Bringing the SciBar Detector to the Booster Neutrino Beam

June 11, 2005

S. J. Brice[2], Y. Hayato[7], K. Hiraide[3], Y. Kurimoto[3], Y. Kurosawa[3], J. Monroe[1], T. Nakaya[3], R. Stefanski[2], H. Tanaka[3], R. Van de Water[4], M. O. Wascko[5], M. Wilking[6], M. Yokoyama[3], G. P. Zeller[1]

[1]*Columbia University*
[2]*Fermi National Accelerator Laboratory*
[3]*Kyoto University*
[4]*Los Alamos National Laboratory*
[5]*Louisiana State University*
[6]*University of Colorado, Boulder*
[7]*High Energy Accelerator Research Organisation (KEK)*

Executive Summary

This document presents the physics case for bringing SciBar, the fully active, finely segmented tracking detector at KEK, to the FNAL Booster Neutrino Beam (BNB) line. This unique opportunity arose with the termination of K2K beam operations in 2005. At that time, the SciBar detector became available for use in other neutrino beam lines, including the BNB, which has been serving neutrinos to the MiniBooNE experiment since late 2002.

The physics that can be done with SciBar/BNB can be classified into three categories, each of which cover several measurements. First, are measurements which improve upon existing or planned MiniBooNE neutrino cross section measurements and the understanding of the BNB, both in neutrino and anti-neutrino mode. Second, are neutrino cross section measurements of processes that are the signal and primary background channels for the upcoming T2K experiment. Third, are measurements which are interesting in their own right, including analyses of multi-particle final state neutrino interactions, with unprecedented statistics.

For each of these proposed measurements, the SciBar/BNB combination either presents a unique opportunity or will significantly improve upon current or near-future experiments for three reasons. First, the fine granularity of the SciBar detector allows detailed reconstruction of exclusive final states not possible with the MiniBooNE detector. Second, the BNB neutrino energy spectrum is a close match to the expected T2K energy spectrum in a region where cross sections are expected to vary dramatically with energy. As a result, the SciBar/BNB combination will provide cross-section measurements in an energy range complementary to MINERνA and complete our cross section knowledge in the entire energy range of interest to the upcoming off-axis experiments. Finally, some measurements require SciBar and MiniBooNE to act in concert.

SciBar and BNB have both been built and operated with great success. As a result, the cost of SciBar/BNB is far less than building a detector from scratch and both systems are well understood with existing detailed and calibrated Monte Carlo simulations. The performance expectations assumed in this document are therefore well-grounded in reality and carry little risk of not meeting expectations.

Included in this document is a site optimization study which investigates the trade-offs of the excavation costs associated with placing the detector at different angles from the axis of the BNB and the physics which can be performed with the neutrino flux expected at these locations. Table 1 provides a summary of the impact of placing the SciBar at these locations on the proposed measurements. The overwhelming conclusion of this study is that an on-axis location presents the best physics case and offsets the additional costs due to excavation. The estimated cost of the detector enclosure at the desired on-axis location is $505K.

Several time constraints affect the process of bringing SciBar to the BNB. The beam is only approved to operate through the end of FY2006. Since running past this date is not guaranteed, the studies in this document are limited to the physics SciBar could achieve in the scheduled FY2006 beam time. Current schedules indicate that if approval were given by the start of July 2005, SciBar could become operational in the BNB partway through FY2006. If it is not possible to accelerate this schedule by devoting more lab resources, then the proper approach will be to restrict attention to those analyses that can be done with significantly fewer data since many of the proposed analyses need only 0.5×10^{20} POT (see Tab. 1). Concurrently there will also be a request submitted for running of the BNB into FY2007. If the beam is approved to run beyond FY2006 then there is certainly good additional physics that can be performed with SciBar subject to the second time constraint that SciBar will be needed back in Japan in about 2008 for inclusion in the T2K beam.

			Location A (on-axis)	Location B	Location C	Location D	Location H	Mini-BooNE alone	K2K, MINOS, MINERνA
Distance from MB target			100m	100m	100m	100m	250m	541m	—
Height above beam center			0cm	300cm	500cm	700cm	300cm	0cm	—
Total ν flux ($\times 10^{-10}$cm^{-2}POT^{-1})			350	250	180	140	40	5	160 (K2K)
Peak ν energy (GeV)			0.6	0.45	0.35	0.25	0.6	0.6	1.2,3,7,12
Enclosure cost			\$505k	\$431k	\$292k	\$219k	\$431k	—	—
Leverage MB	WS BG	$\bar{\nu}$:1.5×10^{20} POT	★★★ (E_ν)	★	★	★	★	★★★ (N_ν)	$\times$
	ν_μ Disappearance	ν:0.5×10^{20} POT $\bar{\nu}$:1.5×10^{20} POT	ν: ★★ ; $\bar{\nu}$: ★★★	$\times$	$\times$	$\times$	$\times$	ν: ★★★ ; $\bar{\nu}$: ★★	$\times$
	Intrinsic ν_e	ν:0.5×10^{20} POT	★★ (cross-check)	$\times$	$\times$	$\times$	$\times$	★★★	$\times$
Help T2K	ν_μ CCπ^+	ν:0.5×10^{20} POT	★★★	★	$\times$	$\times$	★	★★★	$\surd$
	ν_μ NCπ^0	ν:0.5×10^{20} POT	★★★	★	$\times$	$\times$	★	★★★	$\surd$
	anti-ν Measurements	ν:0.5×10^{20} POT $\bar{\nu}$:1.5×10^{20} POT	★★★	$\times$	$\times$	$\times$	$\times$	★★	$\times$
Scibar Physics	Exclusive anti-ν π-p	$\bar{\nu}$:1.5×10^{20} POT	★★★	★	★	★	★	$\times$	?
	NCπ^0 Energy Dependence	ν:0.5×10^{20} POT	★★★	★	★	★	★	$\times$	$\surd$

Table 1: *Relative performance merit for each of the measurements at each of the detector locations. The number of stars indicates the precision of the measurement, $\times$ indicates that the measurement is not possible at that location, and $\surd$ indicates that a measurement can be made, but not in the energy range of interest to MiniBooNE or T2K.*

Contents

Chapter 1

Introduction

The American Physical Society's Divisions of Nuclear Physics and Particles and Fields, together with the Divisions of Astrophysics and the Physics of Beams, have recently conducted a "Study on the Physics of Neutrinos". The resulting APS report [1] stated:

> *We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos.*

This document presents the physics case for installing the SciBar detector of the K2K experiment in the BNB at Fermilab. K2K beam operations were terminated in 2005. SciBar then became available for use in other neutrino beam lines, including BNB, which has been serving neutrinos to the MiniBooNE detector since late 2002.

The physics that can be accomplished with this configuration directly addresses the high priority recommendation of the APS study, and, more specifically, addresses two special points also mentioned in the report:

> *Support for decisive resolution of the high-Δm^2 puzzle. This issue is currently addressed by a single experiment now running in a neutrino beam at Fermilab. Ultimately, a decisive resolution of the puzzle may require additional studies with beams of antineutrinos.*

and

> *The precise determination of neutrino cross sections is an essential ingredient in the interpretation of neutrino experiments and is, in addition, capable of revealing exotic and unexpected phenomena.*

The marriage of SciBar and the BNB presents a low risk opportunity for improved physics. Both are already built and have been operated very successfully. This means that:

1. the cost of bringing SciBar to Fermilab is far smaller than building a new detector from scratch,

2. both systems are very well understood with detailed and calibrated Monte Carlo simulations—the predictions of performance in this document have already been demonstrated with real operation.

The remainder of this introduction provides the information necessary to follow the physics case outlined in the later chapters. The BNB is described in Section 1.1 and the SciBar detector in Section 1.2. The specific locations where the SciBar detector might be placed in the BNB are discussed in Section 1.3, and the expected event rates at each location are detailed in Section 1.4. The introduction ends with a discussion of time constraints in Section 1.5.

Since the Booster Neutrino Beam is only approved to run through the end of FY2006, the rest of this document builds a physics case assuming only FY2006 running. Three distinct types of measurements become possible with SciBar in the BNB. First, there are ways that SciBar can leverage the existing investment in the MiniBooNE detector. Chapter 2 describes the ways in which SciBar can improve measurements using MiniBooNE tank data. Next, Chapter 3 describes the reasons why the K2K collaboration would like to place SciBar in the BNB, and describes how a number of cross section measurements can be made that are vital to T2K reaching their desired oscillation sensitivity. The last class of measurements, in Chapter 4, cover physics topics that can be addressed by SciBar/BNB alone.

For each SciBar measurement this document is careful to point out:

1. why the measurement is interesting,

2. how many protons on target (POT) are needed and whether the beamline needs to be in neutrino or antineutrino mode,

3. why the measurement cannot be done at all or as well by any other past, present, or near future experiment, and

4. how the different potential detector locations for SciBar in the Booster Neutrino Beam affect the measurement.

Table 1 provides a handy summary of the potential for success of each of the proposed measurements at each of the detector locations considered. The document concludes with discussion of schedule and costs in Chapter 5.

1.1 Booster Neutrino Beam Description

To create the BNB, 8 GeV protons are extracted from the Booster and steered to strike a 71 cm long, 1 cm diameter beryllium target. This target sits at the upstream end of a magnetic focusing horn that is pulsed with $\sim$170 kA to focus the mesons produced by the proton-Be interactions. Following the horn is a 50 m long decay pipe that gives the pions a chance to decay and produce neutrinos, before the mesons encounter an absorber and then dirt which serve to remove all but the neutrinos from the beam.

The protons from the Booster arrive in batches of 84 bunches, each of which is ∼4 ns wide with ∼19 ns peak-to-peak separation, giving a length of ∼1.6 μs to the whole batch. The batches are extracted at a maximum rate of 5 Hz, a limit set by the horn, and each contains $\sim 4.5 \times 10^{12}$ protons. This timing structure is carried through to the neutrino beam, and provides a tight constraint on cosmic backgrounds.

In its current mode of operation, the horn focuses π^+ and defocuses π^- thus producing a ν_μ beam. By reversing the polarity of the horn current π^- are focused and a predominantly $\bar{\nu}_\mu$ beam is created. In addition there is an absorber that can be lowered into the beam at 25 m. Though currently not in use, the absorber would alter the beam spectrum and composition in ways that may prove useful for background checks or to reduce the effects of beam parallax on a nearby detector.

1.1.1 Expectations for Proton Delivery

The Booster Neutrino Beam saw first protons on target (POT) in September of 2002 and Fig. 1.1 records the weekly and cumulative proton delivery since then.

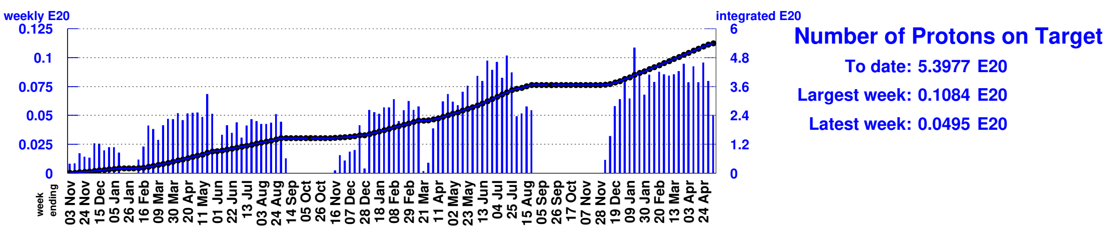


Figure 1.1: *Proton delivery to the Booster Neutrino Beam target from the start of operations in late 2002 to present (May 2005). The histogram records the weekly proton rate and the curve shows the cumulative total.*

At present, the NuMI beam is starting up and the Booster Neutrino Beam can expect to start receiving significantly fewer protons. The letter from the Fermilab Director to MiniBooNE entitled "Prospects for the Booster Neutrino Beam," and dated August 6, 2004 states:

> *Collaborations proposing experiments to run in the Booster neutrino beam in FY2006 and beyond should plan their physics program on the basis of* $1 - 2 \times 10^{20}$ *POT per year. Proponents may want to discuss what additional physics could be done with somewhat more protons, but they should understand that is beyond our present expectations for the beam.*

In this document, we make the assumption that 2×10^{20} POT will be delivered to the BNB in FY2006. This may seem optimistic, but the improvements in proton delivery made since the Director's letter and indicated in the latter portions of Fig. 1.1 justify such optimism.

It has not yet been decided whether the BNB will operate in neutrino or antineutrino mode in FY2006. This decision will hinge on whether or not MiniBooNE sees a

ν_e appearance oscillation signal; the MiniBooNE collaboration intends for this result to be out later in 2005. If MiniBooNE sees a signal then the case for installing SciBar in the beam becomes very strong as it will provide a powerful check on the ν_μ spectrum and will reduce the uncertainty on the intrinsic ν_e background by measuring it at a near location (see Chapter 2 for details). If MiniBooNE does not see a ν_e oscillation signal then the beamline will most likely switch to antineutrino mode in FY2006. The physics justification for this switch is laid out in [2]. For these reasons this document focuses on the case where MiniBooNE does not see a ν_e appearance signal and FY2006 is largely run in antineutrino mode. In this scenario, we assume that in FY2006 0.5×10^{20} POT will be delivered in neutrino mode and 1.5×10^{20} POT in antineutrino mode.

1.2 SciBar Detector Description

1.2.1 The K2K SciBar Detector

SciBar [4] is a fully active, finely segmented tracking detector consisting of plastic scintillator bars. The detector was constructed in summer 2003 as a new near detector for the K2K experiment, and operated until late 2004. The cost of SciBar was approximately $2M, not including contingencies or the cost of labor for construction.

A schematic view of SciBar is shown in Figure 1.2. The SciBar tracker consists of 14,848 extruded scintillator strips, each of dimension $1.3 \times 2.5 \times 300$ cm^3. The scintillator strips are arranged vertically and horizontally to construct a $3 \times 3 \times 1.7$ m^3 volume with a total mass of 15 tons, and a fiducial mass of 9.38 tons. Each strip is read out by a wavelength-shifting (WLS) fiber attached to a 64-channel multi-anode PMT (MA-PMT). Charge and timing information from each MA-PMT is recorded by custom designed electronics [5]. The specification of each component of SciBar is summarized in Table 1.1.

An electromagnetic calorimeter (EC) is installed downstream of SciBar. The purpose of the EC is to measure the ν_e contamination in the beam and the π^0 yield from neutrino interactions. The EC consists of 32 (vertical) and 30 (horizontal) modules re-used from the CHORUS experiment [6]. Each module is made of 1 mm diameter scintillating fibers embedded in the grooves of 1.9 mm thick lead foils. The dimensions of each module are $4.0 \times 8.2 \times 262$ cm^3. The light from the module is read out by two 1 " PMTs on both sides. The EC has a thickness of $11X_0$ along the beam direction. The energy resolution of the EC is $14\%/\sqrt{E\ [\mathrm{GeV}]}$, where E is the electron energy.

A muon range detector (MRD) [7] is located downstream of the EC. The MRD at KEK consists of 12 layers of iron plates sandwiched between vertical and horizontal drift-tube layers. The cross sectional size of a layer is approximately 7.6 m $\times$ 7.6 m. The four upstream iron plates are 10 cm thick and the eight downstream are 20 cm thick. The total iron thickness of 2.0 m covers up to 2.8 GeV muons.

Not including the MRD, the actual size of the SciBar detector's experimental area at K2K is approximately 5.5 m wide and 2 m along the beam direction; SciBar, the EC, and two electronics racks were installed in that space.

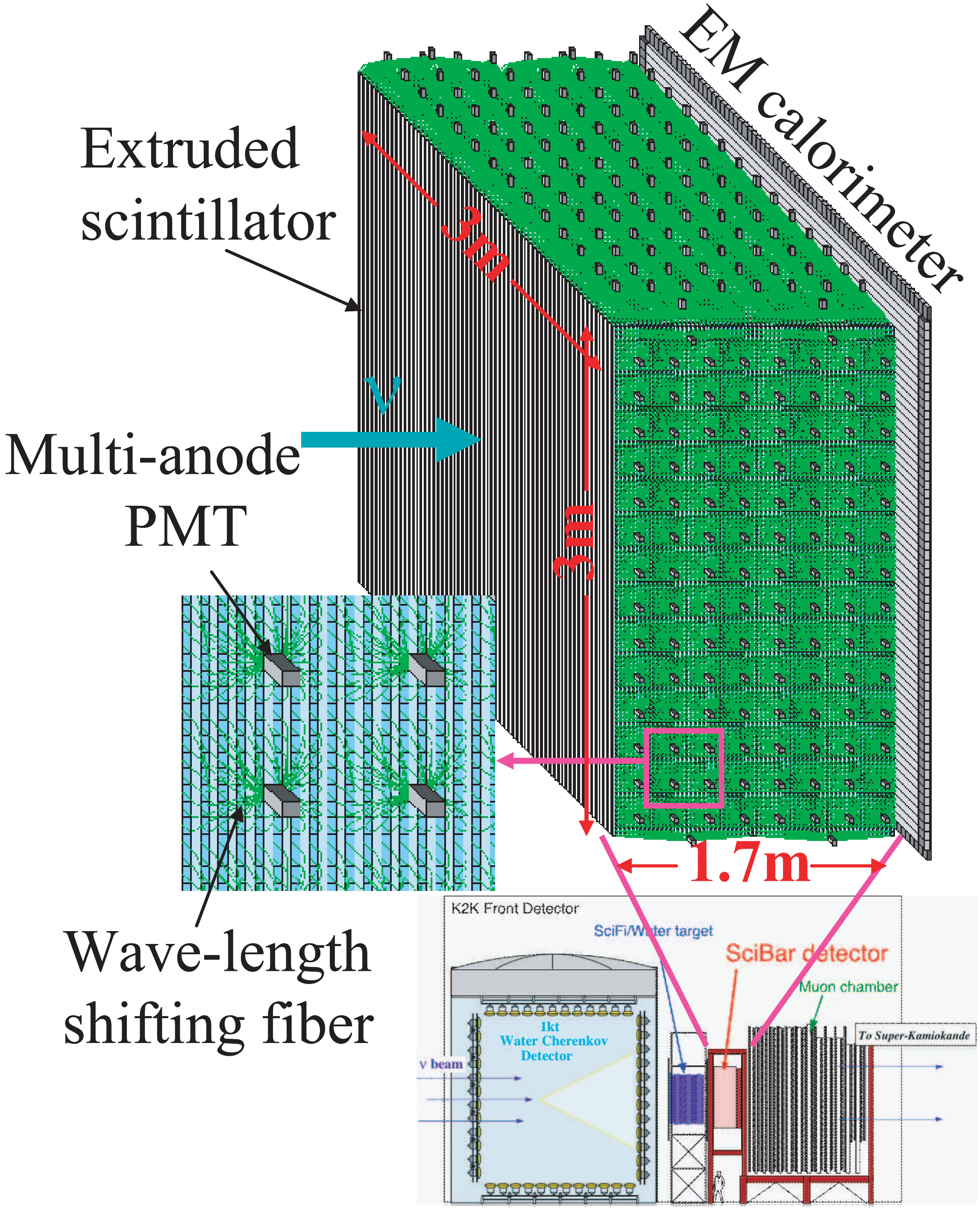


Figure 1.2: *Schematic view of SciBar. Extruded scintillator strips are arranged vertically and horizontally, with WLS fibers embedded in each strip. Each WLS fiber is read out by a 64-channel MA-PMT. An electromagnetic calorimeter sits immediately downstream of SciBar.*

Table 1.1: *Specification of each component of SciBar*

Structure	Dimensions	3 m (horizontal), 3 m (vertical), 1.7m (thickness)
	Weight	15 tons
	Number of strips	14,848
	Number of PMTs	224
Scintillator	Material	Polystyrene with PPO(1%) and POPOP(0.03%)
	Size	$2.5 \times 1.3 \times 300$ cm^2
	Coating	0.25 mm (TiO_2)
	Emission wavelength	420 nm (peak)
Fiber	Type	Kuraray Y11(200)MS
	Diameter	1.5 mm
	Reflective index	1.59 (outer)/ 1.50 (middle)/ 1.42 (inner)
	Absorption wavelength	430 nm (peak)
	Emission wavelength	476 nm (peak)
	Attenuation length	350 cm
PMT	Model	Hamamatsu H8804
	Cathode material	Bialkali
	Anode	8×8 (2×2 mm^2/pixel)
	Quantum efficiency	12% for 500 nm photons
	Typical gain	6×10^5 at ~ 800 V
	Response linearity	200 PE at gain of 6×10^5
	Cross talk	4% (adjacent pixel)
DAQ	VA/TA ASIC	IDEAS VA32HDR11 and TA32CG
	Shaping time	1.2 μsec (VA), 80 ns (TA)
	Noise	0.3 PE
	Response linearity	5% at 300 PE
	TDC resolution	0.78 ns
	TDC full range	50 μsec

1.2.2 Past Detector Performance

The SciBar detector was operated at K2K from October 2003 to November 2004. During the period, the number of dead channels was monitored and only six dead channels were identified out of 14,336 channels. Operationally, SciBar performed very well, requiring only two detector accesses over the duration of SciBar's neutrino beam run.

Light yield in SciBar was measured using cosmic ray data. The average light yield is 18 photoelectrons (PE) for a 1.0 cm muon track at 40 cm from the PMT along the fiber. The light yield is sufficient for track finding and particle identification. The stability of the light yield is also checked using cosmic ray data. With PMT gain corrections, the light yield was found to be stable at the 0.7% level.

Figure 1.3 shows a display of an actual charged-current quasi-elastic (CC QE)

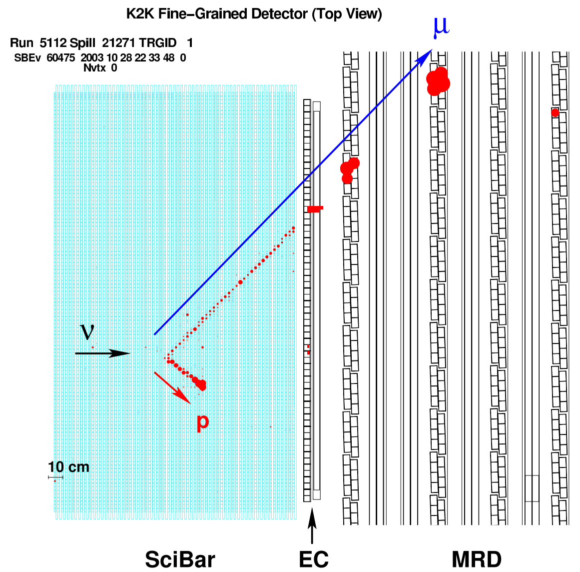


Figure 1.3: *Event display of a typical CC-QE candidate. The red circles show the hit cells, and their areas are proportional to the recorded ADC counts.*

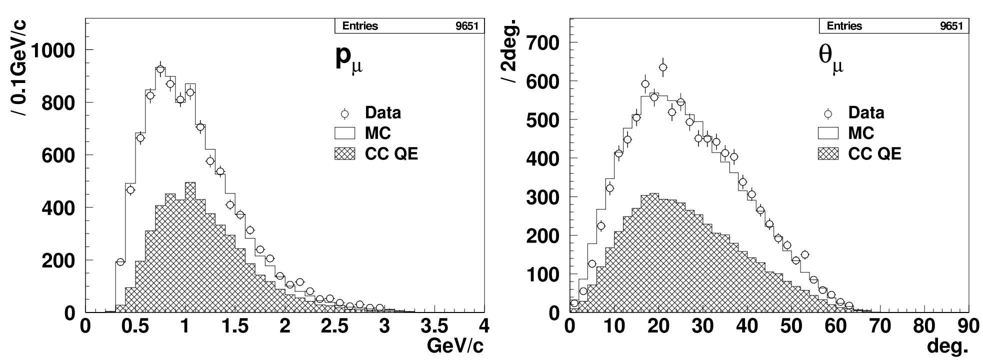


Figure 1.4: *Muon momentum distribution (left) and angular distribution (right). Open circles and solid lines are data and MC simulation, respectively. The MC distributions are normalized by entries.*

candidate event in SciBar. We can clearly identify the muon track and the proton track by their energy deposition. The track finding efficiency of a muon generated in a charged-current neutrino interaction in SciBar is approximately 94%, estimated using real data.

Figure 1.4 shows the distributions of muon momentum (p_μ) and angle with respect to the beam (θ_μ), with the requirement that a track created in SciBar match a track (or hits) found in the MRD. The data and MC agree well except for the forward ($\theta_\mu < 10$ degrees) region, which may point to new physics, rather than a detector deficiency [21]. The energy resolution and angular resolution of the muons are 0.08 GeV and 1.6 degrees, respectively. The muon energy resolution is dominated by the MRD resolution. More detailed detector performance can be found elsewhere [8].

1.2.3 Modifications to Detector Configuration

The detector configuration will be modified slightly for this experiment. The detector complex will consist, as before, of three detectors: SciBar, the EC and the MRD. All SciBar components and most EC components will be brought from KEK to Fermilab, and their configuration will not change. In order to save costs, the MRD, will be assembled from detector components salvaged from past FNAL experiments, rather than be shipped from Japan. Currently, we intend to use steel plates and scintillator with a cross sectional area of 3.5 m $\times$ 4 m and plate thicknesses of 2.5 and 5 cm. Note that we will use plastic scintillators for the active detector elements instead of drift tubes. We are currently conducting studies under the assumption that we will have 60 cm of iron total, which is sufficient to stop muons with kinetic energy of 1 GeV. Monte Carlo studies indicate that this smaller MRD size is adequate, reducing the efficiency for SciBar-MRD track matching by only 10-20%, depending on the interaction type.

1.3 Discussion of Specific Locations

In pursuing this project, we have explored potential detector sites both on and off the beam axis. In this section, we explore the variations in flux and spectrum with detector location, with the goal of selecting the detector location which best maximizes the physics output. We do this by comparing predicted event rates at the various locations, based on current neutrino interaction cross sections and the known efficiencies of the SciBar detector, and estimating the measurements within reach based on those predicted event rates and spectra.

We begin with a general discussion of the Booster neutrino flux. Figure 1.5 shows the expected total flux and mean energy of all neutrino species as a function of distance from the target in the beam direction ($\hat{z}$) and the vertical direction ($\hat{y}$). In the figure, the horizontal axis represents the distance from the neutrino target in the beam direction ($\hat{z}$), measured in cm, and the vertical axis represents the vertical ($\hat{y}$) distance from the beam axis measured in cm.

From Fig. 1.5(top), we see that there are contours of constant flux, roughly ellipsoidal in shape with the major axis aligned with the beam direction, emanating from

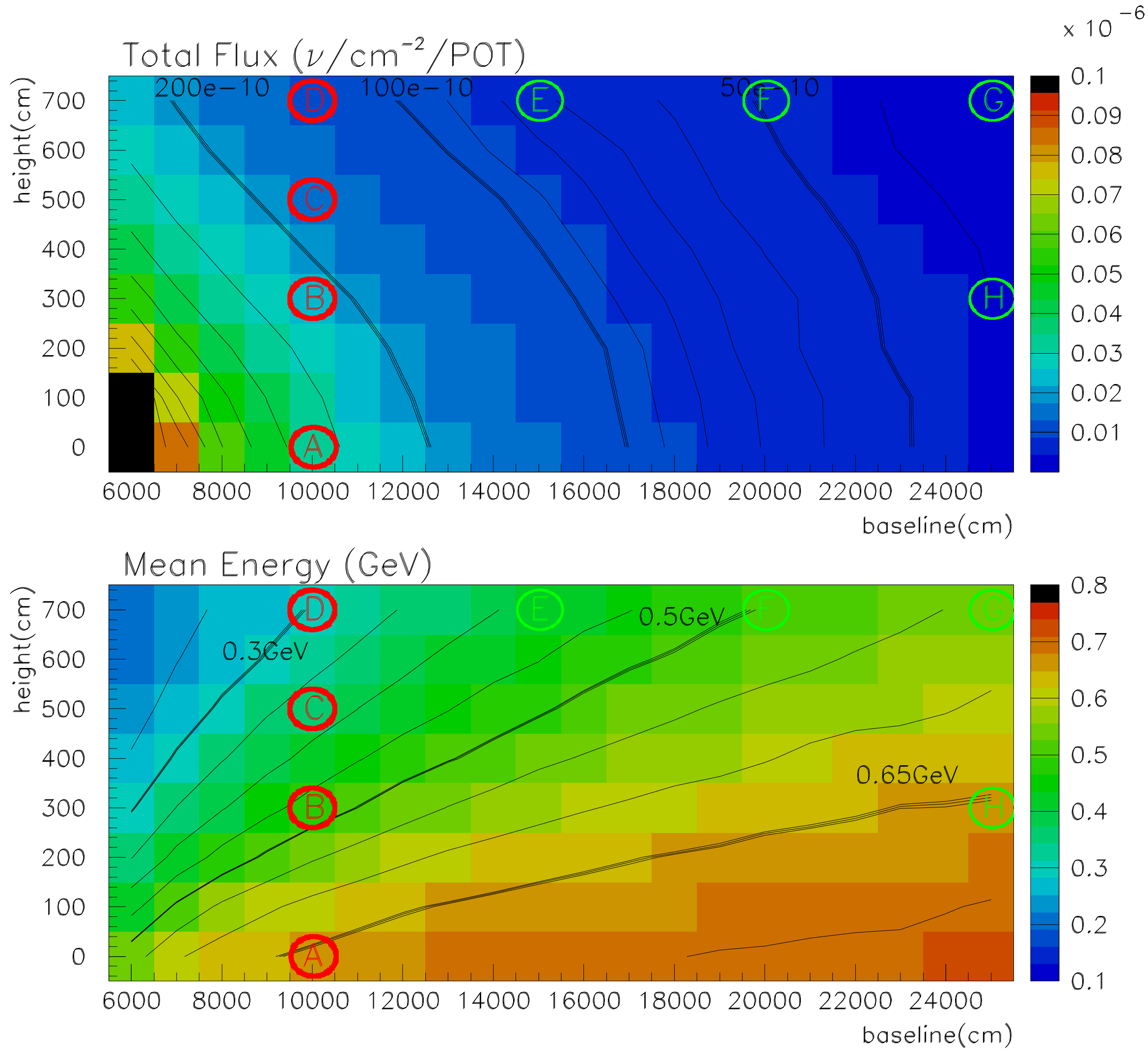


Figure 1.5: *Total neutrino flux (top) and average neutrino energy (bottom) as a function of distance from the MiniBooNE target, in both longitudinal and vertical directions. The flux is given in units of $\nu/cm^2/POT$, and the energy is given in units of GeV. The origin of beam coordinate system coincides with the neutrino production target, and is not shown in the plots.*

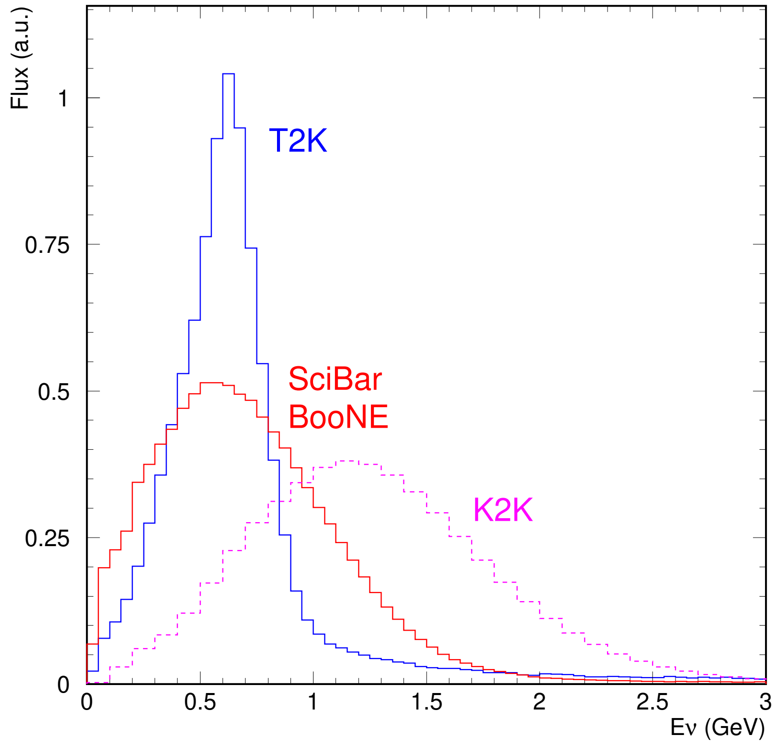


Figure 1.6: *Comparison of the ν_μ flux spectra at K2K, T2K, and the on-axis location at 100m.*

the neutrino target. As an example, the flux line at z=125 m, y=0 m indicates that we expect $200\times10^{-10}\nu/\mathrm{cm}^2/\mathrm{POT}$ at that location. Following this flux line, we see that this same total flux is expected at many more locations, for example at z=100 m, y=4 m and z=75 m, y=7 m.

Following the contour lines of constant flux allows one to optimize the detector with regard to total neutrino flux. Alternatively, one can optimize with regard to the energy spectrum. Fig. 1.5(bottom) shows contours of constant mean energy, for neutrinos less than 2 GeV[1]; these contour lines appear to radiate from the neutrino target position. Following the previous example which examined a line of constant flux, we now follow a line of constant mean energy. Noting that at z=100 m, y=0 m the mean neutrino energy is ∼0.65 GeV, we follow the ∼0.65 GeV line and find that at z=250m, y=3m we expect the same mean energy.

In this discussion, we consider eight different detector locations: four locations at z=100 m, ranging vertically from 0 m (on-axis) to 7 m (on the surface), and four on the surface, ranging from 100 m to 250 m from the proton target. We also consider one location at z=250 m, y=3 m. As discussed in Section 1.4, several locations were eliminated immediately because they would produce extremely poor statistics.

Not surprisingly, we find that the on-axis location at a distance of 100 m from the neutrino target is the best choice, providing the largest possible physics reach.

[1]For this plot, the calculation of the neutrino mean energy was found using only neutrinos below 2 GeV, to remove the effect of the high energy tails.

Discussion of On-Axis Spectrum

Figure 1.6 shows a comparison of the ν_μ flux spectra for K2K, T2K and this on-axis location. This figure indicates why the BNB is of direct interest to T2K: the energy peaks of the two fluxes coincide and the entire range of the T2K energy flux is encompassed within the flux peak of the BNB. Thus, cross section measurements made at FNAL will have direct relevance to neutrino events at T2K.

Discussion of Spectra at Off-axis Locations

Figure 1.7(left) reveals in detail the effects of going off-axis in the vertical direction. The figure demonstrates that at increasingly off-axis positions, the peak of the neutrino flux moves to lower energy, and the overall flux decreases. This behavior was first seen in the discussion of Figure 1.5. The off-axis behavior of the $\bar{\nu}_\mu$ flux expected for antineutrino running mode is shown in Figure 1.7(right), and is seen to exhibit the same behavior.

We have also considered several locations on the surface, at increasing distance from the proton target. These locations provide different off-axis angles, but roughly equal costs because they all involve the same excavation needs. We have also selected a location, at z=250 m, y=3 m, which gives a very similar energy spectrum to the on-axis location at z=100 m. However, all of these locations yield event rates that are too low to make interesting measurements on the time scales of this project.

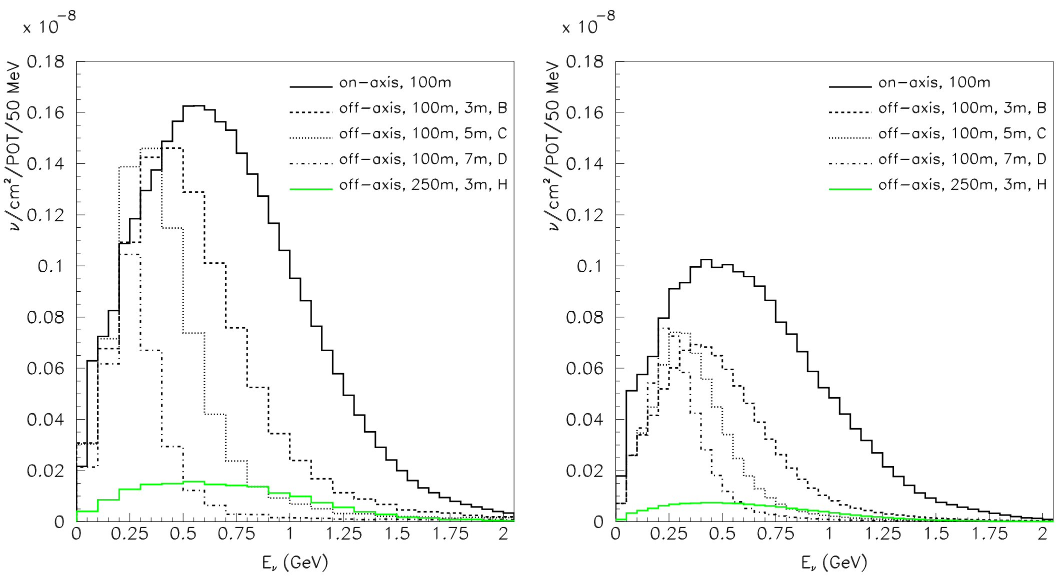


Figure 1.7: *Comparison of neutrino (left) and antineutrino (right) mode energy spectra for several different detector locations as indicated in Figure 1.5.*

1.4 Expected Event Rates

Expected event rates in the SciBar detector for a variety of Booster beamline locations were estimated using the NEUT Monte Carlo simulation which has been demonstrated

Reaction	# ν_μ events
CC QE	31,720
CC resonant $1\pi^+$	14,108
NC elastic	13,751
CC multi-π	5,279
NC resonant $1\pi^0$	3,723
CC resonant $1\pi^0$	3,106
NC resonant $1\pi^\pm$	2,372
NC multi-π	1,723
CC coherent $1\pi^+$	1,432
NC coherent $1\pi^0$	746
total	77,960

Table 1.2: *Total number of ν_μ events expected in neutrino mode assuming 9.38 ton fiducial volume, 0.5×10^{20} POT, and on-axis z=100m SciBar location. $\bar{\nu}_\mu$ events have been omitted from this table as they contribute $< 2\%$ to the total event rate.*

to perform well in modeling SciBar data taken at K2K [9]. This section presents the number of events anticipated for various neutrino reactions and detector sites assuming a 9.38 ton fiducial CH target and a total of 2×10^{20} POT (0.5×10^{20} POT in neutrino mode, and 1.5×10^{20} in antineutrino mode).

1.4.1 On-Axis

The largest number of events are expected for the on-axis detector location at 100m. Tables 1.2 and 1.3 present these anticipated rates for on-axis running in both neutrino and antineutrino configurations. Because wrong-sign backgrounds are non-negligible in antineutrino running, the neutrino rates in this mode are explicitly provided (Table 1.3). As can be seen from both tables, the most copious interactions in the Booster beamline are CC QE. A total of $\sim 80,000$ interactions are expected in the full on-axis neutrino exposure (0.5×10^{20} POT) and a total of $\sim 60,000$ for on-axis antineutrino running (1.5×10^{20} POT).

1.4.2 Off-Axis

Table 1.4 shows the number of neutrino events expected for the variety of off-axis SciBar detector locations that were considered (Figure 1.5). The expected energy distributions of events at these sites are shown in Figure 1.8. In general, the collected event samples decrease and the energy spectra become softer as one moves off-axis. The event rate decreases by a factor two in moving 3m vertically from the beam axis at z=100m (site B), and is down by a factor ~ 13 at the surface (site D).

Reaction	# $\bar{\nu}_\mu$ events (RS)	# ν_μ events (WS)
CC QE	18,623	7,884
NC elastic	7,563	3,516
CC resonant $1\pi^-$	4,494	0
CC resonant $1\pi^+$	0	4,481
CC coherent $1\pi^-$	2,150	0
CC coherent $1\pi^+$	0	377
NC resonant $1\pi^0$	2,150	1,115
CC multi-π	1,635	2,760
NC resonant $1\pi^\pm$	1,227	735
CC resonant $1\pi^0$	1,127	960
NC coherent $1\pi^0$	1,109	207
NC multi-π	710	891
total	40,685	22,925

Table 1.3: *Total number of ν_μ events expected in antineutrino mode assuming 9.38 ton fiducial volume,* 1.5×10^{20} *POT, and on-axis z=100m SciBar detector location.*

1.5 External Time Constraints

There are two time constraints that affect when SciBar can operate in the BNB. The SciBar detector will be needed back in Japan for insertion into the T2K beamline sometime in 2008. This sets the duration of a possible SciBar run in the BNB. An even stronger constraint arises from the scheduled operation of the BNB. In November of 2004, MiniBooNE was given approval by the Fermilab Director to run through the end of FY2006 and so the beamline will operate at least through to that time. The BNB may, in principle, run beyond FY2006, but we realize that this is not guaranteed.

In the following three sections describing the physics that could be done by SciBar/BNB it is assumed that the detector would be exposed to 2×10^{20} POT in FY2006. The current schedule presented in Chapter 5 assumes the start of SciBar operations in February, 2006. If it is not possible to accelerate this schedule by devoting more lab resources, we will restrict attention to those analyses that can be done with significantly fewer data, since many of the proposed analyses require only 0.5×10^{20} POT (see Table 1). Concurrently there would also be an additional request submitted for running of the BNB into FY2007.

	on-axis z=100m d=0m	B z=100m d=3m	C z=100m d=5m	D z=100m d=7m	E z=150m d=7m	F z=200m d=7m	G z=250m d=7m	H z=250m d=3m
$< E_\nu >$	0.92	0.76	0.64	0.60	0.60	0.61	0.61	0.94
$\#\nu_\mu$	78,397	37,230	19,357	6,001	3,791	2,807	2,200	8,112
$\#\bar{\nu}_\mu$	1,138	636	467	176	113	88	67	109
$\#\nu_e$	669	415	268	128	68	46	39	61
# CC ν_μ	55,983	26,244	13,530	4,103	2,588	1,932	1,513	5,807
# MRD	18,500	7,000	2,970	850	520	390	310	1,970

Table 1.4: *Number of events expected in neutrino mode assuming 9.38 ton and* 0.5×10^{20} *POT for the various SciBar detector locations as identified in Figure 1.5. The first row reports the mean neutrino energy of the events in GeV. The last row indicates the number of events with a matching track in the MRD.*

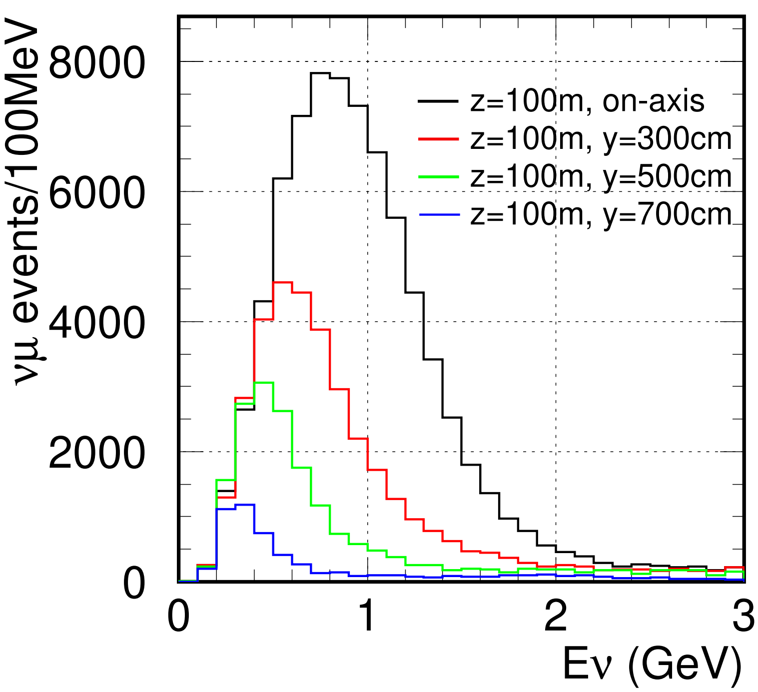


Figure 1.8: *Expected neutrino energy distributions (cross section weighted) for various SciBar on-axis and off-axis detector locations at z=100m.*

Chapter 2

Leveraging MiniBooNE

MiniBooNE is a neutrino oscillation experiment at Fermilab, whose primary physics goal is the confirmation or refutation of the LSND oscillation signal [10]. A description of MiniBooNE's detector and analysis methods can be found elsewhere [3].

2.1 Wrong-Sign Backgrounds

Having precise knowledge of neutrino ("wrong-sign") backgrounds in data collected in antineutrino mode running is important for any antineutrino cross section measurements, including those being planned with phase II running at MiniBooNE [2]. At MiniBooNE, these wrong-sign backgrounds comprise $\sim 30\%$ of the anticipated total antineutrino mode event rate (Figure 2.1), and contribute a direct source of error on any potential antineutrino cross section measurements. Using a combination of several novel techniques for directly measuring the wrong-sign rates in the MiniBooNE detector [2], MiniBooNE has reduced this background contribution to a few-% uncertainty on their projected antineutrino cross sections measurements.

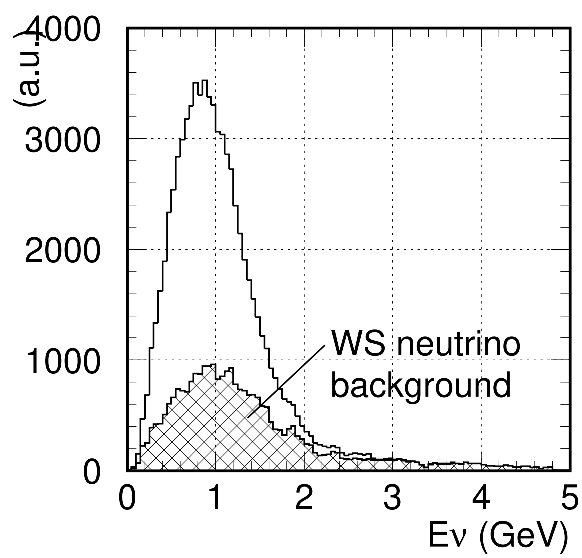


Figure 2.1: *Expected energy distribution for antineutrino (unfilled) and neutrino (hatched) events in antineutrino mode for the on-axis (A) SciBar detector location.*

SciBar is uniquely suited to provide an additional measurement of the wrong-sign contamination in the antineutrino Booster beam by exploiting the fact that, unlike MiniBooNE, the fine-grained detector can differentiate between final states with protons versus neutrons, and hence can distinguish neutrino versus antineutrino QE interactions on an event-by-event basis:

$$\nu_\mu \, n \to \mu^- \, p \tag{2.1}$$
$$\bar{\nu}_\mu \, p \to \mu^+ \, n \tag{2.2}$$

Based on their differing final state composition, QE neutrino interactions are expected to have two tracks (one each from the muon and proton) while antineutrino interactions are expected to have only one track (from the muon). Figure 2.2 shows the reconstructed energy distributions for QE events passing one and two track selection in the SciBar detector. Assuming a 1.5×10^{20} POT antineutrino run on-axis, the one track requirement yields a sample of $\sim 20,000$ events, of which 59% are $\bar{\nu}_\mu$ QE interactions, 10% are CC 1π backgrounds, and 29% are ν_μ QE wrong-sign backgrounds. On the other hand, further requiring there to be two tracks in the event isolates a sample of $\sim 1,400$ events that is 80% pure ν_μ QE wrong-sign backgrounds. Because this selection can be made on an event-by-event basis, this yields a direct and direct measurement of the energy spectrum of the neutrino background (Figure 2.2 right panel). Such a spectral constraint is not possible using MiniBooNE tank data alone.

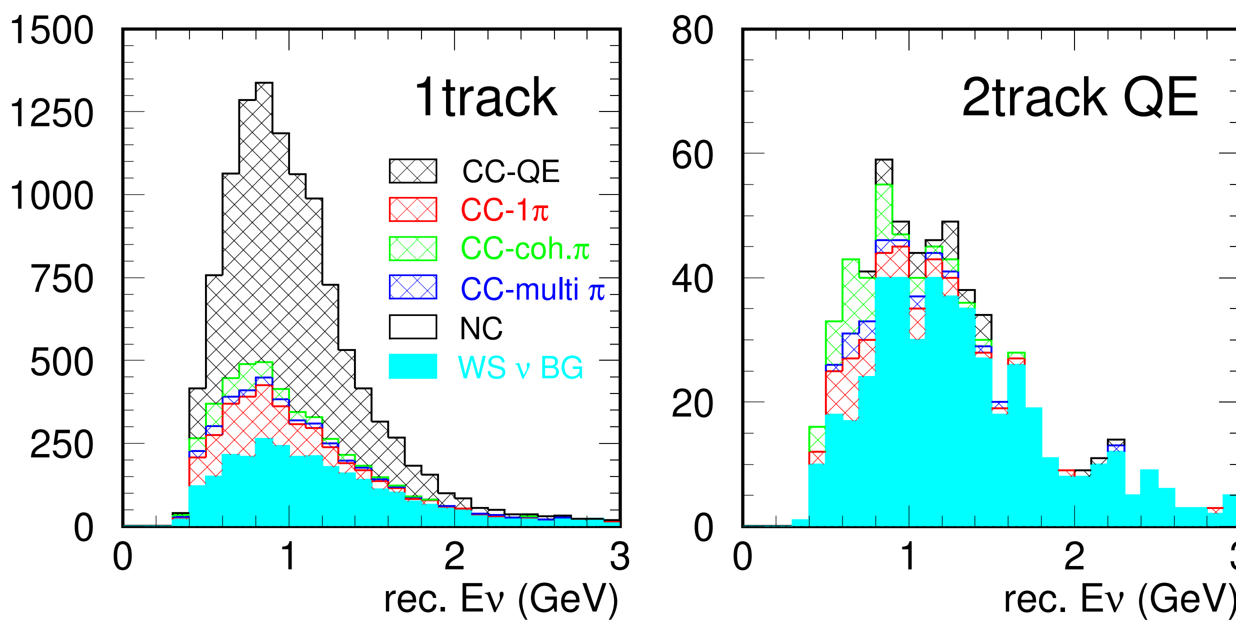


Figure 2.2: *Monte Carlo generated reconstructed energy distributions for antineutrino mode QE events in the SciBar detector passing 1 track (left) and 2 track (right) selection requirements. These particular plots were generated assuming* 1×10^{20} *POT in* $\bar{\nu}$ *mode, assuming an on-axis location at z=100 m.*

In this way, SciBar can provide the only experimental constraint on the energy spectrum of wrong-sign background events in antineutrino running at MiniBooNE. Combining this spectral constraint with measurements of the overall wrong-sign rate obtained in the MiniBooNE detector will lend further confidence and precision to MiniBooNE antineutrino cross section measurements, especially those that are binned in energy.

This wrong-sign event contamination actually increases as the SciBar detector is moved off-axis because one loses the focusing benefits of the horn (the wrong-sign fraction increases from 30% on-axis to 50% by the time one reaches the surface at z=100m). Despite this, off-axis measurements of the neutrino energy spectrum in the antineutrino beam are not easily transportable as constraints on the on-axis MiniBooNE beam. This is largely due to the fact that the spectrum shifts toward lower energies as one moves off-axis (Figure 2.3). In addition, for a detector location at z=100, the 300cm off-axis wrong-sign event samples are down by a factor of two, and are decreased by a factor of four at the surface. This combination of sampling a different wrong-sign energy distribution than the on-axis MiniBooNE location and the degradation in the event sample make it less clear how useful off-axis running is toward constraining neutrino backgrounds in antineutrino running at MiniBooNE. To gain full benefit, one really needs to be on-axis to provide a useful spectral measurement.

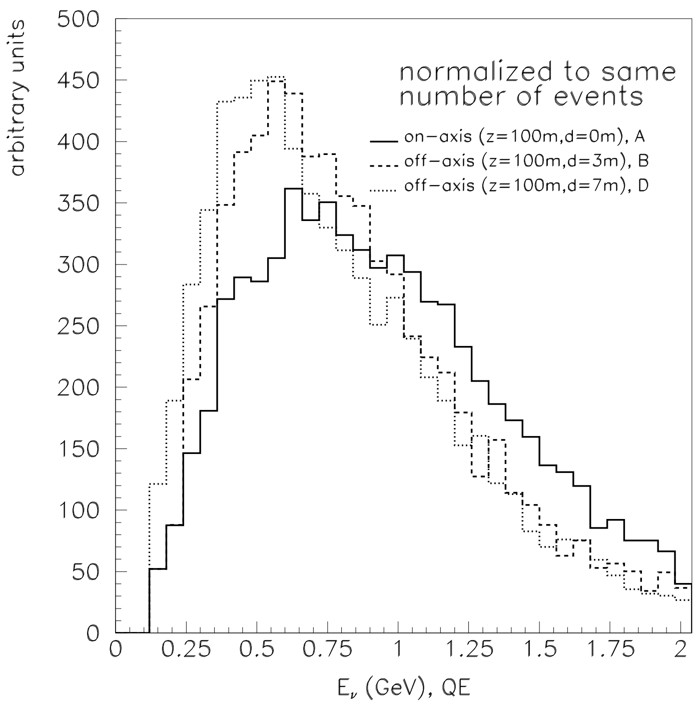


Figure 2.3: *Generated neutrino energy distributions for wrong-sign QE neutrino events in antineutrino mode for z=100m detector locations on-axis (A) and two off-axis locations at 300m cm (B) on the surface (D). The three distributions have been relatively normalized so as to compare spectral shapes.*

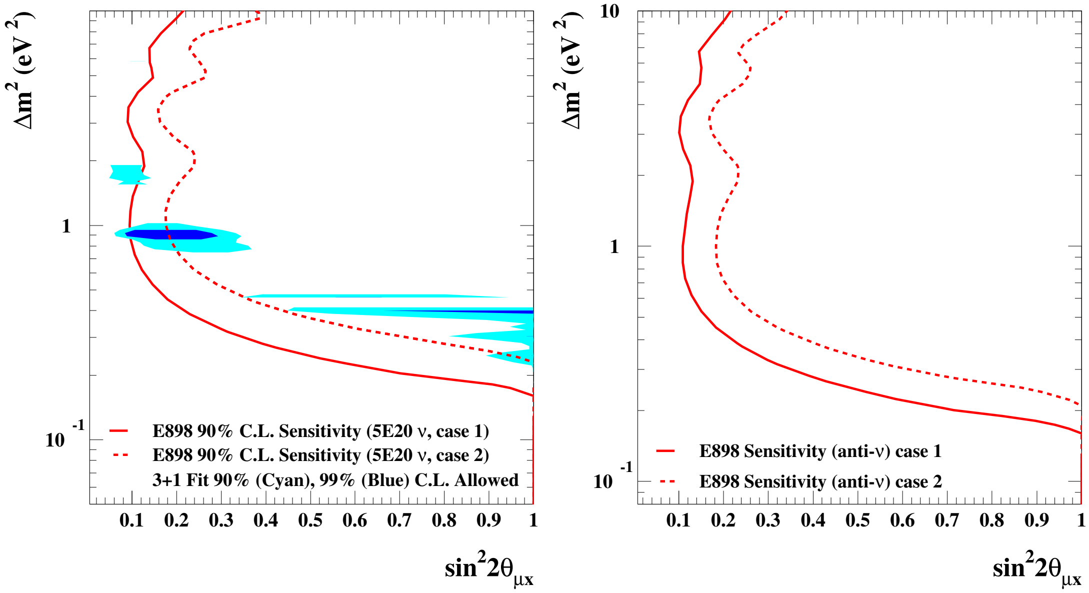


Figure 2.4: *The MiniBooNE 90% confidence level sensitivity to $\nu_\mu \rightarrow \nu_x$ (left, 5×10^{20}POT) and $\bar{\nu}_\mu \rightarrow \bar{\nu}_x$ (right, 1.5×10^{20}POT) oscillations. The projected MiniBooNE sensitivity is shown for two cases of systematic uncertainties; the solid line indicates case 1: 5% shape and 10% normalization errors, and the dotted line indicates case 2: 10% shape and 25% normalization errors. In the left hand panel, we include the allowed regions for 3+1 sterile neutrino models, and note that the case 2 sensitivity curve does not cover these.*

2.2 ν_μ Disappearance

In models with sterile neutrino flavors, the rate of ν_μ or $\bar{\nu}_\mu$ disappearance can be significantly greater than ν_e or $\bar{\nu}_e$ appearance. Thus, such searches provide information on additional mixing parameters beyond confirmation of the LSND signal.

The availability of a near detector significantly extends MiniBooNE's ν_μ disappearance reach by offering a measured constraint on the un-oscillated ν_μ flux normalization and energy spectrum of the BNB. This benefit is only realized if SciBar is placed in the on-axis location.

In the following section, we present two ν_μ disappearance studies using the MiniBooNE CC QE selection cuts for both ν and $\bar{\nu}$ modes [3], [19]. We do not present detailed near/far event spectrum ratio studies; rather, we show only how changes in the systematic errors affect the oscillation sensitivities.

2.2.1 ν Running

For neutrino running, the use of a near detector will not improve the sensitivity to ν_μ disappearance with only 0.5×10^{20} POT [18]. It is crucial to use concurrent data for such analyses, and the short neutrino run will not provide sufficient statistics to perform a joint ν_μ disappearance search with SciBar and MiniBooNE data that will approach the expected sensitivity of the MiniBooNE neutrino run up to that time. It will, however, independently measure the un-oscillated ν_μ flux, and thus provide an external constraint on the flux normalization and spectrum. We show the expected 90% confidence level $\nu_\mu \rightarrow \nu_x$ sensitivity curves under two different systematic error assumptions in Figure 2.4(left). The figure demonstrates the effects of increased normalization and shape systematics, and thus indicates the importance of understanding these uncertainties.

2.2.2 $\bar{\nu}$ Running

A disappearance search in antineutrino mode, when compared with a disappearance search in neutrino mode, provides a powerful test of CPT invariance. While CP violation can only be observed in an *appearance* experiment — by observing an asymmetry between the appearance rates in neutrinos and antineutrinos — the appearance mode is unable to distinguish if the asymmetry is the result of CP or CPT violation. As a result, one needs to additionally search for an asymmetry in a *disappearance* experiment. Moreover, the potential for a larger disappearance rate means that a disappearance asymmetry may be observable even if an appearance asymmetry is not.

As described in Section 2.1, the SciBar detector would allow us to extract the energy spectrum of the wrong-sign backgrounds in $\bar{\nu}$ running. Exploiting this reduces the systematic error on the shape of the $\bar{\nu}_\mu$ flux for $\bar{\nu}_\mu$ disappearance analyses. In Figure 2.4(right), we show the expected sensitivity to $\bar{\nu}_\mu \rightarrow \overline{\nu}_x$ oscillations for two cases of systematic errors. The sensitivity region is noticeably expanded with reduced systematic errors.

2.3 Intrinsic ν_e Contamination

The primary purpose of MiniBooNE is the investigation of the LSND indication of neutrino oscillations , by searching for ν_μ to ν_e transitions at a relatively short baseline. The precision of this measurement is limited, in part, by knowledge of the flux of intrinsic ν_es coming from decays of K^+, K^0_L, and μ^+ in the 50 m beam decay region. MiniBooNE has a variety of ways of constraining these different components, and expects to reach a $\sim 5\%$ uncertainty on the intrinsic ν_e background.

For 0.5×10^{20} POT, there should be $\sim$490 charged current ν_e interactions in SciBar. Based on detailed Monte Carlo simulations, SciBar is expected to have a ν_e cut efficiency of 21% and a purity of 88% for electrons above 0.5 GeV (performance numbers for lower energy electrons are not available at this time). Additionally, just from geometry, some of the ν_e passing through SciBar will not pass through the MiniBooNE tank. These uncertainties make it difficult to make a confident statement about SciBar's ability to measure the MiniBooNE ν_e contamination, but statistically a 10-20% measurement of the intrinsic ν_e component of the beam can be achieved.

Although a 10-20% measurement of the intrinsic ν_e flux does not compete with the $\sim 5\%$ level expected from other sources, it has one very important feature: it is a *direct* measurement of the ν_es in the same beam that goes through the MiniBooNE tank. All the other ways in which MiniBooNE can determine the ν_e flux are indirect to varying degrees. There is no reason to doubt the other, more accurate, measures of the ν_e flux, but a cross-check of the actual ν_es themselves would be very reassuring. This cross-check is, of course, only valuable if the detector is on-axis. At the off-axis locations, the ν_e event statistics drop rapidly; more importantly, the flux through SciBar would no longer be the same flux that passes through the MiniBooNE tank.

Chapter 3

Measurements that Help T2K

T2K [11] is a next-generation long baseline neutrino oscillation experiment at the J-PARC facility [12] in Tokai, Japan. T2K is an approved and funded experiment, and currently under construction aiming for a start in 2009. T2K uses Super-Kamiokande [13] as a far detector with a neutrino flight distance of 295 km. A high neutrino oscillation sensitivity is achieved using an intense neutrino beam with a peak energy of 750 MeV, matching the neutrino oscillation maximum for $\Delta m^2_{23} = 2.5 \times 10^{-3}$ eV^2. The two main physics goals of T2K are (1) a precise measurement of neutrino oscillation parameters in $\nu_\mu \to \nu_X$ disappearance: $\delta(\Delta m^2_{23}) \sim 10^{-4}$ eV^2 and $\delta(\sin^2 2\theta_{23}) \sim 0.01$, and (2) a sensitive search for the unmeasured mixing angle θ_{13} in $\nu_\mu \to \nu_e$ appearance: $\sin^2 2\theta_{13} \geq 0.008$ at the 90% C.L.

Given the good match between the MiniBooNE neutrino spectrum and that expected by T2K as shown in Figure 1.6, there are a variety of cross-section measurements that can be made by SciBar/BNB that would greatly assist T2K. Here, only three such measurements will be considered, as these are examples where there is clear guidance from the T2K collaboration on the level to which each must be known. The neutrino energies at K2K, MINOS, and MINERνA are higher and these experiments have limited statistics in the range useful to T2K. We note the cases in which the SciBar measurements are superior to those made using MiniBooNE tank data alone.

3.1 ν_μ CCπ^+

In T2K, the near maximal value of θ_{23} causes a large distortion in the ν_μ spectrum that can be measured with ν_μ CC QE interactions. T2K will use this to measure θ_{23} accurately. The background to this channel (referred to generically as non-QE events) is dominated by charged current events with a charged pion in the final state (CCπ^+), coming from either a Δ resonance or by coherent production from the entire nucleus. Figure 3.1 shows the effect on the oscillation parameter measurements of making a 20% mistake or a 5% mistake in predicting this background. This figure makes it clear that the CCπ^+ cross-section at these energies needs to be known to 5% to keep any resulting error on the oscillation parameters within statistical uncertainties.

Fig. 3.2 shows the current state of knowledge of the CC1π^+ interaction cross section in the 1 GeV range. This plot shows that the current uncertainty on the

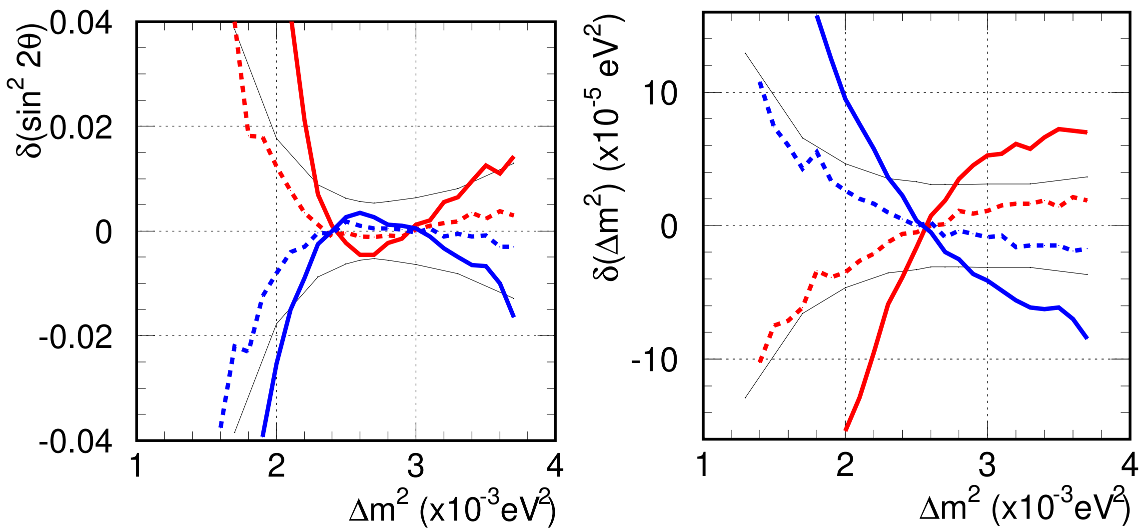


Figure 3.1: *The shift in the measurement of the atmospheric oscillation parameters as a function of true Δm^2 when an error of 20% (solid) and 5% (dashed) is assumed in predicting the the non-QE/QE ratio. The effect of shifting the background upward is shown by the blue line , and downward by the red line. The thin black line shows the irreducible uncertainty from statistics alone.*

CC1π^+ cross-section on bare protons (deuterium is almost bare) is ∼20%. For carbon and oxygen targets there are no data below 4.7 GeV; hence, the uncertainty increases to 25-30%, as nuclear model uncertainties become important.

Clearly, additional measurements are needed to get the uncertainty on the CC1π^+ cross-section down to the desired 5% level. As shown in Table 1.2 the expected number of CC1π^+ interactions in SciBar is over 14,000 assuming 0.5×10^{20} POT. Even when cut efficiencies are folded in, it will be trivial to reach the 5% level statistically. SciBar's ability to resolve final state particles should also make it possible to keep the systematic error below the desired level. This ability will give SciBar a cleaner sample of CC1π^+ events, but it will also enable SciBar to more accurately reconstruct the neutrino energy. The fact that SciBar can separate the final state pion from the final state muon and any protons that may be emitted means that, in many cases, it can actually reconstruct the invariant mass of the resonant state as well as the incoming neutrino energy.

Since the neutrino energy can be reconstructed for CC1π^+ interactions, K2K, MINOS, and MINERνA could, in principle, measure the cross-section despite having higher energy neutrino spectra. That being said, at these low energies these experiments will suffer from larger feed down from inelastic backgrounds. Some details on how well K2K might be able to do can be found in [21]. For MINERνA, 1 GeV is about as low as the measurement could go. MiniBooNE will make such a measurement, but it does not have SciBar's ability to cleanly resolve final states. Currently MiniBooNE anticipates being able to make a 10% measurement of the CC1π^+ cross-section as a function of neutrino energy, where the limit comes from the systematic errors associated with the complexity of the final state.

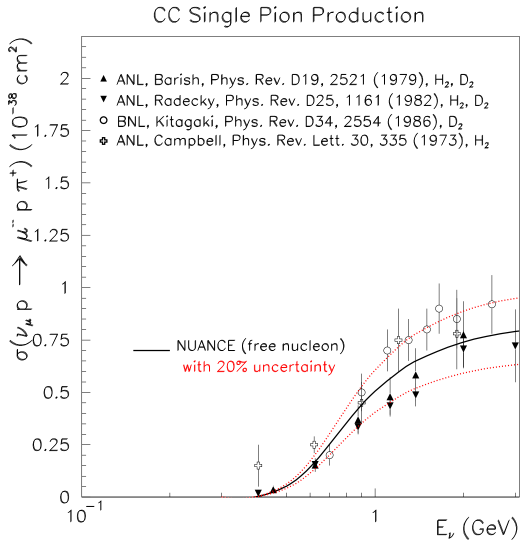


Figure 3.2: *The current measurements of the $\nu_\mu p \rightarrow \mu^- p\pi^+$ (CC1π^+) cross section. Also shown is a 20% uncertainty band around the predicted cross-section. Note that there is no data for any target heavier than deuterium at these energies.*

A more precise CC1π^+ cross section measurement can be made with a SciBar/BNB on-axis location. The off-axis location B would be acceptable as it maintains some of the flux in the energy region of the T2K beam, but the statistics drop significantly as the threshold for the process is approached. By the time locations C and D are reached, the flux is too far from the T2K spectrum to provide useful measurements. At the off-axis location H, that maintains the same mean energy as location A, the rate has dropped by an order of magnitude. The statistics will still allow for a 5% measurement of the integrated CC1π^+ rate at that position, but any binned measurements will suffer statistically.

3.2 ν_μ NCπ^0

The primary purpose of T2K will be the search for ν_μ to ν_e transitions, and a measurement of the unknown mixing angle θ_{13} (more usually expressed as a measurement of $\sin^2 2\theta_{13}$). This measurement will have significant background contributions coming from intrinsic ν_es, and ν_μ events mis-identified as ν_e interactions.

As a function of exposure time, Fig. 3.3 shows the effect on the T2K sensitivity for measuring $\sin^2 2\theta_{13}$ assuming three different levels of uncertainty in the subtraction of the ν_μ mis-ID and intrinsic backgrounds. It is clear that for these exposures the difference between 10% and 0% uncertainty is minor, but between 10% and 20% there is a noticeable change. For this reason a 10% uncertainty on the NCπ^0 cross section is desired if this process is not to the dominate sensitivity for measuring $\sin^2 2\theta_{13}$.

Currently the cross-section for NCπ^0 production is poorly known, with uncertainties well in excess of 10% and with only one or two measurements at energies in the

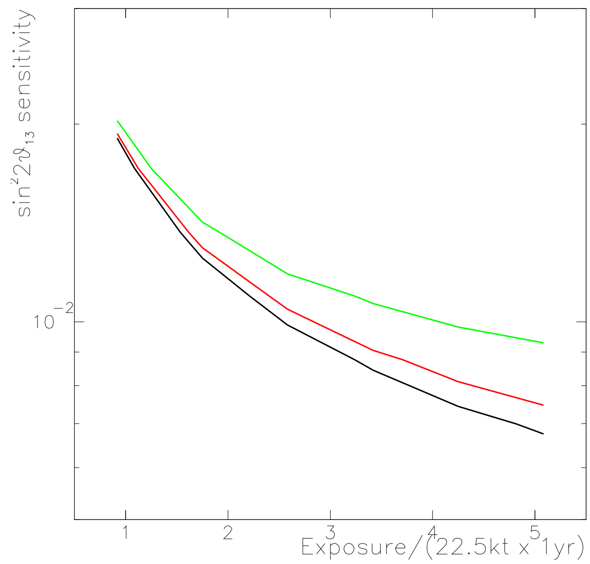


Figure 3.3: *The expected 90% CL and 3σ sensitivities for measuring* $\sin^2 2\theta_{13}$ *for uncertainties of 0% (bottom curve), 10% (middle curve), and 20% (top curve) in background subtraction.*

few GeV range. Because this is a neutral current process it is not possible to measure the incoming neutrino energy on an event by event basis, since the outgoing neutrino energy is unknown. This means that the higher energy neutrino beams of the K2K, MINOS, and MINERνA experiments do not allow these experiments to place useful constraints on the NCπ^0 rate that might be expected in T2K. The fact that these experiments measure the NCπ^0 rate at higher energies is of itself very interesting, however, as this allows the cross-section as a function energy to be mapped, as described in Sec. 4.2.

Since the neutrino spectrum in the MiniBooNE beamline is so well matched to that of T2K a measurement of the NCπ^0 production rate there is much more directly applicable to T2K. The difference between these two beams in the high energy tail does mean, however, that the NCπ^0 production rate in the MiniBooNE beamline will not be exactly the same as that in the T2K beam. Table 1.2 shows that about $\sim$3700 NCπ^0 events would be expected from 0.5×10^{20} POT with SciBar on-axis in the BNB and 100 m from the target. It is expected that a 10% uncertainty on the total rate can be reached. The same holds true for MiniBooNE, which has already about ten times the statistics than expected at SciBar/BNB. However, SciBar has one key advantage: it tends to be the high momentum π^0s that are most easily confused with electrons, but it is hard to identify a sample of these in a Cerenkov detector like MiniBooNE as it becomes harder to tell the two rings from one another, which is the same reason they are misIDed as electrons. SciBar has superior final state separation capabilities, and hence can distinguish the two EM showers from the π^0 decay for higher π^0 momenta (see the NCπ^0 candidate event in Figure 3.4). Thus SciBar will be able to make a better measurement of the NCπ^0 production rate at the critical highest π^0 momentum than is achievable at MiniBooNE.

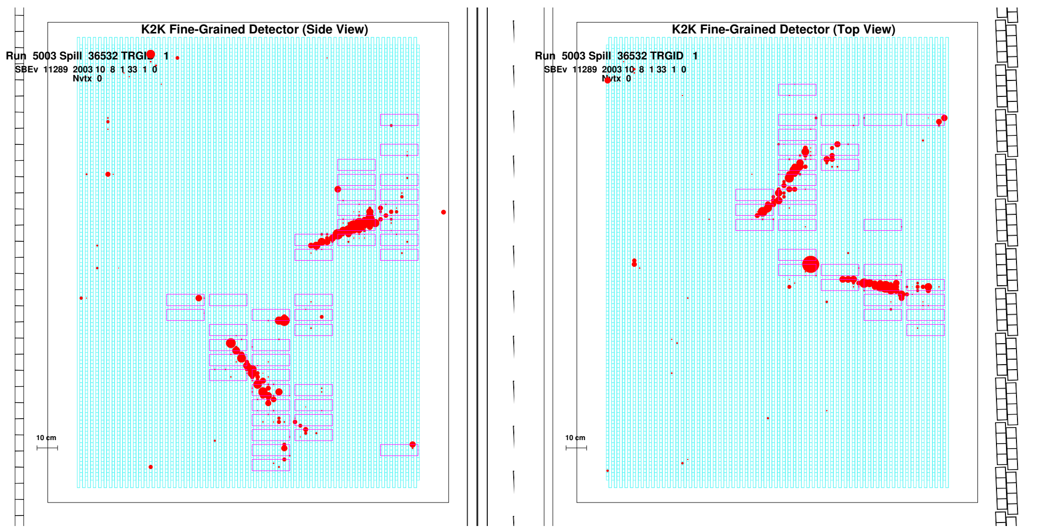


Figure 3.4: *SciBar event display of an NCπ^0 candidate from K2K data.*

The on-axis location A is, almost certainly, the best position for SciBar to measure NCπ^0 production as this location maximizes the rate. The off axis location B is intriguing, however, as its flux has a better match to the high energy tail of the T2K flux than the on-axis location A. NCπ^0 production comes largely from this tail and so, even though the mean energy is wrong at location B, it may prove to be a better location for inferring a T2K NCπ^0 production rate from SciBar/BNB. The hit in statistics from the farther off-axis locations C and D render them unusable for this measurement, the same holds true for location H.

3.3 Antineutrino Measurements

T2K is expected to run in neutrino mode for its first five years of operation. If there are indications of a finite θ_{13}, T2K will likely be upgraded, increasing to a 4 MW proton source and a much larger water Cerenkov detector (HyperK). With these upgrades the experiment would search for CP violation in the neutrino sector, requiring oscillation measurements of both neutrinos and antineutrino beams. It will therefore be critical to have good knowledge of antineutrino cross-sections at this stage.

The state of antineutrino cross-section knowledge in the $\sim$1 GeV energy range is very poor with only a handful of low statistics measurements [2]. If MiniBooNE runs in antineutrino mode in FY06, its primary goal will be to vastly improve this cross-section knowledge. There are a few ways in which SciBar can further improve these MiniBooNE measurements. The two channels of the previous two sections (CC1$\pi^{+}/-$ and NCπ^0) will be important backgrounds to the disappearance and appearance channels in antineutrino mode and the advantages of a SciBar measurement described in the previous two sections for neutrino mode will hold for antineutrino mode as well.

In addition, as was pointed out in Sec 2.1, SciBar can measure the spectrum of contaminant neutrinos in antineutrino mode in the BNB and thus improve an antineutrino CC QE cross-section made with MiniBooNE tank data. SciBar can also use its antineutrino CC QE events to measure this cross section. The statistics will be lower than the data from the MiniBooNE tank (assuming they have the same beam exposure), but this will be a systematics limited measurement (unless very finely binned) and SciBar can benefit from some cancellation of systematics by virtue of the fact that it measures both the antineutrino CC QE events and the neutrino CC QE contamination in the same detector.

SciBar/BNB antineutrino measurements will require $\sim 1.5 \times 10^{20}$ POT in antineutrino mode. These will provide healthy numbers for an antineutrino CC QE measurement and sufficient numbers for the CC1$\pi^{+}/-$ and NCπ^{0} measurements. This will also ensure that the separation of neutrino CC QE from antineutrino CC QE in antineutrino mode will be robust. In any of the other locations there will probably be insufficient statistics to make SciBar measurements superior to the ones that will be done using MiniBooNE neutrino mode tank data.

K2K never ran in antineutrino mode and, since the experiment has been terminated, will not in future. The NuMI beamline is capable of switching to antineutrino mode and so MINERνA and MINOS will probably make antineutrino measurements at some point in the future, but NuMI is a shared beamline and the needs of the oscillation measurements will likely come first. It is therefore unlikely that these experiments would be able to operate in antineutrino mode for several years. When they do they will be at higher energy which will provide an attractive complement to the lower energy SciBar and MiniBooNE measurements.

Chapter 4

SciBar Physics

The fine segmentation and multi-track reconstruction capabilities of the SciBar detector combined with the addition of an antineutrino beam exposure enable additional low energy cross section measurements that can not be performed elsewhere. Two such opportunities are described here.

4.1 Exclusive π-p Antineutrino Measurements

Both K2K and MiniBooNE will provide direct measurements of the inclusive neutrino NC $1\pi^0$ cross section at low energy. K2K has already published an 11% measurement of the NC $1\pi^0$/total CC ratio in their 1 kton water Cerenkov detector [14]. MiniBooNE is expected to have results soon from their neutrino mode running. However, what is lacking in Cerenkov-ring based detection is the ability to identify the final state nucleons in the event (most, if not all, of the nucleons are below Cerenkov threshold). Because of this, such detectors cannot provide separate measurements of the contributing resonant cross sections, and hence, cannot separate $\nu_\mu\, p \rightarrow \nu_\mu\, p\, \pi^0$ versus $\nu_\mu\, n \rightarrow \nu_\mu\, n\, \pi^0$ reactions.

K2K, with their currently collected near detector data, will make a separate measurement of the $\nu_\mu\, p \rightarrow \nu_\mu\, p\, \pi^0$ cross section in SciBar at their mean beam energy. This result will be further discussed in the next section. In contrast, MiniBooNE cannot measure such an exclusive final state, but has plans to measure the inclusive $\bar{\nu}_\mu$ $1\pi^0$ cross section in an antineutrino exposure [2]. This leaves the exclusive $\bar{\nu}_\mu\, p \rightarrow \bar{\nu}_\mu\, p\, \pi^0$ cross section unmeasured. Figure 4.1 shows the current available data on this particular reaction, a single measurement on aluminum at ~ 2 GeV appearing as a footnote in their publication [15].

SciBar/BNB expects $\sim 1,100$ $\bar{\nu}_\mu\, p \rightarrow \bar{\nu}_\mu\, p\, \pi^0$ interactions in antineutrino mode running for an on-axis detector location (Table 1.3). Using this sample, the experiment can make a 25% measurement of this exclusive channel. Such a measurement would be the first of its kind in the 1 GeV energy range (Figure 4.1).

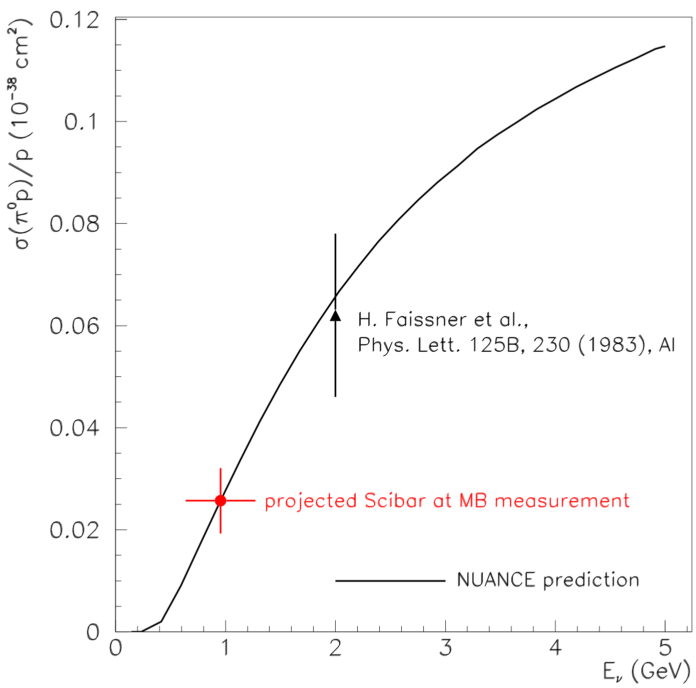


Figure 4.1: *Experimental measurement [15] of the per nucleon cross section for the antineutrino resonant reaction, $\bar{\nu}_\mu\, p \rightarrow \bar{\nu}_\mu\, p\, \pi^0$. Also plotted is the prediction from the NUANCE Monte Carlo [16] (which has not been corrected for an aluminum target). The expected measurement from SciBar/BNB, plotted at the Monte Carlo predicted central value, includes both statistical and systematic uncertainties.*

4.2 Energy Dependence of NC $1\pi^0$ Cross Section

Because of the uncollected energy carried away by the final state neutrino in NC interactions, experiments are forced to report flux-averaged NC $1\pi^0$ cross sections at a single energy point. Figure 4.2 shows two such published measurements that were both made near 2 GeV.

Given that future ν_e appearance experiments rely on precise knowledge of their NC $1\pi^0$ backgrounds at low energy, and given the sharp turn-on of this cross section in this energy region, one would like to have solid experimental confirmation of the energy dependence of the NC $1\pi^0$ cross section. SciBar can uniquely provide such a measure in combining a NC $1\pi^0$ cross section measurement made *in situ* in the higher energy KEK beam with a measurement made with the same detector in the Booster neutrino beamline at Fermilab. With the 850 $\nu_\mu\, p \rightarrow \nu_\mu\, p\, \pi^0$ events already collected with the SciBar detector at K2K, we estimate that a $\sim 15\%$ cross section measurement can be made at the higher energy point. With the expected sample of $\sim 1,900$ such interactions for the on-axis SciBar location at MiniBooNE (assuming 0.5×10^{20} POT), a 15% cross section measurement can be obtained at the lower energy point (Figure 4.2).

The dual measurements at 1.3 GeV and 800 MeV would provide the first mapping of this cross section in the region where it is varying most rapidly. Moreover, performing these measurements in the same detector, with the same reconstruction, systematics, and model assumptions, will provide an unprecedentedly powerful constraint. Additionally, such information could be combined with NC $1\pi^0$ cross section measurements made at higher energy using the LE (3 GeV), sME (7 GeV), and sHE (12 GeV) beam configurations at MINERνA [20] to completely map out the NC $1\pi^0$ cross section across the entire energy range.

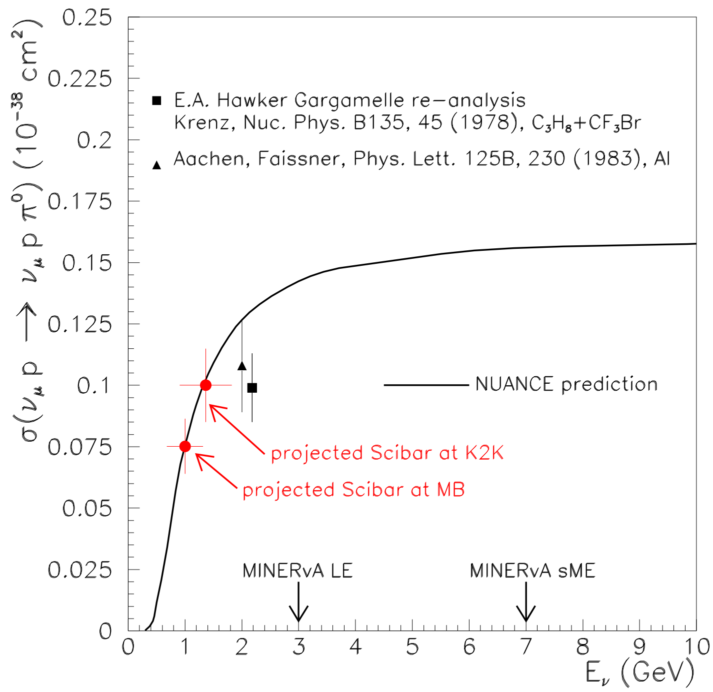


Figure 4.2: *Experimental measurements [15, 17] of the per nucleon cross section for the neutrino resonant reaction, $\nu_\mu\, p \rightarrow \nu_\mu\, p\, \pi^0$. Also plotted is the prediction from the NUANCE Monte Carlo [16] (which has not been corrected for either the aluminum or propane-freon target data). The projected measurements from SciBar at both K2K and the BNB, plotted at the Monte Carlo predicted central value, include both statistical and systematic uncertainties.*

It may be possible to further bin the SciBar NC cross section measurements in energy by fully reconstructing the final state proton and π^0 in the event. As an example, such a binned NC measurement has been reported in the past for the $\nu_\mu\, n \rightarrow \nu_\mu p\, \pi^-$ channel by a previous bubble chamber experiment at Argonne [22]. So while it may be possible to map out the energy dependence more finely than as presented in Figure 4.2, this requires further detailed study.

Chapter 5

Cost and Schedule

There is a window of opportunity to bring SciBar to Fermilab, but this window will only remain open as long as the BNB continues to operate. Fermilab's schedule closes the BNB by the end of 2006. A study carried out by Fermilab and KEK indicates that an operating SciBar could occupy the beam by April 1, 2006, providing a (possibly) nine month run. This requires a decision to commit funds and resources by July 1, 2005.

There are three sub-detectors in SciBar, described in Section 1.2. SciBar and the EC will be shipped from KEK, whereas the MRD can be easily assembled at Fermilab using materials from retired fixed-target experiments. The installation of an enclosure in the BNB, shipping and assembly of detectors at Fermilab, and construction and assembly of the MRD will take about nine months from July 2005 to April 2006.

The schedule depends on successfully decoupling the larger tasks, so that they can proceed in parallel. Reconstruction of SciBar and the EC will take place at the New Muon Lab. They will each be mounted on a platform, so that at completion they will be lifted onto a flatbed truck, and taken, fully constructed, to the detector enclosure for installation. SciBar weighs about 15 tons - the New Muon Lab has a 25 ton crane. Each subdetector will be mounted on a platform so that it can be brought by truck to the detector enclosure. The MRD will be built in two modules to assure that we keep the weight of each module below 15 tons. Placing the sub-detectors on the floor of the detector enclosure will require rental of a 100 Ton mobile crane for about one week.

The materials needed for the MRD have already been identified, and their assembly could be done before the arrival of the detector from KEK, so that technician and physicist time would be free for the assembly of SciBar and the EC.

If a decision to proceed is made by July 1, SciBar could arrive at Fermilab as early as the end of October. This allows four months for assembly of SciBar and the EC at Fermilab. The schedule is as follows:

1. July: KEK will prepare to disassemble the detector, making all of the arrangements to commit students and technicians to work on the project.

2. August: KEK will disassemble cables, front-end electronics, PMTs and fibers.

3. September: The scintillator in SciBar and the EC will be disassembled. Shipping should take approximately one month.

Installation at Fermilab will includes about two weeks to install the scintillator into the frame to reconstruct the SciBar detector. Then a month will to to connect the fibers, PMTs, and front-end electronics. At this point the detector can be tested with cosmic rays. After the detector is installed in the beam, about two weeks will be needed to connect cables, back-end electronics, and the DAQ system. These time estimates are based on experience from installation at K2K.

The critical path for occupancy in the beam will be the construction of the detector enclosure. A design study was carried out by FESS and PPD engineers to derive a cost estimate and schedule for the detector enclosure. These are given in Appendix A. The detector enclosure will be a vertical shaft, twenty feet deep. The shaft will be capped with a shed made of light materials and with a removable roof. Installation of the detectors will be done by a mobile crane - the detectors lowered through the roof onto the floor of the shaft. After the detectors are installed, a mezzanine will be placed a few feet above to provide room for electronics racks. Cables from the detector will run directly into the bottom of the relay-racks. One relay-rack will be required on the enclosure floor next to the SciBar detector. The Data Acquisition System will come from Japan; on-site data storage and analysis will be done with ENSTORE and MiniBooNE computing.

Two vertical ladders will provide access to the detector enclosure. The top ladder starts at grade and terminates at the mezzanine. The lower ladder leads from the mezzanine to the enclosure floor. The shaft will have minimal need for lighting and environmental controls, since most of the work associated with assembly of the detectors will be done in the New Muon lab. In four months of running at KEK, access to the detector was required only twice. Dehumidification will be needed only to keep the enclosure air below the dew-point. A gas fire protection system will be used to avoid any need to bring ICW water to the building. This is currently under review. Power will be brought in from the nearby MI12 service building as a 480 V service, using a small step-down transformer at the enclosure to convert to 120 V house power. A communication line will also be run between MI12 and the SciBar enclosure for telephone and Ethernet connections.

The construction of the beam enclosure requires about nine months; the design process takes about two months; two months are also required for the procurement process: placing an ad for an RFP, evaluating and selecting a bid, etc. The period of construction is about 4.5 months. See Appendix A for more details.

FESS has prepared a cost estimate for civil construction, which is given in Appendix A. The anticipated cost for the civil contract is about \$290,000. Engineering costs at (21% of contract price) would be about \$60,000. Contingency and overhead at nearly 50% add approximately \$160,000 to the total project cost.

The assembly of the detectors onto platforms, and installation into the detector enclosure will add ∼\$5,000 each for the four sub-detectors. Crane rental for a week is ∼\$5,000. A rigging crew may be needed for about one week. This adds up to ∼\$30,000 in Laboratory M&S.

KEK will be responsible for the cost to disassemble, package and ship the detector to Fermilab, and to return it to Japan. However, Fermilab may need to provide funds initially, and receive compensation from KEK after procurement of funding from the Japan-U.S. Research Fund in 2006.

Chapter 6

Conclusions

The marriage of K2K's fine-grained SciBar detector and the Booster Neutrino Beamline presents a unique, low risk, and low cost opportunity for low energy neutrino and antineutrino measurements that enhance the physics reach of MiniBooNE and are useful to the neutrino community at large. This effort complements the existing and future neutrino program at Fermilab, providing important input to MiniBooNE as well as crucial cross section measurements for off-axis neutrino programs, most especially T2K. This project utilizes a pre-existing detector and an operating beamline which are both well understood and have both demonstrated high quality performance.

However, the window of opportunity for this marriage is short. Because the beam is approved to run only through FY2006, and the detector is due back in Japan in 2008, we must act quickly to achieve these goals.

Appendix A

Civil Construction Documents

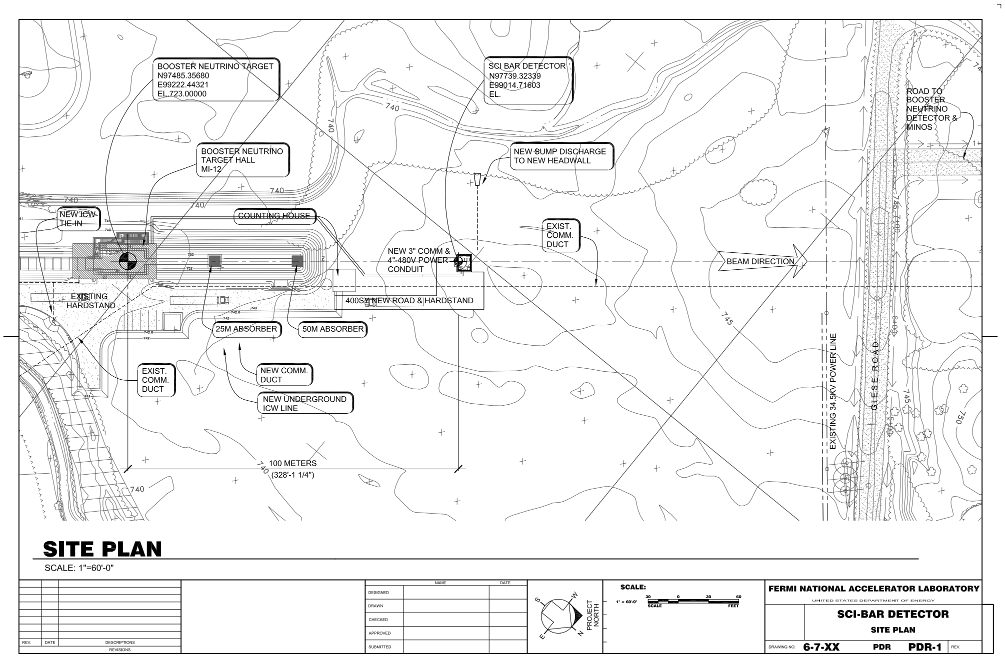


Figure A.1: *Site Drawing.*

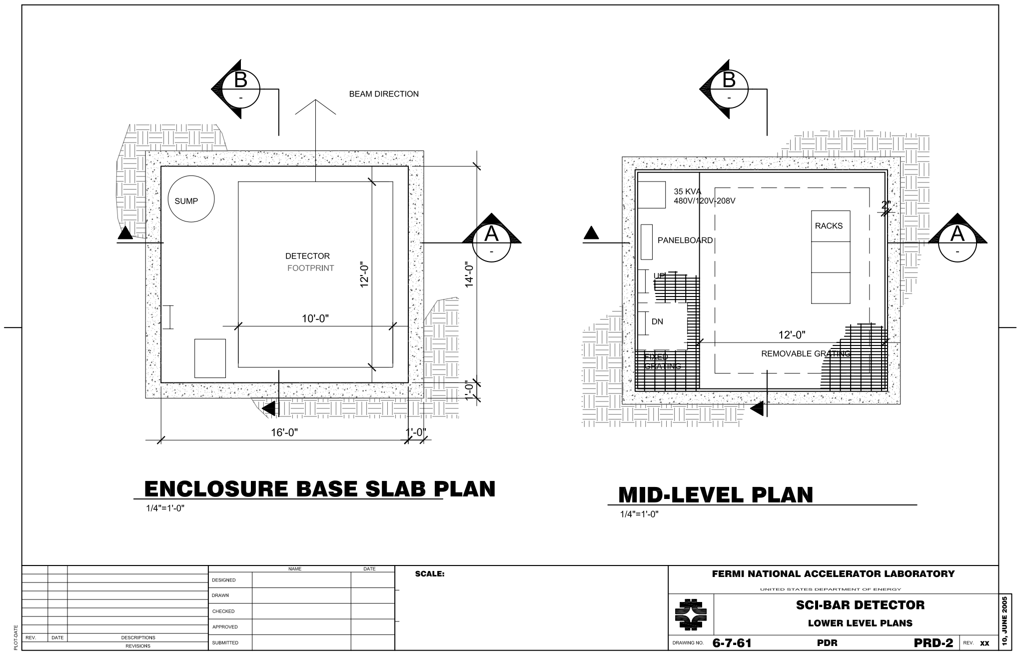


Figure A.2: *Sketch of the floor level of the enclosure.*

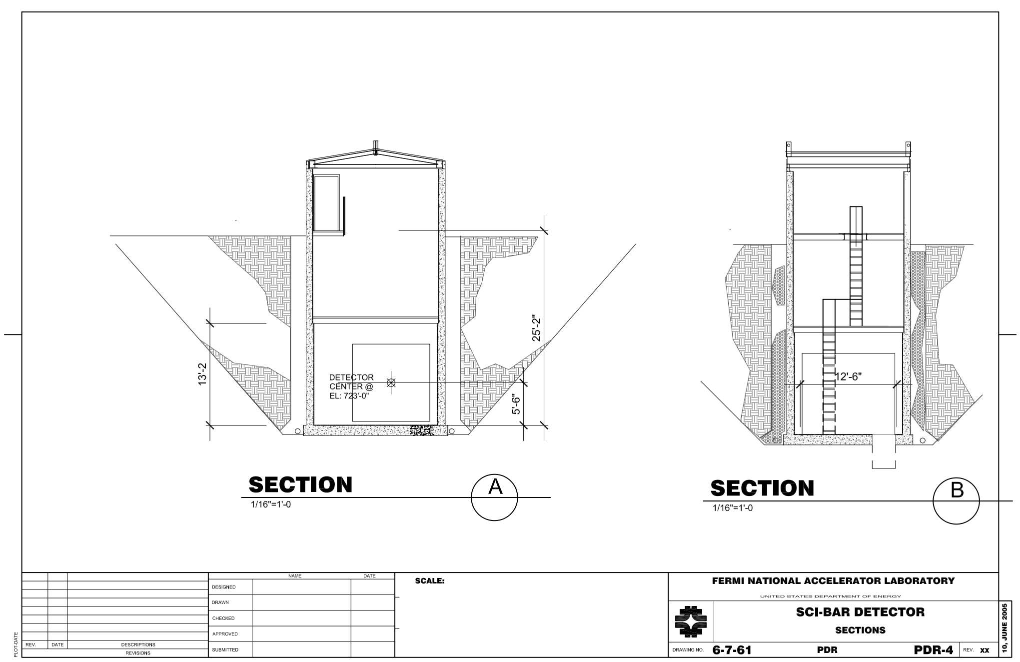


Figure A.3: *Views of the beam enclosure elevations.*

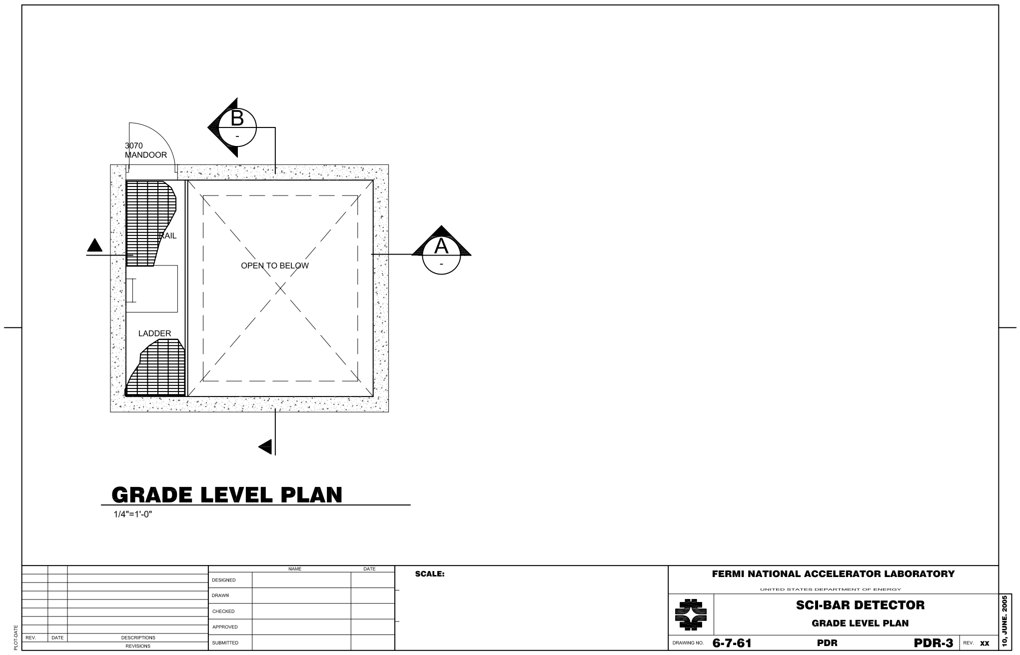


Figure A.4: *Plan view of the enclosure at grade level.*

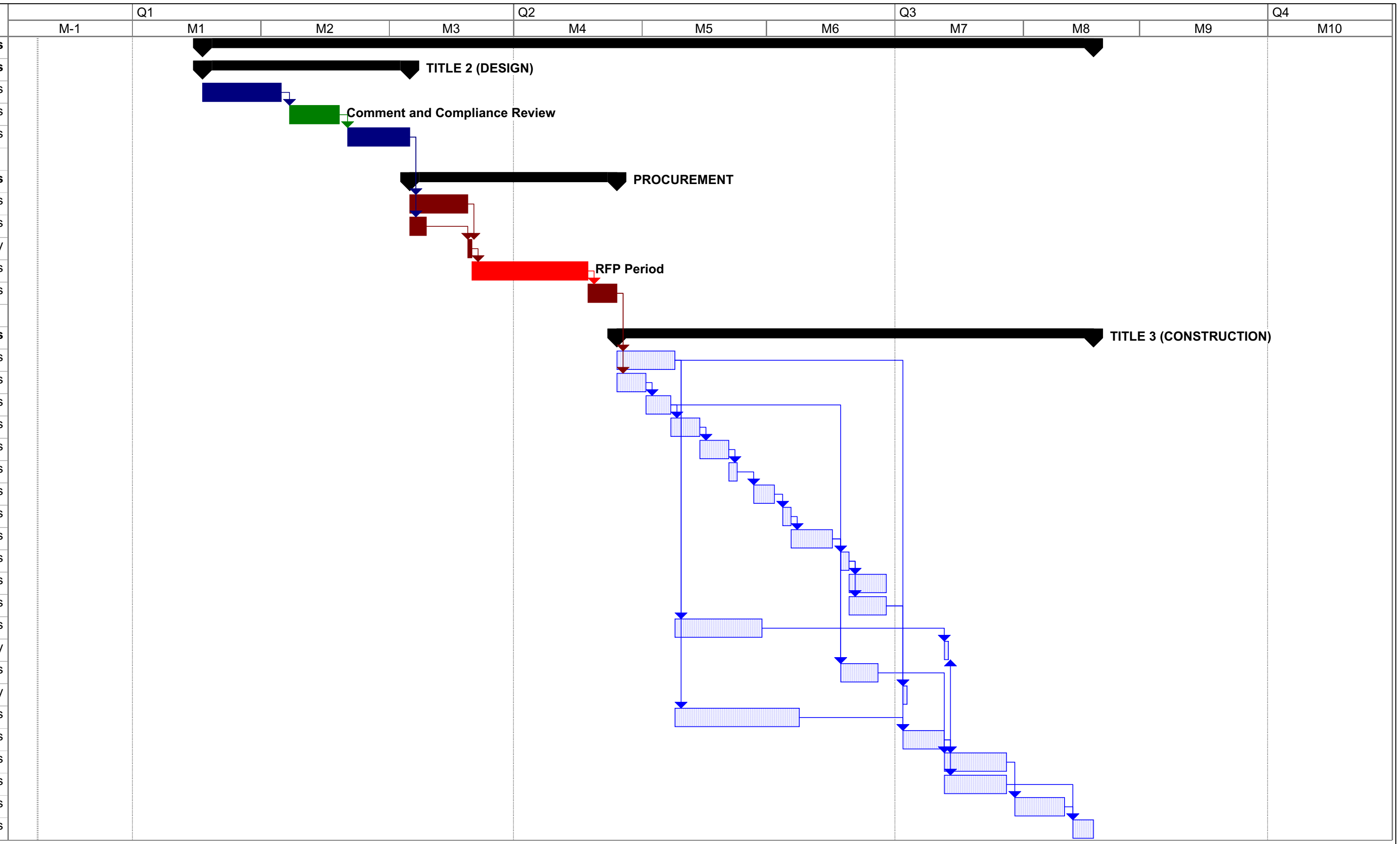
Project Title: SciBar Enclosure			Project No. 6 7 61	Status: Prel.	Date: 6/8/2005	Revision Date:
	DESCRIPTION OF WORK:		QUANITY	UNITS	UNIT PRICE	EXTENDED PRICE
01	**SITE CONSTRUCTION**	$75,250				
	Mobolize		1	Lot	$ 5,000.00	$5,000
	Soil Erosion Control		1	Lot	$ 5,000.00	$5,000
	Clear and Grub		0.11	Ac.	$ 5,000.00	$550
	Remove Topsoil		400	CY	$ 12.00	$4,800
	Stone Road & Hardstand		400	cy	$ 18.00	$7,200
	Excavate		1450	CY	$ 12.00	$17,400
	Backfil		1050	CY	$ 18.00	$18,900
	Haul excess materials		1300	CY	$ 6.00	$7,800
	2' Stone Along Wall		120	CY	$ 30.00	$3,600
	Final Seeding and Grading		1	Lot	$ 5,000.00	$5,000
	Concrete	$45,755				
	Mud Slab		3	CY	$ 200.00	$600
	Base Slab		16.2	CY	$ 300.00	$4,860
	Lower wall at 12"		31	CY	$ 500.00	$15,500
	Mid Tier Wall at 10"		23.6	CY	$ 500.00	$11,800
	Above Grade Walls		15.75	CY	$ 500.00	$7,875
	Increase for A Grade Exposed Forming		10	SF	$ 512.00	$5,120
						$0
	Steel	$24,047				
	Floor Framing		1.68	Ton	$ 3,900.00	$6,552
	Grating		280	SF	$ 26.50	$7,420
	Misc Framing		1	Lot	$ 2,000.00	$2,000
	Roof (Hatch) Framing		1.75	Ton	$ 3,900.00	$6,825
	Ladder		25	LF	$ 50.00	$1,250
	Doors and Moisture protection	$9,150				
	3' x 7' Man door		1	Ea.	$ 700.00	$700
	Metal Roofing		375	SF	$ 12.00	$4,500
	Semi Rigid Insul		1150	SF	$ 3.00	$3,450
	Misc Caulk and Sealants		1	Lot	$ 500.00	$500
	Finishes	$11,800				
	Painting Concrete		2100	SF	$ 3.00	$6,300
	Painting Steel		1	Lot	$ 1,500.00	$1,500
	Dampproofing		1600	SF	$ 2.50	$4,000
	Mechanical & Plumbing	$13,103				
	Sump Pump (Single sewage package system 1.5 HP		1	EA	$ 1,000.00	$1,000
	Install Sump Pump		1	Lot	$ 200.00	$200
	Underdrain Piping		70	LF	$ 9.00	$630
	PVC Discharge		40	LF	$ 20.24	$810
	Dehumidifier		1	EA	$ 3,775.00	$3,775
	Condensate Drain Piping		25	LF	$ 13.00	$325
	Unit Heater 5 KW		1	Ea	$ 550.00	$550
	AC unit		1	Ea	$ 5,113.00	$5,113
	Install AC Unit		1	Lot	$ 700.00	$700
	Fire Detection	$20,000				
	Fire Detection		1	Lot	$20,000.00	$20,000
	Electrical	$39,060				
	Trench Power & Comm from MI-12		350	LF	$ 30.00	$10,500
	3" Rigid from MI-12 Comm. & Firus		350	LF	$ 27.00	$9,450

Project Title: SciBar Enclosure	Project No. 6 7 61	Status: Prel.	Date: 6/8/2005	Revision Date:
DESCRIPTION OF WORK:	QUANITY	UNITS	UNIT PRICE	EXTENDED PRICE
3" Rigid from MI-12 Power	350	LF	$ 27.00	$9,450
Elec Cable	4	CLF	$ 220.00	$880
480V Power Disconects	3	Ea.	$ 795.00	$2,385
120/208V Panelboard (225 Amp)	1	Ea.	$ 400.00	$1,850
Transformer	1	Ea.	$ 3,645.00	$3,645
Utility Outlets	3	Ea.	$ 100.00	$300
Lights 4' Fluor.	3	Ea.	$ 100.00	$300
Exit Lights	1	Ea.	$ 100.00	$100
Emerg. Lights	2	Ea.	$ 100.00	$200

SciBar Enclosure	Project No. 6 7 61	Status: Prel.	Date: 6/8/2005	Revision Date:
Construction Contract				
Subtotal				$238,165
O&P @20 %				$47,633
Anticipated Contract Price				**$285,798**
Project Overheads				
EDIA @21%				$60,017
Subtotal				$345,815
Contingency and Management Reserve @25%				$86,454
Other Overhead (G&A)				$72,731
Plant Project Total				**$505,000**

Figure A.5: *Fully loaded cost estimate developed by Fermilab's FESS department.*

ID	Task Name	Duration
1	**SCiBAR**	**147 days**
2	**TITLE 2 (DESIGN)**	**35 days**
3	Design	15 days
4	Comment and Compliance Review	10 days
5	Complete Design	10 days
6		
7	**PROCUREMENT**	**36 days**
8	Start Req/Circulate for Signatures	10 days
9	Assemble Documents	4 days
10	Issue RFP	1 day
11	RFP Period	20 days
12	Issue NTP	5 days
13		
14	**TITLE 3 (CONSTRUCTION)**	**76 days**
15	Shop Drawings	10 days
16	Mobilize	5 days
17	Excavation	4 days
18	Base Slab	5 days
19	Lower Wall F/B/P	5 days
20	Lower Wall Strip Forms	2 days
21	Mid Wall F/B/P	5 days
22	Mid Wall Strip Forms	2 days
23	Upper Wall F/B/P	8 days
24	Upper Wall Strip Forms	2 days
25	Underdrains/Backfill	5 days
26	Paint Walls	5 days
27	Fabricate Roof	13 days
28	Install Roof	1 day
29	Install Electrical/Comm from MI-12	5 days
30	Install Door	1 day
31	Fabricate Platforms and Ladders	20 days
32	Install Platforms/Ladders	8 days
33	Electrical	10 days
34	Mechancial	10 days
35	Fire Detection	10 days
36	Testing/Trim Out	5 days



41

Project: SciBar
Date: Wed 6/8/05

Task		Progress		Summary		External Tasks		Deadline
Split		Milestone		Project Summary		External Milestone		

Bibliography

[1] "The Neutrino Matrix," Report from the APS DNP/DPF/DPB Joint Study on the Future of Neutrino Physics, available from http://www.aps.org/neutrino.

[2] MiniBooNE Collaboration, *"Addendum to the MiniBooNE Run Plan: MiniBooNE Physics in 2006,"* available from http://www-boone.fnal.gov/publicpages/loi.ps.gz.

[3] MiniBooNE Collaboration, *"The MiniBooNE Run Plan"* available from http://www-boone.fnal.gov/publicpages/runplan.ps.gz

[4] K. Nitta *et al.*, Nucl. Instrum. Meth. A **535**, 147 (2004).

[5] M. Yoshida *et al.*, IEEE Trans. Nucl. Sci. **51**, 3043 (2004).

[6] S. Buontempo *et al.*, Nucl. Phys. Proc. Suppl. **54B**, 198 (1997).

[7] T. Ishii *et al.*, Nucl. Instrum. Meth. A **482**, 244 (2002).

[8] H. Maesaka, Ph. D. thesis, Kyoto University (2005).

[9] Y. Hayato, Nucl. Phys. Proc. Suppl. **112**, 171 (2002).

[10] A. Aguilar *et al.*, Phys. Rev. D **64**, 112007 (2001).

[11] K. Nishikawa *et al.* (T2K Collaboration), "Letter of Intent for a Neutrino Oscillation Experiment at JHF", KEK Report (2003), http://neutrino.kek.jp/jhfnu.

[12] http://jkj.tokai.jaeri.go.jp.

[13] Y. Fukuda *et al.* (Super-Kamiokande Collaboration), Nucl. Instrum. Meth. **A501**, 418 (2003).

[14] S. Nakayama *et al.*, *hep-ex/0408134*, submitted to Phys. Lett. B.

[15] H. Faissner *et al.*, Phys. Lett. **125B**, 230 (1983).

[16] D. Casper, Nucl. Phys. Proc. Suppl. **112**, 161 (2002).

[17] E. A. Hawker, NuInt02 proceedings, to be published in Nucl. Phys. Proc. Suppl.

[18] L. Bugel *et al.*, FINeSSE proposal, *hep-ex/0402007*.

[19] J. Monroe, Proceedings of the 39th Recontres du Moriond on Electroweak Interactions and Unified Theories, *hep-ex/0406048*.

[20] D. Drakoulakos *et al.*, MINERvA proposal, *hep-ex/0405002*.

[21] M. Hasegawa *et al.*, "Search for Coherent Charged Pion Production in Neutrino-CArbon Interactions", *hep-ex/0506008*.

[22] M. Derrick *et al.*, Phys. Lett. **B92**, 363 (1980).