Updated MiniBooNE Neutrino Oscillation Results within the Context of Global Fits to Short-Baseline Neutrino Data

Alejandro Diaz
Massachusetts Institute of Technology
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Outline

• LSND
• MiniBooNE
  – Old Data
  – New Data
• Global Fits
  – 3+1 Model
  – 3+1+Decay
Liquid Scintillator Neutrino Detector

- LSND used a 800 MeV proton beam to impinge a target to create $\pi^+$, which would then decay-at-rest to a $\mu^+$, which also decayed-at-rest:
  \[
  \pi^+ \rightarrow \mu^+ + \nu_\mu
  \]
  \[
  \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu
  \]
- Searched for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations
- Observed a $3.8\sigma$ excess of $87.9 \pm 22.4 \pm 6.0 \bar{\nu}_e$-like events above background.
If interpreted as an oscillation from a two neutrino model, the results have a best fit of $\sin^2(2\theta) = 0.003$ and $\Delta m^2 = 1.2 \text{ eV}^2$.

Would require at least one additional (sterile) neutrino.

A. Aguilar-Arevalo et al. [LSND Collaboration], Phys. Rev. D 64, 112007 (2001) [hep-ex/0104049].
MINIBOONE
MiniBooNE

MiniBooNE was proposed to investigate the LSND anomaly. Miniboone differed from LSND in several ways:

• Was Decay-in-Flight (DIF)
• Could choose between $\nu_\mu \rightarrow \nu_e$ or $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation searches
• $\sim 15 \times$ larger energy and baseline, kept L/E approximately equal
• Higher backgrounds than LSND, but more statistics

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2(2\theta)\sin^2\left(1.27 \frac{\Delta m^2 L}{E_\nu}\right)$$
MiniBooNE

target and horn  decay region  absorber  dirt  detector

Booster

primary beam (protons)  secondary beam (mesons)  tertiary beam (neutrinos)

$\nu_\mu \rightarrow \nu_e$ ???

~500 meters

~500 MeV
MiniBooNE

- Three typical event signatures
  - $\nu_\mu$ CCQE events deposits a sharp ring of photons to PMTs
  - $\nu_e$ CCQE events leaves a fuzzy ring
  - $\nu_\mu$ NC produce $\pi^0$, which decays to $2\gamma$ which leave a fuzzy ring each.

- Cannot distinguish between electron and single photon
MiniBooNE – Old Results

• Neutrino mode saw an excess of $160.0 \pm 47.8$ above the null, primarily under 475 MeV, and almost none above.

• Antineutrino mode saw an excess of $78.4 \pm 28.5$ events, both above and below 475 MeV.

• Antineutrino mode was consistent with LSND, but neutrino mode saw some tension.
MiniBooNE – Old Results

Neutrino Mode

Anti-Neutrino Mode
MiniBooNE – New Data Set

Up to 2012
\( \nu \) mode: \( 6.46 \times 10^{20} \text{ POT} \)
\( \bar{\nu} \) mode: \( 11.27 \times 10^{20} \text{ POT} \)
MiniBooNE – New Data Set

Up to 2012
\( \nu \) mode: 6.46\( \times 10^{20} \) POT
\( \bar{\nu} \) mode: 11.27\( \times 10^{20} \) POT

Doubled \( \nu \) data!

Now 2012
\( \nu \) mode: 12.84\( \times 10^{20} \) POT
\( \bar{\nu} \) mode: 11.27\( \times 10^{20} \) POT

Note: The diagram shows the cumulative POT (Pile-up Observing Time) over time, with a color-coded legend indicating different data modes and periods.
Total neutrino data observes an excess of $381.2 \pm 85.2 \ (4.5\sigma)$ $\nu_e$-like events.

Combined with antineutrino data, total excess is $460.5 \pm 95.8 \ (4.8\sigma)$

Neutrino and Antineutrino excess become consistent with each other.

A.A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], arXiv:1805.12028
MiniBooNE – New Data Set

Comparing Old and New neutrino data, we find the two distributions to be consistent (KS test = 76%)
MiniBooNE – New Data Set

\[(\Delta m^2, \sin^2 2\theta) = (0.037 \text{ eV}^2, 0.958)\]
\[\chi^2/ndf = 10.0/6.6 \text{ (prob = 15.4\%)}\]

\[(\Delta m^2, \sin^2 2\theta) = (0.041 \text{ eV}^2, 0.958)\]
\[\chi^2/ndf = 19.5/15.4 \text{ (prob = 20.1\%)}\]
MiniBooNE – New Data Set

• The MiniBooNE excess is now consistent with LSND’s excess.
• Combined fit of MiniBooNE + LSND data gives a significance of $6.1\sigma$
MiniBooNE – Summary

• MiniBooNE has doubled its neutrino mode data set
• Neutrino and antineutrino data are now consistent with LSND oscillations
• MiniBooNE will continue to take data, and future analysis will include improvement on background constraints.
• MicroBooNE will confirm if excess is due to electrons or photons.
GLOBAL FITS
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ or $\nu_\mu \rightarrow \nu_e$

LSND: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

KARMEN: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

MiniBooNE:
  BNB: $\nu_\mu \rightarrow \nu_e$
  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

NuMI: $\nu_\mu \rightleftharpoons \nu_e$

NOMAD: $\nu_\mu \rightleftharpoons \nu_e$
\( \nu_e \rightarrow \nu_e \) or \( \bar{\nu}_e \rightarrow \bar{\nu}_e \)

**KARMEN/LSND:** \( \nu_e \leftrightarrow \nu_e \)

**BUGEY:** \( \bar{\nu}_e \rightarrow \bar{\nu}_e \)

**Gallium:** \( \nu_e \rightarrow \nu_e \)
\[ \nu_\mu \rightarrow \nu_\mu \text{ or } \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \]

SciBooNE-MB: \( \nu_\mu \rightarrow \nu_\mu \)
\( \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \)

CCFR84: \( \nu_\mu \rightarrow \nu_\mu \)

CDHS: \( \nu_\mu \rightarrow \nu_\mu \)

MINOS: \( \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu \)

ATM: \( \nu_\mu \rightarrow \nu_\mu \)
3+1: All Data

Best fit:

\[ \Delta m_{41}^2 = 1.75 \text{ eV} \]
\[ |U_{e4}| = 0.159 \]
\[ |U_{\mu 4}| = 0.110 \]

\[ \sin^2(2\theta_{\mu e}) = 1.24 \times 10^{-3} \]

\[ \chi^2 = 297 \text{ (318 dof)} \]
\[ \chi^2_{null} = 329 \text{ (315 dof)} \]

\[ \Delta \chi^2_{null-min} \text{ (dof)} = 32 \text{ (3)} \]
Tension

Appearance

Disappearance
3+1+DECAY (PRELIMINARY)
Sterile Neutrino Decay

Visible Decay

\[ \nu_i \rightarrow ig_{ij} \rightarrow \nu_j \]

Invisible Decay

\[ \nu_4 \rightarrow ig_{ij} \rightarrow \psi \]

Our Model
Sterile Neutrino Decay - Motivation

• As an example, consider IceCube’s Sterile Neutrino Search. Due to matter effects, a sterile neutrino in the preferred parameter spaces would lead to resonance effects that would strengthen atmospheric $\nu_\mu$ disappearance.
Sterile Neutrino Decay - Motivation

• But giving $\nu_4$ a finite lifetime would result in decoherence in neutrino propagation, resulting in no enhancement in $\nu_\mu$ disappearance.

For animation, please download .pptx file

$1.80 < \log_{10}(\tau) < 2.00$
### Sterile Neutrino Decay - Best Fit

| Best Fit          | $\Delta m^2 (\text{eV}^2)$ | $|U_{e4}|$ | $|U_{\mu 4}|$ | $\tau (\text{eV}^{-1})$ |
|-------------------|----------------------------|-----------|-------------|---------------------|
| Null              | ---                        | ---       | ---         | ---                 |
| 3+1               | 1.75                       | 0.16      | 0.11        | ---                 |
| 3+1+Decay         | 0.89                       | 0.21      | 0.14        | 5.3                 |

### Best Fit

<table>
<thead>
<tr>
<th>Best Fit</th>
<th>$\chi^2$ (dof)</th>
<th>$\Delta \chi^2$ (dof)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Null</td>
<td>328.8 (315)</td>
<td>---</td>
</tr>
<tr>
<td>3+1</td>
<td>297.1 (312)</td>
<td>31.7 (3)</td>
</tr>
<tr>
<td>3+1+Decay</td>
<td>290.6 (311)</td>
<td>38.2 (4)</td>
</tr>
</tbody>
</table>
DOES DECAY RELIEVE TENSION?
Tension is still there

Appearance

Disappearance

\[ \Delta m^2_{41}/\text{eV}^2 \]

\[ \sin^2 2\theta_{\mu e} \]

\[ \Delta m^2_{41}/\text{eV}^2 \]

\[ \sin^2 2\theta_{\mu e} \]
Conclusion

• MiniBooNE
  – Neutrino data doubled
  – Confirms previous neutrino and antineutrino anomaly to $4.8\sigma$
  – MiniBooNE excess is consistent with self and LSND.

• Sterile Neutrino Global Fit
  – Introduced in an attempt to relieve tensions seen in global fit
  – Best fit of $\tau \approx 5 \text{ eV}^{-1}$ found
  – Modest relief in tension
Future

• MiniBooNE will continue to collect neutrino data as the SBN program proceeds. Improvements in analysis await.

• Await to see from MicroBooNE to see if excess is due to $\nu_e$ or photons.

• Expand global fits to include new reactor experiments, such as NEOS and DANSS, and incorporate IceCube. Paper coming soon!

• Refine neutrino decay model.
THANK YOU! QUESTIONS?