



E1 Working Group Summary: Neutrino Factories and Muon Colliders

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We are in the middle of a time of exciting discovery, namely that neutrinos have mass and oscillate. In order to take the next steps to understand this potential window onto what well might be the mechanism that links the quarks and leptons, we need both new neutrino beams and new detectors. The new beamlines can and should also provide new laboratories for doing charged lepton flavor physics, and the new detectors can and should also provide laboratories for doing other physics like proton decay, supernovae searches, etc. The new neutrino beams serve as milestones along the way to a muon collider, which can answer questions in yet another sector of particle physics, namely the Higgs sector or ultimately the energy frontier. In this report we discuss the current status of neutrino oscillation physics, what other oscillation measurements are needed to fully explore the phenomenon, and finally, what other new physics can be explored as a result of building of these facilities.

I. INTRODUCTION

The experimental study of the fundamental properties of neutrinos is one of the most challenging in particle physics, but it has also produced some of the most exciting and revolutionary physics insights, both on microscopic and astrophysical scales [1]. The discovery of the electron neutrino emitted in beta decay in the 1950s confirmed the hypothesis in the early 1930s by Pauli and Fermi of the existence of the electron neutrino. Shortly thereafter its left-handed nature was confirmed, the muon neutrino was discovered, and oscillations among three neutrino flavors were predicted. Neutrino neutral currents were pivotal in the confirmation of the Standard Model in the 1970s. The number of active neutrino flavors was measured to be three by the LEP experiments and by SLD. However, despite immense experimental efforts, discovery of neutrino mass and flavor mixing remained beyond reach until deep underground experiments were carried out to observe neutrinos of extra-terrestrial origins.

The study of the fundamental properties of neutrinos is now in a major discovery phase. There are good reasons to expect important neutrino discoveries to continue through the next two decades using new accelerator based neutrino sources, as will be summarized in this report. The rich new physics that can be explored will test the most basic tenets of particle theory: the masses and mixing of fermions and CP violation.

II. EVIDENCE FOR NEUTRINO OSCILLATIONS

One crucial breakthrough in neutrino mass studies occurred in the measurements of neutrinos produced in the atmosphere by cosmic ray interactions. The decays of pions and muons produced by cosmic rays give a roughly isotropic flux of neutrinos at energies of a few GeV that has the composition of about two ν_μ to one ν_e . Instead, the first experiments to measure neutrinos of atmospheric origin found a ν_μ/ν_e ratio which was about 60% of the expected value. This deficit was soon interpreted as evidence that oscillations occurred between the two flavors, but to decide which oscillations took place and the mass scale of the oscillations required larger detectors. The construction of the SuperKamiokande detector with 22.5 kilotons of ultra-pure water fiducial volume collected large statistics. A dependence of the ν_μ/ν_e event ratio on the zenith angle of the neutrino was found, with down-going neutrino events in agreement with expectation and up-going events a factor of about two below expectation [2]. This important result, also confirmed by other experiments [3][4][5], establishes that muon neutrinos disappear as the baseline increases, while electron-neutrinos are observed at the expected rate at all baselines. The limits from reactor experiments support the latter inference. The most economical theoretical interpretation is that ν_μ 's oscillate to ν_τ 's with large mixing ($\sin^2 2\theta \simeq 1$) and mass-squared difference $\delta m^2 \simeq 3 \times 10^{-3} \text{ eV}^2$. The early results from the K2K experiment are more consistent with the oscillation interpretation than with no oscillations [6]; the future MINOS and CNGS long-baseline experiments have the potential to provide more precision and may for the first time observe the appearance of ν_τ or even ν_e events from oscillations.

Another important breakthrough is that the long-standing solar neutrino problem is now known to be caused by the oscillation of electron neutrinos, at a mass scale well below that probed by atmospheric neutrino experiments. Measured deficits in the solar neutrino flux of 1/2 to 1/3 compared to Standard Solar Model predictions defied astrophysical explanation. Now, when the electron neutrino flux measurement from the SNO experiment is combined with the solar flux from SuperKamiokande, it is deduced that muon neutrino and tau neutrino contributions are seen at the 3 sigma level, confirming that neutrino flavor oscillations have occurred [7]. Global analyses of solar neutrino data find that the Large Mixing Angle (LMA) solution at $\delta m^2 \simeq 5 \times 10^{-5} \text{ eV}^2$ is preferred, which is very fortunate since future long-baseline experiments can probe this mass scale. The KamLAND experiment is expected to measure both the square of the δm^2 and $\sin^2 2\theta$ to 10% accuracy if the solar solution is LMA [8][9].

A complication to a three-neutrino oscillation interpretation is the LSND data, which give evidence for $\nu_\mu \rightarrow \nu_e$ oscillations at around the 1 eV^2 scale, with a very small mixing amplitude [10]. To have oscillations at three distinct mass-squared difference scales, a sterile neutrino with no Standard Model weak interactions must be invoked. The atmospheric and solar data still allow sterile neutrinos. The MiniBooNE experiment will test the LSND result in the near future [11]. For most of this report we concentrate on the three neutrino

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scenario for brevity, but even richer oscillation phenomena may exist. Sterile neutrinos have also been invoked in r-process nucleosynthesis and as warm dark matter. Their existence is a profound issue that can only be directly probed in oscillation studies.

The discovery of flavor oscillations has given us a first glimpse of the physics of neutrino mass, which has proven to be extremely interesting. The approximate bimaximal mixing form of the neutrino mixing matrix was totally unexpected, and shows us that the physics of the lepton sector is not a copy of the physics of the quark sector, wherein all mixings are small. The immediate challenge before us is to measure the small mixing angle between the first and third generation neutrino mass states, since that mixing is vital to neutrino interactions in matter and to CP violation in the lepton sector. In principle, the lepton sector is a better probe of fermion mass physics than the quark sector, since there are no complications from the strong interactions. The tools to develop neutrino mass physics into a precision science, using intense accelerator neutrino beams and large detectors, are within reach and the first steps with superbeams can be made at reasonable cost. Long baselines are essential to probe both the atmospheric and solar mass scales, so the experiments necessarily involve different laboratories and possibly even different countries, making this a truly international scientific enterprise. More than one facility will be needed to resolve the fundamental questions before us.

III. NEUTRINO OSCILLATION OVERVIEW

The neutrino flavor eigenstates ν_α ($\alpha = e, \mu, \tau$) are related to the mass eigenstates ν_j ($j = 1, 2, 3$) in vacuum by $\nu_\alpha = \sum U_{\alpha j}^* \nu_j$, where U^* is the 3×3 mixing matrix. It can be parametrized by

$$U^* = \begin{pmatrix} c_{13}c_{12} & c_{13}s_{12} & s_{13}e^{i\delta} \\ -c_{23}s_{12} - s_{13}s_{23}c_{12}e^{-i\delta} & c_{23}c_{12} - s_{13}s_{23}s_{12}e^{-i\delta} & c_{13}s_{23} \\ s_{23}s_{12} - s_{13}c_{23}c_{12}e^{-i\delta} & -s_{23}c_{12} - s_{13}c_{23}s_{12}e^{-i\delta} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2} & 0 \\ 0 & 0 & e^{i(\phi_3+\delta)} \end{pmatrix} \quad (1)$$

where $c_{ij} = \cos \theta_{ij}$ and $s_{ij} = \sin \theta_{ij}$. The extra diagonal phases are present for Majorana neutrinos but do not affect oscillation phenomena.

The vacuum oscillation probabilities are given by

$$P(\nu_\alpha \rightarrow \nu_\beta) = -4\Re(U_{\alpha 2}U_{\alpha 3}^*U_{\beta 2}^*U_{\beta 3})\sin^2 \Delta_{32} - 4\Re(U_{\alpha 1}U_{\alpha 3}^*U_{\beta 1}^*U_{\beta 3})\sin^2 \Delta_{31} - 4\Re(U_{\alpha 1}U_{\alpha 2}^*U_{\beta 1}^*U_{\beta 2})\sin^2 \Delta_{21} \pm 2JS, \quad (2)$$

where $J = \Im(U_{e2}U_{e3}^*U_{\mu 2}^*U_{\mu 3})$, is the CP -violating invariant, and $S = \sin 2\Delta_{21} + \sin 2\Delta_{32} - \sin 2\Delta_{31}$, is the associated dependence on L and E_ν . Here, $\Delta_{jk} \equiv \delta m_{jk}^2 L/4E_\nu = 1.27(\delta m_{jk}^2/\text{eV}^2)(L/\text{km})(\text{GeV}/E_\nu)$. The plus (minus) sign is used when α and β are in cyclic (anticyclic) order, where cyclic order is defined as $e\mu\tau$. The physical variable is L/E_ν , where L is the baseline from source to detector and E_ν is the neutrino energy. Only for the LMA solution is the secondary mass scale sufficiently large that CP -violation can be probed at long baselines [12–14].

The propagation of neutrinos through matter is described by the evolution equation [15, 16]

$$i\frac{d\nu_\alpha}{dx} = \sum_\beta \frac{1}{2E_\nu} (\delta m_{31}^2 U_{\alpha 3} U_{\beta 3}^* + \delta m_{21}^2 U_{\alpha 2} U_{\beta 2}^* + A\delta_{\alpha e}\delta_{\beta e}), \quad (3)$$

where $x = ct$ and $A/2E_\nu$ is the amplitude for coherent forward charged-current ν_e scattering on electrons, with

$$A = 2\sqrt{2}G_F Y_e \rho E_\nu = 1.52 \times 10^{-4} \text{eV}^2 Y_e \rho (\text{g/cm}^3) E_\nu (\text{GeV}). \quad (4)$$

Here $Y_e(x)$ is the electron fraction and $\rho(x)$ is the matter density. In the Earth's crust and mantle, the average density is typically 3–5 gm/cm³ and $Y_e \simeq 0.5$. The evolution equations can be solved numerically taking into account the dependence of the density on depth using the density profile from the Preliminary Reference Earth Model[17].

With three neutrinos there are two independent δm^2 , and $|\delta m_{31}|^2 \gg |\delta m_{21}|^2$ is indicated by the atmospheric and solar oscillation evidence. A recent analysis of the Super-Kamiokande (79 kton-yr) and the MACRO atmospheric neutrino data finds $1.5 \times 10^{-3} < \delta m_{31}^2 < 4.5 \times 10^{-3} \text{eV}^2$ and $\sin^2 2\theta_{23} > 0.84$ at the 95% confidence level with the best-fit at $|\delta m_{31}|^2 = 2.7 \times 10^{-3} \text{eV}^2$ and $\sin^2 2\theta_{23} = 0.96$ [5, 18]. The best fit solution to the latest solar neutrino data, $\delta m_{21}^2 = 4.9 \times 10^{-5} \text{eV}^2$ and $\sin^2 2\theta_{12} = 0.79$, lies in the LMA region with $2 \times 10^{-5} < \delta m_{21}^2 < 2 \times 10^{-4} \text{eV}^2$ and $\sin^2 2\theta_{12} > 0.6$ at the 95% confidence level [2, 19]. Note that the MSW solution selects $\delta m_{21}^2 > 0$. The sign of δm_{31}^2 can be either positive or negative, corresponding to having the

most widely separated mass eigenstate above or below the other two mass eigenstates. The current generation of nuclear reactor experiments (Palo Verde and CHOOZ) find null oscillation results and rule out $\bar{\nu}_e \rightarrow \bar{\nu}_x$ oscillations for $\delta m_{31}^2 > 10^{-3} \text{ eV}^2$ at maximal mixing and $\sin^2 2\theta_{13} > 0.1$ for larger δm_{31}^2 (at the 95% confidence level) [20, 21].

Approximate formulas for the oscillation probabilities in matter of constant density in the limit $|\delta m_{21}^2| \ll |\delta m_{31}^2|$, have been derived [22–24]. Expanding in $\alpha \equiv \delta m_{21}^2 / \delta m_{31}^2$, the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ probabilities for $\delta m_{31}^2 > 0$ are

$$P(\nu_\mu \rightarrow \nu_e) = x^2 f^2 + 2xyfg(\cos \delta \cos \Delta - \sin \delta \sin \Delta) + y^2 g^2, \quad (5)$$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = x^2 \bar{f}^2 + 2xy\bar{f}g(\cos \delta \cos \Delta + \sin \delta \sin \Delta) + y^2 g^2, \quad (6)$$

respectively, where $\Delta \equiv \delta m_{31}^2 L / 4E_\nu = 1.27 \delta m_{31}^2 (\text{eV}^2) L (\text{km}) / E_\nu (\text{GeV})$, $\hat{A} \equiv A / \delta m_{31}^2$, and

$$x \equiv \sin \theta_{23} \sin 2\theta_{13}, \quad y \equiv |\alpha| \cos \theta_{23} \sin 2\theta_{12}, \quad f, \bar{f} \equiv \sin((1 \mp |\hat{A}|)\Delta) / (1 \mp |\hat{A}|), \quad g \equiv \sin(|\hat{A}\Delta|) / |\hat{A}|. \quad (7)$$

Note that the existence of matter effects ($A \neq 0$) makes it possible to discriminate between $\Delta > 0$ and $\Delta < 0$, and thereby determine if there are two heavy mass eigenstates or just one (assuming the mass differences themselves are on the order of the highest mass eigenstate). The corresponding probability for a T -reversed channel is found by changing the sign of the $\sin \delta$ term. The formulas are valid at $E_\nu > 0.5 \text{ GeV}$ and $L < 4000 \text{ km}$ for all values of δm_{21}^2 currently favored by solar neutrino experiments. The corresponding expansion in α and θ_{13} in vacuum can be found by the substitutions $\sin((\hat{A} - 1)\Delta) / (\hat{A} - 1) \rightarrow \sin \Delta$ and $\sin(\hat{A}\Delta) / \hat{A} \rightarrow \sin \Delta$. Approximate analytic expressions for the probabilities for low energy beams have been derived in Ref. [25].

Neutrino oscillations can probe violations of the discrete symmetries CP , T and CPT . CPT invariance is a basic property of local quantum field theory and no deviations from it have been found to date, but CPT non-conservation may occur in string theory. If $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha)$ or $P(\nu_\alpha \rightarrow \nu_\alpha) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha)$, then CPT is violated. If $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$, CP is not conserved. If $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\nu_\beta \rightarrow \nu_\alpha)$ then T invariance is violated. When neutrinos propagate through matter, fake CP and CPT violation effects may be observed even if the mass matrix is CP conserving. However, matter-induced T -violating effects are negligible and are completely absent if the matter density-profile is symmetric with respect to the locations of the source and detector.

IV. THE NEED FOR NEW FACILITIES AND NEW DETECTORS

The first imperative for the currently planned experiments is that they achieve their primary goals for sensitivity to $\sin^2 2\theta_{23}$ and δm_{23}^2 . The next imperative is the detection of ν_μ to ν_e at a baseline corresponding to the atmospheric mass splitting, and the determination of the angle θ_{13} , for which there presently exists only an upper limit. The MINOS and CNGS experiments will have sensitivity down to $\sin^2 2\theta_{13} = 0.02$, and the JHF proposal is slightly more sensitive (and will be discussed more in detail later), but the appearance amplitude could be much smaller. In fact, some theoretical models suggest that $\sin^2 2\theta_{13}$ could be at the 10^{-3} to 10^{-4} level [26]. The value of θ_{13} is crucial to differentiate theoretical models of neutrino mass generation. Only after θ_{13} is measured can CP studies and the determination of the sign of δm_{13}^2 be achieved.

The logical path to increased sensitivity at a reasonable cost is to upgrade conventional beams to higher intensity and concurrently construct a large underground detector at a suitable distance. The energy of the neutrino superbeam and the baseline to the detector must be selected to optimize the physics reach [27]. For the ν_μ to ν_e oscillation to be nearly maximal, the average neutrino energy at a given baseline L should be chosen such that $\Delta_{31} = (2n + 1)\pi/2$. This choice also makes the ν_μ to ν_τ oscillation maximal, which aids in τ -appearance studies with a neutrino energy well above the τ -threshold energy of 3.56 GeV. Additionally, for CP studies, the δ dependence here is pure $\sin \delta$, with no $\cos \delta$ contribution, which eliminates a θ_{13} - δ ambiguity. The above statements remain valid even in the presence of matter. A narrow band neutrino beam is advantageous in order to have all neutrinos near the same L/E_ν value and to eliminate backgrounds, which are significant in conventional beams.

To learn the most physics for the given investment of a large neutrino detector, it is important that the detector be chosen and housed such that it can also be used to study other phenomena. Important areas of study which could also benefit from a new large underground detector include atmospheric and solar neutrino studies, and searches for both proton decay and neutrinos from supernovae. The lower the detector energy threshold, and the deeper underground the detector, the more physics it can access. Since we do not know where the next hint of physics beyond the Standard Model will lie, it is important to keep as many avenues open as possible.

TABLE I: Physics Sensitivity for Current Superbeam Proposals

Name	Years of Running	kton	$\sin^2 2\theta_{13}$ sensitivity (3σ)	CP Phase δ sensitivity (3σ)	ν Energy (GeV)
JHF to SuperK	5 years ν	50	0.016	none	0.7
SJHF to HyperK	2 years ν , 6 years $\bar{\nu}$	1000	0.0025	$> 15^\circ$	0.7
CERN to UNO	2 years ν , 10 years $\bar{\nu}$	400	0.0025	$> 40^\circ$	0.3

The following sections of this report describe a set of conventional neutrino beamlines and detectors that could be used to take the next step in neutrino oscillation physics. Where relevant, other non-accelerator physics possibilities will be mentioned. The physics capabilities for these conventional beamlines will be described, followed by a discussion of the capabilities of a neutrino factory. In fact, what new measurements the neutrino factory can provide depend critically on what the next few years of neutrino experimentation will tell us: What are the parameters of the solar neutrino oscillation? Is there a sterile neutrino sector? Is the small mixing angle between the third and first generation more than a per cent or so? We conclude this section with a discussion of the different possible answers to these questions, and what we would learn in each case from a neutrino factory.

A. Current Superbeam Proposals

There are currently three superbeam proposals which involve new neutrino beamlines directed towards large underground water Čerenkov detectors. Because of the wealth of experience now with water Čerenkov detectors at extremely low neutrino energies (at the sub-GeV level), and the fact that a 50 kton detector already exists, the reaches of these proposals have been evaluated with known detector effects and beam-related backgrounds. Table I shows a summary of the physics reach of these proposals. In summary, the JHF-based proposals involve building a beamline which can focus different momentum pions to make a narrow band beam to run at the oscillation peak, as is suggested above [28]. The CERN to UNO proposal starts with a much lower energy proton beam and has inherently lower backgrounds, so they can reach comparable sensitivities with a wide band low energy neutrino beam [29].

The JHF project involves building a new neutrino beamline at the Japanese Hadron Facility and aiming it toward the SuperKamiokande detector, at a distance of 295 km. This project has a few different models for narrow-band beams, each starting with the new 50 GeV proton source. The JHF facility itself has begun construction and is expected to finish in 2007. The neutrino beamline could conceivably begin operations by 2008, and is being designed to receive protons from a 0.77 MW proton source. Assuming that δm_{32}^2 is above $1 \times 10^{-3} eV^2$, this facility could see $\nu_\mu \rightarrow \nu_e$ at the three σ level if $\sin^2 \theta_{13}$ is larger than 0.016, and after five years of data-taking.

The JHF neutrino program also has an upgraded proposal, whereby both the beamline and the detector is augmented. The proton source itself would be upgraded to 4 MW, and the beamline elements would have to be fortified accordingly. The new detector proposed, HyperKamiokande, is another water Čerenkov device, but with 20 times the fiducial mass of the SuperKamiokande detector, located under the same mountain as the SuperKamiokande detector. With this increase of 100 in exposure (in terms of kton-years) they expect to be able to see $\nu_\mu \rightarrow \nu_e$ at 3σ if $\sin^2 2\theta_{13}$ is larger than 0.0025. If $\sin^2 2\theta_{13}$ is 0.01, and δm_{21}^2 is $1 \times 10^{-4} eV^2$, then CP violation could be observed if the CP phase δ is above 15 degrees (assuming the expected mass hierarchy for matter effects), assuming a two year neutrino run, and a six year antineutrino run.

Finally, there is a proposal which makes use of the Superconducting Proton Linac at CERN, which will be a 2.2 GeV proton source, operating potentially at 4 MW. The 2.2 GeV proton beam will be used to make a 300 MeV neutrino beam, with very low (and variable) intrinsic ν_e background. By aiming this beam at a cavern in the Frejus tunnel, located 150 km away, they could measure $\nu_\mu \rightarrow \nu_e$ if $\sin^2 2\theta_{13}$ is larger than 0.0025, similar to the SJHF to HyperK proposal. CP violation could be observed if the phase δ is larger than 40 degrees (for the same parameters mentioned above) assuming a two year neutrino run, and a ten year antineutrino run.

B. Choosing a Neutrino Energy

The choice to use low energy neutrino beams in the experiments in table I was motivated by several factors: for the CERN to UNO proposal, the intense proton source will be at 2.2 GeV, requiring a very low energy beam, which has in turn a very low electron neutrino background. Also for these experiments, the performance of Water Čerenkov at these energies is very well understood. In the following section a case will be made for more

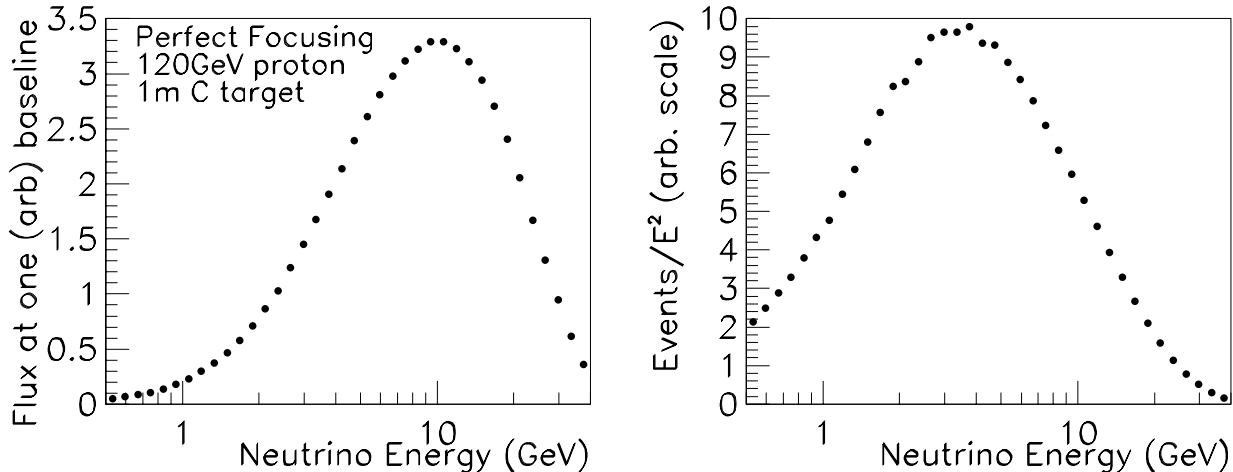


FIG. 1: Fluxes (arbitrary normalization) for a series of perfectly focused “monochromatic” neutrino beams, coming from 120GeV protons striking a 1m long graphite target. The left plot shows the flux at one baseline for several different focused energies, and the right plot shows the unoscillated event rate comparison (arbitrary scale) scaled by $1/L^2$, at the oscillation peak, or $(1/E_\nu^2)$.

than one superbeam, and in particular one at significantly higher energies than these two proposals. It is an important exercise, however, to understand how different energy beamlines compare. In the following section, it is assumed the flux achievable at one baseline is constant with energy as an exercise.

To produce an on-axis narrow band neutrino beam one focuses a given momentum bite of pions. However, for different momentum bites, one would want to direct the beam to different baselines. Figure 1 (left) shows the event distribution at 730 km coming from for a perfectly focused “monochromatic” pion beams, which were produced by 120GeV protons striking a 1 m graphite target [30]. To understand how the unoscillated fluxes would scale for perfectly focused narrow band beams, the distribution is shown in fractional energy bands (i.e. assume a perfectly focused pion beam with a constant fractional momentum bite at each energy). The most useful way to understand the beamline capability as a function of energy is to divide the event rate for that momentum bite by the square of the energy, since if one is operating at a given multiple of the peak the baseline (L) scales like the energy, and of course the event rate for these baselines scales like $1/L^2$. The result of that operation is shown in figure 1 on the right, for the same target and proton beam. As the pions one is trying to focus get higher in energy they are boosted more forward, so the far detector sees even more events than the $1/L^2$ scaling takes away. However, once the ν energies are above about 5 GeV the scaled rates drop, because much fewer high energy mesons are produced by 120GeV protons. Also, the finite length of the decay tunnel will also affect the highest energies—for the plot shown here the entire beamline is assumed to be 725m long. Clearly one also needs to understand how efficient the focusing can be as a function of pion energy, as well as the possibilities for off-axis neutrino beams, which can also provide narrow neutrino energy spectra.

C. The case for more than one Superbeam

The measurement of the transition of $\nu_\mu \rightarrow \nu_e$ is extremely important and helps link the solar and atmospheric anomalies together. Although any one superbeam measurement would signal a breakthrough in our understanding of the mixing matrix, the nature of superbeams is such that the signal will not be background-free, and the interpretation of the result will depend significantly on the ability of any experiment to predict its background. Furthermore, while the experiments outlined above have impressive sensitivity to the small mixing angle itself, they have no sensitivity to the sign of the largest mass splitting. In order to get the most information out of the $\nu_\mu \rightarrow \nu_e$ transition, it is important that there be an experiment which is sensitive to matter effects. Superbeams in principle may be able to measure matter effects if θ_{13} is large enough, but not the programs outlined above. Finally, the SJHF-HyperKamiokande proposal shows that matter effects are the same size as a change in the phase δ of about 8 degrees, in the LMA scenario. If that experiment does indeed see evidence for CP violation before the sign of matter effects is known, then there will be an additional uncertainty in whether or not CP violation in the lepton sector does actually occur.

Extensive studies have already been made of superbeams from BNL and Fermilab upgrades [31]. For the

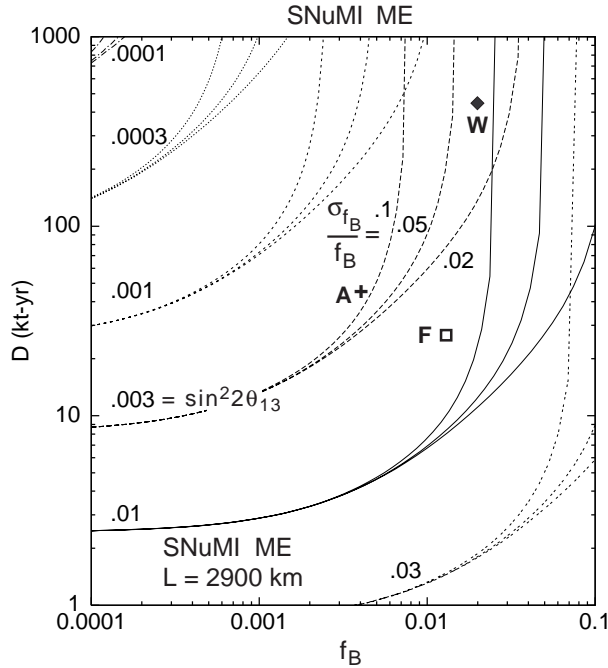


FIG. 2: Contours of constant $\sin^2 2\theta_{13}$ reach that correspond to a $\nu_\mu \rightarrow \nu_e$ signal that is 3σ above background for an upgraded NuMI medium energy beam with detector at $L = 2900$ km. The contours are shown in the (D, f_B) -plane, where D is the data-sample size. Curves are shown for systematic uncertainties $\sigma_{f_B}/f_B = 0.1, 0.05,$ and 0.02 . Three typical detector scenarios are shown: A (liquid Argon), F (steel-based), and W (water cerenkov) (from Reference 17).

discussion below we focus on physics results [32] that could be achieved with a 1.6 MW proton driver at Fermilab to obtain a factor of four intensity increase over the NuMI medium energy beam. Similar fluxes could be obtained with a BNL superbeam, so our conclusions should apply generally to either facility. To represent the anticipated flux loss in making a narrow band neutrino beam, we divide the flux estimate by a factor of five. Both liquid argon and megaton water Čerenkov detectors are under active consideration, and similar sensitivities to oscillation physics can be achieved with either detector. Our examples of the physics reach below are based on a liquid argon detector with an effective 70 kt-yr of data accumulation for detecting ν_e 's (e.g., a 70 kt liquid argon detector with 50% efficiency with 2 years of running). For ν_τ detection a 3.3 kt-yr exposure will be assumed (e.g. a 5 kt detector with 33% efficiency and 2 years of data taking). Antineutrino event rates are three to six times lower than neutrino rates, and correspondingly longer running times are required to accumulate comparable numbers of events. We assume a ν_e fractional background (f_B) (which includes both detector and beam backgrounds) of 0.4% of the unoscillated CC signal, and a fractional uncertainty on the background of σ_{f_B}/f_B of 10%. For concrete illustrations, we assume $\delta m_{31}^2 = 3.5 \times 10^{-3} \text{ eV}^2$, $\theta_{23} = \pi/4$, $\delta m_{21}^2 = 5 \times 10^{-5} \text{ eV}^2$, $\theta_{12} = 0.55$, recognizing that the physics reach is somewhat dependent on the oscillation parameters. Matter effects are taken into account. A range of baselines from 350 km to 2900 km is considered, with the corresponding optimal energies from 1 GeV to 8.2 GeV, respectively.

In this superbeam scenario, the neutrino event rate in two years running at a 350 km baseline (e.g., BNL to Cornell) would be 15 times that expected for 5 years running in the JHF to SuperKamiokande experiment at a 295 km baseline. Hence, superbeams offer a dramatic improvement in the $\sin^2 2\theta_{13}$ reach. The ν_μ to ν_e appearance sensitivity at 3σ for baselines from 350 km to 2900 km is, respectively, 0.002 to 0.003, an order of magnitude below the reach of the upcoming long baseline experiments with conventional beams. Figure 2 shows the typical sensitivity of the $\sin^2 2\theta_{13}$ reach to f_B and σ_{f_B}/f_B . The sensitivity of a liquid argon or steel-based detector is best improved by increasing the size, while for a water Čerenkov detector it is best improved by lowering the backgrounds and/or systematic uncertainty on the background. The CP phase δ can be measured down to 40 degrees at 3σ for $\sin^2 2\theta_{13} = 0.01$. However, at the short 350 km baseline, matter effects are small, so there is very little sensitivity to the sign of δm_{13}^2 .

At baselines above 1200 km, matter significantly affects appearance rates and the neutrino mass-hierarchy can be resolved. For example, at 1290 km (e.g., Fermilab to Homestake) the sign of δm_{13}^2 can be determined at a three σ reach of 0.01 on $\sin^2 2\theta_{13}$, which improves by a factor of two at 2900 km. Moreover, due to the higher optimal energies for long baselines, ν_τ appearance studies become feasible at distances of 1290 km and

above. For example, 14 ν_τ events would be observed at 1290 km (77 ν_τ events at 1770 km, FNAL-Carlsbad or BNL-Soudan). However, there is no sensitivity to the CP phase at these distances.

A novel idea for a superbeam which resembled the front end of a neutrino factory was proposed at this workshop. With all the proposals outlined above, the assumption is that the secondary beam focusing will be done primarily with horns, and so the beam will be either neutrinos or antineutrinos. For the target and focusing of a neutrino factory, there will be solenoidal focusing and therefore a mixed ($\nu + \bar{\nu}$) beam. If the far detector could measure the outgoing charge of the electron (and muon) then it could search for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ simultaneously. Also, a solenoidal focusing system would have a much lower failure rate than a horn system at a high proton power source, since there would be no material in the secondary beam. Recent studies have shown that a liquid argon calorimeter might be able to measure the charge of outgoing electrons up to a GeV [33], so for a low energy solenoid-focused neutrino superbeam, this could be an attractive option [34]. A superbeam detector which could identify lepton charge could then also be used as the far detector for a neutrino factory beam.

Furthermore, longer baselines (for example, those where $L_n = (2n + 1) \frac{2\pi E_\nu}{\delta m_{31}^2}$) with superbeams may be useful for studies of CP violation, due to the fact that the asymmetry increases linearly with baseline length in the small $\delta m_{21} L/E$ approximation [35]. If the asymmetries one is trying to measure are larger, then fixed fractional uncertainties on background fluxes, detector acceptances, etc, become less important. The challenge in that case is to provide an intense enough neutrino flux to produce enough events in the far detector, and to make sure that matter effects do not enter in so much as to obscure the asymmetry.

There is thus a complementarity of superbeam experiments at short and long baselines. Experiments at the first oscillation maximum can search for the oscillation itself and are most sensitive to seeing θ_{13} if it is very small. Experiments at higher multiples of the oscillation maximum may be able to test for CP violation in the lepton sector. Experiments at higher energies and long baselines can determine the neutrino mass hierarchy and measure ν_τ appearance. We conclude that the full physics of the neutrino sector can only be explored with superbeams at short and long baselines.

D. Detector options for superbeams

The first two requirements for a neutrino detector for a superbeam is that it can identify both ν_μ and ν_e charged current interactions, and measure the total neutrino energy of the neutrino interaction. At lower neutrino energies the neutrino cross section is primarily quasielastic, so the detector simply must identify an outgoing muon or electron. However, for neutrino energies above a GeV there is substantial hadronic activity accompanying most neutrino scattering events, and the difference between the detectors discussed below lies in their abilities to identify that accompanying hadronic activity.

It is important, however, that these large superbeam detectors also contribute to other important areas of physics, since they will no doubt be costly devices. By housing these detectors deep underground, they could also make advances in the search for proton decay, supernovae detection, and solar and atmospheric neutrino studies. Since we do not know where the next physics beyond the Standard Model will surface, it is important that we not neglect these other areas.

1. Water Čerenkov

Water Čerenkov detectors have been the most studied devices for superbeams, since they have provided some of the most convincing signals for neutrino oscillation. Also, SuperKamiokande is the most massive neutrino detector constructed to date that would work in a superbeam. Although they have been proven to work extremely well at neutrino energies below 1 GeV, it remains to be seen how well the detector concept would work for higher energy neutrino beams. The largest uncertainty is how well they could reject backgrounds from higher energy neutrino neutral current interactions which contain energetic π^0 's which decay asymmetrically, producing an electromagnetic-like ring in the detector. There is much work continuing on different techniques for Čerenkov light collection, as well as different techniques for focusing the light itself to improve the signal.

A novel idea proposed at this workshop is similar to a segmented iron calorimeter but uses water as the sensitive material. The Čerenkov light is reflected inside a long thin water tank oriented transversely to the incoming neutrino direction (a tank could be $1m \times 1m \times 10m$, and a calorimeter would consist of several hundred of these tanks). and is collected at the end of the tank by small photomultipliers. Such a detector might be built at a moderate cost compared to a steel-based detector. A water tank prototype has been built at IHEP, Beijing, and tests with cosmic rays are underway. Preliminary Monte Carlo study shows that its performance is similar to or better than those of steel-based calorimeters or Čerenkov ring imaging detectors, particularly at energies

higher than a few GeV. Unfortunately the limited number of photoelectrons for this configuration prevents it from being used for low energy physics, such as solar neutrino studies, in contrast to the single-volume water Čerenkov devices.

2. Liquid Argon Calorimeter

A liquid argon TPC, such as the one being built by the ICARUS collaboration, would be an extremely powerful device to use for a neutrino superbeam. The detector is basically an electronic bubble chamber, and would be able to detect individual tracks in the hadronic showers. Studies based on GEANT simulations of the detector show that the neutral current background could be suppressed by three orders of magnitude, simply by looking at the energy loss in the first few radiation lengths of the electron candidate in the neutrino event. Because of the superior vertexing, most shower-related backgrounds vanish. There is currently half of a 600ton module of instrumented liquid argon taking data on cosmic rays, and the data there look promising [36]. Although the readout cost and cryogenics prohibit detectors on the 500kton scale, as have been proposed with water Čerenkov detectors, the improved signal reconstruction and background rejection may provide a high enough signal efficiency to make the technology competitive.

One important unknown about the liquid argon technique is how large a single volume could be used. The ICARUS proposal now has 600ton modules, but to avoid being prohibitively expensive, a much larger module size must be achieved. If one could instrument a volume the size of the SuperKamiokande detector with liquid argon, then it would be 70ktons. If the signals could then be made to drift across 5m then a detector this massive would not be prohibitively expensive [37], [38]. Discussions with mining engineers have begun and have been encouraging [39]. Furthermore, a small volume of this detector should be placed in a neutrino beam shortly both to measure neutrino cross sections [33], and to understand how closely the actual performance mirrors the Monte Carlo prediction. Finally, if a magnetic field could be introduced in this detector, then it could be used for the solenoid-focused proposal discussed earlier, but would ultimately make an ideal detector for a neutrino factory beam. Its low detector threshold and particle identification make it particularly attractive for proton decay and supernovae searches.

3. Steel-Based Detector

A steel-based detector is the most coarse-grained of the detector options being considered for neutrino superbeams. Although they have typically been used for higher energy neutrino beams, with enough transverse and longitudinal segmentation they too can provide discrimination between ν_μ and ν_e charged current events. They typically have neutral current rejection on the order of a few per cent; additional kinematic cuts must be used to reduce that background to the few times 10^{-3} level [40]. In order to make them particularly interesting for atmospheric neutrino studies, they would be magnetized, allowing atmospheric neutrino studies to be performed on ν_μ and $\bar{\nu}_\mu$ separately. Unfortunately, however, steel-based detectors have a detector threshold which would prevent them from being used for solar neutrino studies or proton decay searches.

E. Physics Reach of a Neutrino Factory

It is extremely likely that a superbeam facility would not completely determine the neutrino mixing matrix or measure the CP violating phase. In that circumstance a neutrino factory, a natural progression from a superbeam, will be needed to provide intense beams. This ultimate neutrino source will enable precision measurements of the crucial remaining parameters that could test Grand Unified and other theories of neutrino mass. The physics of flavor is one of the major unanswered problems in particle physics, and complete knowledge of the flavor changing neutrino processes is essential in developing the theory of flavor violations.

The neutrino factory concept is to create a millimole per year muon source, rapidly accelerate the muons to the desired energy, and then inject them into a storage ring with a long straight section that is directed towards a far detector. The decays of the muons in the ring give ν_e and $\bar{\nu}_\mu$ beams for stored positive muons and $\bar{\nu}_e$ and ν_μ beams for stored negative muons. Thus, for the first time, intense electron neutrino beams would be available. The resulting neutrino beams will have an energy spectrum that is well understood from the kinematics of muon decay. The $\nu_e \rightarrow \nu_\mu$ appearance channels, which lead to wrong-sign muons, yield relatively background-free signals, above a muon production threshold of about 4 GeV, which in turn mandates a minimum stored muon energy of 20 GeV. For such energies, long baselines (> 1800 km) are optimal for oscillation studies. An entry level neutrino factory may have 20 GeV stored muons with 10^{19} muon decays in the beam-forming straight

section. A high performance factory would be a 50 GeV ring delivering 10^{20} muons per year, yielding 10^{22} kt-decays after a few years of running. A 50 kt iron scintillator target is nominally considered for the detector.

What new physics can be explored at a neutrino factory? First, a neutrino factory could measure $\sin^2 2\theta_{13}$ down to 10^{-4} . If this mixing angle is indeed below 10^{-3} , a factory is the only way to measure it. Second, with a detector located at a long baseline, both the sign of δm_{13}^2 and the CP phase can be determined. Interestingly, the intrinsic CP violating effects are absent at 7300 km (e.g., Fermilab to Gran Sasso) and maximal CP violation occurs at a baseline of about 2900 km [41–43], as shown in Fig. 3. The sign of δm_{13}^2 can be determined via matter effects down to $\sin^2 2\theta_{13}$ of 10^{-4} . If $\sin^2 2\theta_{13}$ is 0.01 and δm_{12}^2 is 1×10^{-4} , as was assumed for the sensitivities quoted in table I, then a neutrino factory can in three years μ^+ running and six years μ^- running, see a three σ CP violation effect down to $\delta = 12^\circ$ with a 50kton detector. However, if $\sin^2 2\theta_{13}$ is as low as 2×10^{-4} , then CP violation can still be detected at three σ if δ is above 40° .

Simulations [22, 43, 44] have been made that demonstrate determinations of all the oscillation parameters, including the CP phase, to impressive accuracies. Figure 4 shows representative results from one such study. Figure 5 compares the physics reach of superbeams and neutrino factories in the parameters $\sin^2 2\theta_{13}$ and δm_{21}^2 . The strength of the neutrino factory lies in the precision achievable if $\sin^2 2\theta_{13}$ is large, and in the reach of the mixing angle itself if $\sin^2 2\theta_{13}$ is small.

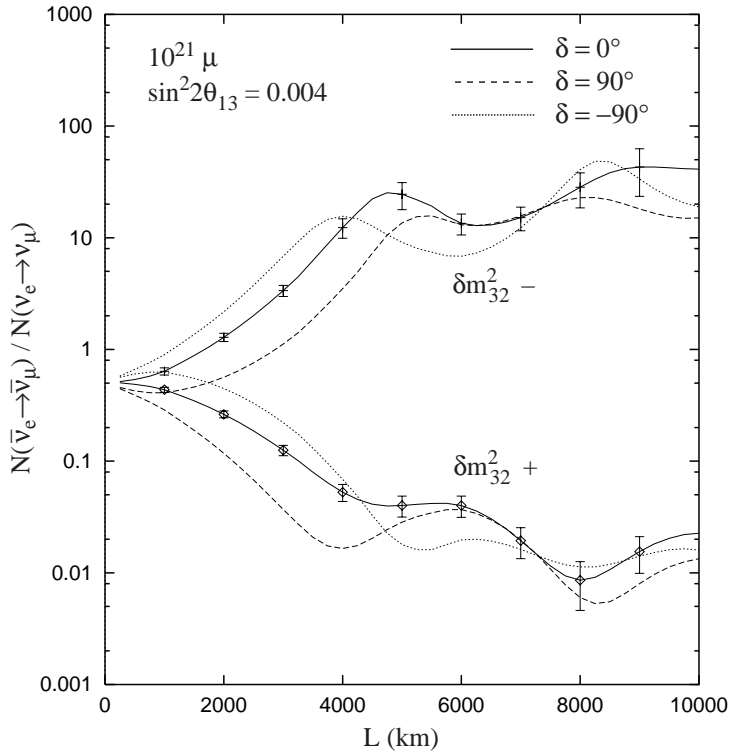


FIG. 3: The ratio of event rates at a 20 GeV neutrino factory for $\delta = 0, \pm\pi/2$. The upper group of curves is for $\delta m_{32}^2 < 0$, the lower group is for $\delta m_{32}^2 > 0$ and the statistical errors correspond to 10^{21} muon decays of each sign and a 50 kt detector. The oscillation parameters correspond to the LMA solution with $|\delta m_{32}^2| = 3.5 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta_{13} = 0.004$. See Ref. [45].

F. Scenarios Leading to Neutrino Factory Measurements

It is important to understand what a neutrino factory has to offer depending on what scenarios turn out to be true in neutrino oscillation physics. Keep in mind that at the time of this document we only know that there are three indications of oscillations with non-overlapping mass splittings, and that for at least one of those mass splittings, the corresponding mixing angle appears to be large.

The physics that a neutrino factory can provide depends on a few key factors, all of which will be determined within the next 5 years or so:

1. whether or not the LSND signature is due to oscillations;

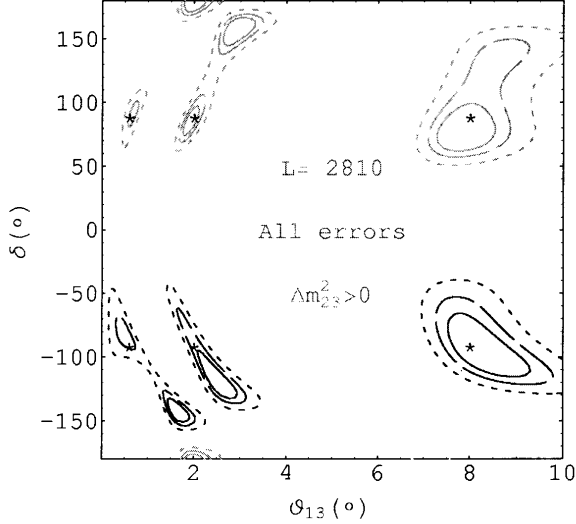


FIG. 4: Fits of δ and θ_{13} for various central values of δ and θ_{13} in simulations of neutrino factory capabilities at $L = 2810$ km. See Ref. [46].

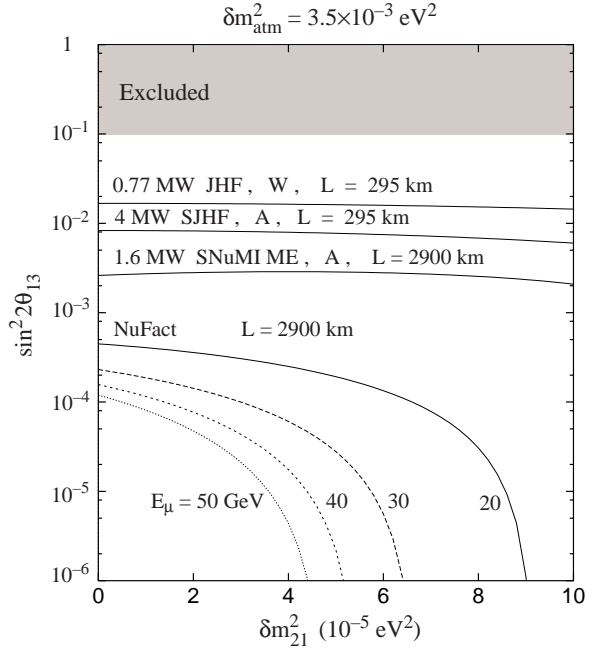


FIG. 5: A comparison of the physics reach of superbeams and neutrino factories. Adapted from the study in Ref. [27].

2. if the solar neutrino anomaly is described by the LMA solution; and
3. if the next generation of neutrino experiments sees ν_μ to ν_e (in other words, if $\sin^2 2\theta_{13}$ is up to a factor of 3 below the current limit from CHOOZ)

If the LSND signature is in fact due to oscillations, then a neutrino factory is basically the only way we can access the sterile neutrino sector. In this scenario it becomes extremely important to try to measure every transition as accurately as possible, to try to understand the structure of the sterile neutrino sector: is there more than one sterile neutrino? High energy neutrino beams will be needed at short baselines to study ν_μ and ν_e transitions to ν_τ at the LSND mass difference, as well as the antineutrino transitions. It becomes possible to observe CP violation in ν_μ to ν_e at atmospheric mass difference baselines. The requirements for the short baseline experiments are much more modest in this scenario, and one can already start defining the sterile neutrino sector with an order of magnitude fewer muon decays per year than what has already been described in study II [47]. MiniBooNE will have adequate sensitivity over the entire LSND signal region to determine conclusively whether or not we are in this scenario [11].

If the LSND signature is not due to oscillations, then the next question that defines the scope of a neutrino factory is whether or not the solar neutrino anomaly is described by the large mixing angle solution, as is currently the most favored region. This will be determined by the KAMLAND experiment, again in just a few years from now.

If KAMLAND does see neutrino oscillations, then whether or not CP violation is accessible depends on the value of the smallest mixing angle, $\sin^2 2\theta_{13}$. If the next generation of neutrino oscillation experiments sees $\nu_\mu \rightarrow \nu_e$, then CP violation may be able to be probed by a conventional neutrino experiment. In order for CP violation to be seen, δ must be large or matter effects must be measured, and the experiments proposed require extremely long run times (see table above) and depend on high background rejection in both neutrino and antineutrino running. In this scenario, the reach of a neutrino factory will be purely statistics limited, and precision measurements of all of the oscillation parameters would be achievable.

If KAMLAND does see neutrino oscillations but the next generation of neutrino experiments does not see evidence for $\sin^2 2\theta_{13}$ being non-zero, then CP violation and the sign of matter effects would only be accessible at a neutrino factory, as long as $\sin^2 2\theta_{13}$ was larger than a few 10^{-4} . For values smaller than that, ν_e to ν_μ might still be seen, but it would be due to sub-leading oscillations, or the solar mass scale.

If KAMLAND does not see neutrino oscillations, then CP violation measurements are not accessible at either a neutrino factory or a superbeam, and the physics we can hope to understand from oscillation measurements is “only” the size of $\sin^2 2\theta_{13}$ and the sign of the largest mass splitting. Again, if evidence for $\sin^2 2\theta_{13}$ is seen

at the next generation of neutrino experiments, a neutrino factory could provide much better precision on this angle, as well as a guaranteed measurement of the sign of the largest mass splitting. If θ_{13} is not seen at the next generation of experiments, then neutrino factories have extremely good reach in this angle, since the subleading contributions due to the solar neutrino oscillations would not contribute significantly to the probability.

It is clear that regardless of the outcomes of the next generation of neutrino experiments, a neutrino factory would provide a laboratory to extend our understanding of the lepton mixing sector. The fact that both the ν and $\bar{\nu}$ rates are so high, and the backgrounds in both beams are so low allow huge leaps in measurement precision.

V. PAVING THE ROAD TO A NEUTRINO FACTORY AND MUON COLLIDER

While the lead time to completing the R& D for a neutrino factory is long, the machine itself can be constructed in stages to provide important physics opportunities at each step along the way [49]. Because we do not know where the next big discovery will lie, it is important to pursue the physics accessible at each of these stages. The stages themselves can be described (simplifying) as follows:

1. Upgraded Proton Source
2. Intense Muon Source: 200 MeV
3. Intense Muon Source: 2-3 GeV
4. 20-50 GeV Muon Storage Ring
5. Muon Collider: from a Higgs factory to the energy frontier

In the first part of this document we described the oscillation physics accessible with the neutrino beams which can come from this facility. In the remainder of this document we discuss briefly the wealth of other measurements which can be made at the beamlines listed above.

Aside from just the physics that we know can be done at these new facilities, it is important that R& D be pursued for a neutrino factory for the following reason: the neutrino factory itself came only as a byproduct of people trying to understand how to use muons to get to the energy frontier. By exploring all the avenues we can for new experiments, we are opening the door for still more unforeseen techniques which may prove to be themselves landmark experiments in physics areas which we have yet to uncover.

VI. INTENSE MUON SOURCE PHYSICS

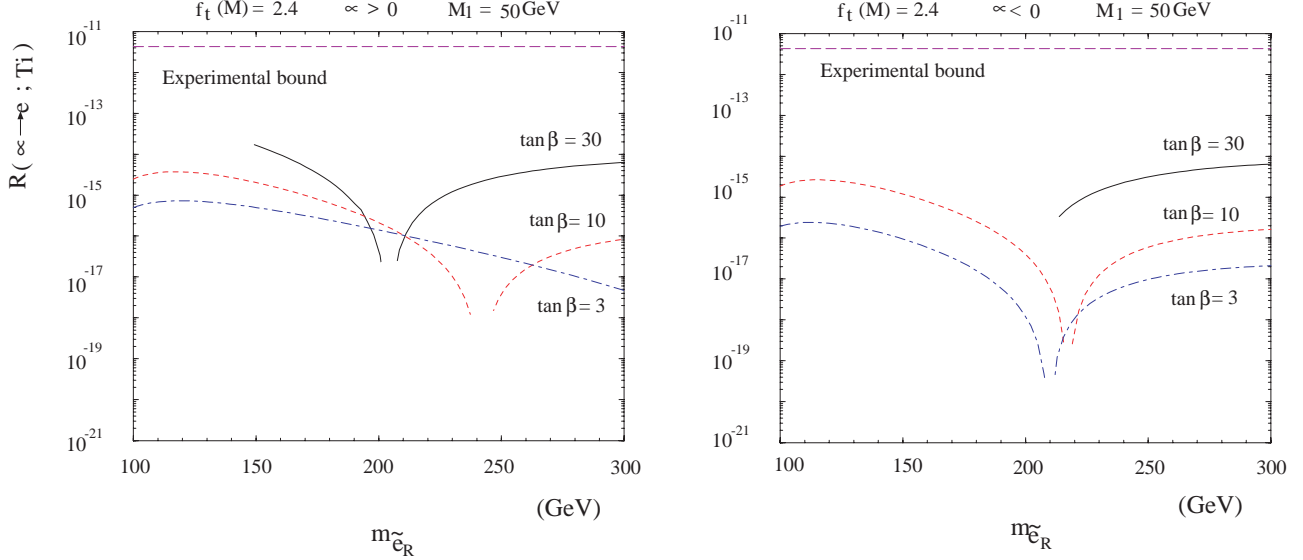
A. Overview

An intense muon source, such as that provided for the front end of a neutrino factory/muon collider, could yield significant improvements in our exploration of muon physics. The expected intensity of such a source is $10^{13} - 10^{14} \mu^\pm/s$, *i.e.*, five or six orders of magnitude higher than that presently available. Examples of particle physics programs which might be pursued with intense muon sources are (1) muon lepton flavor violation (LFV) and (2) muon moments such as the anomalous magnetic moment ($g - 2$) and the electric dipole moment (edm) of the muon. The former programs can best be done with low-energy muons (mostly stopped muons), while the latter could be carried out employing in-flight muons in a ring.

At present it appears that these muon physics programs would benefit significantly from the staging accelerator scenario of a neutrino factory. The coupling between the physics programs and staging is illustrated in Table II. Stage I, a proton driver with 1–4 MW beam power, would yield significant improvements in the LFV and muon moment experiments. Stage II with a 200 MeV cooled muon beam would match well to an improved muon edm experiment. Because the beam repetition rate of such a source is low, however, new ideas on how to handle high instantaneous rates would be necessary to utilize Stage II for LFV. With the 3 GeV cooled muon beams of Stage III, the new generation muon ($g - 2$) experiment could be realized.

TABLE II: muon physics programs in the accelerator staging approach.

Stage	Accelerator Component	Physics Programs
I	high intense proton driver	LFV, muon edm, muon g-2
II	200 MeV cooled muon beam	muon edm, (LFV)
III	3 GeV cooled muon beam	muon g-2

FIG. 6: Prediction of $\mu^- - e^-$ conversion in SUSY SU(5).

B. Muon Lepton Flavor Violation

1. Physics Motivation

In the Standard Model (SM), LFV in charged lepton processes is suppressed even with non-zero neutrino masses. However, in extensions of the minimal SM LFV could occur from various sources [50]. Important LFV processes involving muons are $\mu^+ \rightarrow e^+ \gamma$, $\mu^- - e^-$ conversion in a muonic atom ($\mu^- + N \rightarrow e^- + N$), $\mu^+ \rightarrow e^+ e^+ e^-$ and so on.

Recently, considerable interest in LFV has arisen based on supersymmetric (SUSY) extensions to the SM, in particular supersymmetric grand unified theories (SUSY-GUT). In many models of SUSY-GUT, LFV can be naturally introduced. For instance, in supergravity-mediated SUSY models, radiative corrections in the renormalization group evolution from the GUT scale to the weak-energy scale lead to finite mixing in the slepton mass matrix, even when it is assumed to be diagonal at the Planck scale. Recently, Barbieri and Hall [51] found that the slepton mixing thus generated is very large owing to the surprisingly large top quark Yukawa coupling. Through loop diagrams $\mu \rightarrow e$ transitions then occur due to this slepton mixing. The predicted branching ratio ranges between the current bounds and a few orders of magnitude smaller [52], and could be experimentally measurable. The predicted branching ratio of $\mu^- - e^-$ conversion in a muonic atom in SUSY SU(5) is shown in figure 6.

Furthermore, the existence of massive neutrinos and their mixing, as suggested by the recent solar and atmospheric neutrino measurements, might allow additional LFV contributions in the SUSY-GUT models. Such models include a heavy right-handed majorana neutrino of $10^{14} - 10^{15} \text{ GeV}/c^2$ with $\nu_\mu - \nu_\tau$ mixing of $\sin^2(2\theta_{32}) \sim 1$. The predicted branching ratio for $\mu \rightarrow e \gamma$ is shown in figure 7.

CP violation in lepton flavor violation has been pointed out to be important to study the Majorana CP phase of the heavy neutrino in the see-saw model in a class of SUSY models [53]. It could be studied by T-odd correlation in $\mu^+ \rightarrow e^+ e^+ e^-$ decay and the muon edm.

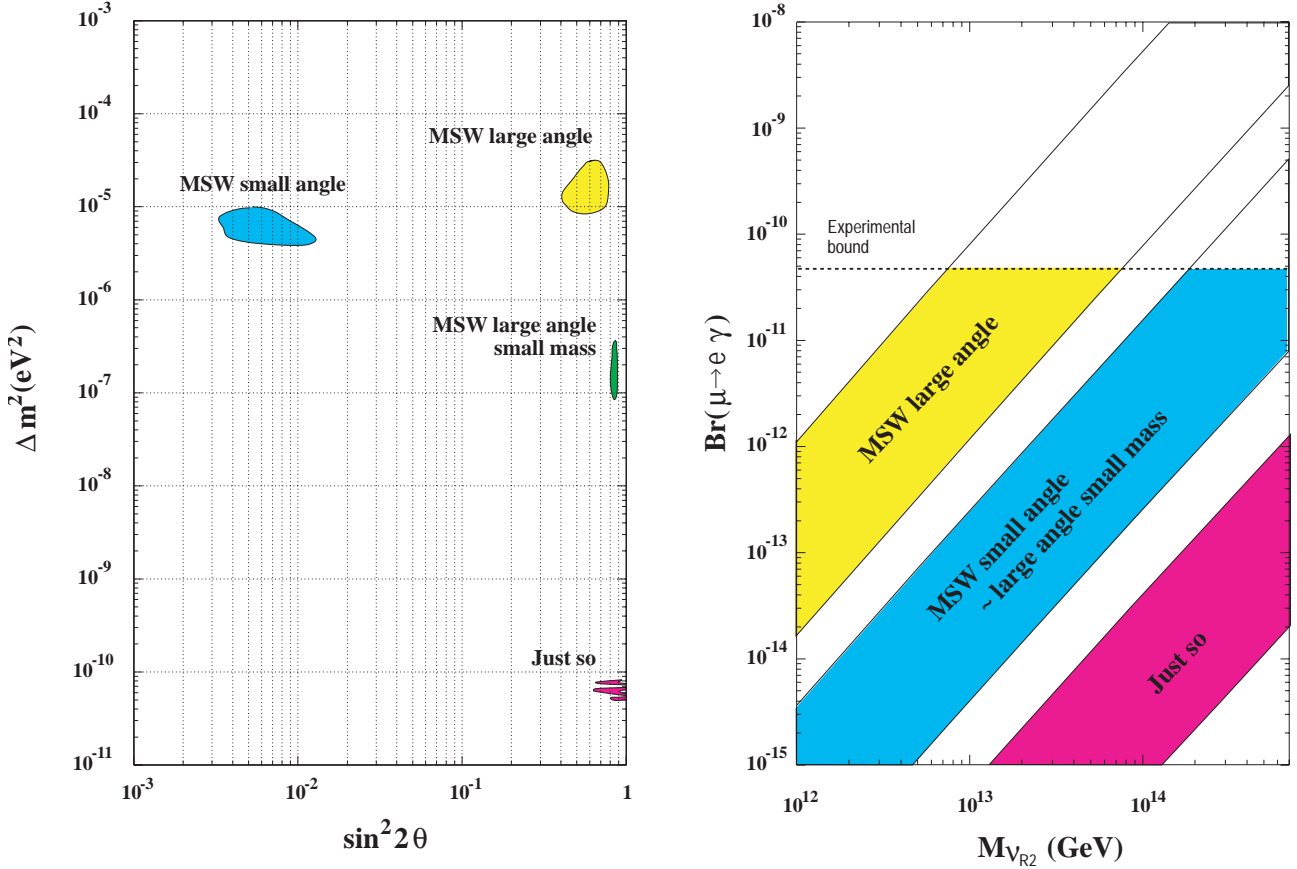


FIG. 7: Left: The allowed region in parameter space for solar neutrino oscillations. The regions in yellow, blue, and red correspond to the LMA, SMA, and VAC solutions, respectively. Right: Prediction of the $\mu \rightarrow e\gamma$ branching ratio in SUSY models with heavy right-handed neutrinos.

2. Experimental Prospects

Most of the LFV experiments could use stopped muons. There are the three such processes to study: (a) $\mu^- + N \rightarrow e^- + N$, (b) $\mu^+ \rightarrow e^+\gamma$, and (c) $\mu^+ \rightarrow e^+e^+e^-$. The latter two require a continuous beam in order to minimize accidental backgrounds. For a proton driver such as suggested for Stage I to be a source for these experiments, slow beam extraction with a high duty factor would be needed. On the other hand since process (a) is based on single particle detection it does not suffer from accidental backgrounds, and therefore is the best suited for high rate muon beams.

In what follows we discuss several experiments presented at the Snowmass conference.

3. $\mu^+ \rightarrow e^+\gamma$

A detector for $\mu^+ \rightarrow e^+\gamma$ has to have good energy and position resolutions as well as timing resolution for e^+ and γ . A new experiment to aim at a sensitivity of 10^{-14} at PSI is being prepared, with a xenon photon calorimeter. To go beyond, a detector improvement is necessary before an increase of a muon beam intensity.

4. $\mu^- - e^-$ conversion in a muonic atom

The current upper limit of $B(\mu^- + \text{Ti} \rightarrow e^- + \text{Ti}) < 6 \times 10^{-13}$ comes from the SINDRUM-II experiment at PSI. A new experiment, E940 (MECO) is being prepared at BNL-AGS [54]. It aims to search for $\mu^- + \text{Al} \rightarrow e^- + \text{Al}$ at a sensitivity better than 10^{-16} . The experimental setup is shown in figure 8. A pulsed proton beam of about 600 kHz with pulse width of 50 nsec is used to minimize beam-associated backgrounds. The muon beam rate

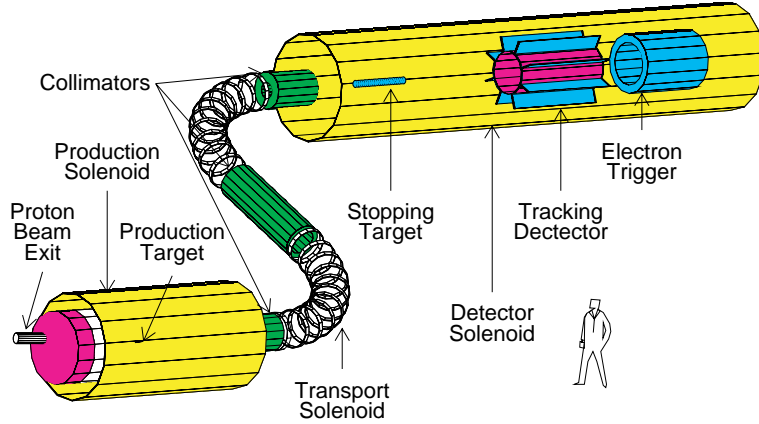


FIG. 8: Schematic layout of the MECO detector.

of $10^{-11} \mu^-$ per second stopping in the target is expected with 50 kW proton target energy deposit. The single rate of detector chambers is as high as 500 kHz.

What would be possible upgrades once an intense proton driver and the front end of neutrino factory are available? The MECO detector is optimized for the current BNL-AGS beam rate. If an intense proton driver (of 1-4 MW) were available, further detector optimization would be needed to reduce the singles rates, but such optimization is feasible. At stage II it would be advantageous to use a cooled muon beam with a smaller energy spread and smaller beam size. However, the low repetition rate (a few tens of Hz) would be a drawback. Perhaps a smart detector system might be developed to handle the high instantaneous rates.

In Japan, a dedicated facility called PRISM (=Phase Rotated Intense Slow Muons) is being considered for the JHF. It employs phase rotation to reduce the beam energy spread, and has a long flight path in a fixed-field-alternating-gradient synchrotron ring (FFAG) to remove the surviving pion contamination in the muon beam.

Whatever the nature of an intense muon source, a next-generation experiment could aim at a sensitivity of 10^{-18} .

C. Muon Moments

1. Muon $g - 2$ Magnetic Moment

The recent observation of a 2.6σ deviation from the Standard Model prediction of the anomalous magnetic moment of the muon ($g - 2$) is a dramatic and exciting result for particle physics.[55]. It might well be an indicator of physics beyond the Standard Model. If such new physics originates from SUSY, it may also give rise to muon LFV; non-Standard Model $g - 2$ is sensitive to the diagonal matrix elements of the slepton mass matrix, while LFV senses the off-diagonal matrix elements.

Now that $g - 2$ has been measured to the parts per million (ppm) level an improved understanding of systematic uncertainties in this type of measurement is available. It is anticipated that in a new experiment the the basic technique would not change: a weak focusing storage ring operating at 3.1 GeV, with electrostatic quadrupoles providing vertical focusing, and electrons from decaying stored muons being observed. A more uniform magnetic field, smaller storage aperture, and better magnetometer and beam inflector, along with the reduced phase space and more intense beam provided by a Stage III cooled muon beam, could provide a significantly improved measurement. Increased polarization with a small sacrifice in intensity is an added benefit. All of the above improvements would serve to provide a more precise measurement with smaller systematic uncertainty.

On the theoretical side, more precise experimental measurements of hadron production from e^+e^- collisions at low energies and τ lepton decays coupled with better lattice calculations could reduce uncertainties in $g - 2$ due to the hadronic contribution.

2. Muon Electric Dipole Moment

There are already stringent limits on the edm of first generation particles (electron and neutron). It is very important to do a sensitive search for the edm of a second generation particle. The Feynman diagram is the same as for the muon anomalous magnetic moment, but with a CP violating phase. The Standard Model prediction for all edm's is unmeasurably small. Therefore, any measured value indicates new physics such as supersymmetry. Several models predict values for the muon edm at the few $\times 10^{-23}$ e-cm level, consistent with electron edm limits and the muon $g - 2$ value.

The last measurement of the muon edm gave $(3.7 \pm 3.4) 10^{-19}$ e-cm. There is an LOI for a dedicated muon electric dipole moment experiment at the BNL-AGS. It plans to use the $g - 2$ storage ring, but its field would be set below the magic momentum used by the $g - 2$ experiment (3.1 GeV/c). Presently, the optimum momentum is believed to be between 0.2 and 0.5 GeV/c.

Such an experiment is envisioned to proceed in three stages:

(1) Needed statistics: $NP^2 = 10^{12}$, where N is the number of muon decays accumulated and P is the polarization. The existing $g - 2$ ring would be changed to weak magnetic focusing (instead of electrostatic). The level of sensitivity to the edm would be $\sim 10^{-22}$ e-cm after about 400 hours of physics running, and the systematic uncertainties could be measured with an accuracy of 10^{-24} e-cm. This stage provides very important information about the real problems in such a measurement.

(2) $NP^2 = 10^{14}$. The $g - 2$ storage ring would be further modified to strong focusing. The level of sensitivity to the edm would then be $\sim 10^{-23}$ e-cm after about 4000 hours of physics running. A Proton Driver would reduce the 4000 hour to 500 hours.

(3) $NP^2 = 10^{16}$. This probably requires stage II of the front end of neutrino factory [56]. At this stage, $NP^2 = 10^{16}$ can be accumulated in about one year of physics running. Almost certainly, a new storage ring would be necessary, optimized for this measurement. Note that unlike the $g - 2$ experiment, it is not necessary to keep the homogeneity of the magnetic field to the 10^{-7} level, but only to what is usually required for storage rings (about three orders of magnitude worse). The required beam specification is (a) muon beam momentum: 0.2-0.5 GeV/c, (b) muon beam intensity: 10^{11} /sec, (c) NP^2 : 10^{16} , (d) dp/p: 1%, (e) angular divergence: ≈ 10 mrad, (f) beam size: ≈ 100 mm, (g) bunch duration: < 30 ns, (h) time between bunches: 20 ms, (i) polarization: as large as practical (a modest 16% in the neutrino factory design report).

D. Applications

Once an intense muon source is available, other applications can be considered. They are, for instance, muon catalyzed fusion, and life science studies by μ SR (muon spin rotation). For the former, a small size target of D-T mixture could be exposed to extreme conditions with a high intensity μ^- beam. For the latter, the use of a smaller sample with a small phase space, highly polarized muon beam could provide critical next-generation experiments. Besides these two, various applications to materials science are also envisaged.

VII. NEUTRINO SCATTERING PHYSICS

A. Introduction

There is still much to be learned **from** neutrinos as well as much to be learned **about** neutrinos. Although neutrino oscillation experiments certainly will drive the construction of new neutrino beamlines, these new very intense beamlines also allow us to continue an active research program at a detector located close to the production target. At such a near detector, associated with a superbeam or neutrino factory, the event rates will be much higher than at the previous generation of neutrino beam facilities allowing the use of much lighter targets and avoiding the large and unknown nuclear effects which complicate the interpretation of current neutrino scattering experimental results.

B. Low Energy Neutrino Physics

There are many interesting topics which can be studied as part of a low energy neutrino program at a superbeam facility. Some of these are only possible with the high intensities expected there. Physics topics using low energy, high intensity neutrino beams explored at Snowmass include:

- $\nu_\mu e^-$ elastic scattering at low- Q^2 ; the neutrino magnetic moment.
- Quasi-elastic scattering; the strange-spin of the nucleon, Δs
- Lepton number violating processes (non-oscillations)

1. Neutrino-electron elastic scattering- Search for nonzero neutrino magnetic moment

The recent discoveries in the neutrino sector in the Standard Model have opened a new frontier in high energy physics. Understanding neutrinos and how they interact is crucial to continuing to verify the Standard Model and look for physics beyond the Standard Model. Searches for electromagnetic properties of neutrinos, such as a non-zero neutrino magnetic moment, can set limits on beyond Standard Model physics in the neutrino sector and in other sectors as well as addressing a number of important astrophysical limits.

Neutrino magnetic moments can arise through a variety of beyond the Standard Model mechanisms. In the minimally extended Standard Model massive Dirac neutrinos of mass m_ν can have a non-zero neutrino magnetic moment of the size $\mu_\nu = \frac{3eG_F}{8\sqrt{2}\pi^2} m_\nu \sim 3 \times 10^{-19} \mu_B \frac{m_\nu}{1eV}$ arising from one loop radiative corrections in diagrams with W-boson exchange. Extensions to the Standard Model such as the supersymmetric left right model and models including large extra dimensions predict neutrino magnetic moments ranging up to $10^{-11} \mu_B$ [57, 58]. A non-zero neutrino magnetic moment would also have important implications in cosmology in the development of stellar models. Astrophysical limits such as plasmon decay rates from horizontal branching stars and neutrino energy loss rate from supernovae allow a neutrino magnetic moment as large as $10^{-11} \mu_B$ [59, 60].

A non-zero neutrino magnetic moment can give rise to an electromagnetic contribution to neutral current neutrino scattering. This is most easily measured using neutrino-electron elastic scattering. Present experimental limits for the muon neutrino magnetic moment come from the LSND experiment which sets an upper limit of $\mu_{\nu_\mu} < 6.8 \times 10^{-10} \mu_B$ [61] by measuring the total $\nu-e$ elastic scattering cross section.

At low $y = \frac{E_e}{E_\nu}$ the electromagnetic contribution to the $\nu-e$ cross section increases rapidly while the Standard Model contribution increases only gradually. This shape dependence can be used to look for a signal and possibly greatly extend our sensitivity to a non-zero neutrino magnetic moment into the region where beyond the Standard Model theories predict and astrophysical limits allow non-zero neutrino magnetic moments. A high intensity, low energy ($E_\nu \sim 1 GeV$) neutrino beam such as that available at a proton driver or superbeam facility can make this measurement possible.

The sensitivity to a neutrino magnetic moment in a stage I neutrino beam has been calculated, assuming a MiniBooNE-size detector located 100 m from the neutrino source (assuming a proton driver upgrade to the MiniBooNE beamline). For a reasonable range in detectable recoil electron energy thresholds, the statistical sensitivity on μ_{ν_μ} is in the few times 10^{-11} range.

If a 10% systematic error due to the flux is included, the dominant systematic error in such experiments, the sensitivity to μ_ν becomes $2.2 \times 10^{-10} \mu_B$ and the experiment becomes systematics-limited. A better method for determining any electromagnetic contribution to the cross section is to take advantage of the shape dependence of the differential cross section on an electromagnetic component of the interaction. This method does not require precise knowledge of the flux. Work on determination of sensitivity to μ_ν using this method continues.

Non-traditional methods to search for neutrino magnetic moment using higher energy neutrino beams are discussed in reference [62], but their feasibility has not yet been demonstrated.

2. A Future Experiment to Measure Δs with a high intensity neutrino source

A topic of large and continuing interest in nuclear and particle physics is the role of strange quarks in the properties of the nucleon. Neutrino nucleon elastic scattering is sensitive to an isoscalar contribution to the nucleon spin via the νp axial coupling. This is presumably the same contribution responsible for the surprising results from the EMC experiment (and subsequent) that show a violation of the Ellis-Jaffe sum rule.

A measurement of νp elastic scattering in the kinematic range accessible to the MiniBooNE experiment ($0.1 < Q^2 < 1.0 GeV^2/c^2$) with sufficient reduction of systematic errors allows for a precise extraction of the νp axial form factor (G_A) and the contribution of strange quarks to the spin of the nucleon, Δs .

By measuring νp elastic (neutral current) scattering and comparing to νn quasi-elastic (charged current) scattering, a sensitive measurement of the “strange” part of G_A , G_s , may be obtained with little systematic error due to the uncertainty in the neutrino flux. (Note in the limit $Q^2 = 0$, $G_s(0) = \Delta s$.)

In addition, if it is possible to measure νn elastic scattering with sufficient precision, and the neutral and charged current cross sections with antineutrinos, this data set would allow a very robust extraction of Δs along with the axial form factor mass, M_A .

The detector for this measurement would require high segmentation for tracking to separate the final state particles. It would also need a moderate level of particle identification capability to distinguish the possible background reactions.

A high intensity neutrino source such as a proton driver beam or a superbeam would benefit this experiment by increasing the events rates tremendously. This could allow a smaller detector with better segmentation and tighter cuts on the event sample to better understand systematic errors.

C. Medium-to-High Energy Neutrino Physics

A superbeam or neutrino factory providing intense neutrino beams in the 2 - 20 GeV range will enable a study of the surprisingly still poorly understood region of neutrino resonance production, the transition from resonance to DIS and certain kinematic regions of DIS. To study these mechanisms by scattering neutrinos off a light target will allow us to finally answer many pending questions.

1. Neutrino Deeply Inelastic Scattering

Neutrino-nucleon experiments offer a rich source of information about the quark structure of the proton. [63] Neutrino-nucleon deeply inelastic scattering (DIS) is arguably the most direct measurement of the proton structure functions. However, at low- Q^2 , and high- x disentangling perturbative effects from nuclear effects and higher-twist effects becomes extremely difficult. The neutrino DIS events with $Q^2 < 1.25 \text{ GeV}^2$ and for $x < 0.1$ as well as $x > 0.6$ are largely unused because of these effects.

With the high statistics foreseen at a superbeam or a neutrino factory, allowing the use of light targets, as well as the special attention to minimizing neutrino beam systematics necessary for neutrino oscillation experiments, it should be possible for the first time to determine the separate structure functions $2F_1^{\nu N}(x, Q^2)$, $2F_1^{\bar{\nu} N}(x, Q^2)$, $F_3^{\nu N}(x, Q^2)$ and $F_3^{\bar{\nu} N}(x, Q^2)$ where N is an isoscalar target. In leading order QCD (used for illustrative purposes) these four structure functions are related to the parton distribution functions by:

$$\begin{aligned} 2F_1^{\nu N}(x, Q^2) &= u(x) + d(x) + s(x) + \bar{u}(x) + \bar{d}(x) + \bar{c}(x) \\ 2F_1^{\bar{\nu} N}(x, Q^2) &= u(x) + d(x) + c(x) + \bar{u}(x) + \bar{d}(x) + \bar{s}(x) \\ xF_3^{\nu N}(x, Q^2) &= u(x) + d(x) + s(x) - \bar{u}(x) - \bar{d}(x) - \bar{c}(x) \\ xF_3^{\bar{\nu} N}(x, Q^2) &= u(x) + d(x) + c(x) - \bar{u}(x) - \bar{d}(x) - \bar{s}(x). \end{aligned}$$

Note that taking differences and sums of these structure functions would then allow extraction of individual parton distribution functions in a given x, Q^2 bin:

$$\begin{aligned} 2F_1^{\nu N} - 2F_1^{\bar{\nu} N} &= [s(x) - \bar{s}(x)] + [\bar{c}(x) - c(x)] \\ 2F_1^{\nu N} - xF_3^{\nu N} &= 2[\bar{u}(x) + \bar{d}(x) + \bar{c}(x)] \\ 2F_1^{\bar{\nu} N} - xF_3^{\bar{\nu} N} &= 2[\bar{u}(x) + \bar{d}(x) + \bar{s}(x)] \\ xF_3^{\nu N} - xF_3^{\bar{\nu} N} &= [\bar{s}(x) + s(x)] - [\bar{c}(x) + c(x)]. \end{aligned}$$

As we increase the order of QCD and allow gluons into consideration we need to bring in global fitting techniques into the extraction of the parton distribution functions. However, if the statistical and systematic errors can be kept manageable, the ability to isolate individual parton distribution functions will be dramatically increased by measuring the full set of separate ν and $\bar{\nu}$ structure functions.

2. High- x Parton Distribution Functions

There is considerable interesting physics in the region of high x . This region can be described as the ‘‘bridge’’ between perturbative QCD and non-perturbative QCD, a bridge that Lattice Gauge Theory is trying to construct. This is a region that requires much additional study with both electroproduction and the weak current of neutrino nucleon interactions.

In global fits of experimental data to extract the parton distribution functions, the functions – even the gluon distribution – are fairly well known from very small x up to x of around 0.5. Above this value there is very

little data and, in particular, all neutrino data in the region is on heavy nuclear targets and subject to strong nuclear effect which have never been measured. A high statistics neutrino/antineutrino exposure in H_2 and D_2 provides the most direct way of studying this rich region of phase space.

The uncertainties at high x in current nucleon parton distribution functions are of two types: the ratio of the light quark PDF's, $d(x)/u(x)$, as $x \rightarrow 1$ and the role of leading power corrections (higher twist) in the extraction of the high x behavior of the quarks. These higher twist (or power suppressed) corrections represent a long-standing hurdle to making accurate theoretical predictions for structure function data over the full kinematic range. Higher twist corrections should not simply be avoided; accurate characterization of higher twist corrections provides new information on parton-parton correlations within the nucleus.

The kinematic limits where considerations of higher twist contributions become important are 1) at high- x , and 2) at low Q^2 where terms of order Λ^2/Q^2 become significant. In the high- x region, the limiting factor is primarily statistics. In the low Q^2 region the statistics are generally adequate, but if the data is taken on heavy targets the higher twist effects are entangled with nuclear effects.

Consequently, the ideal testing ground would be to have high statistics measurements on a light target. This would allow systematic separation of the higher twist effects from the nuclear effects, and better allow us to learn about both in the process.

Another challenge of high- x physics is the long-standing problem in QCD – the calculation of the cross section for the production of heavy quarks both in hadroproduction and leptoproduction mode. In the case of the b -quark, for example, there are large discrepancies between data and theory both at the Tevatron and at HERA facilities. Another unsettling aspect of heavy quark production is the relatively large theoretical uncertainty remaining in the calculations, despite the existence of next-to-leading order calculations.

One degree of freedom that has not been fully studied or exploited in this area is the issue of an “intrinsic” heavy quark component. While the question of intrinsic heavy quarks has been discussed in the literature for many years, it still remains unresolved: a definitive experiment is needed! A particularly incisive test of this theory would be to make precise measurements of heavy quark production in the threshold region. In this kinematic regime, the usual “perturbative” heavy quark component arising from gluon splitting ($g \rightarrow Q\bar{Q}$) is comparatively small; therefore a measurement in this region has more discriminating power to confirm or refute the “intrinsic” heavy quark component once and for all. Experiments studying heavy quark production would occur at the 20-50GeV neutrino factory (Stage IV).

3. A Detector for Future Neutrino Scattering Experiments

A number of proposed projects that use a high-luminosity proton driver to generate a neutrino beam for oscillation physics could add a light mass detector for the purpose of studying low- Q^2 neutrino DIS.

Conceptually, the type of detector that would be required would be one which has excellent hadronic and muon energy and angle resolution as well as particle identification. Due to the considerable resonance contribution to the neutrino cross section at low energies, particle id is required for identification of resonance events.

Examples of low-mass detectors which have the required particle id are liquid-He or liquid- H_2 time projection chambers. The information acquired from these chambers is very similar to that of bubble chambers. These detectors feature excellent particle identification and good momentum and energy resolution.

D. Neutrino Flavor Violation Physics –non-oscillations

A lepton flavor violation program involving *neutrinos* rather than muons would nicely complement the muon physics and neutrino oscillation physics programs at a staged neutrino factory. Several signatures could be looked for in a neutrino experiment with a short enough baseline so that oscillations can be neglected. For example, in the case of neutrino production from μ^+ decays, the detection of wrong sign muons, positrons, taus of both signs would all signal new physics in the decay or in the neutrino interaction in the detector. In particular, μ^- could arise from the standard CC interaction of muon neutrinos from the flavor violating decay $\mu^+ \rightarrow e^+ \nu_\mu \bar{\nu}_l$ ($l = e, \mu, \tau$), as well as from the non-standard $\bar{\nu}_\mu$ interaction $\bar{\nu}_\mu e^- \rightarrow \bar{\nu}_l \mu^-$ or the non-standard ν_e interactions $\nu_e d \rightarrow \mu^- u$, $\nu_e e^- \rightarrow \nu_e \mu^-$. Analogously, positrons could be produced in the standard CC interactions of electron antineutrinos from $\mu^+ \rightarrow e^+ \nu_l \bar{\nu}_e$ or from the process $\bar{\nu}_\mu u \rightarrow e^+ d$ in the detector. In each case, observation would immediately point to new physics well beyond the implications of the Standard Model.

Particularly interesting from the experimental point of view is the wrong sign muon signature. By using a $L = 100$ m baseline, a muon energy of 2 GeV (Stage III), and a 10 ton detector, the sensitivity on the branching

ratios $\text{BR}(\mu^+ \rightarrow e^+ \nu_\mu X)$ and $\text{BR}(\mu^- \rightarrow e^- \bar{\nu}_\mu X)$ is improved by two orders of magnitude below current values, which only extend to the 10^{-2} level [64].

In the case of higher neutrino energies, it is possible for neutrino detectors to be sensitive to additional lepton family violating channels. Specifically, for neutrino energies above 10.7 GeV (stage IV), one can be sensitive to the reaction $\bar{\nu}_\mu e^- \rightarrow \mu^- \bar{\nu}_e$. Such an interaction is both sensitive to new physics, such as left-right symmetry and dileptons, and has the very clean wrong sign muon signature. In addition, because the target is an electron, the muon emanating from the reaction will have very small opening angle ($p_t^2 \leq m_e E_\nu/2$), which can be used as an additional handle to distinguish events from Standard Model and non-Standard Model background. This possibility has also been studied in [65]. The same detectors as outlined in Silicon CCD or liquid methane TPC detectors can be used which provide excellent charge, vertex, and angular resolution [66]. Projected sensitivities at Stage IV would improve over current limits by 3-4 orders of magnitude and, if backgrounds can remain under control, reach the 10^{-6} or 10^{-7} level.

The scale of new physics that can be probed with such a sensitivity depends on the specific model one considers. However, the cleanliness of the experimental signature and its complementarity to neutrino oscillation experiments makes lepton flavor violation searches an attractive feature of a stage IV neutrino factory program.

VIII. MUON COLLIDER PHYSICS

Although muon colliders were discussed at Snowmass '96 as energy frontier machines, much has been learned in the meantime about what physics could be achieved on the way to such a device. The experiments described in this document have so far borne little resemblance to the experiments that were proposed at the previous Snowmass workshop. In this last section we describe the motivation for using a muon collider as a Higgs factory (i.e., still much lower in energy than was originally proposed), what physics it could provide, and what some of the detector concerns are for this experiment.

A. Physics Issues

At a muon collider [67] the Higgs boson would be produced through the s -channel, so the production cross section is thousands of times larger than the cross section at an s -channel e^+e^- collider. Because a muon beam energy spread as small as $\sim 10^{-5}$ may be possible, there is a possibility of measuring m_H to a few hundred keV and a direct measurement of the width to about 1 MeV. If only one light Higgs boson were observed, it would be crucial to measure its properties to infer whether it is a Standard Model or supersymmetric Higgs. The CP properties of the Higgs bosons can be measured through asymmetries with transversely polarized μ^+ and μ^- beams [68]. In the case of heavy MSSM Higgs bosons, the large coupling to $\mu^+\mu^-$ may be necessary for their direct observation.

Although the Higgs boson mass must be known to a few per cent [68] before knowing at what energy to build a muon collider as a Higgs Factory, it is believed that that mass is low. Once a beam of 50 GeV muons can be collected and stored in a ring to do neutrino experiments, the remaining task to get to a Higgs factory would be mostly an issue of beam cooling, since the center of mass energy of two 50 GeV muon beams is expected to be relatively close to the Higgs mass.

In order to measure the width of a narrow (2-3 MeV) Higgs boson of mass (120 GeV), one needs to have beam energy spread and stability of order 10^{-5} and also to measure the energy of the bunches to 10^{-6} . The latter measurement is feasible using $g-2$ spin precession of the muons by measuring [69] the energy spectrum of the decay electrons turn by turn.

Indirect information about the mass of the Standard Model Higgs boson can be obtained from fits to the precision electroweak data taken at the Z^0 resonance at LEP and the SLC, and from neutrino-Nucleon Deep Inelastic scattering cross section measurements. The Z -pole cross sections and asymmetries are sensitive to the mass of the top quark m_t , the mass of the W boson m_W , the QCD coupling constant α_s . Most electroweak observables are sensitive to the log of the mass of the Higgs boson m_H through radiative corrections. The electroweak data fit gives [70] $m_H = 88_{-35}^{+53}$ GeV and $m_H < 196$ GeV at 95% C.L.

Although electroweak fits suggest a light Higgs, searches thus far have produced only lower bounds on the mass. At LEP the SM Higgs boson is expected to be produced mainly through the Higgs-strahlung process $e^+e^- \rightarrow H^0 Z^0$, with contributions from the WW fusion channel below 10%. The lower bound coming from a combined analysis of the four LEP experiments is $m_H > 114.1$ GeV at 95% C.L. (115.4 GeV expected).

1. Implications for Supersymmetry

The hints for a Higgs boson with a low mass and the disagreement of $(g - 2)_\mu$ with the Standard Model expectation [55] are consistent with the following general scenario [68]:

- In the Minimal Supersymmetric Standard Model (MSSM), $m_h \sim 115$ GeV indicates a large value of $\tan \beta$.
- The disagreement of $(g - 2)_\mu$ also indicates a large value of $\tan \beta$.
- If the disagreement of $(g - 2)_\mu$ is explained by supersymmetry, then the sign of the supersymmetry parameter μ is consistent with $b \rightarrow s\gamma$.
- In the decoupling limit, the lighter Higgs boson h^0 has couplings like the Standard Model Higgs, but the heavier Higgs bosons H^0 , A^0 have non-Standard Model couplings: their coupling to gauge bosons is greatly suppressed.
- For larger values of $\tan \beta$, there is a range of heavy Higgs boson masses for which discovery is not possible at the LHC or an e^+e^- linear collider.
- In the MSSM, the heavy Higgs bosons are largely degenerate, especially in the decoupling limit. Very precise center-of-mass energy resolution will be needed to separate them.

B. Muon Collider Detectors

Figure 9 shows a trial muon collider detector for a Higgs factory simulated in GEANT. The background from muon decay sources has been extensively studied [67]. At the Higgs factory, the main sources of background are from photons generated by the showering of muon decay electrons. At the higher energy colliders, Bethe-Heitler muons produced in electron showers become a problem. Work was done to optimize the shielding by using specially shaped tungsten cones [67]. The background rates obtained were shown to be similar to those predicted for the LHC experiments. It still needs to be established whether pattern recognition is possible in the presence of these backgrounds.

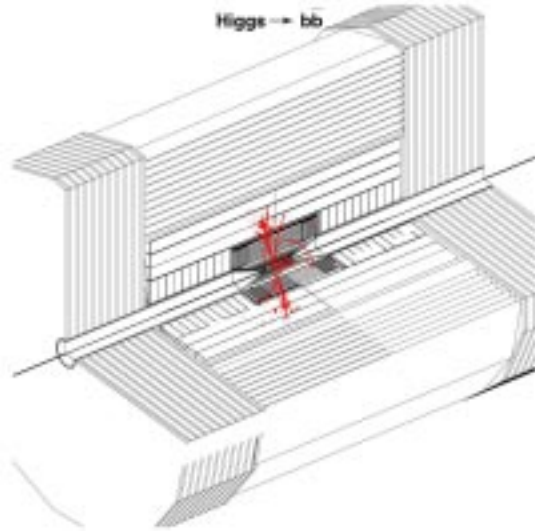


FIG. 9: Cut view of a potential detector in GEANT for the Higgs factory with a $Higgs \rightarrow b\bar{b}$ event superimposed. No backgrounds are shown. The tungsten cones on either side of the interaction region mask out a 20° area.

IX. CONCLUSIONS

The recent discovery of neutrino oscillations is a profound discovery. The US should strengthen its lepton flavor research program by expediting construction of a high-intensity, conventional neutrino beam ("superbeam") fed by a 1-4MW proton source.

A superbeam will probe the neutrino mixing angles and mass hierarchy, and may discover leptonic CP violation. The full program will require neutrino beams at a number of energies, and massive detectors at a number of baselines. These facilities will also support a rich program of other important physics, including proton decay, particle astrophysics and charged lepton CP- and flavor- violating processes.

The ultimate laboratory for neutrino oscillation measurements is a neutrino factory, for which the superbeam facility serves as a strong foundation. The development of the additional needed technology for neutrino factories and muon colliders requires an ongoing vigorous R&D effort in which the US should be a leading partner.

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- [1] For a comprehensive list of neutrino experiments see http://www.hep.anl.gov/ndk/hypertext/nu_industry.html or <http://pheno.physics.wisc.edu/physics.html#neutrino>.
- [2] K. S. Hirata et al., Phys. Lett. **B205**, 416; *ibid.* **280**, 146 (1992); Y. Fukuda et al., Phys. Lett. **B335**, 237 (1994); S. Hatakeyama et al. Phys. Rev. Lett. **81**, 2016 (1998).
- [3] D. Casper et al., Phys. Rev. Lett. **66**, 2561 (1991); R. Becker-Szendy et al., Phys. Rev. **D46**, 3720 (1992); Phys. Rev. Lett. **69**, 1010 (1992).
- [4] W. Allison et al., Phys. Lett. **B391**, 491 (1997); Phys. Lett. **B449**, 137 (1999); W. A. Mann, Nucl. Phys. Proc. Suppl. **91**, 134 (2000).
- [5] MACRO Collab., M. Ambrosio et al., Phys. Lett. **B478**, 5 (2000); hep-ex/0001044; B. Barish, Nucl. Phys. Proc. Suppl. **91**, 141 (2000); hep-ex/0101019.
- [6] S. H. Ahn et al, hep-ex/0103001; Y. Oyama, hep-ex/0104014; K. Nishikawa, talk at NuFact01.
- [7] Q.R.Ahmad *et al.*, Phys. Rev. Lett **87**, 071301 (2001).
- [8] KamLAND Collaboration, "KamLAND: A Reactor Neutrino Experiment Testing the Solar Neutrino Anomaly", Nucl. Phys. Proc. Suppl. **91**, 99 (2001).
- [9] V. Barger, D. Marfatia and B. P. Wood, Phys. Lett. B **498**, 53 (2001).
- [10] C. Athanassopoulos et al., Phys. Rev. Lett. **77**, 3082 (1996); Phys. Rev. Lett. **81**, 1774 (1998); A. Aguilar et al., hep-ex/0104049.
- [11] MiniBooNE Collaboration, "MiniBooNE: Status of the Booster Neutrino Experiment", Nucl.Phys.Proc.Suppl.**91**, 210 (2000)
- [12] V. Barger, K. Whisnant and R. J. Phillips, Phys. Rev. Lett. **45**, 2084 (1980).
- [13] S. Pakvasa in *High Energy Physics-1980* edited by L. Durand and L. Pondrom, AIP Conf. Proc. No. 68 (AIP New York, 1981), p. 1164.
- [14] A. De Rujula, M. B. Gavela and P. Hernandez, Nucl. Phys. B **547**, 21 (1999).
- [15] L. Wolfenstein, Phys. Rev. **D17**, 2369 (1978). V. Barger, S. Pakvasa, R.J.N. Phillips, and K. Whisnant, Phys. Rev. **D22**, 2718 (1980). S. P. Mikheyev and A. Smirnov, Yad. Fiz. **42**, 1441 (1985) [Sov. J. Nucl. Phys. **42**, 913 (1986)].
- [16] T. K. Kuo and J. Pantaleone, Rev. Mod. Phys. **61**, 937 (1989).
- [17] A. Dziewonski and D. Anderson, Phys. Earth Planet. Inter. **25**, 297 (1981).
- [18] N. Fornengo, M. Maltoni, R. T. Bayo and J. W. Valle, data," hep-ph/0108043.
- [19] G. L. Fogli, E. Lisi, D. Montanino and A. Palazzo, hep-ph/0106247.
- [20] F. Boehm et al., Phys. Rev. Lett. **84**, 3764 (2000); Phys. Rev.**D62**, 072002 (2000).
- [21] M. Apollonio et al., Phys. Lett. **B420**, 397 (1998); Phys. Lett. **B466**, 415 (1999).
- [22] A. Cervera, A. Donini, M. B. Gavela, J. J. Gomez Cadenas, P. Hernandez, O. Mena and S. Rigolin, Nucl. Phys. B **579**, 17 (2000) [Erratum-*ibid.* B **593**, 731 (2000)].
- [23] M. Freund, Phys. Rev. D **64**, 053003 (2001).
- [24] I. Mocioiu and R. Shrock, hep-ph/0106139.
- [25] J. Arafune, M. Koike and J. Sato, Phys. Rev. D **56**, 3093 (1997) [Erratum-*ibid.* D **60**, 119905 (1997)]
- [26] C.H. Albright and S. Geer, "GUT Model Predictions for Neutrino Oscillation Parameters Compatible with the Large Mixing Angle MSW Solution", hep-ph/0108070
- [27] V. Barger, S. Geer, R. Raja and K. Whisnant, Phys. Rev. D **63**, 113011 (2001).
- [28] Y. Itow *et al.*, "The JHF-Kamioka Neutrino Project", hep-ex/0106019.
- [29] The UNO Whitepaper, D. Casper, C. K. Jung, C. McGrew, C. Yanagisawa (ed.'s), "Physics Potential and Feasibility of UNO" SBHEP01-3 (2001), accessible from <http://superk.physics.sunysb.edu/uno/>
- [30] Comes from PBEAM, a fast neutrino beamline simulation, used primarily by the MINOS experiment.
- [31] V. Barger et al, hep-ex/0103052
- [32] V. Barger, D. Marfatia and K. Whisnant, hep-ph/0108090; and paper in preparation.

- [33] See M. Campanelli, these proceedings, and “Neutrino Cross Section Measurement with Neutrinos from Muon Decay” M. Campanelli, S. Navas-Concha, A. Rubbia, presented at NuFact01 *hep-ph/0107221*
- [34] See the talks: “A Neutrino Superbeam Physics Program as a First Stage of a Neutrino Factory”, K.T. McDonald, presented at Snowmass01 (July 14, 2001), <http://www.hep.princeton.edu/~mcdonald/nufact/snowmassstrans071401.ps> and “Brookhaven Super-Neutrino Beam Scenario”, Steve Kahn (Aug. 15, 2001), <http://pubweb.bnl.gov/users/kahn/www/talks/SuperBeam15Aug01.pdf>
- [35] W.Marciano, *hep-ph/0108181*
- [36] Reference for ICARUS 600T module performance (could be A. Rubbia, Les Houches). See also <http://pcnometh4.cern.ch/>
- [37] “LANND, A Massive Liquid Argon Detector for Proton Decay, Supernova and Solar Neutrino Studies, and a Neutrino Factory Detector”, D. B. Cline *et al.*, *astro-ph/0105442*
- [38] “On the possibility to extrapolate Liquid Argon Technology to a supermassive detector for a future Neutrino Factory”, F. Sergiampietri, presented at NuFact’01, Tsukuba, Japan, http://www.hep.princeton.edu/~mcdonald/nufact/sergiampietri_nufact01.pdf
- [39] “Proposal for Evaluation of Underground Sites for Neutrino Detector in Massachusetts and New York”, Brierley Associates (Aug. 15, 2001), http://www.hep.princeton.edu/~mcdonald/nufact/brierley_proposal_081501.pdf
- [40] See for example: M. Diwan, M. Messier, B. Viren, L. Wai, “A study of $\nu_\mu \rightarrow \nu_e$ ”, NuMI-L-714, Feb 2001.
- [41] V. Barger, S. Geer, R. Raja and K. Whisnant, *Phys. Rev. D* **62**, 013004 (2000).
- [42] M. Campanelli, A. Bueno and A. Rubbia, *hep-ph/9905240*.
- [43] M. Freund, P. Huber and M. Lindner, *hep-ph/0105071*.
- [44] J. Pinney and O. Yasuda, at neutrino factories,” *hep-ph/0105087*.
- [45] V. Barger, S. Geer, R. Raja and K. Whisnant, *Phys. Rev. D* **62**, 073002 (2000)
- [46] J. Burguet-Castell, M. B. Gavela, J. J. Gomez-Cadenas, P. Hernandez and O. Mena, *Nucl. Phys. B* **608**, 301 (2001).
- [47] <http://www.cap.bnl.gov/mumu/studyii/FS2-report.html>
- [48] V. Barger, S. Geer, R. Raja and K. Whisnant, *Phys. Rev. D* **63**, 033002 (2001).
- [49] R. Raja, *et al.*, “The Program in Muon and Neutrino Physics: Super Beams, Cold Muon Beams, Neutrino Factory and the Muon Collider”, *hep-ex/0108041*, submitted to Snowmass 2001.
- [50] Y. Kuno and Y. Okada, *Rev. Mod. Phys.* **73** (2001) 151–202.
- [51] R. Barbieri and L. Hall, *Phys. Lett. B* **338** (1994) 212.
- [52] For an update of the predictions in the previous reference, see A. Romanino and A. Strumia, *hep-ph/0108275*
- [53] J. Ellis, in this Snowmass 2001 workshop.
- [54] W. R. Molzon *et al.*, <http://meco.ps.uci.edu/rsvp.html>.
- [55] Muon $g - 2$ collaboration, *Phys. Rev. Lett.* **86** (2001) 2227–2231.
- [56] R. C. Fernow, J. C. Gallardo, W. M. Morse, Y. K. Semertzidis, “Phase III of the Dedicated Muon EDM Experiment using Muons from Stage II of the Neutrino Factory”, unpublished.
- [57] M. Frank, *Phys. Rev. D* **60**,093005 (1999)
- [58] G. C. McLaughlin, and J. N. Ng, *hep-ph(9909558)*
- [59] M. Fukugita and S. Yazaki, *Phys. Rev.* **D36** (1987) 3817.
- [60] R. Barbieri and R. N. Mohapatra, *Phys. Rev. Lett.* **61** (1988) 27, and J. M. Lattimer and J. Cooperstein, *Phys. Rev. Lett.* **61** (1988) 23.
- [61] L. B. Auerbach *et al.*, *hep-ex(0101039)*
- [62] C. Albright *et al.*, “Physics at a Neutrino Factory,” FERMILAB-FN-692, Aug 2000. 133pp. e-Print Archive: *hep-ex/0008064*. and I. Bigi *et al.*. “The Potential for Neutrino Physics at Muon Colliders and Dedicated High Current Muon Storage Rings”, submitted to Physics Reports, Jan. 2001.
- [63] J. M. Conrad, M. H. Shaevitz, and T. Bolton, *Rev. Mod. Phys.* **70** 4,(1998).
- [64] A. Bueno, M. Campanelli, M. Laveder, J. Rico and A. Rubbia, *JHEP* **0106**, 032 (2001) [*hep-ph/0010308*].
- [65] J. A. Formaggio *et al.* [NuTeV Collaboration], To be published on PRL (2001).
- [66] I. Bigi *et al.*, *hep-ex/0106177*, submitted to *Phys. Rept.* (2001).
- [67] C. M. Ankenbrandt *et al.* (Muon Collider Collaboration) *Phys. Rev. ST Accel. Beams* **2**, 081001 (1999) (73 pages), <http://publish.aps.org/ejnl/przfetch/abstract/PRZ/V2/E081001/>
- [68] V. Barger, M. S. Berger, J. F. Gunion, and T. Han, “Physics of Higgs Factories,” in *Higgs Factory Muon Collider*, D. B. Cline and G. G. Hanson, editors, submitted to Snowmass 2001. See <http://www.physics.ucla.edu/snowmass>.
- [69] R. Raja and A. Tollestrup, “Calibrating the energy of a 50-GeV x 50-GeV muon collider using spin precession” *Phys. Rev. D* **58**, 013005 (1998).
- [70] D. Charlton, “Experimental Tests of the Standard Model.” Proceedings of the International Europhysics Conference on High Energy Physics EPS-HEP 2001, Budapest, Hungary, July 12-18, 2001. See <http://www.hep2001.elte.hu/>.