RESULTS FROM MINIBOONE

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Abstract

We present the results from the MiniBooNE neutrino oscillations search at the $\Delta m^2 \sim 1\text{eV}^2$ scale. No significant excess of events is observed above background for reconstructed neutrino energies greater than 475 MeV, as expected for no oscillations within a two-neutrino appearance only model. An excess of 186 ± 27 (stat) $\pm$ 33 (syst) events that cannot be explained by such model is observed below this threshold. We also present a recent analysis that combines two largely independent ν_e samples with a high statistics ν_μ sample used to reduce the effect of systematic uncertainties (all MiniBooNE data) in the oscillations fit. Recent advances on the understanding of the excess of low energy events are discussed, including a study of ν_μ and ν_e events from the nearby NuMI neutrino source.

1 Introduction

MiniBooNE was motivated by the result of the LSND experiment [1] which observed a $\sim 3.8\,\sigma$ excess of $\bar{\nu}_e$ events over its expectation for a pure $\bar{\nu}_\mu$ beam. When interpreted as $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillations in the $\Delta m^2 \sim 1$ eV^2 scale (determined by the experiment's neutrino energy and baseline) this excess corresponds to a $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probability of $0.26 \pm 0.08\%$. When the positive observations of solar and atmospheric neutrinos are taken into account, the LSND result requires the existence of at least one non-interacting (*sterile*) neutrino [2] to give a consistent picture. MiniBooNE probed the same region of the oscillations parameter space as LSND by having the same L/E ratio but a higher neutrino energy and baseline distance. The oscillation analyses presented here are preformed within a two neutrino appearance-only $\nu_\mu \to \nu_e$ oscillation model where ν_μ events are used to constrain the predicted ν_e rate.

2 The MiniBooNE Experiment

The experiment uses neutrinos from the Fermilab Booster neutrino beam (BNB) produced when 8.89 GeV/c momentum protons hit a 71 cm long beryllium target located inside a magnetic focusing horn. Typically, pulses of 4×10^{12} protons hit the target within a ~ 1.6 μs spill at a rate of 4 Hz. Positive mesons are focused by the toroidal magnetic field of the horn and are allowed to decay along a 50 m long cylindrical decay region The neutrino beam comes predominantly from the decay of π^+ and K^+ into ν_μ, having an intrinsic component of ν_e from K^+ and μ^+ decay with a flux ratio of $\nu_e/\nu_\mu = 0.5\%$. The detector, located 541 m downstream of the beryllium target is a spherical steel tank with inner radius 610 cm and is filled with 800 tons of pure mineral oil. Charged particles moving through the oil medium produce prompt directional Cherenkov light and delayed isotropic scintillation light The detector is divided into an inner spherical region 575 cm in radius and an optically isolated outer shell 35 cm thick used as veto. The inner region is viewed by 1280 8-inch photomultiplier tubes (PMTs) providing a $\sim 10\%$ photocathode coverage, while the veto region is viewed by 240 8-inch PMTs. The apparatus can detect ν events with energies ranging from ~ 100 MeV to a few GeV, and can reconstruct event vertices, particle tracks, measure the incident ν energy, and is able to separate events induced by ν_e from those induced by ν_μ. Integrated over the entire flux, the dominant ν interactions are charged-current quasi-elastic (CCQE) scattering (39%), neutral-current (NC) elastic scattering (16%), charged current (CC) single pion production (29%), and NC single pion production (12%).

3 Data analysis and event reconstruction

The PMT time and charge information in a 19.2 μs data acquisition (DAQ) window containing the beam spill is used to reconstruct ν interactions by forming charge and time likelihoods maximized to fit the observed hit patterns. Clusters of PMT hits within 100 ns are used to define "subevents" within the DAQ window. Candidate ν_e events are required to have only one subevent (as expected for ν_e CCQE events), with fewer than 6 hits in the veto and more than 200 in the main tank (above the endpoint of the spectrum from muon-decay electrons); fully contained ν_μ CCQE events have 2 subevents. Particle types can be identified by their time structure and hit patterns: muons have a sharp outer Cherenkov ring that is filled in by the muon travel distance, NC π^0 events have two Cherenkov rings from the two photons of π^0 decays, and signal-like electrons have a single ring that appears diffused due to multiple scattering and the electromagnetic shower process.

Two particle identification (PID) algorithms were used to isolate a rich sample of ν_e-induced CCQE events. One is based on likelihood ratios extracted from fits to the PMT hit patterns using a detailed light emission model from extended tracks, which we refer to as the track-based likelihood (TBL) analysis. The other is based on a boosted decision tree (BDT) machine learning technique [4] and was used as a complementary analysis. For the TBL analysis, the PMT hit patterns in the events are reconstructed under four hypotheses: *i*) a single electron-like Cherenkov ring, *ii*) a single muon-like ring, *iii*) two photon-like rings with unconstrained kinematics, and *iv*) two photon-like rings with $M_{\gamma\gamma} = m_{\pi^0}$. To identify ν_e-induced events and reject events with μ and π^0 in the final state, visible energy ($E_{\rm vis}$) dependent cuts are applied on $\log(L_e/L_\mu)$, $\log(L_e/L_{\pi^0})$, and $M_{\gamma\gamma}$, where L_e, L_μ, and L_{π^0} are the likelihoods for each event maximized under hypotheses *i*, *ii*, and *iv*, respectively, and $M_{\gamma\gamma}$ is obtained from the fit to hypothesis *iii*. The reconstruction used in the BDT analysis uses a simpler model of light emission and propagation. A single PID classifier variable is derived from 172 quantities such as charge and time likelihoods in angular bins, $M_{\gamma\gamma}$, and likelihood ratios (e/π^0 and e/μ) which are inputs to a BDT algorithm trained on sets of simulated signal events and background events with a cascade-training technique [5].

4 Neutrino Oscillation Analyses

In April of 2007 [3] MiniBooNE reported the agreement of the observed number of ν_e-induced events with background expectations in the absence of $\nu_\mu \to \nu_e$ appearance-only oscillations of the LSND [1] type in the range of 475 MeV to 3000 MeV of reconstructed ν energy, E_ν^{QE}, using the TBL analysis cuts. The analysis used a high statistics sample of ν_μ CCQE events to correct the number of expected background events to the $\nu_\mu \to \nu_e$ oscillations search, and to reduce the magnitude of the systematic uncertainties associated with these predictions. The corrected predictions and reduced errors were then used in a fit of the E_ν^{QE} distribution to a two-ν appearance-only oscillations model. Backgrounds are separated into ν_e-induced and ν_μ-induced. The intrinsic ν_e from μ, π, and K that survive the analysis cuts can be distinguished from the expected signal by their energy spectrum. The dominant ν_μ-induced backgrounds are from NC π^0 production events in which one of the photons from the π^0 decay is missed mimicking a single electron event from a ν_e CCQE interaction. A dedicated measurement of the NC π^0 events in π^0 momentum bins was used to constrain the Monte Carlo prediction of these events [6]. Interactions in the dirt surrounding the detector are also constrained with a dedicated sample of high radius inward-going events. Systematic uncertainties from the flux predictions, cross section models, and optical modeling of the oil are included in a fully correlated matrix in E_ν^{QE} bins. The predicted number of background events with 475 MeV $< E_\nu^{QE} <$ 1250 MeV after the complete TBL selection is applied is 358 ± 35(syst). For comparison, the estimated number of ν_e CCQE signal events is 126 ± 21(syst) for the LSND central expectation of 0.26% $\nu_\mu \to \nu_e$ transmutation. The data showed 380 ± 19(stat) events in this energy range. This agreement implies that there is no indication of an oscillation signal in the MiniBooNE data. The best fit parameters are $(\Delta m^2, \sin^2 2\theta) = (4.0\text{eV}^2, 0.001)$, with at probability of 99% as compared to a 93% probability for the null hypothesis.

Fig.1 shows the E_ν^{QE} distribution of ν_e candidate events in the TBL analysis. The vertical dashed line indicates the minimum E_ν^{QE} used in the oscillation analysis. There is no significant excess of events (22 ± 19 stat $\pm$

35 syst) in the analysis region, however, an excess (186 ± 27 stat $\pm$ 33 syst) is observed below 475 MeV that cannot be explained by a two-ν oscillations model. A single-sided raster scan of the parameter space is performed with events in the energy range 475 MeV $< E_{\nu}^{QE} <$ 3000 MeV to find the 90% C.L. limit corresponding to $\Delta\chi^2 = \chi^2_{\text{limit}} - \chi^2_{\text{best fit}} = 1.64$ shown in fig.2. The complementary analysis based on the BDT algorithm yielded a consistent result (dashed curve in fig.2) using the technique of introducing its own ν_{μ} CCQE sample[1] into the χ^2 minimization of the oscillations fit to constrain the systematic uncertainties and achieve the desired sensitivity.

4.1 Combining the ν_e-BDT ν_e-TBL and ν_{μ}-CCQE samples

The TBL and BDT analyses make use of distinct but complementary ν_e candidate samples. An error matrix in bins of E_{ν}^{QE} is calculated containing the correlations between the three samples (ν_e-TBL,ν_e-BDT, and ν_{μ}-CCQE) that are due to systematic effects. Inclusion of the shared events in the two ν_e samples requires knowledge of the statistical correlations that are induced in their E_{ν}^{QE} distributions by the event overlap ($> 22\%$). These correlations produce off-diagonal elements in the statistical component of the error matrix, which in in the absence of overlap would be diagonal[2] . The total error matrix is the sum in quadrature of the systematic and statistical components. With this matrix a χ^2 statistic is calculated comparing the observed energy distributions for the ν_e and ν_{μ} samples with the predictions for a given point in the oscillations parameter space. The use of both ν_e candidate samples yields a significantly higher sensitivity to oscillations ($\sim$ 20% more coverage) than that obtained when only one of the ν_e samples is used in combination with the ν_{μ} sample, which was the case of the BDT analysis put forward in our first publication. Fig.3 (left) shows the E_{ν}^{QE} distributions of the ν_{μ}-CCQE sample (top) and the two ν_e candidate samples (BDT -middle- and TBL -bottom-) after the fit. The smooth dashed curves represent the systematic uncertainties constrained by the use of the observed ν_{μ}-CCQE data in the fit. For the ν_{μ}-CCQE sample the systematic errors are forced to be of the size of the negligibly small statistical uncertainty. On the right hand side plot in fig.3 we compare the result in

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[1] Different from that used for the first TBL analysis; it is discussed in Ref. [7].

[2] For a more detailed discussion see Ref. [9].

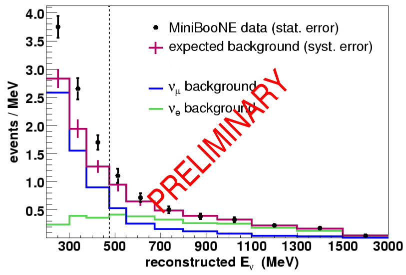

Figure 1: E_ν^{QE} distribution for ν_e candidate events in the TBL analysis. The points represent the data with statistical errors. The top-most histogram is the expected background with total systematic errors. The vertical dashed line indicates the oscillation analysis threshold.

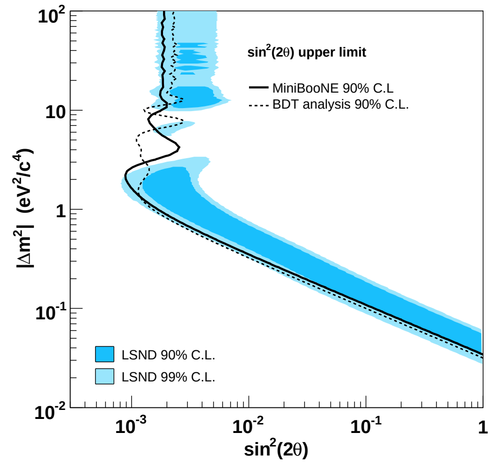

Figure 2: The MiniBooNE 90% C.L. limit (thick solid curve) from the TBL analysis for events with 475 MeV $< E_\nu^{QE} <$ 3000 MeV within a two-ν appearance only oscillations model. Also shown is the limit from the boosted decition tree (BDT) analysis (dashed curve) for events with 300 MeV $< E_\nu^{QE} <$ 3000 MeV.

Table 1: Preliminary results for the predicted background and observed data in three E_ν^{QE} bins.

E_ν^{QE} (MeV)	200-300	300-475	475-1250
Total Background	284 ± 25	274 ± 21	358 ± 35
ν_e intrinsic	26	67	229
ν_μ induced	258	207	129
NC π^0	115	76	62
NC $\Delta \rightarrow N\gamma$	20	51	20
Dirt	99	50	17
other	24	30	30
Data	375 ± 19	396 ± 19	380 ± 19
Data-Background	91 ± 31	95 ± 28	22 ± 40

Ref. 3) with this fit. The details of the limit at high Δm^2 are determined by how the fit responds to the specific fluctuations in the ν_μ and ν_e data distributions, and in this case the analysis does not improve the limit at the highest Δm^2 values. However, an increase of 10%-30%, depending on the Δm^2 value, in the coverage of the region below $\Delta m^2 < 1.2$ eV^2 is achieved, which is a significant gain over the first publication.

5 Investigations of the low energy excess with the TBL analysis

The collaboration has explored several possible sources of the excess events below 475 MeV in the TBL analysis, ranging from detector reconstruction issues to incorrect or new sources of background. Explanations involving new backgrounds or signal sources could be relevant for future experiments like T2K and NOvA. All of the excess events have been visually scanned and found to be consistent with single-ring electromagnetic-like events. Since MiniBooNE cannot distinguish electrons from photons the excess could be of either type. Table 1 lists the event numbers in three E_ν^{QE} bins detailing their background composition. In the bin corresponding to the oscillation analysis, the main background are intrinsic ν_e from μ and K decay. In the lower energy bins the ν_μ-induced backgrounds from NC π^0, Δ decays, and "Dirt" become dominant over the ν_e backgrounds. MiniBooNE constrains these background types using observed events, so their enhancement beyond the systematic uncertainties shown in Table 1 would contradict these observations. One possibility are pho-

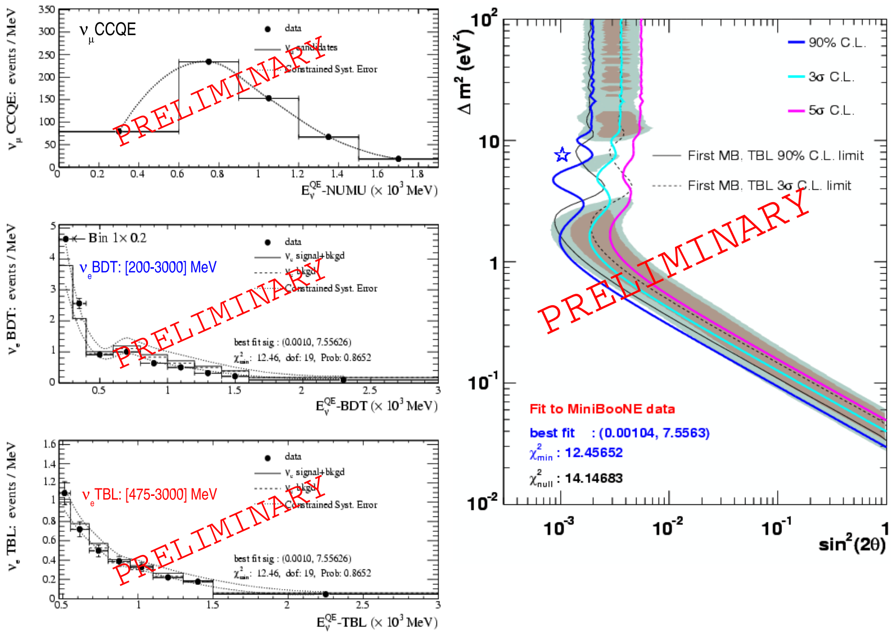

Figure 3: Left: The E_ν^{QE} distributions for the ν_μ CCQE sample (top), the BDT ν_e candidate sample (middle), and the TBL ν_e candidate sample (bottom) that result from the combined fit described in the text. The dashed curves represent the total constrained systematic uncertainties. For display purposes, the first bin in the BDT distribution has been scaled to 20% of its value. Right: C.L. limits (90% in blue, 3σ in cyan, 5σ in magenta) obtained with the combined technique, compared to the previous result [3] (90% in black solid and 3σ in black dashed), which used a different technique.

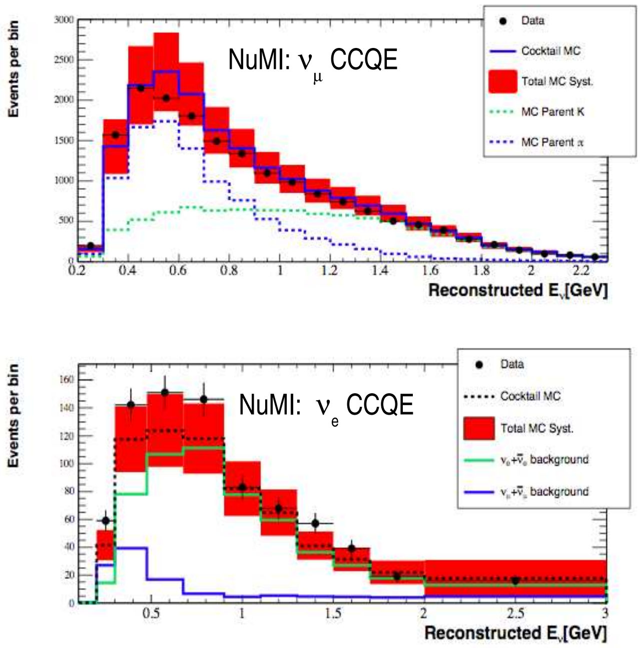

Figure 4: Data *vs.* Monte Carlo comparison of the E_ν^{QE} distribution for ν_μ (top) and ν_e (bottom) CCQE candidate events from the NuMI beam at MiniBooNE.the red bands represent the total systematic errors. The π and K components of the ν_μ fistribution are displayed in the top plot. In the bottom plot the ν_μ and ν_e induced components are shown.

tonuclear processes that are not currently in the simulation and could absorb one of the gammas from a NC π^0 giving a single-gamma background. Initial estimates are at the 10-20% level in the two lowest E_ν^{QE} bins. The standard model process of anomaly-mediated single photon production has been recently proposed [8] as a possible source of the excess. This process has never been observed and the MiniBooNE excess could be the first observation if the rates and kinematic distributions are shown to be consistent.

MiniBooNE also observes off-axis neutrinos from the NuMI/MINOS beam [10, 11]. These events can provide an important cross check on the nature of the low energy excess since their energy and distance is similar to those from the BNB. In addition, their background composition is significantly different, being dominated by intrinsic ν_e at low energies. The E_ν^{QE} distribution of observed ν_μ and ν_e candidate events from the NuMI beam are shown in fig.4 compared to the simulation, showing that there is good agreement between data and Monte Carlo. The systematic uncertainties are large at this stage, leaving room for the observed discrepancies, but will be constrained by applying similar techniques to those used in the oscillation analyses in the near future.

6 Summary

MiniBooNE has ruled out the LSND result interpreted as two-ν, $\nu_\mu \rightarrow \nu_e$ oscillations described by the standard L/E dependence. At low energies outside of the oscillation search region, MiniBooNE observes an excess of ν_e events; studies are currently underway to determine if these events are from unexpected backgrounds or possibly an indication of a new physics process. A recent analysis combining two largely independent ν_e samples has been conducted and shown to enhance the rejection of the LSND allowed region below $\Delta m^2 < 1.2$.

Acknowledgements

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