Confronting Neutrino Mass Generation Mechanism with MiniBooNE Anomaly

POND²

Sudip Jana

Fermilab 2018

Three-neutrino oscillation: Not the full picture?

Short Baseline Anomalies

Long and Medium Baseline
LSND detected more $\bar{\nu}_e$ than expected:

$$87.9 \pm 22.4 \pm 6.0 \text{ events}$$

$$3.8 \sigma \text{ excess}$$
To test the LSND indication of anti-electron neutrino oscillations

- Keep L/E same, change beam, energy, and systematic errors
- Baseline: L = 540 meters, \( \sim x \times 15 \) LSND
- Neutrino Beam Energy: \( E \sim x (10-20) \) LSND
- Different systematics: event signatures and backgrounds different from LSND High statistics: \( \sim x \times 6 \) LSND
- Perform experiment in both neutrino and anti-neutrino modes.

- Neutrino and anti neutrino modes see excesses of \( \nu_e \) and \( \bar{\nu}_e \) (Combined is also 3.8 \( \sigma \) excess)
MiniBooNE’s Low Energy Excess

- Observation of a Significant Excess of Electron-Like Events in the MiniBooNE Short Baseline Neutrino Experiment
- Double neutrino-mode data in 2016-2017 (6.46×10^{20} + 6.38×10^{20} POT)
- Event excess: 381.2 ± 85.2 (4.5σ)

MiniBooNE Collaboration hep-ex/1805.12028
MiniBooNE observed a large excess in the much lower energy region.

This is the region that the LSND oscillation should have appeared.
What is going on???

- What is the nature of the excess?
- Possible detector anomalies or reconstruction problems?
- Incorrect estimation of the background?
- New sources of background?
- New physics including/excluding exotic oscillation scenarios?

The origin of such excess is unclear – it could be the presence of new physics, or a large background mismodeling. However, the MiniBooNE result, if due to new physics, would revolutionize the field of particle physics.

What sort of new physics can explain these anomalies?
What about eV Sterile Neutrino Interpretation??

\[
P_{\alpha\alpha}^{\text{SBL}} = 1 - 4|U_{\alpha4}|^2(1 - |U_{\alpha4}|^2) \sin^2 \left( \frac{\Delta m^2_{41} L}{4E} \right)
\]

\[
P_{\alpha\beta}^{\text{SBL}} = 4|U_{\alpha4}|^2|U_{\beta4}|^2 \sin^2 \left( \frac{\Delta m^2_{41} L}{4E} \right)
\]

\[
sin^2 2\theta_{\mu e} = 4 |U_{e4} U_{\mu4}|^2
\]

Leads to $\nu_e$ disappearance

Leads to $\nu_\mu$ disappearance
What about eV Sterile Neutrino Interpretation??

\[ \sin^2 2\theta_{\mu e} = 4 |U_{e4} U_{\mu 4}|^2 \]

Leads to $\nu_\mu$ to $\nu_e$ disappearance

- 2 variables: $U_{e4}$, $U_{\mu 4}$
- 3 data sets: $\nu_e$ - Disappearance
  $\nu_\mu$ - Disappearance
  $\nu_e$ - Appearance

Mona Dentler et al. JHEP 1808 (2018) 010
What about eV Sterile Neutrino Interpretation??

\[ \sin^2 2\theta_{\mu e} = 4 |U_{e4} U_{\mu 4}|^2 \]

4.7 \sigma tension between Appearance and Disappearance data sets under eV sterile interpretation

Mona Dentler et al. JHEP 1808 (2018) 010
Collin et al. 1602.00671
Gariazzo et al 1703.00860
Shortcoming:
Failure to accommodate MiniBooNE low-energy excess.

“3+N STANDARD STERILE NEUTRINOS”: INSUFFICIENT

D. Cianci, et al. (Talk presented at Applied Antineutrino Physics Workshop 2018)
Explanation of MiniBooNE’s low energy excess

- Sterile ν at the eV scale present strong tension between data sets
- Cosmological bounds further threat the eV sterile ν hypothesis
- Is there an explanation that is not ruled out?
- Is there a “real model” for these explanations?
- Can this relate to any of the theoretical problems of the SM?
MiniBooNE is a mineral oil (CH$_2$) detector that can observe Cherenkov radiation of charged particles.

Crucially, it could not distinguish electron induced Cherenkov cones from photon induced Cherenkov cones.

Excess is correlated with beam in power, angle and timing. It is present in positive and negative horn polarities. It is not present in beam dump configuration.
Explanation of MiniBooNE’s low energy excess

- Angular spectrum is forward, but not that much
- Scattering on electrons would typically lead to $\cos\theta > 0.99$
- Decays of invisible light (<10 MeV) particles produced in the beam would also lead to forward spectrum
Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR – THE IDEA

There is a dark sector with a novel interaction

ZD

Bertuzzo et al. 1807.09877
Bertuzzo et al. 1808.02500
Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500
Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500
Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR – THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector
- Mixing between $Z_D$ and photon leads to interaction with protons

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500
Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR - THE IDEA

- There is a dark sector with a novel interaction
- Right-handed neutrinos are part of the dark sector and are subject to new interaction
- Mixing between RH and LH neutrinos leads to interaction in active neutrino sector
- Mixing between $Z_D$ and photon leads to interaction with protons

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500
Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR - THE IDEA

➢ There is a dark sector with a novel interaction
➢ Right-handed neutrinos are part of the dark sector and are subject to new interaction
➢ Mixing between RH and LH neutrinos leads to interaction in active neutrino sector
➢ Mixing between $Z_D$ and photon leads to interaction with protons
Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR – THE IDEA

➢ There is a dark sector with a novel interaction

➢ Right-handed neutrinos are part of the dark sector and are subject to new interaction

➢ Mixing between RH and LH neutrinos leads to interaction in active neutrino sector

➢ Mixing between $Z_D$ and photon leads to interaction with protons

➢ Relevant part of the Lagrangian:

\[
\mathcal{L}_D \supset \frac{m_{Z_D}^2}{2} Z_D\mu Z_D^\mu + g_{D} Z_D^\mu J_D\mu + \epsilon \epsilon^* Z_D^\mu J_{\mu}^{em} + \frac{g}{c_W} \epsilon' Z_D^\mu J_{\mu}^Z
\]

Bertuzzo et al 1807.09877
Bertuzzo et al 1808.02500
❖ Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR – THE IDEA
Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR – THE IDEA

If $e^+e^-$ pair is collimated ($\cos\theta_{ee} > 0.99$-ish), it will be classified as e-like
Explanation of MiniBooNE’s low energy excess

A LIGHT DARK SECTOR – THE IDEA

We have to get this angular spectrum
\( N_D \) should be heavy (> 100 MeV) so its decay products are not so boosted

\( Z_D \) should be light (< 60 MeV) so that the e+e- pair is collimated
Explanation of MiniBooNE’s low energy excess

Fit to energy spectrum only
(Official MB data release)
Benchmark Points:

- $m_N = 420$ MeV
- $m_{ZD} = 30$ MeV
- $|U_{\mu 4}|^2 = 9 \times 10^{-7}$
- $\alpha_D = 0.25$
- $\alpha\epsilon^2 = 2 \times 10^{-10}$
- $\chi^2$/dof = 33.2/36

Bertuzzo et al 1807.09877
See also Ballett et al 1808.02915 for different realization of the mechanism
Constraint on Light Dark Sector

➢ $Z_D$ phenomenology is similar to dark photon case

➢ LHC constraints are not expected to be stringent below 1 GeV

Model Independent Constraint on Heavy Sterile Neutrino
Explanation of MiniBooNE’s low energy excess

Region of our model in the $|U_{\mu 4}|^2$ versus $m_{N_D}$ plane satisfying MiniBooNE data at 1\(\sigma\) to 5\(\sigma\) CL, for the hypothesis $m_{Z_D} = 30$ MeV, $\alpha_{Z_D} = 0.25$ and $\alpha\epsilon^2 = 2 \times 10^{-10}$. The region above the red curve is excluded at 99\% CL by meson decays, the muon decay Michel spectrum and lepton universality.

Bertuzzo et al 1807.09877
Connection to Neutrino Mass Generation Mechanism
Neutrino Mass
New physics beyond SM:

Masses (eV)

$\nu_e \sim y^{\text{eff}} \sim 10^{-12}$
Small Neutrino masses

- "Technically natural" in t’Hooft sense. Small values are protected by symmetry. At a cut-off scale $\Lambda$:
  - "natural" - $\delta m_f \sim g^2/(16\pi^2) m_f \ln(\Lambda^2/m_f^2)$
  - "unnatural" - $\delta m_H^2 \sim - y_t^2/(8\pi^2) \Lambda^2$

- Two ways to generate small values naturally:

  - Suppression by integrating out heavy states: the higher dimension $1/\Lambda^n$, the lower $\Lambda$ can be.
  - Suppression by loop radiative generation: the higher loops $1/(16\pi^2)^n$, the lower cut off scale can be.
Neutrino Mass Models

- Lowest higher dim. operator \( O^{d=5} : \mathcal{L}_{d=5} = \frac{1}{\Lambda_{NP}} LLHH \)

Realization of Weinberg op. —

- **See-saw:** there are many seesaw realizations —
  - Type-I: Minkowski (77), Ramond, Slansky (79), Yanagida (79), Glashow (79), Mohapatra, Senjanovic (80)
  - Type-II: Schechter, Valle (80), Lazarides, Shafi, Wetterich (81), Mohapatra, Senjanovic (81)
  - Type-III: Foot, Lew, He, Joshi (89), Ma (98)
  - Linear, Inverse, etc ...

- **Loop-induced:**
  - 1-loop: Zee (80), Ma (99)
  - 2-loop: Babu (88)
**Standard/Type I Seesaw**

\[ y^2 H \ell H + M_N \ell \ell N N \]

\[ m_\nu \sim \frac{y^2 v^2}{M_N} \]

\[ y^2 v^2 \]

\[ m_\nu \sim 0.1 \text{eV} \quad y \sim 0.1 \quad M_N \sim 10^{12} \text{GeV} \]

Lepton number is broken at very high scale \( M_N \).
Inverse Seesaw

\[ y \bar{\Psi}^c H \ell + m_\Psi \bar{\Psi} \Psi^c + \frac{1}{2} \mu \bar{\Psi} \Psi \]

\[ m_\nu \sim \frac{y^2 v^2}{m_\Psi^2} \mu \]

\[ y \sim 0.1 \quad m_\Psi \sim 1\text{TeV} \quad \mu \sim 1\text{keV} \]

- Why \( \mu \) is much smaller than TeV scale?
Scale of Seesaw Mechanism

- Seesaw I mechanism with TeV scale heavy neutrinos
  - Standard Seesaw with small Yukawa couplings \( Y_\nu \approx 10^{-6}\sqrt{M_N/\text{TeV}} \)
  - “Bent” Seesaw I mechanisms (e.g. Inverse Seesaw)
    - Decouple \( \Delta_{\text{LNV}} \) from heavy neutrino mass
    - Example
      \[
      \begin{pmatrix}
        0 & Y_\nu \langle H \rangle & 0 \\
        Y_\nu \langle H \rangle & \mu & M \\
        0 & M & \mu
      \end{pmatrix}
      \]
    - Large Yukawa couplings \( \approx 10^{-2} \)
    - Quasi–Dirac heavy neutrino
Despite numerous searches for neutrino mass models (at TeV scale) at high-energy colliders, no compelling evidence has been found so far.

Is it really sufficient to search for new physics scale behind neutrino mass generation mechanism at LHC only?

The new physics scale behind neutrino mass generation mechanism might be at low scale and which is less sensitive to high energy collider experiments.

It may show up at low energy neutrino experiments at near future.
Despite numerous searches for neutrino mass models (at TeV scale) at high-energy colliders, no compelling evidence has been found so far.

Is it really sufficient to search for new physics scale behind neutrino mass generation mechanism at LHC only?

The new physics scale behind neutrino mass generation mechanism might be at low scale and less sensitive to high energy collider experiments.

It may show up at low energy neutrino experiments at near future.
Neutrino masses from light physics

In an effective theory, the Lagrangian should be described as

\[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda_{\text{NP}}} \mathcal{O}^{d=5} + \frac{1}{\Lambda_{\text{NP}}^2} \mathcal{O}^{d=6} + \frac{1}{\Lambda_{\text{NP}}^3} \mathcal{O}^{d=7} + \ldots \]

Neutrino masses from a $n$-loop-induced dim-$d$ operator

\[ m_{\nu} = v \times \left(\frac{1}{16\pi^2}\right)^n \times \left(\frac{v}{\Lambda_{\text{NP}}}\right)^{d-4} \]
Neutrino masses from light physics

Gauge $U(1)_D$: SM has no charge, RH neutrinos $N$ have charge $+1$

Anomaly cancellation: $N'$ with opposite charge should be included

walks and quacks like inverse seesaw

$$M_\nu = \begin{pmatrix} 0 & m & 0 \\ m & 0 & M \\ 0 & M & \mu \end{pmatrix}_{\begin{array}{c} \nu \\ N \\ N' \end{array}} \begin{pmatrix} 0 \\ N \\ - \end{pmatrix} \implies m_\nu = \mu \frac{m^2}{M^2}$$

$m$ and $\mu$ are forbidden by dark symmetry, they need to be generated dynamically

Bertuzzo et al 1808.02500
**Neutrino masses from light physics**

**Minimum scalar content**

\[ M_\nu = \begin{pmatrix}
0 & y\phi_1 & 0 \\
y\phi_1 & 0 & M \\
0 & M & y's_2
\end{pmatrix} \]

- \( \phi_1 = \) doublet with dark charge +1
- \( s_2 = \) singlet with dark charge +2

Add \( s_1 \) with charge +1 and something special happens:
- \( \phi_1 \) and \( s_2 \) start with no vevs, \( s_1 \) develops a vev like the Higgs
- \( \phi_1 \) and \( s_2 \) vevs are **induced**, like in type II seesaw, and thus can be naturally very small!
\[ y\Psi^c H\ell + m_\Psi \Psi\Psi^c + \frac{1}{2} \mu \Psi \Psi \]

\[ m_\nu \sim \frac{y^2 v^2}{m_\Psi^2} \mu \]

\[ y \sim 0.1 \quad m_\Psi \sim 1 \text{ TeV} \quad \mu \sim 1 \text{ keV} \]

- Why \( \mu \) is much smaller than TeV scale?
Neutrino masses from light physics

Minimum scalar content

\[ M_\nu = \begin{pmatrix} 0 & y\phi_1 & 0 \\ y\phi_1 & 0 & M \\ 0 & M & y's_2 \end{pmatrix} \]

\( \phi_1 = \text{doublet with dark charge +1} \)

\( s_2 = \text{singlet with dark charge +2} \)

Add \( s_1 \) with charge +1 and something special happens:

\( \phi_1 \) and \( s_2 \) start with no vevs, \( s_1 \) develops a vev like the Higgs

\( \phi_1 \) and \( s_2 \) vevs are \textbf{induced}, like in type II seesaw, and thus can be naturally very small!
Neutrino masses from light physics

\[ M_\nu = \begin{pmatrix} 0 & y\phi_1 & 0 \\ y\phi_1 & 0 & M \\ 0 & M & y's_2 \end{pmatrix} \]

\[ \mathcal{L}_\nu = -y_\nu \bar{L} \phi N + y_N S_2 \bar{N} N^c + y_{N'} S_2' \bar{N}' N'^c + m \bar{N} N^c + \text{h.c.} \]

Add \( s_1 \) with charge +1 and something special happens: \( \Phi_1 \) and \( s_2 \) start with no vevs, \( s_1 \) develops a vev like the Higgs

\( \Phi_1 \) and \( s_2 \) vevs are induced, like in type II seesaw, and thus can be naturally very small!
Neutrino masses from light physics

\[ \mathcal{L}_\nu^{d=9} \sim \frac{\mu^2}{M_{H_D}} \frac{\mu'}{M_{S_D}'} \frac{(L^c H) (H^T L)}{m^2} (S_1^* S_1)^2 \]

Neutrino masses from D=9 operator

All scales involved may be below electroweak

Light $Z_D$, $\nu$-$N$ mixing, $Z_D$-$\nu$-$N$ coupling, kinetic mixing unavoidable
Neutrino masses from light physics

Vacuum Expectation Values

<table>
<thead>
<tr>
<th>$v$ (GeV)</th>
<th>$\omega_1$ (MeV)</th>
<th>$v_\phi$ (MeV)</th>
<th>$\omega_2$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>246</td>
<td>136</td>
<td>0.176</td>
<td>0.65</td>
</tr>
</tbody>
</table>

Coupling Constants

<table>
<thead>
<tr>
<th>$\lambda_{\tilde{H}}$</th>
<th>$\lambda_{H\phi} = \lambda_{\tilde{H}\phi}$</th>
<th>$\lambda_{HS_1}$</th>
<th>$\lambda_{HS_2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.129</td>
<td>$10^{-3}$</td>
<td>$10^{-3}$</td>
<td>$-10^{-3}$</td>
</tr>
<tr>
<td>$\lambda_{S_1 S_2}$</td>
<td></td>
<td>$2$</td>
<td>$0.01$</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td></td>
<td>$2$</td>
<td>$0.01$</td>
</tr>
<tr>
<td>$\mu$ (GeV)</td>
<td>$\mu'$ (GeV)</td>
<td>$\alpha$</td>
<td>$g_D$</td>
</tr>
<tr>
<td>0.15</td>
<td>0.01</td>
<td>$10^{-3}$</td>
<td>0.22</td>
</tr>
</tbody>
</table>

Bare Masses

<table>
<thead>
<tr>
<th>$m_\phi$ (GeV)</th>
<th>$m_2$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>5.51</td>
</tr>
</tbody>
</table>

Masses of the Physical Fields

<table>
<thead>
<tr>
<th>$m_{h_{SM}}$ (GeV)</th>
<th>$m_{H^\pm}$ (GeV)</th>
<th>$m_{S^\mp}$ (MeV)</th>
<th>$m_{S^0_2}$ (MeV)</th>
<th>$m_{H^0_1}$ (GeV)</th>
<th>$m_{A_D}$ (GeV)</th>
<th>$m_{a_D}$ (MeV)</th>
<th>$m_{Z_D}$ (MeV)</th>
<th>$m_{N_D}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>100</td>
<td>272</td>
<td>320</td>
<td>100</td>
<td>100</td>
<td>272</td>
<td>30</td>
<td>150</td>
</tr>
</tbody>
</table>

Mixing between the Fields

| $\theta_{H^\pm}$ | $\theta_{HS_1}$ | $\theta_{HS_2}$ | $\theta_{S_1 S_2}$ | $\theta_{S_2 S_1}$ | $\theta_{S_1 S_2}$ | $ee$ | $e'e'$ | $|U_{eN}|^2$ |
|-------------------|-----------------|-----------------|--------------------|--------------------|--------------------|------|--------|-------------|
| $1.3 \times 10^{-6}$ | $2.1 \times 10^{-6}$ | $10^{-8}$ | $1.2 \times 10^{-3}$ | $8.3 \times 10^{-7}$ | $3.4 \times 10^{-2}$ | $2 \times 10^{-4}$ | $3.6 \times 10^{-14}$ | $O(10^{-6})$ |

$$V = -m_H^2 (H^\dagger H) + m_\phi^2 (\phi^\dagger \phi) - m_{S_1 S_1}^2 S_1 + m_{S_2 S_2}^2 S_2$$

$$- \left[ \frac{\mu}{2} S_1 (\phi^\dagger H) + \frac{\mu'}{2} S_2^2 S_2^* + \frac{\alpha}{2} (H^\dagger \phi) S_1 S_2^* + \text{h.c.} \right]$$

$$+ \lambda_{H\phi} \phi^\dagger H H^\dagger \phi + \sum_{\{H,\phi,S_1,S_2\}} \lambda_{\phi} (\phi^\dagger \phi)^2$$

$$+ \sum_{\varphi < \varphi'} \lambda_{\phi\varphi'} (\phi^\dagger \varphi)(\varphi^\dagger \phi').$$

$$v_\phi \simeq \frac{1}{8\sqrt{2}} \left( \frac{\alpha \mu' v_\omega^2}{M_{S_D}^2 M_{H_D}^2} + 4 \mu_w v_\omega^2 \right)$$

$$\omega_2 \simeq \frac{1}{8\sqrt{2}} \left( \frac{\alpha \mu v_\omega^2}{M_{S_D}^2 M_{H_D}^2} + 4 \mu' v_\omega^2 \right)$$
**Phenomenology on other neutrino experiment**

**MiniBooNE’s signature:** Collimated $e^+e^-$ pair in MINOS+, NOvA, or T2K is likely be tagged as $\nu_e$ event

**General signature:**
Heavy enough $Z_D$ can decay to $\mu^+\mu^-$ or $\pi^+\pi^-$ pair, much easier signature (MINOS+ is magnetized...)

Lower energy experiments (reactor and solar neutrinos) as well as electron scattering may lack energy to produce N
What happens at the SBN program?

- No baseline dependence
- Almost no hadronic activity to tag interaction vertex
- Decays to collimated $e^+e^-$ pairs
- More events due to coherence:
  - $^6\text{C}$ vs $^{18}\text{Ar}$ ~ 3 times more events for same exposure
- Hard to probe !!!
Conclusions:

- Novel explanation of MiniBooNE
- Agreement with all EXP data
- Novel, simple framework
- Deep connection to neutrino mass generation mechanism
- A realistic “complete” model below EW scale to explain neutrino mass generation
- Solves the hierarchy of Inverse Seesaw
- Rich phenomenology
DO YOU KNOW MY ORIGIN?

PROBABLY YES!
DO YOU KNOW MY ORIGIN?

PROBABLY YES!

MiniBooNE
Thank you!