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

Kathryn Sutton

On behalf of the MicroBooNE Collaboration
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Overview

- MiniBooNE “Low Energy Excess” anomaly
- Photon-like and electron-like interpretations
- MicroBooNE experiment as follow up to MiniBooNE
- MicroBooNE single-photon search and status
Interpreting the MiniBooNE Anomaly
MiniBooNE “Low Energy Excess”

- **MiniBooNE** is a Cherenkov detector along the Fermilab Booster Neutrino Beam (BNB) that took data from 2002-2019
- BNB is ~94% pure $\nu_\mu$ beam, <1% $\nu_e$ contamination, with a mean energy of ~800 MeV
- Observed **excess of electromagnetic events at low energy**$^*$ in the $\nu_e$ selection

*Phys. Rev. D 103, 052002 (2021)
Sterile Neutrino Interpretation

- MiniBooNE result could be interpreted as a **sterile neutrino** oscillation to an electron (anti)neutrino.
- This would mean the observed excess is **electron neutrinos from** $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ oscillation.
Sterile Neutrino Interpretation

- MiniBooNE results could be interpreted as a **sterile neutrino** oscillation to an electron (anti)neutrino.
- This would mean the observed excess is **electron neutrinos from** $\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$ oscillation.

However, because MiniBooNE was a Cherenkov detector, the question remains whether the observed excess of electromagnetic showers is **photon-like** or **electron-like**.
Electron/Photon Separation in MiniBooNE

Photon backgrounds

Hard to distinguish

$\gamma \rightarrow e^+e^-$

overlapping Cherenkov rings

Single $e^-$ Cherenkov ring

Electron/Photon Interpretation of MiniBooNE

Photon backgrounds

A source of electron neutrinos that isn't accounted for in the prediction. This could be a sign of sterile neutrinos.

\[ \gamma \rightarrow e^- e^- \]

\[ e^+ e^- \]

\[ e^- \]

\[ \Delta \rightarrow N \gamma \]

\[ \pi^0 \text{ misid} \]

\[ \text{dirt} \]

\[ \text{other} \]

\[ \nu_e \text{ from }\mu^+ \nu^- \]

\[ \nu_e \text{ from } K^+ \nu^- \]

\[ \nu_e \text{ from } K^- \]

Photon backgrounds

$\gamma \rightarrow e^-e^-$

overlapping Cherenkov rings

Single $e^-$

Cherenkov ring

A source of electron neutrinos that isn't accounted for in the prediction. This could be a sign of sterile neutrinos.

This could be a SM or exotic process.

A source of neutrino-induced photon interaction that isn't accounted for in the prediction.

The MicroBooNE Detector
MicroBooNE is a liquid argon time projection chamber (LArTPC) detector that took BNB data from 2015-2021. It's collected the largest sample of neutrino-Ar data to date.

Introduction to MicroBooNE and SBN in talk yesterday.
A LArTPC takes images of neutrino interactions. Charged particles that pass through the Ar create ionization tracks which are collected by the wire planes. These 2D projections of interactions are then reconstructed into 3D using timing information from the PMTs.
Investigating MiniBooNE with a LArTPC Detector

Neutrino interaction shown as a 2D projection on a single wire plane in MicroBooNE

LArTPCs demonstrate precise spatial and calorimetric resolution, which makes them ideal for distinguishing between photons and electrons.

MicroBooNE experiment motivated as a follow up to investigate the MiniBooNE anomaly.
Single Photon Interpretation: NC Delta Radiative Decay Mis-Estimation Hypothesis
Delta Radiative Decay

- $\Delta\rightarrow N\gamma$ is a rare process with a single photon in the final state that was the **leading single-photon background in MiniBooNE**
- It is predicted by the Standard Model but has **never been directly measured** in neutrino scattering
- For $\Delta(1232)$, the branching ratio according to the PDG is:
  - $\Delta\rightarrow N\pi^0$ (99.4%)
  - $\Delta\rightarrow N\gamma$ (0.6%)
- This is based off of a phenomenological calculation using pion photon-production data*.

Photon Backgrounds in MiniBooNE

- **MiniBooNE estimated NC $\Delta \rightarrow N \gamma$ rate** in MC from an in situ NC $\pi^0$ measurement using branching ratio
- **Could an enhanced rate of $\Delta \rightarrow N \gamma$ could explain the observed excess** under a photon-like hypothesis?

Current Limits on NC $\Delta \rightarrow N\gamma$

- Current best limit in the neutrino energy range $<1$ GeV is from T2K measurement made in the tracker near detector
- 2019 T2K 90% C.L. is $\mathcal{O}(100x)$ the SM prediction

Using the MiniBooNE Nuance MC, it was found that 3.18x predicted rate of NC $\Delta \rightarrow N\gamma$ could explain MiniBooNE anomaly*

Currently well within the experimental limits but even an enhanced rate of this rare process is challenging to measure

The MicroBooNE Single Photon Search
Selection Stages

1. Take reconstructed tracks and showers
2. Find candidate vertices matching $1\gamma$ topologies
3. Apply pre-selection cuts to remove obvious backgrounds
4. Remove backgrounds using tailored boosted decision trees (BDTs)

Goal is a high sensitivity search for NC $\Delta \rightarrow N\gamma$ events over background prediction, fit to an excess using in-situ NC $\pi^0$ constraint.
Selection Stages

Take reconstructed tracks and showers*

Find candidate vertices matching $1\gamma$ topologies

Topological Selections

$^{1\gamma}p$ is our primary analysis. The existence of a short proton-like track improves reconstruction efficiency. **45.3% of true $1\gamma$ events.**

$^{1\gamma}p$ is slightly more difficult, but provides a secondary dataset for comparison and a joint fit yields maximum sensitivity. **54.7% of true $1\gamma$ events.**
Selection Stages

Take reconstructed tracks and showers

Find candidate vertices matching $1\gamma$ topologies

Apply pre-selection cuts to remove obvious backgrounds

These target obvious backgrounds like cosmic events and mis-reconstructions. Includes cuts on:

- Fiducial volume and containment
- Minimum shower energy
- Track calorimetry (1p only)
1γ1p Topological+Precuts Selection Stage

- Showing results using a small unblinded data set
- Applied topological requirements and pre-selection cuts
- Signal:background ~1:300
- Would expect signal events to peak around \( \Delta \) invariant mass but background events skew to low reconstructed invariant mass

\[ M_\Delta = 1.232 \text{ GeV} \]

Apply pre-selection cuts to remove obvious backgrounds

**Diagram:**
- Reconstructed Invariant Mass of Photon-Proton Pair (GeV)
- Events vs. Data/Prediction
- 1γ1p = 1 track + 1 shower

**Legend:**
- 1x SM NC \( \Delta \) Radiative 0.92
- NC 1 x° Coherent 1.09
- NC 2+ π° 0.97
- BNB Other 89.82
- Dirt 15.92
- Flux & XS Systematics : 283.39
- x2 SM NC \( \Delta \) Radiative (LEE) 1.84
- NC 1 π° Non-Coherent 48.09
- CC ν\(_e\) 1 π° 15.56
- CC ν\(_e\)/ν\(_\mu\) Intrinsic 7.52
- Run 1 Cosmic Data 101.68
- Run 1 On-Beam Data 283.00
Selection Stages

1. Take reconstructed tracks and showers
2. Find candidate vertices matching $1\gamma$ topologies
3. Apply pre-selection cuts to remove obvious backgrounds
4. Remove backgrounds using tailored boosted decision trees (BDTs)
BDT Structure For Selections

For each topology ($1\gamma 1p$ and $1\gamma 0p$) a series of BDTs targeting key backgrounds trained independently and the selection cuts optimized simultaneously.

Each BDT trains on tailored set of kinematic and calorimetric variables and output a score per event from background-like to signal-like.

For $1\gamma 1p$ there are 5 BDTs:
- Cosmic
- NC $\pi^0$
- Second shower $\pi^0$ mis-ID
- $\nu_e$
- All other neutrino backgrounds

For $1\gamma 0p$ there are 3:
- Cosmic
- NC $\pi^0$
- All other neutrino backgrounds.

Because there are fewer reconstructed parameters for a single shower topology with no track the background training, the definitions for $1\gamma 0p$ were consolidated (i.e. all other neutrino encompasses $\nu_e$ rejection).
The $dE/dx$ is the energy deposited per unit length at the start (4cm) of the shower.

Because photons pair produce into $e^+e^-$, they deposit twice the charge as a single $e^-$. A minimum ionizing particle deposits $2\text{MeV/cm}$ in Ar:

- single $e^+/-$ → $2\text{ MeV/cm}$
- $\gamma \rightarrow e^-e^+ \rightarrow 4\text{ MeV/cm}$
$1\gamma 1p\,\nu_e$ Background Rejection BDT

- Trains on $1\gamma 1p$ signal and $\nu_e$ background
- See strong separation between signal and background
- Majority of $\nu_e$ background events clustered at 0 showing strong rejection $e/\gamma$ separation

Remove backgrounds using tailored boosted decision trees (BDTs)
$1\gamma 1p \nu_e$ Background Rejection BDT Cut

Optimized BDT cut at 0.57 removes 96.8% of $\nu_e$ background events relative to pre-selection cuts stage.
Selection Stages

1. Take reconstructed tracks and showers *
2. Find candidate vertices matching $1\gamma$ topologies
3. Apply pre-selection cuts to remove obvious backgrounds
4. Remove backgrounds using tailored boosted decision trees (BDTs)

Goal is a high sensitivity search for NC $\Delta \rightarrow N\gamma$ events over background prediction, fit to an excess using in-situ NC $\pi^0$ constraint
Final Selection

- **1γ1p final selection** with topological, pre-selection, and 5 optimized BDT cuts applied
- Showing results using the unblinded sample, full data set is ~25x larger
- See 2 data events, expect ~3 events from MC that are mostly backgrounds

Goal is a high sensitivity search for NC $\Delta \rightarrow N\gamma$ events
Goal is a high sensitivity search for NC $\Delta \rightarrow N \gamma$ events

- Reject >99% of total backgrounds relative to the precuts stage, strong rejection of $\nu_e$ backgrounds to test photon hypothesis
- NC $\pi^0$ events comprise >85% selected backgrounds
- Note that selected photons from the NC $\pi^0$ background overlap in shower energy with the signal.
Selected Data Candidate Events

Selected data $1\gamma p$ NC $\Delta$ radiative signal candidate with 1 shower

MicroBooNE Data, Run 5462 Subrun 14 Event 732

Selected data $1\gamma 0p$ NC $\Delta$ radiative signal candidate with 1 shower

MicroBooNE Data, Run 5187 Subrun 188 Event 9430
Projected Final Selection

- MC prediction for final selections scaled to full MicroBooNE data set
- Systematic errors on the order of ~25-30%, can fit simultaneously to MicroBooNE in situ NC \( \pi^0 \) selections to reduce flux and cross section uncertainties

Goal is a high sensitivity search for NC \( \Delta \rightarrow \nu N \gamma \) events.
Projected Sensitivity
MicroBooNE Projected Sensitivity

90% C.L. for 50% data

3x SM rate $\Delta \rightarrow N\gamma$

90% C.L. for 100% data

GENIE flux averaged xsec
MicroBooNE Projected Sensitivity

>30x improvement over current best limit from T2K

Expect to be able to probe into region of 3x SM rate for MiniBooNE interpretation with full data set.

90% C.L. for 100% data

GENIE flux averaged xsec
Conclusions
MicroBooNE Single Photon Analysis

- Expecting publication soon on world-leading constraint neutrino-induced NC $\Delta \rightarrow N\gamma$, and this result will offer a first look at the true source of the MiniBooNE anomalous excess.
- For the full MicroBooNE data set (12.25e20 POT), projected to exclude the MiniBooNE anomalous excess in favor of the Standard Model NC $\Delta \rightarrow N\gamma$ hypothesis at >95% C.L. under a photon hypothesis.
- MicroBooNE is demonstrating how LArTPC detector technology can be used to search for rare neutrino interactions with a photon in the final state. In the near future these include coherent photon production and more exotic photon-like processes.
Thanks!
Backup
Photon Conversion Distance

In a LArTPC we can observe the photon conversion distance:

- A single electron will immediately start to ionize the Ar starting at the interaction vertex.
- A photon travels before it pair-produces into $e^+e^-$ creating a gap between the vertex and the shower start. The photon conversion length in Ar is ~20cm*.

T2K NC Single Photon Search

- Used the ND280 tracker detector, the T2K near detector
- Peak neutrino energy similar to BNB, ~0.6GeV
- NEUT as neutrino event generator
- Define signal topology as two tracks from $e^+e^-$ pair
- Final selection 95% photons but dominated by external backgrounds (photons that originate outside the detector) and NC $\pi^0$, sensitivity limited by associated uncertainties

Example T2K NC1γ data candidate

Reconstructed photon energy of the T2K NC1γ selection

MicroBooNE eLEE Searches

Three independent, complementary analyses are underway, targeting different topologies (1e and 0p, Np, or CC inclusive) and using different end-to-end reconstruction, particle identification, and selection methods:

1. **Pandora Based**

2. **Deep Learning Based**

3. **Wire Cell + Pandora Based (Hybrid)**

Strategy shared among all eLEE analyses:

- Reduction of cosmogenic background
- Reduction of $\pi^0$ background and validation through NC/CC $\pi^0$ sidebands
- Constraint of intrinsic $\nu_e$ CC background through $\nu_\mu$ CC sidebands

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]

\[ e^+ + \bar{\nu}_\mu + \nu_e \]

\[ \nu_e \text{ background} \]

\[ \text{primary } \nu_\mu \text{ flux} \]
Total NC Single Photon Cross Section

<table>
<thead>
<tr>
<th>Percent</th>
<th>Resonance</th>
<th>Mass [MeV]</th>
<th>BR to $N\gamma$</th>
<th>$\xi$</th>
</tr>
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<tr>
<td>44.79</td>
<td>$\Delta^0$</td>
<td>1230</td>
<td>0.55-0.65</td>
<td>49.9%</td>
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<tr>
<td>37.07</td>
<td>$\Delta^+$</td>
<td>1230</td>
<td>0.55-0.65</td>
<td>41.3%</td>
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<td>3.37</td>
<td>$N^0$</td>
<td>1535</td>
<td>0.01-0.25</td>
<td>1.44%</td>
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<td>2.45</td>
<td>$N^0$</td>
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<td>0.31-0.52</td>
<td>2.18%</td>
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<tr>
<td>1.96</td>
<td>$N^+$</td>
<td>1535</td>
<td>0.15-0.30</td>
<td>1.01%</td>
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<td>1.50</td>
<td>$N^0$</td>
<td>1440</td>
<td>0.02-0.04</td>
<td>0.10%</td>
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<td>1.36</td>
<td>$N^+$</td>
<td>1520</td>
<td>0.3-0.53</td>
<td>1.24%</td>
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<tr>
<td>0.987</td>
<td>$N^+$</td>
<td>1440</td>
<td>0.035-0.048</td>
<td>0.08%</td>
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<tr>
<td>0.686</td>
<td>$N^0$</td>
<td>1720</td>
<td>0.0-0.016</td>
<td>0.03%</td>
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<tr>
<td>0.734</td>
<td>$\Delta^{++}$</td>
<td>1230</td>
<td>0.55-0.65</td>
<td>0.81%</td>
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<tr>
<td>0.647</td>
<td>$N^0$</td>
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<td>0.021-0.046</td>
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<tr>
<td>0.616</td>
<td>$\Delta^0$</td>
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<td>0.22-0.60</td>
<td>0.63%</td>
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<tr>
<td>0.514</td>
<td>$\Delta^+$</td>
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<td>0.22-0.60</td>
<td>0.53%</td>
</tr>
<tr>
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<td>$N^+$</td>
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<tr>
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<td>0.21-0.32</td>
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<tr>
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<td>0.01-0.05</td>
<td>0.02%</td>
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<tr>
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<td>1950</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.130</td>
<td>$\Delta^+$</td>
<td>1950</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
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<td>$\Delta^0$</td>
<td>1620</td>
<td>0.03-0.10</td>
<td>0.02%</td>
</tr>
<tr>
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<td>1675</td>
<td>0-0.15</td>
<td>0.03%</td>
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<tr>
<td>0.102</td>
<td>$\Delta^+$</td>
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</tr>
<tr>
<td>0.101</td>
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<td>1650</td>
<td>0.04-0.20</td>
<td>0.03%</td>
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<tr>
<td>0.0964</td>
<td>$\Delta^0$</td>
<td>1920</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.0856</td>
<td>$\Delta^+$</td>
<td>1920</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>0.0768</td>
<td>$N^+$</td>
<td>1710</td>
<td>0.0-0.02</td>
<td>&lt;0.01%</td>
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<tr>
<td>0.0689</td>
<td>$\Delta^0$</td>
<td>1910</td>
<td>0.0-0.02</td>
<td>&lt;0.01%</td>
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<tr>
<td>0.0640</td>
<td>$N^0$</td>
<td>1650</td>
<td>0.003-0.17</td>
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<tr>
<td>0.0630</td>
<td>$N^0$</td>
<td>1700</td>
<td>0.01-0.13</td>
<td>0.01%</td>
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<tr>
<td>0.0512</td>
<td>$\Delta^+$</td>
<td>1910</td>
<td>0.0-0.02</td>
<td>&lt;0.01%</td>
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</table>

MicroBooNE MC uses GENIE neutrino event generator.

This isn't a generic NC single photon search:

- Not considering higher order resonances (~8%): these decay channels not enabled in GENIE by default
- Not considering other modes of $\Delta$ production like coherent (~10%) that would be subleading, not currently simulated in GENIE

Expect resonant NC $\Delta(1232) \rightarrow N\gamma$ signal to account for ~80% of the expected single photon events at energies <1GeV.

Estimated contributions to $N\gamma$ rate for each parent resonance
Dirt events are neutrino interactions that occur outside of the active TPC volume. Although they comprise only ~6% of total background events here, they were an important category for MiniBooNE.
NC $\pi^0$ Background Example

- If second photon shower is missed/ mis-reconstructed, looks nearly identical to signal
- Reconstructed invariant mass can be close to expected value of $M_\Delta$ if second photon is low energy

\[ \nu_\mu + p \to \nu_\mu + \Delta^+ \]

This is one of the most signal-like candidate data events, although it isn't selected in the final stage. The reconstructed $M_\Delta = 1.17$ GeV.
1γ1p BDT Responses: Cosmic

Top training variables:
1. Reconstructed track truncated mean dE/dx
2. Ratio of the shower impact parameter to the shower conversion distance
3. Reconstructed Δ momentum in the Z direction
4. Pandora neutrino score
5. Pandora track score
1γ1p BDT Responses: Nue

Top training variables:
1. Reconstructed shower conversion distance
2. Reconstructed $\Delta$ invariant mass
3. Minimum distance from the shower to the track start or end
4. Reconstructed shower dE/dx
5. Minimum distance between any point in the track and any hit in the shower
1γ1p BDT Responses: NC π⁰

Top training variables:
1. Reconstructed Δ invariant mass
2. Ratio of the shower impact parameter to the shower conversion distance
3. Reconstructed shower energy
4. Photon transverse momentum
5. Distance from shower end to active TPC boundary
1γ1p BDT Responses: SSV

Top training variables:
1. Number unassociated hits within 10cm of vertex
2. Conversion distance of the closest 2D hit cluster candidate
3. Best reconstructed invariant mass of any 2D hit cluster candidate
4. Impact parameter of the closest 2D hit cluster candidate
5. Reconstructed shower energy of the closest 2D hit cluster candidate
Top training variables:
1. Ratio of the shower impact parameter to the shower conversion distance
2. Pandora shower score
3. Reconstructed track truncated mean dE/dx
4. Minimum distance from the shower to the track start or end
5. Reconstructed Δ invariant mass
In-Situ NC $\pi^0$ Measurement

Single photon $1\gamma_{0p}$ and $1\gamma_{1p}$ selections

Complementary NC $\pi^0$ $2\gamma_{0p}$ and $2\gamma_{1p}$ selections
NC $\pi^0$ Systematics Constraint for Single Photon Selection

Constrained Systematics

Unconstrained Systematics

Kathryn Sutton
NuFact 2021
Sept 7th 2021
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Short Baseline Anomalies: LSND

- LSND was a scintillation detector at LANL operating from 1993-1998
- Measured neutrinos from a $\mu^+$ decay-at-rest source with a peak neutrino energy <60MeV
- Saw an excess of events, attributed to an anomalously high $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Tension with Sterile Neutrino Interpretation

One of the largest tensions is that given the observed increase in $\nu_\mu \rightarrow \nu_e$ (appearance), there has not been evidence of a corresponding decrease in $\nu_\mu \rightarrow \nu_\mu$ (disappearance), including in MiniBooNE.

The evidence for the existence of steriles is currently inconclusive and alternate interpretations are needed to fully understand these anomalies.

Dentler et al., 10.1007/JHEP08(2018)010

MiniBooNE and LSND fall in electron (anti)neutrino appearance allowed region

99.73% CL 2 dof

Appearance

Disappearance

Dentler et al., 10.1007/JHEP08(2018)010
Coherent NC $\gamma$ in MicroBooNE

- **$\sim$10% increase in NC $\gamma$** in MicroBooNE by including coherent interaction
- **Peak in $\gamma$ energy $\sim300\text{MeV}$**, strongly **forward-peaked** in beam direction
- Potentially can distinguish incoherent (resonant $\Delta$ production) from coherent with sufficient angular resolution

Predicted NC coherent and incoherent single photon events in MicroBooNE
Z' Boson Decay

E.g., Z' mediated heavy neutrino production and decay into e+e- pair

Neutrinos up-scatter into heavy state, which promptly decays into a pair of electrons.

Presence of hadronic activity and pointing or forwardness/opening angle of e+e- shower(s) can help resolve between different models and model parameters