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

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MiniBooNE observed a low-energy excess (LEE) of CC $\nu_e$-like events, predominately below 800 MeV reconstructed neutrino energy, with a significance of $\sim 4.8 \sigma$ when combining all neutrino mode data.

MiniBooNE Collaboration: arxiv:2006.16883
Electrons or Photons?

Being a mineral oil (CH$_2$) Cherenkov detector, MiniBooNE observed **true electrons** originating from **intrinsic $\nu_e$** in the beam (**green** histograms) by its Cherenkov rings.

MiniBooNE Collaboration: arxiv:2006.16883
Electrons or Photons?

However, the bulk of backgrounds at lower reconstructed neutrino energies are photons such as NC $\pi^0$'s (red) and $\Delta$ radiative decay (tan).

Photons pair-producing tightly collimated $e^+e^-$ pairs produce Cherenkov cones in that are indistinguishable from that of a single electron in MiniBooNE.

I will only be speaking about the photon interpretation in this talk, See Hanyu Wei's next talk for more on uBooNE's search for the electron-like interpretation! [Link]
Enter MicroBooNE

MicroBooNE is an 85-ton surface based Liquid Argon Time Projection Chamber (LArTPC) that has been collecting data in the same neutrino beam as MiniBooNE since Autumn 2015.

One of its primary goals is to identify if the origin of the observed MiniBooNE Low Energy Excess (LEE) is due to electrons or photons.

This can be achieved due to LArTPC's excellent spatial resolution and calorimetry.

*Primary but by no means only, See talks by Marina Reggiani Guzzo, Wenqiang Gu, Krishan Mistry, Pawel Guzowski and Maya Wospakrik!
**Spatial Resolution:** Photon Conversion Distance

LArTPC’s are like a digital bubble chamber. In argon photons travel with a mean free path of ~15cm before pair converting, and as the photons are neutral this appears as a distinct gap.
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**Calorimetry:** Shower $dE/dx$

Photons producing $e^+e^-$ pairs tend to **deposit twice the energy per unit length** as a single electron.

Example of shower $dE/dx$ for candidate neutrino events in the NuMI beam at MicroBooNE: [arXiv:2101.04228](https://arxiv.org/abs/2101.04228)
Photon interpretations of the MiniBooNE excess

Although there are several sources of photons in MiniBooNE, this search is focusing on NC $\Delta$ radiative decay ($\Delta \rightarrow N\gamma$). Motivation for this is 3-fold:

- **SM process**, no need to invoke existence of sterile neutrinos
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- The shape of the $\Delta$ Radiative Decay events agree extremely well with the observed low-energy excess, can explain it if the rate were increased by a factor of ~ $x3$ from its standard model predictions.

[Diagrams showing photon interpretations]

A $\sim 3x$ flat scaling to NC $\Delta \rightarrow N\gamma$ can explain the observed MiniBooNE excess. Use this as a $\gamma$LEE signal template for $\mu$BooNE.
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- The shape of the $\Delta$ Radiative Decay events agree extremely well with the observed low-energy excess, can explain it if the rate were increased by a factor of ~ $x_3$ from its standard model predictions
- The rate of neutrino induced $\Delta$ Radiative Decay has **never been observed**, with the strongest bounds in this energy region from T2K being $O(100)$ times larger than current prediction
NC $\Delta$ Radiative Decay in MicroBooNE

In MicroBooNE we are searching NC $\Delta$ radiative events both with a visible proton ($1\gamma 1p$ topology) and without ($1\gamma 0p$ topology) although in this talk I will be focusing on the primary $1\gamma 1p$ analysis.

Use Pandora Multi-Algorithm Pattern Reconstruction [Eur. Phys. J. C78, 1, 82 (2018)] framework to find all candidate neutrino events where there is exactly 1 shower and 1 track which share a common vertex (although shower can be displaced significantly).
Topological Selection Stage

- Just asking for the existence of a single reconstructed track and a shower
- At this stage, our signal is massively dominated by Cosmic, BNB Charged current (CC) $\nu_\mu$ backgrounds and Dirt (Neutrino events that interacted outside of the TPC and scattered in)
- Signal-to-background ratio $\sim 1:1000$
- Showing results using a small sample of unblinded data ($0.4x10^{20}$ POT). First results will be with $\sim 17x$ (First 3 years) more data, with final dataset being $\sim 30x$ what I show today (Full 5 years)

The true $\Delta$ Invariant Mass, $M_\Delta = 1.232$ GeV
Pre-Selection Stage

We can reduce backgrounds by over an order of magnitude by first implementing a series of **pre-selection cuts** to remove the more clear cut backgrounds. Examples include:

- Ensuring the *track is contained* inside the TPC eliminates many cosmic muons entering
- Enforcing a *shower energy threshold of 40 MeV* reduces Michel electrons contamination
We can reduce backgrounds by over an order of magnitude by first implementing a series of **pre-selection cuts** to remove the more clear cut backgrounds. Examples include:

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At this stage, we are still dominated by many cosmic and beam induced backgrounds. We train five tailored Boosted Decision Trees (BDT) each targeting a key background:

- **Cosmic** Rejection BDT
- **Intrinsic** $\nu_e$ Rejection BDT
- **Two** NC$\pi^0$ Rejection BDT's
  - One focused on $\pi^0$ kinematics, and the other looking to veto the existence of a non-reconstructed secondary shower
- **BNB “Other”** Rejection BDT
  - Primarily CC $\nu_\mu$ events
Example: NC $\pi^0$ Rejection BDT

Here only showing example of $1\gamma 1p$ NC $\pi^0$ rejection BDT response, showing good modelling of the backgrounds across the entire region of phase space.

The NC $\pi^0$ BDT tries to make use of variables that would be sensitive to the parent $\Delta$ kinematics or the missing secondary shower of the $\pi^0$ decay such as
- The reconstructed invariant mass of the photon-proton pair
- Photon Transverse Momentum

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More NC $\pi^0$ Background-like

More NC $\Delta$ Radiative Signal-like
Example: NC $\pi^0$ Rejection BDT

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We then place a simultaneous cut on all five BDT response scores in an effort to maximize the sensitivity of the analysis to observing NC $\Delta$ Radiative decay.
Post BDT cut, $1\gamma 1p$ Final Selection

- Reminder, Showing results using **small sample unblinded data**, full data set is ~30x larger
- Observe 2 events with an expectation of 2.6 for the SM scenario.
- This targeted BDT approach has resulted in extremely strong rejection of Cosmics, Dirt, and CC backgrounds, to the extent they are no longer a major concern.
- By **far** the **dominant background** is **NC $\pi^0$** events (~90%) and it’s easy to see why by looking at some events.
NC single photon candidate $1\gamma 1p$ data event

MicroBooNE Data, Run 5462 Subrun 14 Event 732
NC single photon candidate $1\gamma 1p$ data event

NC $\pi^0 + 1$ Proton ($2\gamma 1p$) Candidate data event
NC single photon candidate $1\gamma 1p$ data event

Hypothetical NC $\pi^0$ Event

- Topologically **indistinguishable** from our single photon signal
- Both cases have **true photon** and a **true proton**

Hypothetical: Subleading photon from $\pi^0$ exits detector before pair converting and is thus not reconstructed
There are many ways with which the secondary shower is lost:

- Escapes the detector before pair-converting
- Highly overlapping with leading shower
- Very low energy (< 30 MeV) where reconstruction efficiency is lower
- Interference with coincident cosmic rays
In-Situ NC $\pi^0$ Measurement

To *constrain* this dominating background we have utilized the same BDT based framework to develop a complementary in-situ *high statistics NC $\pi^0$ measurement*, in which both showers were reconstructed.

**Sneak Preview**: See Andrew Mogan’s Flash Talk for much more details [Friday 26th 11:45 @ Room 1 [Link]]

Highest-statistics sample of NC $\pi^0$ events in a LArTPC!
The NC $\pi^0$ Constraint

Side-by-side fit to $1\gamma$ and $2\gamma$ selections indirectly constraints NC $\pi^0$ background

Scale our prediction up to the full dataset (~30x).
The NC $\pi^0$ Constraint

Side-by-side fit to 1$\gamma$ and 2$\gamma$ selections indirectly constraints NC $\pi^0$ background.
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Correlation Matrix

1$\gamma$1p
1$\gamma$0p
2$\gamma$1p
2$\gamma$0p
NC $\pi^0$
NC $\pi^0$
The NC $\pi^0$ Constraint

Side-by-side fit to $1\gamma$ and $2\gamma$ selections indirectly constrains NC $\pi^0$ background

Correlation Matrix

Effectively reduces the systematic uncertainty on the signal selections by a factor of 2-3
Current Status of $\mu$BooNE’s Single-Photon Search

Analysis is frozen. $1\gamma$ selections have been validated with current small unblinded data sets, and analysis of $\sim x17$ larger signal blind sidebands is ongoing (first 3 years of data).

Projected sensitivity to the the NC $\Delta$ radiative process:

$\sim 40x$ more sensitive measurement than current world's best limit in this energy range (T2K [J. Phys. G: Nucl. Part. Phys. 46 08LT01])
Conclusions

- Utilizing the unique capabilities of LArTPC technology, MicroBoone has developed a full end-to-end analysis searching for **Neutral Current $\Delta$ radiative decays**.

- Projected to produce a **world-leading constraint** on the SM NC $\Delta$ radiative process, never directly measured in neutrinos before!

- **Worlds largest selection of NC $\pi^0$ in a LArTPC** provides a strong constraint to the primary backgrounds that remain in the selection.

- Currently wrapping up studies of signal-blind sidebands, and are on the cusp of unblinding the signal box for the first result with 3 years of data ($6.9 \times 10^{20}$ POT).

- More information on this analysis can be found in the MicroBooNE single-photon public note: [MICROBOONE-NOTE-1087-PUB](#).
Backup Slides
MicroBooNE Run Periods

Start of MicroBooNE running, October 2015

Software trigger at start of Run 1

Partial CRT during Run 2

Full CRT during Run 3 and onward

Brand-new, preliminary results shown today span data sets from this period ($6.9 \times 10^{20}$ POT)

Over its 5-year run, $\mu$BooNE has collected data corresponding to $12.25 \times 10^{20}$ POT (past quality cuts)

Run 1, $1.7 \times 10^{20}$ POT
Run 2, $2.7 \times 10^{20}$ POT
Run 3, $2.6 \times 10^{20}$ POT
Run 4, $3.2 \times 10^{20}$ POT
Run 5, $2.2 \times 10^{20}$ POT

Lower $e$ lifetime during Run 4

Missed points
Example: Cosmic Rejection BDT

More Cosmic-like

More NC Δ Radiative Signal-like
Shower Conversion Distance

2γ1p 5.84E20 POT
MicroBooNE Preliminary

(Data/MC: 0.90)  (KS: 0.990)  ($\chi^2$/nDOF: 28.36/34)  ($\chi^2$ P-val: 0.740)
The MicroBooNE Detector

MicroBooNE is an 89-ton surface based Liquid Argon Time Projection Chamber (LArTPC) that has been collecting data in the same Fermilab BNB since Autumn 2015.

One of its primary goals is to definitively identify if the origin of the observed MiniBooNE Low Energy Excess (LEE) is due to electrons or photons.

This can be achieved due to LArTPC’s excellent spatial resolution and calorimetry.

For further details and the working principles of the MicroBooNE Detector itself see Ralitsa’s talk.
MicroBooNE Cosmic Ray Tagger

Theory Prediction, Single Photon production

\[ \nu(p) + N \rightarrow \nu(p) + N + \gamma, \]  \hspace{1cm} (1)

is defined by the set of Feynman diagrams for the hadronic current shown in Fig. 1.

![Feynman diagrams](https://arxiv.org/pdf/1407.6060.pdf)

**Fig. 1.** (Color online) Feynman diagrams for the hadronic current of NC photon emission considered in Ref. [18]. The first two diagrams stand for direct and crossed baryon pole terms with nucleons and resonances in the intermediate state: BP and CBP with \( B = N, \Delta(1232), N^*(1440), N^*(1520), N^*(1535) \). The third diagram represents the \( \tau \)-channel pion exchange: \( \pi Ex \).

![Graphs](https://arxiv.org/pdf/1407.6060.pdf)

**Fig. 4.** (Color online) \( E_{QE}^{\nu} \) distributions of total NC\( \gamma \) events for the \( \nu \) (left) and \( \bar{\nu} \) (right) modes. Our results, given by the red solid lines are accompanied by grey error bands corresponding to a 68% confidence level. The curves labeled as “no \( N^* \)” show results from our model without the \( N^*(1440), N^*(1520) \) and \( N^*(1535) \) contributions. The “MB” histograms display the MiniBooNe estimates [20]. \( \Delta_{QE} \) denotes the size of the \( E_{QE}^{\nu} \) bin in the experimental setup.
MiniBooNE

In situ $\pi^0$ constraint

FIG. 7: An absolute comparison of the $\pi^0$ reconstructed mass distribution between the neutrino data ($12.84 \times 10^{20}$ POT) and the simulation for NC $\pi^0$ events (top). Also shown is the ratio between the data and Monte Carlo simulation (bottom). The error bars show only statistical uncertainties.
This *data event scores very highly as signal* in tailored background rejection BDT's.

Overall topology, kinematics and calorimetry match that of a NC $\Delta$ radiative decay extremely well.

However,...
Single-Photon candidate event in data (Likely NC $\pi^0$ background)

Zooming out:

Missed secondary shower makes it much more likely to be NC$\pi^0$ event

Coincidence intersecting cosmic muon increased probability that second shower was tagged as a delta-ray off the cosmic muon
**Key takeaway:** NC $\pi^0$ events outnumber true single-photon NC $\Delta$ radiative events by over **100-to-1** and there are *many ways* for the $\pi^0$'s to mimic our signal.