Short-Baseline Neutrino Oscillation Program at Fermilab

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Motivation: SBL Anomalies in ν-Physics

Reactor neutrino anomaly

Observed rates of interactions in detectors between 10 and 100 meters from the reactors are, on average, 6-7% lower than the expected.

Gallium anomaly

Calibration data in (Gallium) solar neutrino experiments reveal a deficit of electron neutrinos relative to the predicted rate.

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

Decay At Rest pion beam $\rightarrow \bar{\nu}_\mu$ beam [20-53] MeV about 30 m from a liquid scintillator-based detector

$\bar{\nu}_\mu \rightarrow (\text{oscillation}) \rightarrow \bar{\nu}_e + p \rightarrow e^+ + n$

$n + p \rightarrow d + \gamma$
Motivation: SBL Anomalies in $\nu$-Physics

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

Decay In Flight pion beam $\rightarrow$ predominately $\nu_\mu$ flavour broad beam with peak energy $\sim 700$ MeV at 540 m downstream of the BNB target at Fermilab

\[ \nu_\mu \xrightarrow{\text{(oscillation)}} \nu_e + n \rightarrow e^- + p \]
\[ \bar{\nu}_\mu \xrightarrow{\text{(oscillation)}} \bar{\nu}_e + p \rightarrow e^+ + n \]

Muon and electron neutrinos are identified in CC interactions by the characteristic signatures of Cherenkov rings:

MiniBooNE measured a low energy excess of electron-like events
While each of these measurements taken separately lack the significance to claim a discovery, together these signals could be hinting at important new physics.

The most common interpretation is as evidence for the existence of one (or more) additional, mostly “sterile” neutrino state with masses at or below the few eV range.

Definitive evidence for sterile neutrinos would be a revolutionary discovery, with implications for particle physics as well as cosmology.

Worldwide program proposing/building experiments to confirm/rule out these signals.
SBN@FNAL

✓ An accelerator-based neutrino beam facility provides a rich oscillation program with a single experiment:

• both neutrino and antineutrino modes
• $\nu_\mu \to \nu_e$ appearance
• $\nu_\mu$ and $\nu_e$ disappearance
• CC and NC interactions

✓ Detectors that can **distinguish electrons from photons** to reduce key backgrounds

✓ **Multiple detectors at different baselines** are key for reducing systematic uncertainties

<table>
<thead>
<tr>
<th>Detector</th>
<th>Distance from BNB Target</th>
<th>LAr Total Mass</th>
<th>LAr Active Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAr1-ND</td>
<td>110 m</td>
<td>220 t</td>
<td>112 t</td>
</tr>
<tr>
<td>MicroBooNE</td>
<td>470 m</td>
<td>170 t</td>
<td>89 t</td>
</tr>
<tr>
<td>ICARUS-T600</td>
<td>600 m</td>
<td>760 t</td>
<td>476 t</td>
</tr>
</tbody>
</table>
LAr TPC

- Passing charged particles ionize argon
- Electric field drifts electrons meters to wire chamber planes
- Induction/Collection planes image charge, record $dE/dx$
- Scintillation light produced copiously in liquid Argon: $t_0$ determination, rejection of cosmic rays, energy reconstruction or particle identification
**LAr TPC: electron/photon separation**

Significantly reduction in the backgrounds in searches for $\nu_e$ appearance relative to other technologies.
LAr TPC: electron/photon separation

Significantly reduction in the backgrounds in searches for $\nu_e$ appearance relative to other technologies
Multiple detectors

\[ N_{ND}^{data}(\nu_\mu) = \Phi_{ND}(\nu_\mu) \otimes \varepsilon_{ND}(\nu_\mu) \otimes \sigma_{ND}(\nu_\mu) \]

\[ N_{FD}^{expected}(\nu_\mu) = N_{ND}^{data}(\nu_\mu) \otimes \frac{\Phi_{FD}(\nu_\mu)}{\Phi_{ND}(\nu_\mu)} \otimes P(\nu_\mu \rightarrow \nu_\mu) \otimes \frac{\varepsilon_{FD}(\nu_\mu)}{\varepsilon_{ND}(\nu_\mu)} \otimes \frac{\sigma_{FD}(\nu_\mu)}{\sigma_{ND}(\nu_\mu)} \]

\( \nu_e \) cross section uncertainties

Uncertainty on the ratio of MicroBooNE to LAr1-ND due to cross section uncertainties

10-15% few %

arXiv:1503.01520v1
Multiple detectors

\[ N_{\text{ND}}^{\text{data}}(\nu_\mu) = \Phi_{\text{ND}}(\nu_\mu) \times \varepsilon_{\text{ND}}(\nu_\mu) \times \sigma_{\text{ND}}(\nu_\mu) \]

\[ N_{\text{FD}}^{\text{expected}}(\nu_\mu) = N_{\text{ND}}^{\text{data}}(\nu_\mu) \times \frac{\Phi_{\text{FD}}(\nu_\mu)}{\Phi_{\text{ND}}(\nu_\mu)} \times P(\nu_\mu \rightarrow \nu_\mu) \times \frac{\varepsilon_{\text{FD}}(\nu_\mu)}{\varepsilon_{\text{ND}}(\nu_\mu)} \times \frac{\sigma_{\text{FD}}(\nu_\mu)}{\sigma_{\text{ND}}(\nu_\mu)} \]

\( \nu_e \) cross section uncertainties

\( \nu_e \) cross section correlation matrix

![Graph showing uncertainties in \( \nu_e \) cross section with energy on the x-axis and uncertainty percentage on the y-axis.](#)

![Correlation matrix with few % uncertainty around the diagonal and 10-15% uncertainty off-diagonally.](#)

arXiv:1503.01520v1
Sensitivities:

We will use the “3+1” model as our baseline

\[ P_{\nu_\mu \to \nu_e}^{3+1} = \sin^2 2\theta_{\mu e} \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E_\nu} \right); \]

- Oscillation prob. increases along our BL
- At the far location it shifts towards the peak of the SBN flux
- ND measurements are an excellent constraint on the intrinsic beam content

The sensitivity is calculated by computing a \( \chi^2 \) surface in the \((\Delta m_{41}^2, \sin^2 2\theta_{\mu e})\) oscillation parameter plane according to:

\[
\chi^2(\Delta m_{41}^2, \sin^2 2\theta_{\mu e}) = \sum_{ij} \left[ N_i^{null} - N_i^{osc}(\Delta m_{41}^2, \sin^2 2\theta_{\mu e}) \right] (E_{ij})^{-1} \left[ N_j^{null} - N_j^{osc}(\Delta m_{41}^2, \sin^2 2\theta_{\mu e}) \right]
\]
Sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation signals

$\Delta m^2$ (eV$^2$)

$\sin^2 2\theta_{\mu e}$

T600, 6.6e+20 POT (600m)
MicroBooNE, 1.32e+21 POT (470m)
LAr1-ND, 6.6e+20 POT (100m)

INTERNAL
$\nu$ mode, CC Events
Reconstructed Energy
80% $\nu_e$ Efficiency
Stat., X-Sec., Flux, Cosmics, Dirt
$\nu_e$ Only Fit

90% CL
3$\sigma$ CL
5$\sigma$ CL

LSND 90% CL
LSND 99% CL
LSND Best Fit

Global Best Fit (arXiv:1303.3011)
Global Fit 90% CL (arXiv:1303.3011)

Global Best Fit (arXiv:1308.5288)
Global Fit 90% CL (arXiv:1308.5288)

Sensitivity to $\nu_\mu \rightarrow \nu_e$ oscillation signals

arXiv:1503.01520v1
$\nu_\mu \rightarrow \nu_X$ disappearance sensitivity

SBN can extend the search for muon neutrino disappearance an order of magnitude beyond the combined analysis of SciBooNE and MiniBooNE.
Conclusion:

✓ The Fermilab Short-Baseline Neutrino program will provide a definitive answer about whether the short-baseline anomalies can be attributed to neutrino oscillations

✓ Definitive evidence for sterile neutrinos would be a revolutionary discovery
Back-Up
Current experimental results

Radioactive sources

Reactors
**Electron Appearance Analysis: Event Selection**

- Events are selected based upon their topology.

- We require that the event occurs away from the detector boundaries and that there is no gap between the shower and an energetic vertex:
  - Vertices must have $>50\text{MeV}$ to be detected and the shower must be $>3\text{cm}$ away to be rejected.
  - Reduces possible photon backgrounds.

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Muon Disappearance Analysis: Event Selection

- We select events with a fully contained muon
  - To measure the energy of this muon we would leverage the calorimetry
- If the muon track exits the volume we would rely on the multiple coulomb scattering of the track to determine its energy
  - This requires at least a 1 m track to correctly assess
  - Therefore we require that all exiting tracks be at least 1 m in length

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• The horn focuses charged pions which in-turn decay into muon neutrinos as they propagate down the 50m long decay pipe

• Additional hadrons and muons also produce neutrinos including electron neutrinos

• It is important that we understand the beam composition

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