New MiniBooNE Results

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The MiniBooNE experiment at Fermilab was designed to be a definitive test of the LSND evidence for neutrino oscillations and has recently reported first results of a search for electron-neutrino appearance in a muon-neutrino Booster beam. No significant excess of events was observed at higher energies, but a sizable excess of events was observed at lower energies. The lack of the excess at higher energies allowed MiniBooNE to rule out simple two-neutrino oscillations as an explanation of the LSND signal. However, the excess at lower energies is presently unexplained.

A new data set of neutrinos from the NuMI beam line measured with the MiniBooNE detector at Fermilab has been analyzed. The measurement of NuMI neutrino interactions in MiniBooNE provide a clear proof-of-principle of the off-axis beam concept that is planned to be used by future neutrino experiments such as T2K and NOvA. Moreover, it complements the first oscillation results and will help to determine whether the lower-energy excess is due to background or to new physics.

New results from the re-analysis of low energy excess from the Booster beam line and the results from measurements of neutrino interactions from NuMI beam line are discussed. MiniBooNE observes an unexplained excess of $128.8 \pm 20.4 \pm 38.3$ electron-like events in the energy region $200 < E_\nu < 475$ MeV. The NuMI data sample currently has a large systematic errors associated with $\nu_e$ events, but shows an indication of an excess.

1. Introduction

The existence of neutrino oscillations have been confirmed in the results of solar-neutrino [1], reactor-neutrino [2], atmospheric-neutrino [3], and accelerator-neutrino [4] experiments. These results implied the existence of two independent $\Delta m^2$ regions, with $\Delta m^2 \sim 8 \times 10^{-5}$ eV$^2$ in the solar, and with $\Delta m^2 \sim 3 \times 10^{-3}$ eV$^2$ in the atmospheric sector. The discovery of nonzero neutrino masses through the neutrino oscillations has raised a number of very interesting questions about neutrinos and their connections to other areas of physics and astrophysics. Unconfirmed evidence for neutrino oscillations, however, came from the LSND [5] experiment with $\Delta m^2$ at $\sim 1$ eV$^2$ value. One question is whether there are sterile neutrinos at $\Delta m^2$ at $\sim 1$ eV$^2$ mass scale that do not participate in the standard weak interactions. This question is primarily being addressed by the MiniBooNE experiment. The MiniBooNE experiment was designed to confirm or refute the LSND result with higher statistics and different sources of systematic error. If the LSND neutrino oscillation evidence was confirmed, it would, together with solar, reactor, atmospheric and accelerator oscillation data, imply Physics Beyond the Standard Model such as the existence of light sterile neutrino [6]. LSND observed an excess of $\bar{\nu}_e$ events in a $\bar{\nu}_\mu$ beam. MiniBooNE is performing both $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ searches. An additional data sample measured by the MiniBooNE detector comes from neutrinos produced in the NuMI (Neutrinos from Main Injector) beam line.

2. The MiniBooNE Experiment

MiniBooNE is a fixed target experiment currently taking data at the Fermi National Accelerator Laboratory. The neutrino beam is produced from 8.89 GeV/c protons, from Fermilab Booster, impinging on a 71 cm long and 1 cm diameter beryllium target. The target is located inside a magnetic focusing horn that increases the neutrino flux at the detector by a factor of $\sim 5$, and can operate in both negative and positive polarities for $\nu$ and $\bar{\nu}$ running. MiniBooNE collected approximately $6.6 \times 10^{20}$ protons on target (POT) in neutrino mode, and approximately $3.3 \times 10^{20}$ POT in anti-neutrino mode, using the Booster neutrino beam (BNB). These data samples are currently used in the neutrino oscillation analysis. Only the neutrino analysis will be discussed in this report. Results of a detailed anti-neutrino analysis are anticipated soon.

Mesons produced in the target decay-in-flight in a 50 m long decay pipe. The neutrino beam is composed of $\nu_\mu$s from $K^-/\pi^- \rightarrow \mu^- + \nu_\mu$ decays. The neutrino beam propagates through 450 m of dirt before entering the
detector. There is a small contamination from $\nu_e$; the processes that contribute to the intrinsic $\nu_e$ in the beam are $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$, $K^+ \rightarrow \pi^0 e^+ \nu_e$, and $K_L^0 \rightarrow \pi^\pm e^\mp \nu_e$. The flux modeling uses a GEANT4-based simulation of beam line geometry. Hadron production in the target is based on the Sanford-Wang parametrization of $p - Be$ cross-section, with parameters determined by a global fit to $p - Be$ particle production data. The details are described in Ref. \[7\].

Simulated neutrino flux has an energy distribution with a peak at $E_\nu \sim 0.7$ GeV. Therefore, the average $L/E_\nu$ ratio is $\sim 0.8$ km/GeV compared to LSND’s $L/E_\nu \sim 1$ km/GeV, where $L$ is the neutrino travel distance.

The neutrinos produced by the Booster are detected in the MiniBooNE detector \[8\] which is a 12.2 m spherical tank filled with 800 tons of pure mineral oil. The main MiniBooNE trigger is an accelerator signal indicating a beam spill. Every beam trigger opens a 19.2 $\mu$s window in which all events are recorded. The time and charge of photomultiplier tubes (PMT) in the detector are used to reconstruct the interaction point, event time, energies, and particle tracks resulting from neutrino interactions. Neutrino interactions in the detector are simulated with the NUANCE event generator package, with modifications to the quasi-elastic (QE) cross-section as described in \[9\]. Particles generated by NUANCE are propagated through the detector, using a GEANT3-based simulation which describes the emission of optical and near-UV photons via Cherenkov radiation and scintillation. Neutrino induced events are identified by requiring the event to occur during the beam spill, after rejection of cosmic ray muons and muon decay electrons.

### 3. First MiniBooNE Oscillation Result

The MiniBooNE collaboration reported initial results of $\nu_\mu \rightarrow \nu_e$ search \[10\] with the data sample of $5.58 \times 10^{20}$ POT. Neutrino interactions are identified with the likelihood-based algorithm, where the event parameters are varied to maximize the likelihood of the observed PMT hits. MiniBooNE conducted a blind analysis in order to complete an unbiased oscillation search. That means that the region where the oscillation $\nu_e$ candidates were expected was closed for the analysis until the reconstruction software and events selection cuts were finalized. After the analysis cuts were set, an oscillation analysis was performed in the range of reconstructed neutrino energy, $475 < E_\nu < 1250$ MeV. The estimated number of background events in the range, $475 < E_\nu < 1250$ MeV, after the selection cuts were applied was $358 \pm 35(syst)$. The estimate includes systematic uncertainties associated with neutrino flux, neutrino cross sections, and the detector model. The flux prediction has the uncertainties corresponding to the production of $\pi$, $K$, and $K_L$ particles in the MiniBooNE target. These uncertainties are quantified by a fit to external data sets from previous experiments on meson production. The cross section uncertainties are evaluated by varying underlying cross section model parameters in the Monte Carlo constrained by MiniBooNE data. Uncertainties on the parameters modeling the optical properties of the oil in the MiniBooNE detector are constrained by a fit to the calibration sample of Michel electrons.

An observation of neutrino oscillation in MiniBooNE would have corresponded to an excess of candidate electron neutrino events over expected backgrounds. The number of observed events in the analysis region, $475 < E_\nu < 1250$ MeV, was $380 \pm 19(stat)$. Therefore, we observed no significant excess of $22 \pm 19(stat) \pm 35(syst)$ events. When an oscillation fit was performed, assuming $\nu_\mu \rightarrow \nu_e$ oscillation hypothesis, we found the best fit oscillation parameters $(\Delta m^2, \sin^2 2\theta) = (4.0 \text{ eV}^2, 0.001)$ with 99% probability, compared to a null oscillation hypothesis probability of 93%. Therefore, we found no significant excess of $\nu_e$ events for neutrino energy above 475 MeV, suggesting that the data are inconsistent with models explaining LSND with a significant component of $\nu_\mu \rightarrow \nu_e$ oscillations. More details may be found in Ref. \[10\].

When the analysis was extended to lower energies we observed an excess of $\nu_e$-like events in the region below 475 MeV. The difference between the data and the prediction was found to be $188 \pm 27(stat) \pm 47(syst)$ events in the energy range $200 < E_\nu < 475$ MeV.

Published explanations for the low-energy excess include anomaly-mediated neutrino-photon coupling \[11\] and neutrino oscillations involving sterile neutrinos \[6\] \[12\] \[13\] \[14\] \[15\].
4. New Analysis Results

This section concentrates on investigation of the low-energy electron-like events. In the course of this investigation the data sample increased from $5.58 \times 10^{20}$ POT to $6.46 \times 10^{20}$, by including all available data collected in neutrino mode. The updates in the analysis included improved measurement of NC $\pi^0$ events and incorporation of coherent production [16]. Several strong interaction processes have been added to the detector model. However, only photo-nuclear interactions had a sizable effect. These interactions can cause a photon from $\pi^0$ decay in the detector to be missed, leaving a single photon than cannot be distinguished from an electron. The addition of photo-nuclear interactions increased the estimated background from NC $\pi^0$ by about 30% in the $200 < E_\nu < 475$ MeV neutrino energy range. Another improvement comes from improved measurement and rejection of the dirt events, i.e. background events at low energy caused by $\nu_\mu$ interactions in the tank wall and dirt surrounding the detector.

Fig. 1 shows reconstructed $E_\nu$ distribution of $\nu_e$ CCQE candidates (left). The data is shown as the points with statistical error. The background prediction is shown as the histogram with systematic errors and includes the improvements in the analysis mentioned above. The right panel of Fig. 1 shows the difference between the data and predicted backgrounds as a function of reconstructed neutrino energy. The error bars include both statistical and systematic components.

Table I shows observed data and predicted background event numbers in three $E_\nu$ bins. The total background is broken down into the intrinsic $\nu_e$ and $\nu_\mu$ induced components. The $\nu_\mu$ induced background is further broken down into its separate components. Therefore, MiniBooNE observes an unexplained excess of $128.8 \pm 20.4 \pm 38.3$

Figure 1: Left: Reconstructed $E_\nu$ distribution of $\nu_e$ CCQE candidates. The data is shown as the points with statistical error. The background prediction is shown as the histogram with systematic errors. Right: The difference between the data and predicted backgrounds as a function of reconstructed neutrino energy. The error bars include both statistical and systematic components.

electron-like events in the energy region $200 < E_\nu < 475$ MeV. The details the analysis of the low energy electron-like events are described in [17]. The oscillation fit performed in the energy range 475 to 1250 MeV does not change with the updates in the analysis. The limit to $\nu_\mu$ to $\nu_e$ oscillations is shown in Fig. 2 with $5.58 \times 10^{20}$ protons on target (red curve), and with $6.46 \times 10^{20}$ protons on target (blue curve) data set.

It is clear that more information is needed to understand the difference between the data and prediction in the low-energy region. Fortunately, additional handles will come from the data collected in the MiniBooNE detector with the anti-neutrinos coming from the BNB beam line, and from the data collected in the same detector from the NuMI neutrino beam.

5. Events from NuMI beam line observed by MiniBooNE detector

Fermilab has two beam lines producing neutrinos: the BNB and NuMI beamline, as shown in Fig. 3.
### Table I: Observed data and predicted background event numbers in three $E_\nu$ bins. The total background is broken down into the intrinsic $\nu_e$ and $\nu_\mu$ induced components. The $\nu_\mu$ induced background is further broken down into its separate components.

| $E_\nu[\text{GeV}]$ | 0.2-0.3 | 0.3-0.475 | 0.475-1.25 |
|----------------------|---------|-----------|------------|
| Total Bkgd           | 186.8±26 | 228.3±24.5 | 385.9±35.7 |
| $\nu_e$ induced      | 18.8    | 61.7      | 248.9      |
| $\nu_\mu$ induced    | 168     | 166.6     | 137        |
| NC $\pi^0$           | 103.5   | 77.8      | 71.2       |
| NC $\Delta \to N\gamma$ | 19.5   | 47.5      | 19.4       |
| Dirt                 | 11.5    | 12.3      | 11.5       |
| Other                | 33.5    | 29        | 34.9       |
| Data                 | 232     | 312       | 408        |
| Data-MC              | 45.2±26 | 83.7±24.5 | 22.1±35.7  |
| Significance         | 1.7$\sigma$ | 3.4$\sigma$ | 0.6$\sigma$ |

The MiniBooNE detector, located at an angle of 110 mrad (6.3°) with respect to the NuMI beam axis, provides a unique opportunity to perform the first measurement of neutrino interactions from an off-axis horn-focused beam. Future neutrino oscillation searches by the T2K [18] and NOνA [19] experiments plan to use off-axis horn-focused beams. The details of the NuMI beam line with respect to the MiniBooNE detector are shown in Fig. 4. The NuMI beam points toward the MINOS Far Detector, located in the Soudan Laboratory in Minnesota. Neutrinos are produced by 120 GeV protons incident on a carbon target. Positive $\pi$ and $K$ mesons produced in the target are focused down the decay pipe using two magnetic horns. The NuMI neutrino flux at the MiniBooNE detector is shown in Fig. 5. Detailed GEANT3-based Monte Carlo (MC) simulations of the beam, including secondary particle production, particle focusing, and transport, are performed to calculate the flux as a function of neutrino flavor and energy. The yield of pions and kaons from the NuMI target is calculated using the FLUKA cascade model [20]. The beam modeling includes downstream interactions in material other than the target that produce hadrons decaying to neutrinos. These interactions are modeled using a GEANT3 simulation, configured to use either GFLUKA [21] or GCALOR [22] cascade models.

Pions and kaons produce neutrinos with average energies of about 0.25 GeV and 2 GeV, respectively. The peak structure in the NuMI off-axis flux distribution is a consequence of the two-body decay kinematics. The energy of $\nu_\mu$s from two-body decays is given by

$$E_\nu \approx \frac{1 - m_{\pi,K}^2}{1 + \gamma^2 \tan^2 \theta} E_{\pi,K},$$

where $m_{\pi,K}$ ($E_{\pi,K}$) is the mass (energy) of the $\pi$, $K$ parent, and $m_\mu$ is the muon mass. Therefore at a suitable off-axis angle $\theta$, the neutrino flux is confined to a relatively narrow band of energies, which is useful in limiting backgrounds in searches for the oscillation transition $\nu_\mu \to \nu_e$.

Samples of charged current quasi-elastic $\nu_\mu$ and $\nu_e$ interactions were analyzed. The high rate and simple topology of $\nu_\mu$ CCQE events provided a useful sample for understanding the $\nu_e$ spectrum and verifying the MC prediction for $\nu_e$ production. The identification of $\nu_\mu$ CCQE events was based upon the detection of the primary stopping muon and the associated decay electron as two distinct time-related clusters of PMT hits, called ‘subevents’: $\nu_\mu + n \to \mu^- + p, \mu^- \to e^- + \nu_\mu + \bar{\nu}_e$. The reconstructed neutrino energy, $E_\nu$, distribution of selected $\nu_\mu$ CCQE events is shown in Fig. 6 along with the MC prediction. A total of 17659 data events passed this $\nu_\mu$ CCQE selection criteria, compared to the prediction of $18247\pm3189$; the uncertainty includes systematic errors associated with the neutrino flux, neutrino cross-sections, and detector modeling. The flux uncertainties included particle production in the NuMI target, modeling of the downstream interactions, and kaons stopped in the NuMI beam dump. The $\pi/K$ yields were tuned to match the MINOS Near Detector data [23] in several of the NuMI beam configurations. Such tuning has a negligible effect on the off-axis beam at MiniBooNE. However, the difference between untuned and tuned $\pi/K$ yields
Figure 2: The oscillation fit performed in the energy range 475 to 1250 MeV does not change with the updates in the analysis. The limit to $\nu_\mu$ to $\nu_e$ oscillations obtained with $5.58 \times 10^{20}$ protons on target (red curve) data set, and with $6.46 \times 10^{20}$ protons on target (blue curve) data set.

is treated as an additional systematic effect. The cross-section uncertainties and the uncertainties in the parameters describing the optical properties of the MiniBooNE detector are quantified in the way described in the analysis of the BNB events. The agreement between data and the prediction of the neutrino flux from $\pi/K$ parents indicates that the NuMI beam modeling provides a good description of the observed off-axis $\nu_\mu$ flux in MiniBooNE.

The $\nu_e$ CCQE events consist of a single subevent of PMT hits ($\nu_e + n \rightarrow e^- + p$). The majority of the remaining background is NC $\pi^0$ and the dirt events with only a single reconstructed electromagnetic track that mimics a $\nu_e$ CCQE event. To test our NC $\pi^0$ prediction, a clean sample of NC $\pi^0$ events is reconstructed, as shown in Fig. 7 (left). This sample demonstrates good agreement between data and MC. Fig. 7(right) shows the sample of the dirt events that originate from outside of the MiniBooNE detector. The variable shown is the distance from the detector wall measured along the track the particle created. The events are separated in the components originating outside the detector (shown in brown), and the component originating within the detector (shown in red). This distribution shows good agreement between data and MC and therefore shows that the backgrounds at low energy that result from neutrino interactions in the tank wall and dirt surrounding the detector are understood. A total of 780 data events pass all of the $\nu_e$ CCQE selection criteria. The MC prediction is $660 \pm 129$ with a $\nu_e$ CCQE efficiency of 32% and purity of 70%. The corresponding energy distribution is shown in Fig. 6 (right side).

To facilitate further comparison, the low energy and high energy regions are divided at 0.9 GeV. The number of
Figure 3: Fermi Nation Accelerator Laboratory is currently running two beam lines producing neutrinos. The Booster Neutrino Beam is producing neutrinos used in the MiniBooNE experiment. The NuMI Beam is emitting neutrinos intended for use in the MINOS experiment.

data and Monte Carlo events in these two energy regions is given in Table II. There is an indication of an excess in the data at above $1 \sigma$ level in the region of reconstructed neutrino energy $E_\nu < 0.9$ GeV. The details are given in Ref. [24].

Therefore, both samples of charged current quasi-elastic $\nu_\mu$ and $\nu_e$ interactions are found to be in agreement with expectation. This directly verifies the expected pion and kaon contributions to the neutrino flux and validates the modeling of the NuMI off-axis beam. In particular, the $\nu_\mu$ CCQE sample demonstrates an excellent understanding of the details of both the pion and kaon contributions to the neutrino beam. The $\nu_e$ CCQE sample also agrees with the prediction, but with some indication of a slight excess for neutrino energies below 0.9 GeV. In addition to demonstrating the off-axis beam technique, the measurement verifies the predicted fluxes from $\pi/K$ parents in the NuMI beam, and probes the off-axis intrinsic $\nu_e$ contamination, required for future $\nu_\mu \rightarrow \nu_e$ appearance searches.

After the demonstration of the off-axis concept, useful in limiting backgrounds in searches for the oscillation transition $\nu_\mu \rightarrow \nu_e$, the analysis is currently directed toward examining the low-energy region and searching for oscillation. In this way it will complement the analysis done with MiniBooNE using neutrino and anti-neutrino BNB data, but with different systematics. It is worth noting that the NuMI $\nu_e$ CCQE sample has a very different composition when compared to the BNB neutrino $\nu_e$ CCQE sample. The BNB $\nu_e$ sample originates mostly from decays of pions produced in the target, and contains large fraction of $\nu_\mu$ mis-identified events. On other hand, the
Figure 4: Plan and elevation views of the NuMI beam line with respect to the MiniBooNE detector.

Figure 5: Comparison of the predicted NuMI off-axis, NuMI on-axis, and MiniBooNE fluxes including all neutrino species. The off-axis flux is separated into contributions from charged π and K parents.

NuMI $\nu_e$ CCQE sample is produced mostly from decay of kaons, and contains a dominant fraction of intrinsic $\nu_e$ events. The analysis will be done by forming a correlation between the large statistics $\nu_\mu$ CCQE sample and $\nu_e$ CCQE, and by tuning the prediction to the data simultaneously. This is a method equivalent to forming a ratio between near and far detectors in two-detector experiments where the near detector detects $\nu_\mu$ CCQE events, while the far detector samples $\nu_e$ CCQE events. The result is that the prediction is being tuned to the data, and common systematics cancel; this might reveal something profound about the nature of the $\nu_e$ sample.

| $E_\nu$ [GeV] | 0.2-0.9 | 0.9-3.0 |
|---------------|---------|---------|
| Total Bkgd    | 401±78  | 259±56  |
| $\nu_e$ induced | 311     | 231     |
| $\nu_\mu$ induced | 90      | 28      |
| NC $\pi^0$   | 28      | 25      |
| NC $\Delta \rightarrow N\gamma$ | 14  | 1      |
| Dirt          | 36      | 1       |
| Other         | 12      | 1       |
| Data          | 496±22  | 284±17  |
| Data-MC       | 95±81   | 25±58   |

Table II: Observed data and predicted background event numbers in two $E_\nu$ bins. The total background is broken down into the intrinsic $\nu_e$ (and $\bar{\nu}_e$) and $\nu_\mu$ (and $\bar{\nu}_\mu$) induced components. The $\nu_\mu$ (and $\bar{\nu}_\mu$) induced background is further broken down into its separate components.
Figure 6: Left: Reconstructed $E_\nu$ distribution of $\nu_\mu$ CCQE events. The band indicates the total systematic uncertainty associated with the MC prediction. Also shown are the contributions from pion (52%) and kaon (48%) parents of neutrinos. Right: Reconstructed $E_\nu$ distribution of $\nu_e$ CCQE candidates. The prediction is separated into contributions from neutrino parents. The band indicates the total systematic uncertainty associated with the MC prediction. Kaon parents contribute 93% of the events in this sample.

Figure 7: Left: Mass distribution of NC $\pi^0$ candidates for data (points) and MC (solid histogram). The dashed histogram is the subset of predicted events with at least one true $\pi^0$. Predicted non-$\pi^0$ backgrounds are either from $\nu_\mu$ and $\overline{\nu}_\mu$ (dash-dotted line) or $\nu_e$ and $\overline{\nu}_e$ (dotted line) interactions. Kaon parents contribute 84% of the events in this sample. Right: The distribution of he distances from the detector wall measured along the track the particle created. The events are separated in the components originating outside the detector (shown in brown), and the component originating within the detector (shown in red).

6. Conclusion

The MiniBooNE experiment detected an unexplained excess of $128.8 \pm 20.4 \pm 38.3$ electron-like events in reconstructed neutrino energy range from 200 to 475 MeV. The excess might originate either from an unknown background component, or could be explained with a new physics process. The NuMI data sample currently has a large systematic errors associated with $\nu_e$ events, but shows an indication of a similar excess. Incoming analysis of the NuMI data with constrained systematic errors, and anti-neutrino data sample collected with the Booster beam will help distinguish various possibilities.

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