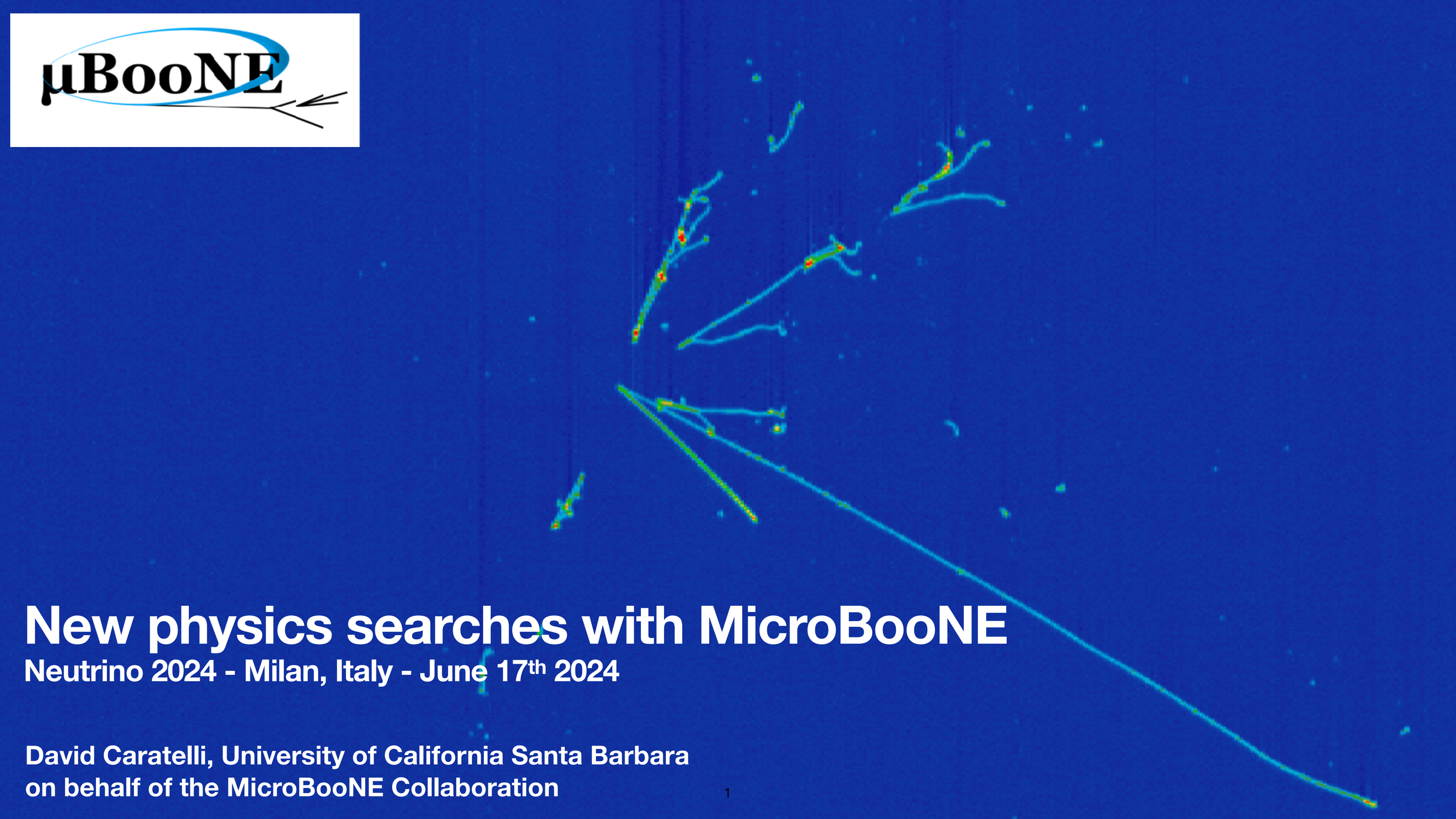


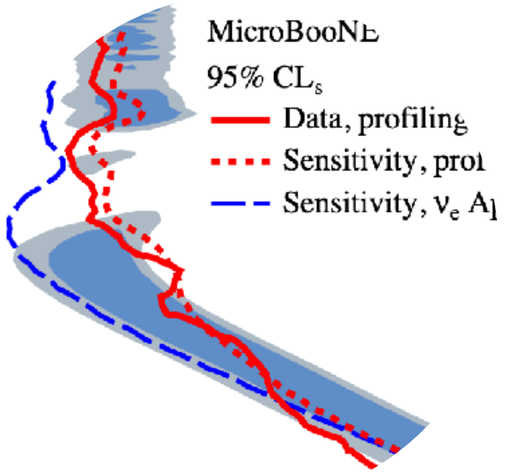
New physics searches with MicroBooNE

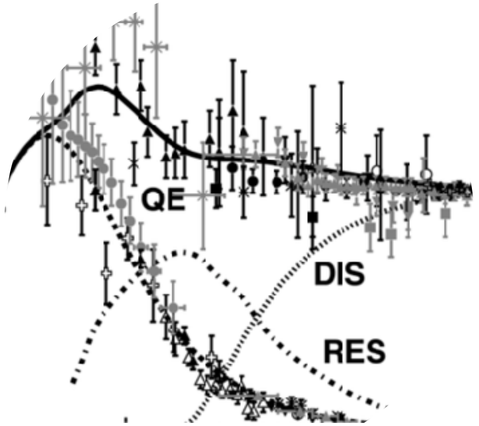
Neutrino 2024 - Milan, Italy - June 17th 2024

David Caratelli, University of California Santa Barbara
on behalf of the MicroBooNE Collaboration

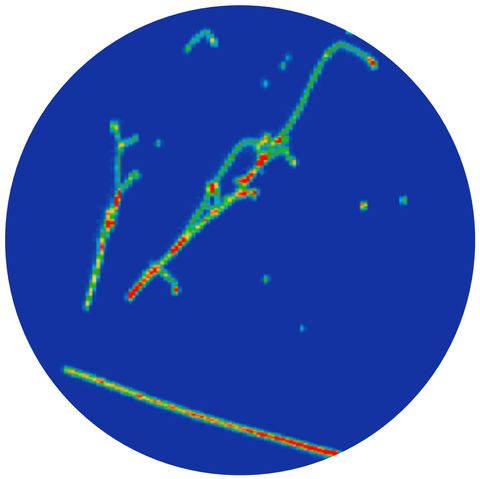
MicroBooNE's Physics Program

Beyond the Standard
Model physics searches





ν - Ar scattering

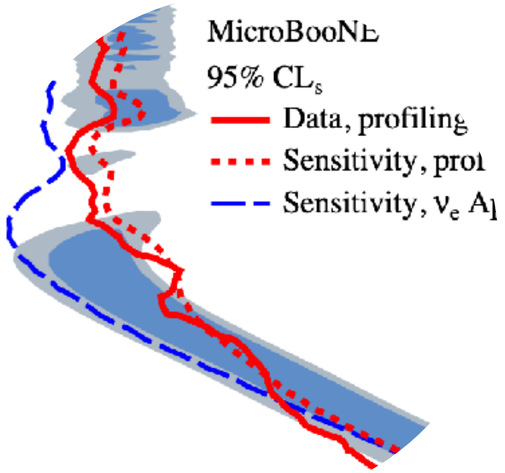


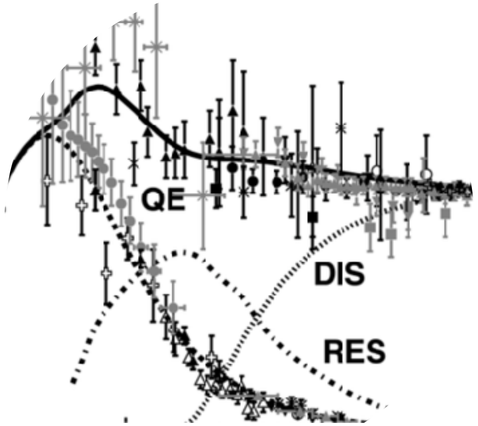
advancing LArTPC
technology capabilities

μBooNE

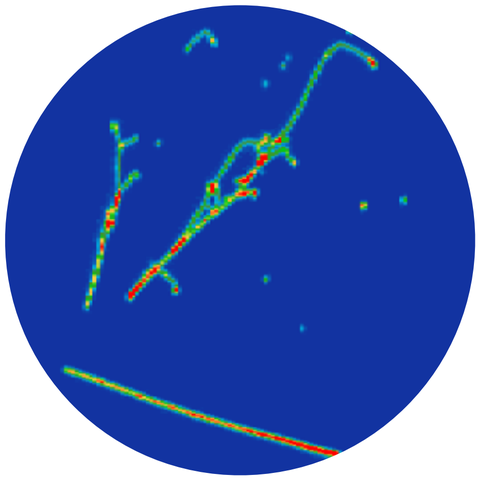
MicroBooNE's Physics Program

Beyond the Standard Model physics searches





ν - Ar scattering

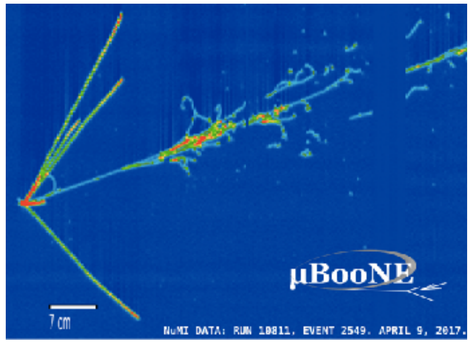


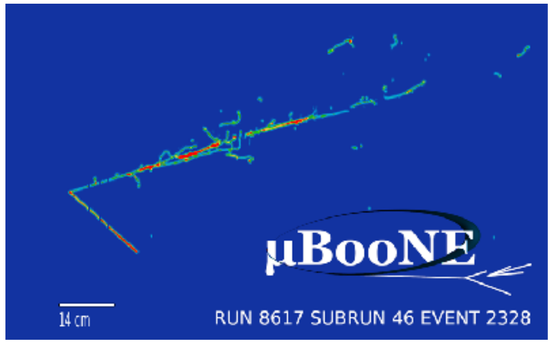
advancing LArTPC technology capabilities

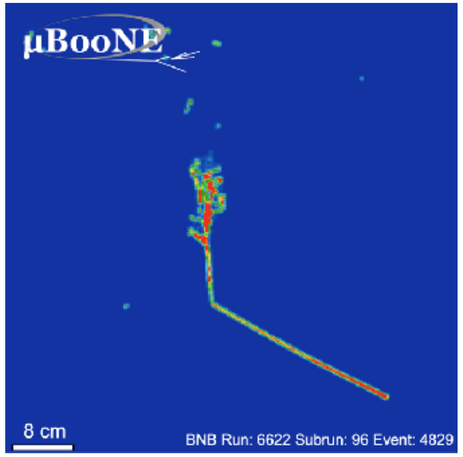
See Afroditi Papadopoulou's talk on Friday!

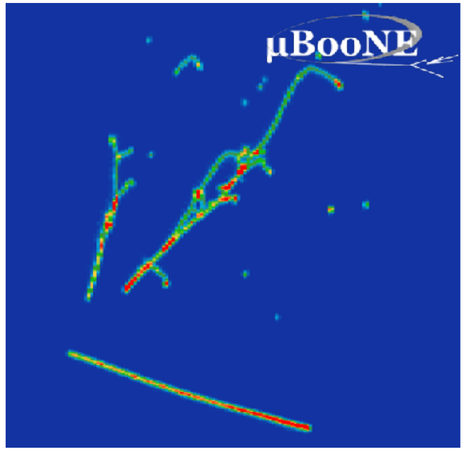
μBooNE

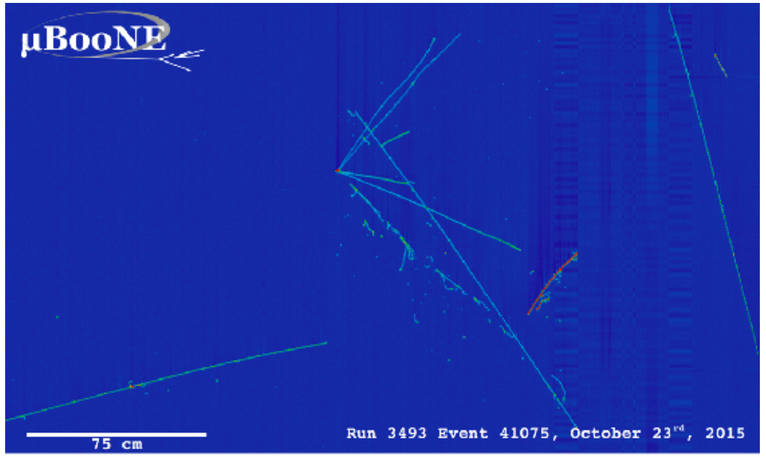
MicroBooNE's LArTPC detector

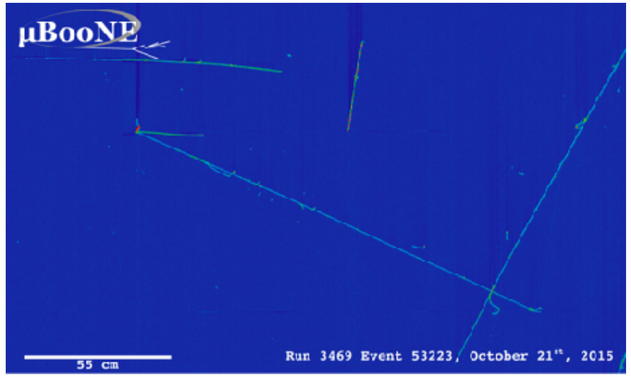


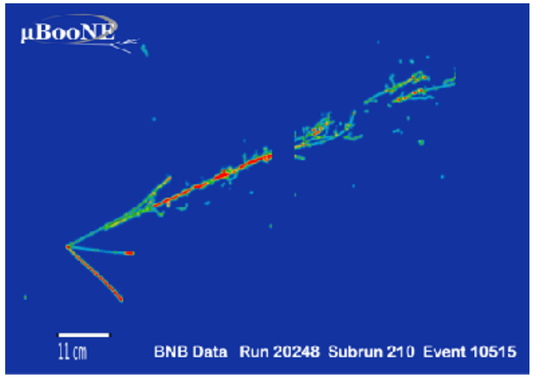


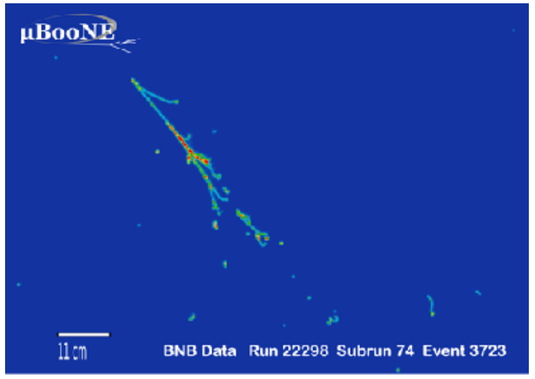










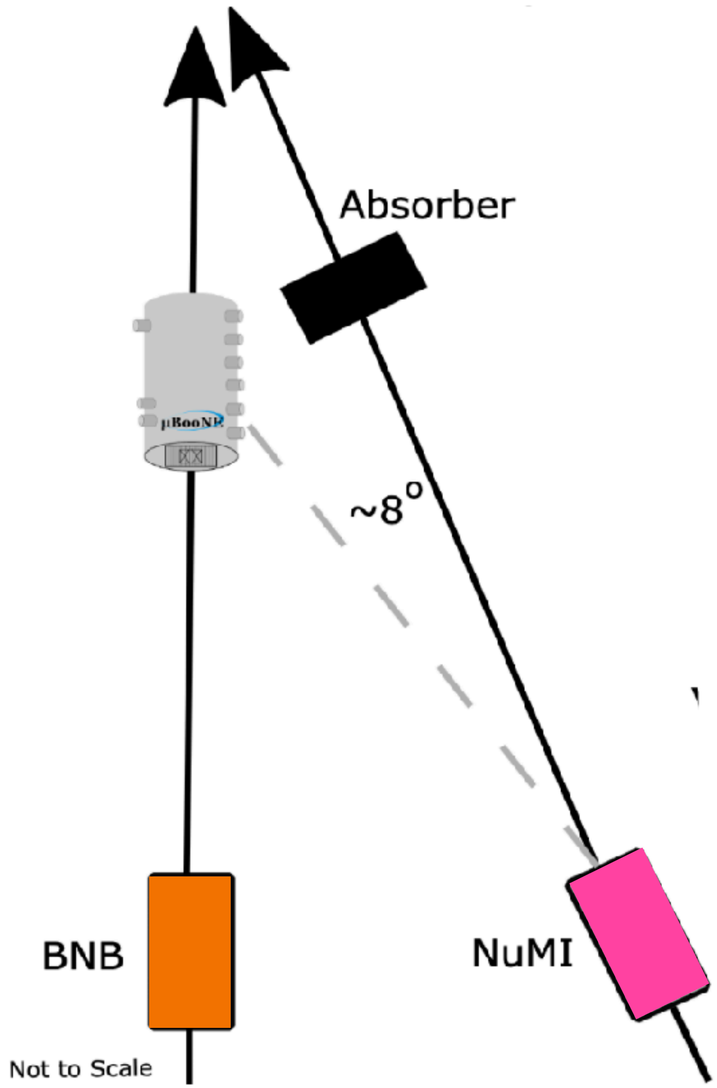


μBooNE

Liquid Argon Time Projection Chamber

- millimeter spatial resolution
- excellent calorimetry & Particle ID

MicroBooNE's neutrinos: BNB & NuMI



Booster Neutrino Beamline:

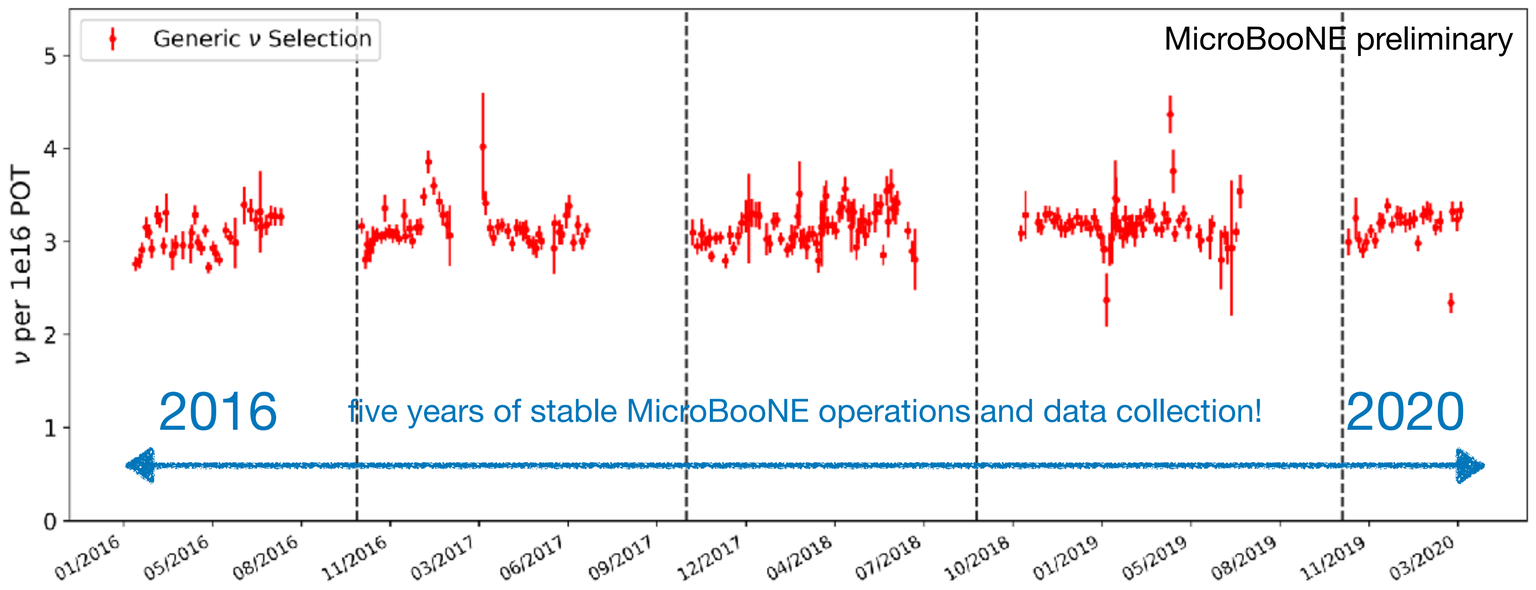
- on-axis
- 99.5% ν_μ / 0.5% ν_e
- 0.1 - 1 GeV energy
- 470 meter baseline

NuMI:

- 8 degrees off-axis
- 95% ν_μ / 5% ν_e
- 50/50 $\nu/\bar{\nu}$
- Flux from target and absorber

O(500k) neutrino interactions collected

Five years of neutrino data!



Longest continuously operating LArTPC

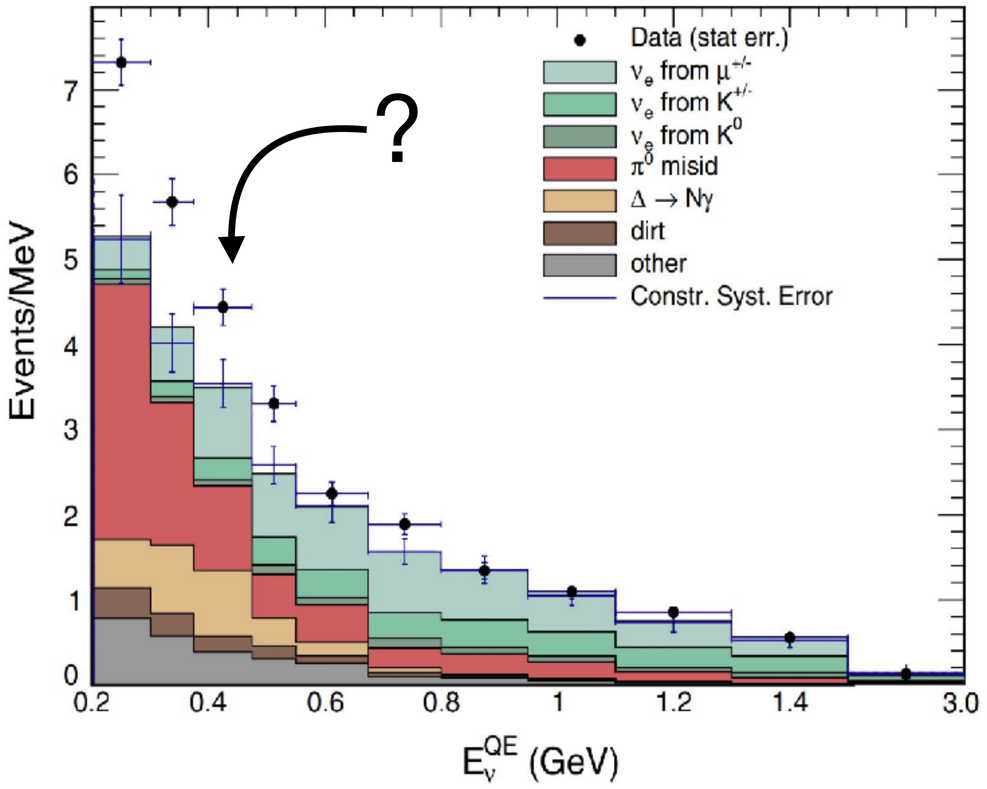
Five years of data @ Fermilab '15 - '20

195 collaborators from 38 institutions

MicroBooNE papers on iNSPIRE

MicroBooNE's BSM physics program

Phys. Rev. D 103, 052002 MiniBooNE Collab.



Investigate the MiniBooNE "Low Energy Excess"

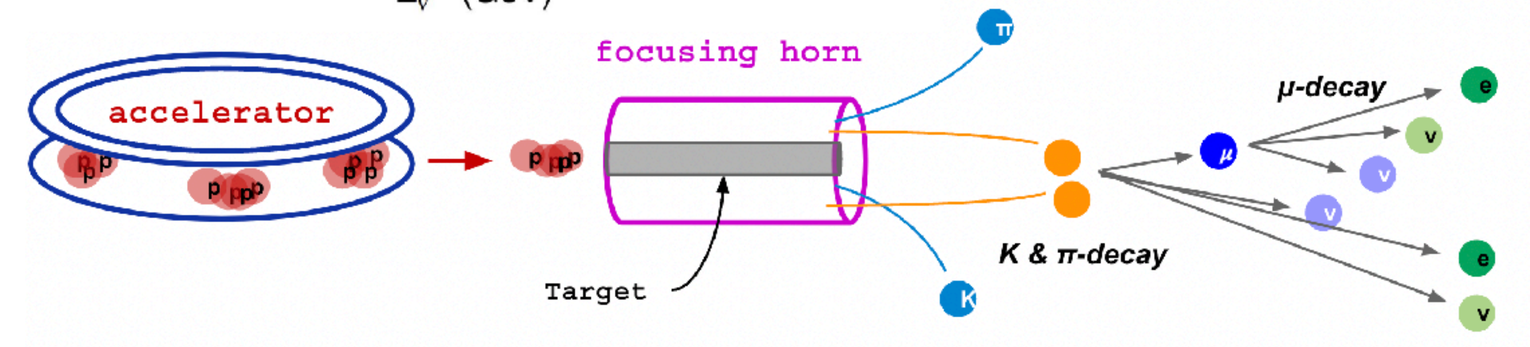
Outstanding anomaly for > 10 years

same BNB beam
same baseline
new detector!

broad physics program

Leverage BNB & NuMI beam lines

search for feebly interacting BSM particles



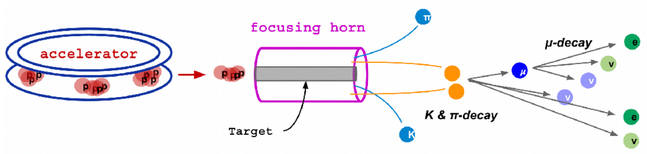
$\chi\bar{\chi}$ ------->

νN --->

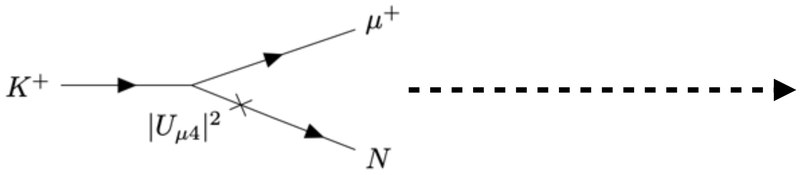
Z' ------->

Heavy Neutral Lepton searches

New Results!

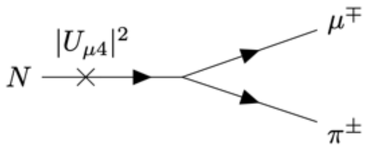


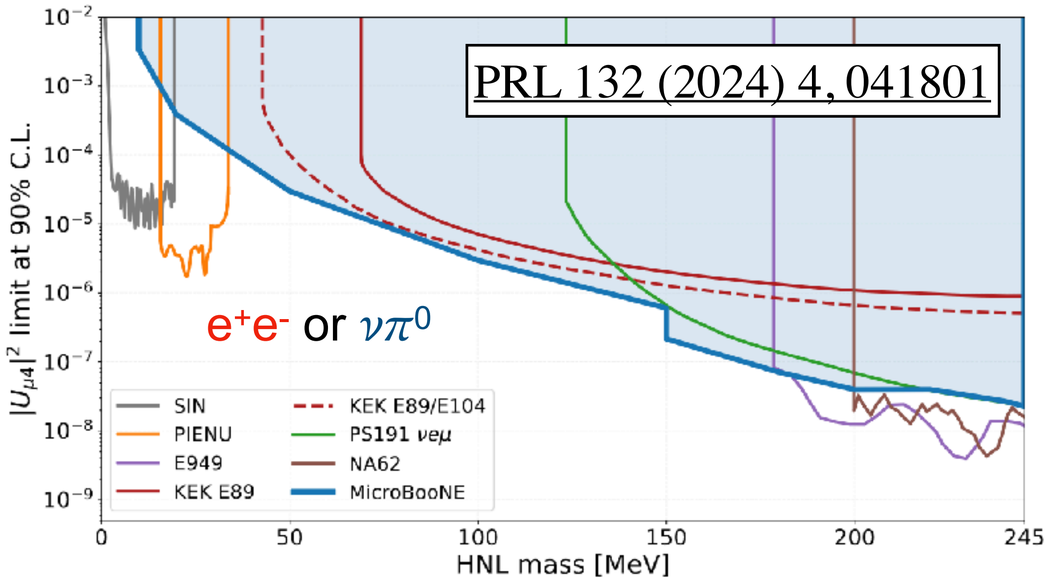
produced in beam via mixing



μBooNE

decay in the detector



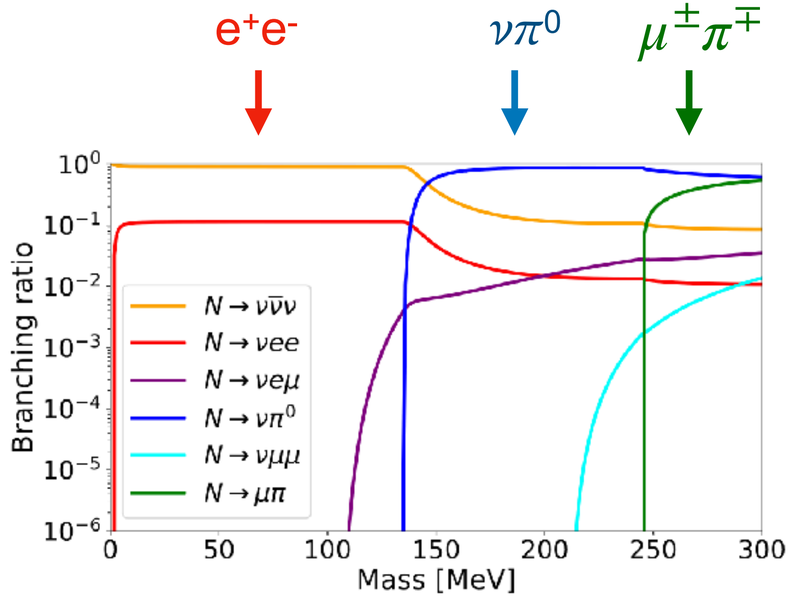


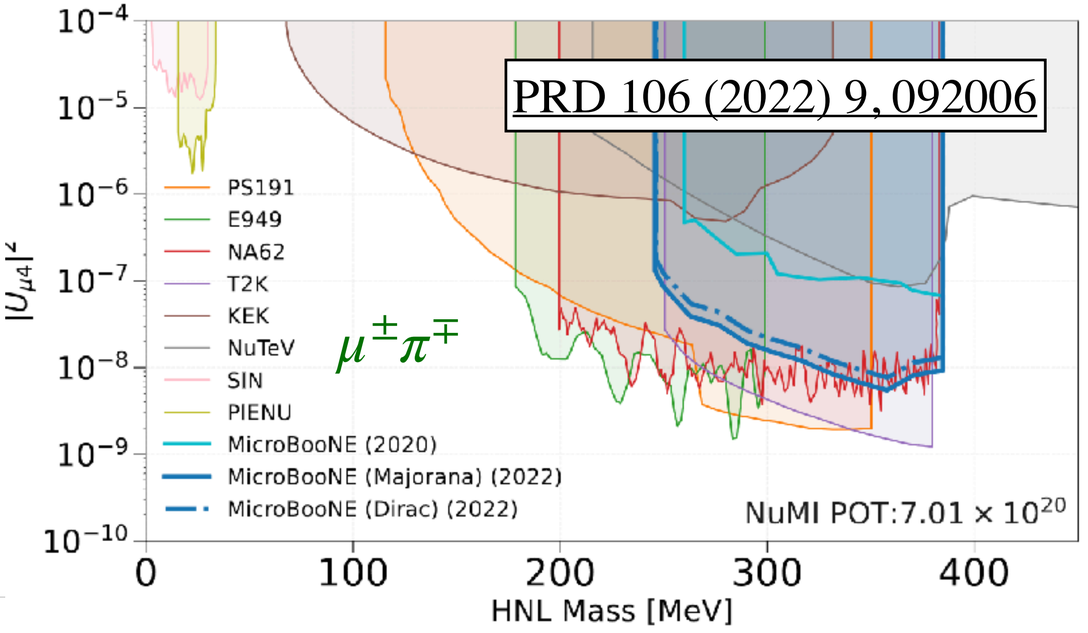
Heavy Neutral Leptons tied to:
- origin of neutrino mass
- Baryon asymmetry
- Dark Matter

Improve on past uB results:

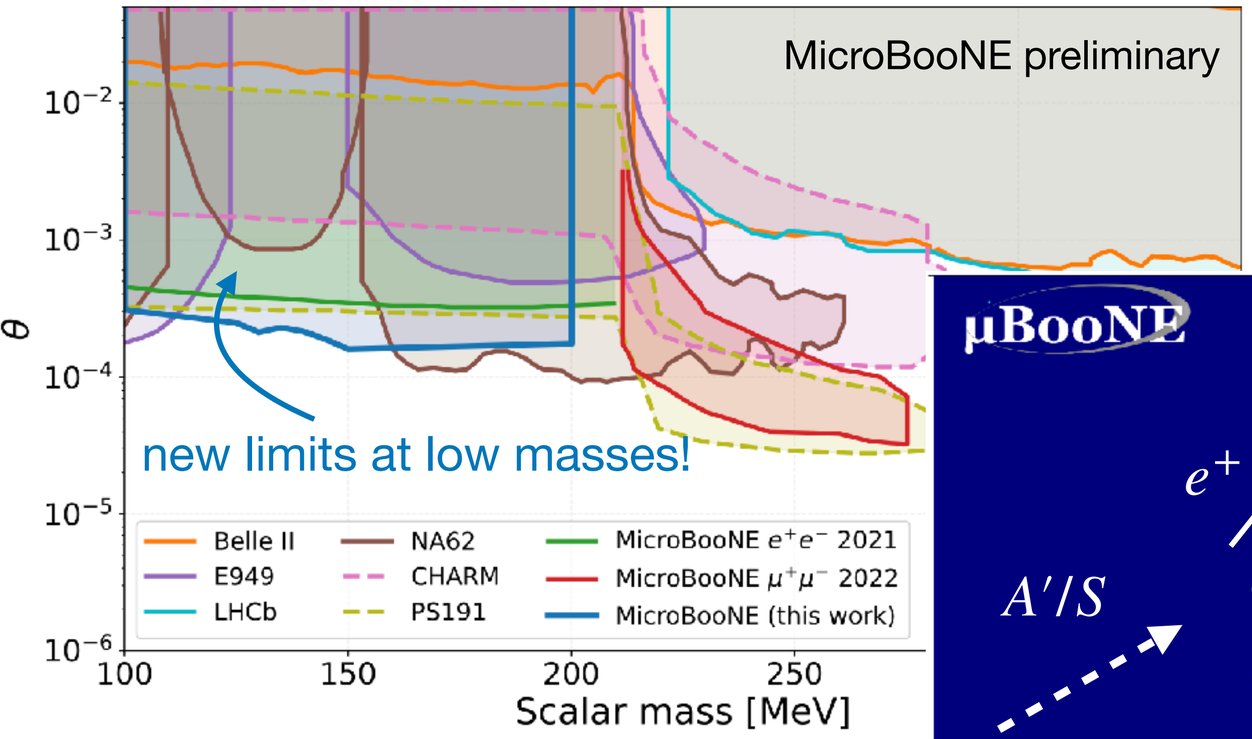
- NuMI absorber
- e^+e^- / π^0 sensitive to lower HNL masses.

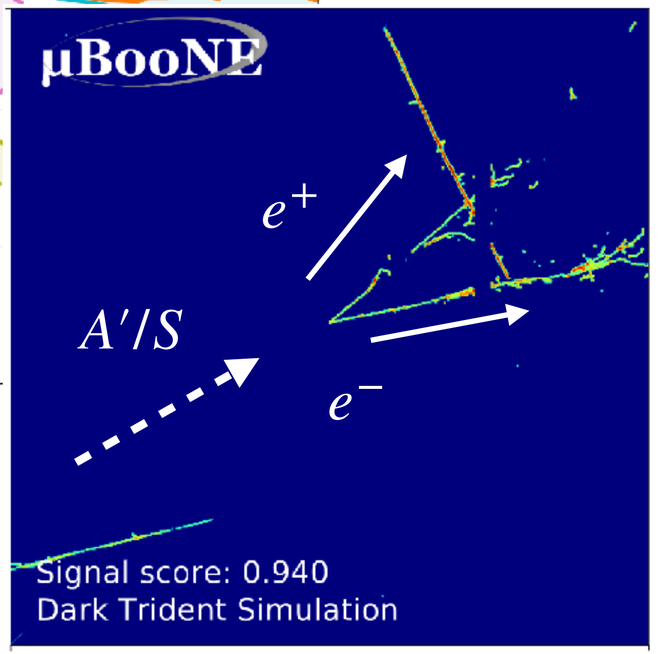
leading limits at low mass

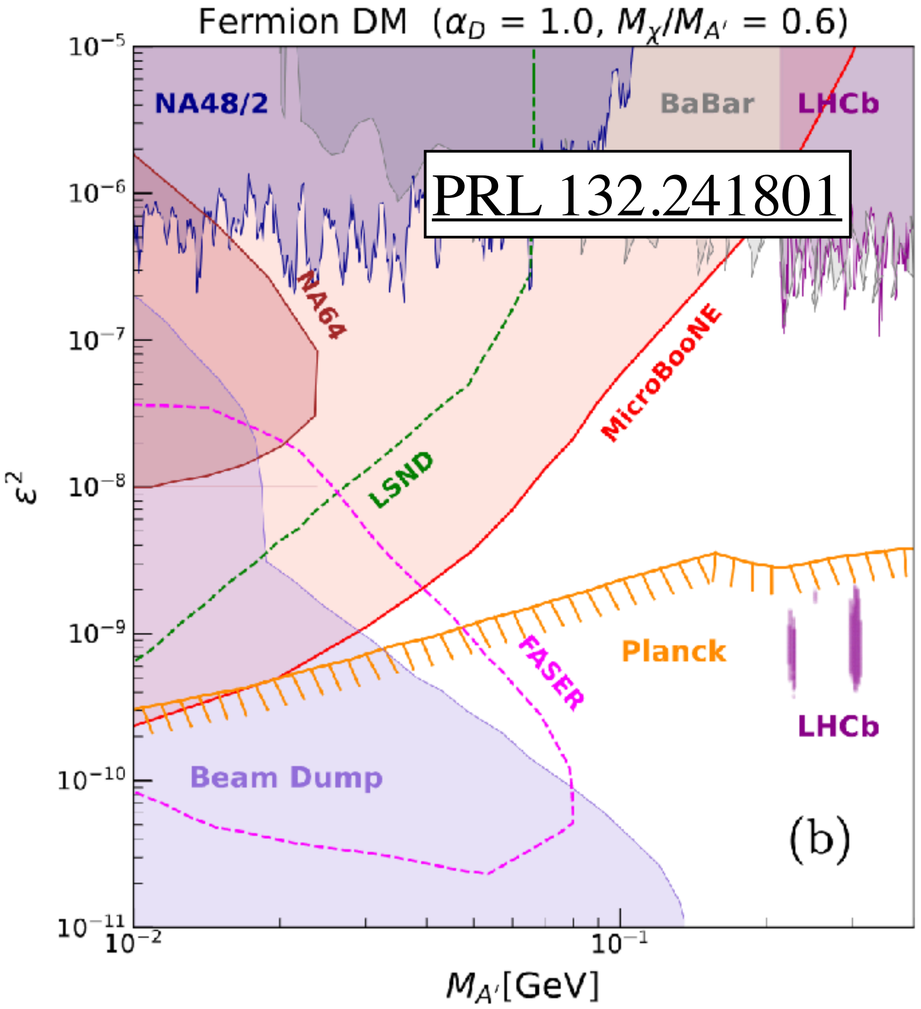




Dark Tridents & Higgs Portal Scalars New Results!







sub-GeV **Dark Sector** searches:

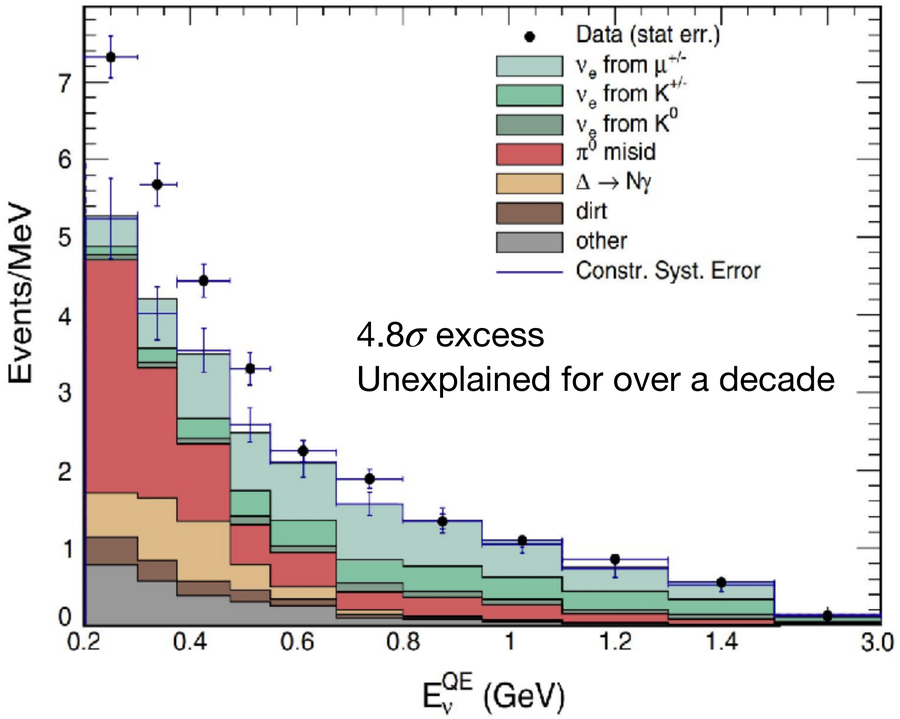
Dark Tridents: “vector portal”
Higgs Portal Scalar: “Higgs portal”

Can decay to e^+e^- final-state in TPC

“Dark Sector Searches with MicroBooNE”
POSTER #634 [Friday]

“Low Energy Excess” search

Phys. Rev. D 103, 052002 MiniBooNE Collab.



ν_e ? ν_s ? single-γ ?

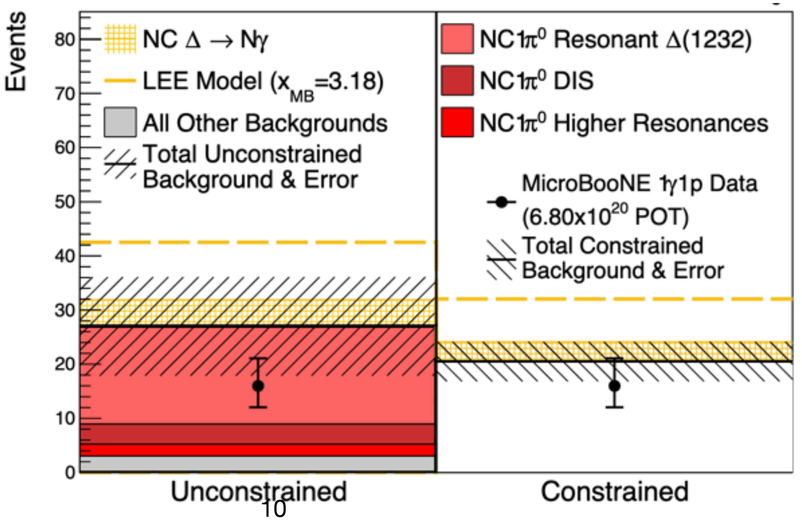
e^+e^- ?

“Low Energy Excess Searches” POSTER #628 [Tuesday]

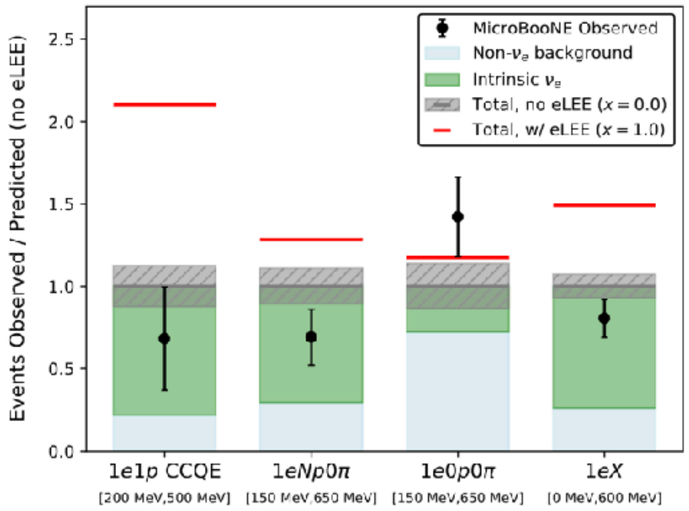
Expanding on MicroBooNE’s ‘21 results:

- new e^+e^- BSM-focused analyses
- comprehensive single-γ searches
- expanded ν_e excess analysis

PRL 128 (2022) 111801



PRL 128 (2022) 24, 241801



LEE Search: BSM e^+e^-

Dark Neutrinos decaying to e^+e^- pairs.

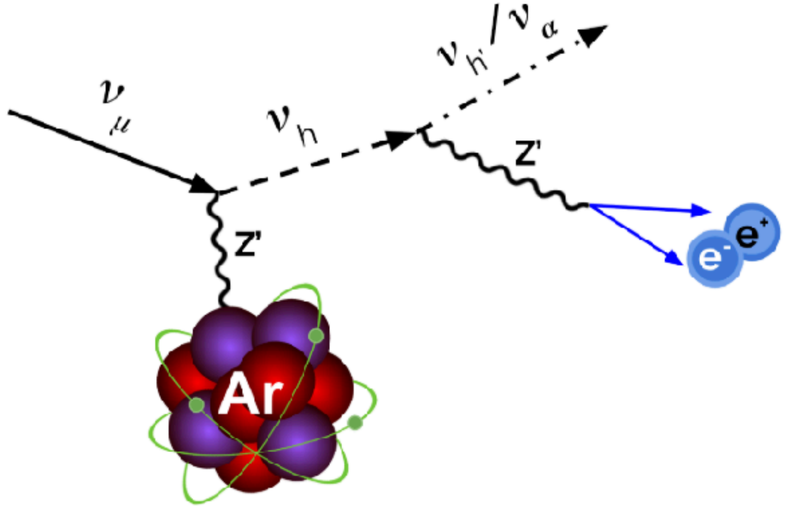
Based on:

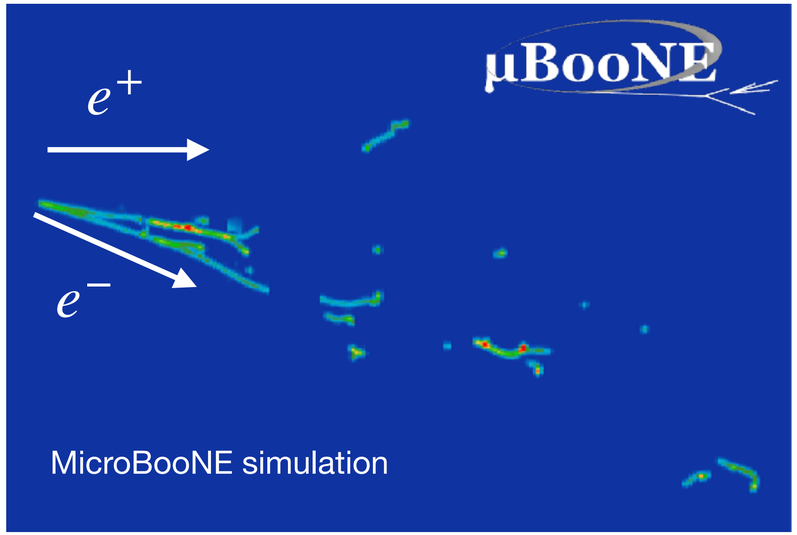
Ballet, Pascoli, Ross-Lonergan
PRD 99 (2019) 071701

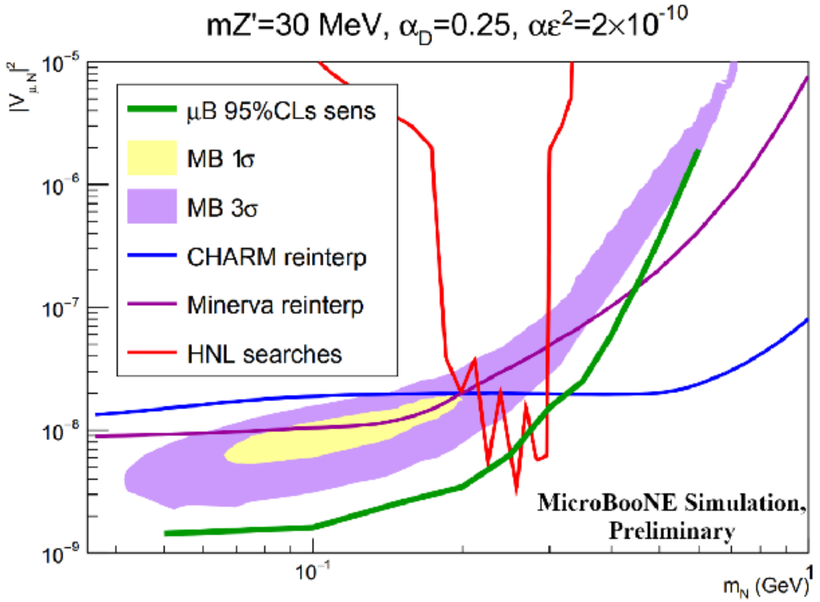
Bertuzzo, Jana, Machado, Zukanovich Funchal
PRL 121 (2018) 24, 241801

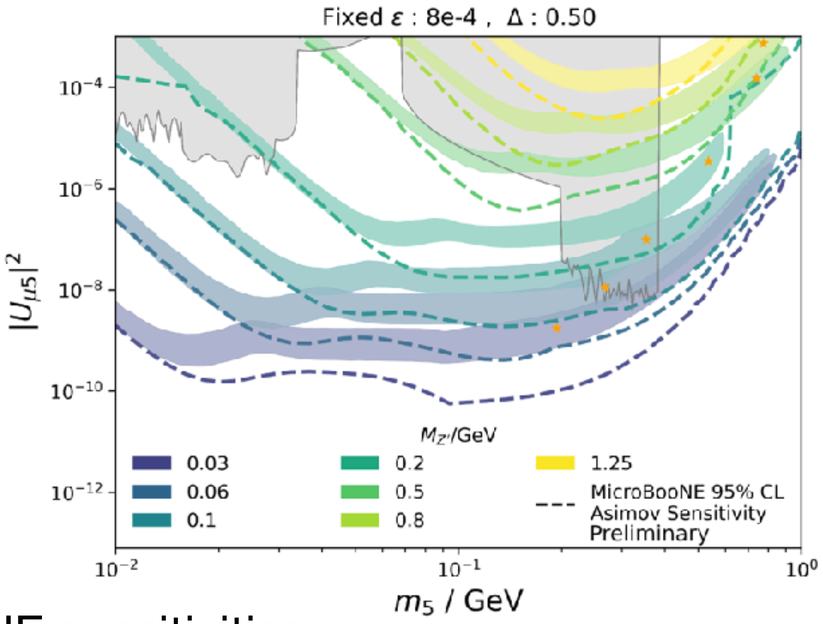
Sensitive to MiniBooNE allowed region for these models at > 95% CL

More details at:
MICROBOONE-NOTE-1124-PUB





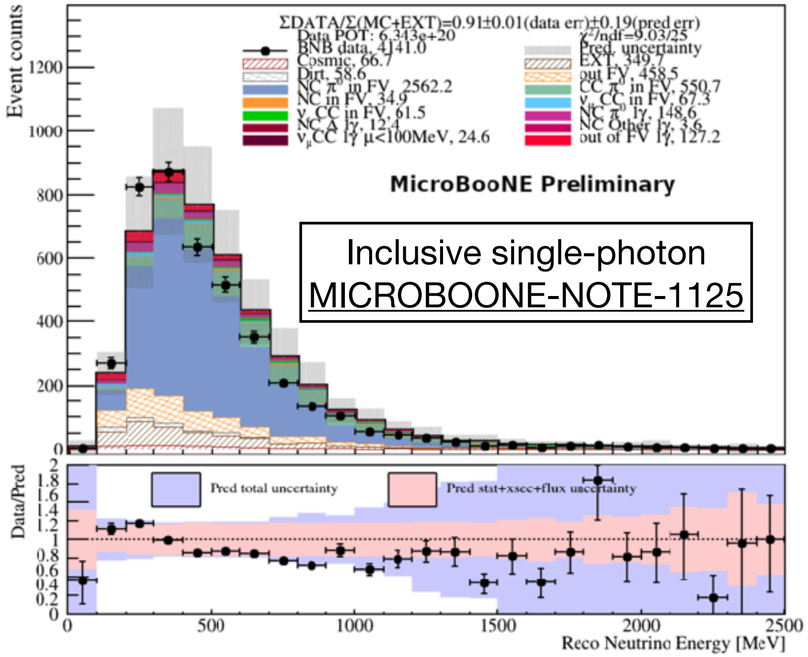




MicroBooNE sensitivities

"Low Energy Excess Searches" POSTER #628 [Tuesday]

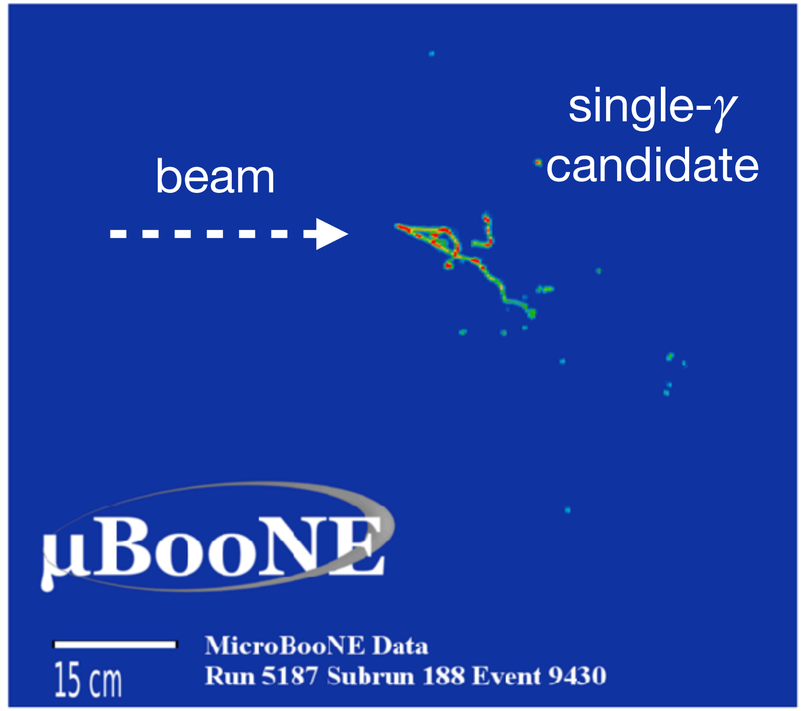
LEE Search: single photons

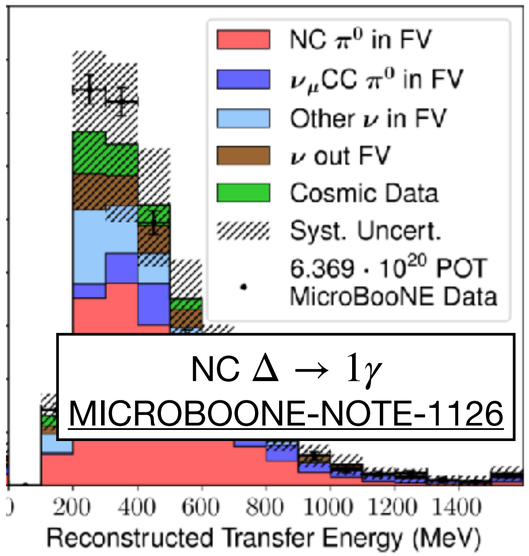


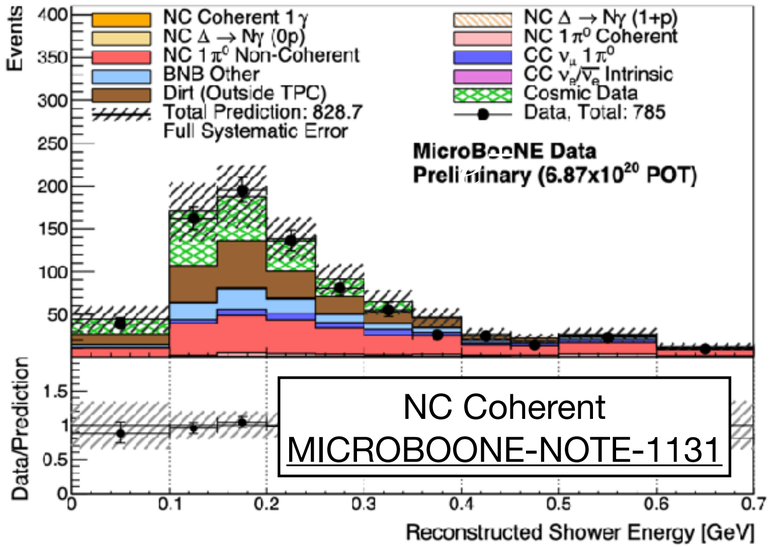
Past MicroBooNE results focused on NC $\Delta \rightarrow 1\gamma$ SM background

Three new analyses:

- NC coherent
- inclusive single-γ
- updated NC $\Delta \rightarrow 1\gamma$.







Now casting a wide net on γ-channel no matter the origin.

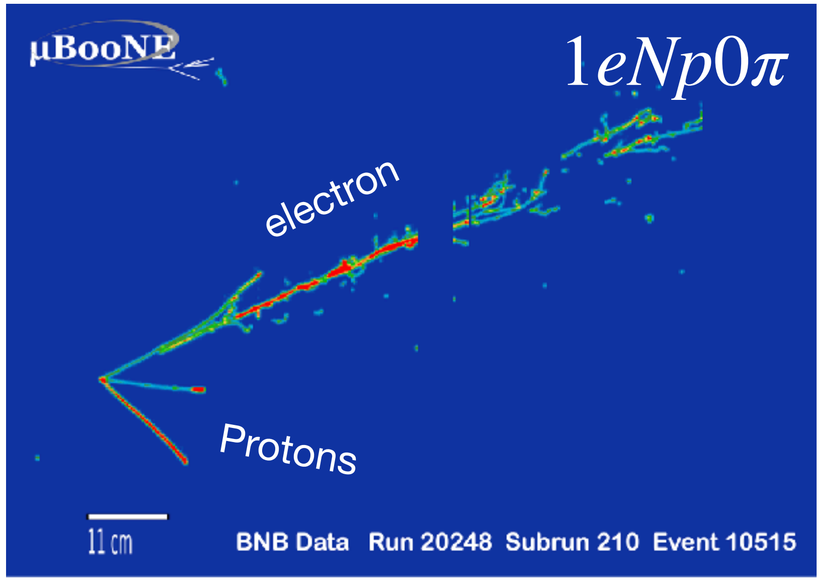
← NC π^0 rich sidebands for these analyses

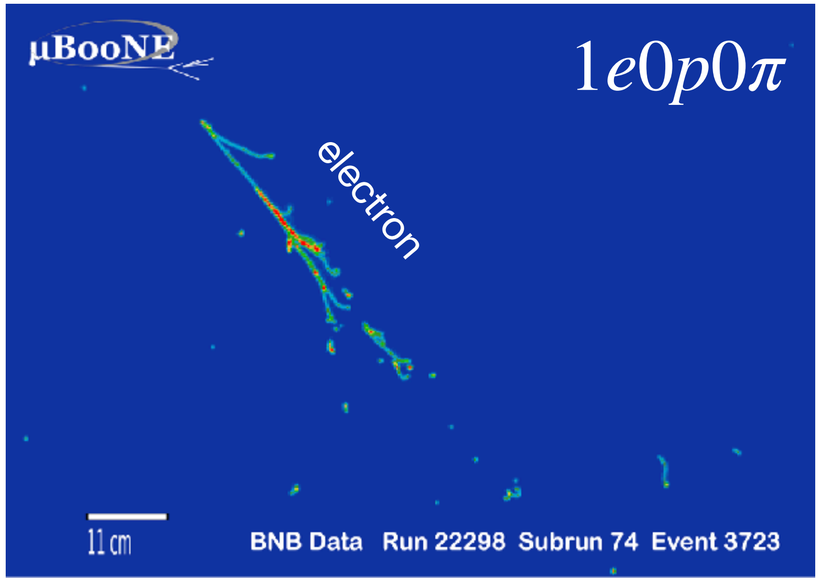
"Low Energy Excess Searches" POSTER #628 [Tuesday]

LEE Search: electron neutrinos New Results!

pionless ν_e LEE analysis

- same topology as MiniBooNE LEE
- update of PRD 105 (2022) 11, 112004



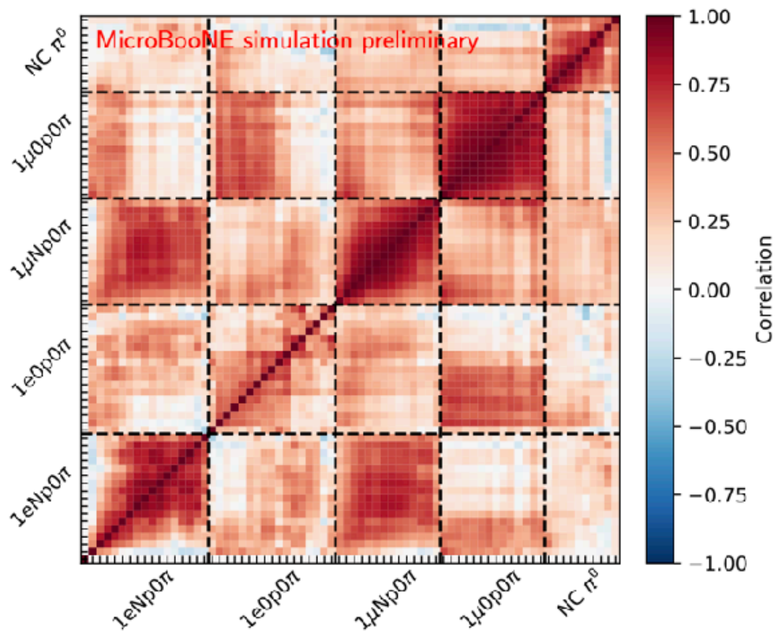


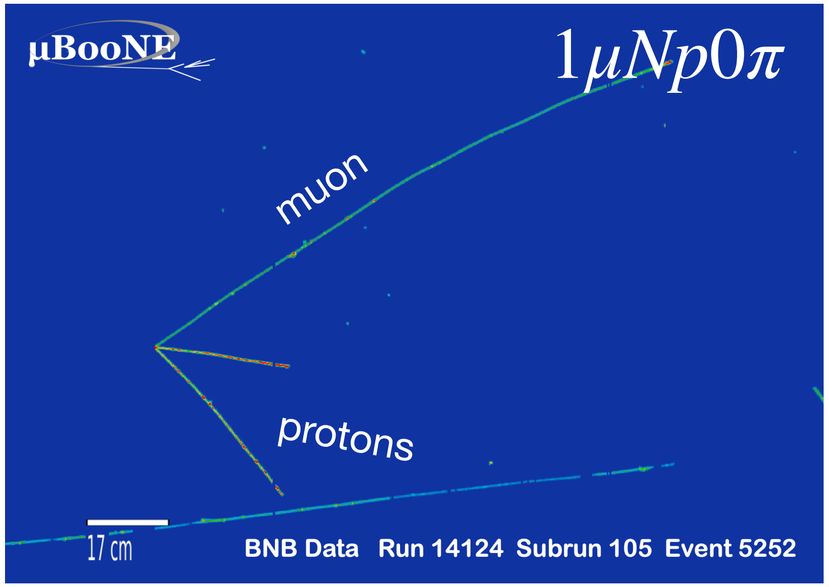
First analysis using data from all five runs of MicroBooNE (2016-2020)

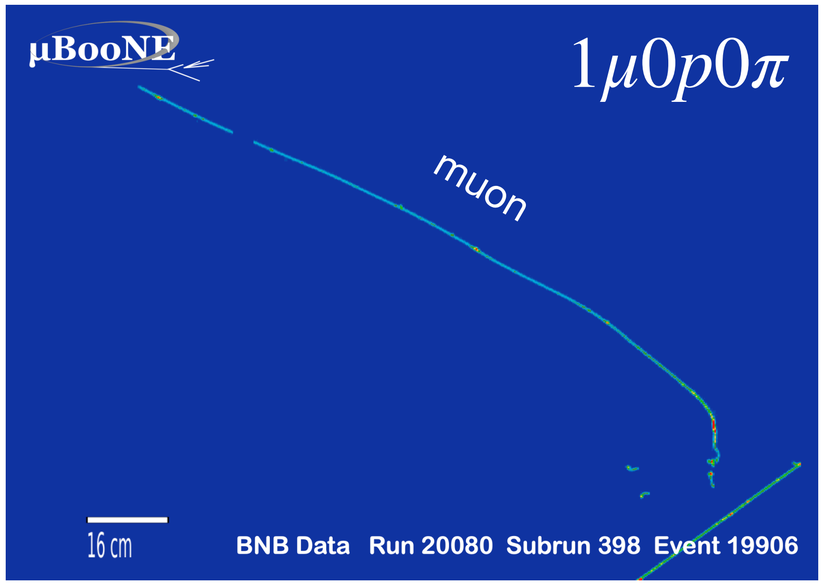
$6.8 \times 10^{20} \rightarrow 11.1 \times 10^{20}$ POT of BNB data

"Low Energy Excess Searches" POSTER #628 [Tuesday]

LEE Search: ν_e sideband constraint

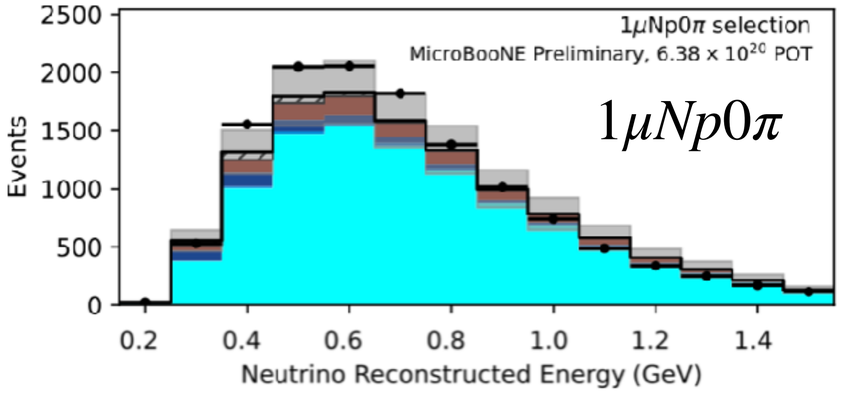


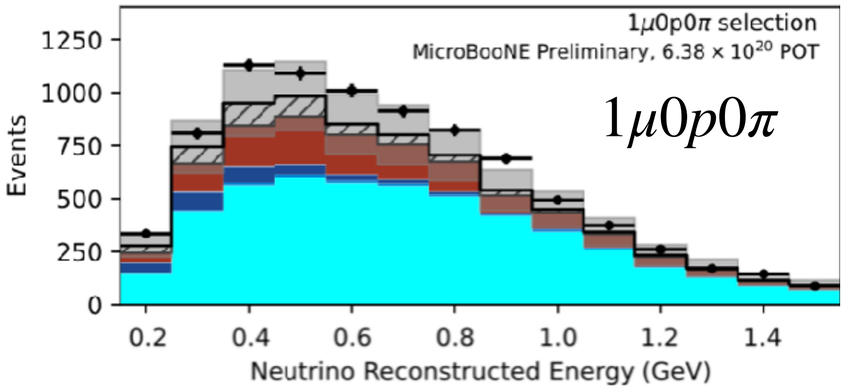




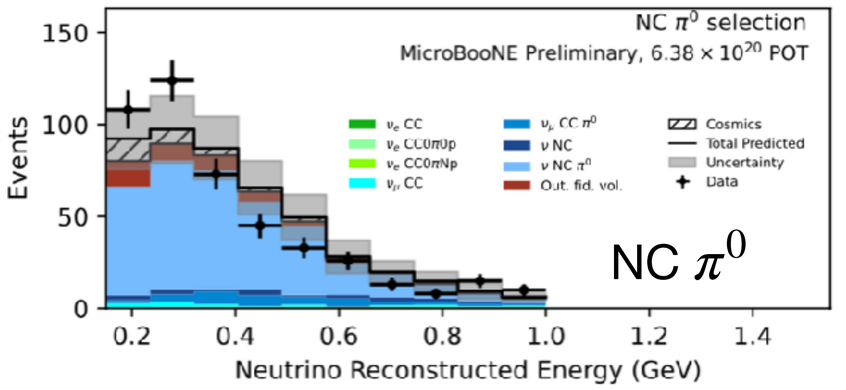
Updated ν_μ sidebands to better constrain intrinsic ν_e and background π^0

match hadronic final states of ν_e signal channel

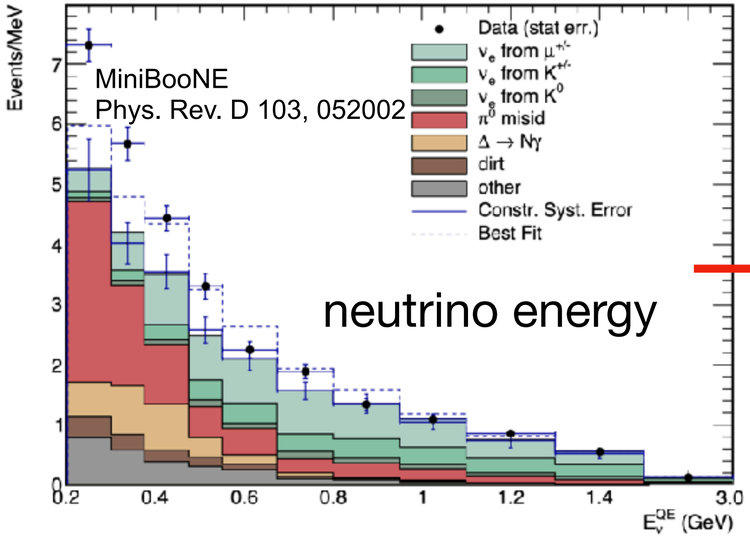


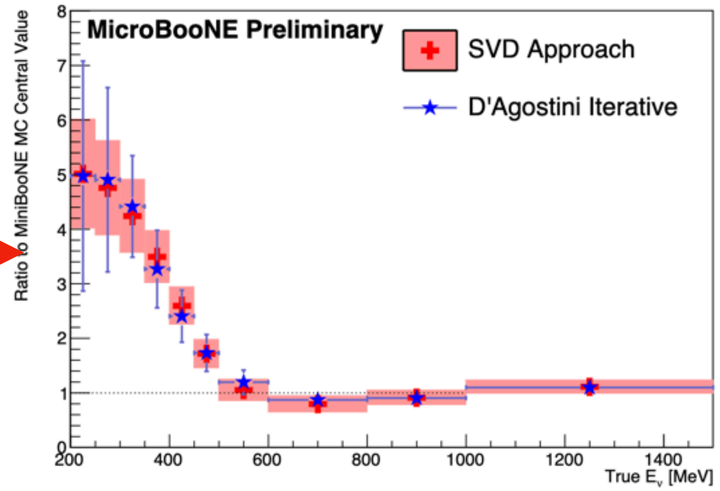


constrain dominant π^0 background

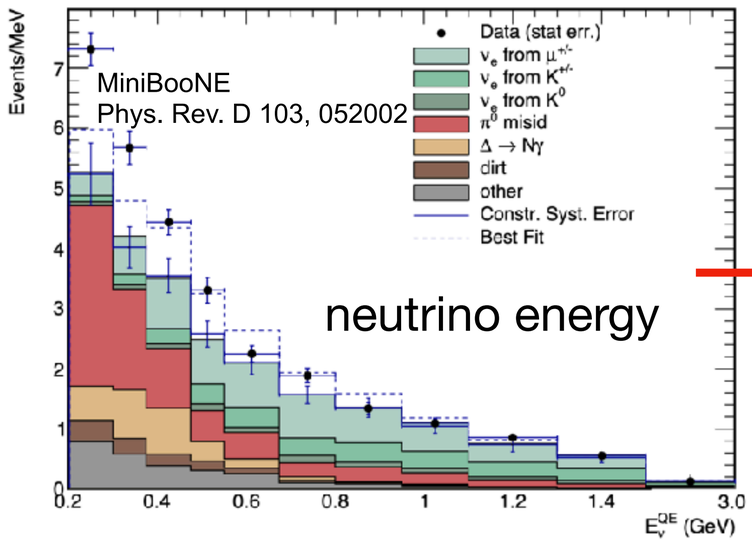


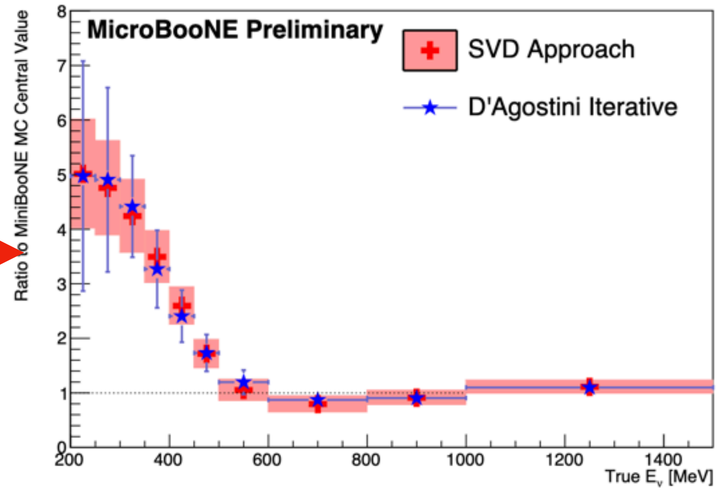
LEE Search: ν_e signal model(s)

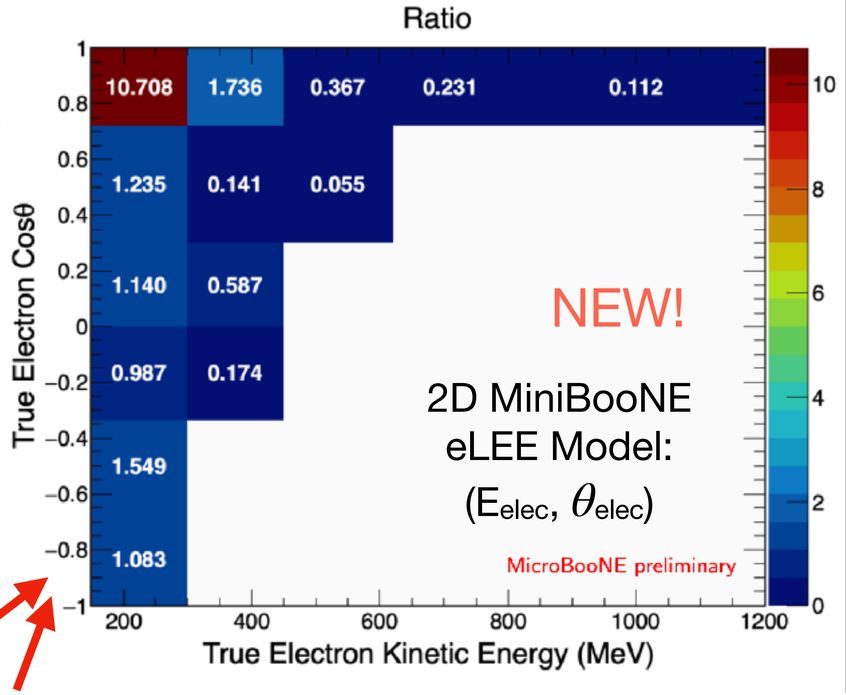


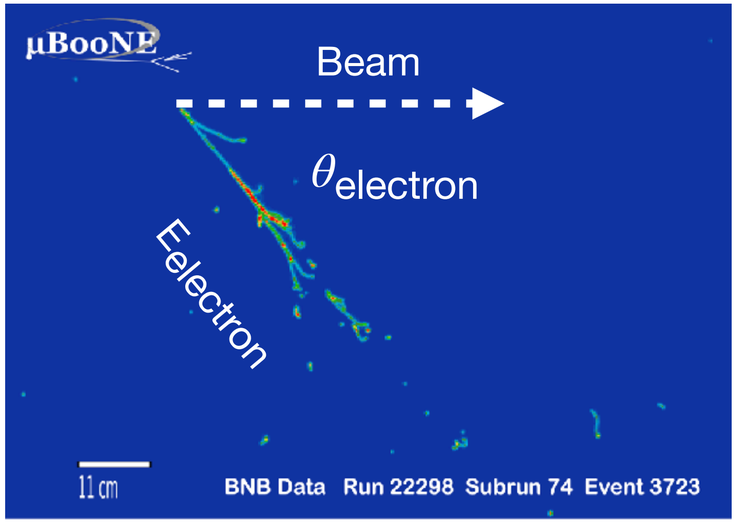


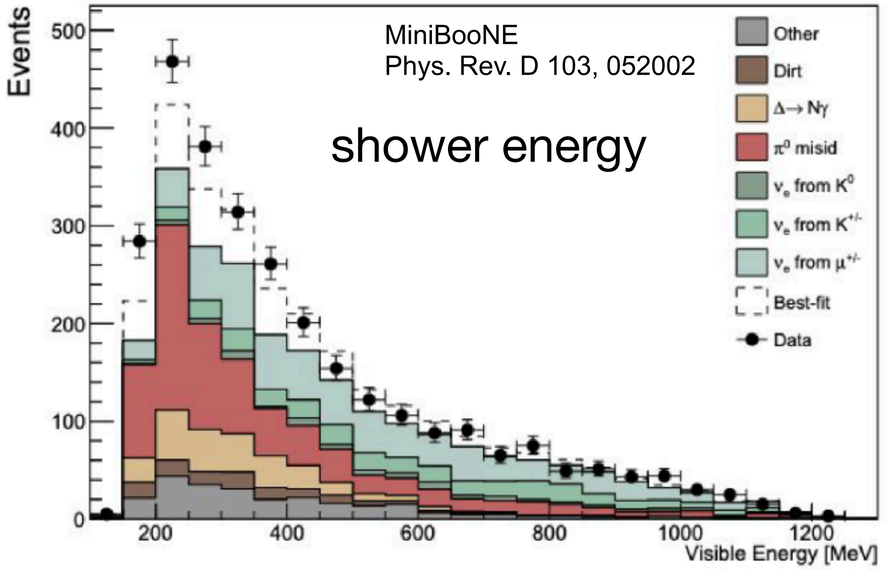
LEE Search: ν_e signal model(s)

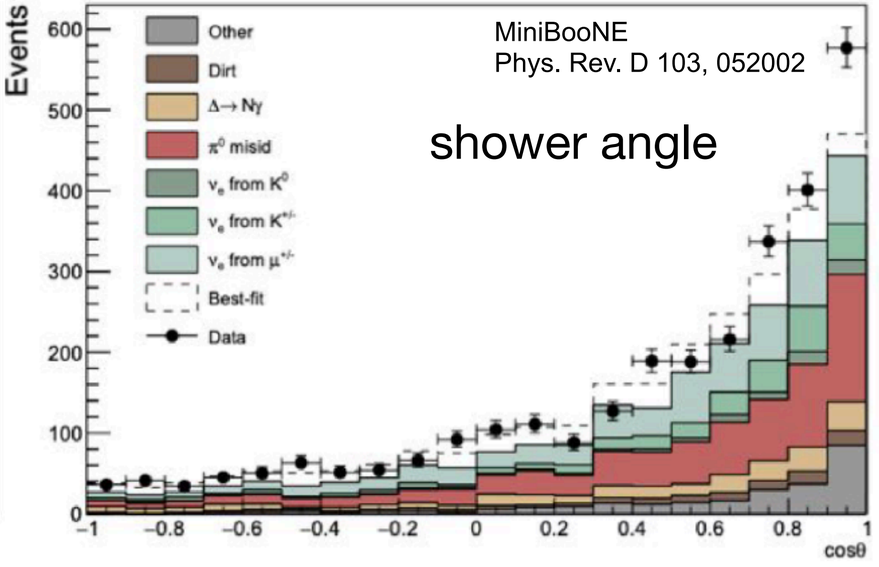






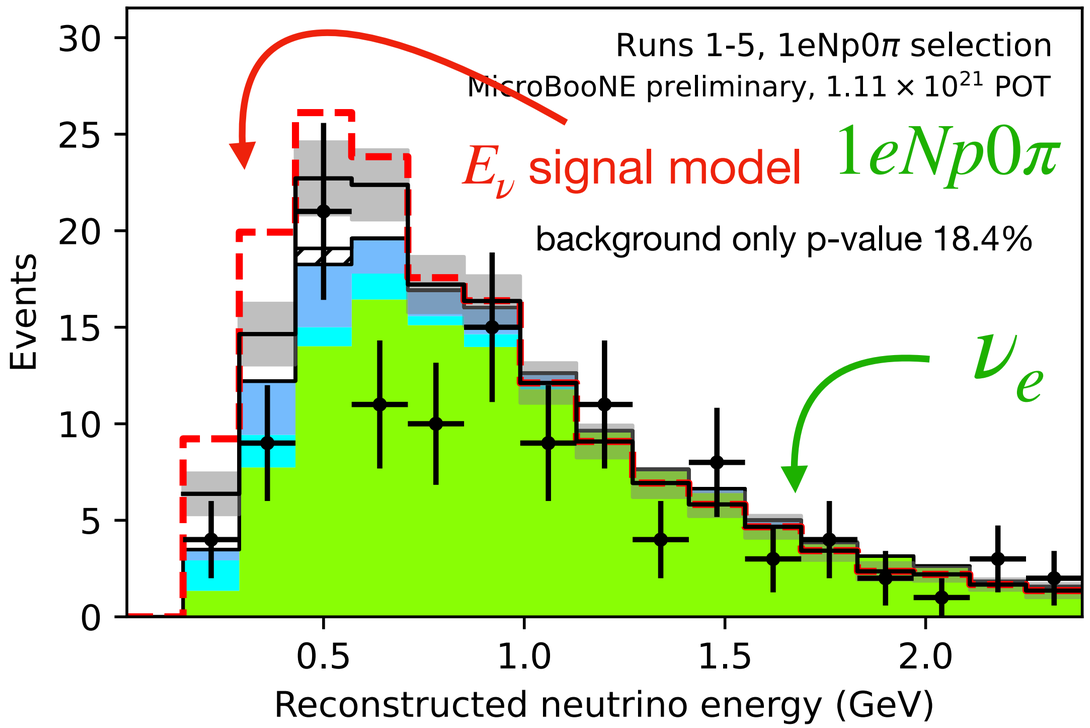


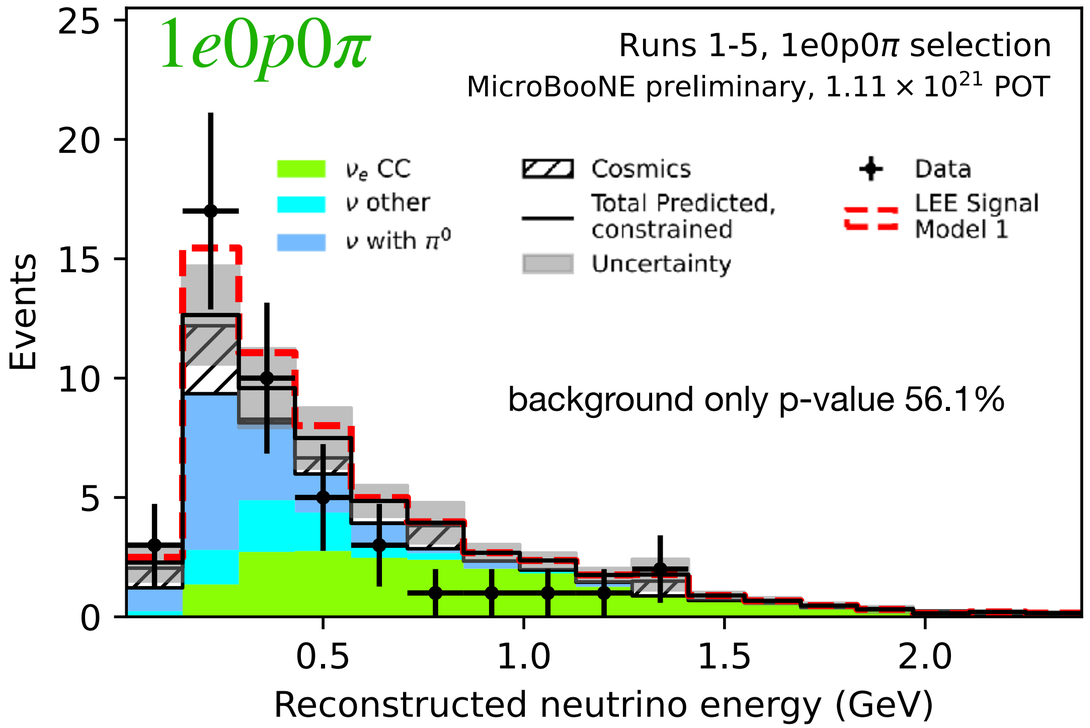




Complementary excess hypotheses expand analysis reach and help solidify conclusions.

LEE Search: ν_e results

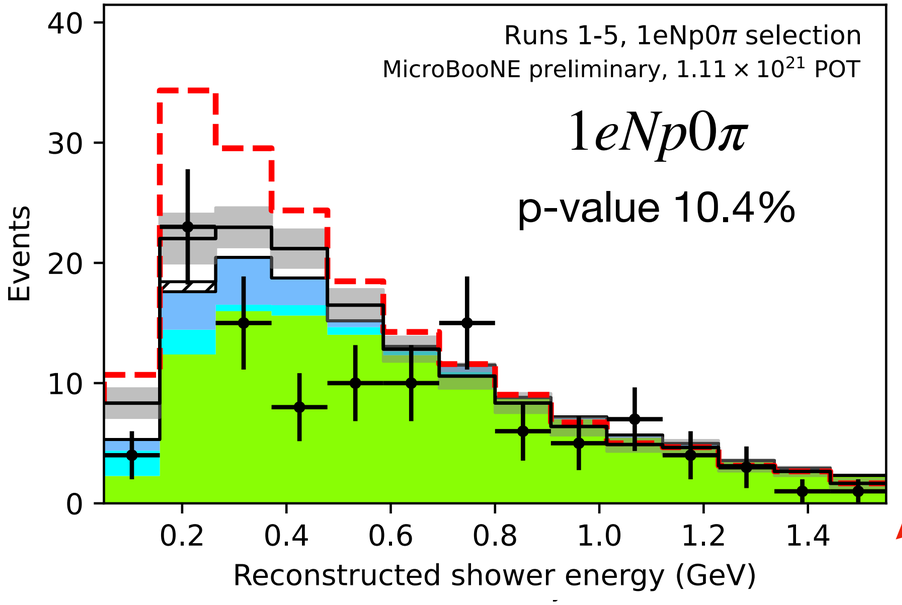


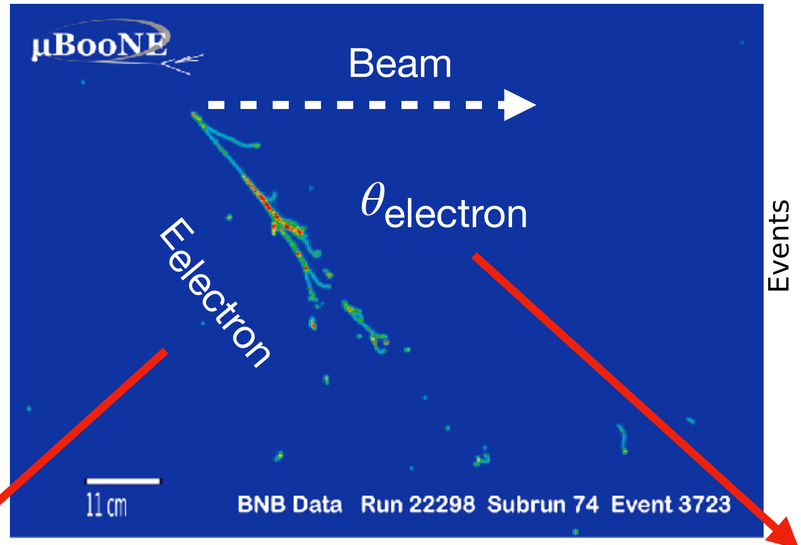


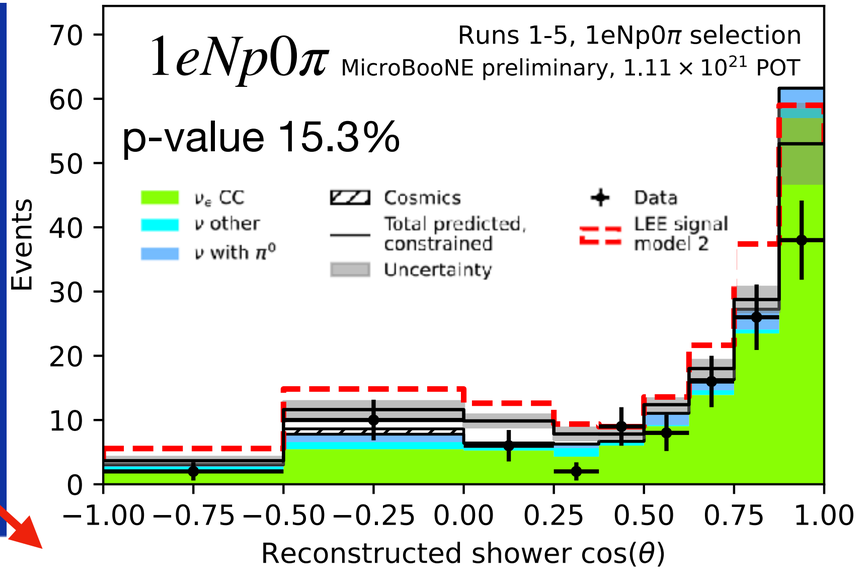
Test MB excess under hypothesis of a neutrino energy dependent ν_e rate scaling.

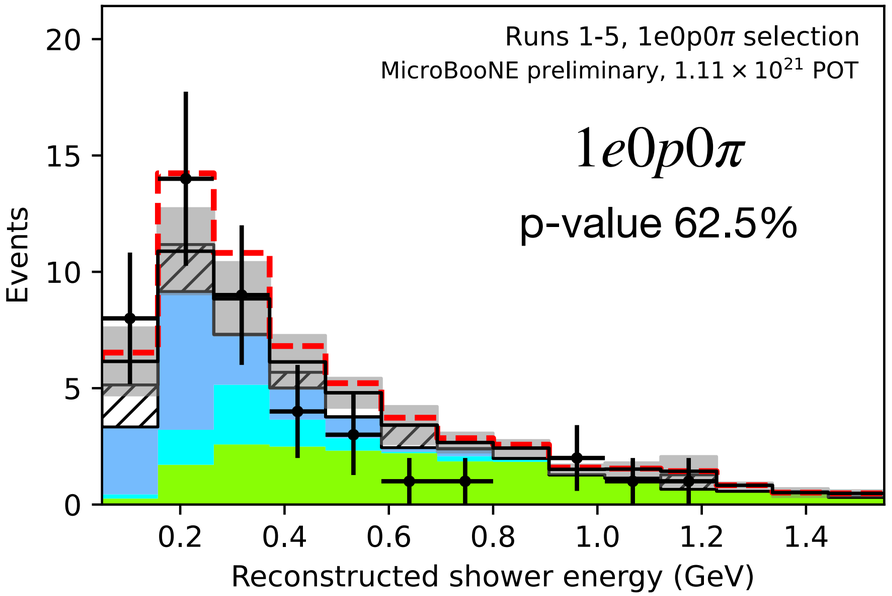
- Same model tested in first round of analysis.
- Data in overall agreement with intrinsic ν_e flux prediction.
- Rule out ν_e excess model @ 99.5% CL in Np & 0p combined channels.

LEE Search: ν_e results





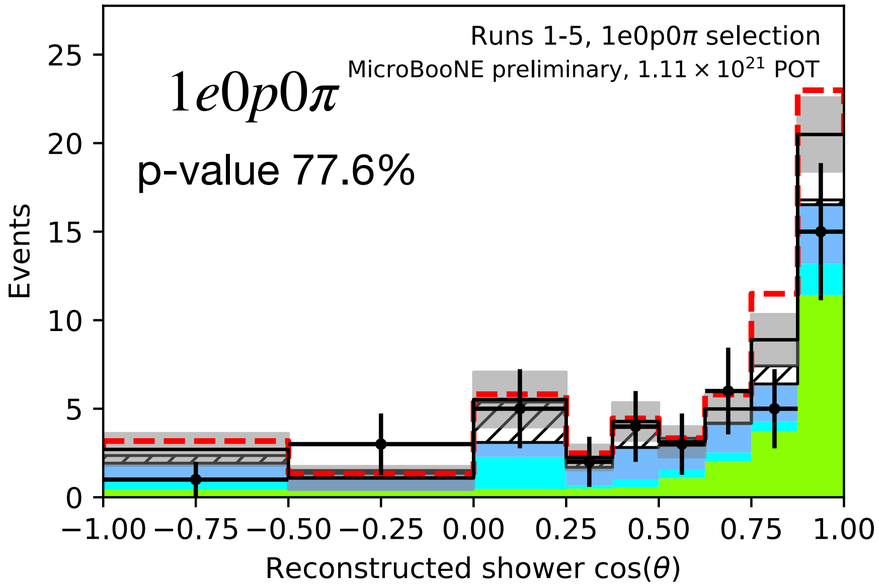




Shower kinematics-based model:

combined Np & 0p channels:

exclude model at > 99.9% CL



LEE Search: ν_e

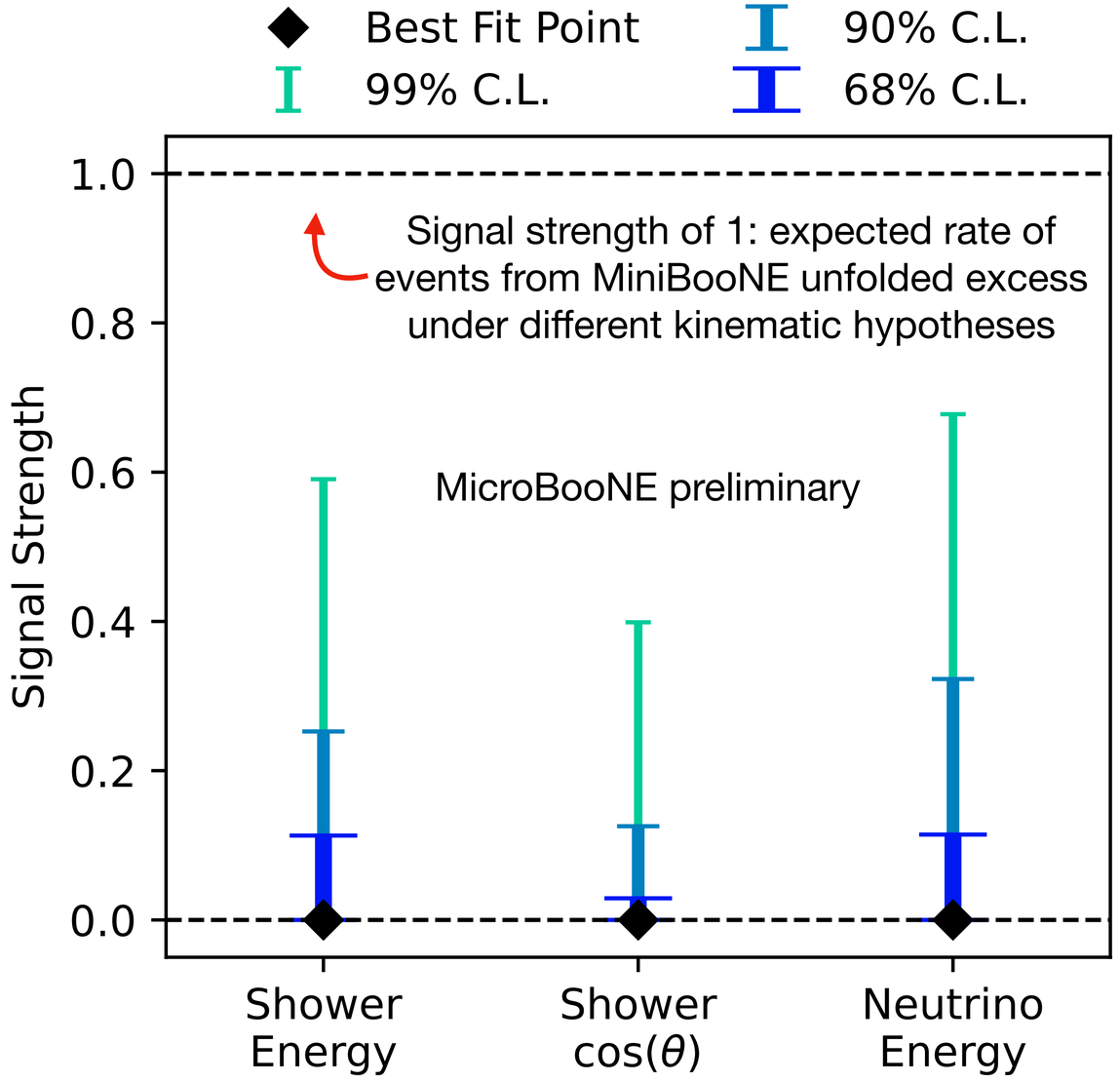
Expanded investigation of electron excess hypothesis:

- 6.86e20 —> 11.1e20 POT of data
- new constraint of intrinsic ν_e and π^0 backgrounds
- complementary signal hypotheses: E_ν, E_{elec}, and θ_{elec}

Results:

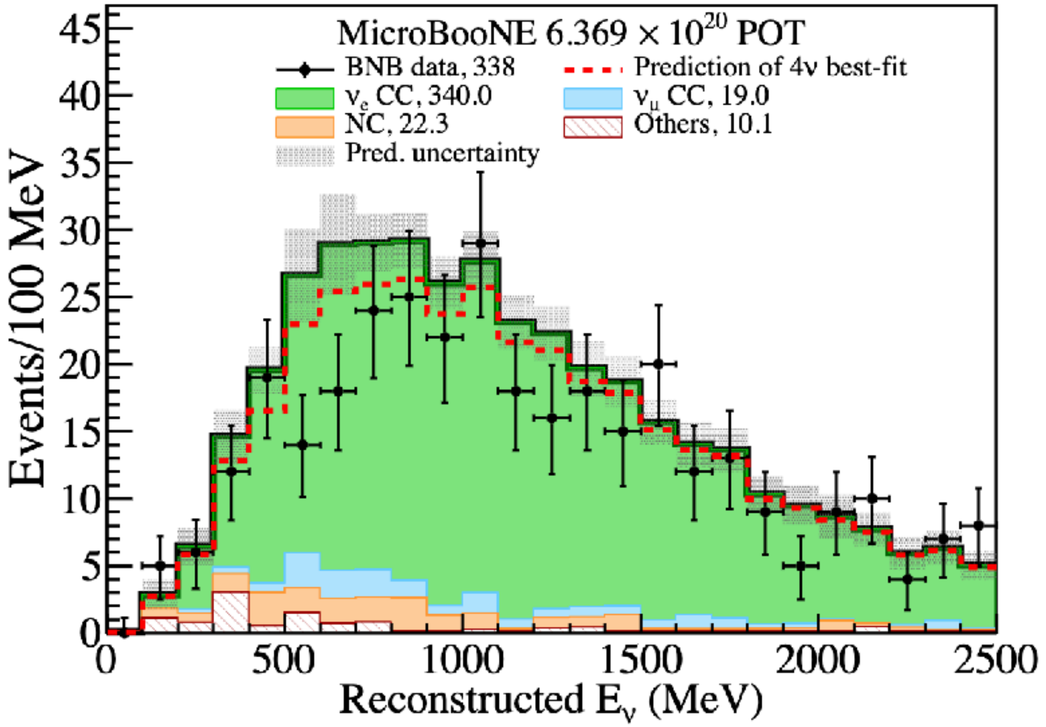
- data compatible with background-only prediction
- **data inconsistent with ν_e-like excess at > 99% CL**
- results consistent across kinematic variables tested.

More details in MICROBOONE-NOTE-1127-PUB



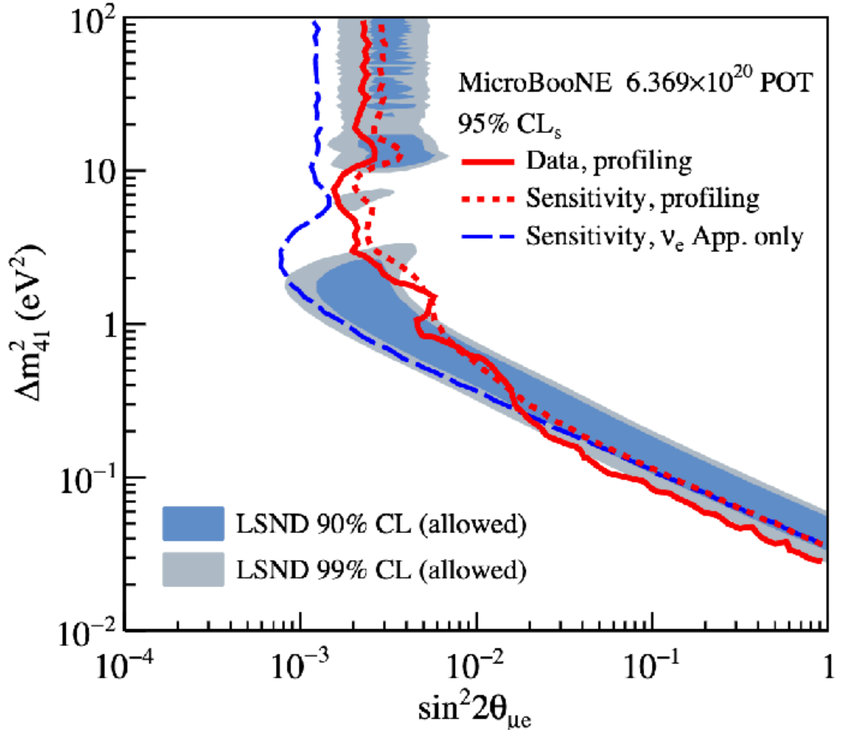
"Low Energy Excess Searches" POSTER #628 [Tuesday]

3+1 sterile neutrino search with BNB



ν_e ? ⟶ ν_s ?

Reinterpret LEE ν_e analysis under 3+1 sterile neutrino oscillation framework



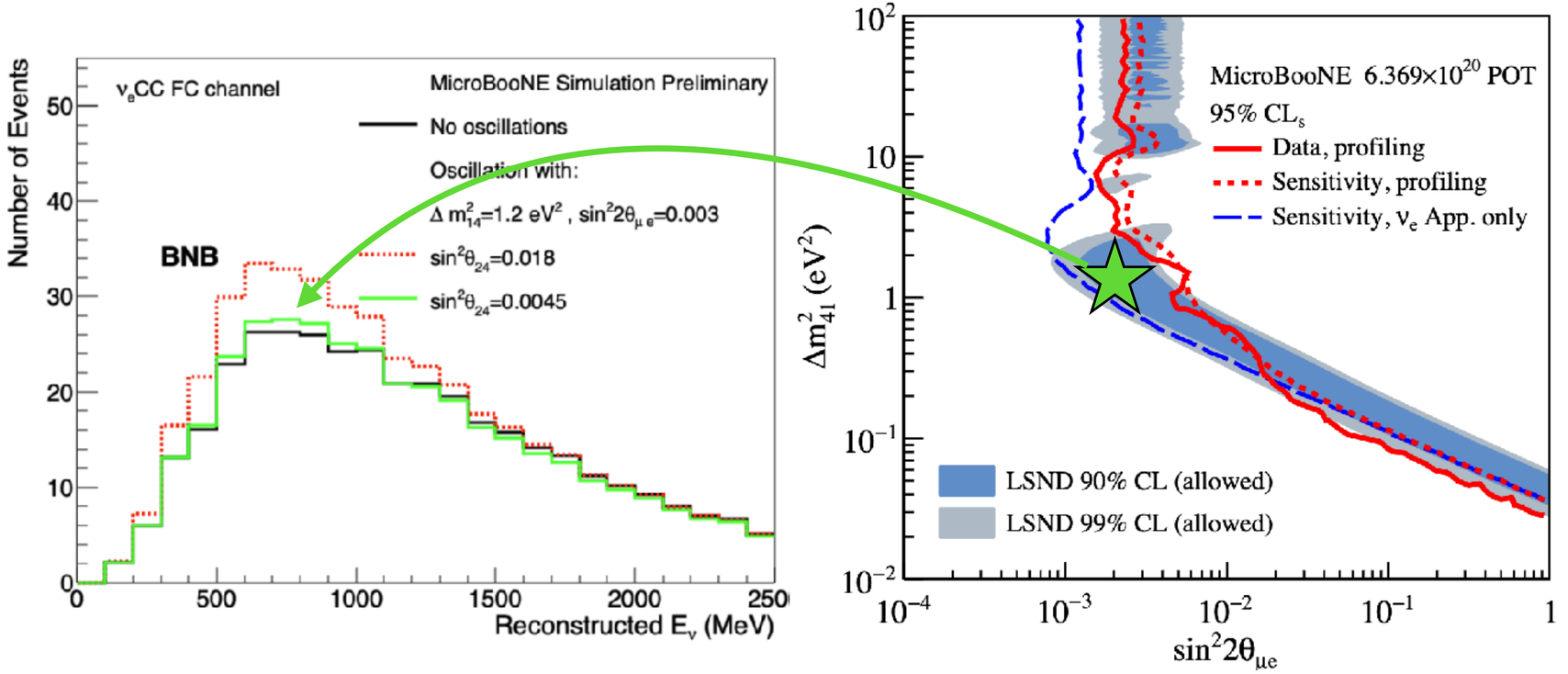
MicroBooNE's first 3+1 sterile neutrino search ('22)

PRL 130 (2023) 1, 01180

inclusive ν_e analysis. performed with BNB data.

Sensitivity *not* statistics limited!

3+1 sterile neutrino search: degeneracy

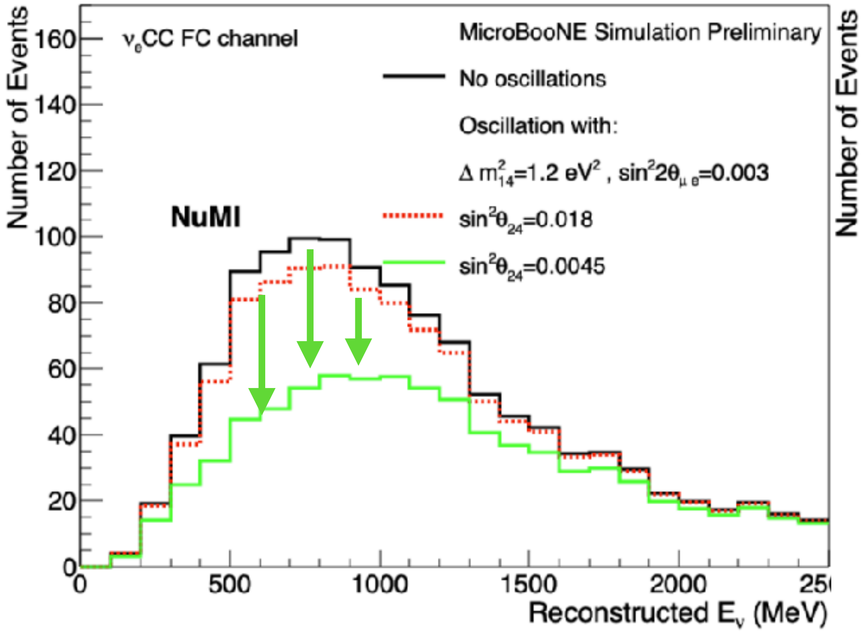


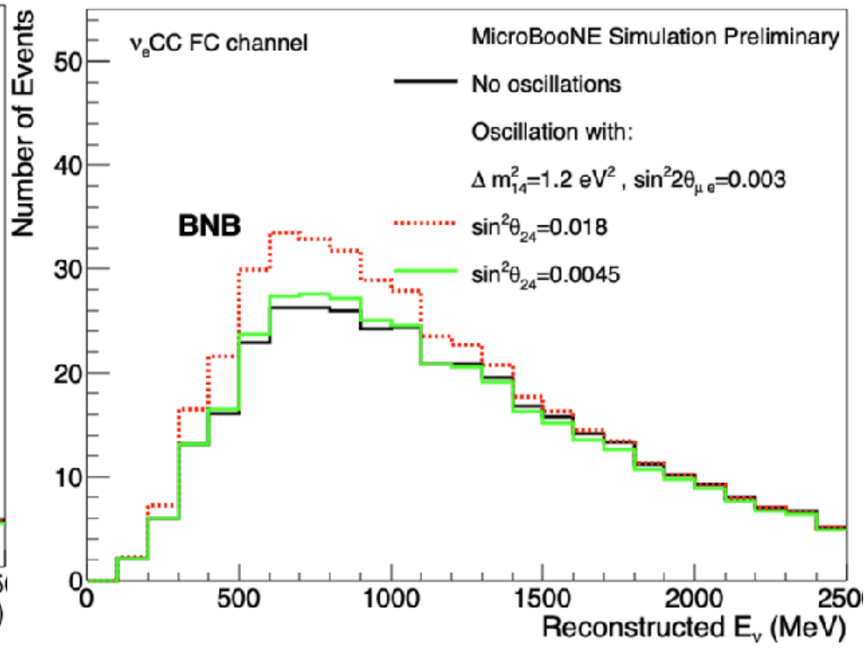
3+1 degeneracy: ν_e appearance cancels out ν_e disappearance

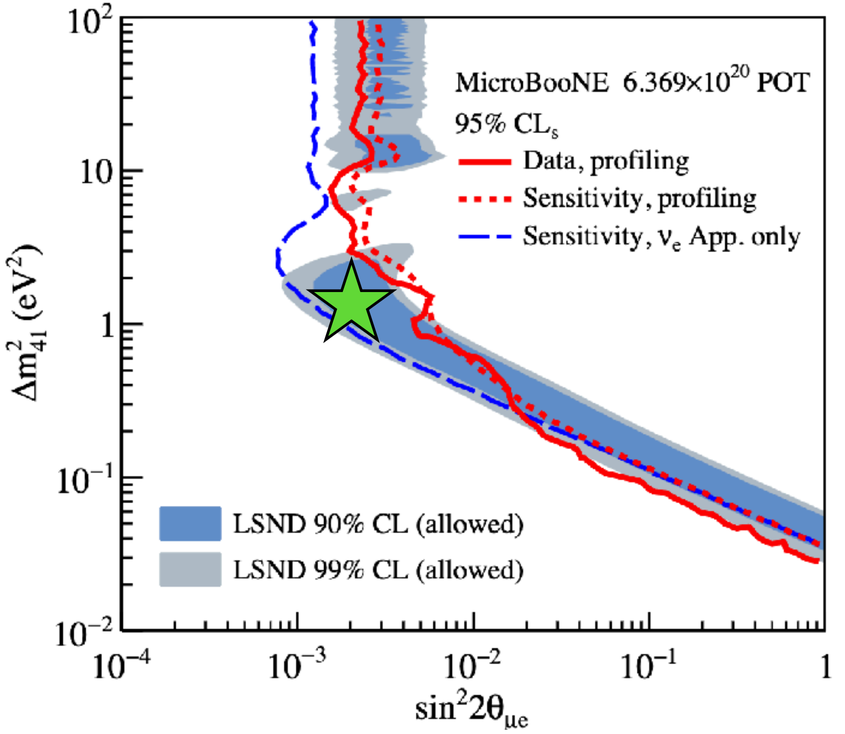
Degeneracy depends on intrinsic rate of ν_e vs. ν_μ in the beam.

For BNB $\frac{N_{\nu_\mu}}{N_{\nu_e}} \sim 200.$

3+1 sterile neutrino search: NuMI







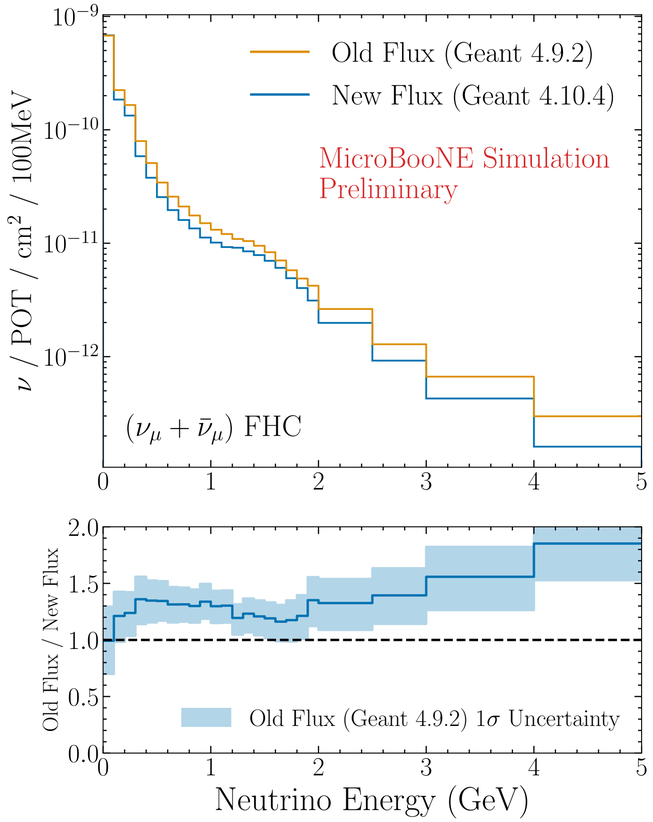
For the same mixing angles, impact on NuMI ν_e spectrum is large due to the different $\frac{N_{\nu_\mu}}{N_{\nu_e}} \sim 25$

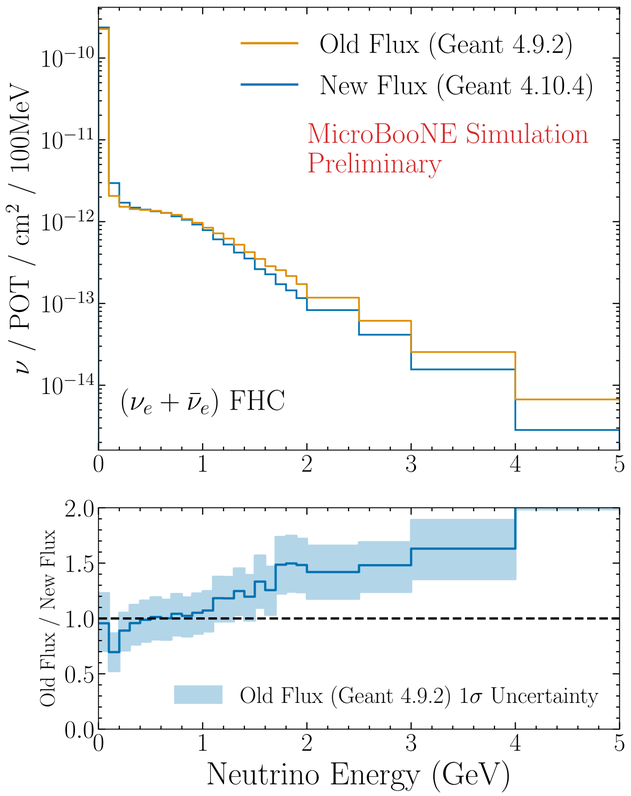
NuMI beam allows us to break the degeneracy

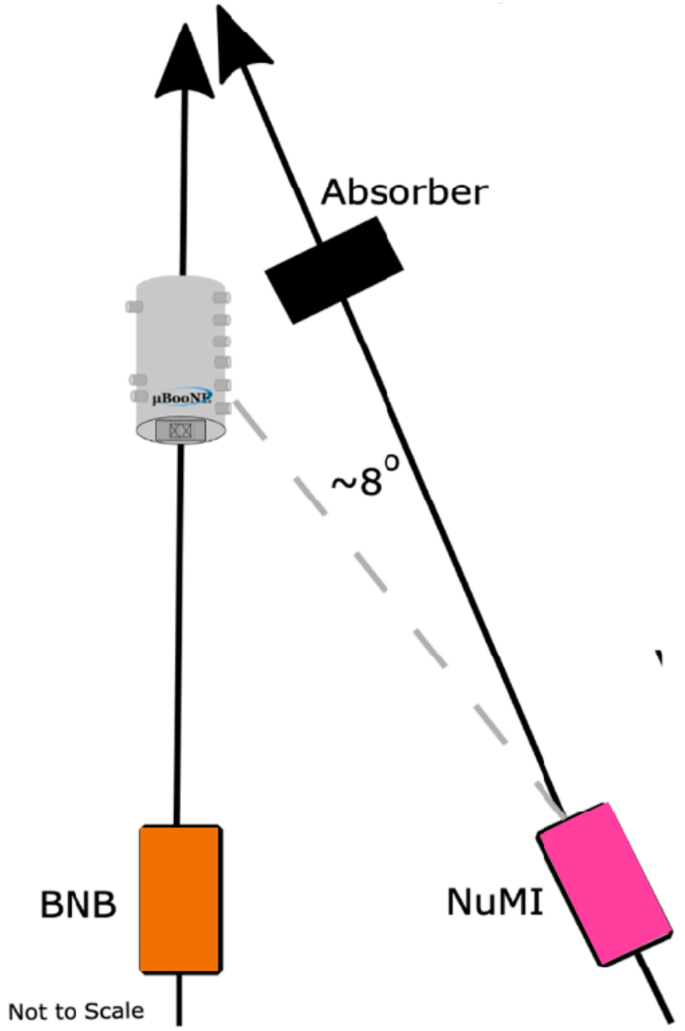
Updated NuMI flux @ MicroBooNE

MicroBooNE sits highly off-axis (~8 degrees) to the NuMI beam:

- flux dominated by hadron re-interactions with detector hall material
- phase space for hadron production not fully covered by world data
- flux simulation upgrade: beam line geometry, Geant4 version, systematics.



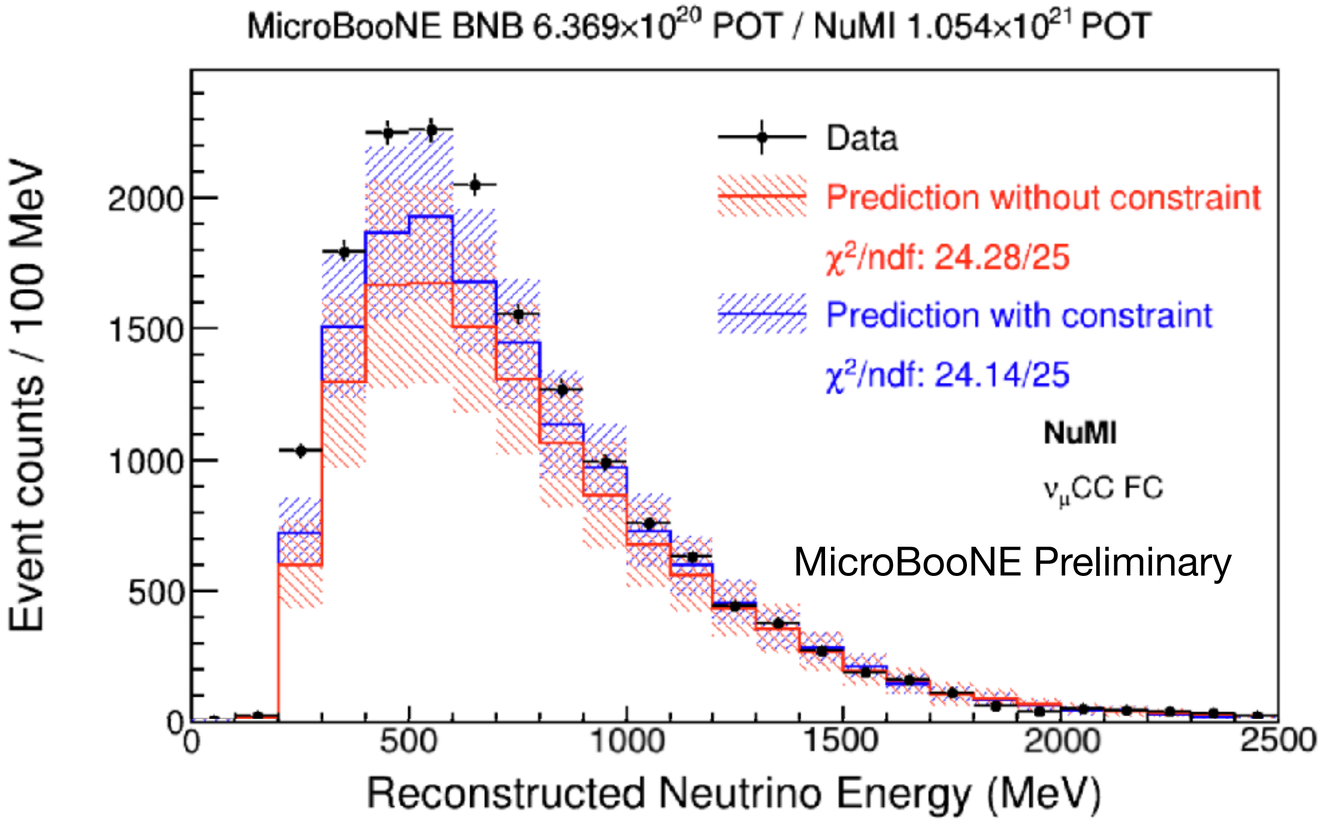


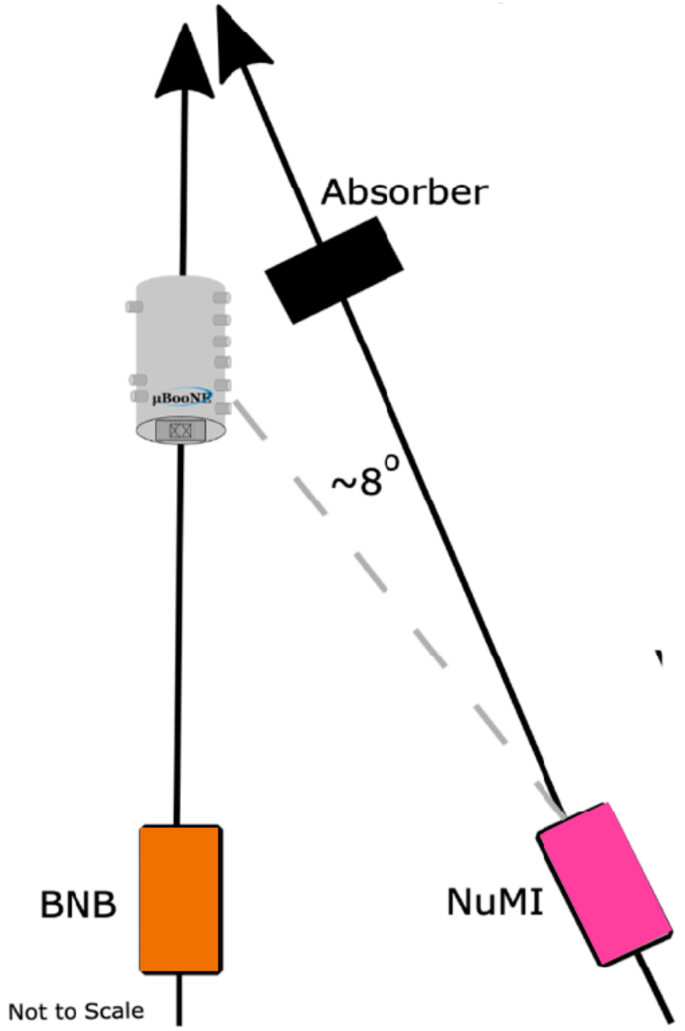


Updated NuMI flux at MicroBooNE
More details in MICROBOONE-NOTE-1129-PUB

Updated NuMI flux @ MicroBooNE

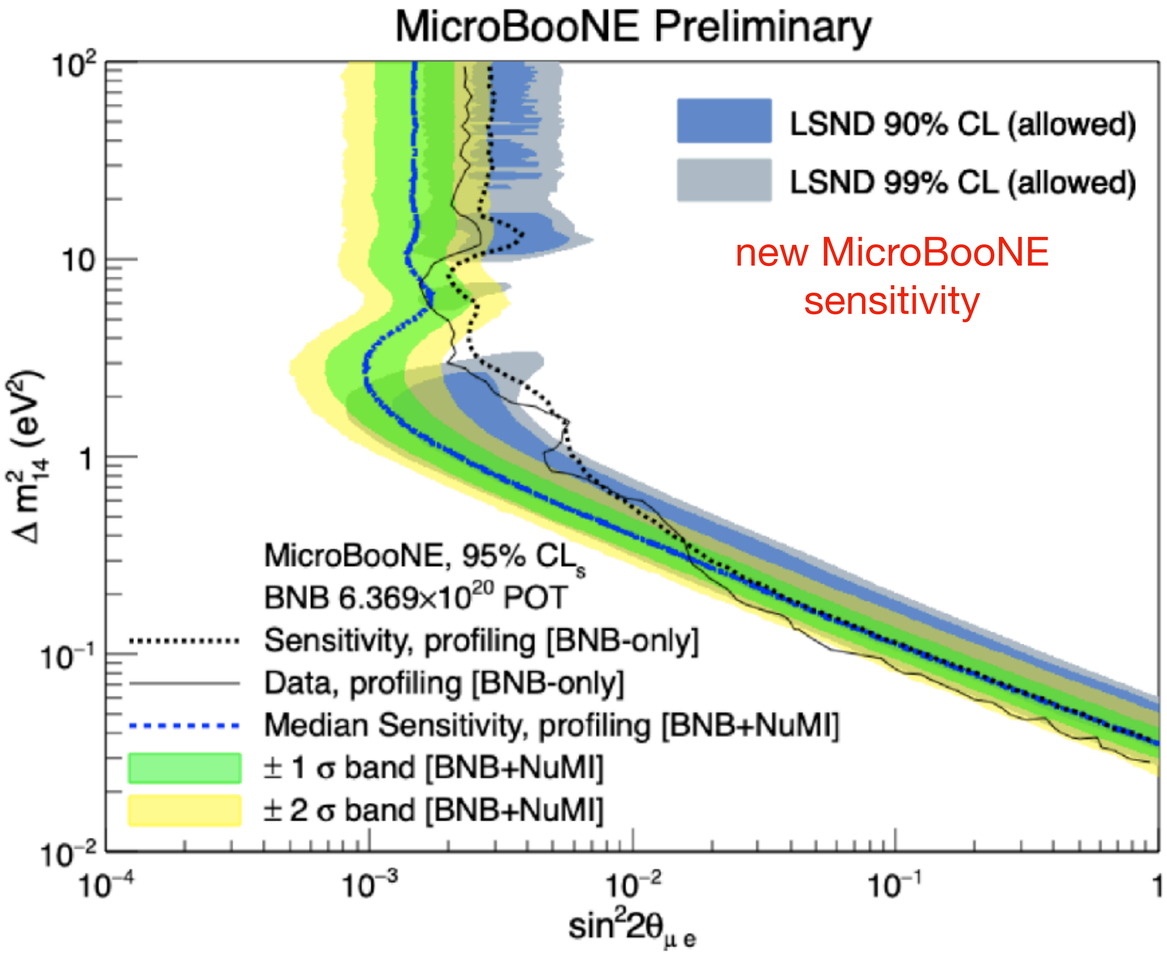
MicroBooNE's updated NuMI flux prediction vs. ν_μ data:





Good data/MC agreement. Blue histogram shows NuMI ν_μ prediction constrained by BNB ν_μ which largely cancels out cross section and detector systematics.

3+1 sterile neutrino search: new sensitivities



"one detector, two beams"

Joint 3+1 analyst with BNB + NuMI allows significant enhancement to sensitivity!

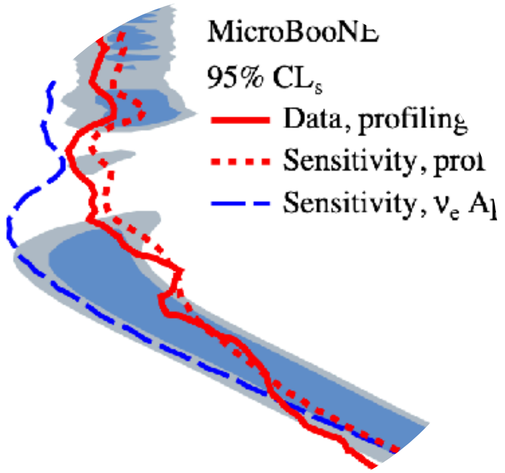
Stay tuned for upcoming results from MicroBooNE!

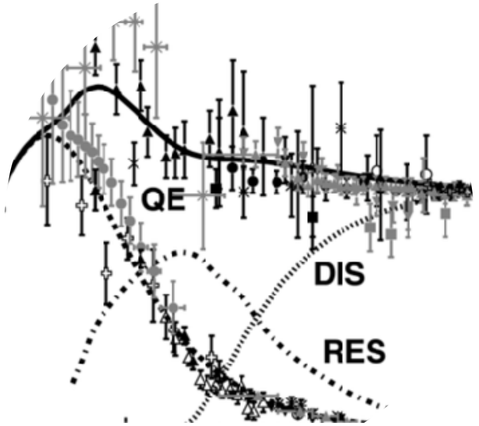
more details in MICROBOONE-NOTE-1132-PUB

Sterile Neutrino Search @ MicroBooNE POSTER #144 [Tuesday]

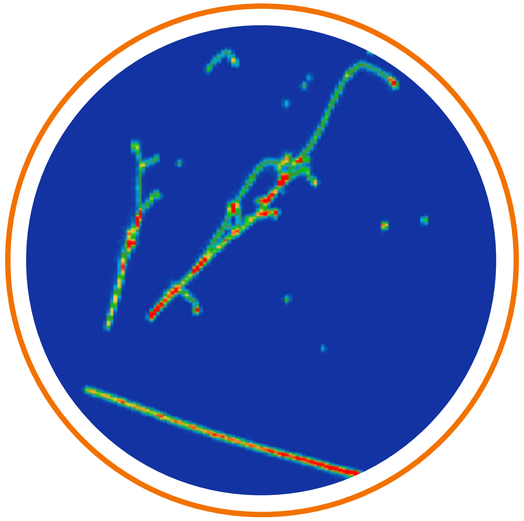
MicroBooNE's Physics Program

Beyond the Standard
Model physics searches





ν - Ar scattering



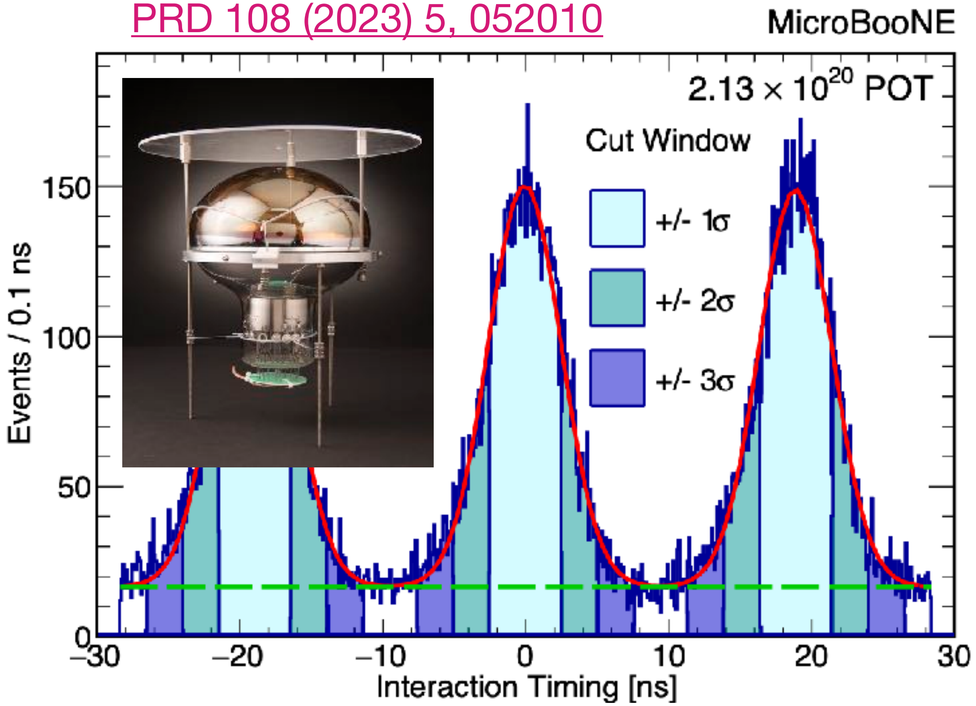
advancing LArTPC
technology capabilities

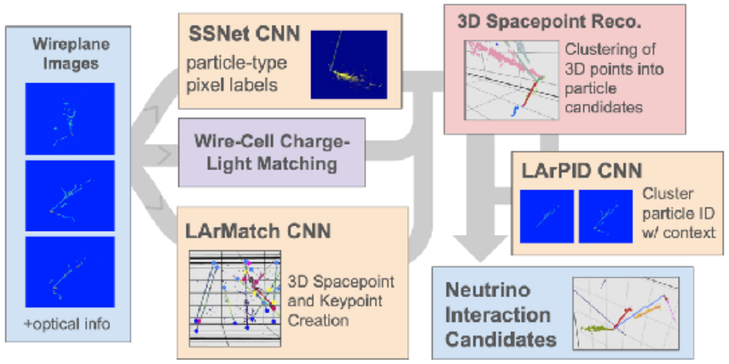
μBooNE

Novel Tools & Techniques for LArTPC detectors

nanosecond timing in LArTPCs
Enhance BSM long-lived particle searches

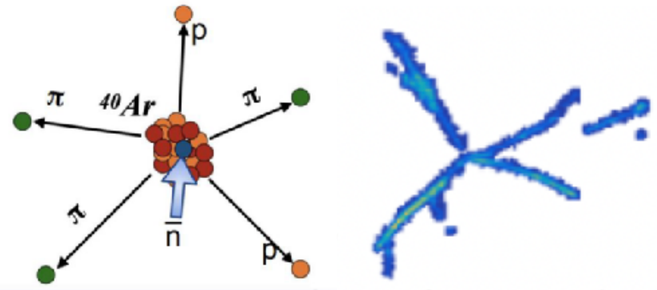
PRD 108 (2023) 5, 052010





New capabilities for LArTPC detectors!

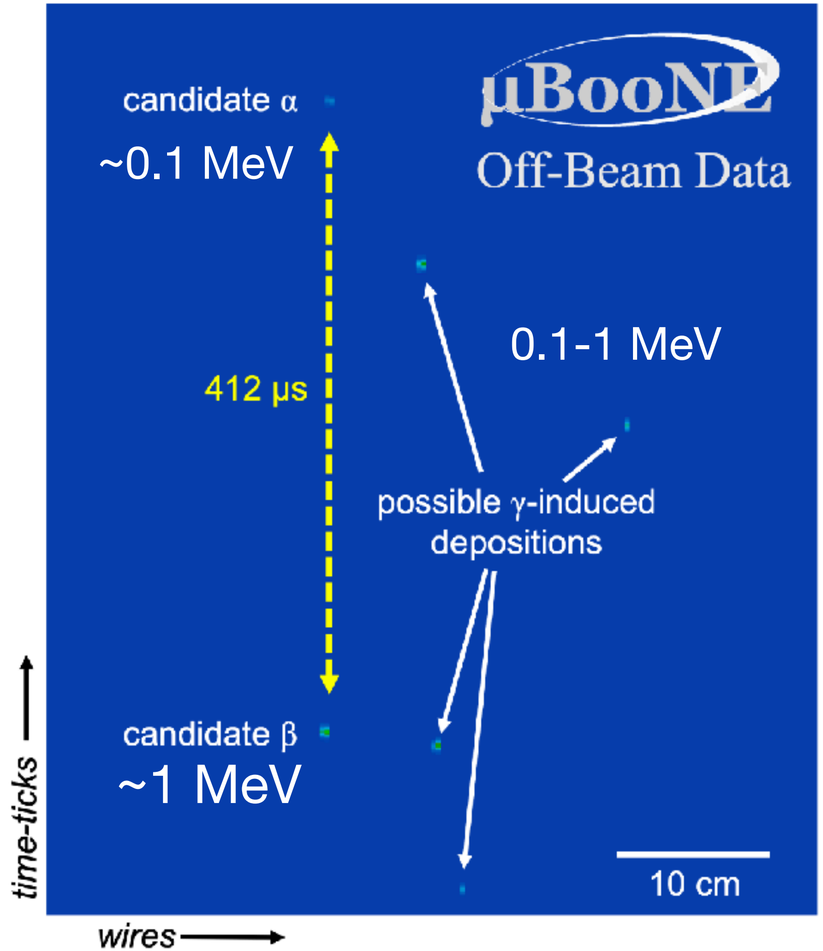
n-nbar LArTPC demonstration
[POSTER #189, Friday]



ML & **Deep Learning** Reconstruction
[POSTER #398, Tuesday]
MICROBOONE-NOTE-23-PUB

arXiv:2406.10123

PRD109 (2024) 052007

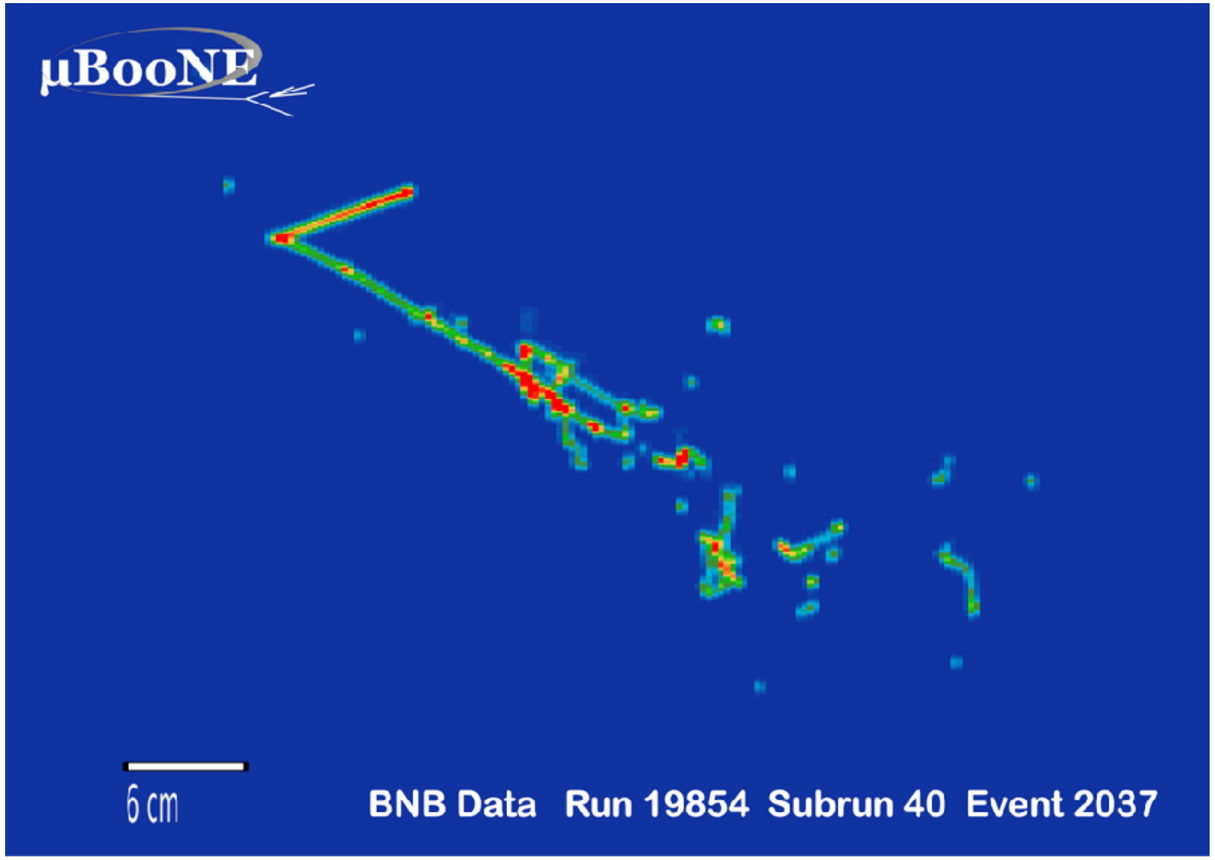


MeV scale physics capabilities
LArTPC astrophysics & more!
[POSTER #186, Tuesday]

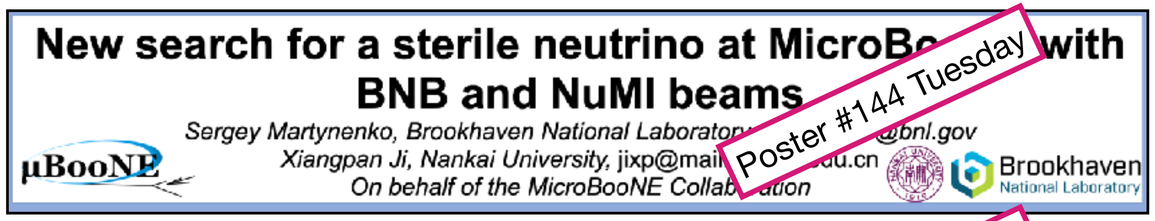
Conclusions

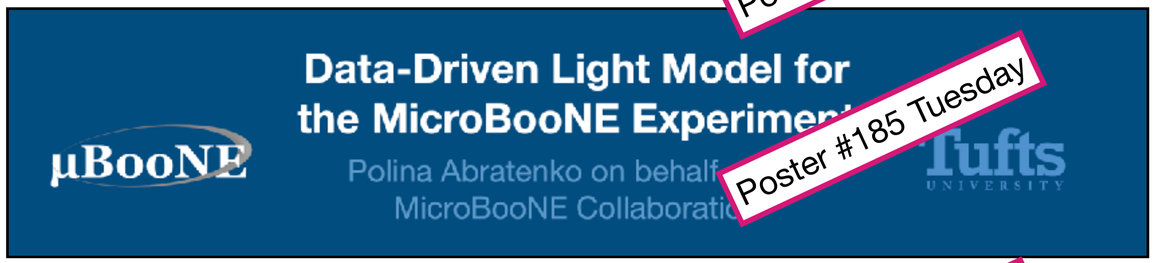
MicroBooNE has an active physics program:

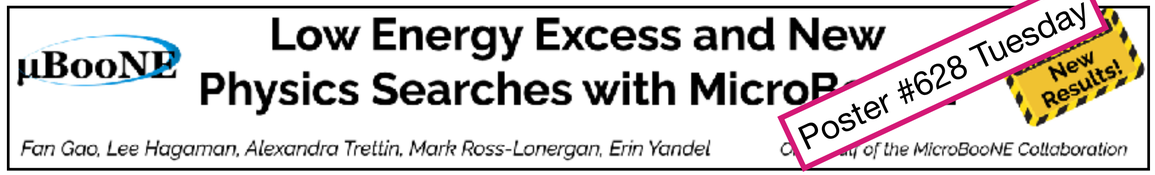
- World-leading limits on low-mass BSM particles
- New ν_e Low Energy Excess and upcoming results in single-γ and e^+e^- channels.
- Novel “one detector - two beams” 3+1 sterile search
  - Leverage BNB + NuMI beams
- Many new LArTPCs developments and more to come with full 5-year dataset!

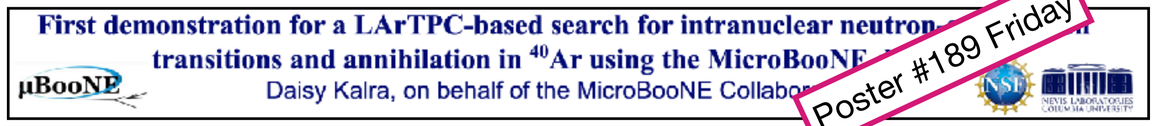


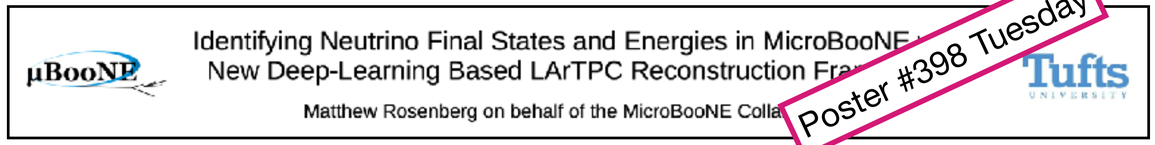
More from MicroBooNE @ Neutrino '24







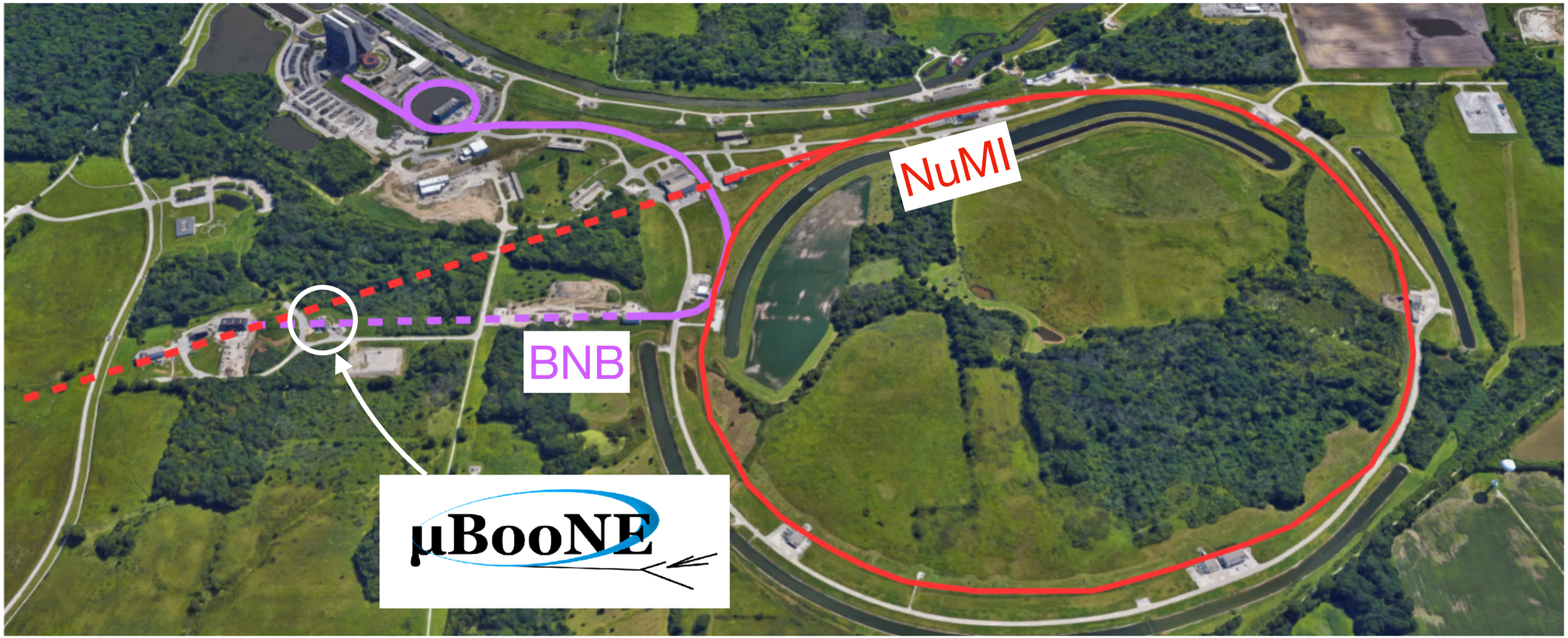




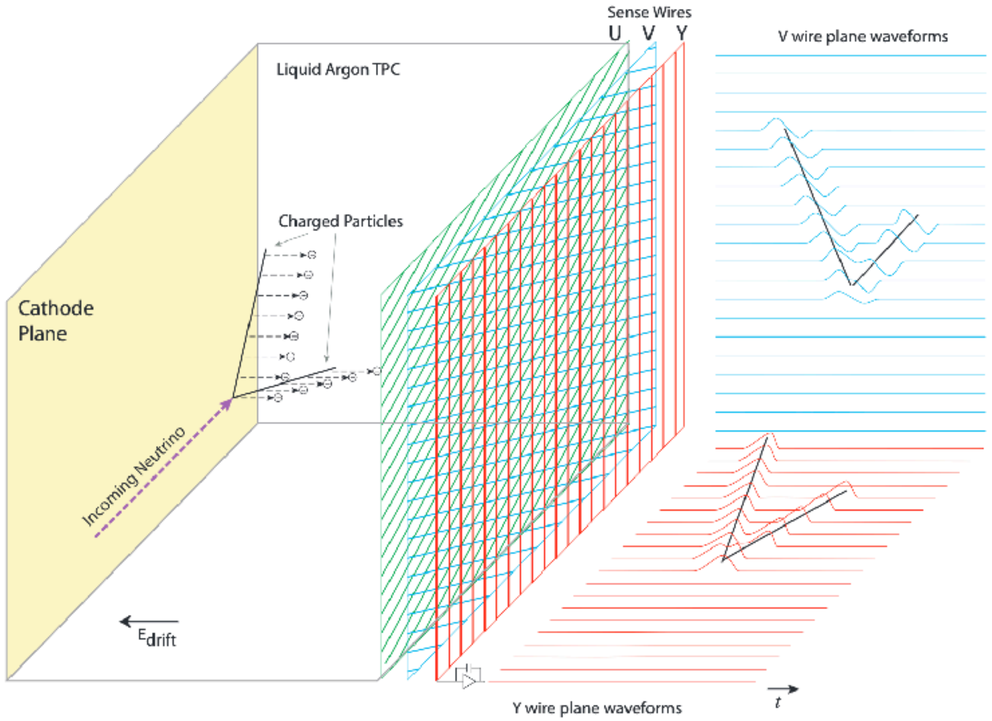
MicroBooNE cross section talk:
"*High-precision neutrino interaction measurements with MicroBooNE*"
A. Papadopoulou, Friday @ 11 AM

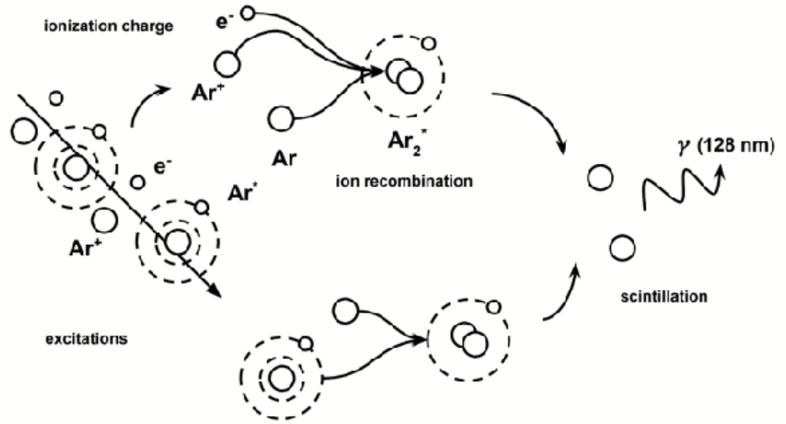
Backup

BNB & NuMI At MicroBooNE



Liquid Argon Time Projection Chamber





MicroBooNE detector paper: JINST 12 (2017) 02, P02017

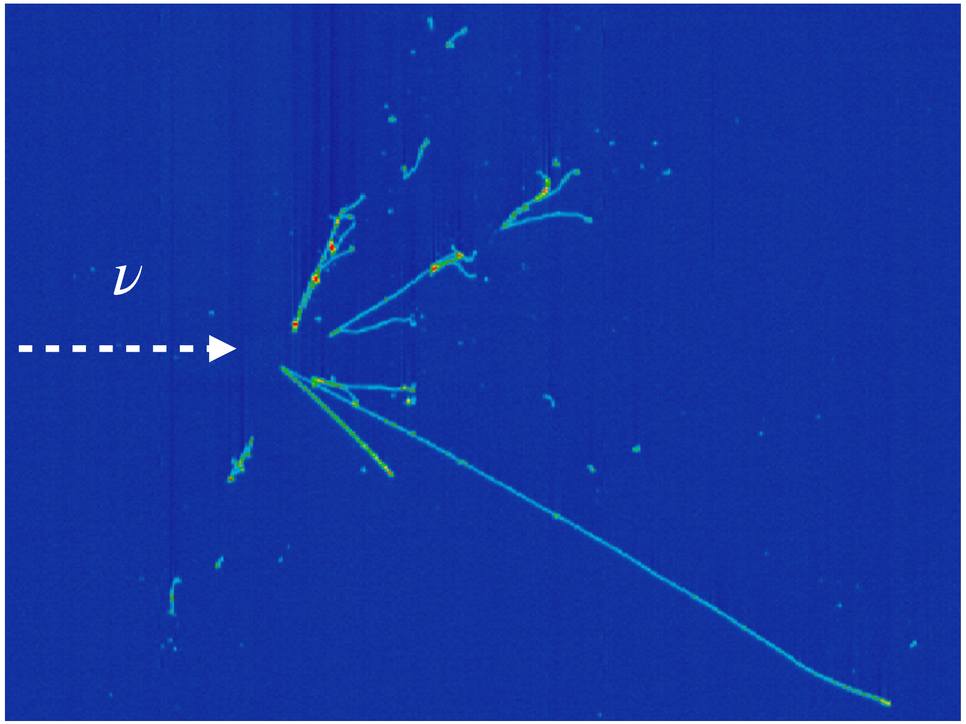
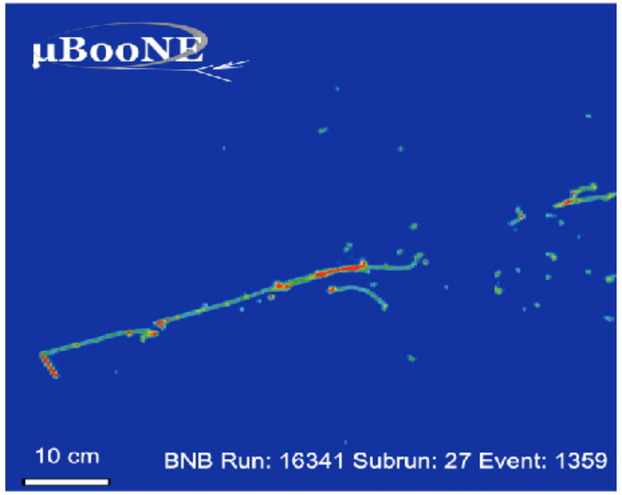


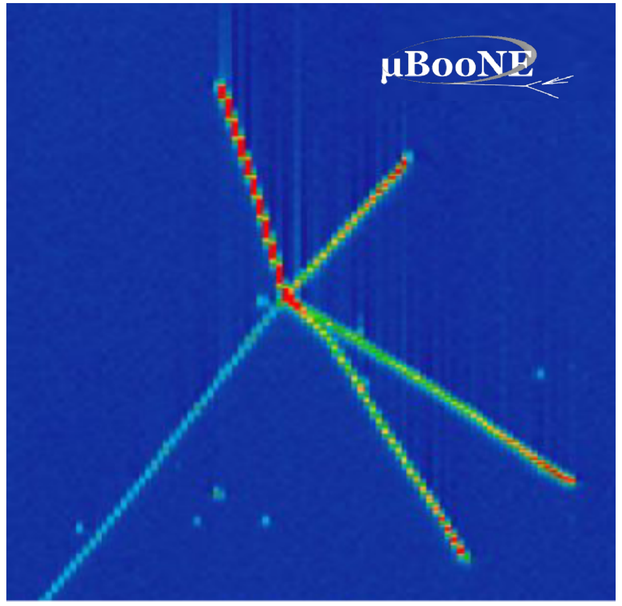
Image neutrino interactions leveraging:

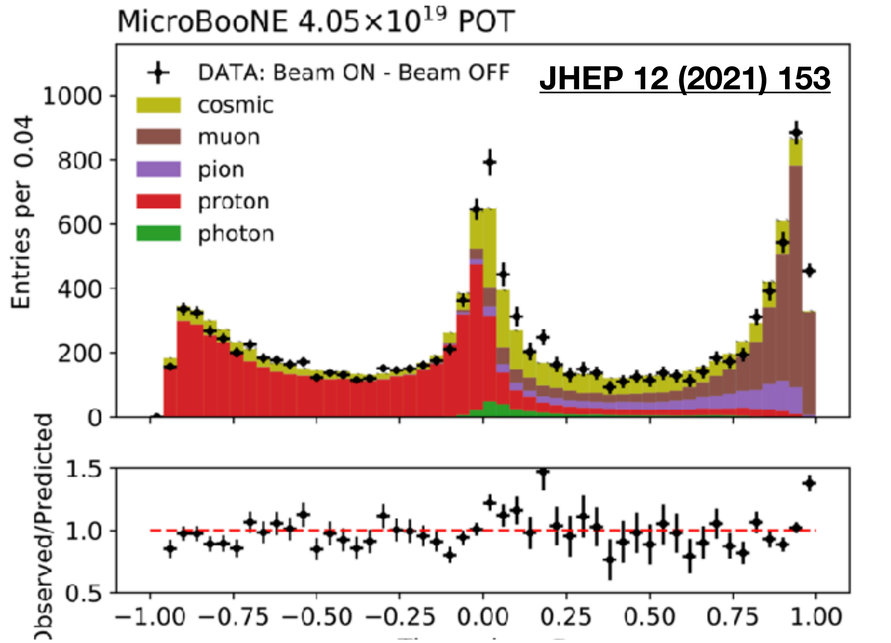
Ionization electrons:
- 30:1-50:1 signal-to-noise
- millimeter spatial resolution
- %-level calorimetry

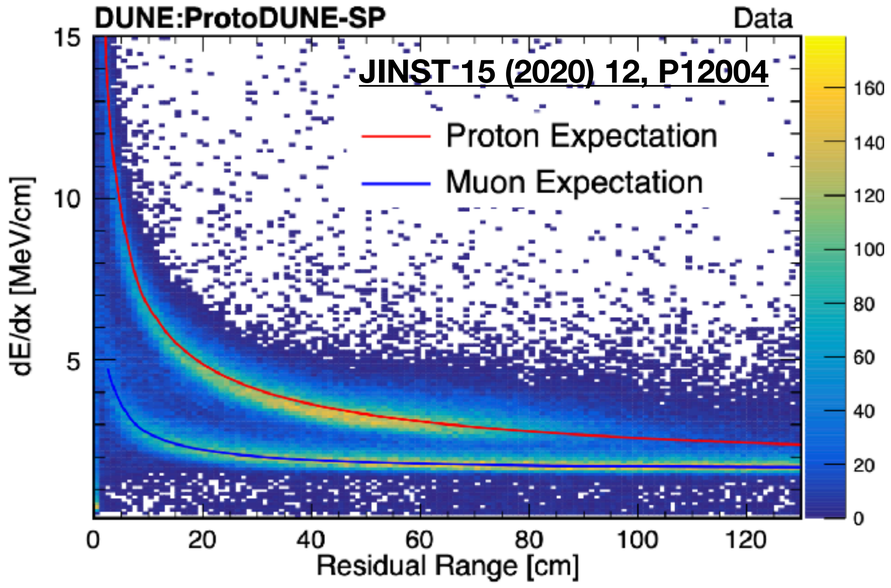
Scintillation photons:
- nanosecond timing resolution

Particle Identification in MicroBooNE

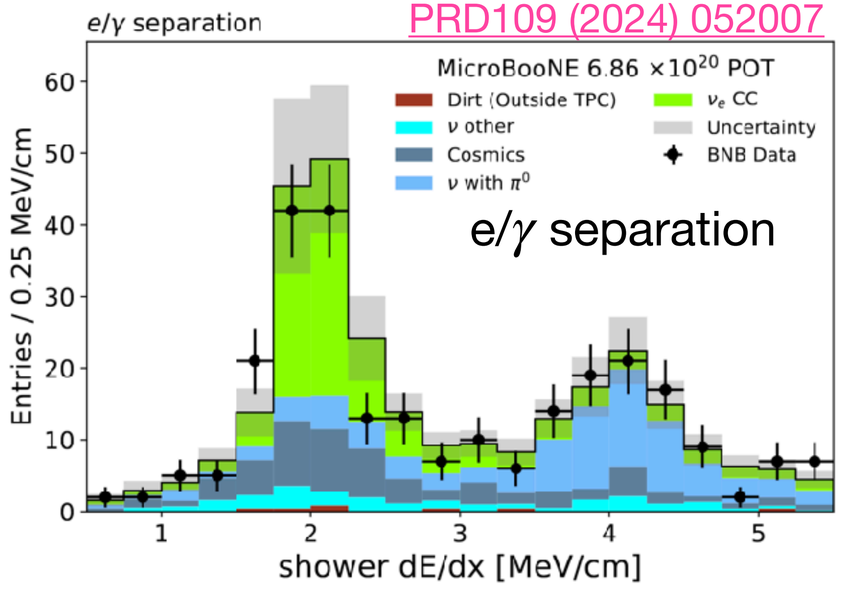




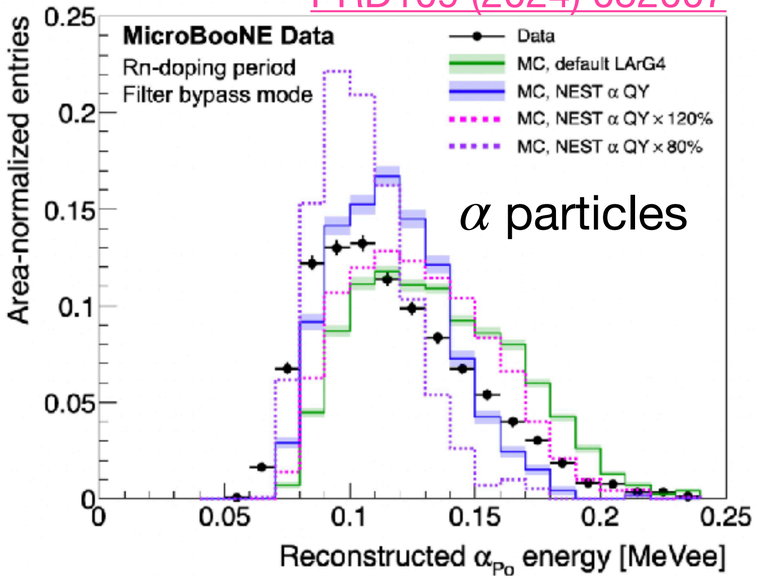




PRD109 (2024) 052007



PRD109 (2024) 052007

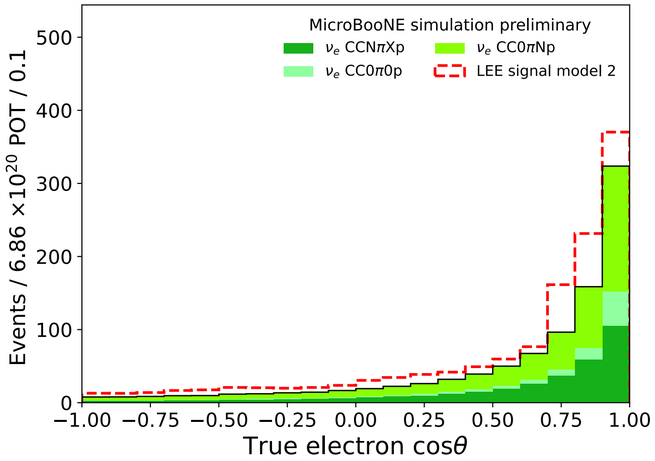


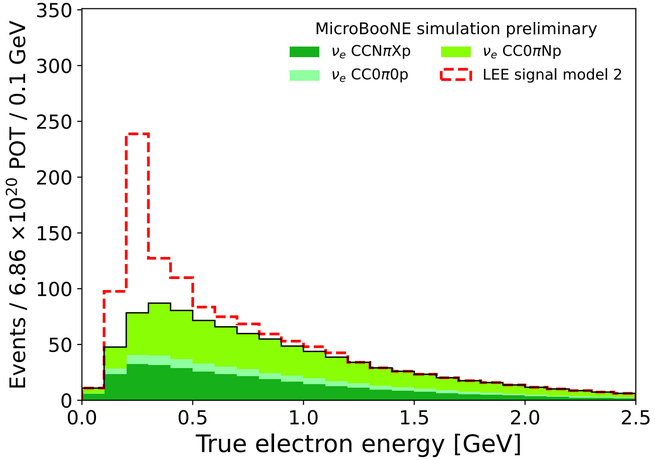
MicroBooNE papers

2017 2018 2019 2020 2021 2022 2023 2024

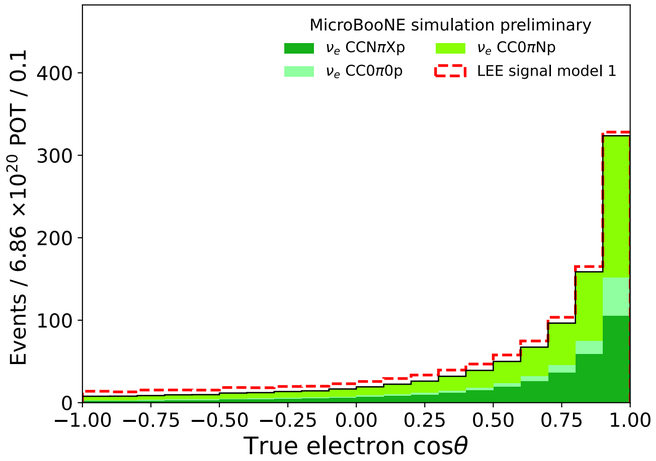
- Published and submitted articles on iNSPIRE
- MicroBooNE website (https://microboone.fnal.gov)
  - Public Notes webpage.
  - MicroBooNE public datasets webpage.
- MicroBooNE on social media: twitter & Facebook

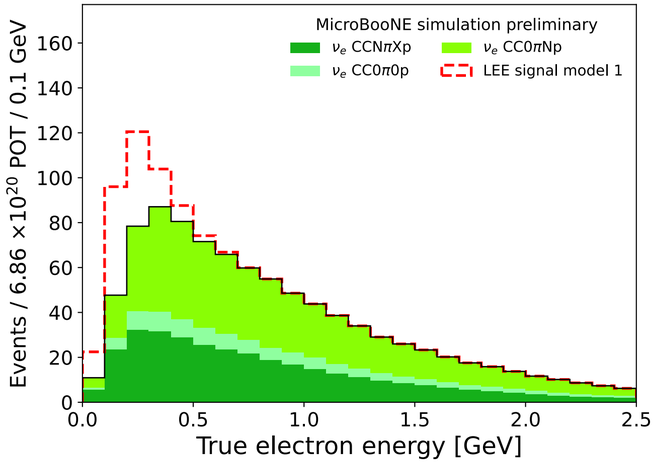
ν_e LEE models and results





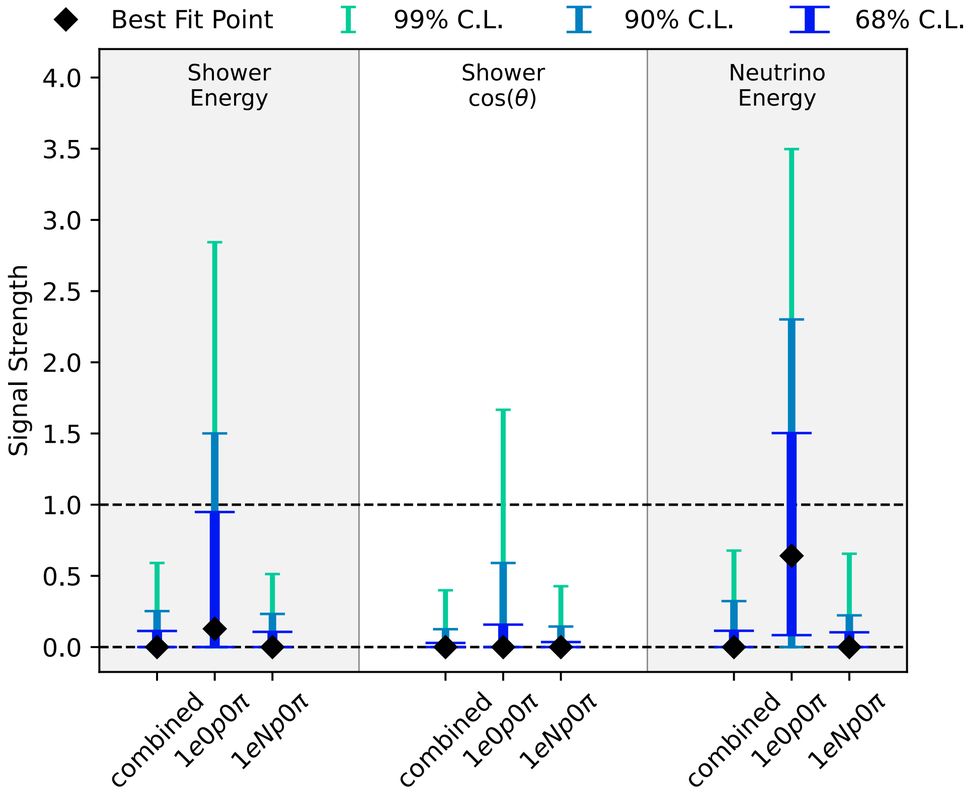
shower kinematics signal model [model #2]





Neutrino energy signal model [model #1]

ν_e LEE analysis



Results in Np / 0p channels separately and combined

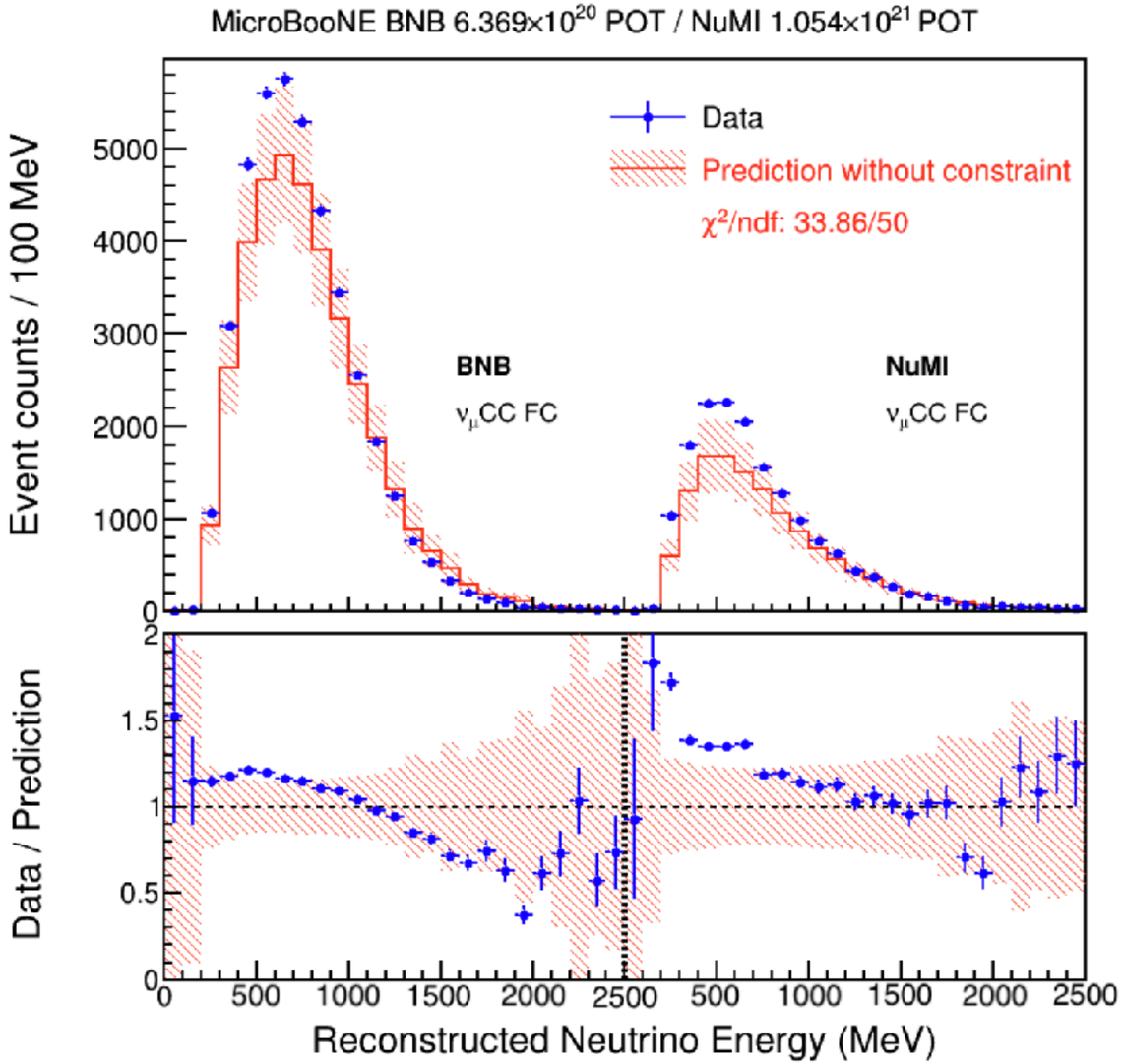
3+1 parametrization

Full 3+1 search ⟶

$$P_{\nu_e \to \nu_e} = 1 - 4(1 - |U_{e4}|^2)|U_{e4}|^2 \sin^2 \Delta_{41},$$
$$P_{\nu_\mu \to \nu_\mu} = 1 - 4(1 - |U_{\mu 4}|^2)|U_{\mu 4}|^2 \sin^2 \Delta_{41},$$
$$P_{\nu_\mu \to \nu_e} = 4|U_{\mu 4}|^2|U_{e4}|^2 \sin^2 \Delta_{41}.$$

$\sin^2 2\theta_{ee}$	$= \sin^2 2\theta_{14}$	$= 4(1 - \lvert U_{e4}\rvert^2)\lvert U_{e4}\rvert^2$
$\sin^2 2\theta_{\mu\mu}$	$= 4 \cos^2 \theta_{14} \sin^2 \theta_{24} \left(1 - \cos^2 \theta_{14} \sin^2 \theta_{24}\right)$	$= 4(1 - \lvert U_{\mu 4}\rvert^2)\lvert U_{\mu 4}\rvert^2$
$\sin^2 2\theta_{\mu e}$	$= \sin^2 2\theta_{14} \sin^2 \theta_{24}$	$= 4\lvert U_{\mu 4}\rvert^2\lvert U_{e4}\rvert^2$
$\sin^2 2\theta_{es}$	$= \sin^2 2\theta_{14} \cos^2 \theta_{24} \cos^2 \theta_{34}$	$= 4\lvert U_{e4}\rvert^2\lvert U_{s4}\rvert^2$
$\sin^2 2\theta_{\mu s}$	$= \cos^4 \theta_{14} \sin^2 2\theta_{24} \cos^2 \theta_{34}$	$= 4\lvert U_{\mu 4}\rvert^2\lvert U_{s4}\rvert^2$

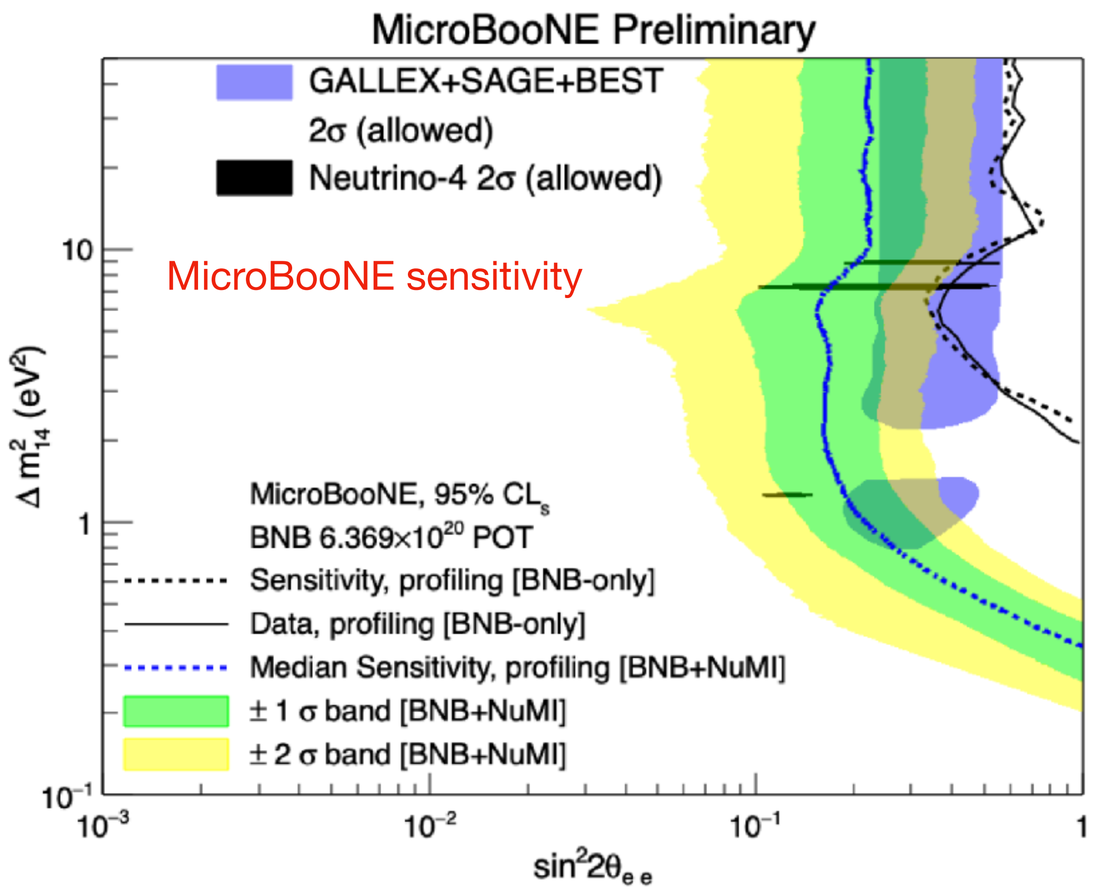
NuMI ν_μ data-simulation comparison

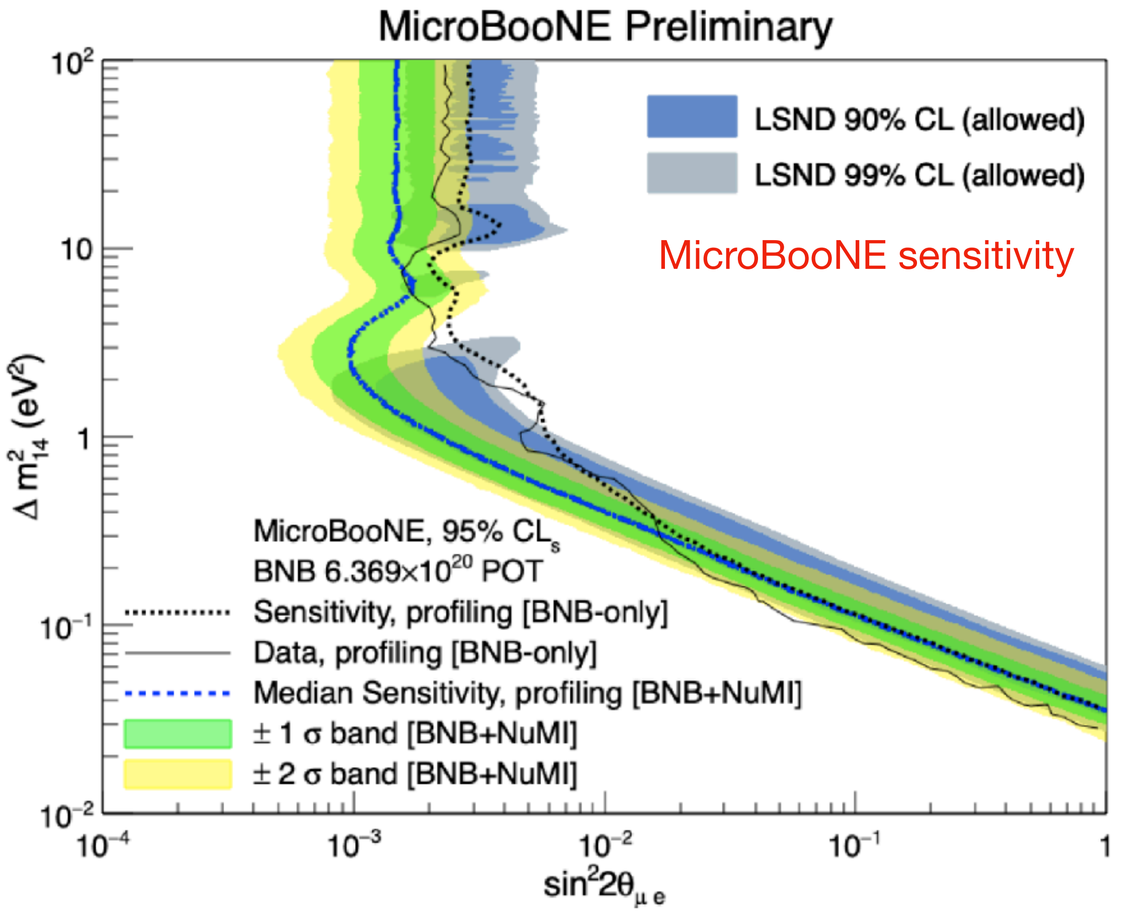


BNB and NuMI data/MC comparison side-by-side. Refers to both channels combined, with full correlation across the two channels.

MICROBOONE-NOTE-1132-PUB

3+1 sensitivities





BNB + NuMI 3+1 MicroBooNE sensitivities