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# Overview of MicroBooNE Results

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These proceedings summarize results from MicroBooNE's first direct tests of the MiniBooNE anomaly, which were released in October 2021, and follow-up searches for new physics, including sterile neutrino oscillation search results released during summer 2022.

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MicroBooNE, operated at the Booster Neutrino Beamline (BNB) at U.S. Fermi National Lab during 2015-2021, has been a flagship accelerator-based neutrino experiment in the U.S., making use of the liquid argon time projection chamber (LArTPC) detector technology, and demonstrating the power of this technology in making precision measurements of neutrino interactions. It has already delivered more than fifty publications on its main physics and R&D goals, including first direct tests of the MiniBooNE anomaly [1, 2], the world's first high-statistics, precision cross-section measurements on argon (see, e.g. [3, 4]), and additional searches for new physics.

MicroBooNE was designed to search for and unambiguously identify the nature of the "low-energy excess" (LEE) events previously observed by the MiniBooNE experiment [5]. The key characteristic of this excess in the MiniBooNE Cherenkov detector was the presence of an electromagnetic shower in each event, presumably from the outgoing $e$ in a $\nu_e$ charged-current (CC) quasi-elastic (QE) interaction. The same signature, however, is shared by a $\gamma$ that could be produced in a $\nu_\mu$ neutral-current (NC) interaction, making rare and not-well-understood single-photon-inducing $\nu_\mu$ backgrounds another leading candidate interpretation of the MiniBooNE LEE. For a broad overview of Standard Model (SM) and beyond-SM (BSM) interpretations, see [6]. MicroBooNE can differentiate $e$- from $\gamma$-induced electromagnetic showers on the basis of topological and calorimetric information available through its LArTPC technology, by identifying a gap between the shower and the interaction vertex, and/or by measuring a twice-as-high (on average) ionization $dE/dx$ in the beginning of a $\gamma$ shower as opposed to an $e$ shower. As such, it is capable of resolving the nature of the MiniBooNE LEE as $e$-like or $\gamma$-like.

MicroBooNE's first LEE results addressed the leading background hypothesis for the MiniBooNE LEE, by searching for an excess of neutrino-induced NC $\Delta$ radiative decay events ($\Delta \to N\gamma$, where $N = p$ or $n$) [2]. This interaction is the dominant source of SM-expected single-$\gamma$ production at BNB energies, and has never been directly measured with neutrinos before. In the MiniBooNE measurement, it was only indirectly constrained by exploiting its theoretically predicted branching fraction and correlation with NC $\Delta \to N\pi^0$. A factor of 3.18 enhancement on the absolute rate of this process on carbon could fully explain the MiniBooNE LEE. To search for this signal, MicroBooNE developed a search through two exclusive channels, one with a $\gamma$ and proton ($1\gamma1p$), and one with $\gamma$ and no hadronic activity ($1\gamma0p$) in the final state. The expected number of background events for the $1\gamma1p$ ($1\gamma0p$) channel was 20.5±3.6 (145.1±13.8), whereas MicroBooNE observed 16 (153) data events. The lack of significant excess allowed MicroBooNE to rule out the interpretation of the MiniBooNE excess as enhanced NC $\Delta \to N\gamma$ at >95% confidence level (CL). The result has also been translated into a world-leading limit on the branching fraction of this SM process that represents a 50-fold improvement over the previous best limit from T2K experiment.

A second series of measurements [1, 7–9] addressed the $\nu_e$ CC interpretation of the MiniBooNE LEE signal. To search for this signal, MicroBooNE developed three independent analyses, all of which looked for an excess at low energy modeled as an energy-dependent intrinsic $\nu_e$ background enhancement, from MiniBooNE data unfolding. The first of the three analyses used deep learning (DL)-based reconstruction and selection to isolate a very $\nu_e$ CCQE-pure event sample, with one proton and one $e$ ($1e1p$) in the final state; the second one focused on MiniBooNE-like $\nu_e$ final states, selecting events with an $e$, no pions, and either zero ($1e0p0\pi$) or any number of protons ($1eNp0\pi$) in the final state, all using Pandora [10] "particle flow" reconstruction; the third one used tomography techniques (using WireCell [11]) to reconstruct and select a high-statistics $\nu_e$ event sample, inclusive of all final states with one $e$ and any number of pions or protons ($1eX$). All three analyses found agreement between data and background prediction within uncertainty, observing a slight data deficit, with the exception of the $1e0p$ channel of the Pandora-based analysis, which observed an insignificant excess. Based on these results, MicroBooNE was able to exclude the possibility that the MiniBooNE anomalous excess is composed entirely of $\nu_e$ events at 95% CL.

More recently, the measured $\nu_e$ and $\nu_\mu$ spectra in the DL and WireCell-based analyses have been further analyzed to constrain light sterile neutrino oscillations. Albeit strongly constrained by global short-baseline experimental data, such oscillations could be partly responsible for the MiniBooNE observed LEE [6]. Oscillation fits to WireCell-based spectra considered simultaneously the effects of $\nu_\mu$ disappearance, $\nu_e$ appearance, and and $\nu_e$ disappearance under a "3 active plus 1 sterile neutrino" (3+1) oscillation hypothesis, excluding part of the parameter space allowed by experimental anomalies at 95% CL [12]. Exclusive searches for electron and muon disappearance have also been performed using the DL-based spectra [13, 14], with a combined $\nu_e$ appearance and $\nu_e/\nu_\mu$ disappearance search forthcoming. Further constraints will be provided by the inclusion of the NuMI beam data set collected by MicroBooNE in the fit, which benefits from an 8× higher $\nu_e$:$\nu_\mu$ flux ratio, mitigating oscillation parameter ambiguity from $\nu_e$ appearance and disappearance cancellation effects. The combination is expected to yield enhanced sensitivity, covering the full LSND-allowed region at 95% CL [15].

Further MicroBooNE physics data analysis is ongoing, incorporating additional statistics (nearly doubling the data set analyzed so far), and expanding beyond the simplest interpretations of the MiniBooNE LEE. This effort benefits from an extensive body of theoretical work on alternative interpretations of the MiniBooNE and other short-baseline neutrino anomalies over the past decade [6]. Of particular interest are "dark sector" physics models, predicting, e.g., neutrino up-scattering to a heavier neutrino and subsequent production of an $e^+e^-$ pair, or other exotic production of $e^+e^-$ pairs such as from axion-like particles, or new scalars. Beyond single-$e$ and single-$\gamma$ interpretations, multiple MicroBooNE analyses have been launched and are ongoing to search for exotic $e^+e^-$ production. These analyses are investigating what we can learn with better reconstruction and event selection, and with potential reconstruction of the $e^+e^-$ pair's opening angle and/or invariant mass.

Beyond LEE interpretations, MicroBooNE has carried out searches for other BSM physics, including decays of Heavy Neutral Leptons and Higgs Portal Scalars [16–18]. Beyond MicroBooNE, a new phase of precision searches for new physics will be possible with the upcoming Short Baseline Neutrino (SBN) program, currently ramping up in the BNB [19]. SBN is capable of searches for light sterile neutrino oscillations with enhanced sensitivity, and provides unique opportunities for dark sector physics searches.

In summary, MicroBooNE has collected its full data set, and released first LEE results (using half its data) in 2021, disfavoring the leading photon background candidate interpretation to the MiniBooNE LEE, and seeing no evidence of electron neutrino background rate enhancement at low energy and no evidence of light sterile neutrino oscillations. More sensitive light sterile neutrino oscillation searches are expected with additional MicroBooNE data at hand, and with the upcoming SBN program. MicroBooNE is also charting new territory in the search for new physics with rich phenomenology at short baselines, where new results on exotic searches with a focus on $e^+e^-$ production are forthcoming.

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