Overview of MicroBooNE Results

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Neutrino Oscillation Workshop 2022
Rosa Marina (Ostuni, Italy)

ALFRED P. SLOAN FOUNDATION

MicroBooNE turns 15 years old this October!

Proposal: 2007 *(addendum, 2008)*

Construction: 2010-2012

Installation & Commissioning: 2012-2015

Operations: 2015-2020

R&D Phase: 2021

Detector shutdown: 2022

Physics data analysis continues…

More than 45 publications within the last 5 years

More than 75 public notes sharing with the community as we go

MicroBooNE: 2007-today

MicroBooNE has been a flagship neutrino LArTPC experiment in the U.S. over the past decade, demonstrating the power of the technology in making precision measurements. It has already delivered on its main physics goals:

- First direct tests of the MiniBooNE anomaly
- The world's first high-statistics precision cross-section measurements on argon
- Further searches for new physics

[See talks by K. McFarland, Monday, and S. Gardiner, Friday]

MicroBooNE is also laying the groundwork for upcoming and future LArTPC detector programs:

- Short Baseline Neutrino (SBN) program (SBND and ICARUS)
- Deep Underground Neutrino Experiment (DUNE) [See talk by L. Stanco, Tuesday]

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- The world's first high-statistics precision cross-section measurements on argon
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"Low Energy Excess (LEE)" results, October 2021

This talk!

Latest sterile neutrino oscillation search results, this summer

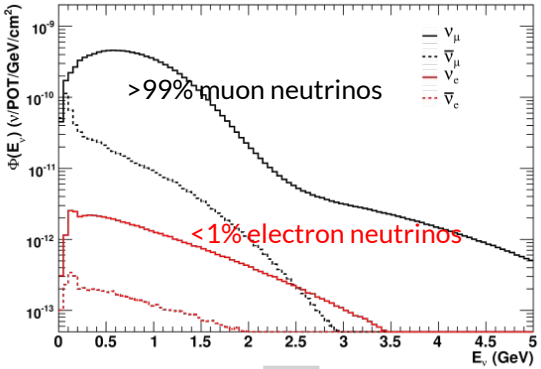
This talk!

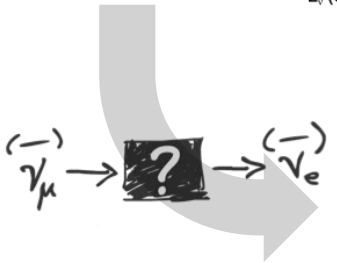
MicroBooNE is also laying the groundwork for future LArTPC detector programs:

- Short Baseline Neutrino (SBN) program (SBND and ICARUS)
- Deep Underground Neutrino Experiment (DUNE)

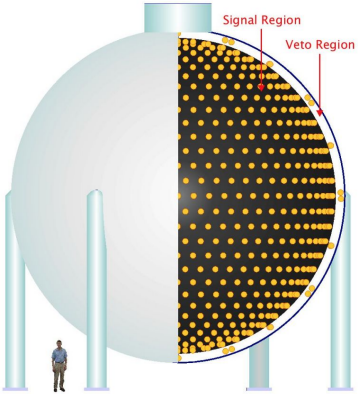
MiniBooNE Anomaly (2000's)

Fermilab Booster Neutrino Beam:
(neutrinos from $\pi^{\pm} \rightarrow \mu^{\pm}$ decay in flight, 500m baseline)

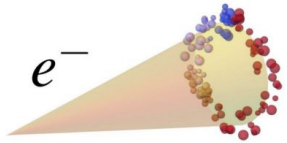




MiniBooNE Detector



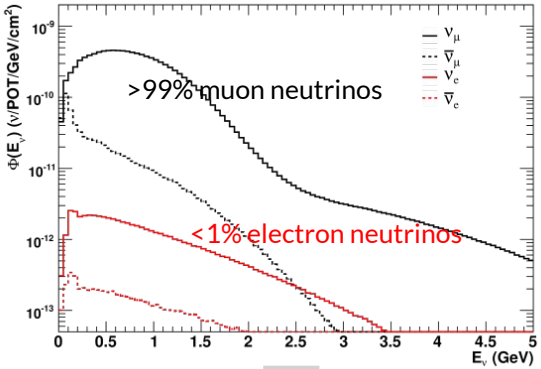
Electron neutrino signature:
Fuzzy cherenkov ring from electromagnetic shower from the electron produced in $\nu_e + n \rightarrow p + e^-$ scattering

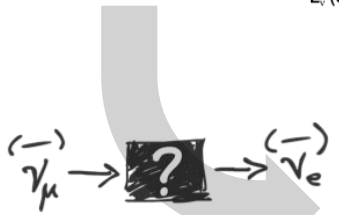


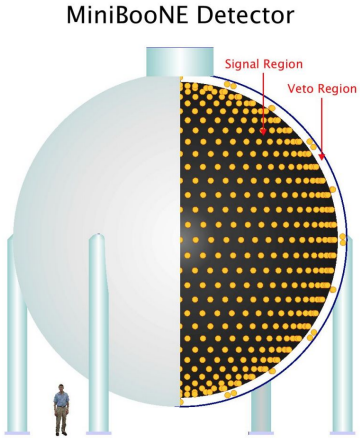
(proton usually below cherenkov threshold)

MiniBooNE Anomaly (2000's)

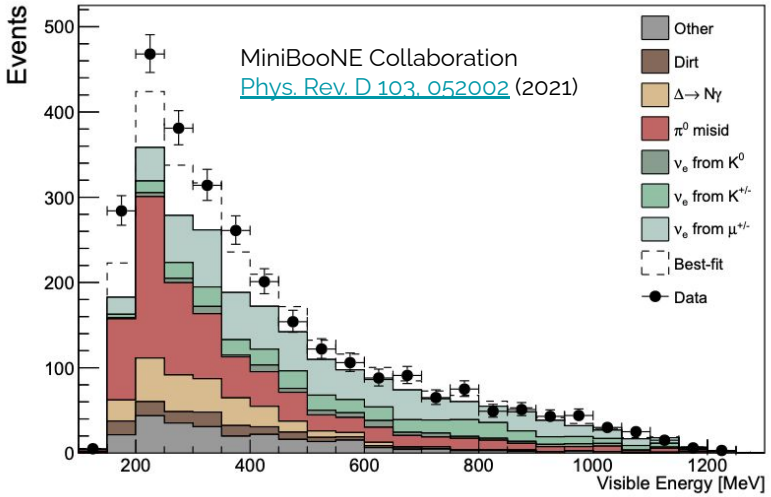
Fermilab Booster Neutrino Beam:
(neutrinos from $\pi^{\pm} \rightarrow \mu^{\pm}$ decay in flight, 500m baseline)

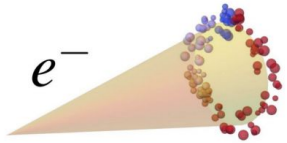






Observation: Excess ν_e in a ν_μ dominated beam, 4.8σ

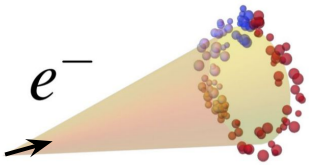


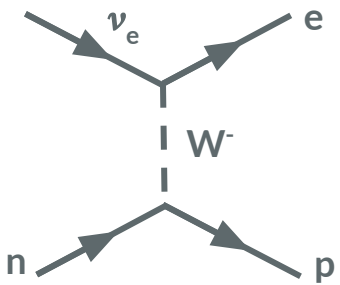


Primarily at low reconstructed ν energy: "Low Energy Excess"

What is the source of the MiniBooNE Low Energy Excess?

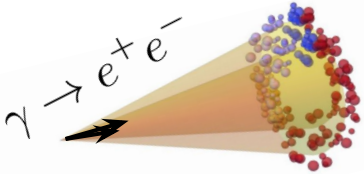
Key observation: **electromagnetic shower from ν_e CC interactions**

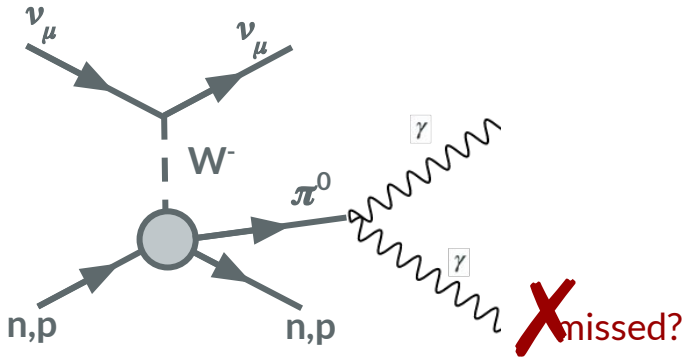




For a broad review of Standard Model and beyond-Standard Model interpretations, see the "Snowmass 2022 NF02 White Paper": arXiv:2203.07323

But, the same signature is shared by a **photon**, e.g. from ν_μ **NC interactions**





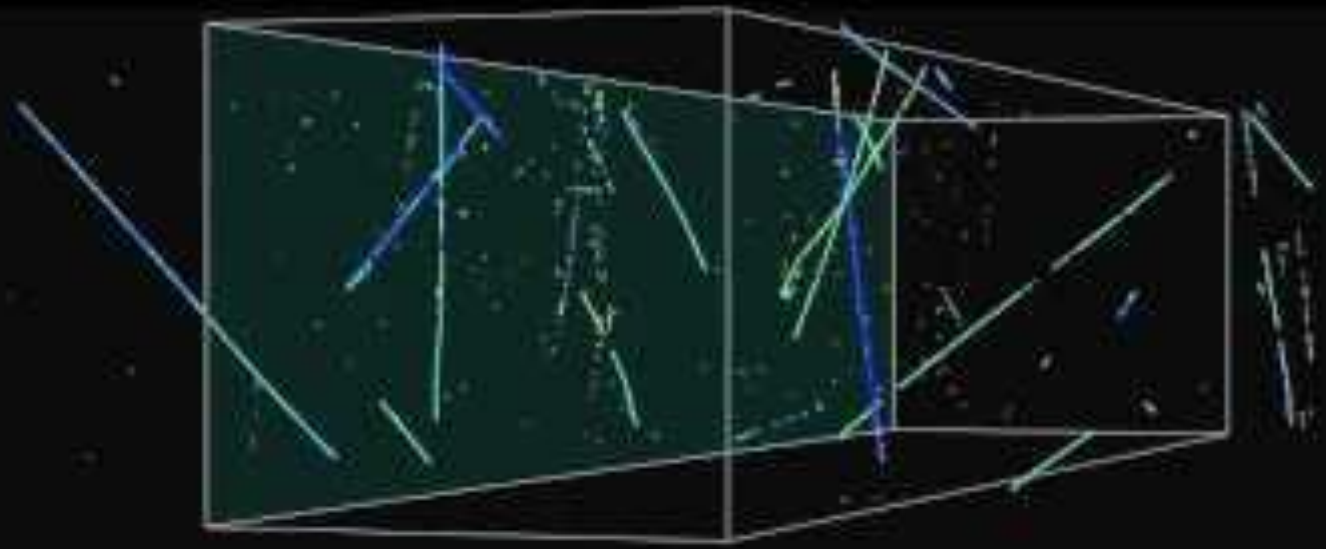
Could the MiniBooNE excess be a misunderstood photon background?

MicroBooNE at Fermilab

Part of the ongoing Short Baseline Neutrino (SBN) program at Fermilab

Same neutrino beam and ~location as MiniBooNE →
Direct test of MiniBooNE anomaly: Is it e or γ?

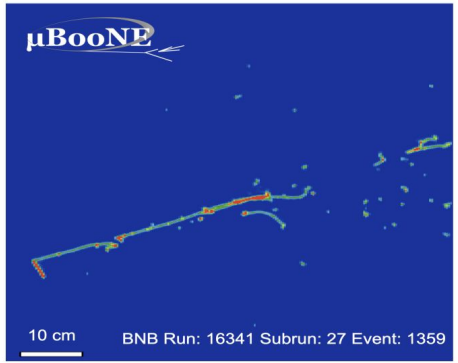
Much more advanced detector:
Liquid Argon Time Projection Chamber (LArTPC)

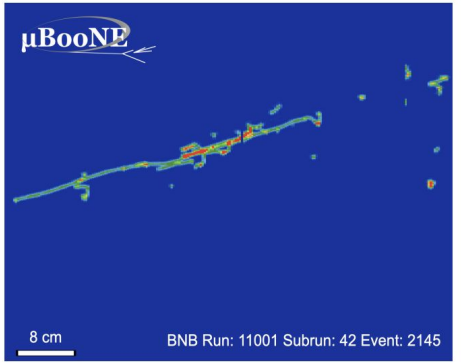


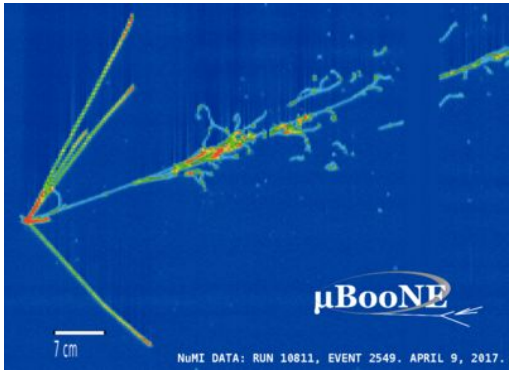
Unprecedented look at neutrino interaction final states!

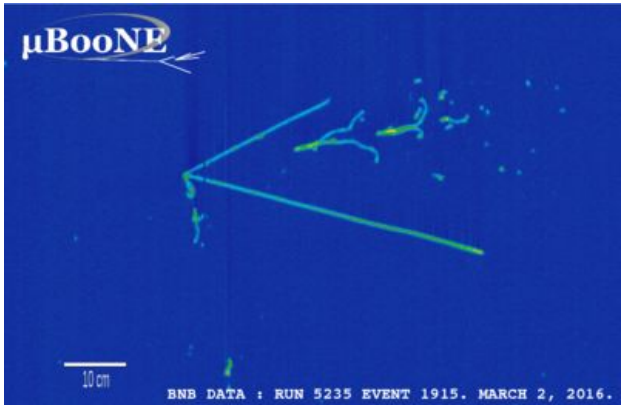
ν_e or ν_μ differentiation based on electron (shower) vs. muon (track)

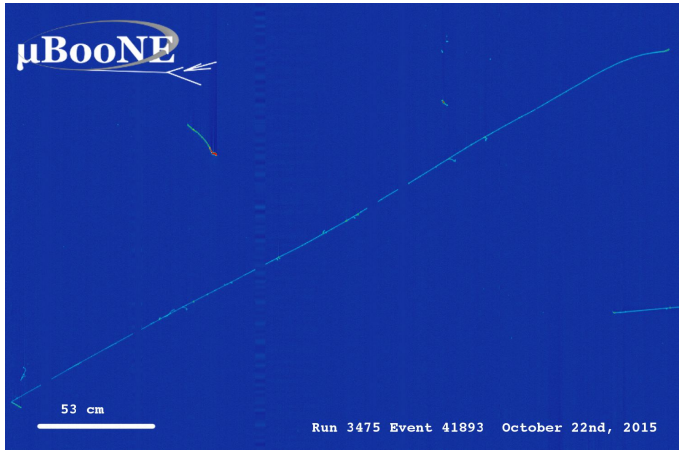
unique strength of LArTPC technology:
ability to identify explicitly the way each ν_e or ν_μ interacts! (resonantly, coherently, …)



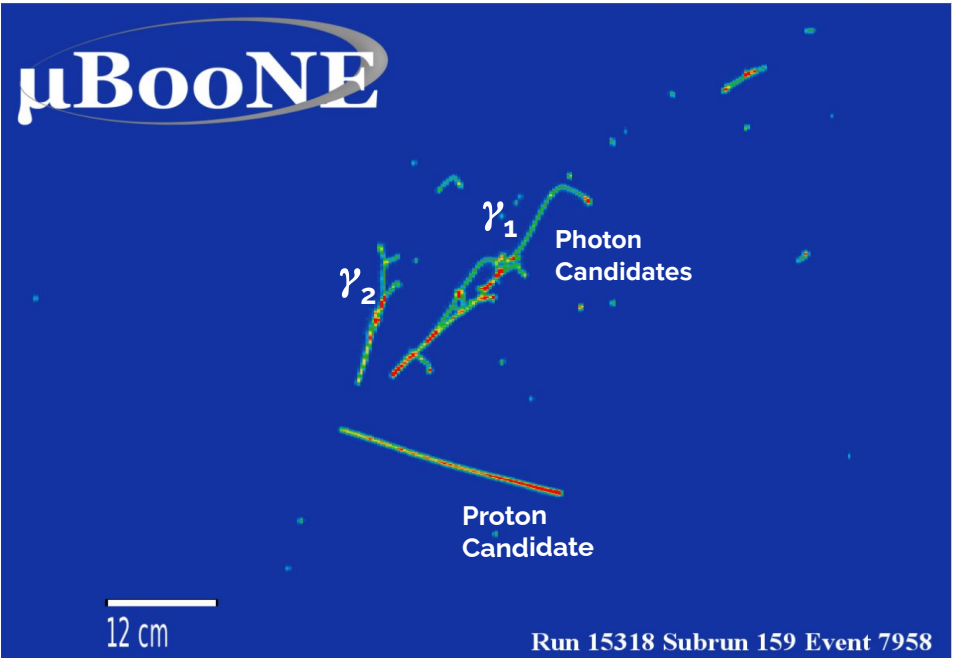




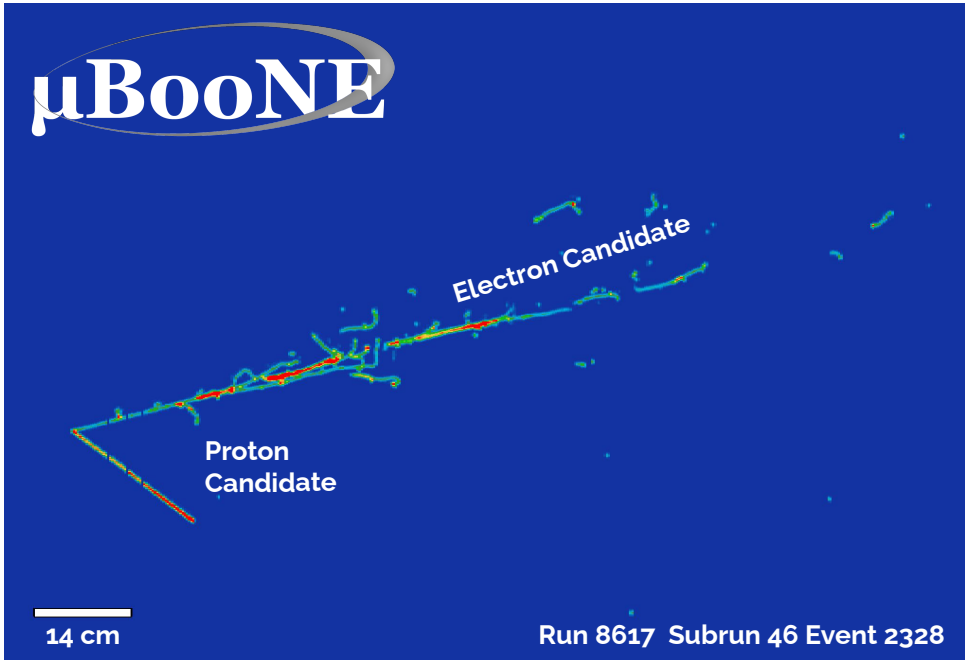




MicroBooNE can resolve electrons/photons!



ν_μ NC π^0 candidate data event



ν_e CC candidate data event

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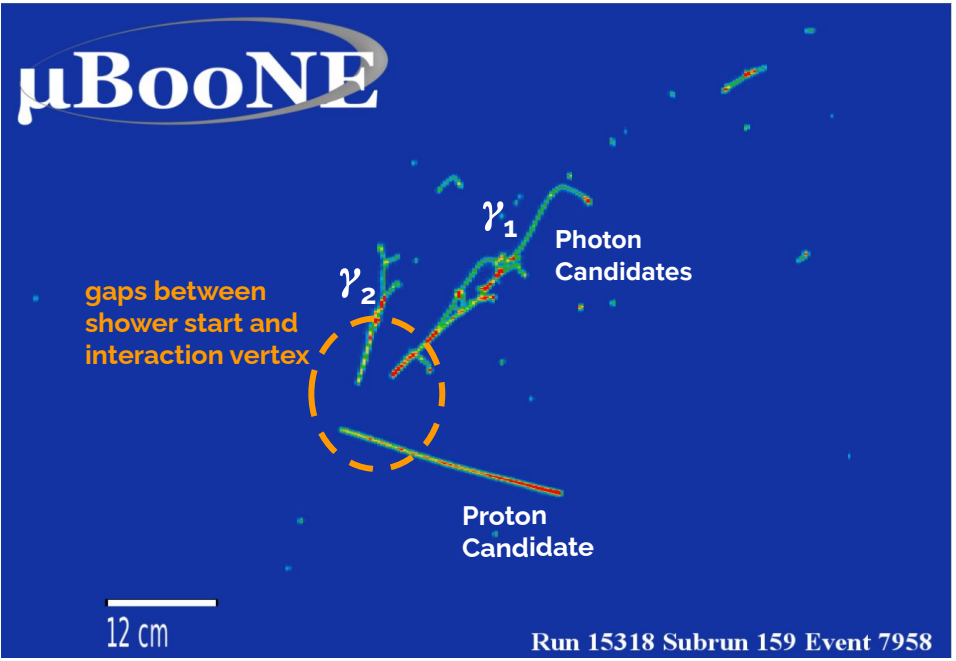
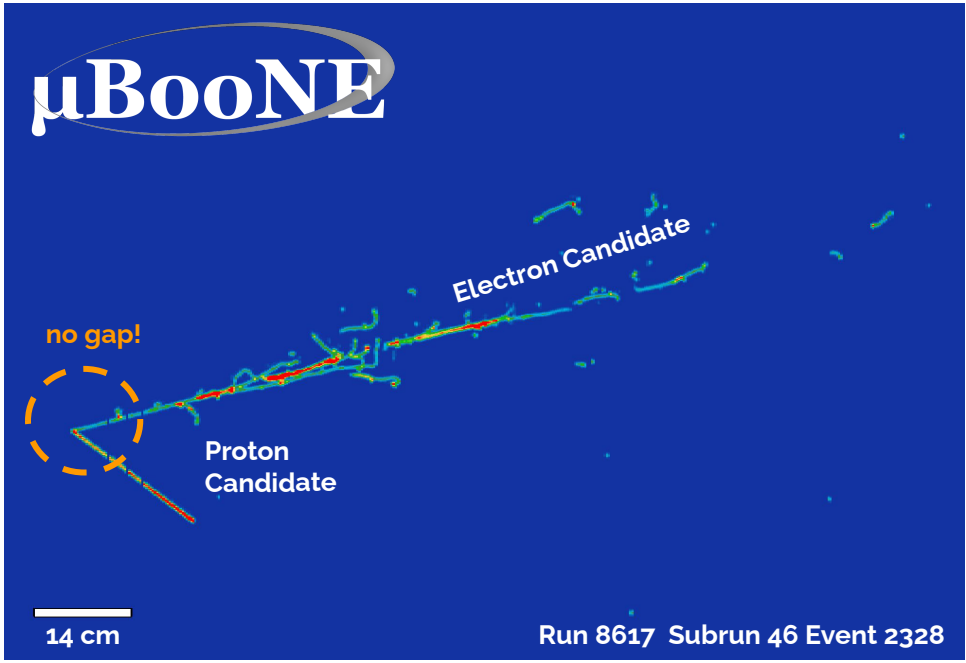


ν_μ NC π^0 candidate data event



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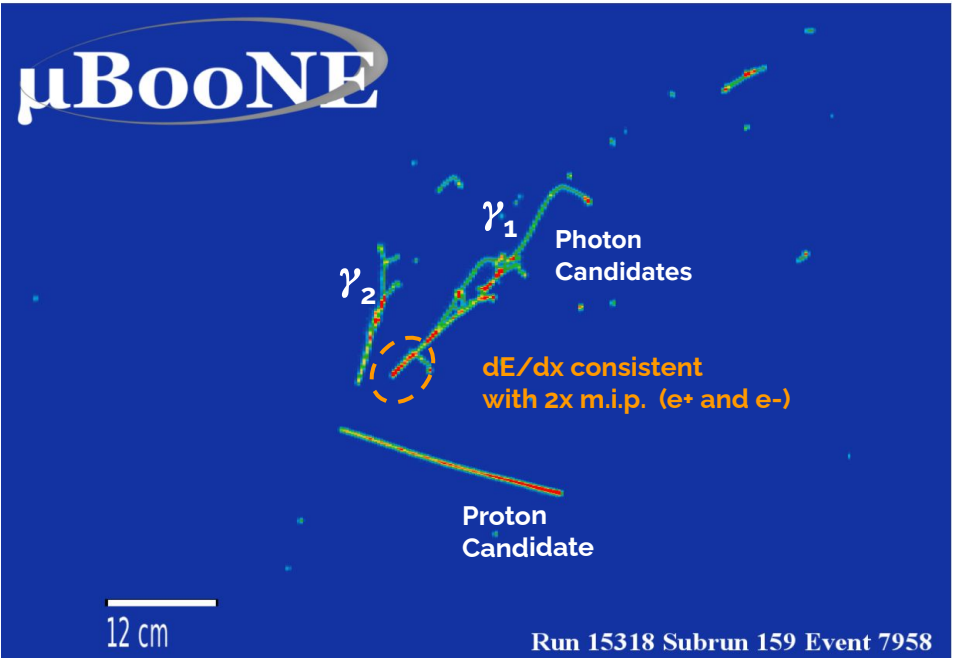

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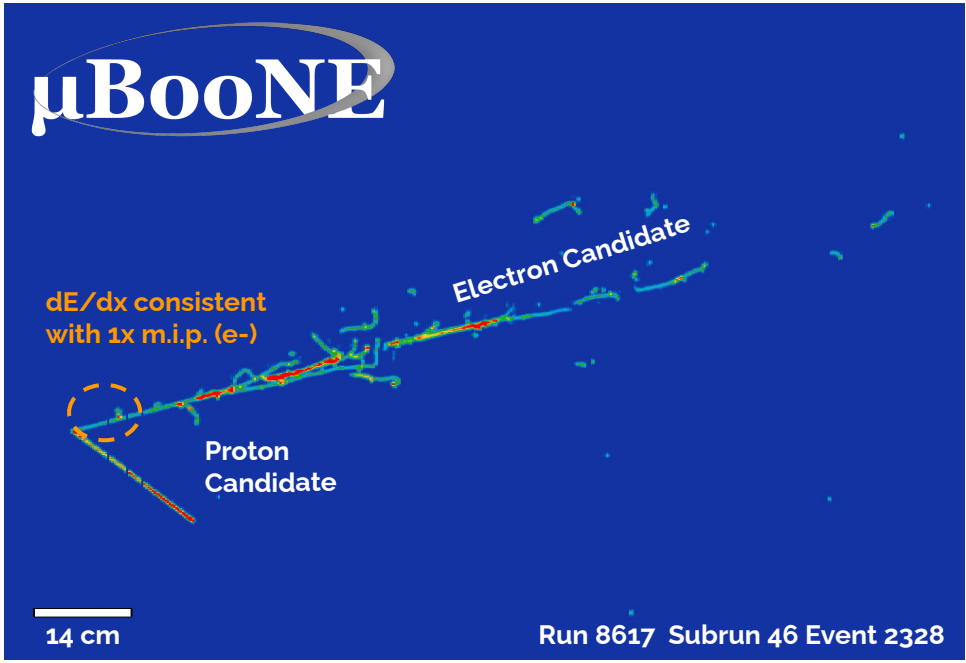


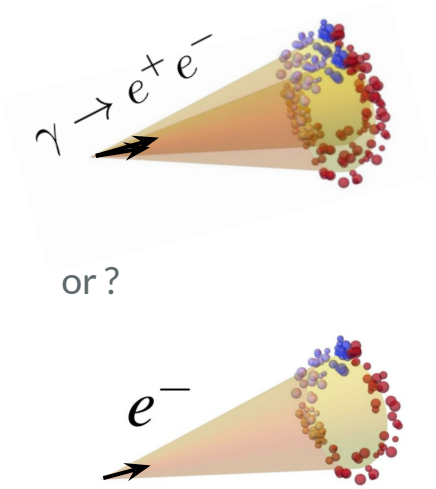
ν_e CC candidate data event

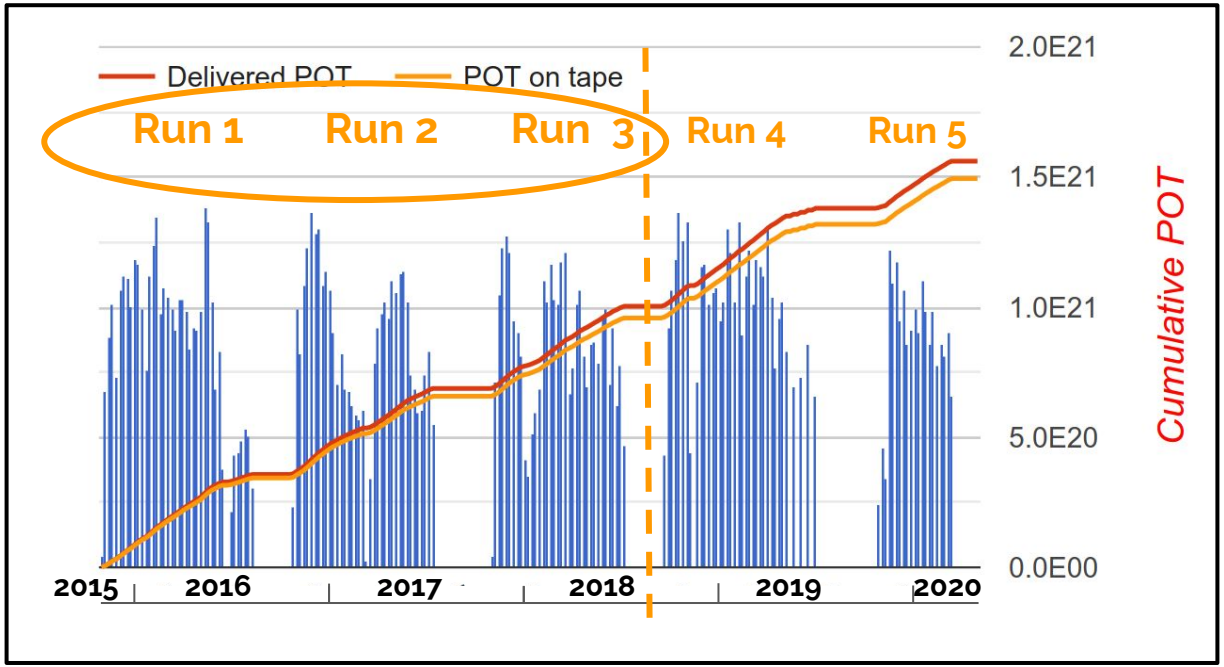
First low-energy excess search results in October 2021!

MicroBooNE’s first direct tests of the MiniBooNE anomaly

First low-energy excess search results in October 2021!

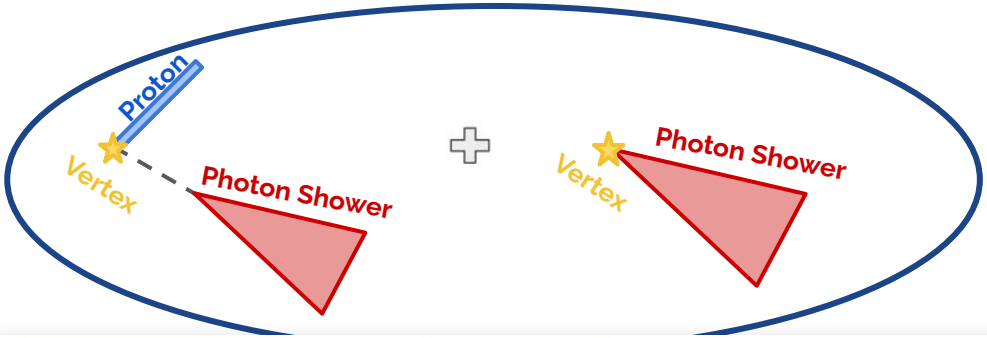
Making use of **only half of the total dataset** collected by MicroBooNE during its entire operations timeline





MicroBooNE photon search

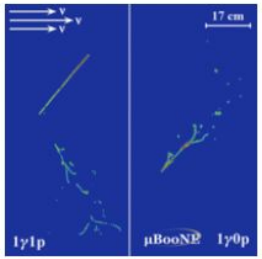
Is the MiniBooNE excess single-photons?



Search for Neutrino-Induced Neutral-Current Δ Radiative Decay in MicroBooNE and a First Test of the MiniBooNE Low Energy Excess under a Single-Photon Hypothesis

P. Abratenko *et al.* (MicroBooNE Collaboration)

Phys. Rev. Lett. **128**, 111801 (2022) – Published 14 March 2022



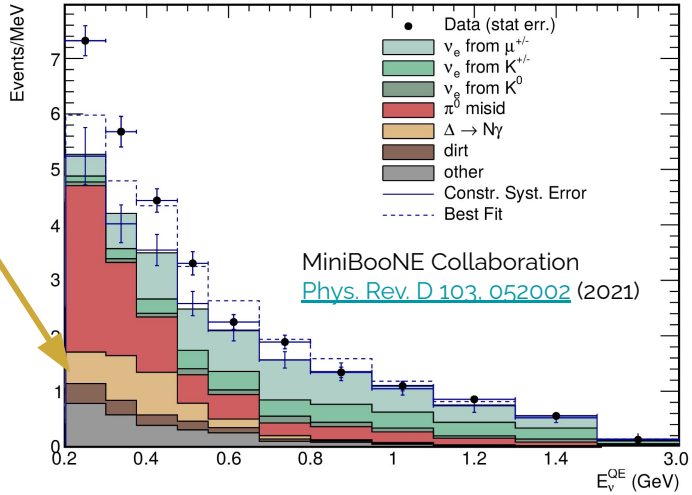
The MicroBooNE collaboration rules out a promising standard model explanation for the MiniBooNE low-energy excess: Δ baryon radiative decay.

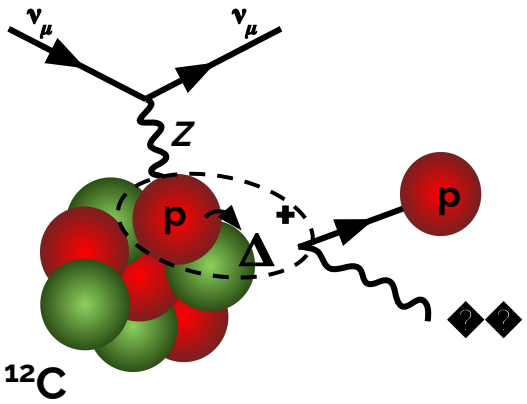
Show Abstract +

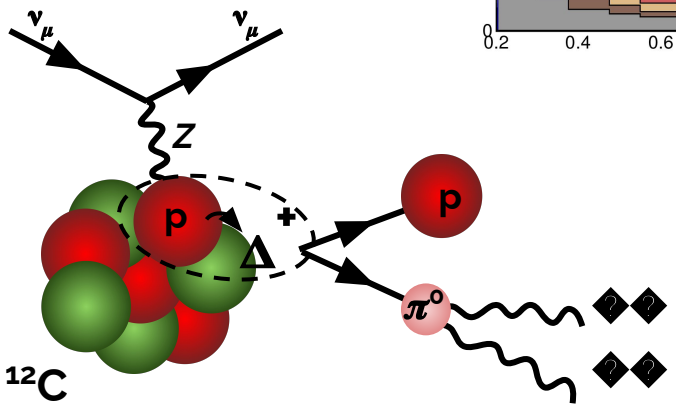
MicroBooNE photon search

Is the MiniBooNE excess mis-estimated x3.18 NC $\Delta \rightarrow N\gamma$?

- **Dominant source of Standard-Model-expected single-photon processes** at MiniBooNE beam energies
- **Never been directly measured** in neutrinos before
- **Only indirectly constrained** in the MiniBooNE analysis





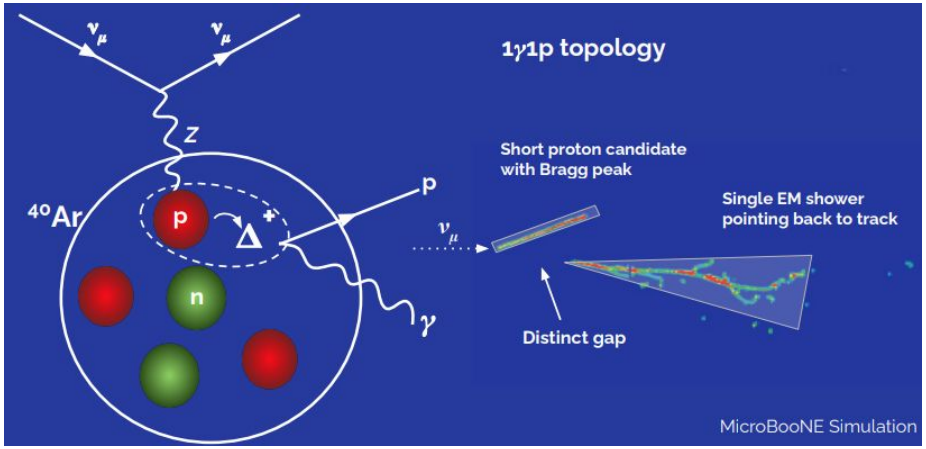


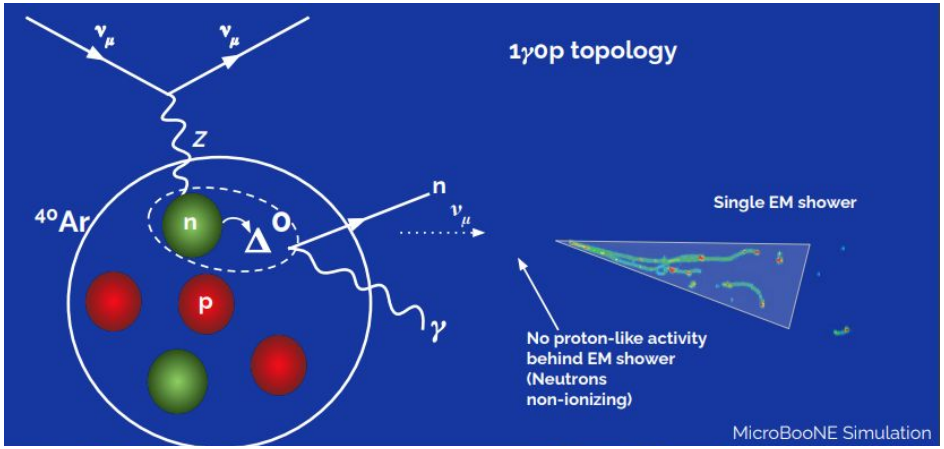
NC $\Delta \rightarrow N\gamma$ and
NC $\Delta \rightarrow N\pi^0$ rates
are correlated

MicroBooNE photon search

MicroBooNE Collab. Phys. Rev. Lett. 128, 111801 (2022)

NC $\Delta \rightarrow N\gamma$: Delta (1232MeV) baryon resonance production, followed by radiative decay:





A rare Standard Model-expected process

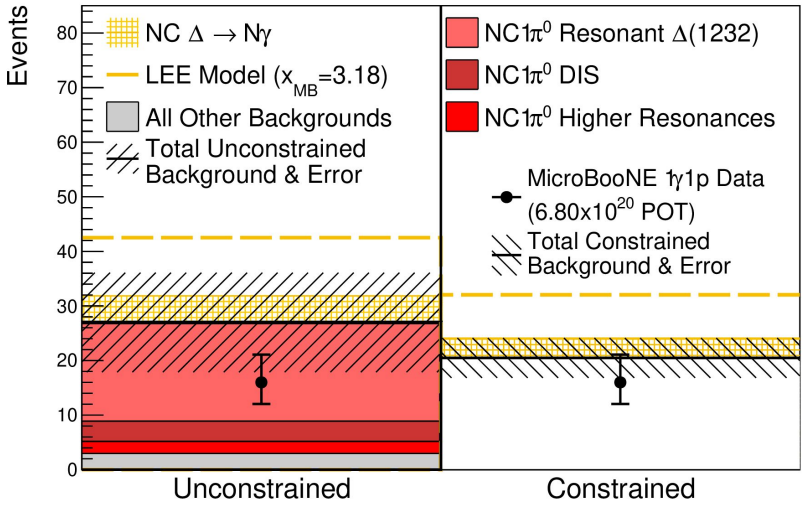
We expect only 124.1 such events in Run 1-3 data!

two mutually exclusive "selections"

MicroBooNE photon search results!

MicroBooNE Collab. Phys. Rev. Lett. 128, 111801 (2022)

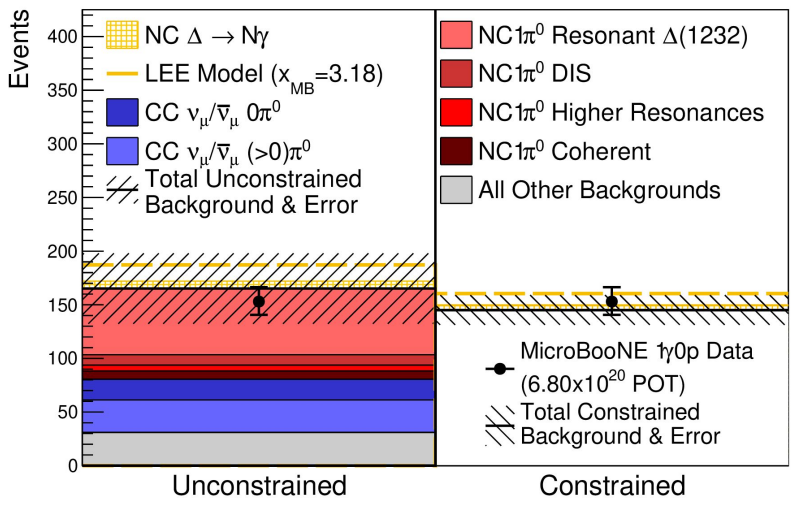
1γ1p



1γ1p	
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC Δ → Nγ	+ 4.88
LEE ($x_{MB} = 3.18$)	+ 15.5

16 Data Events Observed

1γ0p



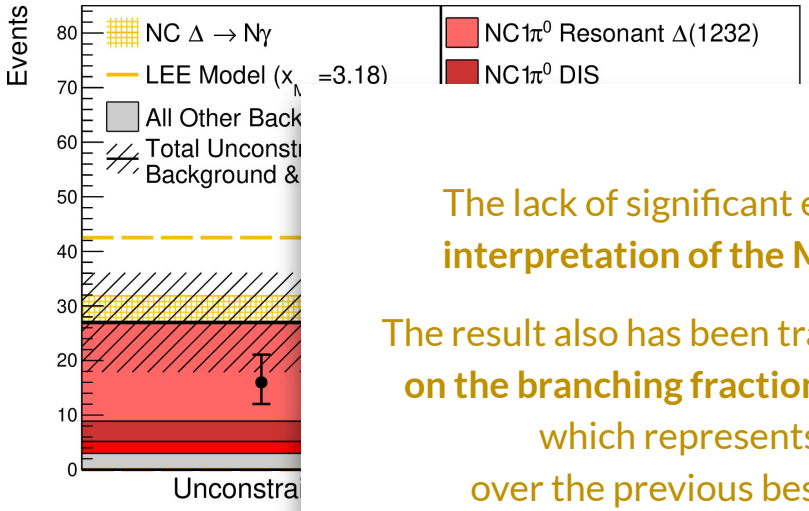
1γ0p	
Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC Δ → Nγ	+ 6.55
LEE ($x_{MB} = 3.18$)	+ 20.1

153 Data Events Observed

MicroBooNE photon search results!

MicroBooNE Collab. Phys. Rev. Lett. 128, 111801 (2022)

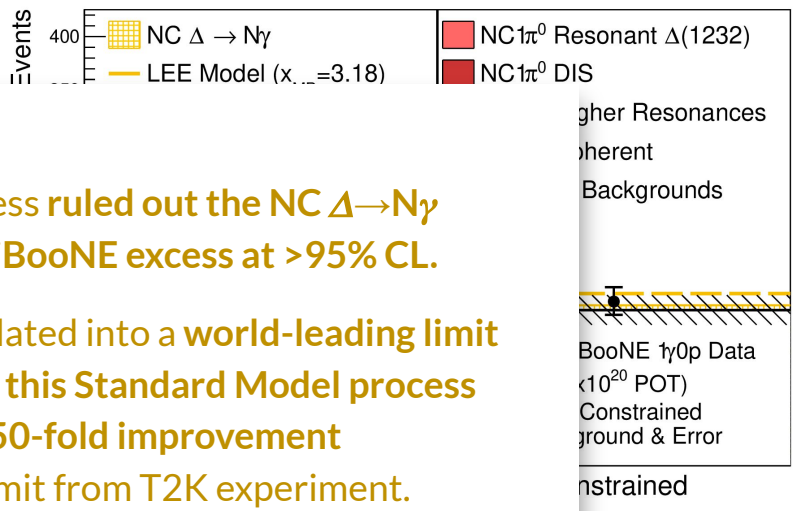
1γ1p



1γ1p	
Unconstr. bkgd.	[illegible]
Constr. bkgd.	20.5 ± 3.6
NC Δ → Nγ	+ 4.88
LEE ($x_{MB} = 3.18$)	+ 15.5

16 Data Events Observed

1γ0p



1γ0p	
Unconstr. bkgd.	[illegible]
Constr. bkgd.	145.1 ± 13.8
NC Δ → Nγ	+ 6.55
LEE ($x_{MB} = 3.18$)	+ 20.1

153 Data Events Observed

The lack of significant excess **ruled out the NC Δ→Nγ interpretation of the MiniBooNE excess at >95% CL.**

The result also has been translated into a **world-leading limit on the branching fraction of this Standard Model process** which represents a **50-fold improvement** over the previous best limit from T2K experiment.

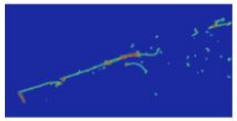
MicroBooNE electron search

Is the MiniBooNE excess single-electrons?

Search for an Excess of Electron Neutrino Interactions in MicroBooNE Using Multiple Final-State Topologies

P. Abratenko *et al.* (MicroBooNE Collaboration)

Phys. Rev. Lett. **128**, 241801 (2022) – Published 13 June 2022



New neutrino-oscillation data show no sign of an anomalous signal seen in previous studies, but the analyses can't yet fully rule out its presence.

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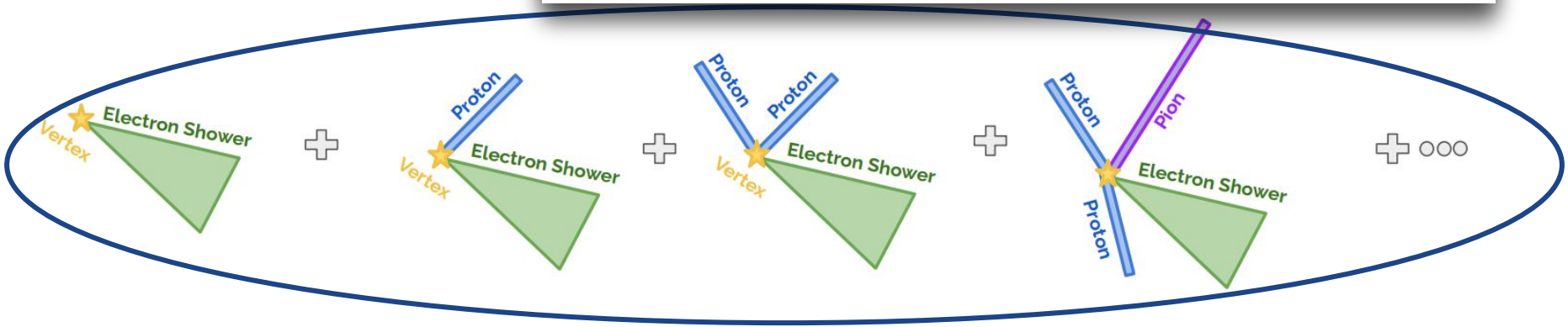
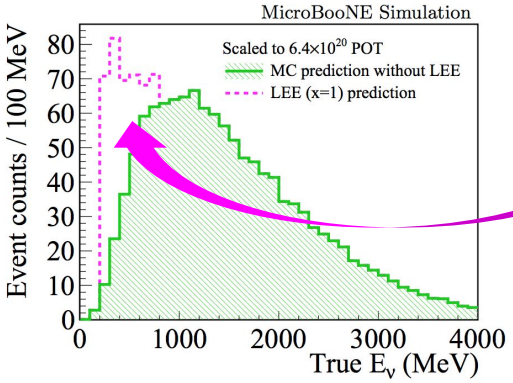
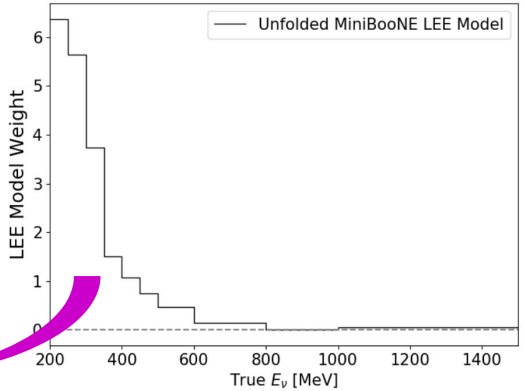
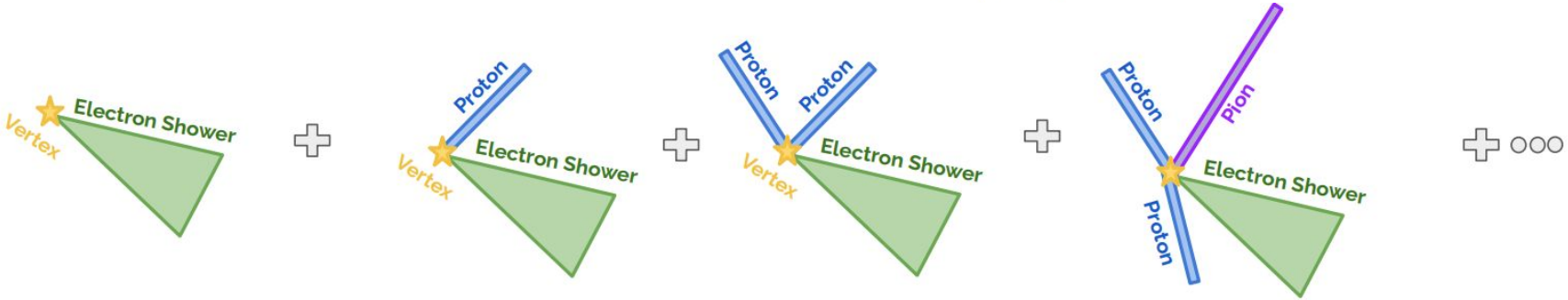


MicroBooNE electron search

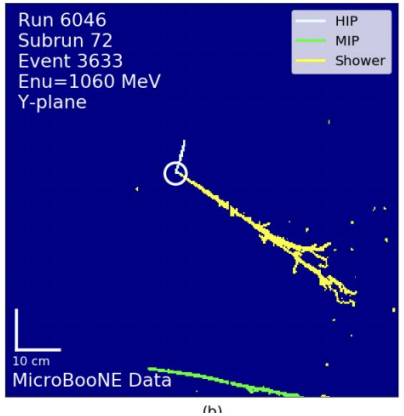
Three (3) independent analyses:
All search for a ν_e **excess at low energy modeled as intrinsic electron neutrino background enhancement**, from MiniBooNE unfolding







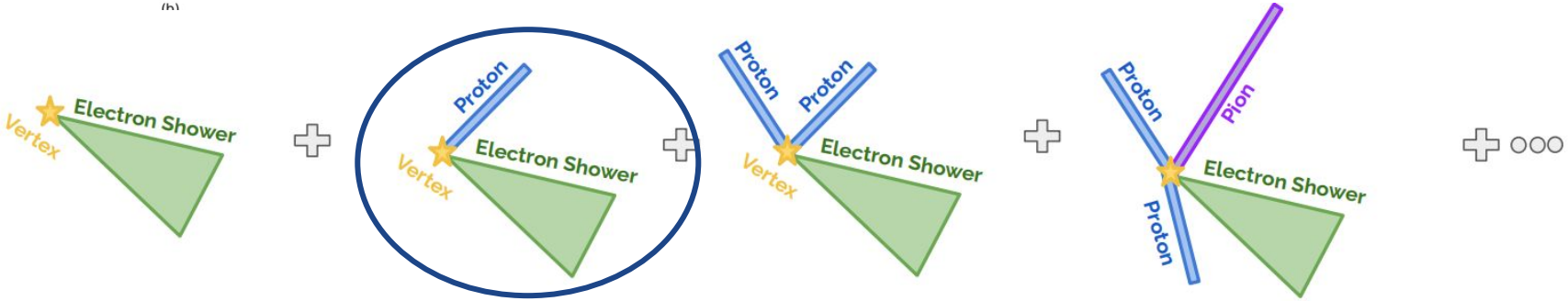
MicroBooNE electron search



Analysis 1:

Very ν_e-pure (charged-current quasi-elastic kinematics)
Deep Learning-based reconstruction

MicroBooNE Collab, arXiv:2110.14080, accepted by PRD (2022)
MicroBooNE Collab, arXiv:2110.14054, accepted by PRL (2022)

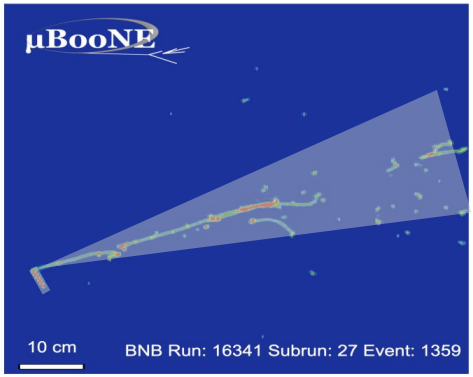


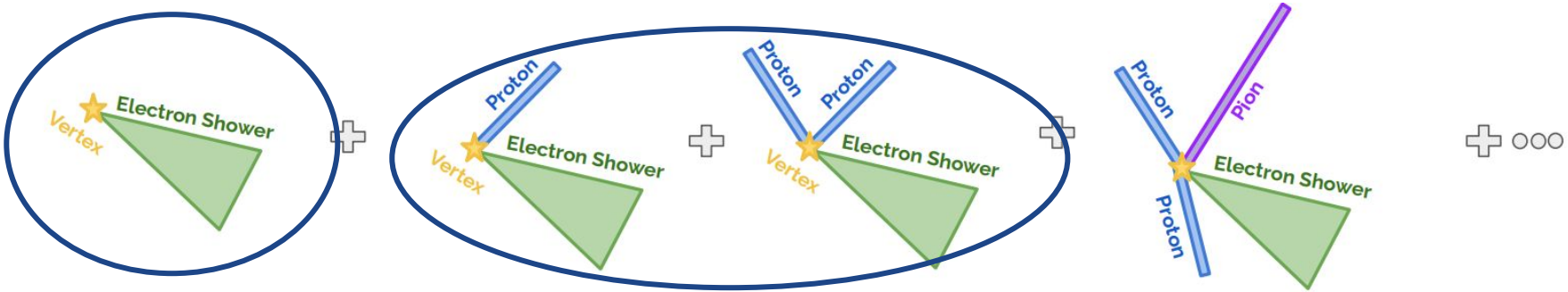
MicroBooNE electron search

Analysis 2:

MiniBooNE-like final states
Pandora "particle flow" reconstruction

MicroBooNE Collab, arXiv:2110.14065, accepted by PRD (2022)
MicroBooNE Collab, arXiv:2110.14054, accepted by PRL (2022)

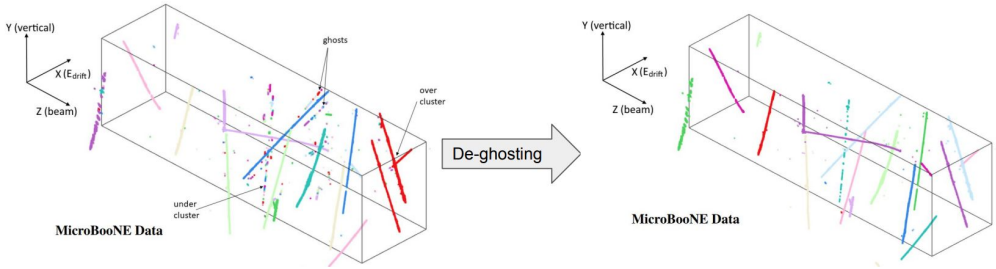




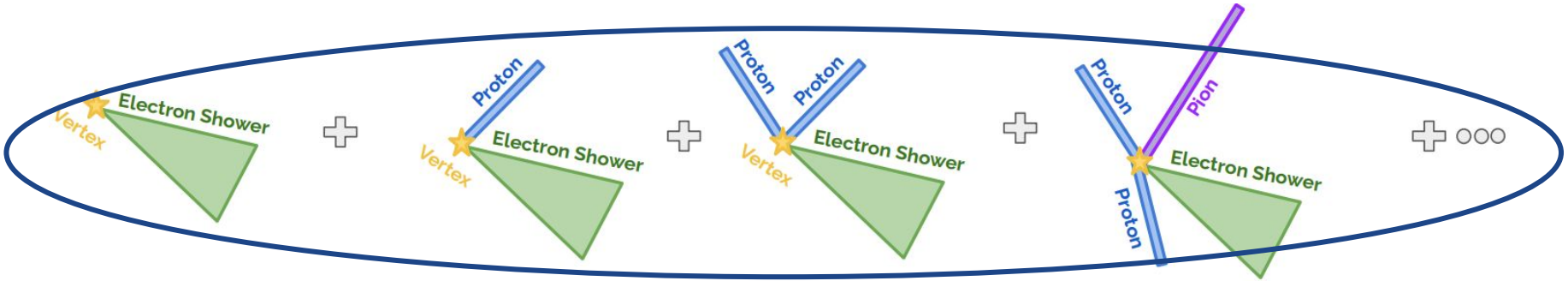
MicroBooNE electron search

Analysis 3:

All-inclusive final states, **high statistics**
Tomographic reconstruction techniques



MicroBooNE Collab, [arxiv:2110.13978](), accepted by PRD (2022)
MicroBooNE Collab, [arXiv:2110.14054](), accepted by PRL (2022)



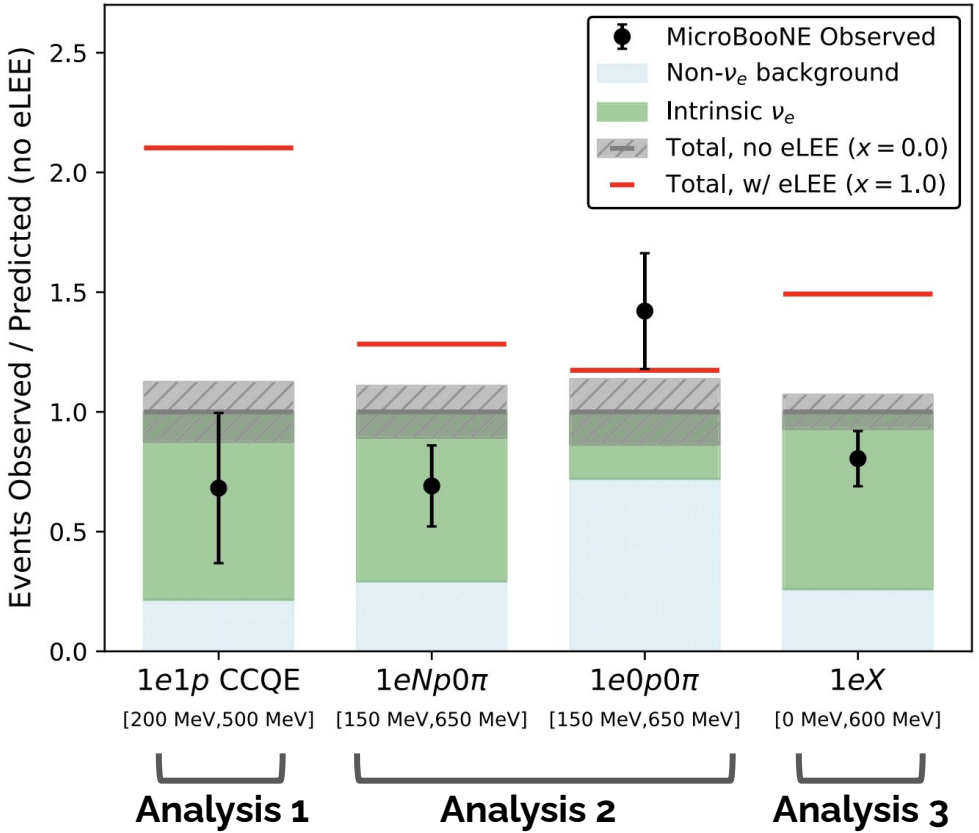
MicroBooNE electron search

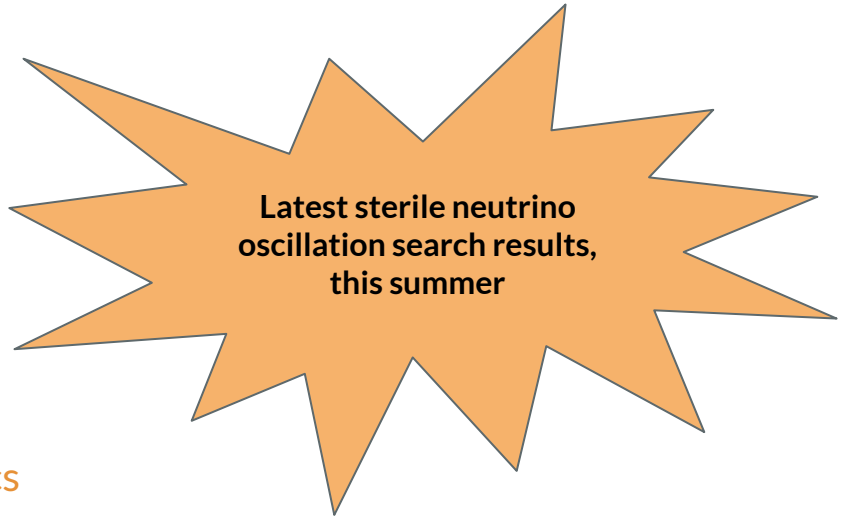
No significant ν_e excess observed

Conclusion:
MiniBooNE anomalous excess cannot be all ν_e

Phys.Rev.Lett. 128 (2022) 24, 241801

Electron neutrino LEE search has also been reinterpreted as a search for light sterile neutrino oscillations



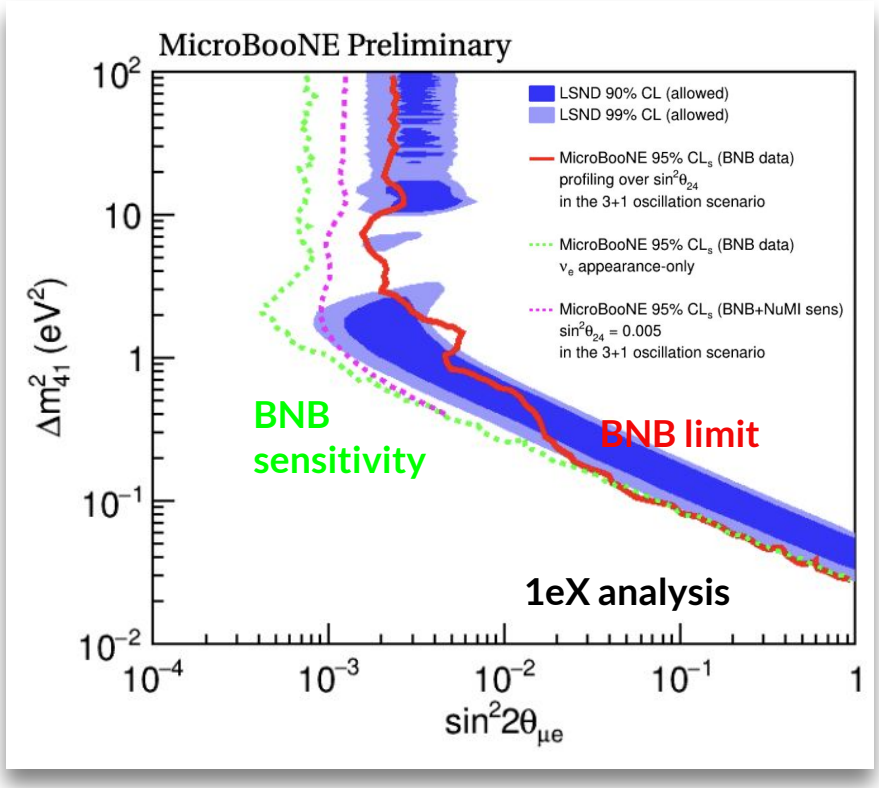


Further searches for new physics
with MicroBooNE

MicroBooNE search for sterile neutrino oscillations

Electron LEE search results re-interpreted under a sterile neutrino oscillation hypothesis, combining:

Muon neutrino **disappearance**, and
Electron neutrino **appearance** and **disappearance**



MICROBOONE-NOTE-1116-PUB

MicroBooNE search for sterile neutrino oscillations

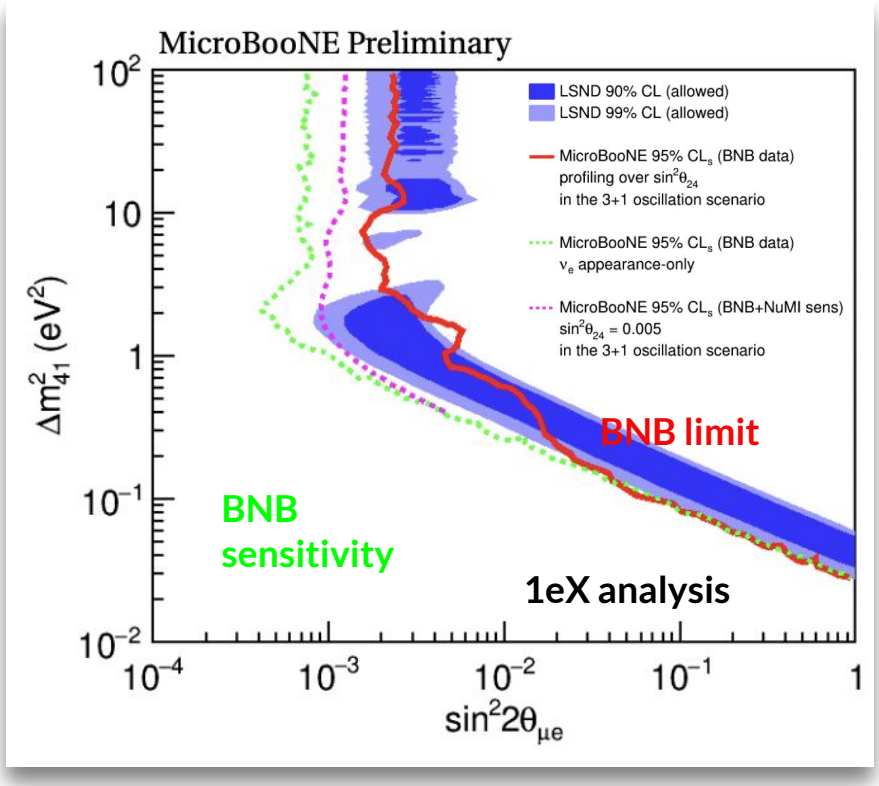
Electron LEE search results re-interpreted under a sterile neutrino oscillation hypothesis, combining:

Muon neutrino **disappearance**, and
Electron neutrino **appearance** and **disappearance**

can lead to cancellation of signal and oscillation parameter degeneracy

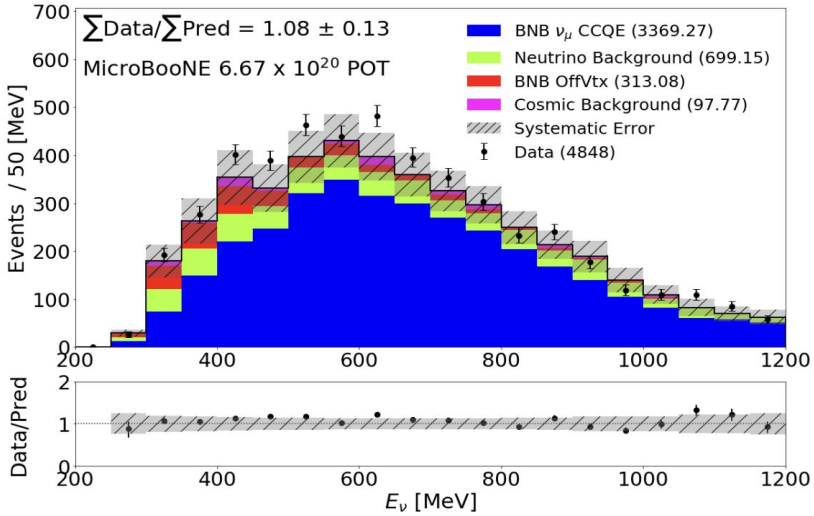
Forthcoming: **BNB** and **NuMI beam** combined fits provide additional handle for resolving ambiguities
→ enhanced sensitivity (full LSND allowed region coverage at 95% CL)

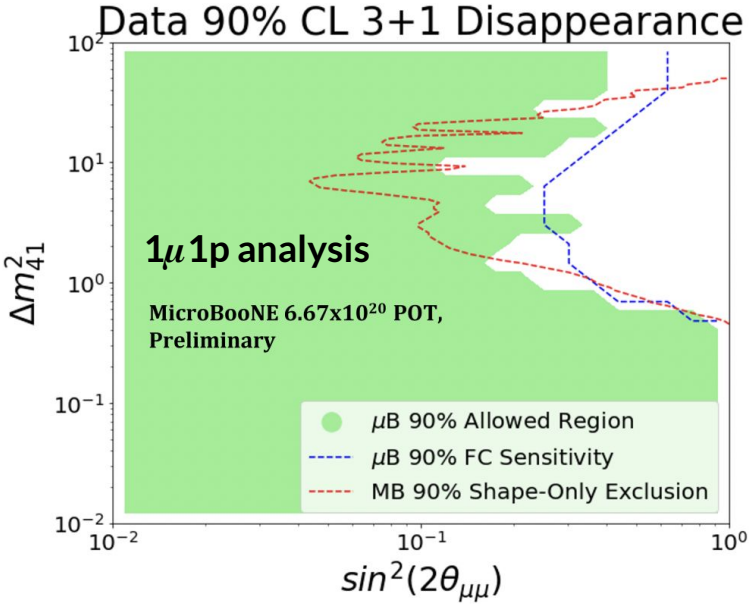
[MICROBOONE-NOTE-1116-PUB]



MicroBooNE search for sterile neutrino oscillations

Exclusive electron and **muon neutrino disappearance** limits:



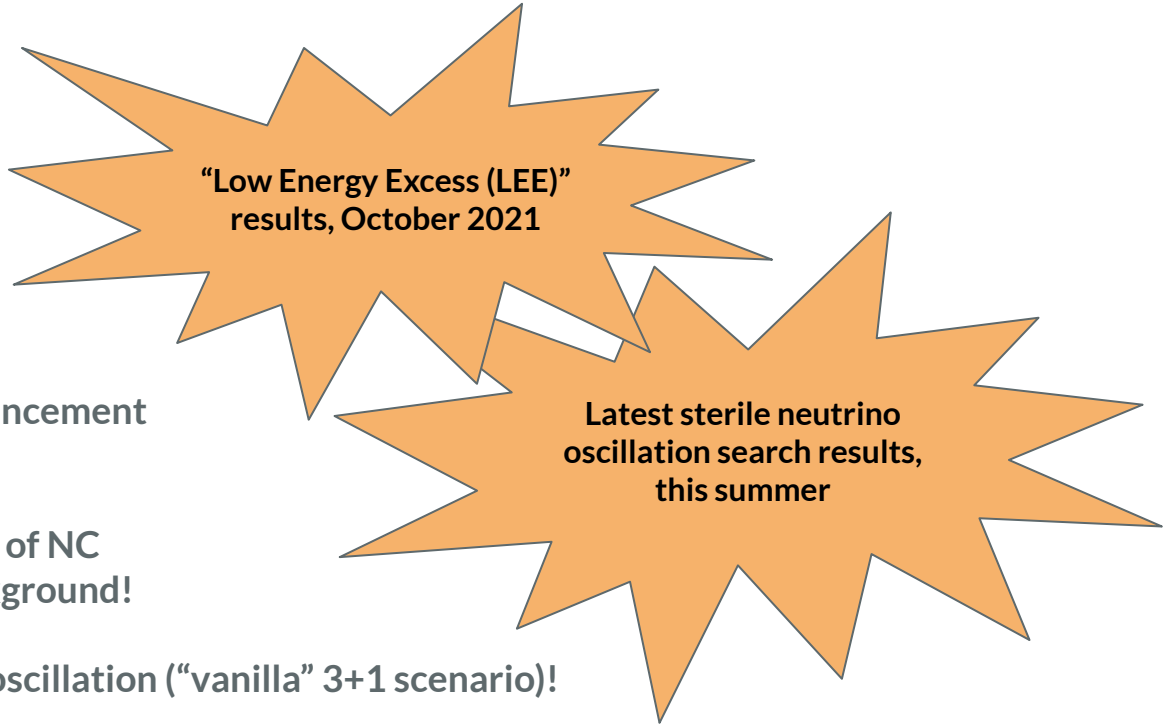


data consistent with background prediction

[MICROBOONE-NOTE-1106-PUB](#)

Also forthcoming: 1e1p + 1m1p combined search,
[MICROBOONE-NOTE-1105-PUB](#)

What have we learned?



No evidence of electron neutrino background enhancement at low energy!

No evidence of underestimation of NC Delta radiative decay background!

No evidence of sterile neutrino oscillation ("vanilla" 3+1 scenario)!

Where next?

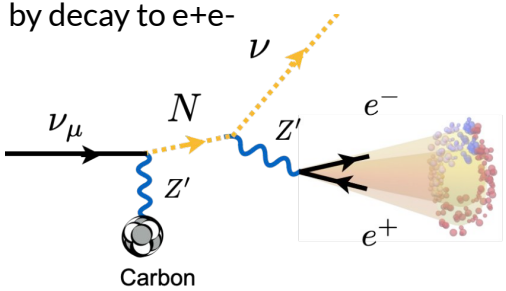
Beyond “vanilla” scenarios!

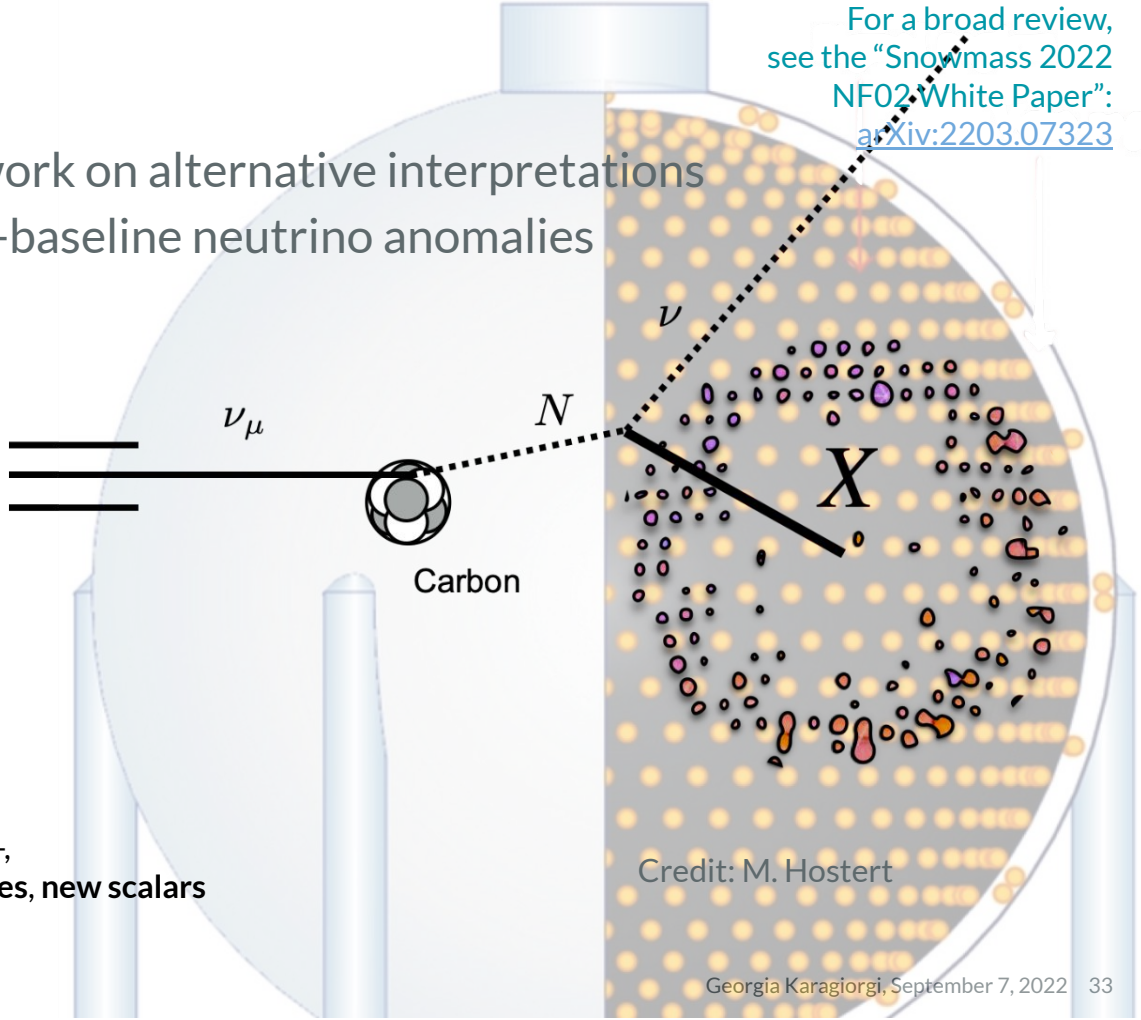
Where next?

For a broad review, see the "Snowmass 2022 NF02 White Paper": arXiv:2203.07323

An extensive body of theoretical work on alternative interpretations of the MiniBooNE and other short-baseline neutrino anomalies over the past decade!

Of particular interest, "Dark Sector" physics models, e.g. **neutrino up-scattering** to heavy neutrino through **dark photon**, followed by decay to e+e-



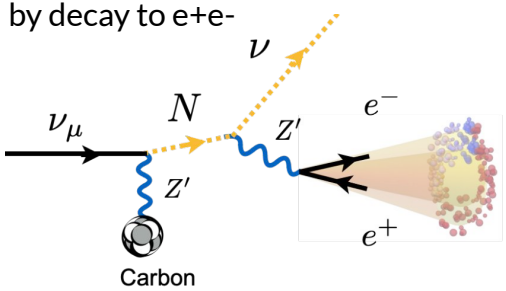


Credit: M. Hostert

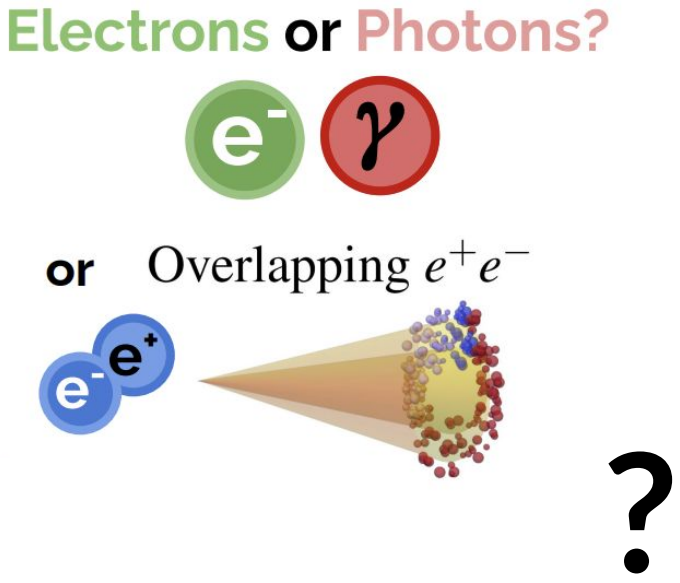
+ other exotic decays to e+e-,
e.g. **axion-like particles**, **new scalars**

Digging deeper

Of particular interest, “Dark Sector” physics models, e.g. **neutrino up-scattering** to heavy neutrino through **dark photon**, followed by decay to e+e-



+ other exotic decays to e+e-,
e.g. **axion-like particles**, **new scalars**



Digging deeper

Multiple ongoing analyses searching for exotic e+e- production due to dark neutrinos as a potential MiniBooNE LEE explanation

What can we learn with better reconstruction and selection?
e+e- opening angle?
invariant mass?

Analyses ongoing

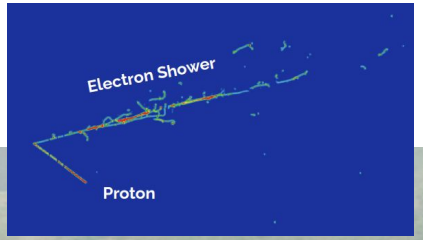
Published results on decays of Heavy Neutral Leptons and Higgs Portal Scalars

New results this summer

arXiv.2207.03840
Phys.Rev.D 101 (2020) 5, 052001
Phys.Rev.Lett. 127 (2021) 15, 151803

A new phase of precision searches at short baselines

ICARUS and SBND, alongside MicroBooNE, form the SBN program, currently ramping up!

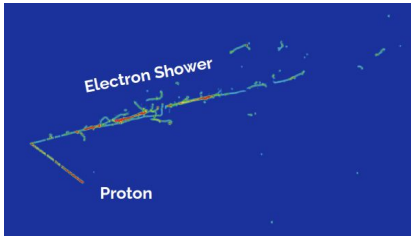


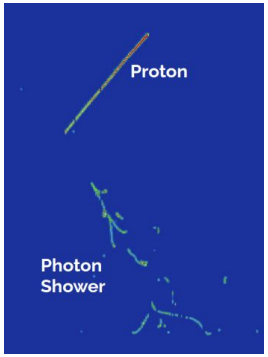
SBN Program at Fermilab is capable of **multi-channel searches with enhanced sensitivity to light sterile neutrino oscillations and unique opportunities for dark sector searches**

SBN Collab, arXiv:1503.01520, also Ann.Rev.Nucl.Part.Sci. 69 (2019) 363-387

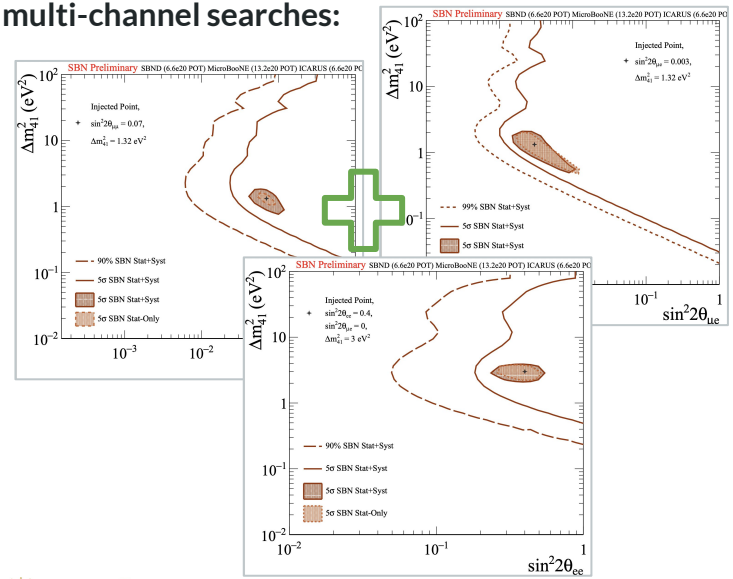
A new phase of precision searches at short baselines

ICARUS and SBND, alongside MicroBooNE, form the SBN program, currently ramping up!

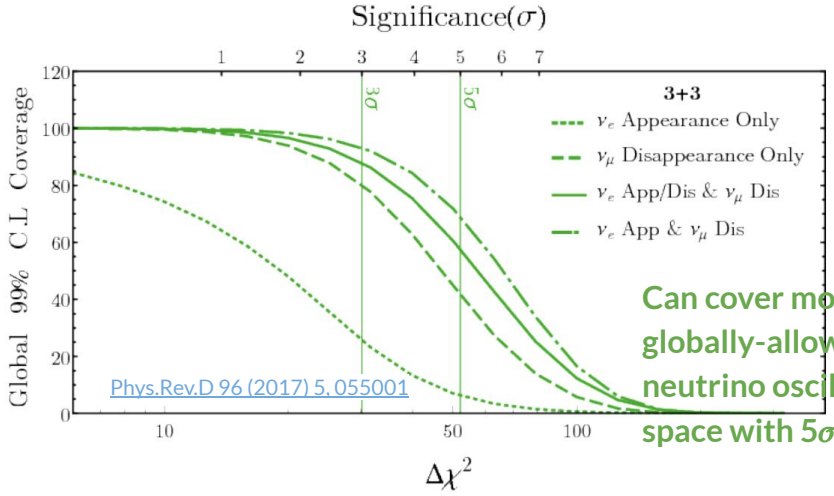




Sensitivity to 3+N oscillations is achieved through combined, multi-channel searches:



Can inclusively and exhaustively probe 3+N oscillations:



Phys.Rev.D 96 (2017) 5, 055001

Can cover more than 50% of the globally-allowed 3+3 sterile neutrino oscillation parameter space with 5σ sensitivity

ALFRED P. SLOAN FOUNDATION

Summary

- **MicroBooNE has collected its full data set!**
- Nearly a year after the release of MicroBooNE's first low energy excess results (using half its data):
  - **The leading photon background candidate interpretation to the MiniBooNE low-energy excess has been ruled out**
  - **MicroBooNE sees no evidence of electron neutrino background rate enhancement at low energy, and no evidence of light sterile neutrino oscillations**
- **More sensitive light sterile neutrino oscillation searches** are expected with additional MicroBooNE data at hand, and with the upcoming SBN program
- MicroBooNE is charting new territory in the search for new physics with rich phenomenology at short baselines
  - **New results on exotic searches, with e+e- focus** are forthcoming!

ALFRED P. SLOAN FOUNDATION

Thank you!

on behalf of the MicroBooNE collaboration

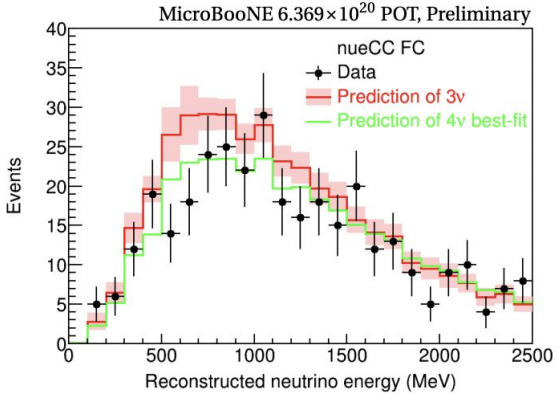
ALFRED P. SLOAN FOUNDATION

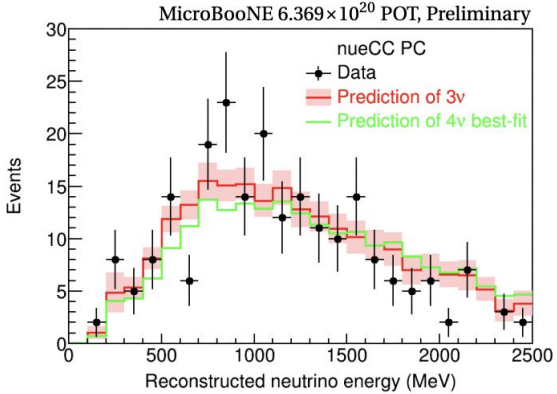
Backup

MicroBooNE search for sterile neutrino oscillations

Electron LEE search results re-interpreted under a sterile neutrino oscillation hypothesis, combining:

Muon neutrino **disappearance**, and
Electron neutrino **appearance** and **disappearance**





1eX analysis

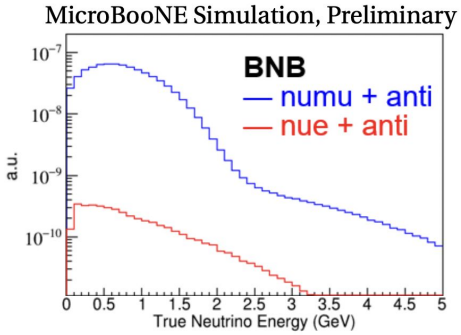
[MICROBOONE-NOTE-1116-PUB]

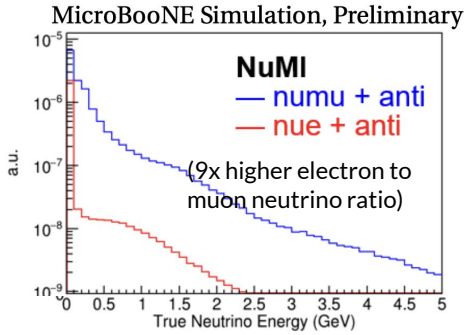
MicroBooNE search for sterile neutrino oscillations

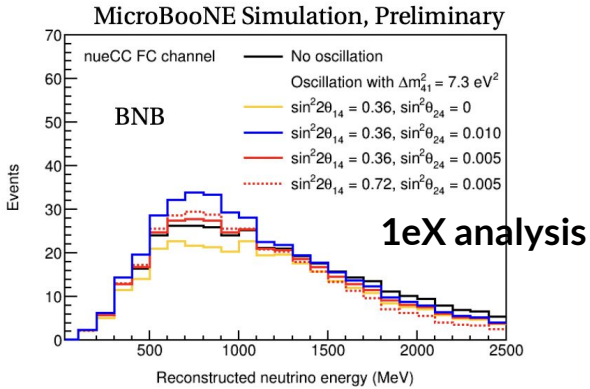
Electron LEE search results re-interpreted under a sterile neutrino oscillation hypothesis, combining:

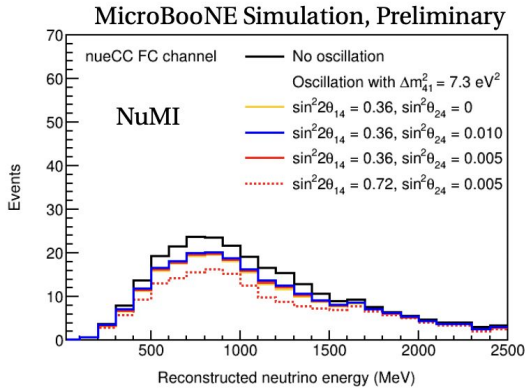
BNB and **NuMI beam** spectra (forthcoming!)

provides additional handle for resolving ambiguities → enhanced sensitivity sensitive to full LSND allowed region (95% CL)





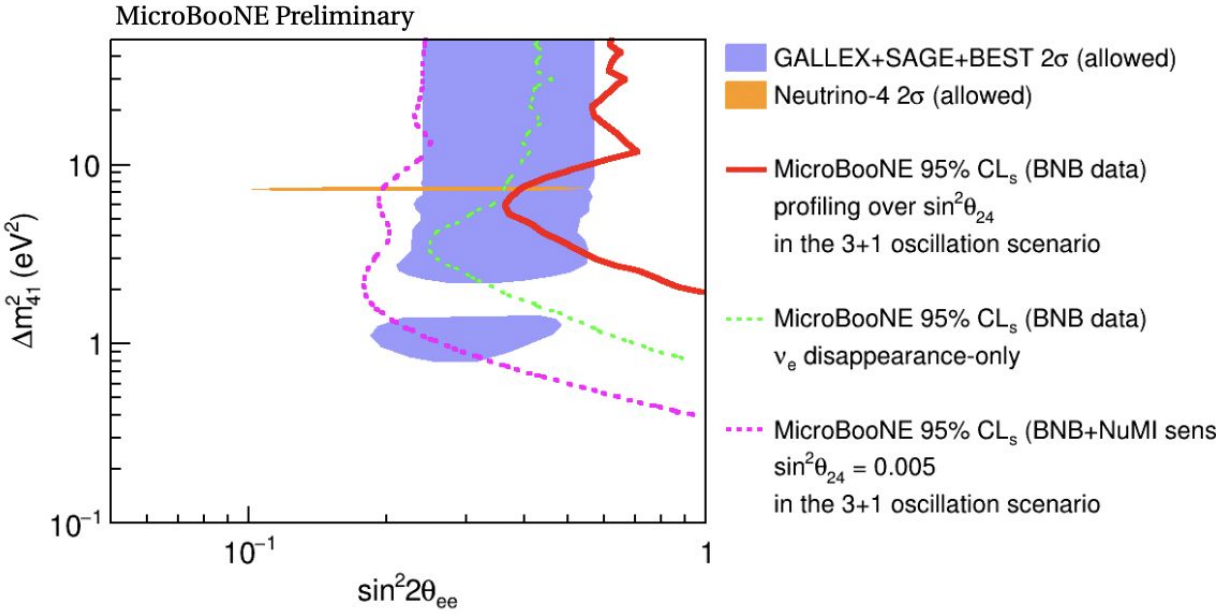




MICROBOONE-NOTE-1116-PUB

MicroBooNE search for sterile neutrino oscillations

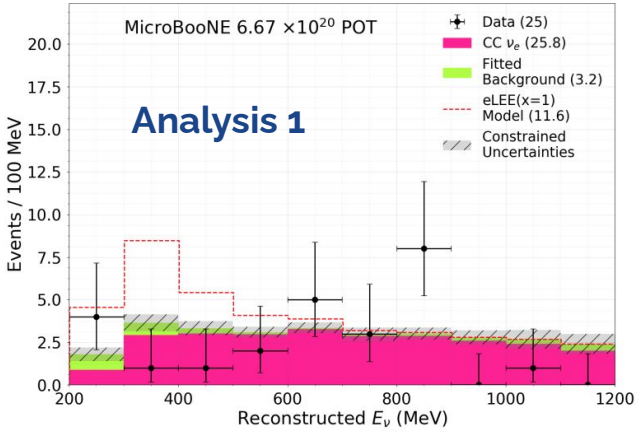
Exclusive **electron** and muon **neutrino disappearance** limits:

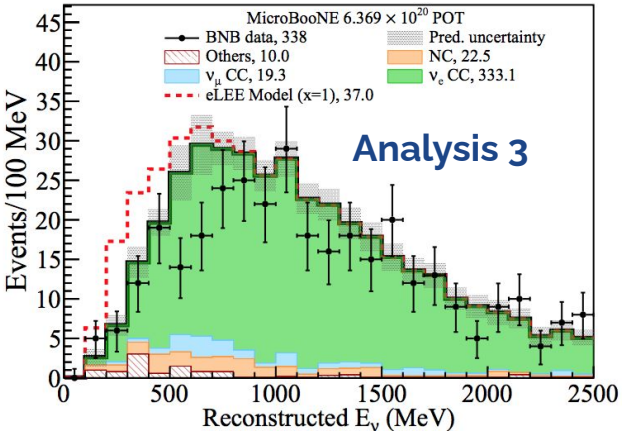


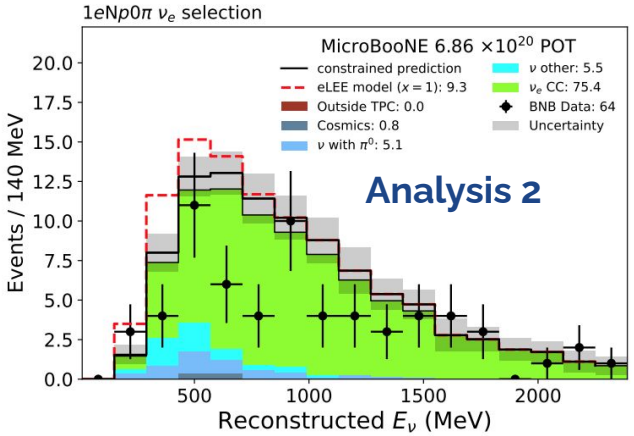
[MICROBOONE-NOTE-1116-PUB]

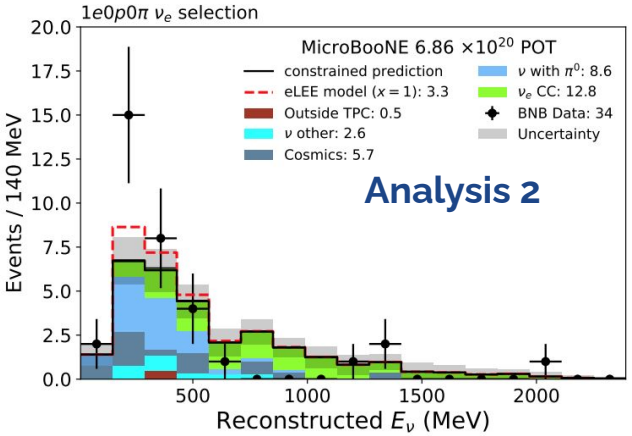
Electron Results

The results are found to be consistent with the nominal ν_e CC rate expectations from the BNB, and no significant excess of ν_e CC events is observed







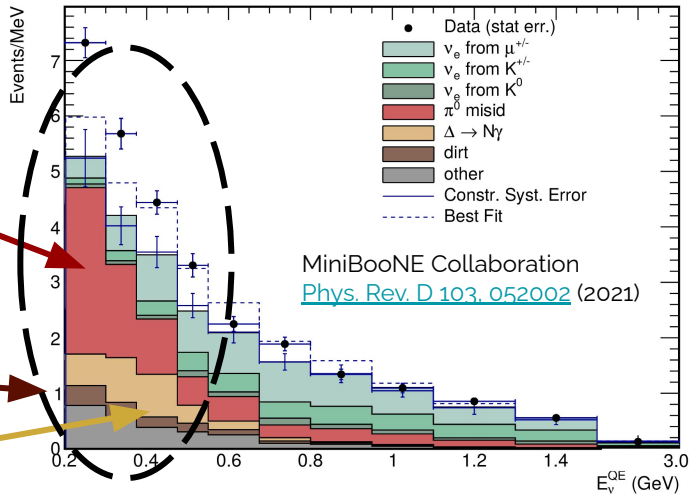


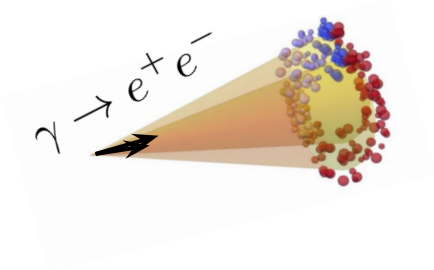
Is the MiniBooNE excess a misunderstood γ background?

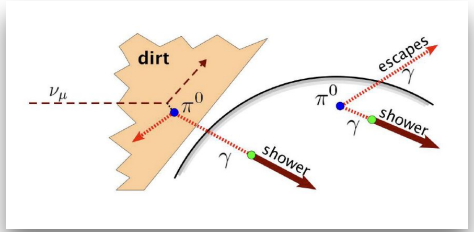
- **Neutral Current (NC) π^0 production** followed by $\pi^0 \rightarrow \gamma\gamma$ decay and mis-identification
  - **Constrained in situ**

- **"Dirt"** (mostly π^0 events with γ's scattering in from outside the detector)
  - **Constrained in situ**

- A Standard Model-expected, rare process: **NC $\Delta \rightarrow$ Nγ**
  - **A factor of x3.18 increase could explain the MiniBooNE low-energy excess!**
  - **Needed a direct check!**







MicroBooNE photon search

MicroBooNE Collab. Phys. Rev. Lett. 128, 111801 (2022)

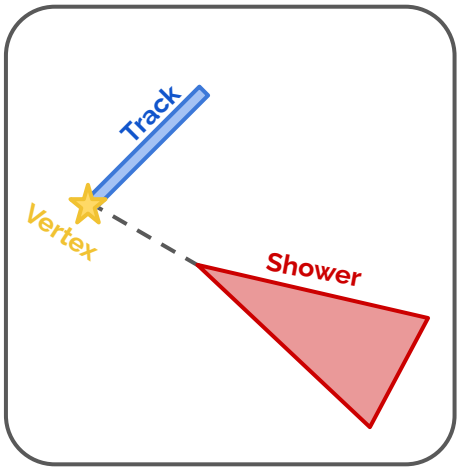
Data or MC → Pandora Reco → Flash matching → Topological Selection → Pre-Selection Cuts → BDT Selection → Final Selections

At this selection stage, >100,000 single-shower background events!

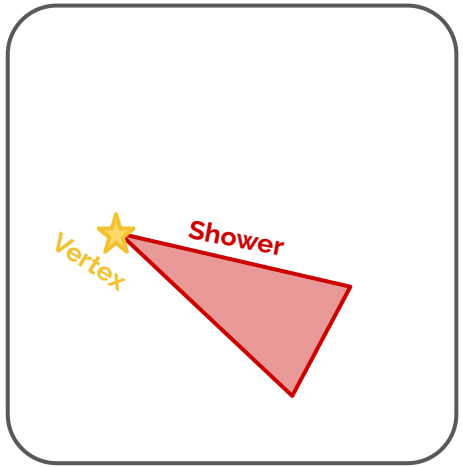
Additional machine learning algorithms target the key back-grounds to the NC $\Delta \rightarrow N\gamma$ signal.

Leverage the known kinematics of the $\Delta \rightarrow N\gamma$ decay products, particularly for the $1\gamma 1p$ selection.

$1\gamma 1p$



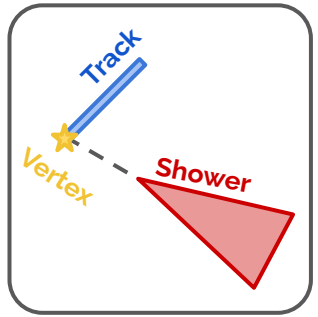
$1\gamma 0p$

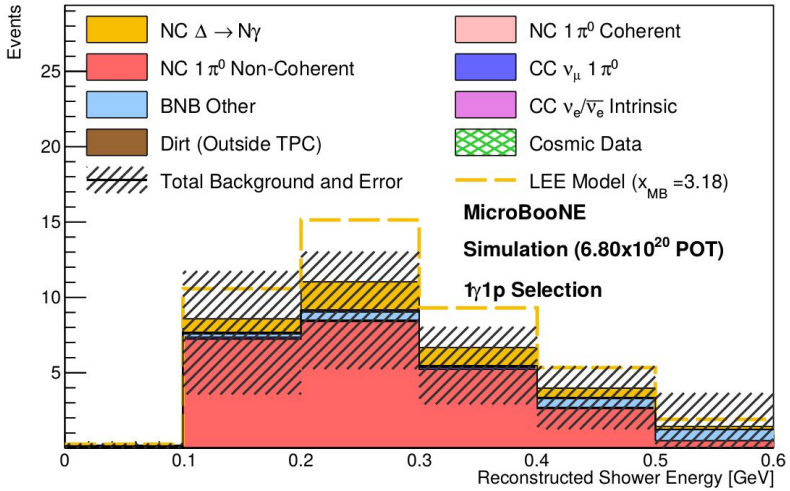


Two mutually exclusive NC $\Delta \rightarrow N\gamma$ rich **single-photon** selections

MicroBooNE photon search

1γ1p final selection





Overall **signal efficiency** 3.9%

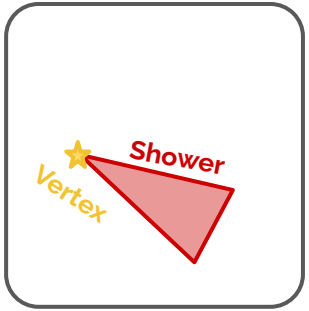
Process	$1\gamma 1p$
Total Background	27.0
NC $\Delta \rightarrow N\gamma$	4.88
LEE ($x_{\mathrm{MB}} = 3.18$)	15.5

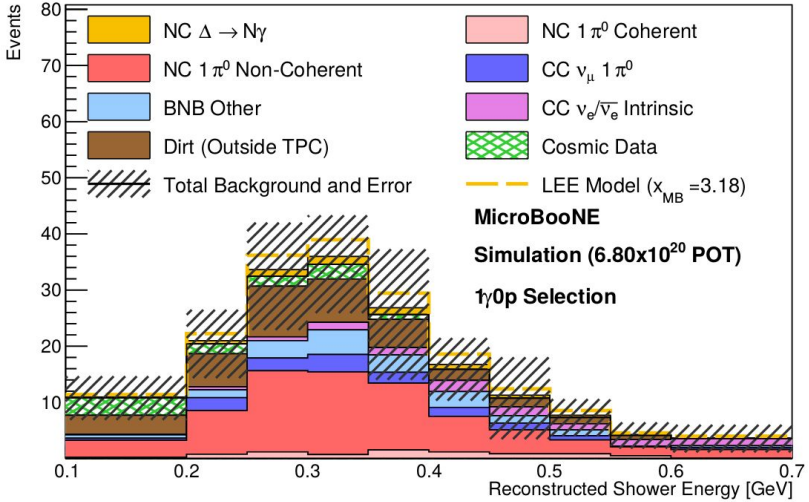
A **97.2% pure photon sample** with overall background rejection at **99.98%** relative to all reconstructed single-shower events.

ν_e rejection at **99.8%** (relative to all reconstructed single-shower + single-track events).

MicroBooNE photon search

1γ0p final selection





Overall **signal efficiency** 5.2%

Process	$1\gamma 0p$
Total Background	165.4
NC $\Delta \rightarrow N\gamma$	6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	20.1

A **83.2% pure photon sample** with overall background rejection at **99.8%** relative to all reconstructed single-shower events.

ν_e rejection at **87.6%** (relative to all reconstructed single-shower events).

This selection lacks the track vertex information → not as good handle on backgrounds