Search for Muon Neutrino Disappearance in a Short-Baseline Accelerator Neutrino Beam
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Abstract
We report a search for muon neutrino disappearance in the $\Delta m^2$ region of $0.5 - 40$ eV$^2$ using data from both SciBooNE and MiniBooNE experiments. SciBooNE data provides a constraint on the neutrino flux, so that the sensitivity to $\nu_\mu$ disappearance with both detectors is better than with just MiniBooNE alone. The preliminary sensitivity for a joint $\nu_\mu$ disappearance search is presented.

1. Introduction
Neutrino oscillations have been observed and confirmed at mass splitting ($\Delta m^2 > 10^{-3}$ eV$^2$) and $\sim 10^{-3}$ eV$^2$, called the “solar” and “atmospheric” regions, respectively. The observed mixing is consistent with three generations of neutrinos. However, the LSND experiment observed an excess of $\tau_e$ in a $\nu_\tau$ beam, indicating a possible oscillation in the $\Delta m^2 \sim 1$ eV$^2$ region [1]. To explain LSND with oscillations requires more than three generations of neutrinos or other exotic physics beyond the Standard Model.

To test the oscillation at $\Delta m^2 \sim 1$ eV$^2$, the MiniBooNE experiment recently made searches for both $\nu_e$ appearance [2, 3] and $\nu_\mu$ disappearance [4] in this parameter region. The experiment observed no significant $\nu_e$ appearance signal and ruled out as being due to 2-neutrino oscillations. However, the sensitivity of MiniBooNE-only $\nu_\mu$ disappearance search was limited by the large flux and neutrino interaction cross-section uncertainties.

Here, we discuss an improved search for $\nu_\mu$ disappearance using data from both the SciBooNE [5] and the MiniBooNE experiments, where SciBooNE detector is used to constrain flux and cross-section uncertainties.

2. Experimental Setup
2.1. Fermilab Booster Neutrino Beam

The experiments use the Booster Neutrino Beam (BNB) at Fermilab [6]. The primary proton beam, extracted with a kinetic energy of 8 GeV, strikes a 71 cm long, 1 cm diameter beryllium target. The mesons, primarily $\pi^+$, generated by the $p$–Be interactions are focused with a magnetic horn and decay in the following 50 m decay volume, producing an intense neutrino beam with the peak energy of $\sim 0.7$ GeV. When the horn polarity is reversed, $\pi^-$ are focused and hence a predominantly antineutrino beam is created.

2.2. SciBooNE Detector
The SciBooNE detector [5] is located 100 m downstream from the beryllium target. The detector complex consists of three sub-detectors: a fully active fine grained scintillator tracking detector (SciBar), an electromagnetic calorimeter (EC) and a muon range detector (MRD).

The SciBar detector consists of 14,336 extruded plastic scintillator strips (CH), each with dimension of 1.3 x 2.5 x 300 cm$^3$. The scintillators are arranged vertically and horizontally to construct a $3 \times 3 \times 1.7$ m$^3$ detector. The detector itself is the neutrino target and its fiducial volume is 10.6 tons.

The EC is installed downstream of the SciBar, and is made of scintillating fibers embedded in lead foil. The MRD is located downstream of the EC in order to measure the momentum of muons up to 1.2 GeV/c using the muon range. It consists of 12 layers of 2”-thick iron plates sandwiched between layers of 6 mm-thick plastic scintillator planes.

The SciBooNE experiment ran from June 2007 until August 2008, collecting a total of $2.52 \times 10^{20}$ Protons on Target (POT) for physics analysis; $0.99 \times 10^{20}$ POT in neutrino mode and $1.53 \times 10^{20}$ POT in antineutrino mode.

2.3. MiniBooNE Detector
The MiniBooNE detector [7] is located 440 m downstream from the SciBooNE detector. The detector is a 12 m diameter spherical tank filled with 800 tons of mineral oil (CH$_2$). The MiniBooNE experiment has been taking beam data since 2002, including the SciBooNE and MiniBooNE joint-run period. The collected number of POT after data quality cut in the neutrino mode is $5.579 \times 10^{20}$ in addition to the data from the joint-run period.

3. $\nu_\mu$ Disappearance Analysis
3.1. Analysis Overview
In this paper, we report only the neutrino data ($\nu_\mu \rightarrow \nu_e$) disappearance analysis. We search for muon neutrino disappearance by comparing neutrino fluxes at SciBooNE and MiniBooNE detectors.

The analysis is performed in the following three steps: (1) Neutrino flux measurement at SciBooNE, (2) Flux extrapolation to MiniBooNE, and (3) Oscillation fit.

At each step, systematic errors are estimated and propagated to the final prediction. The majority of the flux and cross-section uncertainties cancels since the neutrino interaction target in both detectors is effectively carbon, and the two detectors are on the same beam line.

We describe these steps in detail in the following sections.
3.2. Neutrino Flux Measurement at SciBooNE

Charged Current Event Selection

For the spectrum analysis at SciBooNE, we use inclusive $\nu_\mu$ charged current (CC) interactions, whose signature is long muon tracks. First, we identify muons by selecting the longest track with energy deposit consistent with a minimum-ionizing particle. Second, we require the vertex of the track to be within the SciBar fiducial volume. The events are further divided into two subsamples based on the location of the muon track end points: a “SciBar-stopped” sample containing muons that have stopped inside the SciBar detector and a “MRD-stopped” sample with muons that have stopped in the MRD. These two samples each contain approximately 14k and 20k events with mean energies of 0.8 and 1.1 GeV, respectively.

Spectrum Fitting

The neutrino spectrum at SciBooNE is extracted by fitting muon momentum ($P_\mu$) and muon angle ($\theta_\mu$) distributions from each sample.

We prepare MC templates for $P_\mu$ and $\theta_\mu$ distributions for several true neutrino energy ($E_\nu$) regions. The $E_\nu$ regions are divided by 250 MeV up to 1.25 GeV, and a single region is assigned for $E_\nu > 1.25$ GeV. Then, the scale factors for each $E_\nu$ region are determined to minimize the $\chi^2$ between data and MC. Figure 2. shows the fit result. The systematic errors from SciBooNE detector response and neutrino cross-section models are estimated and shown in the plot.

Figure 3. is the $P_\mu$ and $\theta_\mu$ distributions of SciBooNE’s MRD-stopped sample, after applying scale factors obtained by the spectrum fitting. We confirm the MC distributions agree well to data after fitting.

3.3. Flux Extrapolation to MiniBooNE

MiniBooNE Event Selection

We select events in MiniBooNE by requiring single muon and its decay electron. Neutrino energy is reconstructed from muon kinematics by assuming CC Quasi Elastic (CCQE) interaction ($\nu_\mu n \rightarrow \mu^- p$):

$$E_{\nu}^{\text{Rec}} = \frac{2(M_n - E_B)E_\mu - (E_B^2 - 2M_nE_B + \Delta M + M_\mu^2)}{2(M_n - E_B) - E_\mu + p_\mu \cos \theta_\mu},$$

where $\Delta M = M_n^2 - M_\mu^2$, $M$ indicate the muon, proton, or neutron mass with appropriate subscripts; $E_B$ is the nucleon binding energy; $E_\mu$ is the reconstructed muon energy.

MiniBooNE $E_{\nu}^{\text{Rec}}$ prediction

To predict the $E_{\nu}^{\text{Rec}}$ distribution at MiniBooNE, we extrapolate the measured SciBooNE flux to MiniBooNE in two steps.

First, we apply MiniBooNE/SciBooNE flux ratio to make a prediction of the true neutrino energy distribution at MiniBooNE. Then, we smear the true neutrino energy prediction to the reconstructed neutrino energy.

Systematic uncertainties for the flux ratio is estimated by varying the cross-section and flux models. Additionally, the uncertainties of the smearing function, which convert true $E_\nu$ to $E_{\nu}^{\text{Rec}}$, is estimated by varying the cross-section models.

Finally, we add MiniBooNE detector response error to the $E_{\nu}^{\text{Rec}}$ prediction.

The predicted MiniBooNE reconstructed neutrino energy distribution and its systematic uncertainties are shown in the Figure 4.

3.4. Oscillation Fit and Sensitivity

Fit Method

We test the oscillation hypothesis assuming the mixing between 2 neutrino flavors; $\nu_\mu$ and $\nu_\tau$. The $\nu_\mu \rightarrow \nu_\tau$ disappearance probability is given as

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2 \theta \sin^2 (1.27 \Delta m^2 L/E),$$

where $\theta$ is the mixing angle, $\Delta m^2 [eV^2]$ is the mass splitting between 2 flavors, $L [\text{km}]$ is the distance traveled and $E [\text{GeV}]$ is the neutrino energy.
We fit the MiniBooNE $E_{\nu}^{\text{Rec}}$ distribution to find the best fit parameter minimizing the $\chi^2$: value:

$$\chi^2 = \sum_{i,j}^{16 \text{ bins}} (N_{i}^{\text{data}} - N_{i}^{p})M_{ij}^{-1}(N_{j}^{\text{data}} - N_{j}^{p}),$$

where $i, j$ denote $E_{\nu}^{\text{Rec}}$ bins, $N_{i}^{\text{data}}$ and $N_{i}^{p}$ denote observed and predicted number of events at each bin, respectively, and $M_{ij}$ represents statistical and systematic uncertainties for the final $E_{\nu}^{\text{Rec}}$ prediction.

Then we define the allowed region by $\Delta \chi^2 = \chi^2(\text{true}) - \chi^2(\text{best})$ values, where $\chi^2(\text{true})$ is the $\chi^2$ at the oscillation prediction being tested, and $\chi^2(\text{best})$ is the smallest $\chi^2$ value across the $(\Delta m^2, \sin^2 2\theta)$ plane.

To obtain the confidence level at each oscillation parameter point $(\Delta m^2, \sin^2 2\theta)$, we use Feldman-Cousins' method [8]. In this method, 1000 “fake-data” predictions are formed, using random draws of the statistical and systematic uncertainties and some underlying oscillation hypothesis. Then, each fake-data is fit to obtain the relation between the $\Delta \chi^2$ values and the corresponding probabilities. This process is repeated for each pair of $(\Delta m^2, \sin^2 2\theta)$ true oscillation parameter being tested.

**Expected Limit**

The sensitivity is defined as the average of limits obtained from fake experiments with null underlying oscillation. Figure 5. shows the 90% CL sensitivity for the $\nu_\mu$ disappearance. The expected ±1σ band is also shown in the plot. The expected sensitivity directly supersedes the MiniBooNE only $\nu_\mu$ disappearance result, as substantial flux and cross section uncertainties have been reduced.

**Summary and Prospects**

We present SciBooNE-MiniBooNE joint analysis of a search for $\nu_\mu$ disappearance in an accelerator neutrino beam. The analysis is sensitive to the oscillation at the $\Delta m^2$ region of $0.5 - 40 \text{ eV}^2$. The sensitivity to $\nu_\mu$ disappearance has been improved relative to the MiniBooNE shape-only analysis, with results to be released soon. In addition, a joint anti-neutrino oscillation analysis will be performed using the anti-neutrino data set.

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**References**