Constraining the NC $\pi^0$ Background for MicroBooNE’s Single Photon Search

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On behalf of the MicroBooNE Collaboration
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The MicroBooNE Experiment

- 170-ton (89 ton active volume) Liquid Argon Time Projection Chamber (LArTPC)
- Operating along Fermilab’s Booster Neutrino Beam (BNB) since 2015
- Primary goal: investigation of the MiniBooNE Low-Energy Excess (LEE)
MiniBooNE Low-Energy Excess

- Observed excess of electron neutrino-like events below 600 MeV
- Cherenkov detector; difficulty distinguishing photons and electrons
  - **Photon-like** and electron-like hypotheses
- MicroBooNE is searching for $\Delta \rightarrow N\gamma$ to investigate photon-like hypothesis
  - See K. Sutton’s talk from NP 1.0
Neutral Current (NC) $\pi^0$

- NC $\pi^0$'s comprise ~80% of backgrounds for the NC $\Delta$ radiative decay search
  - $\Delta \rightarrow N\gamma$ branching ratio: ~0.6%
  - $\Delta \rightarrow N\pi^0$ branching ratio: ~99.4%
- NC $\pi^0$ events in which only one photon is reconstructed look nearly identical to radiative decays
- Plan: use single-photon framework to select NC $\pi^0$ events for data-driven rate constraint
Analysis Flow

1. Select Signal Topology
   - Start with reconstructed tracks and showers [1]
   - Select events with two shower (2γ) and either one or zero tracks (1p or 0p)

2. Reject Backgrounds
   - Use tailored Boosted Decision Tree (BDT) [2] trained on background events
   - Reject backgrounds by cutting on BDT response

3. High-Stats NC π⁰ Selection
   - Result is the world’s highest-stats NC π⁰ selection on Argon
   - Constrain single-photon NC π⁰ background

Signal Topology

$2\gamma_1p$

- Neutrino Vertex
- Proton Track
- Primary Photon Shower
- Secondary Photon Shower

$2\gamma_0p$

- Neutrino Vertex
- Primary Photon Shower
- Secondary Photon Shower
Pre-Selection Distributions

- Before BDTs, apply some conservative pre-selection cuts
  - Shower energies, conversion distance, etc.
- Signal (red) dominated by off-beam (green) and on-beam backgrounds (blue and brown)
BDT Training

- Train BDT on various kinematic and calorimetric variables in simulation
- Training variables chosen based on separation power between signal and background
- Example: track dE/dx (left)
  - dE/dx: energy deposition per unit length
  - Separates events with proton-like track for 2g1p selection
  - Peak at 2 MeV/cm mostly from minimally-ionizing muon tracks
**BDT Response**

- Cut on BDT response to maximize efficiency times purity in the final selection

![BDT Response Diagram](image-url)

**Signal-like**

**Background-like**

(Data/MC: 0.94) (KS: 0.360) ($\chi^2$/nDOF: 16.06/30) ($p_{val}$: 0.982)

(Data/MC: 0.94) (KS: 1.000) ($\chi^2$/nDOF: 24.56/30) ($p_{val}$: 0.746)
2γ1p Final Selection

- ~20% normalization difference between data and MC
- Covered by systematic uncertainties
- Gaussian fit to mass peak gives a mean of $137.6 \pm 2.1$ MeV and a width of $44.1 \pm 1.8$ MeV
2γ0p Final Selection

- Normalization difference < 10%
- Gaussian fit to mass peak gives a mean of $140.2 \pm 2.8$ MeV and a width of $49.9 \pm 2.7$ MeV

Purity: 64.1%
Efficiency: 50.9%
• Demonstrated world’s highest-stats NC $\pi^0$ selection on Argon
  • Still more data to process!
• Constraint provides $\sim 3x$ reduction in single-photon systematics
  • See talk by G. Yarborough
Backup
Pre-Selection Cuts

• 2g1p pre-selection cuts:
  • 5 cm fiducial volume on vertex
  • Both shower conversion distances > 1 cm
  • Leading shower energy > 30 MeV
  • Subleading shower energy > 20 MeV
  • Distance from track start point to vertex < 10 cm

• 2g0p pre-selection cuts:
  • 5 cm fiducial volume on vertex
  • Leading shower energy > 30 MeV
  • Subleading shower energy > 20 MeV
Training Variables

- **2g1p Training variables:**
  - Both shower conversion distances
  - Both shower impact parameters
  - Track length
  - Track $\theta_{yz}$
  - Distance from track end point to nearest TPC wall
  - Track mean truncated dE/dx (shown here)
  - Ratio of track start/end dE/dx

- **2g0p Training variables:**
  - Both shower conversion distances
  - Both shower impact parameters
  - Both shower energies
  - Both ratios of shower length/energy
  - Leading shower $\theta_{yz}$
  - Pandora neutrino slice score
BNB Backgrounds in Final Selection

<table>
<thead>
<tr>
<th>Background</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$ Charge Exchange</td>
<td>11.9</td>
</tr>
<tr>
<td>CC Multi-$\pi^0$</td>
<td>5.3</td>
</tr>
<tr>
<td>CC Other</td>
<td>14.7</td>
</tr>
<tr>
<td>NC Other</td>
<td>6.3</td>
</tr>
<tr>
<td>$\eta$</td>
<td>18.8</td>
</tr>
<tr>
<td>Overlay</td>
<td>28.3</td>
</tr>
<tr>
<td>Other</td>
<td>14.8</td>
</tr>
</tbody>
</table>

- Percentages relative to BNB Other, which comprise ~10% of final selection
- Single largest component is cosmic contamination
- Other large backgrounds include general CC events, $\eta$’s, and “other”
CC $\pi^0$ Backgrounds in Final Selection

- Percentages relative to CC $\pi^0$, which comprise ~10% of final selection
- Most have track matched to proton, not muon
  - Muon tracks sometimes not reconstructed
  - Looks exactly like signal

<table>
<thead>
<tr>
<th>Background</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton track</td>
<td>49.6</td>
</tr>
<tr>
<td>Muon track</td>
<td>11.5</td>
</tr>
<tr>
<td>Shower Mis-ID</td>
<td>31.4</td>
</tr>
<tr>
<td>Overlay</td>
<td>2.2</td>
</tr>
<tr>
<td>Other</td>
<td>5.4</td>
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</tbody>
</table>
## 2g1p Signal Composition

<table>
<thead>
<tr>
<th></th>
<th>Generated NC $\pi^0$</th>
<th></th>
<th>Signal NC $\pi^0$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Resonant</td>
<td>DIS</td>
<td>QE</td>
<td>Coherent</td>
</tr>
<tr>
<td>Run 1</td>
<td>77.2%</td>
<td>19.7%</td>
<td>0.82%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Run 3</td>
<td>77.7%</td>
<td>19.3%</td>
<td>0.80%</td>
<td>2.2%</td>
</tr>
</tbody>
</table>
Center-of-Mass Decay Angle

Lab Frame

γ_μ (beam direction)

π^0

γ_1

γ_2

CM Frame

Boost

π^0

θ

p_{π, Lab}

\cos θ^CM = \frac{1}{β_{π^0}} \frac{|E_{γ^1} - E_{γ^2}|}{E_{γ^1} + E_{γ^2}} = \frac{|E_{γ^1} - E_{γ^2}|}{p_{π^0}}