THE NEUTRINO FACTORY THE FINAL FRONTIER IN NEUTRINO PHYSICS ? *

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Abstract

This talk will present arguments that the Neutrino Factory — an extremely intense source of flavor-tagged neutrinos from muon decays in a storage ring — gives the best physics reach for CP violation, as well as virtually all parameters in the neutrino oscillation parameter space. It will describe the physics capabilities of a baseline Neutrino Factory as compared to other possible future facilities (beta-beam and super-beam facilities), give an overview of the accelerator complex, describe the current international R&D program and present a potential time line for the design and construction of the facility. Although the baseline study focuses on a facility with muon energy of 25 GeV, a concept for a Low-Energy (~ 4 GeV) Neutrino Factory has been developed and its physics reach will also be discussed. Finally, it will be shown that a facility of this type is unique in that it can present a physics program that can be staged, addressing exciting new physics at each step. Eventually it can lead to an energy-frontier muon collider. A muon accelerator facility is a natural extension that can exploit the high intensity potential at FNAL starting with Project X.

INTRODUCTION

It has been over 10 years since the discovery that neutrinos have mass and can oscillate [1] and we now understand that most experimental data are well described by the 3ν mixing model [2]. Many parameters in this model have now been measured, but there are still unknowns: whether neutrinos are Dirac or Majorana particles (are they their own antiparticle?), the neutrino mass ordering (are there two light neutrinos and one heavy neutrino, normal hierarchy, or two heavy and one light, inverted hierarchy?), what is the absolute neutrino mass scale, what is the value of the unknown mixing angle θ_{13}, and is CP violation present in the leptonic sector. In order to measure these unknowns, experiments with unprecedented sensitivity are needed. The systematics of the neutrino beam determine, to a large degree, the ultimate sensitivity of a neutrino oscillation experiment. In order to address the precision needed for future neutrino oscillation experiments, the Neutrino Factory was proposed by Geer [3]. In the Neutrino Factory, the neutrino beam is generated from muons which decay along the straight section of a race track-like decay ring and since the decay of the muon is well understood, the systematic uncertainties associated with a neutrino beam produced in this manner are very small. In addition since the muon (anti-muon) decays produce both muon and anti-electron neutrinos (anti-muon and electron neutrinos), many oscillation states are accessible from a Neutrino Factory and the reach in the oscillation parameter space is extended. The oscillation processes accessible at a Neutrino Factory are given in Table 1.

Table 1: Oscillation channels accessible at a Neutrino Factory

$\mu^+ \to e^+\nu_e\overline{\nu}_\mu$	$\mu^- \to e^-\overline{\nu}_e\nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

In the so-called "golden" channel listed in Table 1, the experimental signature in the neutrino detector is the presence of a muon with the "wrong" sign — a muon with the opposite sign to that which is stored in the decay ring. This requires that the neutrino detector be magnetized, but for Neutrino Factories with stored muons with energy of approximately 25 GeV, this represents standard neutrino detector technology [4]. It has been shown [5] that for a "magic" baseline of approximately 7500 km, the "golden" channel offers unprecedented sensitivity for the determination of the unknown mixing angle θ_{13} and the mass hierarchy. As we shall see, a Neutrino Factory that points beams to 2 detectors, one at the magic baseline and one at a shorter baseline, offers the best sensitivity over the full neutrino-oscillation parameter space.

THE INTERNATIONAL SCOPING STUDY

Over the last decade there have been a number of studies [6-9] that have explored the physics reach of Neutrino Factories to measure θ_{13}, determine the mass hierarchy and determine the CP violating phase, δ. The most recent study to be completed [10], the International scoping study of a future Neutrino Factory and super-beam facility (ISS), studied the physics capabilities of various future neutrino facilities: super-beam, β-Beam and Neutrino Factory. Within the study, the accelerator working group developed a full concept specification for the Neutrino Factory accelerator facility based on the physics requirements and detector performance parameters developed within the study. The Neutrino Factory facility consists of (see Fig. 1):

- a 4 MW proton driver.
- a Liquid Hg jet target station.
- a 201 MHz capture and phase rotation section

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- approximately 70m of transverse muon ionization cooling.
- acceleration using a linac and recirculating linear accelerators (RLAs) with superconducting RF, followed by FFAGs, accelerating the muons to a final energy of 25 GeV.
- two decay rings.

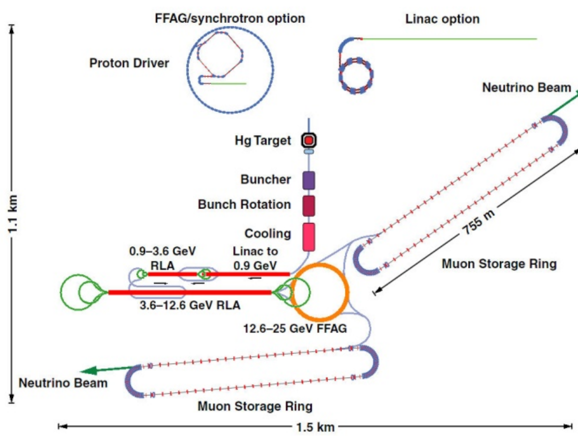

Figure 1: (Color) ISS Neutrino Factory facility baseline.

ISS Neutrino Factory Baseline Detectors

As was mentioned above, Neutrino Factory detectors need to be magnetized, but for the 25 GeV muon storage ring in the ISS, a more or less conventional detector is all that is required. For the ISS, the primary detector is the magnetized iron neutrino detector (MIND) which produces a toroidal magnetic field in iron and uses scintillator strip readout following the example of the MINOS detector [11]. A schematic of MIND is shown in Fig. 2. In addition at the shorter baseline, the ISS detector configuration includes a Magnetized Emulsion Cloud Chamber (MECC) for the detection of the "silver channel" (ν_τ appearance) indicated in Table 1 in addition to a 50 kT MIND.

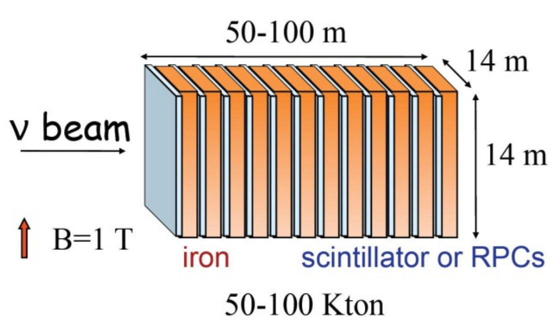

Figure 2: (Color) Schematic of the MIND concept for the Neutrino Factory.

The ISS Physics Study

The ISS physics study [12] set out as a goal "to establish the strong physics case for the various proposed facilities and to find the optimum parameters of the accelerator facility and detector systems from a physics point of view." The study looked at super-beam facilities, a β-beam facility and the Neutrino Factory. The 5 facilities that were studied are:

1. a 4 MW facility at CERN (SPL) pointing to a 1 megaton water Cerenkov detector at a baseline of 130 km (super-beam).
2. a 4 MW facility at JPARC (T2HK) pointing to a 1 megaton water Cerenkov detector at a baseline of 295 km (super-beam).
3. A 2 MW facility at FNAL (WBB) pointing to a 1 megaton water Cerenkov detector at a baseline of 1300 km (super-beam).
4. a high-energy β-beam facility (BB350) pointing to a 1 megaton water Cerenkov detector at a baseline of 730 km.
5. a 4 MW Neutrino Factory pointing to two 50 kT MIND detectors at baselines of 4000 and 7500 km plus a 10 KT MECC at 4000 km.

The results of the study are shown in Figures 3a-c where 3σ exclusion contours are shown for the discovery reach in θ_{13}, the determination of the mass hierarchy and the CP violating phase δ, respectively.

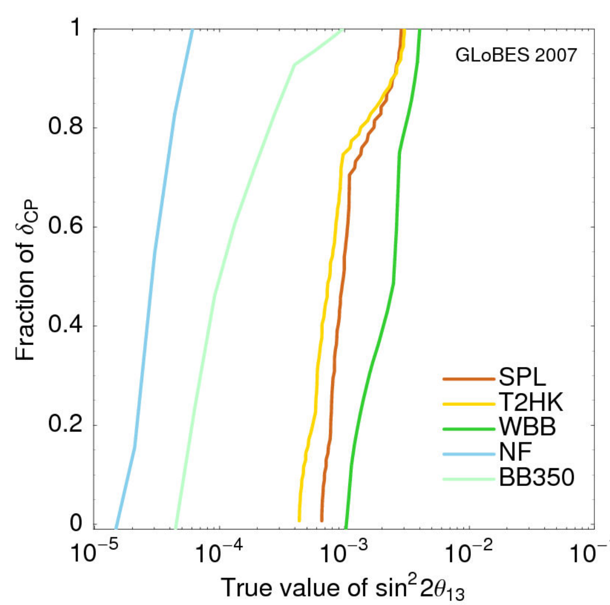

Figure 3a: (Color) Discovery reach for θ_{13}.

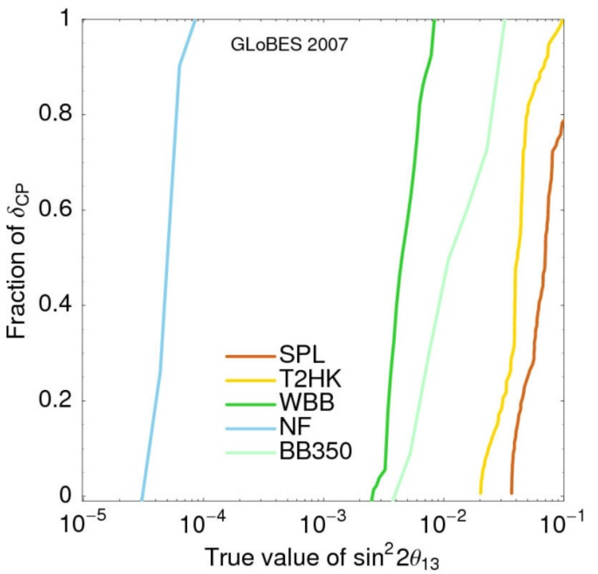

Figure 3b: (Color) Reach for determination of the mass hierarchy.

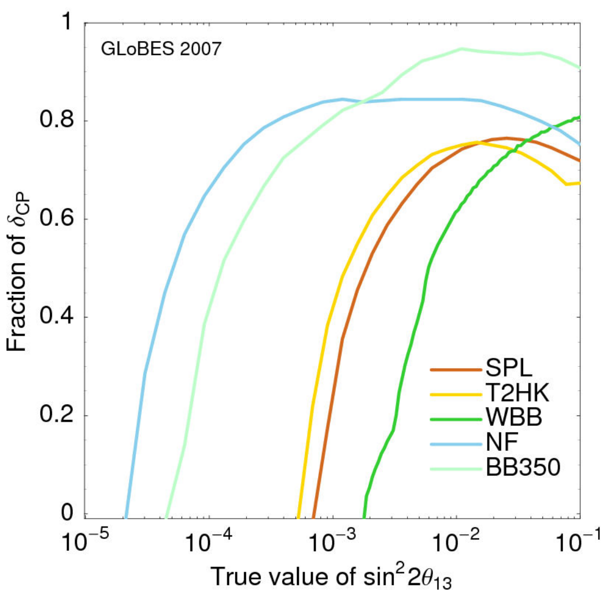

Figure 3c: (Color) Reach in the CP phase δ.

As can be seen from the data in Figures 3a-c, the Neutrino Factory offers the best possible reach for measuring a non-zero θ_{13} and gives the best capability for determining the mass hierarchy and CP violating phase for small θ_{13}. The executive summary of the ISS physics report states: "Studies so far have shown that the Neutrino Factory, an intense high-energy neutrino source based on a stored muon beam, gives the best performance over virtually all of the parameter space; its time scale and cost, however, remain important question marks."

CONTINUING INTERNATIONAL R&D ON THE NEUTRINO FACTORY

The "cost and time scale" of the Neutrino Factory that were alluded to above have been the focus of four completed studies, three hosted in the US [7, 13, 14] and the ISS detailed above. The ISS successfully "Internationalized" the effort and this is continuing in the on-going International Design Study for the Neutrino Factory (IDS-NF) [15]. The goal of the IDS-NF is to deliver a Reference Design Report (RDR) in which the physics performance of the Neutrino Factory is detailed and the specification of each of the accelerator, diagnostic, and detector systems that make up the facility is defined. An interim design report is to be delivered in 2010 with a final RDR delivered in the 2012—2013 time frame. The RDR would present the engineering basis for moving the Neutrino Factory into the project phase. The major technical challenges facing the NF design are the design of a high power proton source, a pion production target system that can handle multi-MW beam power, efficient pion capture and phase rotation, an ionization cooling channel and rapid acceleration. Multi-MW proton source design is being pursued at many laboratories around the world in the context of supporting broad physics programs at the intensity frontier. The prospects for a proton source of the power required for a Neutrino Factory being available on the time scale for the start of a Neutrino Factory construction project are quite promising.

Key R&D Issues

Many of the key technologies and components for the Neutrino Factory are currently under study. The MERIT experiment [16] has successfully tested the concept of the liquid Hg jet target and it has shown very promising results which indicate that this type of target system can operate at a power level of 4 MW and above. The Muon Ionization Cooling Experiment, MICE [17], is preparing to perform a demonstration and engineering test of 4D muon ionization cooling utilizing 201 MHz RF and liquid hydrogen absorbers. The MuCool [18] program is investigating operation of vacuum RF cavities in the presence of high magnetic fields, has made preliminary studies on liquid hydrogen absorbers and will also be studying the use of LiH absorbers as an alternative to using liquid hydrogen absorbers in the muon cooling channel. The MuCool program focuses on component R&D and, in addition to the capability to test RF components at high power, will have the capability to test cooling channel components with a high-intensity proton beam from the Fermilab linac. The Electron Model with Many Applications (EMMA) [19] experiment will study the properties of FFAGs which are a candidate for part of the acceleration system in the Neutrino Factory.

Of all the underlying accelerator technologies that are required for the Neutrino Factory complex, it can be argued that RF technology is the single most important "Limiting-Technology." It is of fundamental importance for these facilities in that it is needed in: 1) Muon capture, bunching and phase rotation; 2) Muon Cooling; and 3) Acceleration. Both normal conducting RF (front-end, 1 and 2 above) and superconducting RF (acceleration) are required.

A crucial challenge for the Neutrino Factory front-end design and cooling channels is the operation of high-gradient normal-conducting RF (NCRF) in the presence of high magnetic field. This problem has been the primary focus of the MuCool program. What has been observed in MuCool is that the safe operating gradient limit degrades significantly when a NCRF cavity is operated in magnetic field, Fig. 4. The data shown in Fig. 4 are for an 805 MHz pillbox test cavity and seem to follow a universal curve. The maximum stable gradient degrades quickly with increasing B field. There are a number of models that have been developed that attempt to describe this phenomenon, but all involve field emission from emitters (surface field enhancements in the regions of high gradient) in the cavity. The interaction of the field emission with the magnetic field can cause surface imperfections on the cavity to break off which then produces a plasma under bombardment by the field emission current. The plasma then initiates a breakdown. In order to address this problem, three approaches are being investigated.

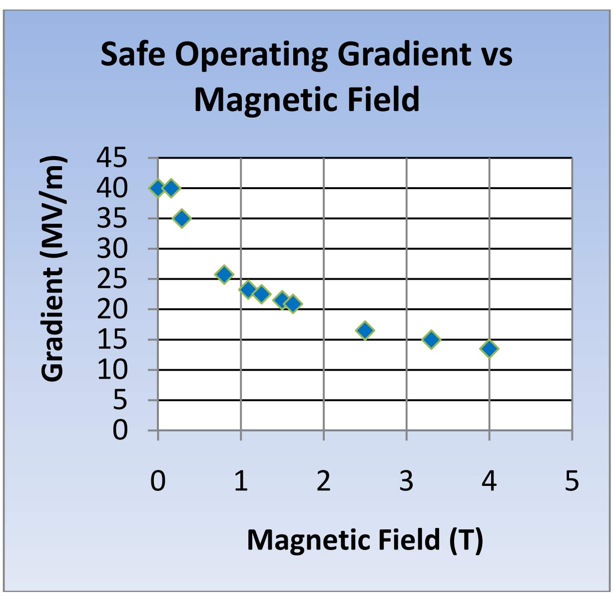

Figure 4: (Color) Maximum safe operating gradient v. magnetic field.

The first is to eliminate field emission by processing the NCRF copper cavities using superconducting RF (SCRF) or more advanced techniques. A 201 MHz copper cavity (prototype for MICE) was processed using SCRF techniques and tested in the MuCool program. This cavity reached a stable operating gradient of 21 MV/m (the design gradient was 16 MV/m) in the absence of B field. Tests at low magnet field did show a significant drop off in stable operating gradient, but the cavity behaved very differently from the 805 MHz pillbox with respect to X-ray emission [18]. Other processing techniques include coating the cavity utilizing the Atomic Layer Deposition process [20]. Other possible approaches to eliminating the magnetic field effect are to operate the cavities filled with high-pressure H_2 gas [21] and to investigate fabricating the cavities with materials other than copper where Al is a promising candidate.

IDS-NF Timeline

As was mentioned above, the goal of the IDS-NF is to have a reference design document ready in the time frame of 2012—2013. The IDS-NF community feels that this is an extremely important time frame in that by this time there will be many new results from existing and soon to turn on neutrino experiments (MINOS, OPERA, Double Chooz, Daya Bay, T2k, NOνA) which will give physicists new insights on the requirements for future neutrino facilities. Figure 5 shows the "aspirational" timeline that was presented at NuFact07 and is the goal of the IDS-NF.

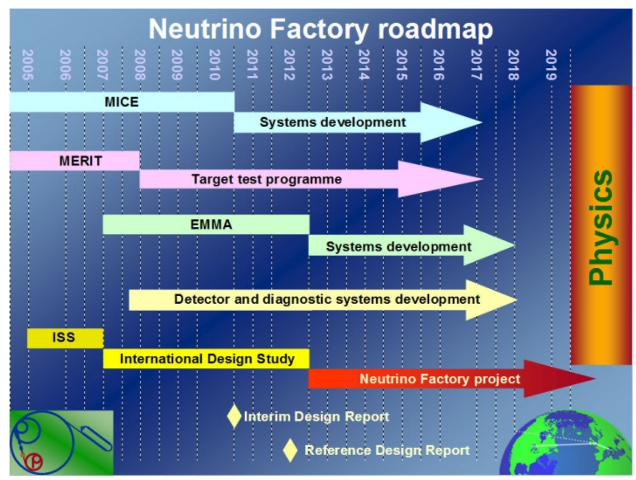

Figure 5: (Color) Aspirational timeline for a Neutrino Factory leading to a Neutrino Factory Project circa 2013.

THE CASE FOR A NEUTRINO FACTORY IF θ_{13} IS LARGE

One can ask what is the case for a Neutrino Factory if θ_{13} is possibly measured before the final technical case for the facility can be made and its costs are better determined. One scenario being considered within the IDS-NF is a Low-Energy Neutrino Factory (LENF) [22]. At a baseline of the order of 1300 km, a LENF utilizing stored muons of energy of ≈ 4 GeV produces a neutrino oscillation pattern that is very rich and with an appropriate detector the θ_{13} reach can extend down to approximately 10^{-4} ($\sin^2 2\theta_{13}$). A detector with low neutrino event energy threshold and excellent event energy resolution is required, but a concept that uses a totally active scintillator detector in an air-core solenoid [22] shows very interesting possibilities. The baseline is that of Fermilab to DUSEL, so studies of the LENF are synergistic with the ongoing work studying a wide-band super-beam to DUSEL [23].

Even if other facilities can access the neutrino oscillation physics for the case where θ_{13} is relatively large, new physics such as non-standard interactions (NSI) [24] are likely to only be accessible with a Neutrino Factory (high-energy). In addition the precision to which the oscillation parameters can be measured at a Neutrino Factory is unsurpassed.

Finally if data from the ILC point to the need for a multi-TeV Lepton collider, then the Neutrino Factory can be considered part of a Muon Accelerator Complex that includes a Muon Collider [25]. Figure 6 indicates how a Muon Facility might evolve at Fermilab.

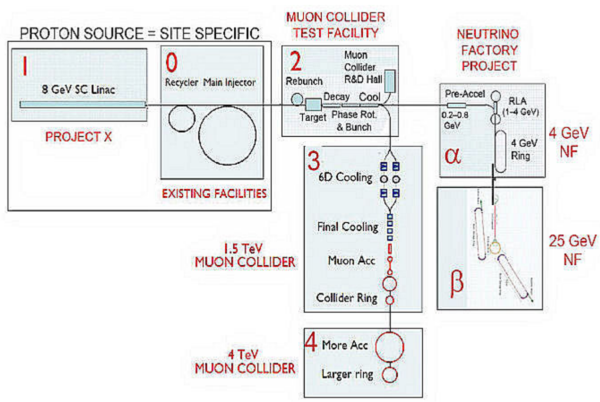

Figure 6: (Color) Muon Accelerator Complex "Vision" for Fermilab.

CONCLUSIONS

So in the end, the Neutrino Factory may not only be the "Final Frontier" in neutrino physics, but may also be a first step on the way to the energy frontier with a muon collider.

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REFERENCES

[1] Y. Suzuki, "Solar neutrino results from Super-Kamiokande", Nucl. Phys. Proc. Suppl., **77**, 1999.
[2] See, T. Schwetz, et al., New J.Phys.10:113011, 2008.
[3] S. Geer, Phys. Rev. **D57** (1998) 6989.
[4] A. Cervera, et al Nucl. Phys. **B579**, 17 (2000).
[5] P. Huber and W. Winter Phys. Rev. **D68** (2003) 037301.
[6] S. Geer, H. Schellman (Eds.) hep-ex/0008064.
[7] N. Holtkamp and D. Finley (Eds.) Fermilab-Pub-00/108-E.
[8] Autin B, Blondel A, Ellis J. CERN-99-02 ; DeRujula A, Gavela M, Hernandez P. Nucl. Phys. **B547** (1999) 21.
[9] Y. Mori J. Phys. G: Nucl. Part. Phys. **29** (2003) 1527:1536.
[10] RAL-TR-2007-019, 023, 024.
[11] P. Adamson et al., "The MINOS scintillator calorimeter system," IEEE Trans. Nucl. Sci. **49**, 861-863 (2002), Nov. 2001.
[12] S. King et al., "Physics at a future Neutrino Factory and super-beam facility," arXiv:0802.4023, to be published in Rep. Prog. Phys.
[13] S. Osaki, R. Palmer, M. Zisman, J. Gallardo (Eds.) BNL-52623.
[14] S. Berg et al. Phys. Rev. STAB **9** (2006) 011001.
[15] A. Kurup and K. Long, "The International Design Study for a Neutrino Factory," WE6RFP067 (these proceedings). See also: https://www.ids-nf.org/wiki/FrontPage.
[16] K. McDonald, "The MERIT High-Power Target Experiment at the CERN PS," TU4GRI03 (these proceedings).
[17] D. Kaplan and K. Long, "MICE: The International Muon Ionization Cooling Experiment," XXIII International Symposium on Lepton and Photon Interactions at High Energy (LP07), Daegu, Korea, August, 2007.
[18] J. Norem, et al., "Recent Results from the MuCool Test Area," PAC07, Albuquerque, June 2007, WEPMN090, p. 2239; http://www.JACoW.org.; D. Huang et al., "RF Studies at Fermilab MuCool Test Area," TU5PFP032, these proceedings.
[19] C. Johnstone et al, Nucl. Phys. B (Proc. Suppl.) **155** 2006.
[20] J. Norem *et al., "Results from Atomic Layer Deposition and Tunneling Spectroscopy for Superconducting RF Cavities,"* in the Proceedings of 11th European Particle Accelerator Conference (EPAC 08), Magazzini del Cotone, Genoa, Italy, 23-27 Jun 2008, pp WEPP099.
[21] K. Yonehara et al., Nucl. Phys B (Proc. Supp.) **149** (2005).
[22] S. Geer, O. Mena, S. Pascoli, Phys. Rev. **D75**, 093001 (2007); A. Bross, M. Ellis, S. Geer, O. Mena, S. Pascoli, Phys. Rev. **D77**, 093012 (2008); C. Ankenbrandt et al. FERMILAB-PUB-09-001-APC (2009).
[23] N. Saoulidou, Journal of Physics, Conference Series **136** (2008) 022021.
[24] T. Ota, J. Sato, and N.Yamashita, "Oscillation enhanced search for new interaction with neutrinos," Phys. Rev. **D65** (2002).
[25] S. Geer, submitted to Annual Reviews of Nuclear and Particle Science.