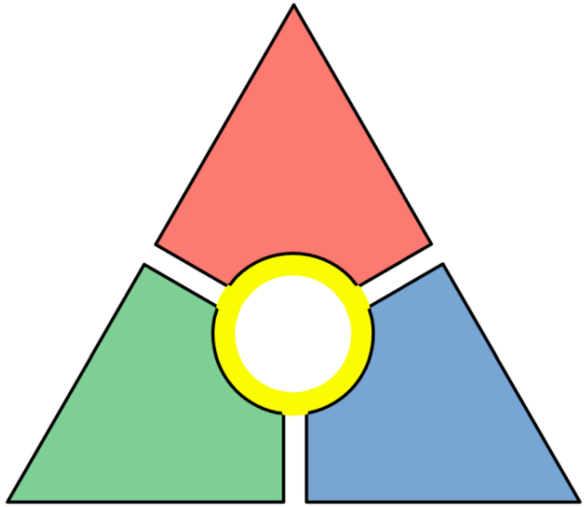
Recent Results from MicroBooNE

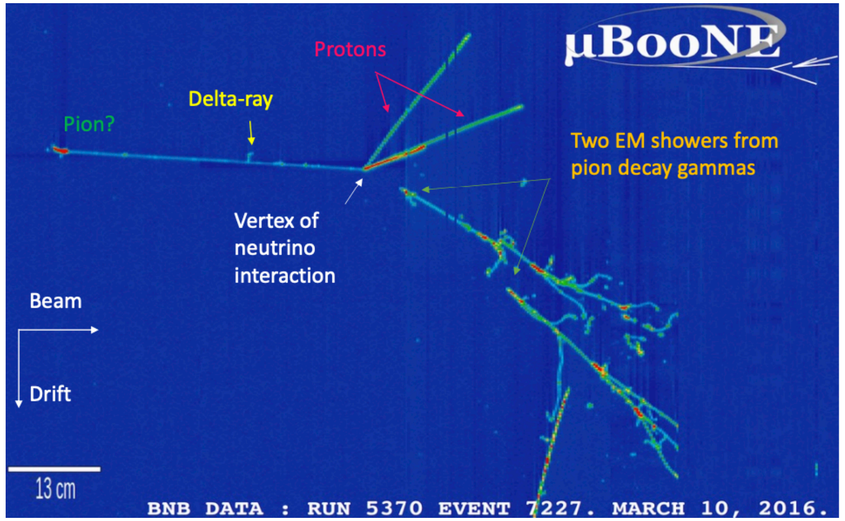
NuFact 2024
Nitish Nayak
(For the MicroBooNE Collaboration)

Sept 17th, 2024

MicroBooNE Science Goals

- Investigate MiniBooNE Low Energy Excess (LEE)
- Search for BSM Physics





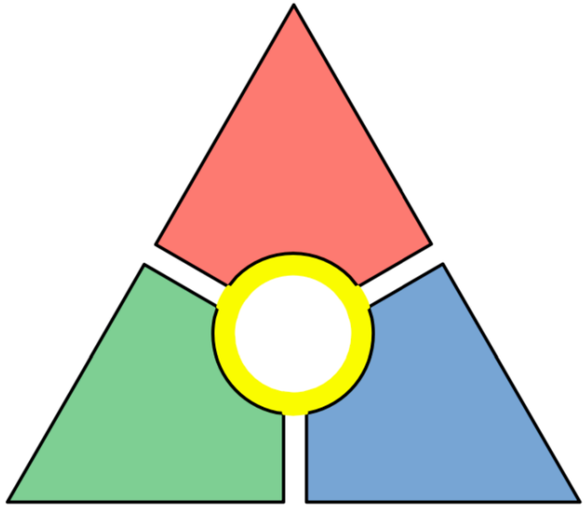
- Advance LArTPC capabilities for next generation neutrino experiments (SBN program, DUNE)

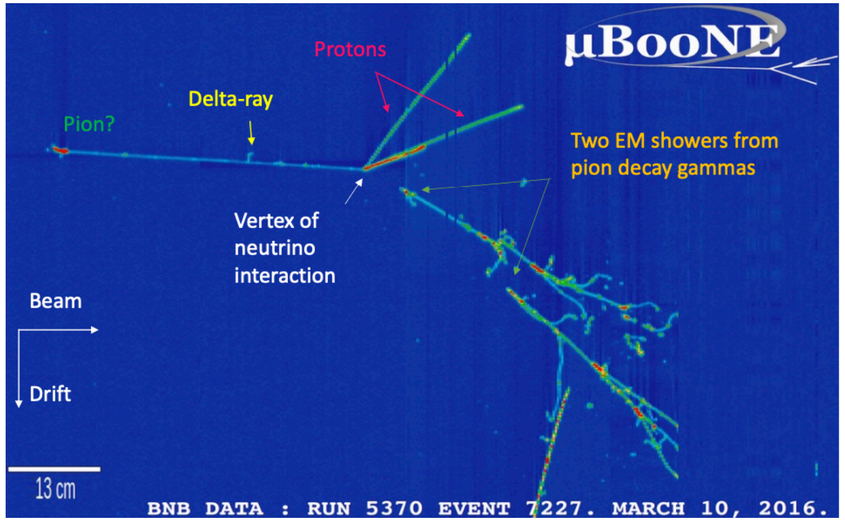
- Illuminate ν-Ar scattering physics across many topologies

MicroBooNE Science Goals

New Results!

- Investigate MiniBooNE Low Energy Excess (LEE)
- Search for BSM Physics





- Advance LArTPC capabilities for next generation neutrino experiments (SBN program, DUNE)

- Illuminate ν-Ar scattering physics across many topologies

MicroBooNE @ NuFact 2024

Parallel Talks

- MicroBooNE's BSM Program - Keng Lin (Monday)
- Anomalous γ and e^+e^- Searches - Erin Yandel (Monday)
- ν_e Low Energy Excess Search - Fan Gao (Thursday)

- Inclusive and Pionless Measurements - Dan Barrow (Thursday)
- Pion Production Measurements - Patrick Green (Thursday)

- MeV-Scale Radon Measurements - Will Foreman (Wednesday)

Posters

- NC $\Delta \rightarrow 1\gamma$ - Lee Hagaman

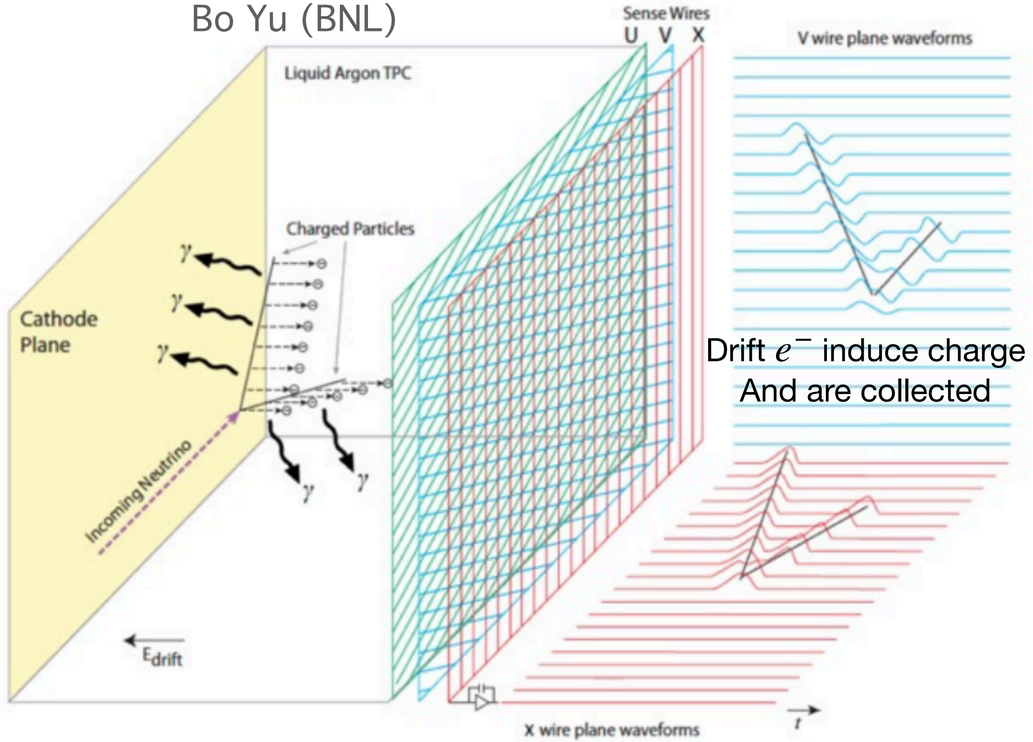
- $\nu_\mu CC$ Inclusive - London Cooper-Troendle
- $\nu_\mu CC2p$ - Dan Barrow
- $\nu_\mu CC0\pi$ - Panos Englezos
- $\nu_\mu CC0p/Np$ - Ben Bogart
- Rare Mesons - Jairo Rodriguez
- Charged Pions - Philip Detje

- MeV-Scale Physics - Diego Andrade

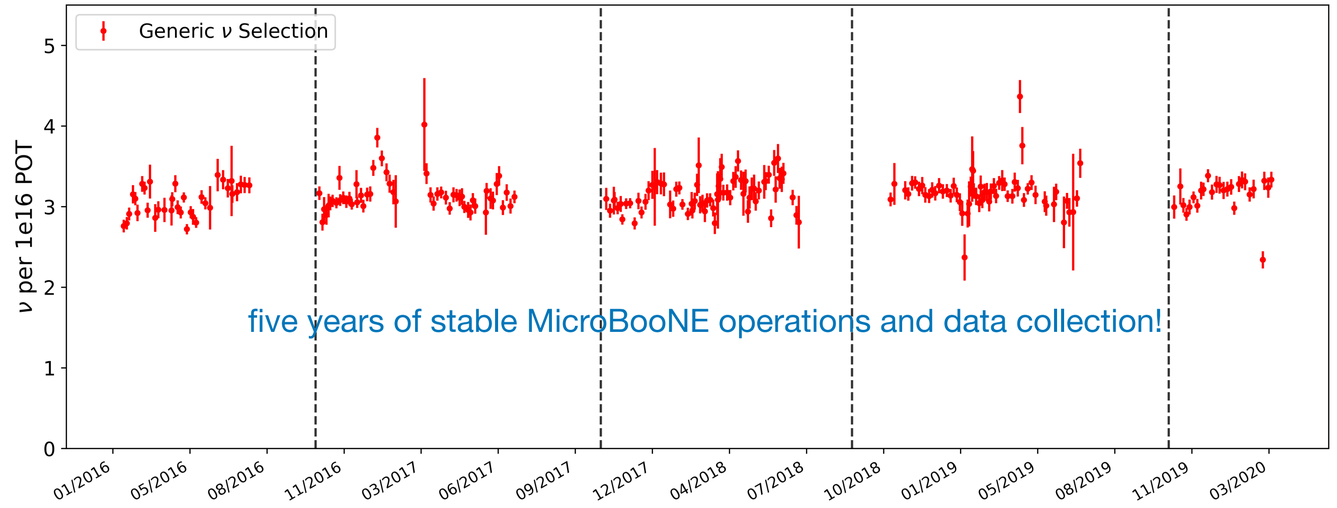
🧐 <- Lookout for this throughout the talk!

The Experiment

Bo Yu (BNL)



Drift e^- induce charge
And are collected



five years of stable MicroBooNE operations and data collection!

MicroBooNE Papers

μBooNE

2017 2018 2019 2020 2021 2022 2023 2024

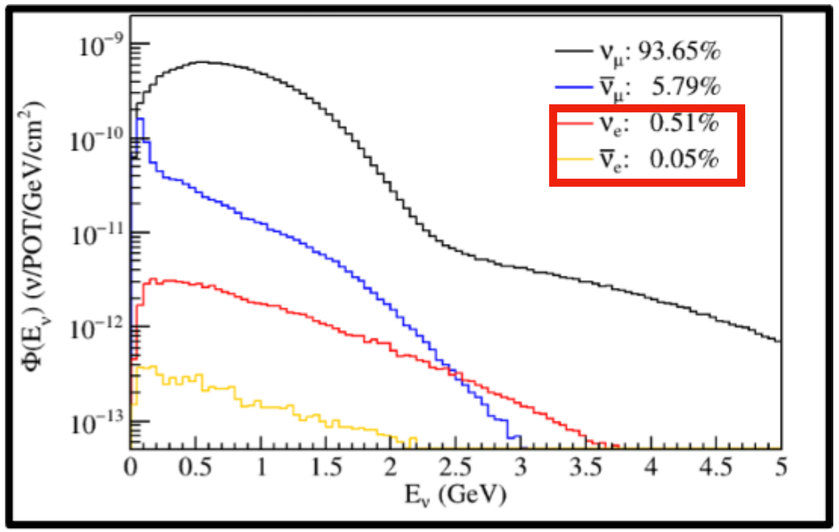
69 papers

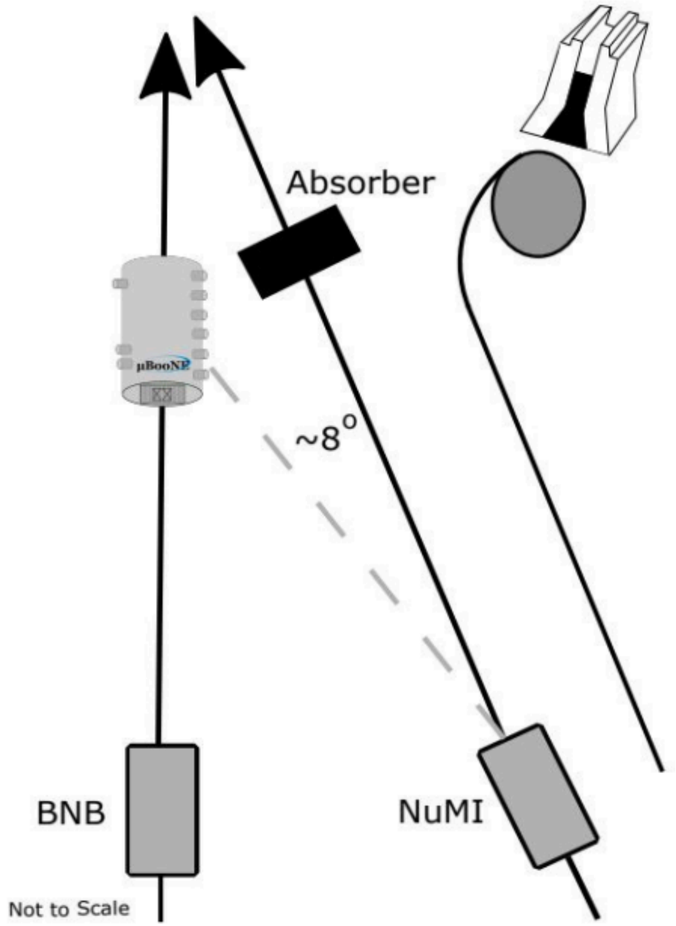
and counting!

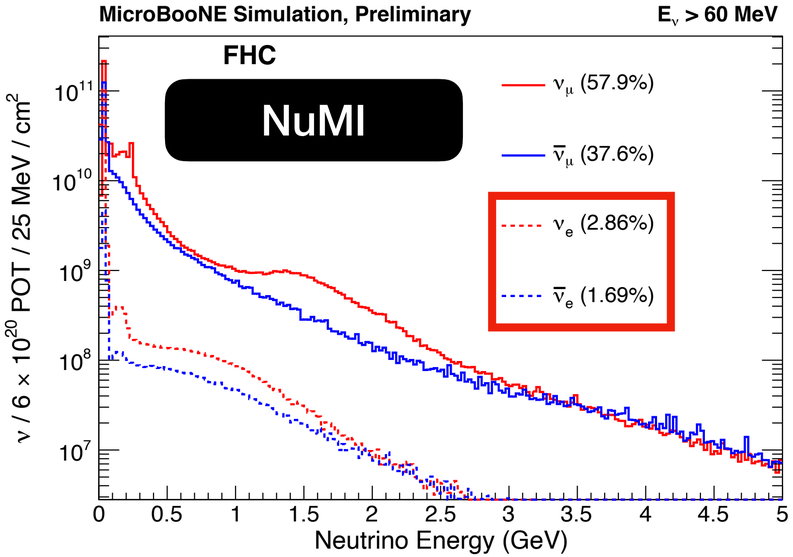
Neutrino Beams @ MicroBooNE

- MicroBooNE's placement enables "one detector, two beams" concept
- $\mathcal{O}$(500k) interactions across both beams
  - BNB is on-axis
  - NuMI spans 8° (target) -> 120° (absorber) and has significantly more ν_e / $\bar{\nu}_e$

BNB

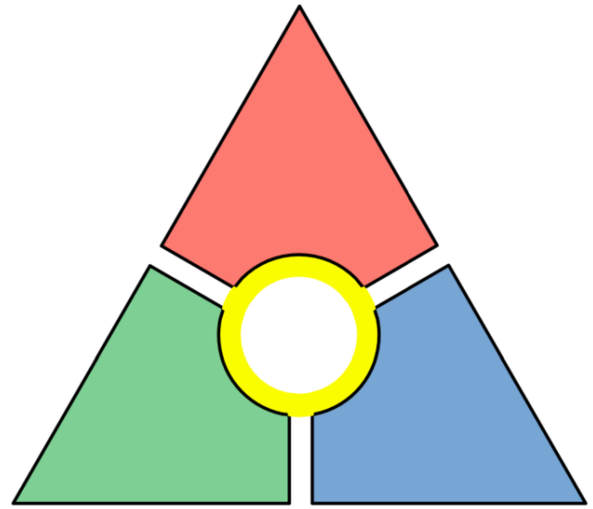






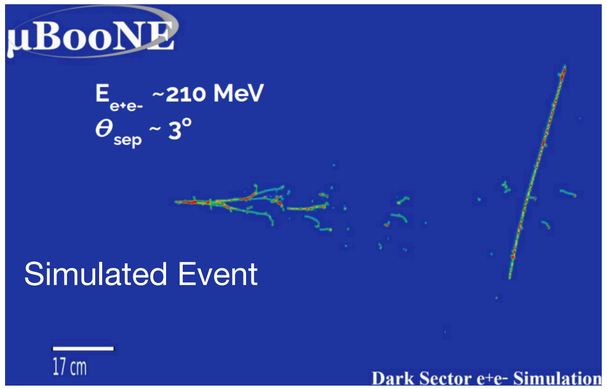
MicroBooNE Science Goals

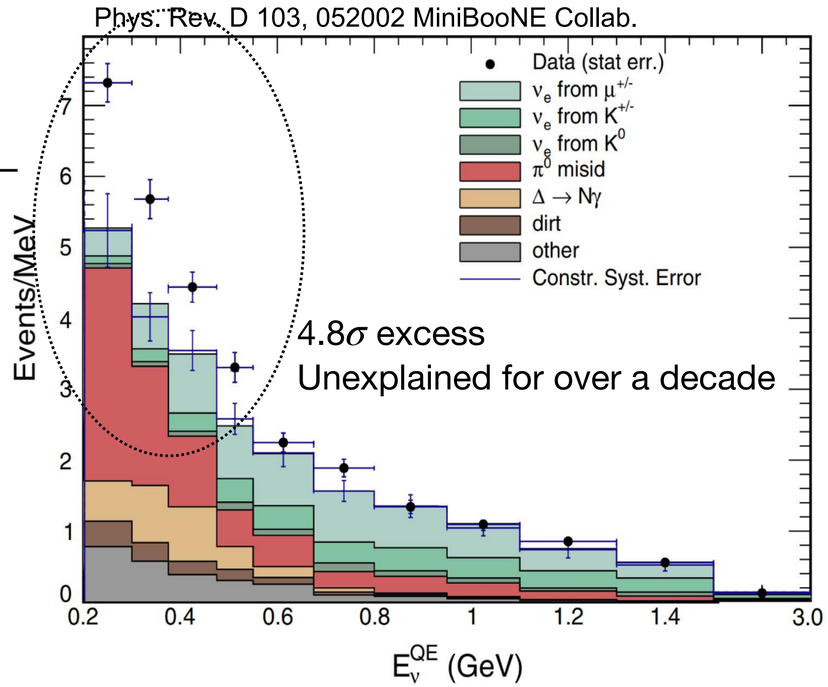
Enhancing our previous BSM searches



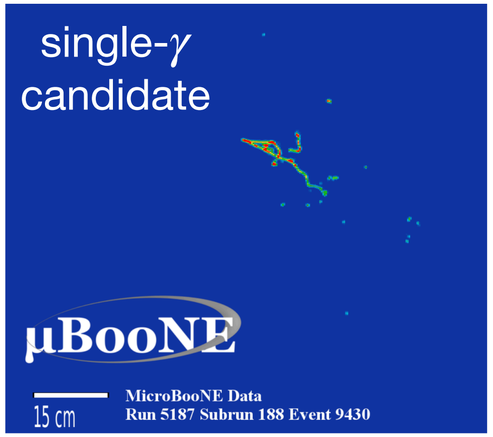
Low Energy Excess Search

e^+e^- ?





single-γ ?

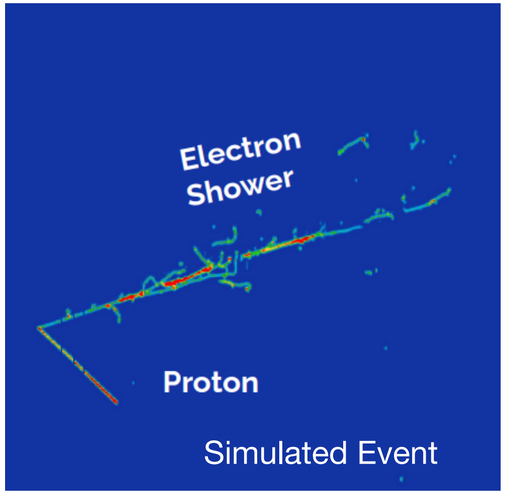


PRL 128 (2022) 111801

ν_e ?

ν_s ?

First generation analyses



PRL 128 (2022) 24, 241801

PRL 130 (2023) 1, 01180

- Famous MiniBooNE/LSND anomaly that is consistent with well-motivated BSM models!
  - Sterile neutrinos, Dark neutrinos, enhancements to SM 1γ production etc
- MicroBooNE has much better e/γ separation capabilities
- Can shed light on the sources of this anomaly - ongoing/updated analyses targeting all topologies

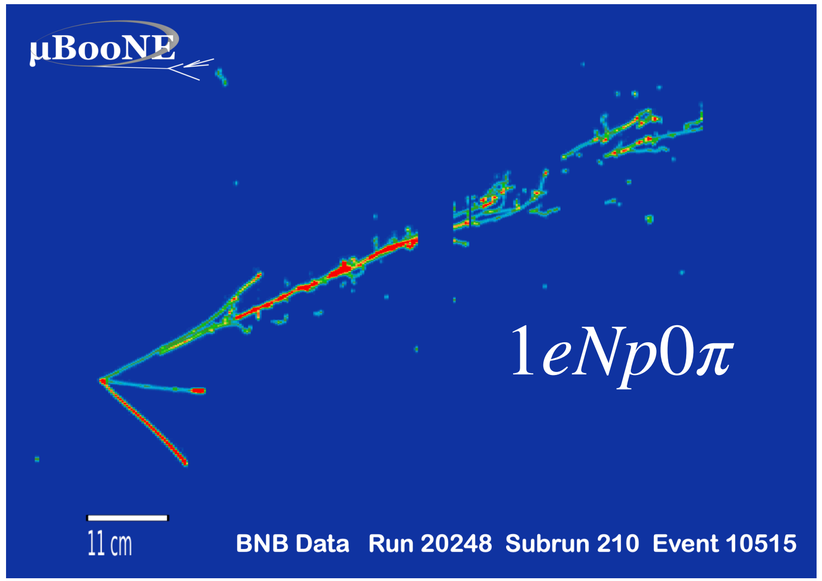
LEE Search (ν_e-like)

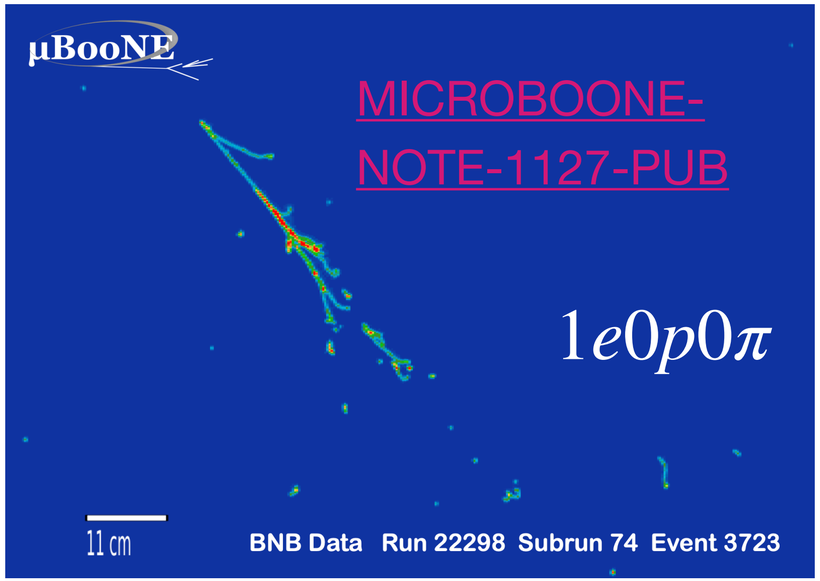
BNB

New Results!

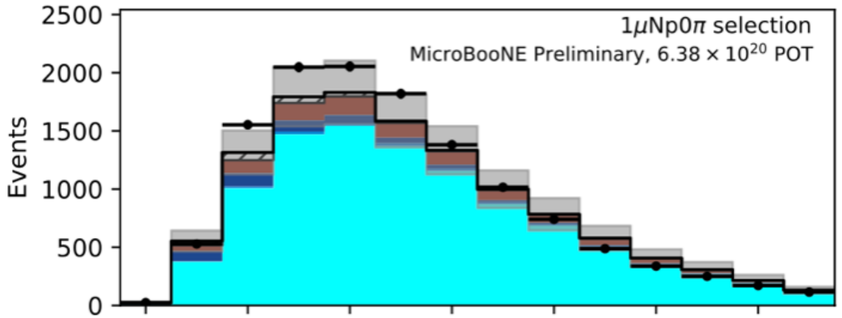
🧐 - ν_e Low Energy Excess Search - Fan Gao

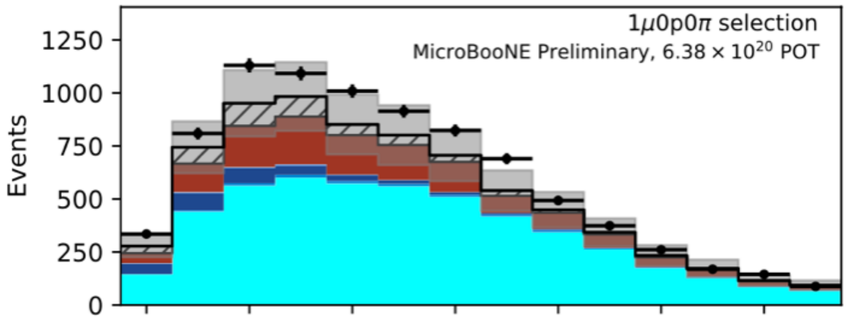
- 1st Round - saw no evidence of ν_e - like excess
- Since then, updates to PRD 105 (2022) 11, 112004
  - Same topology as MiniBooNE LEE ($\nu_e CC0\pi$)
- First analysis to use full MicroBooNE dataset!
  - $6.8 \times 10^{20} \rightarrow 11.1 \times 10^{20}$ POT
- New background constraint from $\nu_\mu CC$ and $NC\pi^0$ rich sidebands



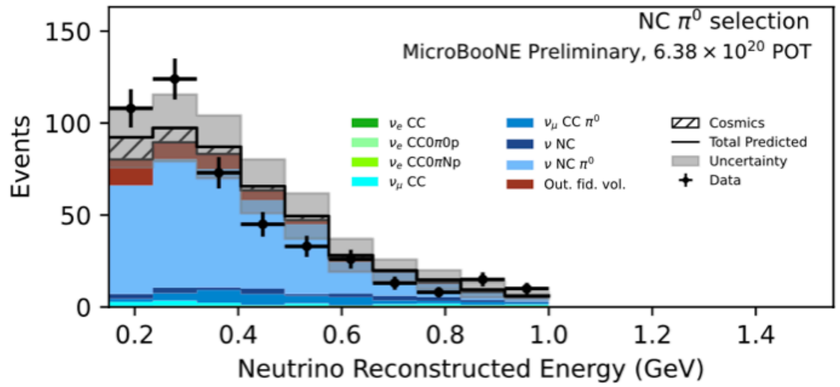


match hadronic final states of ν_e signal channel





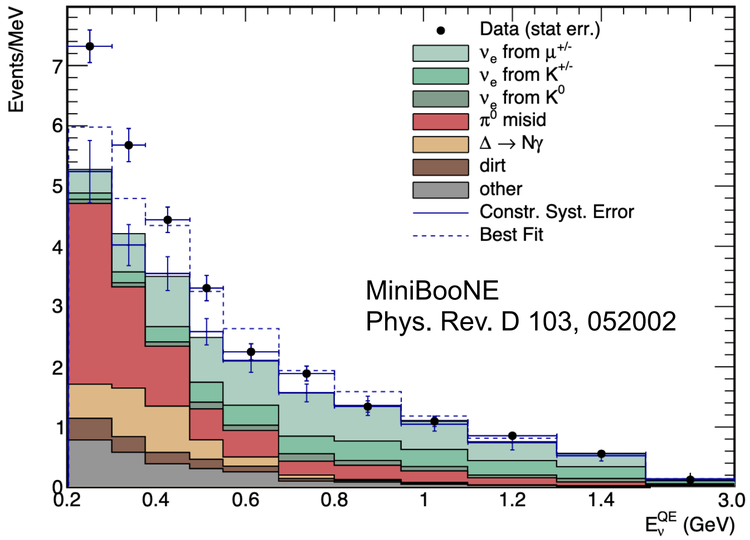
constrain dominant π^0 background



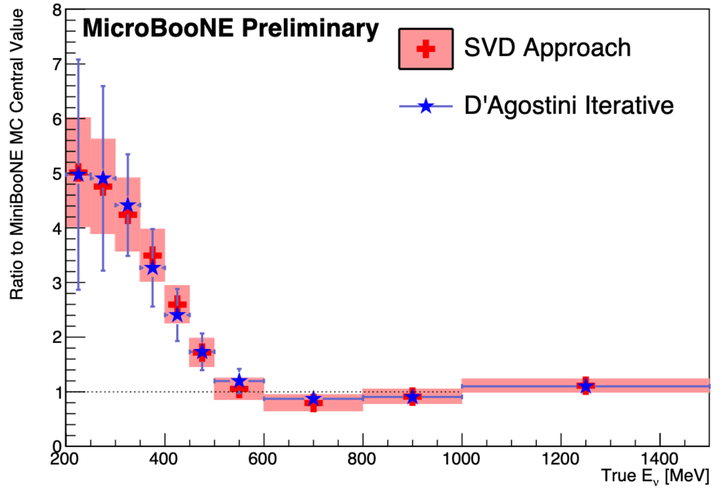
LEE Search (ν_e-like)

BNB

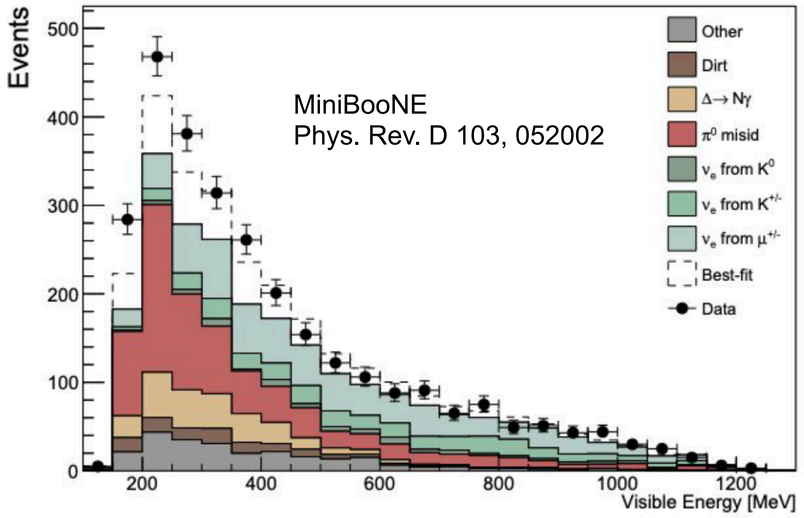
- Previously :
  - MiniBooNE-like excess based on enhancement in true E_ν
- Update to include :
  - Enhancement in true E_e, $\cos\theta_e$ (shower kinematics) as well
- MiniBooNE LEE hypothesis for ν_e-like is more comprehensive



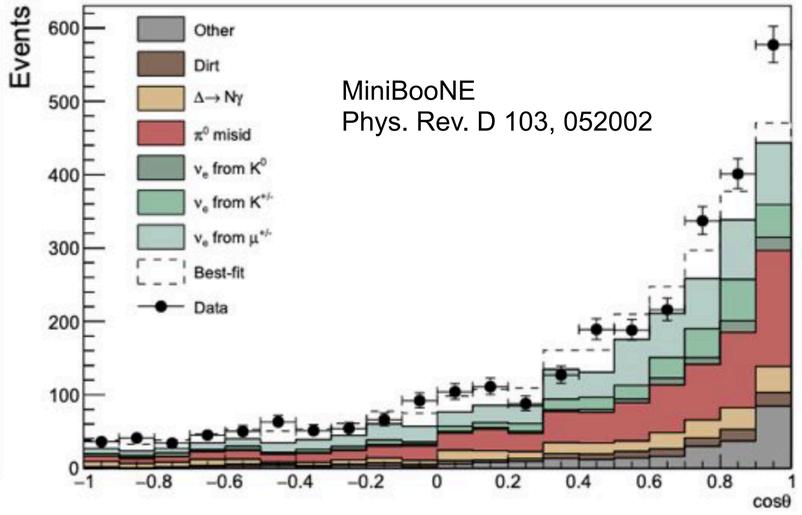
Unfolded MiniBooNE LEE models



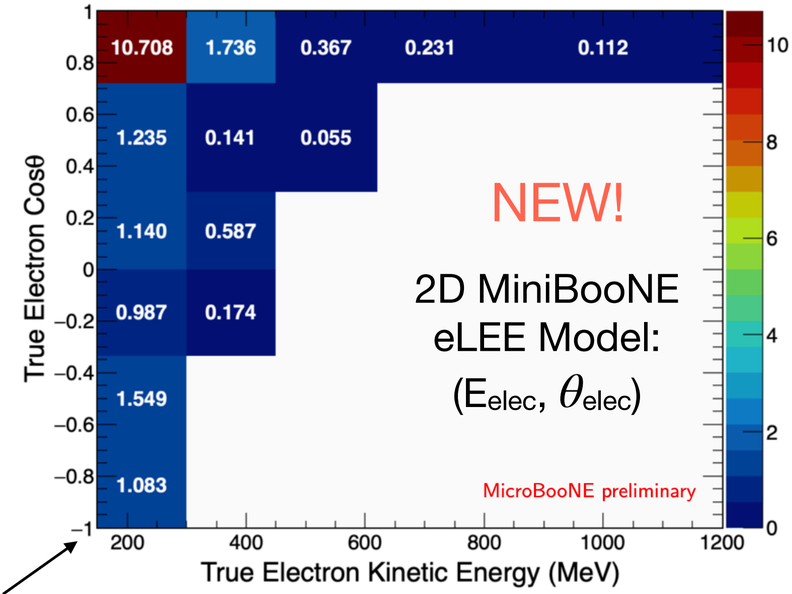
Shower energy



Shower angle

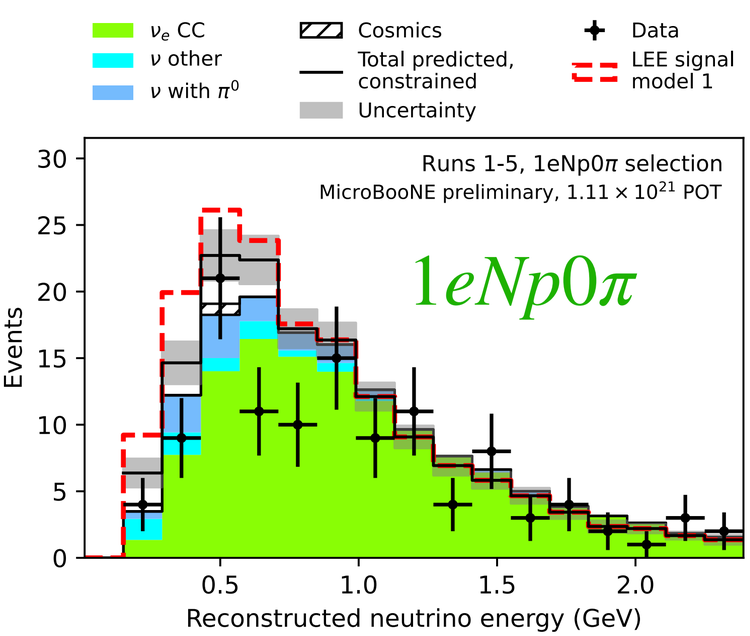


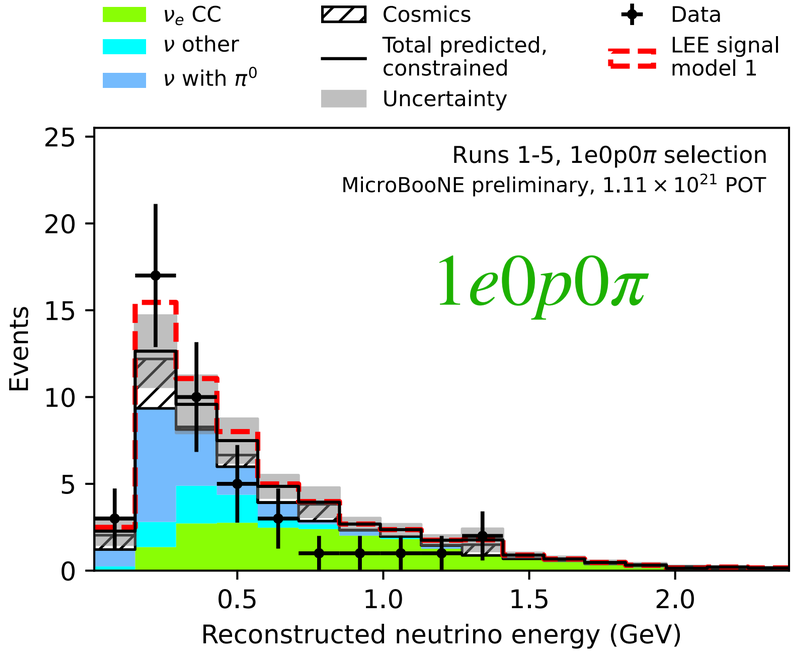
Ratio

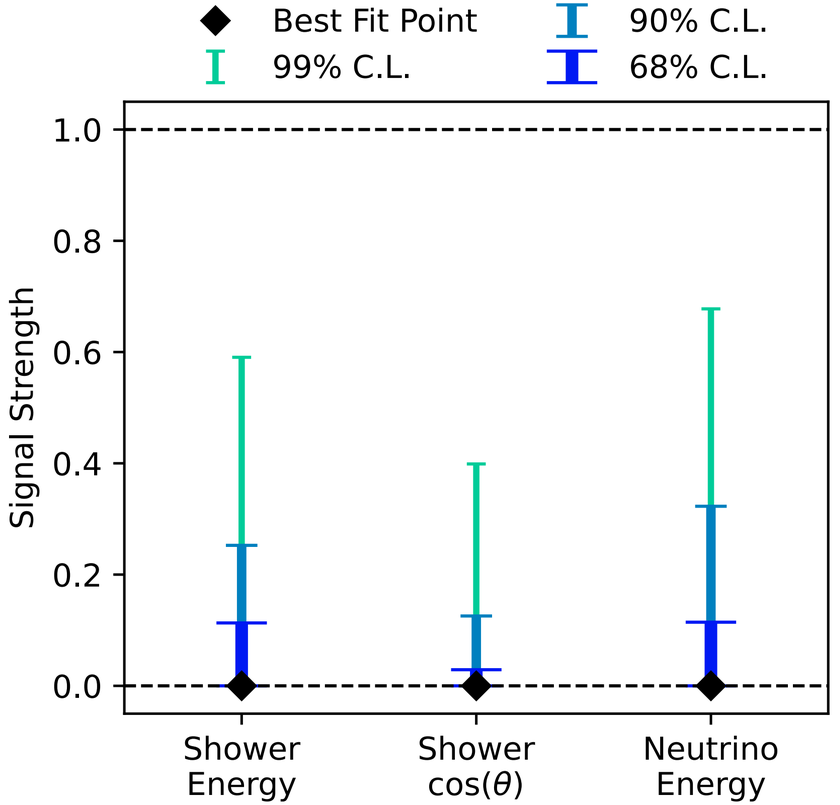


LEE Search (ν_e-like)

BNB



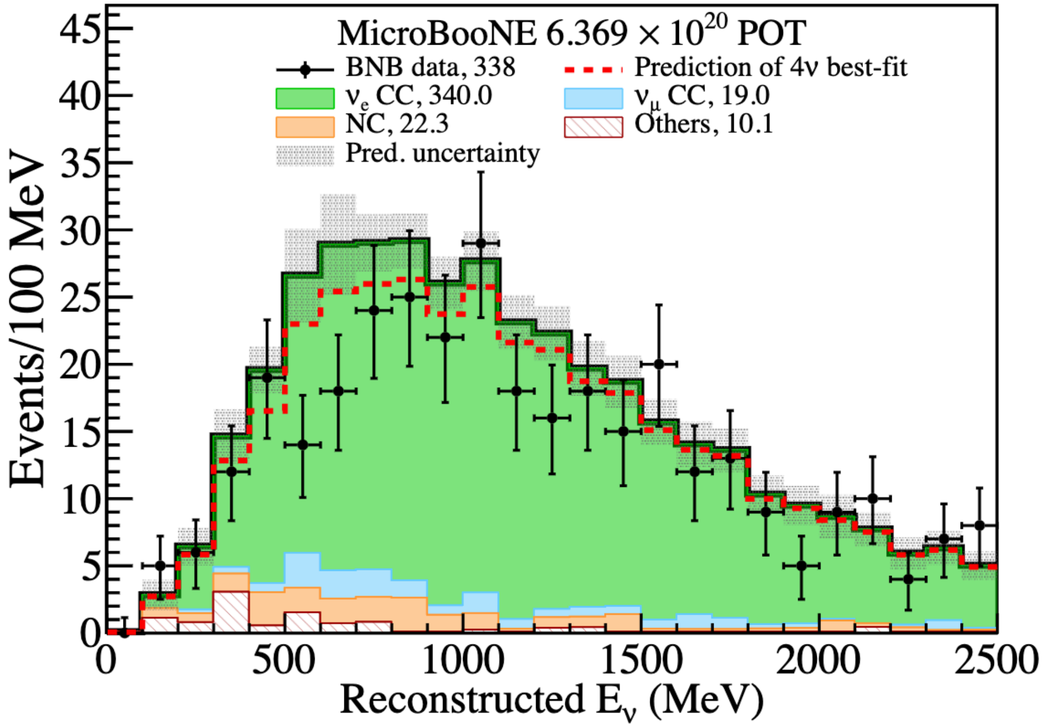




- With ~65% more stats and new sideband constraints => able to provide strong limits on the MiniBooNE LEE-like models
- Inconsistent with ν_e-like excess at > 99% CL!
- Consistent results across all kinematic observables

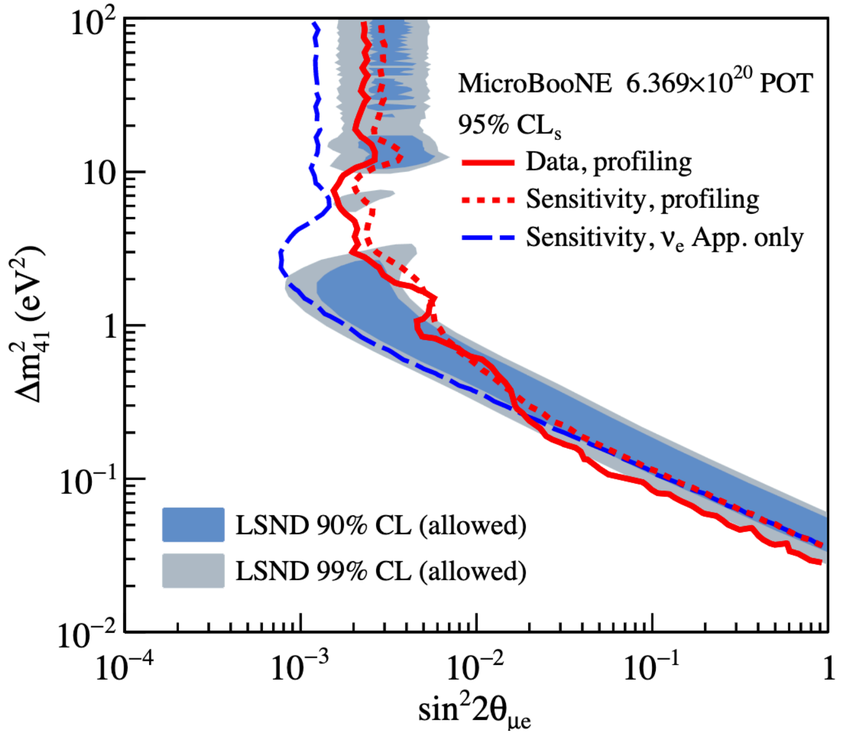
3+1 ν_s Oscillations

BNB + NuMI



$$\nu_\mu \rightarrow \nu_s \rightarrow \nu_e$$

$$\nu_e \rightarrow \nu_s$$

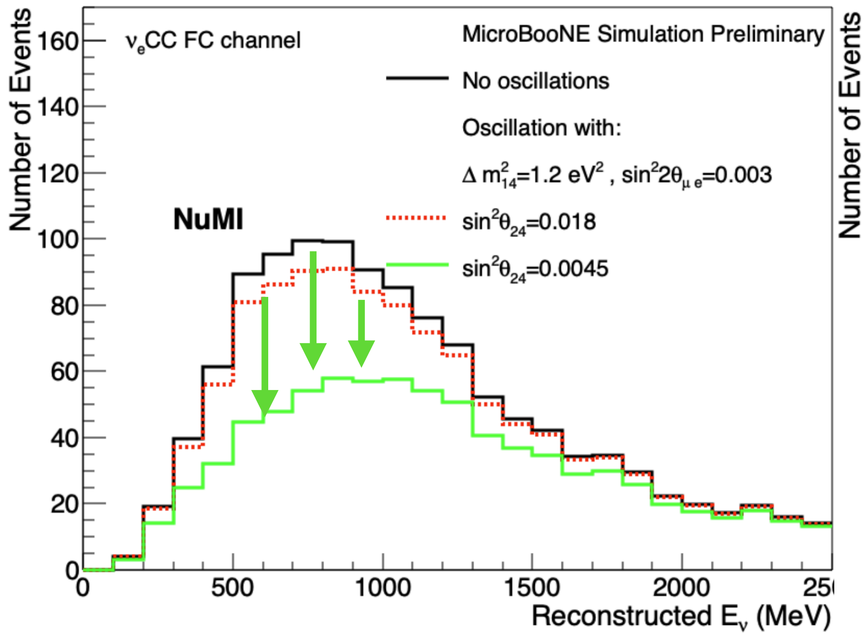


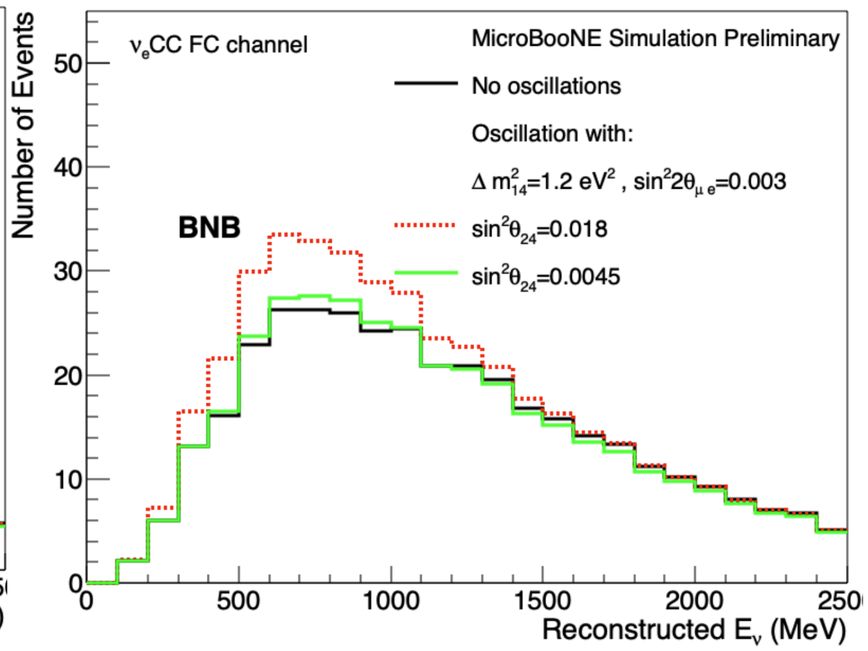
PRL 130 (2023) 1, 01180

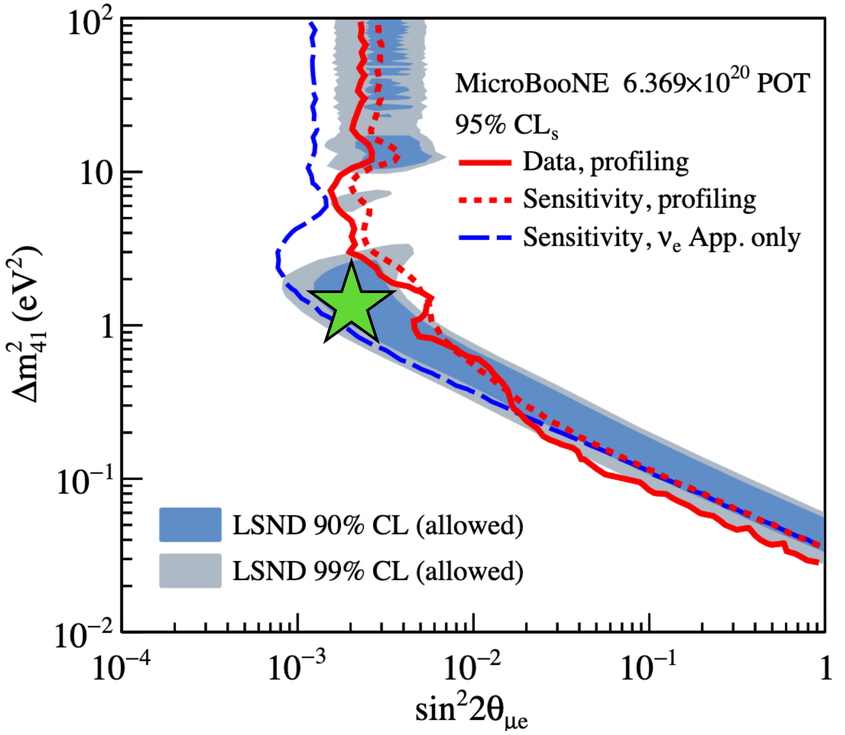
- Previously, 3+1 ν_s search based on BNB-only ν_e analysis (inclusive $\nu_e CC$)
- Able to reject some LSND allowed regions at 95% CL
- However, sensitivity limited by cancellation effect of ν_e-appearance and ν_e disappearance @ BNB

3+1 ν_s Oscillations

BNB + NuMI



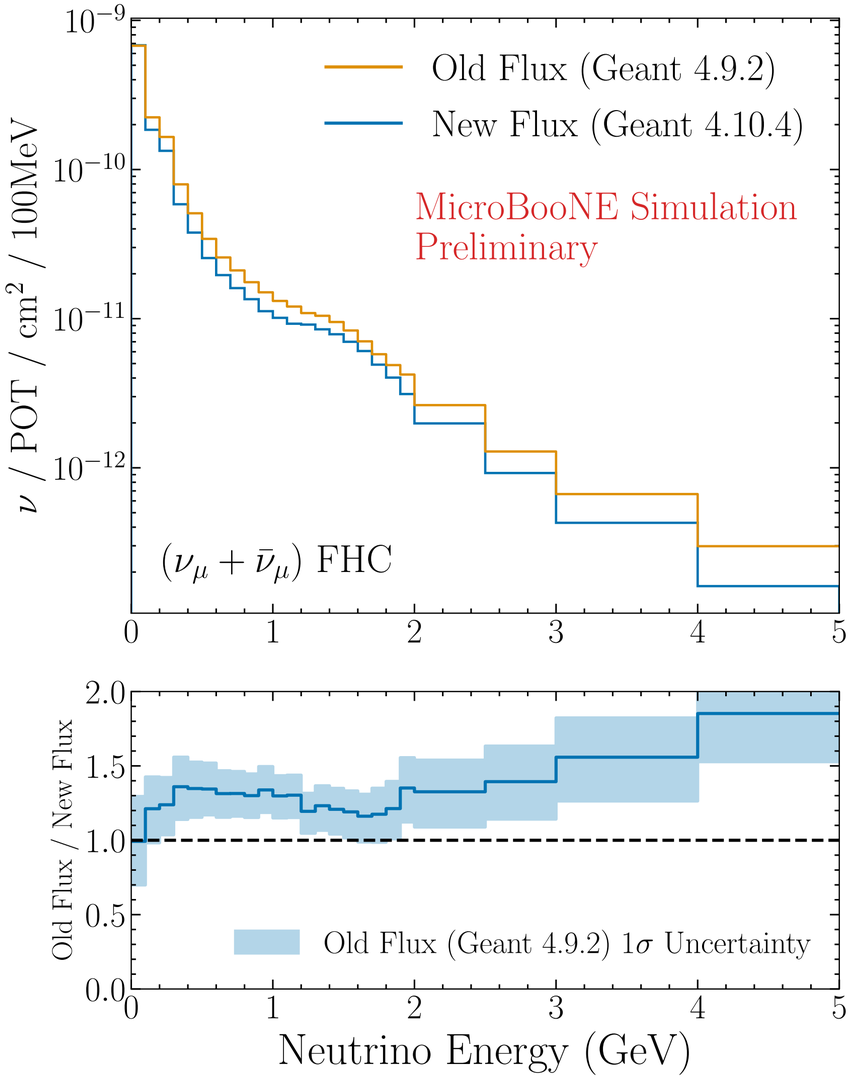


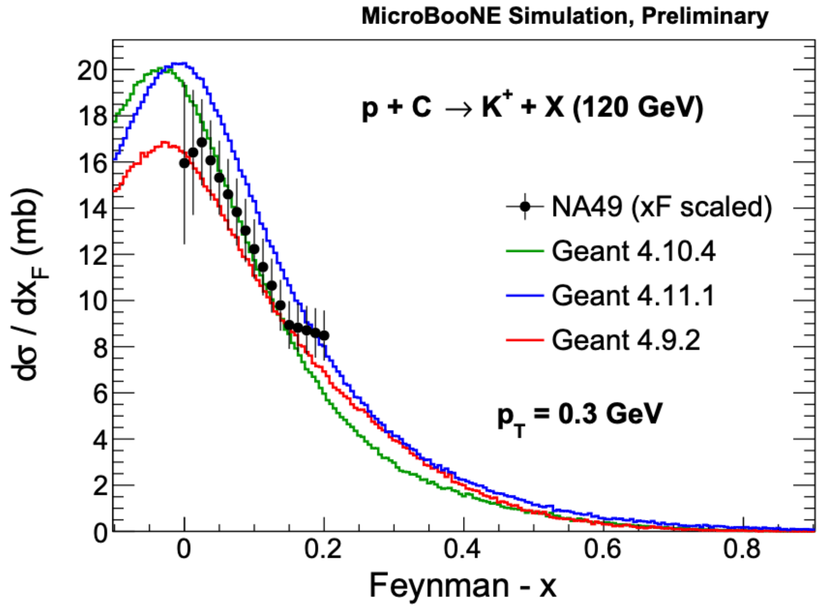


- This appearance-disappearance degeneracy can be broken by using NuMI sample
- Different baseline, different intrinsic ν_e contribution in flux (~4% vs 0.5% in BNB => disappearance effect dominates relative to BNB)
- Pioneering “one detector, two beams concept”

Updating the NuMI simulation

- More details at MICROBOONE-NOTE-1129-PUB

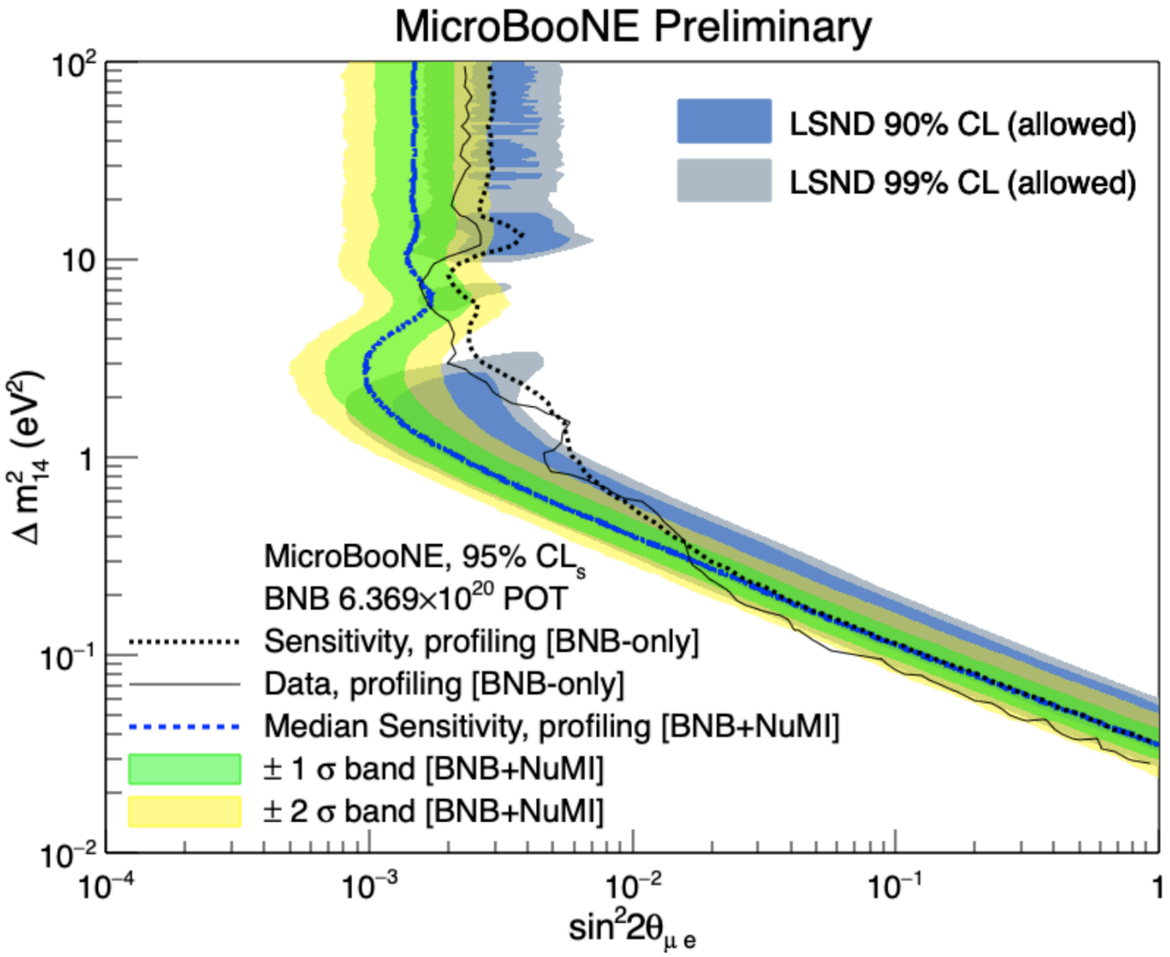




- NuMI sits at ~8° (highly off-axis!) => very little phase space coverage for external hadron production data
- We have overhauled our NuMI simulation
  - Beamline geometry updates
  - Updated to a modern G4 version (4.10) for a better base model
  - Constraints from NA49 and others similar to NOvA, MINERvA
  - Conservative treatment of uncertainties outside data coverage

3+1 ν_s Oscillations

BNB + NuMI

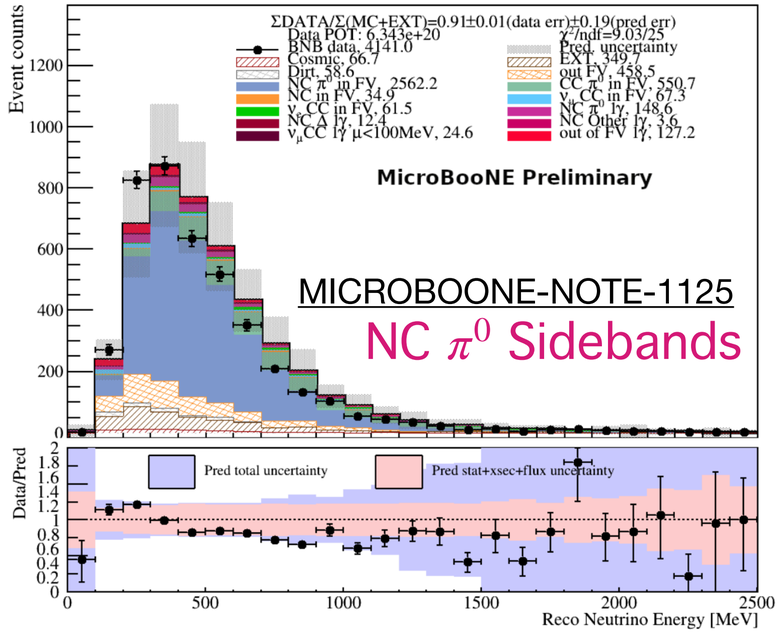


- Allows for significant increase in sensitivity when including both beams!
- Stay tuned for upcoming results!
- More details in MICROBOONE-NOTE-1132-PUB

LEE Search (single-γ)

BNB

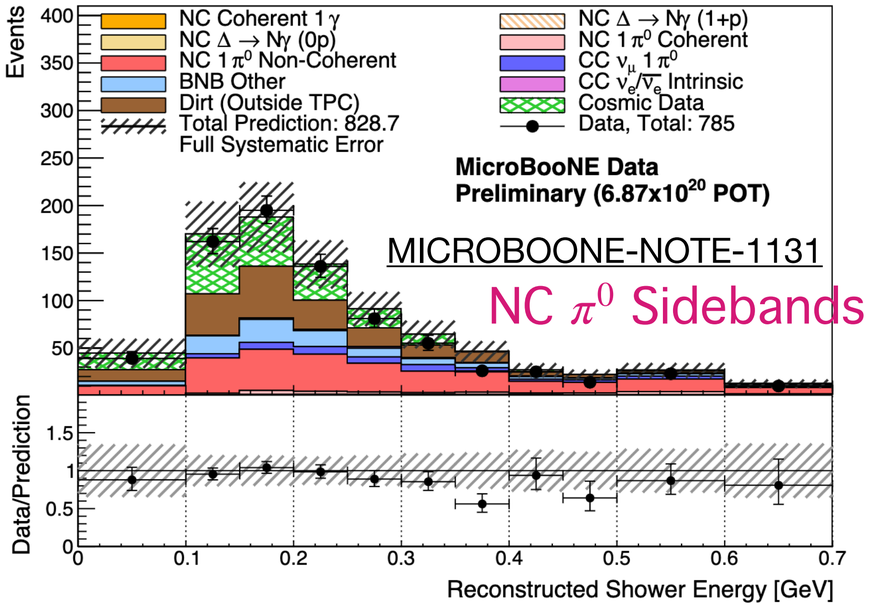
Inclusive single-γ



MICROBOONE-NOTE-1125

NC π^0 Sidebands

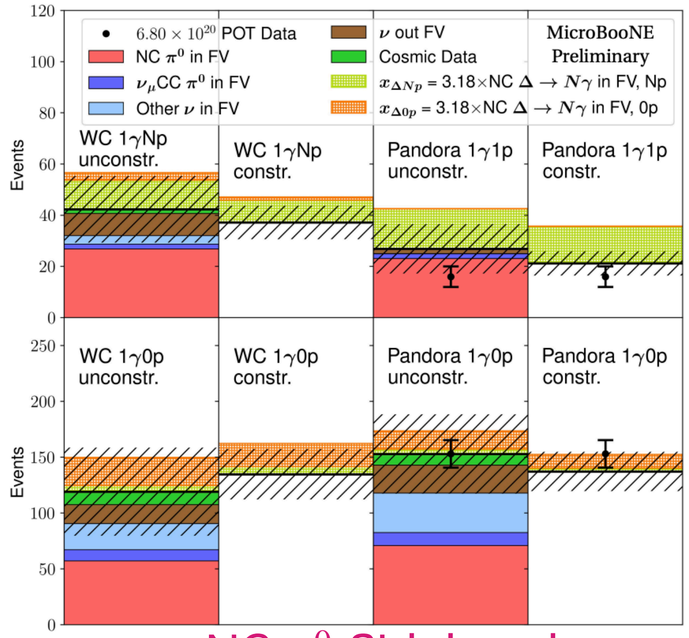
Enhancement in NC Coherent



MICROBOONE-NOTE-1131

NC π^0 Sidebands

Enhancement in NC $\Delta \rightarrow 1\gamma$



NC π^0 Sidebands

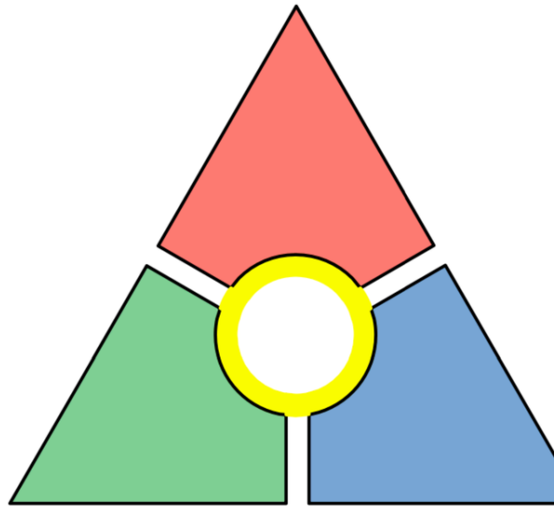
MICROBOONE-NOTE-1126

- Previously, saw no evidence of enhancement to NC $\Delta \rightarrow 1\gamma$
  - Disfavor sole MiniBooNE explanation at 95% CL
- Now, casting a wider net with new and updated analyses - both generic (inclusive) and specific enhancements
- Stay tuned for results!

- 🙂 - Anomalous γ and e^+e^- Searches - Erin Yandel
- 🙂 - NC $\Delta \rightarrow 1\gamma$ - Lee Hagaman

MicroBooNE Science Goals

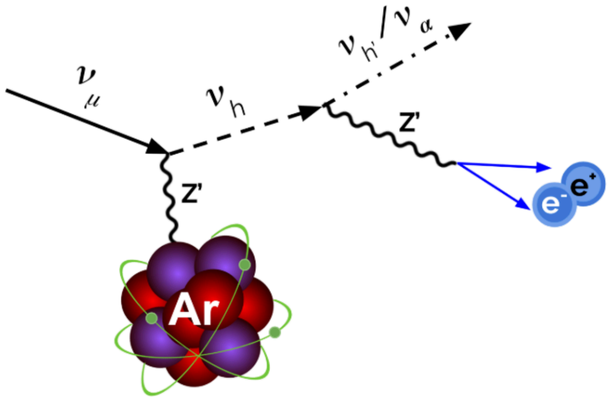
Extending our BSM program

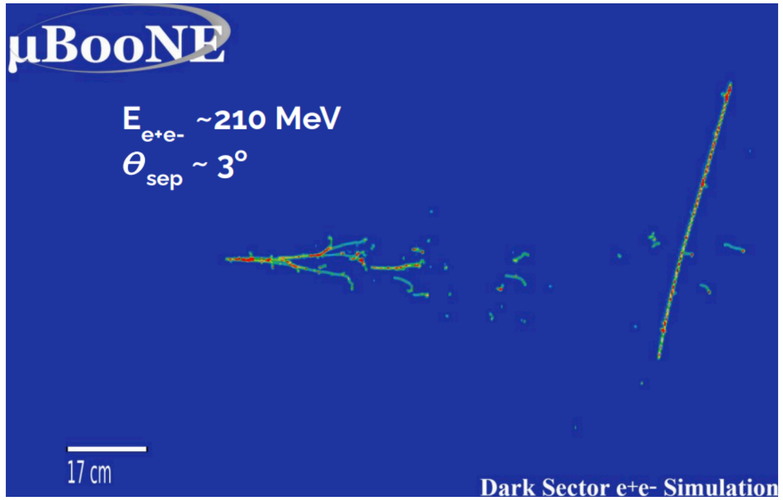


LEE Search (BSM e^+e^-)

BNB

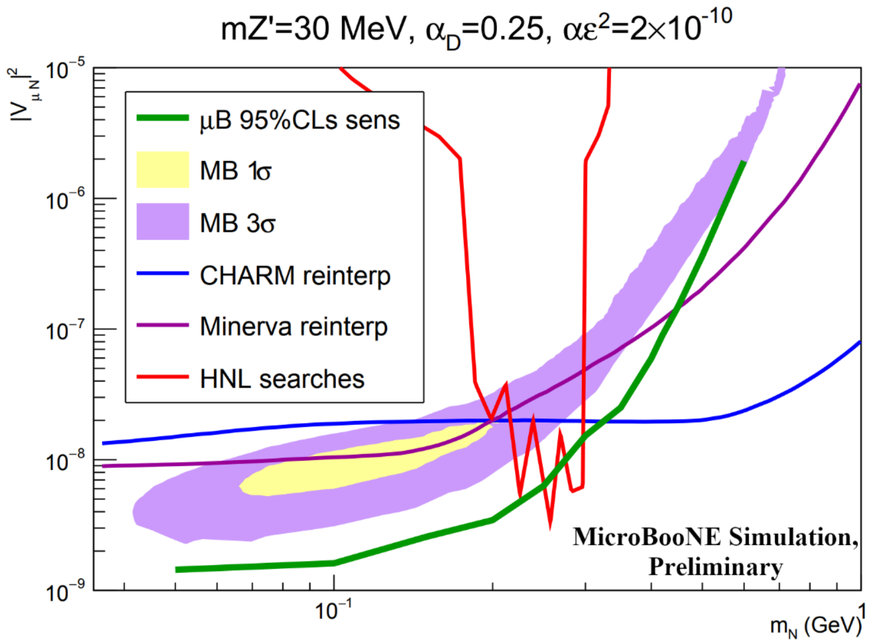
- Dark neutrino models
- Decay into ~collinear e^+e^- pairs via dark gauge boson, Z'
- Mimics LEE signature with single shower topology
- Single or multiple dark neutrino states



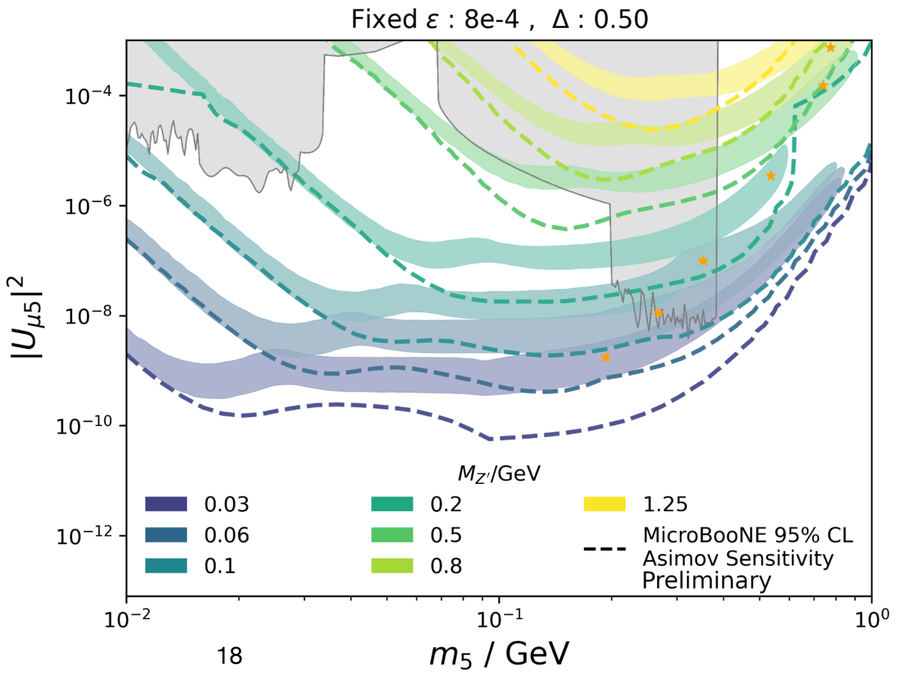


Ballet, Pascoli, Ross-Lonergan
PRD 99 (2019) 071701

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



MicroBooNE sensitivities



More details at:
MICROBOONE-NOTE-1124-PUB

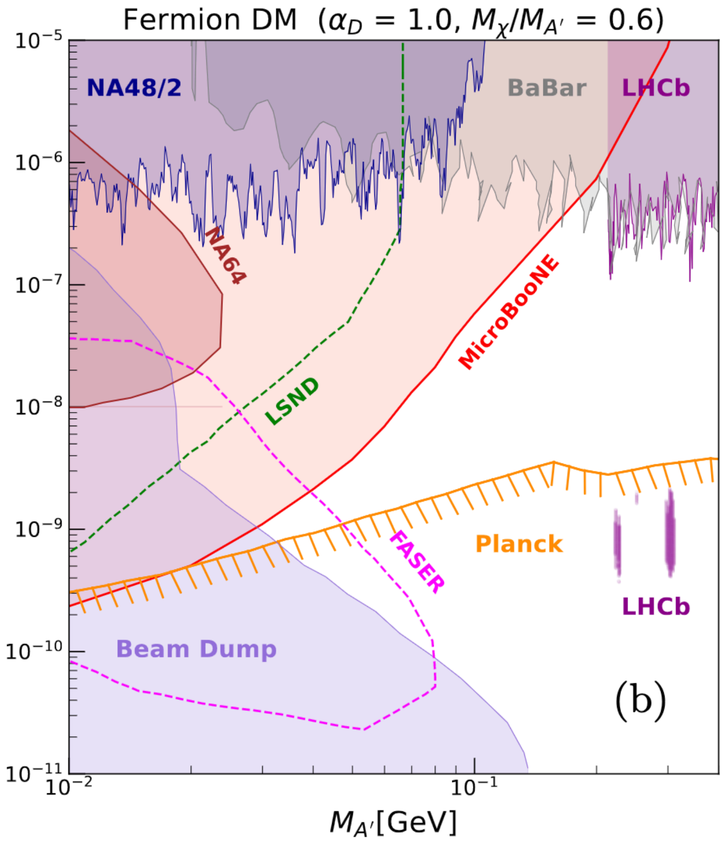
🧐 - Anomalous γ and e^+e^- Searches - Erin Yandel

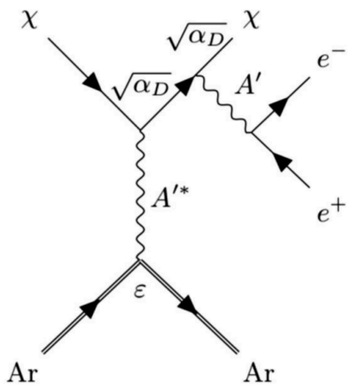
HNL/Dark Sector Searches

NuMI

New Results!

🧐 - MicroBooNE's BSM Program - Keng Lin



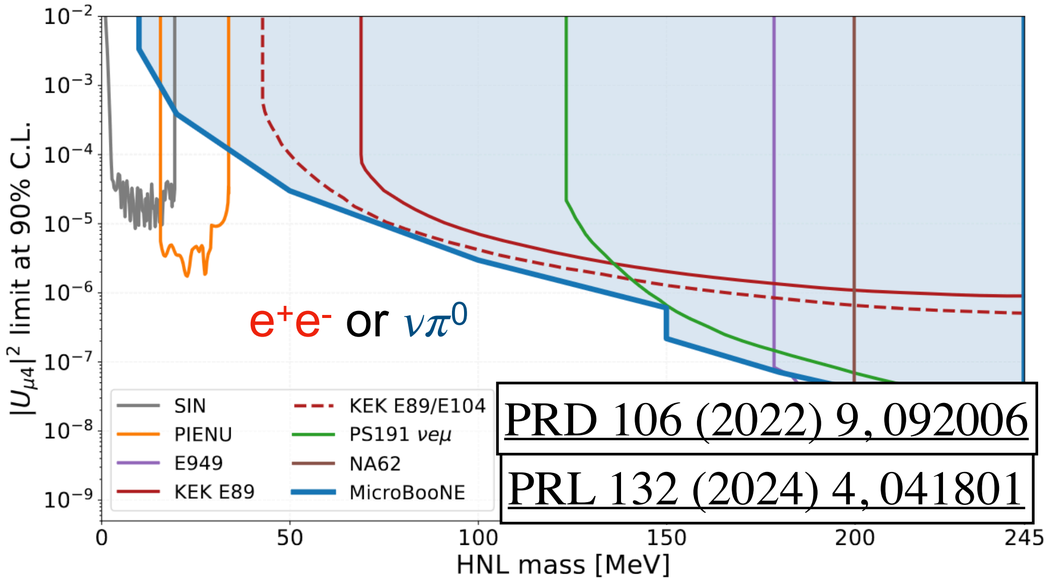


- Dark tridents -> light dark matter production via dark photon mediation -> e^+e^- topologies
- Higgs portal searches -> scalar Higgs produced via kaon decay @ NuMI -> di-lepton topologies
- Exploring new phase space and setting competitive limits!

- HNLs relevant for neutrino mass (see-saw), Baryon asymmetry, Dark matter
- Competitive limits across broad range of HNL mass, including < 100 MeV (multiple final states)

produced in beam via mixing

decay in the detector

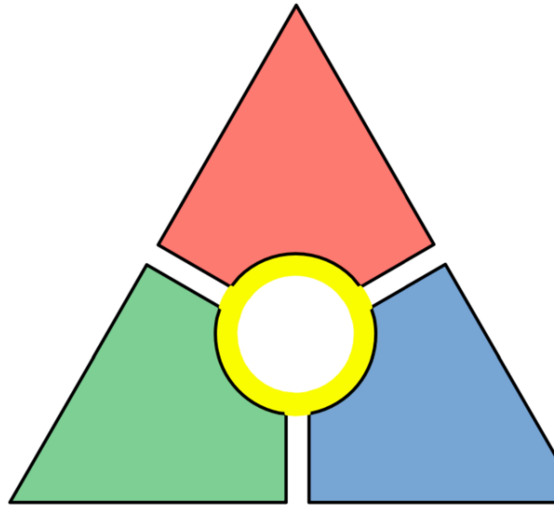


PRD 106 (2022) 9, 092006

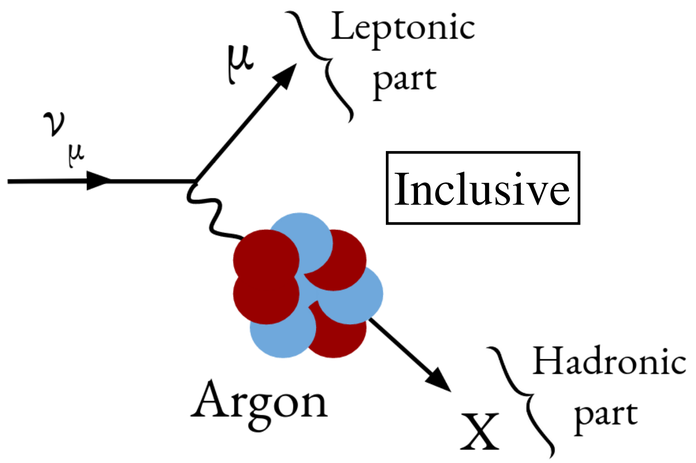
PRL 132 (2024) 4, 041801

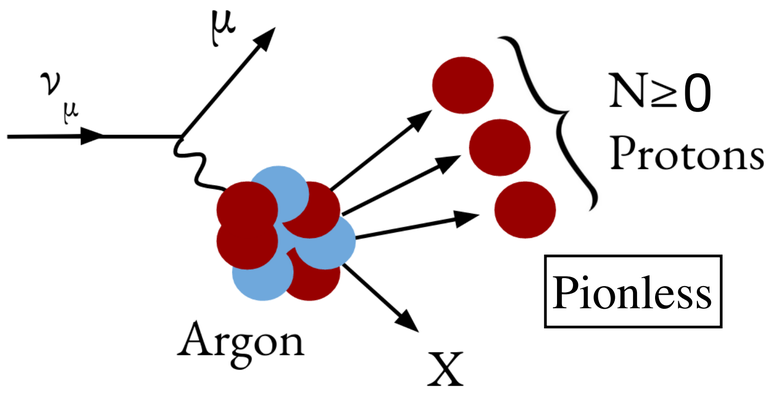
MicroBooNE Science Goals

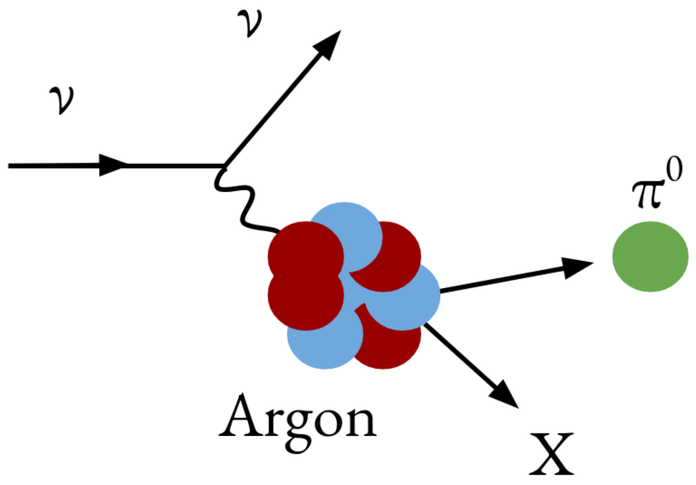
Looking Ahead to the Future



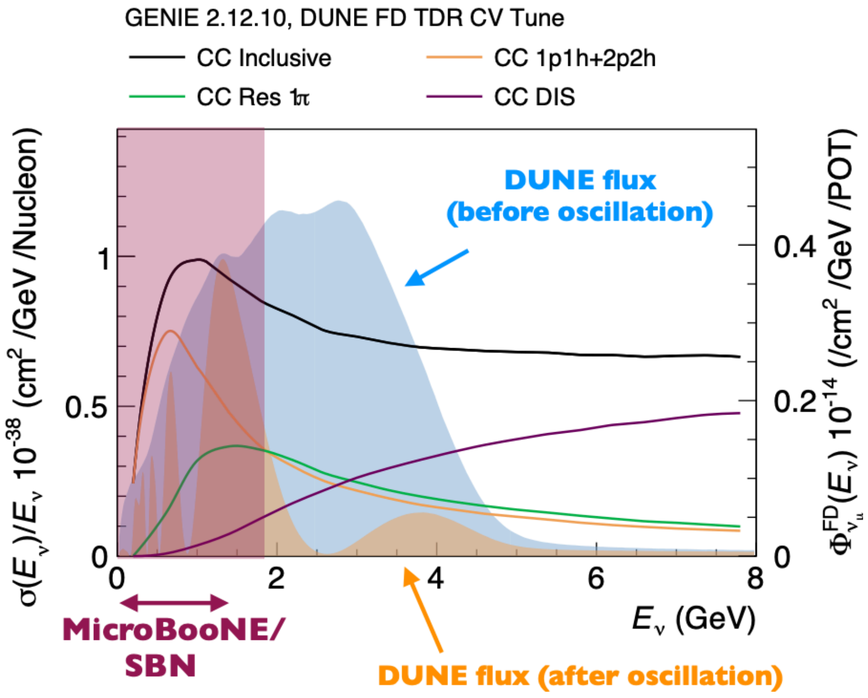
Neutrino Interactions







Pions (Charged/Neutral)



- MicroBooNE has a large and comprehensive neutrino cross-section program
- Aims to support both our BSM program and future LArTPC experiments like DUNE
- Probes nuclear effects at the GeV scale across multiple final state topologies

$\nu - Ar$ Datasets from MicroBooNE

CC inclusive

- 1D ν_μ CC inclusive @ BNB, Phys. Rev. Lett. 123, 131801
- 1D ν_μ CC E_ν @ BNB, Phys. Rev. Lett. 128, 151801
- 3D CC E_ν @ BNB, arXiv:2307.06413
- 1D ν_e CC inclusive @ NuMI, Phys. Rev. D104, 052002, Phys. Rev. D105, L051102
- 2D ν_μ CC0pNp inclusive @ BNB, arXiv:2402.19216, arXiv:2402.19281

Pion production

- ν_μ NCπ^0 @ BNB, Phys. Rev. D 107, 012004
- 2D ν_μ NCπ^0 @ BNB, arXiv:2404.10948
- ν_μ CCπ^0 @ BNB, arXiv:2404.09949

CC0π

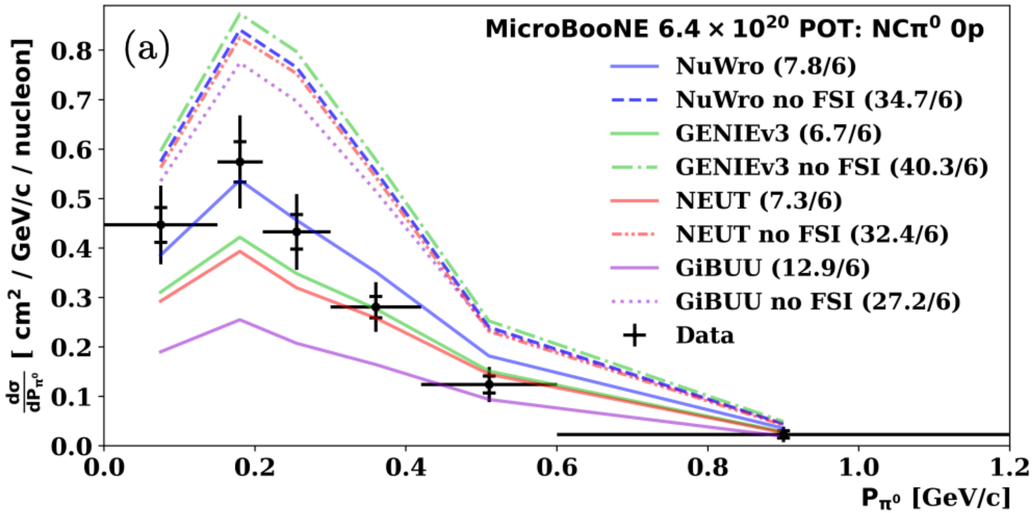
- 1D ν_e CCNp0π @ BNB, Phys. Rev. D 106, L051102
- 1D & 2D ν_μ CC1p0π transverse imbalance @ BNB, Phys. Rev. Lett. 131, 101802, Phys. Rev. D 108, 053002
- 1D & 2D ν_μ CC1p0π generalized imbalance @ BNB, Phys. Rev. D 109, 092007
- 1D ν_μ CC1p0π @ BNB, Phys. Rev. Lett. 125, 201803
- 1D ν_μ CC2p @ BNB, arXiv:2211.03734
- 1D ν_μ CCNp0π @ BNB, Phys. Rev. D102, 112013
- 2D ν_μ CCNp0π @ BNB, arXiv:2403.19574

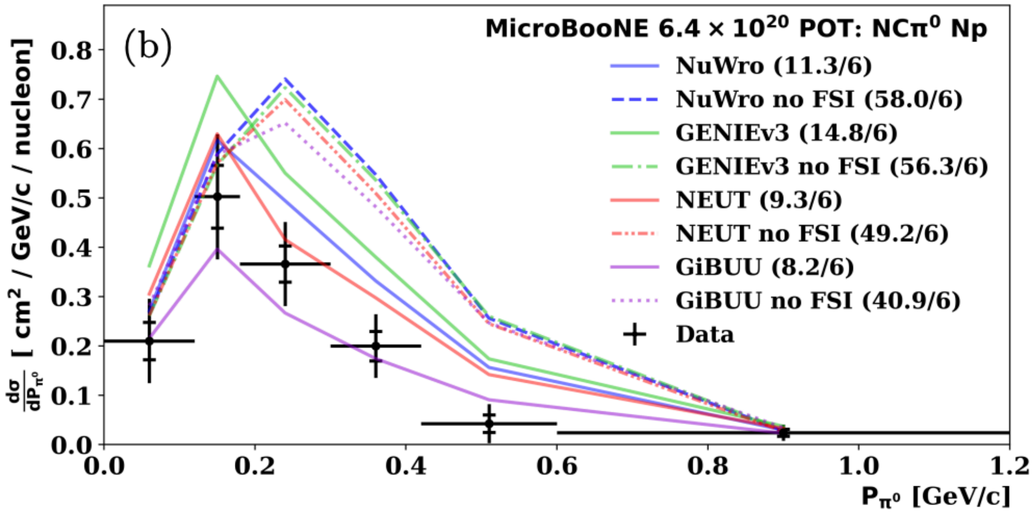
Rare channels & novel identification techniques

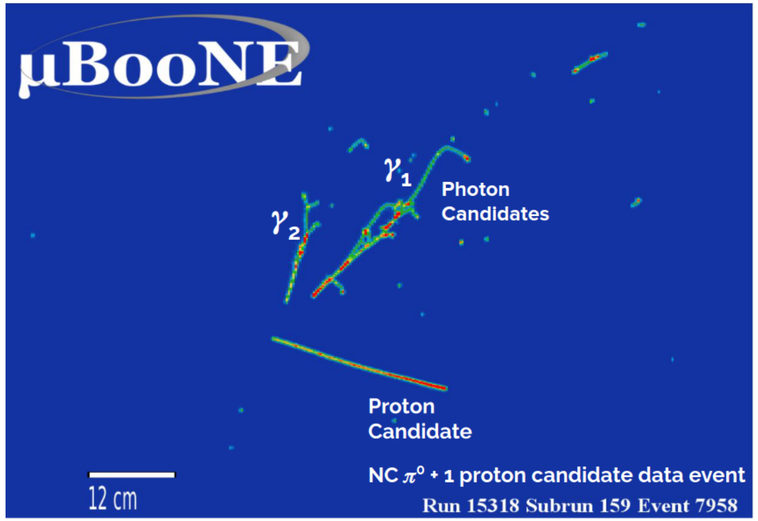
- η production @ BNB, Phys. Rev. Lett. 132, 151801
- Λ production @ NuMI, Phys. Rev. Lett. 130, 231802
- Neutron identification, arXiv:2406.10583

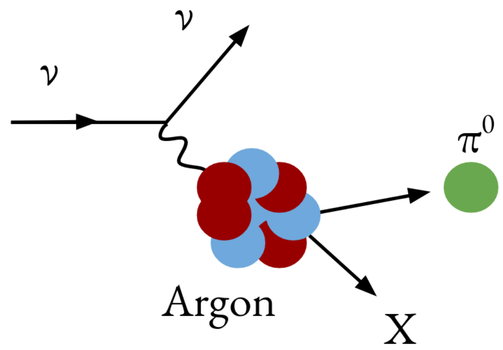
Measurements with Pions

New Results!









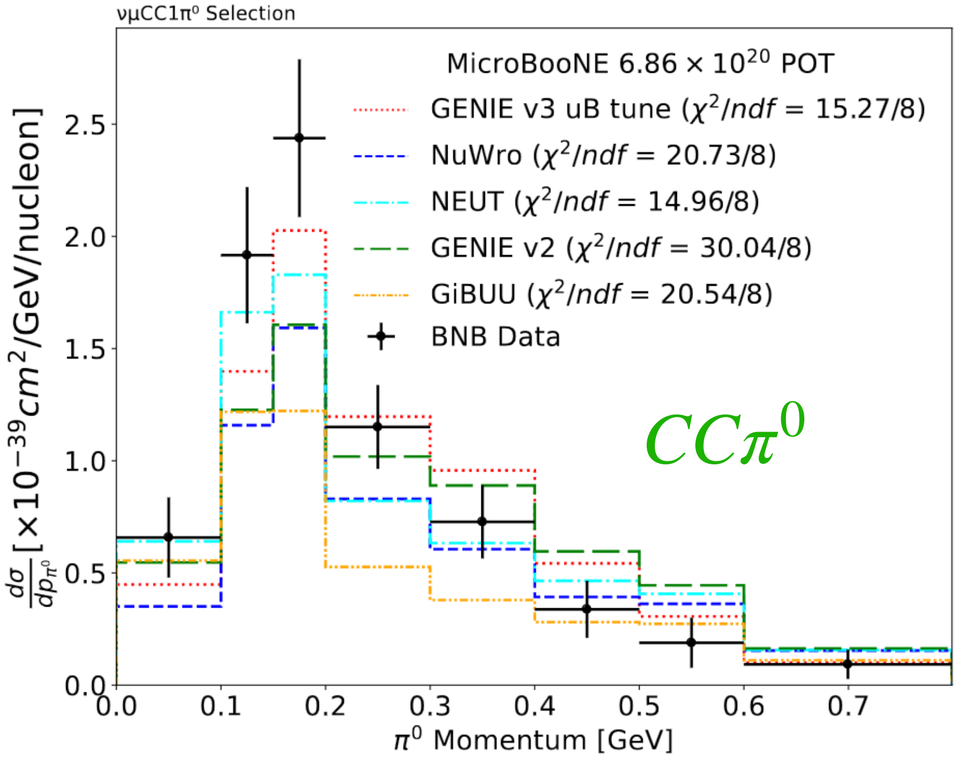
$NC\pi^0$

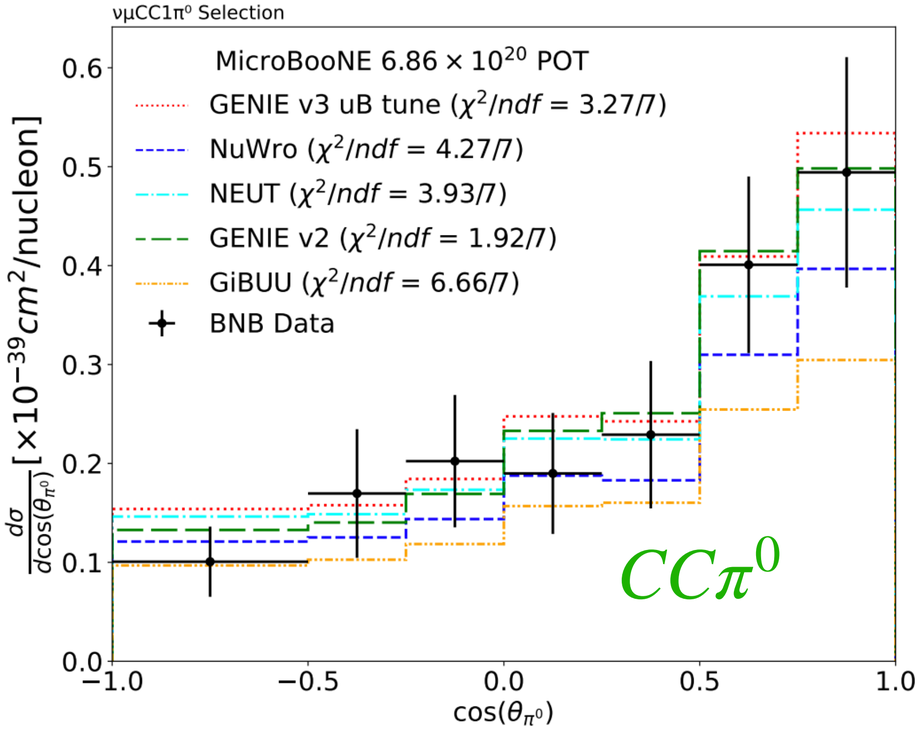
- All single-γ analyses have $NC\pi^0$ as main background
- We have dedicated cross-section measurements for this channel
- Informs not just nuclear modeling uncertainties but acts as an important SM-level handle

🧐 - Pion Production Measurements - Patrick Green

Measurements with Pions

New Results!



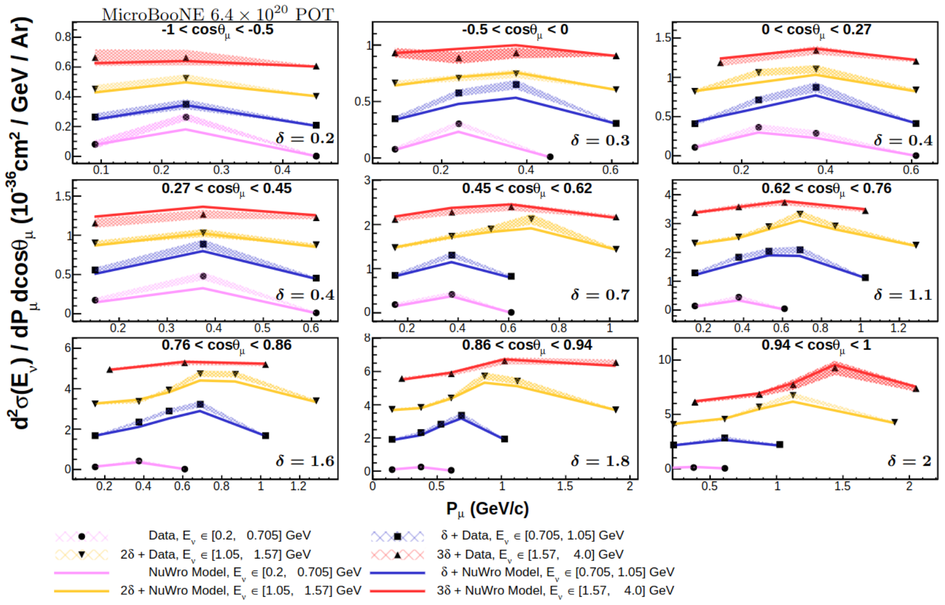


- Measurements in the resonance (RES) regime - $\Delta(1232)$
  - NC and CC π^0 released, $\pi^{\pm}$ final states also being analysed
  - Detailed description over π^0 kinematics
- Also able to measure higher order resonances with η-production
  - Novel EM calibration sources, improvements to reconstruction relevant for proton decay @ DUNE

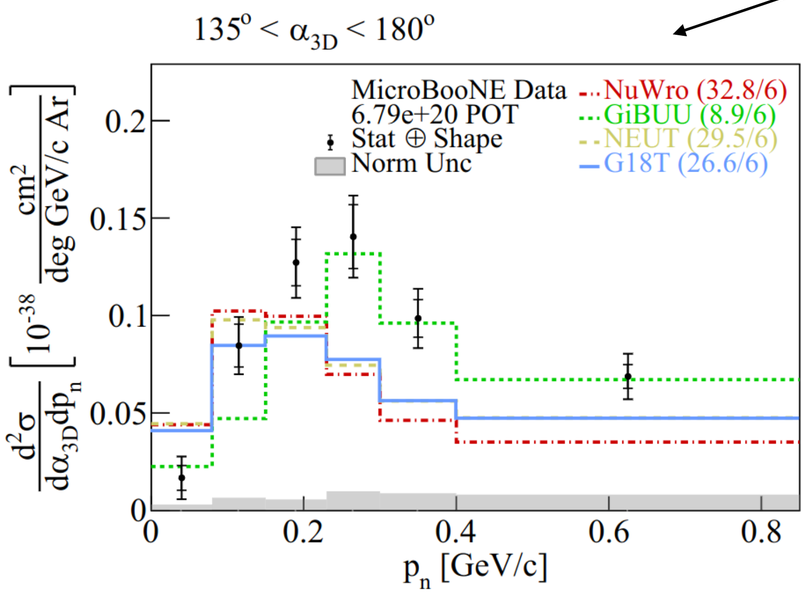
- 😳 - Pion Production Measurements - Patrick Green
- 😳 - Rare Mesons - Jairo Rodriguez
- 😳 - Charged Pions - Philip Detje

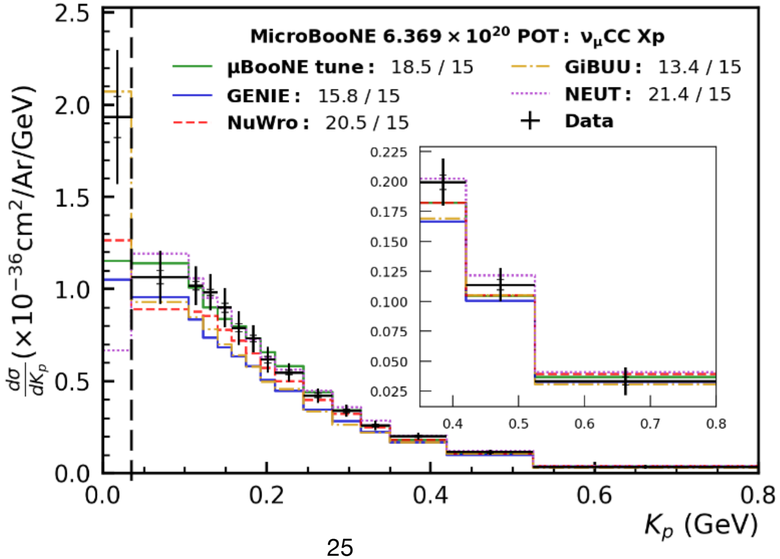
$\nu_\mu CC$ Inclusive + Pionless

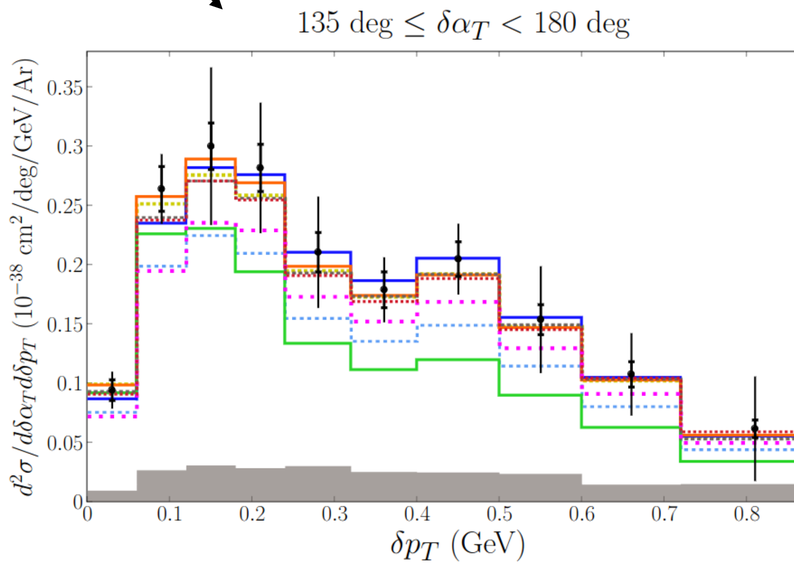
New Results!



- High statistics based, 3D phase space coverage with $\sigma(E_\nu\ ,\ P_\mu\ ,\ \cos\theta_\mu)$ measurement
- Further probe hadronic modeling using 0p/Np topologies
- Measurement in kinematic imbalance variables (missing momentum etc) to get sensitive probe into final-state interactions and other nuclear effects
- Significant model discrimination power across the board! Will inform next generation improvements in interaction model

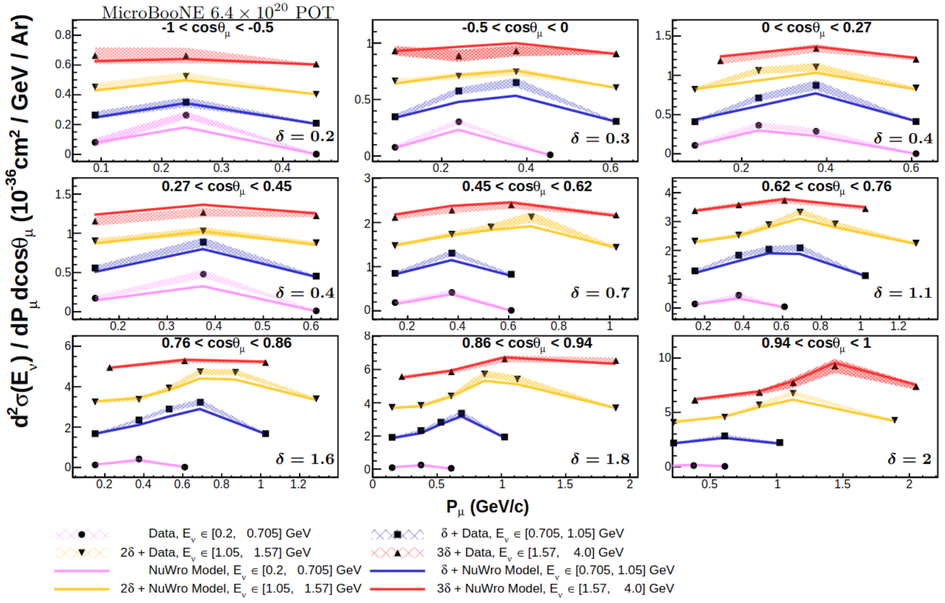




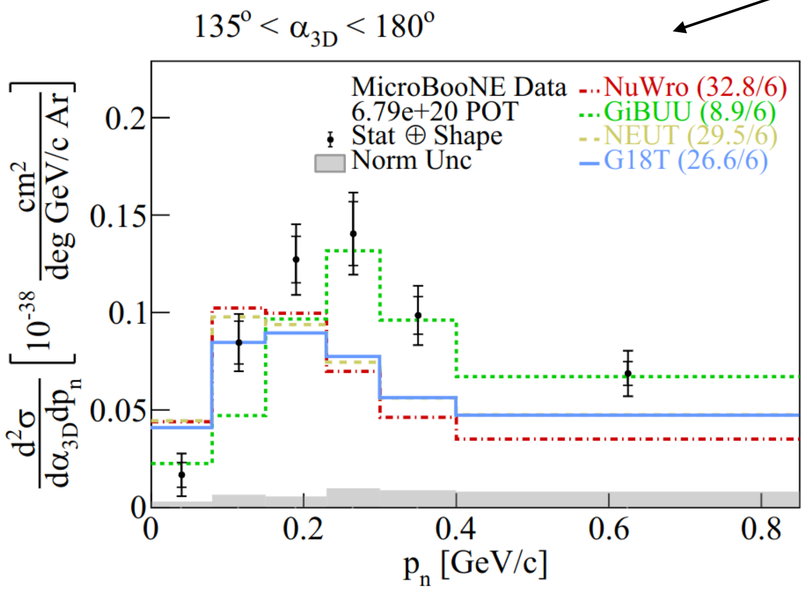


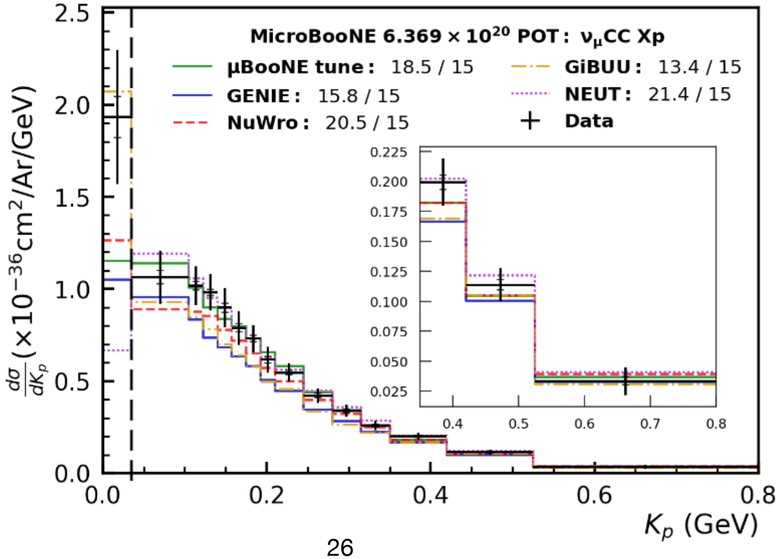
$\nu_\mu CC$ Inclusive + Pionless

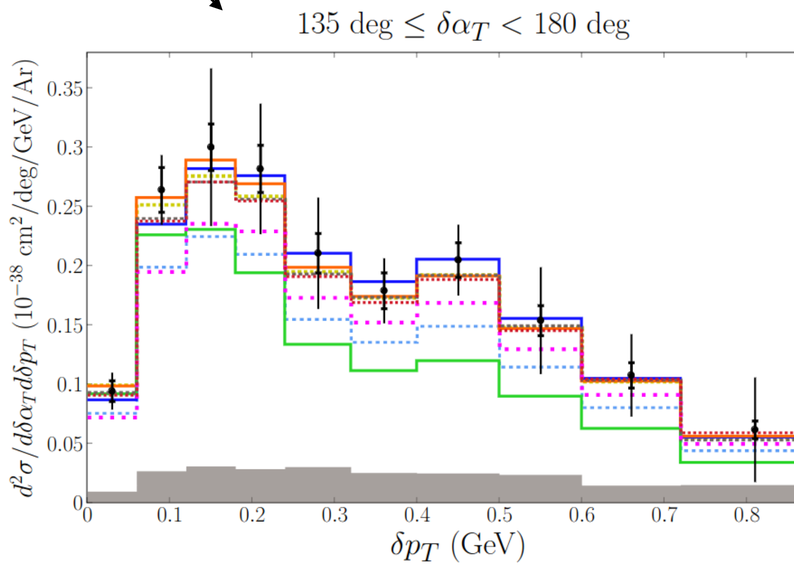
New Results!



- 🧐 - Inclusive and Pionless Measurements - Dan Barrow
- 🧐 - $\nu_\mu CC$ Inclusive - London Cooper-Troendle
- 🧐 - $\nu_\mu CC2p$ - Dan Barrow
- 🧐 - $\nu_\mu CC0\pi$ - Panos Englezos
- 🧐 - $\nu_\mu CC0p/Np$ - Ben Bogart





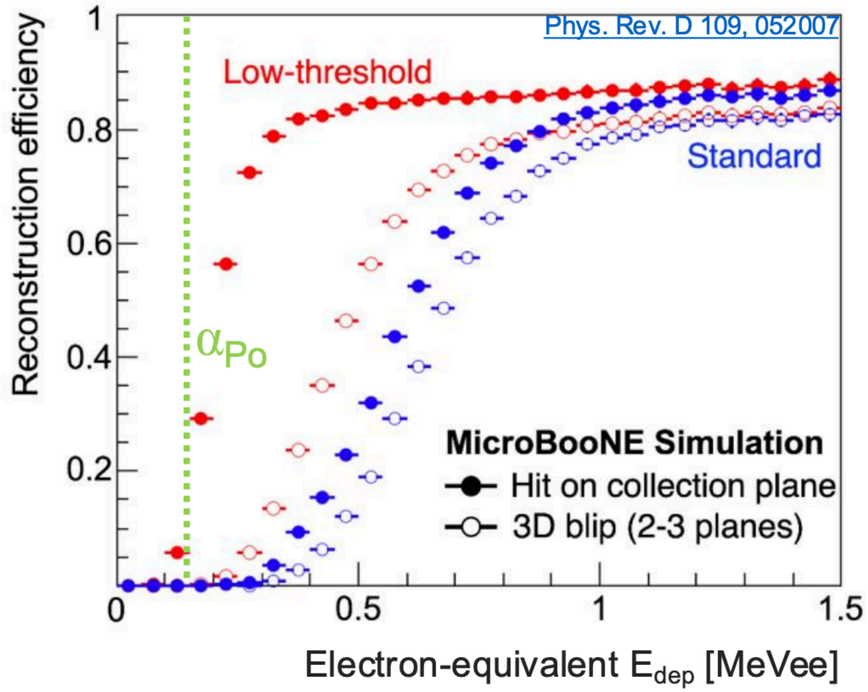


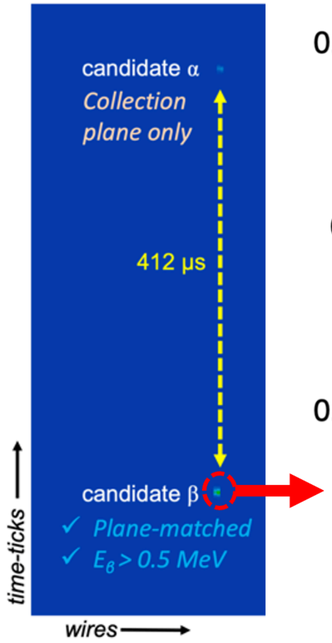
MeV-scale physics

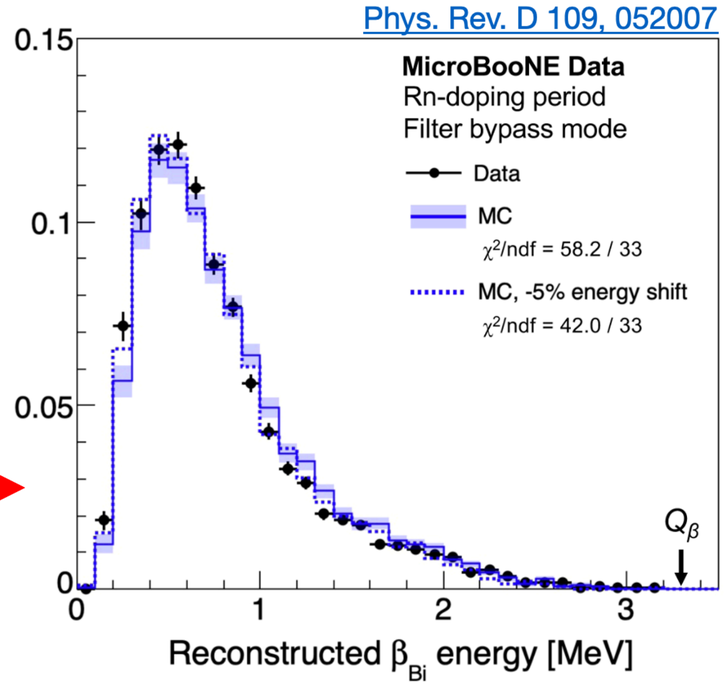
New Results!

PRD109 (2024) 052007

$^{214}Bi \rightarrow ^{214} Po$ decays







- Techniques to reconstruct “blips” (isolated $\mathcal{O}$(MeV) energy depositions from various sources) pioneered at ArgoNeut
- Can leverage to dramatically improve thresholds at low energies
- Measurements of Rn^{222} decays during calibration runs
  - Important for assessing radiopurity and radiological backgrounds
  - Important for DUNE supernova and BSM physics

- 🧐 - MeV-Scale Radon Measurements - Will Foreman
- 🧐 - MeV-Scale Physics - Diego Andrade

Novel LArTPC techniques

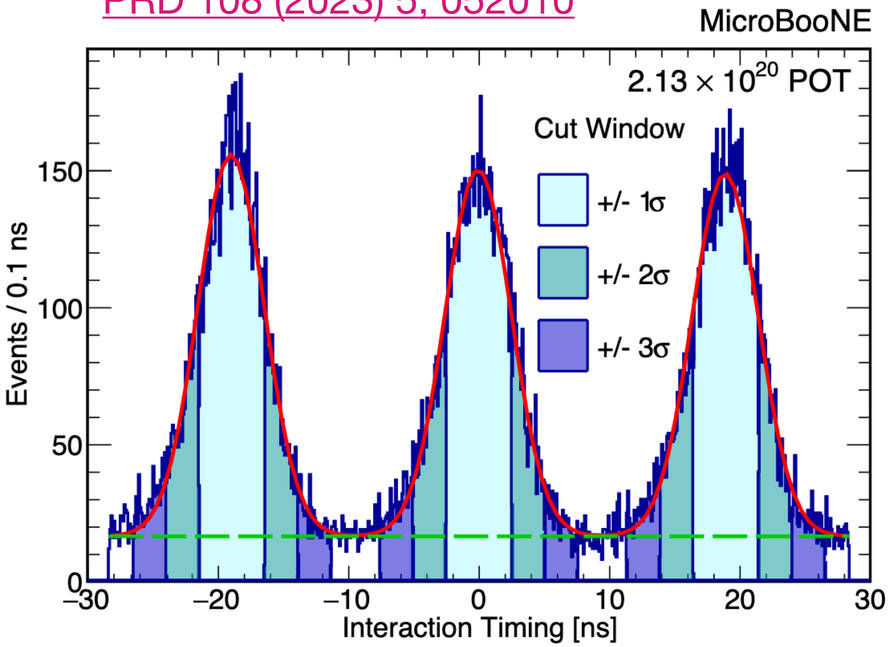
New Results!

nanosecond beam timing in LArTPCs

First n-nbar demonstration in LArTPCs!

Other Deep-learning based reconstruction

PRD 108 (2023) 5, 052010



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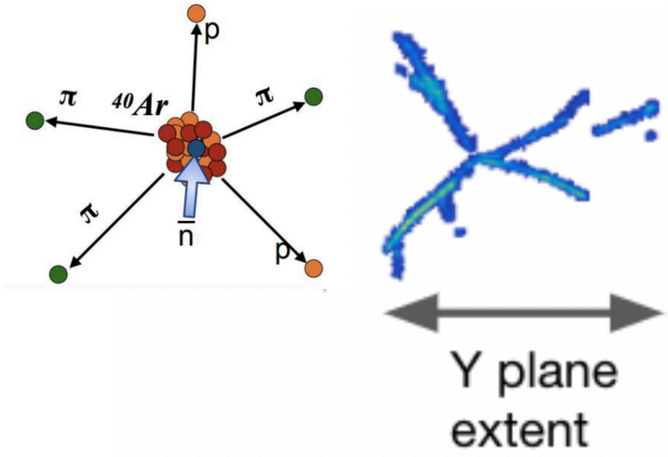

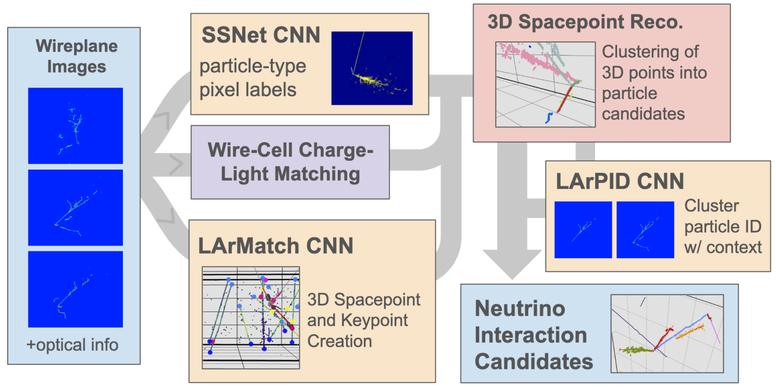

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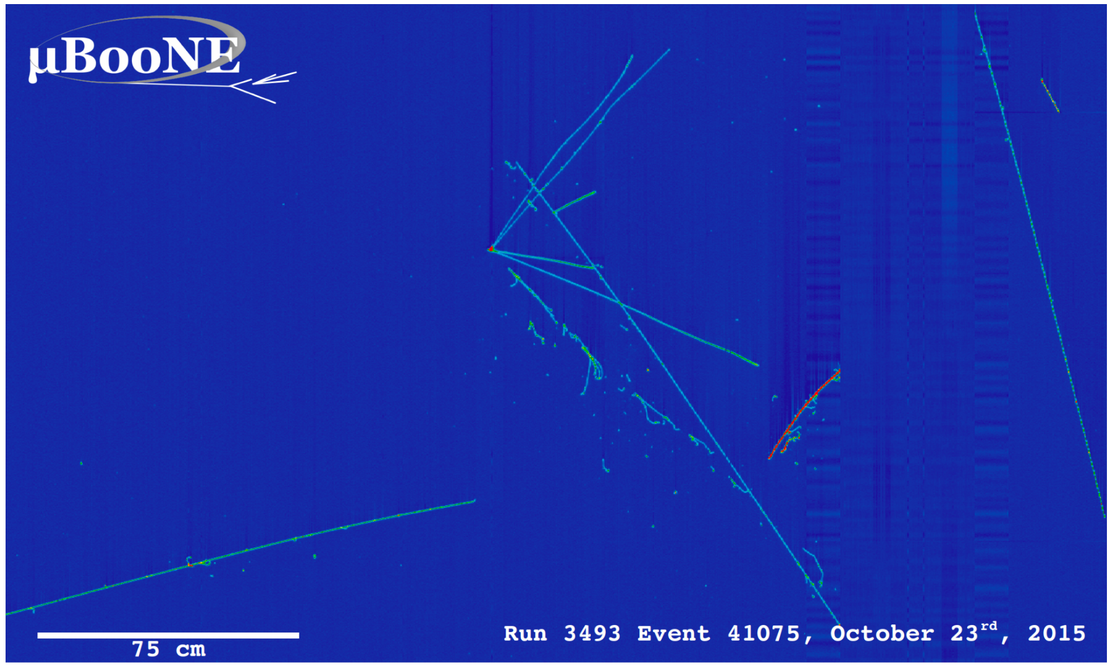
arXiv:2406.10123

- Use fine-timing from PMTs and beam spill to extract ns-resolution
  - Enables long-lived BSM particle searches, better cosmic rejection
- Demonstrate new LArTPC reconstruction techniques for exotic topologies, deep-learning based methods for 3D reconstruction, neutrino energy estimation etc

Conclusions

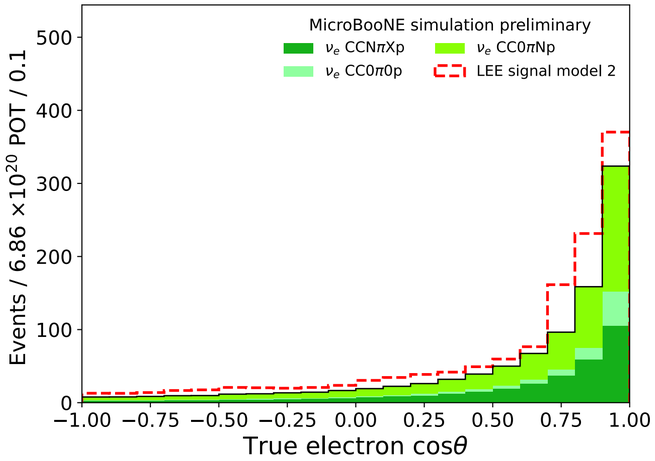
- Wealth of new results across its science program
  - New LEE results rejecting ν_e-like interpretation at >99% CL!
  - New results on HNLs and Dark tridents
  - Upcoming results for single-γ and e^+e^- based BSM searches
  - Upcoming 3+1 sterile neutrino search with unique “one detector, two beams” analysis
  - Continues to lead the community in its cross-section program with diverse results across multiple topologies
    - Able to probe much deeper into nuclear initial state and final state modeling
  - Pioneering new techniques for MeV-scale reconstruction
  - Other novel techniques for LArTPCs looking forward to next generation experiments
- Stay tuned for more results!

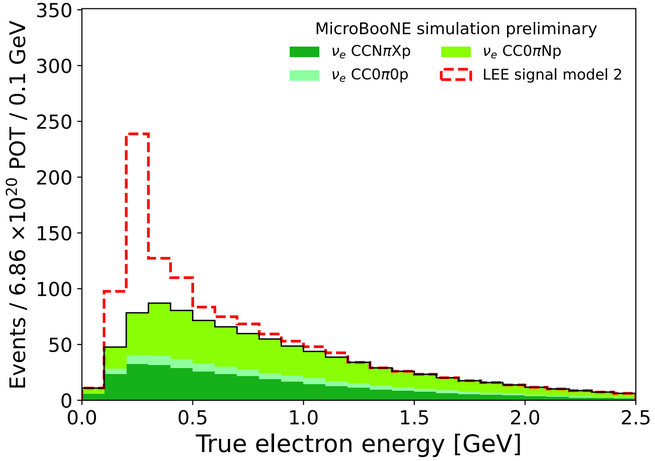


Thank you!

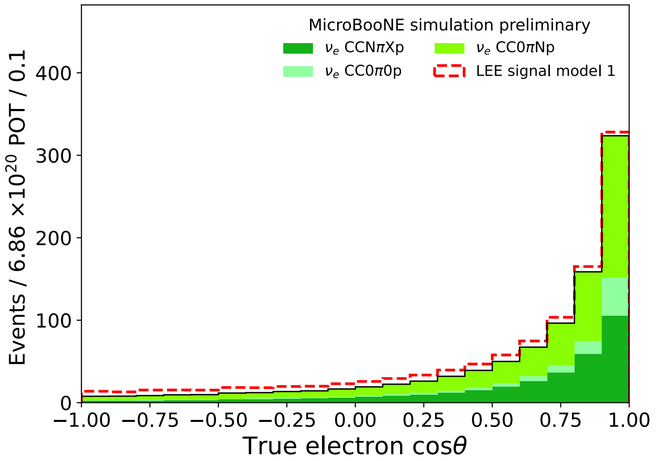
Backup

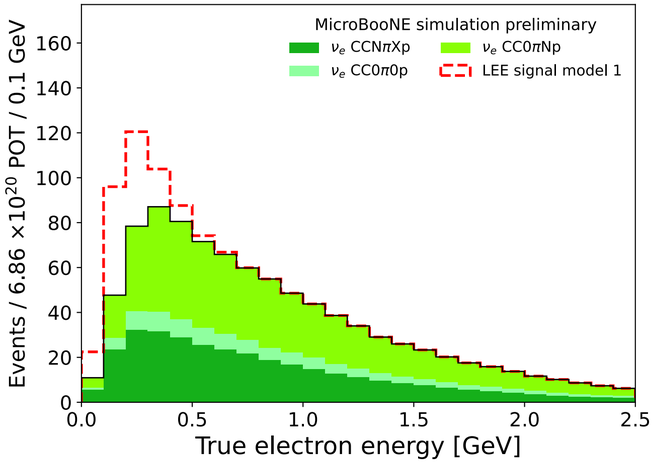
ν_e LEE models and results





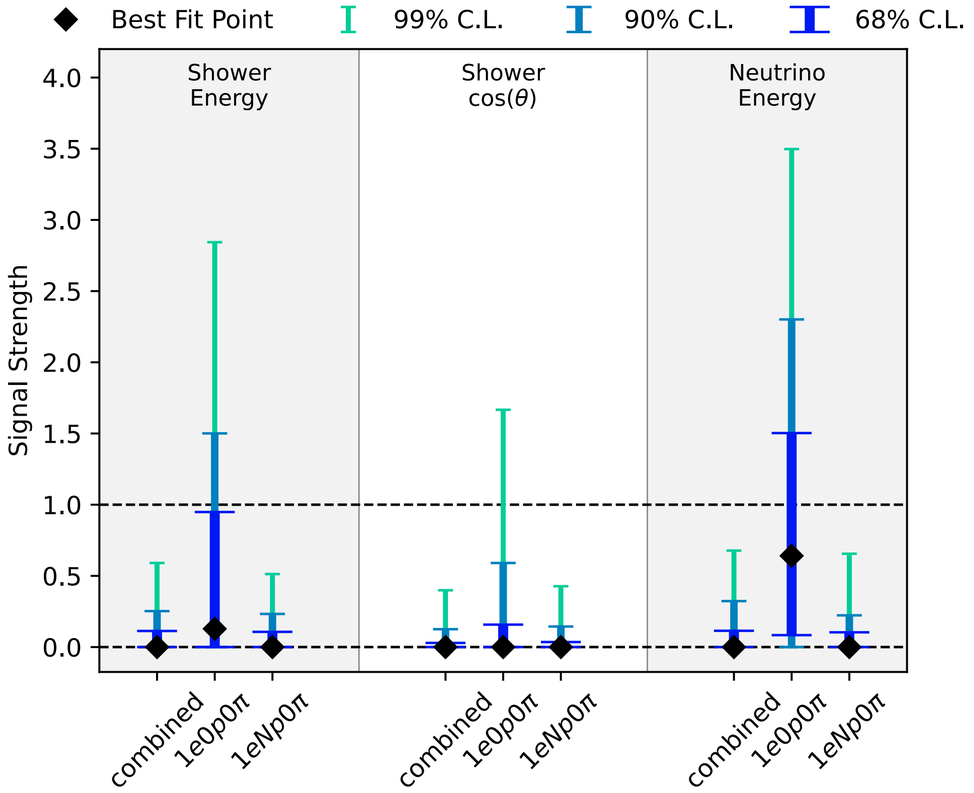
shower kinematics signal model
[model #2]





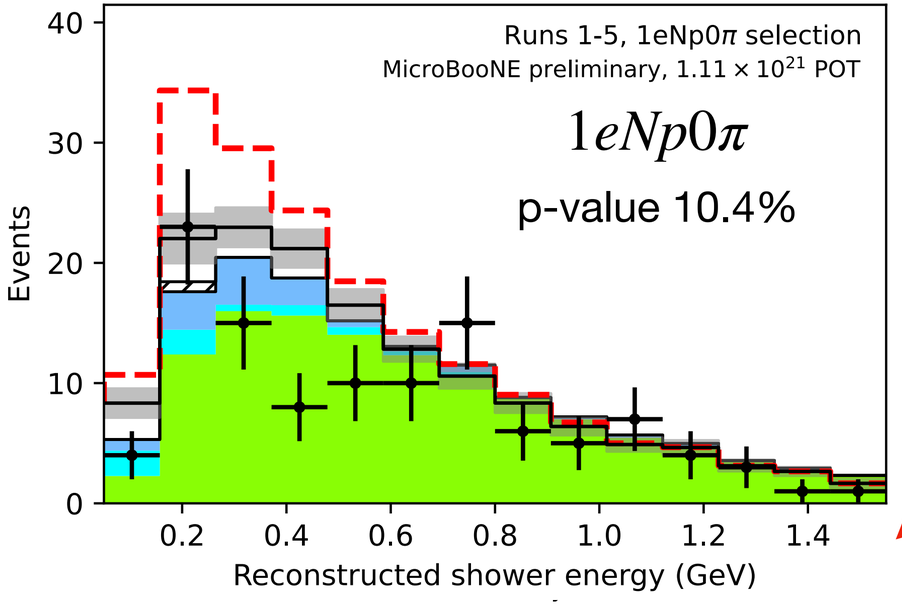
Neutrino energy signal model
[model #1]

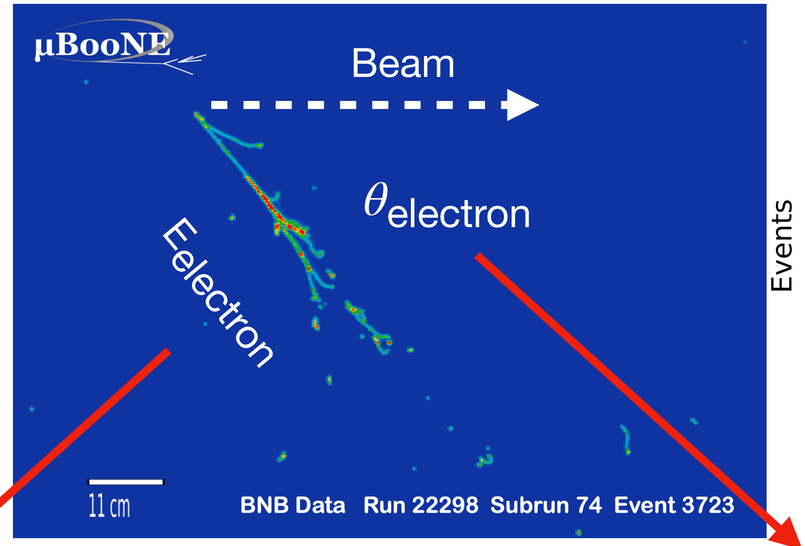
ν_e LEE analysis

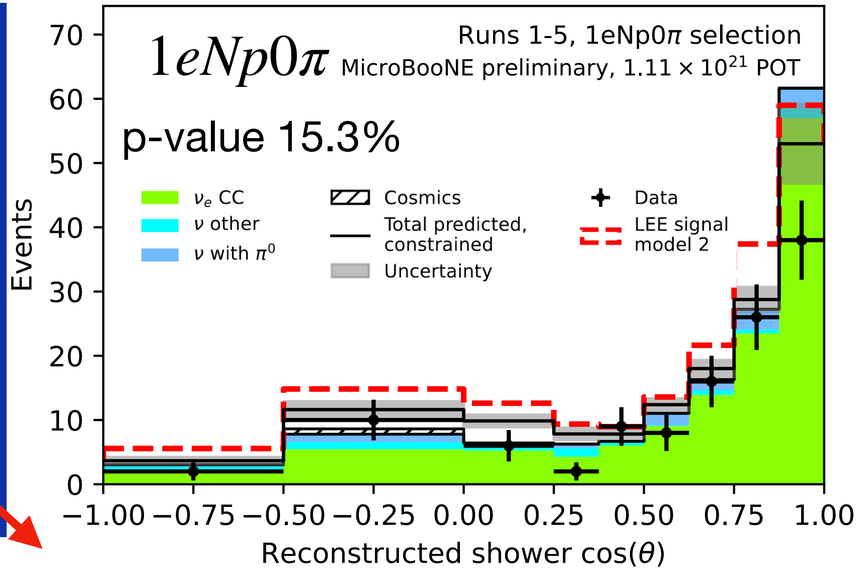


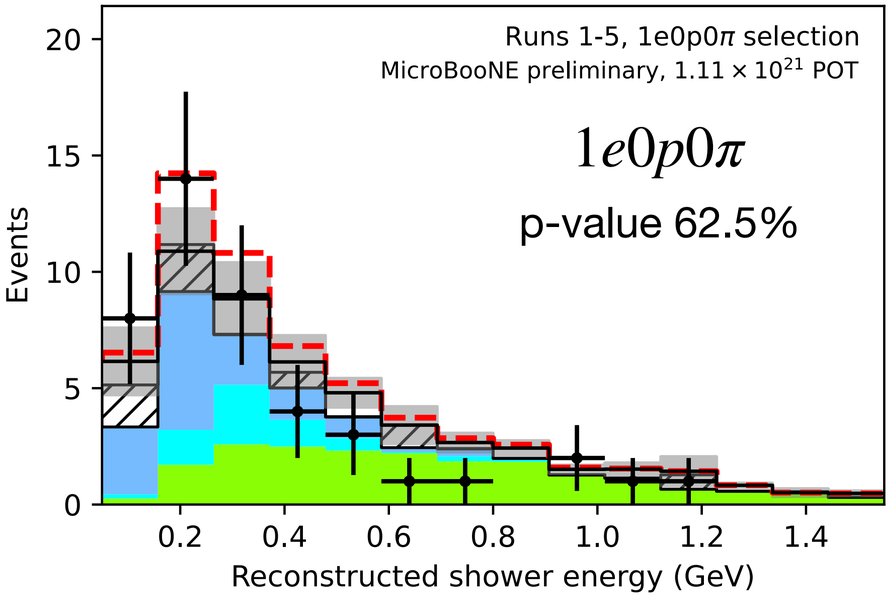
Results in Np / 0p channels separately and combined

LEE Search: ν_e results





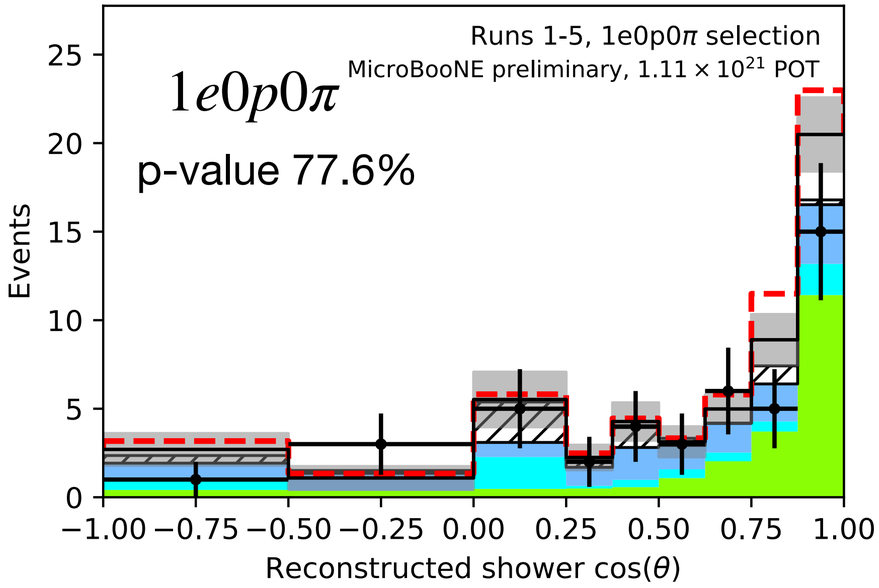




Shower kinematics-based model:

combined Np & 0p channels:

exclude model at > 99.9% CL



3+1 parametrization

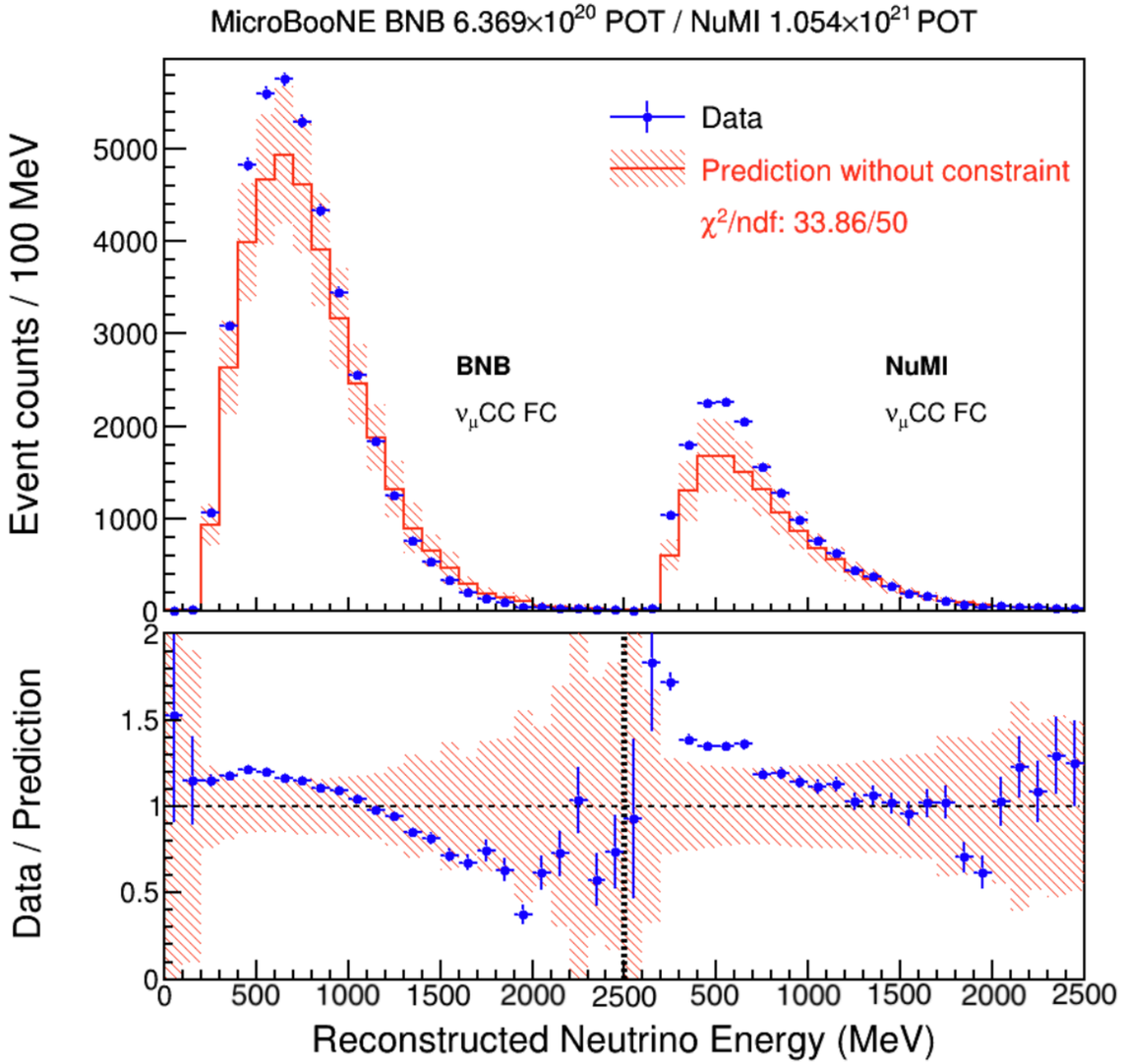
Full 3+1 search ⟶

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

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

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}$$
$$= N_{\text{intrinsic } \nu_e} \cdot \left[1 + (R_{\nu_\mu / \nu_e} \cdot \sin^2 \theta_{24} - 1) \cdot \sin^2 2\theta_{14} \cdot \sin^2 \Delta_{41}\right],$$

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.

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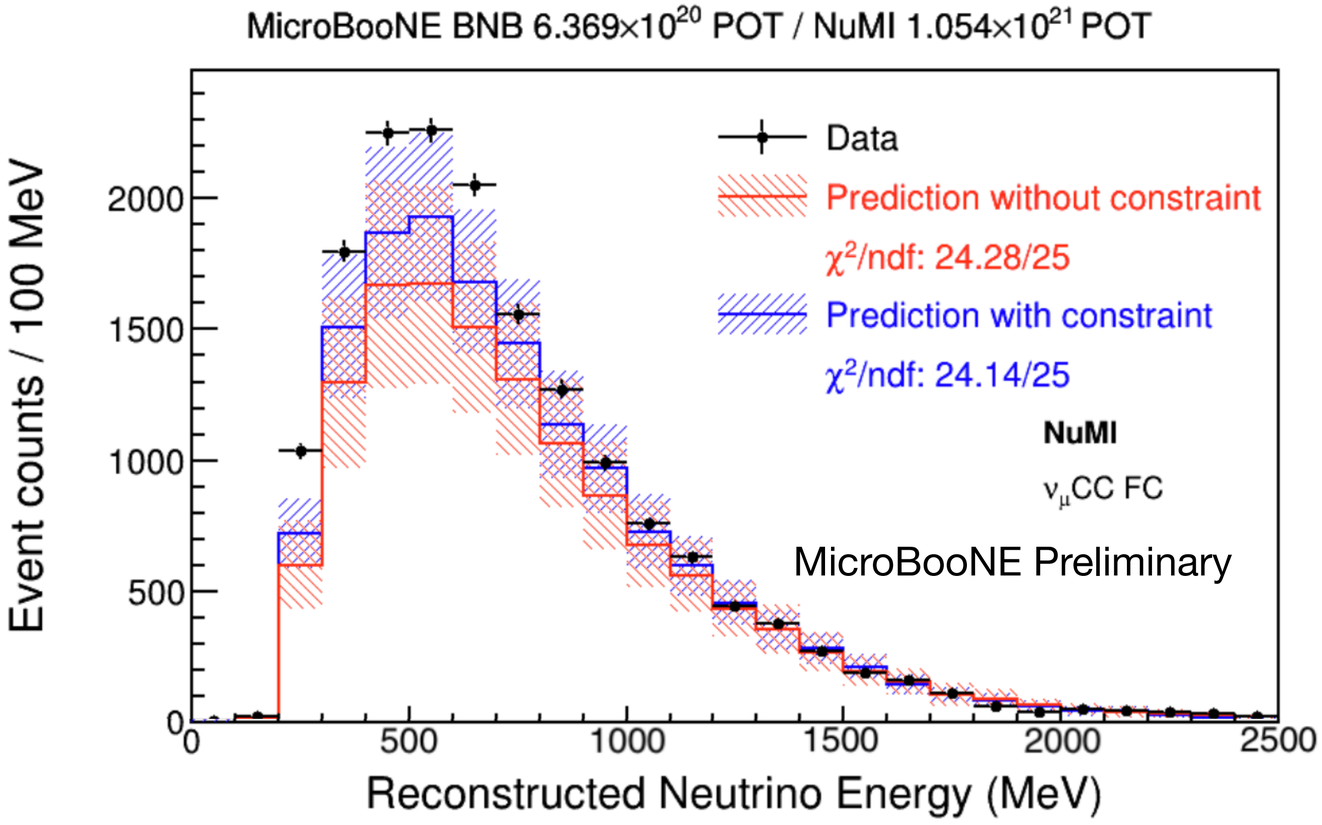
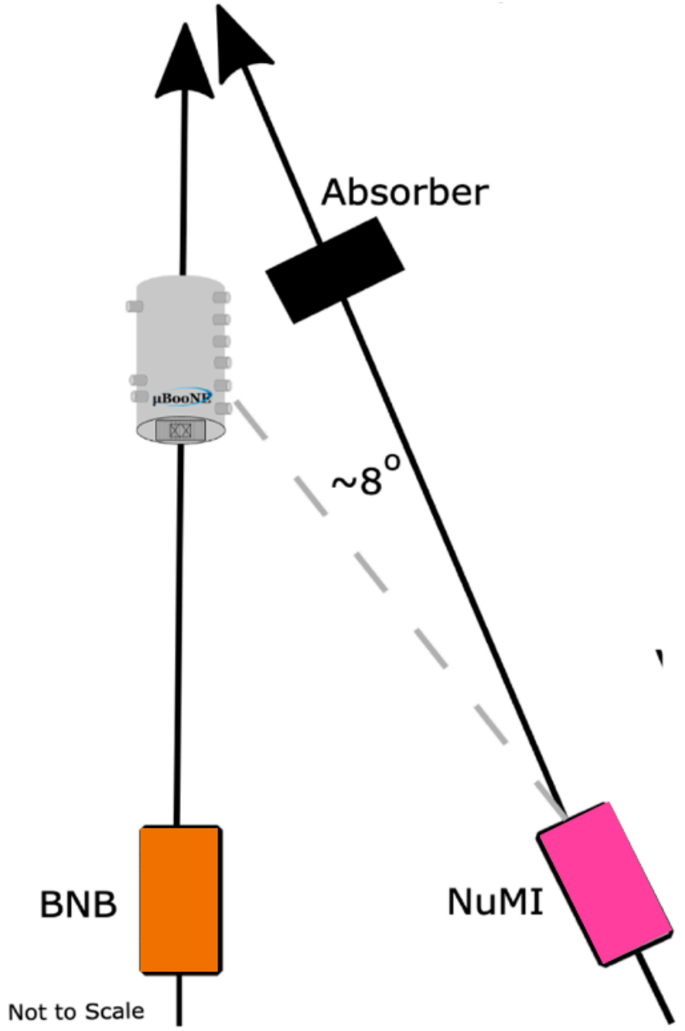
Updated NuMI flux @ MicroBooNE

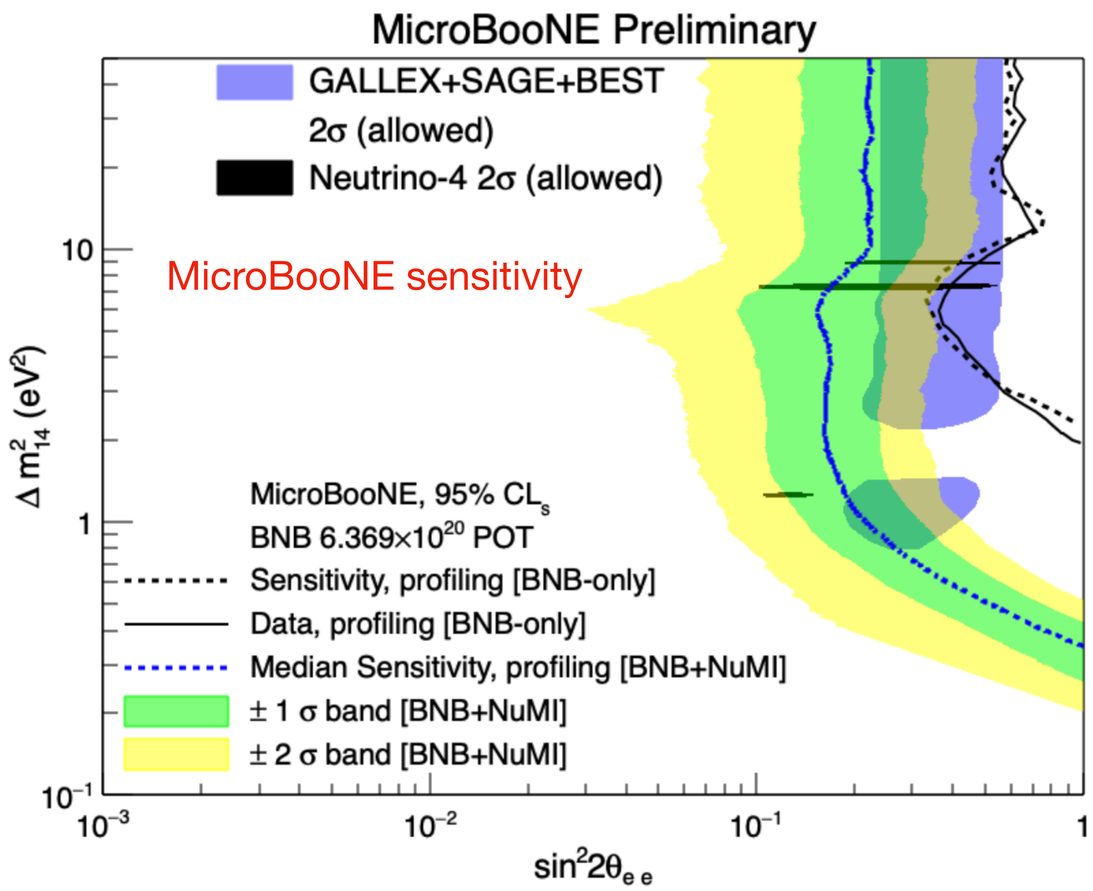
MicroBooNE's updated NuMI flux prediction vs. ν_μ data:

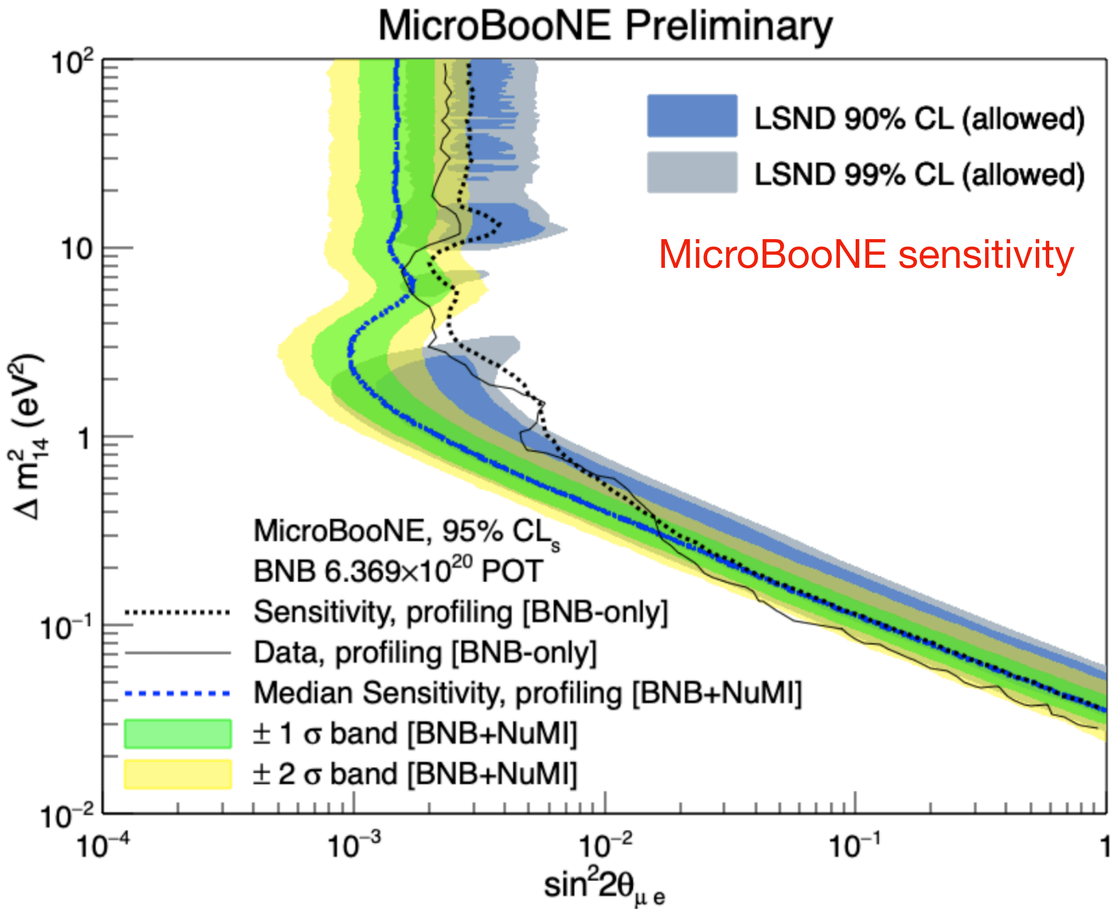




Good data/MC agreement. Blue histogram shows NuMI ν_μ prediction constrained by BNB ν_μ which largely cancels out cross section and detector systematics.

3+1 sensitivities

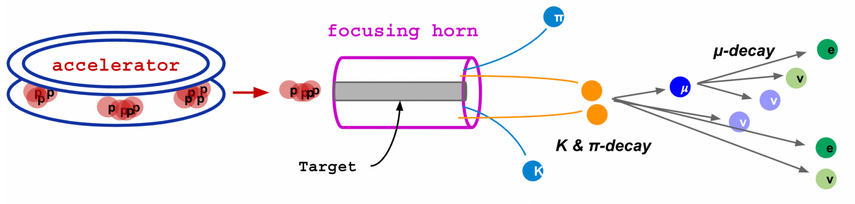




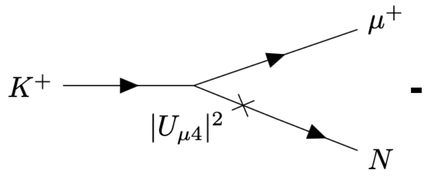
BNB + NuMI 3+1 MicroBooNE sensitivities

Heavy Neutral Lepton Searches

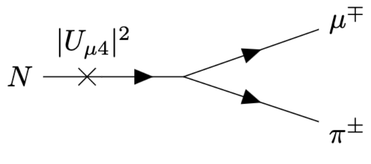
NuMI



produced in beam via mixing



decay in the detector



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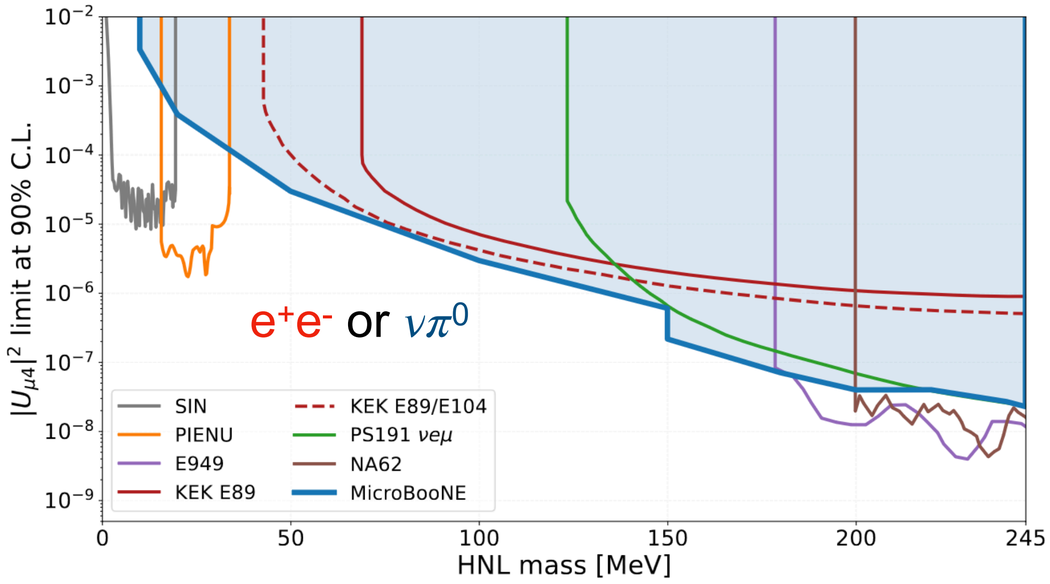

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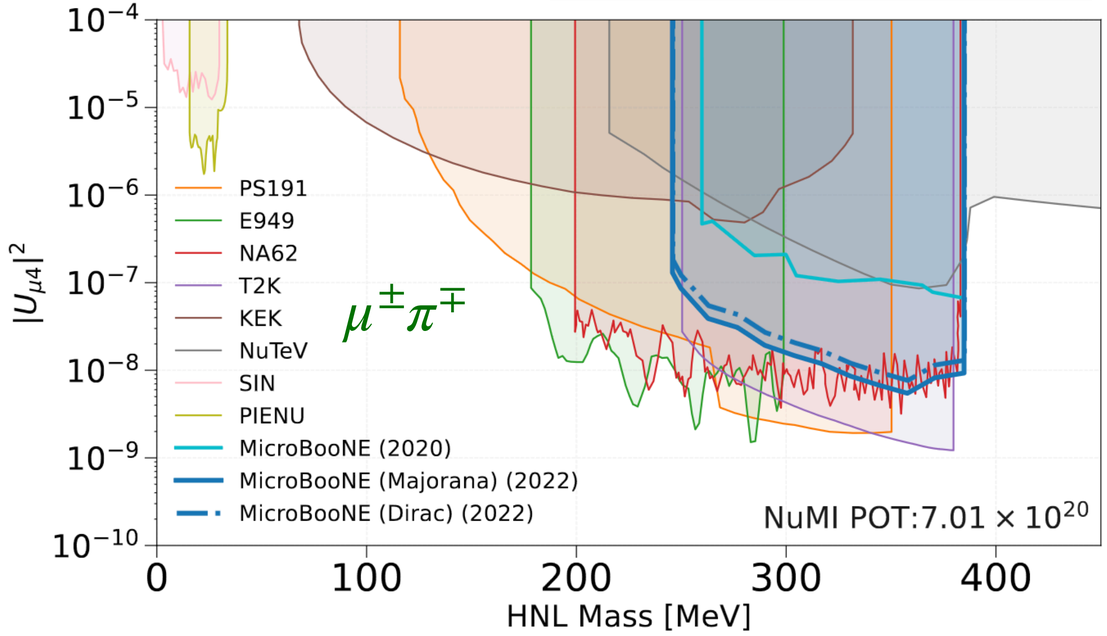
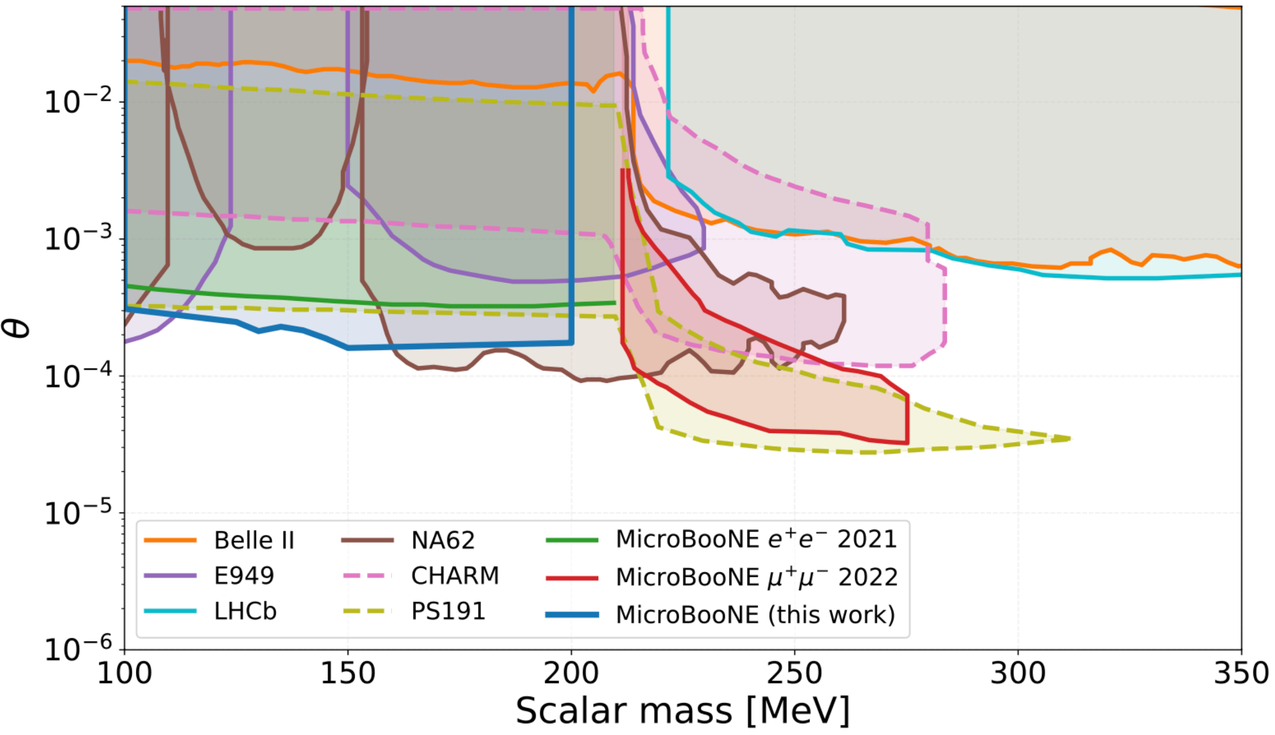
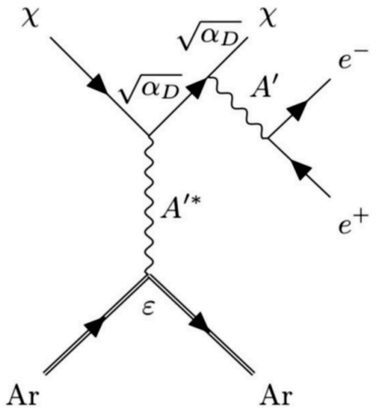
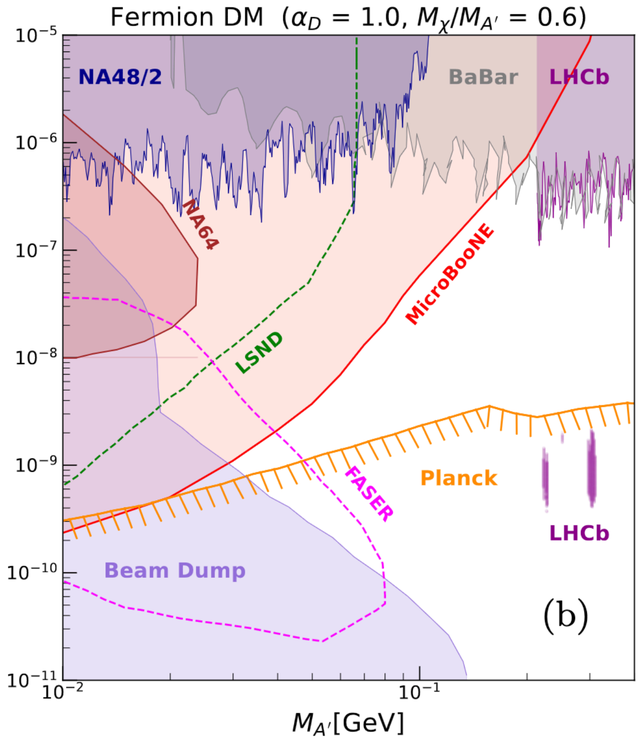


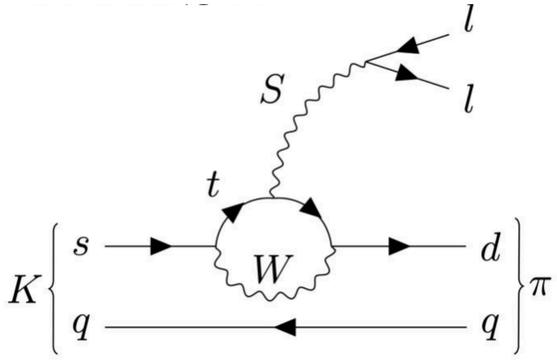
Dark Tridents and Higgs Portal

NuMI









Rare Mesons and Baryons