx (4.0 - 9.0) \times 10^{-6}$ eV$^2$ and $\sin^2 2\theta_{12} \approx (0.001 - 0.01)$,
- Large mixing angle (LMA) MSW solution, $\Delta m^2_{12} \approx (0.2 - 2.0) \times 10^{-4}$ eV$^2$ and $\sin^2\theta_{12} \approx (0.65 - 0.96)$.

For the VO, Low, and SMA MSW solutions, the expressions for the various transition/oscillation probabilities at distances which can be reached on earth simplify: they reduce essentially to the two-neutrino mixing expressions. Neglecting the possible matter effects for simplicity, we can write them in the form

$$P(\nu_e \to \nu_\mu) = \sin^2(2\theta_{13}) \sin^2(\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{23} L}{E_\nu}\right), \tag{4}$$

$$P(\nu_e \to \nu_\tau) = \sin^2(2\theta_{13}) \cos^2(\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{23} L}{E_\nu}\right), \tag{5}$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4(\theta_{13}) \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{23} L}{E_\nu}\right). \tag{6}$$

In the case of the large-mixing-angle (LMA) MSW solution there is a known small but non-negligible correction in the above expressions due to the $\Delta m^2_{12}$.

Another type of interpretation is often made of these data, in which the mass $m$ of a light neutrino is related to an intermediate mass scale $m_I$ and an heavy mass scale $m_H$ according to the “seesaw” mechanism [40] which predicts

$$m = \frac{m_I^2}{m_H}. \tag{7}$$

There remains considerable flexibility in the choice of these mass scales, but a particularly suggestive version [41] invokes the vacuum expectation value, 250 GeV, of the Higgs field as the intermediate mass, so that estimating $m \approx \sqrt{\Delta m^2(\text{atmospheric})} \approx 0.06$ eV yields $m_H \approx 5 \times 10^{15}$ GeV. This scale is commonly associated with the supersymmetric unification scale in SO(10) models. Hence, there is optimism that neutrino mass is evidence that supersymmetry exists at the GUT scale. Only a small additional dose of optimism is required to expect that the supersymmetric partners of known particles have masses near the intermediate scale, $m_I \approx 250$ GeV, and will be found during the next decade.

## 2.2 The Next Generation of Neutrino Experiments

With four interpretations of the solar neutrino data, and the two interpretations of the LSND data as either right or wrong, there are a total of eight scenarios for explanations of the data. The experimental challenge is to reduce these to a unique scenario, and to make accurate measurements of the parameters of that scenario.

It is likely that the next generation of short-baseline accelerator neutrino experiments mentioned previously [18, 19, 20] will clarify the status of the LSND result within 5 years.

Continued operation of Super-Kamiokande, plus the new long-baseline mentioned previously [15, 16, 17] will firm up the physics closely associated with the atmospheric neutrino anomaly over the next decade, but will have limited ability to explore more than a two-neutrino interpretation.

The solar neutrino spectrum is complex, and all interpretations of the solar neutrino deficit invoke fortuitous energy dependence in the models. This should permit new critical tests of these models as new detectors come into operation with different energy sensitivities.

Super-Kamiokande and the SNO experiment [42] (which has just started operation) have good sensitivity to higher-energy solar neutrinos, whose flux is predicted to rise with energy in the “just-so” models. However, precise interpretation may be elusive here even with improved statistics, due to uncertainties in the production rate of *hep* neutrinos in the Sun.

These high-statistics experiments will also provide more-significant tests of the dependence of oscillation rates on varying path length (seasonal variation) implied in the “just-so” models, and on traversal of varying amounts of matter (day/night effect) which affect some of the MSW solutions.

At the other end of the energy spectrum, the BOREXino liquid scintillator experiment [43] should be sensitive to the 0.8-MeV $^7$B neutrinos.

Even more ambitious projects, HELLAZ [45] and HERON [44], plan to use cryogenic techniques to lower their sensitivities to below the 0.4-MeV maximum of the *pp* neutrinos whose numbers dominate the solar neutrino spectrum.

A qualitatively different phenomenon accessible to the SNO experiment is the comparison of the rates of the reactions $\nu + ^2\text{H} \to p + p + e$ and $\nu + ^2\text{H} \to p + n + \nu$. The first reaction can only proceed via an electron neutrino, while any neutrino flavor can initiate the second. Hence, if solar electron neutrinos have indeed transformed to other flavors, the ratio of reaction rates will be less than one. Such a result will be unambiguous evidence for neutrino oscillations by itself.

This extensive program of solar neutrino experiments will certainly greatly constrain the four present interpretations of the solar neutrino data over the next decade, although one cannot predict with certainty that only a single interpretation will then remain.

None of the experiments discussed thus far addresses the long-standing question of whether neutrinos, if massive, are Dirac neutrinos (with particles and antiparticles being different: $\nu \neq \overline{\nu}$) or Majorana neutrinos (with particles and antiparticles the same, as for photons: $\nu = \overline{\nu}$) [46]. Theoretically, Majorana neutrinos are more "natural", but the question should be settled experimentally. This is extremely difficult because neutrinos are always (thus far) produced in weak interactions with a unique helicity, which provides a practical distinction between neutrino and antineutrino even if there is none in principle. Instead, experimental resolution of the question is based on the search for neutrinoless double beta decay, (A,Z $\to$ (A,Z + 2) + $2e^-$, which can proceed via annihilation of virtual $\nu_e$ and $\overline{\nu}_e$ as permitted for Majorana, but not for Dirac, neutrinos. The present (model dependent) limit based on nonobservation of such a decay of $^{76}$Ge is that $m < 0.1$ eV for Majorana neutrinos. This limit may be pushed as low as 0.001 eV in the next decade.

## 2.3 The Opportunity for a Neutrino Factory

Now that there are rough experimental guidelines as to the parameters of neutrino masses and mixings, one can begin to plan for more extensive studies than those described in the previous section. Two prominent features of such a plan are the need for more neutrinos, and that accelerator experiments with GeV-energy neutrinos can probe a large fraction of the relevant parameter space.

The need for more GeV-energy neutrinos leads to a need for GeV proton sources in the megawatt power range. Such power sources, when available, could be used to produce neutrinos via horn beams in the conventional manner. However, an option has emerged with greater physics flexibility while maintaining a comparable or even larger $\nu/p$ ratio than that from horn beams. Namely, neutrino beams derived from the decay of muons in a storage ring. Technical aspects of muon-based neutrino beams are discussed in sec. 4. Here, we review the physics opportunities with such beams.

Both $\mu^-$ and $\mu^+$ can be stored in the ring, but only one sign will be used at a time. When, say, $\mu^-$ are stored their decay,

$$\mu^- \to \; e^- \, \nu_\mu \, \overline{\nu}_e, \tag{8}$$

leads to beams that contain nearly equal numbers of $\nu_\mu$ and $\overline{\nu}_e$ with spectra that are extremely well known.

At the detectors, the neutrino and the antineutrino may or may not have changed their flavor, leading to the appearance of a different flavor or the disappearance of the initial flavor, respectively. When detected by a charged-current interaction, there are 6 classes of signatures in a three-neutrino model:

$$\nu_\mu \to \; \nu_e \to e^- \qquad \text{(appearance)}, \tag{9}$$

$$\nu_\mu \to \ \nu_\mu \to \mu^- \qquad \text{(disappearance)}, \tag{10}$$
$$\nu_\mu \to \ \nu_\tau \to \tau^- \qquad \text{(appearance)}, \tag{11}$$
$$\overline{\nu}_e \to \ \overline{\nu}_e \to e^+ \qquad \text{(disappearance)}, \tag{12}$$
$$\overline{\nu}_e \to \ \overline{\nu}_\mu \to \mu^+ \qquad \text{(appearance)}, \tag{13}$$
$$\overline{\nu}_e \to \ \overline{\nu}_\tau \to \tau^+ \qquad \text{(appearance)}. \tag{14}$$

A similar list of processes can be written for operation with positive muons.

Of special interest is process (13) where a muon of sign different from the parent muon appears. This is a unique feature of the neutrino factories based on muon beams since they are the only sources of intense high energy electron (anti)neutrino beams.

The cases (11) and (14) of $\tau$ appearance are only practical for neutrino beams with 10's of GeV energy.

### 2.3.1 Measurements of Masses and Mixing Angles

First, the high flux of neutrinos coming from the decay ring is ideal to measure precisely the various neutrino cross sections and to explore scenarios with more than three massive neutrinos, using a compact detector located at a short distance.

By the time a muon storage ring would be built it is expected that two angles $\theta_{23}$ and $\theta_{12}$, and the magnitudes of two mass squared differences $\Delta m^2_{23}$ and $\Delta m^2_{12}$ would be known. This knowledge would come from the solar and atmospheric neutrino measurements which would have been verified by long baseline and reactor experiments, for example, MINOS and KamLAND. The remaining pieces of the puzzle would be $\theta_{13}$, the CP-violating phase $\delta$ and the signs of the $\Delta m^2_{ij}$. In addition, the indicated long-baseline experiments will not be sensitive to the matter effects in neutrino oscillations because the distances between the sources and detectors are not sufficiently large. It would be of fundamental importance to verify experimentally the existence of matter effects in neutrino oscillations by observing directly the modification of the neutrino oscillation probabilities by these effects.

The third mixing angle $\theta_{13}$ can be measured in several channels at a neutrino factory [47], as can be seen from the expressions (4)-(6) for various transition probabilities. The detector must be far to avoid background but not too far ($< 1000$ km) so that the effects of $\Delta m^2_{12}$ remain negligible and thus $\delta$ can formally be set to zero. Figure 1 shows the achievable sensitivity to the yet-unknown value of $\theta_{13}$.

### 2.3.2 Measurement of CP Violation

The measurement of $\delta$ in a three-neutrino scenario [48] relies either on CP violation through the expression

$$A_{\mathrm{CP}} = \frac{P(\nu_e \to \ \nu_\mu) - P(\overline{\nu}_e \to \ \overline{\nu}_\mu)}{P(\nu_e \to \ \nu_\mu) + P(\overline{\nu}_e \to \ \overline{\nu}_\mu)}, \tag{15}$$

or on time-reversal violation using

$$A_{\mathrm{T}} = \frac{P(\nu_e \to \ \nu_\mu) - P(\nu_\mu \to \ \nu_e)}{P(\nu_e \to \ \nu_\mu) + P(\nu_\mu \to \ \nu_e)}. \tag{16}$$

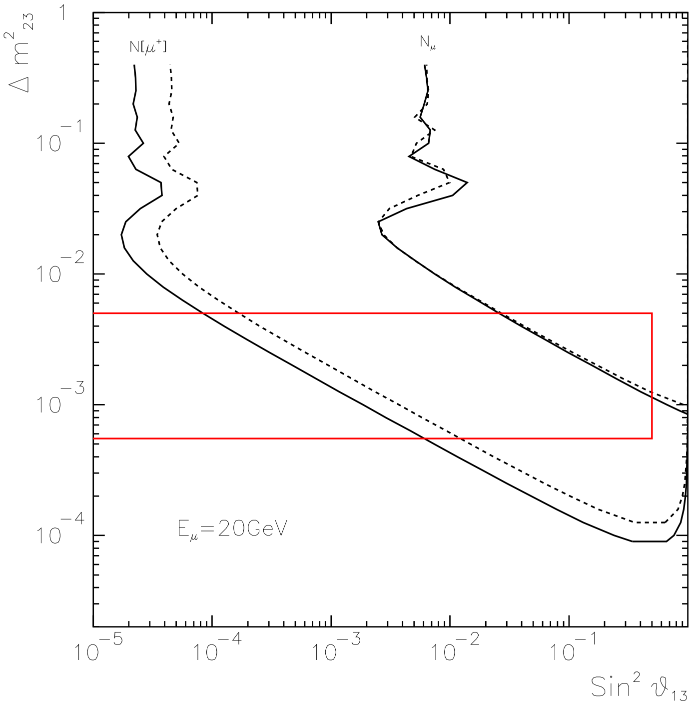


Figure 1: Sensitivity reach in the $(\sin^2\theta_{13}, \Delta m^2_{23})$ plane for a 10 kton detector and a neutrino beam from $2 \times 10^{20}$ decays of 20 GeV muons in a storage ring at distance 732 km. The appearance process $\overline{\nu}_e \to \overline{\nu}_\mu \to \mu^+$, shown by the lines on the left, has much greater sensitivity than the disappearance process $\nu_\mu \to \nu_\mu \to \mu^-$, shown by the lines on the right. The interior of the box is the approximate region allowed by Super-Kamiokande data (hep-ph/9811390).

The asymmetry (15) can be measured using wrong-sign muons and the two polarities of the muon beam. However, the genuine CP violating contribution to (15) due to a nonvanishing phase $\delta$ competes with terms related to matter effects, *i.e.*, to the different rates of scattering of $\nu_e$ and $\overline{\nu}_e$ between source and detector. The relative strength of the matter-induced asymmetry increases quadratically with distance, and dilutes the signal of CP violation in a far detector.

If the solution of the solar neutrinos problem is that involving large mixing angles and matter enhancement (LMA MSW, $\sin^2 2\theta_{12} \approx \sin^2 2\theta_{23} \approx 1$), then there is a possibility of measuring the CP violating asymmetry (15), whose value is then

$$A_{\mathrm{CP}} \approx \left| \frac{2\sin\delta}{\sin 2\theta_{13}} \sin\left(\frac{1.27\Delta m^2_{12} L}{E}\right) \right|, \tag{17}$$

provided the detector is located sufficiently far and high statistics ($> 10^{21}$ muons per year) are available. For all the other solar neutrino solutions $A_{\mathrm{CP}}$ is extremely small, being suppressed by a factor of either $\sin^2 2\theta_{12}$ or $\Delta m^2_{12}$. Figure 2 illustrates the experimental sensitivity to in a large angle MSW scenario.

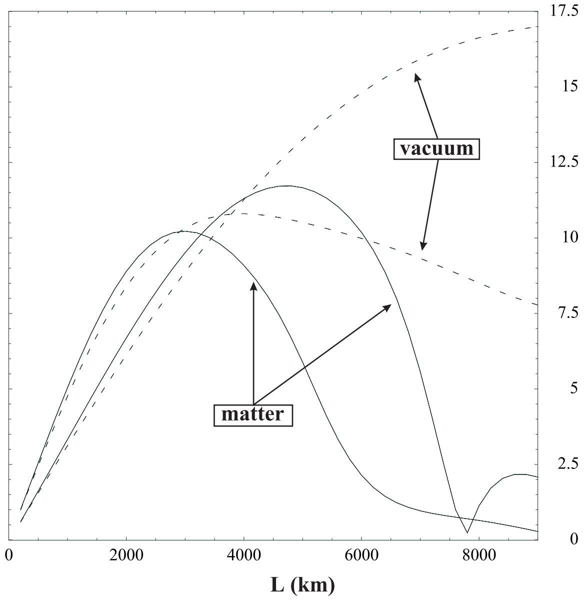


Figure 2: The CP violating asymmetry (15) divided by statistical uncertainties *vs.* distance $L$ for a 10 kton detector in a beam from $2 \times 10^{21}$ muon decays. A large angle MSW scenario is supposed, with $\Delta m^2_{12} = 10^{-4}$ eV$^2$, $\Delta m^2_{23} = 2.8 \times 10^{-3}$ eV$^2$, $\theta_{12} = 22.5°$, $\theta_{13} = 13°$, $\theta_{23} = 45°$, and $\delta = -90°$ (corresponding to maximal CP violation). The dashed curves ignore matter effects, while the solid curves include them; the matter effects dominate the asymmetry for distances beyond 1000 km. The lower (upper) curves are for $E_\mu = 20$ (50) GeV. From hep-ph/9909254.

The asymmetry (16) is not sensitive to matter effects, but relies on distinguishing the process $\nu_\mu \to \nu_e \to e^-$ from $\overline{\nu}_e \to \overline{\nu}_e \to e^+$. It will be very difficult to distinguish electrons from positrons in the detector, but the relative $\nu_\mu$ and $\overline{\nu}_e$ fluxes can be varied by varying the polarization of the muons in the storage ring [49].

If future experiments confirm the interpretation of the LSND data that more than three massive neutrinos exist, then the use of the flavor-rich beams of a neutrino factory is even more of an imperative because the parameter space for CP/T violating effects is considerably enlarged and can be successfully explored in experiments with such beams [50].

### 2.3.3 Detector Issues

In view of the various experimental signatures (9)-(14), an ideal detector would provide identification of both flavor and charge of all three leptons $e$, $\mu$, and $\tau$. Muons are the easiest to identify, $\tau$'s are the next easiest if only because of their decay to muons, and finally electrons are the most difficult. Fortunately, there is a very rich program for detectors that only measure the charge of muons, and hence the oscillation processes (10) and (13) and their conjugates.

### Baseline Detector Capability

A magnetized steel/scintillator sampling calorimeter would be one of the far detectors at a muon storage ring experiment. It could have a hadron energy resolution of $0.76/\sqrt{E_{\rm had}[{\rm GeV}]}$, a hadron angular resolution of $17/\sqrt{E_{\rm had}[{\rm GeV}]}+12/E_{\rm had}[{\rm GeV}]$, and much better muon energy and angular resolution.

The largest forseeable background in such a detector is charm production. The appearance signal for process (13) is a "wrong-sign" muon. However, if there is enough energy for charm production in process (10), the charmed particle produced will decay 10% of the time to a wrong-sign muon in the final state. There is a chance that the associated muon from the neutrino interaction vertex is low energy and/or undetected. With kinematic cuts on the muon momentum and its component transverse to the hadronic shower, the signal efficiency would be reduced by 25 to 30%, but the backgrounds would be reduced by a factor of $10^{-5}$ to $10^{-6}$ depending on the neutrino energy. The rejection rate improves faster with energy than does the background, favoring the use of higher energy muons in the storage ring.

Thus, such a baseline detector would be sufficient for measurements of $\theta_{13}$ via process (13), and the CP-violating phase $\delta$ via the asymmetry (15), both of which are unlikely to be measured elsewhere and would contribute enormously to the field.

Measurement of the T-violating asymmetry (16) requires separation of process (9) from (12), ideally performed by measuring the sign of the electron, and both of these from neutral-current scattering off electrons. Depending on the transverse and longitudinal segmentation of the scintillator, electron identification is possible, although not on an event-by-event basis. Electron-neutrino charged-current interactions would be distinguished on average by an energy deposition that was much closer to the neutrino interaction vertex, and at an angle with respect to the outgoing hadronic shower. Charge identification would not be possible, although from varying the polarization of the muon beam one could see how many electron-like events were from $\overline{\nu}_e$'s, and how many were from $\nu_\mu$'s [49].

Since a muon-based neutrino factory is a pulsed device with a small duty factor, cosmic-ray backgrounds will be relatively unimportant. Hence, there is the option to locate the detectors at the surface of the Earth, where available infrastructure is more favorable for very large devices.

Finally, such a baseline detector would have modest detection efficiency for $\tau$'s via their decay to $\mu$'s, permitting study of process (11) and (14) if sufficiently large numbers of neutrinos are available.

### Beyond the Baseline Detector

Additional technologies must be employed to achieve electron and $\tau$ identification and charge measurement on an event-by-event basis.

One category of new detectors uses thin ($\sim 100\,\mu$m) sheets of emulsion combined with thin ($\sim 300\,\mu$m) lead or steel spacers to measure kinks that occur when a $\tau$ decays. MINOS is studying the performance of this geometry combined with steel for $\tau$ appearance measurements and is likely to install such a device if they do see oscillations. By comparing the change in slope between a few hundred of these sheets, one could make a 4-$\sigma$ event-by-event measurement on electron or $\tau$ charge. This technique is practical only in relatively small volumes, and is perhaps best suited for the near detector, or for the extraordinarily well collimated neutrino beams from a TeV muon collider.

Detectors which have slightly more promise for use on the 10-kton scale identify $\tau \to \mu$ decays by their difference in kinematics, although they don't see the kink from the decay itself. ICARUS, which uses a Liquid Argon TPC detector, has the necessary charged track resolution to measure the acoplanarity of an event and determine the likelihood of its being a $\tau$ candidate.

# 3 Precision High-Rate Neutrino Physics

The advent of a muon storage ring would not only bring about new neutrino oscillation measurements, but would also usher in a new era for high-precision neutrino scattering experiments [51]. For example, with a detector located 30 m from a 150 m straight section of a 50-GeV, $10^{21}$-$\mu$/yr muon storage ring, the event rate is 40 million events per kilogram per year over a 10 cm radius.

To assist in the interpretation of oscillation-related measurements, precision measurements would be made of the total neutrino and antineutrino cross sections, as well as of the beam divergence.

The neutrinos would also be used as precision probes of nuclear and nucleon structure, providing additional information to that obtained in related study using charged lepton beams. As is well known, neutrino scattering allows a clean separation of the valence and sea quark distributions, and use of a polarized target permits characterization of the spin dependence of these distributions. The near detector is thus the natural successor to nucleon structure measurements now underway at HERA, HERMES, Jefferson Lab, RHIC and elsewhere.

Combined analysis of the scattering of the four neutrino types $\nu_\mu$, $\overline{\nu}_\mu$, $\nu_e$, and $\overline{\nu}_e$ off electrons should permit measurement of the Weinberg angle ten times better than presently known.

A high-flux multi-GeV neutrino beam is also a charm factory, in which a $\nu_\mu$ beam leads only to $c$ quarks that are tagged by a final-state $\mu^-$ ($\nu_\mu d \to \mu^- c$), while $\overline{\nu}_\mu$ beam leads only to tagged $\overline{c}$ quarks. For the beam parameters described above, there would be $10^7$ leptonic tagged charm decays in only 40 kg-years (not kton-years!), permitting measurements of $V_{cd}$ to fraction of a percent, and perhaps even direct observation of $D^0 - \overline{D}^0$ mixing.

# 4 A Neutrino Factory

Relatively complete sketches of a neutrino factory based on a muon storage ring have emerged only recently via a convergence of earlier visions during the NuFact'99 workshop [27, 28]. Here, we present recent scenarios that consider BNL and FNAL sites as examples [52], but note that the conceptual details of a neutrino factory are evolving rapidly.

## 4.1 Introduction

Conventional neutrino beams employ a proton beam on a target to generate pions, which are focused and allowed to decay into neutrinos and, incidentally, muons [53]. The muons are discarded (stopped in shielding) and the neutrinos ($\nu_\mu$) are directed to the detector. In a neutrino factory, pions are made the same way and allowed to decay, but it is the decay muons that are captured and used. The initial neutrinos from pion decay are discarded, or used in a parasitic low-energy neutrino experiment. The muons are accelerated and allowed to decay in a storage ring with long straight sections. It is the neutrinos from the decaying muons (both $\nu_\mu$ and $\overline{\nu}_e$) that are directed to the detectors.

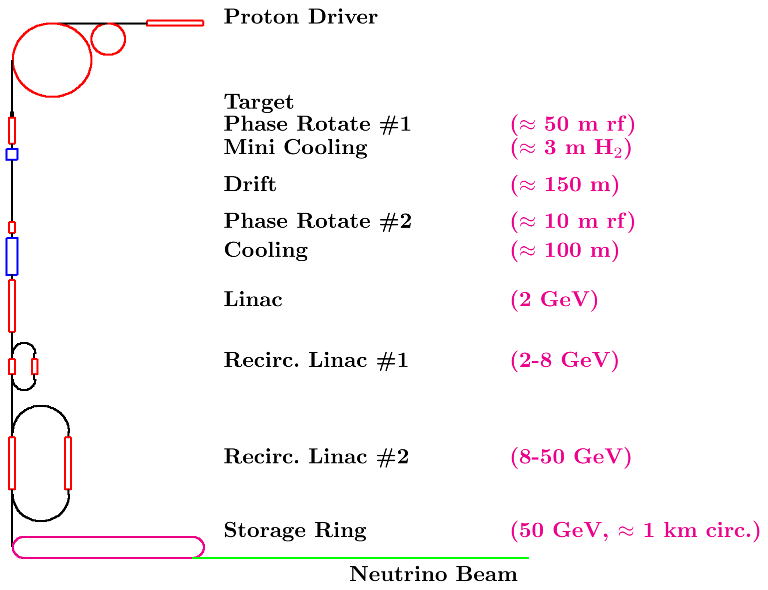


Figure 3: Overview of a neutrino factory based on a muon storage ring.

The main components of the scenario described here are shown in Fig. 3, and are:

- A proton driver of moderate energy ($<$ 50 GeV) and high average power (1-4 MW) similar to that needed for a muon collider, but with less stringent requirements on the charge per bunch and somewhat less need for power.
- A target and pion capture system that can be identical to that for a muon collider.
- Reduction of the muon energy spread at the expense of spreading them out over a longer time interval (longitudinal phase rotation). The system can be designed to correlate the muon polarization with time, allowing control of the relative intensity of $\nu_\mu$ and $\overline{\nu}_e$ in a forward beam. All this could probably be identical to that for a muon collider.
- A limited amount of cooling: about a factor of 50 in six phase-space dimensions, compared with the factor of $10^6$ needed for a muon collider.
- Fast muon acceleration to 50 GeV in a system of an induction linac and two recirculating linear accelerators (RLA's). This could probably be identical to that for a muon collider designed for Higgs production (Higgs Factory).

- A collider ring with long straight sections that could point to one or more distant neutrino detectors for oscillation studies, and to one or more near detectors for high intensity studies. This ring is rather different from one that maximizes luminosity of muon-muon collisions.

Advantages of a neutrino factory are:

- The spectrum of the neutrinos from muon decay are very well defined, particularly compared to conventional neutrino beams from pion decay where proton beam size and position, horn current and timing, and the condition of the target and horn can all affect the fluxes and backgrounds.
- There are almost equal electron and muon neutrino types made, and both neutrinos and antineutrinos can be obtained. In beams from pion decay, only 6muon neutrinos are available with small backgrounds of the other types.
- The numbers of neutrinos per initial proton are comparable in the two schemes, and for low energy neutrinos there is no flux advantage in the factory. But for high energy neutrinos, the conventional approach requires high energy protons, of which, for a given power, there will be fewer. The neutrino factory can, in principle, use the same relatively low energy protons to produce the same number of neutrinos at any energy independent of the neutrino energies, and the number can remain high. For 50 GeV neutrinos, the gain is between one and two orders of magnitude over conventional beams.
- The intensities are sufficiently high that one can use oscillation baselines of the order of the Earth's diameter. One could build a neutrino factory in the US and detect neutrino oscillations in the Gran Sasso detector in Italy, or build the factory in Europe and direct a beam to the US. Such intensities and distances also allow the study of the neutrino-matter interaction (MSW effect). Measurements at multiple distances would, in principle, allow the complete determination of the neutrino mass matrix (the equivalent of the CKM matrix), including CP violations, while also addressing the possible existence of sterile neutrinos.
- A neutrino factory is also a first step towards a muon collider. It would be simpler build than a muon collider, would demonstrate most of the components of a collider, and might be upgradable to a collider.

In the remainder of this section, we discuss the various components of a neutrino factory in greater detail.

## 4.2 Proton Driver

The number of pions per proton produced with an optimized system varies linearly with the proton energy [54]. Thus, the number of pions, and the number of muons into which they decay, is proportional to the proton beam power. This might suggest that the proton energy could be selected arbitrarily, but the situation is more complicated.

The total six-dimensional emittance of the produced muons depends on, among other things, the pion bunch length, and thus on the rms proton bunch length $\sigma_p$ if that length is longer than a length $c\ \tau_{\text{decay}}$ that is characteristic to the decay process:

$$\tau_{\text{decay}} = \frac{(m_\pi - m_\mu)}{m_\pi}\ \frac{1}{\gamma_\pi^2}\ \tau_\pi, \tag{18}$$

where $\tau_\pi$ is the pion lifetime and $\gamma_\pi m_\pi$ is the pion energy. The pion yield peaks at $E_\pi \approx 300$ MeV, which gives $\tau_{\text{decay}} \approx 1$ nsec. This, if the proton energy is low, can imply a large tune shift in the proton ring prior to extraction:

$$\Delta\nu\ \propto\ \frac{n_p\ C}{\sigma_t\ \epsilon_\perp\ \gamma_p^2}\ \propto\ \frac{n_p}{\langle B\rangle\ \ \sigma_t\ \epsilon_\perp\ \gamma_p}, \tag{19}$$

where $n_p$ is the number of protons in a bunch, $C$ is the circumference of the proton driver, $\langle B\rangle$ is the average bending field, and $\epsilon_\perp$ is the transverse emittance of the protons. The above dependency favors a higher proton energy.

It also favors a high repetition rate with relatively fewer protons per bunch, but once again the situation is complicated. The total six-dimensional emittance of the produced pions depends also on the number of proton bunches employed to fill the storage ring. This favors a small number of large proton bunches in the driver, and thus a larger tune shift.

However, a high driver repetition rate with smaller numbers of protons per fill would not increase the emittance per fill and would still reduce the tune shift. The difficulty with this approach is that the higher repetition rate increases the wall power required for the pulsed rf needed for acceleration and cooling.

These considerations favor a proton driver of 15-25 GeV energy, 1-4 MW power, with a ring cycling at 5-15 Hz, and a bunch length of order 1 nsec. Each cycle accelerates about $10^{14}$ protons in 4-6 bunches space about 150 m apart. Such a proton driver has significantly higher power than any in present use in the high energy community, and is comparable to those under design for neutron spallation sources.

## 4.3 Target and Capture

To maximize the muon yield from pion decay, pions are captured from the peak of their production spectrum at around 300 MeV/$c$ longitudinal momentum. The corresponding transverse momenta extend to beyond 200 MeV/$c$, so a rather diffuse cloud of pions must be captured. This is best done with a solenoidal magnetic field, whose acceptance of particles at large angles is much superior to that of a sequence of quadrupoles. Indeed, solenoid magnets must be used to contain the pion/muon beam over much of its length. The target is surrounded by a 20-T hybrid solenoid magnet [55], followed by an adiabatic transition to the 1-T field of the decay and phase rotation channel.

The large pulse of energy deposited by the 1-4 MW proton beam in the target on nsec time scales lead to transient pressure waves that are problematic for the long-term survival of solid targets. Therefore, a target based on a free mercury jet is under serious study [54], with a moving belt target as a backup concept [56]. At lower beam powers, a radiatively cooled carbon target may be viable. However, the yield of pions per proton is higher for a high-$Z$ target material.

The target and proton beam are at an angle to the axis of the capture system to minimize re-absorption of the spiralling pions in the target, and to permit dumping of the proton beam to the side of the system, perhaps in a pool of mercury. Figure 4 sketches the main features of the target and capture apparatus, along with the beginning of the phase rotation channel.

The capture system is very similar to that considered for a muon collider source [23].

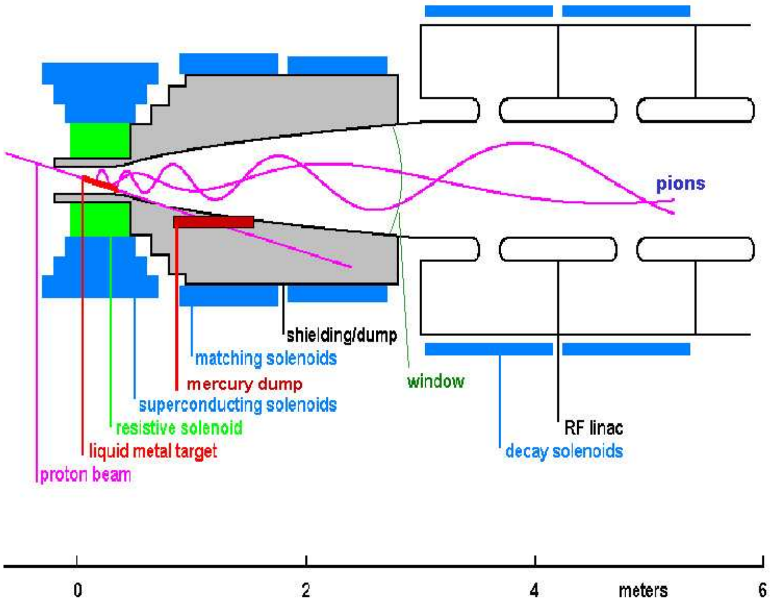


Figure 4: Targetry, pion capture, and beginning of phase rotation.

## 4.4 Phase Rotation #1

An early, high-gradient phase rotation is required if muon polarization is to be selected without particle loss. Forward decays, having one polarization, yield higher energy muons than backward decays, which have the other. If full phase rotation occurred before decay, then polarization and final energy are fully correlated, but significant correlation is obtained even with partial rotation before decay. The essential requirement is that significant energy changes occur before the decay. Phase rotation after decay cannot distinguish energy changes due to decay kinematics from the energy spread of the initial pions, so there is no way to separate the different polarizations.

The first phase rotation is accomplished by a sequence of low-frequency rf cavities that reside inside a solenoid magnet which contains the beam transversely. The first cells of this are sketched in Fig. 4. At the end of this first phase rotation stage, the bunch length has increased by a factor of 6 and the energy spread has decreased by the same amount. Figure 5 shows a simulation of the bunch at the end of the first phase rotation.

Alternative scenarios without this first stage of phase rotation are under study [58], always with the result that the polarization separation will be lost.

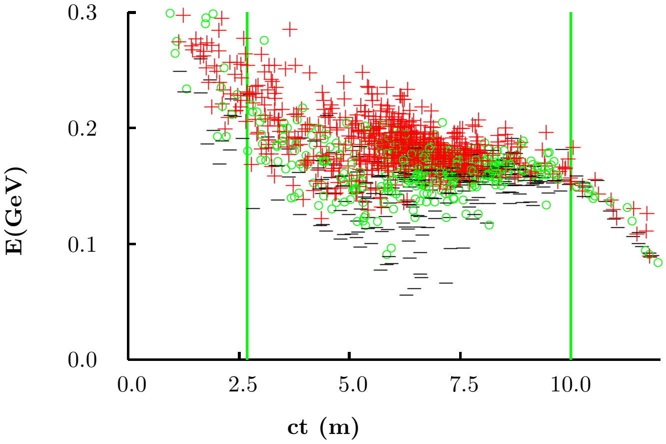


Figure 5: The longitudinal-phase-space distribution of the muon bunch at the end of the first phase rotation. Color and symbols indicate polarization $P$: + (red): $P > 0.3$, o (green): $0.3 > P > -0.3$, $-$ (black): $-0.3 < P$.

## 4.5 Mini Cooling

Reduction of the phase volume of the muon beam must be accomplished before the muons decay, which limits the applicability of stochastic cooling and electron cooling. Rather, we propose to use the technique of ionization cooling [59] in which the muons lose both transverse and longitudinal momentum while passing through bulk matter, and only longitudinal momentum is restored via rf acceleration. This technique is uniquely applicable to muons because of their minimal interaction with matter, and can be performed in less than a microsecond.

The first stage of cooling at a neutrino factory, called mini cooling, consists simply of a hydrogen absorber in a solenoidal field, and serves two purposes. It reduces the muon energies so that the subsequent drift length for a second phase rotation could be kept short. It also lowers the transverse emittance by almost a factor of two.

In a current simulation [52], the mini cooling was done in a single hydrogen absorber placed in a fixed magnetic field of 1.25 T, with simulated results as shown in Fig. 6. Such cooling introduces canonical angular momentum and it will probably be desirable to do the mini cooling in two stages with a field reversal between them.

## 4.6 Phase Rotation #2

The purpose of phase rotation is to minimize the muon momentum spread, which can be done at the expense of lengthening the bunch up to a distance approaching the initial proton bunch spacing (≈ 150 m in the example discussed here). The very long resulting bunch is then rebunched at a higher frequency (≈ 175 MHz), yielding a train of about 30 individual muon bunches for every initial proton one.

In addition, this phase rotation results in the polarization being correlated with time, *i.e.*, bunch number, instead of energy. This correlation can, in principle, be preserved thereafter.

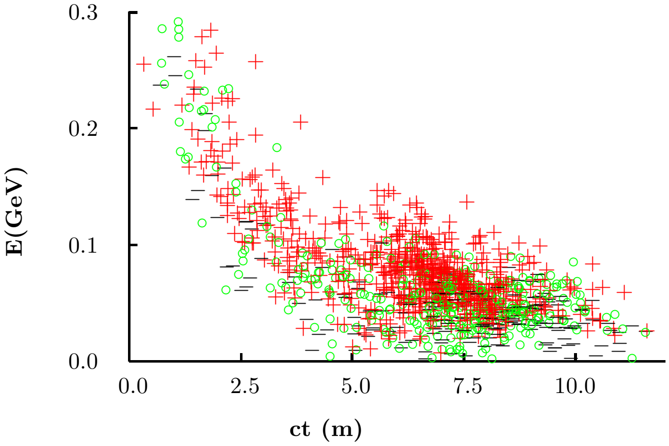


Figure 6: The longitudinal-phase-space distribution of the muon bunch after the mini cooling by liquid hydrogen. Color and symbols indicate polarization $P$: + (red): $P > 0.3$, o (green): $0.3 > P > -0.3$, − (black): $-0.3 < P$.

The second phase rotation is performed by a drift ($\approx$ 150 m), followed by energy correction, followed by bunching.

In the present example, an induction linac ($\approx$ 100 MeV acceleration) is used in which the pulse shape is tailored to correct the time-energy correlation generated by the drift. The induction linac must supply a rapid train of accelerations, spaced by the proton bunch spacing, and equal in number to the number of proton bunches.

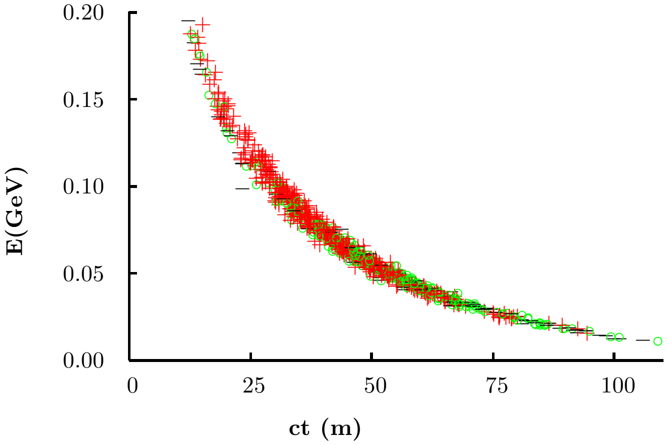
Figure 7 shows the simulated energy *vs.* time distributions after the drift, and and after the energy correction in the induction linac. The simulated final polarizations *vs.* bunch position are shown in Fig. 8. The maximum muon polarization is a rapid function of the initial proton bunch length, as shown in Fig. 9. In the simulation, the average muon polarization at the end of the induction linac is 0.37, and the momentum spread is $dp/p \approx 2$ %. If only 20% of the muons are kept, the polarization could be 0.6.

Bunching can be done either before or after the energy correction. The bunching frequency considered here is a multiple of 350 MHZ, the frequency of the superconducting cavities that are assumed to be used in the later acceleration.

More efficient bunching may be possible if the initial energy is lower and the bunching is done together with acceleration [58]. This suggests that a second mini cooling with about 1 m of hydrogen could be used to lower the muon energies to about 25 MeV, followed by the bunching and acceleration back to 100 MeV. The addition of the second mini cooling would further reduce the required conventional cooling to follow [60].

## 4.7 Cooling

A simple comparison of the total produced six-dimensional emittance and the total acceptance of a plausible storage ring indicates that cooling should not be needed. But without cooling, the muon accelerator would have to have a transverse rms acceptance of $\approx 20\ \pi$ mm-rad (full acceptance $\approx 0.2\ \pi$ m-rad). This we have shown is possible with large-aperture



After Acc to 100 MeV

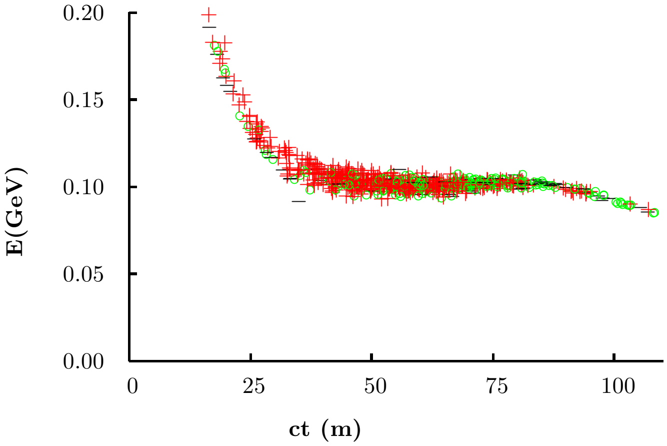


Figure 7: The longitudinal-phase-space distribution of the muon bunch after the second phase rotation (top), and after the induction linac (bottom). Color and symbols indicate polarization $P$: + (red): $P > 0.3$, o (green): $0.3 > P > -0.3$, $-$ (black): $-0.3 < P$.

solenoid focusing and low-frequency rf, but would be expensive.

A more reasonable acceleration scheme considers an rms transverse acceptance of $\approx 1.5\ \pi$ mm-radians. A cooling scenario based on the so-called super-FOFO [61] lattice of confining magnets (Fig. 10) is under study. The current simulation, using a fixed lattice and operating at a central momentum of 185 MeV/$c$ cools to below 3 $\pi$ mm-radians, as shown in Fig. 11. It does not achieve the required 1.5 $\pi$ mm-radians because of Coulomb scattering at the end. Other lattices, with stronger fields easily reach the required final emittance, but do not accept the full initial emittance. More work is needed here.

In a bunched beam, particles with large transverse amplitude must have higher total velocity (higher energy) so that their longitudinal velocity, $v_z$, remains matched to that of

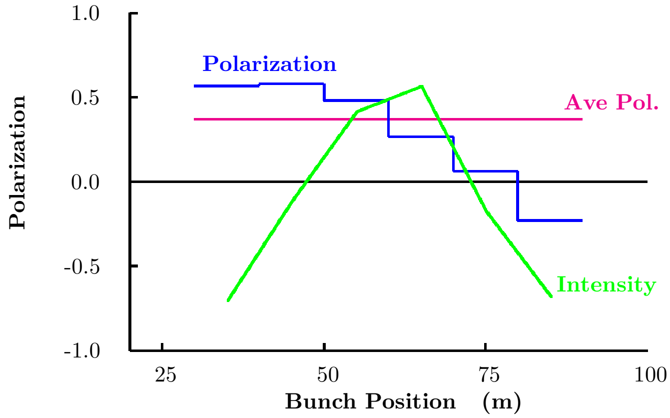


Figure 8: The muon polarization and intensity as a function of position in the bunch train after the induction linac.

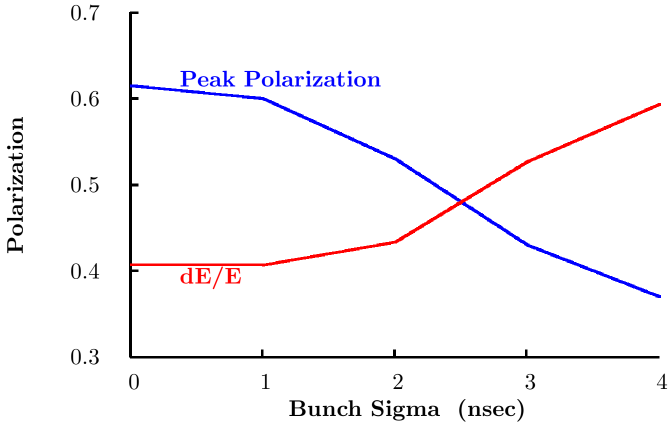


Figure 9: The muon polarization after the induction linac as a function of the proton driver bunch length.

the bunch. This is not practical for relativistic beams, but can be arranged for nonrelativistic beams such as considered here.

If the phase-rotation drift and buncher have a lattice with the same amplitude-$v_z$ properties as the cooling lattice, then the correlation is automatically generated. Remember: the drift sorts particles by $v_z$, not energy. After the drift, their longitudinal position is a function of that $v_z$ which is the required correlated combination of energy and amplitude. The bunching, done in the same lattice (or one with the same properties) is also a bunching by $v_z$, not energy, so the correlation is preserved. And so into the cooling.

Note that a simple solenoid will NOT do for the drift or bunching, since $v_z$ is a function not only of amplitude, but also of angular momentum. A solenoid of one sign gives a higher $v_z$ for one angular momentum sign than the other. Both drift and bunching must done with alternating fields of some kind that maintain the canonical angular momentum near zero. The super-FOFO lattice satisfies this requirement.

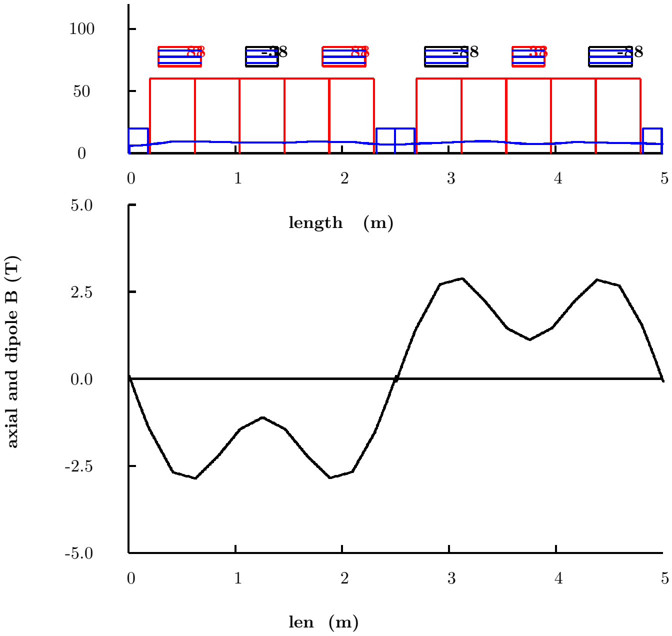


Figure 10: Top: half section through a super-FOFO cell of the cooling apparatus, showing the coil configurations, rf cells, and hydrogen absorbers. Bottom: the axial magnetic field *vs.* position.

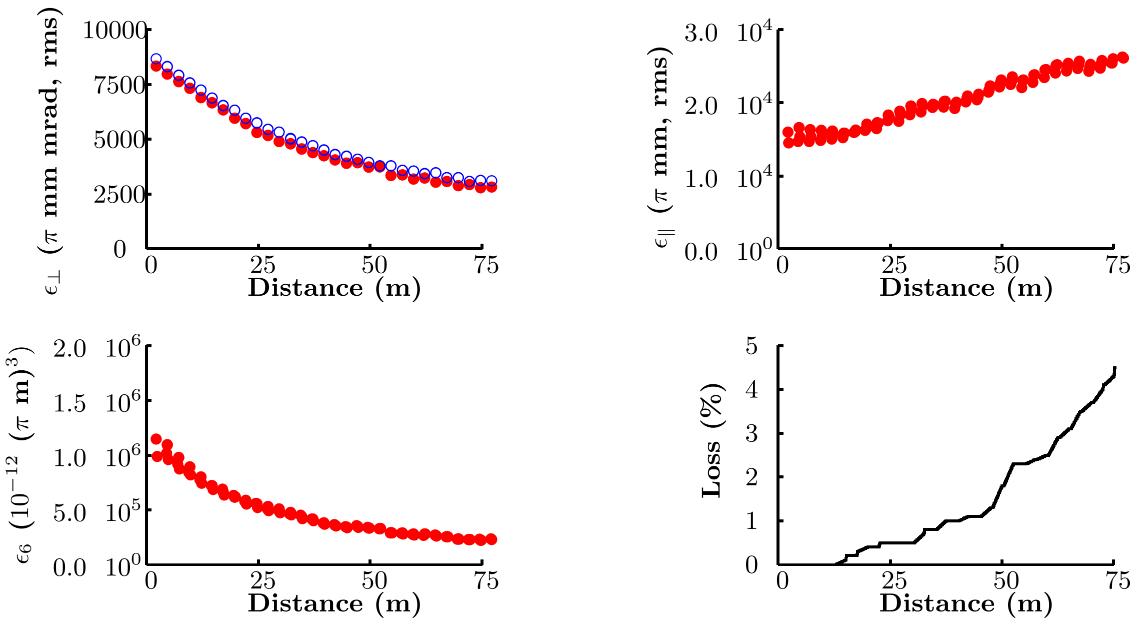


Figure 11: Transverse emittance (top left), longitudinal emittance (top right), 6-d emittance (bottom left), and particle loss (bottom right) *vs.* position during cooling.

## 4.8 Acceleration

Acceleration of the cooled muon beam from 185 MeV/$c$ ($\approx$ 100 MeV) to 50 GeV is achieved by a linac followed by two recirculating linear accelerators (RLA's).

The present assumption is that the larger second (and possibly also the first) recirculating accelerator uses LEP superconducting cavities, or cavities with the same parameters and dimensions. The use of these cavities sets constraints on the minimum energy for which the required emittance can be transported. If the full ($\approx$ 10 m long) cryostats, containing four cavities, are used as is, then this minimum energy is approximately 8 GeV. This is taken as the approximate injection energy into the second RLA. If the cavities are rehoused individually in new cryostats, then the minimum energy is approximately 2 GeV. This is used as the approximate injection energy the first RLA.

More detailed considerations of the RLA's, and of the storage ring lattice, are given in [62].

## 4.9 Storage Ring

### Geometries

The geometry of the storage ring is site specific, being a function of both the ring and detector locations. Figure 12 shows directions and direct distances from rings at BNL or FNAL to Gran Sasso, Soudan, and SLAC. The circumference of such rings for 50 GeV muons must be of order 1 km, even using bend magnets of several Tesla, so that a large fraction of the length can be in neutrino-beam-producing straight sections.

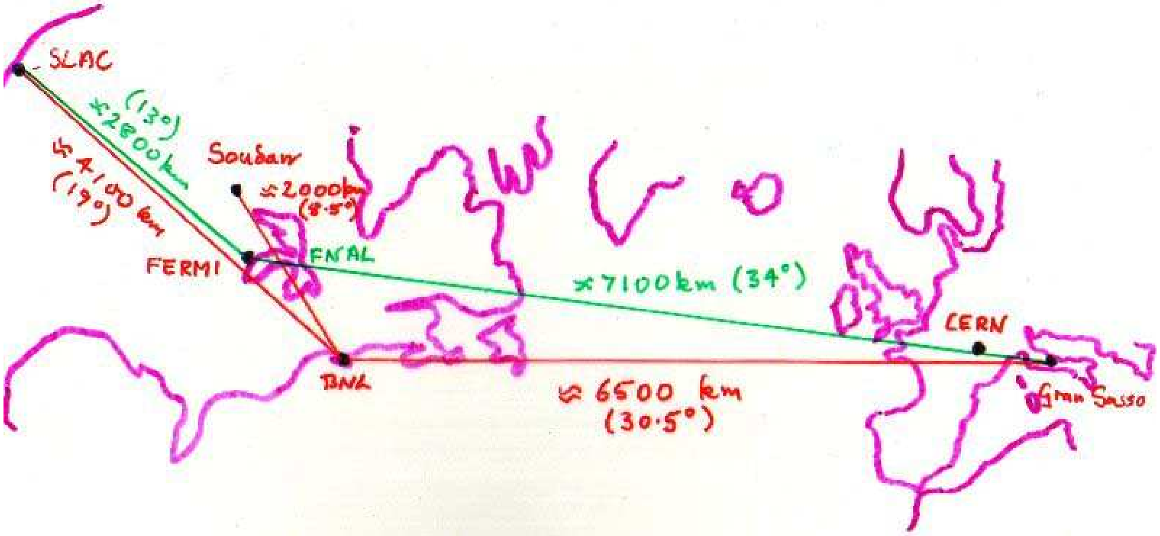


Figure 12: Neutrino beam paths between various possible sites for source and detectors.

For physics reasons (to separate MSW from vacuum oscillations), two differing ring to detector distances are required. If the two detectors lie in approximately opposite directions from the ring then it seems reasonable to design the ring with long sides that point to the two detectors, adding, if needed, a third straight to close the ring. Two geometries are of particular interest (Fig. 13):

- A triangular geometry lying in a tilted plane. This minimizes the amount of bending required and maximizes the total straight for a given circumference. But, the lengths of the straights pointing at the two distant detectors is NOT maximized.
- A "bowtie", or figure-of-eight geometry, also lying in a tilted plane. This geometry uses more total bending, but does maximize the important straights. It also has the interesting feature of not precessing the muon spins. A variant of the bowtie looks much the same but does not lie in a plane, so that there is a significant separation of the beams where they cross. In this case there is a slow precession of spin.

  The bowtie can be made asymmetric so as to maximize the length of the upward straight.

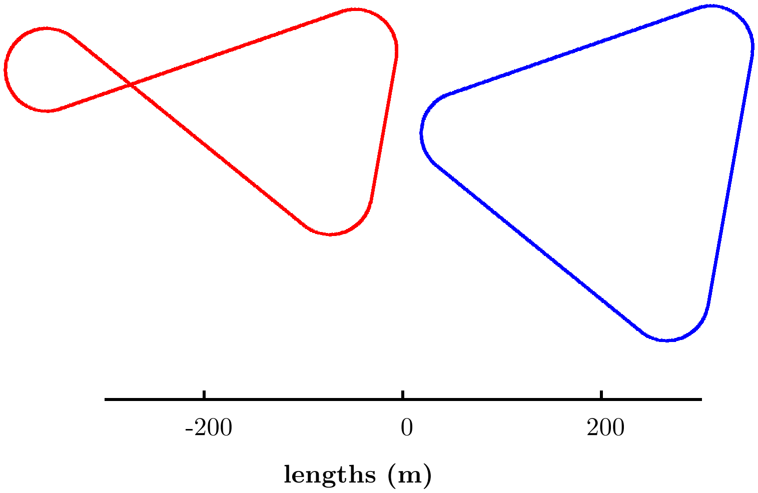


Figure 13: Possible bowtie and triangular geometries for a muon storage ring designed to deliver neutrino beams to two distant detectors.

To send a neutrino beam to a detector on another continent, a straight section in the storage ring must have angle at least 30° to the horizontal. The resulting vertical extent of the storage ring is at least 100 m. If the ring is below the surface, various geological issues must be addressed. It may be more practical to build the ring above ground and bury it under an artificial hill.

### Lattice

The emittance that the storage ring must accept is estimated by supposing there is 20% emittance growth in the accelerator in each of three directions. We require an acceptance of 3 $\sigma$ in each of the 6 dimensions. If the bunch spacing is 1.7 m (corresponding to the 175 MHz bunching used here), then a reasonable maximum rms bunch length in the collider would be 6 cm. Thus the minimum momentum spread in this case would be $\sigma_p = 0.1\%$.

The rms beam divergence in the straight sections should be $\approx 0.1/\gamma$ in order a) to maximize the dependence of the $\nu_\mu$ to $\nu_e$ ratio on the polarization; and b) to assure that the flux observed is not significantly affected by the exact magnitude of this divergence. To achieve this low divergence, the required beta function in the major straights is $\beta_{\text{major straights}} \geq 75$ m. For the up-going straight, aimed at a near detector on the surface, there is probably not such a stringent requirement on the beam divergence. If the divergence here is required to be below 1/3 of $1/\gamma$, then $\beta_{\text{upgoing straight}} \geq 8$ m.

## 4.10 A First Look at Event Rates

The numbers of surviving muons, per incident proton, at various stages of the accelerator complex are summarized in Table 1.

Table 1: The numbers of surviving muons after various stages in the accelerator complex.

| $p$ driver energy (GeV) |  | 24 | 16 |
|---|---|---|---|
|  | Factor | $\mu$/p | $\mu$/p |
| Pions after Match ($<$ 1 GeV, forward) |  | 0.66 | 0.44 |
| After Phase Rotation #1 (selected) | 0.45 | 0.3 | .2 |
| After Phase Rotation #2 (selected) | 0.7 | 0.21 | .14 |
| After RF Capture | 0.7 | 0.15 | .1 |
| After Cooling | 0.9 | 0.13 | .09 |
| After Acceleration | 0.7 | 0.092 | .061 |
| $n_\mu/(n_p\ E_p)$ (GeV$^{-1}$) |  | .0038 | .0038 |

The number of neutrino interactions per unit mass of a detector at distance $L$ from a muon storage ring operating at energy $E_\mu$ scales as

$$N_{\text{events}} \propto N_\mu\, E_\mu^3\, L^{-2}. \tag{20}$$

For a proton power of 1.5 MW, and the muon survival efficiencies given in Table 1, we would, in a year of $10^7$ s of operation, obtain $4 \times 10^{20}$ muons decaying in the storage ring. If we take the fraction of the ring pointing to a given detector to be 0.25 (approximately as in the bowtie geometry), then the number of decays pointing to the given detector will be approximately $10^{20}$.

Table 2 gives charged current neutrino interaction rates per kton-year as a function of baseline length $L$ for an $E_\mu = 50$ GeV muon storage ring in which there are $1 \times 10^{20}$ unpolarized muon decays per year within a neutrino beam-forming straight section [63]. The rates are listed for

(a) $\nu_e \to \nu_\mu$ oscillations with $\Delta m^2_{23} = 3.5 \times 10^{-3}$ eV$^2$/c$^4$ and $\sin^2 2\theta_{23} = 0.1$,

(b) $\nu_e \rightarrow \nu_\mu$ oscillations with $\Delta m^2_{23} = 1 \times 10^{-4}$ eV$^2$/c$^4$ and $\sin^2 2\theta_{23} = 1$,

(c) $\nu_e \rightarrow \nu_\tau$ oscillations with $\Delta m^2_{23} = 3.5 \times 10^{-3}$ eV$^2$/c$^4$ and $\sin^2 2\theta_{23} = 0.1$,

(d) $\nu_\mu \rightarrow \nu_\tau$ oscillations with $\Delta m^2_{23} = 3.5 \times 10^{-3}$ eV$^2$/c$^4$ and $\sin^2 2\theta_{23} = 1$.

Also listed are the rates for the unoscillated neutrino interactions, the corresponding statistical significance of the disappearance signal (numbers in parentheses), and the rates for the antineutrino interactions.

Table 2: Neutrino interaction rates per kton-year at a neutrino factory for four cases of neutrino-mass parameters as given in the text.

| | | Source | BNL | BNL | BNL | FNAL | FNAL | FNAL |
|---|---|---|---|---|---|---|---|---|
| | | Detector | G. Sasso | SLAC | Soudan | G. Sasso | SLAC | Soudan |
| | | $L$ (km) | 6528 | 4139 | 1712 | 7332 | 2899 | 732 |
| | Case | Mode | | | | | | |
| $\mu^+$ | (a) | $\nu_e \rightarrow \nu_\mu$ | 90 | 160 | 190 | 63 | 180 | 200 |
| | | $\nu_e \rightarrow \nu_e$ | 1400 | 3600 | 16000 | 1100 | 8000 | $1.2 \times 10^5$ |
| | | | ($2.4\sigma$) | ($2.7\sigma$) | ($1.5\sigma$) | ($1.9\sigma$) | ($2.0\sigma$) | ($0.6\sigma$) |
| | | $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$ | 890 | 2200 | 9300 | 700 | 4800 | $7.0 \times 10^4$ |
| $\mu^+$ | (b) | $\nu_e \rightarrow \nu_\mu$ | $5 \times 10^{-2}$ | 0.86 | 1.5 | $3 \times 10^{-5}$ | 1.3 | 1.6 |
| | | $\nu_e \rightarrow \nu_e$ | 1500 | 3800 | 16000 | 1200 | 8200 | $1.2 \times 10^5$ |
| | | | ($2.4\sigma$) | ($2.7\sigma$) | ($1.5\sigma$) | ($1.9\sigma$) | ($2.0\sigma$) | ($0.6\sigma$) |
| | | $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$ | 890 | 2200 | 9400 | 700 | 4800 | $7.0 \times 10^4$ |
| $\mu^+$ | (c) | $\nu_e \rightarrow \nu_\tau$ | 31 | 60 | 70 | 20 | 67 | 73 |
| | | $\nu_e \rightarrow \nu_e$ | 1400 | 3700 | $1.6 \times 10^4$ | 1100 | 8000 | $1.2 \times 10^5$ |
| | | | ($2.4\sigma$) | ($2.7\sigma$) | ($1.5\sigma$) | ($1.9\sigma$) | ($2.0\sigma$) | ($0.6\sigma$) |
| | | $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$ | 890 | 2200 | 9400 | 700 | 4800 | $7.0 \times 10^4$ |
| $\mu^-$ | (d) | $\nu_\mu \rightarrow \nu_\tau$ | 450 | 570 | 650 | 410 | 620 | 680 |
| | | $\nu_\mu \rightarrow \nu_\mu$ | 760 | 3100 | $1.7 \times 10^4$ | 490 | 8000 | $1.4 \times 10^5$ |
| | | | ($35\sigma$) | ($23\sigma$) | ($12\sigma$) | ($40\sigma$) | ($16\sigma$) | ($4.6\sigma$) |
| | | $\overline{\nu}_e \rightarrow \overline{\nu}_e$ | 770 | 1900 | 8100 | 600 | 4100 | $6.1 \times 10^4$ |

For comparison, the approximate numbers of events in the proposed CERN - Gran Sasso experiment (NGS) [17], and Minos [16] experiments, are given in Table 3. It is seen that the numbers of events with the 1.5-MW neutrino factory, in a detector at the same 730 km, is approximately 100 times that in the NGS, or about 40 times the highest energy Minos example.

Table 3: Comparison of neutrino interaction rates per kton-year with Minos and NGS for beam conditions and neutrino mixing parameters as in Table 2.

| | $\nu$ Factory | CERN-NGS | FNAL Minos | | |
|---|---|---|---|---|---|
| $\langle E_\nu \rangle$ (GeV) | 40 | 26 | 3 | 6 | 12 |
| $L$ (km) | 730 | 730 | 730 | | |
| $\nu_\mu \to \nu_\tau \to \tau$ | 680 | $\approx 7$ | $\approx 0$ | $\approx 30$ | $\approx 40$ |
| $\overline{\nu}_\mu \to \overline{\nu}_\mu$ | 140k | 1.5k | 0.46k | 1.4k | 3.2k |

# 5 Muon Colliders

A neutrino factory based on a muon storage ring is a possible first step towards a muon collider [23]. This section briefly reviews the motivation for muon colliders, and sketches a sequence of such colliders.

The Standard Model of electroweak and strong interactions has passed precision experimental tests at the highest energy scale accessible today. Theoretical arguments indicate that new physics *beyond the Standard Model* associated with the electroweak gauge symmetry breaking and fermion mass generation will emerge in parton collisions at or approaching the TeV energy scale. It is likely that both hadron-hadron and lepton-antilepton colliders will be required to discover and make precision measurements of the new phenomena.

The next big step forward in advancing the hadron-hadron collider energy frontier will be provided by the CERN Large Hadron Collider (LHC), a proton-proton collider with a center-of-mass (CoM) energy of 14 TeV which is due to come into operation in the latter half of the next decade.

The route towards TeV-scale lepton-antilepton colliders is less clear. The lepton-antilepton colliders built so far have been $e^+e^-$ colliders, such as the Large Electron Positron collider (LEP) at CERN and the Stanford Linear Collider (SLC) at SLAC. In a circular ring such as LEP the energy lost per revolution in keV is $88.5 \times E^4/\rho$, where the electron energy $E$ is in GeV, and the radius of the orbit $\rho$ is in meters. Hence, the energy loss grows rapidly as $E$ increases. This limits the center-of-mass energy that would be achievable in a LEP-like collider. The problem can be avoided by building a linear machine (the SLC is partially linear), but with current technologies, such a machine must be very long (30-40 km) to attain the TeV energy scale. Even so, radiation during the beam-beam interaction (beamstrahlung) limits the precision of the CoM energy [64].

For a lepton with mass $m$ the radiative energy losses are inversely proportional to $m^4$. Hence, the energy-loss problem can be solved by using heavy leptons. In practice this means using muons, which have a mass $\approx 207$ times that of an electron. The resulting reduction in radiative losses enables higher energies to be reached and smaller collider rings to be used [70]. Estimated sizes of the accelerator complexes required for 0.1-TeV, 0.5-TeV and 3-TeV muon colliders [23, 66] are compared with the sizes of other possible future colliders, and

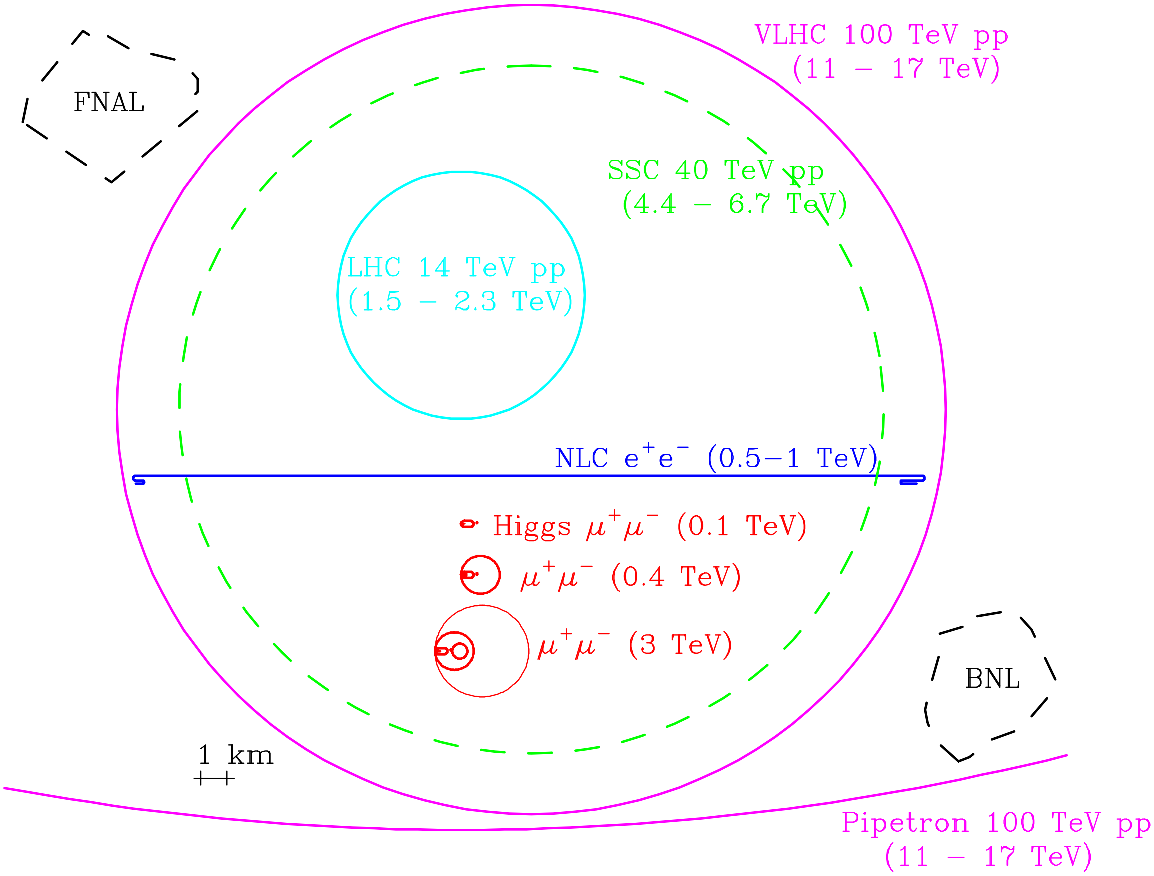


Figure 14: Various proposed high energy colliders compared with the FNAL and BNL sites. The energies in parentheses give for lepton colliders their CoM energies and for hadron colliders the approximate range of CoM energies attainable for hard parton-parton collisions.

with the FNAL and BNL sites in Fig. 14. Note that muon colliders with CoM energies up to $\approx 4$ TeV would fit on these existing laboratory sites. Figs. 15 and 16 show possible outlines of the 0.1 TeV and 3 TeV machines. Parameters for 10 to 100 TeV colliders have also been discussed [65].

Muon colliders offer significant physics advantages. The small radiative losses permit very small beam-energy spreads to be achieved. For example, momentum spreads as low as $\Delta P/P = 0.003\%$ are believed to be possible for a low-energy collider. By measuring the time-dependent decay asymmetry resulting from the naturally polarized muons, the beam energy could be determined with a precision of $\Delta E/E = 10^{-6}$ [67]. The small beam-energy spread, together with the precise energy determination, would facilitate measurements of the masses and widths of any new resonant states scanned by the collider. In addition, since the cross-section for producing a Higgs-like scalar particle in the s-channel (direct lepton-antilepton annihilation) is proportional to $m^2$, this extremely important process could be studied only at a muon collider and not at an $e^+e^-$ collider [68]. And, of course, the decaying muons will produce copious quantities of neutrinos. Even short straight sections in a muon-collider ring

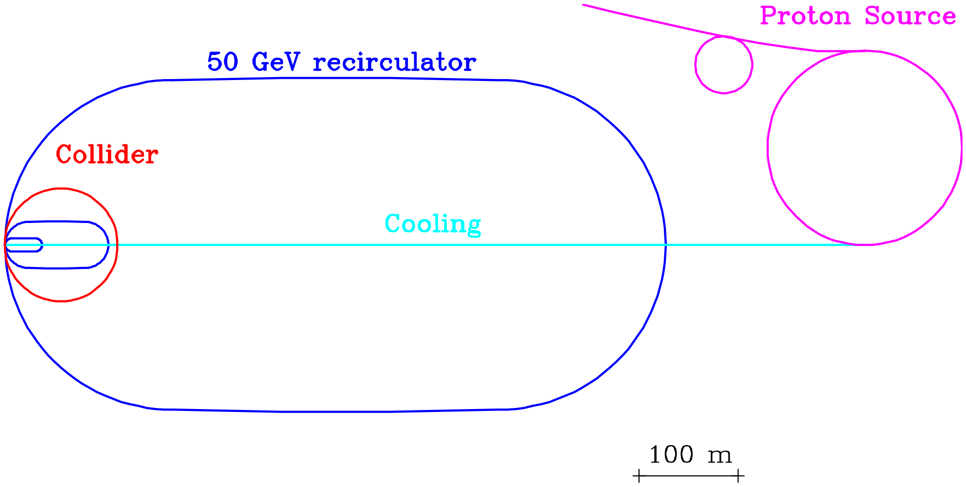


Figure 15: Plan of a 0.1-TeV-CoM muon collider.

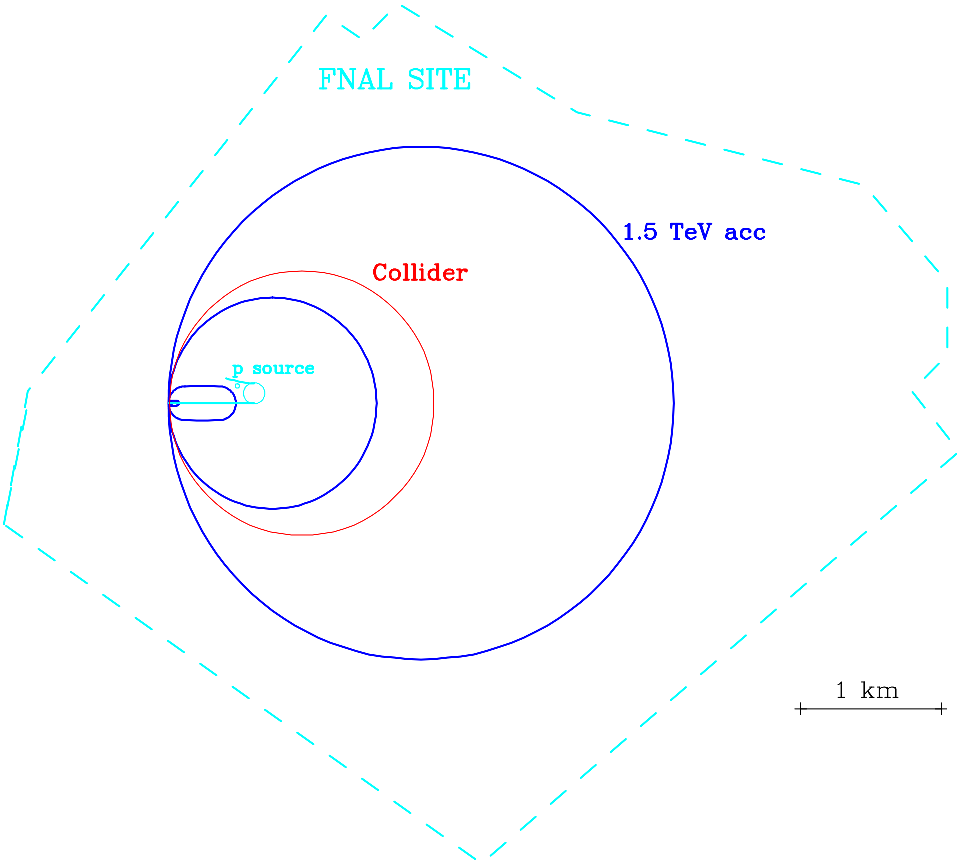


Figure 16: Plan of a 3-TeV-CoM muon collider shown on the Fermi National Laboratory site as an example.

will result in neutrino beams several orders of magnitude higher in intensity than presently available, excellent for nonoscillation neutrino physics in a near detector.

The First Muon Collider will be a unique facility for neutral Higgs boson (or techni-resonance) studies through $s$-channel resonance production, as illustrated in Fig. 17. Measurements can also be made of the threshold cross sections for production of $W^+W^-$, $t\bar{t}$, $Zh$, and pairs of supersymmetry particles – $\chi_1^+\chi_1^-$, $\chi_2^0\chi_1^0$, $\tilde{\ell}^+\tilde{\ell}^-$ and $\tilde{\nu}\bar{\tilde{\nu}}$ – that will determine the corresponding masses to high precision. A $\mu^+\mu^- \rightarrow Z^0$ factory, utilizing the partial polarization of the muons, could allow significant improvements in $\sin^2\theta_{\rm w}$ precision and in $B$-mixing and CP-violating studies.

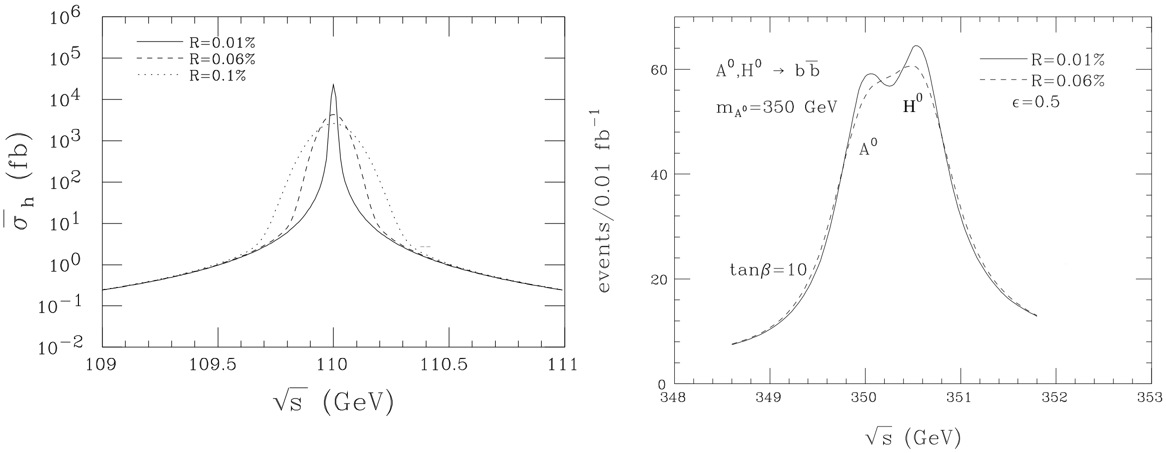


Figure 17: Left: effective $s$-channel Higgs cross section $\bar{\sigma}_h$ obtained by convoluting the Breit-Wigner resonance formula with a Gaussian distribution for resolution $R$. The mass of a light Higgs boson could be determined to 1 MeV at a First Muon Collider. Right: separation of $A^0$ and $H^0$ signals for $\tan\beta = 10$. From Ref. [69].

The Next Muon Collider will be particularly valuable for reconstructing supersymmetric particles of high mass from their complex cascade decay chains. Also, any $Z'$ resonances within the kinematic reach of the machine would give enormous event rates. The effects of virtual $Z'$ states would be detectable to high mass. If no Higgs bosons exist below ∼1 TeV, then the NMC would be the ideal machine for the study of strong $WW$ scattering at TeV energies.

The cost of building a muon collider is not yet known. However, since muon colliders are relatively small, they may be significantly less expensive than alternative machines.

The front end of a muon collider is very similar to that of a neutrino factory, with the important difference that the muon phase volume must be cooled by a factor of $10^6$ rather than $\approx 100$. During this larger cooling, the longitudinal phase volume must shrink along with the transverse. Since ionization cooling as proposed here directly cools only transverse space, a muon collider must include an exchange between longitudinal and transverse phase volumes so that cooling of the latter effectively results in cooling of the former as well.

Another difference between the two machines is that a muon collider must provide muon bunches of both signs simultaneously, while in a neutrino factory only one sign of muons is utilized at any given time. Further, a storage ring with long straight sections optimized for neutrino beams is not ideal for high-luminosity muon-muon collisions, particularly at lower energies.

# 6 Research and Development

## 6.1 Historical Introduction

The interest of the present proponents has evolved from our investigations of muon colliders, the concept of which was introduced by Budker [70], and developed further by Skrinsky *et al.* [71], and by Neuffer [72]. This work pointed out the significant challenges in designing an accelerator complex that can make, accelerate, and collide $\mu^+$ and $\mu^-$ bunches all within the muon lifetime of $2.2\,\mu$s ($c\tau = 659$ m), and provided preliminary sketches of technical solutions.

A concerted study of a muon collider design has been underway since 1992 [73]. By the Sausalito workshop [74] in 1995 it was realized that with new ideas and modern technology, it may be feasible to make muon bunches containing a few times $10^{12}$ muons, compress their phase space and accelerate them up to the multi-TeV energy scale before more than about 3/4 of them have decayed. With careful design of the collider ring and shielding it appears possible to reduce to acceptable levels the backgrounds within the detector that arise from the very large flux of electrons produced in muon decays. These realizations led to an intense activity, which resulted in the muon-collider feasibility study report [75] prepared for the 1996 DPF/DPB Summer Study on High-Energy Physics (the Snowmass'96 workshop).

Encouraged by further progress in developing the muon-collider concept, together with the growing interest and involvement of the high-energy-physics community, the Muon Collider Collaboration became a formal entity in May of 1997 [76, 77]. An overview of the activities and plans of the Muon Collider Collaboration is given in [23].

That a neutrino factory would be a good first step towards a muon collider has been explored in two Collaboration workshops [24, 25] as well as by ECFA/ICFA study groups [26, 78]. The NuFact'99 Workshop [27] in June 1999 provided a focus for international interest in neutrino factories, motivated by the outstanding physics prospects plus the need for truly global facilities for long baseline neutrino physics.

Accordingly, the Muon Collider Collaboration has recently changed its name to the Neutrino Factory and Muon Collider Collaboration, and is redirecting its efforts towards an early realization of a neutrino factory. A Muon Steering Group [79] has been formed in Europe to coordinate efforts there towards the same goal. These two structures are formally distinct, but there is excellent communication among members of the two groups.

The Muon Collider Collaboration has proposed an R&D program that features hardware studies of two key aspects of a muon collider:

- Targetry, capture and phase rotation at a muon source [80],
- Final-stage ionization cooling at a muon collider [81],

in addition to an ongoing program of machine theory and simulation. There has been one outside review of the R&D program [82], conducted in July, 1999 by the Muon Technical Advisory Committee (MUTAC) of the Muon Collider Oversight Group (MCOG). The MUTAC report [83] and the MCOG report [84] following this review emphasized that the R&D program should be conducted in the context of "a more formal, long range, R&D plan" with a "focus on one object for a complete, detailed study". They noted that "a neutrino source appears as the most likely possibility" for that study.

Consistent with the emerging emphasis on a neutrino factory, the Collaboration is re-examining its R&D priorities, as well as seeking broader support for these activities.

## 6.2 R&D Needs for a Neutrino Factory

The overall path of an R&D program involves conceptual design, demonstration of feasibility of novel components, followed by cost optimization. A neutrino factory based on a muon storage ring is still very much in the early phases of conceptual design, with some items identified as needing verification as to their feasibility. Nonetheless, there are some pressures to concern ourselves with cost issues already at this early stage [85].

The prominent R&D issues for a neutrino factory are listed below, following the sequence of components in the accelerator complex.

1. **Coherent design concept** of an entire neutrino factory.

2. **Proton driver**: 1-4 MW, 5-15 Hz, $\approx 5\times10^{13}$ protons per bunch, **1 ns bunch length**. The critical issue of short bunch length in a proton synchrotron is under study by an ANL-BNL-FNAL-KEK-LANL collaboration [86, 87, 88, 89].

3. **Pion yields from proton-nucleus collisions**. A neutrino factory would collect very low energy pions, for which the rate is maximal. Such pions are partially absorbed in the targets of most prior production experiments, so the data are questionable. A recent measurement by members of the Collaboration should improve our knowledge from proton beams of 6-24 GeV [90]. An experiment to study yields from 2-GeV protons is being considered at CERN (sec. 6.4) in the context of the option for a proton driver linac.

4. **Production target**. Proton pulses of 70-280 kJ energy and 1 ns length are incident on the target, leading to substantial issues of "shock" damage, cooling and materials survivability in a high radiation environment. While it is natural to consider solid targets, their viability is considered marginal, and liquid targets are the alternative. For maximal pion production, a free liquid jet target is to be preferred in principle. There is no example of such a target.

5. **Capture solenoid**. Optimal pion yields are obtained when the target is surrounding by a solenoid of field $\approx 20$ T, followed by an adiabatic transition to a solenoidal channel of a few T. Such a magnet would be a superconducting hybrid with a resistive insert [55]. A key question is the effect of radiation damage on such a device.

6. **Beam dump**. The 1-4 MW proton beam is dumped inside the target/solenoid system. A flowing liquid dump may be more appropriate than a solid dump.

7. **First Phase Rotation**. If polarized muon beams are to be obtained, the production target must be quickly followed by a high-gradient, low-frequency rf system, combined with a solenoid channel, to bunch the pion/muon beam. Little is known about the viability of such a system near an intense radiation source.

8. **Mini Cooling**. The use of a passive liquid hydrogen absorber to provide initial transverse cooling of the muon beam by a factor of two is well understood in principle, although it never has been demonstrated.

9. **Second Phase Rotation**. For the second step in the bunching process, the muons must be accelerated by 80-100 MeV to restore the energy lost in the mini cooling. A large acceptance induction linac with a programmed waveform is required. The parameters of the linac are somewhat beyond those presently demonstrated.

10. **Bunching to $\approx$ 400 MHz**. This is believed to be relatively straightforward.

11. **Ionization Cooling**. The challenges of further acceleration and storage of the muon beam will be substantially easier if the transverse phase area of the beam can be reduced by an additional factor of 10. This cannot be accomplished in a single step of ionization cooling, but must involve alternating ionization cooling and rf acceleration, all in a magnetic channel. This is a key area for study, and a hardware demonstration is very appropriate.

12. **Acceleration**. The acceleration from $\approx$ 100 MeV to $\approx$ 50 GeV is best accomplished in recirculating linacs with superconducting rf cavities. Rather large acceptances are required, and the machine parameters are again somewhat beyond those presently demonstrated.

13. **Muon Storage Ring**. The desire for multiply directed neutrino beams with very small angular divergence leads to novel designs for the storage ring, whose plane is far from horizontal. Besides issues of lattice design, there will be considerable civil engineering challenges in building such a ring.

The R&D needs for a muon collider are very similar, but with additional challenges in cooling and storage ring design. At least four orders of magnitude more cooling (including continual exchange between transverse and longitudinal emittance) are required for a muon collider than a neutrino factory, and a rather different ring is needed to maximize collider luminosity than simply to hold the muons while they decay.

A sense of the Collaboration's views as to the relative urgency of addressing the above issues is given by the following ranking. Given in parentheses are the institutions presently involved in R&D into these topics.

1. Coherent design study (the Collaboration as a whole).

2. Target, dump, phase rotation (ANL, BNL, UCLA, CERN, LBNL, ORNL, Princeton).

3. Ionization cooling (ANL, BNL, Budker Inst., UC Berkeley, UCLA, FNAL, IIT, Indiana U., LBNL, NHMFL, Northern Illinois U., Princeton).
4. Induction linac (LBNL).
5. Recirculating linacs, superconducting rf (Jefferson Lab).
6. Storage ring design (BNL, CERN, FNAL, LBNL).
7. RF power sources (BNL, CERN, FNAL, LBL + industry).
8. Effects of radiation on superconducting magnets (MSU).
9. Fabrication of superconducting magnets (LBNL, NHMFL + industry).
10. RF bunching.
11. Engineering of a tilted ring.
12. Engineering of "conventional" facilities (FNAL, ORNL).

Proton driver issues are very site specific, and have been left off the second list as being somewhat outside the scope of the Neutrino Factory and Muon Collider Collaboration. Pion production cross sections were also left off the second list as being adequately addressed by efforts largely outside the Collaboration.

The strategy for pursuit of the R&D topics listed above is an interesting challenge in itself. The variety of questions is large, and several go beyond the scope high-energy accelerator experience. A neutrino factory is still too novel a concept to be sponsored as a well-defined program at a single accelerator laboratory. The cooperative efforts of people at many institutions is needed to bring the concept of a neutrino factory to the stage of a formal Conceptual Design.

The Neutrino Factory and Muon Collider Collaboration has taken responsibility for the coordination of multi-institutional R&D efforts on the non-site-specific aspects of a neutrino factory. While the topic of research is largely accelerator physics, the operation of the Collaboration is more similar to that of a large experimental physics group proposing a novel detector than to that of past accelerator projects. The Collaboration has been successful in providing a means of groups of people working together, as facilitated by numerous workshops [91], video conferences [92], web sites (see links at the primary site [76], and an archive of technical documents [93]. Additional efforts are needed to enhance the coherence of this work, an important step of which will be the appointment of an R&D Coordinator. There remains the issue of the response of the Collaboration to the advice of the MUTAC that "the first round of Design and Simulation activities may requires 10-15 accelerator experts for 1-1/2 to 3 years. The coherence required for success in this activity demands full-time workers in close communication."

To carry out the R&D program sketched above, the Collaboration seeks additional resources in two categories:

1. Support for a core group of physicists, most of whom are in residence at a single site, likely a national laboratory. Support is sought for both staff positions, and for visitors who would locate at the core site for at least several months at a time.

2. Support for the various particular R&D topics listed above, which work may well be effectively pursued at diverse labs and universities.

Partial support for Collaboration efforts in both categories of work is presently available via direct funds from the Advanced Technology R&D Program (and to a much smaller extent from the Physics Research Program) of the U.S. Department of Energy, as well as from discretionary funds at the major U.S. national laboratories. The state of Illinois has made a commitment to a university consortium heading by IIT for funding beginning in year 2000. CERN is starting an R&D program, (sec. 6.4), with initial funding in the present fiscal year.

We have previously estimated that a robust R&D program for muon colliders would require about $15M/year. A very similar figure is appropriate for neutrino factory R&D, as this is effectively a transformed muon collider R&D program. Our present funding is approximately 1/2 of this amount.

The favorable outcome of our R&D program is, of course, the construction of a neutrino factory. Prior to this, we anticipate the elevation of effort to that of a major project at at least one national laboratory. The role of the Collaboration will no doubt evolve significantly in such case, but it can and should continue to play a key role in harnessing the diverse resources needed to design a neutrino factory. The original role of the Collaboration as a vehicle for broad-based efforts towards a muon collider will again be important as a neutrino factory becomes associated with a particular site.

## 6.3 The Potential of Muon-Beam-Based Particle Physics and the NSF-Supported Community

Just 20 years ago the DoE assembled a HEPAP Subpanel on Accelerator R and D. In the letter conveying their report to HEPAP the Subpanel Chair wrote: "You will note that in the 50 odd years of American accelerator science associated with particle physics research, enormous strides in increasing particle beam energies and in decreasing unit costs have been and are being made. ... Our primary conclusion is that, despite the spectacular past and present accomplishments of the field, we must redouble our efforts to improve the cost effectiveness of our accelerators if the needs of US particle physics are to be met in the resource-limited situation in which we find ourselves..."

Unfortunately, as recent history and current events show, this observation is even more apt today than it was those 20 years ago. This is not for want of zeal and good ideas. In the intervening years considerable progress in understanding the fundamentals of "classical" accelerator science and improving classical accelerator technology has been made. There have also been some advances based on technologies not previously used in elementary-particle-physics accelerator work, *e.g.*, laser and plasma technology. It is, however, a fact that none of these efforts, to date, have qualitatively changed the cost of providing significant luminosity at what is now the energy frontier. Consequently, it is not an exaggeration to say that today we are in danger of pricing ourselves out of the market.

In recent years, as accelerator science and technology have become more and more sophisticated and thus more specialized, the task of developing the accelerators needed for the future has more and more been left to experts – specialists in accelerators. They have done an excellent job indeed. The capabilities of today's accelerators would have even been unthinkable 20 years ago.

Nevertheless, we find ourselves in the unenviable position that each new energy-frontier facility being discussed turns out to be in the multi-billion dollar class. This difficulty might find a direct political solution from time to time as history unfolds and the competitive juices flow strongly again. However, if this had been the path followed in the past, elementary particle physics would not be able to ask the compelling questions that it can ask today. Thus, the direct approach of tackling the problem scientifically and technologically is likely to be more dependable – no guarantees. One obvious avenue is to broaden the scientific and technical idea base which might support significant improvements in accelerator cost effectiveness. This implies that the problem, OUR problem, needs to be brought more directly and effectively to the stakeholders in elementary particle physics, that is to say, to the university and laboratory community of experimental and theoretical physicists who now concern themselves primarily with the particle physics and detector instrumentation. This has been tried to some degree in the past, with only modest success. Today the need is more apparent and, in addition, we now have a made-to-order challenge that needs all the new and non expert ideas that it can get - the possibility of doing elementary particle physics with high energy muon beams through muon acceleration and storage for intense neutrino production, and later directly for $\mu$-$\mu$ collisions.

Many aspects of this concept are new enough that even the experts have to start from scratch. This stems from the unusual requirement that the job has to be done quickly owing to the finite life of the beam and, perhaps more importantly, that an enormous spread in beam momenta and angle must be accommodated if the required capture efficiency is to be met. The situation is somewhat analogous to the situation in accelerator science forty-odd years ago when folks tracked particles through magnetic fields using the Runge-Kutta method with a Marchant calculator. All of that calculation with the attendant trial and error struggle to find workable system designs was made obsolete with the elegant theoretical work of Courant, Livingston and Snyder and many others. They discovered powerful methods for dealing with paraxial ray beams of relatively narrow energy spread. These methods are of limited use in studying the optics of a muon-based neutrino source or collider where nonlinearities are controlling rather than perturbations. Not only that, but the main optical components will probably have to be solenoids, a device which has heretofore not been used for the principal focusing and bending elements in high energy machines. Trying to master all this puts everyone more or less on the same footing and begs for some new tactics from the classical mechanics buffs among us. Latter day Courants, Livingstons and Snyders are sorely needed.

There are yet other unprecedented challenges. The science and technology of quickly reducing the phase space volume of the beam needs developing before muon beams of the required brightness can be produced. While basic ideas for accomplishing this via ionization cooling have been around for years, the practical problem of realization is also new to the experts and involves very fundamental physics, some of which is not yet known with the depth required to support the needed technology.

Considerable attention has been focused on the potential physics opportunities for muon-based neutrino science and on possible means for attacking it. A Neutrino Factory and Muon Collider Collaboration (NFMCC), formed of members from the DoE supported Labs, Budker Institute for Nuclear Physics and some universities, has been formed and has been at work for some time. An idea of the progress that has been made is presented in secs. 1-5 of this document, which makes clear that a resolution of the basic particle and accelerator physics issues remains in the future and that more ideas, more work and much R&D lie ahead even in evaluating whether our community can and should propose such a facility.

Taking into account the fact that there is a great deal of talent, knowledge and expertise in the university community – both DoE and NSF supported – not now engaged in addressing the pressing accelerator issues, it would seem most appropriate to try to tap that pool. To make this possible, two things at least are needed. First, they have to be made aware of the possibilities and challenges. This the world community in general and the NFMCC in particular are doing. The NFMCC will be emphasizing this aspect more in the coming year. Second, modest start-up resources are necessary for preliminary engagement with the accelerator challenges, resources such as funding for post docs, some computing and modest beginnings of technical R&D. It is with respect to these needed monetary resources that we are addressing this 1999 MRE Panel.

Within one to two years it may well become apparent that large R&D expenditures, *i.e.*, 10's of M$, by NSF-supported university groups working on the accelerator aspects of muon-beam elementary particle physics, will be appropriate. This would require a joint application for MRE funding. The effort required to plan and justify such an application for review by the physics community, being an unusual enterprise, needs unusual support. Our hope is that this MRE Panel will appreciate this special need and recommend to the NSF that, where possible, they provide start up resources for currently supported university particle physics groups to become so engaged in the knowledge that this work may well lead to an MRE proposal in the not too distant future.

## 6.4 European R&D Activities on Muon Storage Rings and Neutrino Factories

There is growing interest in Europe for muon storage rings and particularly neutrino factories. Several working groups have been set up to study:

1. The accelerator aspects of a neutrino factory at CERN;
2. The physics of neutrino oscillations;
3. The opportunities offered by high-intensity neutrino muon and hadron beams;
4. The physics opportunities of the extension of a neutrino factory to a precision muon collider [78].

Discussions with physicists and accelerator engineers from European institutes and laboratories, and from CERN, have focused on identifying important missing elements in the currently debated designs of muon storage rings, with a view to avoiding duplication of efforts while contributing significantly towards the design of a neutrino factory.

The European community is considering the following R&D projects:

1. **A hadron production experiment at the CERN-PS**. The aim is to measure charged pion production by 2-16 GeV protons, data that are needed for a quantitative design of pion capture and phase rotation. The very same experiment can be extended to hadron production by pions, so as to deliver the entire set of data that is needed for a reliable calculation of the atmospheric neutrino flux.

2. **A large-angle muon scattering experiment.** This experiment would measure with high precision the large-angle scattering of muons with momentum of a few hundred MeV/$c$ in various materials including liquid hydrogen, as theoretical calculations are not reliable enough to assess the performance of ionization cooling of muons.

3. **Exposure of an rf cavity to radiation and a magnetic field.** One of the big unknowns is the reliability of operation of the rf cavities which are currently discussed for pion capture and phase rotation, and which will have to operate in a high-radiation field and possibly in strong solenoidal magnetic fields. Experiments with pulsing rf cavities would also be performed with a view to achieving higher gradients.

4. **High-power target tests.** Current design work is focussed on targets which withstand a beam power of 4 MW or even larger. While not considered impossible, this is a daring goal for which, however, considerable know-how is available in Europe (CERN, GSI, KFA Julich, PSI, RAL), which can and should be channeled towards an interesting and forward-looking challenge.

This proposed program of experimental R&D work in Europe is by and large complementary to the R&D activities planned or under way in the USA. This experimental work is augmented by theoretical studies, both in the area of physics and detectors, and in the area of accelerator design (proton linac, fast-cycling synchrotron, muon recirculators).

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