SUSY 2022

Ioannina Greece, June 30th 2022

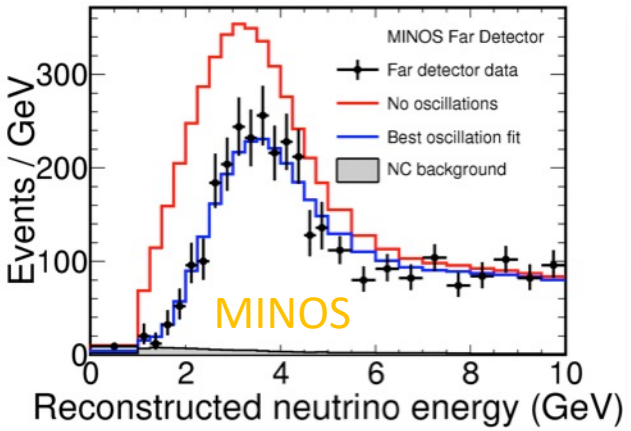
Recent results of new physics searches from MicroBooNE

Xiao Luo, UCSB

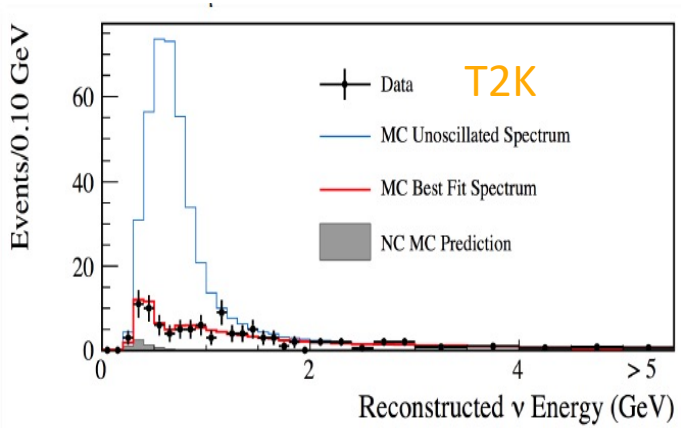
On behalf of the MicroBooNE collaboration

Standard Model neutrinos

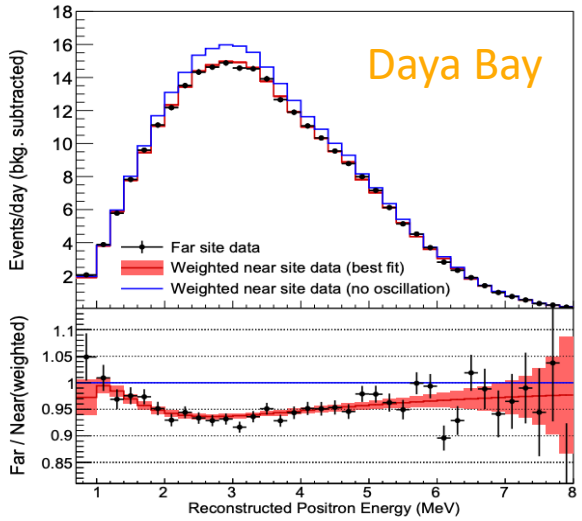
ν_μ disappearance



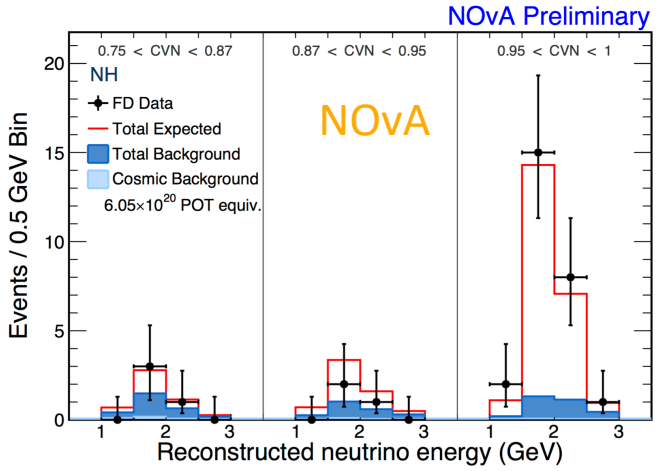
ν_μ disappearance



$\bar{\nu}_e$ disappearance



ν_e appearance



Over two decades of **Oscillation experiments** have established...

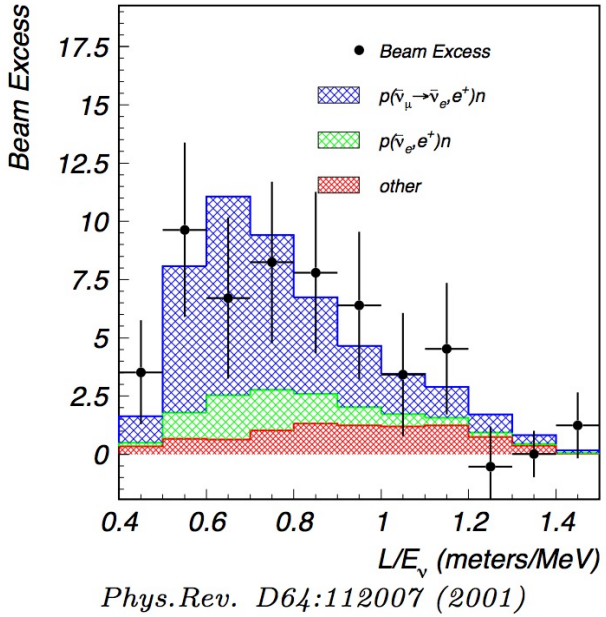
3–ν paradigm

$$|U_{PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.1 \\ 0.5 & 0.6 & 0.7 \\ 0.3 & 0.6 & 0.7 \end{pmatrix}$$

- **3 mixing angles**: $\theta_{12} \sim 33°, \theta_{13} \sim 8°, \theta_{23} \sim 45°$
- **2 mass splittings**: Δm^2_{21} ~ 7.5 X 10^{-5} eV^2, $|\Delta m^2_{32}|$ ~ 2.5 X 10^{-3} eV^2
- **1 CP violation phase δ_{CP}**

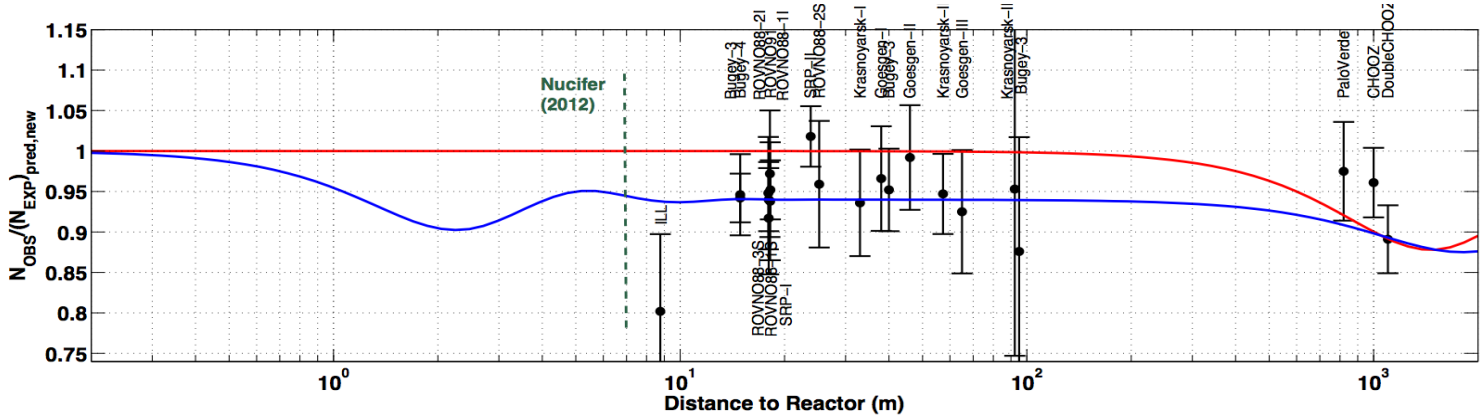
Short Baseline Anomalies

LSND $\bar{\nu}_e$ Excess



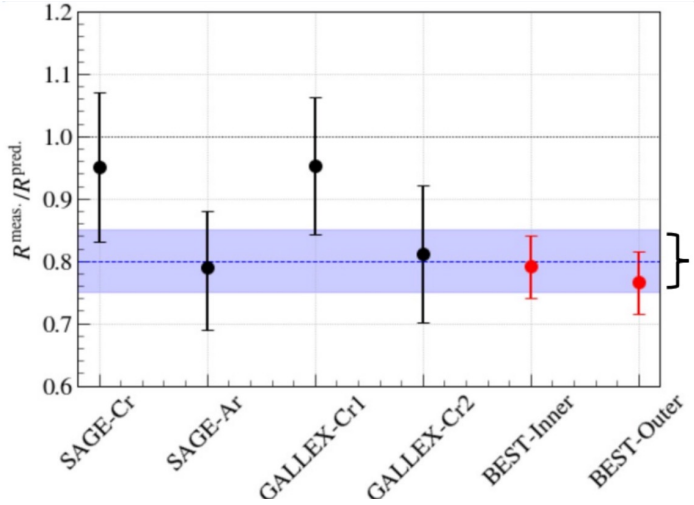
Phys.Rev. D64:112007 (2001)

"Reactor Anomaly" $\bar{\nu}_e$ deficit

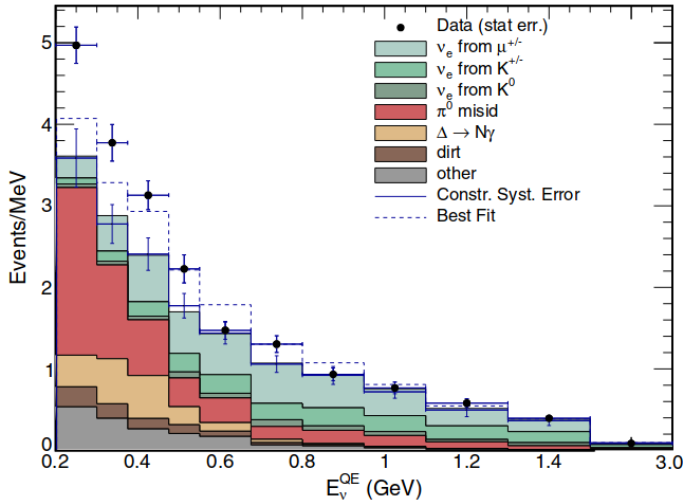


Hint oscillation from additional
"Sterile" neutrino(s)
m_4 ~ 1eV

"Gallium Anomaly" solar ν_e deficit

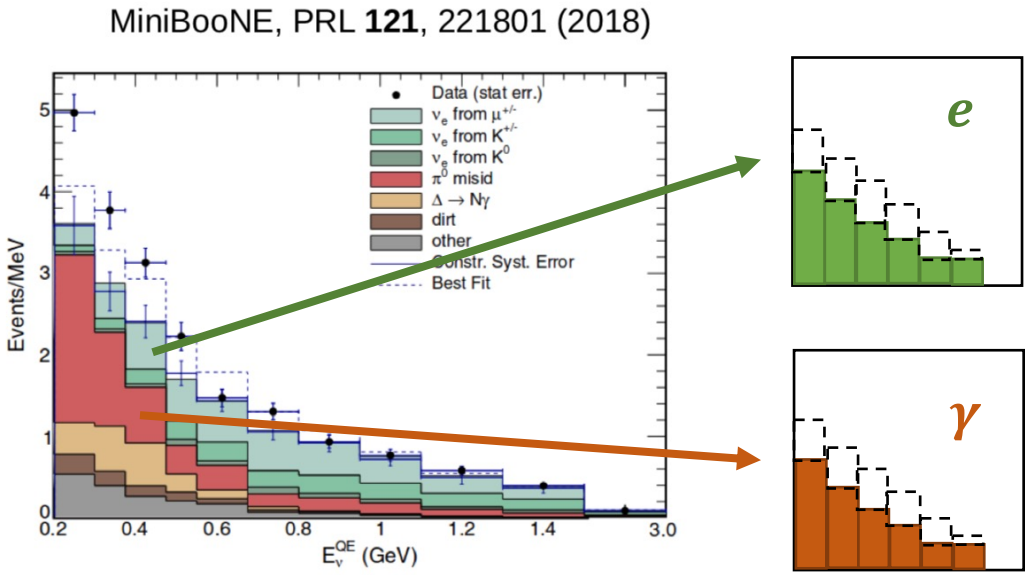


MiniBooNE $\nu_e/\bar{\nu}_e$ Excess at low energy



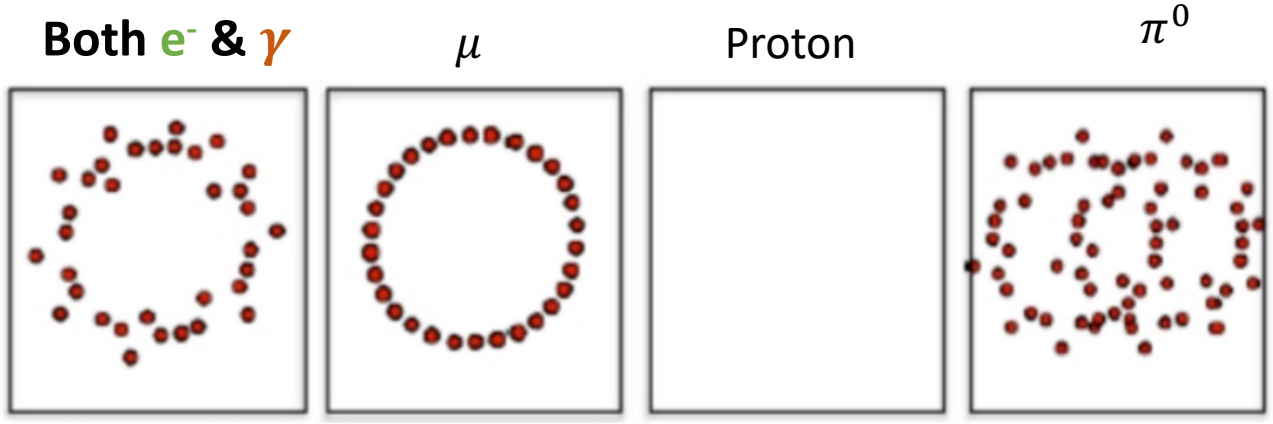
@ Fermilab
On-axis of Booster neutrino beamline

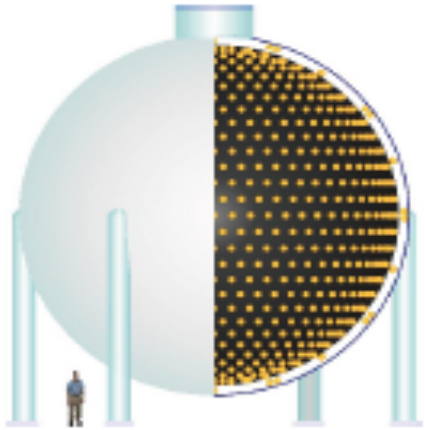
MiniBooNE “Low-Energy-Excess” anomaly



MiniBooNE LEE results

- 4.8σ excess of ν_e-like events at low energy.
- Large photon (γ) backgrounds, MiniBooNE detector is not able to distinguish e^- from γ.

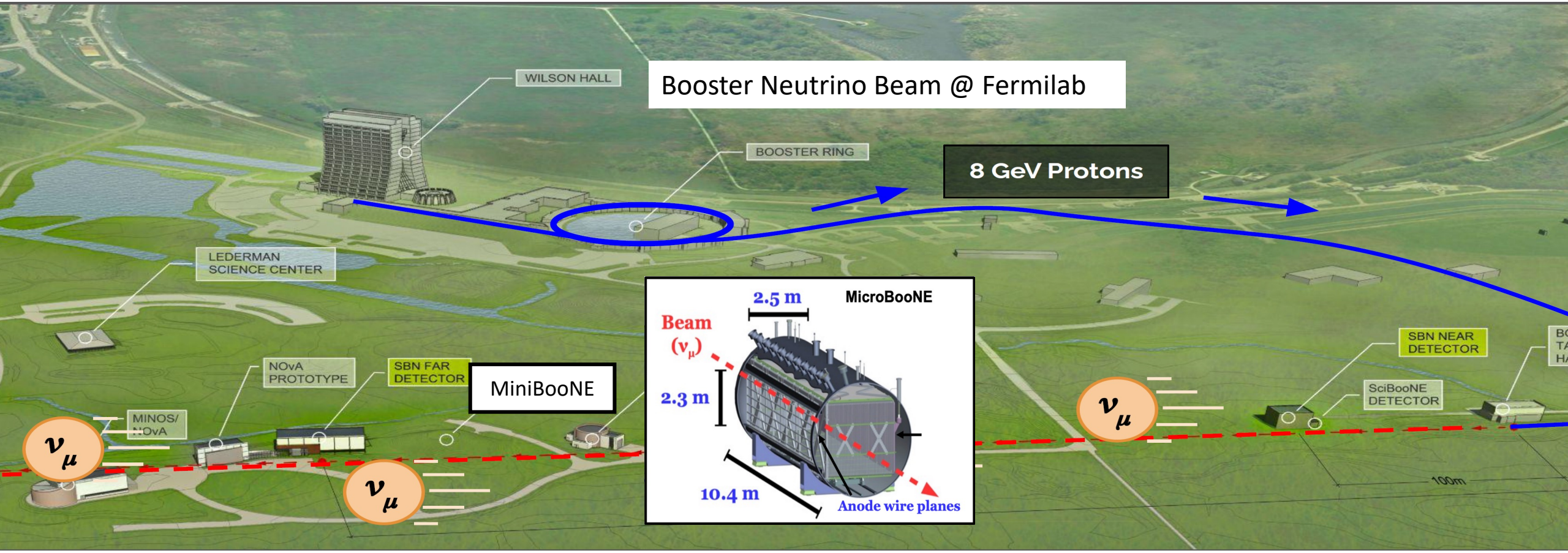




MiniBooNE

- ~820 tonnes oil Cherenkov detector
- Fermilab Booster Neutrnio beam
- L/E ~1 m/MeV

MicroBooNE goes after MiniBooNE Low-Energy-Excess

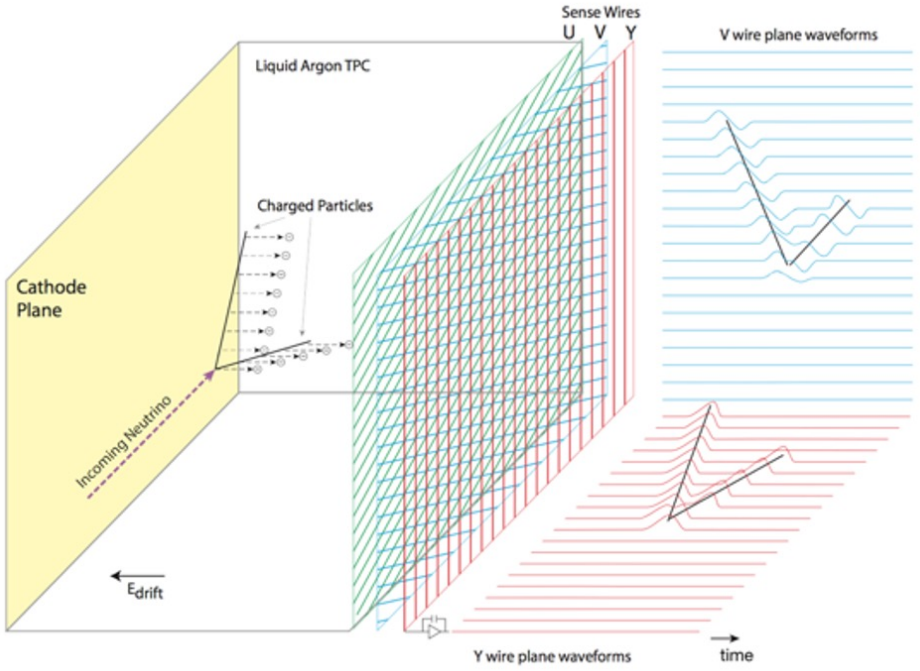


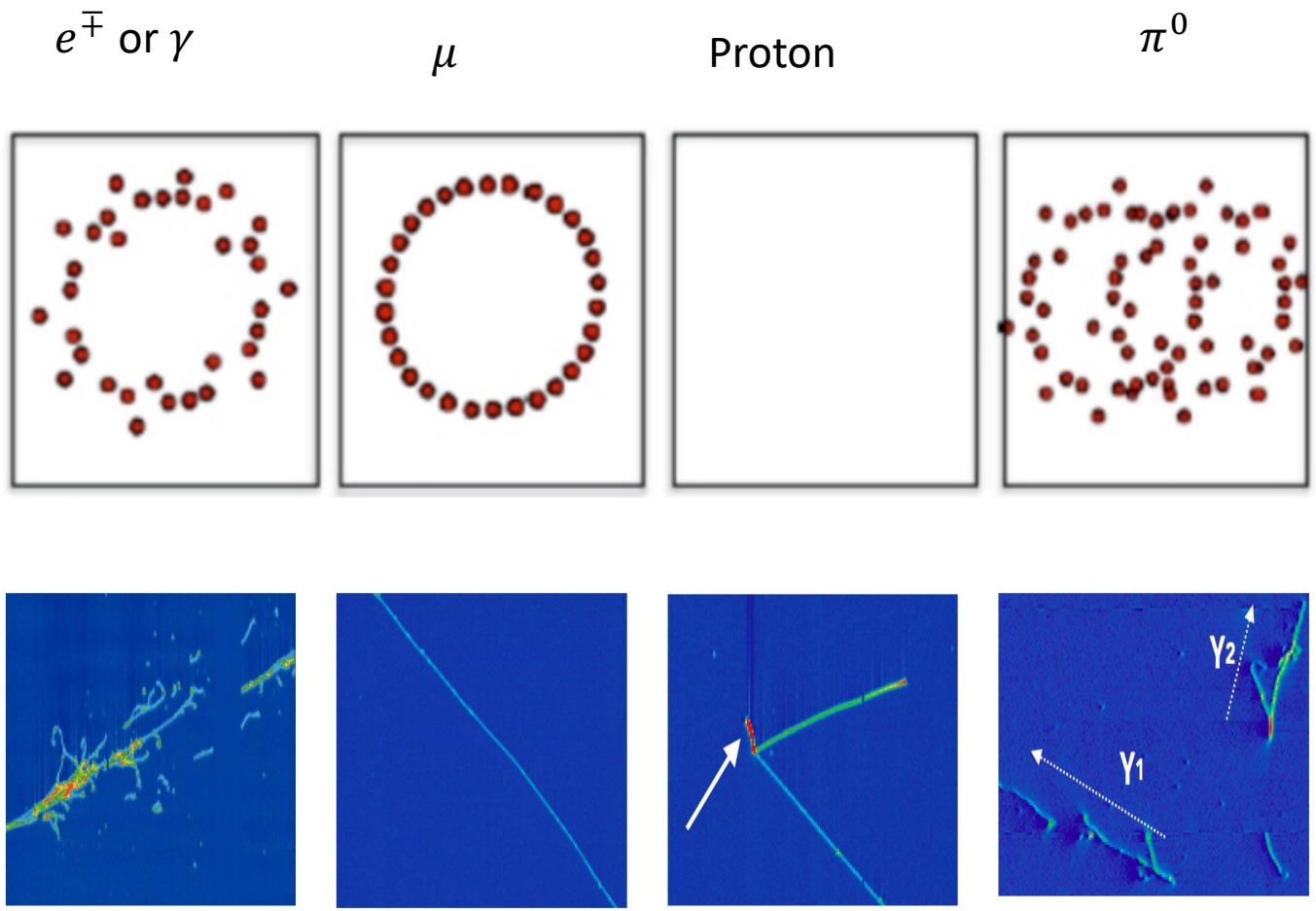
MicroBooNE experiment

- Located on-axis of Fermilab's Booster neutrino beamline (L~470m), same L/E as MiniBooNE.
- Off-axis on NuMI
- A LArTPC detector with 85 tonne active volume

Liquid Argon TPC – advantage on particle ID

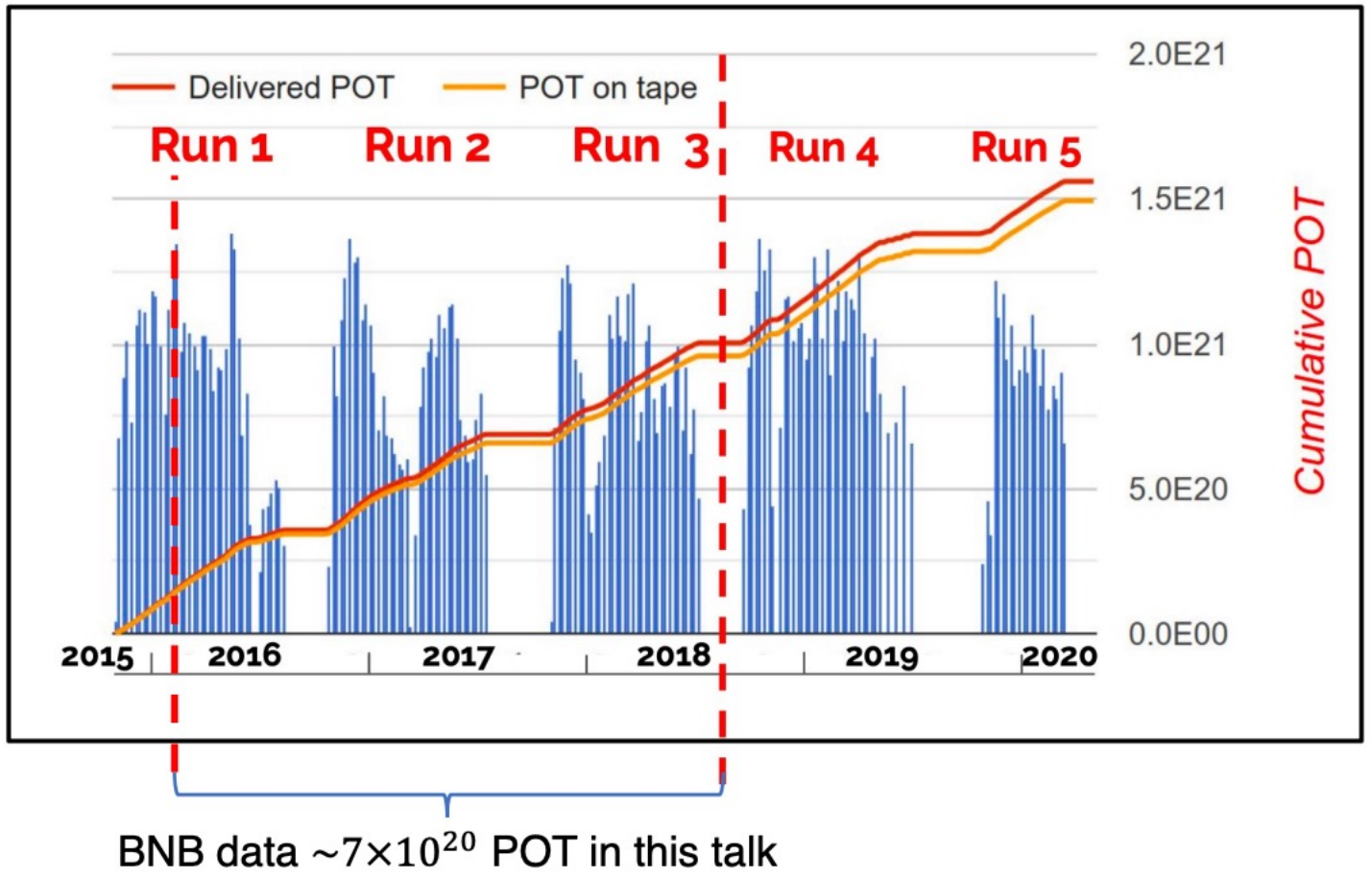
- Two type of detector signals: **scintillation light** and **drift electrons**
- Capable of providing full 3D reconstruction in 4π.
- Capable of calorimetric energy reconstruction.





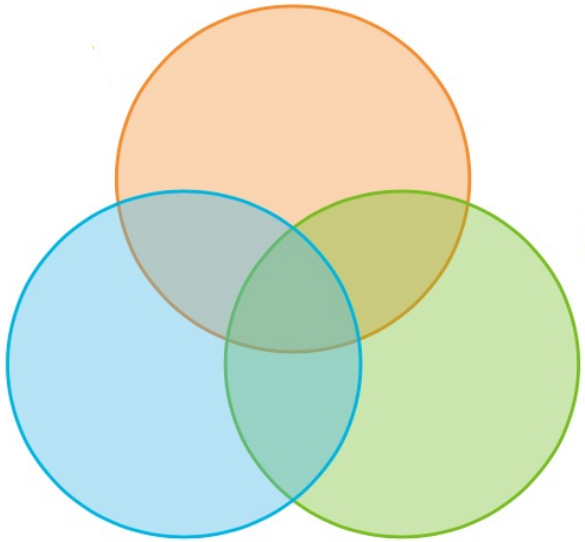
MicroBooNE Operation

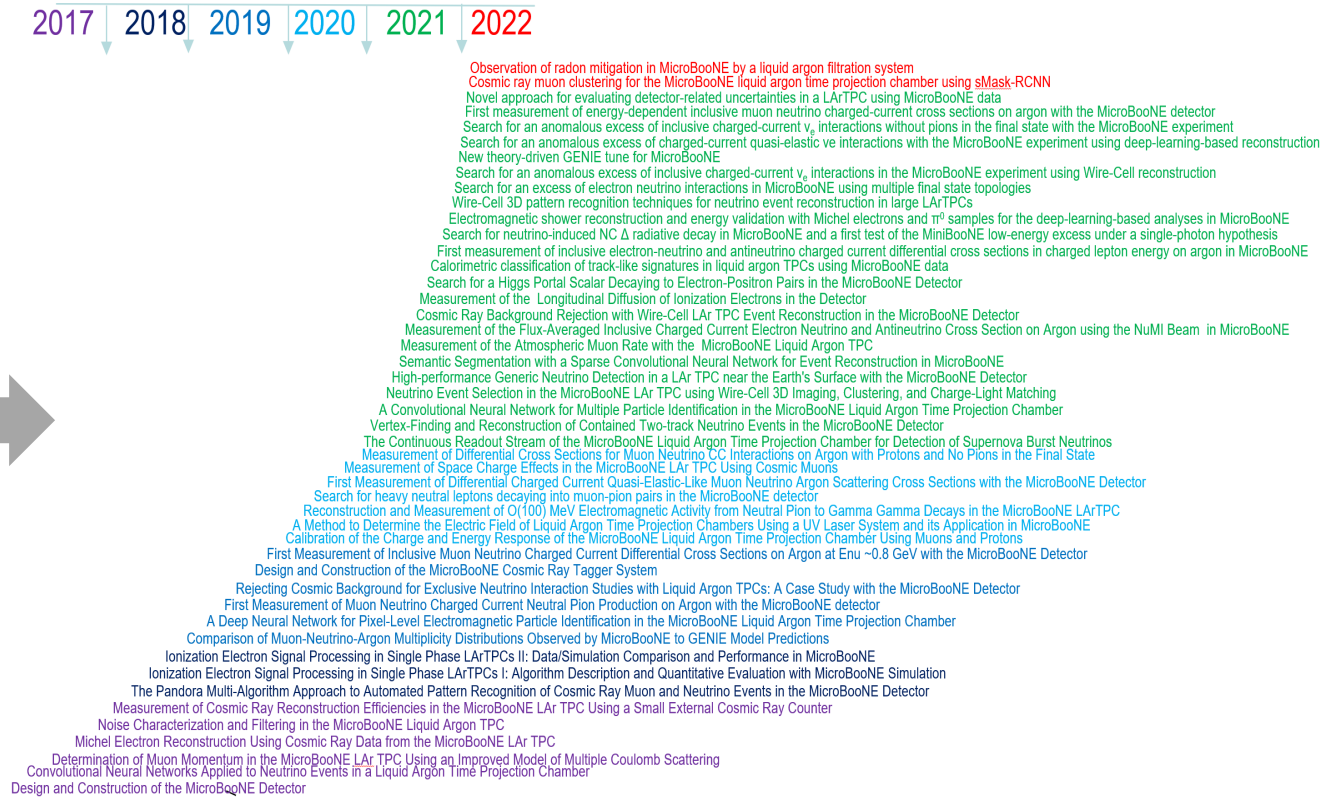
- 5 years operation from 2015 to 2020
- Collected the largest neutrino dataset from a LArTPC detector
- Two post operation runs dedicated for LArTPC detector R&D until 2021
- The analyses results shown here are using about half of the total collected BNB POT



MicroBooNE's mission and science output

Understand MiniBooNE LEE & other New Physics Searches



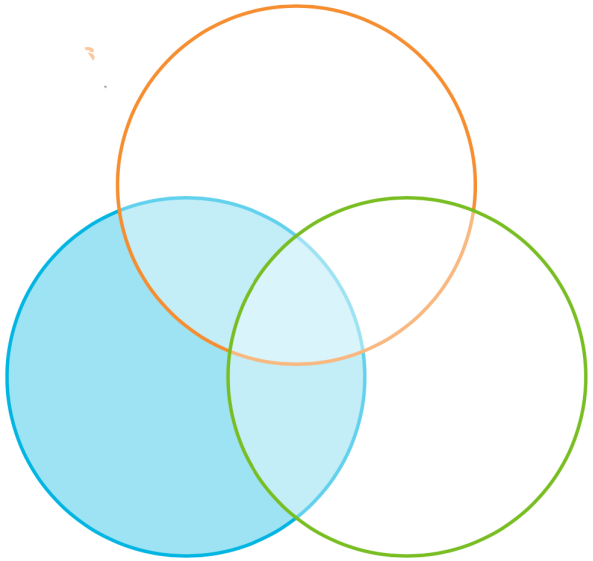


Precision measurements of ν – Ar cross-sections

Pioneering R&D of LArTPC detector technology

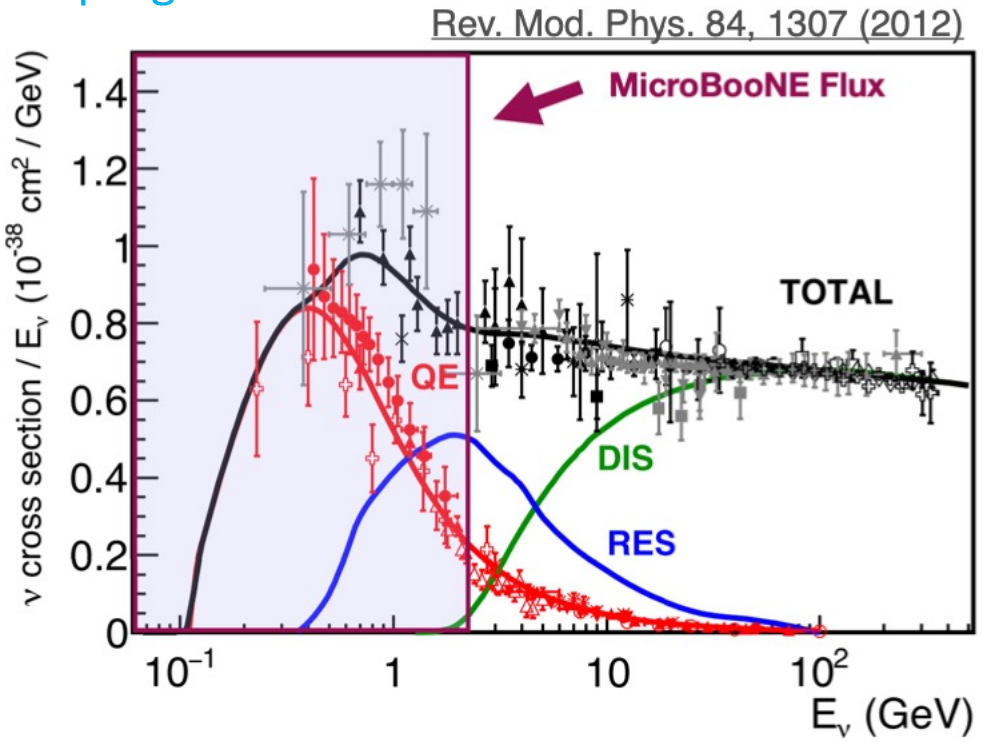
- More than 45 publications in the past 5 years https://microboone.fnal.gov/documents-publications/
- More than 75 public notes sharing progress with community as we go https://microboone.fnal.gov/public-notes/

MicroBooNE's cross-section program



Precision measurements of ν – Ar cross-sections

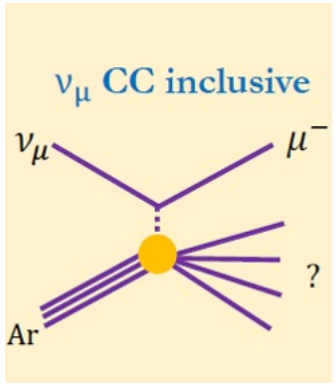
- Prediction of ν – Ar interactions at low energy relies on neutrino generators, which have large uncertainty not verified by experimental data
- MicroBooNE's cross-section program aims to provide direct data constraints of cross-section modeling for its new physics searches.
- Collected 0.5M ν – Ar events, critical input for DUNE's LBL oscillation program.

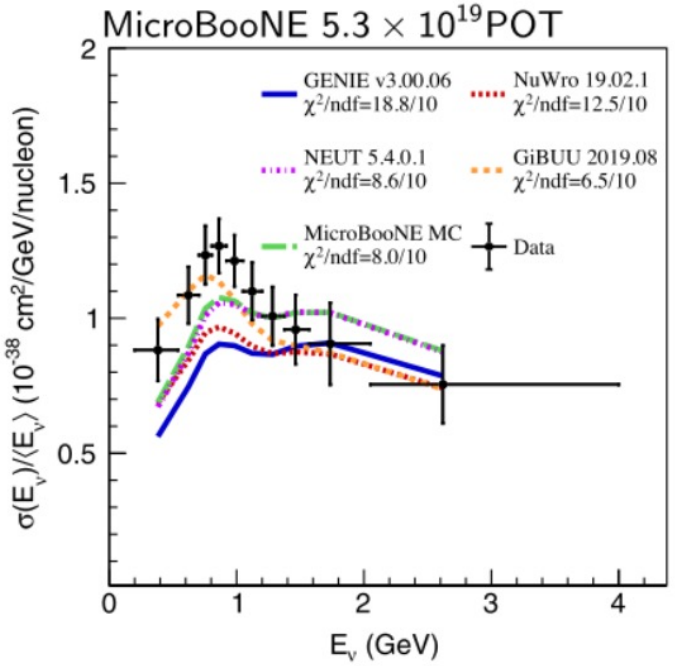


MicroBooNE's cross-section program

Inclusive cross-section

($\nu_\mu CC$ -- Phys. Rev. Lett. 128, 151801)

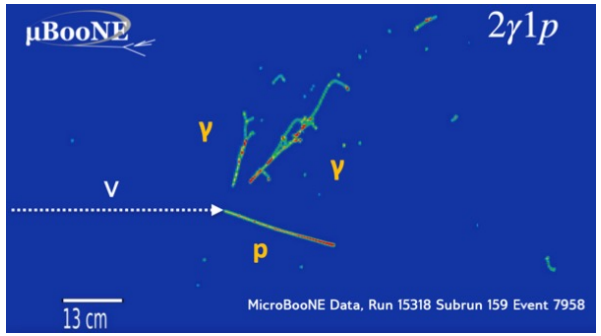




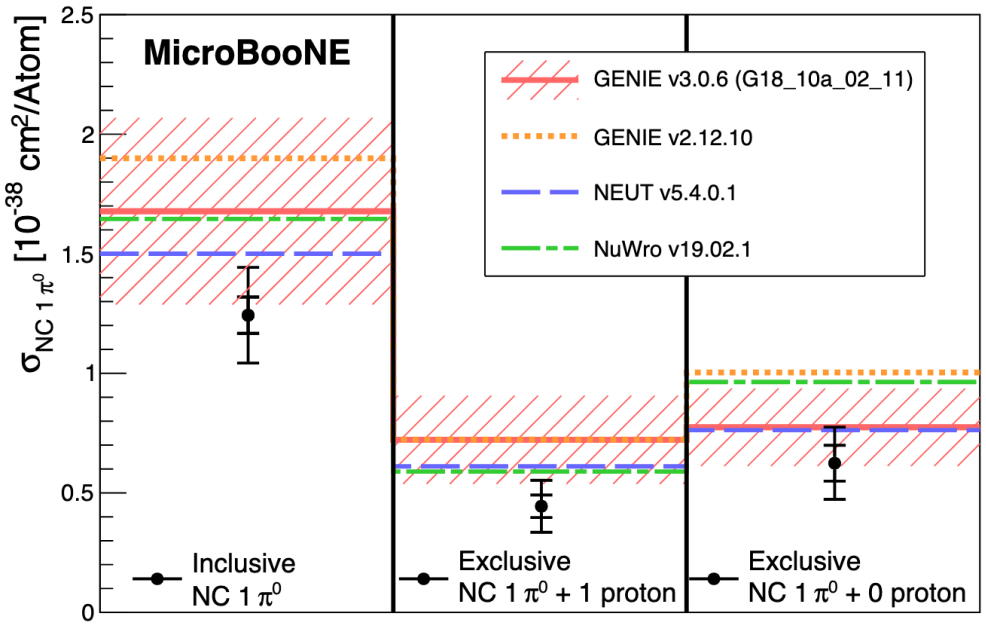
- Neutrino flux in MicroBooNE has 95% of muon neutrinos.
- Inclusive charged current channel is key to oscillation analyses.
- Offers background rates constraints for new physics search (ie. LEE analyses) in all final states.

Exclusive cross-section

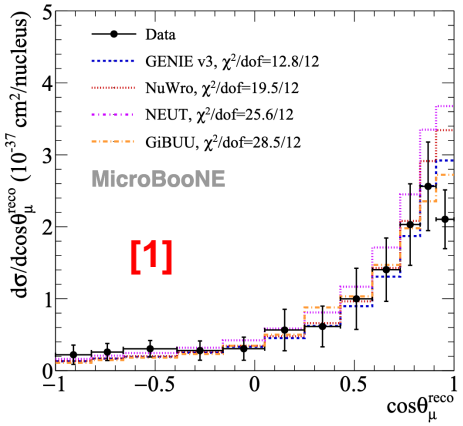
(NCπ^0 -- arxiv2205.07943)

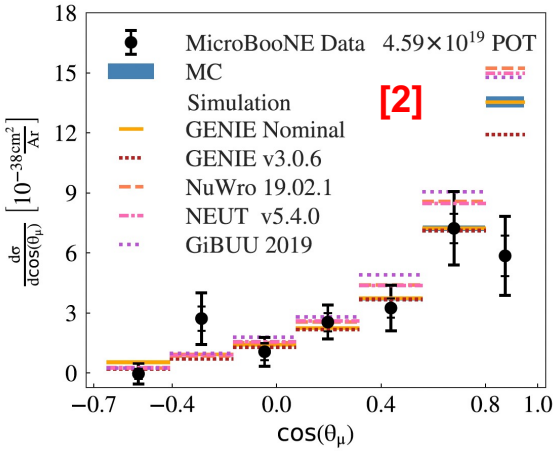


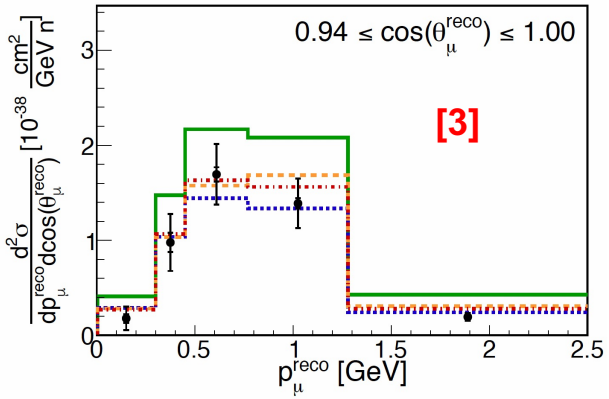
- NCπ^0 (no charge lepton) is dominant background for many BSM searches.
- X-sec measurement to provide data constraint.

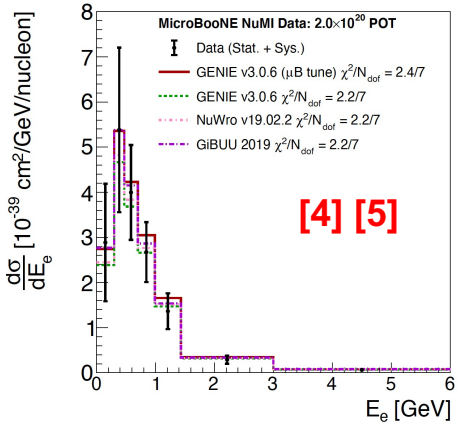


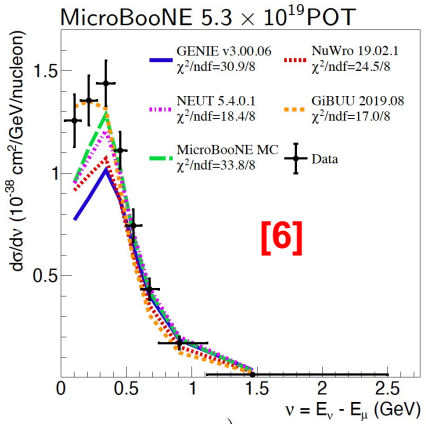
MicroBooNE's cross-section program

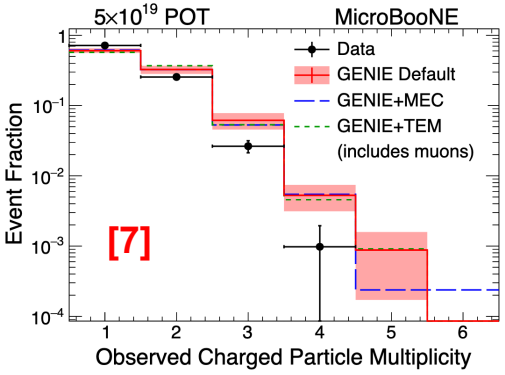


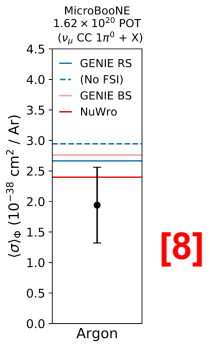


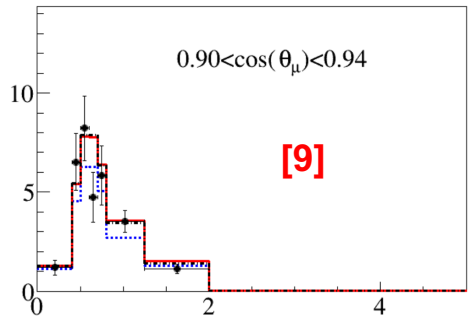


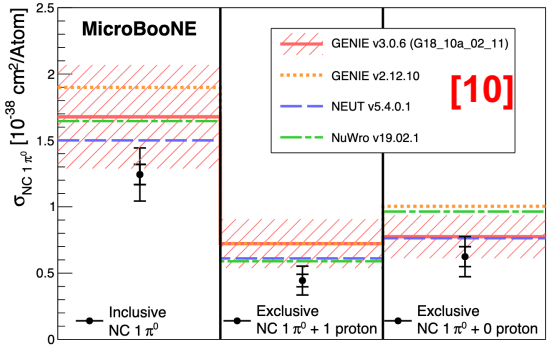












MicroBooNE xsec measurements:

[1] ν_μ CC Np0π [1D differential]
Phys.Rev.D 102 (2020) 11, 112013

[2] ν_μ CCQE-like [1D differential]
Phys.Rev.Lett. 125 (2020) 20, 201803

[3] ν_μ CC inclusive [2D differential]
Phys.Rev.Lett. 123 (2019) 13, 131801

[4] ν_e CC [inclusive]
Phys.Rev.D 104 (2021) 5, 052002

[5] ν_e CC [1D differential]
Phys.Rev.D 105 (2022) 5, L051102

[6] ν_μ CC inclusive [1D differential]
Phys.Rev.Lett. 128 (2022) 15, 151801

[7] Proton multiplicity
Eur.Phys.J.C 79 (2019) 3, 248

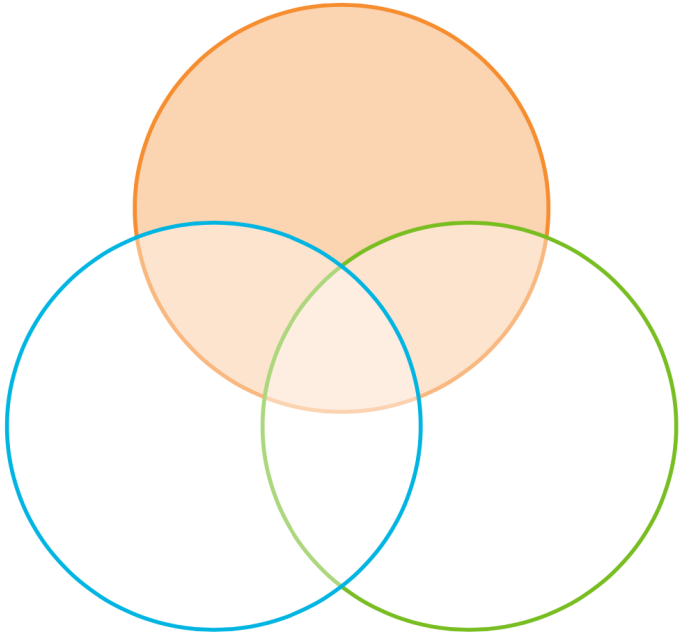
[8] ν_μ CC π^0 [integrated]
Phys.Rev.D 99 (2019) 9, 091102

[9] GENIE-tune paper
Phys.Rev.D 105 (2022) 7, 072001

[10] NC π^0 production [integrated]
arXiv:2205.07943 [submitted to PRD]

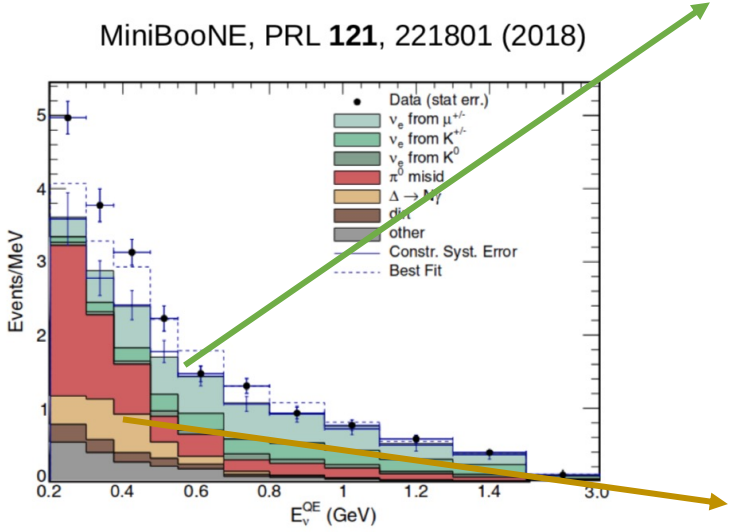
MicroBooNE's flagship analysis – Low-Energy-Excess

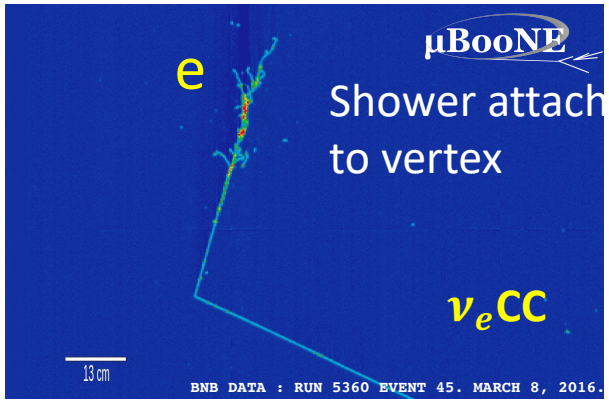
Understand MiniBooNE LEE
& other New Physics Searches

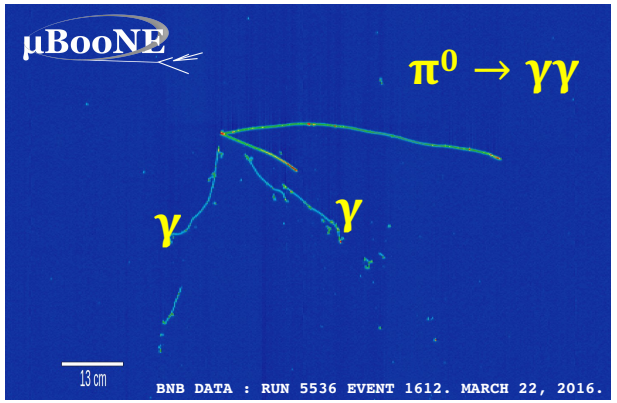


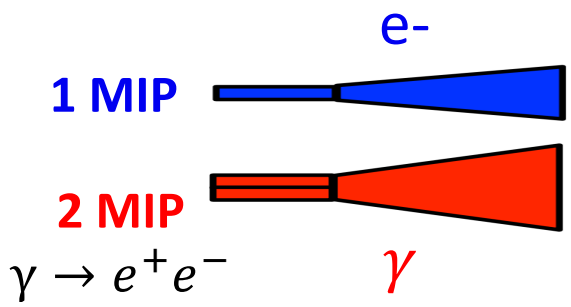
Addressing origin of the MiniBooNE anomaly
- ~eV sterile neutrinos
- Other BSM physics

MiniBooNE's excess events with EM shower





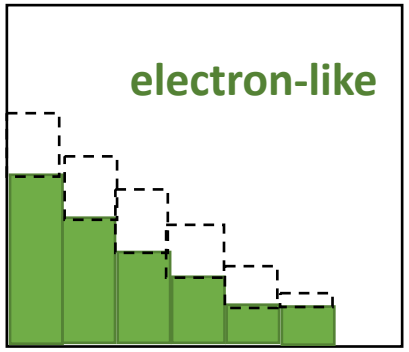




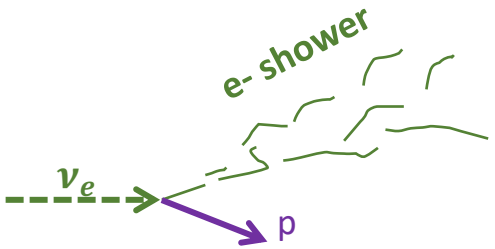
Two Handles for e/γ separation
- Gap Vs no Gap
- 1MIP Vs 2MIP at the shower start

MicroBooNE's 1st round LEE analyses

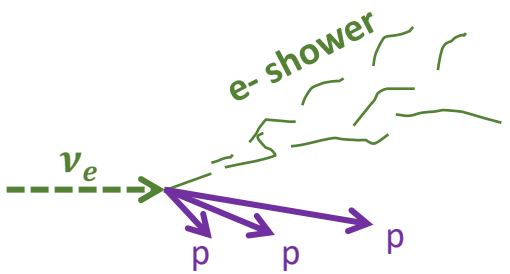
Details see Andrew Morgan's talk on Monday's parallel session @4pm



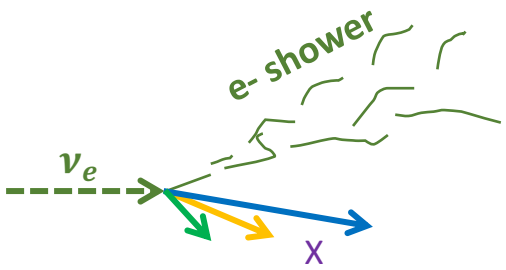
1e + 1 proton

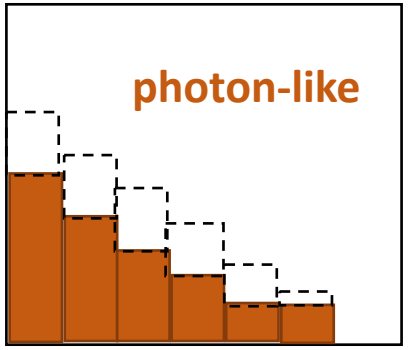


1 e + N proton

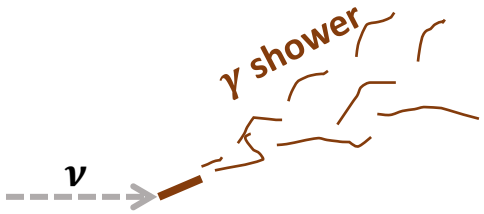


1 e + anything

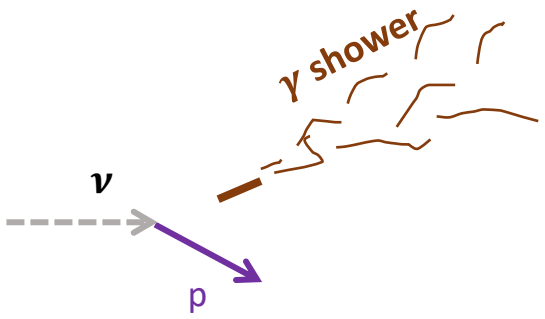




1γ + 0 proton



1γ + 1 proton



Two types of analysis defined by the final state event topologies:

- Electron-like: searching for LEE in the ν_e channel
- Photon-like: searching for LEE in the photon channel

Blind analysis procedure, four independent analysis teams to minimize bias.

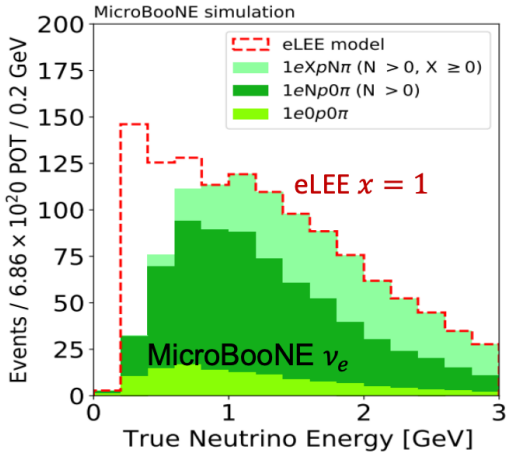
ν_e low-Energy Excess (eLEE) search

Signal model

Empirical signal model assuming MiniBooNE LEE events are entirely electron neutrinos;

See details here: [MICROBOONE-NOTE-1043-PUB]

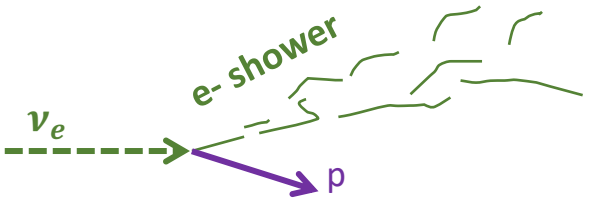
Empirical eLEE model derived from MiniBooNE



3 independent eLEE analyses

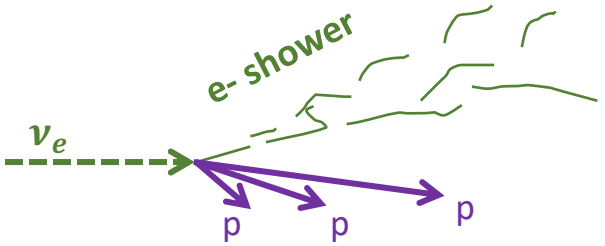
- Different final states
- Different event reconstruction and selection techniques;
- Blind analysis, sensitivity studied with Mock data

1e + 1 proton



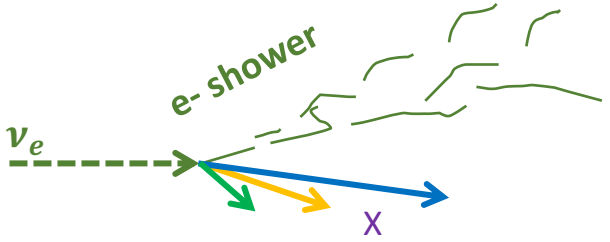
Deep Learning
Simple topology
Simpler E_ν reco (CCQE)
Lower backgrounds

1 e + N proton



Pandora
Larger signal stat.
Less model dependency
MiniBooNE topology

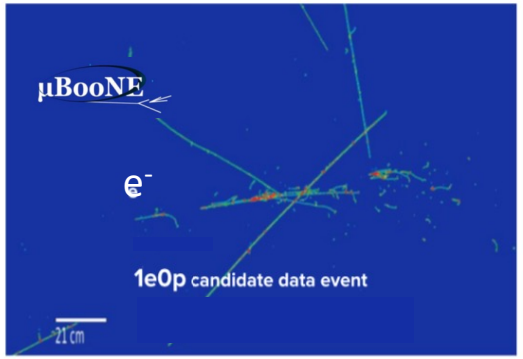
1 e + anything



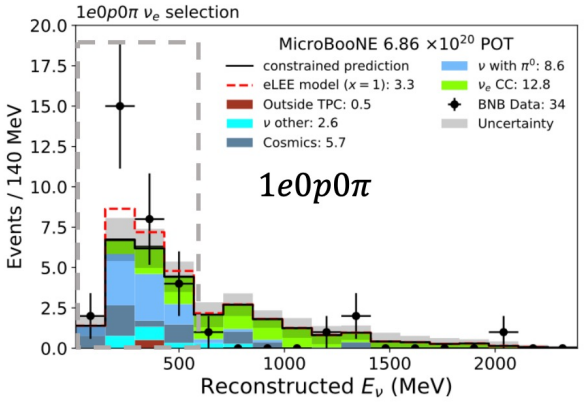
Wirecell
Inclusive -> sensitive
Less model dependency
Most useful for DUNE

eLEE signal events and energy spectra

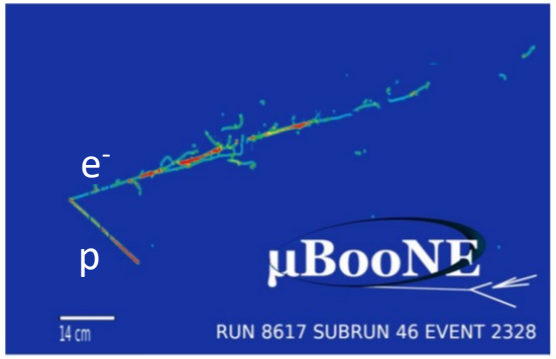
1e0p candidate



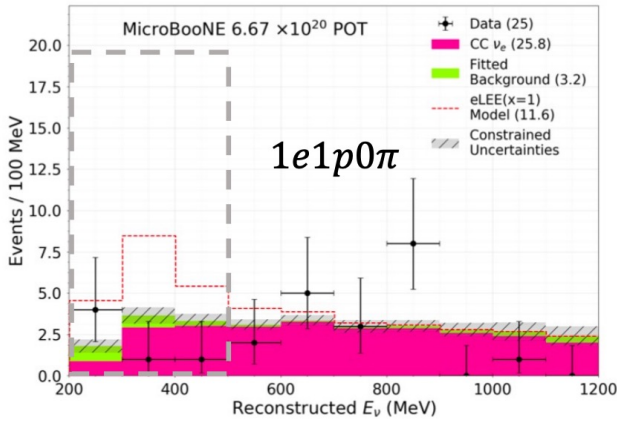
Eff./purity: 9%/43%
Phys. Rev. D105, 112004 (2022)



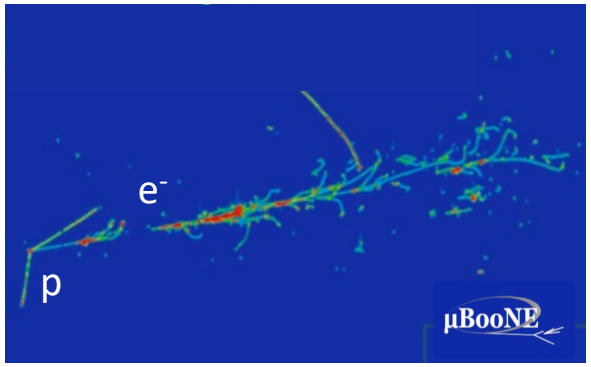
1e1p candidate



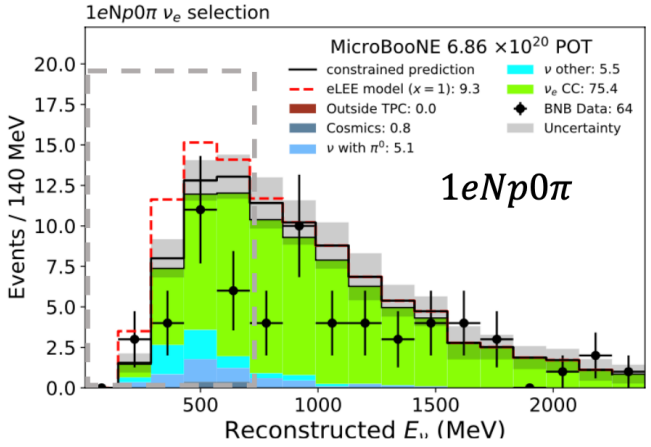
Eff./purity: 7%/75%
Phys. Rev. D105, 112003 (2022)



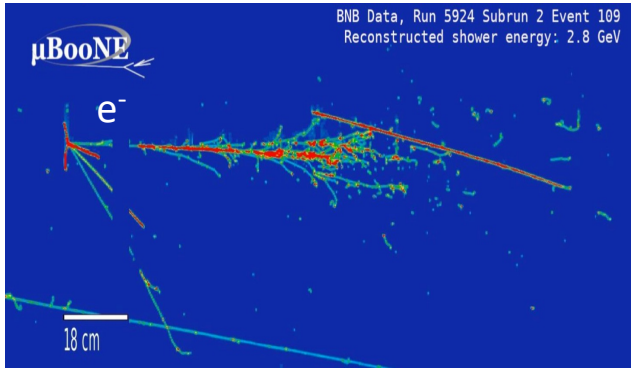
1eNp candidate



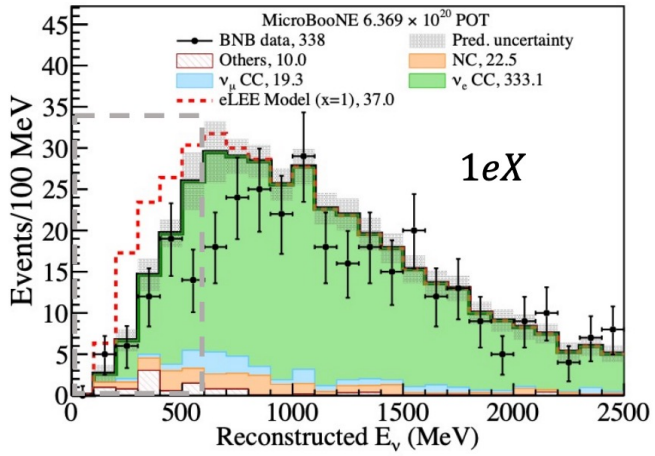
Eff./purity: 15%/80%
Phys. Rev. D105, 112004 (2022)



1eX candidate

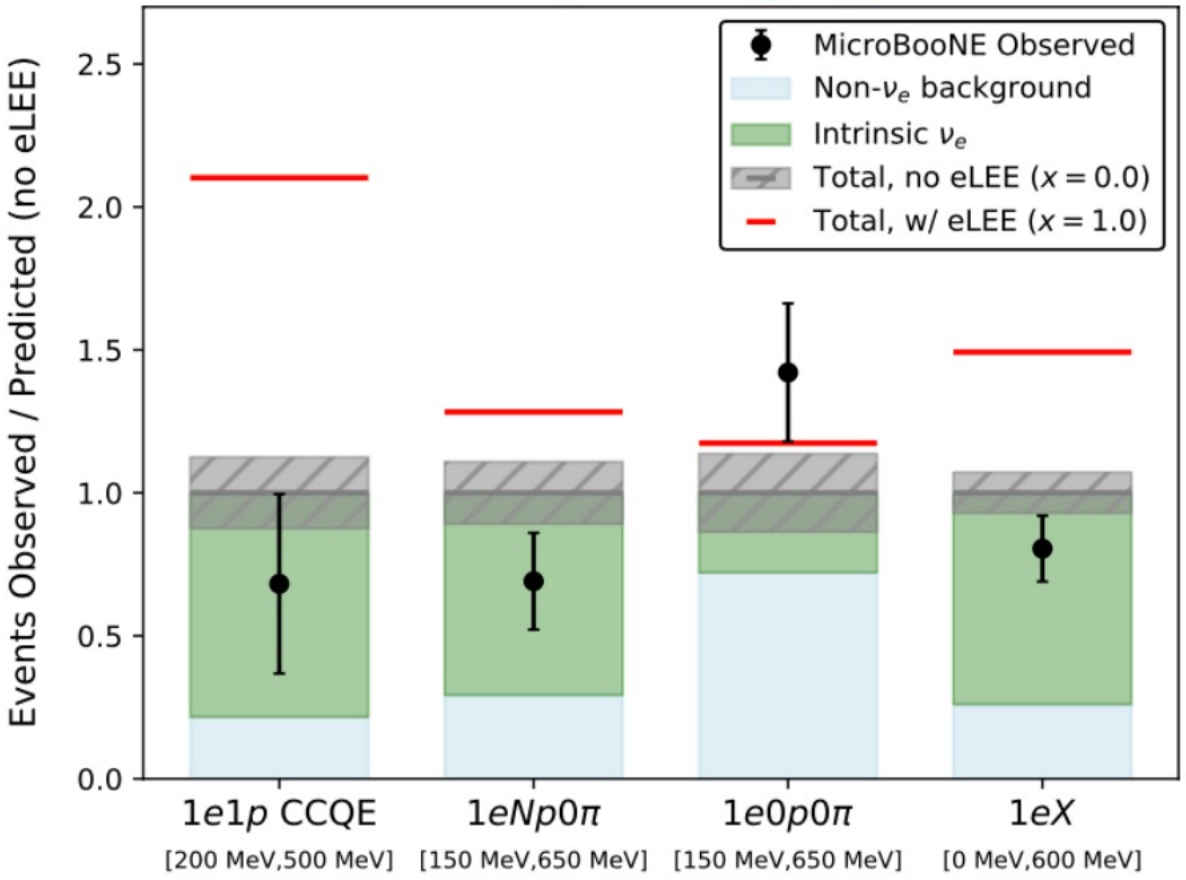


Eff./purity: 46%/82%
Phys. Rev. D105, 112005 (2022)



eLEE search result

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



ν_e unlikely to fully explain the MiniBooNE excess!

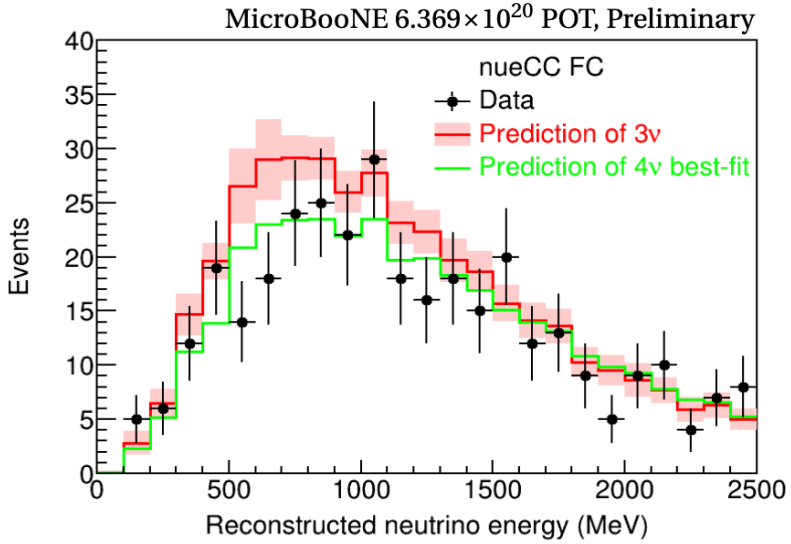
Observed ν_e candidate rates are statistically consistent with the predicted background rates in the LEE region:

- Slight data deficit overall
- 1e0p least sensitive, background dominated

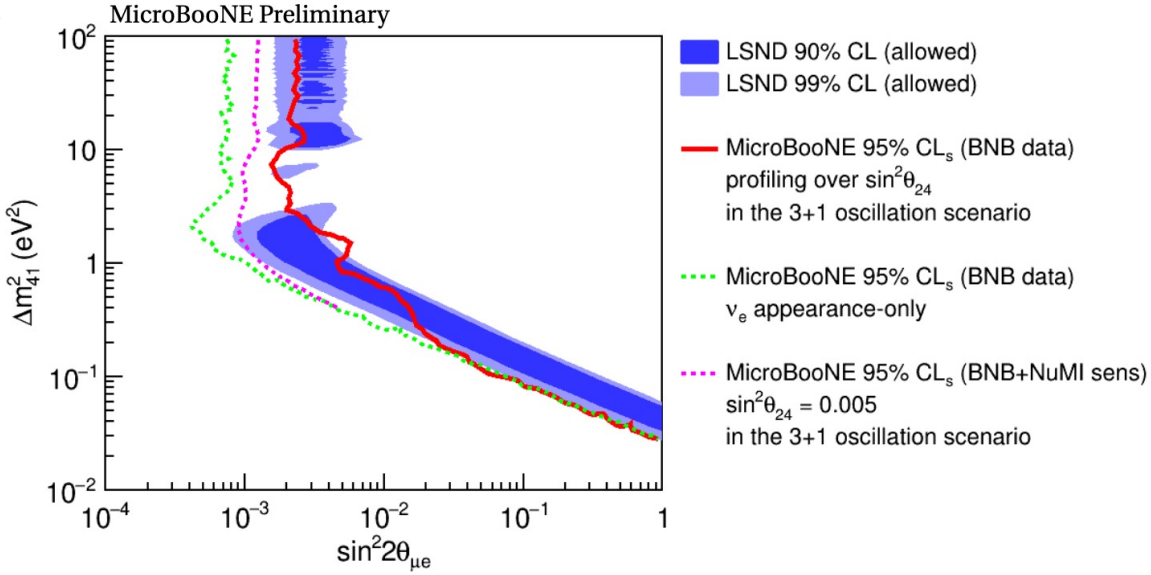
The hypothesis that ν_e events are fully responsible for the median MiniBooNE LEE is rejected at 97% C.L;
>3σ in the inclusive channel

3+1 sterile neutrino search

The selection used for eLEE search can be reinterpreted to test the hypothesis of an extra eV-scale sterile neutrino



With the inclusive ν_e (i.e. 1e+X) selection, a 3+1 oscillation fit framework is developed to search for ν_μ disappearance, ν_e appearance, and ν_e disappearance.



Details on excluding 3+1 sterile neutrino parameter space can be found in MicroBooNE's recent public note: MICROBOONE-NOTE-1116-PUB. Preliminary results using CCQE selection is documented in MICROBOONE-NOTE-1106-PUB and MICROBOONE-NOTE-1105-PUB.

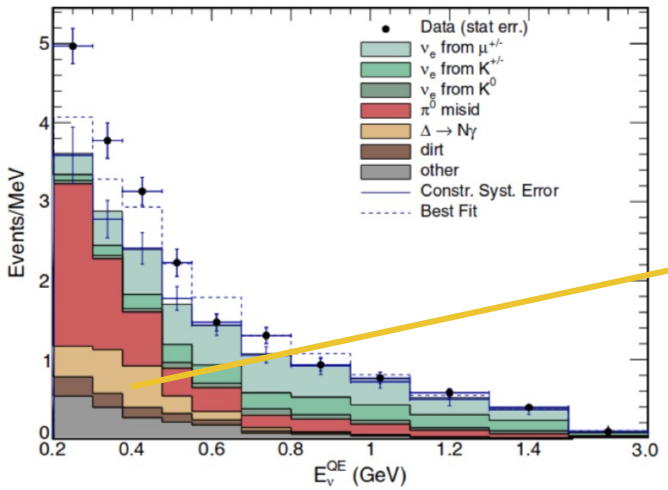
Future analysis developments include using full MicroBooNE dataset and combined analysis with BNB and NuMI data for increased sensitivity, coming soon!

Photon LEE search: Δ radiative decay

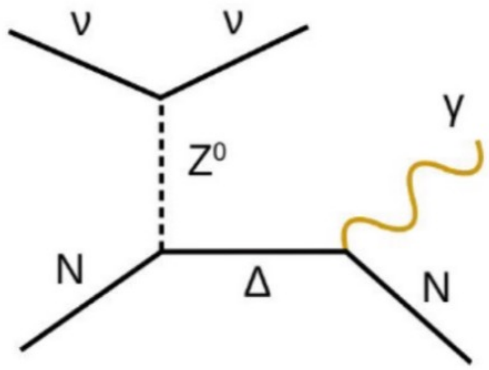
One contributor to the MiniBooNE signal channel is NC $\Delta\rightarrow N\gamma$

A flat factor of 3.18 enhancement of the SM rate of this channel would match the MiniBooNE LEE

MiniBooNE, PRL **121**, 221801 (2018)



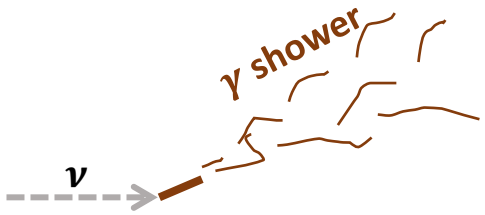
NC $\Delta\rightarrow N\gamma$



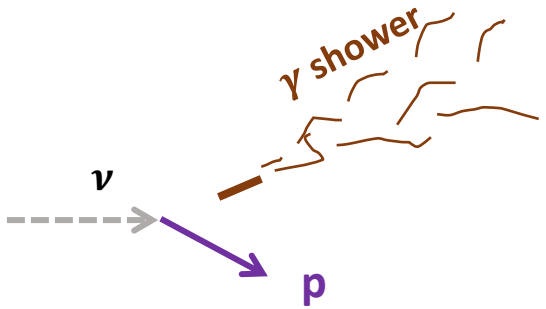
NC $\Delta\rightarrow N\gamma$ is Standard Model process

- Rare, 0.6% branching ratio
- Never been directly observed in neutrino scattering

1γ + 0 proton



1γ + 1 proton



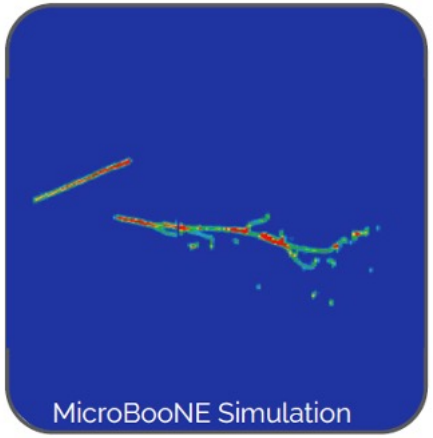
NC $\Delta\rightarrow N\gamma$ signal can manifest to two event topologies:

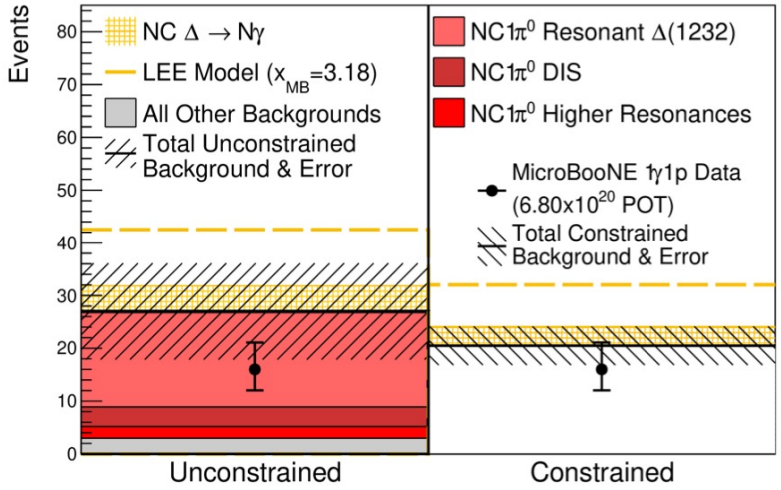
- single photon without proton (N is neutron)
- single photon with one proton (N is proton)

Photon LEE (NC $\Delta\rightarrow N\gamma$) search result

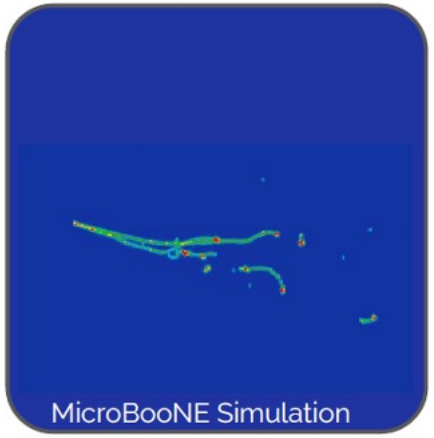
[Phys. Rev. Lett. 128, 111801 (2022)]

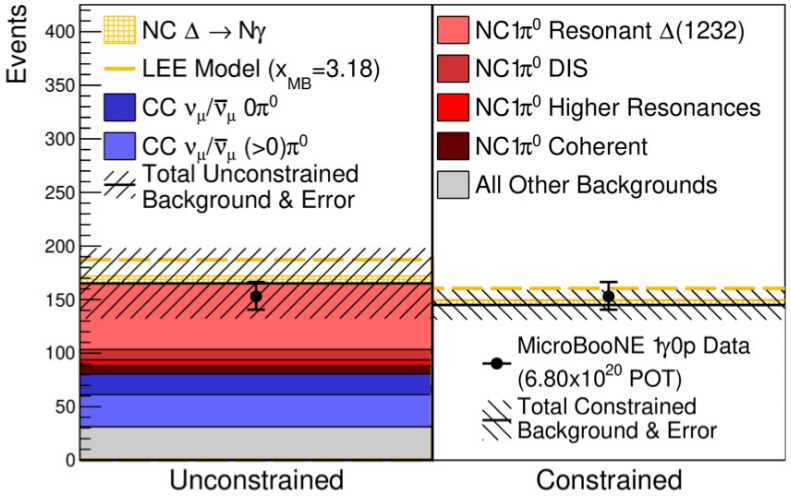
$1\gamma 1p$





$1\gamma 0p$





Analysis

- One-bin analysis
- Use NCπ^0 rich 2γ selection to provide data-driven background constraint

Result

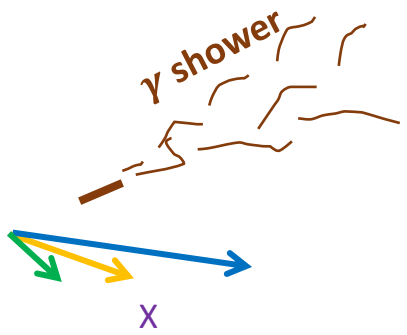
- Observed no data excess in both NC $\Delta\rightarrow N\gamma$ signal channels
- Disfavor NC $\Delta\rightarrow N\gamma$ induced single-photon as a sole source of the MiniBooNE excess
- Set a new best limit of $\Delta\rightarrow N\gamma$ rate (x2.3 SM prediction at 90% C.L.), 50-fold improvement over previous T2K limit in the sub-GeV neutrino range.

NC $\Delta\rightarrow N\gamma$ unlikely the explanation of MiniBooNE excess!

Further LEE investigations in MicroBooNE

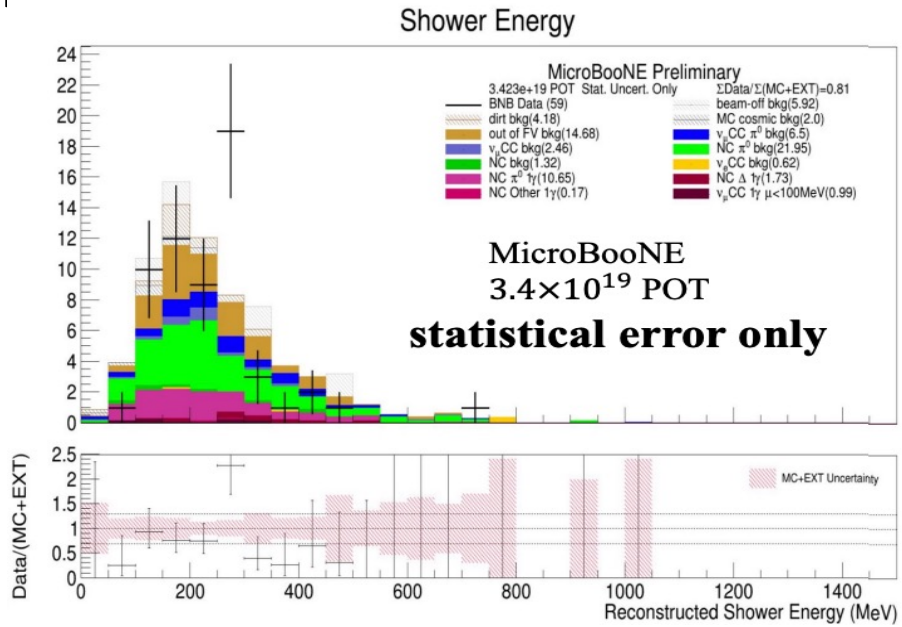
- 1st round of LEE analyses searched for anomaly in ν_e channel and NC $\Delta \rightarrow N\gamma$, no excess has been observed.
- The origin of MiniBooNE LEE is still unknown, and we have not ruled out the possibility of the excess in all the photon-like channels.
- Next immediate question: Do we see an excess in the inclusive photon-like channel?

LEE search
Inclusive photon channel
$(1\gamma + \mathrm{X})$



What physics process can fit in this Signal definition?

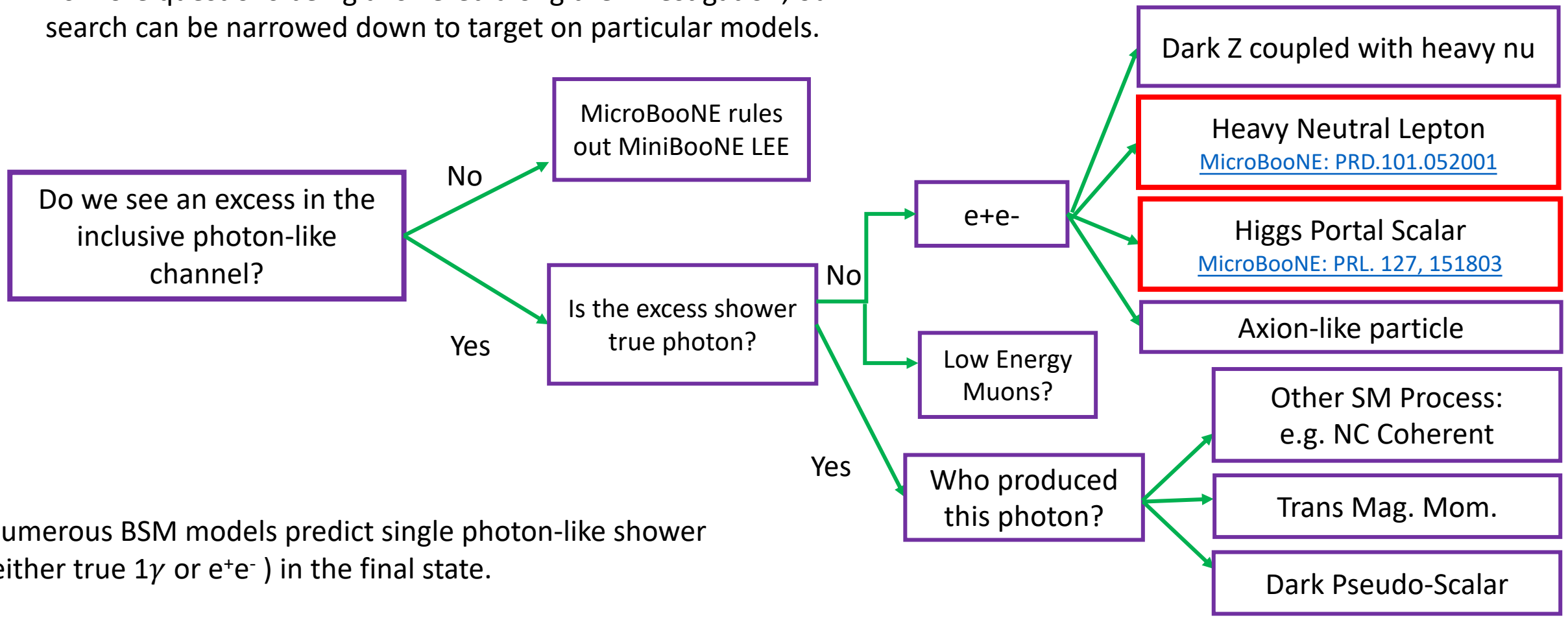
- NC$\pi^0 \rightarrow \gamma\gamma$ with only one visible γ (i.e. escape detector, below detection threshold...)
- Higher resonant radiative decay
- NC coherent
- BSM induced γ or e+e- (collimated) in the final state
- ...



Details of event selection for the LEE search in the inclusive photon channel is:
MICROBOONE-NOTE-1102-PUB

Further LEE investigations in MicroBooNE

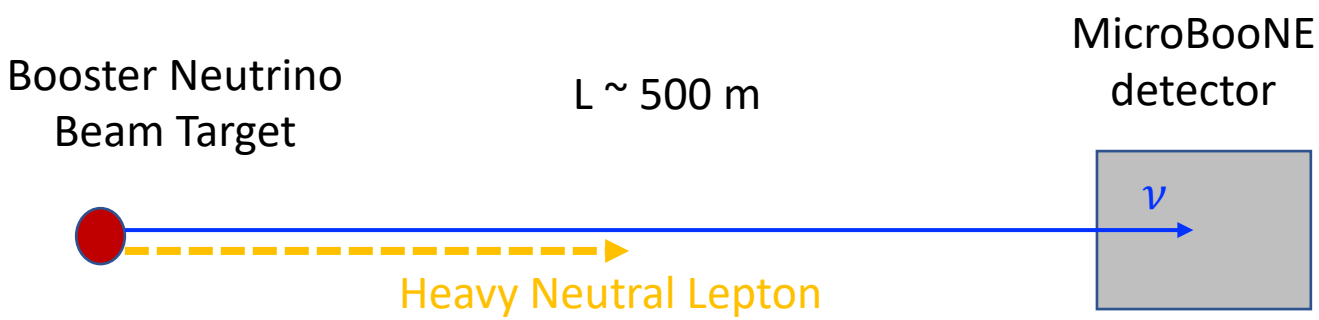
As more questions being answered along the investigation, our LEE search can be narrowed down to target on particular models.



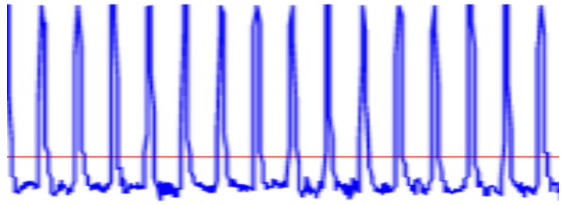
Numerous BSM models predict single photon-like shower (either true 1γ or e^+e^-) in the final state.

Dedicated BSM searches are conducted in MicroBooNE, offering competitive sensitivities in the sub-GeV range.
See Pawel Guzowski's talk (Monday @ 16:20) for exciting progress of BSM searches in MicroBooNE!

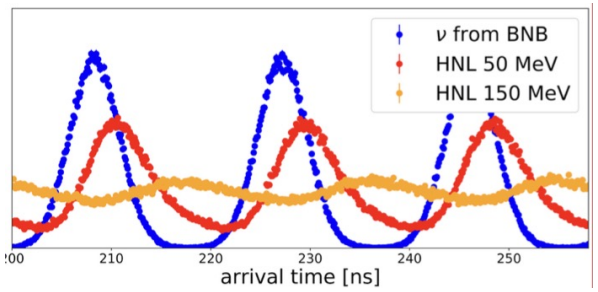
BSM searches with ns timing



BNB time structure

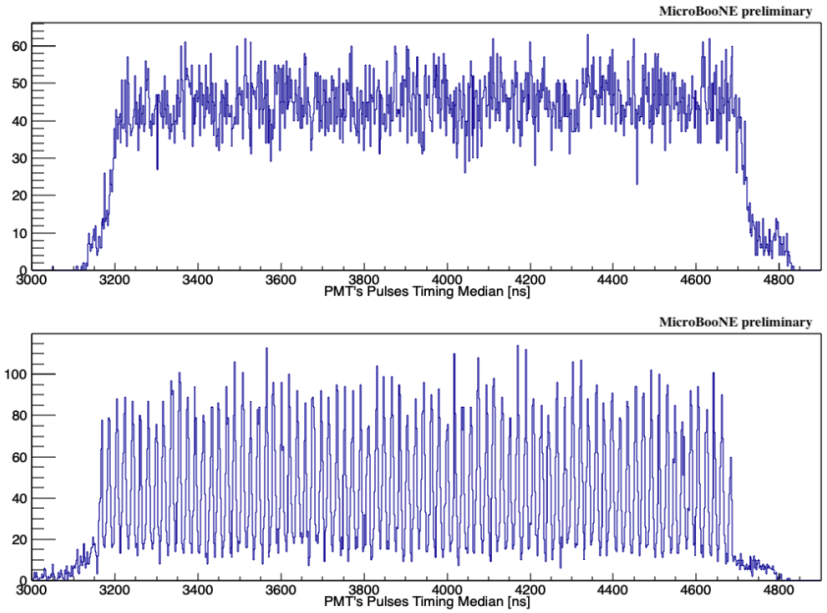


Neutrinos are produced in 2ns bucket with 18ns spacing between bucket



Massive BSM particles, if produced at the target at the same time as neutrinos, will arrive at the detector later than neutrinos due to heavier mass.

Neutrino interactions are the most common background for BSM searches. This difference of arrival time offers an effective handle for neutrino background rejection, only if nanosecond timing resolution is achieved.



MicroBooNE recently improved timing resolution from O(100) to O(1) ns. Details can be found in [MICROBOONE-NOTE-1115-PUB]

Summary & Outlook

1. MicroBooNE recently published its 1st round of LEE result
   - No excess observed in the nue channel
   - No excess observed in the NC $\Delta \rightarrow N\gamma$ channel

2. Continuous investigation on MiniBooNE LEE are progressing:
   - 3+1 sterile neutrino fit
   - Dedicated BSM searches (e.g. HNLs, Higgs Portal Scaler results) with final states of e^+e^- and single photon.

3. With the largest ν-Ar interaction dataset from a neutrino experiment, MicroBooNE has been pioneering LArTPC detector technology and providing critical cross-section measurements for future neutrino oscillation projects such as SBN and DUNE.

Thank you!