Neutrino Oscillation Experiments for Precise Measurements of Oscillation Parameters and Search for $\nu_\mu \rightarrow \nu_e$ Appearance and CP Violation.

LETTER OF INTENT to Brookhaven National Laboratory.

D. Beavis, M. Diwan, R. Fernow, J. Gallardo, S. Kahn, H. Kirk, D. Lowenstein, W. Marciano, W. Morse, Z. Parsa, R. Palmer, T. Roser, N. Samios, Y. Semertzidis, N. Simos, B. Viren, W. Weng

Brookhaven National Laboratory Box 5000, Upton, NY 11973-5000

W. Frati, J. R. Klein, K. Lande, A. K. Mann, R. Van Berg and P. Wildenhain

University of Pennsylvania Philadelphia, PA 19104-6396

R. Corey

South Dakota School of Mines and Technology Rapid City, S.D. 57701

D. B. Cline, K. Lee, B. Lisowski, P. F. Smith

Department of Physics and Astronomy, University of California, Los Angeles, CA 90095 USA

A. Badertscher, A. Bueno, L. Knecht, G. Natterer, S. Navas, A. Rubbia

Institut fr Teilchenphysik, ETHZ, CH-8093 Zürich, Switzerland

R. F. Burkart, W. Burgett, E. J. Fenyves

Department of Physics, University of Texas at Dallas, Richardson, TX 75083 USA

J. G. Learned

Department of Physics and Astronomy, University of Hawaii, Honolulu, HI 96822 USA

V. Palladino

Universita di Napoli "Federico II", 80138 Napoli, Italy

I. Mocioiu, R. Shrock

C.N. Yang Institute for Theoretical Physics, State University of New York, Stony Brook, NY 11974 USA

C. Lu, K.T. McDonald

Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544 USA

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Abstract

The possibility of making a low cost, very intense high energy proton source at the Brookhaven Alternating Gradient Synchrotron (AGS) along with the forthcoming new large underground detectors at either the National Underground Science Laboratory (NUSL) in Homestake, South Dakota or at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico, allows us to propose a program of experiments that will address fundamental aspects of neutrino oscillations and CP-invariance violation. This program of experiments is unique because of the extra-long baseline of more than 2500 km from Brookhaven National Laboratory to the underground laboratories in the West, the high intensity of the proposed conventional neutrino beam, and the possibility of constructing a very large array of water Cerenkov detectors with total mass approaching 1 Megaton. As part of this program we also consider experiments at moderately long baselines ($\sim$400 km) using other detector technologies that can yield valuable and complementary information on neutrino oscillations. This letter of intent focuses on the design and construction of the necessary AGS upgrades and the new neutrino beam which will initially have a proton beam of power $\sim$0.5 MW; the power will then be upgraded to $\sim$1.3 MW in a later phase.

1 Introduction

This is a letter of intent to build a new high intensity neutrino beam at BNL in two phases. The first phase will involve AGS upgrades consisting of an addition to the present LINAC to yield a total LINAC energy of 400 MeV, and an accumulator ring with permanent magnets mounted in the AGS tunnel. This will allow injection into the AGS at 2.5 GeVand an AGS cycle time of 1 Hz. At 28 GeV, the intensity should be 1.2×10^{14} protons per pulse and the power 0.53 MW. The second phase will require new power supplies for the AGS and booster magnets for rapid cycling, an RF upgrade, and additional shielding; these will produce an AGS cycle time of 2.5 Hz and 1.3 MW power. The new intense proton beam will be used to produce a conventional horn focussed neutrino beam directed at the far detectors. We propose to send the beam to two different distances: the very long distance of 2540 km (2880 km) to the Homestake (WIPP) [1, 2] laboratory, and a much shorter distance of 400 km to a new detector location in upstate New York.

It is now well known that the strongest evidence for neutrino oscillations so far comes from astrophysical observations of atmospheric neutrinos with $\Delta m^2_{32} = (1.6-4.0)\times 10^{-3} e\mathrm{V}^2$ and maximal mixing [3] and from solar neutrinos with $\Delta m^2_{21} \sim (2-10)\times 10^{-5} e\mathrm{V}^2$ and the LMA solution for solar neutrinos [5]. The observation by the LSND experiment [6] will soon be re-tested at Fermilab by the mini-Boone [7] experiment, therefore we will not discuss it further in this document. There are several accelerator based experiments (K2K, MINOS, and CNGS) [8, 9, 11, 12] currently in construction phase or taking data to confirm the atmospheric neutrino signatures for oscillations. There is now a consensus that there are four main goals in the field of neutrino oscillations that should be addressed soon with accelerator neutrino beams:

1. Precise determination of Δm^2_{32} and definitive observation of oscillatory behavior.

2. Detection of $\nu_\mu \to \nu_e$ in the appearance mode. If the measured Δm^2 for this measurement is near Δm^2_{32} then this appearance signal will show that $|U_{e3}|^2\,(=\sin^2\theta_{13})$ from the neutrino mixing matrix in the standard parameterization is non-zero.

3. Detection of the matter enhancement effect in $\nu_\mu \to \nu_e$ in the appearance mode. This effect will also allow us to measure the sign of Δm^2_{32}; i.e. which neutrino is heavier.

4. Detection of CP violation in neutrino physics. The neutrino CP-violation in Standard Model neutrino physics comes from the phase multiplying $\sin\theta_{13}$ in the mixing matrix.

This can be detected by observing an asymmetry in the oscillation rates $\nu_\mu \to \nu_e$ versus $\bar{\nu}_\mu \to \bar{\nu}_e$.

In the following we will briefly describe how all of these goals can be achieved under reasonable assumptions for the various parameters using the new intense AGS based beam and the long and very long baselines.

In the first section of this letter of intent we describe the physics purpose of the new beam sent along the baseline of 2540 km (results for 2880 km are similar). The second section describes the physics case for the shorter distance of 400 km. The third section briefly discusses the design and construction of the AGS upgrades. And the last section describes the construction of the new neutrino beam.

2 Very Long Baseline Experiment

The calculated energy distributions of a ν_μ beam produced by 28 GeV protons is shown in Fig. 1 [13]. The 0° calculation has been shown consistent with neutrino beam data [14]. The spectrum peaks at about 1 GeV with a total spread at half intensity of about 1 GeV. Further work on the optimization of this spectrum for the very long baseline experiment is on going. We calculate the event rate without oscillations assuming a 0.5 MW proton beam power with 28 GeV protons (1.1×10^{14} ppp), a 0.5 MT fiducial mass detector and 5 years of running. Because the AGS can run in a parasitic mode to RHIC we expect to get beam for as much as 1.8×10^7 sec per year. However, we conservatively assume only 1.0×10^7 sec of AGS running per year here. Using these parameters and the relevant cross section, we calculate that the number of quasi-elastic charged current muon neutrino events in a detector located at 2540 km will be ~ 5700 in five years running. The number of neutrino events of all types will be approximately twice this number. This large statistics combined with the long baseline makes many of the following important measurements possible.

The angular distribution of the muons from the quasi-elastic process $\nu_\mu + n \to \mu^- + p$ produced by the 0^o beam in Fig. 1 are shown in Fig. 2; the principal background, $\nu_\mu + n \to \mu^- + p + \pi$ is also shown [15]. A variety of strategies are possible to reduce this background further in a water Cerenkov detector. Knowing the direction of an incident ν_μ accurately and measuring the angle of the observed muon allows the energy of the ν_μ to be calculated, up to Fermi momentum effects. This method is used by the currently running K2K experiment [8]. The known capability of large water Cerenkov detectors indicates that at energies lower than

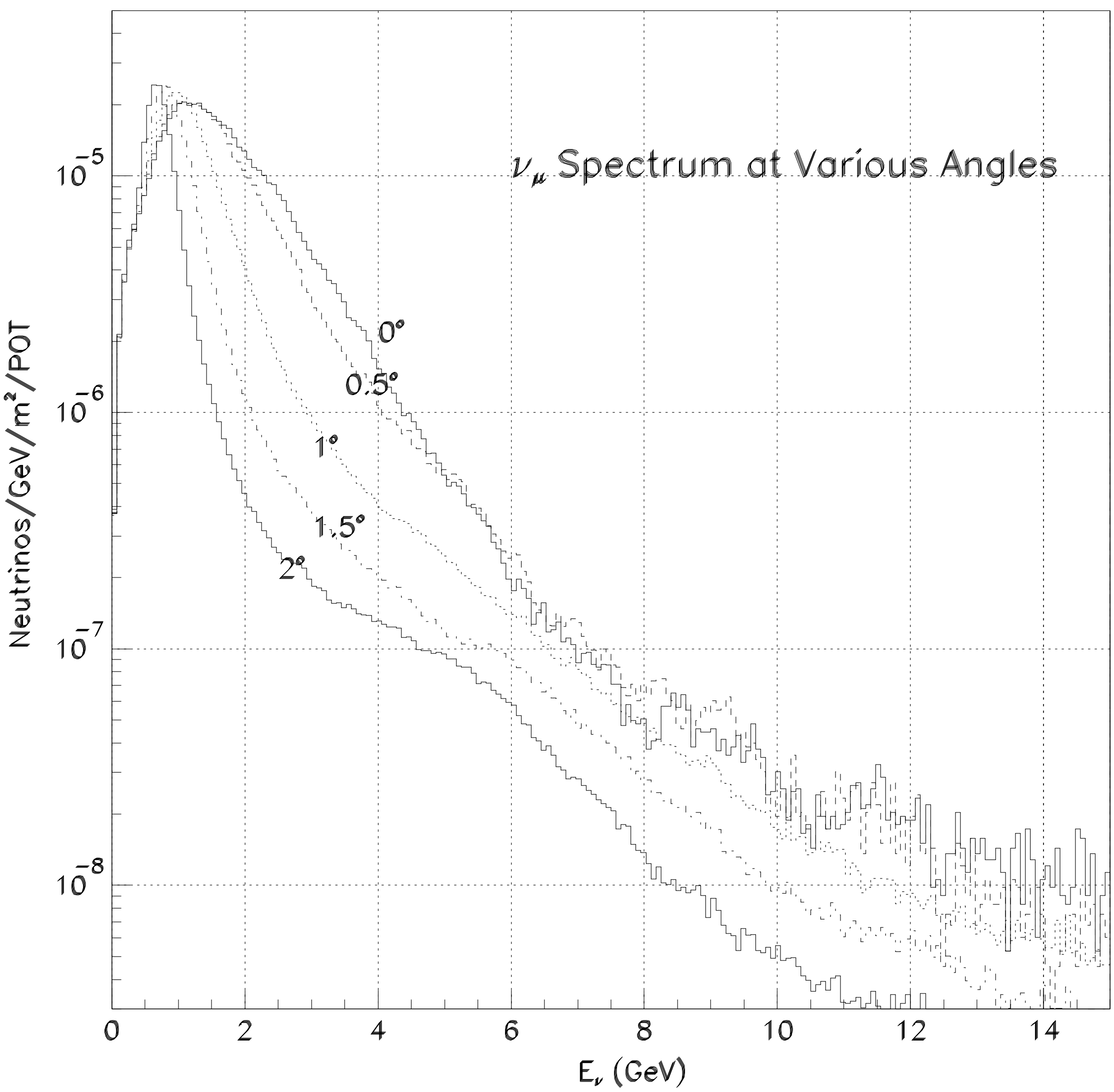

Figure 1: Wide band horn focussed neutrino spectrum for 28 GeV protons. Spectrum of neutrinos are calculated at various angles with respect to the 200 m decay tunnel axis at the AGS and at a distance of 1 km from the target.

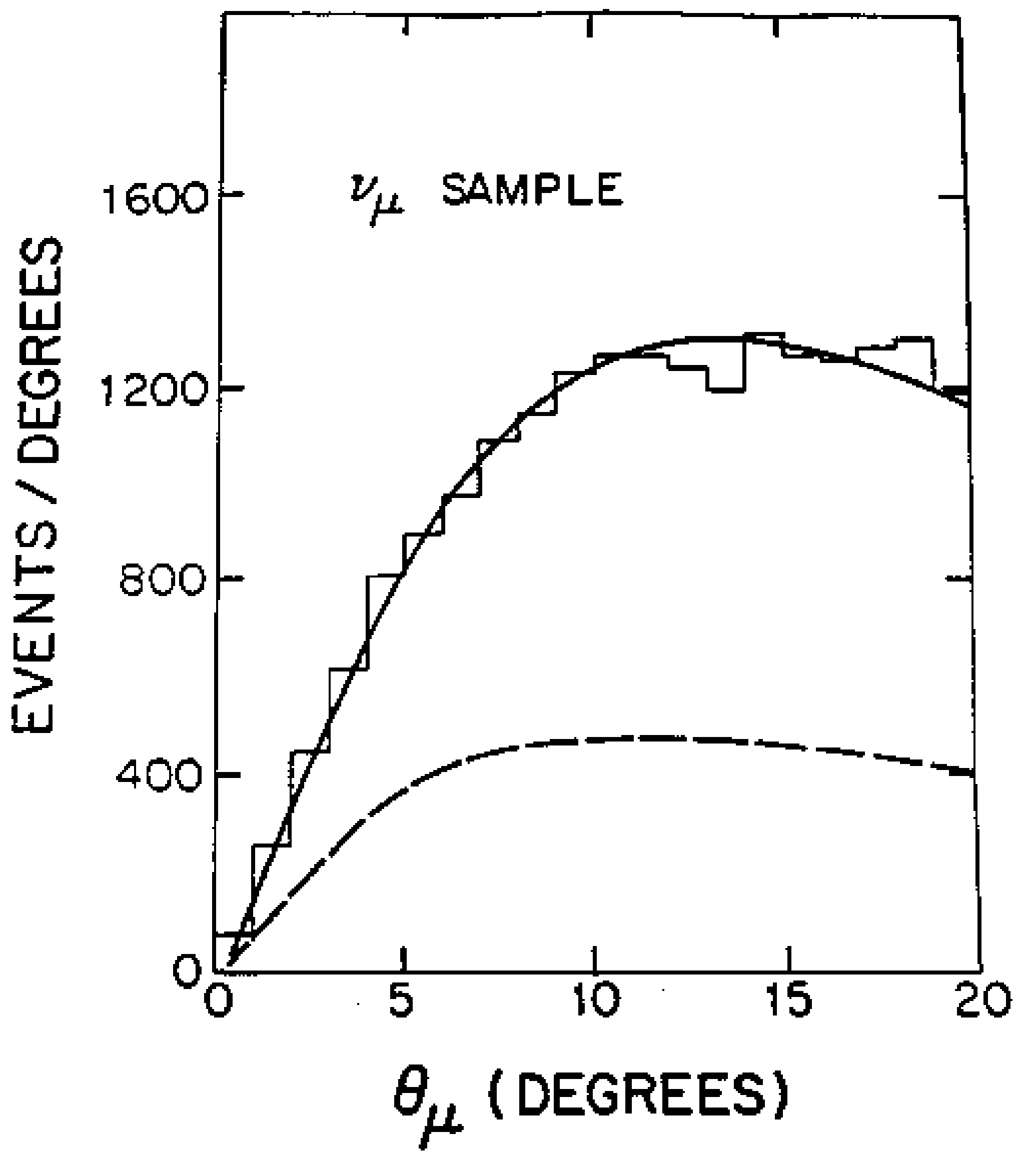

Fig. 10a

Figure 2: Angular distribution of muons from the process $\nu_\mu n \rightarrow \mu^- p$ (top curve) and background from $\nu_\mu N \rightarrow \mu^- N' \pi$ (bottom curve). The histogram is data from E734 and lines are Monte Carlo.

1 GeV the ν_μ energy resolution will be dominated by Fermi motion and nuclear effects[10]. The contribution to the resolution from water Cerenkov track reconstruction depends on the photo-multiplier tube coverage. With coverage greater than $\sim 10\%$, we expect that the reconstruction resolution should be adequate for our purposes. In the following discussion we assume a 10% resolution on the ν_μ energy. This is consistent with the resolution achieved by the K2K experiment.

The range of $\Delta m^2_{32} \sim 1.24 \frac{E_\nu[\text{GeV}]}{L[\text{km}]}$ covered by the proposed experiment using the beam in Fig. 1 extends to the low value of about $5 \times 10^{-4}\ eV^2$. The lower end of this extensive range of values is considerably below the corresponding values for other long baseline terrestrial experiments [11, 12]. If the value of Δm^2_{32} turns out to be towards the lower end ($\sim 10^{-3}$) of its current range or if the value of Δm^2_{21} turns out to be towards its high end ($\sim 10^{-4} eV^2$) then large and very interesting interference effects in the very long baseline experiment will be possible.

Extra-long neutrino flight paths open the possibility of observing multiple nodes (minimum intensity points) of the neutrino oscillation probability in the disappearance experiment. Observation of one such pattern will for the first time directly demonstrate the oscillatory nature of the flavor changing phenomenon. The nodes occur at distances $L_n = 1.24(2n-1)E_\nu/\Delta m^2_{32}$, $n = 1, 2, 3, \ldots$. In Fig. 3, as an example, we show the flight path L versus E_ν relationship of the nodes for $\Delta m^2 = 0.003\text{eV}^2$, a value close to the value measured in atmospheric neutrino experiments [3]. An advantage of having a very long baseline is that the multiple node pattern is detectable over a broad range of Δm^2. This is demonstrated in figures 4 and 5 which shows the disappearance of muon type neutrino events as a function of neutrino energy in quasi-elastic events; the plots do not contain background. For Δm^2_{32} as small as 0.001 eV^2 the oscillation effects will be very large. Even in the presence of background we expect that the statistical error on Δm^2_{32} will be small (~ 0.5 %) and the systematic error from the energy scale of the detector will dominate the total error.

The oscillation of $\nu_\mu \to \nu_e$ is discussed is several recent papers [16, 17, 18]. This oscillation in vacuum is described fully by the following equation:

$$\begin{aligned} P(\nu_\mu \to \nu_e) \; = \; & 4(s_2^2 s_3^2 c_3^2 + J_{CP} \sin\Delta_{21}) \sin^2 \frac{\Delta_{31}}{2} \\ & + 2(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin\Delta_{31} \sin\Delta_{21} \\ & + 4(s_1^2 c_1^2 c_2^2 c_3^2 + s_1^4 s_2^2 s_3^2 c_3^2 - 2 s_1^3 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - J_{CP} \sin\Delta_{31}) \sin^2 \frac{\Delta_{21}}{2} \\ & + 8(s_1 s_2 s_3 c_1 c_2 c_3^2 \cos\delta - s_1^2 s_2^2 s_3^2 c_3^2) \sin^2 \frac{\Delta_{31}}{2} \sin^2 \frac{\Delta_{21}}{2} \end{aligned} \qquad (1)$$

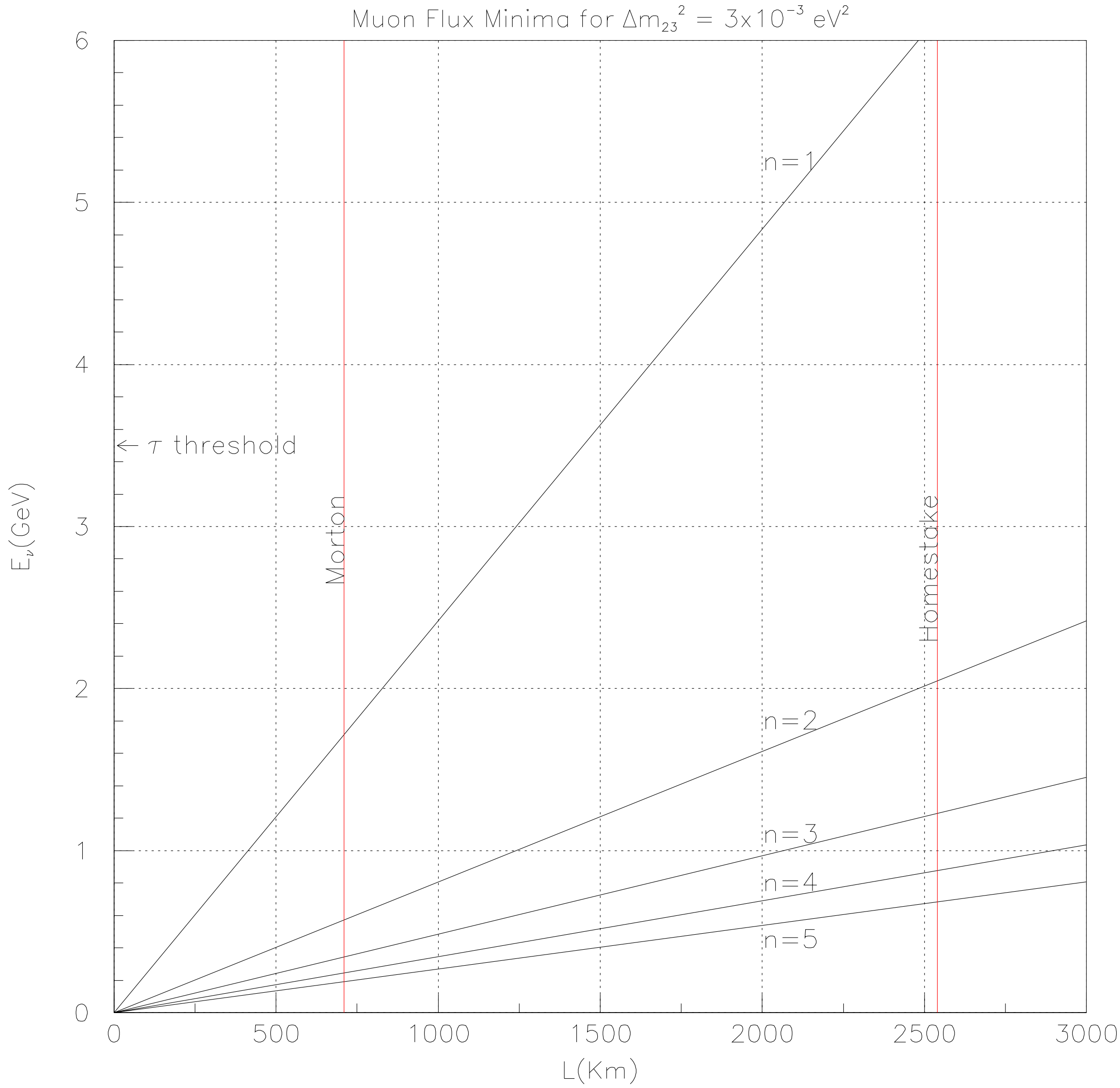

Figure 3: Nodes of neutrino oscillations as a function of oscillation length and energy for $\Delta m^2_{32} = 0.003e\mathrm{V}^2$. Matter effects are not included. The distance to Morton salt works (location of the old IMB experiment [4]) and Homestake is shown by the vertical lines.

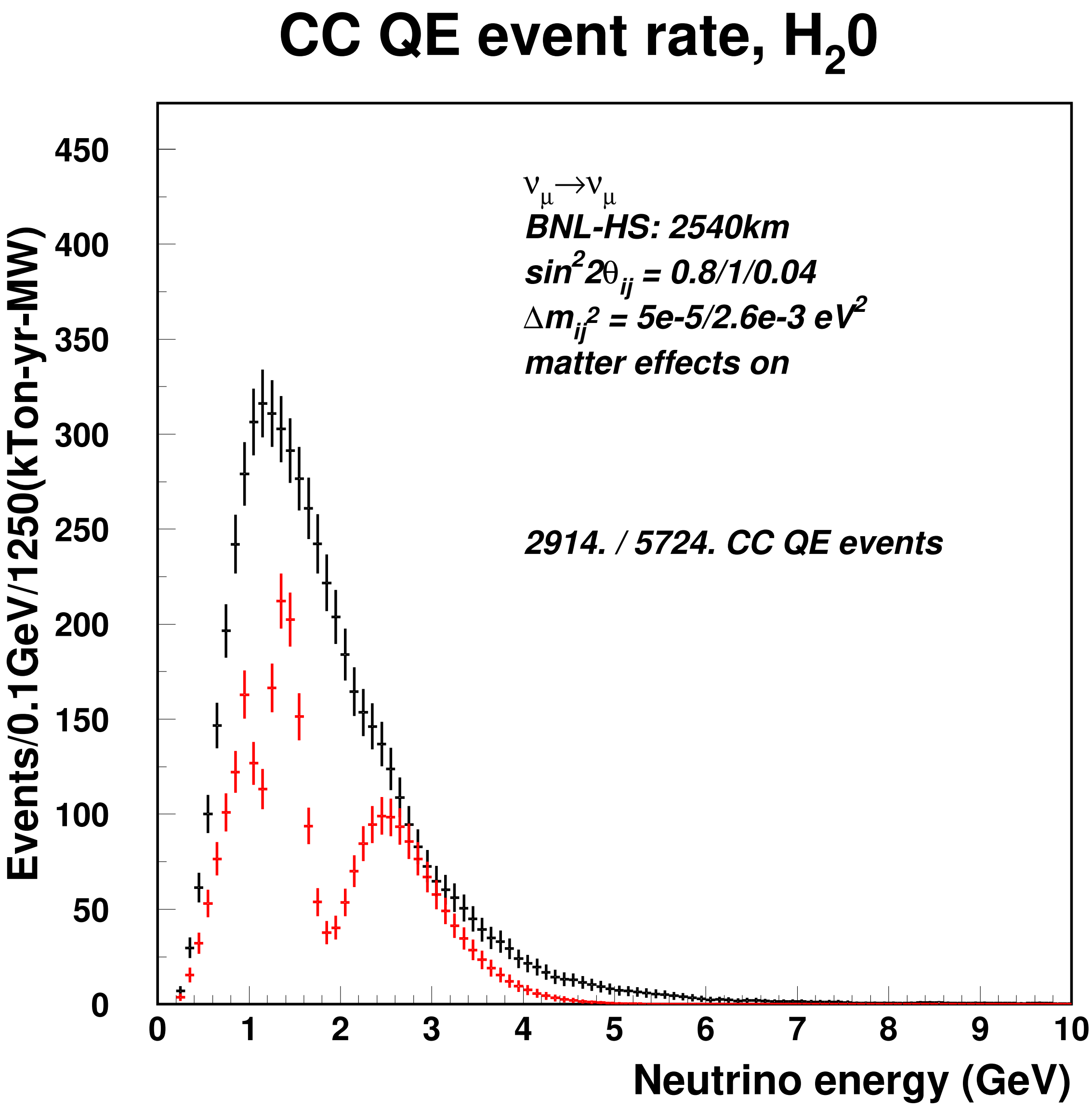

Figure 4: Spectrum of detected quasi-elastic events in a 0.5 MT detector at 2540 km from BNL. We have assumed 0.5 MW of beam power and 5 years of running. The top data points are without oscillations and bottom are with oscillations. This plot is for $\Delta m^2_{32} = 0.0026 e\mathrm{V}^2$. The error bars correspond to the statistical error expected in the bin. A 10 % energy resolution is assumed; this corresponds to the expected resolution due to both nuclear effects and the muon momentum reconstruction in the detector.

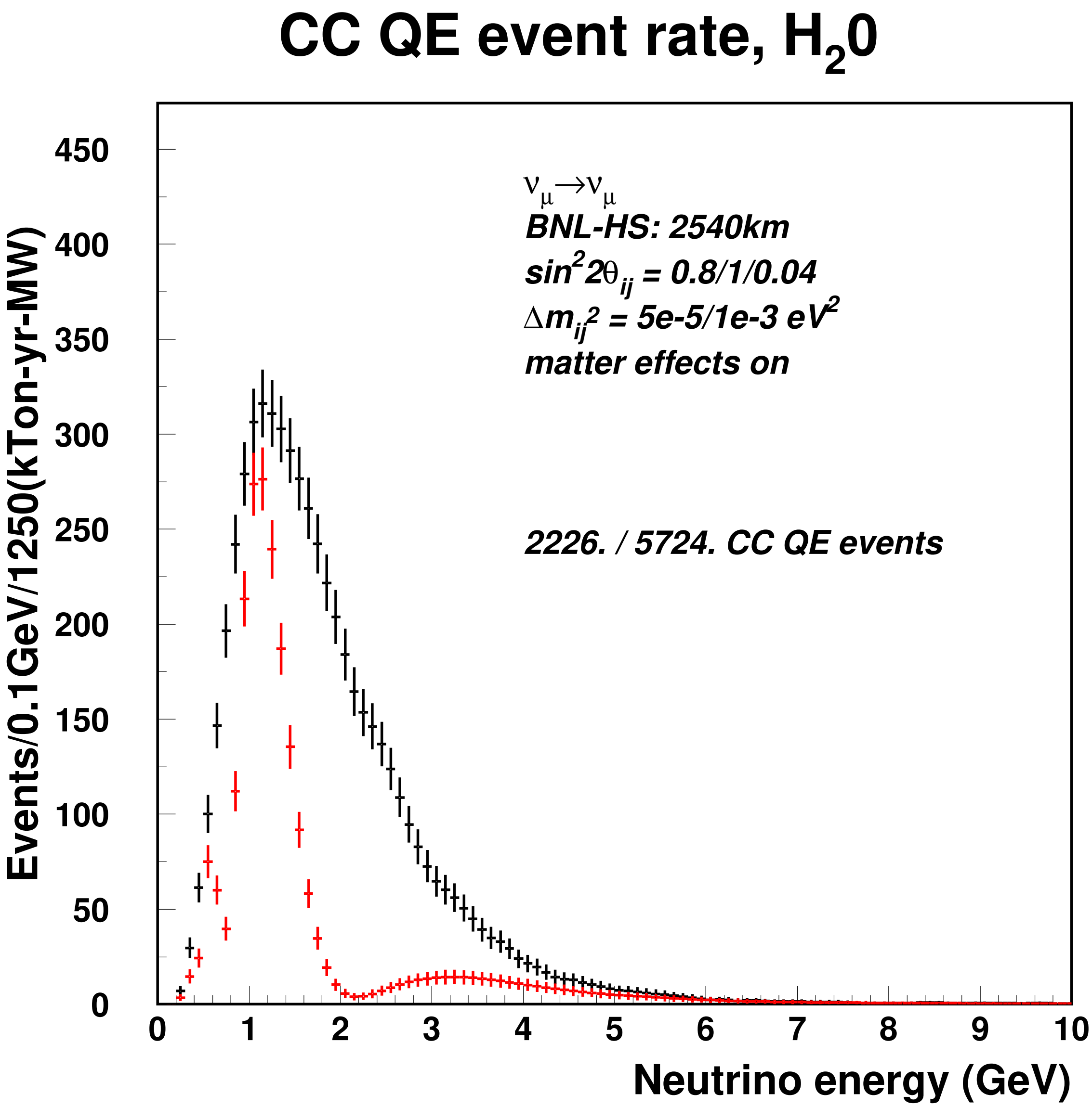

Figure 5: Spectrum of detected quasi-elastic events in a 0.5 MT detector at 2540 km from BNL. We have assumed 0.5 MW of beam power and 5 years of running. The top data points are without oscillations and bottom are with oscillations. This plot is for $\Delta m^2_{32} = 0.001 eV^2$. The error bars correspond to the statistical error expected in the bin. A 10 % energy resolution is assumed; this corresponds to the expected resolution due to both nuclear effects and the muon momentum reconstruction in the detector.

where

$$J_{CP} \equiv s_1 s_2 s_3 c_1 c_2 c_3^2 \sin\delta \tag{2}$$

J_{CP} is an invariant that quantifies CP violation in the neutrino sector. The formula for $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ is the same as above except that the J_{CP} terms have opposite sign. Please see attached appendix (hep-ph/0108181) for definitions of symbols but note that Δ_{31} is the atmospheric term and Δ_{21} is the solar term. The vacuum oscillations for a baseline of 2540 km are illustrated in Fig. 6 as a function of energy for both muon and anti-muon neutrinos. The main feature of the oscillation is due to the term linear in $\sin^2\frac{\Delta_{31}}{2}$. The oscillation probability rises for lower energies due to the terms linear in $\sin^2\frac{\Delta_{21}}{2}$. The interference terms involve CP violation and they create an asymmetry between neutrinos and anti-neutrinos. The vacuum oscillation formula (Eq.1) and Fig. 6 show that the CP asymmetry also grows as $1/E$ in the 0.5-3.0 GeV region. Because of this effect it is argued that the figure of merit for measuring CP violation is independent of the baseline. For very long baselines the statistics for a given size detector at a given energy are poorer by one over the square of the distance, but the CP asymmetry grows linearly in distance [17].

The vacuum oscillation formulation must be modified to include the effect of matter [18]. The $\nu_\mu \to \nu_e$ probability in the presence of matter is shown in Figs. 7 and 8. When compared to Fig. 6 we can see that matter will enhance (suppress) neutrino (anti-neutrino) conversion at high energies and will also lower (increase) the energy at which the oscillation maximum occurs. The effect is opposite (enhancement for anti-neutrinos and suppression for neutrinos) if the sign of Δm^2_{32} is negative. The matter enhancement effect in neutrino oscillations has been postulated for a long time without experimental confirmation [19]. Detection of such an effect by measuring a large asymmetry between neutrino and anti-neutrino oscillations or by measuring the spectrum of electron neutrinos is a major goal for neutrino physics. This measurement will also yield the sign of Δm^2_{32}.

Figures 9, 10 and 11 show the spectrum of electron type neutrinos that will be detected at 2540 km. The signal for $\sin^2 2\theta_{13} \sim 0.04$ will be about 100 events. The background for this signal will come from the intrinsic contamination of ν_e particles in the beam as well as neutral current events producing π^0s. This background will be examined in detail in a future update to this proposal. From past experience using this beam, we expect that the total background in the signal region can be reduced to about 0.5% of the charged current muon neutrino events. The advantages of the very long baseline are in obtaining a large enhancement at higher energies and creating a nodal pattern in the appearance spectrum. Both of these can be used to further improve the sensitivity of the experiment. The very long

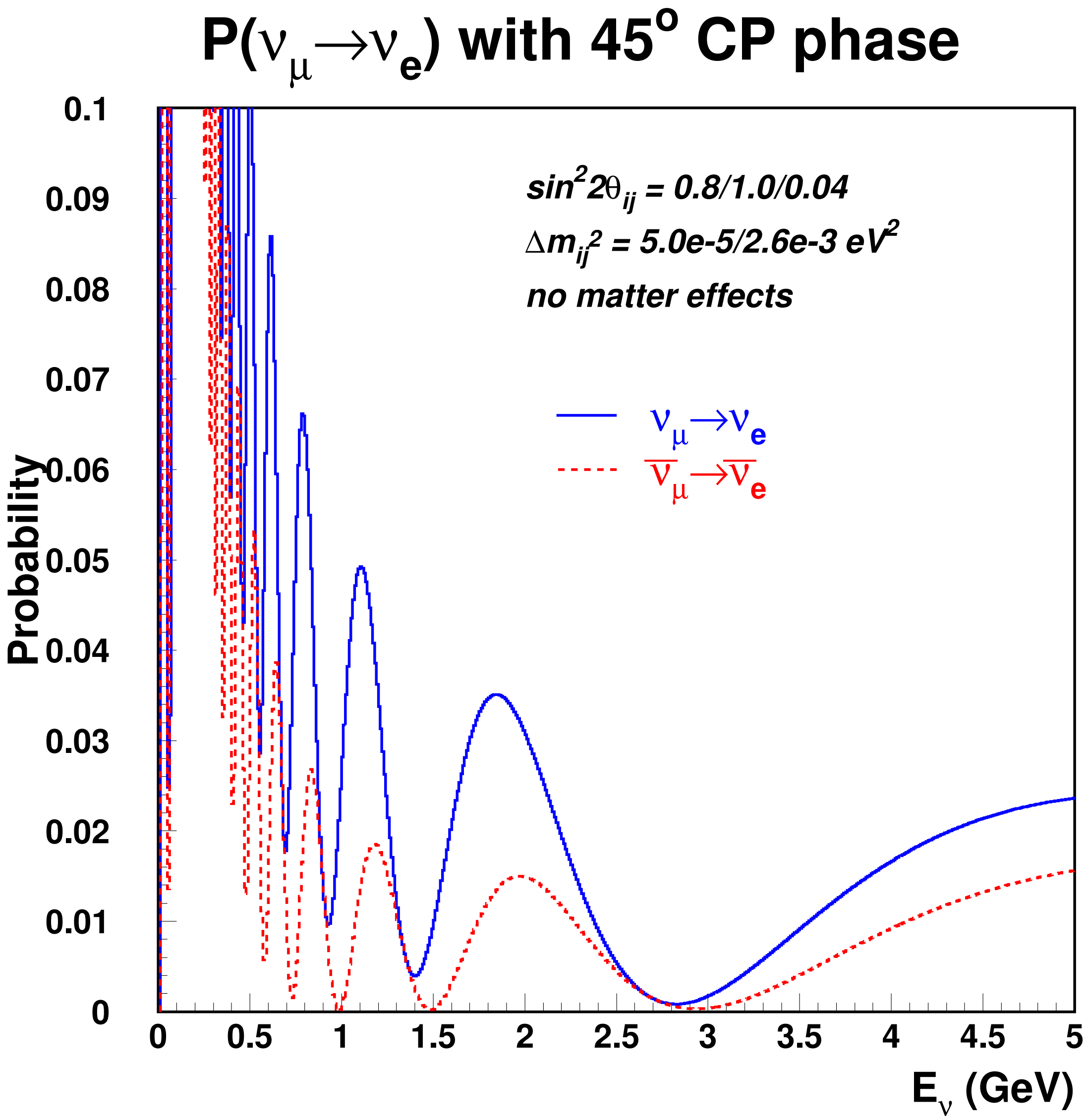

Figure 6: Probability of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations at 2540 km assuming a 45^o CP violation phase. It can be seen that the CP asymmetry between ν_μ and $\bar{\nu}_\mu$ increases for lower energies because the CP asymmetry is proportional to $\Delta m^2_{21} L/E$ which increases for lower energies.

baseline experiment has a great advantage if Δm^2_{21} is found to be somewhat larger within its allowed range $(2-10)\times 10^{-5}e\mathrm{V}^2$. This is shown in Fig. 11. The differences in the electron neutrino spectra are striking within Figs. 9 and 10,11.

To understand CP violation, the effect of matter enhancement must be clearly understood and subtracted from any observation. If CP violation is large and the signal to $\nu_\mu \rightarrow \nu_e$ is also large then it is possible to measure CP violation with just the (ν_μ) neutrino beam. As shown in Fig. 6 the effects of CP violation grow linearly as energy is decreased (or the baseline increased). For a very long baseline experiment it is possible to compare the signal strength in the $\pi/2$ node versus the $3\pi/2$ or higher nodes. Such a comparison will yield a measurement of CP violation. Any such measurement of CP must be augmented by data using a muon anti-neutrino beam. Such a program of measurements will require large statistics. This proposal has the flexibility to obtain much larger data sets because the detector will eventually be upgraded to its final configuration with 1 MT of mass and the AGS accelerator complex can be upgraded up to 2.5 MW of beam power. It is also possible that the conventional neutrino beam which we propose here will be replaced by a neutrino factory based on a muon storage ring [20].

2.1 Detectors for the very long baseline experiment

The conversion of Homestake Gold Mine in Lead, South Dakota, into the National Underground Science Laboratory (NUSL), tentatively to take place in 2002, will provide a unique opportunity for a program of extra-long baseline neutrino oscillation experiments. As explained above these will be possible because of the length of the baseline, 2540 km from the Brookhaven National Laboratory (BNL) to Lead, South Dakota. It is proposed that the NUSL facility will accommodate an array of detectors with total mass approaching 1 Megaton. Most of these will be water Cerenkov detectors that can observe neutrino interactions in the desired energy range with sufficient energy and time resolution [21].

An alternative to Homestake also exists at the Waste Isolation Pilot Plant (WIPP) located in an ancient salt bed at a depth of $\sim 700m$ near Carlsbad, New Mexico. The distance from BNL to WIPP is about 2880 km. The cosmic ray background will be higher at WIPP because the facility is not as deep as Homestake which has levels as deep as $\sim 2500m$. The increased background, although undesirable, is not an insurmountable problem. However, the mechanical design of a large cavity in a salt bed has to be very different because of the slow movement of salt that causes a cavity to slowly collapse in a salt mine. In this LOI we

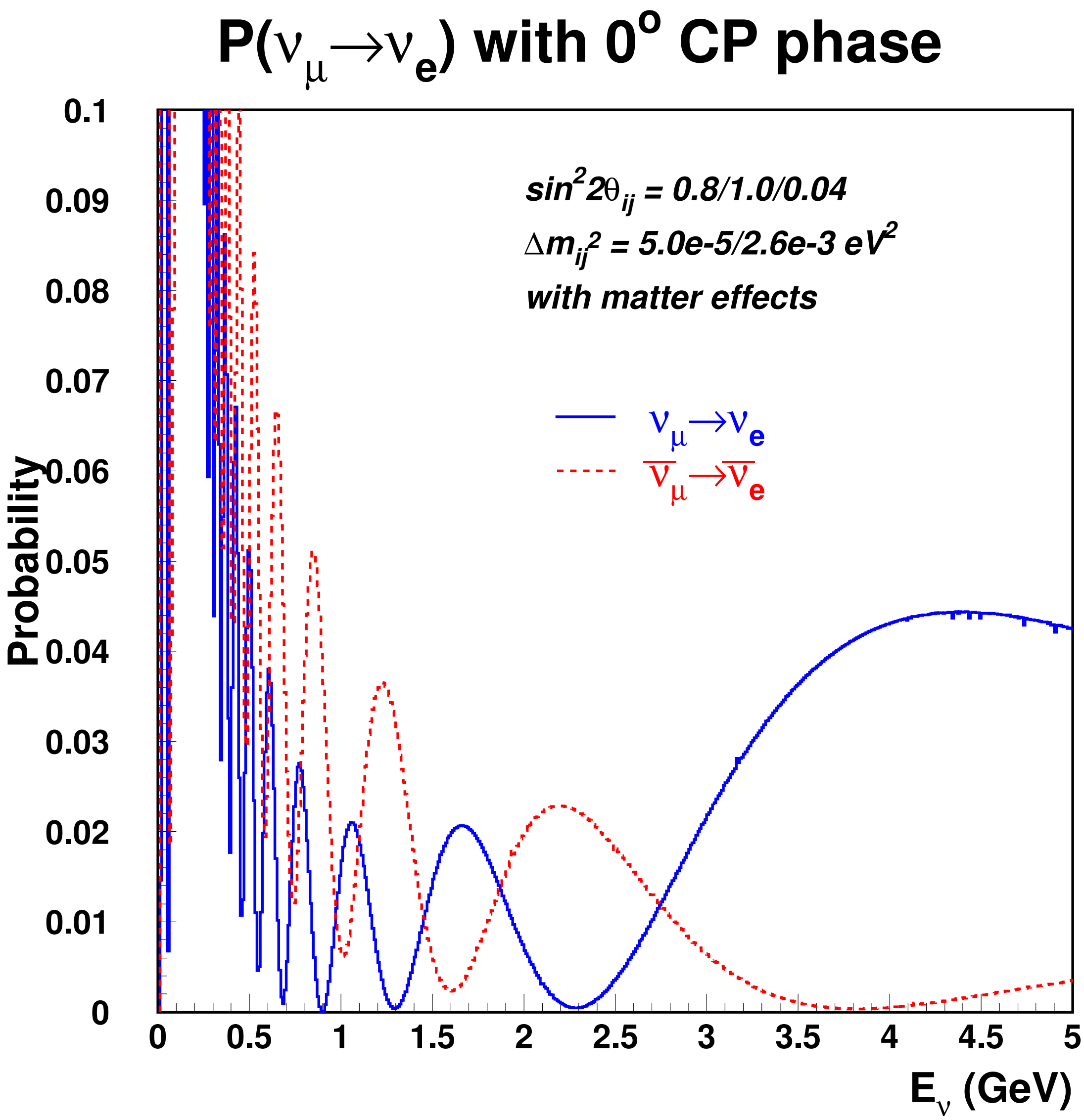

Figure 7: Probability of ν_μ oscillating into ν_e after 2540 km. The parameters assumed are listed in the figures. This plot assumes that there is no CP violation in the neutrino mixing matrix.

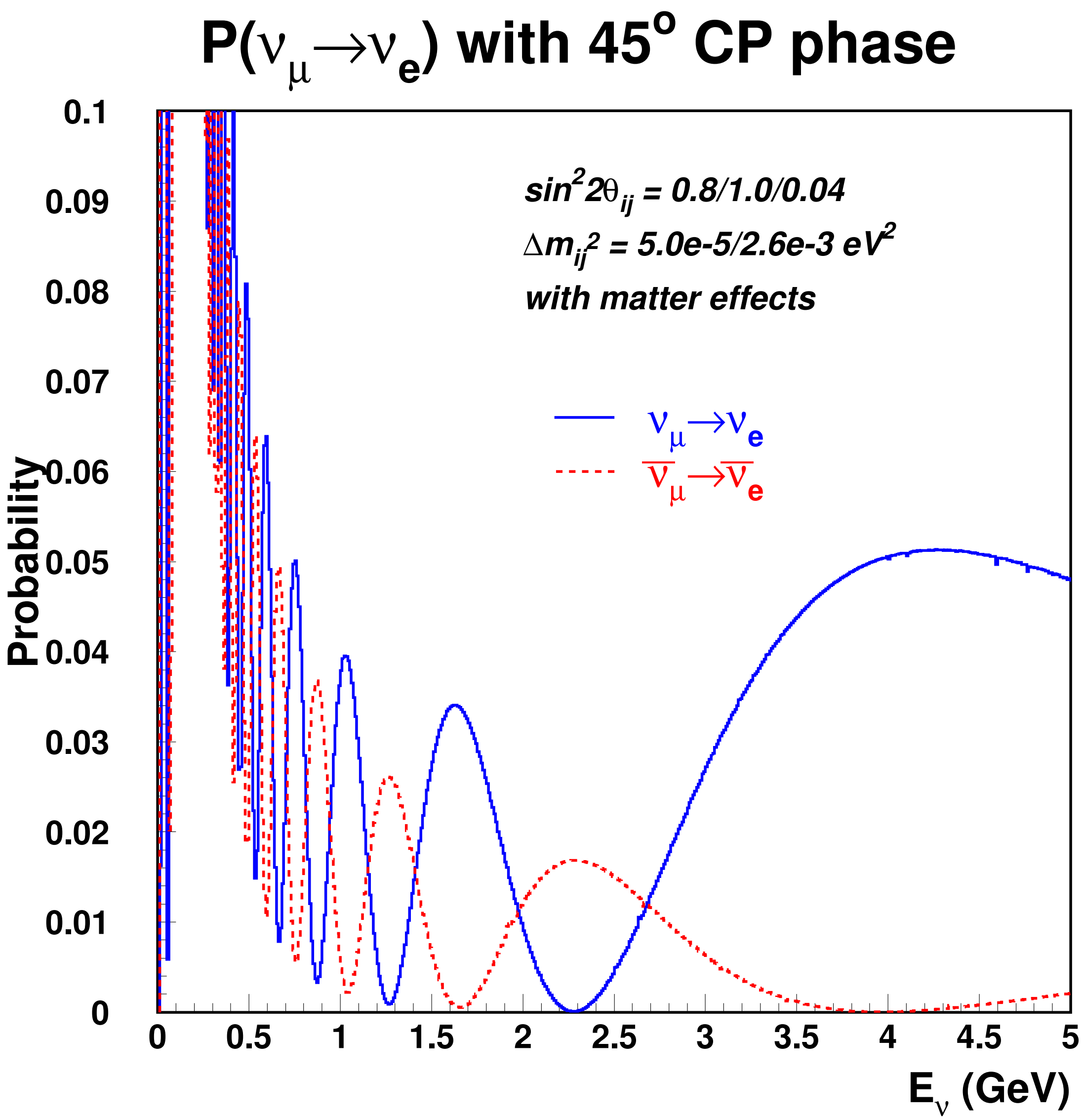

Figure 8: Probability of ν_μ oscillating into ν_e after 2540 km. The parameters assumed are listed in the figures. This plot assumes a CP violation phase of 45^o.

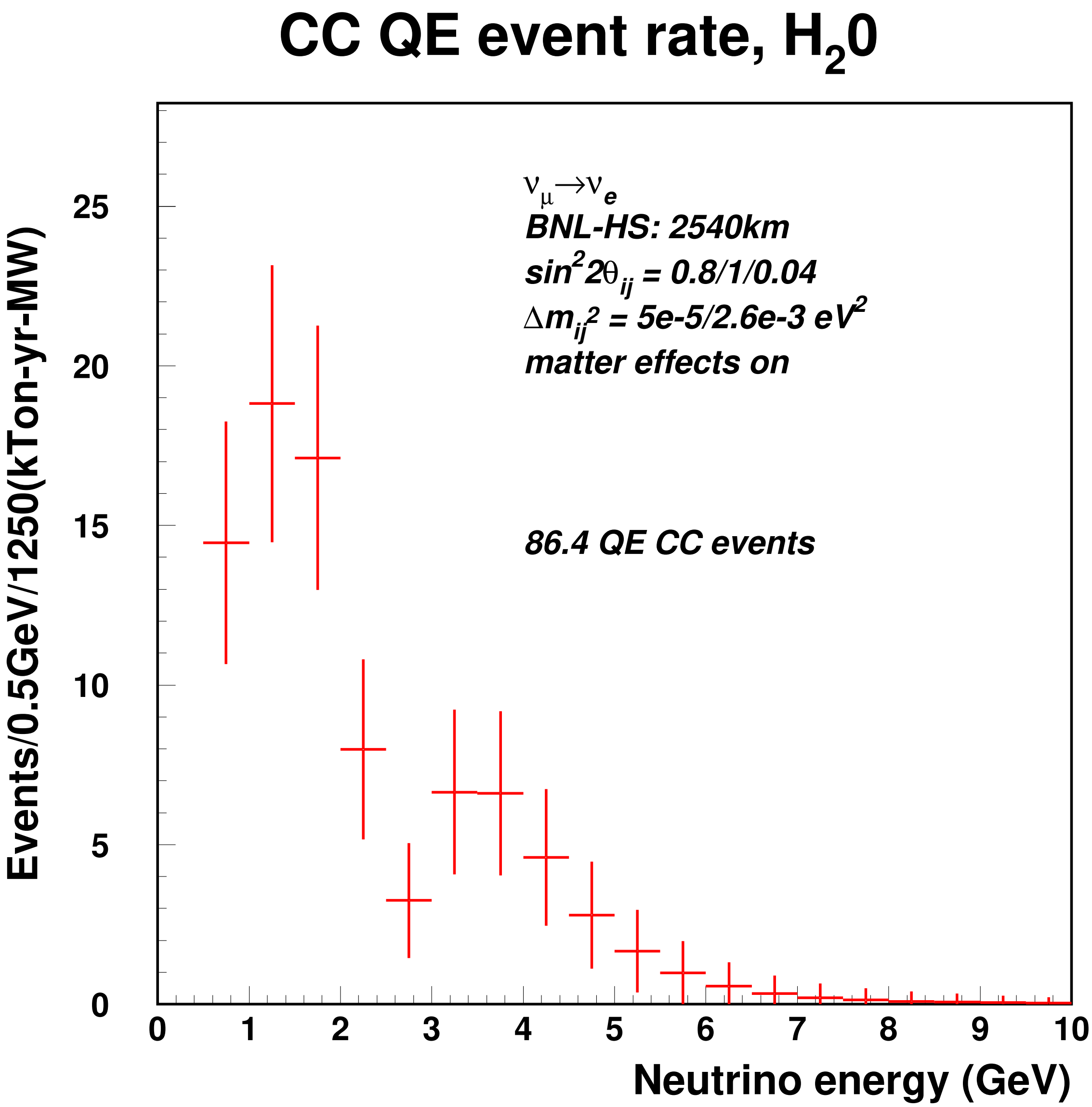

Figure 9: Spectrum of detected quasi-elastic electron neutrino charged current events in a 0.5 MT detector at 2540 km from BNL. We have assumed 0.5 MW of beam power and 5 years of running. This plot is for $\Delta m^2_{32} = 0.0026 e\mathrm{V}^2$. We have assumed $\sin^2 2\theta_{13} = 0.04$ and $\Delta m^2_{21} = 5 \times 10^{-5} e\mathrm{V}^2$. The error bars correspond to the statistical error expected in the bin. A 10 % energy resolution is assumed; this corresponds to the expected resolution due to both nuclear effects and the electron momentum reconstruction in the detector.

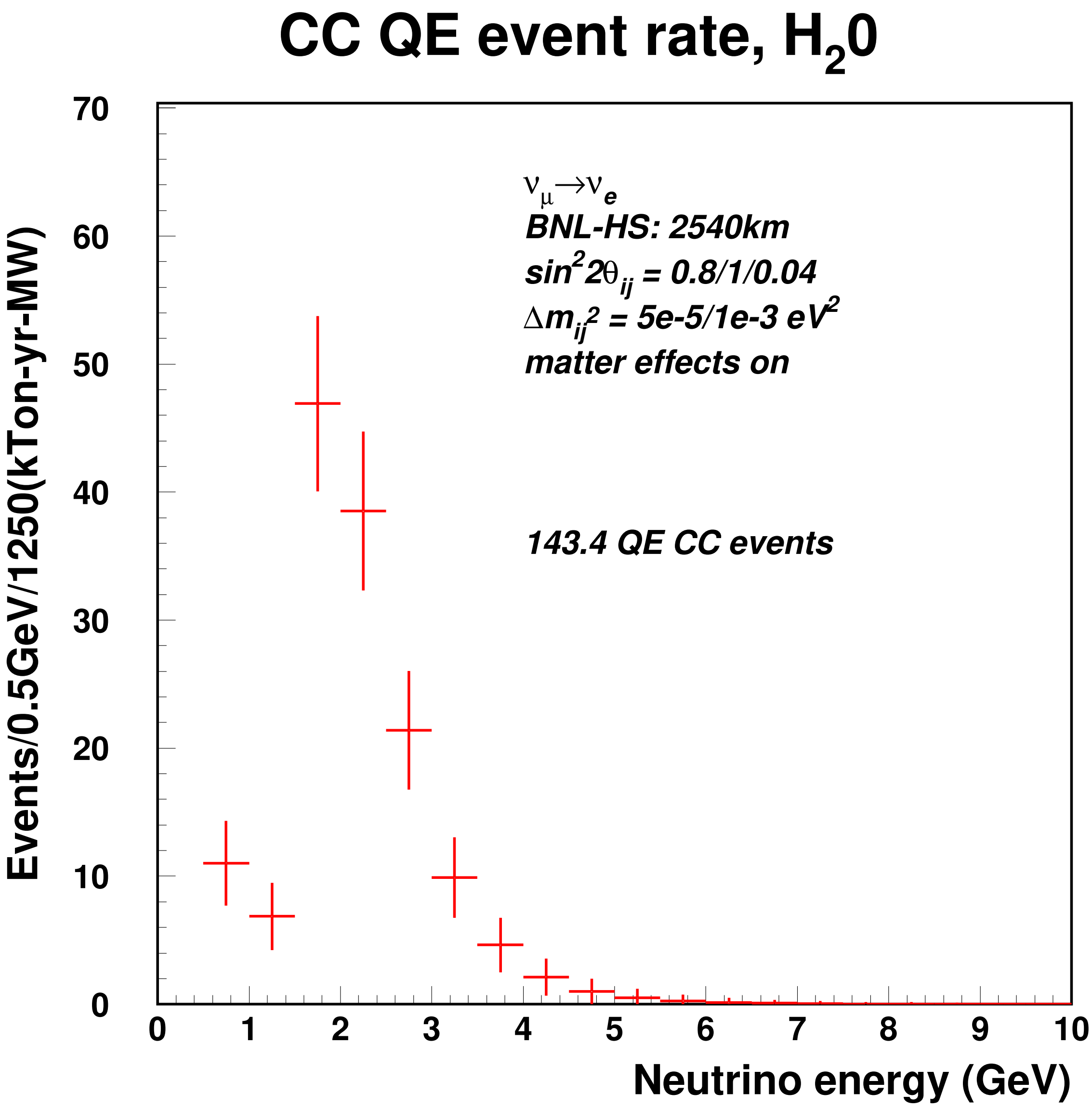

Figure 10: Spectrum of detected quasi-elastic electron neutrino charged current events in a 0.5 MT detector at 2540 km from BNL. We have assumed 0.5 MW of beam power and 5 years of running. This plot is for $\Delta m^2_{32} = 0.001 e\mathrm{V}^2$. We have assumed $\sin^2 2\theta_{13} = 0.04$ and $\Delta m^2_{21} = 5 \times 10^{-5} e\mathrm{V}^2$. The error bars correspond to the statistical error expected in the bin. A 10 % energy resolution is assumed; this corresponds to the expected resolution due to both nuclear effects and the electron momentum reconstruction in the detector.

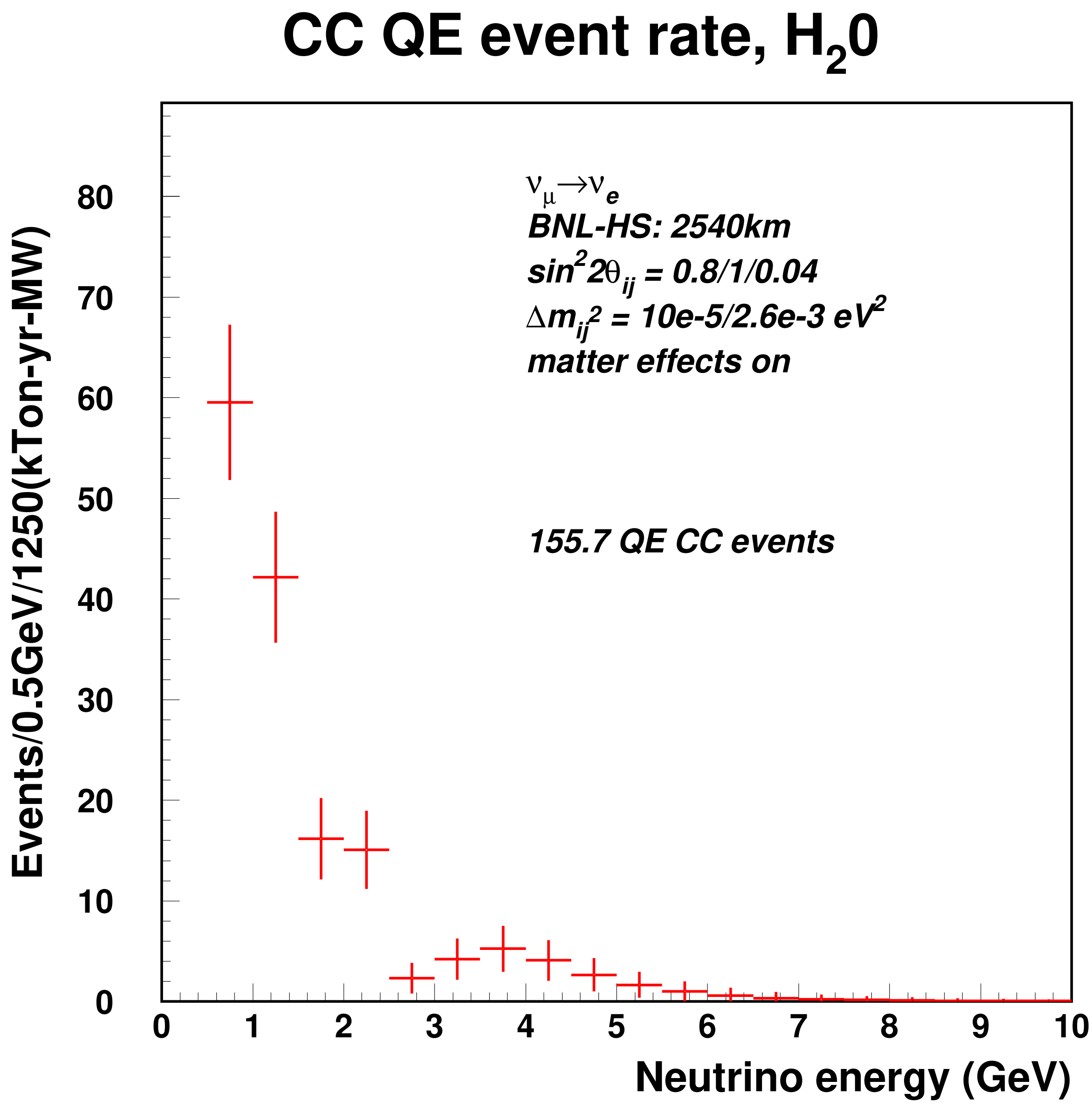

Figure 11: Spectrum of detected quasi-elastic electron neutrino events in a 0.5 MT detector at 2540 km from BNL. We have assumed 0.5 MW of beam power and 5 years of running. This plot is for $\Delta m^2_{32} = 0.0026 e\mathrm{V}^2$ and $\Delta m^2_{21} = 0.0001 e\mathrm{V}^2$. We have assumed $\sin^2 2\theta_{13} = 0.04$. The error bars correspond to the statistical error expected in the bin. A 10 % energy resolution is assumed; this corresponds to the expected resolution due to both nuclear effects and the electron momentum reconstruction.

will not address the detailed issues of detector design and cost. A more detailed study of a very large water Cerenkov detector has been done by the UNO collaboration [22].

Currently, a study is in progress to site the LANNDD, 70 KT liquid Argon detector at WIPP [23]. The key issue at this stage is one of safety and a proposal to the DOE to study this is in preparation. In Figure 12, we show the LANNDD detector in a possible underground location at WIPP. One advantage of the WIPP site is that, it is owned by the DOE and now has a program of underground science. We note that the recent Neutrino Factory Study [20] at BNL identified the WIPP site as one possible location for a far detector, and the current BNL neutrino beam could use the same concept. The LANNDD detector can be used for neutrino physics, as well as the search for proton decay and other astro-particle physics goals. Currently, the ICARUS detector at the Gran Sasso is being constructed with a 3KT detector as a goal. The operation of this detector will provide key information for the eventual construction of LANNDD and for the neutrino physics identified in this LOI.

3 Long Baseline Experiment

A dedicated experiment to detect $\nu_\mu \to \nu_e$ appearance signature in the Δm^2_{32} region of 0.003 $e\mathrm{V}^2$ needs to have low background from the intrinsic ν_e contamination as well as neutral current events that produce π^0s which can mimic the ν_e QE CC signature. This can be achieved by placing a fine grained detector 1.5 degrees off-axis from the BNL neutrino beam. As originally pointed out by the E889 collaboration [13] at angles larger than the divergence of the pion beam the neutrino spectrum is almost independent of the pion energy and has a narrow spectrum peaking at 1 GeV (See Fig. 1). If the value of $\Delta m^2_{32} = 0.003e\mathrm{V}^2$ is known with good precision then the detector could be placed at 412 km which is at the point of the first maximum for oscillations. This is shown in figure 13. At this distance and energy the effect of matter enhancement is small and a very sensitive experiment for $\nu_\mu \to \nu_e$ appearance could be performed with a high resolution fine grained detector such as a liquid argon time projection chamber, with maximum performance achieved if the detector is immersed in a $\sim 1/2$ T magnetic field [23].

We calculate the number of events in a 1.5 degree off-axis beam in a 10 kT liquid Argon detector assuming 0.5 MW of beam power and 5 years of running. In the absence of oscillations there will be about 2000 quasi-elastic muon neutrino events. The total number of events including neutral current events will be about 1.5 times this number. If $\Delta m^2_{32} = 0.003e\mathrm{V}^2$

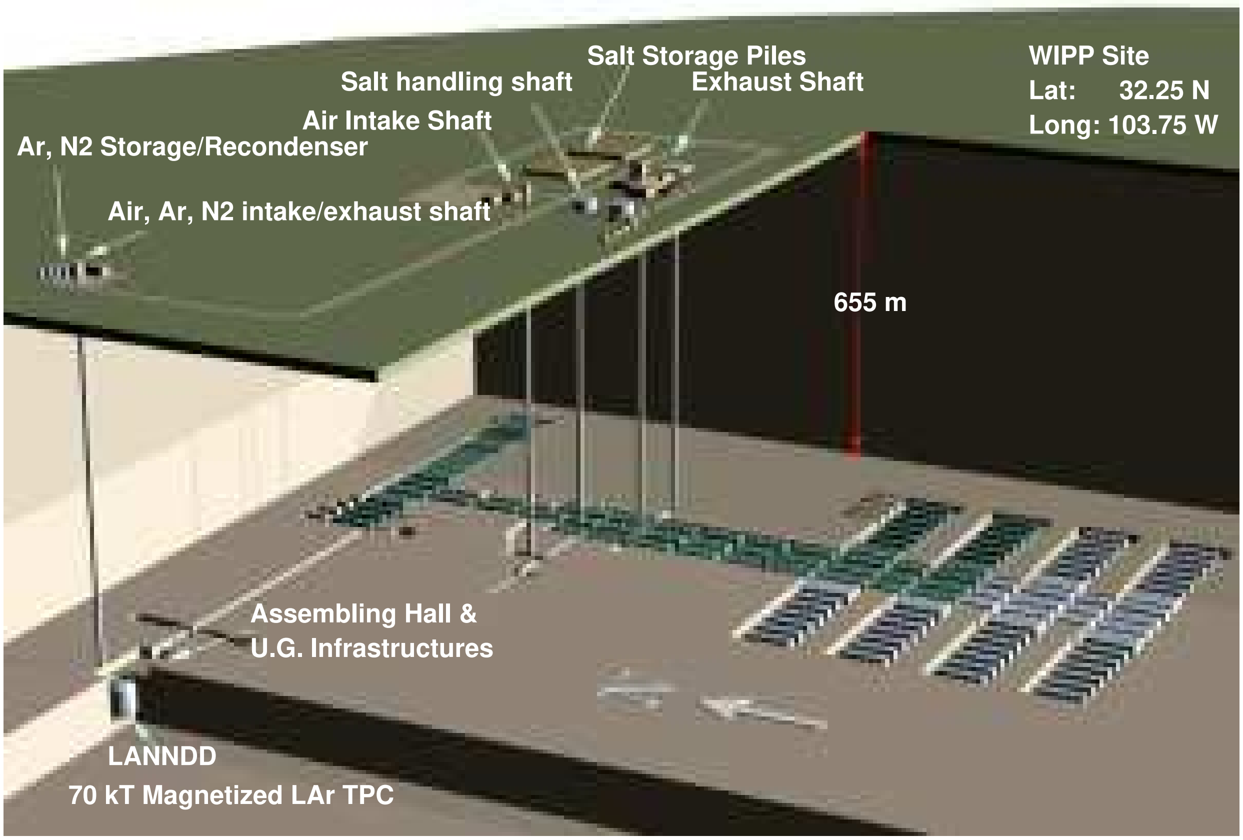

Figure 12: Schematic of the WIPP underground site and a location for the LANNDD detector. A water Cerenkov detector array could also be accommodated at the WIPP site.

the number of muon quasi-elastic events will drop to only ∼200. If $\sin^2\theta_{13} = 0.01$ then the number of electron neutrino quasi-elastic events will be about 40. The background from the electron neutrino contamination in the beam and the neutral current π^0 will be spread widely in energy, but the signal of 40 events will be in the peak of the neutrino spectrum. The high energy resolution of the liquid Argon detector as well as the granularity should make it possible to reduce the neutral current background to a negligible level [24]. The intrinsic electron neutrino background in the AGS neutrino beam is known to be at 0.5 % level [13].

The viability of a large liquid argon detector is presently being demonstrated by the ICARUS collaboration [25] in cosmic-ray tests of a 300-ton module located on the Earth's surface. Fig. 14 shows an example of the detailed tracking information obtainable with this technology.

A magnetized liquid argon detector would give the maximal discrimination against backgrounds in a neutrino beam, would enhance the ability to perform CP violation experiments, and would permit use of a beam produced by a solenoid focussing scheme [26] that contains both neutrinos and antineutrinos. An R&D experiment is proposed to use a prototype liquid argon detector in a magnetic field to determine the sign of electrons via analysis of their electromagnetic showers up to several GeV [27].

4 AGS Upgrade

The preliminary design of the AGS upgrades and the new neutrino beam has been produced by the AGS department to reach an AGS power of 0.53 MW in its first phase and 1.3 MW in the second phase [28]. In the first phase the LINAC will be improved to inject protons to the booster at 400 MeV (at present it is 200 MeV), and the booster energy increased to 2.5 GeV from 1.8 GeV. The addition of a fixed field accumulator storage ring between the booster and the AGS main ring will increase the AGS input beam from the present 4 booster pulses per AGS acceleration to 6 booster pulses per AGS acceleration and, at the same time, increase the AGS frequency from 0.6 Hz to 1.0 Hz. The AGS power increase would be from 0.14 to 0.53 MW. Figures 15 to 17 show the proposed additions. The new accumulator will be in the same tunnel as the AGS. Figure 18 shows the present and proposed AGS injection modes. The AGS intensity upgrades and parameters are shown in Table 1. The location of the accumulator ring in the AGS tunnel is shown in Figs. 16 and 17 and the

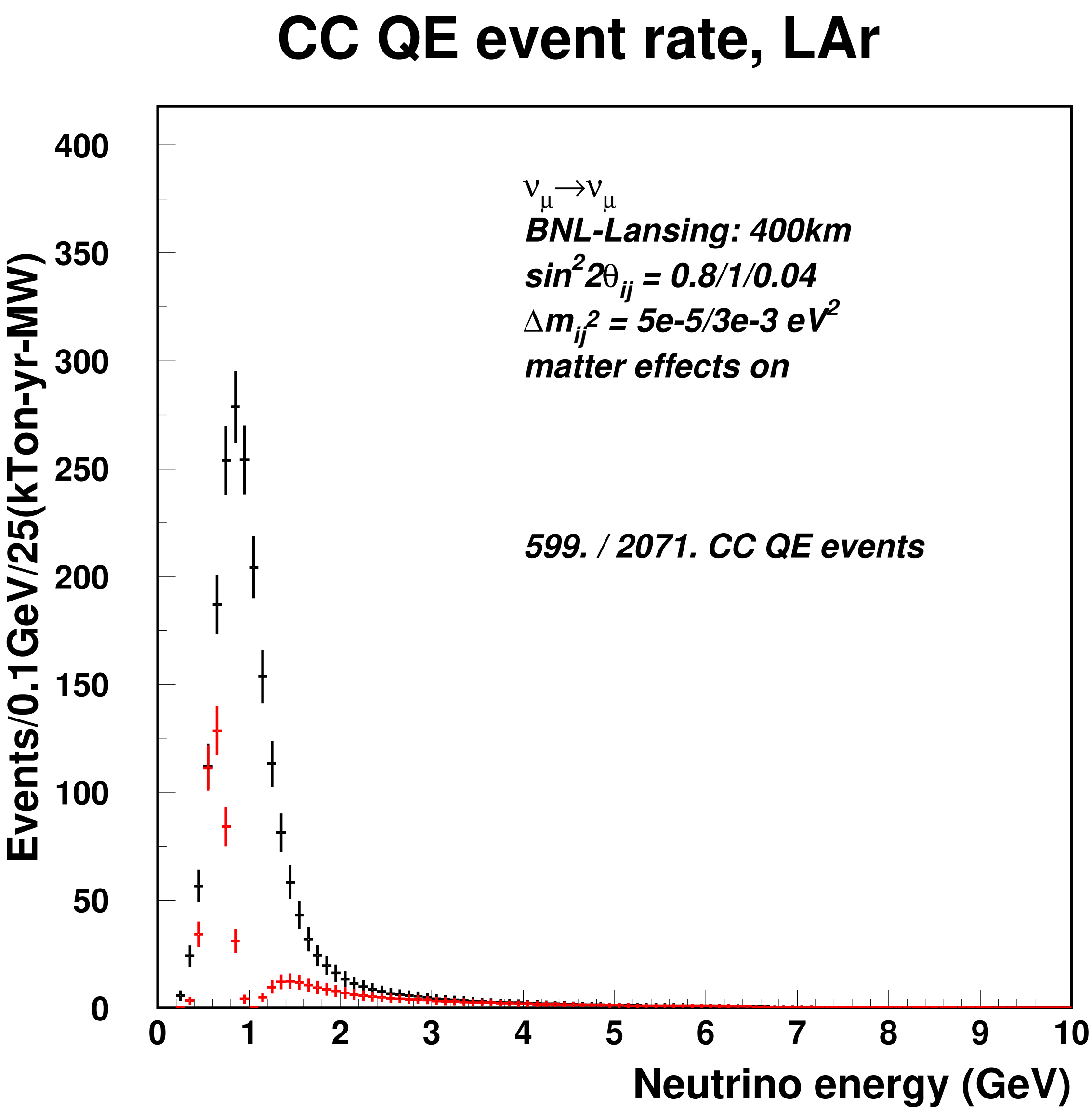

Figure 13: Spectrum of neutrinos at 1.5 degrees with and without oscillations with $\Delta m^2_{32} = 0.003 e\mathrm{V}^2$ and full mixing.

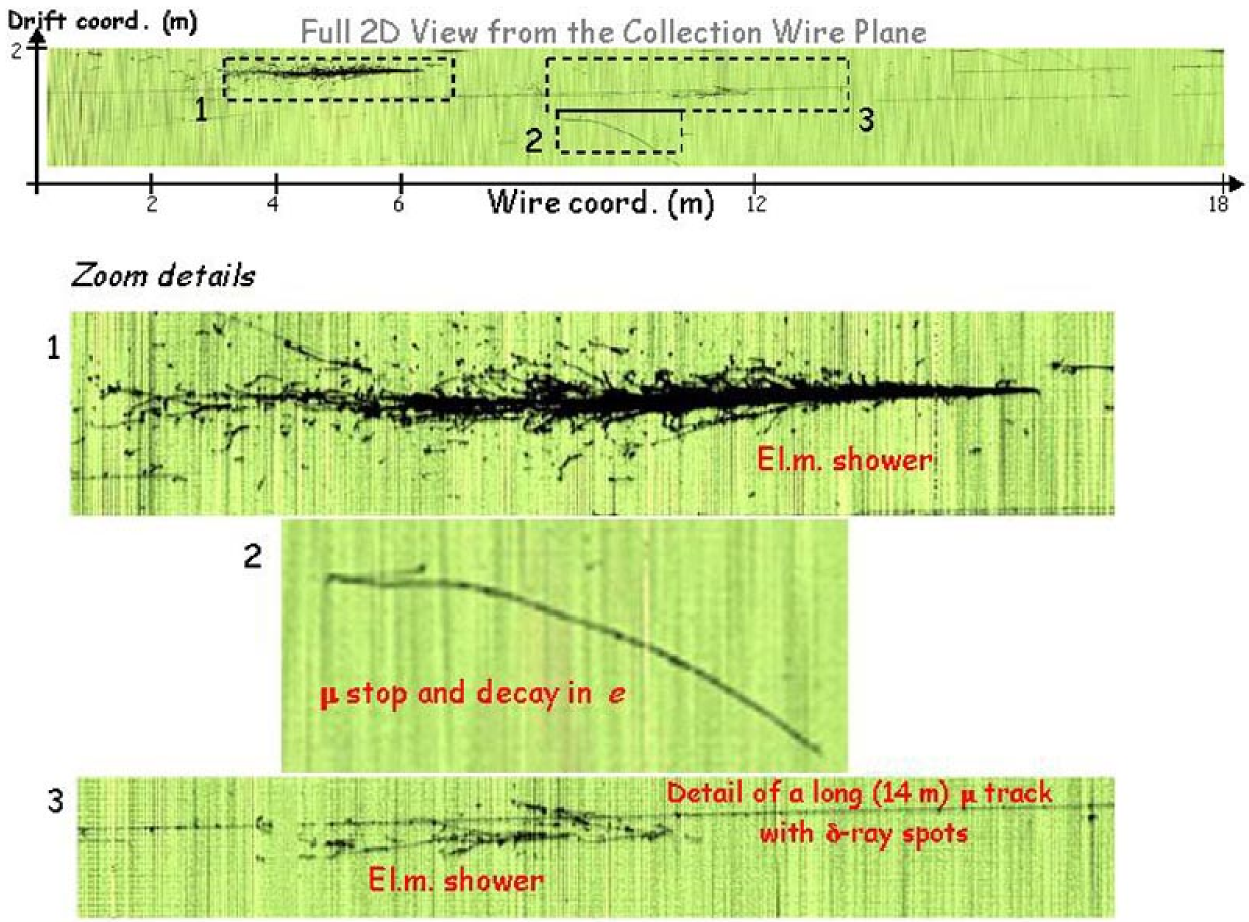

Figure 14: An event from the recent cosmic-ray test run of ICARUS [25], showing excellent track resolution over long drift distances in zero magnetic field.

	Now	400 MeV LINAC	2.5 GeV Accumulator 200 MeV LINAC	2.5 GeV Accumulator 400 MeV LINAC	AGS to 2.5 Hz
LINAC Energy (MeV)	200	400	200	400	400
Booster Intensity (ppp)	1.5×10^{13}	2.0×10^{13}	1.5×10^{13}	2.0×10^{13}	2.0×10^{13}
Booster energy (GeV)	1.8	1.8	2.5	2.5	2.5
Booster Cycles	4	4	6	6	6
AGS energy (GeV)	24	28	28	28	28
AGS Intensity (Tp/sec)	36	48	90	120	300
AGS Rep Rate (Hz)	0.6	0.6	1.0	1.0	2.5
AGS Current (μ A)	5.75	7.7	14.4	19.2	48
AGS Intensity (ppp)	6×10^{13}	8×10^{13}	9×10^{13}	12×10^{13}	12×10^{13}
AGS power (kW)	138	215	403	538	1344

Table 1: AGS Beam Power Upgrade Plan.

accumulator parameters given in Table 2. The fixed field magnets of the accumulator ring will be essentially copies of the magnets produced for a similar purpose at Fermilab [29]. In the second phase of the upgrades the AGS repetition rate will be increased to 2.5 Hz to reach a total beam power of 1.3 MW.

The tentative cost estimates for the various upgrades and improvements are shown in Table 3, separated into two relatively independent phases of roughly equal cost. It is possible to rearrange the order in which the improvements are made. A partial study of the options is shown in Table 1. Three options are shown:

1. only the LINAC is improved,
2. only the accumulator is added,
3. both are done.

Some AGS and booster power supply upgrades are assumed along with the accumulator. A detailed study of space charge, intensity, injection energies, rep rate, power and cost needs to be made to make a much more specific proposal for this upgrade. This would come about with approval of the present letter of intent.

Max. Kinetic Beam Energy	2.5 GeV
Rigidity	13 Tm
Circumference	819.07 m
Number of Superperiods	25
Number of FODO Cells	50
Number of (Combined-Function) Dipoles	100
Dipoles Length/Field	3.25 m/ 0.25 T
Length of FODO Cell	16.45 m
Length of straight sections	8.22 m
Phase Advance per FODO Cell	72 degrees
Vacuum Chamber x/y	150 mm/ 75 mm
Acceptance Geometric x/y	234/58 π mm mrad
Acceptance Normalized 2.5 GeV x/y	744/184 π mm mrad
Space Charge limit:	
(100 π mm mrad, $\delta\nu = 0.3$, 2.5 GeV, debunched)	3.5×10^{14} ppp
Betatron Tunes x/y	10.3/10.5
Chromaticities x/y	-11.7/-12.7
Beta Max. x/y	24.7 m/24.3 m
Beta Min. x/y	7.8m/7.5 m
Dispersion Max.	1.8 m
Transition Gamma	9.6

Table 2: Parameters of the permanent magnet accumulator ring.

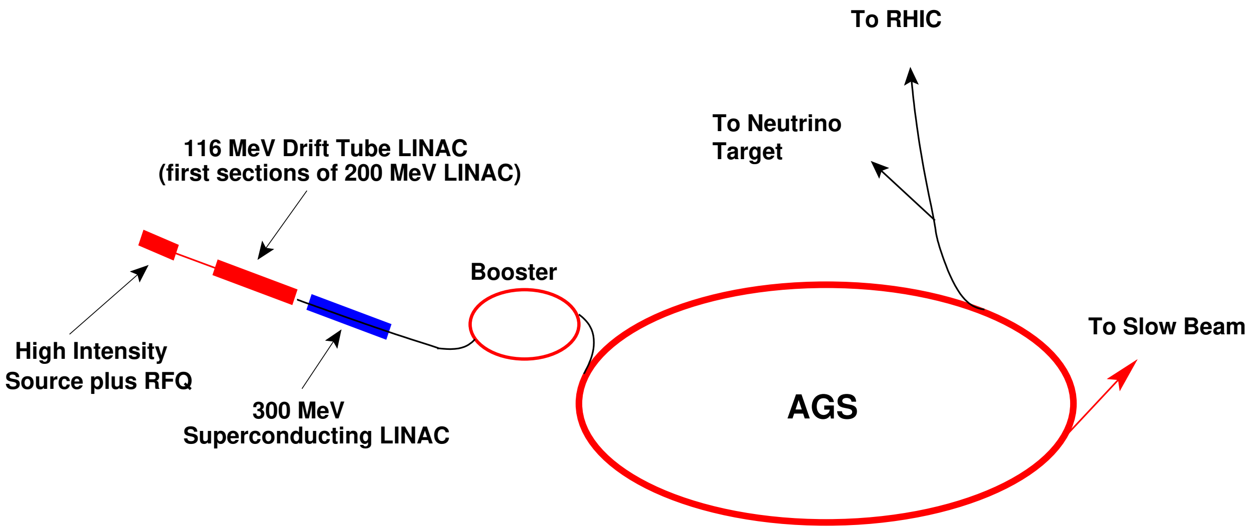

Figure 15: Layout of the AGS facility with the addition of the super conducting LINAC.

Phase I (AGS at 1 Hz)	
300 MeV SRF (116 MeV to 400 MeV)	\$35 M
2.5 GeV AGS accumulator ring	\$25 M
AGS Injection at 2.5 GeV	\$ 5 M
Total for Phase I 0.53 MW	\$65 M
Phase-II (AGS at 2.5 Hz)	
AGS power supply	\$32 M
AGS RF upgrade	\$8.6 M
Booster Power Supply	\$5.5 M
AGS Collimation and Shielding	8.0 M
Total for Phase-II 1.3 MW	\$ 54.1 M

Table 3: Cost of upgrading the AGS in two phases to 1 MW. The superconducting LINAC upgrade could be delayed to be after the accumulator. In this case phase I could deliver about 0.3 MW at a cost of \$30 M. It is assumed that the target station shielding can be retrieved from existing resources.

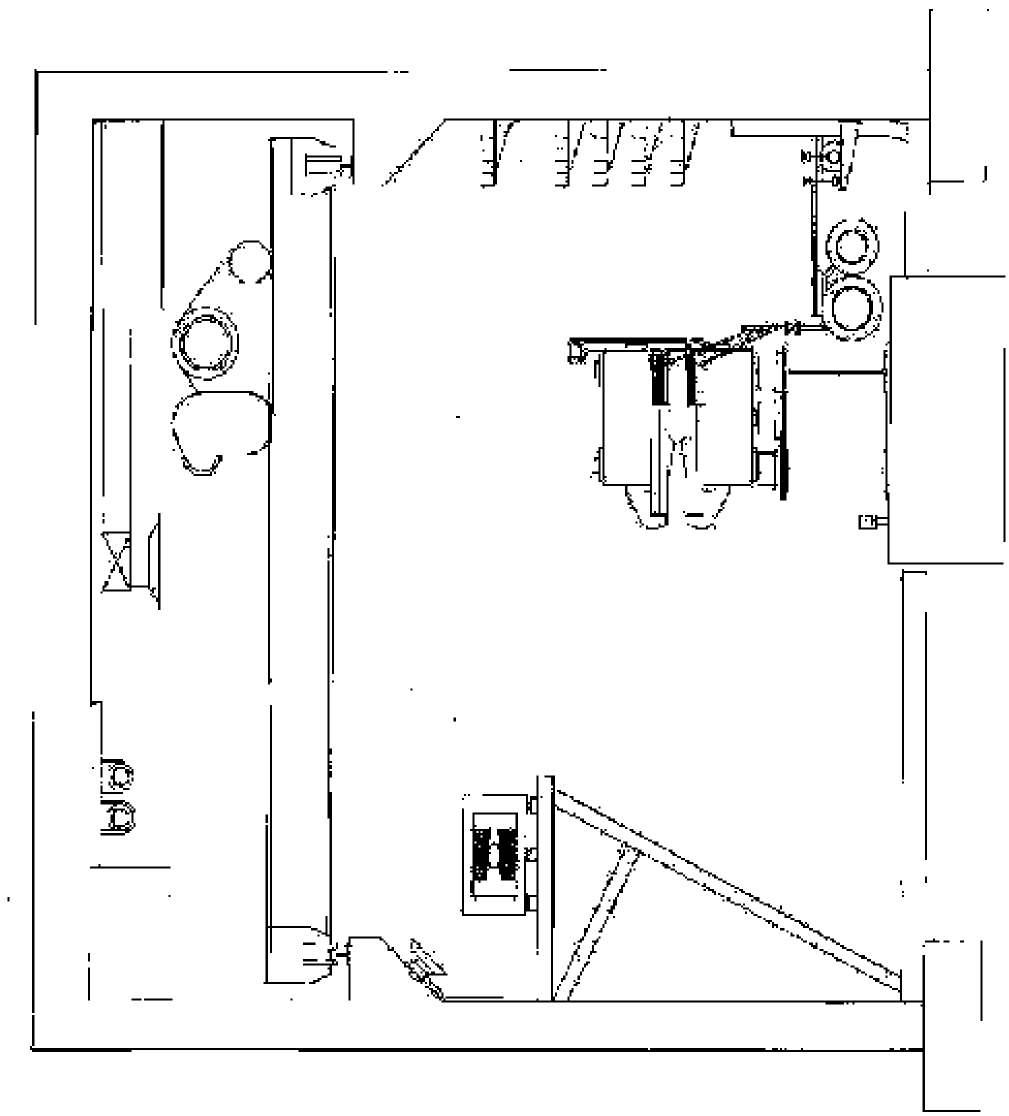

Figure 16: Placement of the permanent magnet accumulator ring inside the AGS tunnel.

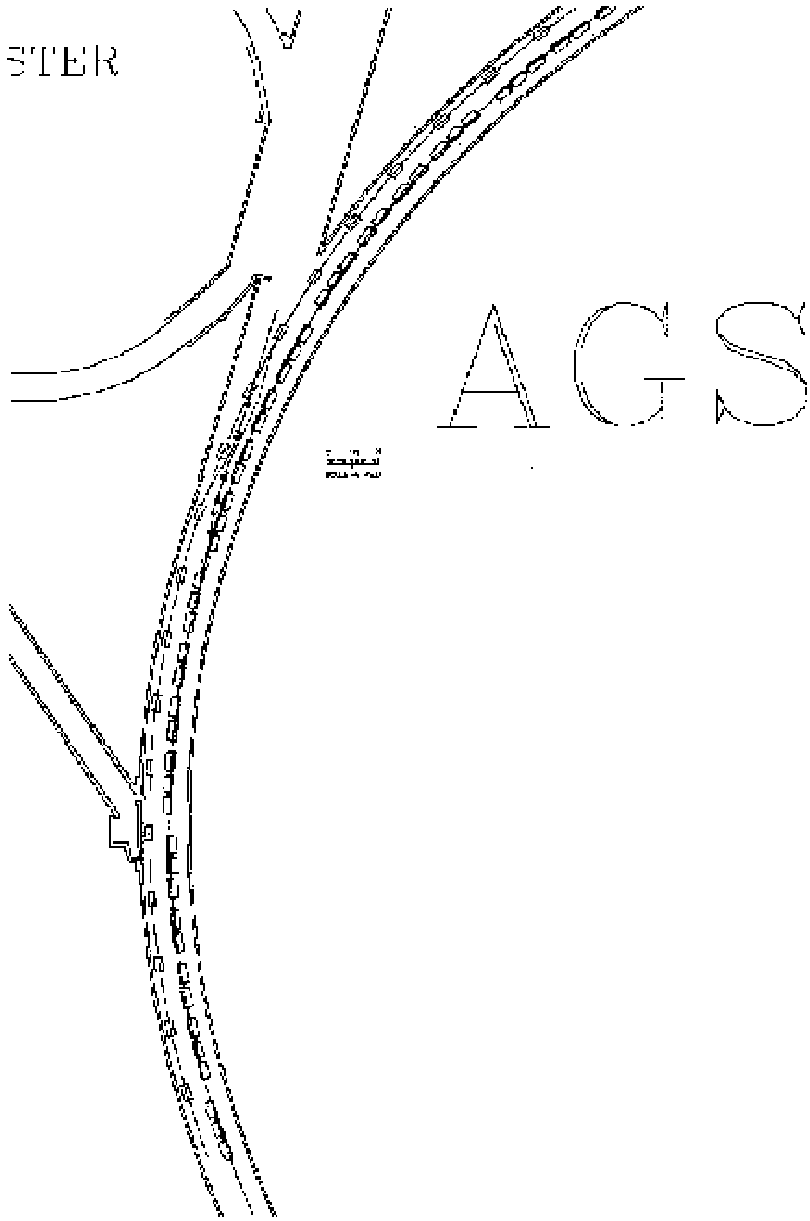

Figure 17: Placement of the permanent magnet accumulator ring inside the AGS tunnel. Satellite view.

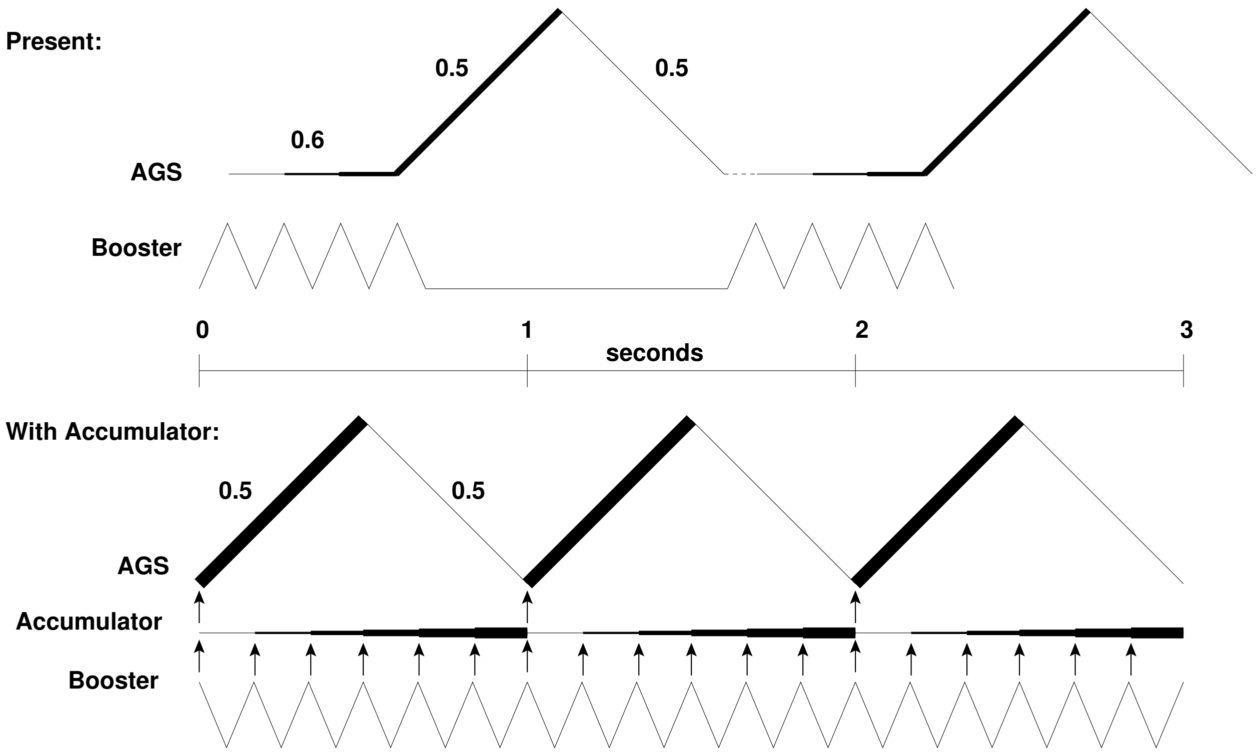

Figure 18: Time sequence of injecting pulses into the AGS. Top picture shows that at the moment 4 booster pulses are injected into the AGS during the period when the AGS magnets are at low field. In the new proposed configuration in the bottom picture the booster will inject 6 pulses into the accumulator which will store the beam until the AGS is at low field and then transfer the beam into the AGS.

5 Neutrino Beam Design

The geographic location of BNL on one side of the continent allows us to send beams to a variety of distances including very long baselines of 2000 km or more. This is shown in Fig. 19. The distances from BNL to Lansing NY, Soudan MN, Lead SD(Homestake), and WIPP in NM are 350, 1770, 2540, and 2880 km, respectively. The respective dip angles are 1.7, 7.9, 11.5, and 13.0 degrees. The difficulty of building the beam and the cost increases with the dip angle.

For the purposes of this LOI we use the design for a conventional wide band horn focussed neutrino beam similar to that used in previous experiments at BNL such as E734 (Fig.20). The design shown uses a water cooled copper target. For much higher intensities this target will have to be redesigned. It is very likely that we can adapt the graphite target design used for NuMI at FNAL. We also need to modify the horn focussing to make a wider band beam to increase the neutrino flux in the 4 GeV region. There are a number of ways to optimize the horn design; we will not discuss them here.

Our preliminary design for a beam to Homestake is shown in figures 21 and 22. This can be adapted to any far location in the western direction. Our design addresses a number of issues. At BNL we are constrained to keep the beam line above the water table which is at a shallow depth ($\sim$ 20 m) on Long Island. Therefore the beam has to be constructed on a hill that is built with the appropriate 11.5 degree slope. Fortunately, it is relatively easy, and inexpensive to build such hills on Long Island because of the flat, sandy geology. It is important to keep the height of the hill low so that the costs are not dominated by the construction of the hill. The proton beam must be elevated to a target station on top of the hill. The cost of the hill can be lowered by bending the proton beam upwards as quickly as possible. We have, however, used the design and bend angle used for the RHIC injection lines for our design because the RHIC injection lines have well known costs.

The new proposed fast extracted proton beam line in the U-line tunnel will be a spur off the line feeding RHIC. It will turn almost due west, a few hundred meters before the horn-target building. In addition to its 90 degree bend, the extracted proton beam will be bent upward through 13.76 degrees to strike the proton target. The downward 11.30 degree angle of the 667.8 ft meson decay region will then be aimed at the 2500 meter level of the Homestake Laboratory. This will require the construction of a 39 meter hill to support the target-horn building, so as to avoid any penetration of the water table. At its midpoint (about Lake Michigan) the center of the neutrino beam will be roughly 120 km below the

Item	basis	200 m	150 m
Proton transport	RHIC injector	\$11.85 M	\$11.85 M
Target/horn	E889	\$3.0 M	\$3.0
Installation/Beam Dump	New	\$2.67 M	\$2.67 M
Decay Tunnel	E889	\$0.45 M	\$0.45 M
Conventional const. (hill)	New	\$8.0 M	\$5.0 M
Conventional const. (other)	E889	\$9.1 M	\$9.1 M
Total		\$35.19	\$32.19

Table 4: Preliminary cost of building the neutrino beam. The third column is for a beam with 200 meter tunnel. The fourth column is for building the beam with a 150 meter tunnel.

Earth's surface.

For a shorter baseline to Lansing NY in approximately the same direction as Homestake, we would not have to build the hill, which would lower the cost by a considerable amount. We are considering a number of strategies for combining the proton transport and the target station for the two different baselines.

A preliminary estimate of the cost without any of the customary burdens is shown in table 4. The costs are based on the the RHIC injector work, as well as the E889 proposal and the neutrino factory study. The conventional construction costs are dominated by the size of the hill which is approximately proportional to the third power of the decay tunnel length. In our cost estimate we assume that we will bury the beam dump underground to reduce the height of the hill. It is assumed that the target station shielding can be retrieved from existing resources. We have also estimated the cost assuming 200 m and 150 m long decay tunnels. The spectra shown in Fig. 1 are based on a 200 m long tunnel. A shorter tunnel could reduce the intensity at higher energies because of the longer flight paths of parent pions. We will study this optimization further in future updates of this proposal.

6 Conclusion

We have outlined the neutrino physics program for an intense new neutrino beam from the Brookhaven AGS. The four goals of accelerator neutrino physics: precise determination of Δm^2_{32}, detection of $\nu_\mu \to \nu_e$ appearance, measurement of the matter effect, and detection

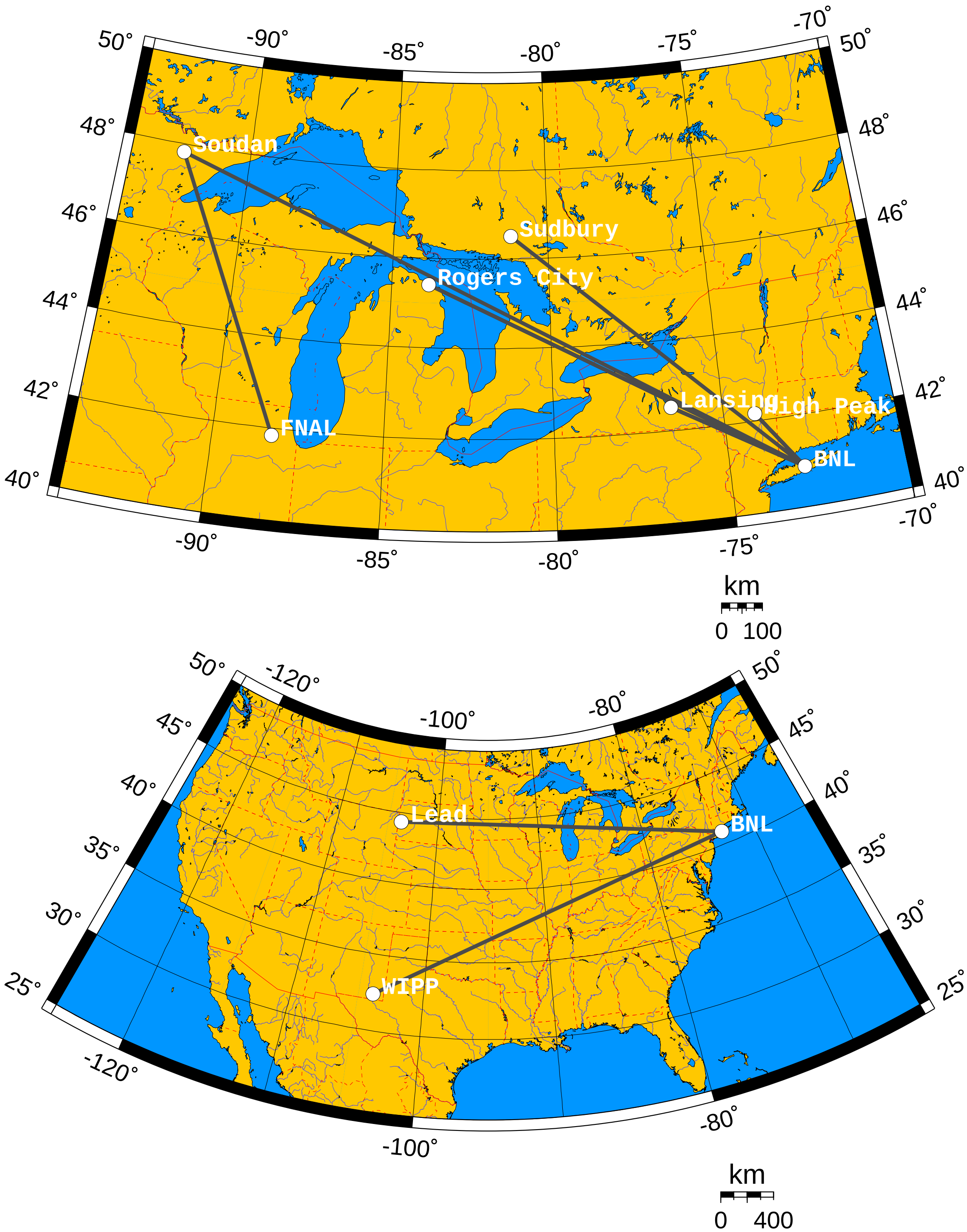

Figure 19: Possibilities for baselines from BNL. The distances from BNL to Lansing, Soudan, Lead (Homestake), and WIPP are 350, 1770, 2540, and 2880 km, respectively.

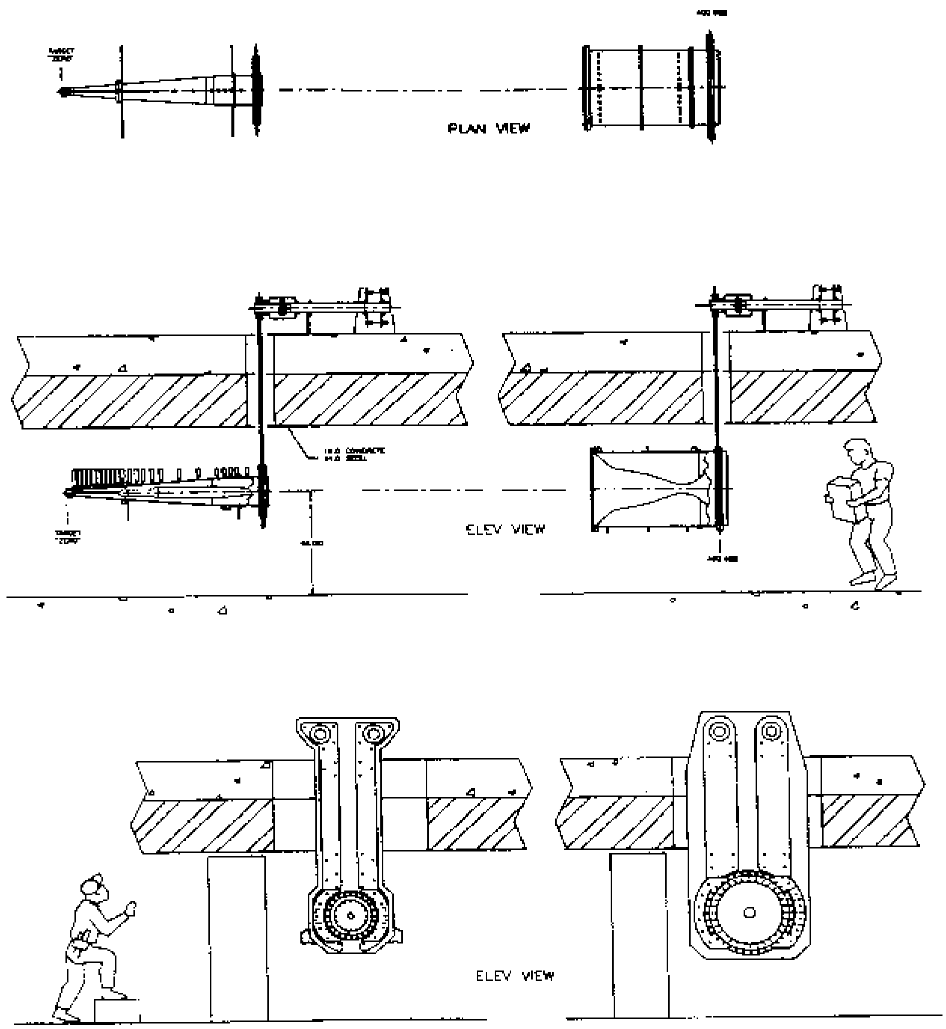

Figure 20: The design of the horn focusing system used for the E734 experiment adapted from the E889 proposal.

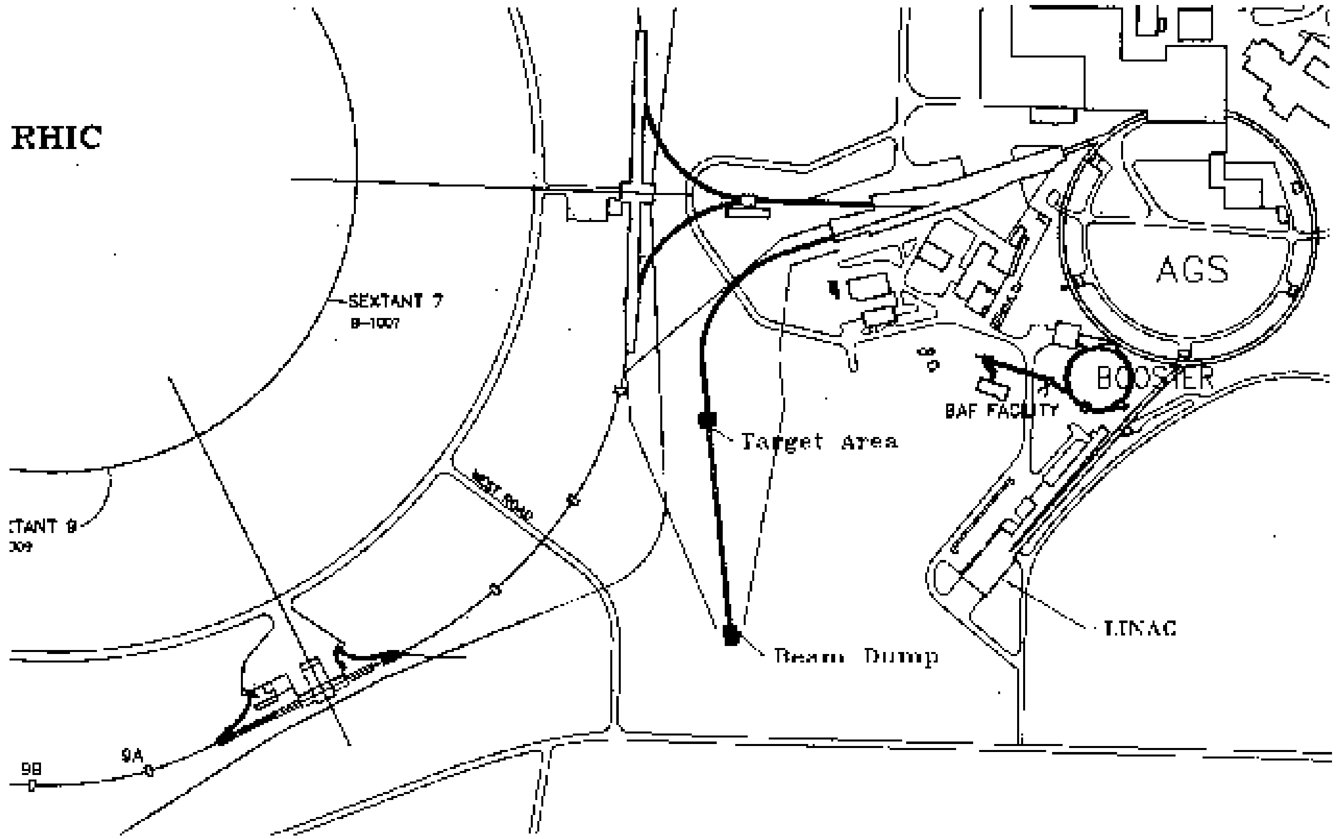

Figure 21: The beam line for sending a neutrino beam to Homestake mine, South Dakota. This same beam line can be adapted for any far location in the Western direction.

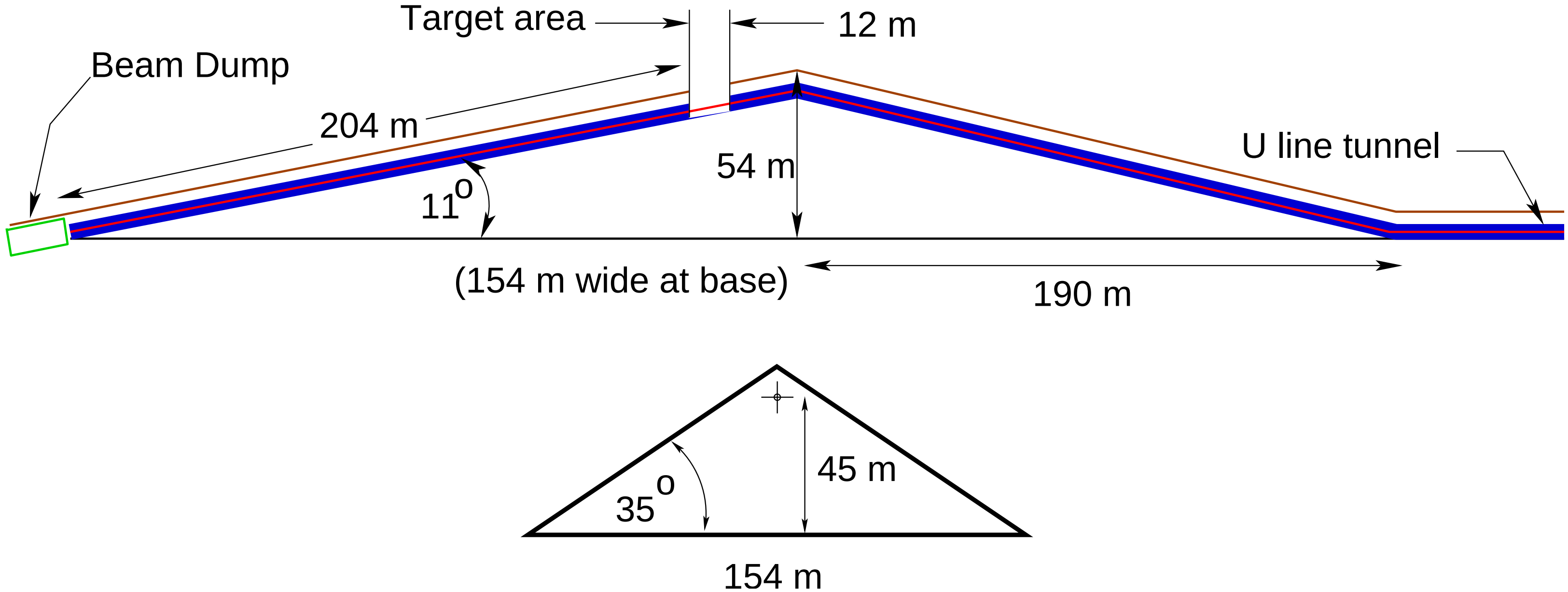

Figure 22: Elevation view of the neutrino beam line to Homestake, South Dakota. For a nearer location a much smaller hill can be constructed. In this beam we assume a decay tunnel length of 200 m. For a shorter tunnel the cost of the hill will reduce as shown in table 4.

of CP asymmetries in the neutrino section are all possible for the proposed complex for reasonable values of the oscillation and mixing parameters, some of which are not yet known. Further surprises in neutrino physics should not be discounted, therefore any new facility must have sufficient flexibility to address new challenges. Our proposal allows such flexibility because of the possibility to mount both very long (over 2500 km) and intermediate (400 km) baseline experiments with beam intensity that can be increased in stages.

The AGS complex is unique because it can be upgraded simply by increasing the repetition rate of the machine. This ability allows us the flexibility to continuously upgrade the facility to as much as 2.5 MW [28]. In this proposal we have examined upgrades up to 1.3 MW. The estimated cost of the first phase of the AGS upgrades to reach 0.53 MW, plus the new neutrino beam directed to Homestake is approximately $100M. With a 30 percent contingency, the total cost is $130M. It is probable that the first three modules of the detector array will be produced in about five years, so that construction of the AGS upgrades and neutrino beam would be planned for that period and involve an average expenditure of approximately $30M/yr. For a detector at intermediate baseline the costs will be less. The total yearly cost to the AGS department to provide protons for and maintain the neutrino beam would be about $9M, approximately equal to the operations expense at present for HEP experiments. Neither the duration of the construction period nor the anticipated cost of the improvements to the BNL AGS complex is large in relation to plans and expenditures now usual for major apparatus in high energy and elementary particle physics. Moreover, the improvements to the AGS and the new beam line will be available for carefully chosen other physics (for example, rare muon and kaon decays as well as muon EDM measurements) in addition to providing important advances in our understanding of this exciting new frontier of elementary particle physics.

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