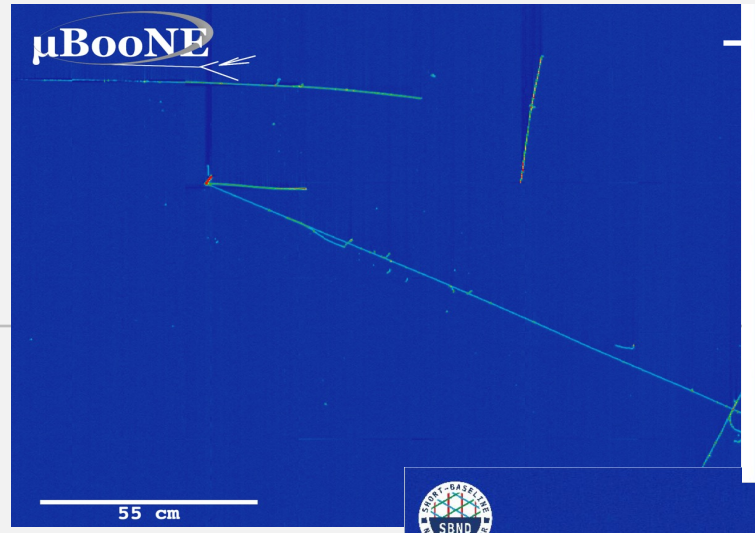
Standard Model and Beyond

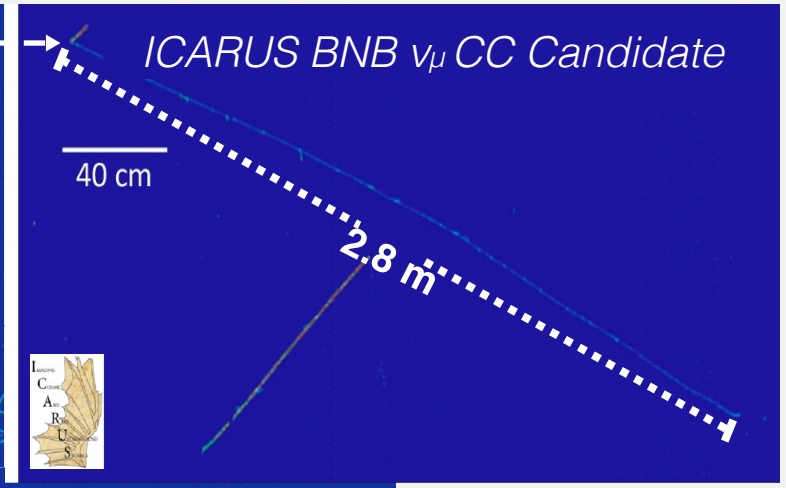
21-23 October 2022
Katowice
Europe/Warsaw timezone

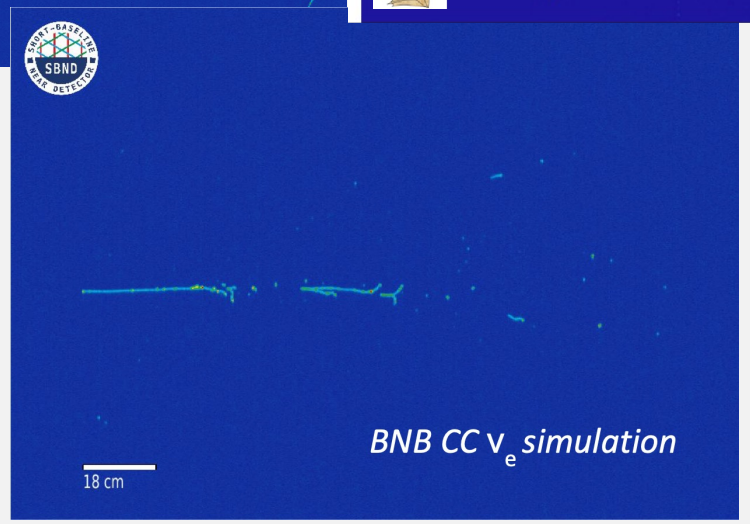
Short-baseline program at Fermilab

Jaroslaw Nowak

for the SBN Collaborations







Lancaster University

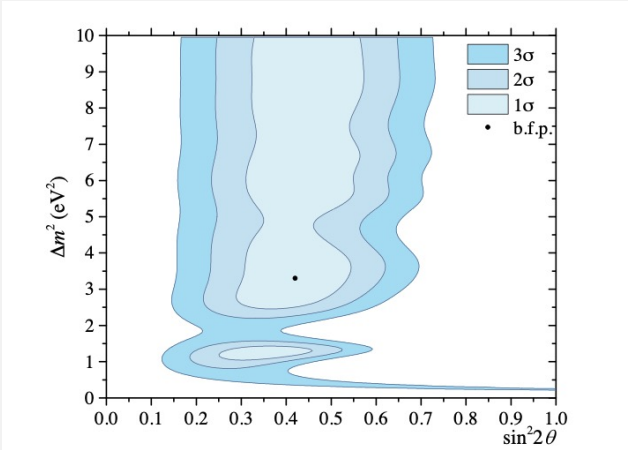
Short-baseline results

BEST Phys. Rev. Lett. **128**, 232501

The 3-(active)ν oscillation parameters have been measured with excellent precision by many experiments.

But questions remains un-answered:

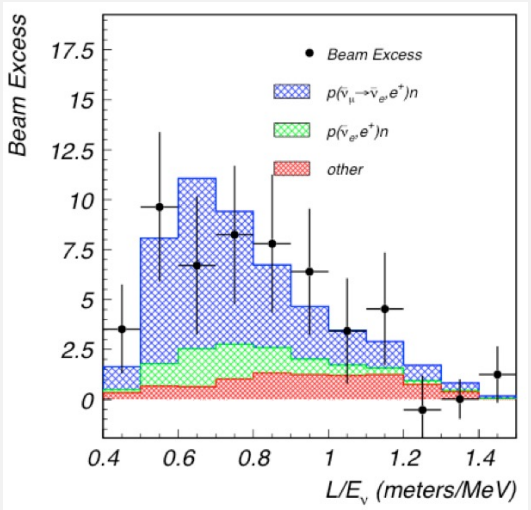
- Are these active neutrinos their own anti-particle **(Majorana)?**
  - Jointly with δ_{CP} they could answer the matter/anti-matter asymmetry.
- Do more exotic **right-handle neutrinos (sterile)** exist **?**

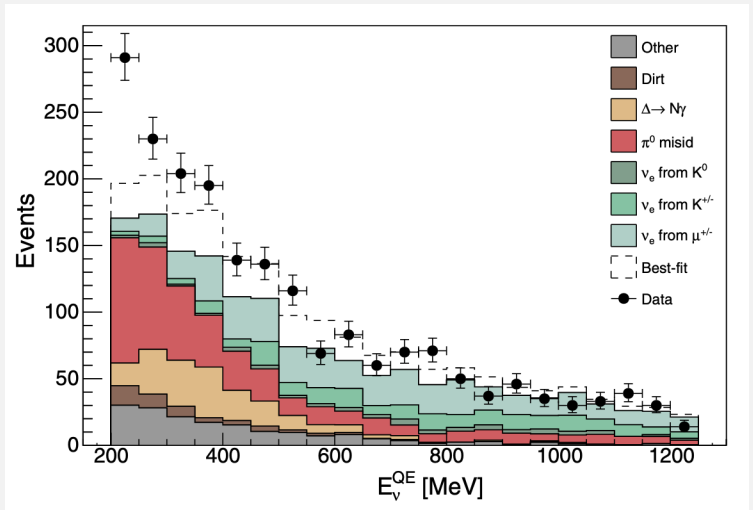


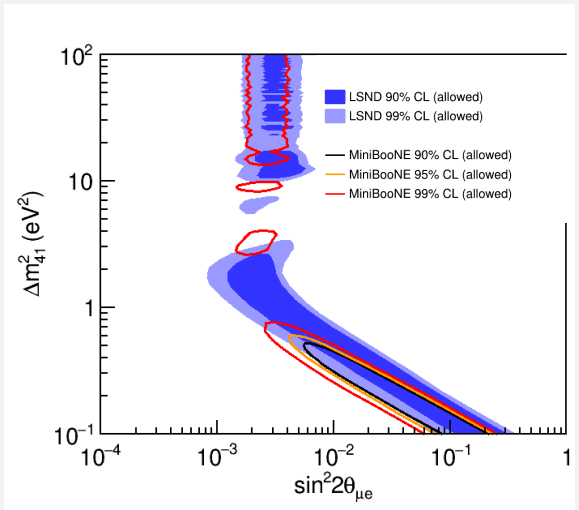
Observed experimental anomalies motivate the search of sterile neutrinos.

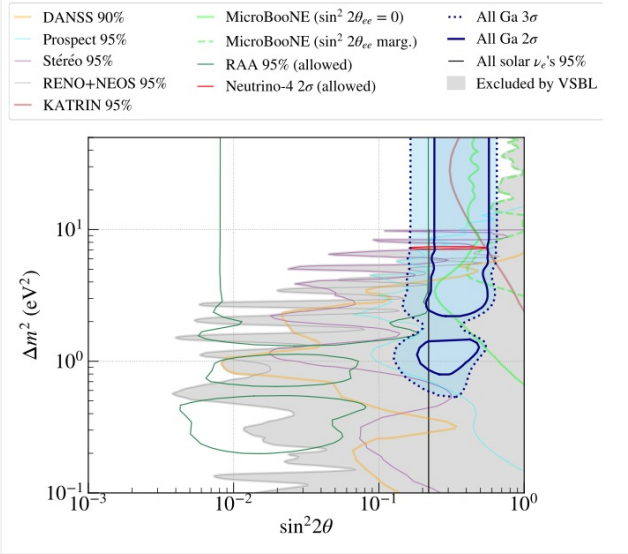
LSND
Phys. Rev. D **64**, 112007

MiniBooNE
PHYS. REV. D 103, 052002 (2021)







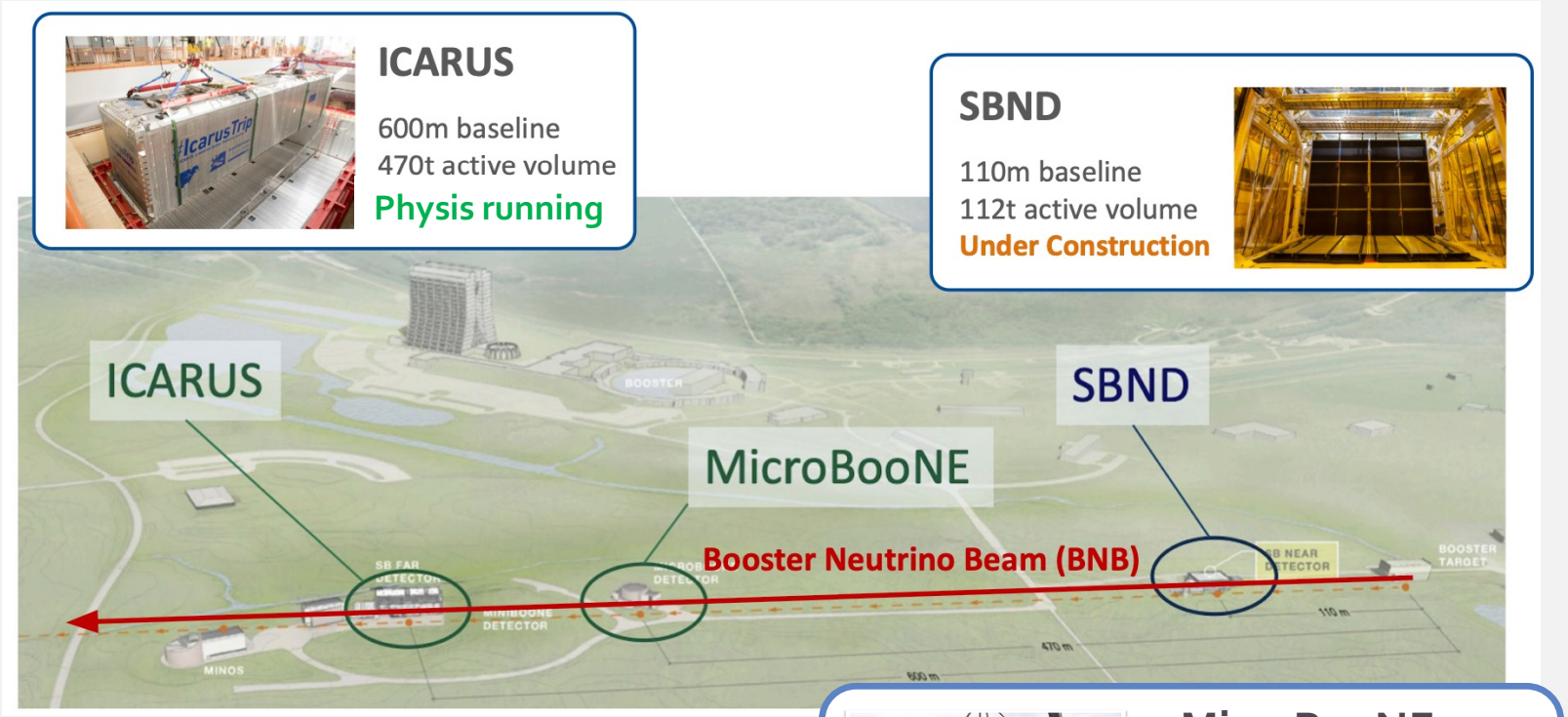


- If interpreted as ν_e appearance through a two-flavour neutrino oscillation, best fit $\Delta m^2 = 0.04$ eV^2

The Short Baseline Neutrino Program at Fermilab

The role of SBN is to perform a robust measurement in the search of sterile neutrinos,

while also provides a broad spectrum of other new physics beyond the standard model.

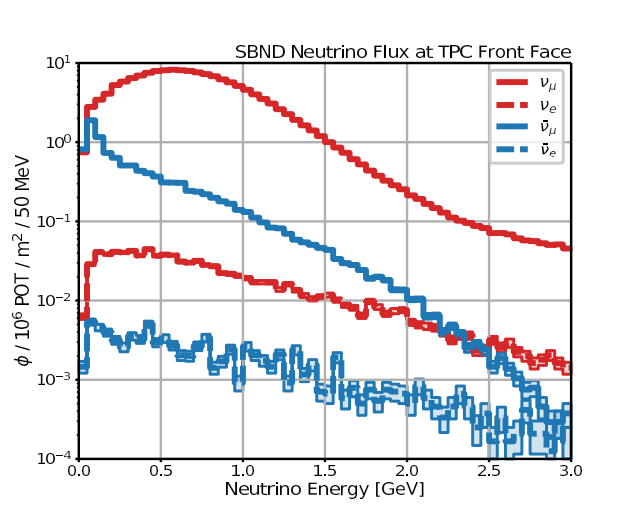


Our strategy to reduce uncertainties:

- Three detectors sampling the same neutrino beam at different distances (BNB)
- Same nuclear target (Ar) and detector technology (LArTPC: liquid argon time projection chambers)

Two Neutrino fluxes

- All SBN detectors are on-axis for the Booster Neutrino Beam



Neutrino flux at the SBND front face.

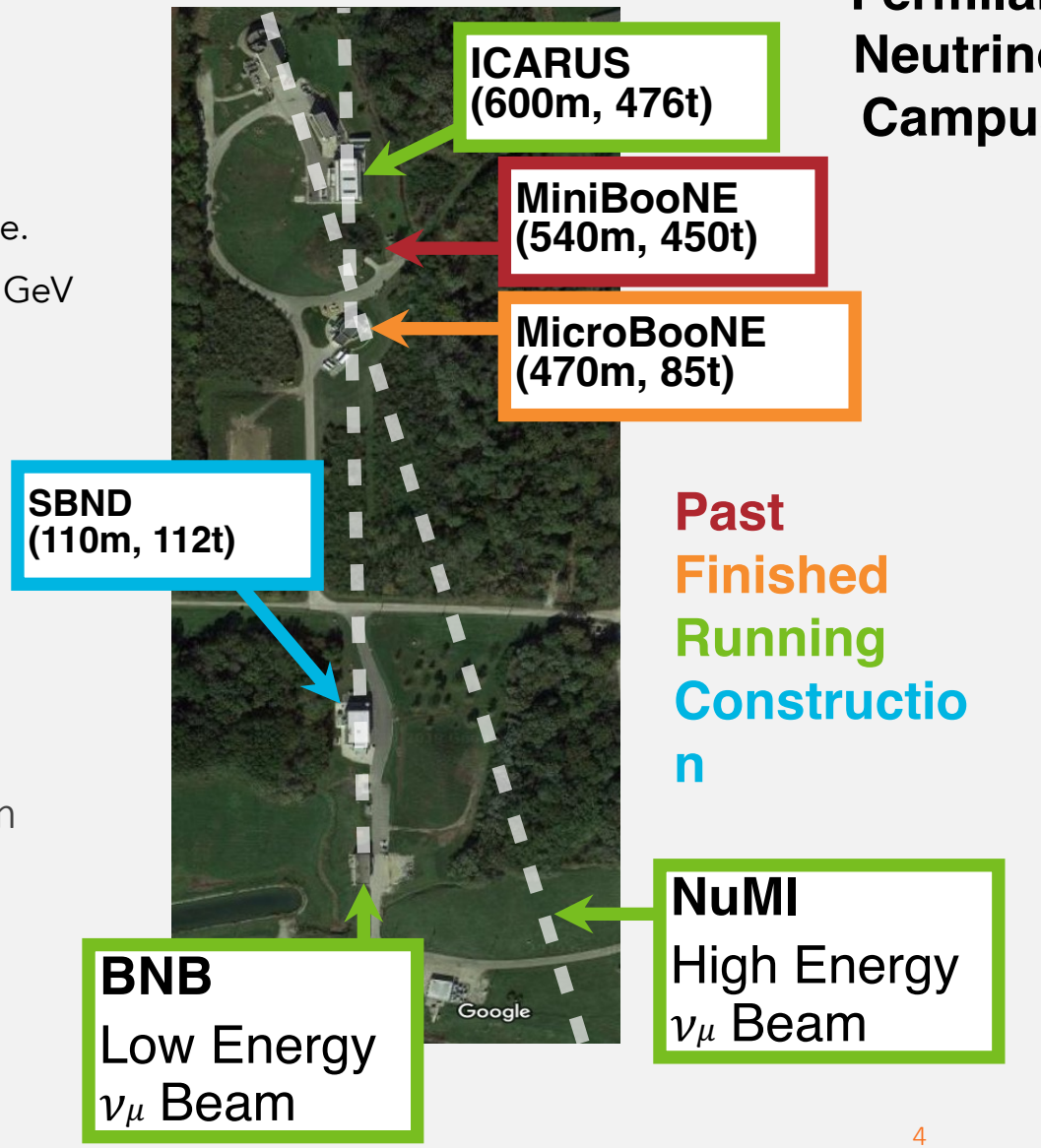
Mean muon-neutrino energy: ~0.8 GeV

Beam composition:

ν_μ (93.6%)

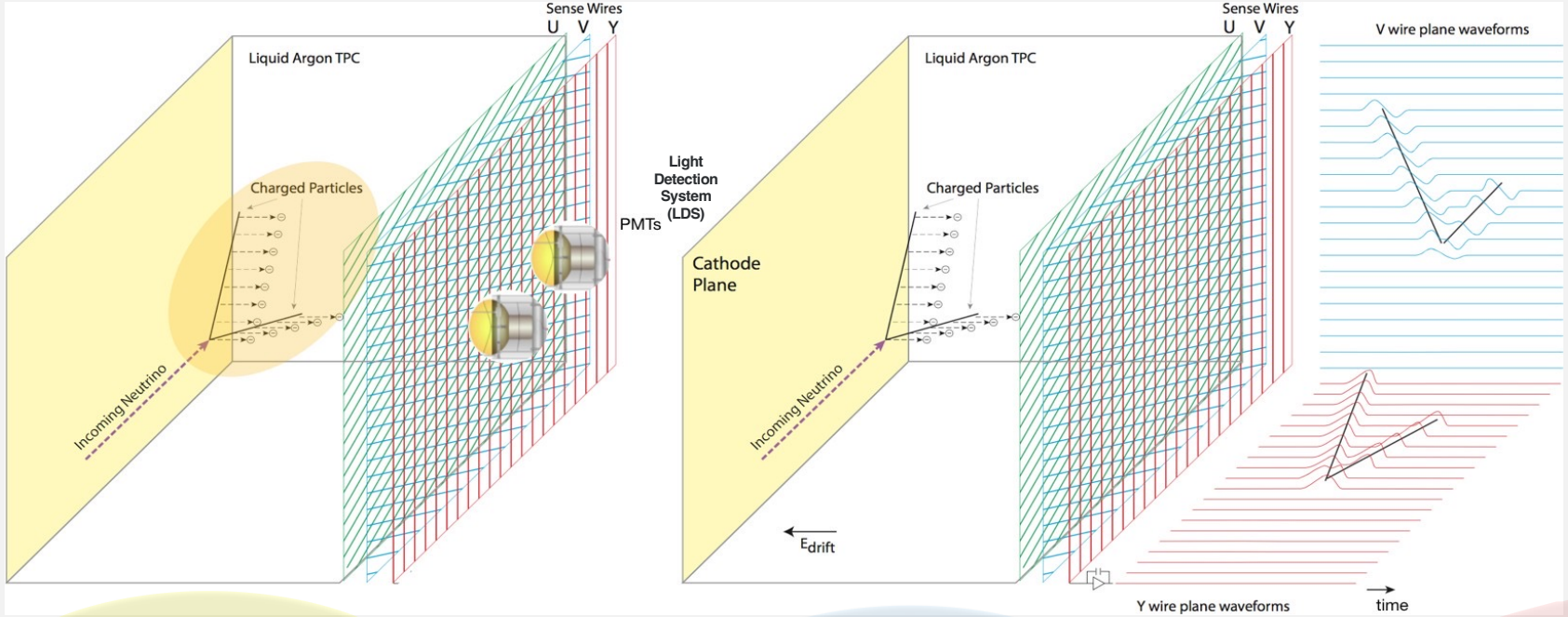
$\bar{\nu}_\mu$ (5.9%)

ν_e+$\bar{\nu}_e$ (0.5%)



- Each of the detector is at different off-axis angle for the NuMI beam
  - Different compositions of the beam (ν_μ/ν_e)
  - Different energies of neutrinos

LArTPC at work



- 3D reconstruction with **mm resolution.**
- Excellent **particle identification** with dE/dx information.
- **Low energy thresholds**, sub-MeV to GeV.

Charged particles in LAr produce free ionization electrons and scintillation light

Ionization charge drifts in a uniform electric field towards the readout wire-planes

Digitized signals from the wires are collected [*time of the wire pulses gives the drift coordinate of the track and amplitude gives the deposited charge*]

m.i.p. at 500 V/cm: ~ 60,000 e/cm
~ 50,000 photons/cm

Electron drift time ~ ms

VUV photons propagate and are shifted into VIS photons

Scintillation light fast signals from LDSs give event timing

Data taking in 2023!

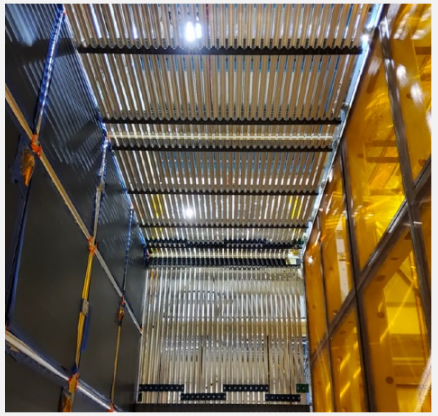
Near Detector: SBND

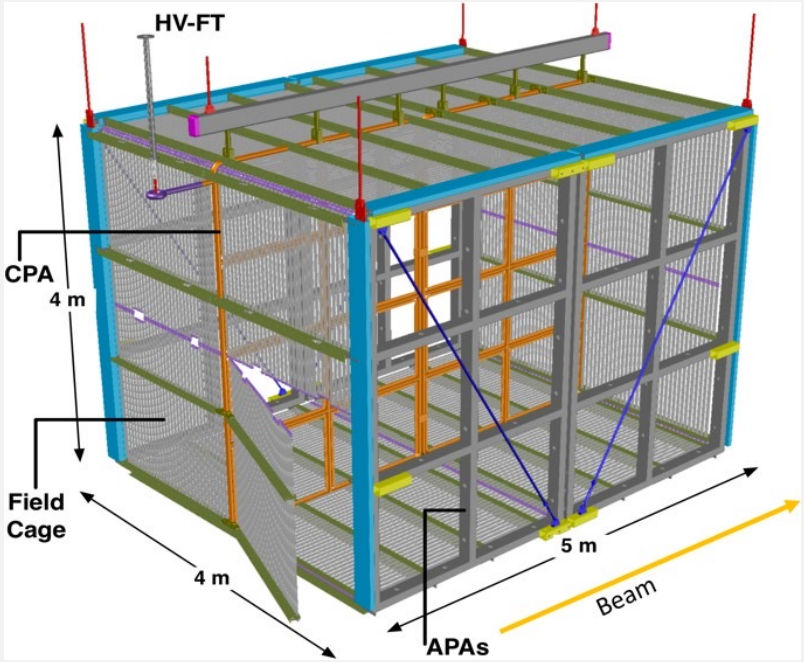
Short-Baseline Near Detector being assembled at Fermilab

Two TPCs ***112 tons of LAr***

HV feedthrough

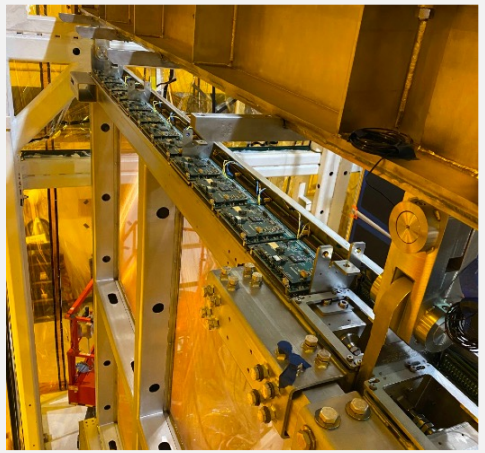
16 field shaping panels





11k wires across two planes

Cold electronics reduce noise



Cathode fitted w/ reflectors

High light collection eff

MicroBooNE detector

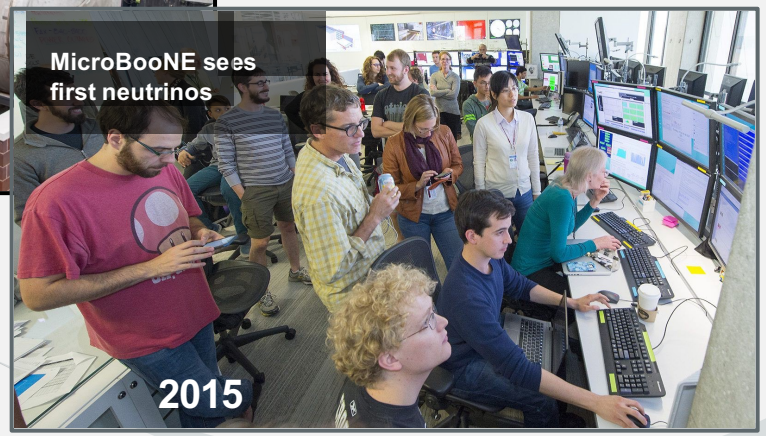
Proposal: 2007 *(addendum, 2008)*

Construction: 2010-2012

Installation & Commissioning: 2012-2015

Operations: 2015-2020

R&D Phase: 2021



More than 50 publications within the last 5 years

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

More than 50 PhDs traning experts in LArTPC technology

Detector shutdown: 2022

Physics data analysis continues…

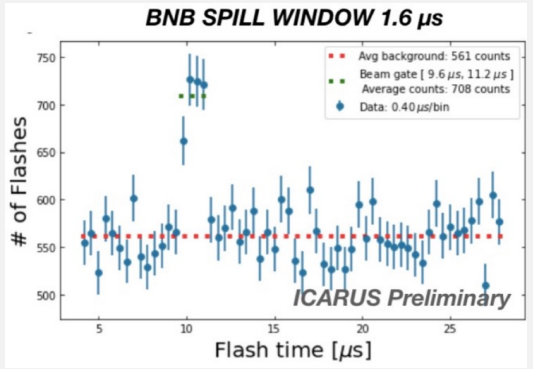
Far Detector: ICARUS

TPC and PMTs
(2 out of 4 TPCs)

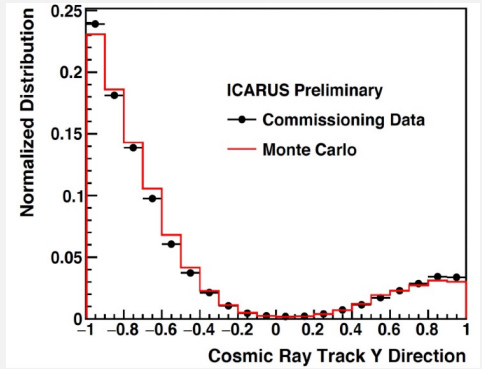
Cosmic Taggers

3 m Overburden

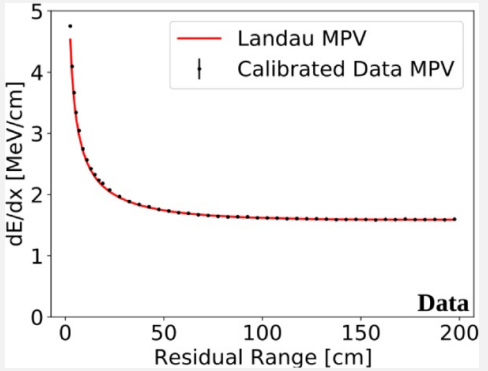
- ICARUS was originally deployed in Gran Sasso and exposed to the LGNS beam before moving to CERN to be refurbished for its run at Fermilab.
- Data taking started fall 2020, with stable noise & electron lifetime (>3 ms)



Commissioning

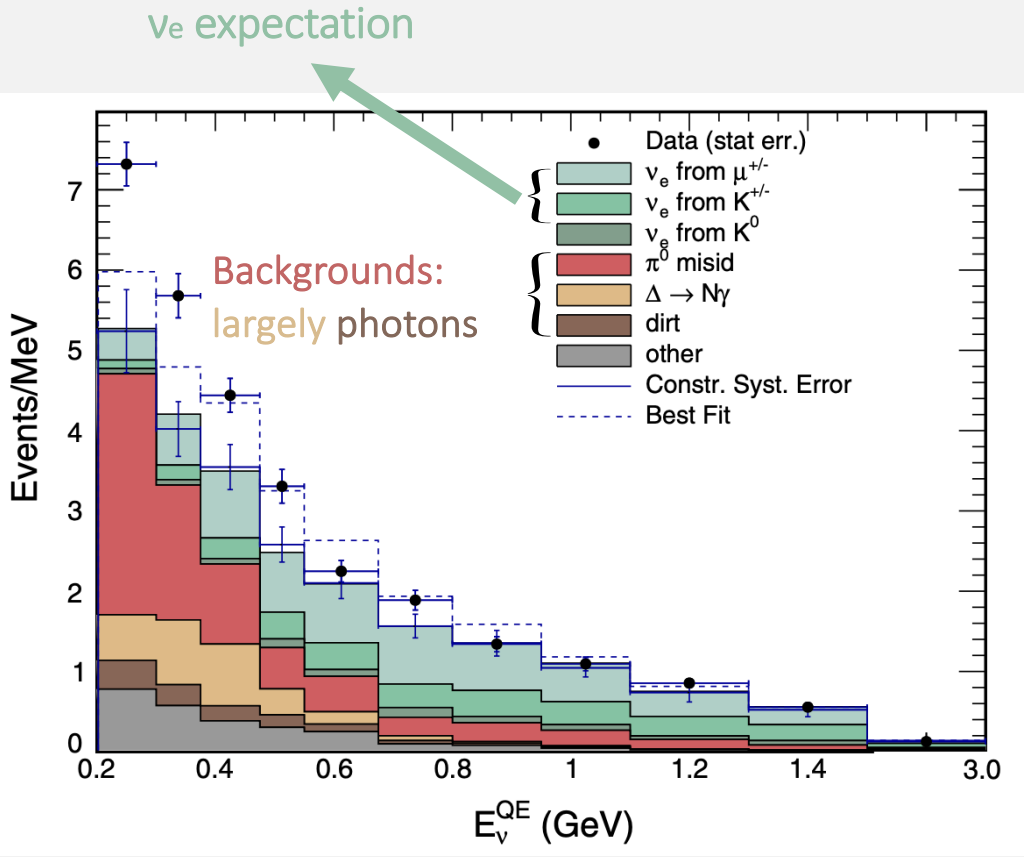


Data-to-MC Comparisons



Calibrations

The MiniBooNE low-energy excess (LEE)

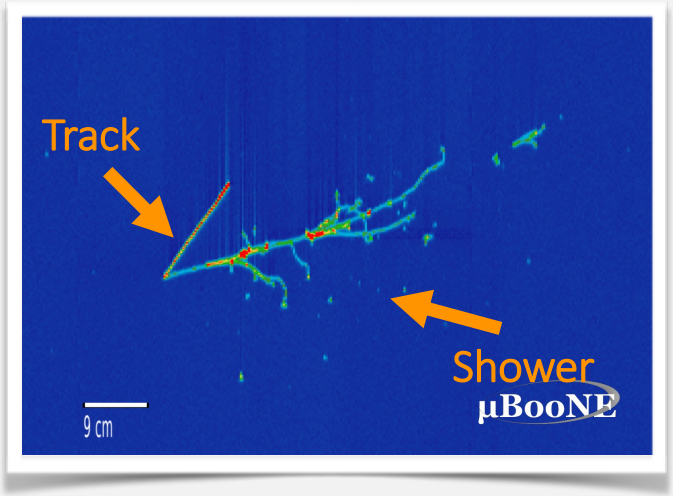


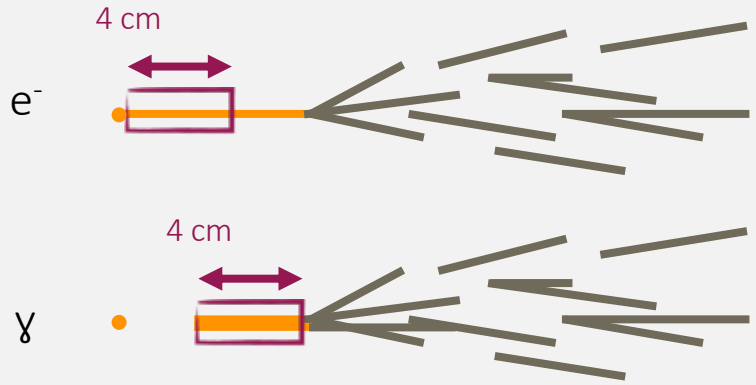
- 4.8σ excess of measured ν_e and $\bar{\nu}_e$ over prediction, focused at low energy
- Consistent with prior results from the LSND experiment: combined significance of 6.1σ
- Source of excess not known:
  - could be ν_e
  - photons look identical to electrons in MiniBooNE detector
  - or something else?

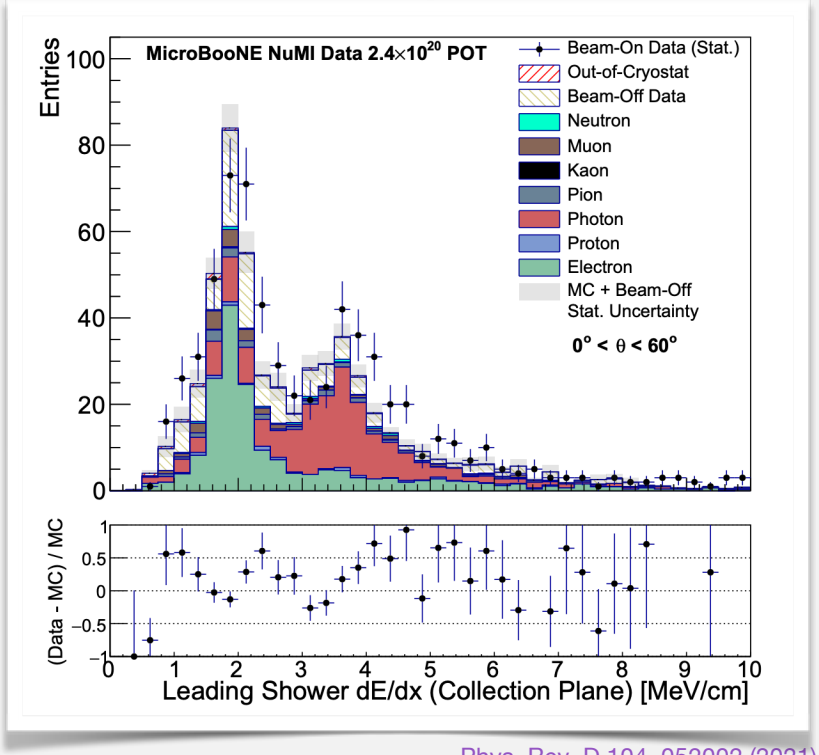
Phys. Rev. D 103, 052002

LArTPC STRENGTH: electrons and photons

- Electrons and photons produce showers in LArTPCs
- Distinguish using dE/dx at start of shower and start point







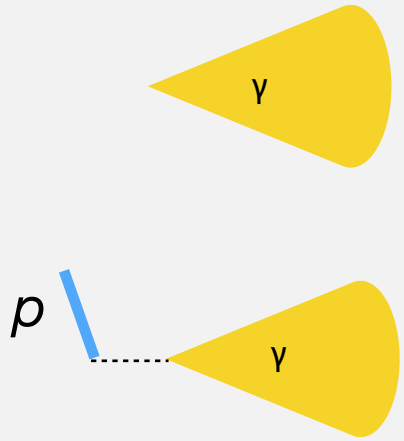
Phys. Rev. D 104, 052002 (2021)

MicroBooNE first investigation of the MiniBooNE low-energy excess

Photon search

Target Δ→Nɣ:

1ɣ0p and 1ɣ1p



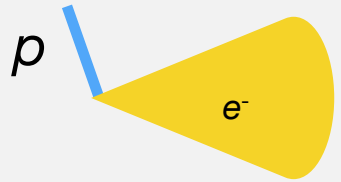
Phys. Rev. Lett. 128, 111801

Phys. Rev. Lett. 128, 241801

Electron searches

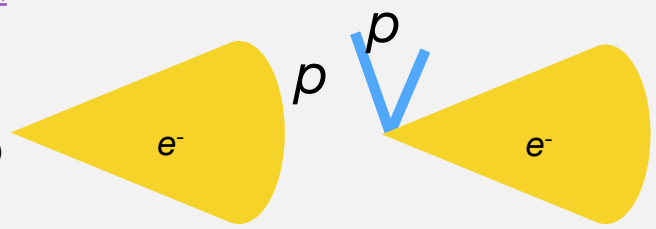
Phys. Rev. D 105, 112003

CCQE-like: 1e1p



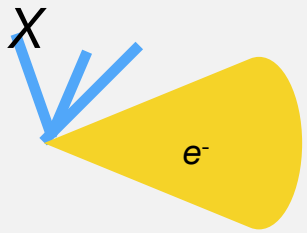
Phys. Rev. D 105, 112004

CC0π:
1e0p and 1eNp



Phys. Rev. D 105, 112005

Inclusive: 1eX

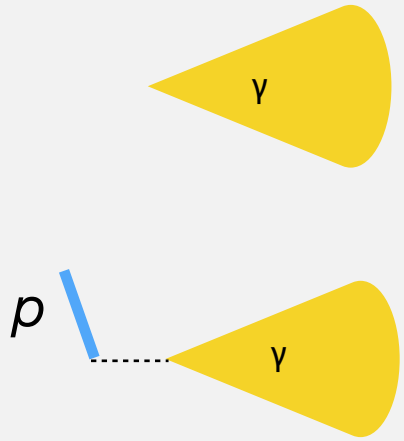


First investigation of the MiniBooNE low-energy excess

Photon search

Target Δ→Nɣ:

1ɣ0p and 1ɣ1p



Phys. Rev. Lett. 128, 111801

Phys. Rev. Lett. 128, 241801

Electron searches

Phys. Rev. D 105, 112003

CCQE-like: 1e1p

Phys. Rev. D 105, 112004

CC0π: 1e0p and 1eNp

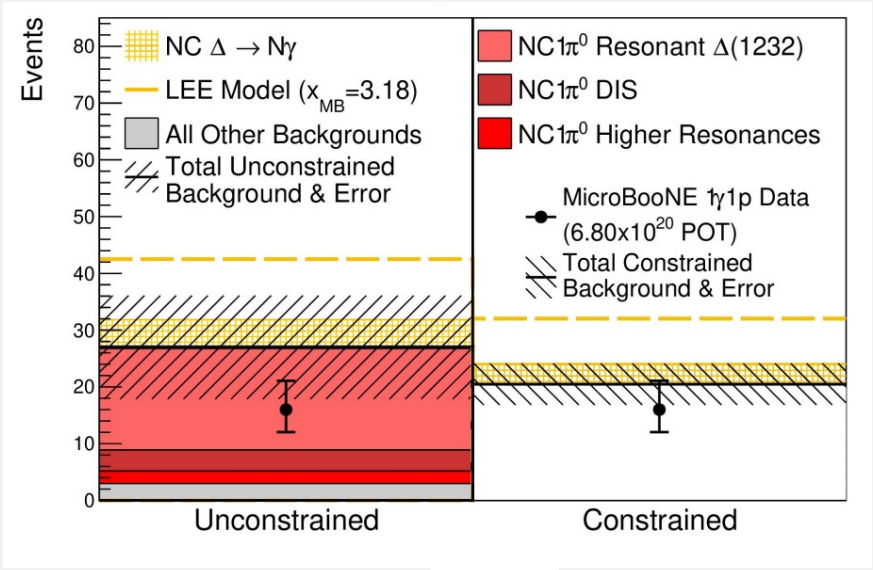
Phys. Rev. D 105, 112005

Inclusive: 1eX

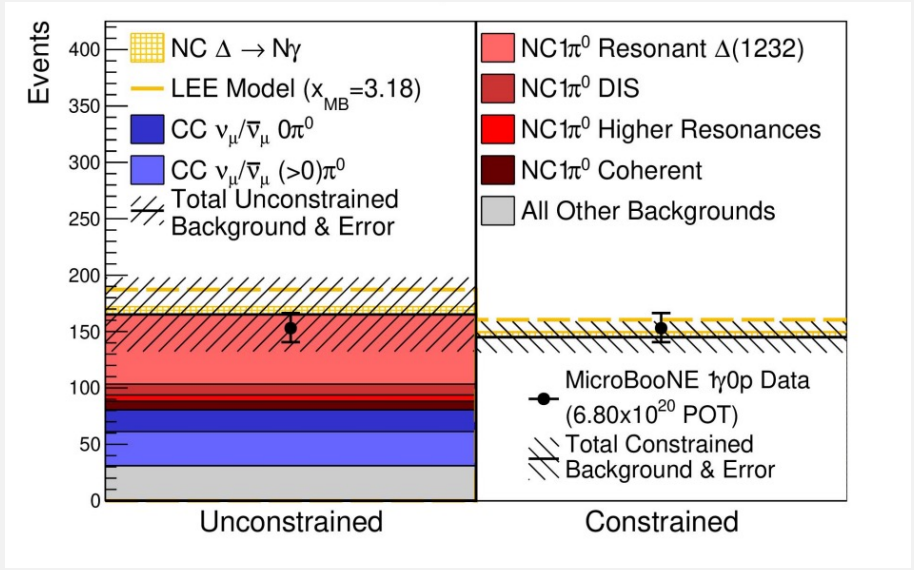
NC-Δ single photon search

Phys. Rev. Lett. 128, 111801

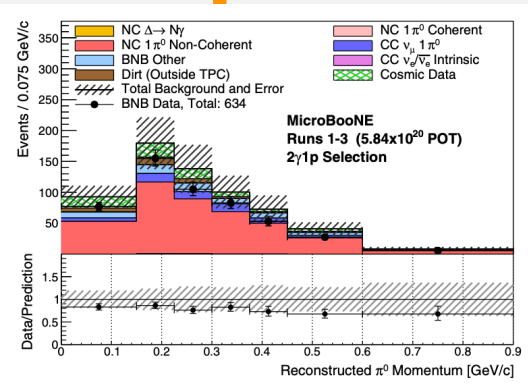
π^0-rich sample → constraint on backgrounds in signal region



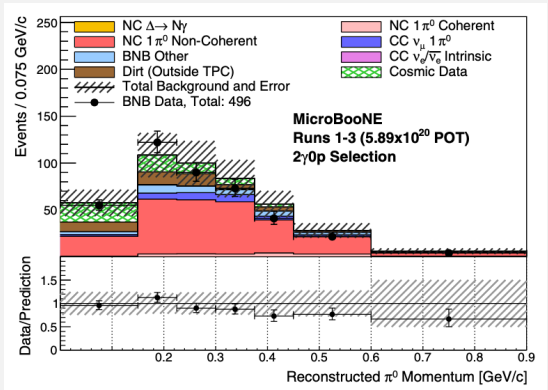
1ɣ1p



1ɣ0p



2ɣ1p



2ɣ0p

No evidence of an excess in either sample

Reject Δ→Nɣ x3.18 increase as explanation of excess at 94.8% CL

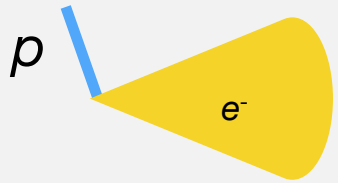
ν_e SEARCH

Phys. Rev. Lett. 128, 241801

Electron searches

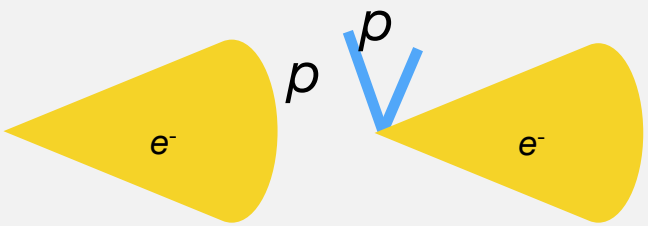
Phys. Rev. D 105, 112003

CCQE-like: 1e1p



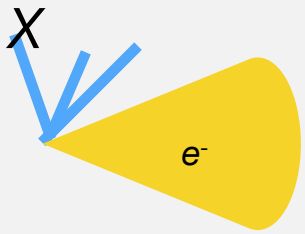
Phys. Rev. D 105, 112004

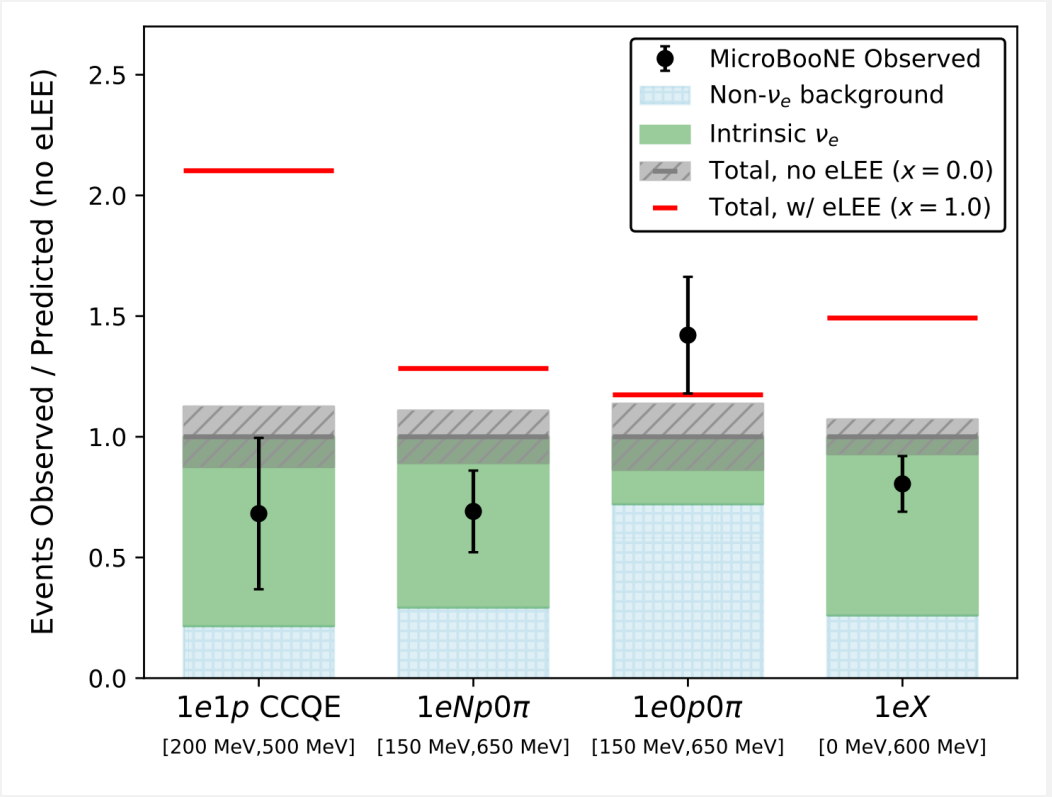
CC0π:
1e0p and 1eNp



Phys. Rev. D 105, 112005

Inclusive: 1eX

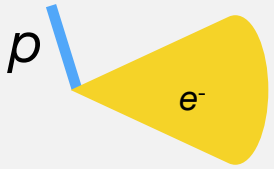


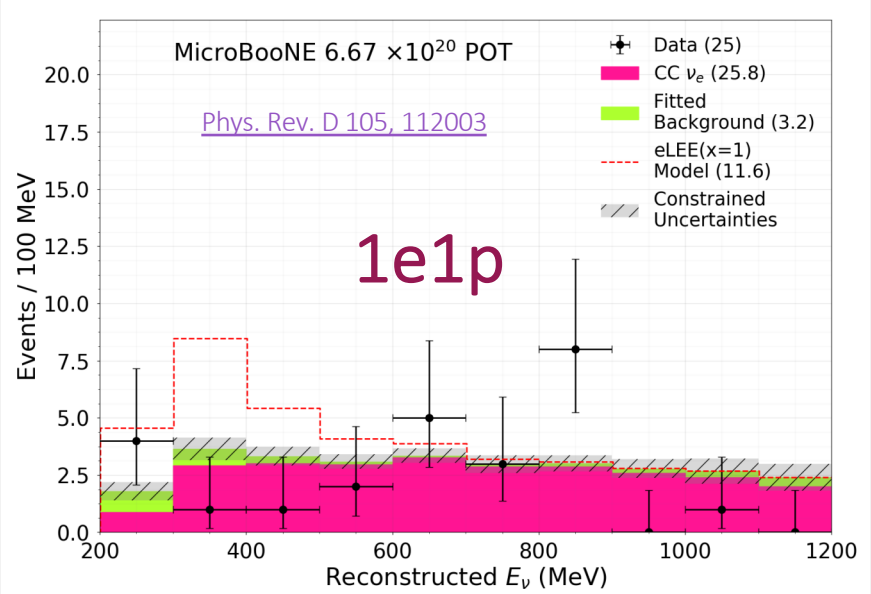


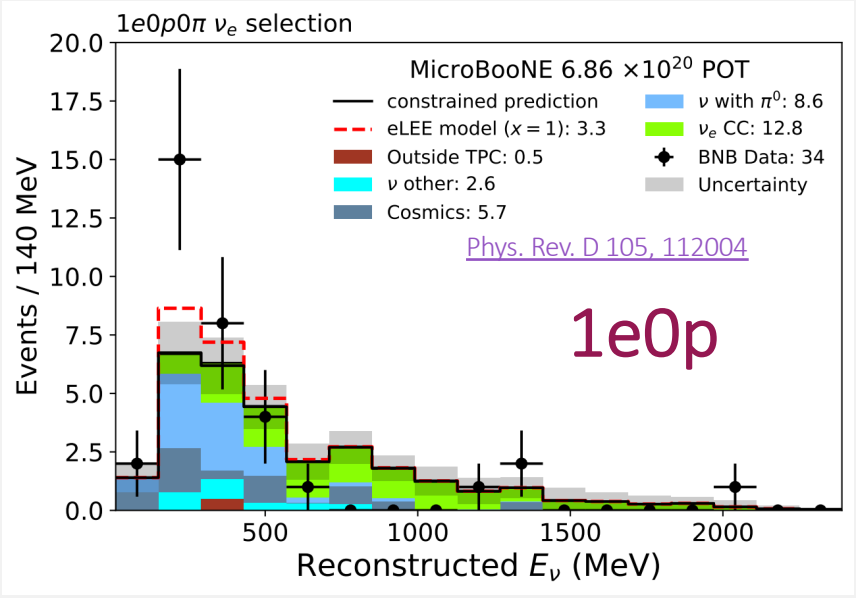
Three high-purity analyses reject ν_e interactions as sole source of excess at >97% CL

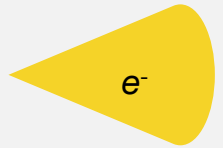
νe SEARCH

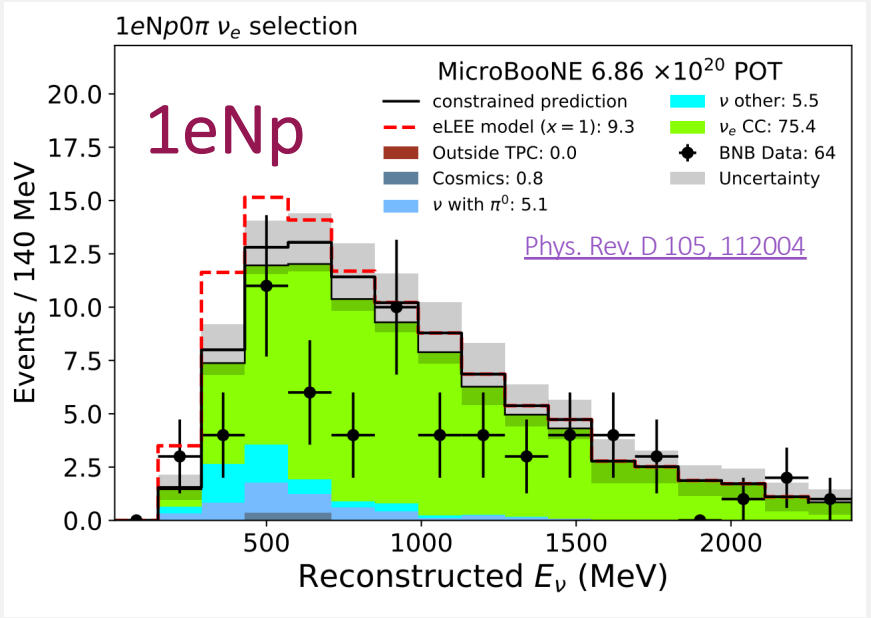
Phys. Rev. Lett. 128, 241801

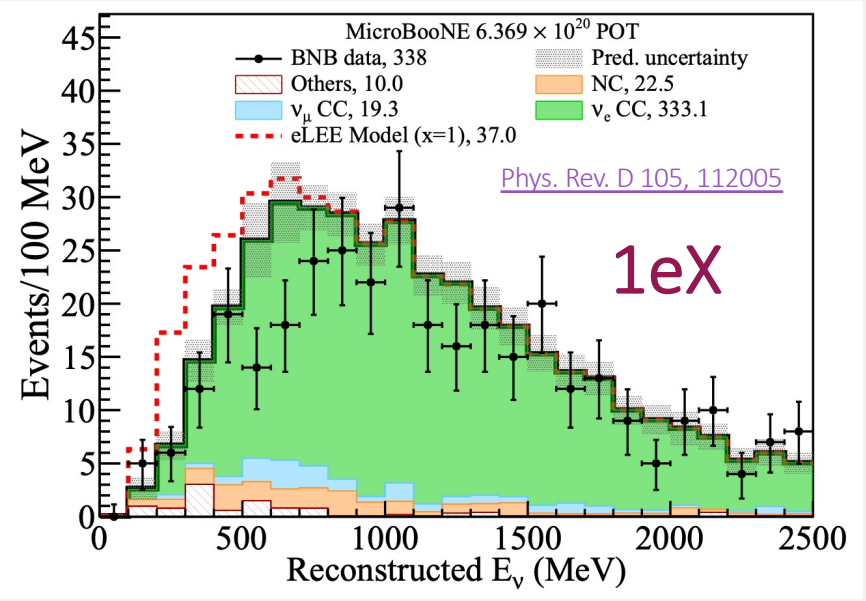


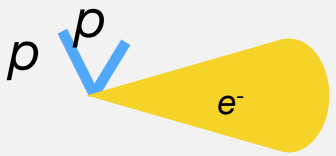


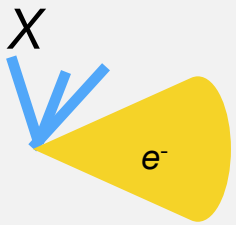












Both initial hypotheses rejected

- Single photon from Δ→Nɣ:
- Single electrons

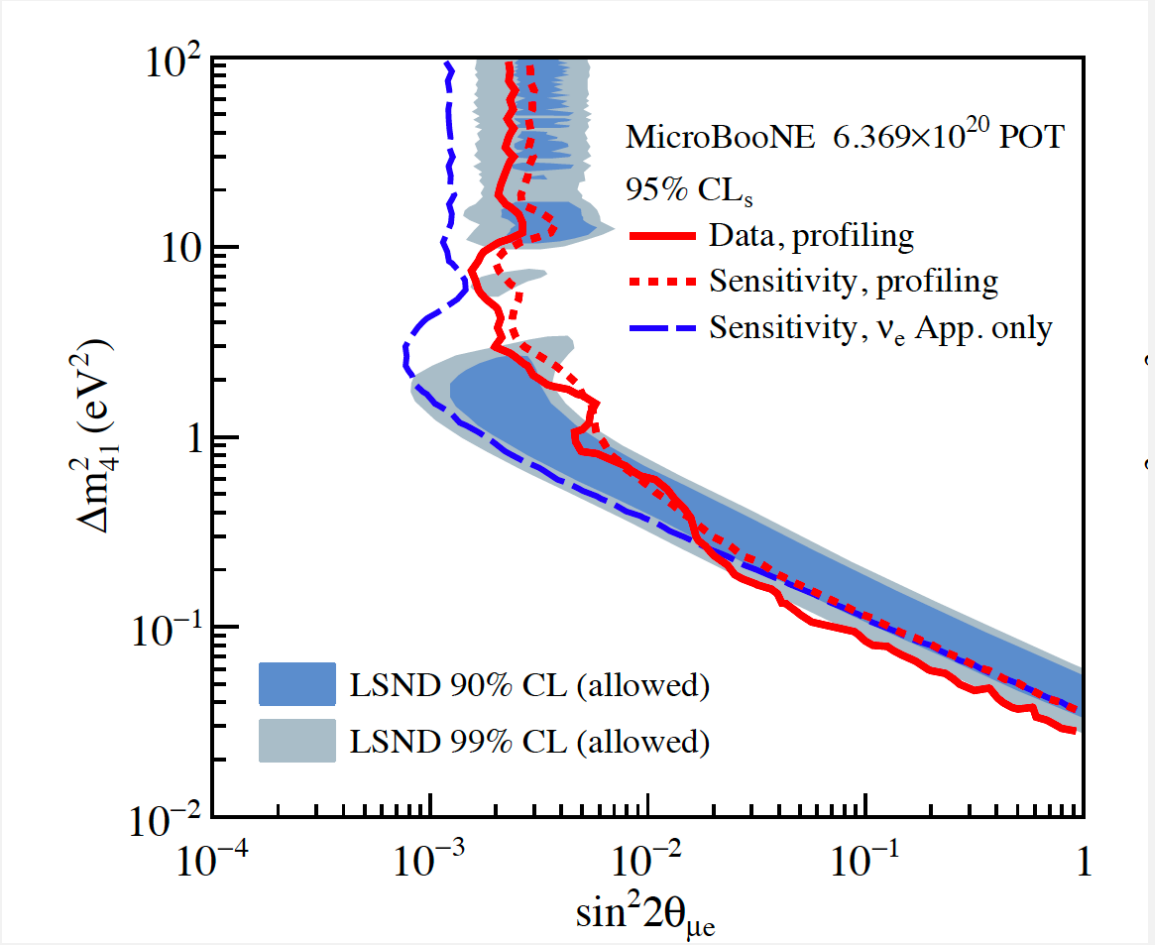
The future searches will include

- Other 1ɣ events
- e^+e^- events

Oscillation hypothesis

- What does this mean for the sterile neutrino hypothesis?
- We haven't seen evidence of an excess → place constraints on oscillation phase space for a new neutrino flavour.

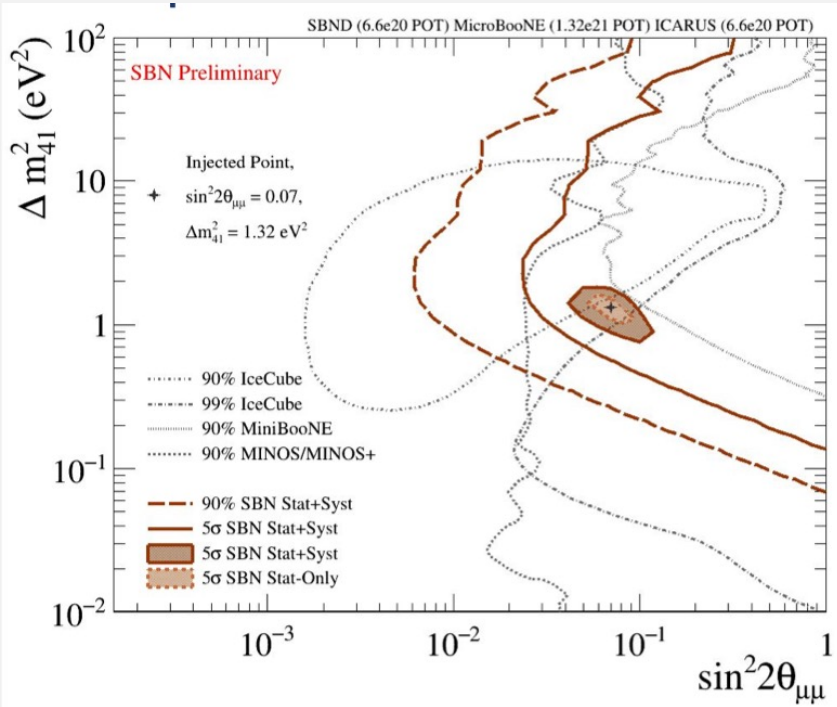
arXiv:2210.10216



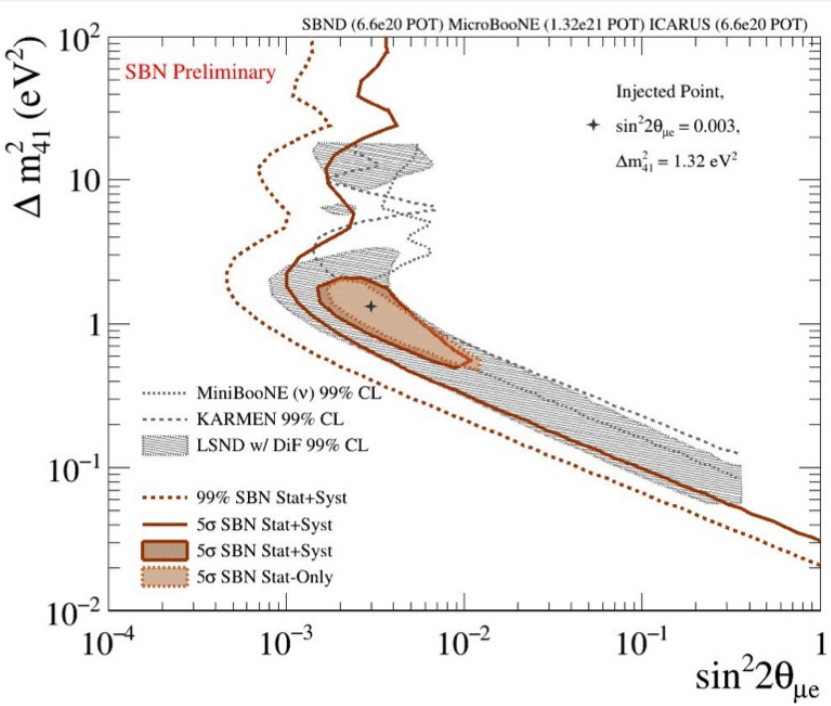
Upcoming BNB + NuMI analysis will be sensitive to full LSND allowed regions

SBN Sterile Neutrinos Sensitivities

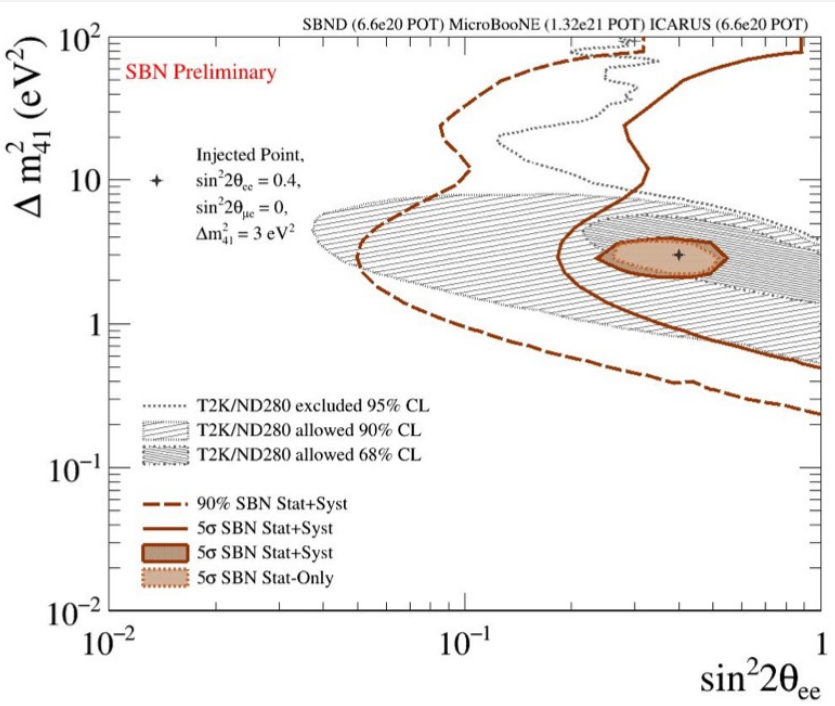
ν_μ disappearance



ν_e appearance



ν_e disappearance

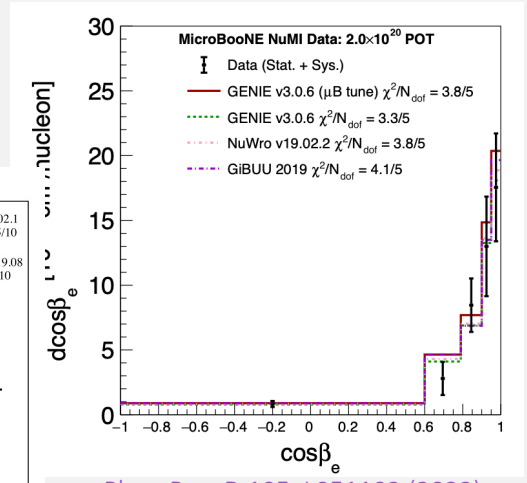


In two/three sterile oscillation channels, SBN will be sensitive to the parameter space favored by previous measurements at the 5σ confidence level.

Complementary measurements in different modes: important for interpretation in terms of sterile neutrino oscillation.

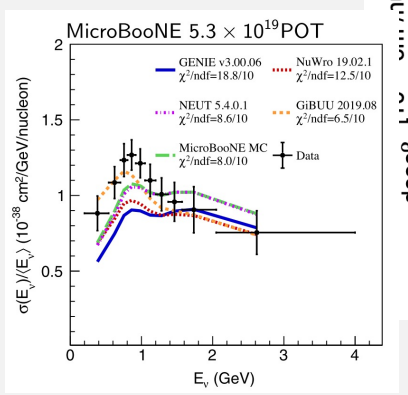
Cross section program

νe CC inclusive



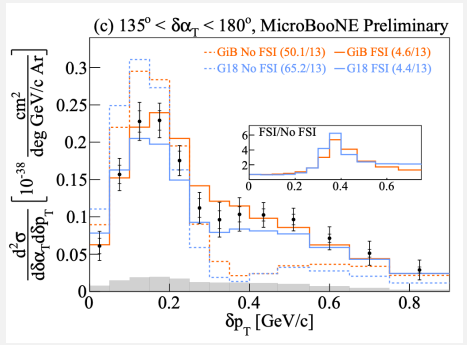
Phys. Rev. D 105, L051102 (2022)

νμ CC inclusive



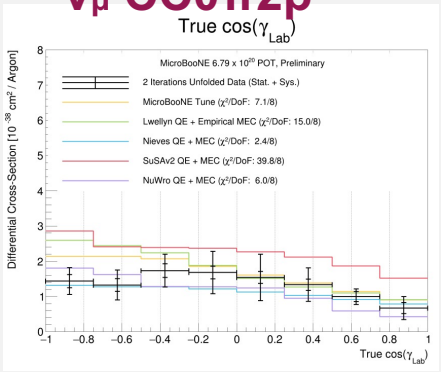
Phys. Rev. Lett. 128, 151801 (2022)

νμ CC0π1p Transverse Variables

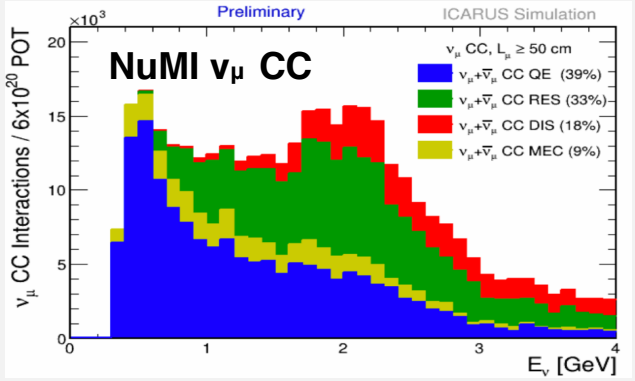


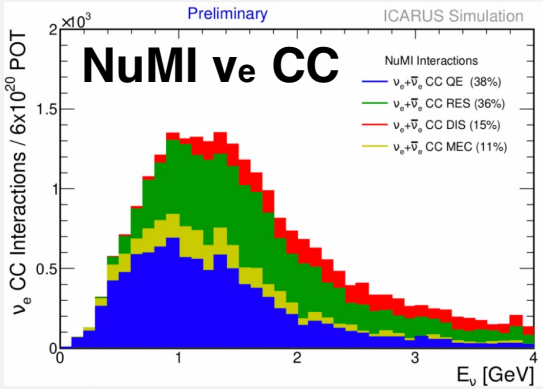
MICROBOONE-NOTE-1117-PUB

νμ CC0π2p



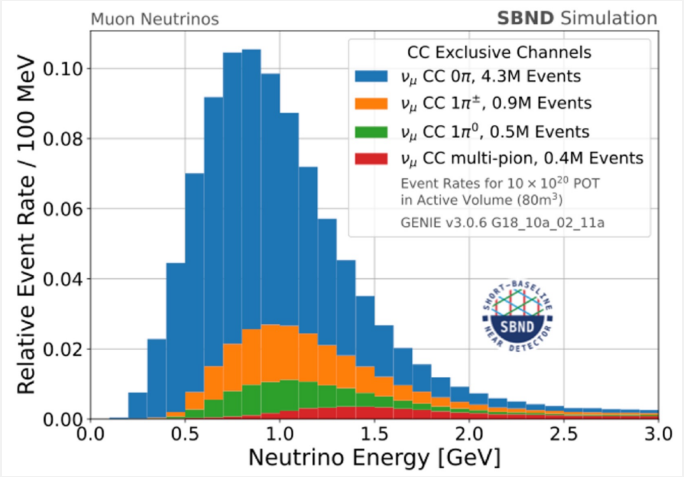
MICROBOONE-NOTE-1108-PUB





ICARUS is exposed to the off-axis (6°) NuMI neutrino beam

- This leads to a strong enhancement in the νe content of the beam
- 5% in NuMI vs. 0.5% in BNB



High-statistics measurements of exclusive final states,rare processes, and tests of ν-Ar models

Uncertainties in neutrino scattering modelling drives uncertainties for oscillation measurement

More exotic searches

SBN can search for a very broad of physics simultaneously

A non-exhaustive list of new physics BSM searches at SBN

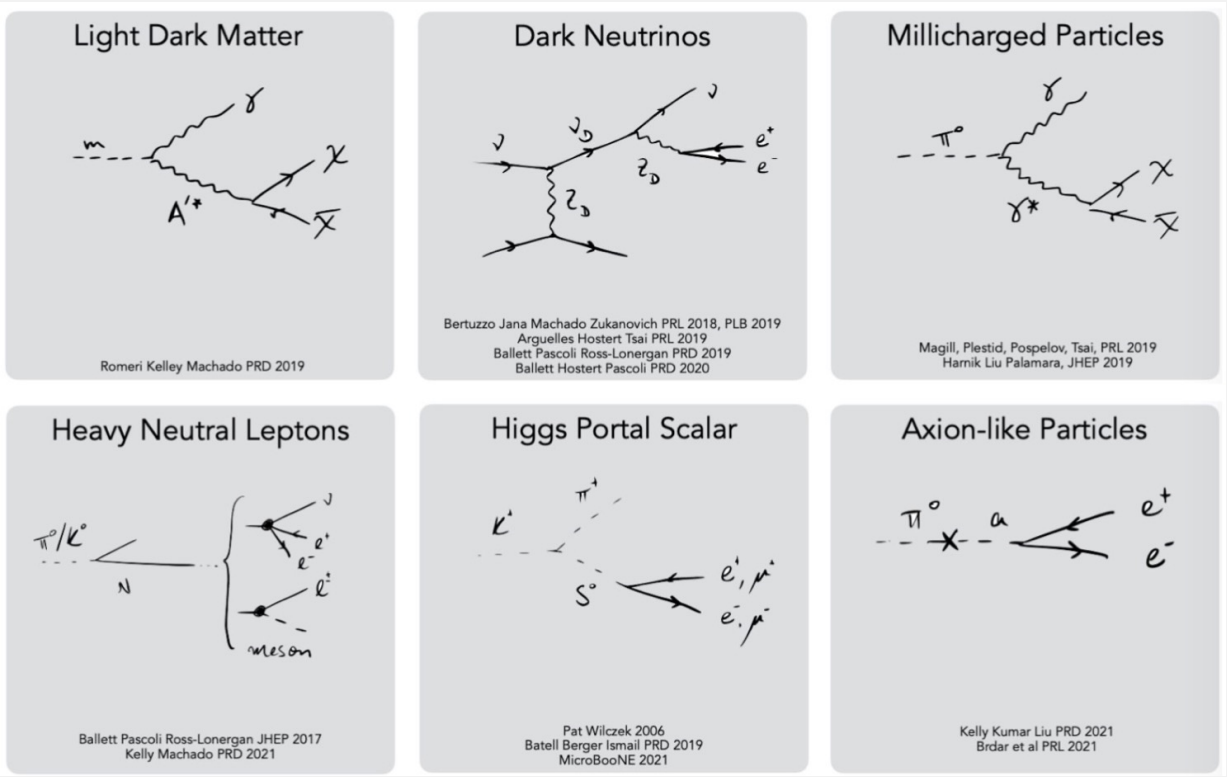
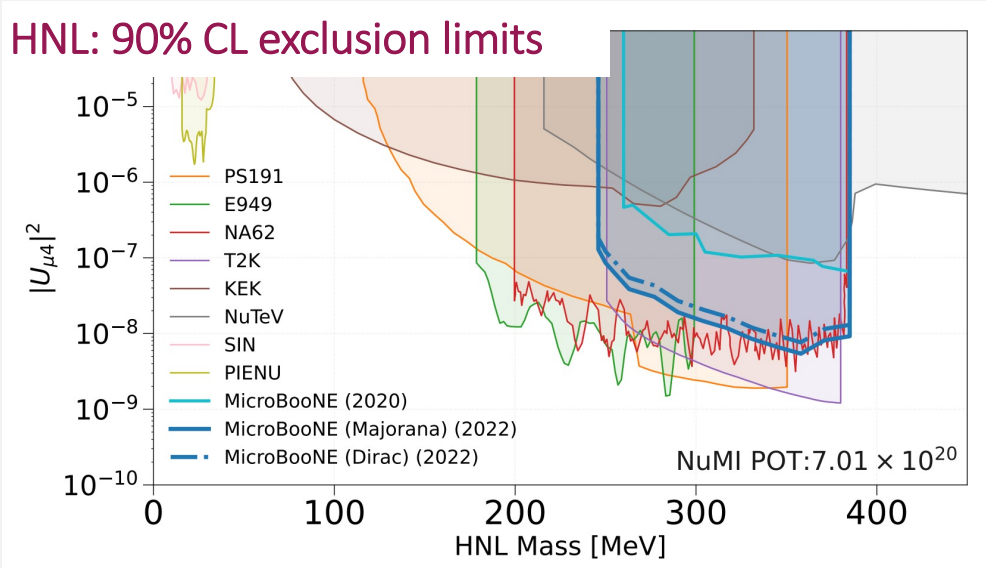
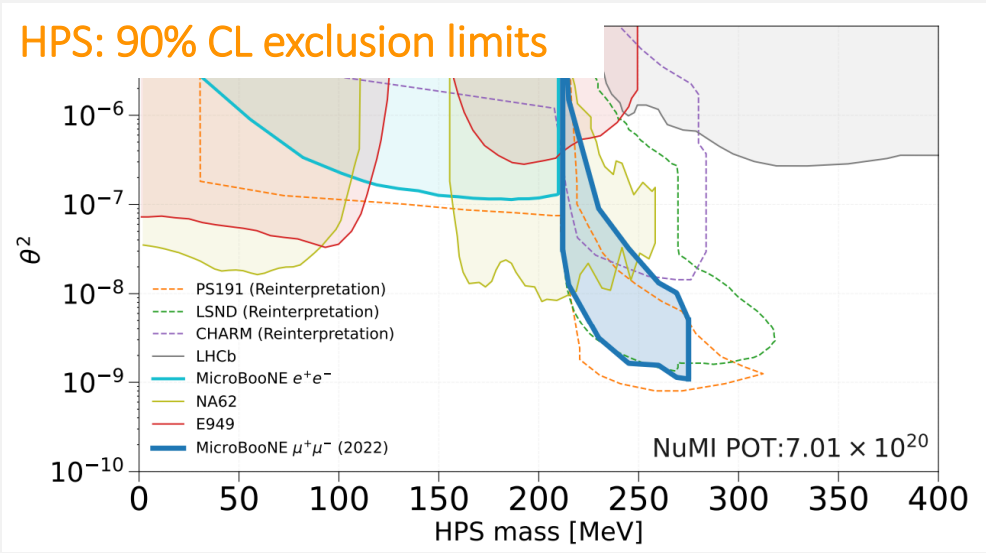


Image credit to Marco del Tutto and Pedro Machado

❑Search for heavy neutral lepton (HNL) decays to $\mu^{\pm}\pi^{\pm}$



❑Search for Higgs portal scalar (HPS) decays to $\mu^{+}\mu^{-}$

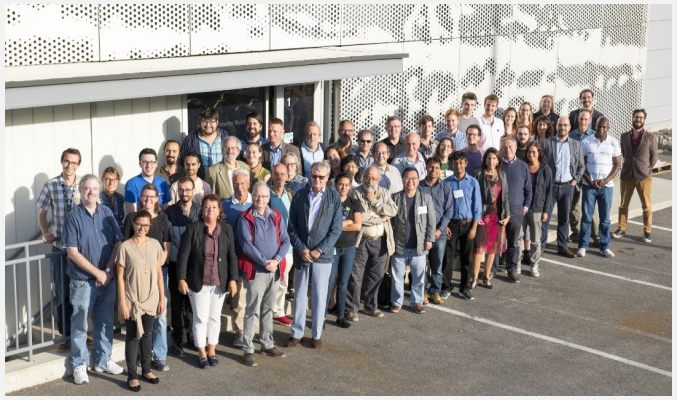


arXiv:2207.03840 [hep-ex]

Summary

- MicroBooNE detailed initial investigations into MiniBooNE anomaly show no evidence for an excess in pure ν_e and NCΔ 1γ channels → the answer is more complicated
- SBND is finishing detector assembly, and ICARUS has started its physics running
- Stay tuned as the ICARUS and SBND join MicroBooNE in results for world-leading ν-Ar cross-section measurements and searches for New Physics.

ICARUS Collaboration



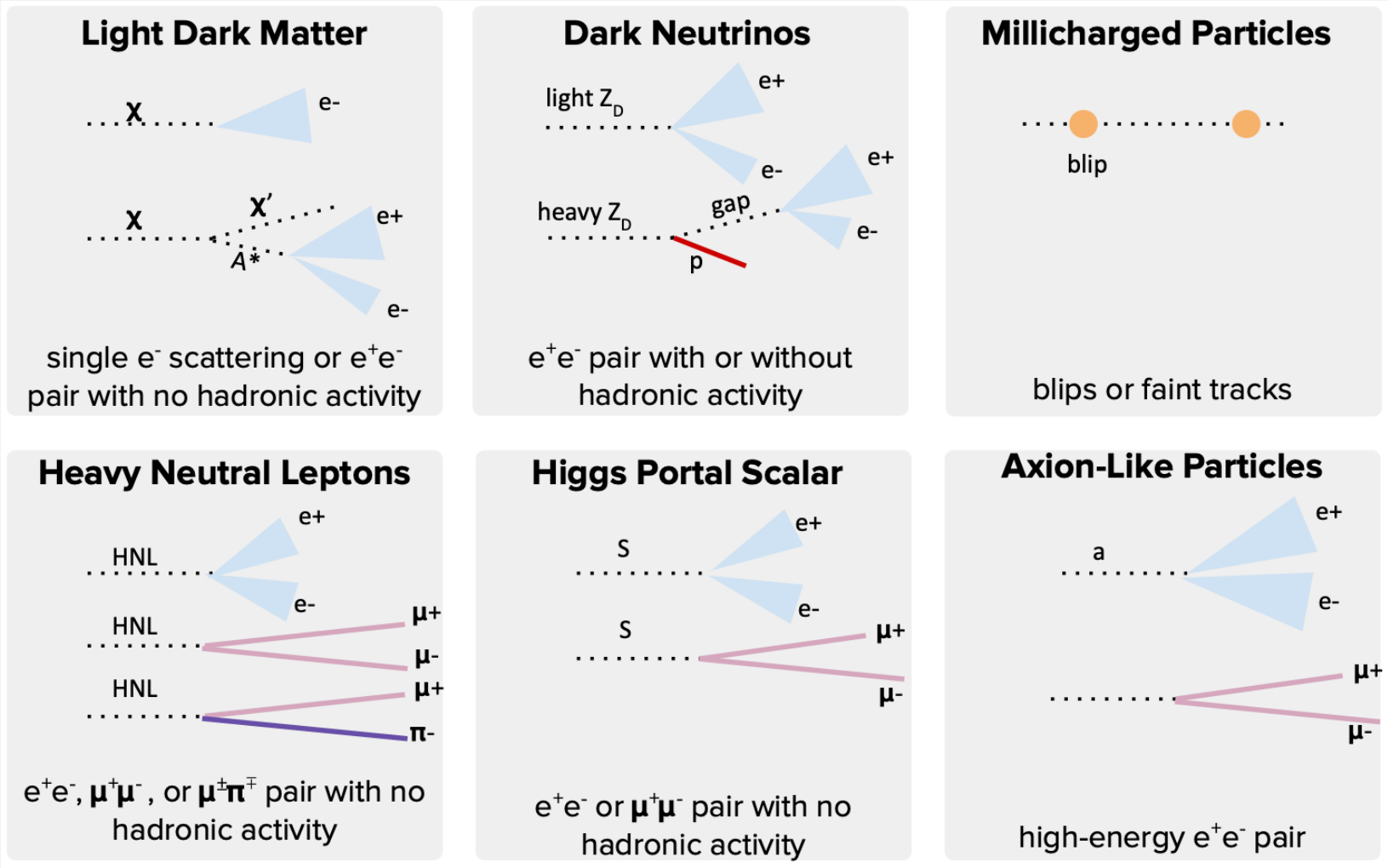
MicroBooNE Collaboration

SBND Collaboration

Backup slides

More exotic searches

Topological (detectable) signatures:



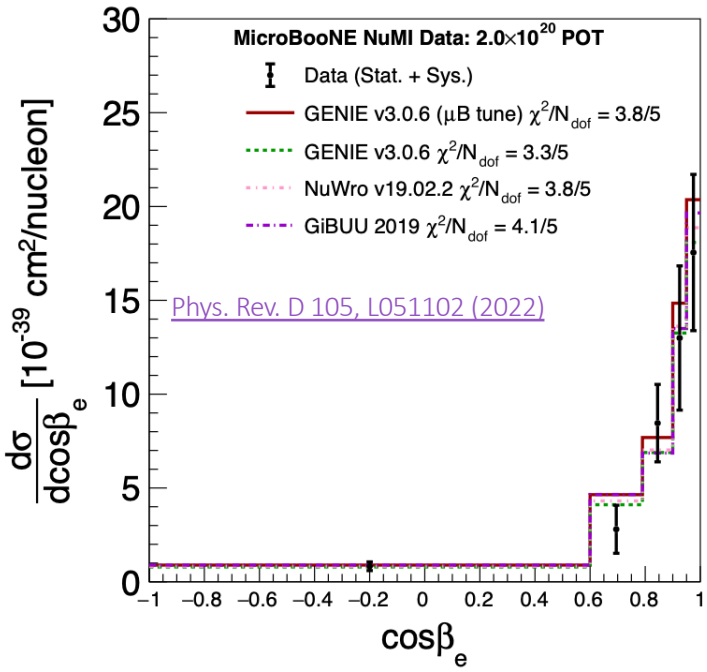
(the main backgrounds are neutrino-argon interactions!)

Image credit to Supraja Balasubramanian

Charged-current Inclusive measurements

ν_e CC inclusive

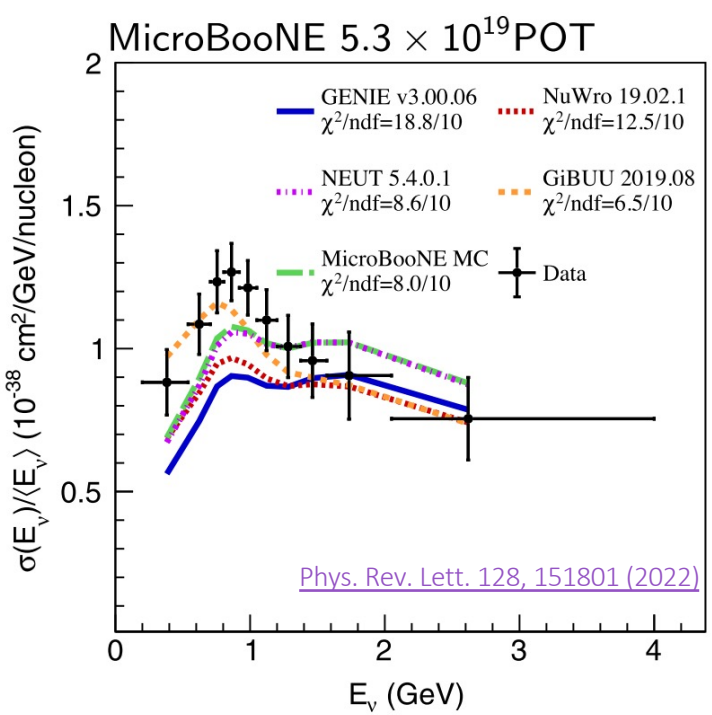
- first measurement on argon as a function of scattering angle and electron energy
- excellent overall test of neutrino-nucleus generator



ν_μ CC inclusive

- first measurement on argon as a function of neutrino energy and energy transfer
- enabled by extensive validation of missing energy model
- stringent test of hadronic part of the interaction

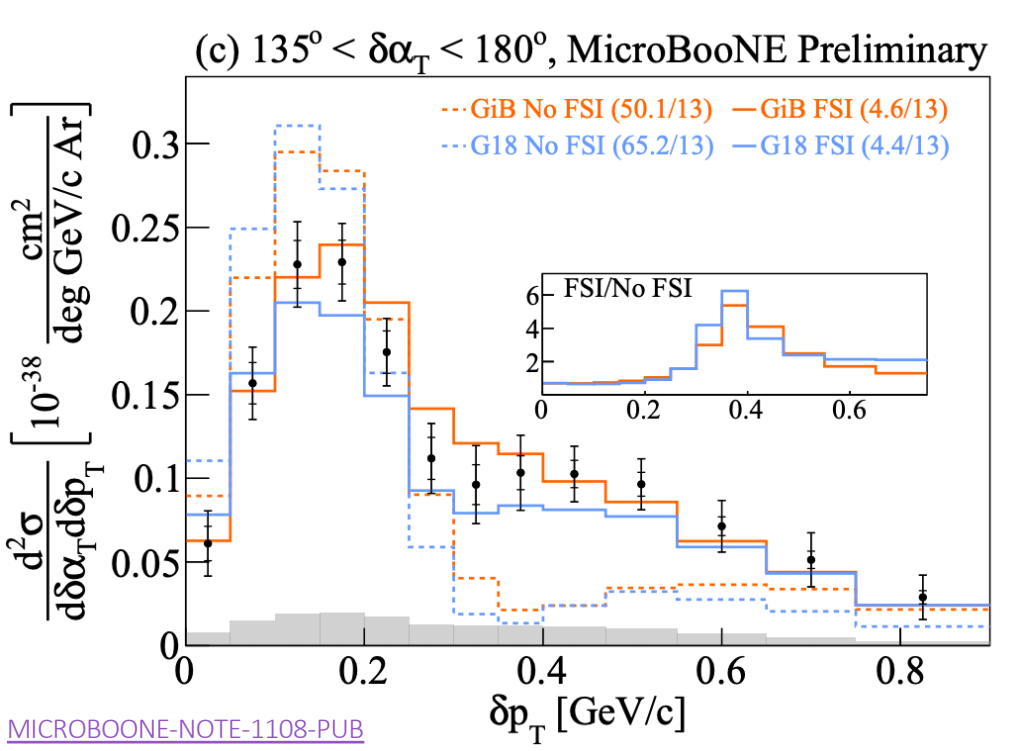
More to come: higher statistics, multi-differential



Exclusive channels, differential cross-sections

ν_μ CC0π1p Transverse Variables

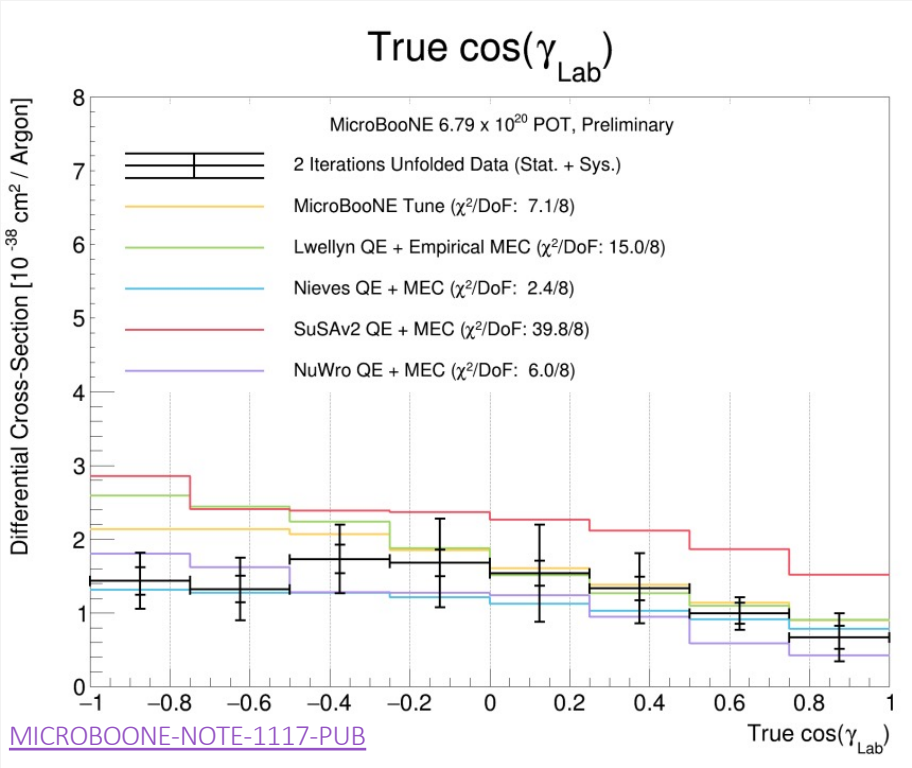
- first double-differential cross section in these variables on argon
- especially sensitive to nuclear effects



MICROBOONE-NOTE-1108-PUB

ν_μ CC0π2p

- first ever direct measurement of 2-proton cross section
- dominated by 2p2h/MEC processes



MICROBOONE-NOTE-1117-PUB

Neutral current neutral pion production

Important background to ν_e searches in LArTPCs (MicroBooNE and future experiments: DUNE, SBN)

- $\pi^0 \rightarrow \gamma\gamma$ looks like ν_e if one photon missed

First NCπ^0 measurement on argon with $\langle E_\nu \rangle \sim 1$ GeV

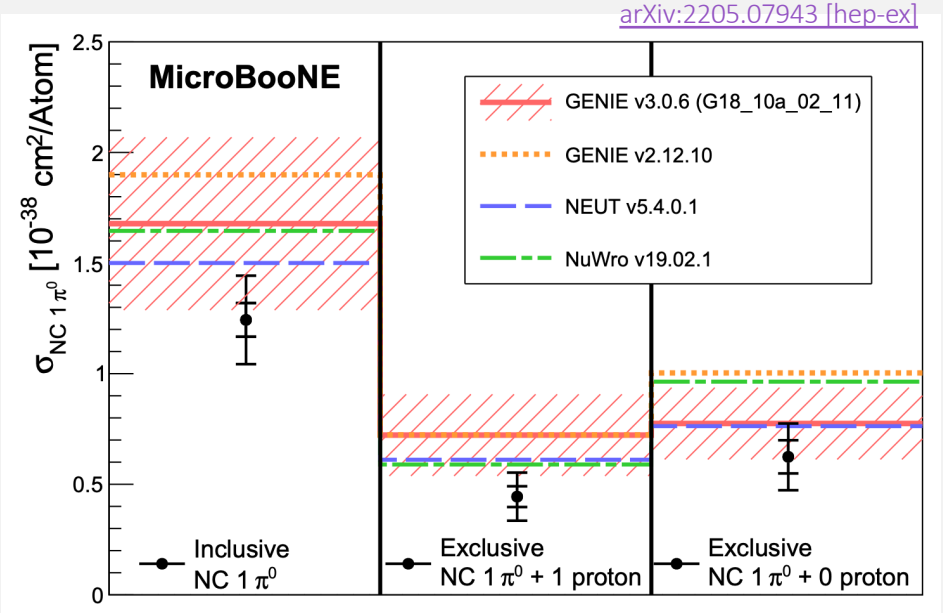
- separated into 0p and 1p channels
- deficit observed compared to all models

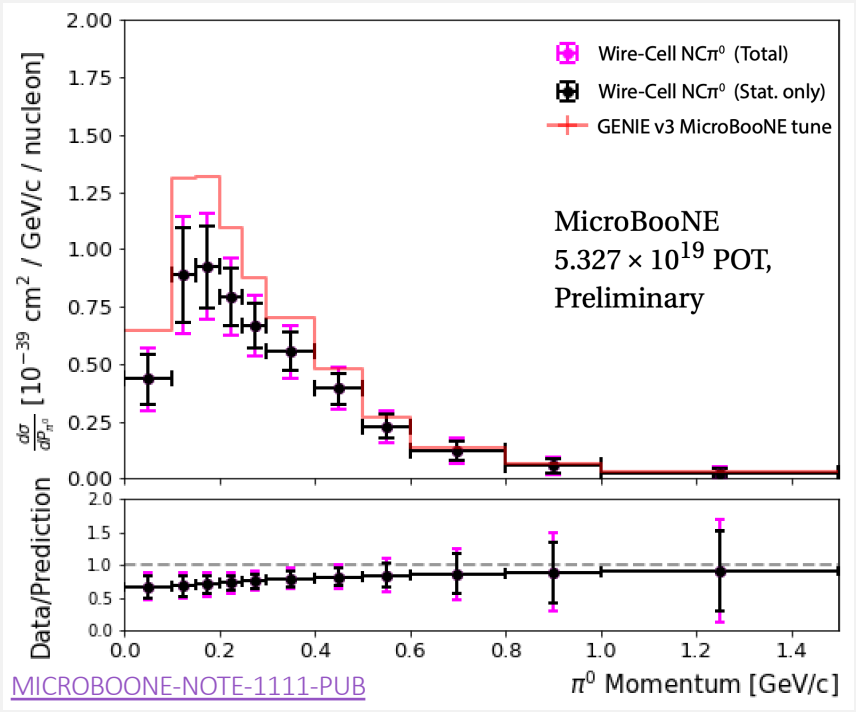
Differential cross-section measurement well under way

- current result limited by statistics (only few % of available data used)

CCπ^0 measurement in progress, along with more rare searches e.g. hyperon production

arXiv:2205.07943 [hep-ex]





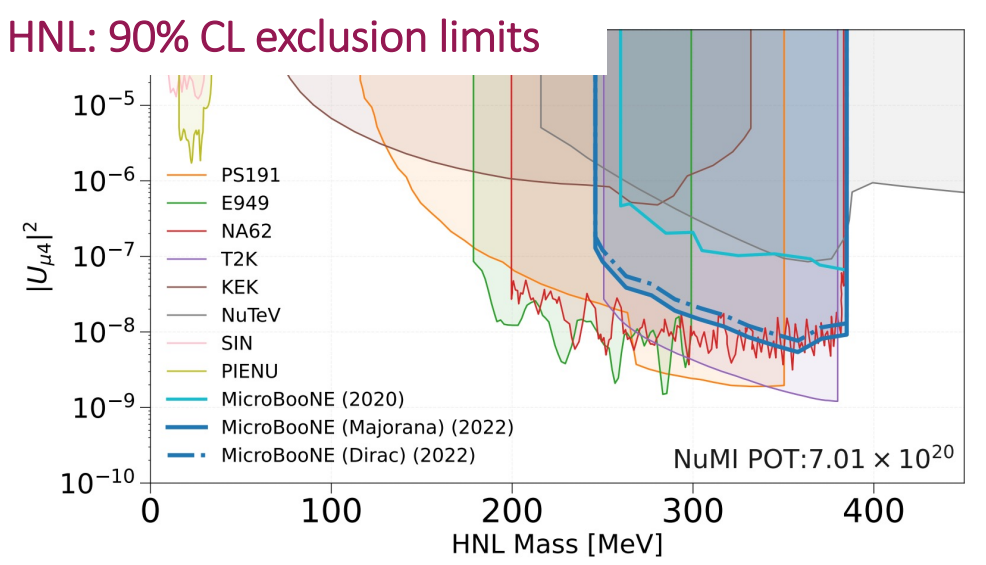
MICROBOONE-NOTE-1111-PUB

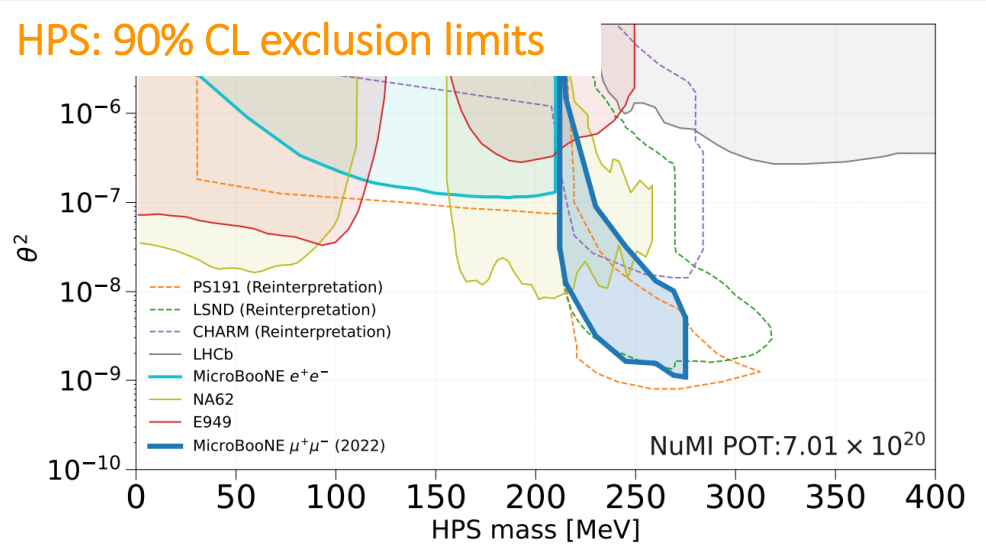
Searching for new physics

SEARCHING FOR OTHER NEW PHYSICS SIGNATURES

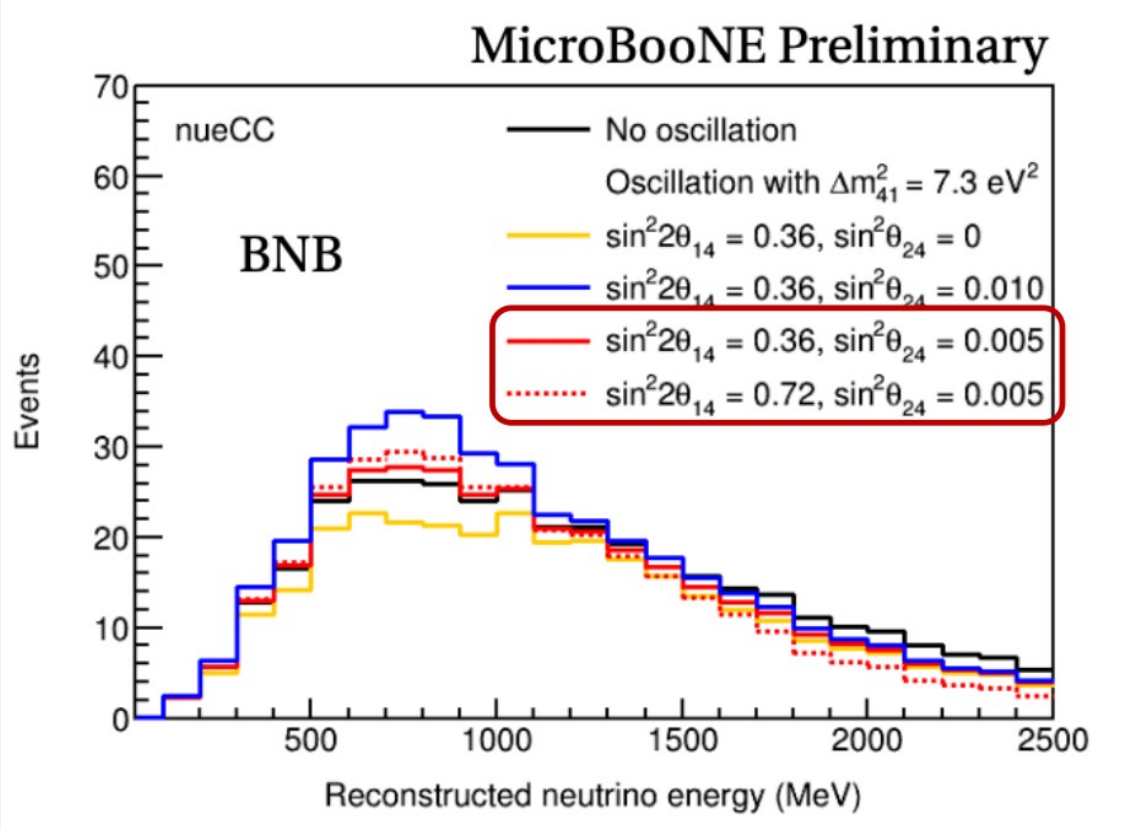
arXiv:2207.03840 [hep-ex]

- Search for **heavy neutral lepton (HNL) decays to $\mu^{\pm}\pi^{\pm}$**
  - similar sensitivity to NA62
  - order of magnitude improvement on previous MicroBooNE results
- Search for **Higgs portal scalar (HPS) decays to $\mu^{+}\mu^{-}$**
  - complementary to previous $e^{+}e^{-}$ MicroBooNE search
  - First constraints on scalar-Higgs mixing angle θ in this mass range from a dedicated experimental search





Oscillation parameter degeneracy



ν_e disappearance

ν_e appearance

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} P_{\nu_\mu \to \nu_e}$$

$$= N_{\text{intrinsic } \nu_e} [1 + (R_{\nu_\mu/\nu_e} \sin^2\theta_{24} - 1) \sin^2 2\theta_{14} \sin^2 \frac{\Delta m^2_{41} L}{4E}]$$

Cancellation if $\sin^2\theta_{24} = R_{\nu e/\nu\mu}$ (ratio of ν_e to ν_μ in beam)

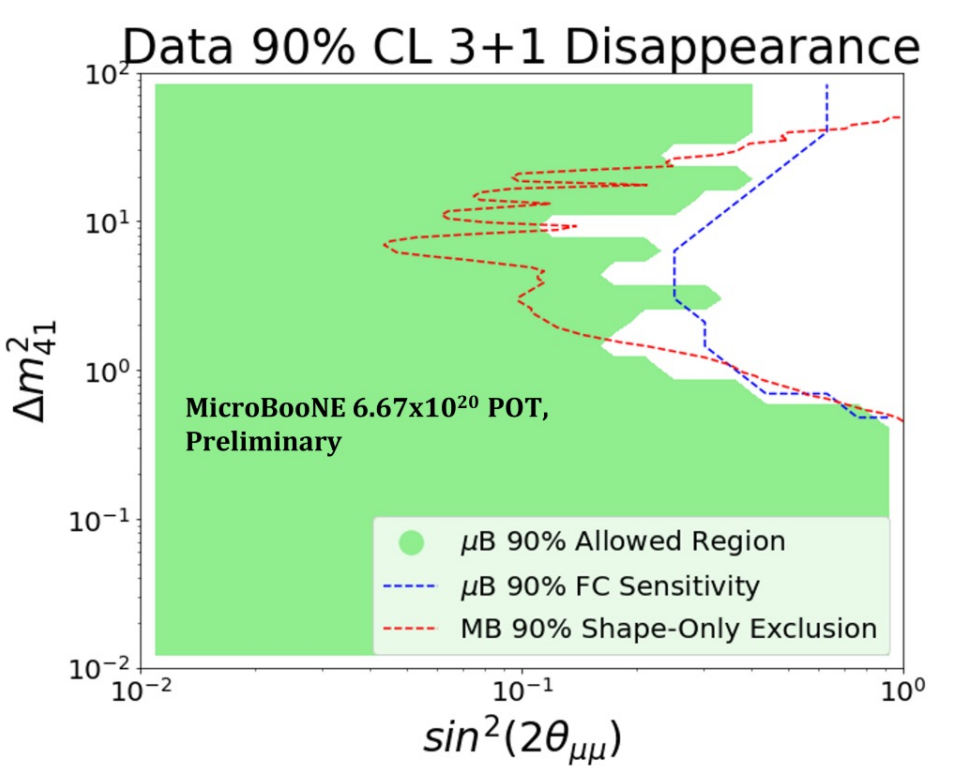
→ about 0.005 in BNB

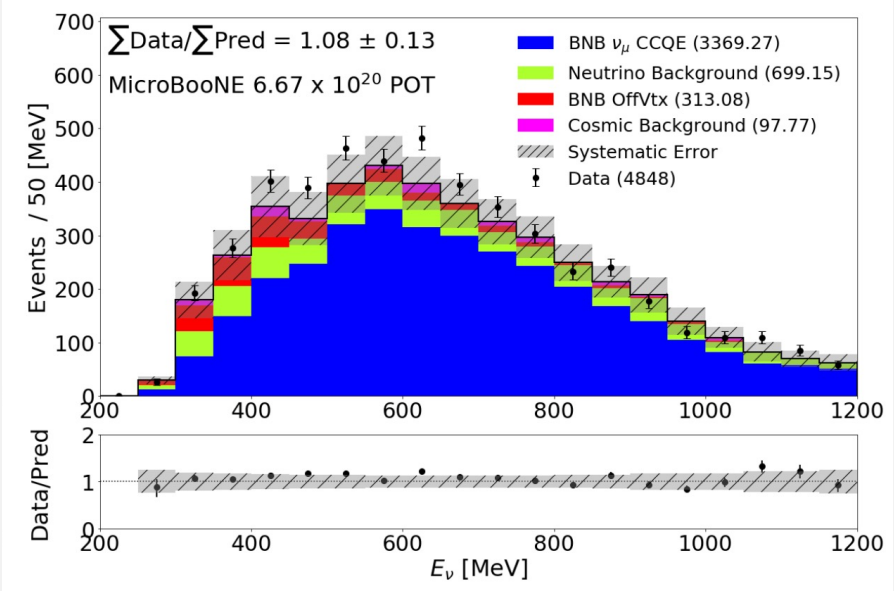
→ about 0.04 in NuMI

1μ1p disappearance exclusion limits

- Use **1μ1p sample** (98% pure ν_μ) to search for **ν_μ disappearance** in BNB
- Data consistent with no oscillation → set Feldman-Cousins **exclusion limits**

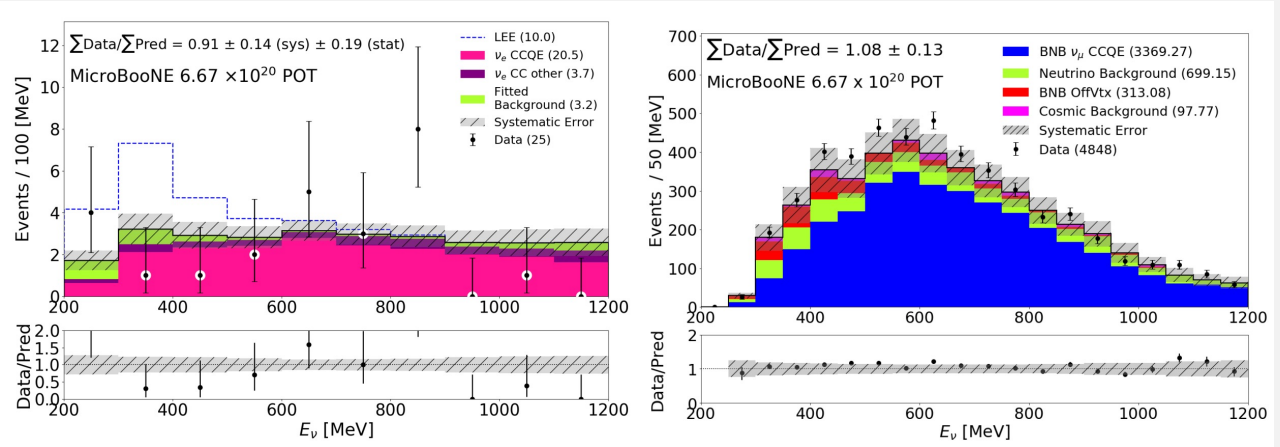
MICROBOONE-NOTE-1106-PUB

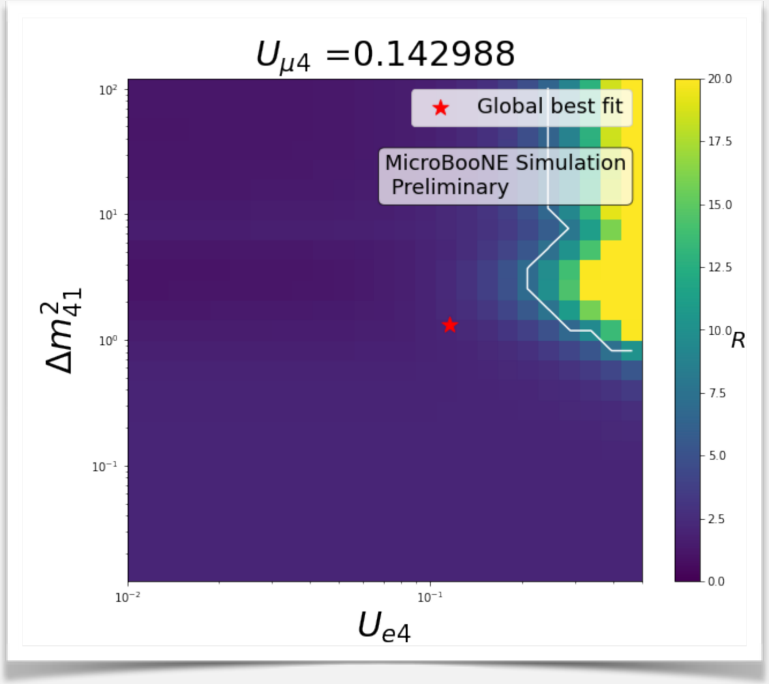




Future 3+1 1e1p and 1μ1p oscillation analysis

- Full 3+1 analysis (as done for inclusive selection) also in progress using **1e1p and 1μ1p samples**
- **Exclusion sensitivity** (assuming no oscillation) using **Wilks' theorem** has been found
- **Feldman-Cousins treatment in progress** for full oscillation results- coming soon!





What does this mean?

- Decay of O(keV) Sterile Neutrinos to active neutrinos
  - *[13] Dentler, Esteban, Kopp, Machado Phys. Rev. D 101, 115013 (2020)*
  - *[14] de Gouvêa, Peres, Prakash, Stenico JHEP 07 (2020) 141*
- New resonance matter effects
  - *[5] Asaadi, Church, Guenette, Jones, Szelc, PRD 97, 075021 (2018)*
- Mixed O(1eV) sterile oscillations and O(100 MeV) sterile decay
  - *[7]Vergani, Kamp, Diaz, Arguelles, Conrad, Shaevitz, Uchida, arXiv:2105.06470*
- Decay of heavy sterile neutrinos produced in beam
  - *[4] Gninenko, Phys.Rev.D83:015015,2011*
  - *[12] Alvarez-Ruso, Saul-Sala, Phys. Rev. D 101, 075045 (2020)*
  - *[15] Magill, Plestid, Pospelov, Tsai Phys. Rev. D 98, 115015 (2018)*
  - *[11] Fischer, Hernandez-Cabezudo, Schwetz, PRD 101, 075045 (2020)*
- Decay of upscattered heavy sterile neutrinos or new scalars mediated by Z' or more complex higgs sectors
  - *[1] Bertuzzo, Jana, Machado, Zukanovich Funchal, PRL 121, 241801 (2018)*
  - *[2] Abdullahi, Hostert, Pascoli, Phys.Lett.B 820 (2021) 136531*
  - *[3] Ballett, Pascoli, Ross-Lonergan, PRD 99, 071701 (2019)*
  - *[10] Dutta, Ghosh, Li, PRD 102, 055017 (2020)*
  - *[6] Abdallah, Gandhi, Roy,Phys. Rev. D 104, 055028 (2021)*
- Decay of axion-like particles
  - *[8] Chang, Chen, Ho, Tseng, Phys. Rev. D 104, 015030 (2021)*
- A model-independent approach to any new particle
  - *[9] Brdar, Fischer, Smirnov, PRD 103, 075008 (2021)*

Produces True Electrons

Produces True Photons

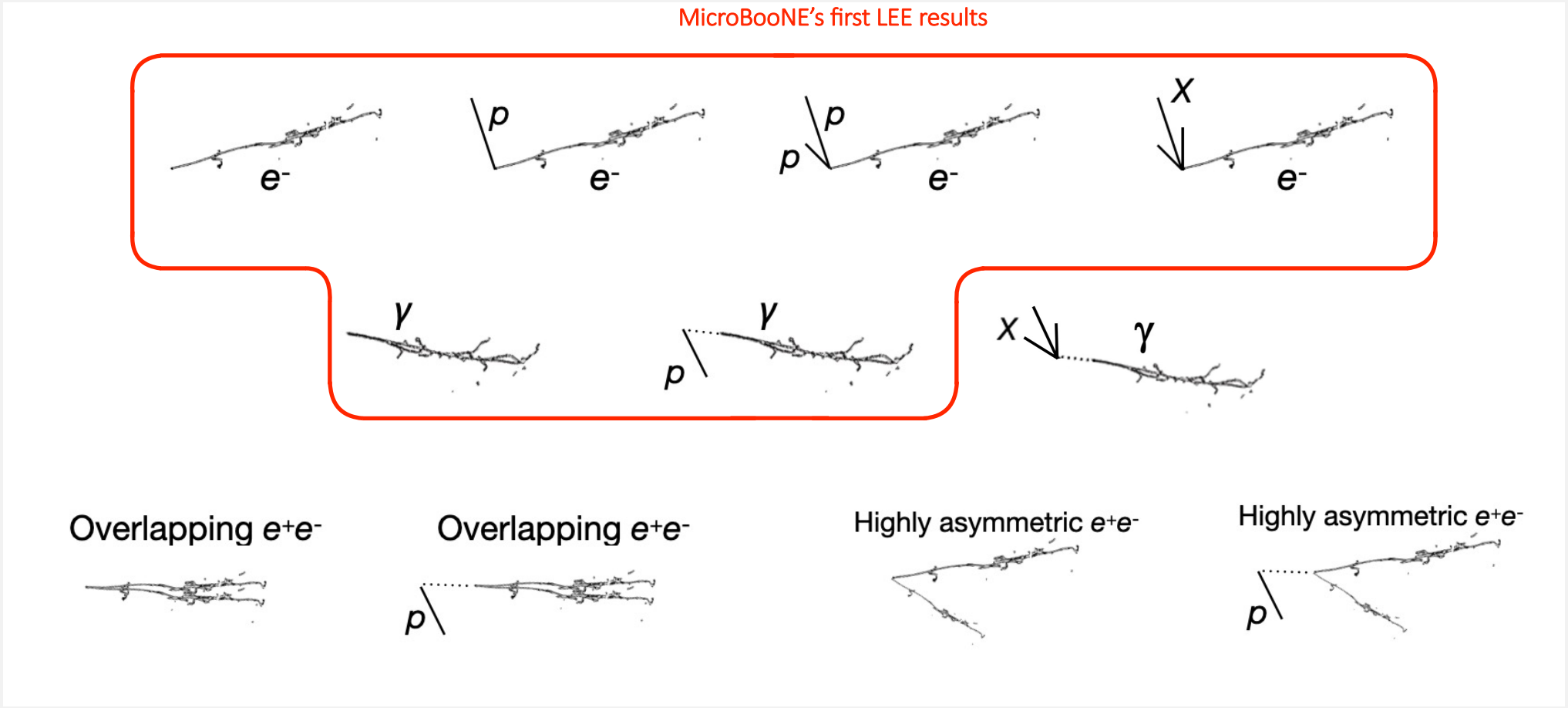
Produces e^+e^- pairs

Caution: not an exhaustive list!

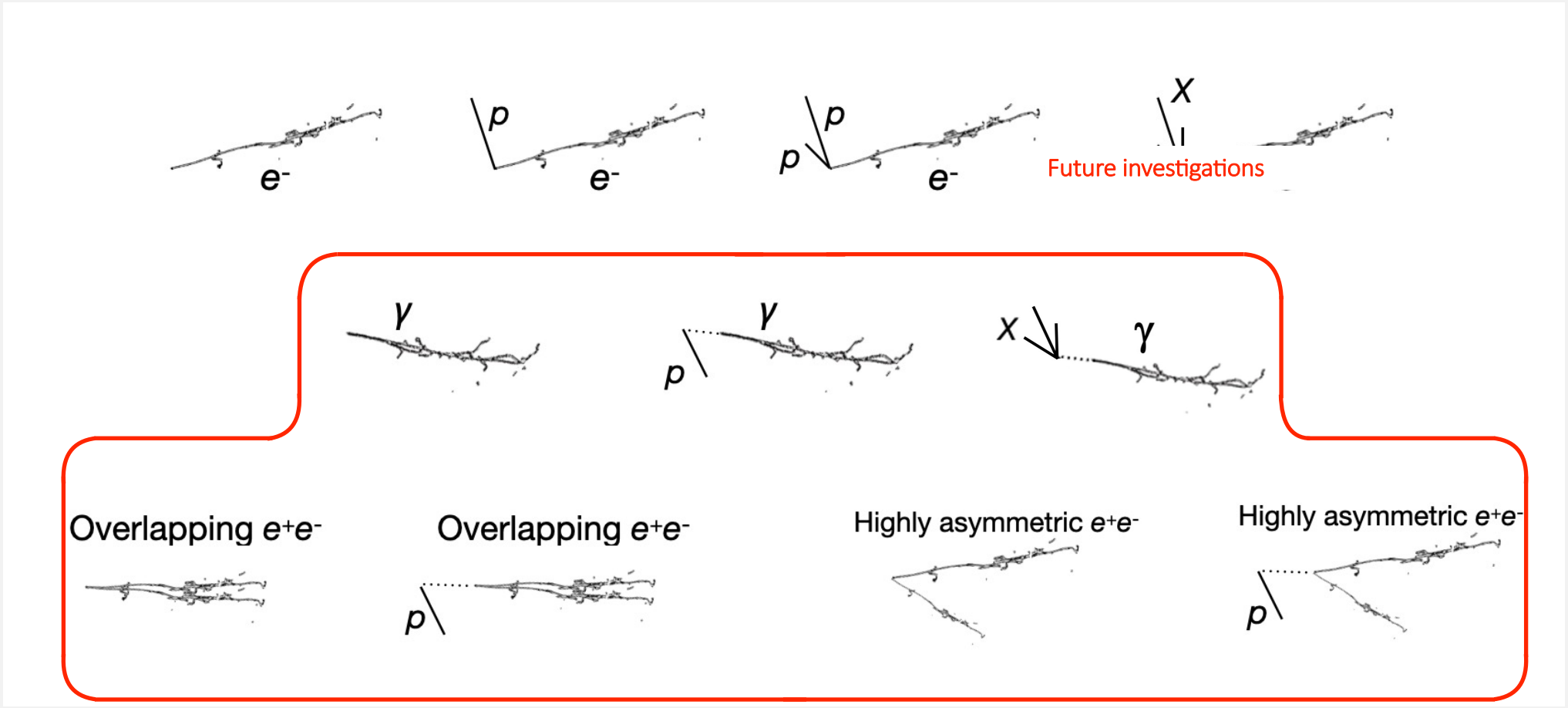
This is meant to be representative only

More information: see P. Machado, Fermilab PAC, November 2021

What does this mean?



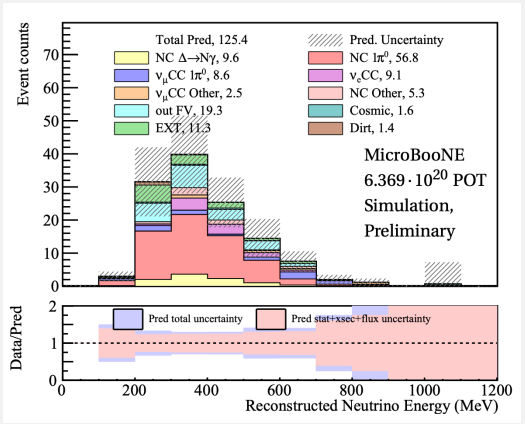
Future investigations



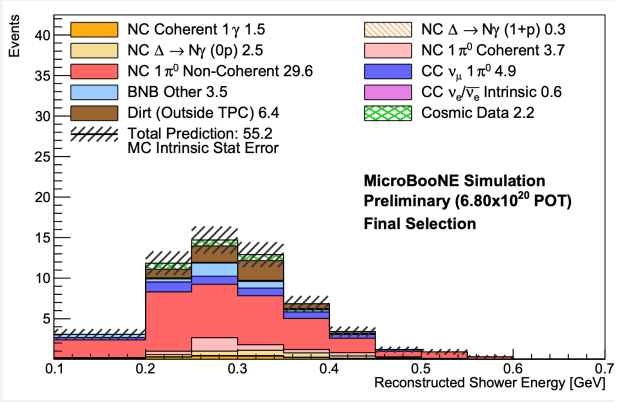
Future investigations

MICROBOONE-NOTE-1104-PUB
MICROBOONE-NOTE-1103-PUB
MICROBOONE-NOTE-1102-PUB

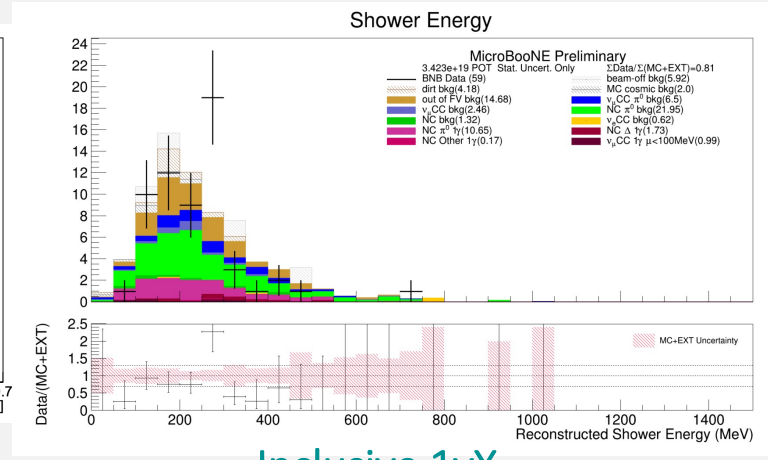
- Further investigations will expand photon-like searches and investigate e^+e^- final states- some preliminary results shown below:
  - **Further investigation of NC Δ model**: independent reconstruction, more sensitivity to potential excess in 1ɣ0p channel
  - **NC-Coherent 1ɣ targeted search**: forward-going photons with no visible hadronic energy
  - **Inclusive 1ɣ search**: generic test of single photon production
- Even more on the way!



1ɣ0p



Coh-1ɣ0p



Inclusive 1ɣX

Future investigations

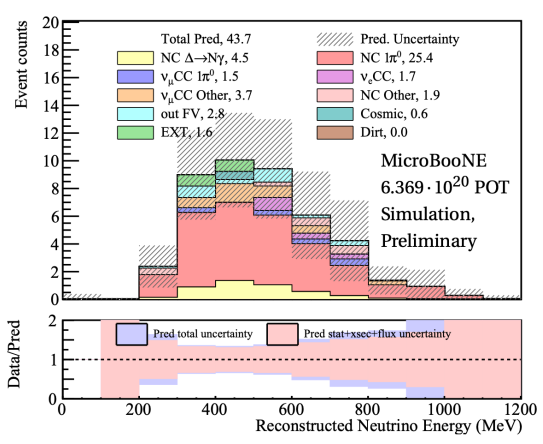
MICROBOONE-NOTE-1104-PUB
MICROBOONE-NOTE-1103-PUB

Further investigation into NCΔ 1ɣ model:

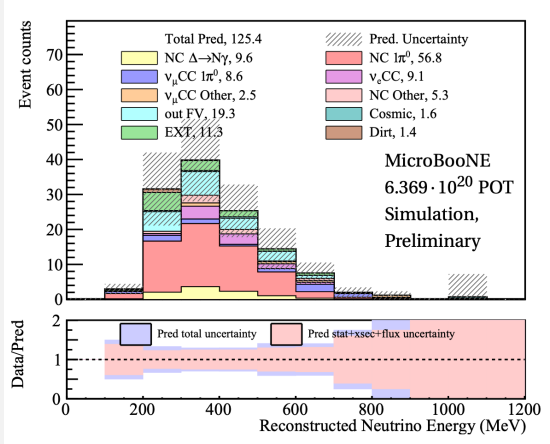
- ❑ Independent reconstruction
- ❑ Larger phase space (including charged pions and multiple protons)
- ❑ More sensitive to potential excess in 1ɣ0p channel

Coherent-like single ɣ search:

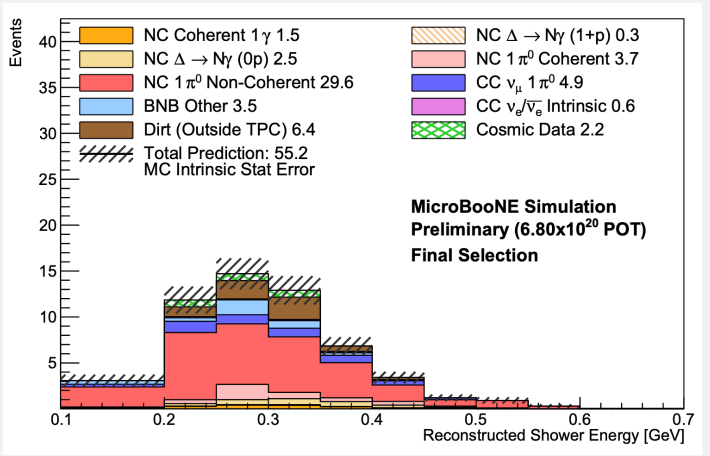
- Focus on forward-going photons with no visible hadronic energy
- More sensitive to potential excess in forward-going and 1ɣ0p channel



1ɣNp (N≥1)



1ɣ0p

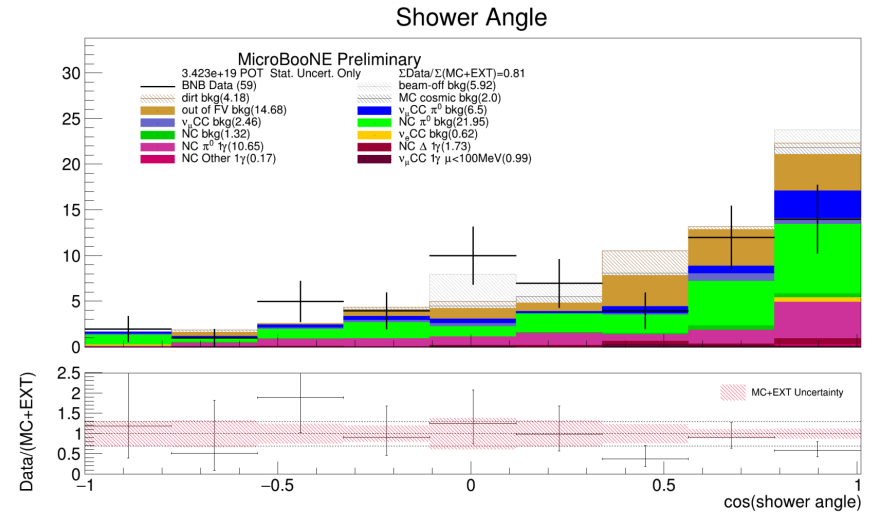


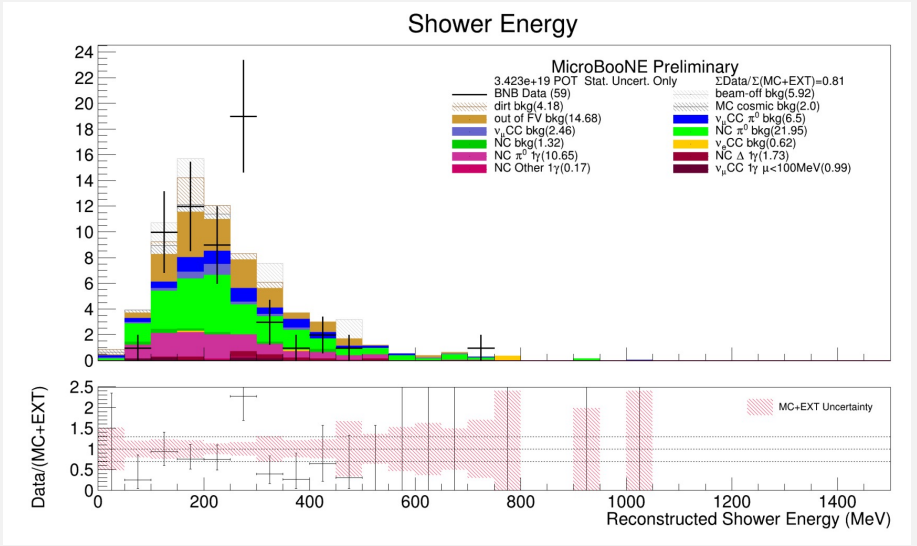
Coh-1ɣ0p

Future investigations

Inclusive single γ selection

- ❑Broader search beyond specific NC Δ model
- ❑Inclusive signal definition: no electrons and exactly one photon with KE>20 MeV. No muons with KE>100 MeV, but any number of hadrons allowed
- ❑Generic test of Standard Model prediction for single-photon events





Single photon search

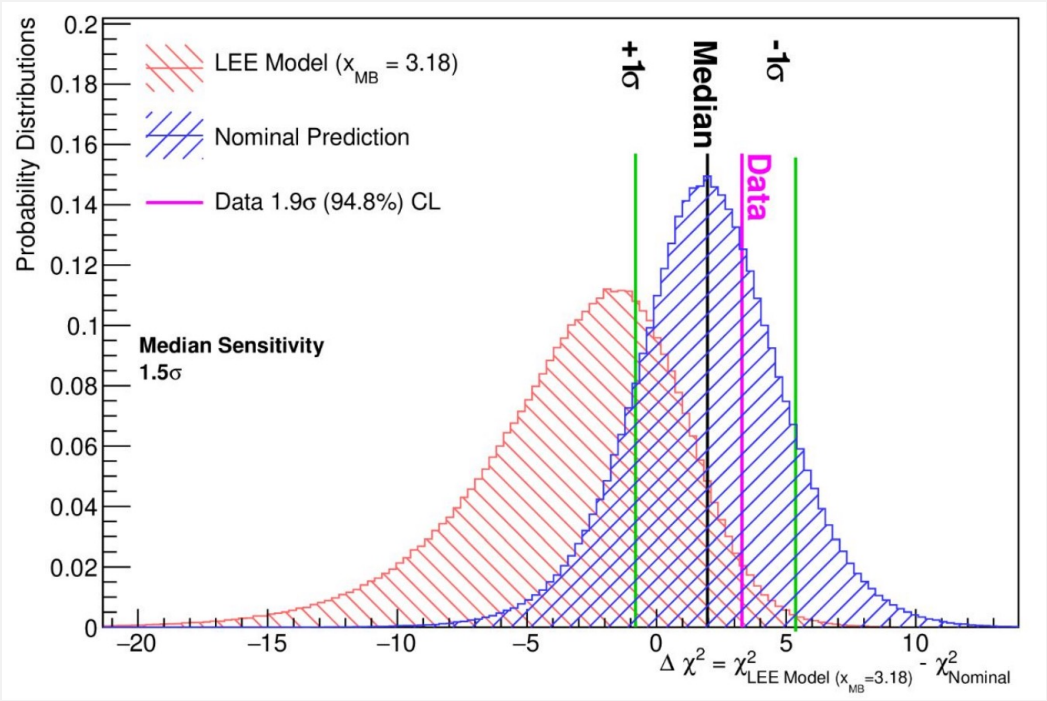
- Simple hypothesis test: use combined Neyman-Pearson χ^2 as test statistic

Nucl. Inst. Meth. A 961 (2020) 163677

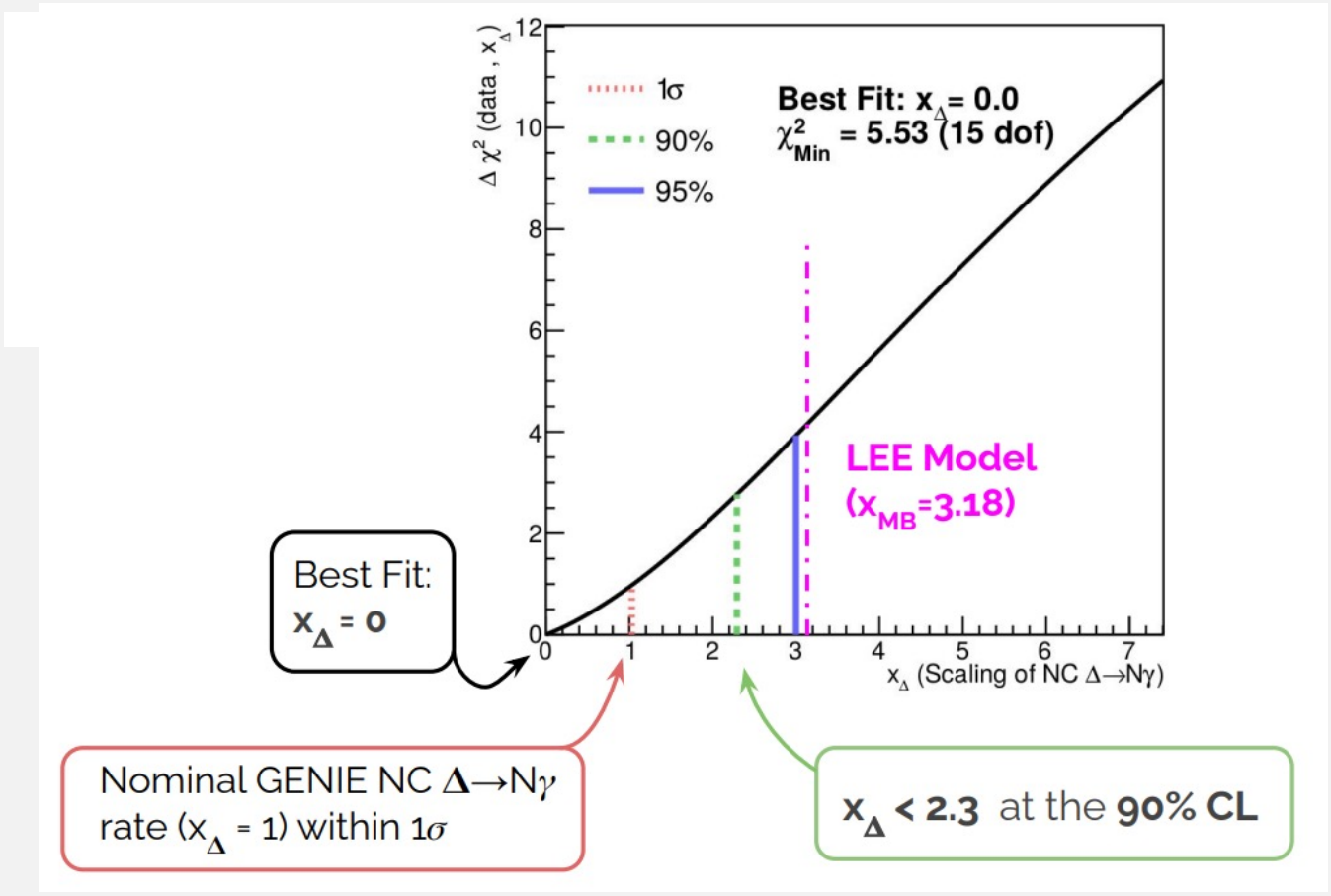
- Data consistent with nominal $\Delta \rightarrow N\gamma$ prediction

- Data **rejects LEE model hypothesis** in favour of nominal prediction at **94.8% CL**

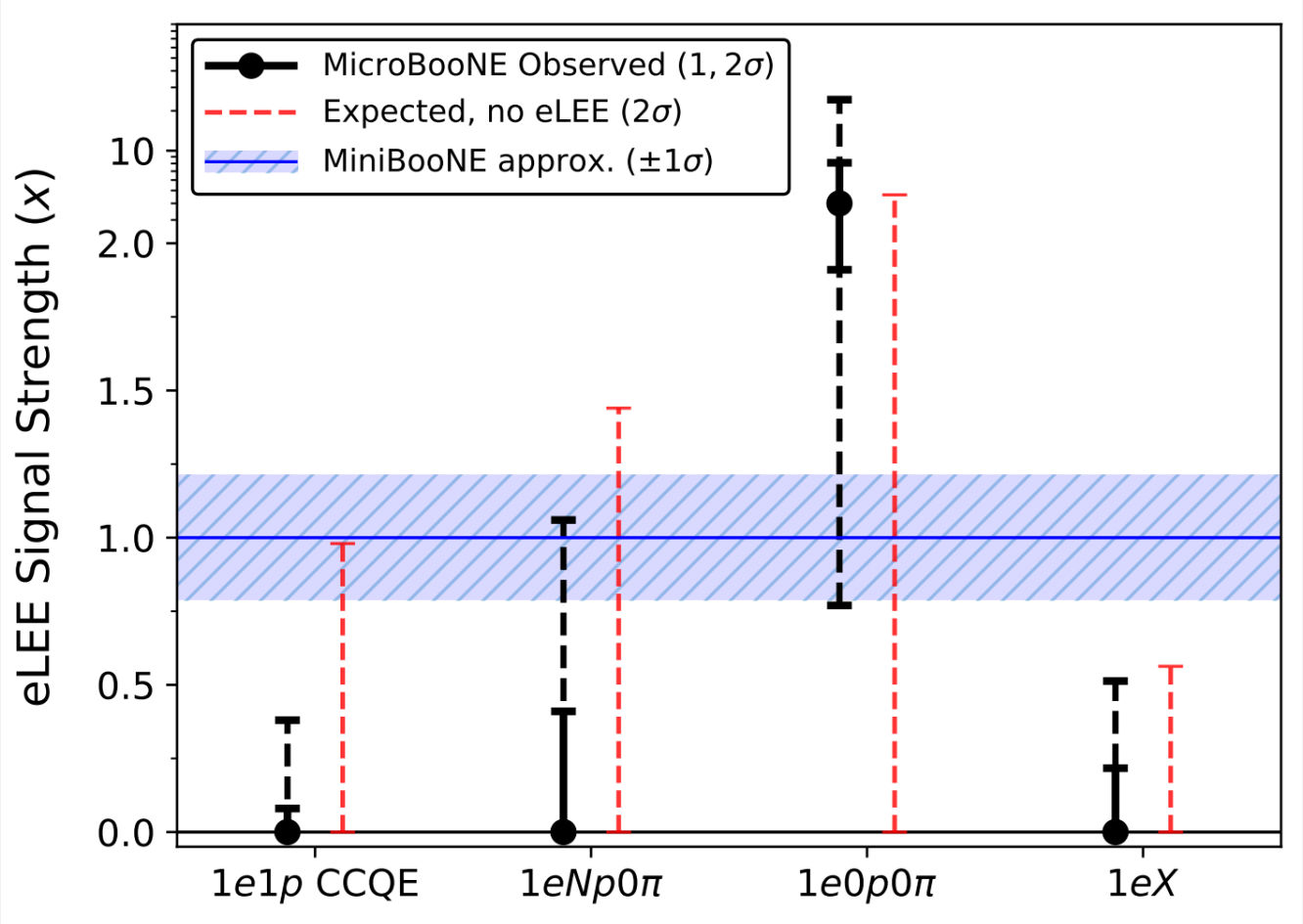
arXiv:2110.00409 [hep-ex]

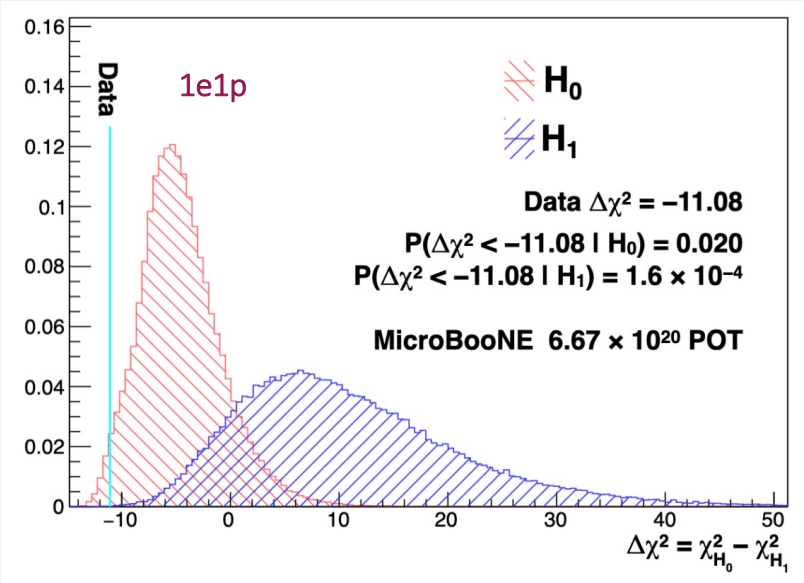


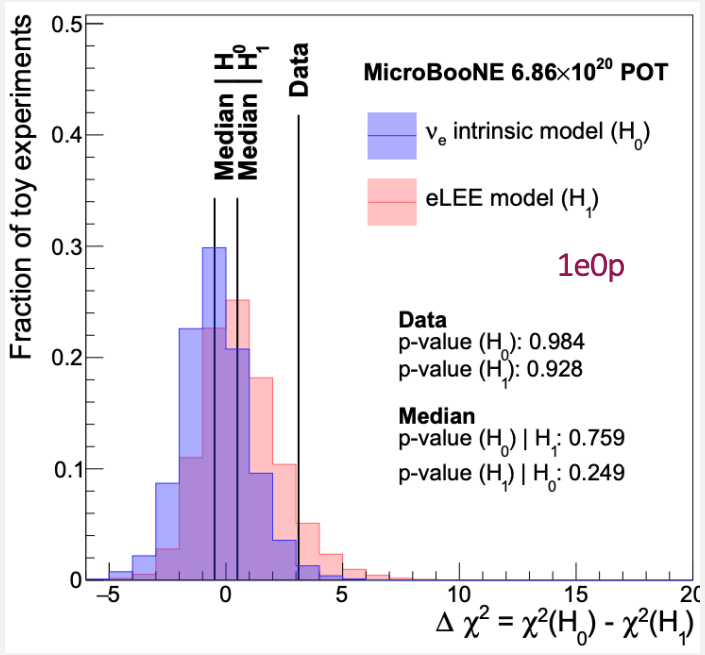
single photon search

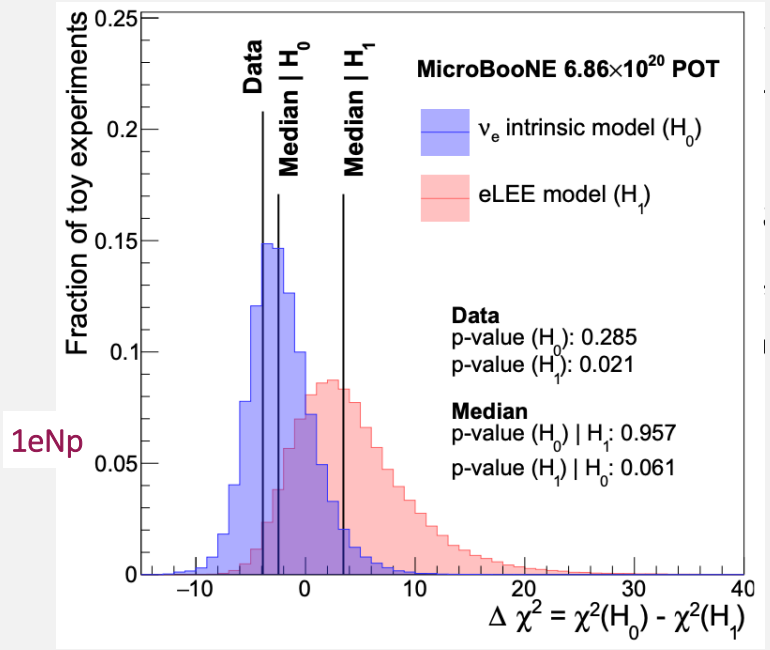


Slide credit: Mark R-L


MicroBooNE Observed (1, 2σ)
Expected, no eLEE (2σ)
MiniBooNE approx. (±1σ)
eLEE Signal Strength (x)
10
2.0
1.5
1.0
0.5
0.0
1e1p CCQE
1eNp0π
1e0p0π
1eX







assuming $eLEE_{x=0}$ hypothesis is true