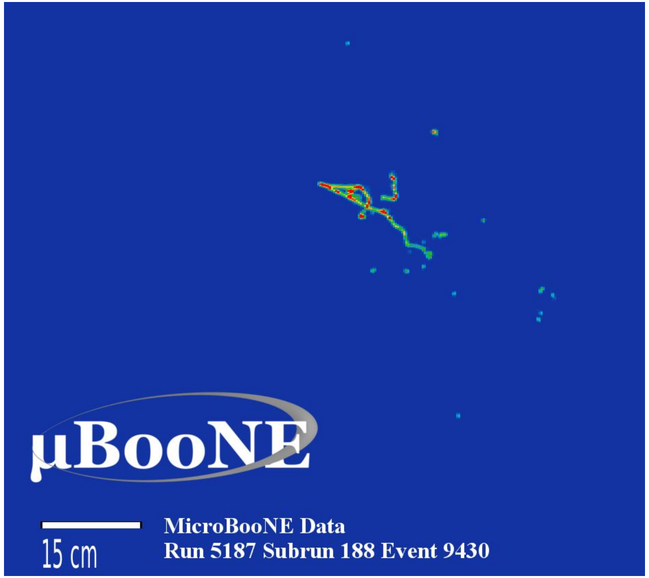
MicroBooNE's Search for Anomalous Single-Photon Production

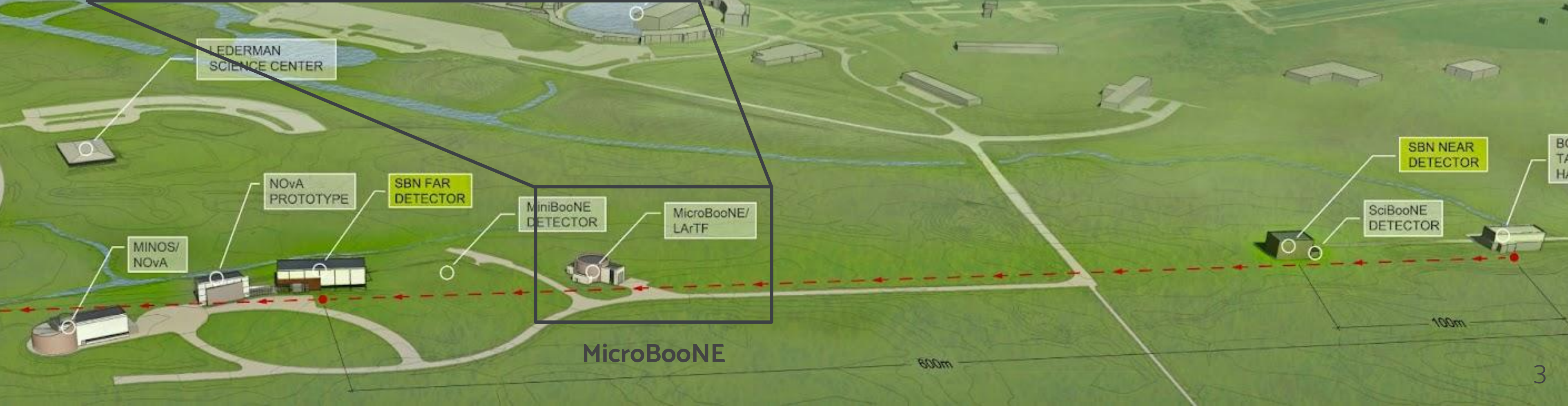
Kathryn Sutton @ Caltech, formerly Nevis Labs
On behalf of the MicroBooNE Collaboration
8/5/22



CONTENTS

The MicroBooNE Experiment

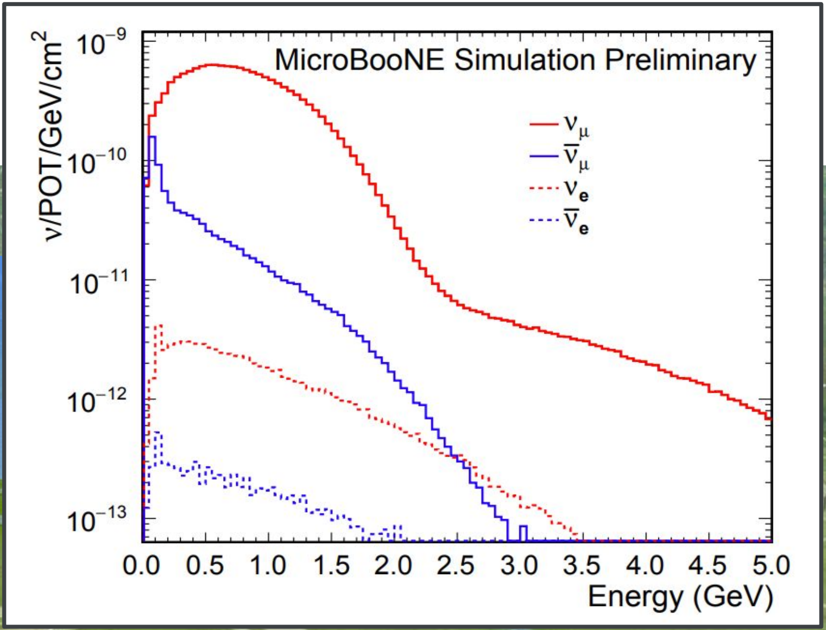
Located along **Fermilab's Booster Neutrino Beam (BNB)** at a baseline of ~500m. It was the first of three **liquid argon time projection chamber (LArTPC)** detectors to be commissioned along the BNB and took data from 2015-2021.



MicroBooNE

See Mark Ross-Lonergan’s talk on Short Baseline from yesterday

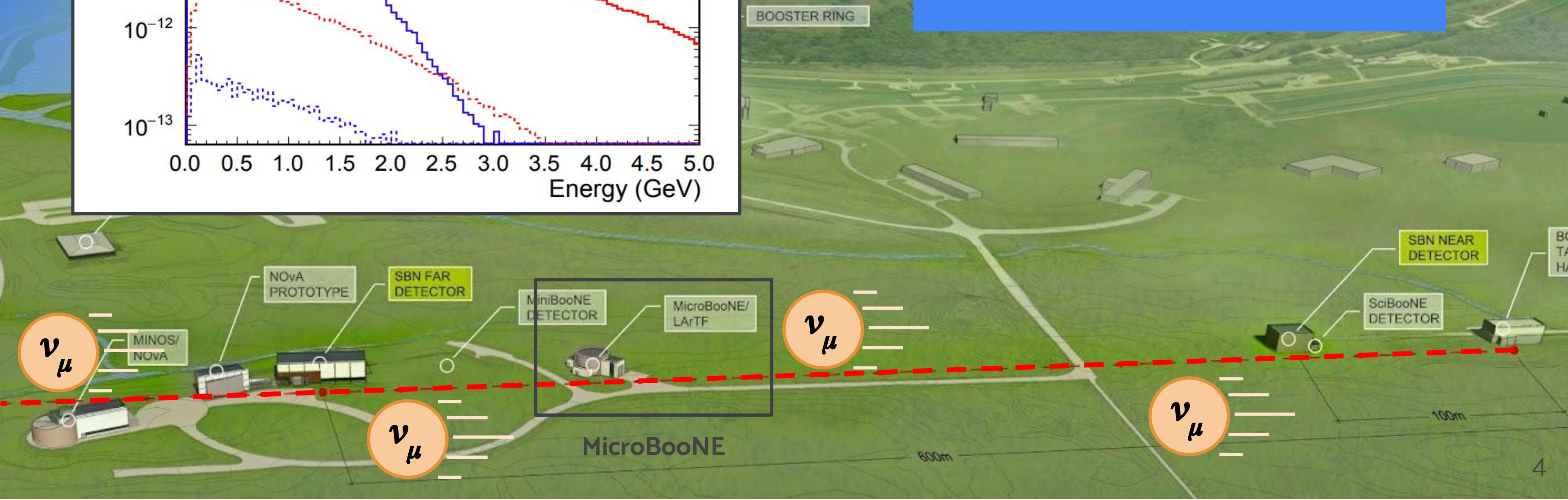
MicroBooNE Public Note 1031



Mean neutrino beam energy of **<0.8> GeV**

Over 99% (anti) ν_μ with only ~ 0.5% ν_e contamination

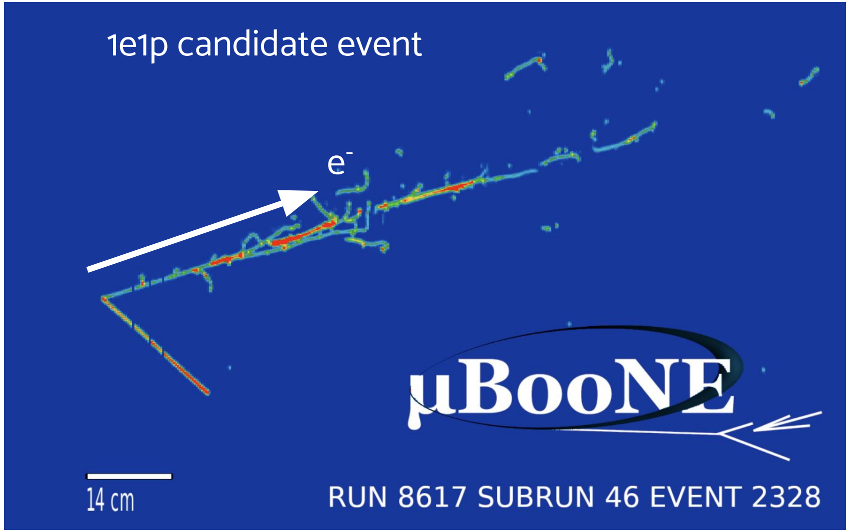
BNB @ FNAL

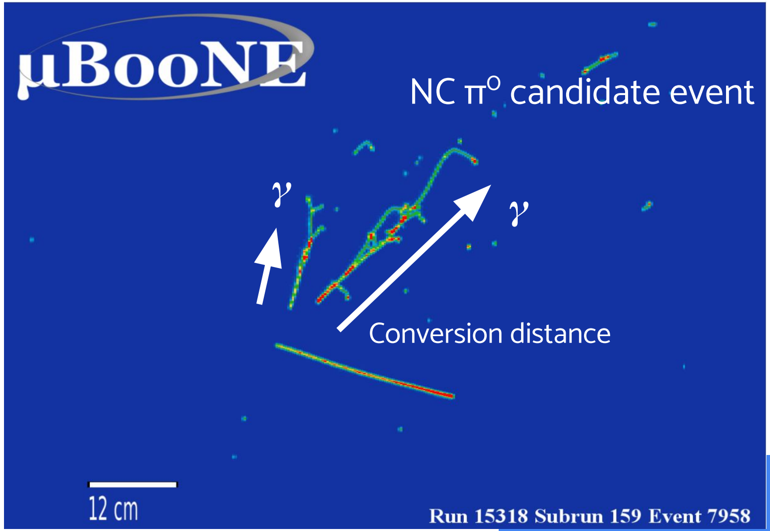


LArTPC Detectors

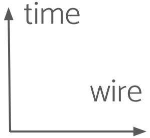
LArTPCs demonstrate precise spatial and calorimetric resolution, which makes them ideal for studying final state topologies in neutrino scattering with more detail than has previously been possible.

In particular this technology allows for clear **separation between photon and electron electromagnetic showers**.





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

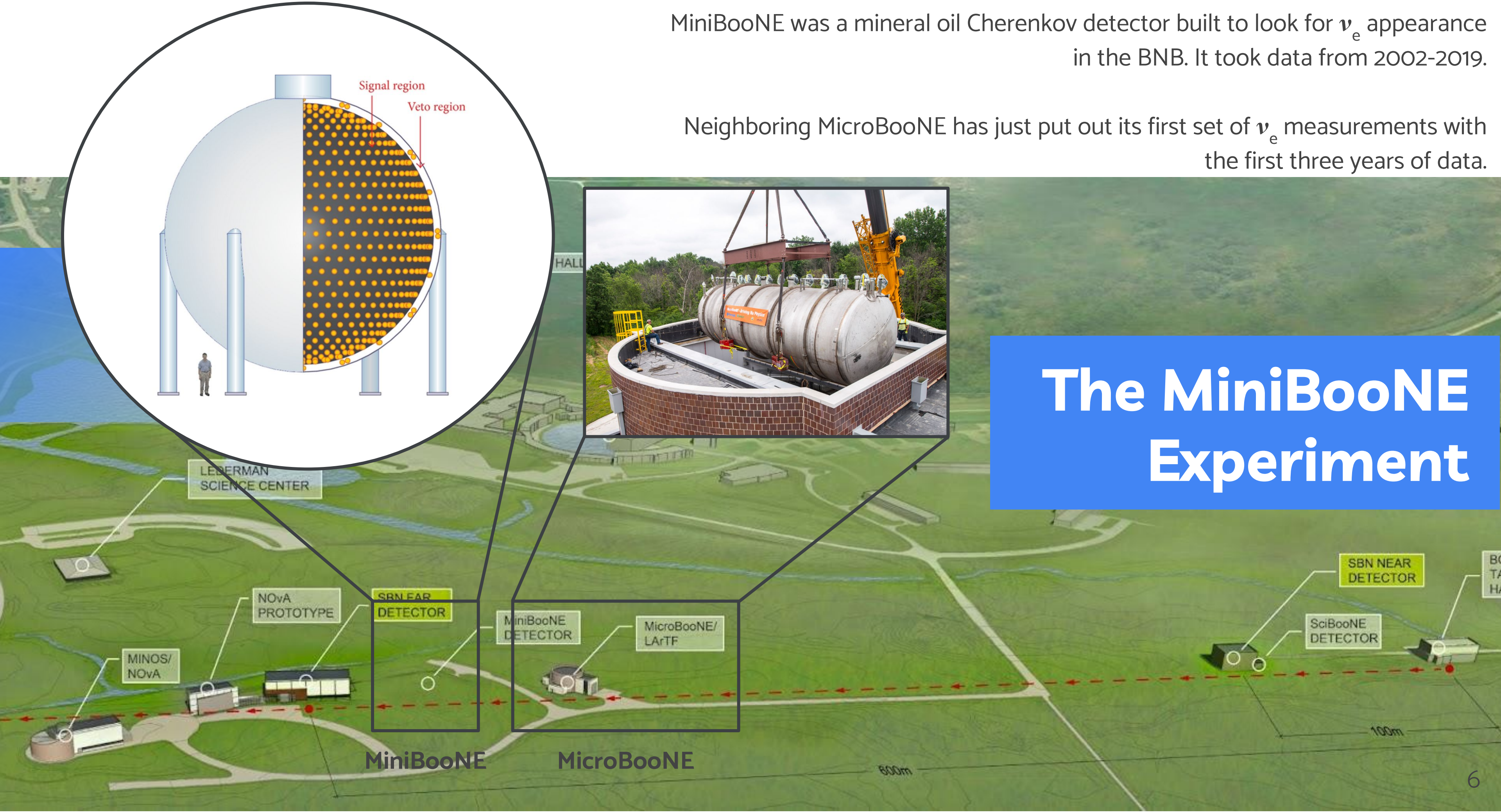


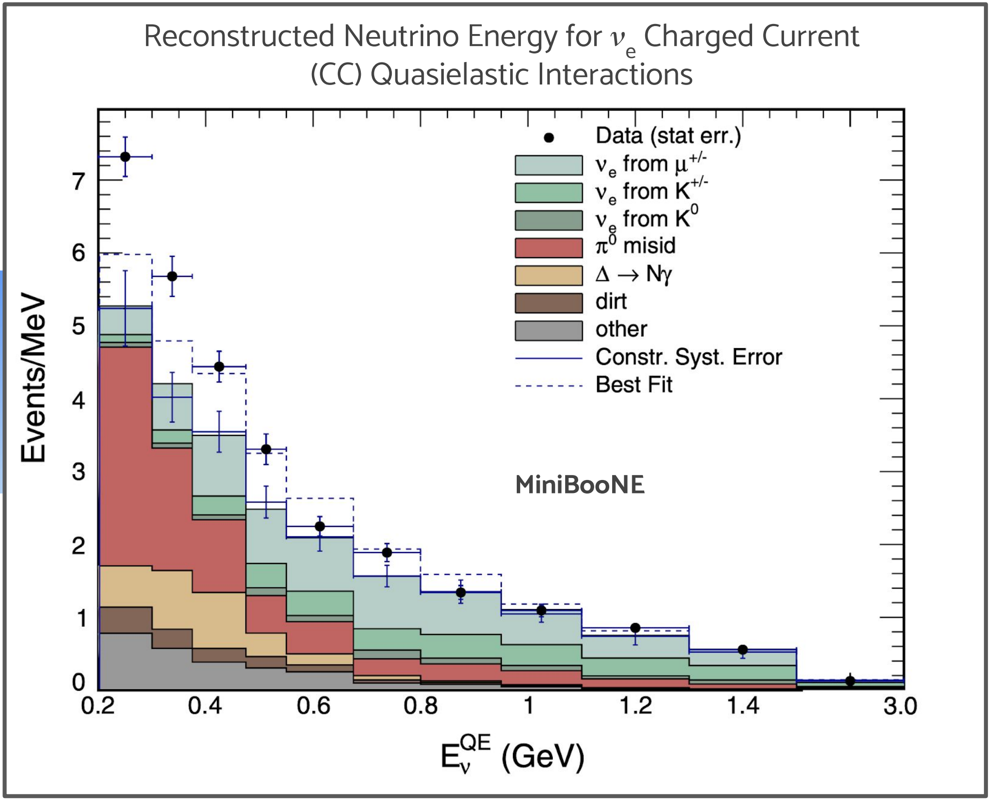
Color scale shows the charge deposited, with red being more ionizing.

The MiniBooNE Experiment

MiniBooNE was a mineral oil Cherenkov detector built to look for ν_e appearance in the BNB. It took data from 2002-2019.

Neighboring MicroBooNE has just put out its first set of ν_e measurements with the first three years of data.





Phys. Rev. D 103, 052002 (2021)

Investigating MiniBooNE

One of the primary goals of MicroBooNE is to follow up on the observed **MiniBooNE excess of low energy electromagnetic events with an overall significance of 4.8σ.**

This could be interpreted as a sterile neutrino oscillation to an electron (anti)neutrino if the excess is comprised of true ν_e events.

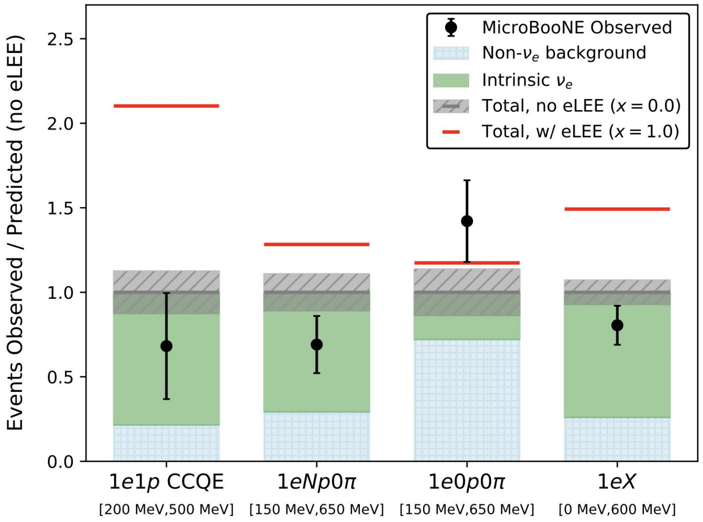
MicroBooNE's ν_e Results

The first CC ν_e results from MicroBooNE where released in Oct. 2021 and corresponding 3+1 sterile fit are the subject of Xiangpan Ji's talk on 8/2 so this is only a brief summary of the takeaways.

Conducted three independent analyses considering both CCQE-like, pion-less (Np and 0p), and inclusive ν_e final state topologies.

See no evidence of an ν_e excess in MicroBooNE, which **rejects the hypothesis that ν_e CC interactions are fully responsible for that excess at >97% CL**.

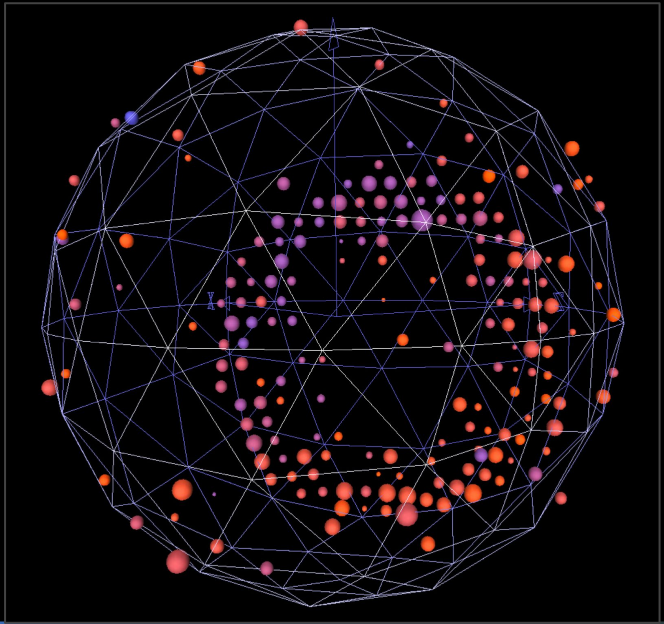
Number of observed CC ν_e data events consistent with background predictions



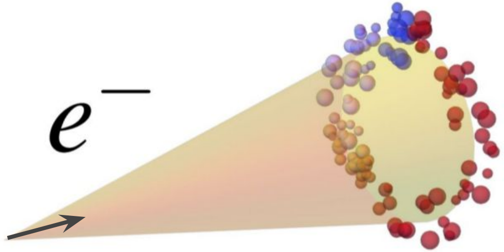
MicroBooNE's 2022 ν_e Publications:
Phys. Rev. D 105, 112003 (2022)
Phys. Rev. D 105, 112004 (2022)
Phys. Rev. D 105, 112005 (2022)
Phys. Rev. Lett. 128, 241801 (2022)

Photon-Like Hypothesis for MiniBooNE

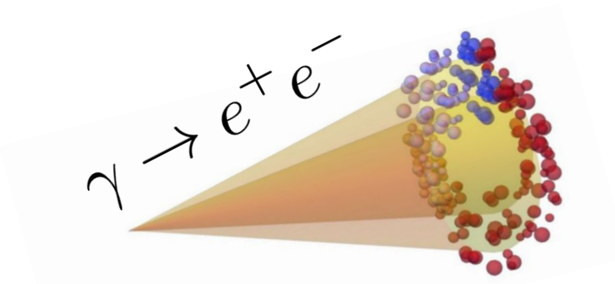
Electron Cherenkov ring event in MiniBooNE Detector



Because MiniBooNE was a Cherenkov detector there was a significant photon background to the ν_e measurement.



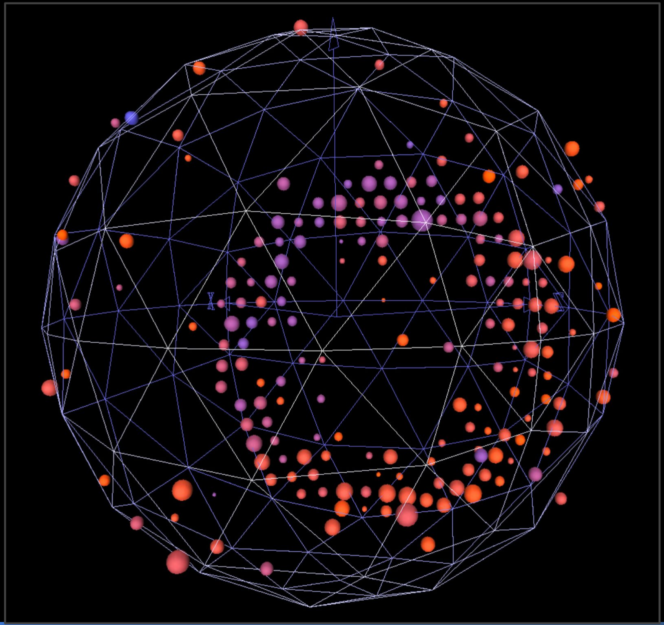
MiniBooNE detected $\boldsymbol{\nu_e}$ by the **electrons** produced in charged current (CC) interactions.

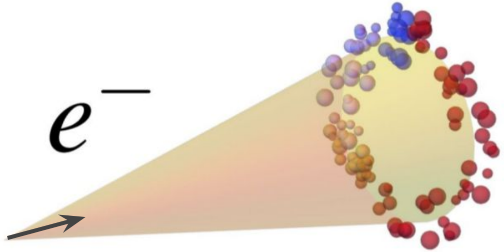


However, **photons**, that pair produce extremely collimated electron/positron pairs produced an identical Cherenkov ring

Photon-Like Hypothesis for MiniBooNE

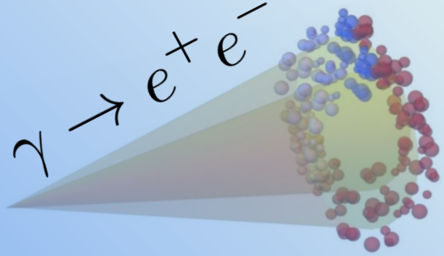
Electron Cherenkov ring event in MiniBooNE Detector





MiniBooNE detected ν_e by the **electrons** produced in charged current (CC) interactions.

Because MiniBooNE was a Cherenkov detector there was a significant photon background to the ν_e measurement. With MicroBooNE we aim to **independently measure neutrino interactions with a single photon in the final state.**

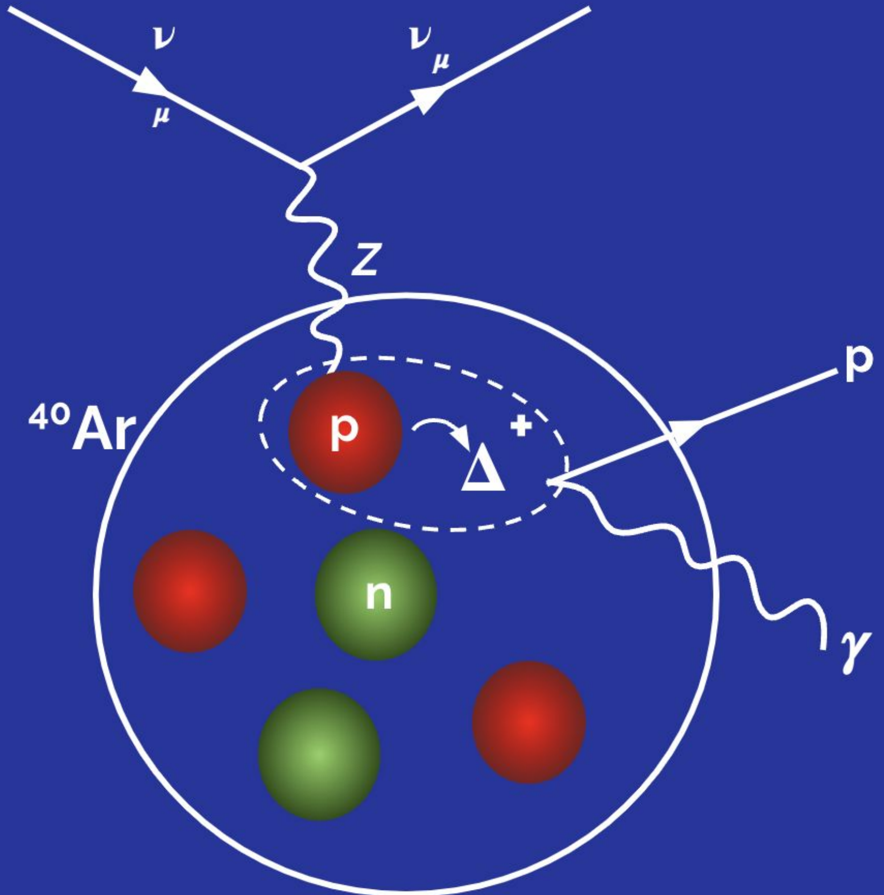


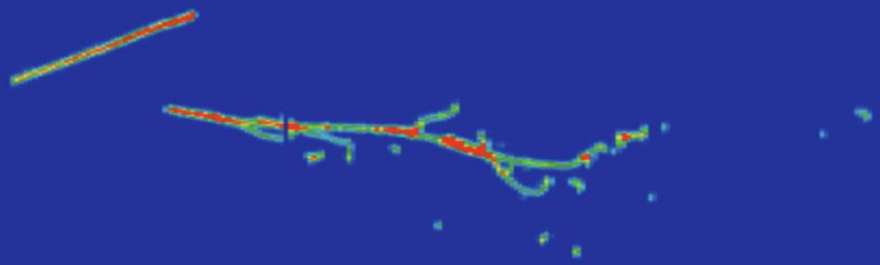
Credit: M. Ross-Lonergan

Here we give and overview of the the analysis and results from MicroBooNE's first single photon search from Oct. 2021 looking for **neutrino induced NC $\Delta \rightarrow N\gamma$ as an explanation for the MiniBooNE excess.**

Full details can be found in Phys.Rev.Lett.128,111801 (2022)

MicroBooNE's Single Photon Search



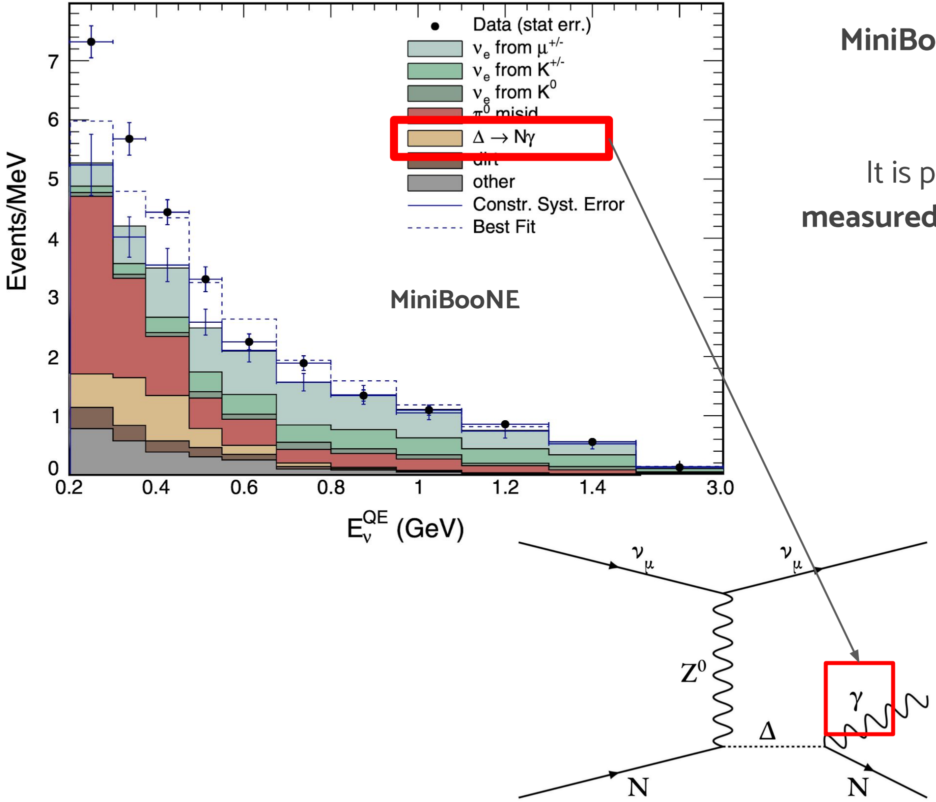


MicroBooNE Simulation

Photon Backgrounds in MiniBooNE

*J. Phys. G 46, 08LT01 (2019)

*Phys. Rev. D 103, 052002 (2021)

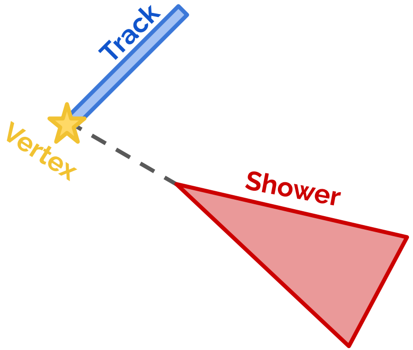


MiniBooNE estimated NC $\Delta \rightarrow N\gamma$ rate in MC from an in situ NC π^0 measurement using branching ratio.

It is predicted by the Standard Model but has **never been directly measured** in neutrino scattering. Prior best limit from T2K in 2019* was O(100x) above the expected rate.

A multiplicative factor of $\mathbf{x_{MB} = 3.18}$ enhancement to the nominal predicted NC $\Delta \rightarrow N\gamma$ rate to explain the MiniBooNE excess.*

Signal Topologies

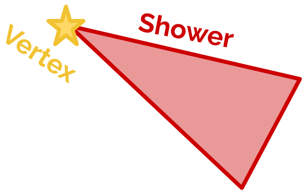


1γ1p is our primary analysis. The existence of a short proton-like track improves reconstruction efficiency. **45.3%* of true 1γ events from NC→Nγ signal.**

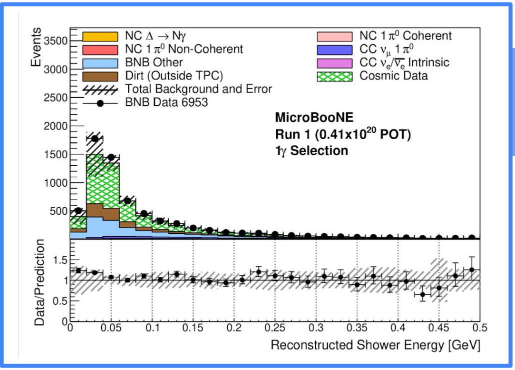
For this analysis signal definition is 0π and excludes Np events resulting from FSI interactions

Expect only ~125 combined events in the first three years of MicroBooNE data

1γ0p has a lower background rejection efficiency, but provides a secondary dataset for comparison and a joint fit yields maximum sensitivity. **54.7%* of true 1γ events from NC→Nγ signal.**

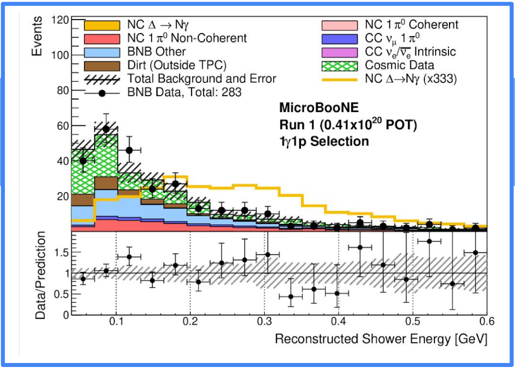


Selection Stages



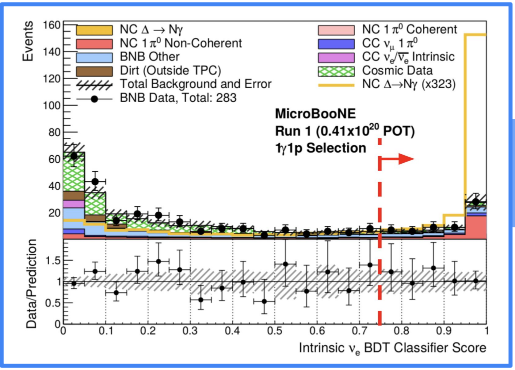
Topological

First select all events with exactly 1 shower, and either 0 or 1 tracks



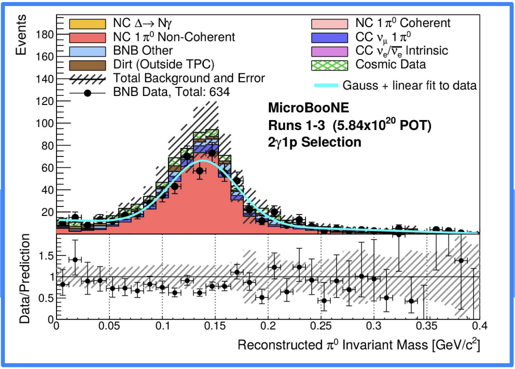
Preselection Cuts

Cuts targeting obvious backgrounds like muons and michel electrons



Background Rejection BDTs

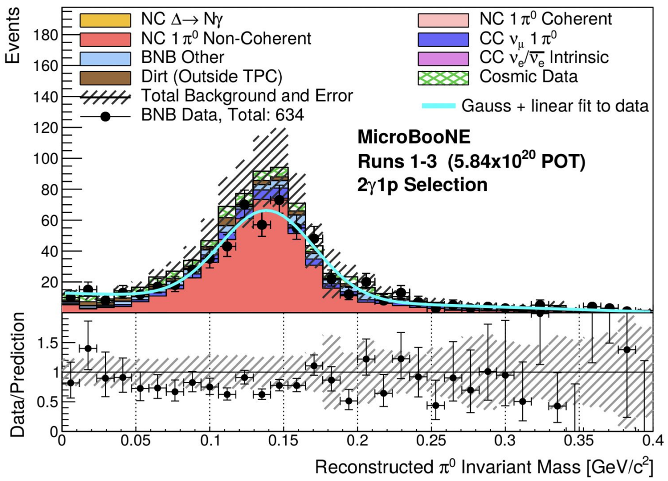
Set of BDTs targeting key backgrounds (cosmic, ν_e, ν_μ, and NC π^0)



NC π^0 Constraint

Fit to excess in combination with in situ NC π^0 measurement

NC π^0 Constraint



*Phys. Rev. C 65, 065204 (2002)

For Δ(1232), the branching ratio* is:

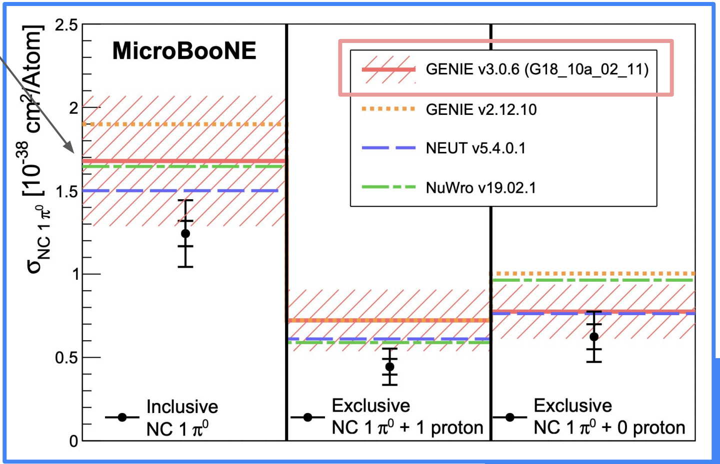
Δ→Nπ^0 (99.4%)

Δ→Nγ (0.6 %)

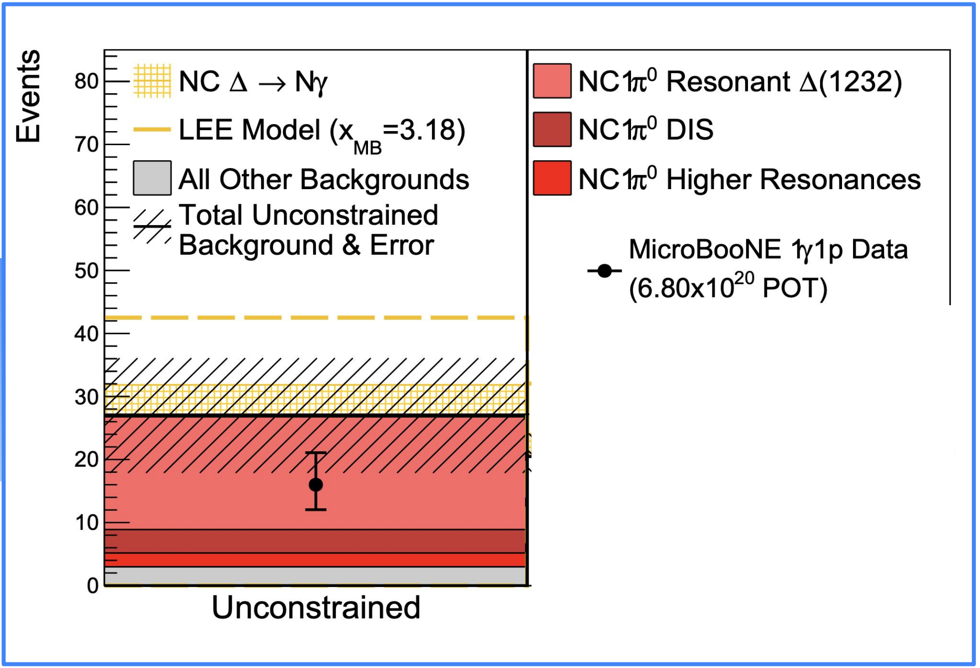
Also measure the NCπ^0 rate in MicroBooNE, have also published new cross section measurement. Also shown in Elena Gramellini's talk in the morning.

Observe the GENIE prediction used in the MicroBooNE Monte Carlo slightly over estimates the total NC π^0 cross section on argon although the data agrees within errors.

Use the **correlations with the NC Δ→Nγ signal** and the fact that it's the dominant background (>80%) to greatly **reduce the systematic uncertainties.**



Purity: ~15.3% Efficiency: ~4.0%

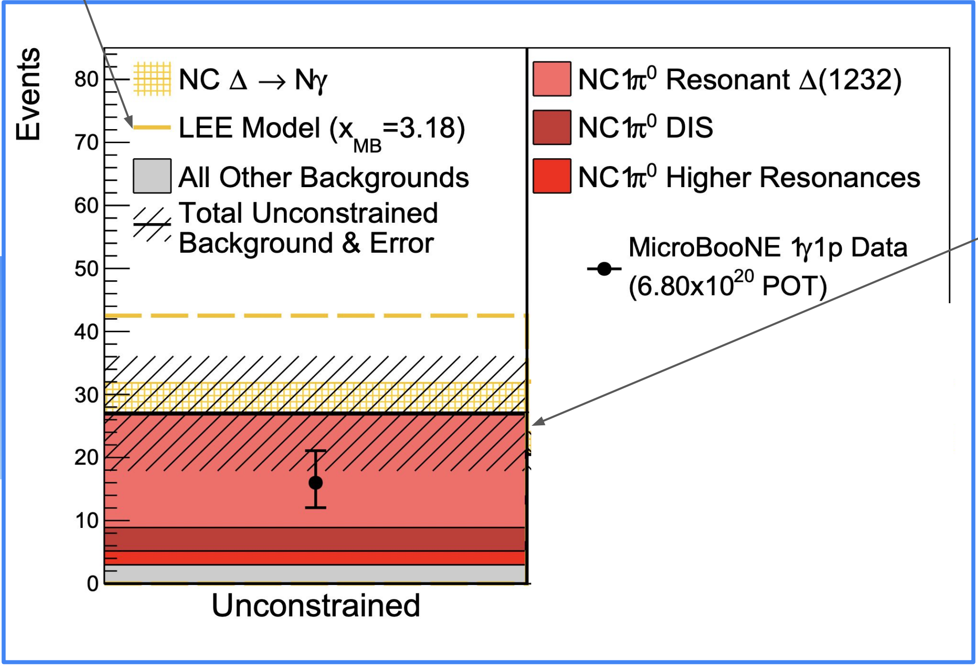


Results 1γ1p

	$1\gamma 1p$
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \rightarrow N\gamma$	4.88
LEE ($x_{\mathrm{MB}} = 3.18$)	15.5
Data	16

Enhanced rate of NC $\Delta \to N\gamma$
to explain MiniBooNE

Purity: ~15.3% Efficiency: ~4.0%



Expected background rate

Results 1γ1p

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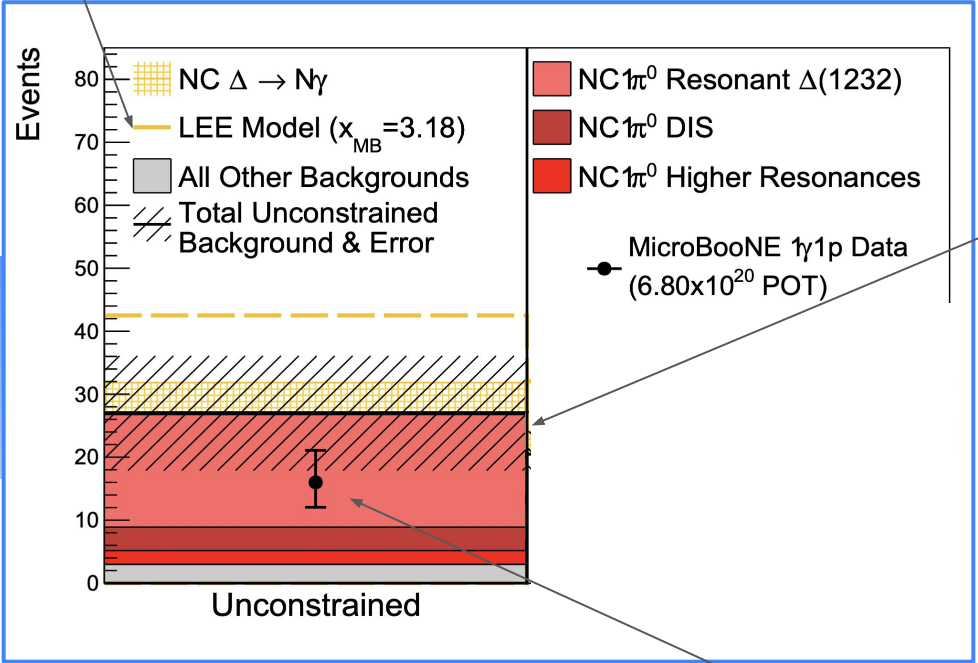

Expected background rate

Results $1\gamma 1p$

Number of data events observed in first three years of data

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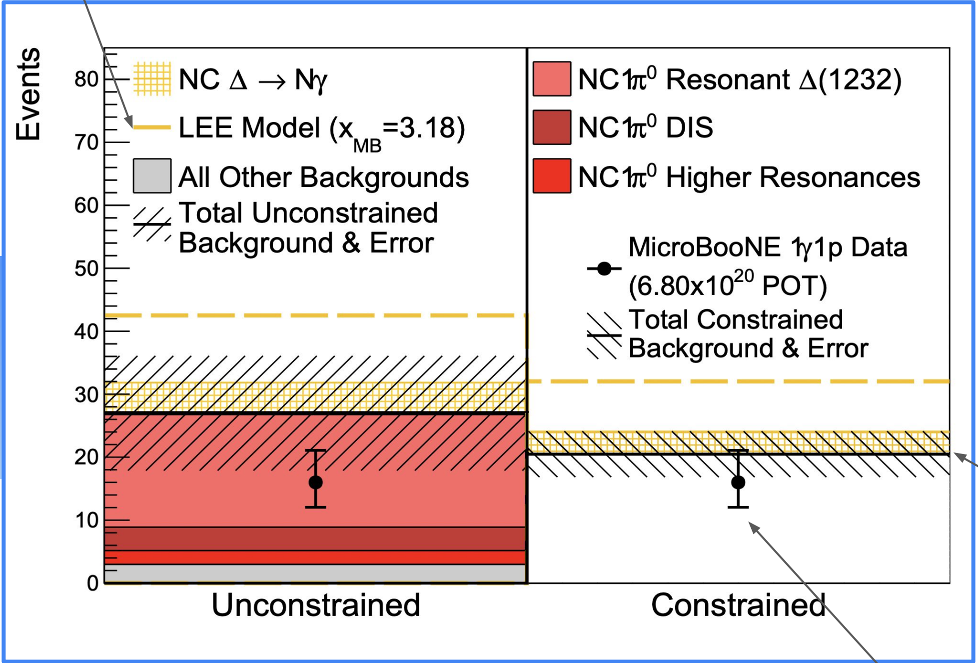

Results $1\gamma 1p$

Constrained background prediction using NCπ^0 measurement

Number of data events observed in first three years of data

	$1\gamma 1p$
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Constr. bkgd.	20.5 ± 3.6
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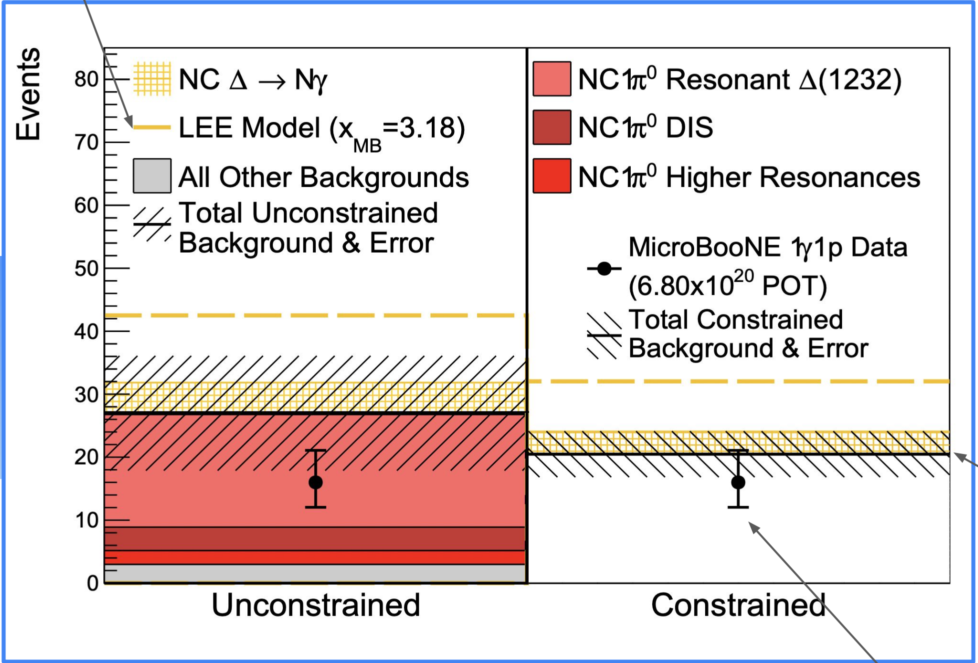
Enhanced rate of NC Δ→Nγ to explain MiniBooNE

Purity: ~15.3% Efficiency: ~4.0%



Background NC π^0 constraint pulls central value lower and reduces the systematic uncertainties.

The observed data is in good agreement with the constrained prediction

Results 1γ1p

Constrained background prediction using NCπ^0 measurement

	$1\gamma1p$
Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	4.88
LEE ($x_{\rm MB} = 3.18$)	15.5
Data	16

16
Data Events Observed

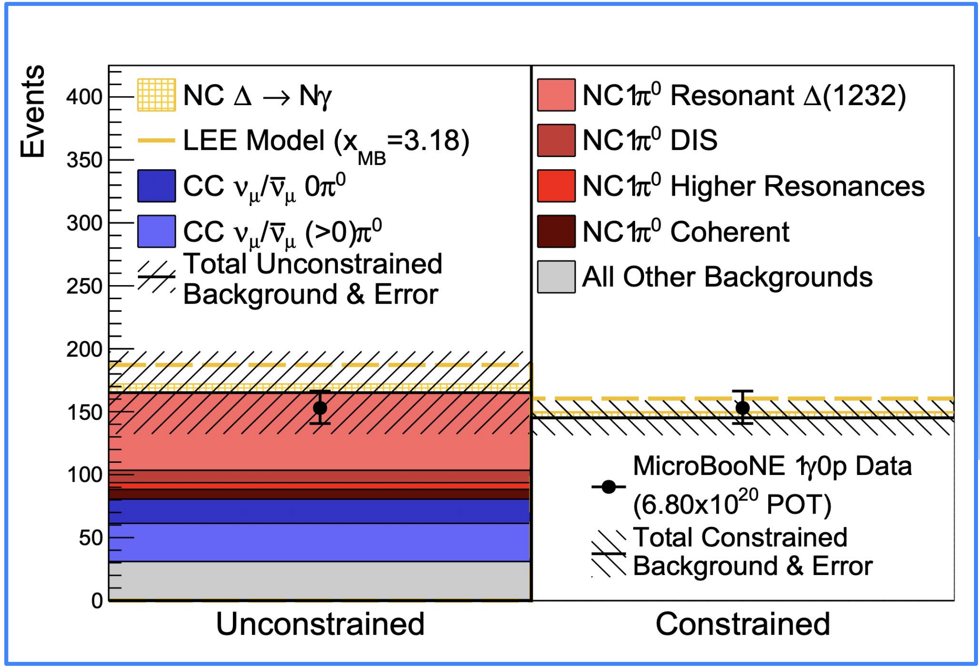
Number of data events observed in first three years of data

Observe a similar number of signal NC $\Delta \rightarrow N\gamma$ events relative to $1\gamma1p$ but less efficient background rejection.

Data agrees with both constrained background prediction and enhanced NC Δ signal due to lower purity.

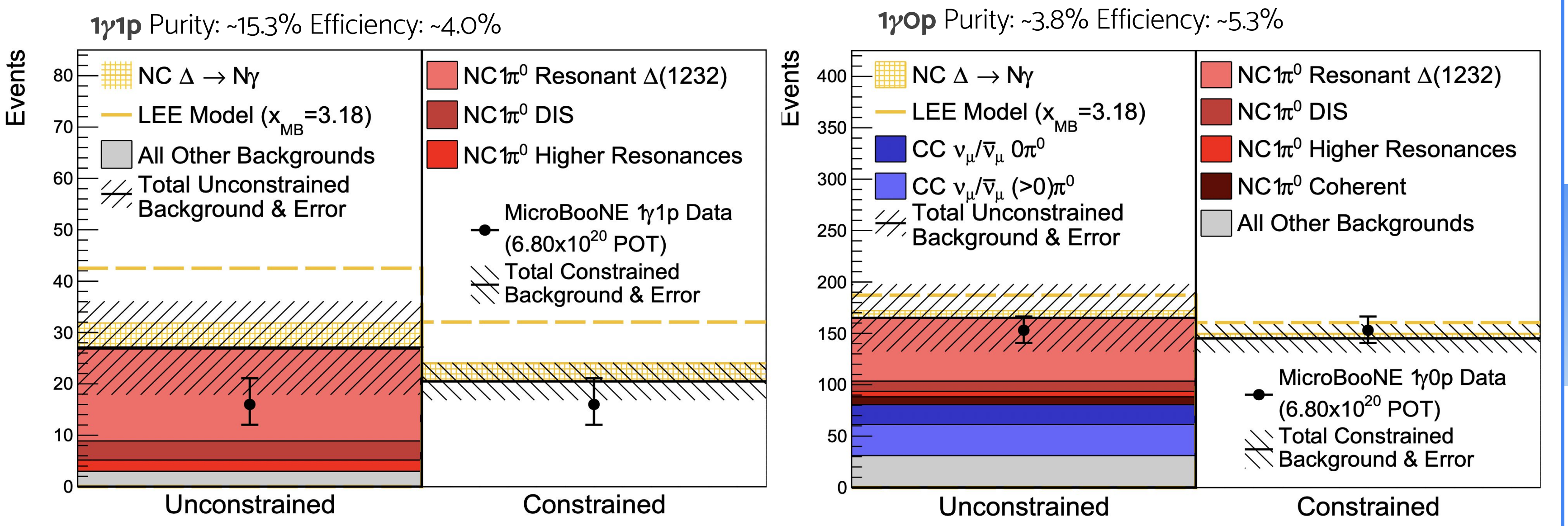
Results $1\gamma0p$

Purity: ~3.8% Efficiency: ~5.3%



	$1\gamma1p$	$1\gamma0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \rightarrow N\gamma$	4.88	6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	15.5	20.1
Data	16	153

153
Data Events Observed



16
Data Events Observed

	$1\gamma 1p$	$1\gamma 0p$
Unconstr. bkgd.	27.0 ± 8.1	165.4 ± 31.7
Constr. bkgd.	20.5 ± 3.6	145.1 ± 13.8
NC $\Delta \rightarrow N\gamma$	4.88	6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	15.5	20.1
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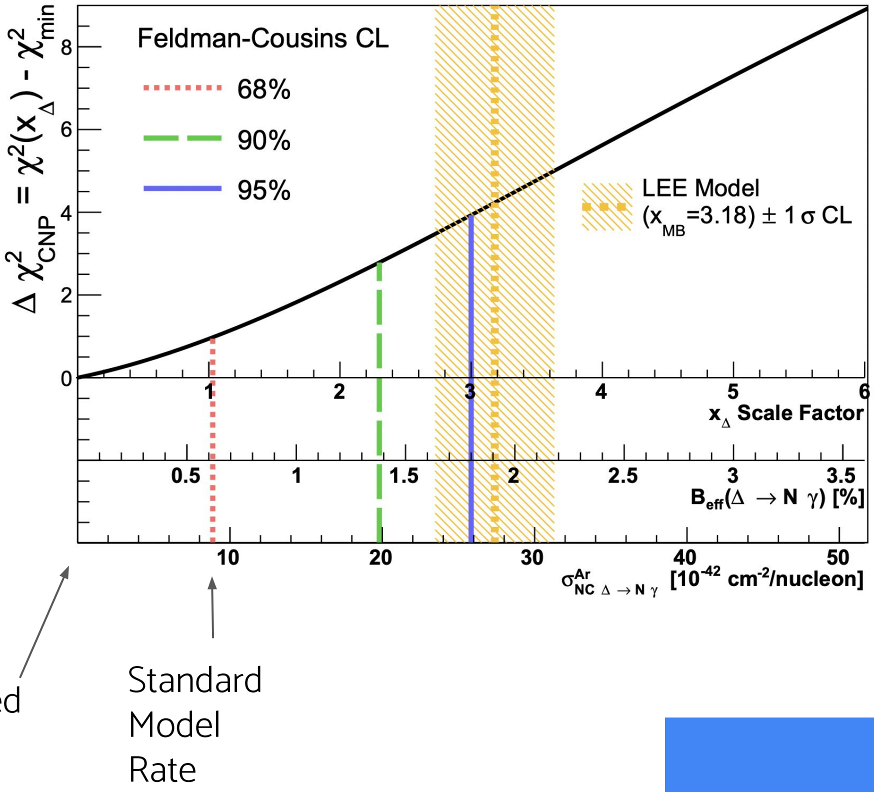
153
Data Events Observed

Bound on Rate of NC $\Delta \to N\gamma$

The resulting $\Delta\chi^2$ curve after fitting to the rate of NC $\Delta \to N\gamma$ using the Feldman-Cousins procedure, showing extracted confidence intervals.

The best fit is found to be at $x_\Delta = 0$ but this agrees with the Standard Model value at the 1σ level.



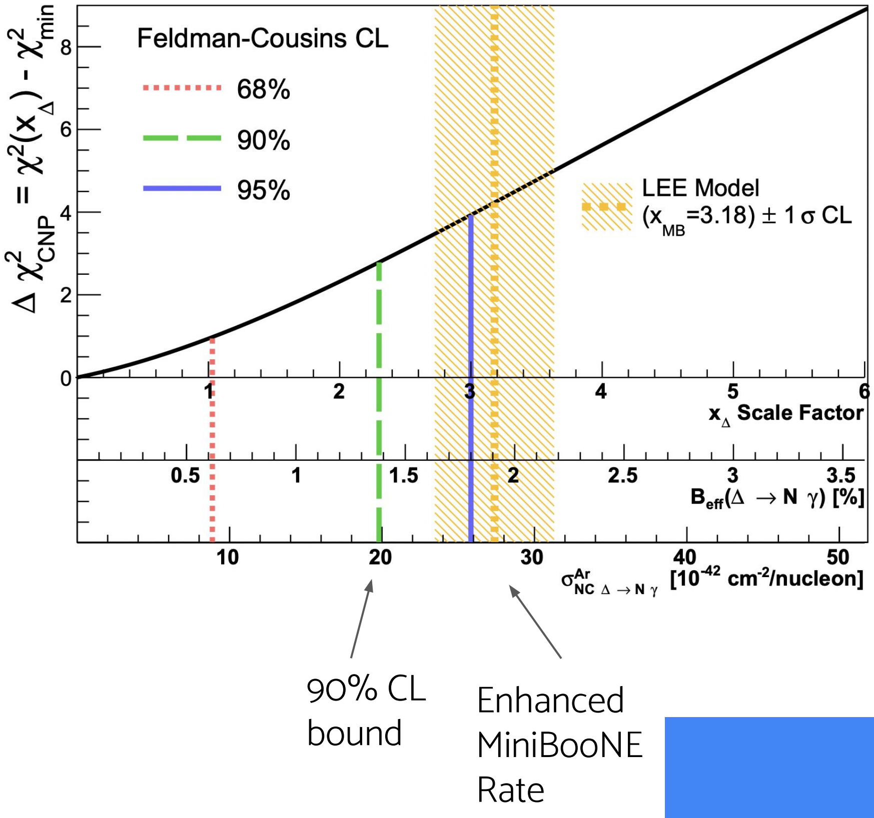
Bound on Rate of NC $\Delta \to N\gamma$

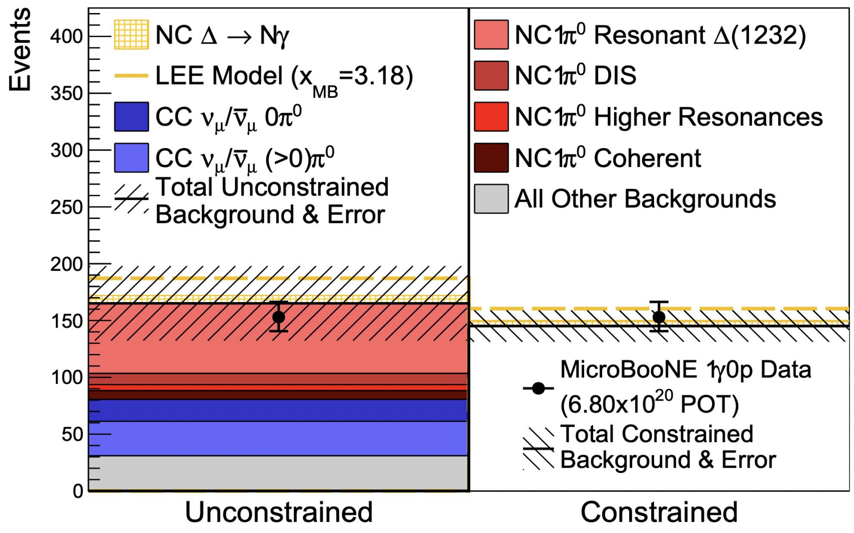
The resulting $\Delta\chi^2$ curve after fitting to the rate of NC $\Delta \to N\gamma$ using the Feldman-Cousins procedure, showing extracted confidence intervals.

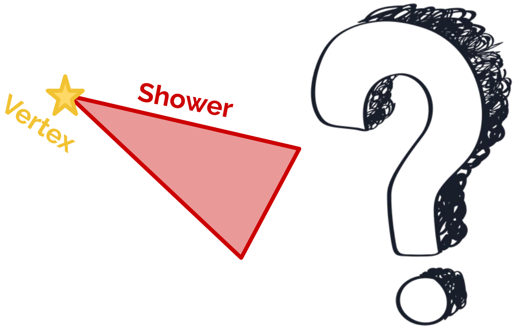
The best fit is found to be at $x_\Delta = 0$ but this agrees with the Standard Model value at the 1σ level.

Place a bound on the rate of NC $\Delta \to N\gamma$ events of $x_\Delta < 2.3$. This is an improvement over T2K prior best limit by a factor of ~50.

The data rules out the interpretation of the MiniBooNE anomalous excess in favor of the nominal prediction at 94.8% CL.







Future Photon Searches

After first MicroBooNE photon-like and electron-like searches, the **true nature of the MiniBooNE anomaly remains mysterious.**

The first result looking at NC $\Delta \rightarrow N\gamma$ demonstrates the capability to probe rare processes in neutrino scattering with a photon in the final state.

Next results aim to improve sensitivity while also targeting a broader range of models, both Standard Model and beyond**.**

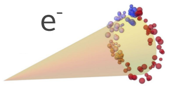
Evolving Phenomenology to Explain MiniBooNE

Credit: M. Ross-Lonergan
Not an exhaustive list!

- Decay of O(keV) sterile neutrinos to active neutrinos
    - Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)
    - de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141
- New resonance matter effects
    - Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)

→ Produces **electrons**

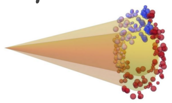
e^-



- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay:
    - Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470
- Decay of heavy sterile neutrinos produced in beam
    - Gninenko, Phys.Rev.D83:015015,2011
    - Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)
    - Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)
    - Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)

→ Produces **photons**

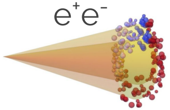
$\gamma \rightarrow e^+e^-$



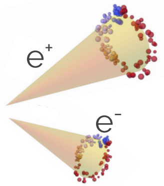
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z’ or more complex higgs sectors
    - Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)
    - Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531
    - Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)
    - Dutta, Ghosh, Li, PRD 102, 055017 (2020)
    - Abdallah, Gandhi, Roy,Phys. Rev. D 104, 055028 (2021)
- Decay of axion-like particles
    - Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)

→ Produces **e^+e^-** pairs

e^+e^-



e^+ e^-



Photon Searches with Wire-Cell

*JINST 17, P01037 (2022)

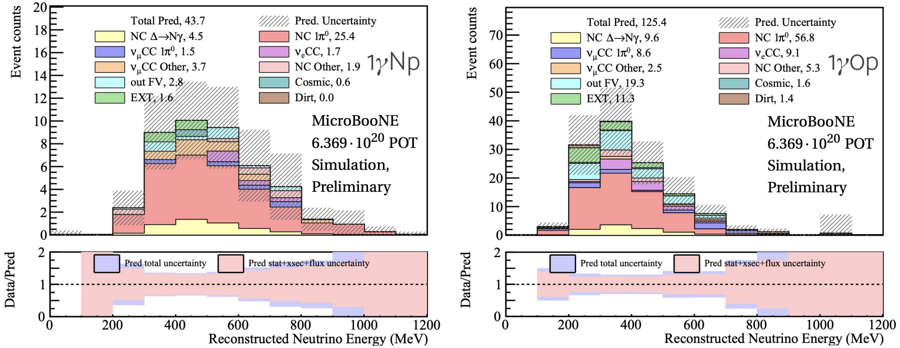
NC Δ→Nγ

Described in MICROBOONE-NOTE-1104-PUB

Targeting an NC Δ→Nγ radiative signal but using an independent reconstruction paradigm, Wire-Cell 3D reconstruction*.

Important cross check of the first result and in particular see **strong gains in the purity and efficiency for the 1γ0p** selections.

Currently studying sidebands to constrain the systematics with a result expected soon.



New analysis with Wire-Cell → Wire-Cell 1g0p; First analysis → Pandora 1g0p

	Wire-Cell 1gNp	Pandora 1g1p	Wire-Cell 1g0p	Pandora 1g0p
NC $\Delta \rightarrow N\gamma$ eff.	4.09%	3.99%	8.78%	5.29%
NC $\Delta \rightarrow N\gamma$ pur.	10.4%	15.3%	7.97%	3.81%

Photon Searches with Wire-Cell

*JINST 17, P01037 (2022)

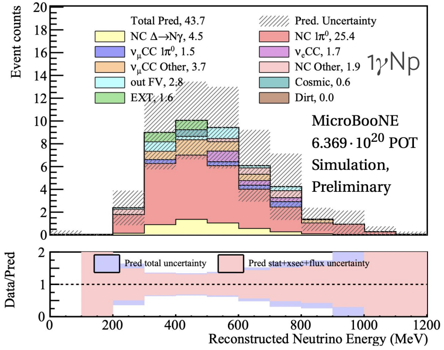
NC $\Delta \rightarrow N\gamma$

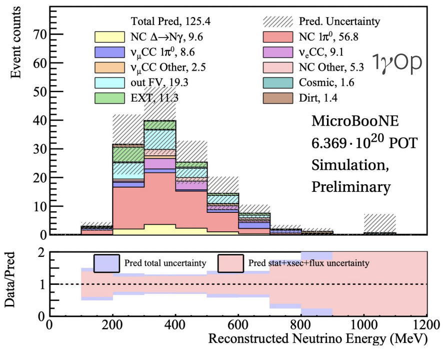
Described in MICROBOONE-NOTE-1104-PUB

Targeting an NC $\Delta \rightarrow N\gamma$ radiative signal but using an independent reconstruction paradigm, Wire-Cell 3D reconstruction*.

Important cross check of the first result and in particular see **strong gains in the purity and efficiency for the $1\gamma 0p$** selections.

Currently studying sidebands to constrain the systematics with a result expected soon.





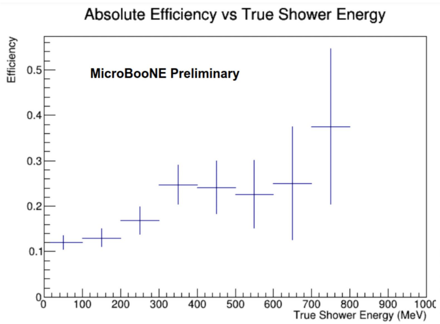
Inclusive Single Photon

Described in MICROBOONE-NOTE-1102-PUB

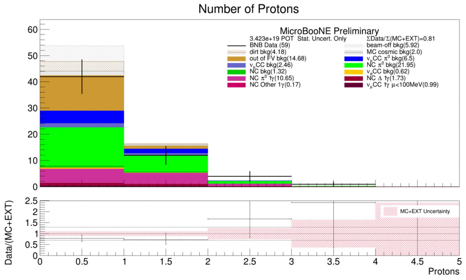
Also uses Wire-Cell 3D reconstruction and is first analysis of an **inclusive single photon selection** in MicroBooNE.

Looking for **all single photon events >20MeV** without a visible muon, rather than those from a single process like $\Delta \rightarrow N\gamma$ decay.

Currently finalizing selections, **15.2% efficiency for the inclusive photon signal** and relatively high efficiency for low energy showers.



Here shown without systematic errors on and using a data test sample.



Searching for New Models

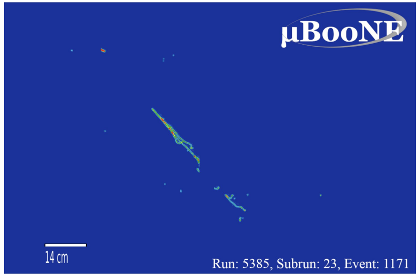
Coherent-Like

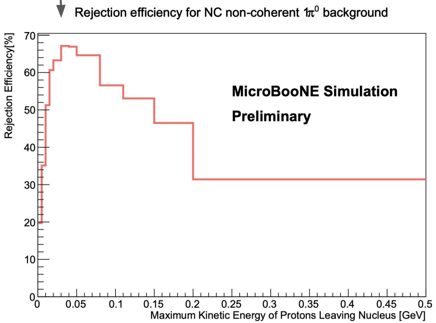
Described in MICROBOONE-NOTE-1103-PUB

Coherent photon production in neutrino scattering is a Standard Model process that also hasn't been directly observed.

Follow on to the first result using the same reconstruction but **targeting specifically the 1γ0p topology.** In particular trying to reject events with unreconstructed protons to isolate true single shower events. With **new proton-stub-veto BDT** see strong proton rejection for very low energy protons.

Example photon event that is rejected because of proton stub candidate





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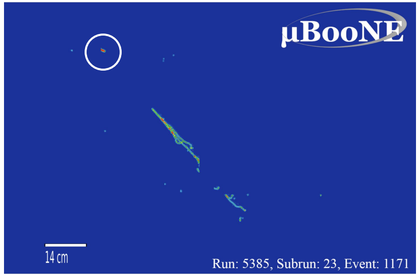
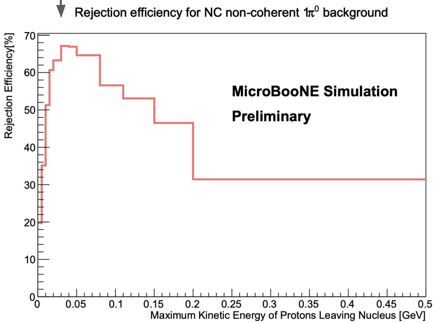




e^+e^- Pairs

Also seen Georgia Karagiorgi's talk on Light Sterile Neutrinos.

In MicroBooNE also considering signals that might look photon-like in the detector but come from collimated e^+e^- pairs. **For this study the model consists of light dark photon mediated neutrino scattering as an explanation of the MiniBooNE excess.**

Credit: A. Abdullahi et al.: More information in Neutrino 2022 poster

Could expect as many as ~40 events that would have been visible in the first NC $\Delta \rightarrow N\gamma$ radiative decay measurement.

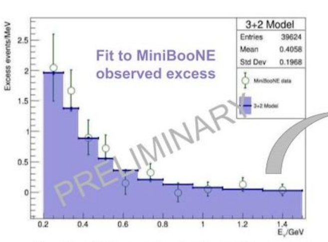
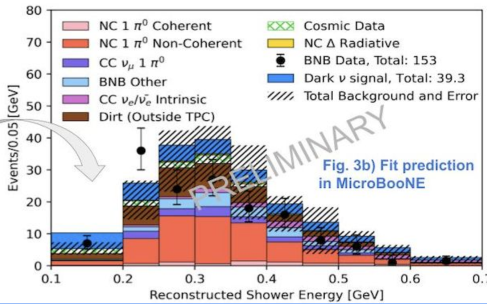
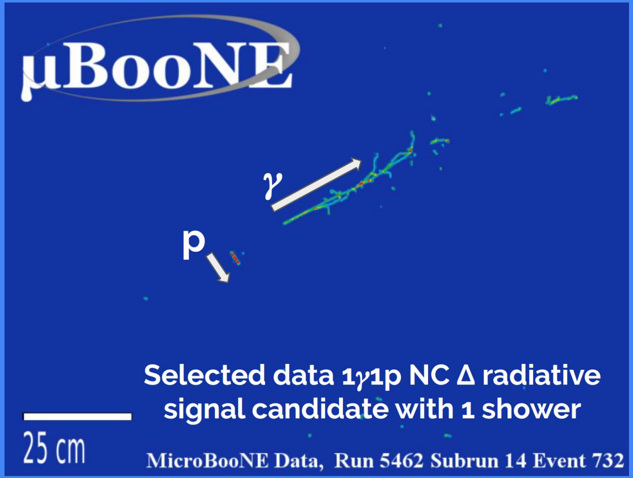
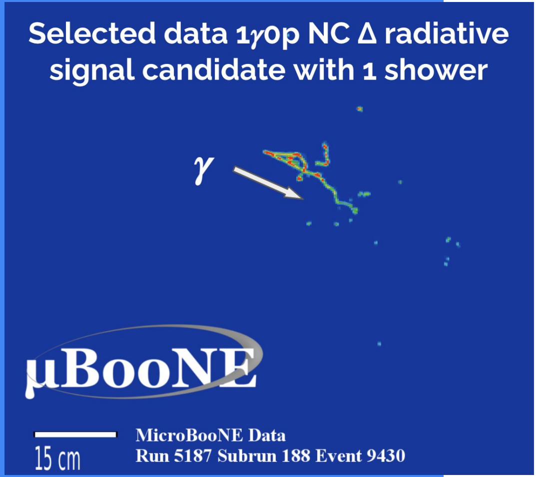


Fig. 3. a) Reconstructed neutrino energy at MiniBooNE for best fit parameters [7].



SUMMARY & OUTLOOK





MicroBooNE has shown that the **LArTPC technology can be used to search for rare neutrino interactions**, like those with with a single photon in the final state.

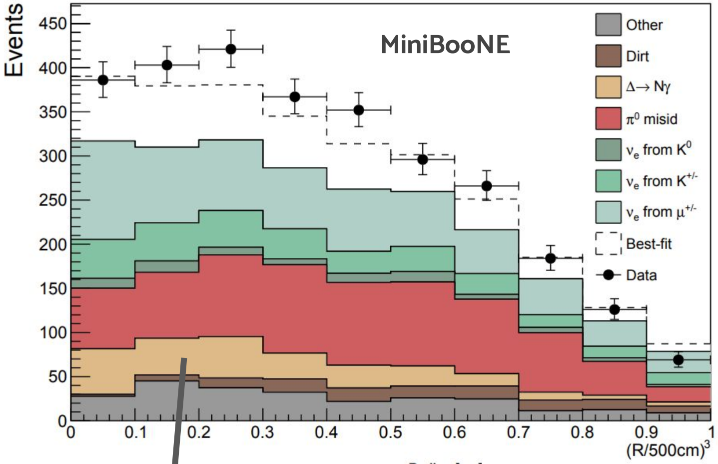
The first MicroBooNE single photon result has set a **world-leading limit on neutrino-induced NC $\Delta \rightarrow N\gamma$** in neutrino scattering and disfavors the hypothesis that the MiniBooNE anomaly was a misestimation of this process.

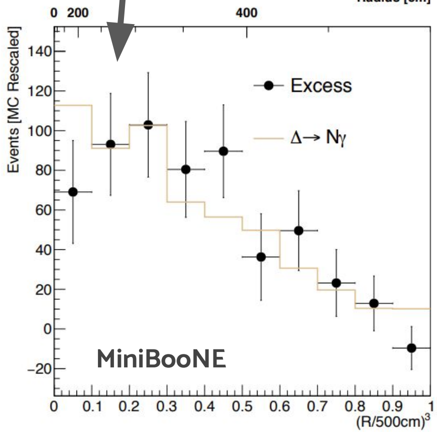
Next generation MicroBooNE measurements will provide further insight into Standard Model and BSM photon(-like) processes.

BACKUP

Enhanced Signal Model

Phys. Rev. D 103, 052002 (2021)



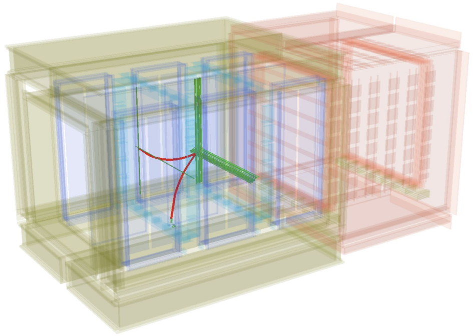


Background studies by MiniBooNE showed that an enhancement of **x3.18** to their predicted NC $\Delta \rightarrow N\gamma$ rate gave excellent agreement with the observed excess in the radial distributions

We use this to define a benchmark **directly testable MiniBooNE model** under a photon-like hypothesis.

Best fit to radial distribution for NC $\Delta \rightarrow N\gamma$ in MiniBooNE

T2K NC Single Photon Search

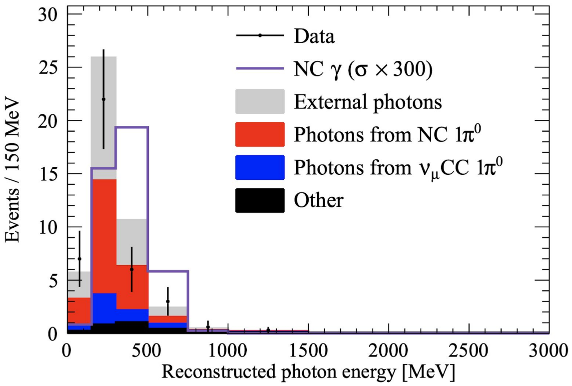


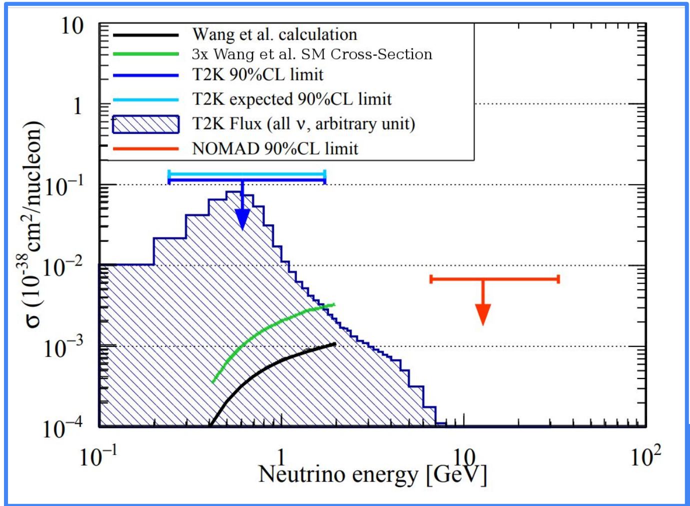
Example T2K NC1γ data candidate

Used the ND280 tracker detector, the T2K near detector with peak neutrino energy similar to BNB, ~0.6GeV.

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 π^0, sensitivity limited by associated uncertainties

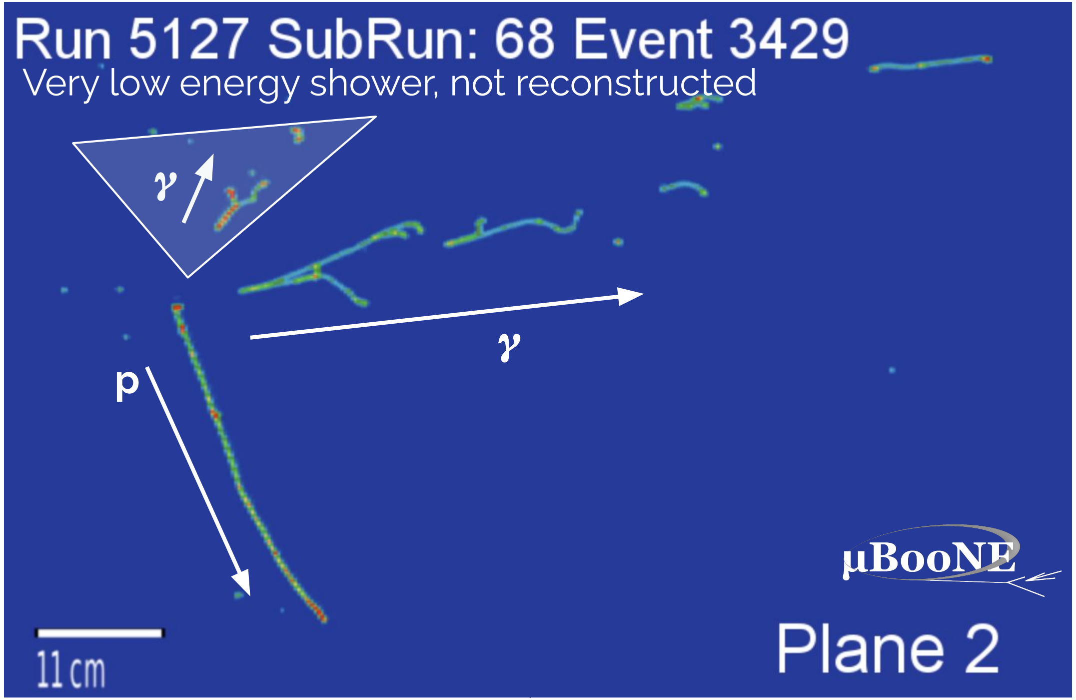
Reconstructed photon energy of the T2K NC1γ selection





J. Phys. G 46, 08LT01 (2019)

NC π^0 Background Example



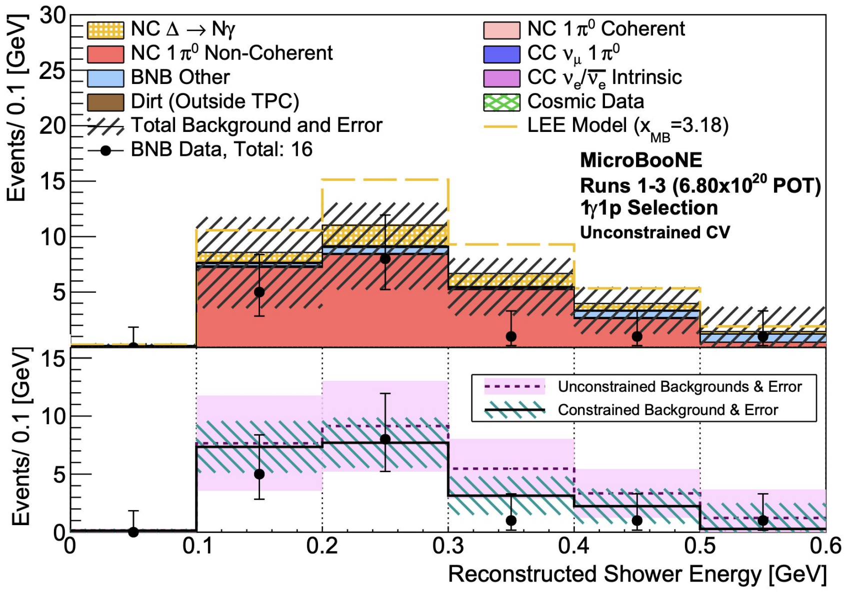
This is one of the most signal-like candidate data events, although it isn't selected in the final stage. The reconstructed M_Δ = 1.17 GeV.

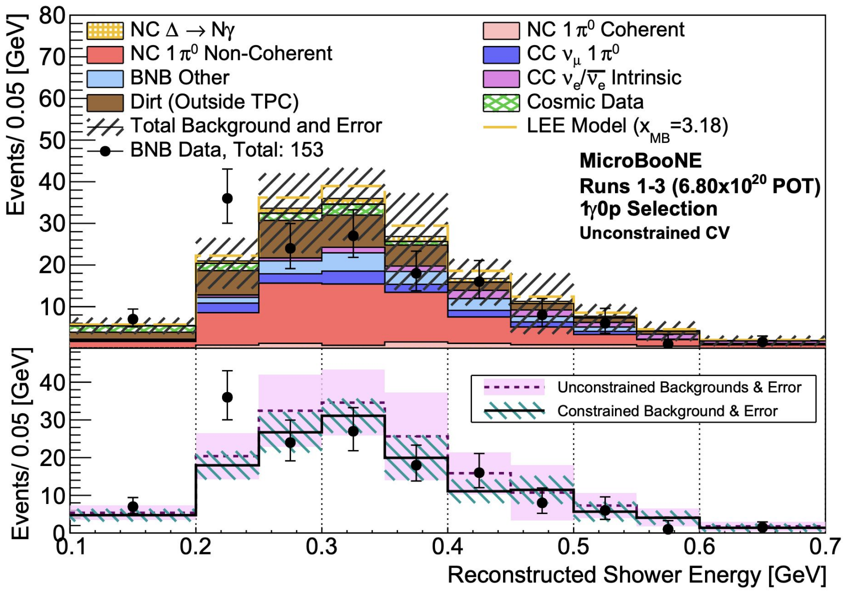
If second photon shower is missed/ mis-reconstructed, looks nearly identical to signal

Reconstructed invariant mass can be close to expected value of M_Δ if second photon is low energy

$$\nu_\mu + p \rightarrow \nu_\mu + \Delta^+$$
$$\Delta^+ \rightarrow p + \pi^0$$
$$\pi^0 \rightarrow \gamma + \gamma$$

Single Photon Plots





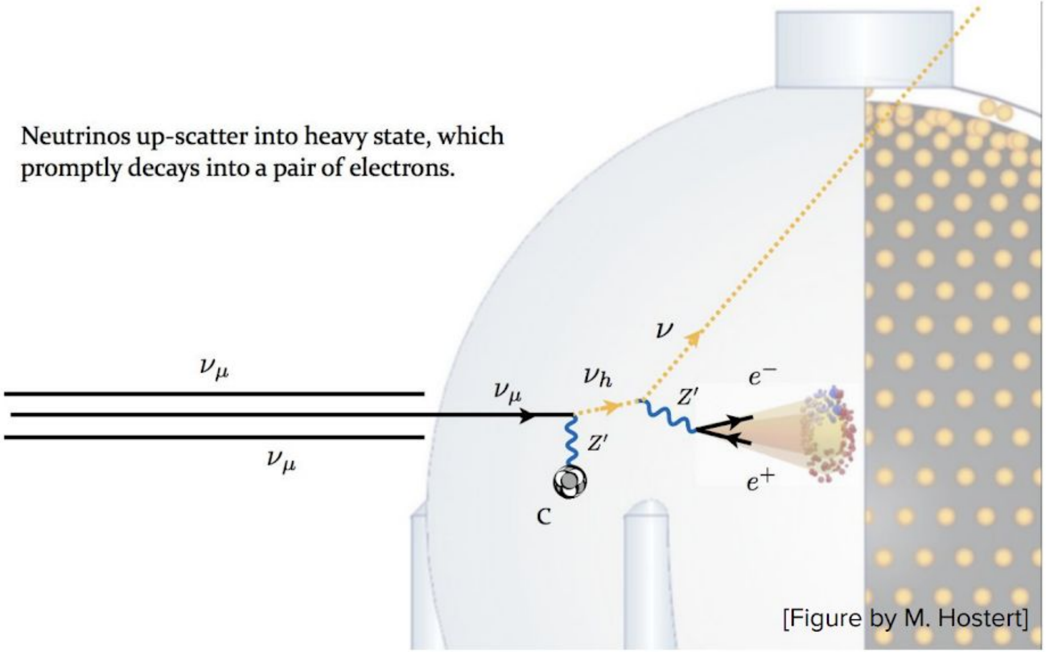
Single Photon Uncertainties and Background Prediction

Type of Uncertainty	$1\gamma 1p$	$1\gamma 0p$
Flux model	7.4%	6.6%
GENIE cross-section model	24.8%	16.3%
GEANT4 re-interactions	1.1%	1.3%
Detector effects	12.2%	6.4%
Finite background statistics	8.3%	4.0%
Total Uncertainty (Unconstr.)	29.8%	19.2%
Total Uncertainty (Constr.)	17.8%	9.5%

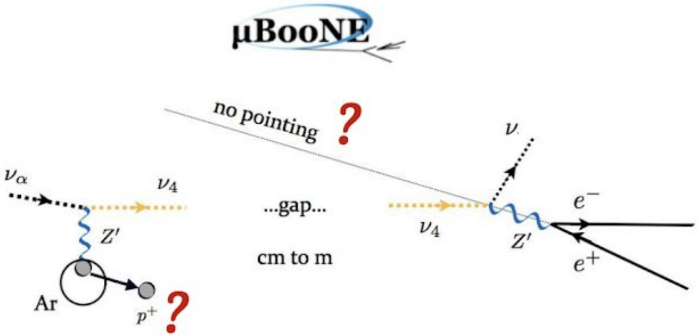
Process	$1\gamma 1p$	$1\gamma 0p$
NC $1\pi^0$ Non-Coherent	24.0	68.1
NC $1\pi^0$ Coherent	0.0	7.6
CC ν_μ $1\pi^0$	0.5	14.0
CC ν_e and $\bar{\nu}_e$	0.4	11.1
BNB Other	2.1	18.1
Dirt (outside TPC)	0.0	36.4
Cosmic Ray Data	0.0	10.0
Total Background (Unconstr.)	27.0	165.4
NC $\Delta \rightarrow N\gamma$	4.88	6.55

Z' Boson Decay

E.g., Z' mediated heavy neutrino production and decay into e+e- pair
[Phys.Rev.D 99 (2019) 071701, *Phys.Rev.D* 101 (2020) 11, 115025]



[Figure by M. Hostert]



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