THE MICROBOONE EXPERIMENT AND THE LOW-ENERGY EXCESS

INTERNATIONAL CONFERENCE ON NEUTRINOS AND DARK MATTER

Wouter Van De Pontseele – On behalf of the MicroBooNE collaboration
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University of Oxford, Harvard University
• **Three neutrino picture** is well understood.
• **Anomalous results** in past neutrino measurements.

1. The low-energy excess.
2. The MicroBooNE experiment.
3. Recent cross-section results.
4. The search for an anomaly.
Neutrino Beams at Fermilab

- Booster $\nu$ beam
  - MicroBooNE, SBN program
  - Proton energy: 8 GeV

- NuMI $\nu$ beam
  - NOvA, MINERvA, MINOS+

- DUNE $\nu$ beam
  - (planned)

Main Injector
- Proton energy: 120 GeV
1. **LSND** sees $\bar{\nu}_e$ appearance from a well understood $\bar{\nu}_\mu$ neutrino source [1].
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2. **MiniBooNE** has different $L, E$, but similar $L/E \sim \text{LSND } \mathcal{O}(1 \text{ m MeV}^{-1})$.

#### The MiniBooNE Low-Energy Excess [2]
- In Fermilab’s Booster Neutrino Beam, since 2002.
- Mineral Oil Cherenkov detector.
- Excess of events observed, as in LSND.
A STEP BACK IN TIME: A PUZZLING COLLECTION OF ANOMALIES

1. **LSND** sees $\bar{\nu}_e$ appearance from a well understood $\bar{\nu}_\mu$ neutrino source [1].

2. **MiniBooNE** has different $L, E$, but similar $L/E \sim LSND \mathcal{O}(1 \text{ m MeV}^{-1})$.

### The MiniBooNE Low-Energy Excess [2]
- In Fermilab’s Booster Neutrino Beam, since 2002.
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3. **MicroBooNE**: same $L, E$ with different technology.
PARTICLE IDENTIFICATION IN MINIBooNE

MiniBooNE sees an excess of low energetic electromagnetic events. No discrimination between a single photon and an electron + insensitive to protons. The origin of the excess remains unclear.

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Physics Goals

- Liquid Argon Time Projection Chamber (LArTPC) R&D.
- Address electromagnetic low-energy excess observed by MiniBooNE.
- Cross-section measurements on argon.
- First step in the Fermilab short baseline neutrino program.
MICROBOONE DATA EVENT

Run 5906, Subrun 74, Event 3710
MicroBooNE Data

Plane 0: Induction

Electromagnetic Shower

Plane 1: Induction

Proton Track

Plane 2: Collection
How to Resolve the Low-Energy Excess Anomaly

Detector Understanding
- Signal processing.
- Detector calibration.
- Event reconstruction.

Systematic Uncertainties
- Neutrino flux from beam.
- Cross-section modelling.
- Detector effects.

Neutrino-Argon Interactions
- First low-energy $\nu$-Ar data, probe little known nuclear effects.
- $\pi^0$ production can mimic electrons.

Search for the Excess
- Different signatures:
  - $e/\gamma$
  - proton tracks, vertex activity
  - energy range
- Selection
- Statistical tests and methods
Three different reconstruction approaches in MicroBooNE:

- First time **fully automatic** event reconstruction used in LArTPC.
- Serve to **cross-check** each other in parallel efforts.
- Essential build-up of **expertise for DUNE, SBND and ICARUS**.
1. Determination of $\nu$ interaction rates.
2. Understand the nuclear model: neutrino-nucleus scattering model and intranuclear processes.
3. Comparison with generators: GENIE 2/3, NuWro, GiBUU.

→ Impact energy reconstruction.
→ Necessary for oscillation measurement.
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First Cross-section results from MicroBooNE

- Using Run 1 data-set, ≈13% of total POT collected.
- Measurement of $\nu_\mu$ Charged-Current $\pi^0$ Production on Argon [6]
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Cross-section talk tomorrow by Steve Dytman!
TWO POSSIBLE MODELS TO EXPLAIN THE LOW-ENERGY EXCESS

Electron-like Search
Electron neutrinos from oscillation

Photon-like Search
Neutral current $\Delta \rightarrow N\gamma$
Unfolding the MiniBooNE excess (MICROBOONE-NOTE-1043-PUB)

Electron-like Search

Photon-like Search

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**PARTICLE IDENTIFICATION: PHOTONS VS ELECTRONS**

- \( e/\gamma \) separation due to differences in the start of the electromagnetic shower.

- Demonstrated using photons from \( \pi^0 \) decay [7].

1. \( dE/dx \)
2. Detached shower start point
• Neutral current \(\Delta \rightarrow N\gamma\) has never been measured in neutrino scattering → large cross-section uncertainties.

• Boosted decision trees to reject:
  1. Cosmogenic backgrounds
  2. Neutrino induced backgrounds

• **Dominating background** is neutral current \(\pi^0\)
  → Second shower difficult to reconstruct!

MICROBOONE-NOTE-1041-PUB
• ≈ 15k cosmic muons per neutrino interaction.
• ≈ 200 $\nu_\mu$ per $\nu_e$ in the beam if no additional oscillations.

→ Needle in haystack situation!

• Blinded search: Selection being developed on 4% of the data (Booster Neutrino Beam).

• Covering all bases!
  Simultaneously targeting different final states:
  • $1e0\pi Np$: low energy, vertex activity, golden channel.
  • $1e0\pi0p$: lowest energy, difficult to select.
  • $1eX$: Inclusive channel, important model independent cross-check.

→ Current status: MICROBOONE-NOTE-1038-PUB
→ New results soon!
The Off-axis NuMI beam offers the chance to develop an inclusive electron neutrino selection at similar energy on a large data-set.
**Constraining the Uncertainties with Muon Neutrinos**

$\nu_\mu$ and $\nu_e$ have much in common:

- **Flux:** both species of neutrinos come from the same beam, from decays of the same populations of hadrons.

  Dominant production modes:
  
  - $\nu_\mu$: $\pi^+ \rightarrow \mu^+ \nu_\mu$ \hspace{1cm} 94%
  - $\nu_e$: $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ \hspace{1cm} 52%

  Other sources of systematic uncertainty:
  
  - **Cross-Section:** both neutrinos interact with argon nuclei.
  - **Detector:** systematic detector effects affect different channels in the same way.
→ **Reduced systematic uncertainties** in a combined analysis:

1. Using multiple selections and observables.
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Simulation-based exercise of **constraining the flux and cross-section systematics** on the $\nu_e$ selection using muon neutrinos.
THE SHORT BASELINE PROGRAMME (SBN) AT FERMILAB [8]

Sensitivity to the short-baseline anomaly
CONCLUSION

What MicroBooNE Has Archived So Far

- Fully automatic event reconstruction and LArTPC R&D!
- $\nu_\mu$ Charged-Current inclusive double differential cross-section [5].
- Charged-Current $\pi^0$ measurement and $\pi^0$ mass peak [6].

Progress towards Low Energy Excess

- Explicit selections targeting both electron and photon channels.
- $\nu_\mu$ sample is being used to constrain flux and cross-section uncertainties.
- First low energy excess result soon.

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THANK YOU!
& Questions


Neutrino Oscillations: The Current Picture

- Mixing between neutrino flavour and mass eigenstates: PMNS matrix

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U(\theta_{12},\theta_{23},\theta_{13},\delta_{CP})
= \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu1} & U_{\mu2} & U_{\mu3} \\
U_{\tau1} & U_{\tau2} & U_{\tau3}
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- Propagation through vacuum over a length \( L \) for mass eigenstate \( \nu_i \):

\[
|\nu_i(L)\rangle \approx e^{-i \frac{m_i^2 L}{2E}} |\nu_i(0)\rangle.
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\begin{pmatrix}
0.8 & 0.5 & 0.1 \\
0.3 & 0.7 & 0.6 \\
0.4 & 0.5 & 0.8
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

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The combination leads to neutrino flavour oscillations!

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Let’s add a sterile fourth neutrino to the game!

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_S
\end{pmatrix}
= \begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\
U_{S1} & U_{S2} & U_{S3} & U_{S4}
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\begin{pmatrix}
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• Consider experiments where \( \frac{E}{L} \approx \Delta m^2_{41} \) and \( \Delta m^2_{41} \gg \Delta m^2_{21}, \Delta m^2_{32} \).

• If we are only sensitive to electron and muon flavours in the detector: \( U_{e4}, U_{\mu4} \) and \( \Delta m^2_{41} \).
NEUTRINO OSCILLATIONS & THE STERILE NEUTRINO HYPOTHESIS

- Let’s add a sterile fourth neutrino to the game!

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\[
P(\nu_e \rightarrow \nu_e) = 1 - 4(1 - |U_{e4}|^2) |U_{e4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \quad (\nu_e \text{ disappearance})
\]

\[
P(\nu_\mu \rightarrow \nu_\mu) = 1 - 4(1 - |U_{\mu4}|^2) |U_{\mu4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \quad (\nu_\mu \text{ disappearance})
\]

\[
P(\nu_\mu \rightarrow \nu_e) = 4 |U_{e4}|^2 |U_{\mu4}|^2 \sin^2(1.27 \Delta m^2_{41} L/E) \quad (\nu_e \text{ appearance})
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P(\nu_\mu \rightarrow \nu_e) = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(1.27 \frac{\Delta m^2_{41} L}{E}) \quad (\nu_e \text{ appearance})
\]

Appearance and disappearance signals are related!
Radiochemical Experiments

- The SAGE and GALLEX experiments both observed a deficit of electron neutrinos with radioactive isotope sources.

Reactor Experiments

- 3.5% deficit of electron anti-neutrinos in several reactor experiments.

Accelerator Experiments

- Excess of electron neutrinos and anti-neutrinos in the LSND and MiniBooNE experiments.
Radiochemical Experiments

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Hints towards sterile neutrino, but tension in global fits remains.
A STEP BACK IN TIME: THE LSND EXPERIMENT

Liquid Scintillator Neutrino Detector at Los Alamos

- $\bar{\nu}_\mu$ from $\mu^+$ Decay at rest.
- $3.8\sigma$ excess consistent with $\nu_e$ appearance ($\Delta m \approx 1\text{eV}^2$).

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LIQUID ARGON TIME PROJECTION CHAMBER

Cathode Plane

Incoming Neutrino

Scintillation light

E_{drift}

Liquid Argon TPC

Sense Wires

U V Y

Fast light signal captured by 32 PMTs

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BACK TO REALITY: EVENTS CONTAIN A LOT OF COSMIC CHARGE DEPOSITS

Run 1463 Event 28. August 15th 2015 10:37

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Cosmic Activity @ MicroBooNE

- MicroBooNE is a surface detector.
- 5 kHz cosmic muon rate.
- Approximately 24 muons per triggered event

→ Cosmic activity is the dominant background!

MICROBOOONE-NOTE-1005-PUB
\( \nu_\mu \) and \( \nu_e \) have much in common:

- **Flux**: both species of neutrinos come from the same beam, from decays of the same populations of hadrons.
- **Cross-Section**: both neutrinos interact with argon nuclei.
- **Detector**: systematic detector effects affect different channels in the same way.

Strong **correlation** between the \( \nu_\mu \) and \( \nu_e \) cross-section at **low energies**.
MINIBoONE/LSND

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Figure 7
SBN $3\sigma$ (solid red line) and $5\sigma$ (dotted red line) sensitivities to a light sterile neutrino in the $\nu_\mu \rightarrow \nu_e$ appearance channel (left) and $\nu_\mu \rightarrow \nu_\mu$ disappearance channel (right). For comparison, the LSND preferred region at 90% C.L. (shaded blue) and 99% C.L. (shaded gray) is presented (19). Moreover, the global $\nu_e$ appearance (shaded red) and global $\nu_\mu$ disappearance (black line) $3\sigma$ regions from Ref. (33) are also included. Finally, the $3\sigma$ global best fit regions from Ref. (35) are shown in green. The sensitivities are reproduced from the SBN proposal (15).
• $\nu_\mu$ flux peaks at $\approx 0.8$ GeV.
• Small $\nu_e$ component: $\approx 0.57\%$.

→ $\nu_e$'s from Kaons at lowest energies can be constrained by high energy $\nu_\mu$'s.