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THE LSND SIGNAL: PAST, PRESENT AND FUTURE

Ion Stancu – for the MiniBooNE collaboration [1)]
University of Alabama, Tuscaloosa, AL 35487, USA

ABSTRACT

The MiniBooNE experiment at Fermilab has been designed to confirm or dismiss the LSND observation by looking for ν_e appearance in a ν_μ beam. The experiment began taking beam data in September 2002. Here we describe the experiment, the first neutrino candidate events, and our expected sensitivity to a neutrino oscillation signal.

1 Introduction

Neutrino oscillations appear to be a widely-accepted phenomenon which successfully explains the solar electron neutrino deficit, as well as the atmospheric muon neutrino deficit. Moreover, the same deficits have been observed in artificial neutrino sources, as reported by the KamLAND [2)] and K2K [3)] experiments, respectively. The mass squared differences involved in these phenomena are $\Delta m^2_{sol} \approx 7 \times 10^{-5}\,\mathrm{eV}^2/\mathrm{c}^4$ and $\Delta m^2_{atm} \approx 3 \times 10^{-3}\,\mathrm{eV}^2/\mathrm{c}^4$, while the corresponding mixing angles appear to be nearly maximal. In addition, the LSND experiment, which ran at the Los Alamos National Laboratory from August 1993 until December 1998, has also reported evidence for neutrino oscillations in two channels: the decay-at-rest channel $\bar{\nu}_\mu \to \bar{\nu}_e$, and the decay-in-flight channel $\nu_\mu \to \nu_e$. The LSND final result [4], combining all the data, yielded an excess of $87.9 \pm 22.4 \pm 6.0$ events after background subtraction, which corresponds to an oscillation probability of $(0.264 \pm 0.067 \pm 0.045)\%$. The allowed values in the $(\sin^2 2\theta, \Delta m^2)$ parameter space corresponding to this result are shown in Figure 1. Also shown are the 90% confidence level excluded regions

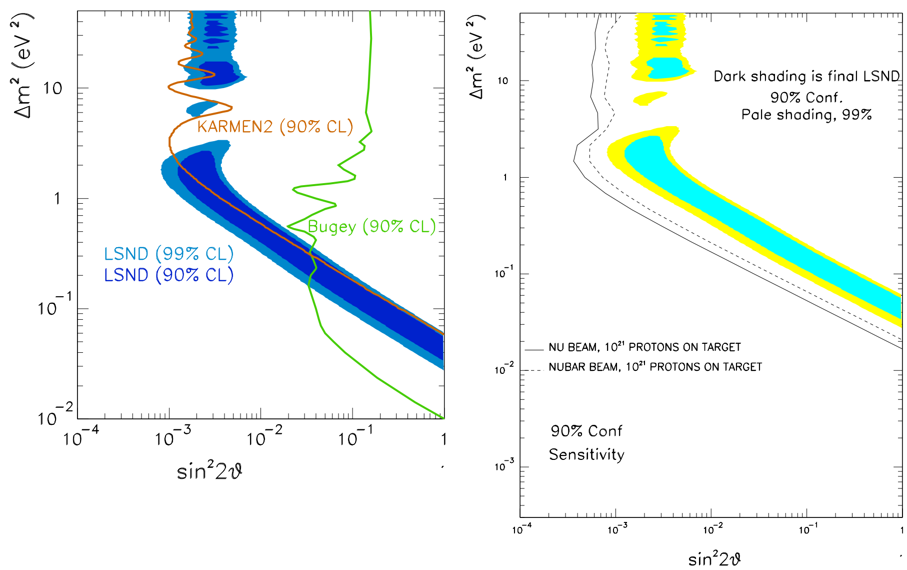

Figure 1: *LSND allowed regions in the* $(\sin^2 2\theta, \Delta m^2)$ *parameter space and MiniBooNE expected oscillation sensitivity after 2 years of running.*

for the Bugey [5] and KARMEN [6] experiments. Despite the fact that the KARMEN data appears to exclude a significant fraction of the LSND-favoured region, a combined analysis of the two data sets showed that practically this entire region is compatible with both experiments at the 90% confidence level [7].

The Booster Neutrino Experiment (BooNE) at Fermilab is a natural follow-up to the LSND experiment, and has been designed to confirm or dismiss the evidence for neutrino oscillations reported by the Los Alamos measurement. The first phase of the project, a single detector known as MiniBooNE (E–898), has become fully operational in September 2002. The experiment has two initial goals: (i) extend the sensitivity for $\nu_\mu \to \nu_e$ oscillations by one order of magnitude in Δm^2 over previous searches; (ii) obtain several hundreds of events per year if the LSND signals are indeed due to neutrino oscillations. Moreover, should neutrino oscillations be observed, MiniBooNE can test for CP violation in the lepton sector by switching to an antineutrino ($\bar{\nu}_\mu$) beam, while the full BooNE project would add a second detector, at a distance dictated by the data themselves, and carefully parameterize the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ mixings.

2 The Neutrino Beam

The MiniBooNE neutrino beam is initiated by a primary beam of 8 GeV protons from the Fermilab Booster accelerator incident on a 71-cm-long Be target within a magnetic horn focusing system, followed by a 50-m-long pion decay volume. The proton beam is delivered to the experiment at a rate of up to 5 Hz and an intensity of approximately 5×10^{12} per spill. Each spill is made up of 84 buckets of beam every 18.8 ns for a total duration of 1.6 μs – which allows for a very low cosmic-ray background in the detector. The Booster can reliably deliver protons for about two thirds of a calendar year, which allows the experiment to receive up to 5×10^{20} protons on target (POT) per year.

The magnetic horn focuses secondary pions and kaons from the primary interactions. It operates at a current of 170 kA for a pulse duration of 140 μs, producing a toroidal magnetic field that focuses π^+ and defocuses π^- (or vice-versa). Therefore, a fairly pure ν_μ or $\bar{\nu}_\mu$ beam can be produced, depending on the horn polarity. Figure 2 shows the shape of the expected neutrino fluxes at the location of the detector.

The neutrino flux at the detector will be determined using a variety of methods. Detailed simulations of the neutrino production processes have been performed and are ongoing. These simulations have been tuned using existing hadron production data, and will be complemented by data from the HARP experiment [8] at CERN – which ran with the MiniBooNE Be target. A measurement of the ν_μ charged-current rate in the detector will check the ν_μ flux, as well as determine the energy distribution of the muons in the decay region – which contribute to the intrinsic ν_e background via $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$. The ν_e

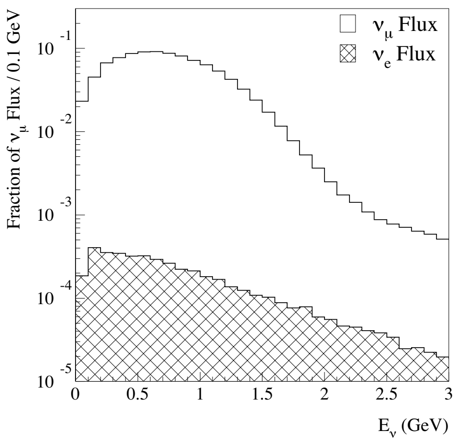

Figure 2: *Calculated MiniBooNE neutrino fluxes at the location of the detector.*

background from $K^+ \to \pi^0 e^+ \nu_e$ decays will be determined by measuring the high-transverse-momentum muons from $K^+ \to \mu^+ \nu_\mu$ decays.

3 The Detector

The MiniBooNE detector is located 500 meters from the neutrino source. It consists of a spherical tank of radius 6.1 m, lined with 1280 8-inch photomultiplier tubes (PMTs) supported on an inner structure of 5.75 m radius. These PMTs point inward and provide 10% photocathode surface coverage. The PMT support structure also provides an optical barrier to create an outer veto region, viewed by 240 8-inch PMTs. The tank is filled with 800 tons of mineral oil, which provides an inner fiducial region of about 500 tons.

The MiniBooNE mineral oil (Exxon/Mobil Marcol 7) has an attenuation length of approximately 26 meters at 450 nm, a density of 0.836 g/cm^3 and an index of refraction of 1.46. This oil produces some scintillation light, so both prompt Čerenkov and delayed scintillation light will be produced for particles with $\beta > 0.68$. The total amount of light provides a good energy measurement for particles above and below the Čerenkov threshold.

A circular room located above the tank vault houses the electronics, data acquisition (DAQ), oil circulation, and calibration systems. The entire structure is covered with a mound of earth to provide some cosmic-ray shielding. Each PMT is attached to one Teflon-jacketed cable which provides the high voltage (HV) and returns the signal as well. The PMT cables are routed out of the tank into the DAQ system, where the signal is picked off the HV cable, amplified, and digitized. The DAQ hardware consists of custom-built cards in 13 VME crates which are read out via MVME2304 single-board computers (SBC). The data is zero suppressed by the SBCs and shipped via ethernet to a single Intel-based computer running Linux. This computer assembles the data and ships it to the Fermilab computer center where it is written to tape.

The trigger consists of an additional VME crate housing custom-built cards that collect PMT multiplicity and beam information to form event triggers. The primary trigger is a "beam-on-target" signal from the accelerator, which initiates a data readout in a $20\,\mu$s window around the $1.6\ \mu$s beam spill (regardless of PMT multiplicity). The DAQ hardware and software have sufficient data buffering capabilities to create a virtually dead-time-free system.

Calibration for the detector is obtained through three different systems. A pulsed laser provides light to four different light-scattering flasks hanging in the inner region of the tank. This light is used to determine the time and gain calibrations of each of the inner PMTs. An array of seven scintillator cubes hanging in the main region of the tank are used to tag a sample of stopping muons in the tank which allows energy calibration with muon tracks of known length. A muon tracker system consisting of 2 horizontal planes of scintillator is installed above the tank. The tracker allows muons of a well-known direction to be tagged and studied for direction calibration. In addition to these systems, the ubiquitous cosmic-ray muons provide a constant source of data with which to study and calibrate the detector. In particular, the stopped cosmic-ray muons provide, through their subsequent decays, an invaluable source of electrons as cross-checks of the Monte Carlo (MC) simulations, energy scale measure, and energy resolution. Preliminary studies indicate an electron energy resolution of 14% at the Michel electron endpoint energy (52.8 MeV).

4 The MiniBooNE Neutrino Oscillations Search

The $\nu_\mu \to \nu_e$ oscillation search will be conducted by measuring the event rate for the ν_e induced reaction, $\nu_e C \to e^- X$, and comparing to the rate expected from background processes. If the LSND result is indeed due to neutrino oscillations, approximately 1000 ν_e-induced events are expected due to $\nu_\mu \to \nu_e$ oscillations in two calendar years of running (10^{21} POT). The three main backgrounds to this search are: the intrinsic ν_e background in the beam from μ and K decay in the decay pipe, mis-identification of μ events ($\nu_\mu C \to \mu^- X$), and mis-identification of π^0 events ($\nu_\mu C \to \nu_\mu \pi^0 X$). The number of events for signal and backgrounds are listed in Table 1. These backgrounds will be

Table 1: *Estimated number of neutrino oscillation signal and background events after 2 years of data taking with neutrinos (10^{21} POT). Also shown are the number of events from other neutrino reactions in MiniBooNE.*

Process	Reaction	Number of events
LSND-based $\nu_\mu \to \nu_e$ signal	$\nu_e C \to e^- X$	1000
Intrinsic ν_e background	$\nu_e C \to e^- X$	1500
Mis-ID μ^- background	$\nu_\mu C \to \mu^- X$	500
Mis-ID π^0 background	$\nu_\mu C \to \nu_\mu \pi^0 X$	500
$\nu_\mu C$ charged-current scattering	$\nu_\mu C \to \mu^- X$	500,000
$\nu_\mu C$ neutral-current π^0 production	$\nu_\mu C \to \nu_\mu \pi^0 X$	50,000
$\nu_\mu e$ elastic scattering	$\nu_\mu e \to \nu_\mu e$	100

measured. As described in Section 2, the number of events from intrinsic ν_e that are produced from μ^+ decays in the target region will be determined from ν_μ charged-current scattering in the detector. Also, the number of intrinsic ν_e from K^+ decays will be determined from the μ detected with the off-axis LMC spectrometer. The number of μ^- and π^0 events mis-identified as e^- events will be measured via the large number of correctly identified $\nu_\mu C \to \mu^- X$ and $\nu_\mu C \to \nu_\mu \pi^0 X$ events, respectively.

5 Preliminary Data

The MiniBooNE detector and beam have been fully operational for over a year and a half now, and data taking has been proceeding very smoothly. The detector has been calibrated with laser calibration events, the energy scale and resolution have been determined from cosmic-ray muons and Michel electrons, and approximately 180,000 clean neutrino events have been recorded with 2.7×10^{20} POT. Figure 3 below illustrates the simple selection criteria which reduce the beam off backgrounds to a 10^{-3} level: a veto shield multiplicity cut $N_{veto} < 6$ eliminates the cosmic-ray muons, while a tank multiplicity cut $N_{tank} > 200$ eliminates the Michel electrons from the decay of the stopped cosmic-ray muons. The beam pulse width of about $1.6\,\mu$s is in clearly seen.

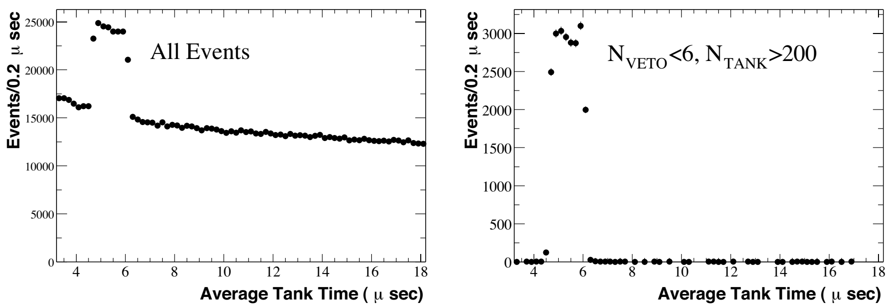

Figure 3: *MiniBooNE event distribution in and around the beam window before and after the simple selection criteria which reduce the beam off background.*

The ν_e appearance search will be a blind analysis. Consequently, despite the fact that MiniBooNE can clearly identify the beam-induced events, one is allowed to either look at all information for some events or some information for all events, but not all information for all events. Meanwhile, in parallel to continuing understanding the detector response and tuning the MC simulations, the experiment is concentrating on other physics analyses which are not only interesting in their own right, but they are also necessary for the $\nu_\mu \to \nu_e$ oscillations analysis: they will check the data/MC agreement, the reliability of the reconstruction and particle-identification algorithms, and provide understanding of the beam-induced backgrounds.

MiniBooNE is clearly identifying charged-current quasi-elastic $\nu_\mu C \to \mu X$ events. These events have a relatively high abundance (about 40%), a simple topology, and can be identified with a relatively high efficiency and purity (of approximately 30% and 90%, respectively). The muons are forward peaked along the incident neutrino beam direction, as clearly seen in Fig. 4 below. The predicted MC distribution is shown superimposed in the same figure, with our current (conservative) estimates for the error bars; they include errors in the neutrino fluxes, cross sections and optical parameters of the detector medium. Both distributions have been normalized to unit area. The visible energy distribution is also in good agreement with the MC expectations, as illustrated in the same figure.

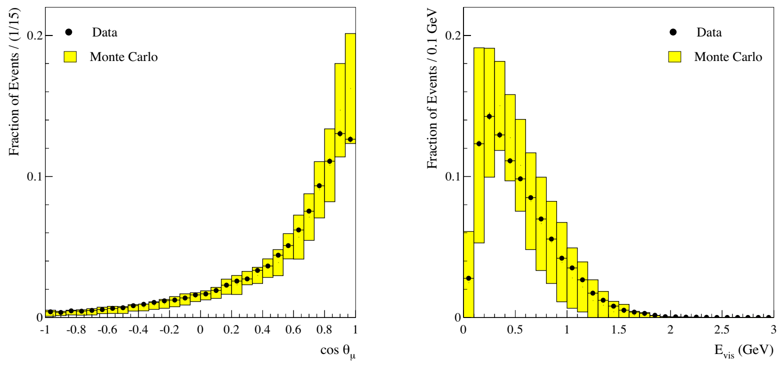

Figure 4: *MiniBooNE reconstructed event direction with respect to the incident neutrino beam and visible (electron-equivalent) energy distributions for $\nu_\mu C$ charged-current quasi-elastic events.*

From a simple kinematic reconstruction one can use the reconstructed muon energy and direction to calculate the incident neutrino energy and also the momentum transfer. These quantities are shown in Fig. 5 below, along with the MC predictions with a relative normalization. The lower-than-predicted

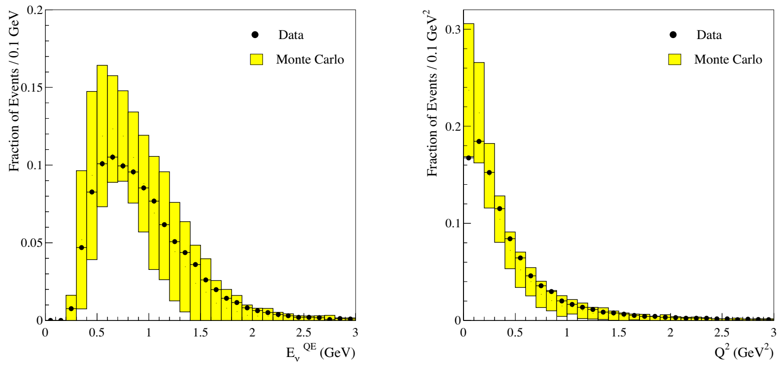

Figure 5: *MiniBooNE reconstructed incident neutrino energy and Q^2 distributions for $\nu_\mu C$ charged-current quasi-elastic events.*

data values at low Q^2 are currently under investigation and can be influenced by a variety of factors, such as nuclear effects, nuclear form factors, etc. This effect is also related to the lower-than-predicted number of events in the most forward direction (first bin in the $\cos\theta_\mu$ distribution of Fig. 4).

MiniBooNE is also clearly identifying and reconstructing neutral current π^0 events from either coherent production $\nu_\mu C \to \nu_\mu \pi^0 X$, or resonant production $\nu_\mu(p/n) \to \nu_\mu \Delta$ and the subsequent Δ decay. These events have a characteristic two ring topology (from the $\pi^0 \to \gamma\gamma$ decay), and the invariant π^0 is reconstructed from the reconstructed energies of the two photons, E_1 and E_2, and their relative angle, θ_{12}: $m_\pi^2 = 2E_1E_2(1 - \cos\theta_{12})$. The distribution of the reconstructed invariant mass is shown in Fig. 6 below, which yields a mass resolution of about 21 MeV. The events contributing to this sample have

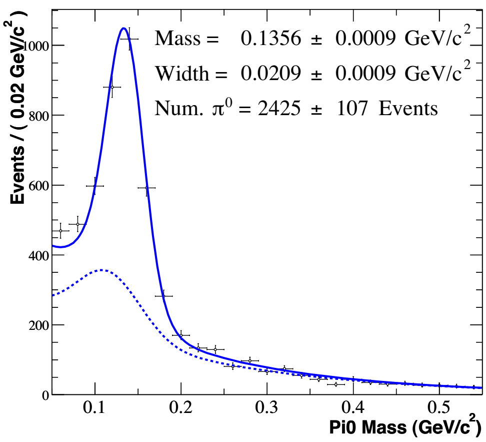

Figure 6: *MiniBooNE reconstructed π^0 mass distribution. The dashed curve denotes the expected background from MC simulations, which is also peaked.*

the standard $N_{veto} < 6$ and $N_{tank} > 200$ selection criteria applied, the event vertex must reconstruct at least 50 cm away from the surface of the PMTs, and each ring must have at least an electron-equivalent energy of 40 MeV.

6 Conclusions

The MiniBooNE detector and beam line have been operating smoothly for over a year and a half now and we are in the process of analyzing different physics channels, while continuously improving our understanding of the detector response and MC simulations. Despite the fact that the total number of protons on target is a factor of 2.5 below the original design intensity, we are convinced that continuing modifications and improvements to the Fermilab Booster will bring the neutrino beam to the required levels in the near future.

The current plan is to run in the ν_μ mode until MiniBooNE collects 5×10^{20} protons on target, with the possibility of changing to the $\bar{\nu}_\mu$ mode afterwards and also 25 m absorber running. The future MiniBooNE schedule is dependent on the number of protons delivered per year to the experiment. First oscillations results are expected by 2005, and if the LSND signal is confirmed, an initial determination of the oscillation parameters can be made. A second detector (BooNE) will then be built at a different distance in order to obtain the highest precision measurement of the oscillation parameters. The neutrino flux goes as r^{-2} to very good approximation, so that a simple ratio of events in the two detectors as a function of energy will cancel most of the systematic uncertainties and will allow Δm^2 to be measured to about $\pm 0.02\,\mathrm{eV}^2/\mathrm{c}^4$.

References

1. The BooNE collaboration consists of the following institutions: University of Alabama, Bucknell University, University of Cincinnati, University of Colorado, Columbia University, Embry Riddle Aeronautical University, Fermi National Accelerator Laboratory, Indiana University, Los Alamos National Laboratory, Louisiana State University, University of Michigan and Princeton University.
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