MicroBooNE’s Search for a Photon-Like Low Energy Excess

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On behalf of the MicroBooNE Collaboration

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MiniBooNE Low Energy Excess (LEE)

- **MiniBooNE** - *Cherenkov detector* along the Booster Neutrino Beam (BNB) at FNAL operating since 2002
- Photon-like and electron-like interpretations

\[ \gamma \text{ vs. } e^- \text{ Cherenkov rings} \]

Overlap of \( e^+e^- \) and other backgrounds.

\[ \nu_e \rightarrow e^- W \rightarrow n p \]
NC $\Delta$ Radiative Decay: What We Know

- Neutral current (NC) $\Delta$ resonant production followed by $\Delta$ radiative decay is a **SM source of single photons**
  - $\Delta \rightarrow N \gamma$ (0.6%) is subdominant to $\Delta \rightarrow N\pi^0$ (99.4%)
- Large associated cross-section uncertainty
NC $\Delta$ Radiative Decay: LEE Interpretation

- Interested in $\Delta$ resonant production + radiative decay to as photon-like interpretation of LEE
- MiniBooNE would require a factor of 3 enhancement to the SM rate to explain excess. We use unfolding to translate that prediction to MicroBooNE: MICROBOONE-NOTE-1043-PUB
Reconstruction in MicroBooNE

- LArTPC's combine time information from PMTs and hits on the wire planes to create 3D reconstructed images

\[ e^-/\gamma \] separation for showers from:
- \( \frac{dE}{dx} \)
- photon conversion distance

![Conversion gap](image-url)
MicroBooNE Single Photon Analysis Overview

1. Take Pandora reconstructed tracks and showers

2. Find candidate vertices with topological selection and pre-selection cuts

3. Remove background using 2 tailored Boosted Decision Trees:
   - Cosmic Rejection
   - BNB (Neutrino) Background Rejection

3.5 Additional background filtering with Deep Learning techniques

4. Goal is a high sensitivity search for NC $\Delta$ Radiative Decays, as an interpretation of the MiniBooNE LEE
1. Take Pandora reconstructed tracks and showers

2. Find candidate vertices with topological selection and pre-selection cuts

3. Remove background using 2 tailored Boosted Decision Trees:
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Topological Selections

1γ1p is our primary analysis. The existence of a short proton-like track improves reconstruction efficiency.

- 45.3% of true 1γ events
- 26% reconstruction efficiency with 1 track and 1 shower requirement and pre-selection cuts

1γ0p is more difficult, but provides a secondary dataset for comparison and verification.

- 54.7% of true 1γ events
- 9% reconstruction efficiency with 0 track and 1 shower requirement and pre-selection cuts

*γ conversion length in Ar ~14cm

2. Find candidate vertices with topological selection
$1\gamma 1p$ Pre-Selection Cuts Stage

- Pre-selection cuts applied

- Find candidate vertices with topological selection

- NC $\Delta$ radiative simulated events with 3x SM prediction

- Signal NC $\Delta$ radiative separated from other NC $\Delta$ radiative with truth-level reconstructability requirements

- Dominated by BNB (neutrino) and cosmic backgrounds, subleading background contributions from dirt interactions

- $4.8e19$ POT is the current unblinded data: <5% of MicroBooNE total expected on-beam data (13.2e20POT)
1. Take Pandora reconstructed tracks and showers

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3.5 Additional background filtering with Deep Learning techniques
Dual Boosted Decision Trees (BDT's)

- BDT’s train on kinematic and calorimetric variables → output a score per event from background-like to signal-like
- Train two BDT’s for BNB (neutrino) and cosmic backgrounds with the NC Δ radiative signal

Higher energy tracks mainly from $\mu$ backgrounds

Cosmic showers point up/down from top of detector

11 BNB BDT Training Variables

13 Cosmic BDT Training Variables
Dual Boosted Decision Tree Cuts

Train two BDTs independently to target BNB and cosmic backgrounds. **BDT cuts optimized simultaneously** → keep only events that pass both cuts for final selection.

3. Remove background using 2 tailored boosted Decision Trees
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1γ1p Final Selection

Purity: 0.12%

Apply BDT cuts

Pre-selection cuts applied

- Predicted $m_\Delta = 1.21 \pm 0.13$ GeV, expected $m_\Delta = 1.232$ GeV
- Apply reconstructed shower energy correction to account for bias toward lower reconstructed than true energy
- Strong rejection of cosmic and dirt backgrounds

4. Goal is a high sensitivity search for NC $\Delta$ Radiative Decays
Remaining Backgrounds

NC $\nu^0$ background:
\[ \nu_\mu + p \rightarrow \nu_\mu + \Delta^+ \rightarrow p + \pi^0 \rightarrow \gamma + \gamma \]

Dominant background is mis-identified NC $\pi^0$ events in which one shower is not reconstructed or associated to the vertex $\rightarrow$ dual approach with targeted NC $\pi^0$ second shower search and NC $\pi^0$ sideband constraint
Simulated $\Delta \rightarrow p\gamma$ event that passes the final selection
Data event that passes the final selection as a $\Delta \rightarrow p\gamma$ candidate event
Second shower candidate likely from $\pi^0 \rightarrow \gamma + \gamma$ is missed in reconstruction because of coincident cosmic ray.
1. Take Pandora reconstructed tracks and showers

2. Find candidate vertices with topological selection and pre-selection cuts

3. Remove background using 2 tailored Boosted Decision Trees:
   - Cosmic Rejection
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3.5 Additional background filtering with Deep Learning techniques

4. Goal is a high sensitivity search for NC $\Delta$ Radiative Decays, as an interpretation of the MiniBooNE LEE
Need to identify NC π⁰'s where the second shower isn't associated to the vertex for background rejection.
Semantic Segmentation Network (SSNet) Shower-Tagging

- Hits-based approach augments Pandora reconstruction by targeting shower candidates
- Convolutional neural net which tags pixels as shower-like or track-like: Phys. Rev. D 99 (2019), 092001

3.5 Additional background filtering using Deep Learning techniques
Summary and Next Steps

- Current $1\gamma 1p$ selection shows **strong rejection of cosmic and dirt backgrounds**
- Additional $1\gamma 0p$ channel increases total sensitivity but likely with higher backgrounds
- Further reducing the dominant NC $\pi^0$ background to $1\gamma 1p$ will significantly improve sensitivity:
  - **Second shower search** to identify mis-reconstructed NC $\pi^0$ events that pass current selection cuts
  - **NC $\pi^0$ sideband constraint**
- Full **systematic uncertainties** studies underway
- Working towards finalizing analysis and results!

Following talk in this session!

Andrew Mogan: “Constraining the Neutral Current $\pi^0$ Background for MicroBooNE’s Single-Photon Search”
Thanks!

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Backup
LArTPC operating at FNAL along the Booster Neutrino Beam (BNB) since 2015
### 1γ1p BDT Training Variables

**Cosmic BDT:**
1. Truncated Mean Track $dE/dx$
2. Shower Energy
3. Shower Theta $yz$
4. Shower Conversion Dist
5. Track Kinetic Energy
6. Shower Length
7. Ratio of track $dE/dx$ start/end
8. Shower Phi $yx$
9. Track Phi $yx$
10. Cosine between Track and Shower
11. Track Theta $yz$
12. Shower Median $dE/dx$ Plane 2
13. Track Length

**BNB BDT:**
1. Truncated Mean Track $dE/dx$
2. Shower Energy
3. Track Kinetic Energy
4. Shower Conversion Dist
5. Shower Length
6. Ratio of track $dE/dx$ start/end
7. Shower Median $dE/dx$ Plane 2
8. Cosine between Track and Shower
9. Shower Theta $yz$
10. Shower Phi $yx$
11. Track Length
$1\gamma 0p$ BDT Responses

In Progress

MicroBooNE $1\gamma 0p$ 4.8e19 POT

- Signal NC $\Delta$ Radiative
- BNB Backgrounds
- Other NC $\Delta$ Radiative
- Dirt Background
- Cosmic Background
- MC Stats Only Error

On-Beam Data

(BN$2\chi^2$/nDOF: 3.57/12)

_data

(BN$2\chi^2$/nDOF: 6.84/11)
$1\gamma_0p$ Final Selection

**MicroBooNE**

- Signal $1$
- BNB Backgrounds
- Cosmic Background
- Other NC $\Delta$ Radiative
- Dirt Background
- MC Stats Only Error

**On-Beam Data**

$1\gamma_0p$ 4.8e19 POT

*In Progress*

([χ²/nDOF: 17.92/24])

**MicroBooNE Simulation**

- Signal NC $\Delta$ Radiative
- BNB Backgrounds
- Cosmic Background
- Other NC $\Delta$ Radiative
- Dirt Background
- MC Stats Only Error

$1\gamma_0p$ 4.8e19 POT

*In Progress*
Reconstructed Shower Energy Correction

- Frequently reconstruction correctly identifies a shower and it’s direction but not all of the hits are included
  - Missed hits → missing energy for reconstructed object
- Apply ~25% scaling to reconstructed shower energy to correct for this bias
- Scaling derived from linear fit to reconstructed vs. true energy distribution for large sample of photons