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A Strategy for Accelerator-Based Neutrino Physics in the USA

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We outline a strategy for next-generation neutrino physics experiments based on beams from accelerators in North America. This strategy is based on the mounting evidence in favor of the large mixing angle solution to solar neutrino problem [1], which implies that in addition to measurement of $\sin^2 2\theta_{13}$ and of the sign of Δm^2_{23}, measurement of CP violation in the neutrino sector is a realizable goal provided $\sin^2 2\theta_{13}$ is not too small

The strategy is to begin with a new detector, 20-30 kton of liquid argon, designed to make best use of the NUMI beam currently under construction at FNAL. Then, after new measurements have made the optimal path clearer, we anticipate choosing among options for neutrino "superbeam" upgrades at BNL and/or FNAL as well as for second new detector of 100-200 kton.

1 Basis of the Strategy

The strategy is based on eight considerations of neutrino physics and neutrino beams:

- Improved measurements of the neutrino mixing parameters Δm^2_{23}, and $\sin^2 2\theta_{23}$, as well as new measurements of $\sin^2 2\theta_{13}$, are best accomplished with a detector located at the first oscillation maximum of $\nu_2 \leftrightarrow \nu_3$, namely $L[\mathrm{km}] = 1.24 E_\nu[\mathrm{GeV}]/\Delta m^2_{23}[\mathrm{eV}^2] \approx 500 E_\nu[\mathrm{GeV}]$, supposing $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2.

- Measurements of CP violation are possible (presuming the LMA solution to the solar neutrino problem holds) with roughly equal accuracy at any maximum of the $\nu_2 \leftrightarrow \nu_3$ oscillation pattern [2], but best accuracy is obtained at the lowest energy practicable.

- The sign of Δm^2_{23} can be determined via matter effects [3, 4], which grow with distance but are very small for $L \lesssim 1000$ km.

- If Δm^2_{12} is at or above the upper limit of the presently allowed value in the LMA solution, as should be clarified in a year or two by KamLAND [5], then two scales of oscillation will be discernible in very long baseline experiments [6].

- Accelerator-based neutrino beams from pion (and kaon and muon) decay are dominantly ν_μ (from positive mesons, and $\bar\nu_\mu$ from negative mesons) with admixtures of ν_e and $\bar\nu_\mu$ at the one percent level. These backgrounds limit the sensitivity of measurements of $\sin^2 2\theta_{13}$ and CP violation, which rely on detection of $\nu_\mu \to \nu_e$ oscillations. Furthermore, if the beam energy is high enough that $\nu_\mu \to \nu_\tau$ oscillations can materialize as τ leptons, the semileptonic decay $\tau \to eX$ causes undesirable backgrounds.

- Accelerator-based neutrino beams will have a broad energy distribution, unless special efforts are made to reduce this, which leads to background to the $\nu_\mu \to \nu_e$ signal from ν_μ neutral-current interactions, and ν_τ charged-current interactions, of higher than nominal energy.

- If we are confident about the value of Δm^2_{23}, it is therefore advantageous to narrow the energy spectrum of the beam, which can be accomplished for low-energy neutrinos by use of an off-axis neutrino beam [7, 8] that enhances the neutrino flux at an angle $\theta \approx 2°/E_\nu$[GeV] (due to the Jacobian peak in the two-body decay kinematics of the pion), as shown in Fig. 1.

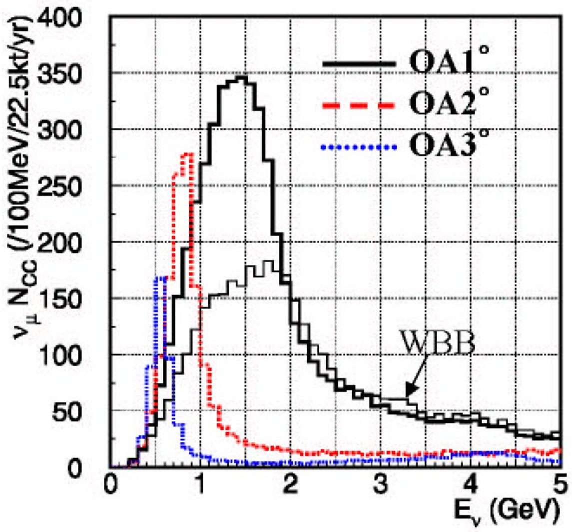

Figure 1: Comparison of neutrino spectra for off axis beams at 1°, 2° and 3° with a wideband beam (WBB) derived from a conventional neutrino horn [9].

- Interactions of neutrino of energies below about 700 MeV with nucleons are primarily quasi-elastic with two body final states that permit further suppression of neutral-current backgrounds [9]. A remaining troublesome background is inelastic scatters with a single π^0 in the final state, whose decay photons can be mistaken for electrons.

2 Phase I of the Program

In Phase I a 20-30 kton liquid argon detector is built at a site near Soudan but 1° off axis from the NUMI beam, with emphasis on measurement of $\sin^2 2\theta_{13}$.

Based on the considerations of sec. 1, Phase-I of the measurement strategy is formulated as follows:

- The broadest program of measurement of neutrino oscillation parameters in accelerator experiments should emphasize a low-energy beam, $E_\nu < 1$ GeV, and a detector at distance < 400 km, while retaining the option for studies at longer baselines.

- However, to begin the program in a timely manner, it should start by using the NUMI beam from FNAL, whose spectrum drops rapidly below 2 GeV, even when enhanced by going $\approx 1°$ off axis.

- Hence, the program should begin with a new detector, sited about 1° off the nominal NUMI line, at about 700 km from FNAL so as to be near the first oscillation associated with Δm^2_{23}. A suitable site would be near Silver Creek, MN (lat. 47.11°, long. −91.58° [10], 640 km from FNAL), where a horizontal tunnel could be dug into a bluff next to Lake Superior to provide $\approx 400'$ overburden. See Fig. 2.

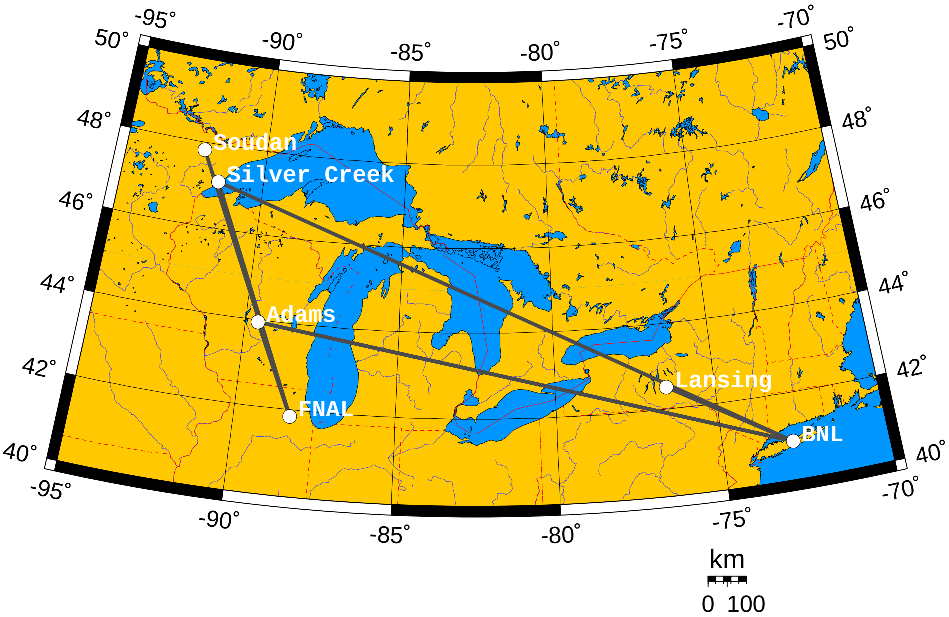

Figure 2: Possible sites for new detectors in neutrino beams from FNAL and BNL. In phase I a 20-30 kton liquid argon detector would be built near Silver Creek, MN. In Phase II a 100-200 kton detector would be built near Adams, WI or Lansing, NY and new neutrino beams built at BNL and FNAL using 1-4 MW proton driver upgrades.

- Among various types of detectors, a liquid argon time projection chamber [11] has the best rejection of background due to neutral-current interactions and low-energy π^0's. This permits measurements of $\sin^2 2\theta_{13}$ and CP violation via $\nu_\mu \to \nu_e$ oscillations with a much smaller detector mass of argon, as illustrated in Fig. 3 from a recent study [12].

- A 300-ton liquid argon detector has recently begun operation [13], with high-quality tracking of particle interactions as shown in Fig. 4. To extend measurements of neutrino oscillation parameters beyond those that will be obtained by other experiments in the next decade, the initial detector mass must be at least 20 kton. In later phases it will be desirable to increase the detector mass to 100-200 kton, possibly at a new site. Cost are minimized when the detector is built as a single module, such as that sketched in Fig. 5 [14, 15].

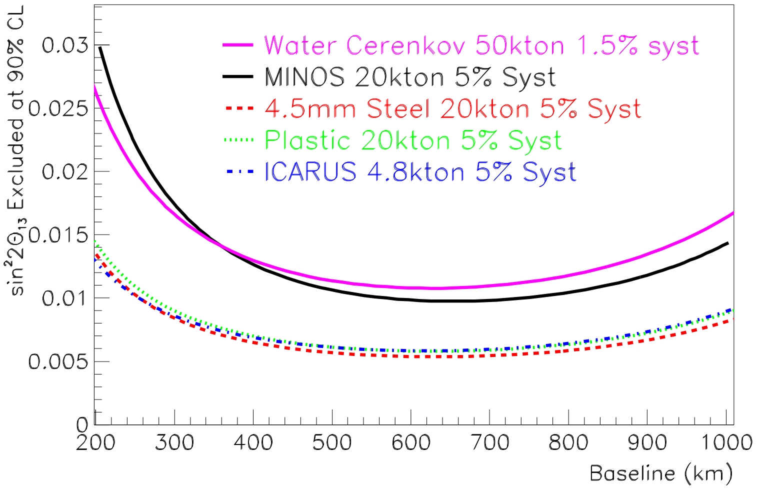

Figure 3: Comparison of several types of detectors in measuring $\sin^2 2\theta_{13}$ in the presence of backgrounds typical of a pion-decay neutrino beam at intermediate baselines [12]. The detector labeled ICARUS [13] is a liquid argon time projection chamber. With a 25-kton liquid argon detector, and an off-axis neutrino beam, as considered in the first phase of the present strategy, the sensitivity to $\sin^2 2\theta_{13}$ would be at least 0.003.

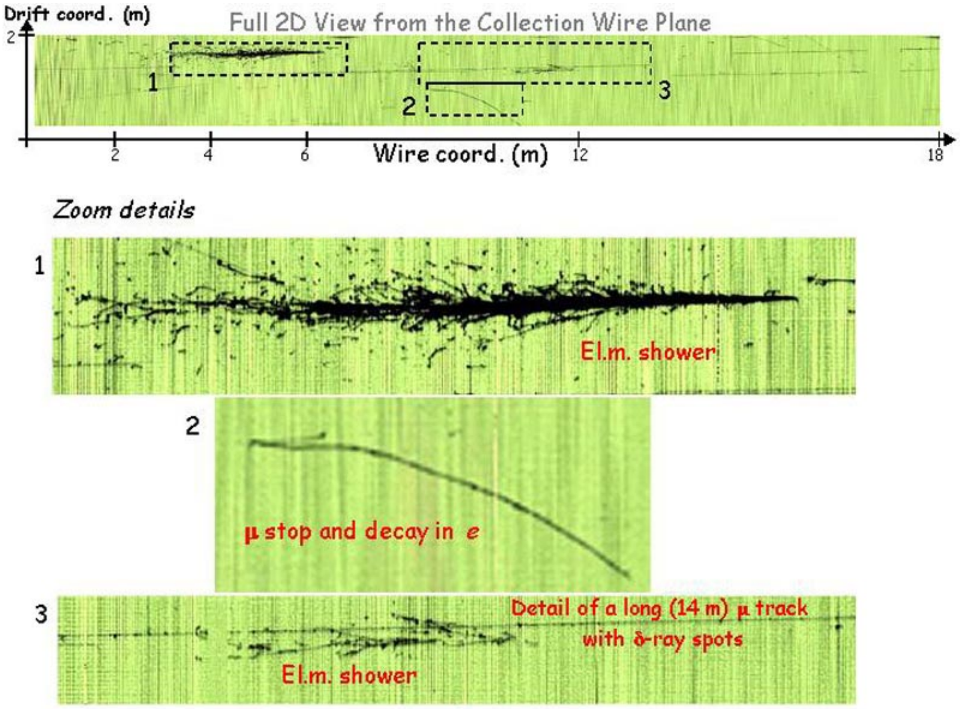

Figure 4: An event from the recent cosmic-ray test run of ICARUS [13], showing excellent track resolution over long drift distances in zero magnetic field.

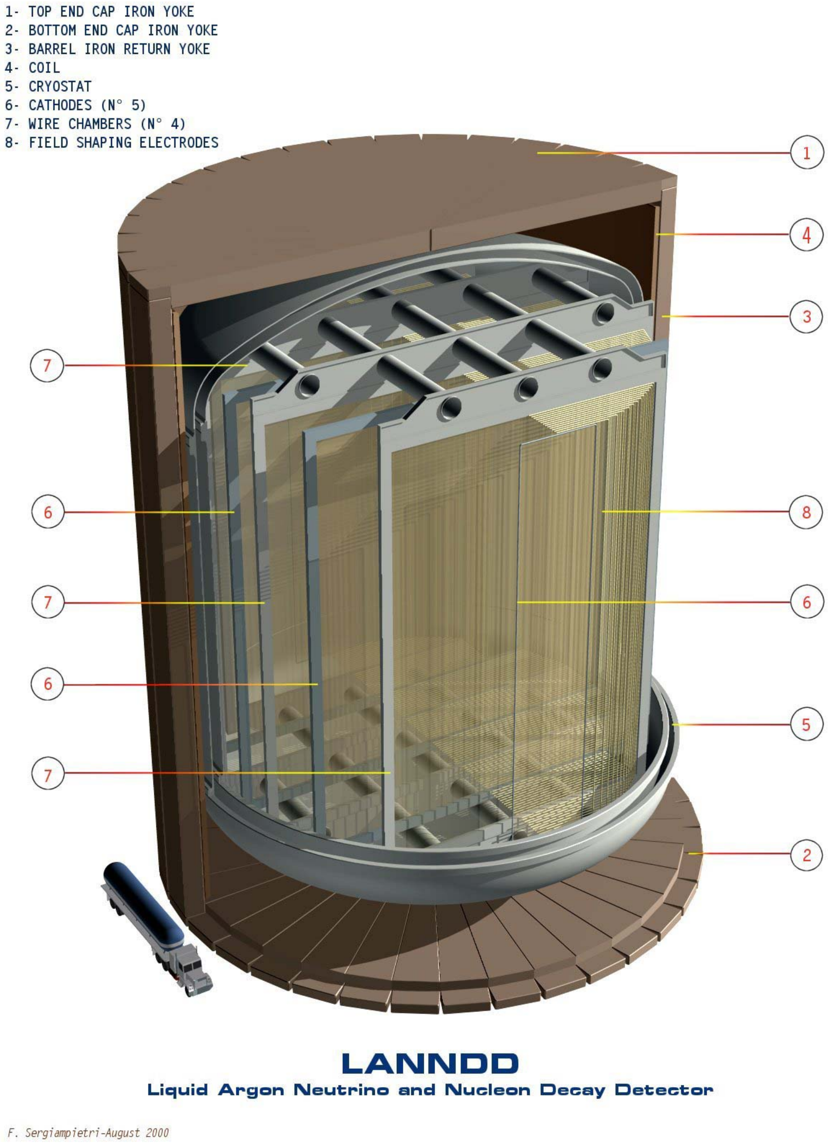

Figure 5: Concept of a 70-kton Liquid Argon Neutrino and Nucleon Decay Detector (LANNDD) [14, 15].

- The detector for an accelerator-based neutrino experiment could be located on the surface of the Earth (or with a cover of $\approx$ 100 m to suppress the cosmic-ray rate) because the beam duty factor is $\approx 10^{-6}$. Because of its excellent characterization of events, even with only 100-m overburden a large liquid argon detector can provide essentially background-free sensitivity to proton decay via the modes $p \to e^+\pi^0$ and $p \to K^+\bar{\nu}$ [16]. A 25 kton liquid argon detector yield a factor of 10 improvement in the sensitivity over present limits to proton decay via the mode $p \to K^+\bar{\nu}$ [17] that is favored in generic SO(10) supersymmetric grand-unified models [18].

3 Phase II of the Program

The first phase of the program, with a 20-30 kton liquid argon detector sited 640 km from FNAL in a 1° off-axis NUMI beam, will clarify whether the next step is a) continued search for $\sin^2 2\theta_{13}$ as it is very small; b) measurement of the sign of ΔM^2_{23}; c) measurement of CP violation. All three options will require increased neutrino flux and will benefit from a larger detector. Option 2 will require a longer baseline to enhance the matter effects, while option 3 would benefit from a shorter baseline and lower energy beam.

A way of characterizing the goal of Phase II is 10 times the sensitivity to $\sin^2 2\theta_{13}$ as in Phase I. Since measurement of $\sin^2 2\theta_{13}$ is background limited, a factor of 10 improvement in sensitivity requires a factor of 100 improvement in the product of neutrino flux and detector mass. Thus, the general strategy is to upgrade the neutrino beam by a factor of 10 (from a 0.4 MW proton driver to a 4 MW one), and also to increase the detector mass by 10 (from 20 to 200 kton).

There is considerable flexibility in the order of implementation of the components of phase II. The major choices are:

1. Build a new large detector close to FNAL, upgrade the FNAL beam to operate at higher intensity and lower neutrino energy to study $\sin^2 2\theta_{13}$ and CP violation, and build a neutrino beam at BNL pointing to the new detector to study the sign of ΔM^2_{23}.

2. Build a new large detector close to BNL, build a new neutrino beam at BNL to study $\sin^2 2\theta_{13}$ and CP violation in the new detector, and build an option into the BNL neutrino beam to be deflected slightly to the Silver Creek detector to study the sign of ΔM^2_{23}.

If it appears appropriate to pursue measurement of the sign of ΔM^2_{23} before CP violation, the second scenario would be favored.

Scenario 1 is more costly than scenario 2 in that beam upgrades at both BNL and FNAL are required. The advantage of scenario 1 is more continuous operation of the program, and the greater ultimate flexibility of having two high-performance beams with different baselines to a single high-quality detector (plus continued operation of the Phase-I detector at a 3rd baseline intermediate between the other two). Scenario 2 has the "cultural" advantage that the new detector could be located close to Cornell University, while the new detector in scenario 1 will of necessity be at a somewhat remote location.

3.1 Phase II with a New Detector near FNAL

The ingredients of this scenario are:

1. A 100-200 kton liquid argon detector sited closer to the neutrino source so that lower-energy neutrinos can be used. An example site is under a bluff at lat. 43.954°, long. −89.585° near Adams, WI, as shown in Fig. 2 [10], where a horizontal tunnel could be dug into the hillside to provide $\approx$ 100 m rock overburden. This site is 260 km from FNAL, and 2.2° off the NUMI beam axis, which is appropriate for a neutrino beam of $\approx$ 700 MeV.

2. Upgrade of the FNAL proton driver to 4 MW. As neutrinos of $\approx$ 700 MeV are desired, the proton beam energy need not be higher than 8 GeV. Hence, the needed proton driver upgrade is based on a high-performance 8-GeV booster [19].

3. Construction of a new neutrino beam at BNL with a proton driver of power 0.5-4 MW as the physics warrants [20, 21]. With this beam pointing to the site of the new large detector, the sign of ΔM^2_{23} can be measured, and additional data taken towards the measurement of CP violation.

3.2 Phase II with a New Detector near BNL

The ingredients of this scenario are:

1. The new 100-200 kton liquid argon detector could be sited in or near the Cargill Salt Mine in Lansing, NY, lat. 42.509°, long. −76.517°, 350 km from BNL, as shown in Fig. 2 [22]. The working depth of the mine is about 1700′. This site is in the municipality immediately north of Cornell University.

2. Upgrade of the BNL proton driver to 4 MW, and construction of a new neutrino beam [20, 21]. The beam would be pointed about 2° below the direction Lansing to obtain an enhancement of neutrino flux near 900 MeV.

3. The angle between BNL-Lansing and BNL-Silver Creek is 5.9° although the azimuthal angle between Lansing and Silver Creek with respect to BNL is only 1°. Thus, neutrinos 4° off-axis from the nominal beam to Lansing would arrive at the Silver Creek detector. This angle is slightly too large to provide a useful neutrino flux. Rather, when it is desired to study the sign of ΔM^2_{23} with a beam from BNL to the Silver Creek detector, the magnets of the target station would have to be rotated downwards by about $2-3°$. That is, useful data could not be taken simultaneously at the Lansing detector and the Silver Creek detector with a beam from BNL. Of course, the Silver Creek detector can continue to take data with the NUMI beam from FNAL at all times.

The conference version of this paper includes additional cartographical information: http://www.hep.princeton.edu/˜mcdonald/nufact/neutrinotrans12.pdf

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