Standard Model neutrinos

Over two decades of Oscillation experiments have established...

3–\(\nu\) paradigm

\[
|U_{PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}
\]

- **3 mixing angles:** \(\theta_{12} \sim 33^\circ, \theta_{13} \sim 8^\circ, \theta_{23} \sim 45^\circ\)

- **2 mass splittings:** \(\Delta m^2_{21} \sim 7.5 \times 10^{-5} \text{ eV}^2\), \(|\Delta m^2_{32}| \sim 2.5 \times 10^{-3} \text{ eV}^2\)

- **1 CP violation phase** \(\delta_{CP}\)
Short Baseline Anomalies

LSND $\bar{\nu}_e$ Excess

"Gallium Anomaly" solar $\nu_e$ deficit

"Reactor Anomaly" $\bar{\nu}_e$ deficit

Hint oscillation from additional "Sterile" neutrino(s) $m_4 \sim 1\text{eV}$

MiniBooNE $\nu_e/\bar{\nu}_e$ Excess at low energy

@ Fermilab
On-axis of Booster neutrino beamline
MiniBooNE “Low-Energy-Excess” anomaly

MiniBooNE LEE results

- 4.8σ excess of ν_e-like events at low energy.
- Large photon (γ) backgrounds, MiniBooNE detector is not able to distinguish e− from γ.

Both e− & γ

Proton

π0

MiniBooNE

- ~820 tonnes oil Cherenkov detector
- Fermilab Booster Neutrino beam
- L/E ~1 m/MeV
MicroBooNE goes after MiniBooNE Low-Energy-Excess

MicroBooNE experiment

- Located on-axis of Fermilab’s Booster neutrino beamline (L~470m), same L/E as MiniBooNE.
  - Off-axis on NuMI
- A LArTPC detector with 85 tonne active volume
Liquid Argon TPC – advantage on particle ID

- Two type of detector signals: **scintillation light** and **drift electrons**
- Capable of providing full 3D reconstruction in $4\pi$.
- Capable of calorimetric energy reconstruction.
MicroBooNE Operation

• 5 years operation from 2015 to 2020

• Collected the largest neutrino dataset from a LArTPC detector

• Two post operation runs dedicated for LArTPC detector R&D until 2021

• The analyses results shown here are using about half of the total collected BNB POT

BNB data $\sim 7 \times 10^{20}$ POT in this talk
MicroBooNE’s mission and science output

• More than 45 publications in the past 5 years [https://microboone.fnal.gov/documents-publications/]
• More than 75 public notes sharing progress with community as we go [https://microboone.fnal.gov/public-notes/]

Understand MiniBooNE LEE & other New Physics Searches

Precision measurements of $\nu$ – Ar cross-sections

Pioneering R&D of LArTPC detector technology

MicroBooNE’s LEE & other New Physics Searches

More than 45 publications in the past 5 years

https://microboone.fnal.gov/documents-publications/

More than 75 public notes sharing progress with community as we go

https://microboone.fnal.gov/public-notes/
MicroBooNE’s cross-section program

- Prediction of $\nu - \text{Ar}$ interactions at low energy relies on neutrino generators, which have large uncertainty not verified by experimental data.
- MicroBooNE’s cross-section program aims to provide direct data constraints of cross-section modeling for its new physics searches.
- Collected 0.5M $\nu - \text{Ar}$ events, critical input for DUNE’s LBL oscillation program.
MicroBooNE’s cross-section program

Inclusive cross-section
($\nu_\mu CC$ -- Phys. Rev. Lett. 128, 151801)

- Neutrino flux in MicroBooNE has 95% of muon neutrinos.
- Inclusive charged current channel is key to oscillation analyses.
- Offers background rates constraints for new physics search (ie. LEE analyses) in all final states.

Exclusive cross-section
($NC\pi^0$ -- arxiv2205.07943)

- $NC\pi^0$ (no charge lepton) is dominant background for many BSM searches.
- X-sec measurement to provide data constraint.
MicroBooNE’s cross-section program

MicroBooNE’s cross-section program:

1. $\nu_\mu$ CC Np0$\pi$ [1D differential]  
   Phys.Rev.D 102 (2020) 11, 112013

2. $\nu_\mu$ CCQE-like [1D differential]  

3. $\nu_\mu$ CC inclusive [2D differential]  

4. $\nu_e$ CC [inclusive]  
   Phys.Rev.D 104 (2021) 5, 052002

5. $\nu_e$ CC [1D differential]  
   Phys.Rev.D 105 (2022) 5, L051102

6. $\nu_\mu$ CC inclusive [1D differential]  
   Phys.Rev.Lett. 128 (2022) 15, 151801

7. Proton multiplicity  

8. $\nu_\mu$ CC $\pi^0$ [integrated]  

9. GENIE-tune paper  
   Phys.Rev.D 105 (2022) 7, 072001

10. NC $\pi^0$ production [integrated]  
    arXiv:2205.07943 [submitted to PRD]
MicroBooNE’s flagship analysis – Low-Energy-Excess

Understand MiniBooNE LEE & other New Physics Searches

Addressing origin of the MiniBooNE anomaly
• ~eV sterile neutrinos
• Other BSM physics

MiniBooNE’s excess events with EM shower

Two Handles for e/γ separation
• Gap Vs no Gap
• 1MIP Vs 2MIP at the shower start
MicroBooNE’s 1st round LEE analyses

Two types of analysis defined by the final state event topologies:
- Electron-like: searching for LEE in the $\nu_e$ channel
- Photon-like: searching for LEE in the photon channel

Blind analysis procedure, four independent analysis teams to minimize bias.

Details see Andrew Morgan’s talk on Monday’s parallel session @4pm
\( \nu_e \) low-Energy Excess (eLEE) search

**Signal model**
Empirical signal model assuming MiniBooNE LEE events are entirely electron neutrinos;

See details here: MICROBOONE-NOTE-1043-PUB

---

**3 independent eLEE analyses**

- Different final states
- Different event reconstruction and selection techniques;
- Blind analysis, sensitivity studied with Mock data

---

**Deep Learning**
Simple topology
Simpler \( E_\nu \) reco (CCQE)
Lower backgrounds

**Pandora**
Larger signal stat.
Less model dependency
MiniBooNE topology

**Wirecell**
Inclusive -> sensitive
Less model dependency
Most useful for DUNE
eLEE signal events and energy spectra

1e0p candidate

Eff./purity: 9%/43%
Phys. Rev. D105, 112004 (2022)

1e1p candidate

Eff./purity: 7%/75%
Phys. Rev. D105, 112003 (2022)

1eNp candidate

Eff./purity: 15%/80%
Phys. Rev. D105, 112004 (2022)

1eX candidate

Eff./purity: 46%/82%
Phys. Rev. D105, 112005 (2022)
Observed $\nu_e$ candidate rates are statistically consistent with the predicted background rates in the LEE region:
- Slight data deficit overall
- 1e0p least sensitive, background dominated

The hypothesis that $\nu_e$ events are fully responsible for the median MiniBooNE LEE is rejected at 97% C.L; $>3\sigma$ in the inclusive channel
3+1 sterile neutrino search

The selection used for eLEE search can be reinterpreted to test the hypothesis of an extra eV-scale sterile neutrino.

With the inclusive $\nu_e$ (i.e. 1e+X) selection, a 3+1 oscillation fit framework is developed to search for $\nu_\mu$ disappearance, $\nu_e$ appearance, and $\nu_e$ disappearance.

Details on excluding 3+1 sterile neutrino parameter space can be found in MicroBooNE’s recent public note: [MICROBOONE-NOTE-1116-PUB](#). Preliminary results using CCQE selection is documented in [MICROBOONE-NOTE-1106-PUB](#) and [MICROBOONE-NOTE-1105-PUB](#).

Future analysis developments include using full MicroBooNE dataset and combined analysis with BNB and NuMI data for increased sensitivity, coming soon!
Photon LEE search: $\Delta$ radiative decay

One contributor to the MiniBooNE signal channel is NC $\Delta \rightarrow N\gamma$

A flat factor of 3.18 enhancement of the SM rate of this channel would match the MiniBooNE LEE

NC $\Delta \rightarrow N\gamma$ is Standard Model process
- Rare, 0.6% branching ratio
- Never been directly observed in neutrino scattering

NC $\Delta \rightarrow N\gamma$ signal can manifest to two event topologies:
- single photon without proton (N is neutron)
- single photon with one proton (N is proton)

$1\gamma + 0$ proton

$1\gamma + 1$ proton
Photon LEE (NC $\Delta \to N\gamma$) search result

**Analysis**
- One-bin analysis
- Use NC$\pi^0$ rich 2$\gamma$ selection to provide data-driven background constraint

**Result**
- Observed no data excess in both NC $\Delta \to N\gamma$ signal channels
- Disfavor NC $\Delta \to N\gamma$ induced single-photon as a sole source of the MiniBooNE excess
- Set a new best limit of $\Delta \to N\gamma$ rate (x2.3 SM prediction at 90% C.L.), 50-fold improvement over previous T2K limit in the sub-GeV neutrino range.

NC $\Delta \to N\gamma$ unlikely the explanation of MiniBooNE excess!
Further LEE investigations in MicroBooNE

- 1st round of LEE analyses searched for anomaly in $\nu_e$ channel and NC $\Delta \rightarrow N\gamma$, no excess has been observed.
- The origin of MiniBooNE LEE is still unknown, and we have not ruled out the possibility of the excess in all the photon-like channels.
- Next immediate question: Do we see an excess in the inclusive photon-like channel?

**LEE search**

**Inclusive photon channel**

$(1\gamma + X)$

What physics process can fit in this Signal definition?

- NC$\pi^0 \rightarrow \gamma\gamma$ with only one visible $\gamma$ (i.e. escape detector, below detection threshold...)
- Higher resonant radiative decay
- NC coherent
- BSM induced $\gamma$ or $e^+e^-$ (collimated) in the final state
- ...

Details of event selection for the LEE search in the inclusive photon channel is: [MICROBOONE-NOTE-1102-PUB](#)
Further LEE investigations in MicroBooNE

As more questions being answered along the investigation, our LEE search can be narrowed down to target on particular models.

Do we see an excess in the inclusive photon-like channel?

- No
- Yes

Is the excess shower true photon?

- No
- Yes

Who produced this photon?

- Low Energy Muons?
- Other SM Process: e.g. NC Coherent
- Trans Mag. Mom.
- Dark Pseudo-Scalar

Numerous BSM models predict single photon-like shower (either true $1\gamma$ or $e^+e^-$) in the final state.

Dedicated BSM searches are conducted in MicroBooNE, offering competitive sensitivities in the sub-GeV range. See Pawel Guzowski’s talk (Monday @ 16:20) for exciting progress of BSM searches in MicroBooNE!
BSM searches with ns timing

Neutrinos are produced in a 2ns bucket with 18ns spacing between bucket

Massive BSM particles, if produced at the target at the same time as neutrinos, will arrive at the detector later than neutrinos due to heavier mass.

Neutrino interactions are the most common background for BSM searches. This difference of arrival time offers an effective handle for neutrino background rejection, only if nanosecond timing resolution is achieved.

MicroBooNE recently improved timing resolution from O(100) to O(1) ns. Details can be found in MICROBOONE-NOTE-1115-PUB
1. MicroBooNE recently published its 1st round of LEE result
   • No excess observed in the nue channel
   • No excess observed in the NC Δ → Nγ channel

2. Continuous investigation on MiniBooNE LEE are progressing:
   • 3+1 sterile neutrino fit
   • Dedicated BSM searches (e.g. HNLs, Higgs Portal Scaler results) with final states of e⁺e⁻ and single photon.

3. With the largest ν-Ar interaction dataset from a neutrino experiment, MicroBooNE has been pioneering LArTPC detector technology and providing critical cross-section measurements for future neutrino oscillation projects such as SBN and DUNE.

Thank you!