Sterile Neutrino Searches at Accelerators

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Are there other neutrinos aside from the three SM neutrinos?

- Probe of sterile neutrinos at accelerators: \(\nu_\mu \rightarrow \nu_e\)

Two-Flavor Approximation:

\[
P_{\alpha \rightarrow \beta, \alpha \neq \beta} = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m^2 L}{E} \right)
\]
Motivation:
**LSND and MiniBooNE**
The LSND Anomaly

- **LSND**: Liquid Scintillator Near Detector (Los Alamos National Lab)
  - Mainly $\bar{\nu}_\mu$ from stopped $\mu^+$ decay at rest
  - $L/E \sim 1 \text{ m/MeV}$ ($L \sim 30 \text{ m}, E \sim 30 \text{ MeV}$)
- Excess of $\bar{\nu}_e$-like events observed
  - $3.8 \sigma$ excess; $\Delta m^2$ in $[0.2, 10]$ eV$^2$ range
MiniBooNE: ~800 t mineral oil Cherenkov detector on FNAL Booster Neutrino Beamline (BNB)

- Mainly $\nu_\mu/\bar{\nu}_\mu$ from $\pi/\mu$ decay in flight
- $L/E \sim 1$ ($L \sim 500$ m, $E \sim 500$ MeV)

17 years of operation in total

- $3 \times 10^{21}$ POT (protons on target)
The MiniBooNE Anomaly

- Low-energy $\nu_e / \bar{\nu}_e$ candidate excess (LEE) also seen at MiniBooNE
  - Baseline too short ($L = 541$ m) for 3-flavor $\nu_\mu \rightarrow \nu_e$ oscillation
  - $4.8 \sigma$ excess $\rightarrow 6.1 \sigma$ when combined with LSND (consistent results)

- No $e^\pm/\gamma$ separation... is excess misunderstood background, sterile neutrino, or... ?

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Some Tension

Tension between $\nu_\mu$ disappearance (left) and $\nu_e$ appearance (right) results, which show incompatibility.

Important to clarify this issue, e.g. by measuring $\nu_\mu$ disappearance and $\nu_e$ appearance at same experiment (SBN).
Some Tension

C. Ternes (Yesterday’s Talk)

- Tension between $\nu_\mu$ disappearance (left) and $\nu_e$ appearance (right) results, which show incompatibility
- Important to clarify this issue, e.g. by measuring $\nu_\mu$ disappearance and $\nu_e$ appearance at same experiment (SBN)
Liquid Argon Time Projection Chambers (LArTPCs)
Introducing... the LArTPC

♦ Liquid Argon Time Projection Chamber

♦ Advantages of LArTPC detectors

  • *Low Thresholds* – important for detecting low-energy particles (e.g. protons from hadronic part of neutrino interactions)
  • *Excellent Calorimetry* – important for precise estimation of neutrino energy, particle ID with dE/dx
  • *High Spatial Resolution* – allows for background rejection and particle ID
  • *Scalability* – large detectors yielding high event rates for precision physics

♦ LArTPCs can help with e/γ separation

  • Addresses limitation at MiniBooNE
Signal Formation

Cathode Plane

$E_{\text{drift}} \sim 500 \text{ V/cm}$

Three Anode Wire Planes
Signal Formation

Cathode Plane

$E_{drift} \sim 500 \text{ V/cm}$

Drift

MicroBooNE Data

Three Images (One Per Wire Plane)
Two ways to discriminate $e/\gamma$ with LArTPCs:

- Shower displacement from vertex ("gap") for $\gamma$ (none for $e$)
- Factor of two difference in $dE/dx$ ($\gamma$ double that of $e$)
Short Baseline Neutrino (SBN) Program
SBN Program: three LArTPC detectors @ FNAL BNB

- Same beamline as MiniBooNE (BNB), but with e/γ discrimination
- SBND (Short Baseline Near Detector): provides flux/xsec constraint
- MicroBooNE/ICARUS: measure oscillated neutrino rate
MicroBooNE (μBooNE)

♦ MicroBooNE: “Micro Booster Neutrino Experiment”

♦ Notable details:
  • Taking data between 2015 and 2021
  • Cold (in LAr) front-end electronics (same for SBND, but not ICARUS)
  • UV laser calibration system

♦ Physics goals:
  • Investigate MiniBooNE low-energy excess (LEE)
  • Measure first low-energy ν-Ar cross sections
  • Key step for SBN Program
  • R&D for Deep Underground Neutrino Experiment (DUNE)
Two distinct LEE approaches:

- $\nu_e$ analyses (three in total):
  - MiniBooNE-like final state ($1eNp/1e0p$)
  - Quasi-elastic kinematics w/ ML ($1e1p$)
  - All $\nu_e$ final states ($1eX$)
- Single photon production ($1\gamma1p/1\gamma0p$)

Expect first public LEE results to come out soon
♦ ICARUS began commissioning in 2020, collecting first neutrino data in June 2021; transitioning to physics data collection in October 2021

♦ Stable noise levels (S/N > 10), good electron lifetime (> 3 ms)

♦ Expected BNB/NuMI rates observed via light flashes in PMTs
ICARUS Status

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♦ Stable noise levels (S/N > 10), good electron lifetime (> 3 ms)

♦ Expected BNB/NuMI rates observed via light flashes in PMTs
ICARUS was the primary BNB user @ FNAL during the full month of June 2021 (“Run 0”)

- $27.8 \times 10^{18}$ POT from BNB and $52.0 \times 10^{18}$ POT from NuMI were collected
♦ Cathode installed in TPC; rest of components ready at FNAL
♦ Warm outer vessel installed in building; cryostat top fabricated and cryogenics/cryostat installation in progress
♦ SBND ready for cold commissioning by end of 2022
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Reflects **2-3 years** of neutrino-mode data-taking at **ICARUS and SBND** (double dataset for MicroBooNE)

**SBN only probe of both** $\nu_e$ **appearance and** $\nu_\mu$ **disappearance**

at same experiment
Beyond SBN
♦ **JSNS²**: J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source – liquid scintillator w/ Gd-doping

♦ **Direct test of LSND anomaly**: nearly identical source (μ DAR), target (liquid scintillator), and baseline (~25 m)

  - First data collection in **June 2020, first half of 2021** (analysis ongoing); upgrade planned w/ more data-taking starting in **2023**
Accelerator neutrino experiments have much to say about potentiality of sterile neutrinos

- Previous anomalies:
  - LSND
  - MiniBooNE

- Running/upcoming experiments:
  - MicroBooNE
  - SBN Program (SBND and ICARUS joining MicroBooNE)
  - JSNS$^2$

Given experimental landscape, next few years should be very exciting for this topic!
Thanks!