Search for a Single Photon Anomalous Excess in MicroBooNE

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Overview

- Where does it all start?
- Single photon analysis flow
- Background modeling cross-check
- Sensitivity Evaluation
Where does it all start?

It started with LSND observing a $3.8\sigma$ excess in anti-$\nu_e$ charge-current quasielastic (CCQE) events in the neutrino oscillation measurement, followed by the excess in low-energy region in $\nu_e$ CCQE-like events in MiniBooNE measurement.

![Graph showing data points and categories](image1)

Given that MiniBooNE is a Cherenkov detector and doesn't have the $e^-$ to photon identification capability, possible interpretations include:

- Excess in $e^-$
- Excess in photon

Both photon and electron produce fuzzy rings

Where does it all start? - MicroBooNE experiment

To resolve the MiniBooNE LEE, MicroBooNE is proposed, which is a liquid argon time projection chamber detector, and shares the same neutrino beam with MiniBooNE.

With the whole detector acting as a calorimeter, MicroBooNE has good separation power between $\text{e}^-$ and photons.

R. Acciarri et al 2017 JINST 12 P02017
Where does it all start? - photon interpretation

- MicroBooNE $1\gamma$ search is focused on excess of photon from neutral current (NC) $\Delta$ resonance ($1232\text{MeV}$) production and its radiative decay ($\Delta \rightarrow \gamma + N$)

- Unfolding result of the MiniBooNE LEE under the hypothesis of increased photon from NC $\Delta$ production and decay has suggested a flat normalization raise of NC $\Delta \rightarrow \gamma + N$ is sufficient to reproduce the excess, which is later determined to be $\sim 3x$

- T2K has measured their limit on total NC$\gamma$ cross section (flux-averaged) which is $O(\text{x}100)$ of the GENIE prediction
Single Photon Analysis Flow

The NC radiative decay ($\Delta \rightarrow \gamma + N$) will create two topologies in MicroBooNE detector due to the fact that neutral particles do not ionize argon and thus leave trace in the detector:

- 1 shower + 1 track (when nucleon is proton)
- 1 shower + 0 track (when nucleon is neutron)

Event passing final 1$\gamma$1p selection

Event passing final 1$\gamma$0p selection
Single Photon Analysis Flow

The analysis is developed with 5% of MicroBooNE full Run 1-5 dataset due to blind analysis policy, and the flow is as follows:

1. **Topology Cut**: require event topology to match 1 shower+1 track or 1 shower+0 track

2. **Pre-selection Cut**: remove badly reconstructed or obvious background by cutting on shower/track energy, shower/track containment etc.

3. **Multivariable Boosted Decision Trees (BDTs)** targeting different backgrounds:
   a. $^{1}\gamma^{1}p$ has 5 BDTs
      i. Cosmic rejection BDT
      ii. $\nu_{e}$ BDT
      iii. NC $\pi^{0}$ BDT, Second Shower Veto BDT
      iv. Other BNB BDT
   b. $^{1}\gamma^{0}p$ has 3 BDTs:
      i. Cosmic BDT
      ii. NC $\pi^{0}$ BDT
      iii. Other BNB BDT
Final distribution with 5% dataset (including LEE prediction - extra 2x GENIE-predicted NC $\Delta$ radiative decay events)

Purity of the signal has greatly improved from 0.6% after pre-selection cut to 32% at final stage in $1\gamma$1p

NC $\pi^0$ event comprise majority of the background in both selections
Background validation → $2\gamma$ Selections

- It's not surprising that NC $\pi^0$ is the major background in $1\gamma$ from $\Delta$ decay search:
  - $\Delta \rightarrow \gamma + N$ has an expected branching ratio (BR) of $\sim 0.6\%$
  - $\Delta \rightarrow \pi^0 + N$ has an expected BR of $\sim 99.4\%$
  - When one photon from $\pi^0$ decay is too low energy to be reconstructed or exists the detector or pair-produces very far from the vertex, $\Delta \rightarrow \pi^0$ events can mimic the $1\gamma$ signal

- Dedicated $2\gamma$ selections focusing on $2\gamma 1p$ and $2\gamma 0p$ topologies, using the same analysis framework as $1\gamma$ selections and MicroBooN Run 1-3 dataset
High-statistics measurement, high purity of NC $\pi^0$ (~60%) in both selections
With flux and cross section uncertainty, data and MC CV agree reasonably well
$\sim$20% and $\sim$7% data deficit observed in $2\gamma$1p and $2\gamma$0p respectively
Background validation - In-situ NC $\pi^0$ Correction?

- Extract normalization factors for NC $\pi^0$ coherent and non-coherent events ($N_{\text{coh}}$, $N_{\text{non-coh}}$)
- Fit to $2\gamma 1p$ and $2\gamma 0p \cos(\theta_{\pi^0})$ distributions simultaneously
- Best fit is found at ($N_{\text{coh}} = 1.4$, $N_{\text{non-coh}} = 0.8$) with $\chi^2$/dof = 2.73/4 and p-value = 0.603
- $\chi^2$/dof of data evaluated with GENIE central value (CV) is 6.97/6 and p-val = 0.324

- While GENIE CV ($N_{\text{coh}} = 1$, $N_{\text{non-coh}} = 1$) sits outside the $1\sigma$ region of the data-derived uncertainty, **data is consistent with MC CV given large GENIE uncertainty**
- Instead of correcting GENIE prediction of NC $\pi^0$, simultaneous fit of both $1\gamma$ and $2\gamma$ selections is performed to constrain background in $1\gamma$ selection
Signal Extraction

The $1\gamma$ and $2\gamma$ selections are highly correlated since majority of both $1\gamma$ and $2\gamma$ are NC $\pi^0$'s and that majority of the NC $\pi^0$ are from $\Delta$ decay.

A simultaneous fit to $1\gamma$ and $2\gamma$ final selections side-by-side to extract the scaling of branching ratio (BR) of NC $\Delta$ radiative decay ($x_\Delta$) is performed, which makes use of the strong correlations between $1\gamma$ and $2\gamma$ selections to

- Indirectly constrain the selected $1\gamma$ rate predictions
- Effectively reduce the systematic uncertainty in $1\gamma$ selection
Signal Extraction

The systematic uncertainty reduction in $1\gamma$ selection (for full dataset - $12.25 \times 10^{20}$ POT)

After the constraint

[Diagram showing event distributions before and after constraint, with labels for categories like 1x SM NC ∆ Radiative 10.30, NC 1×$\pi^0$ Coherent 0.00, etc., and the constraint affecting the signal distribution.]
Final Sensitivity Projection

\[ \Delta : \] the scaling of branching ratio (BR) of NC \( \Delta \) radiative decay

SM: GENIE CV prediction \( (\Delta = 1) \)

LEE: extra 2x GENIE-predicted NC \( \Delta \) radiative events on top of GENIE CV prediction \( (\Delta = 3) \)

With MicroBooNE full Run1-5 dataset:
- The median significance of rejecting the LEE hypothesis \( (\Delta = 3) \) in favor of SM hypothesis \( (\Delta = 1) \), assuming SM is true is 2.1\( \sigma \)
Takeaways

❖ Produced the world’s highest sensitivity to neutrino-induced NC $\Delta$ radiative decay with neutrino beam energy below 1 GeV

❖ Showed high potential of this analysis in probing the hypothesis of anomalous NC $\Delta$ radiative photon excess for MiniBooNE LEE interpretation

❖ Developed with 5% of the MicroBooNE full dataset, the $1\gamma$ part of the analysis will soon be allowed access to MicroBooNE Run1-3 data (x15 more statistics)

❖ Yielded the world’s highest-statistics NC $\pi^0$ sample
  
  ➢ Data deficit in $2\gamma1p$ has motivated a cross section extraction for the NC $\pi^0$ events

❖ Same framework is being explored to do coherent single photon search

❖ Watch out for our new result soon!

Thank you!
Backup Slides
Final Distributions projected to full dataset
Final Sensitivity Projection

\[ x_\Delta : \text{the scaling of branching ratio (BR) of NC } \Delta \text{ radiative decay} \]

SM: GENIE CV prediction \((x_\Delta = 1)\)

LEE: extra 2x GENIE-predicted NC \(\Delta\) radiative events on top of GENIE CV prediction \((x_\Delta = 3)\)

With MicroBooNE full Run1-5 dataset:
- The median significance of rejecting SM hypothesis \((x_\Delta = 1)\) in favor of LEE hypothesis \((x_\Delta = 3)\), assuming LEE is true is 2.3\(\sigma\)
With MicroBooNE full Run1-5 dataset, we expect:

- If no NC $\Delta$ radiative events are observed, the LEE hypothesis could be ruled out at >95% confidence level (C.L.)

- If SM NC $\Delta$ radiative prediction is observed, the LEE hypothesis could be ruled out at >90% C.L.
Coherent single photon search

- This framework is planned to be used for coherent single photon search, for which 1 (statistically more forward along the beam direction) shower, 0 track are expected.

- Of events satisfying $1_{\gamma}0p$ topology, non-negligible amount have proton tracks in truth that are not reconstructed due to low energy/unresponsive wire regions

- Current efforts focusing on vetoing events with low-energy, unreconstructed proton stubs