Sterile Oscillations and the Short-Baseline Neutrino Program at Fermilab

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Prospects in Neutrino Physics, 2018
Current state of the field

- Well established three neutrino mixing and oscillations with the data from solar, atmospheric and accelerator experiments
- "Large" mixing angle $\Theta_{13}$ opened the way to measure $\delta_{\text{CP}}$ and we have the first hints of non-zero $\delta_{\text{CP}}$
- Mass hierarchy, absolute mass, $\delta_{\text{CP}}$ value, existence of sterile neutrinos are some of the remaining open questions
Evidence for an low energy electron-like excess from neutrinos from particle accelerators (the “LSND and Mini-BooNE anomalies”)

- LSND observed a (3.8 sigma) excess of $\nu_e$ events in a very pure $\bar{\nu}_\mu$ anti-numu beam
- MiniBooNe observed a (4.5 sigma) excess of low energy electromagnetic events in neutrino and antineutrino mode in a $\nu_\mu / \bar{\nu}_\mu$ beam
Neutrino anomalies

- $\nu_e$ disappearance signal in the low energy anti-neutrinos from nuclear reactors ("reactor anomaly") and from radioactive neutrino sources in the Gallium experiments ("Gallium anomaly")
Global fits (3+1 model)

- Short-baseline neutrino anomalies are often interpreted as oscillations involving sterile neutrinos with $\Delta m^2 \sim 1 \text{eV}^2$ and an $L/E \sim 1 \text{km}/\text{GeV}$
- However, there is a strong tension with experiments that observe no signal
  - Significant constraints from disappearance measurements, especially recent measurements by IceCube and MINOS+
- To conclude the short-baseline anomalies, new experimental efforts are needed
  - Repeating similar measurements
  - New ways addressing oscillation hypothesis
    - Appearance and disappearance data from the same experiment
Short-Baseline Neutrino (SBN) program at Fermilab

- Three liquid argon time projection chamber (LArTPC) detectors in the Booster Neutrino Beam (BNB) at Fermilab.
Search for sterile neutrinos: $\nu_\mu \rightarrow \nu_e$ appearance

- A large mass far detector and a near detector of the same technology reduces both statistical and systematic uncertainties
- SBN detectors enable $5\sigma$ coverage the 99% C.L. allowed region of the LSND signal and global best fit values

Search for sterile neutrinos: $\nu_\mu$ disappearance

- SBN can extend the search for muon neutrino disappearance an order of magnitude beyond the combined analysis of SciBooNE and MiniBooNE
- Critical aspect to verify an oscillation hypothesis

\( \nu \)-Ar cross section studies

- \( \nu \) oscillation experiments require precise understanding of \( \nu \)-Ar interaction cross section for a correct interpretation of the experimental outcome.
- SBN will provide huge data sets of \( \nu \) – Ar interactions from BNB and off-axis NuMI
  - Large samples in MicroBooNE are already under analysis and first results have recently been published.
  - SBND will record 1.5 million \( \nu_\mu \) CC and \( \sim 12k \nu_e \) CC interactions per year.
  - \( \sim 100k \) NuMI off-axis events in T600 per year.
Fermilab Booster Neutrino Beam

- Fermilab’s low-energy Booster Neutrino Beam (BNB)
  - 8 GeV protons hit on Be target create neutrino flux with 700 MeV peak energy
  - Neutrino and antineutrino modes
  - ~0.5% electron neutrino contamination in neutrino mode
  - Stably running for a decade
SBN experimental setup

ICARUS
- LArTPC
- 600 m from $\nu$ production
- 476 ton active volume
- 4x1.5 m drift length
- 75kV high voltage
- 3 wire planes: horizontal, $\pm 30$ deg, 3mm wire pitch, 53246 wires
- Warm analog and digital electronics
- 360 8” PMTs

MicroBooNE
- LArTPC
- 470 m from $\nu$ production
- 85 ton active volume
- 2.56 m drift length
- 128 kV high voltage
- 3 wire planes: 0, $\pm 60$ deg, 3mm wire pitch, 8256 wires
- Cold analog/warm digital electronics
- 32 8” PMTs

SBND
- LArTPC
- 110 m from $\nu$ production
- 112 ton active volume
- 2x2.0 m drift length
- 100 kV high voltage
- 3 wire planes: 0, $\pm 60$ deg, 3mm wire pitch, 11264 wires
- Cold analog and digital electronics
- 120 8” PMTs & scin. bars

INSTALLATION

RUNNING

UNDER CONSTRUCTION
Phase-1: MicroBooNE

- Installation completed in 2015
- Collection date since October 2015 at BNB line at Fermilab with main goals of
  - Addressing the MiniBooNE low energy access
  - Performing Neutrino -- Argon cross section measurements
  - Performing R&D for future LArTPCs
- >96% uptime during stable operations and so far collected $\sim 10^{21}$ POT
Ongoing efforts and publications

- MicroBooNE is doing an excellent job on LArTPC calibration, simulation, reconstruction and developing analysis tools for future detectors
  - Understanding the detector technology
  - Develop automated LArTPC reconstructions using 2D, 3D and machine learning techniques
  - Constrain ν-Ar interaction models with data
  - Develop multiple independent low energy excess searches

- Public notes:
  - 30 analysis documented in details

- Posters in this conference
  - Thomas Mettler, “The Cosmic Ray Tagger of MicroBooNE”
  - Andy Smith, “The Pandora consolidated multi-algorithm approach to pattern recognition in MicroBooNE”
  - Andrew Furmanski, “MicroBooNE Cross Section Measurements”
Understanding $\nu$-Ar interactions and developing excess searches

- MicroBooNE’s first physics results this year
- Understanding $\nu$-Ar interactions:
  - $\nu_\mu$ CC inclusive cross section
    - Starting point for more exclusive channels
    - First measurement on Ar at low energy
  - $\nu_\mu$ CC pi0 production
    - First such measurement on Argon
    - Enables studies of shower energy reconstruction and resolution in data
  - For more details, see the poster “MicroBooNE Cross Section Measurements” by Andy Furmanski

- Low energy excess searches
  - Blind search strategy (small subset of open data)
  - Independent $e$-like and $\gamma$-like analysis
    - Complementary analysis targeting different final states
  - Completed first iteration of fully-automated $\nu_e$ and single photon selection
Phase-2: MicroBoNE + ICARUS and SBND
The ICARUS detector

- ICARUS is going to be the far detector in the SBN program
- It was operational at LNGS from 2010-2013
- In 2015, sent to CERN for refurbishment
- Shipped to Fermilab in June 2017
Status of ICARUS

- Rigging and placement of the two modules into vessel was completed in August 2018
- Cold shielding and closing of the warm vessel has been finalized
- Process will continue with cryogenics, purification, vacuum and cabling activities
- Commissioning and data taking in 2019
Short-Baseline Near Detector – SBND

- Near detector at SBN with main goals
  - Detailed characterization of beam before oscillation
  - Reduction of the dominant systematics
  - Cross section studies with 1.5 million $\nu_\mu$ CC and 12k $\nu_e$ CC interactions per year
    - see poster from Rhiannon Jones for $\nu_\mu$ CC 0π Selection in SBND
  - Detector R&D for DUNE far detector

- Detector design has been finalized. Components are under construction
- Detector building is ready at Fermilab
SBND detector

- Completely new detector incorporated experience from ICARUS, MicroBooNE
- LArTPC with 112 ton active volume
- Synergies with PrototDUNE for future large LArTPCs
SBND detector construction

For more details, please see the poster “Cosmic background removal with the cosmic ray tagger system in the Short-Baseline Near Detector” by Tom Brooks.
SBND field cage

- Provides uniform electric field inside the active volume and surcharge protection
  - Receives bias voltage from cathode planes, terminates to ground at anode planes
- Mechanically connects anode and cathode planes, maintains the drift distance
- Accommodates laser beam from the laser calibration system to enter into the active volume
- 16 independent modules
  - Aluminium field shaping profiles
  - Reinforced fibreglass mechanical supports
  - Divider and surcharge protection circuits
SBND high voltage feedthrough

- 100 kV nominal SBND high voltage, generated by an external power supply, is delivered to cathode via high voltage feedthrough

Design basics:
- Coaxial design: UHMWPE is interleaved with the stainless steel inner and outer conductors
- Cryo-fit for leak tight seal

Main components
- High voltage cable plug
- Top flanges
- Inner and outer conductors
- UHMWPE insulator
- Bottom spring tip
SBND high voltage feedthrough

- Tested at CERN, in a set up reflecting more extreme boundary conditions than we’ll have in SBND
- Worked perfectly at 150 kV (50% higher than the nominal SBND high voltage)
Conclusions

- SBN program consists of three LArTPCs that will sit in the Fermilab BNB beam and will
  - study the baseline dependence of the appearance and disappearance channels and cover the full LSND allowed parameter space with 5σ
  - make a high precision measurement on ν-Ar cross sections
  - develop LArTPC technology for future large neutrino experiments like DUNE

- A lot of progress has been achieved in the program
  - MicroBooNE is a big success - has already collected $\sim 10^{21}$ pot from BNB, has recently published first physics results and working on it's signature analysis
  - SBND is making excellent technical progress on construction the detector pieces and improving the LArTPCs for future experiments
  - ICARUS detector has been installed and getting ready for commissioning

- Stay tuned for three detector run and physics results