MICROBOONE RESULTS AND NEW CONSTRAINTS ON EV-SCALE STERILE NEUTRINOS

Kirsty Duffy for the MicroBooNE Collaboration
UKRI Future Leaders Fellow, University of Oxford
18th Rencontres du Vietnam, ICISE, Quy Nhon

- MicroBooNE has harnessed the **full power of LArTPC detector technology** to make valuable new precision measurements
  - World's first **high-statistics precision cross-section measurements** on argon
  - Detailed initial **investigations into MiniBooNE anomaly**
  - Further **searches for new physics**
- MicroBooNE is also **laying the groundwork for future LArTPC detector programmes**: SBND, ICARUS (further investigation of the MiniBooNE anomaly) and the future multi-kt neutrino experiment DUNE

MicroBooNE: 85-tonne active mass LArTPC JINST 12 P02017 (2017)

- Sits in **two neutrino beams** at Fermilab: BNB (on-axis, $<E_{\nu\mu}>$=800 MeV) and NuMI (off-axis, $<E_{\nu e}>$=650 MeV)
- Completed 5 years of beam physics data-taking: **world's largest dataset of neutrino interactions on Argon**
- Several post-operations R&D studies

Thank you to Fermilab Accelerator Division, Cryogenics team, and Operations team!

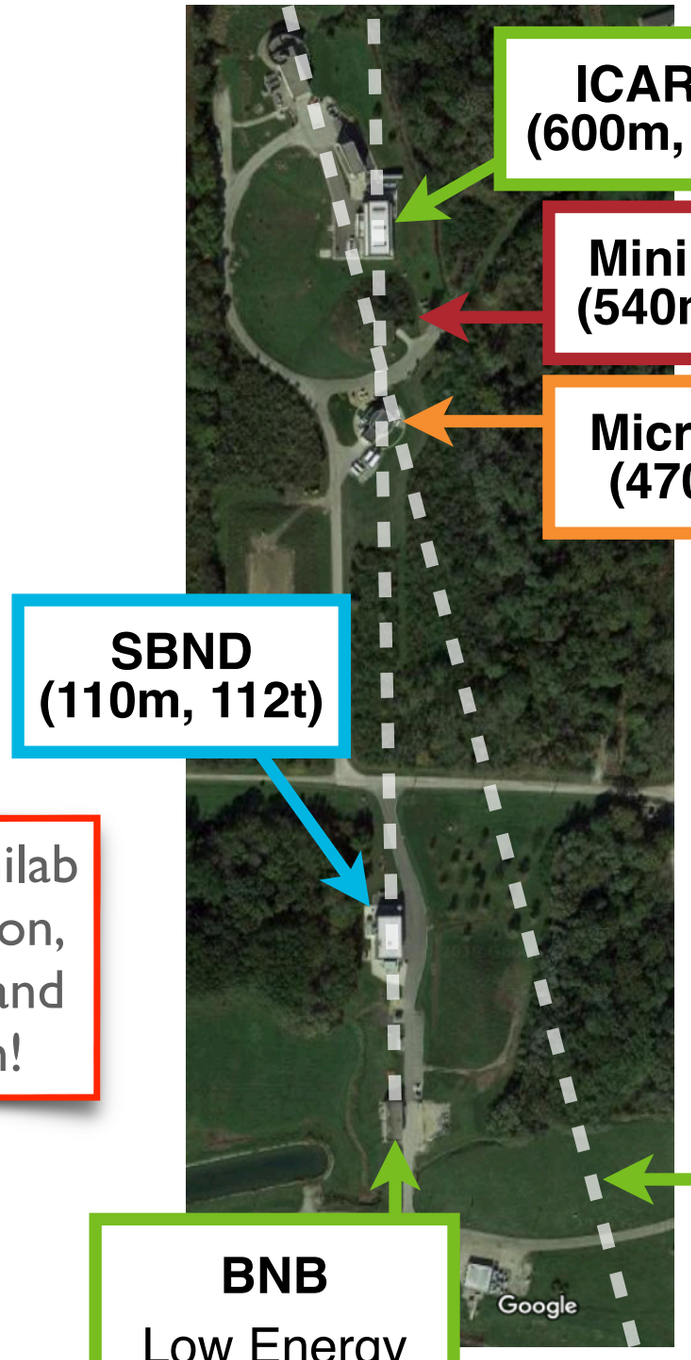
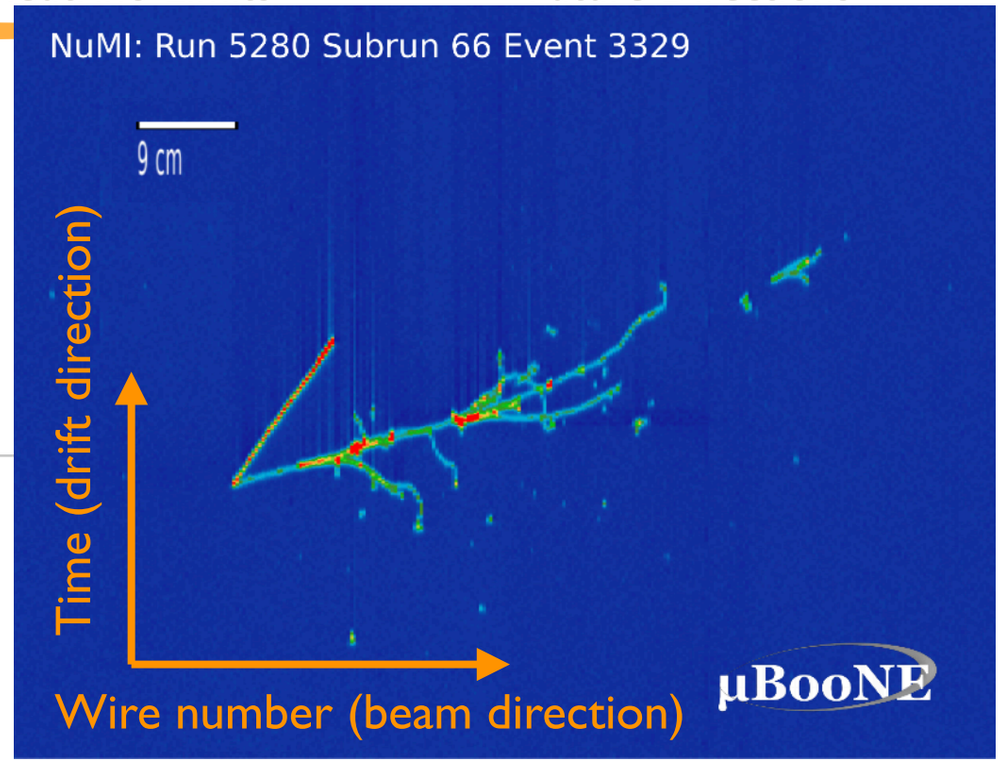
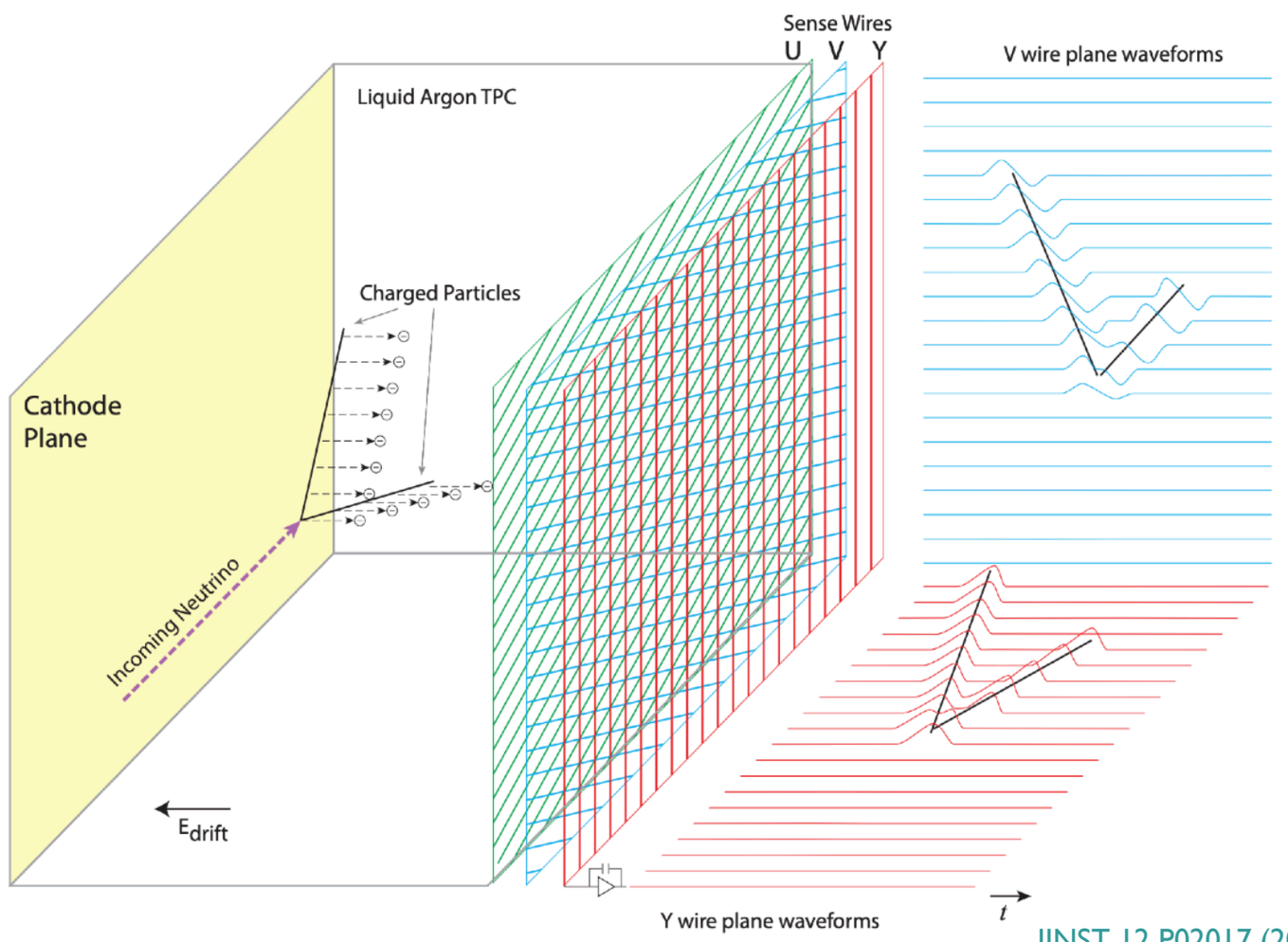


Figure: L. Yates

LIQUID ARGON TIME PROJECTION CHAMBER

- Fully-active tracking calorimeter
- **32 PMTs** collect light from flash at time of interaction
- **3 planes** of wires (vertical, +60°, -60°) with **3mm spacing**
- → mm-level resolution, low thresholds, excellent particle identification
- → incredible precision measurements at scale!

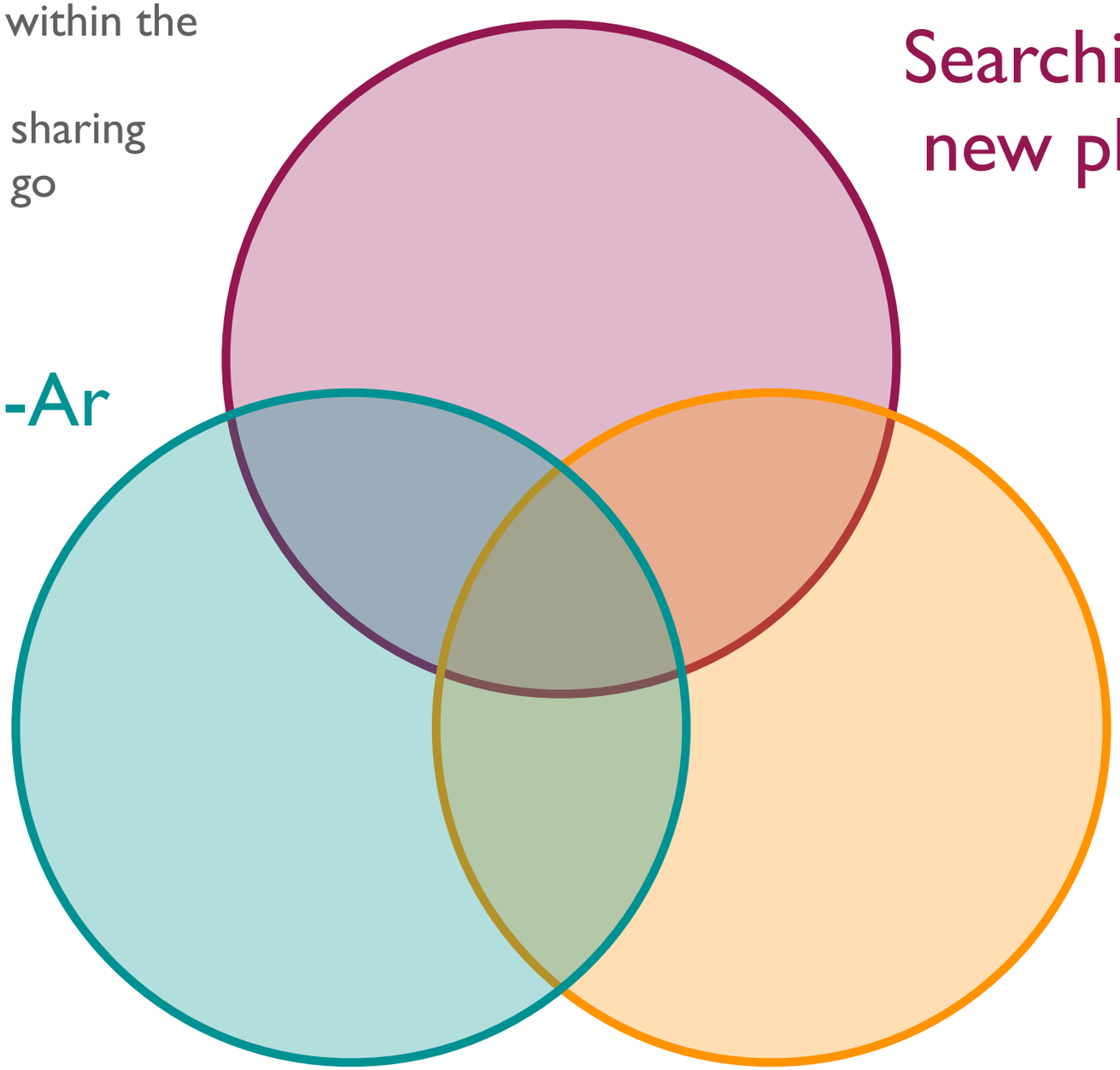




JINST 12 P02017 (2017)

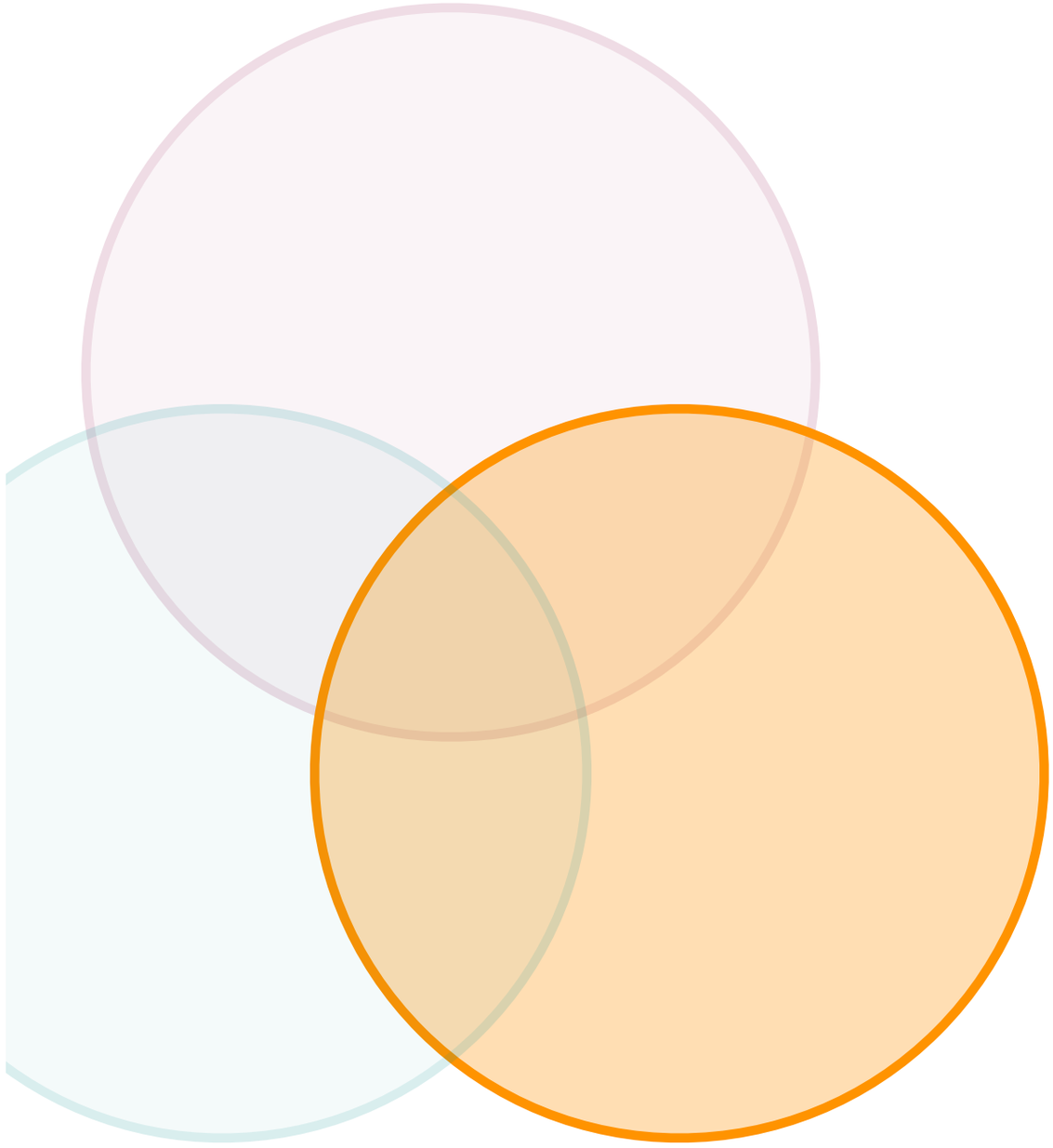
MICROBOONE'S SCIENTIFIC AND TECHNICAL ACCOMPLISHMENTS

More than 45 publications within the last 5 years
More than 75 public notes sharing with the community as we go



MICROBOONE'S SCIENTIFIC AND TECHNICAL ACCOMPLISHMENTS

Radon Mitigation arXiv:2203.10147 [physics.ins-det]
Novel Simulation Modification Eur. Phys. J. C 82, 454 (2022)
Longitudinal Diffusion Measurement JINST 16 P09025 (2021)
Detector design and construction JINST 12 P02017 (2017), JINST 12 P12030 (2017), JINST 14 P04004 (2019), JINST 16 P02008 (2021)
Measurement of Space Charge Effect JINST 15 P12037 (2020
Measurement of O(100) MeV ɣs JINST 15 P02007 (2020)
Laser E-field Measurement JINST 15 P07010 (2020)
Charge/Energy Calibration JINST 15 P03022 (2020)
Noise Characterisation and Filtering JINST 12 P08003 (2017)
Evaluation of Michel electron reconstruction JINST 12 P09014 (2017)
Multiple Coulomb Scattering Method JINST 12 P10010 (2017)
Demonstration of <2ns Timing Resolution MICROBOONE-NOTE-1115-PUB
Deep Learning Reconstruction JINST 12 P03011 (2017), Phys. Rev. D 99, 092001 (2019), JINST 16 P02017 (2021), Phys. Rev. D 103, 092003 (2021), Phys. Rev. D 103, 052012 (2021), JINST 16 T12017 (2021), arXiv:2201.05705 [hep-ex]
Wire-Cell Reconstruction and Signal Processing JINST 13 P07007 (2018), JINST 13 P07006 (2018), JINST 16 P06043 (2021), Phys. Rev. Applied 15, 064071 (2021), JINST 17 P01037 (2022)
Pandora Reconstruction Eur. Phys. J. C 78, 82 (2018), Eur. Phys. J. C 79, 673 (2019), J. High Energ. Phys. 2021, 153 (2021)
Atmospheric muon rate measurement JINST 16 P04004 (2021)



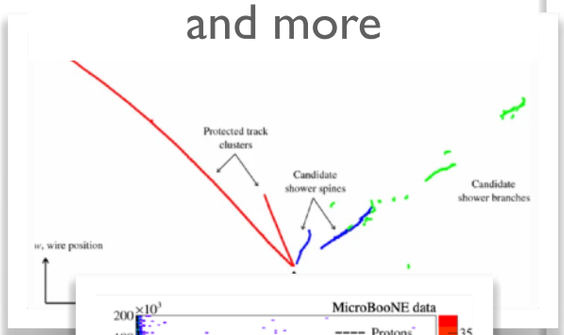
Understanding LArTPCs and developing techniques

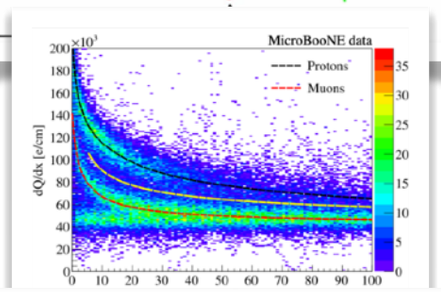
UNDERSTANDING LArTPCs AND DEVELOPING TECHNIQUES

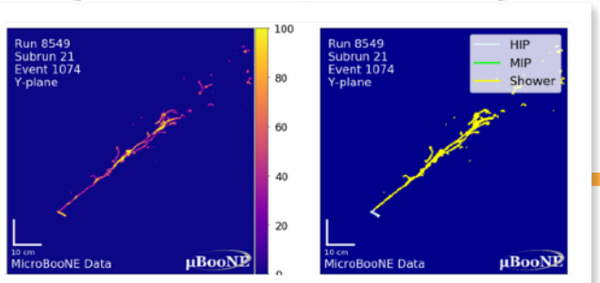
- MicroBooNE has contributed to significant advances in LArTPC detector physics, modelling, and reconstruction
- Post-operations R&D studies are just beginning to bear fruit

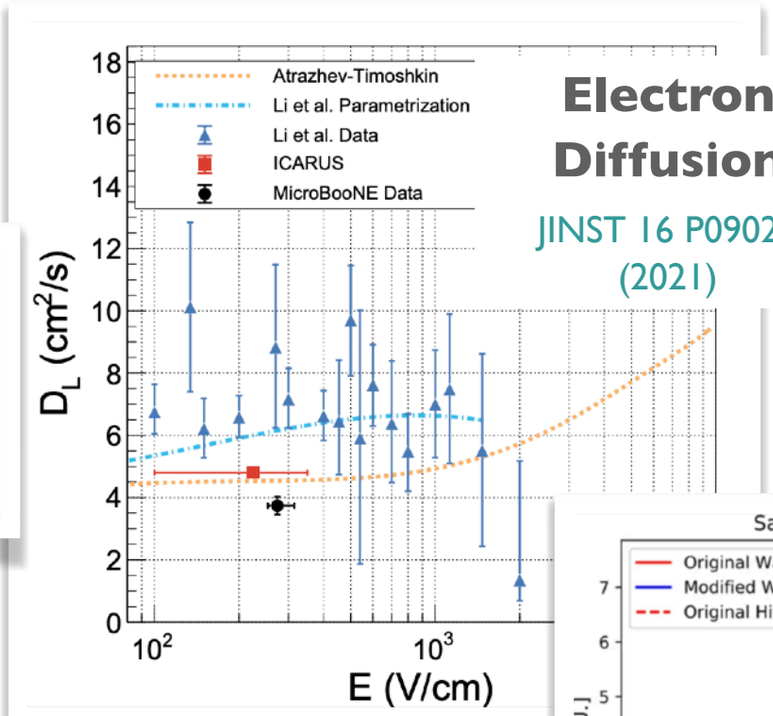
Reconstruction

Eur. Phys. J. C 78, 82 (2018)
JINST 17 P01037 (2022)
Phys. Rev. D 103, 052012 (2021)
and more



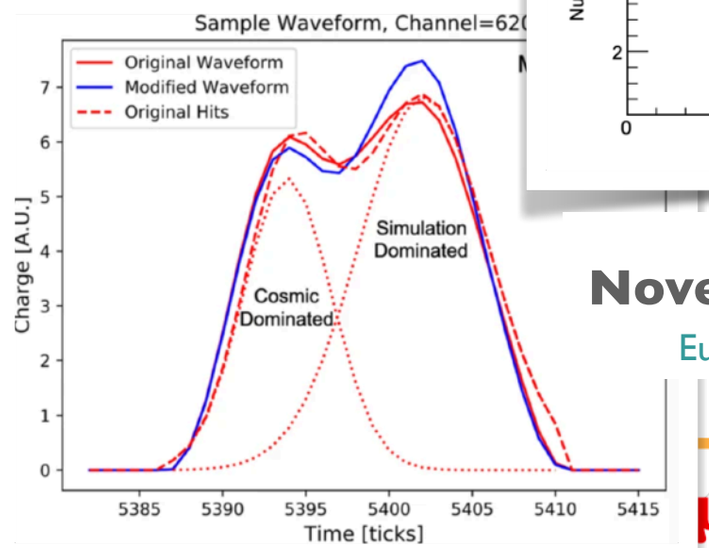


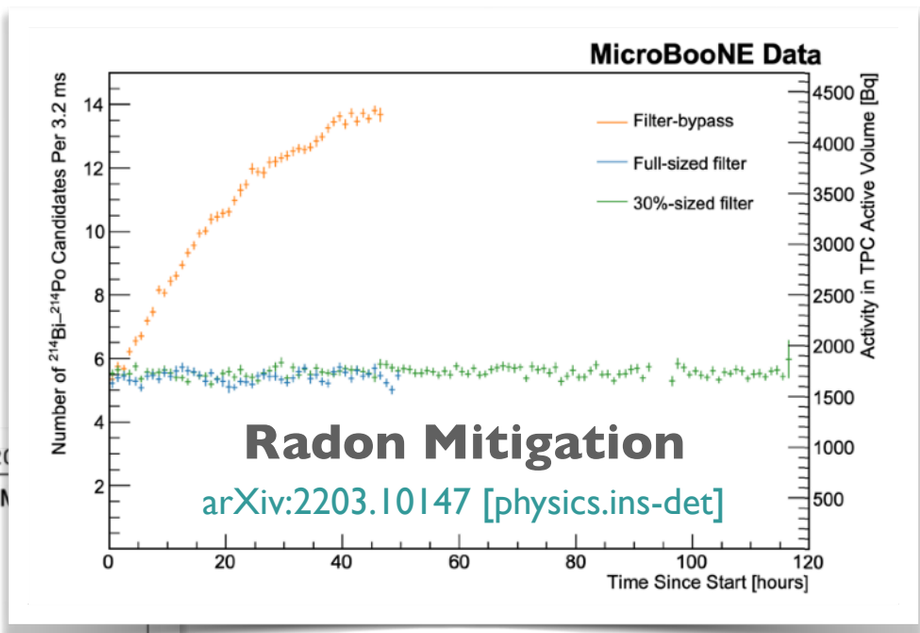




Electron Diffusion

JINST 16 P09025 (2021)





Radon Mitigation

arXiv:2203.10147 [physics.ins-det]

Novel Sim. Modification

Eur. Phys. J. C 82, 454 (2022)

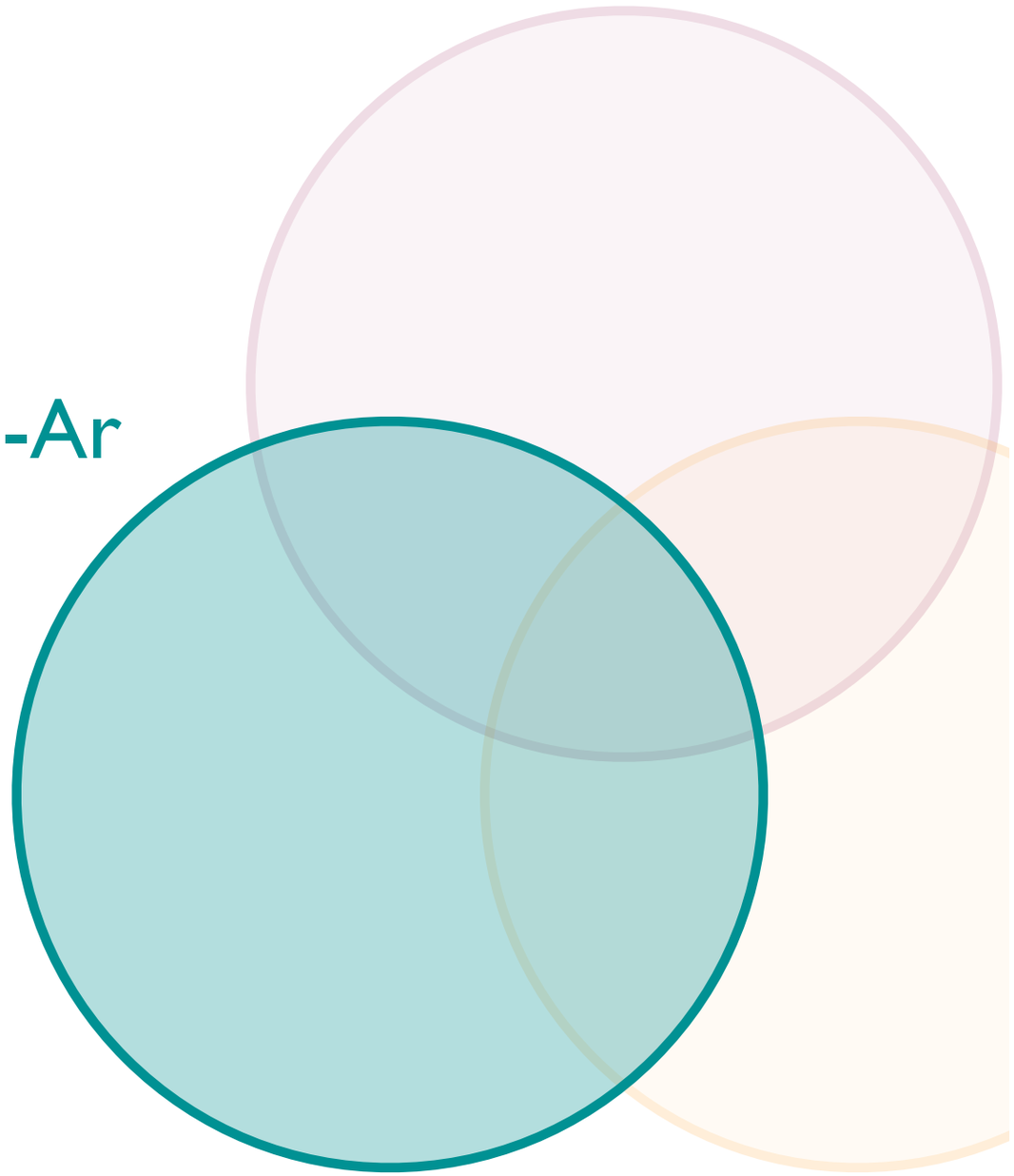
Slide from L. Yates

μBooNE

UNIVERSITY OF OXFORD

MICROBOONE'S SCIENTIFIC AND TECHNICAL ACCOMPLISHMENTS

Understanding ν-Ar interactions



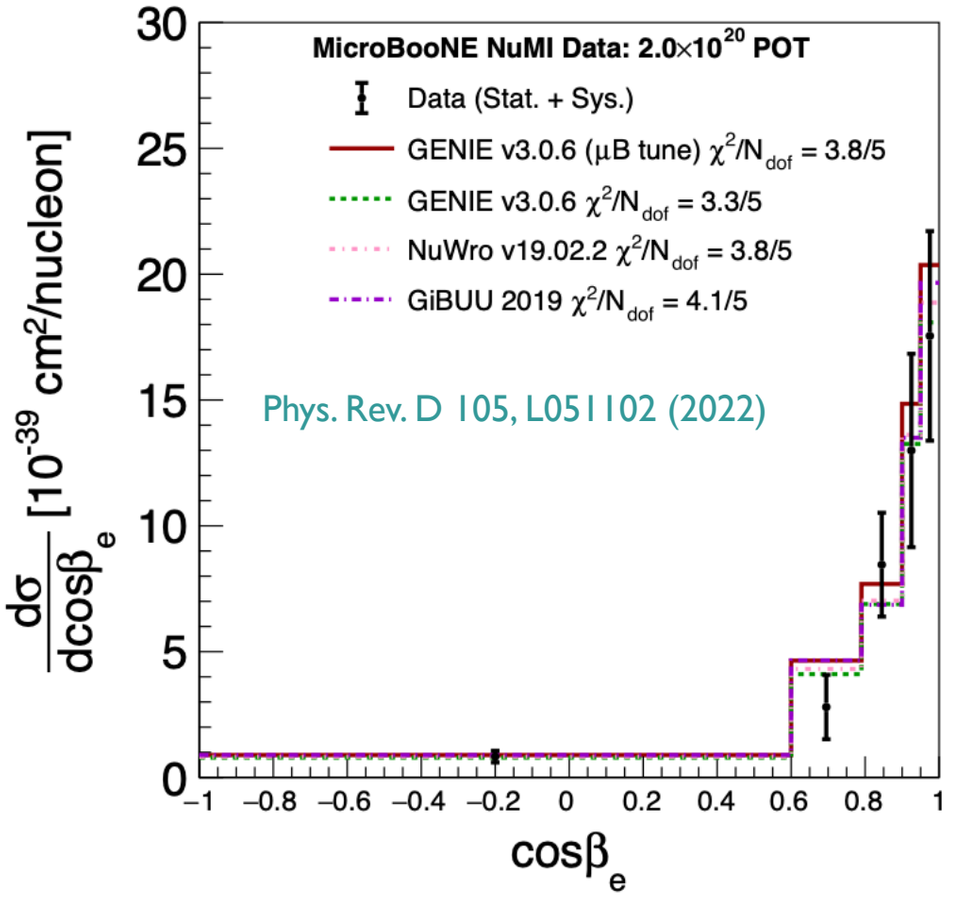
NCπ^0 cross section arXiv:2205.07943 [hep-ex]
CC0π GENIE Tune Phys. Rev. D 105, 072001 (2022)
ν_μ CC inclusive energy-dependent cross section Phys. Rev. Lett. 128, 151801 (2022)
ν_e CC inclusive differential cross section Phys. Rev. D 105, L051102 (2022)
ν_e CC inclusive flux-averaged cross section Phys. Rev. D 104, 052002 (2021)
ν_μ CC0πNp cross section Phys. Rev. D 102, 112013 (2020)
ν_μ CCQE-like cross section Phys. Rev. Lett. 125, 201803 (2020)
ν_μ CC inclusive differential cross section Phys. Rev. Lett. 123, 131801 (2019)
ν_μ CCπ^0 cross section Phys. Rev. D 99, 091102(R) (2019)
Charged particle multiplicity measurement Eur. Phys. J. C 79, 248 (2019)
ν_μ CC0π2p cross section MICROBOONE-NOTE-1117-PUB
ν_μ Lambda production sensitivity MICROBOONE-NOTE-1112-PUB
NCπ^0 differential cross section MICROBOONE-NOTE-1111-PUB
Methodology for ν_μ CCinc multi-dim measurement MICROBOONE-NOTE-1110-PUB
ν_e CC0π cross section MICROBOONE-NOTE-1109-PUB
ν_μ CC0π1p TKI cross sections MICROBOONE-NOTE-1108-PUB
Progress towards ν_μ CCpi0 measurement MICROBOONE-NOTE-1107-PUB
ν_μ NC elastic cross section MICROBOONE-NOTE-1101-PUB
Progress towards CC0πNp multi-differential measurement MICROBOONE-NOTE-1099-PUB

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 predictions



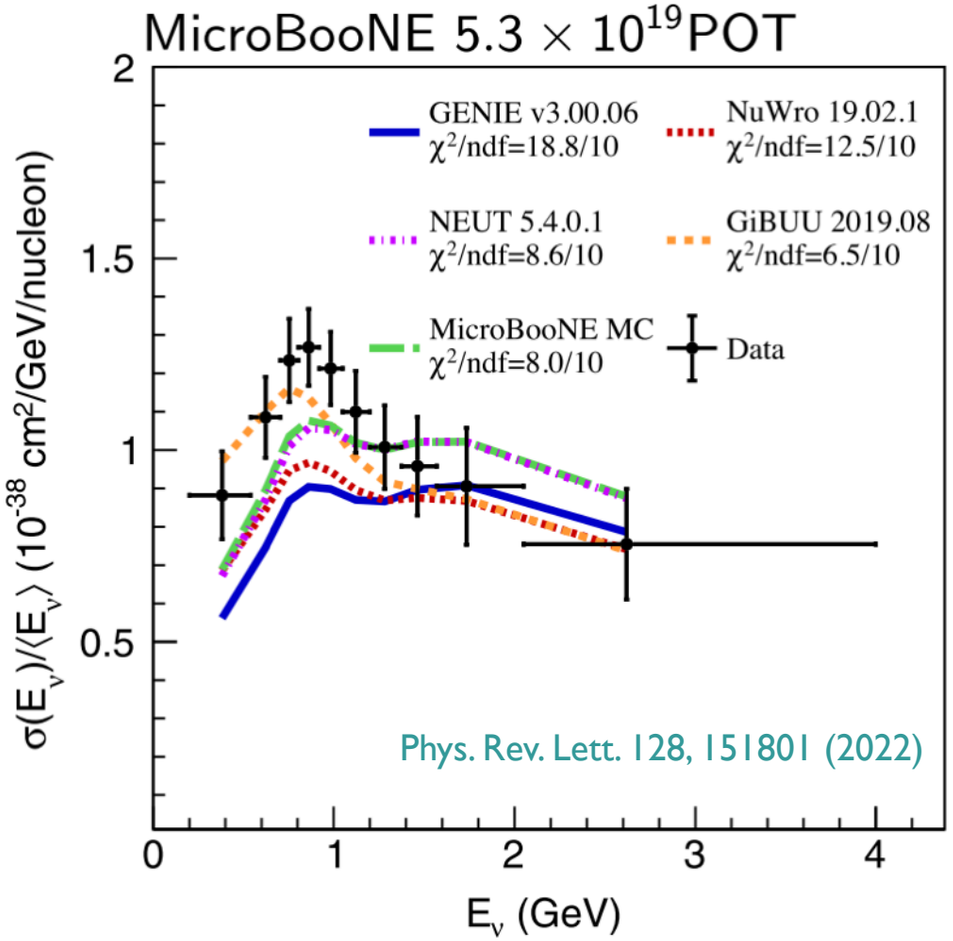
ν_μ CC inclusive

→ 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



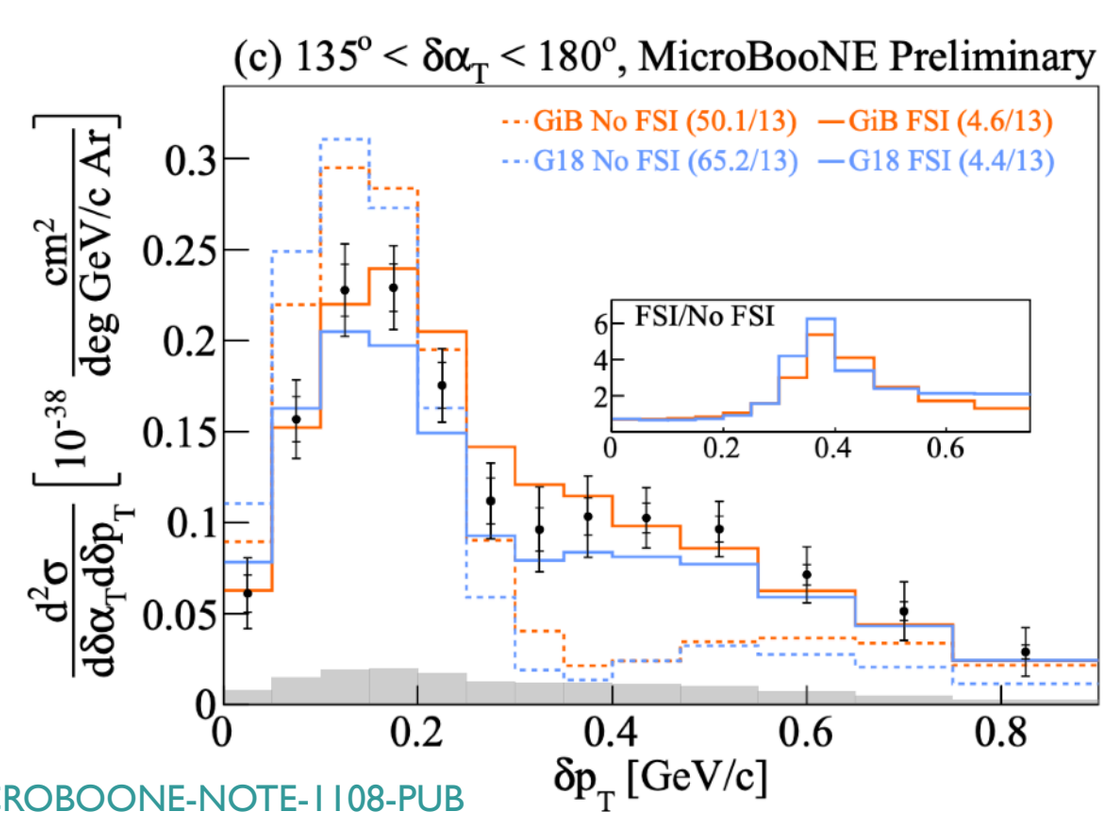
MICROBOONE-NOTE-1110-PUB

LOOKING INTO THE DETAILS

ν_μ CC0π1p Transverse Variables

→ first double-differential cross section in these variables on argon

→ especially sensitive to nuclear effects

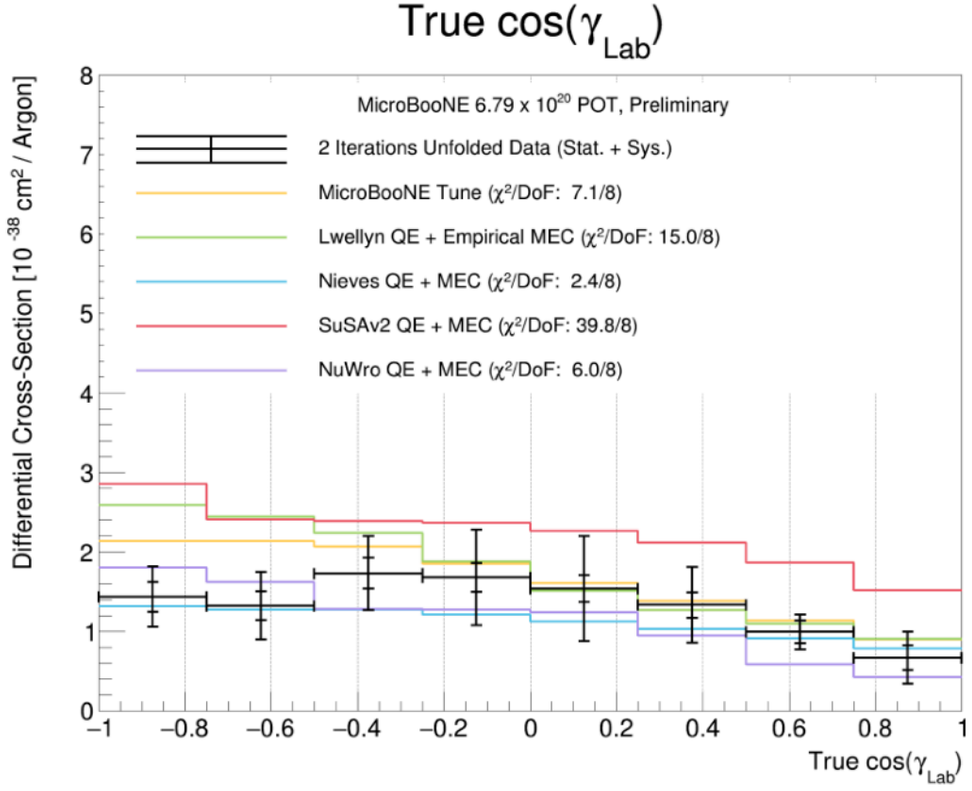


MICROBOONE-NOTE-1108-PUB

ν_μ CC0π2p

→ dominated by 2p2h/MEC processes

→ first ever direct measurement of 2-proton cross section



MICROBOONE-NOTE-1117-PUB

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

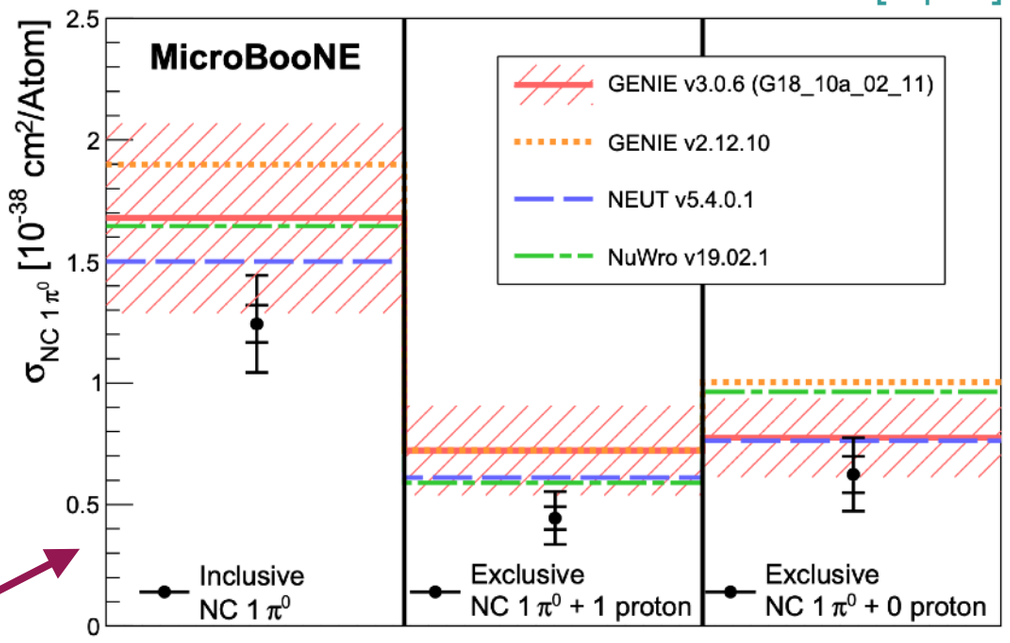
→ deficit observed compared to all models

Differential cross-section measurement well under way

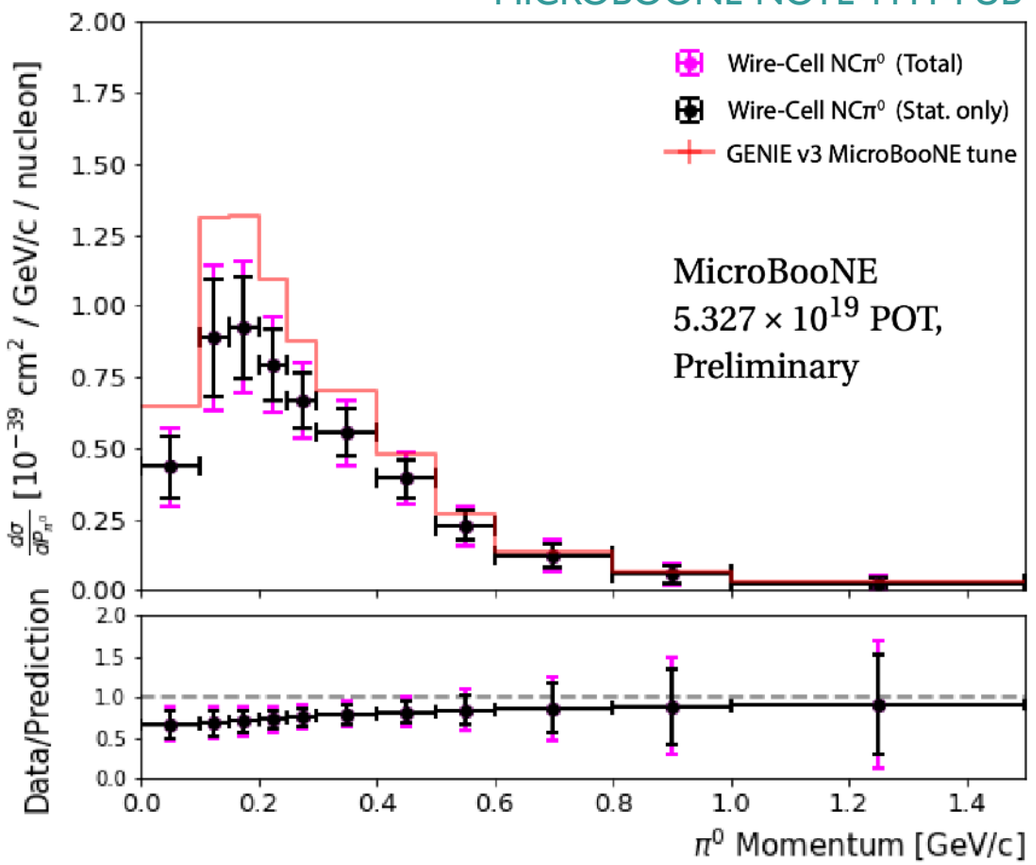
→ current result limited by statistics (only few % of available data used)

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

arXiv:2205.07943 [hep-ex]

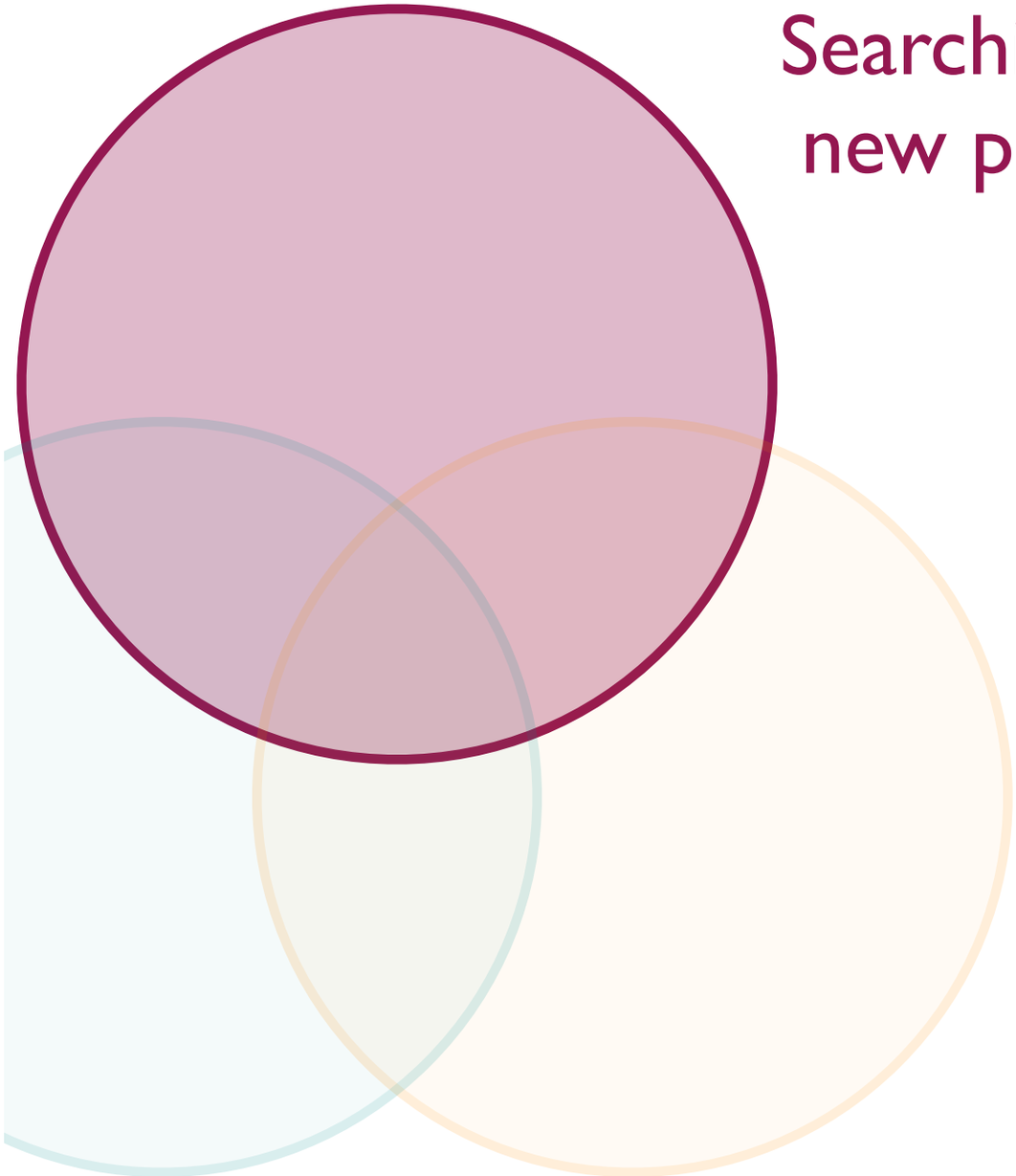


MICROBOONE-NOTE-1111-PUB



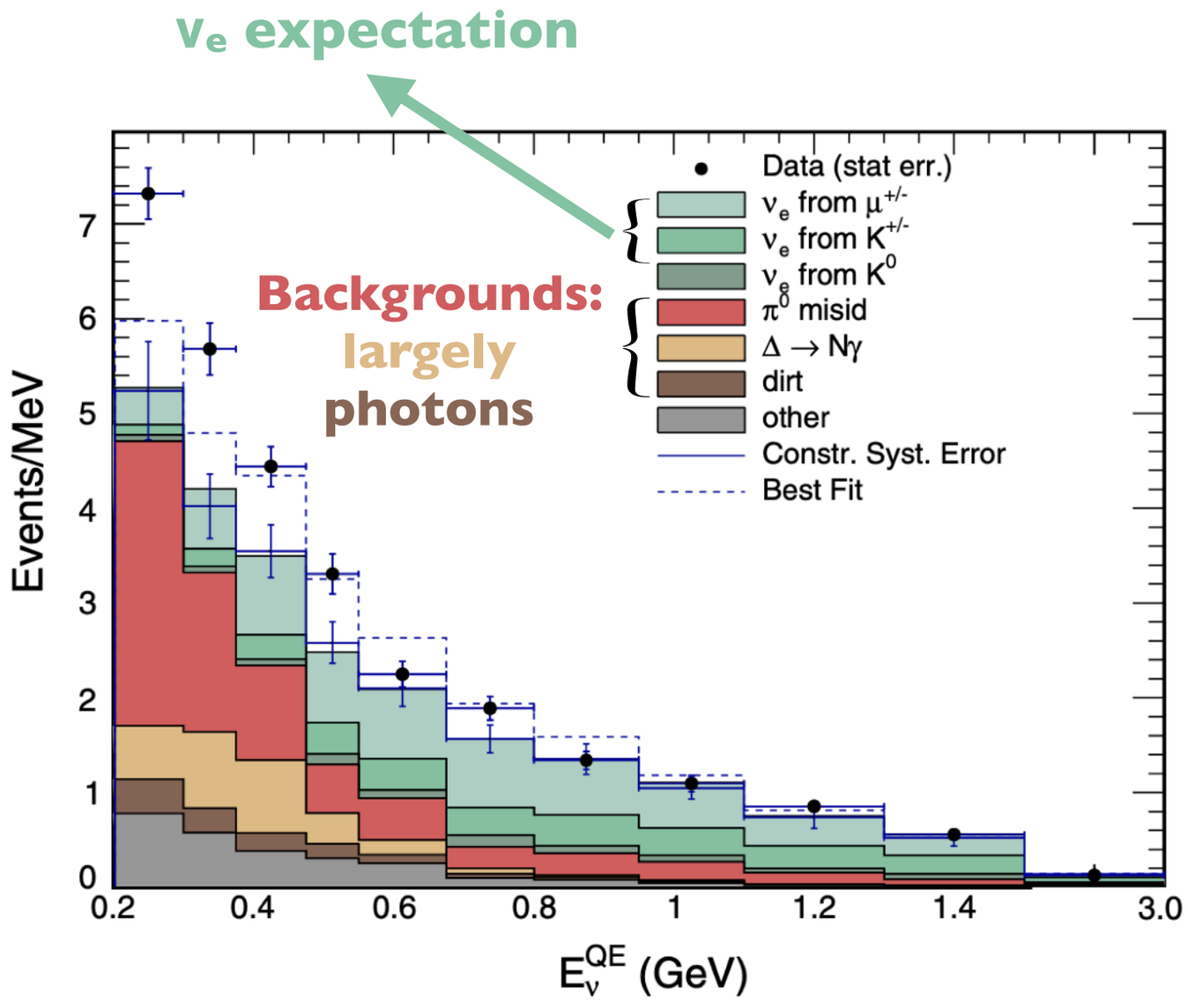
MICROBOONE'S SCIENTIFIC AND TECHNICAL ACCOMPLISHMENTS

NCΔ single-γ low-energy excess search Phys. Rev. Lett. 128, 111801 (2022)
ν_e 1e0π1p low-energy excess search Phys. Rev. D 105, 112003 (2022)
ν_e 1e0πNp low-energy excess search Phys. Rev. D 105, 112004 (2022)
ν_e 1eX low-energy excess search Phys. Rev. D 105, 112005 (2022)
Electron-like low-energy excess search summary Phys. Rev. Lett. 128, 241801 (2022)
Higgs Portal Scalar Search Phys. Rev. Lett. 127, 151803 (2021)
HNL search Phys. Rev. D 101, 052001 (2020)
Updated HNL and HPS search arXiv:2207.03840 [hep-ex]
$\nu_e+\nu_\mu$ inclusive 3+1 oscillation measurement MICROBOONE-NOTE-1116-PUB
Reconstruction impact on ν_e 1e0πNp low-energy excess search MICROBOONE-NOTE-1114-PUB
Neutron-antineutron oscillation MICROBOONE-NOTE-1113-PUB
ν_μ 1μ0π1p disappearance analysis results MICROBOONE-NOTE-1106-PUB
$\nu_e+\nu_\mu$ 0π1p 3+1 oscillation sensitivity MICROBOONE-NOTE-1105-PUB
Progress towards new NCΔ measurement MICROBOONE-NOTE-1104-PUB
NC Coherent single γ search MICROBOONE-NOTE-1103-PUB
Inclusive single γ search MICROBOONE-NOTE-1102-PUB



Searching for new physics

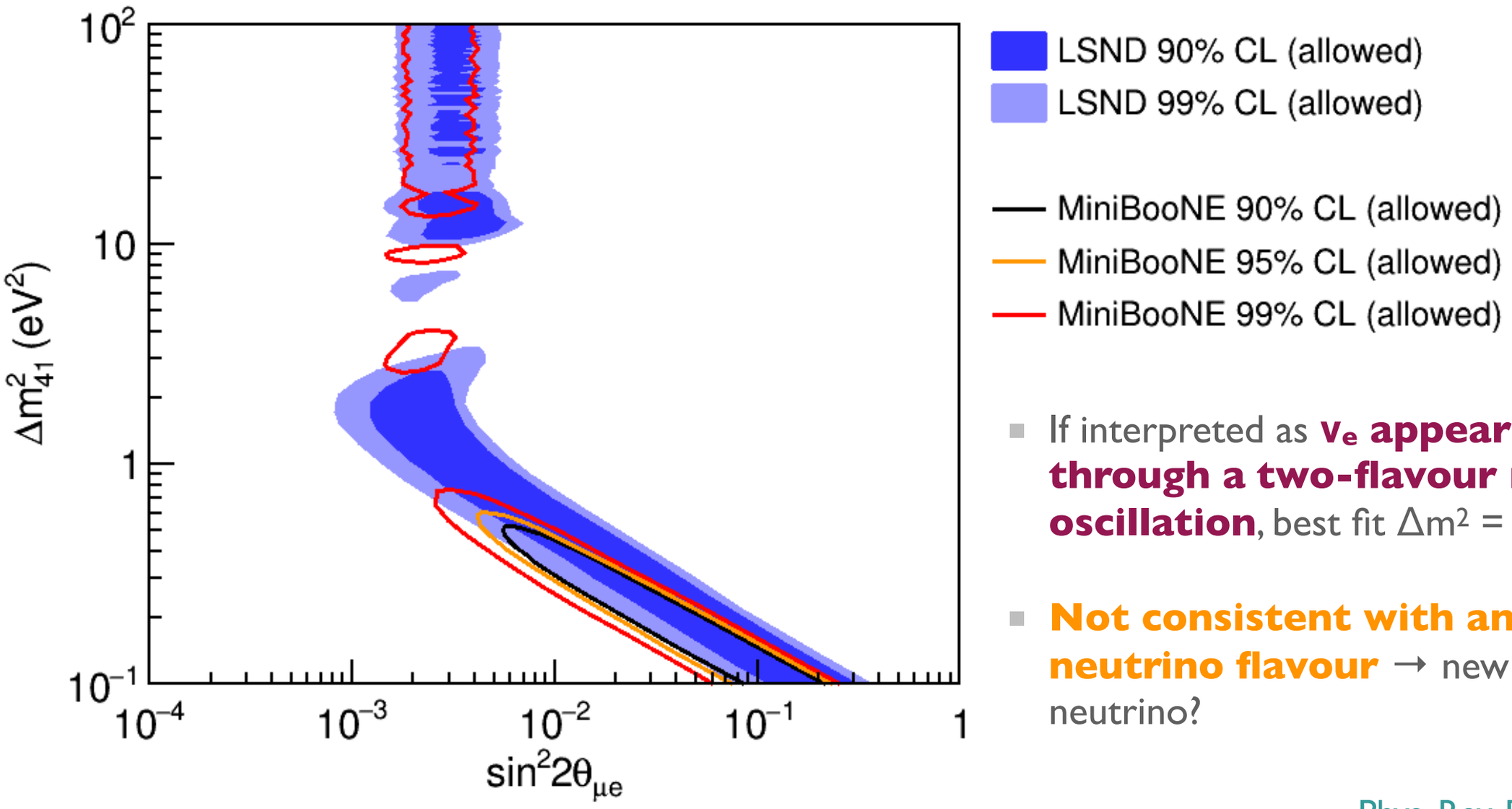
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



- 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 νe in MiniBooNE detector
  - or something else? (I'll come back to this)

Phys. Rev. D 103, 052002

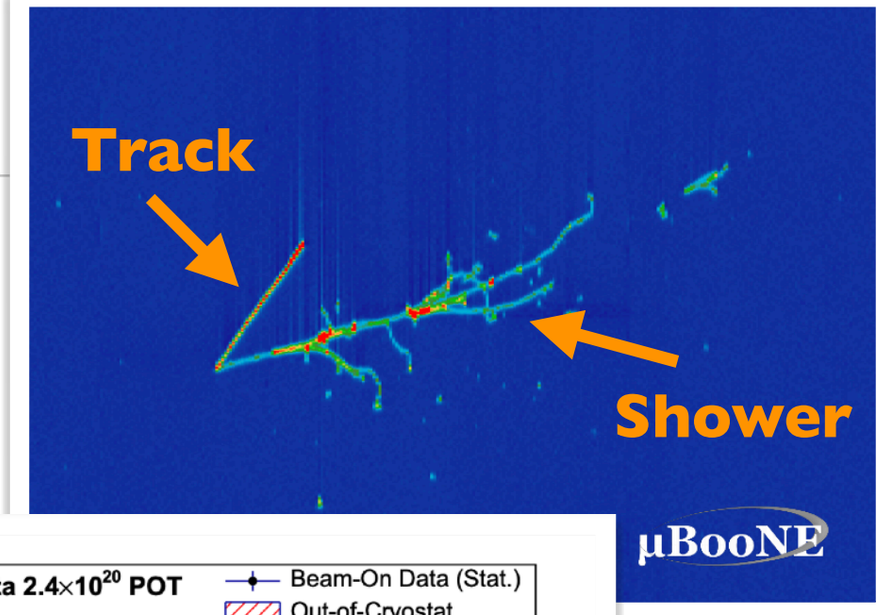
THE MINIBOONE LOW-ENERGY EXCESS (LEE)



- If interpreted as **ν_e appearance through a two-flavour neutrino oscillation**, best fit $\Delta m^2 = 0.04$ eV^2
- **Not consistent with any known neutrino flavour** → new "sterile" neutrino?

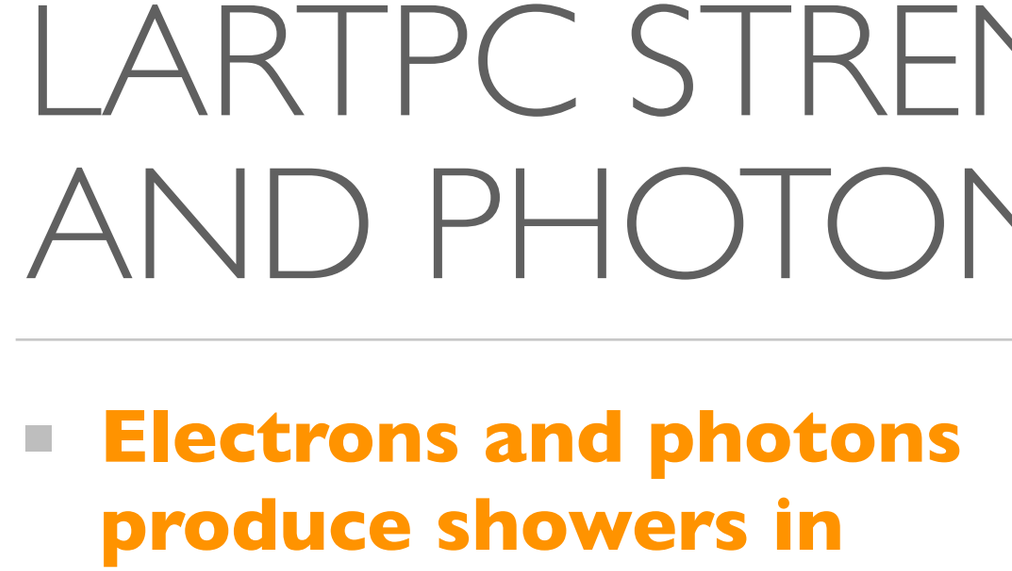
Phys. Rev. D 103, 052002

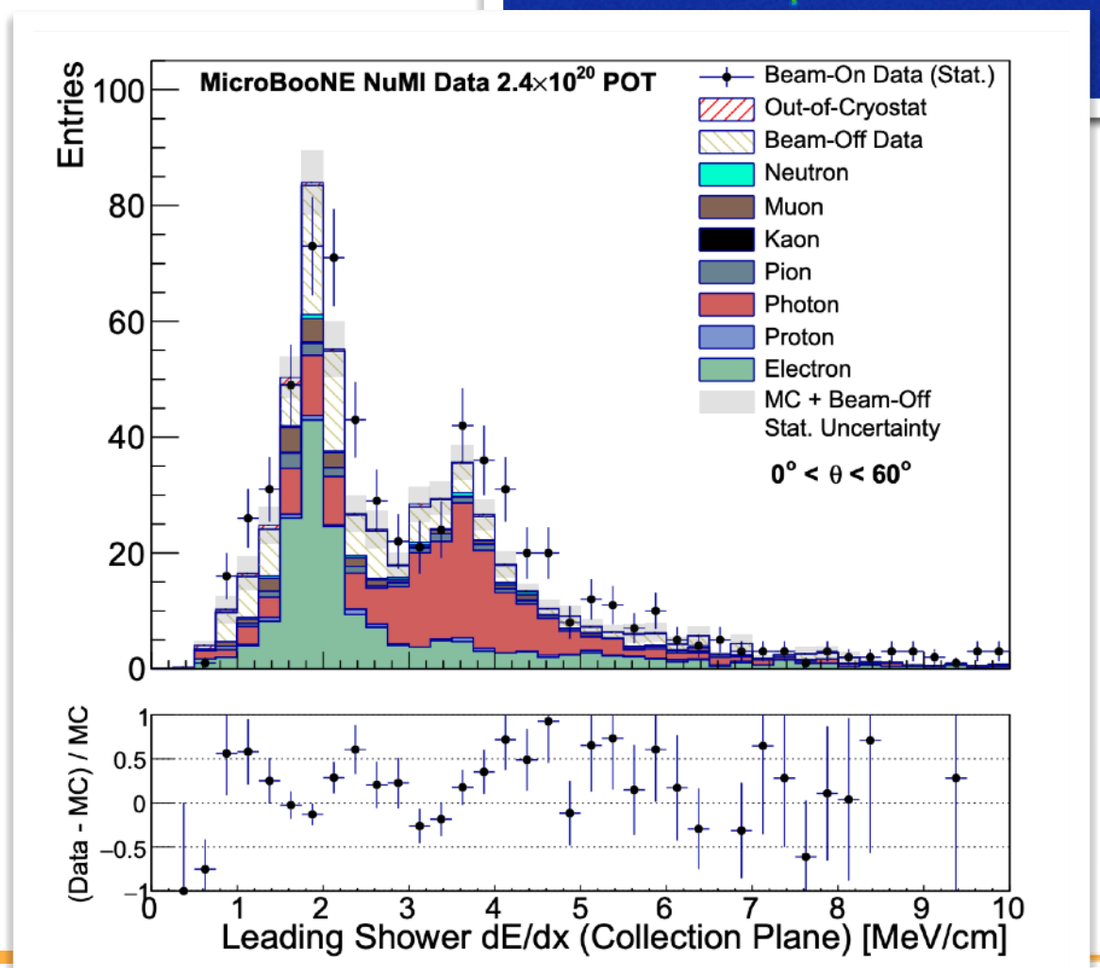
LARTPC STRENGTH: ELECTRONS AND PHOTONS



- **Electrons and photons produce showers in LArTPCs**

- Distinguish using dE/dx at start of shower and start point





Phys. Rev. D 104, 052002 (2021)

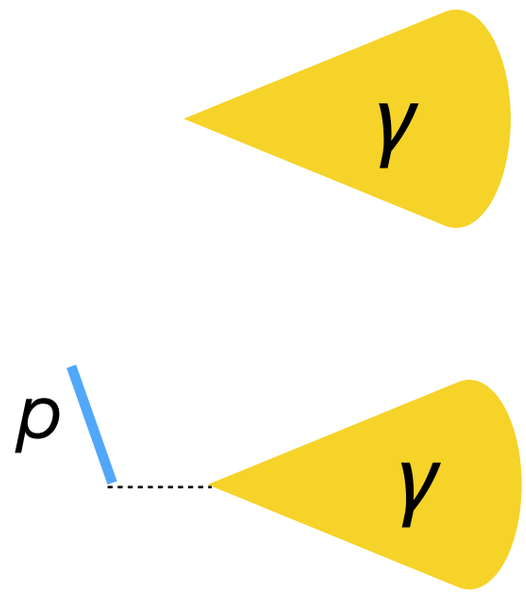
μBooNE

UNIVERSITY OF OXFORD

FIRST INVESTIGATION OF THE MINIBOONE LOW-ENERGY EXCESS

Photon search

Target $\Delta \rightarrow N\gamma$:
1γ0p and 1γ1p

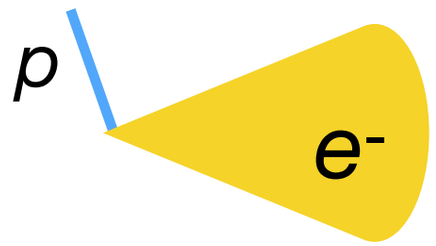


Phys. Rev. Lett. 128, 111801

Electron searches

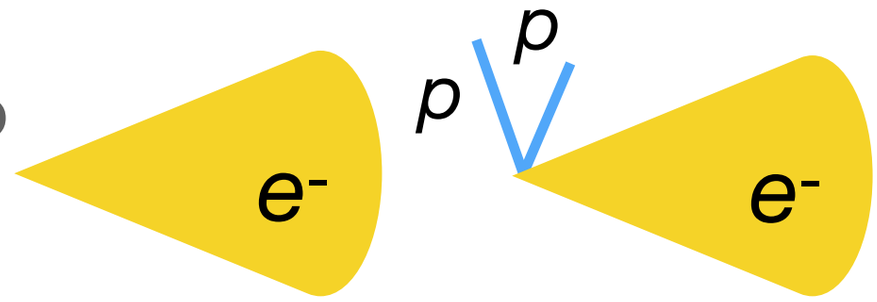
Phys. Rev. D 105, 112003

CCQE-like:
1e1p



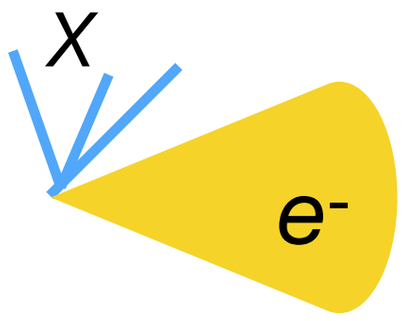
Phys. Rev. D 105, 112004

CC0π: 1e0p
and 1eNp



Phys. Rev. D 105, 112005

Inclusive:
1eX

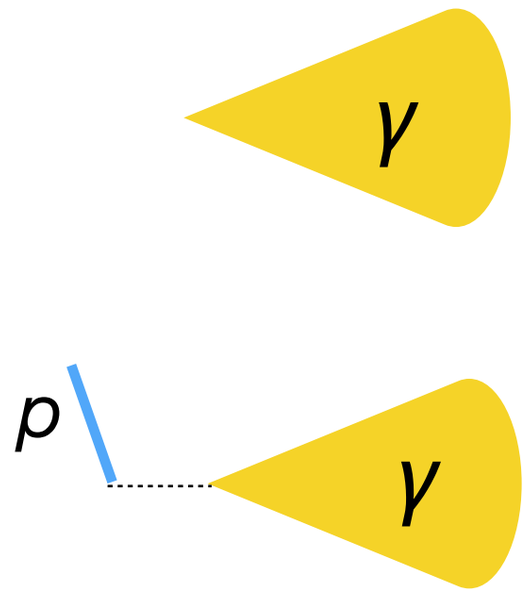


Phys. Rev. Lett. 128, 241801

FIRST INVESTIGATION OF THE MINIBOONE LOW-ENERGY EXCESS

Photon search

Target $\Delta \rightarrow N\gamma$:
1γ0p and 1γ1p

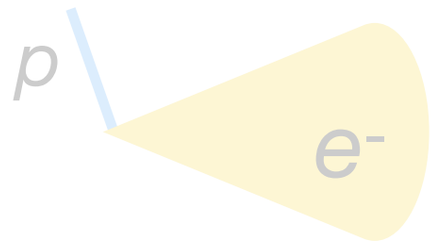


Phys. Rev. Lett. 128, 111801

Electron searches

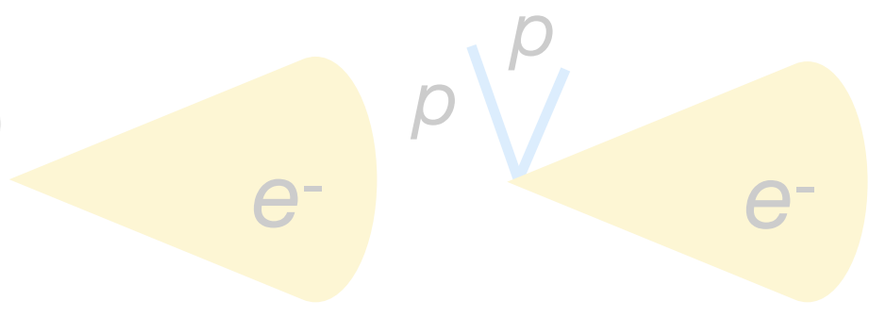
Phys. Rev. D 105, 112003

CCQE-like:
1e1p



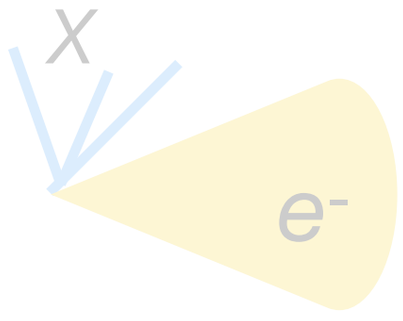
Phys. Rev. D 105, 112004

CC0π: 1e0p and 1eNp



Phys. Rev. D 105, 112005

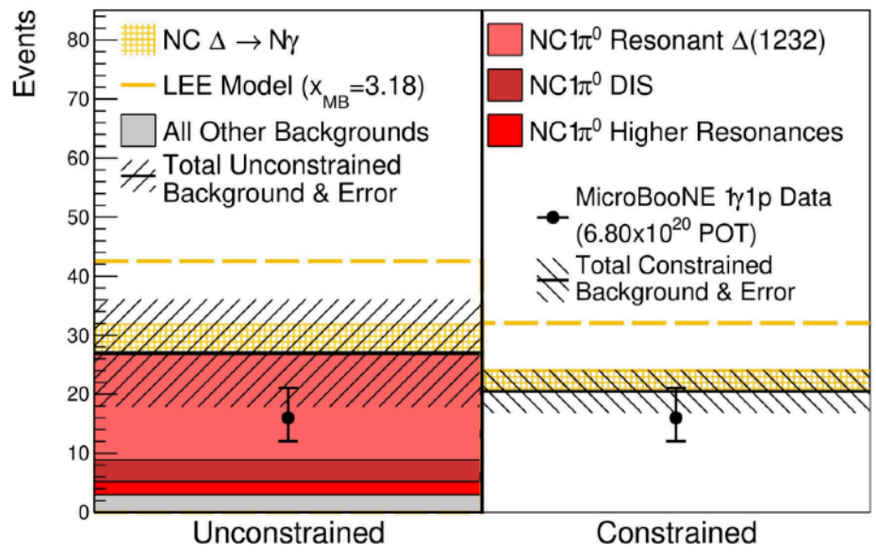
Inclusive:
1eX



Phys. Rev. Lett. 128, 241801

NC-Δ SINGLE PHOTON SEARCH

Phys. Rev. Lett. 128, 111801

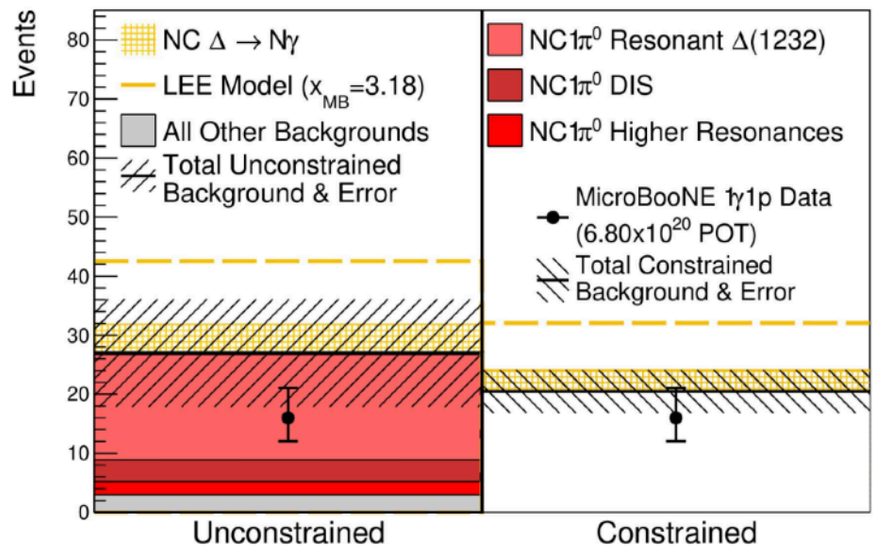


1γ1p

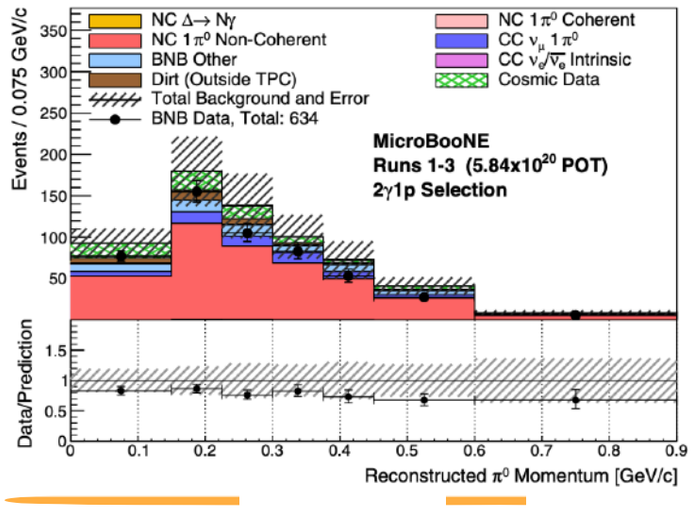
NC-Δ SINGLE PHOTON SEARCH

Phys. Rev. Lett. 128, 111801

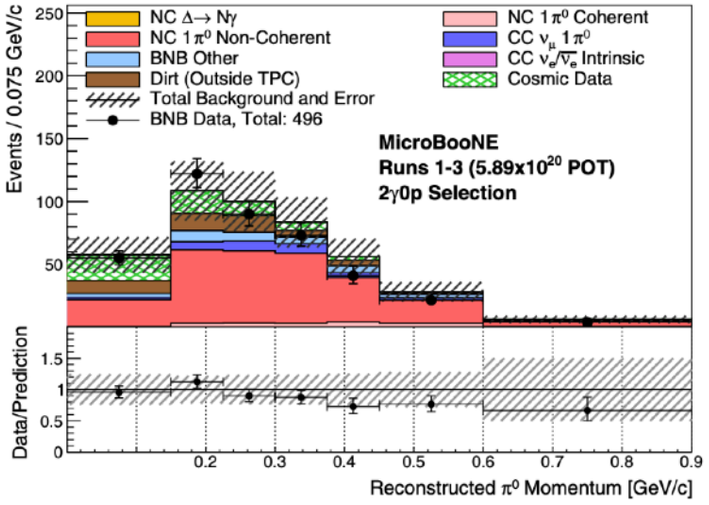
π⁰-rich sample → constraint on backgrounds in signal region



1γ1p



2γ1p

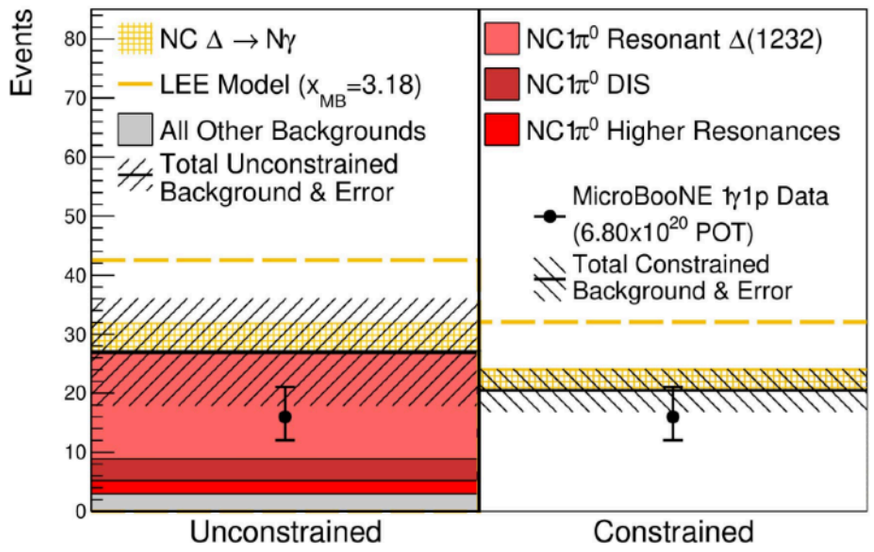


2γ0p

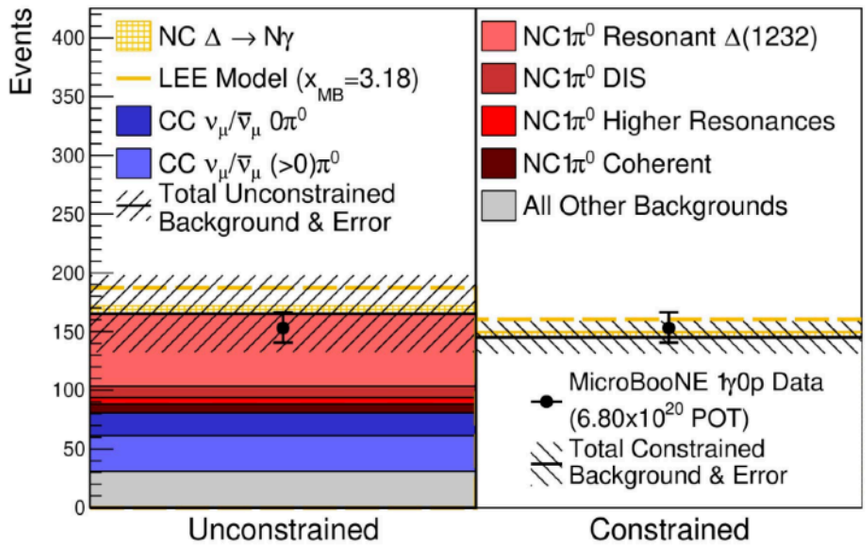
NC-Δ SINGLE PHOTON SEARCH

Phys. Rev. Lett. 128, 111801

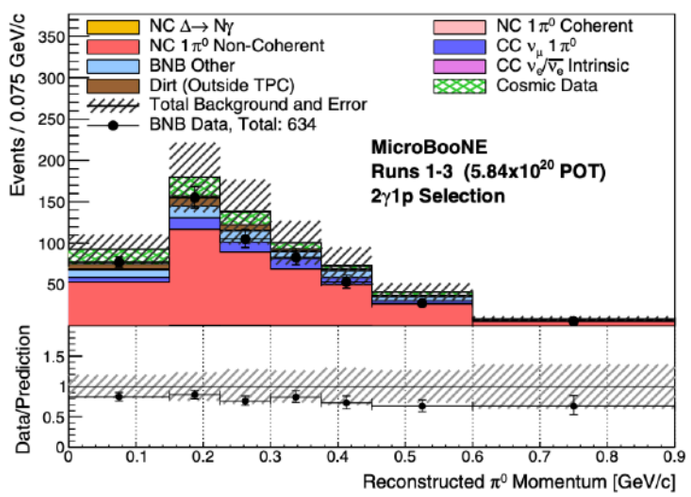
π⁰-rich sample → constraint on backgrounds in signal region



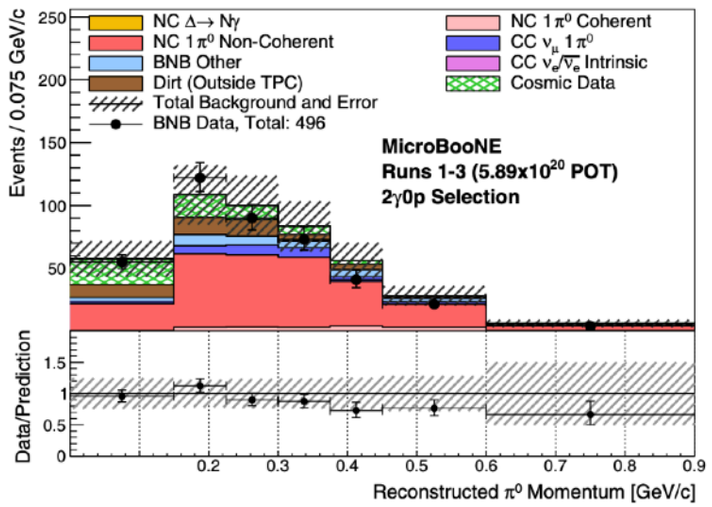
1γ1p



1γ0p



2γ1p



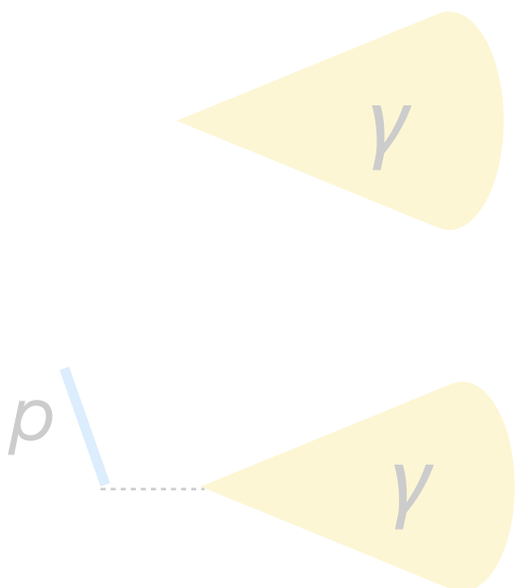
2γ0p

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

FIRST INVESTIGATION OF THE MINIBOONE LOW-ENERGY EXCESS

Photon search

Target $\Delta \rightarrow N\gamma$:
1γ0p and 1γ1p



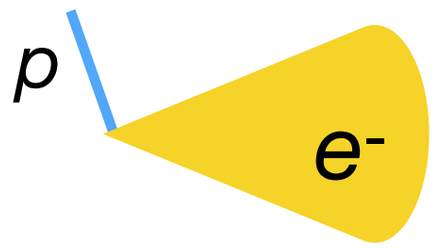
Phys. Rev. Lett. 128, 111801

Electron searches

Phys. Rev. Lett. 128, 241801

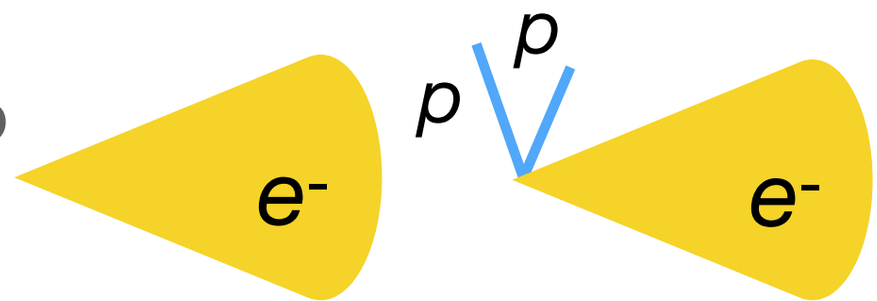
Phys. Rev. D 105, 112003

CCQE-like:
1e1p



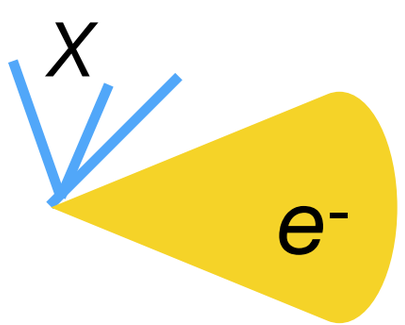
Phys. Rev. D 105, 112004

CC0π: 1e0p
and 1eNp

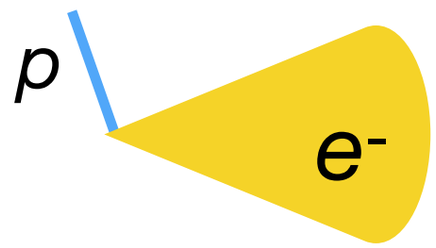


Phys. Rev. D 105, 112005

Inclusive:
1eX

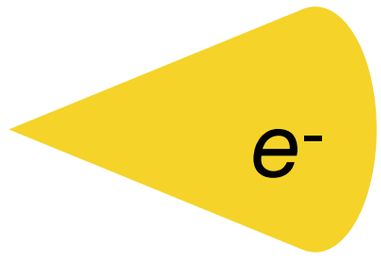


1e1p



Phys. Rev. D 105, 112003

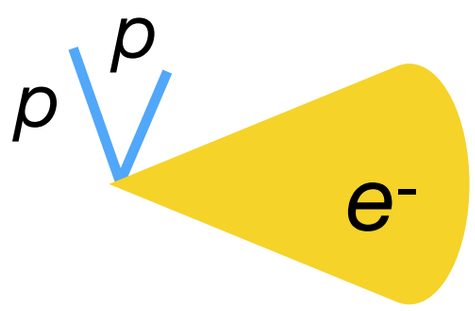
1e0p



Phys. Rev. D 105, 112004

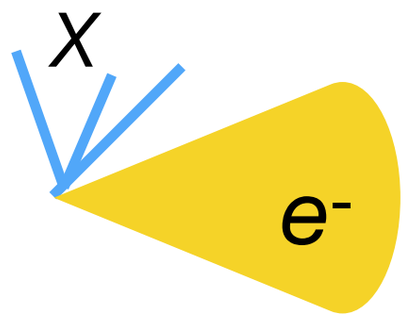
ν_e SEARCH

1eNp



Phys. Rev. D 105, 112004

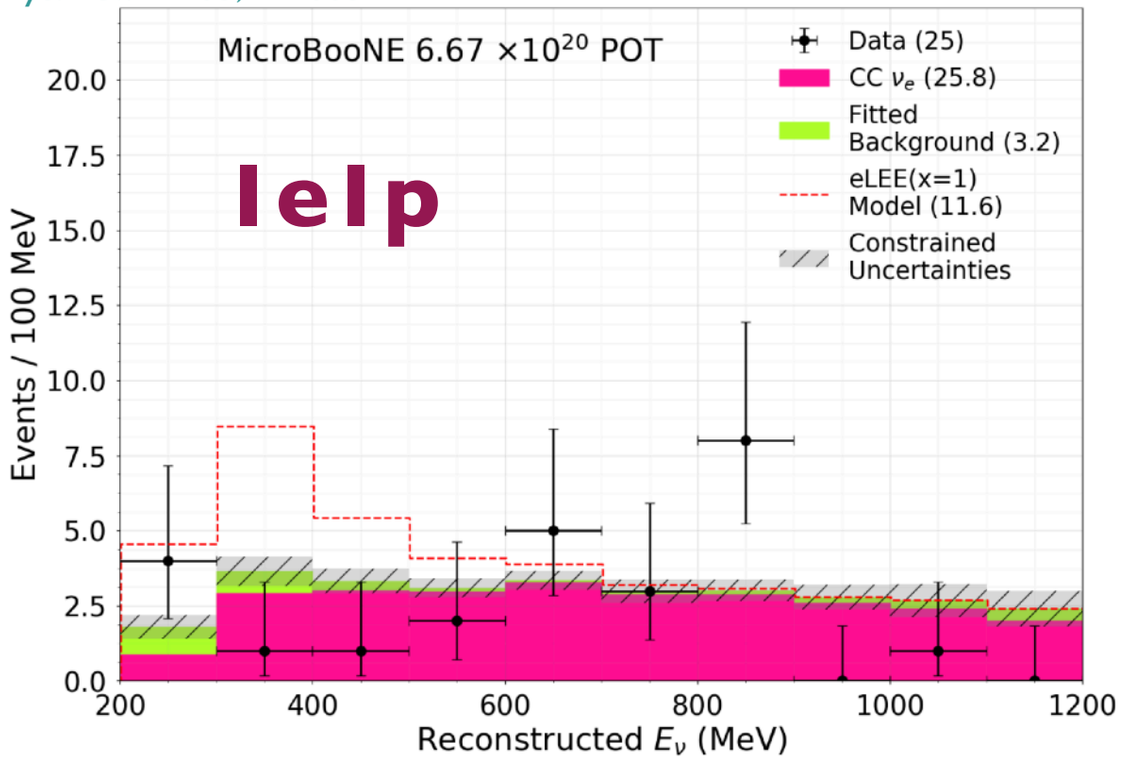
1eX



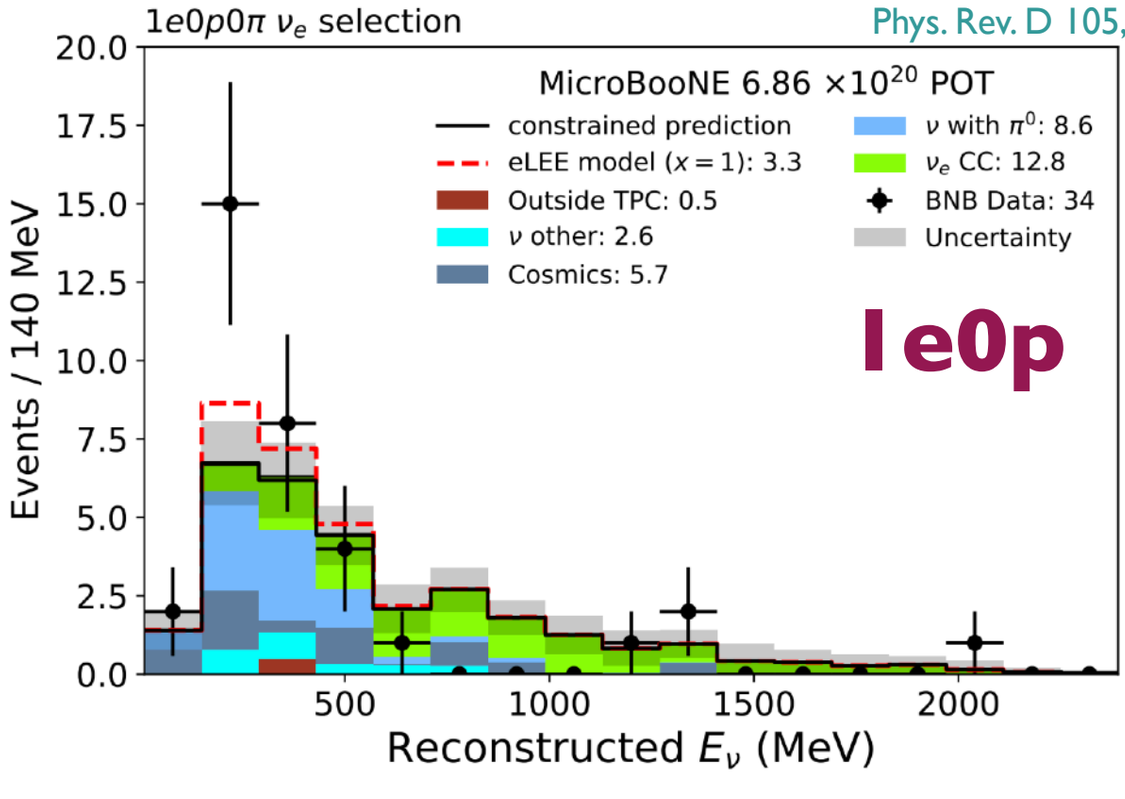
Phys. Rev. D 105, 112005

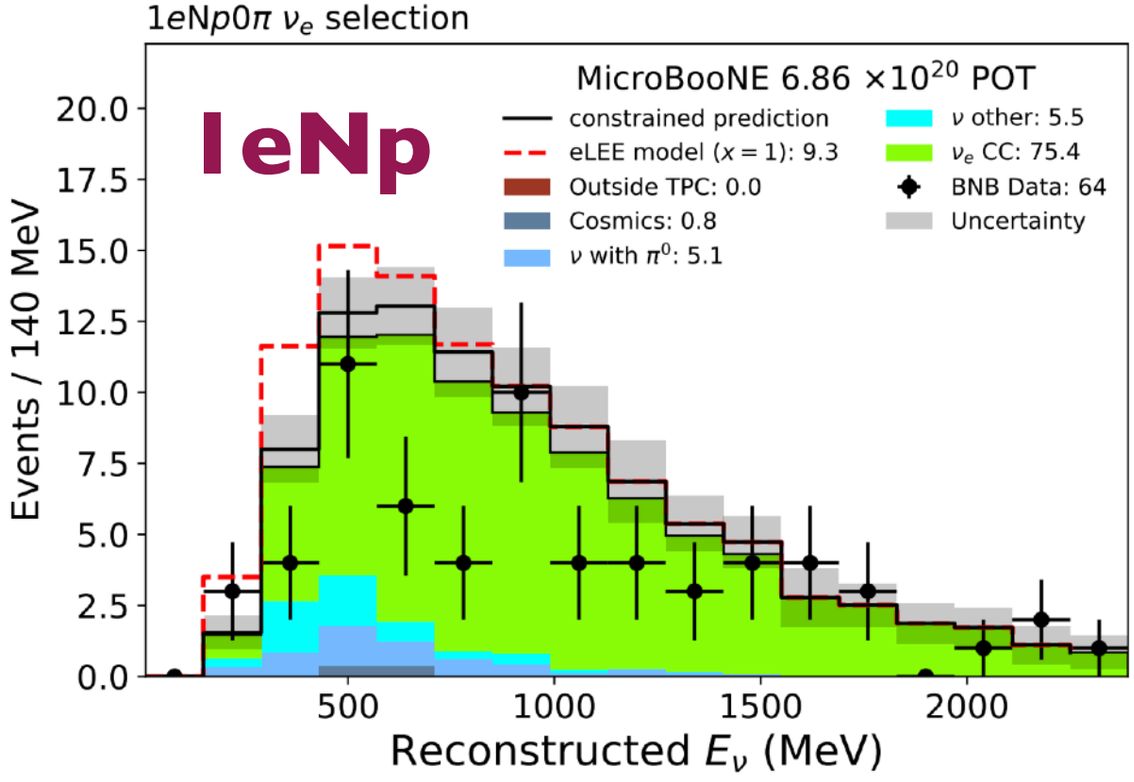
Phys. Rev. Lett. 128, 241801

Phys. Rev. D 105, 112003

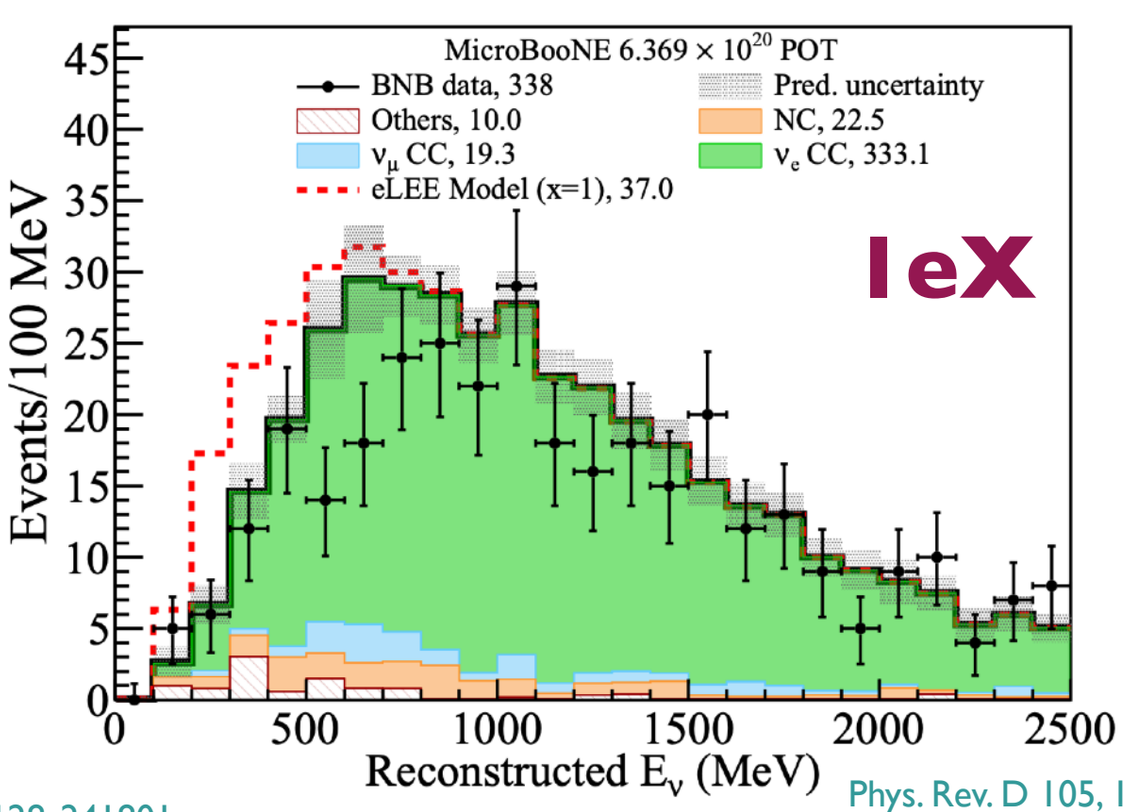


Phys. Rev. D 105, 112004





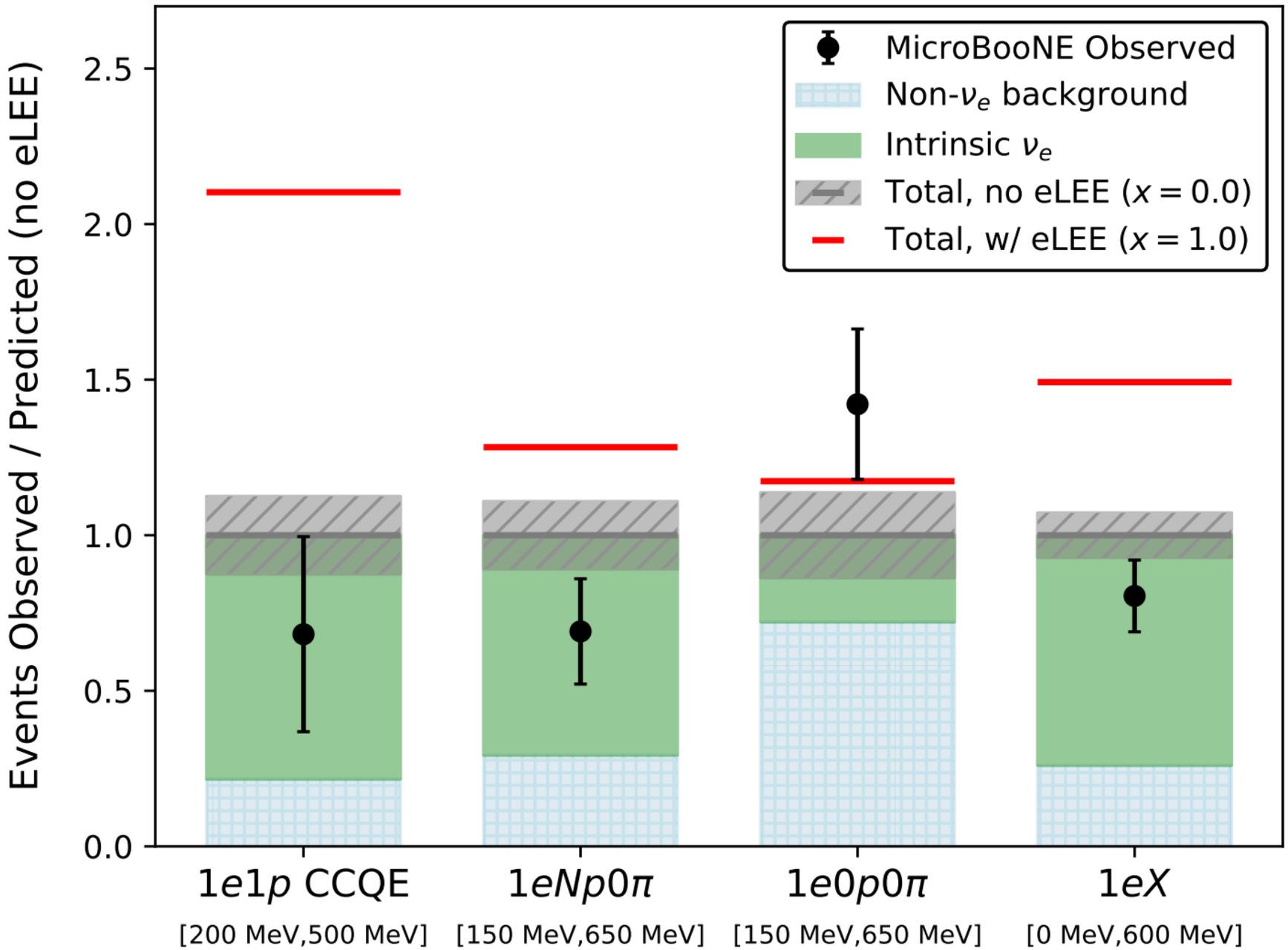
Phys. Rev. D 105, 112004



Phys. Rev. D 105, 112005

Phys. Rev. Lett. 128, 241801

Phys. Rev. Lett. 128, 241801



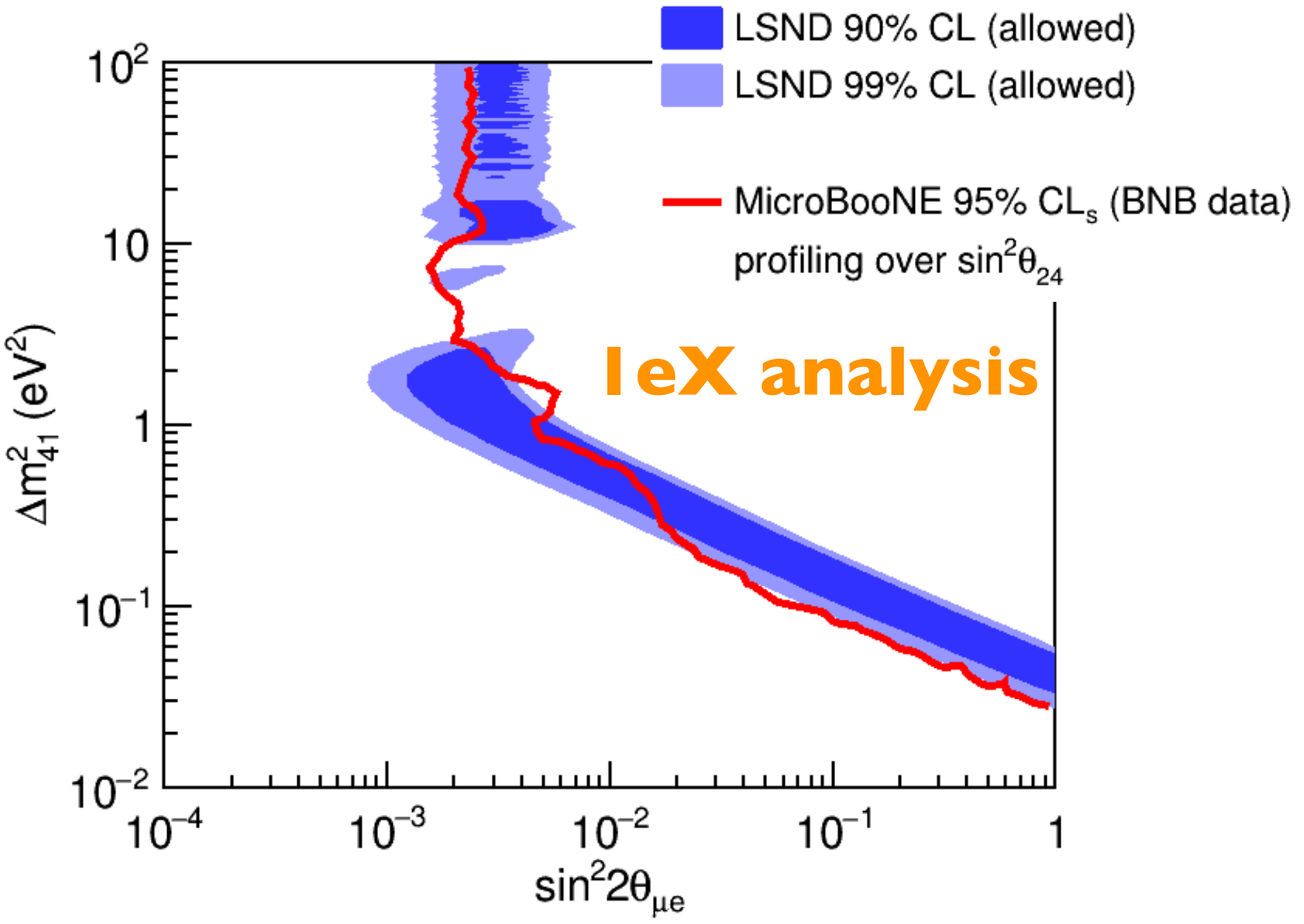
Three high-purity analyses reject ν_e interactions as sole source of excess at >97% CL

EXCLUSION CONTOURS

New summer 2022

MICROBOONE-NOTE-1116-PUB

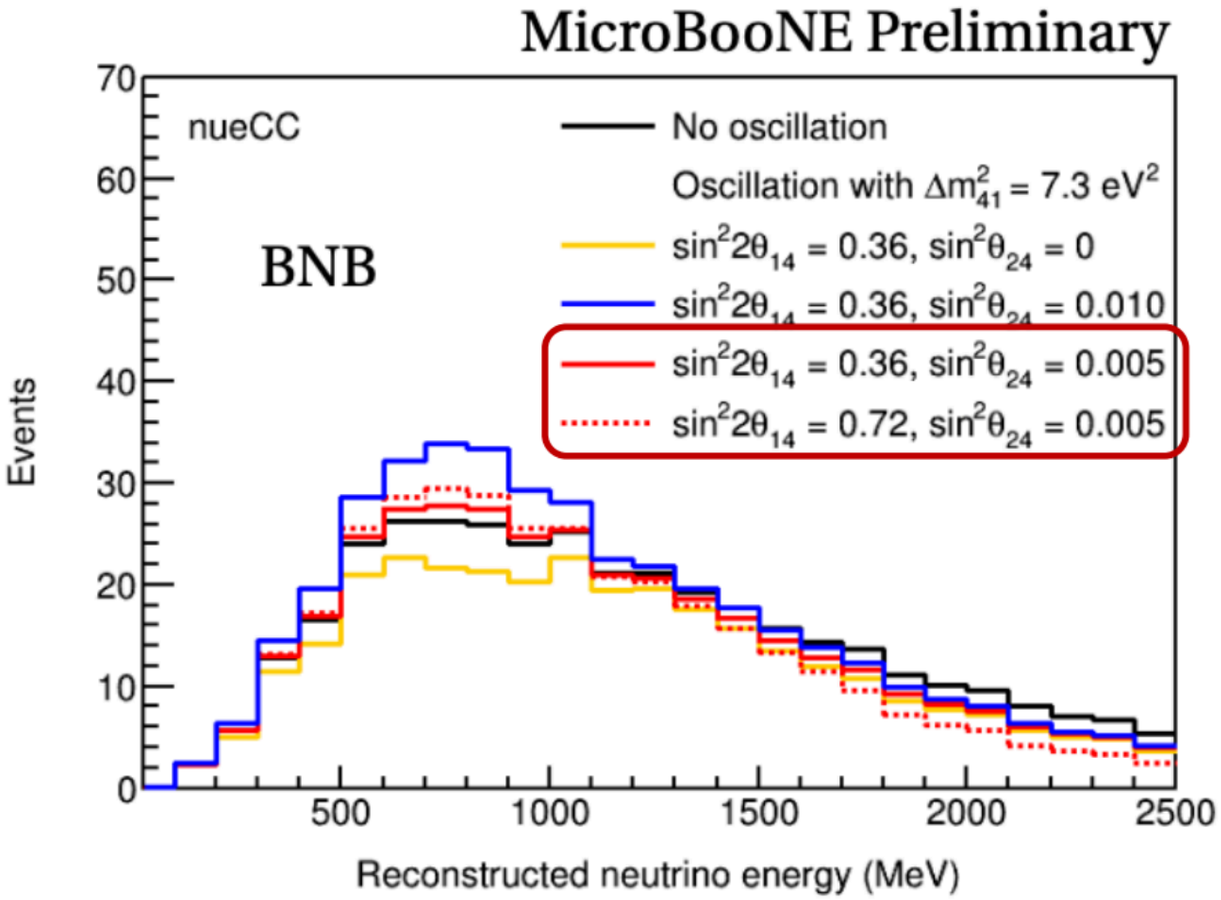
- What does this mean for the sterile neutrino hypothesis?
- We haven't seen evidence of an excess → place constraints on oscillation phase space for a new neutrino flavour



OSCILLATION PARAMETER DEGENERACY

New summer 2022

MICROBOONE-NOTE-1116-PUB



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

FUTURE PROSPECTS: BNB+NUMI

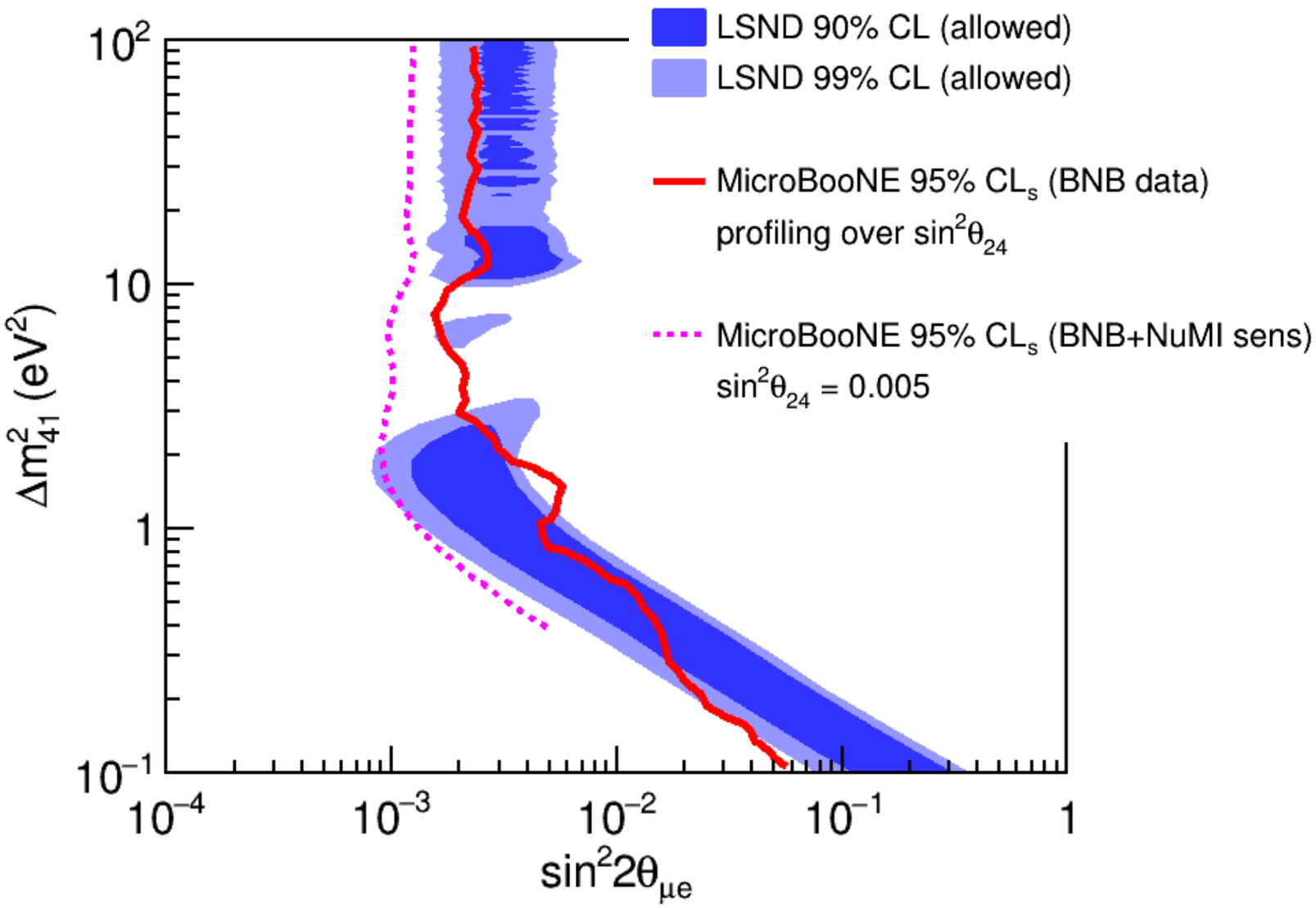
New summer 2022

MICROBOONE-NOTE-1116-PUB

- BNB $R_{ve/v\mu}$: 0.005
- NuMI $R_{ve/v\mu}$: 0.04

- Combining both data sets → significantly improved sensitivity

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

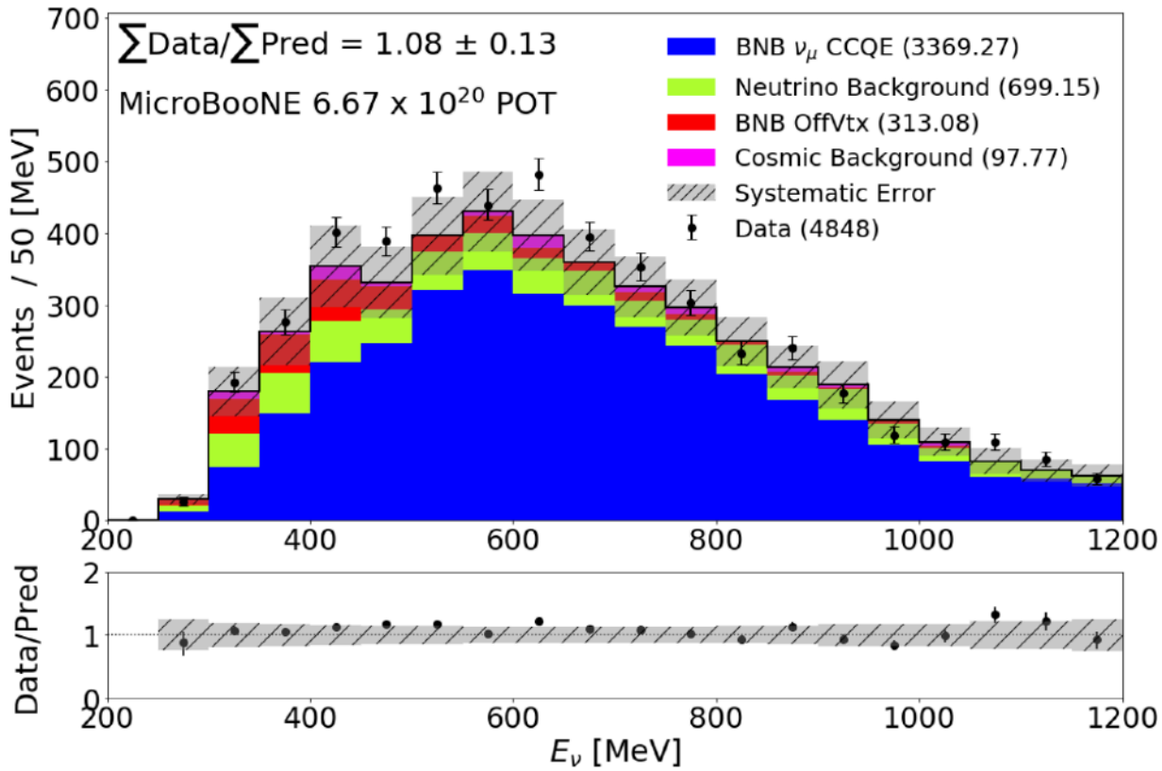


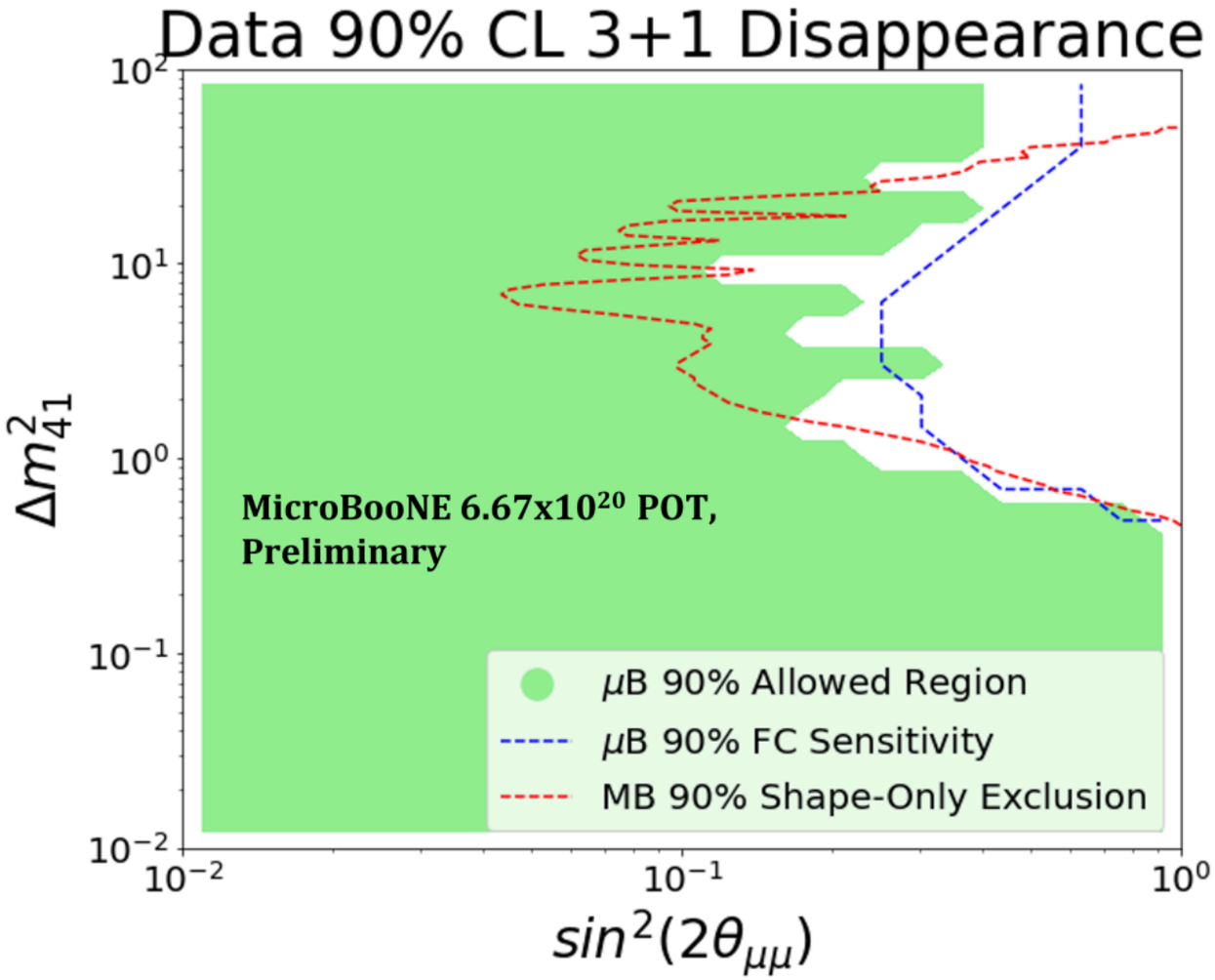
1μ1p DISAPPEARANCE EXCLUSION LIMITS

New summer 2022

MICROBOONE-NOTE-1106-PUB

- 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**



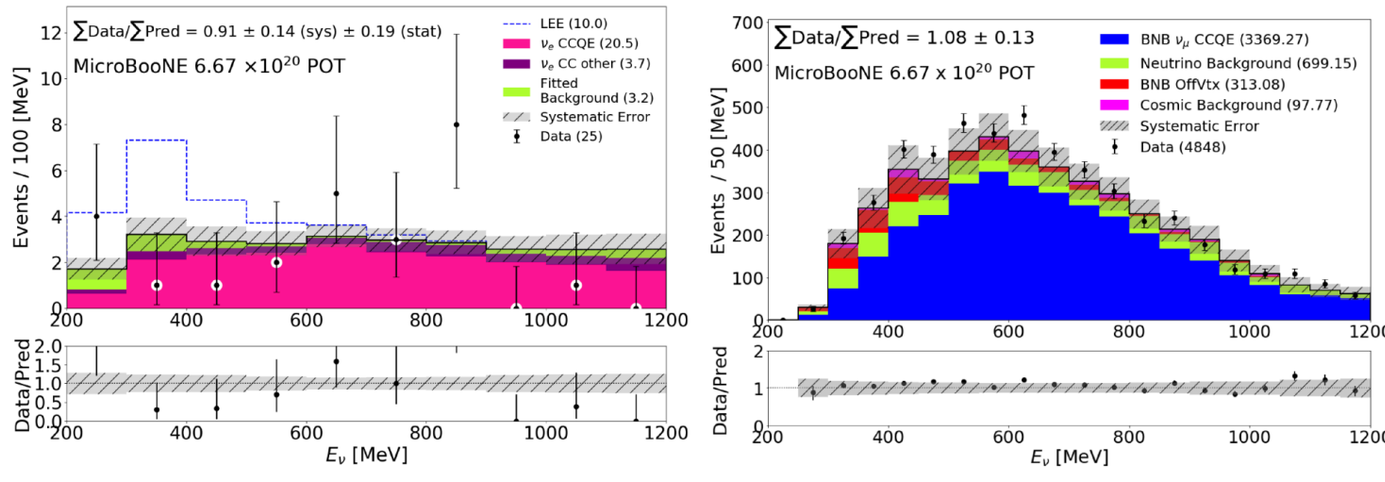


FUTURE 3+1 1e1p AND 1μ1p OSCILLATION ANALYSIS

New summer 2022

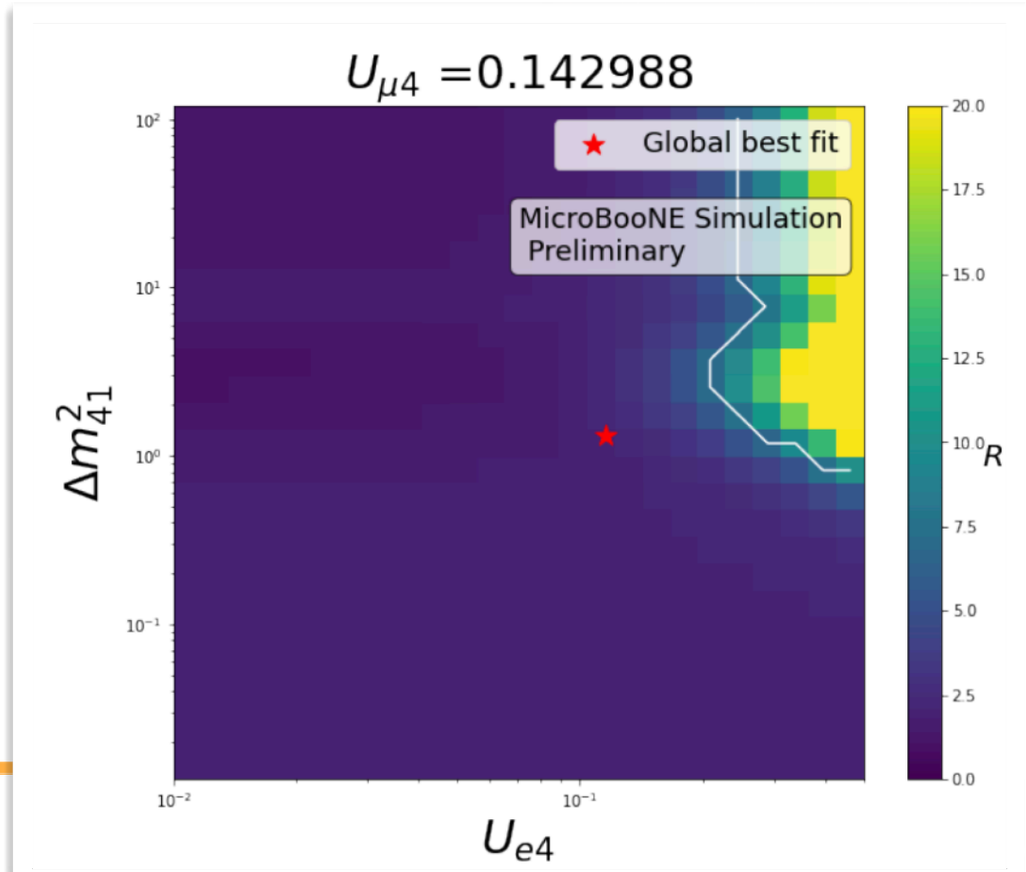
MICROBOONE-NOTE-1105-PUB

- 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

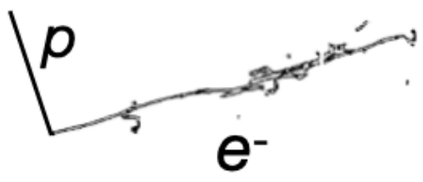
Produces e^+e^- pairs

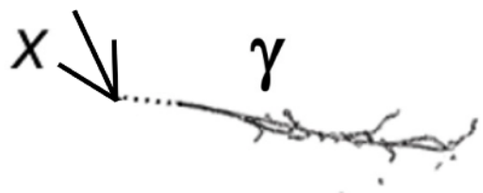
Caution: not an exhaustive list!

This is meant to be representative only

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

WHAT DOES THIS MEAN?





Overlapping e^+e^-

Overlapping e^+e^-

Highly asymmetric e^+e^-

Highly asymmetric e^+e^-

WHAT DOES THIS MEAN?

MicroBooNE's first LEE results

Overlapping e^+e^-

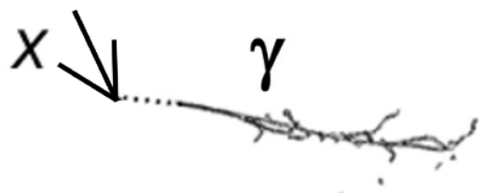
Overlapping e^+e^-

Highly asymmetric e^+e^-

Highly asymmetric e^+e^-

FUTURE INVESTIGATIONS

Future investigations



Overlapping e^+e^-

Overlapping e^+e^-

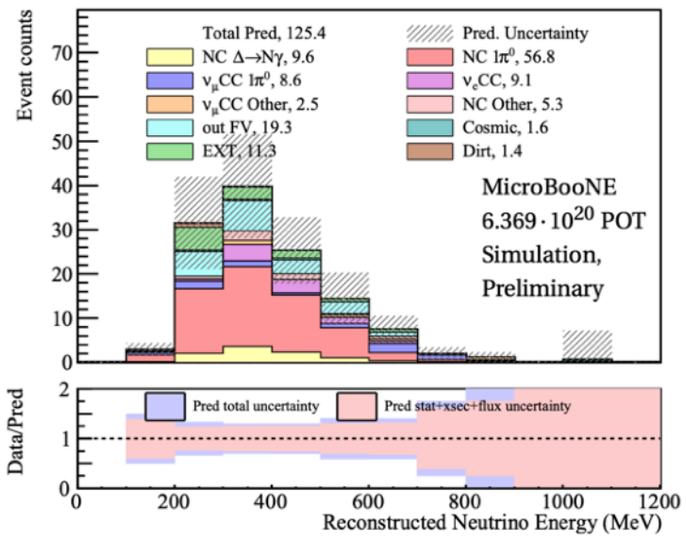
Highly asymmetric e^+e^-

Highly asymmetric e^+e^-

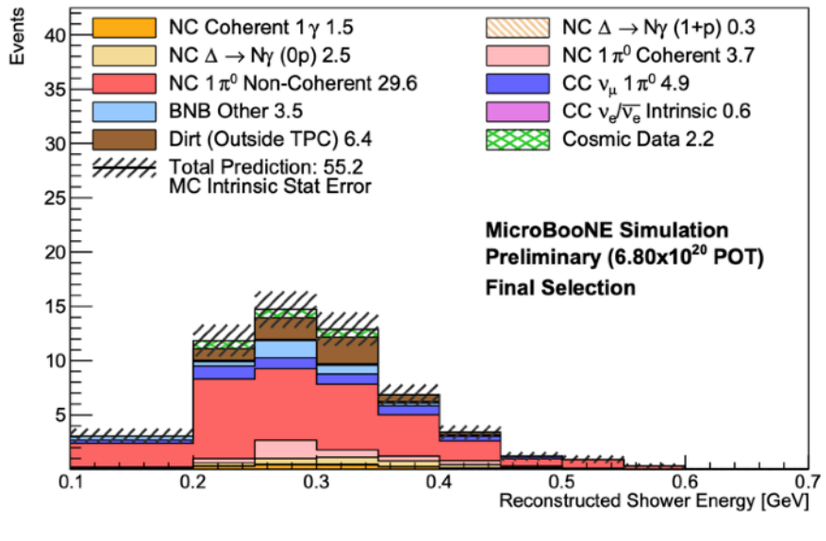
FUTURE INVESTIGATIONS

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

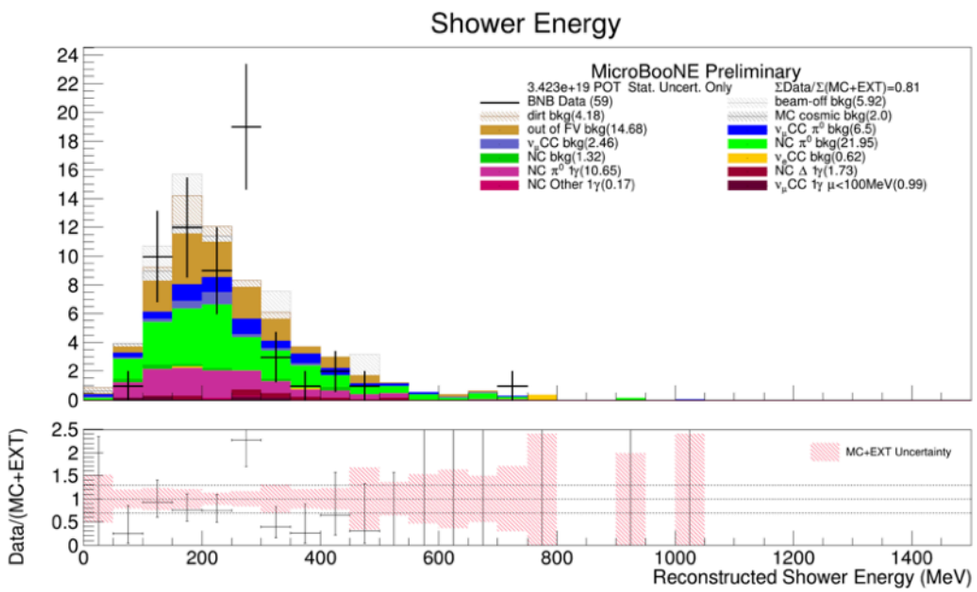
- Further investigations will expand photon-like searches and investigate e^+e^- final states - some preliminary results shown below:
  - **Further investigation of NC Δ model**: independent reconstruction, more sensitivity to potential excess in 1γ0p channel
  - **NC-Coherent 1γ targeted search**: forward-going photons with no visible hadronic energy
  - **Inclusive 1γ search**: generic test of single photon production
- Even more on the way!



1γ0p



Coh-1γ0p



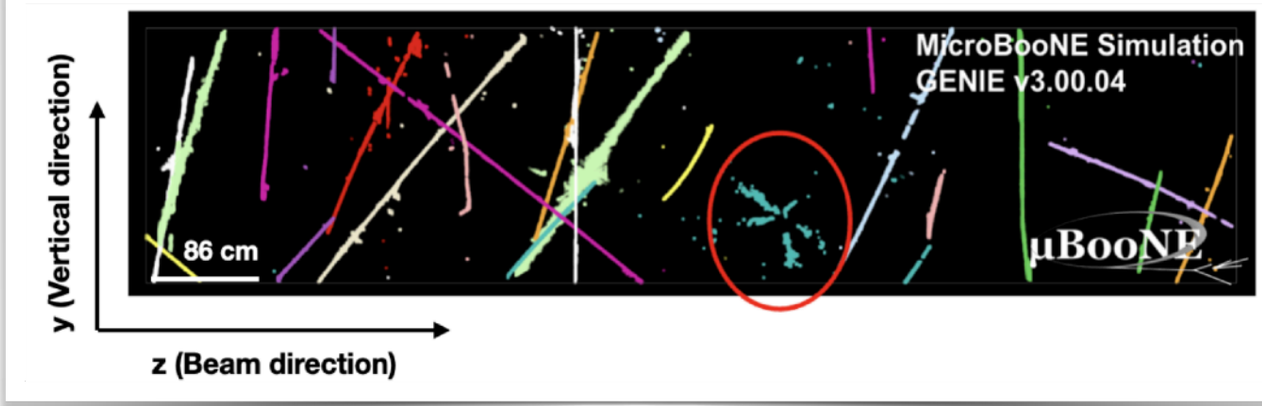
Inclusive 1γX

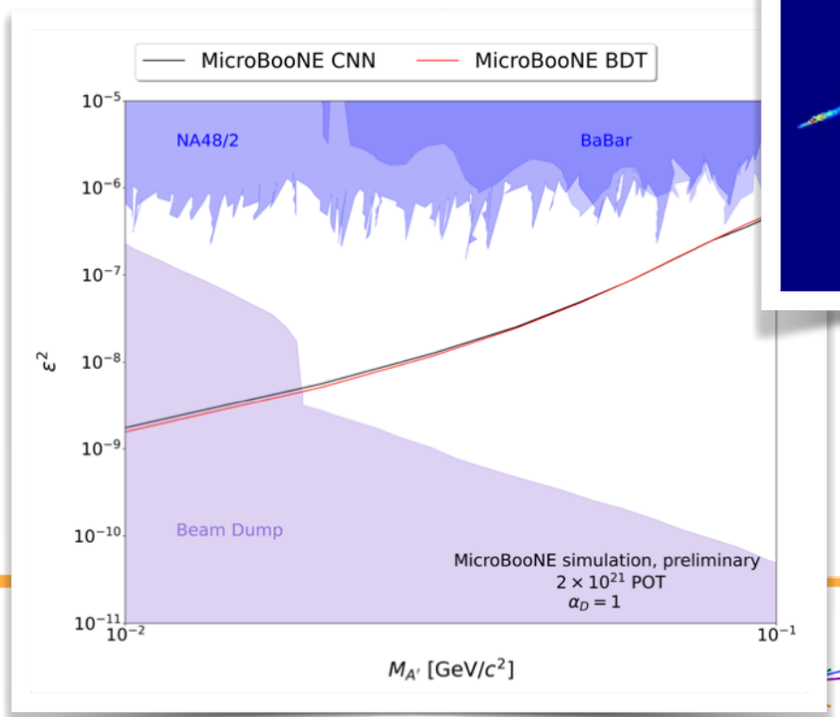
OTHER NEW PHYSICS SIGNATURES

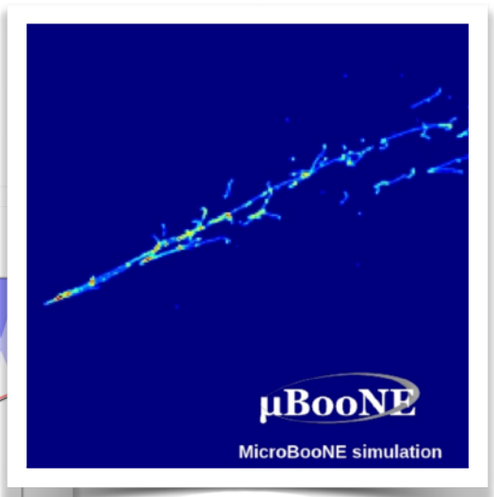
Phys. Rev. Lett. 127, 151803 (2021)
Phys. Rev. D 101, 052001 (2020)
arXiv:2207.03840 [hep-ex]
MICROBOONE-NOTE-1113-PUB
MICROBOONE-NOTE-1118-PUB

MicroBooNE is capable of a **range of Beyond the Standard Model physics searches**, such as:

- Search for **Higgs portal scalars** from NuMI absorber decaying to **e^+e^- pairs**
- Search for **heavy neutral leptons** from the BNB decaying to $\mu^\pm\pi^\pm$ pairs
- Search for **neutron-antineutron oscillation**
- **New!** Progress in search for **dark trident interactions**







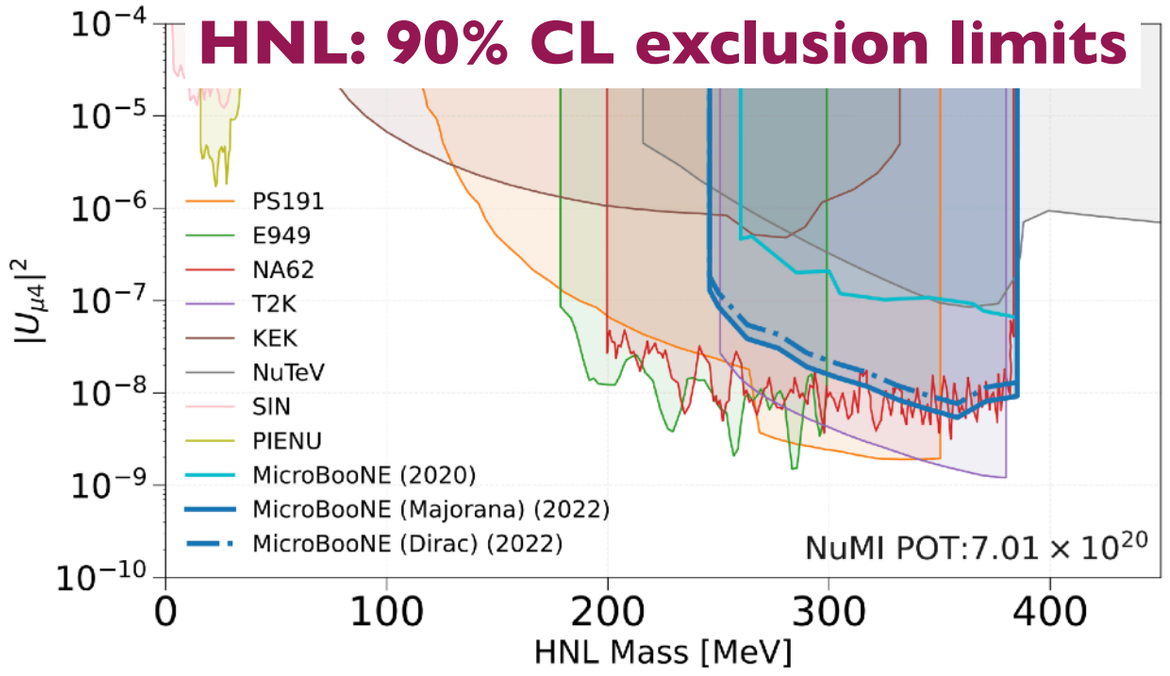
UNIVERSITY OF OXFORD

SEARCHING FOR OTHER NEW PHYSICS SIGNATURES

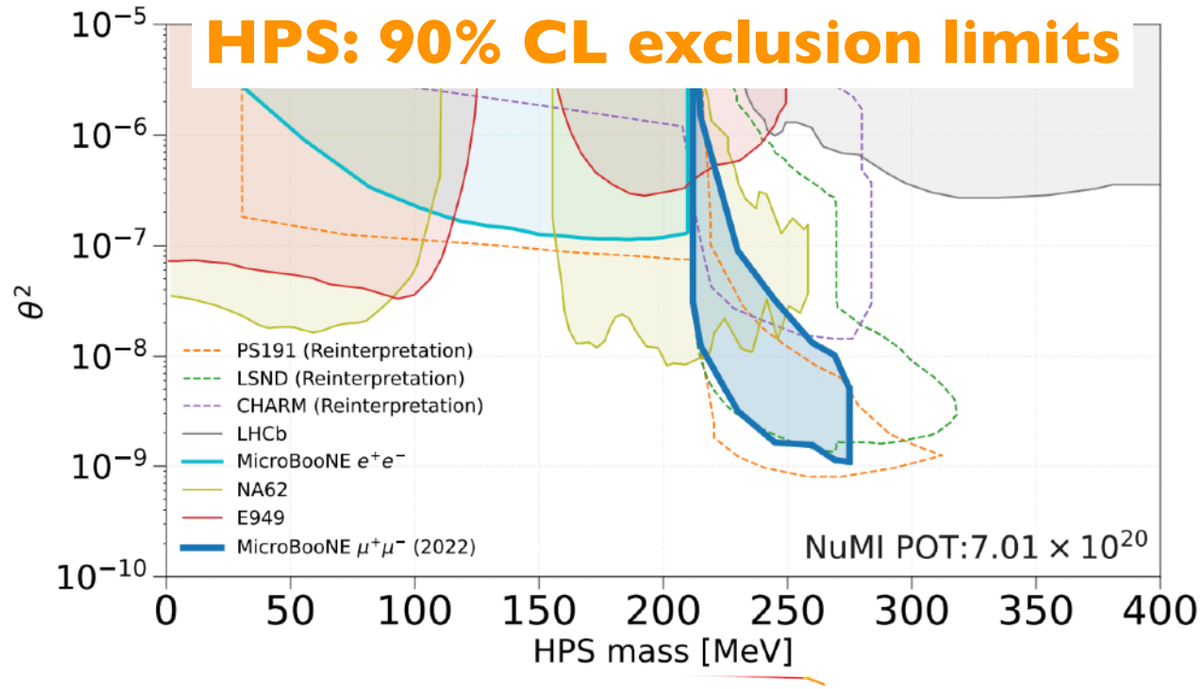
New summer 2022

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

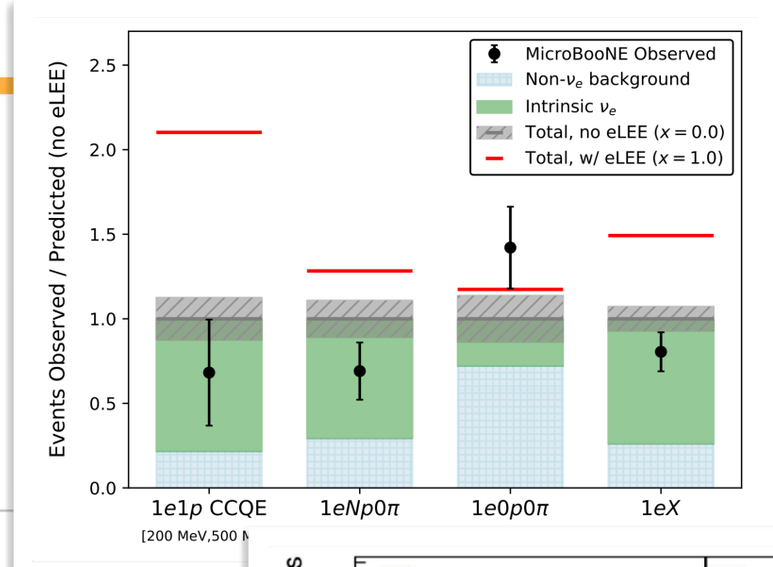


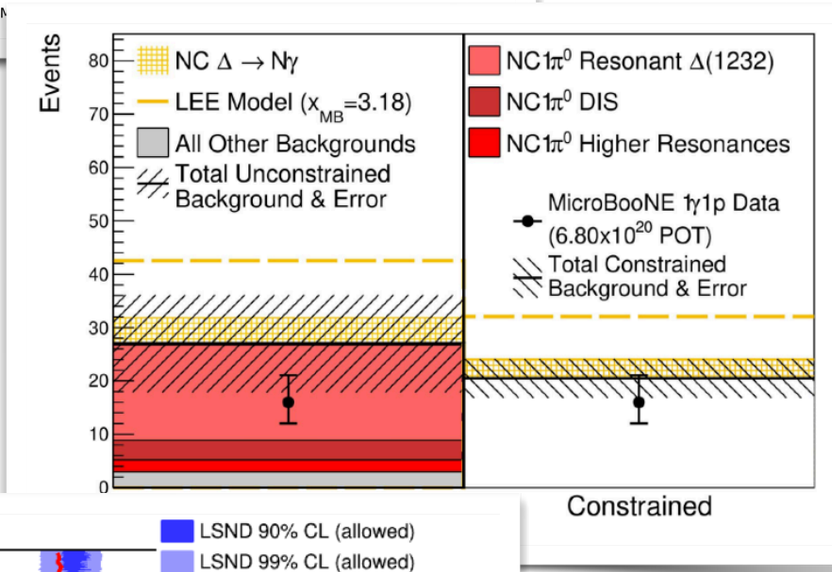
- Search for **Higgs portal scalar (HPS) decays to $\mu^+\mu^-$**
  - → complementary to previous e+e- MicroBooNE search
  - → First constraints on scalar-Higgs mixing angle θ in this mass range from a dedicated experimental search

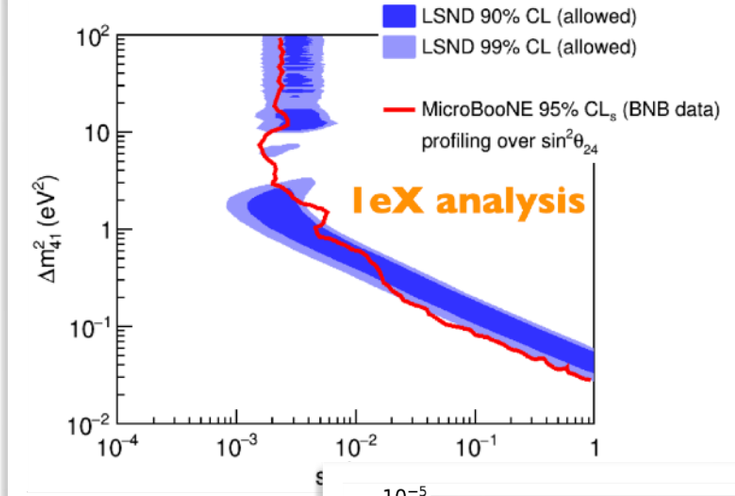


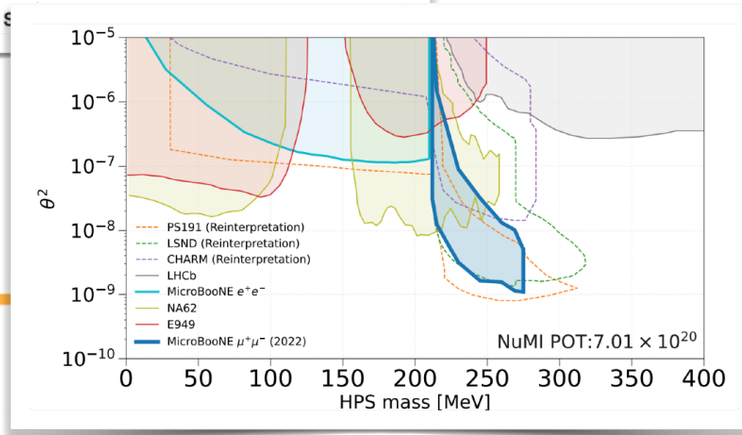
SUMMARY

- MicroBooNE has harnessed the full power of LArTPC detector technology to make **important new precision measurements**
- Detailed initial investigations into MiniBooNE anomaly show **no evidence for an excess** in pure ν_e and NCΔ 1γ channels
- Exclusion limits set and further investigations underway
- MicroBooNE is also **laying the groundwork** for future LArTPC detector programmes: **SBND, ICARUS** (further investigation of the MiniBooNE anomaly) and the future multi-kt neutrino experiment **DUNE**









THANK YOU