Astroparticle and Beyond the Standard Model Capabilities and Results from MicroBooNE

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On behalf of the MicroBooNE Collaboration
The MicroBooNE experiment

- MicroBooNE is an 85t Liquid Argon Time Projection Chamber (LArTPC)
- Exploit scintillation and ionisation signals from charged particles to produce bubble-chamber like images of events

- Advantages:
  - Excellent spatial resolution
  - Excellent calorimetry
  - Powerful particle identification
MicroBooNE’s physics reach

Goals of the MicroBooNE Experiment

- Investigate MiniBooNE Low Energy Excess
  → See Nick Kamp’s talk on Tuesday

- Cross-section measurements
  → See Wenqiang Gu’s talk on Tuesday

- LArTPCs detector physics, R&D

Many more capabilities in astroparticle and exotic physics, that we’ll explore in this talk!
MicroBooNE’s physics reach

- NuMI Neutrino Beam (120 GeV protons)
  - 680m baseline, 8° off-axis
- Booster Neutrino Beam (8 GeV protons)
  - 480m baseline, on-axis
- Continuous readout for supernova detection
- MeV scale reconstruction
- Heavy Neutral Leptons (BNB)
- Higgs Portal Scalars (NuMI)
- Ongoing searches
Continuous readout for supernova neutrino detection

- Detecting a supernova neutrino burst requires continuous data readout (33GB/s raw data from MicroBooNE)
- Pioneered a system to zero-suppress and compress data
- Evaluated performance by looking at reconstruction of Michel electrons
- SN stream could be used for other off-beam physics
- Further work on reconstruction/selection
MeV scale reconstruction

- Standard reconstruction algorithms designed for $O(100 \text{ MeV})$ interactions
  - Not low enough for many low energy studies
  - Might miss part of the deposited energy
- Developed using “blips” of ionisation from low-energy gammas or neutrons (0-5 MeV)

Applications:
- Supernova neutrino reconstruction
- Muon/pion separation
- Some BSM searches e.g. millicharged particles
MicroBooNE’s physics reach

- Continuous readout for supernova detection
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- Heavy Neutral Leptons (BNB)
- Higgs Portal Scalars (NuMI)
Heavy Neutral Leptons - Model

- Searches for neutral leptons in BNB with mass \(O(100\ \text{MeV})\)

- Produced via mass mixing with SM neutrinos with extended PMNS element \(|U_{44}|\)
  
  ‣ Used kaon decays as source for first search

- Decay via weak interaction
  
  ‣ Chose muon + pion channel for this study

- Could decay inside MicroBooNE

Consider only this production mode and this decay mode
Heavy Neutral Leptons - Analysis

- Developed a “late window” trigger specifically for this analysis
  - HNLs travel slower than neutrinos
  - Around ~10% of HNLs arrive after the neutrino spill
  - Late window trigger effectively eliminates in-beam neutrino events which would be background

- BDT based analysis with 10 HNL mass points (260 - 385 MeV)
- Signal region defined as BDT score > 0.95
Heavy Neutral Leptons - Results

- Considered decay mode $K \to \mu N$, and production mode $N \to \mu \pi$
- No excess observed in signal region
- Set limits on $|U_{\mu 4}|^2$ as a function of HNL mass

We will be using more production and decay modes, full trigger window and more data (including NuMI) in the future!
• “Portal” to the dark sector, via a dark scalar mixing with the Higgs (mixing angle $\theta$)
• Similar phenomenology to HNLs
• Search for kaons decaying to scalars in beam
• Scalars decaying to fermions in detector
• First search uses kaons decaying at rest in the NuMI beam dump

$\text{Production in beam line } \propto \theta^2$

$\text{Decay in MicroBooNE } \propto \theta^2$
Higgs portal scalar - Analysis

• Search for e+e- pairs from the decay of a < 200 MeV scalar
• BDT based analysis

Angular distribution (one of the most important BDT variables)
Simulation is well-modelled with respect to the data

BDT distribution is well-modelled with background-only explanation

SIMULATION 150 MeV/c² scalar decay
standard neutrino direction

MICROBOONE-NOTE 1092-PUB
Higgs Portal scalars - Results

- Observed 1 event in signal region (consistent with $1.9 \pm 0.8$ background expectation)
  - Set limits on $\theta$ as a function of scalar mass
- Used only 10% of the NuMI dataset
- More results to come!
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Ongoing searches

**Millicarged particles**

- Particles with a fraction of electric charge, potential dark matter candidates
- Could scatter off atomic electrons and cause “blips” of ionisation in LAr
  - MeV scale reconstruction useful
- MicroBooNE could provide competitive limits

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**Dark Tridents**

- Dark matter produced from meson decays in the beam
- Leads to e⁺e⁻ final states
- Could explain MiniBooNE Low Energy Excess if e⁺e⁻ not resolved

See Luis Mora Lepin’s Poster
Summary

• MicroBooNE is a multi-faceted detector with access to a wide-range of signal sources and signatures

• Lots of R&D efforts to push our capabilities in new areas

• Recent exciting results include:
  • Supernova continuous readout
  • MeV Scale Physics
  • Searches for heavy neutral leptons
  • Higgs portal scalars

• We have only used a fraction of our data

• New BSM era for MicroBooNE!
  • More modes and signatures
  • More models (LEE explanations and more)

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Looking for exotic physics is also looking for MiniBooNE LEE explanations
Backup
Neutron-antineutron oscillations

- Searched for this baryon-number violating process in argon
- Trained a Convolutional Neural Network (CNN) to identify signal over cosmic-induced background
- MicroBooNE pioneered techniques which may be used in DUNE

Signal Simulation

“Star” topology

\[ n\bar{n} \rightarrow \pi^+ + \pi^- + 3\pi^0 \]
Heavy Neutral Leptons - BDT Training

![Graphs showing BDT training results for Heavy Neutral Leptons (HNLs).](image)

- MicroBooNE PGE: 2.0×10⁻¹⁰
- HNL Signal (370 MeV) and Off-beam data
- HNL Signal (285 MeV) and Off-beam data
- HNL Signal (325 MeV) and Off-beam data
- HNL Signal (365 MeV) and Off-beam data
MiniBooNE LEE Excess Theory Landscape

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - [14] de Gouvêa, Peres, Prakash, Stenco JHEP 07 (2020) 141
- New resonance matter effects
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
- Decay of heavy sterile neutrinos produced in beam
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by $Z'$ or more complex higgs sectors
- Decay of axion-like particles
- A model-independent approach to any new particle
Cosmic ray rates

- Used MicroBooNE data to measure the rate of cosmic ray muons at the surface at Fermilab
  - First measurement with a LArTPC
- Found good agreement with a CORSIKA simulation
- Useful for tuning cosmic simulation and as an input for future experiments at Fermilab, including SBN program and DUNE
# MiniBooNE LEE Models Score Card

Looking for exotic physics is also looking for MiniBooNE LEE explanations

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*Requires heavy sterile/other new particles also

First series of results (1/2 the MicroBooNE data set)
• A novel, dark matter based model for the MiniBooNE LEE

• Model with two DM particles and two U(1) dark gauges

• Once DM reaches the detector, can upstater and decay

• $e^+e^-$ signature

• Very early stages of search

arxiv:2110.11944