Explaining the MiniBooNE Excess Through a Mixed Model of Oscillation and Decay


Based on our preprint: 2105.06470
Overview

• Tension in eV-scale oscillation global fits
• The HNL dipole model
• MiniBooNE fit results
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The MiniBooNE Experiment

- 818 ton CH$_2$ Cherenkov detector at Fermilab’s Booster Neutrino Beam
- 4.8$\sigma$ excess of electron-like events in complete neutrino-mode dataset

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eV-scale Sterile Oscillations

The most common model used to explain the MiniBooNE excess invokes short-distance muon-to-electron neutrino oscillations though the addition of a sterile neutrino

![Graph showing results from MiniBooNE experiment]

*Phy. Rev. D 103, 052002*
Global Fit Tension

- One can look for the effect of such a sterile neutrino in other $\nu_e$ appearance experiments (e.g. LSND), $\nu_e$ disappearance experiments (e.g. reactors), and $\nu_\mu$ disappearance experiments (e.g. long baseline accelerators)

$$p_{PG}^{\text{MiniBooNE}} = 8 \times 10^{-7} \ (4.8\sigma)$$
Global Fits Without MiniBooNE

- We can repeat the same procedure after removing MiniBooNE from the list of appearance experiments

\[ p_{PG}^{w/o \text{MiniBooNE}} = 7 \times 10^{-3} \ (2.5\sigma) \]
Global Fits Without MiniBooNE

- We can repeat the same procedure after removing MiniBooNE from the list of appearance experiments.

Clearly removing MiniBooNE from the global fit reduces the tension between appearance and disappearance experiments. But how do we explain the MiniBooNE excess in this picture?

\[ p_{PG}^{w/o \text{MiniBooNE}} = 7 \times 10^{-3} \ (2.5\sigma) \]
Overview

- Tension in eV-scale oscillation global fits
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- MiniBooNE fit results
Dipole + Oscillation Model

\[ \mathcal{L} \supset \mathcal{L}_{SM} + \sum_{j=1}^{3} \bar{N}_j (i \phi - M_j) N_j + \sum_{i=1}^{3} (d_{i,j} \bar{\nu}_i \sigma_{\mu\nu} F^{\mu\nu} N_j + h.c.) \]

- We only consider oscillations involving the lightest HNL, as the masses of the other two are assumed to be too large.
- The dipole term introduces the interactions shown below, where we define \( N \equiv N_3 \).

HNLs In MiniBooNE

1: Dalitz-like Pion Decay

2: Primakoff Upscattering

3: HNL Decay

For the mass range under consideration in this study (10-1000 MeV), Primakoff upscattering is found to be the dominant HNL production mode.
As electrons and photons are indistinguishable in MiniBooNE, this decay would contribute to the electron-like excess.
Simulation Details: Production

- Primakoff upscattering events can happen...
- Coherently off a nucleus or incoherently off a nucleon
- In the dirt before MiniBooNE or within MiniBooNE itself
- The event-by-event HNL kinematics are determined using the differential cross section

\[
\frac{d\sigma}{dt} = \frac{2\alpha d^2}{m} \left[ F_1^2(t) \left( \frac{1}{E_r} - \frac{1}{E_\nu} + m_N^2 \frac{E_r - 2E_\nu - M}{4E_\nu^2E_rM} + m_N^4 \frac{E_r - M}{8E_\nu^2E_r^2M^2} \right) + \frac{F_2^2(t)}{4M^2} \left( \frac{2M}{E_\nu^2} \left( (2E_\nu - E_r)^2 - 2E_rM \right) + m_N^2 \frac{E_r - 4E_\nu}{E_\nu^2} + \frac{m_N^4}{E_\nu^2E_r} \right) \right]
\]

\[E_r = - t/2M \quad E_N = E_\nu - E_r \quad \cos(\theta) = \frac{E_\nu - E_r - ME_r/E_\nu - m_N^2/2E_\nu}{\sqrt{E_\nu^2 + E_r^2 - 2E_\nuE_r - m_N^2}}\]
Simulation Details: Decay

• HNLs that reach MiniBooNE decay with a decay length

\[ L_{\text{decay}} = 4\pi \frac{\beta E_N}{d^2 m_N^4} \]

• The angular distribution of photons from right handed HNLs is given by*

\[ \frac{d\Gamma}{d \cos \theta} \propto 1 - \cos \theta \]

• The photons are boosted to the lab frame, smeared according to the MB energy/angle resolution, weighted by detection efficiency

*requires Dirac HNL among other things (see 1805.00922)
Overview

• Tension in eV-scale oscillation global fits
• The HNL dipole model
• **MiniBooNE fit results**
Energy and Angular Fits

- We consider an oscillation contribution from the best fit to the 3+1 model without MB:

\[ \Delta m^2 = 1.3 \text{ eV}^2 \]
\[ \sin^2(2\theta_{\mu e}) = 6.9 \times 10^{-4} \]

- The remaining excess is fit to the HNL dipole contribution
Energy and Angular Fits

![Graph showing energy and angular fits with data points and error regions labeled LSND $\nu_\mu$ ES, NOMAD, CHARM $\nu_\mu$ ES, SN1987A.](image)

- $d$ [GeV$^{-1}$]
- $d/\mu_B$
- $m_N$ [MeV]

- LSND $\nu_\mu$ ES
- NOMAD
- CHARM $\nu_\mu$ ES
- SN1987A

- $E^Q_{\nu}$ 95% CL
- cos $\theta$ 95% CL
Energy and Angular Fits

These plots correspond to the dipole parameters that give the best energy fit within the joint 95% CL allowed region.

Note: systematic errors are only available for the neutrino energy—the angular fit considers only statistical error.
Final Results

<table>
<thead>
<tr>
<th>Parameters</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(\sin^2 2\theta, d, m_N)$</td>
<td>3 + 1 + $N$</td>
</tr>
<tr>
<td></td>
<td>$E_{\nu}^{QE}$</td>
</tr>
<tr>
<td>(0.30, 3.1, 376)</td>
<td>5.7/8</td>
</tr>
<tr>
<td>(0.69, 2.8, 376)</td>
<td>7.9/8</td>
</tr>
<tr>
<td>(2.00, 5.6, 35)</td>
<td>20.2/8</td>
</tr>
<tr>
<td>(0, 0, 0)</td>
<td>34.1/10</td>
</tr>
</tbody>
</table>

TABLE II. $\chi^2$/dof values for 3 + 1 and 3 + 1 + $N$-decay models obtained by comparing expectations to the MiniBooNE excess in $E_{\nu}^{QE}$ and $\cos \theta$. The parameters in column one refer to $(\sin^2 2\theta_{\mu e} \times 10^{-3}, d \times 10^{-7} \text{[GeV}^{-1}], m_N \text{[MeV]})$. The mass splitting is 1.32 eV$^2$ in all cases. The null case (no oscillations and no HNL decay) is also shown in the last row.

Takeaway: the 3+1+HNL decay model gives a good fit to the MiniBooNE energy and angular distributions while also relieving tension in the global 3+1 picture.
Cross Check: Timing

- MB excess lives within ~4 ns of the proton beam bunch timing
- Simple timing delay calculations are well within those constraints
- Motivates further investigation by MB collaboration

\[
\{d, m_N\} = \{2.8 \times 10^{-7} \text{ GeV}^{-1}, 376 \text{ MeV}\}
\]
Conclusion

• The exclusion of MiniBooNE from the 3+1 model global fit relieves tension between appearance and disappearance experiments

• The combination of oscillations from the MiniBooNE-less 3+1 fit with HNL decays via a dipole model gives a good fit to the energy and angular distributions of the MiniBooNE excess

• This results in a highly predictive HNL dipole model which evades existing experimental limits and can be tested by future experiments

• Preprint available now: 2105.06470
Oscillation Amplitude Range

• The 3+1 fit without MB gives a very tight fit on the mass-squared splitting, but gives a 90% CL allowed range on the oscillation amplitude of roughly [0.0003, 0.002]

• We perform the same HNL dipole fit for each end of this allowed range
Smaller Oscillation Contribution

\[ \Delta m^2 = 1.3 \text{ eV}^2 \]

\[ \sin^2(2\theta_{\mu e}) = 3 \times 10^{-4} \]

- Results are similar to the best fit oscillation amplitude case

\[ \Delta \chi^2(E_{\nu}^{QE}) \]

\[ \Delta \chi^2(\cos \theta) \]
Smaller Oscillation Contribution

$$\Delta m^2 = 1.3 \text{ eV}^2$$

$$\sin^2(2\theta_{\mu e}) = 3 \times 10^{-4}$$

$$\sin^2(2\theta) = 3 \times 10^{-4}$$

$$m_N = 1.3 \text{ eV}$$

$$E_{\nu}^{QE} \text{ 95\% CL}$$

$$\cos \theta \text{ 95\% CL}$$

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Pheno 2021: A Mixed Model of Oscillations and Decay
Smaller Oscillation Contribution

\[ \Delta m^2 = 1.3 \text{ eV}^2 \]

\[ \sin^2(2\theta_{\mu e}) = 3 \times 10^{-4} \]

\[ \{d, m_N\} = \{3.1 \times 10^{-7} \text{ GeV}^{-1}, 376 \text{ MeV}\} \]

Slightly larger dipole coupling preferred compared to the best fit oscillation amplitude case
Larger Oscillation Contribution

\[ \Delta m^2 = 1.3 \text{ eV}^2 \]
\[ \sin^2(2\theta_{\mu e}) = 2 \times 10^{-3} \]

- Results are quite different here—no closed contours at the three sigma level.
Larger Oscillation Contribution

\[ \Delta m^2 = 1.3 \text{ eV}^2 \]

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

\[
\Delta m^2 = 1.3 \text{ eV}^2
\]

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

\[
\{d, m_N\} = \{5.6 \times 10^{-7} \text{ GeV}^{-1}, 35 \text{ MeV}\}
\]

Preference for a smaller HNL mass here, but fits are worse in general.
Data (stat err.)

$\nu_e$ from $\mu^{+/-}$

$\nu_e$ from $K^{+/-}$

$\nu_e$ from $K^0$

$\pi^0$ misid

$\Delta \rightarrow N\gamma$

dirt

other

Constr. Syst. Error

Best Fit

Events/MeV

$E_{\nu}^{QE}$ (GeV)
Events

Visible Energy [MeV]

Other
Dirt
Δ→ Nγ
π⁰ misid
νₑ from K⁰
νₑ from K⁺⁻
νₑ from μ⁺⁻
Best-fit
Data

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Pheno 2021: A Mixed Model of Oscillations and Decay
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\[
\{d, m_N\} = \{2.8 \times 10^{-7} \text{ GeV}^{-1}, 376 \text{ MeV}\} \\
\text{best fit oscillation contribution:} \\
\sin^2(2\theta_{\mu e}) = 6.9 \times 10^{-4}
\]

\[
\{d, m_N\} = \{3.1 \times 10^{-7} \text{ GeV}^{-1}, 376 \text{ MeV}\} \\
\text{low oscillation contribution:} \\
\sin^2(2\theta_{\mu e}) = 3 \times 10^{-4}
\]

\[
\{d, m_N\} = \{5.6 \times 10^{-7} \text{ GeV}^{-1}, 35 \text{ MeV}\} \\
\text{high oscillation contribution:} \\
\sin^2(2\theta_{\mu e}) = 2 \times 10^{-3}
\]