



# *Searches for physics beyond the Standard Model with the MicroBooNE experiment*

*Lepton-Photon 2025*  
*August 25<sup>th</sup>, Madison, WI*

*Diego Andrade (IIT)*  
*On behalf of the MicroBooNE Collaboration*

# MicroBooNE scientific program

New Physics  
Beyond Standard  
Model (BSM)

- Same neutrino beamline & roughly same location as MiniBooNE
- Including MiniBooNE Low Energy Excess (LEE) investigations

**This talk!**

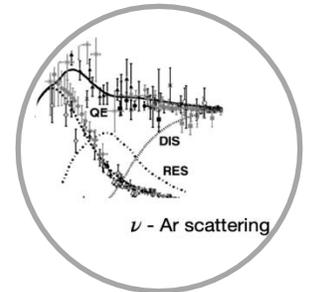


Study of  $\nu$ -Ar  
interactions

- $\nu$ -Ar cross-section measurements

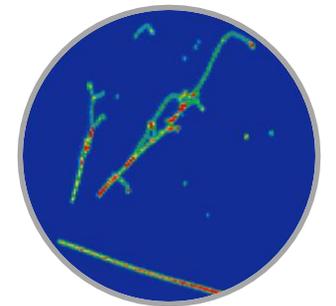
▪ *Neutrino-argon cross-section measurements from the MicroBooNE experiment*

Lepton-Photon - Talk, Aug 26, 2:00 PM by Liang Liu



LArTPC Detector  
R&D

- New LArTPC techniques (hardware and software)

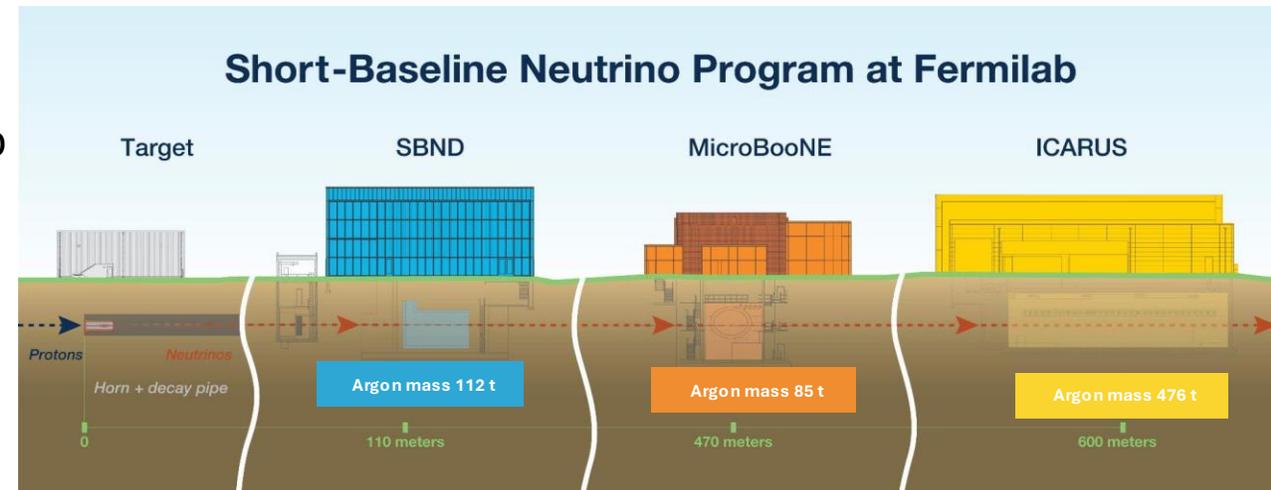


# ■ MicroBooNE

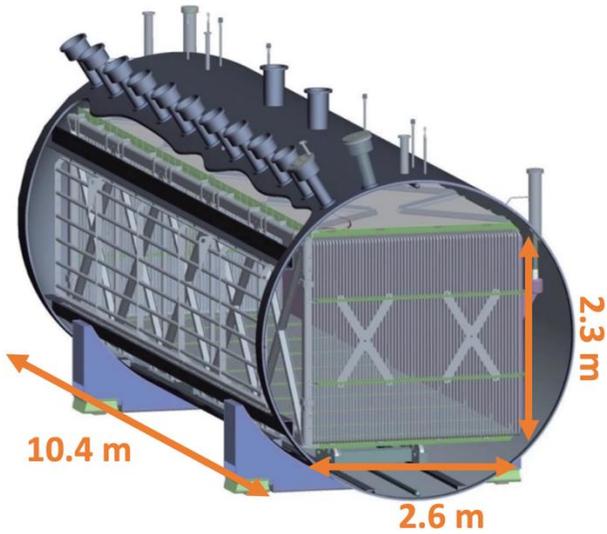


## Micro Booster Neutrino Experiment

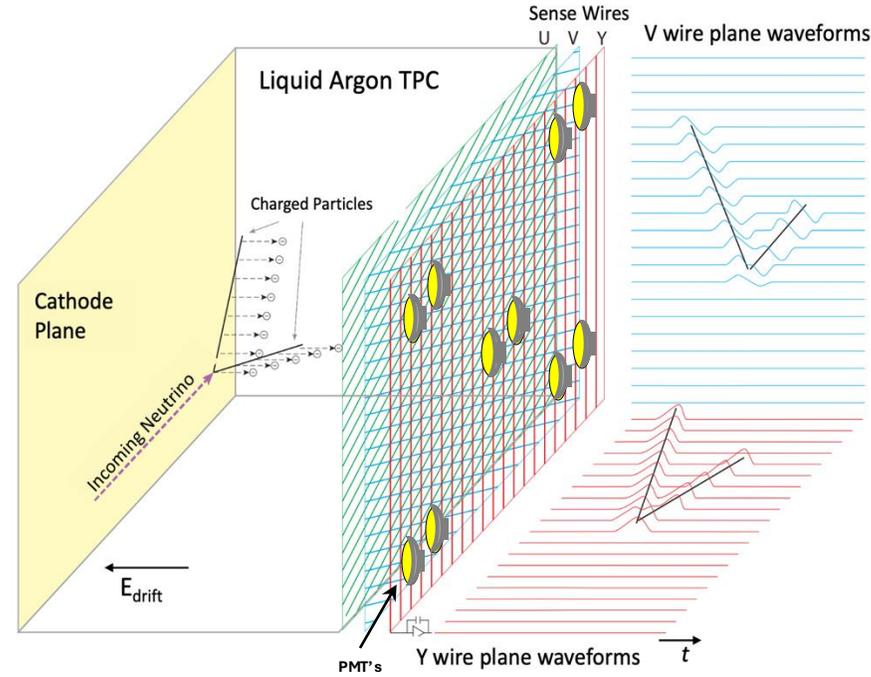
- On-axis of the Booster Neutrino Beam (BNB) at Fermilab
  - Nu data (2015-2020) + R&D (2021)
- Part of the SBN program at Fermilab
- 190 collaborators from 41 institutions  
45 postdocs, 54 grad students



# ■ The MicroBooNE LArTPC



LArTPC model



LArTPC operational principle



MicroBooNE Event display

- 85 metric ton active volume LArTPC
- 3 wire planes (Charge) & 32 PMT's (Light )
- 3 mm wire spacing and E field 274 V/cm

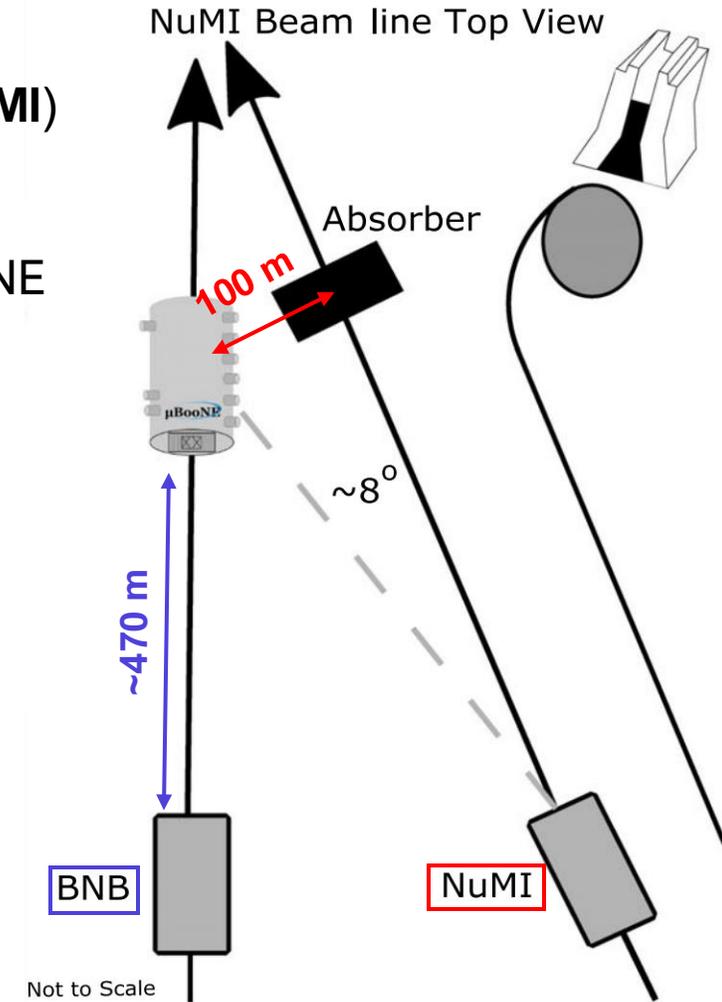
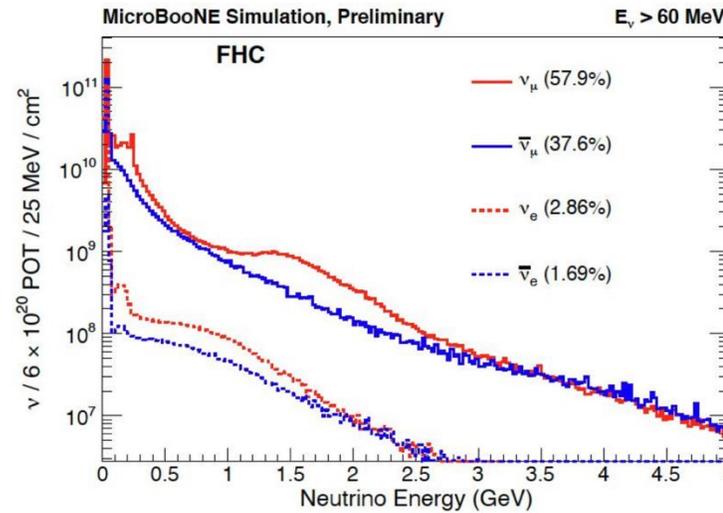
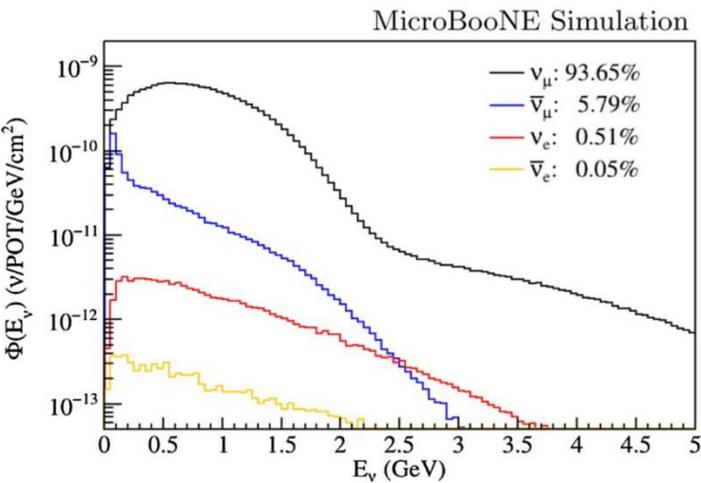
- Low energy detection threshold
- mm-spatial resolution

# Neutrino Beamlines at Fermilab

**MicroBooNE** exposed to two neutrino beams:

- Booster Neutrino Beam (**BNB**)
- On-axis
- 8 GeV protons
- Target ~470 m from MicroBooNE
- $1.1 \times 10^{21}$  POT

- Neutrinos at the Main Injector (**NuMI**)
- ~8° off-axis
- 120 GeV protons
- Absorber ~ 100 m from MicroBooNE
- $2.37 \times 10^{21}$  POT

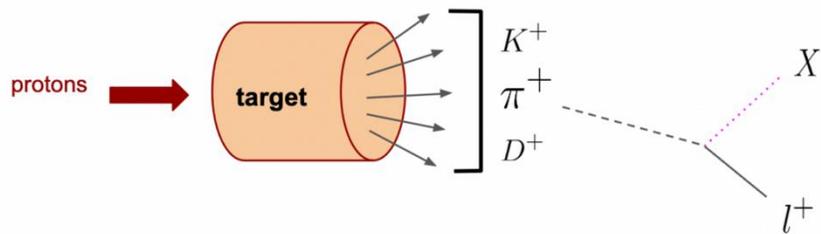


# Neutrino Beamlines at Fermilab

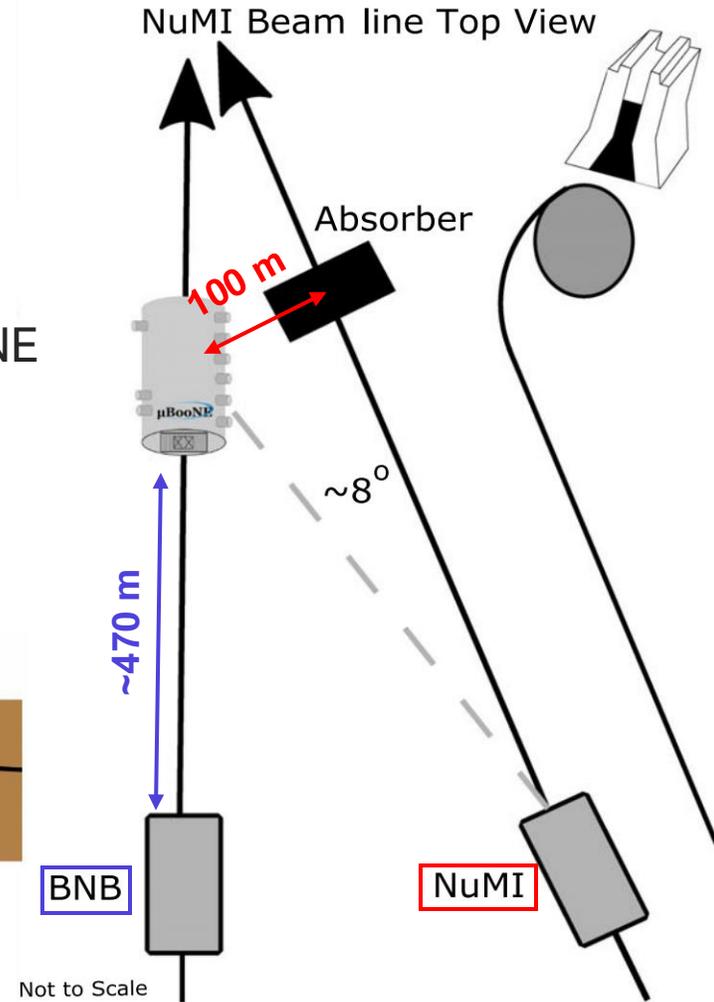
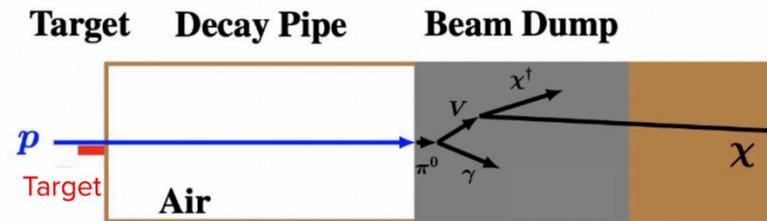
## Beamlines

- Large flux of **charged/neutral mesons** from high intensity proton beams
- New particles can be produced from meson decays
- Proximity to the **NuMI absorber**  
→ Particles survive long enough to reach MicroBooNE

### Meson decay in flight

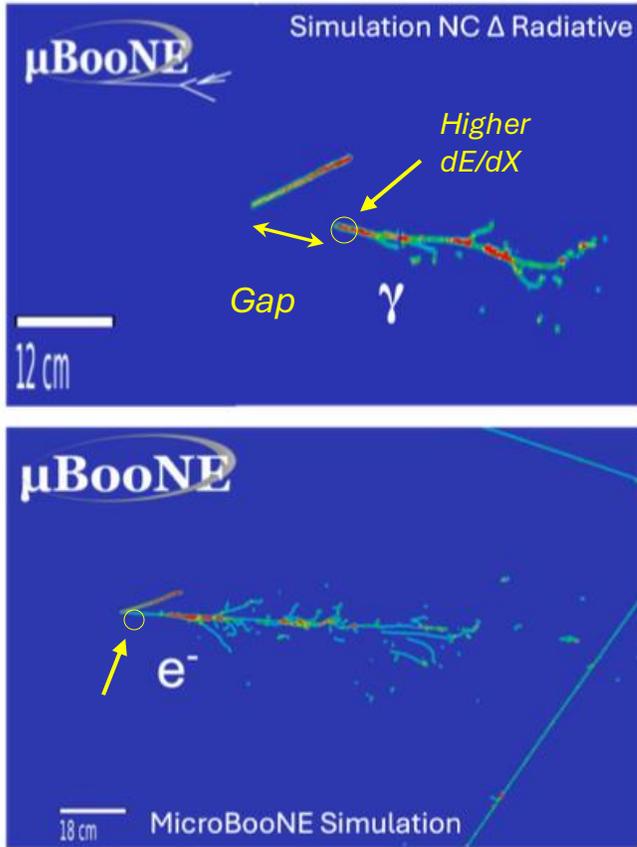


### Beam dump



# MicroBooNE capabilities for BSM searches

## $e^-/\gamma$ shower separation

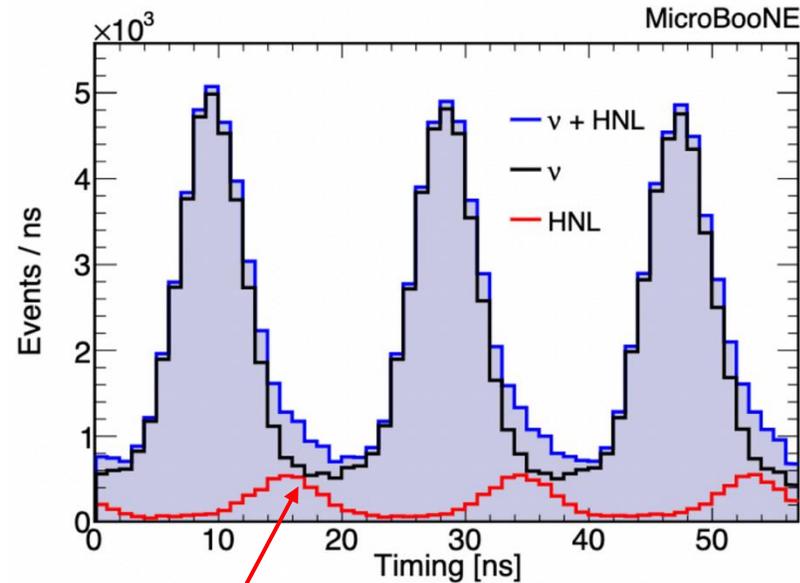


- **Gap** between interaction vertex and start of the shower for photons
- Twice as much  **$dE/dX$**  at the shower start for photons

## $\mathcal{O}(\text{ns})$ Timing Resolution

[Phys. Rev. D \*\*108\*\*, 052010](#)

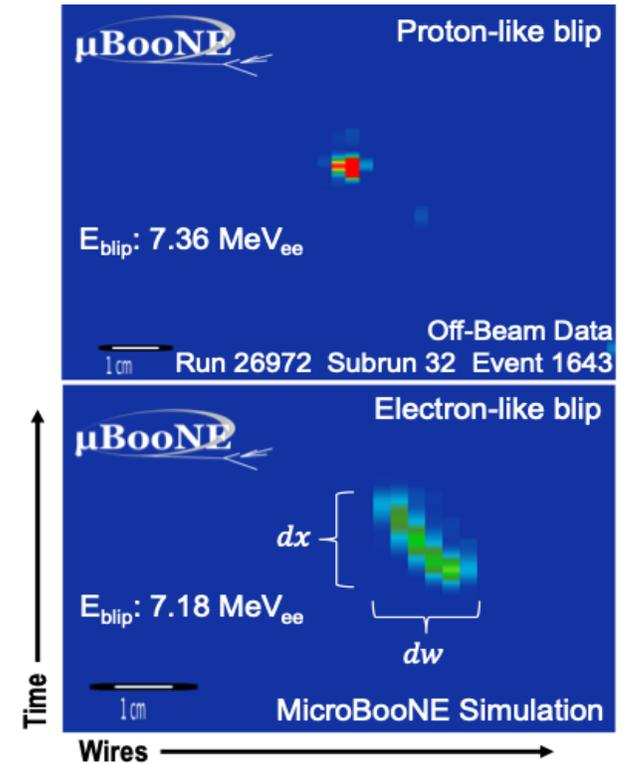
- Demonstrated  $1.73 \pm 0.05$  ns resolution on neutrino interaction time
- Out-of-bunch **BSM searches**
  - Reduction of neutrino background



**HNL shift**

## MeV-Scale Reconstruction

[Phys. Rev. D \*\*109\*\*, 052007](#)  
[Phys. Rev. D \*\*111\*\*, 032005](#)



- Demonstration of electron/proton separation in the MeV-scale regime

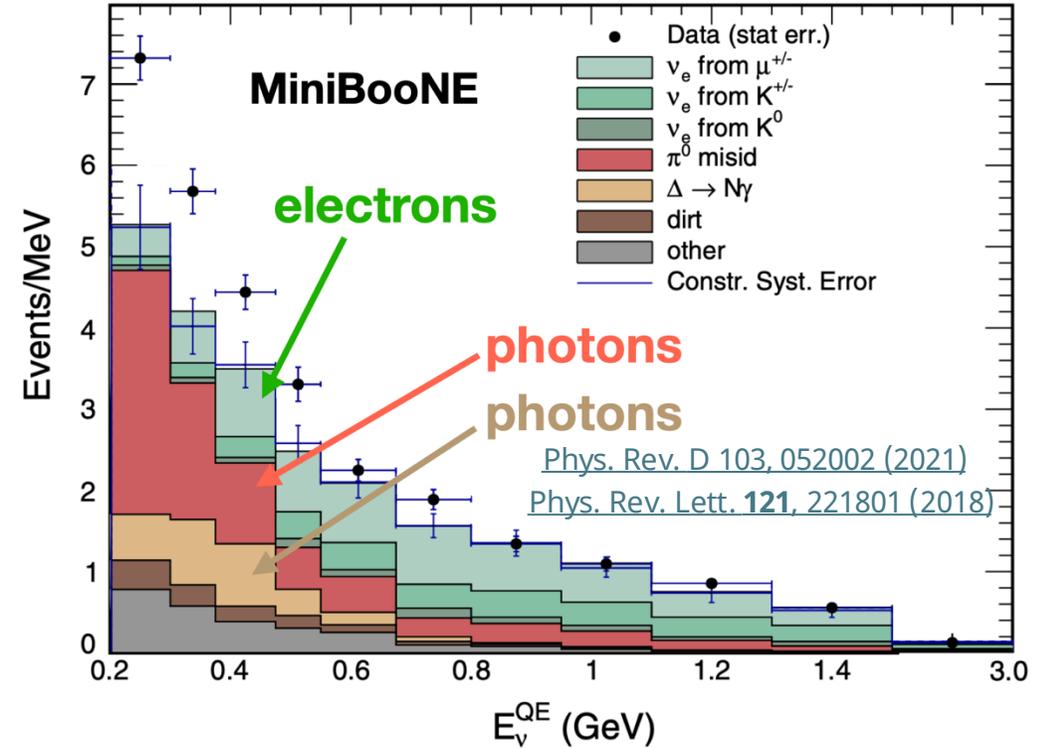
### Full dataset (2015-2020)

- ~500k BNB nu events
- ~300k NuMI nu events

# Neutrino Low Energy Excess (LEE) anomalies

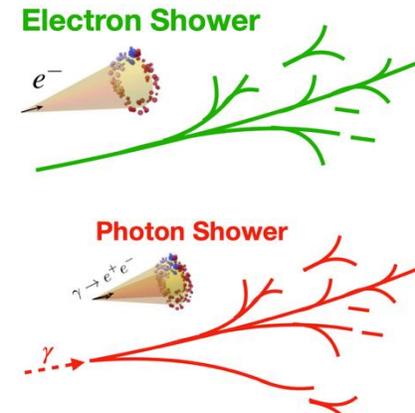
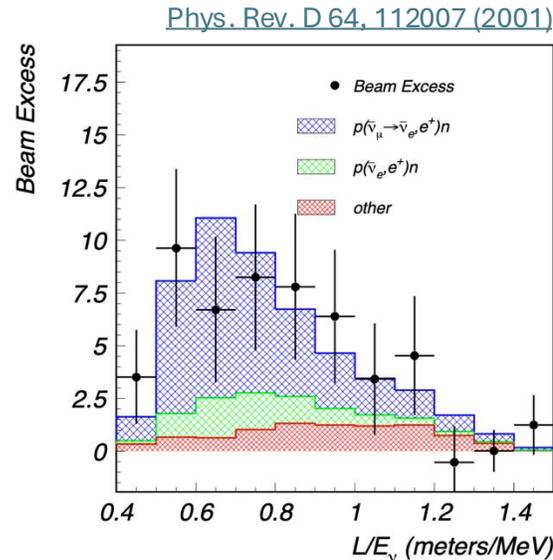
## MiniBooNE

- Same beamline as MicroBooNE (BNB)
- 4.8  $\sigma$  excess of events with a single electromagnetic shower
- Does MiniBooNE LEE consist of electrons or photons?
- Longstanding question on the origin of the LEE
  - Is it BSM?



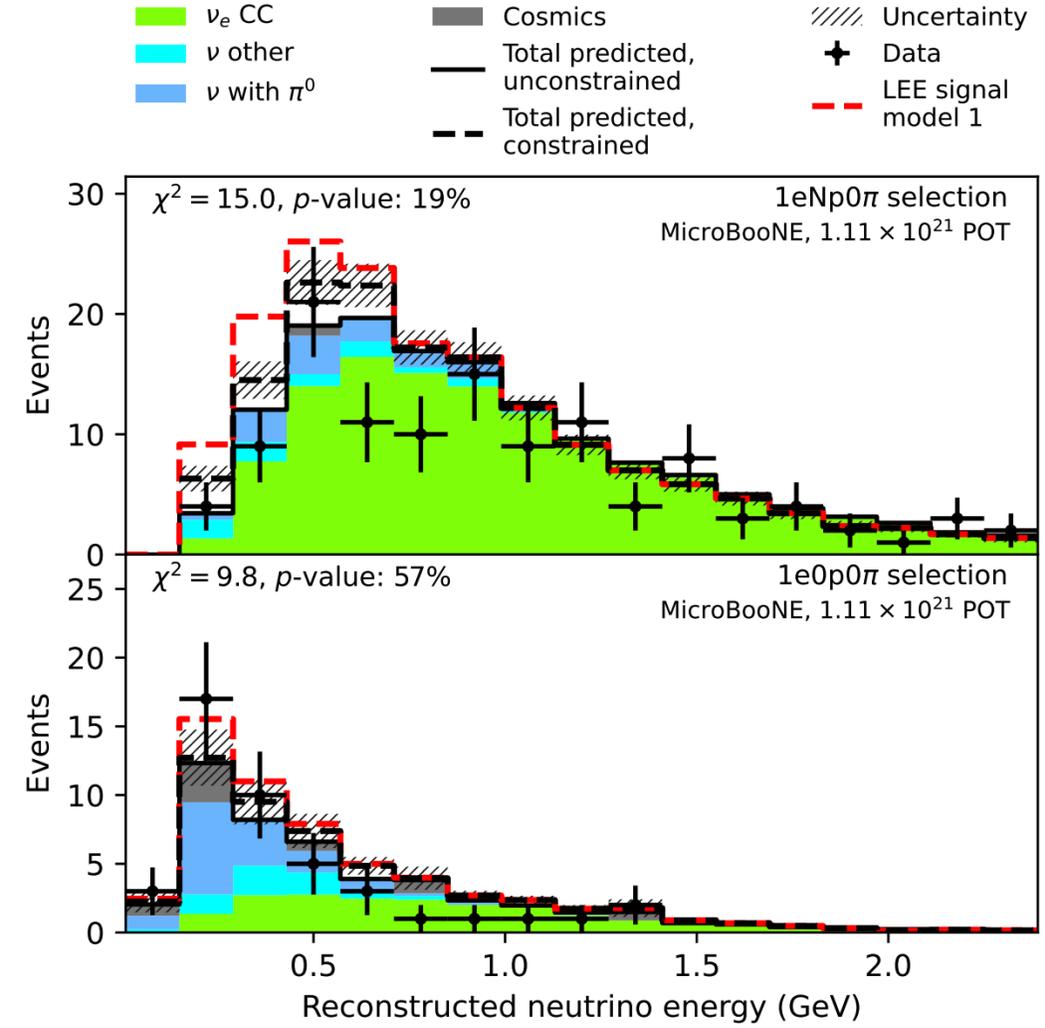
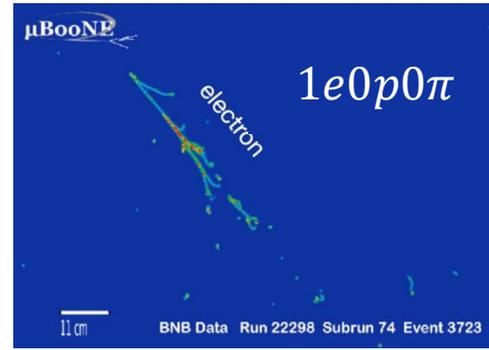
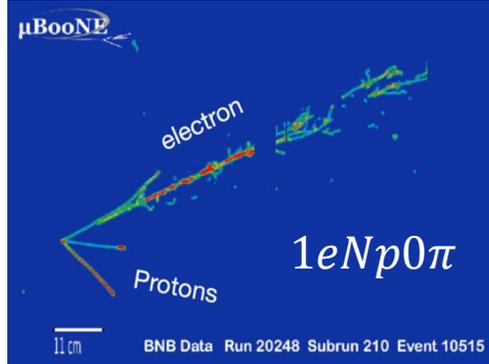
## LSND

- Excess in  $\nu_\mu \rightarrow \nu_e$  channel
- 3.8  $\sigma$  significance
- $L/E \approx 30 \text{ m} / 30 \text{ MeV}$



# Electron like LEE searches

- Investigated  $\nu_e$  CC with no pions in the full MicroBooNE BNB dataset with more LEE models
- We observe no electron-like excess for several topologies:
  - Pionless:  $1e0p0\pi$  &  $1eNp0\pi$
  - QE-like:  $1e1p$
  - Inclusive:  $1eX$
- MiniBooNE LEE as  $\nu_e$  excluded at  $\geq 99\%$  CL using our full BNB dataset!



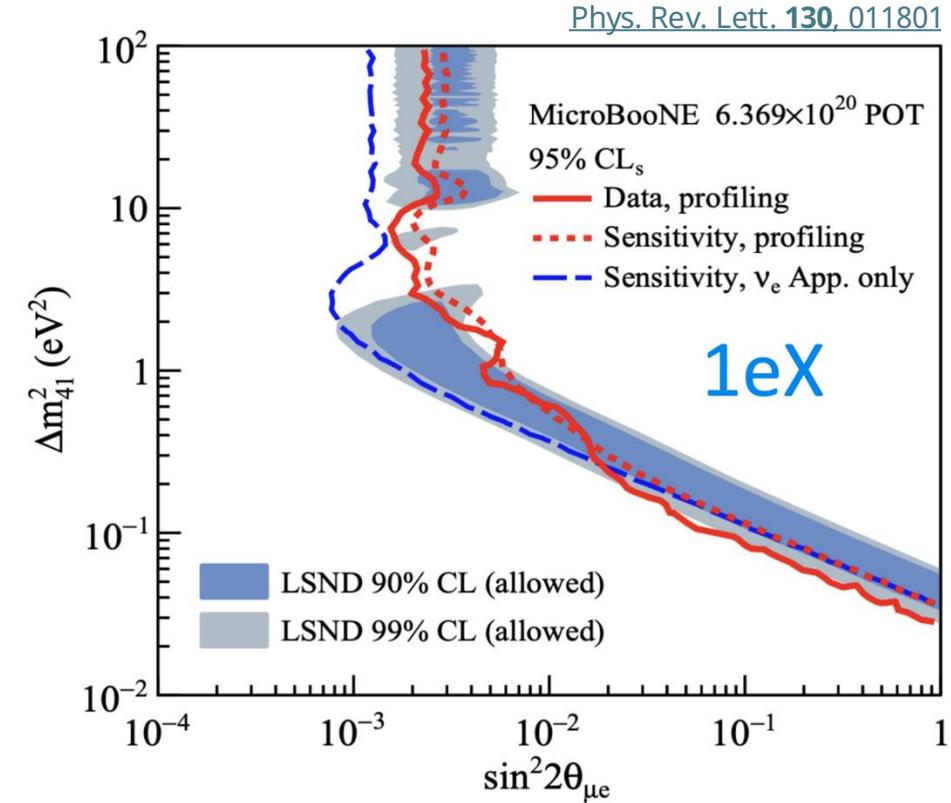
# ■ Sterile neutrino $\nu_s$ -LEE 3+1 Model (Inclusive)

- LEE search reinterpreted under 3+1 sterile neutrino oscillation hypothesis
- Observed  $\nu_e$  events are a combination of  $\nu_e$  appearance and disappearance:

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

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

- Degeneracy when  $\sin^2 \theta_{24} \approx 0.005$  given (BNB)  $R_{\nu_\mu/\nu_e} \approx 185$



# ■ Sterile neutrino $\nu_s$ –LEE 3+1 Model (Inclusive)

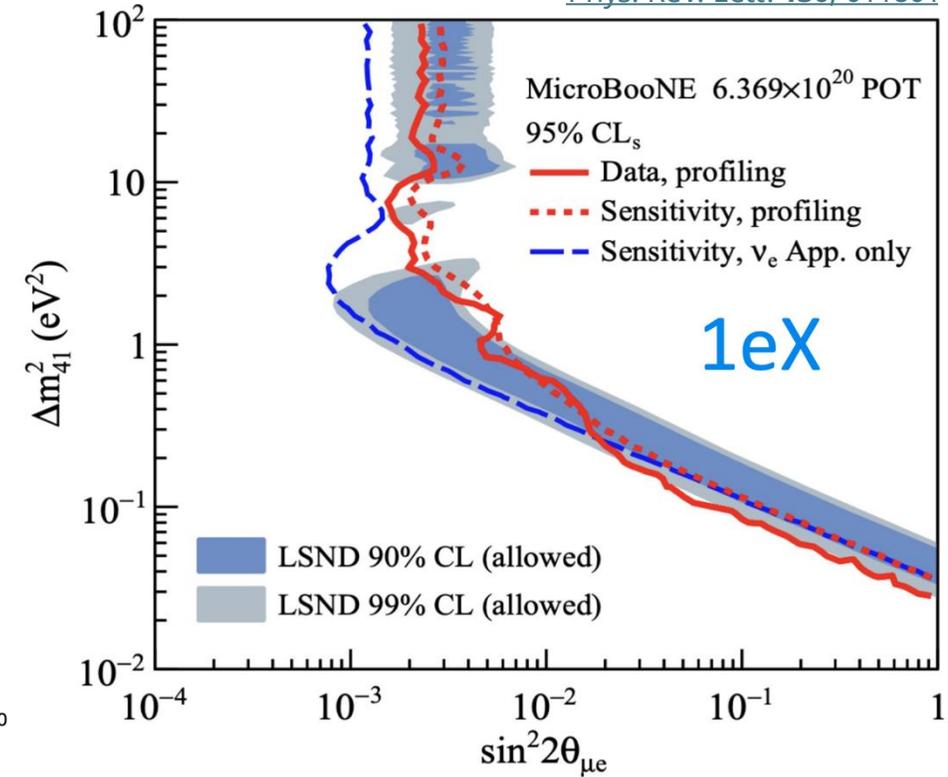
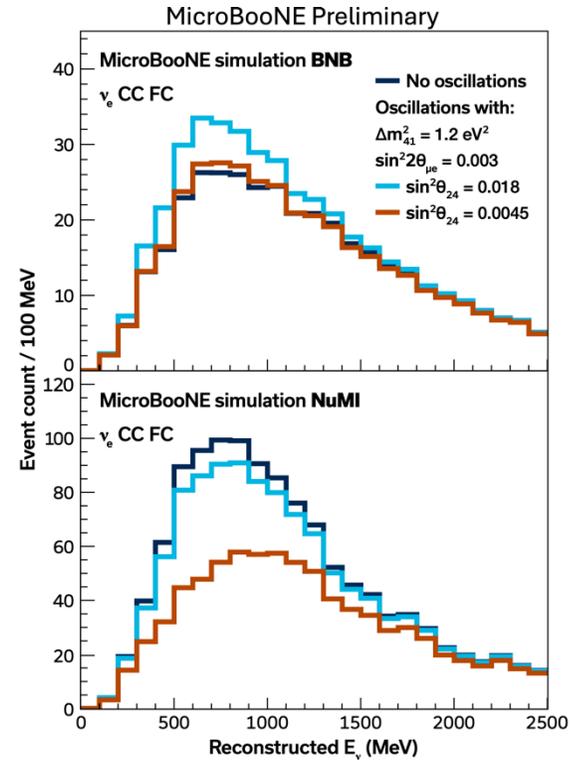
Phys. Rev. Lett. **130**, 011801

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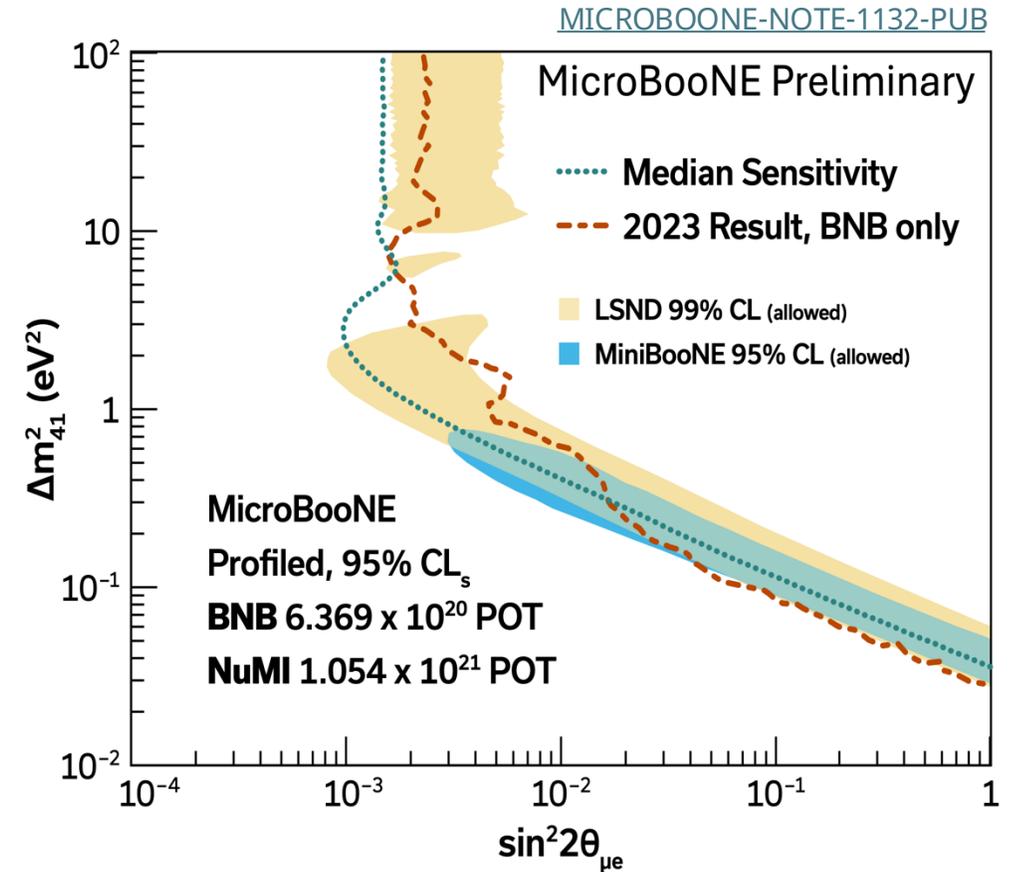
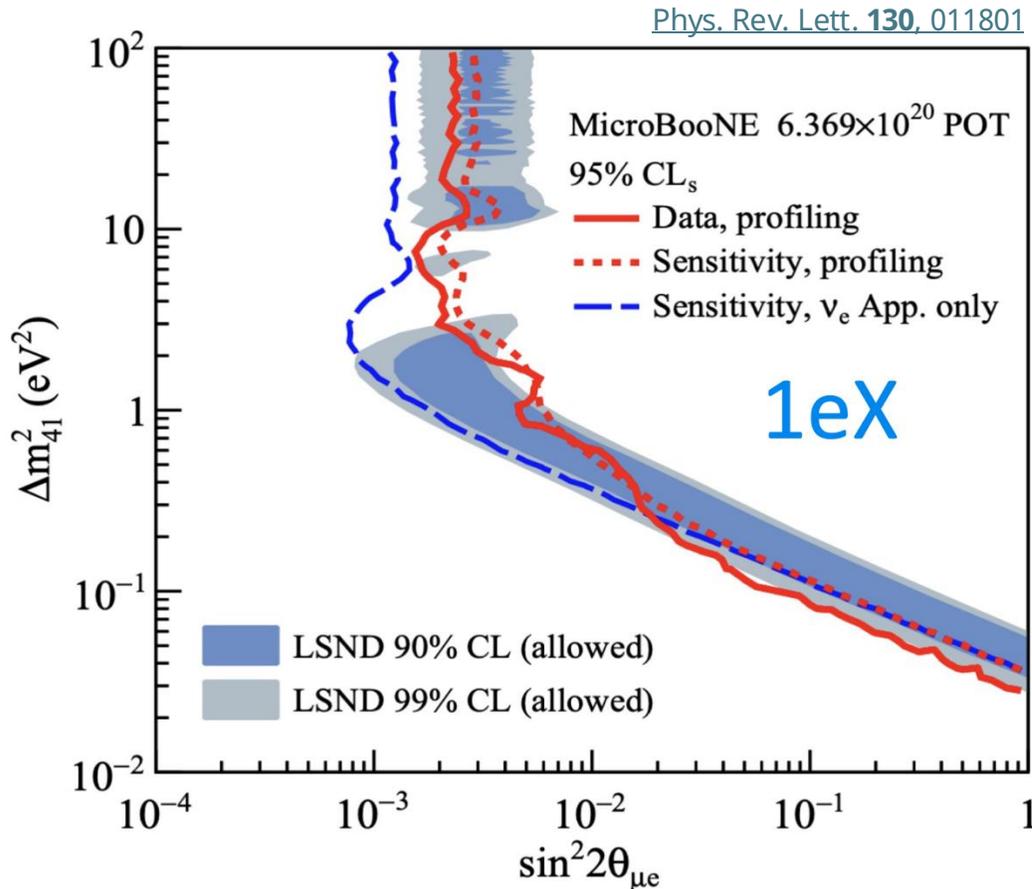
- Degeneracy when  $\sin^2 \theta_{24} \approx 0.005$  given (BNB)  $R_{\nu_\mu/\nu_e} \approx 185$
- Degeneracy mitigated by adding data from NuMI beamline
  - (NuMI)  $R_{\nu_\mu/\nu_e} \approx 21$



# ■ Sterile neutrino $\nu_s$ –LEE 3+1 Model (Inclusive)

- Using inclusive search to look at 3+1 model, large phase space rejected at 95% CLs

- Adding second beam (NuMI) to break  $\nu_e$  appearance/disappearance degeneracy

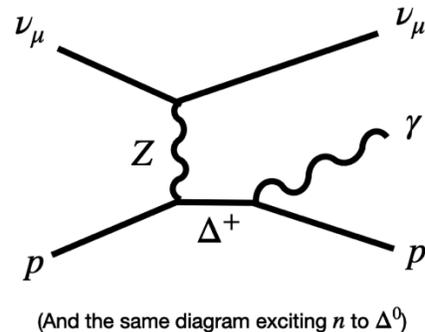
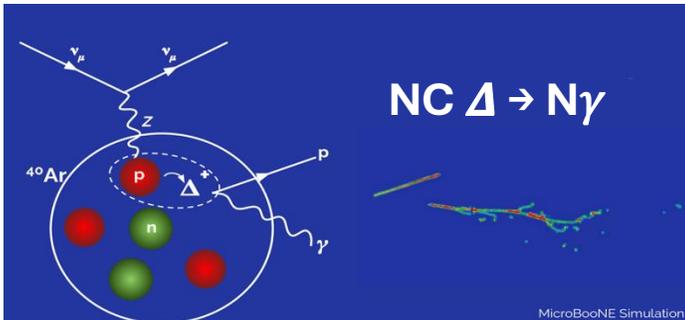
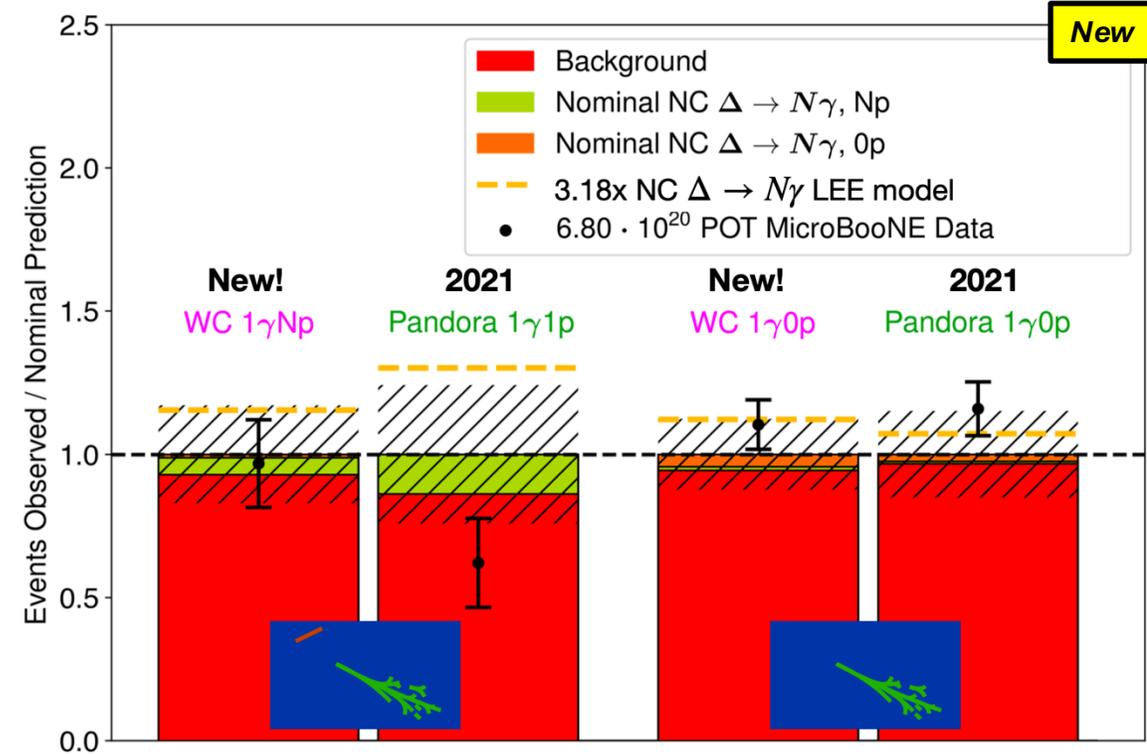


**Stay tuned for the full result!**

# Photon-like searches: NC $\Delta \rightarrow N\gamma$ (Exclusive)



- NC Delta Radiative
- Combined two complementary reconstruction paradigms
- Double the statistics of 2021 result and increased 0p sensitivity but still dominated by  $\pi^0$  backgrounds
- Ruled out a 3.18x enhancement of the NC  $\Delta \rightarrow N\gamma$  rate at 94.4% CL as a possible explanation of the LEE as suggested by MiniBooNE
- Cannot rule out the possibility of an excess only in the zero-proton topology



Signal is split into **Np** and **0p** based on a true proton kinetic energy threshold of 35 MeV

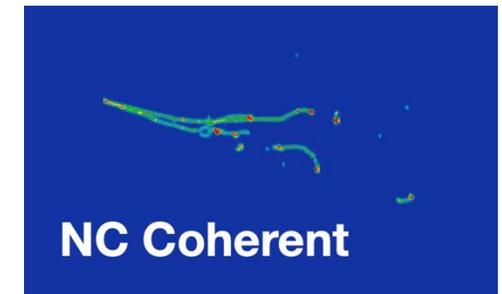
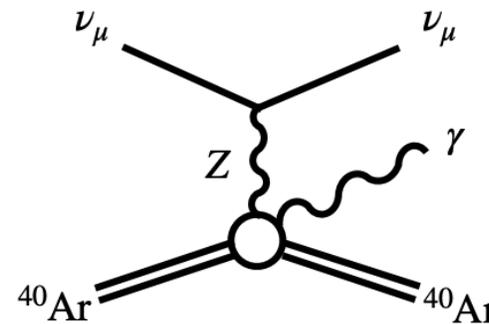
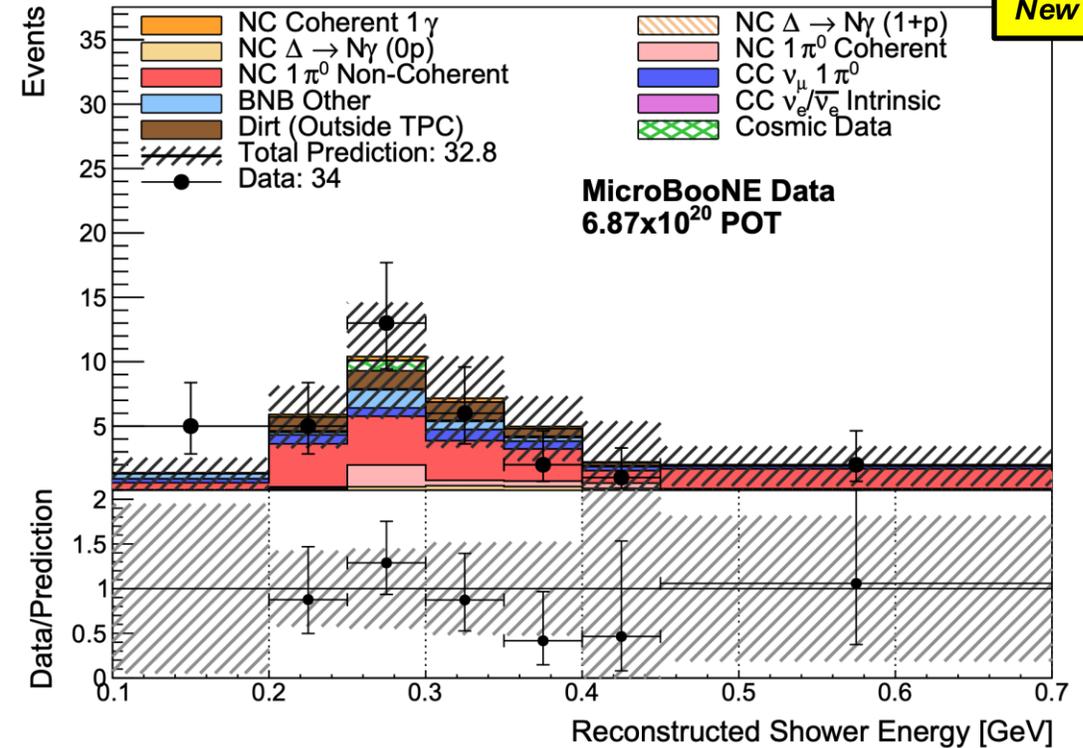
# Photon-like searches: NC Coherent $1\gamma$ (Exclusive)

arXiv:2502.06091



- 10x rarer than NC  $\Delta \rightarrow N\gamma$
- First ever search for neutrino induced single coherent gamma production
- New tools developed to reject non-coherent events with low energy vertex activity
- See no excess on this  $1\gamma$  source
- Set world's first limit on the flux averaged cross section for coherent single photon production:

$$\sigma < 1.49 \times 10^{-41} \text{cm}^2 \text{ at } 90\% \text{ CL}$$



# Photon-like searches: $1\gamma X$ (Inclusive)

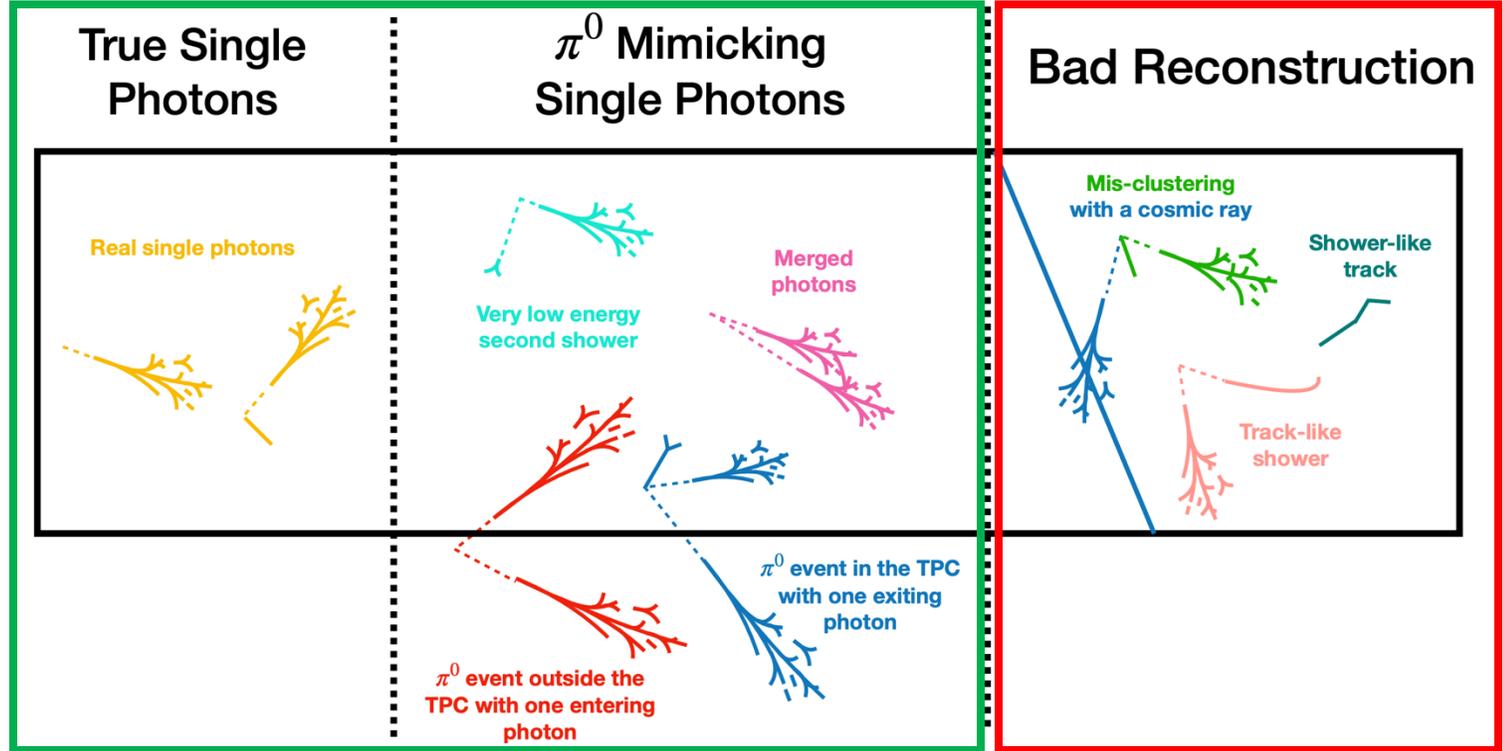


Diagram by Lee Hagaman

Single shower inclusive search

Broader signal definition:

- Actual single photon shower
- Small opening angle between  $\pi^0$  showers
- Entering (Exiting) shower from  $\pi^0$
- Low energy 2<sup>nd</sup> shower from  $\pi^0$

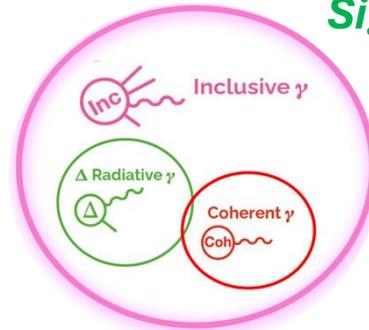


**Inclusive**

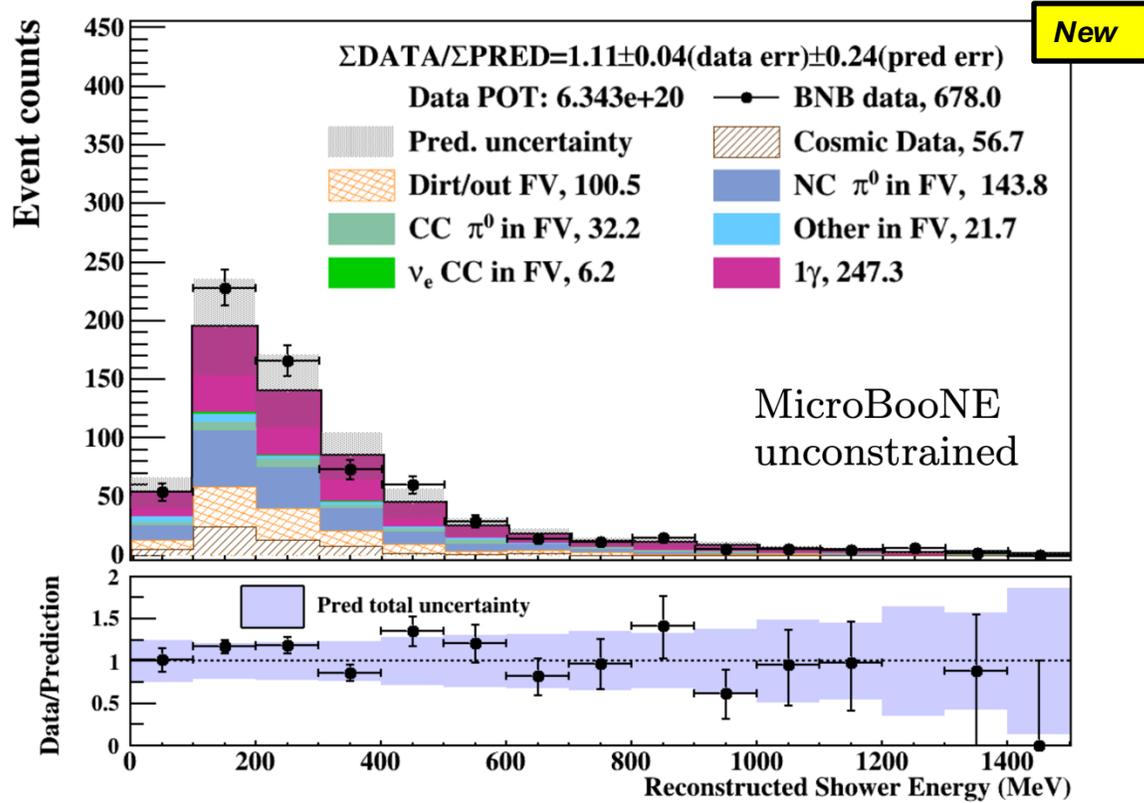
Single photon candidate data event

**Signal**

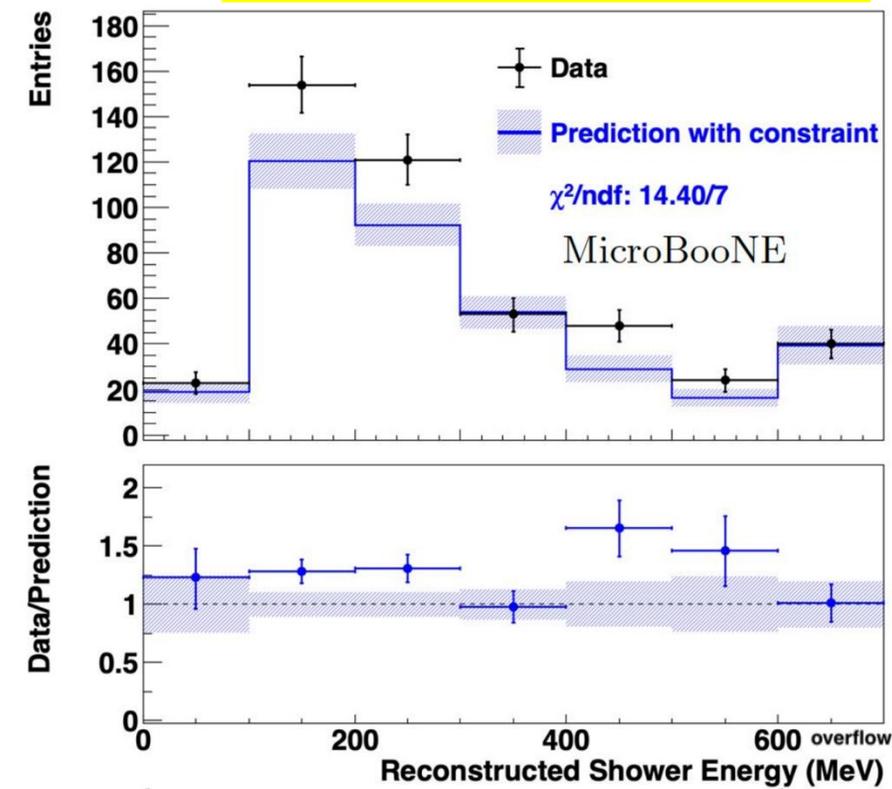
**Background**



# Photon-like searches: Inclusive $1\gamma X$



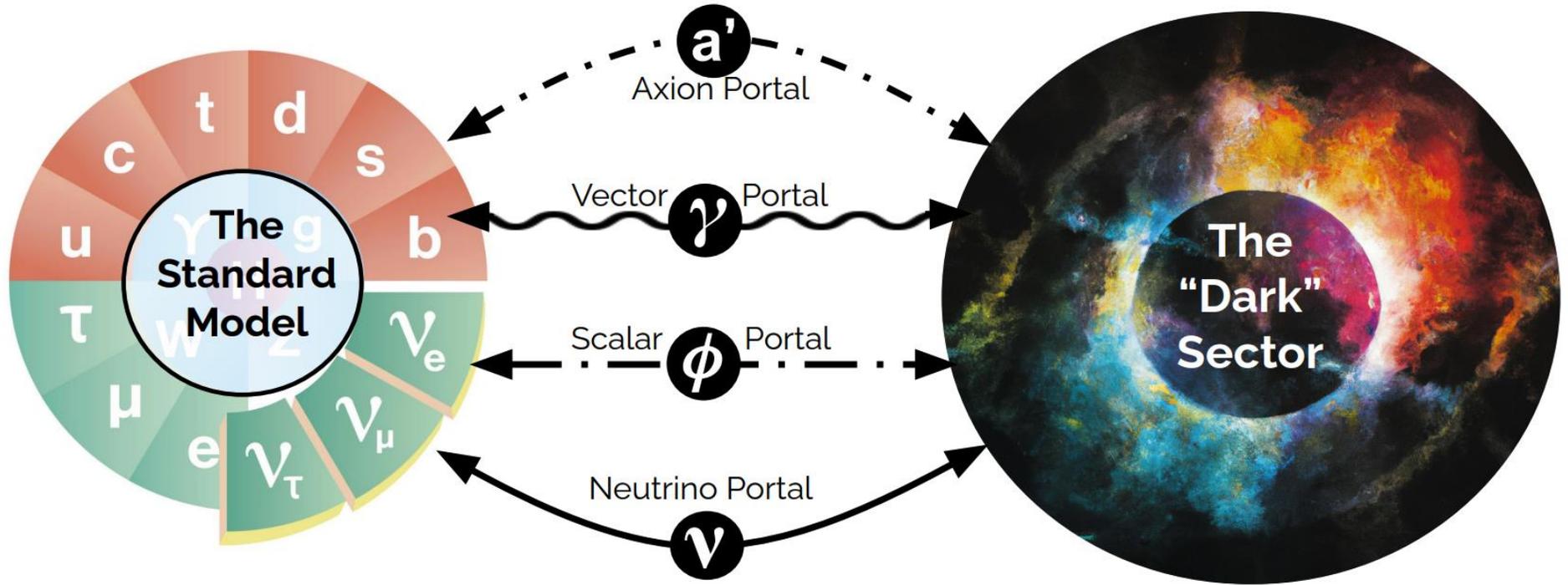
single-photon, zero-proton events



- Overall result in full energy range agrees well with prediction at under  $2\sigma$
- Events with no reconstructed proton:  **$0p$ -events**
  - Threshold for  $p$  reconstruction  $\sim 35$  MeV

- Excess concentrated in **zero proton** events
- Observed excess ( $2.2\sigma$ ) in  **$0p$**  subsample, photon energy  $< 600$  MeV
- Ongoing studies on the zero-proton subsample

# Portals to the Dark Sector



**Neutrino Portal**

$$\mathcal{L} \supset -y^\alpha L_\alpha H N + \text{h.c.}$$

- Light 3+1 sterile Neutrino
- Heavy Neutral Leptons

**Scalar Portal**

$$\mathcal{L} \supset (A S + \lambda S^2) H^\dagger H$$

- Higgs Portal Scalars

**Vector Portal**

$$\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$$

- Light Dark Matter
- Millicharged Particles

**Axion Portal**

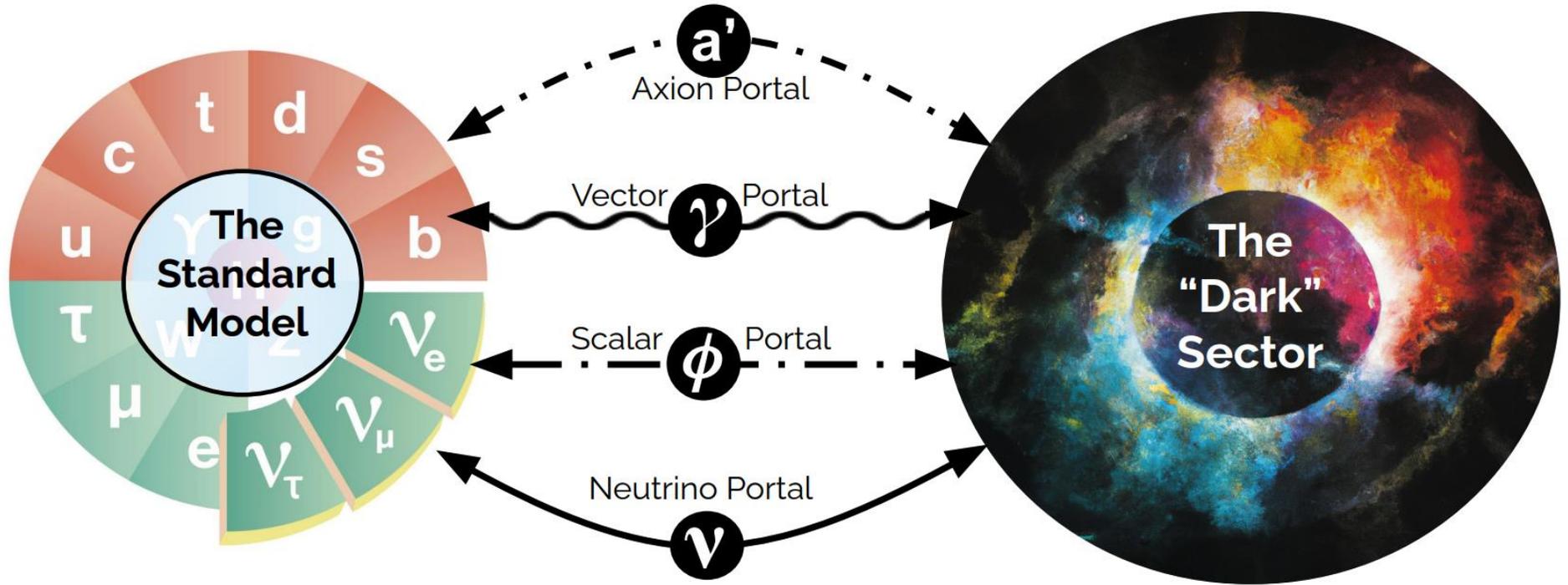
$$\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}$$

- Heavy QCD Axions

**Combined and Non-Minimal Portals**

$$\text{Dark sector } e^+e^-$$

# Portals to the Dark Sector



**$\nu$  Neutrino Portal**  
 $\mathcal{L} \supset -y^\alpha L_\alpha H N + \text{h.c.}$

- Light 3+1 sterile Neutrino
- Heavy Neutral Leptons

**$\phi$  Scalar Portal**  
 $\mathcal{L} \supset (A S + \lambda S^2) H^\dagger H$

- Higgs Portal Scalars

**$\gamma$  Vector Portal**  
 $\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$

- Light Dark Matter
- Millicharged Particles

**$a'$  Axion Portal**  
 $\mathcal{L} \supset c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}$

- Heavy QCD Axions

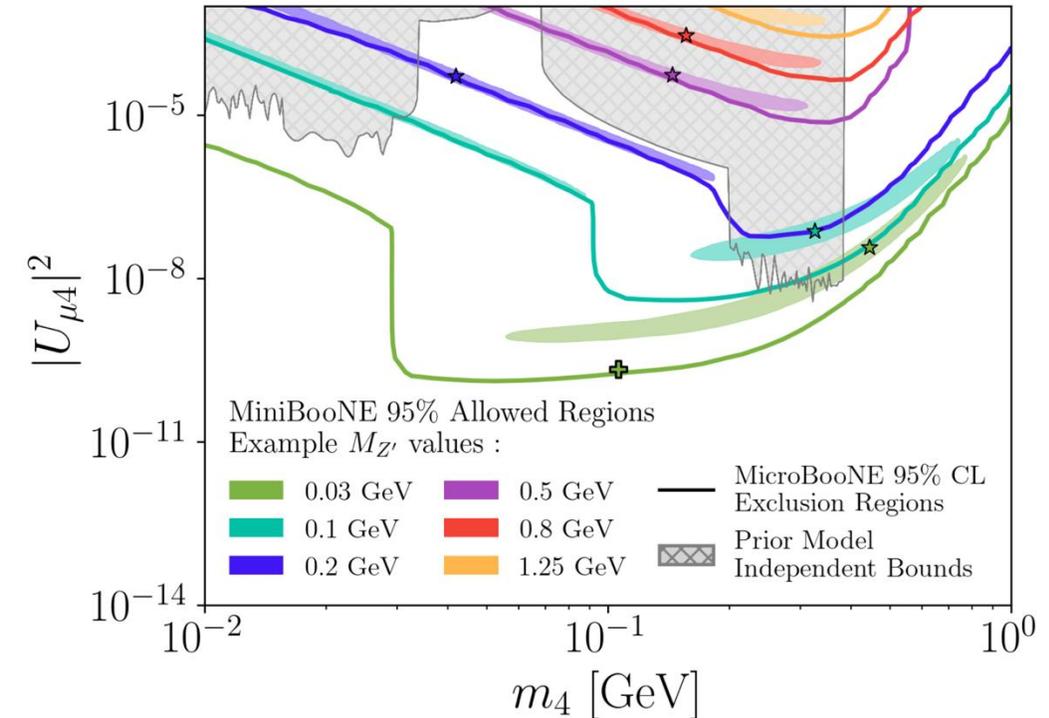
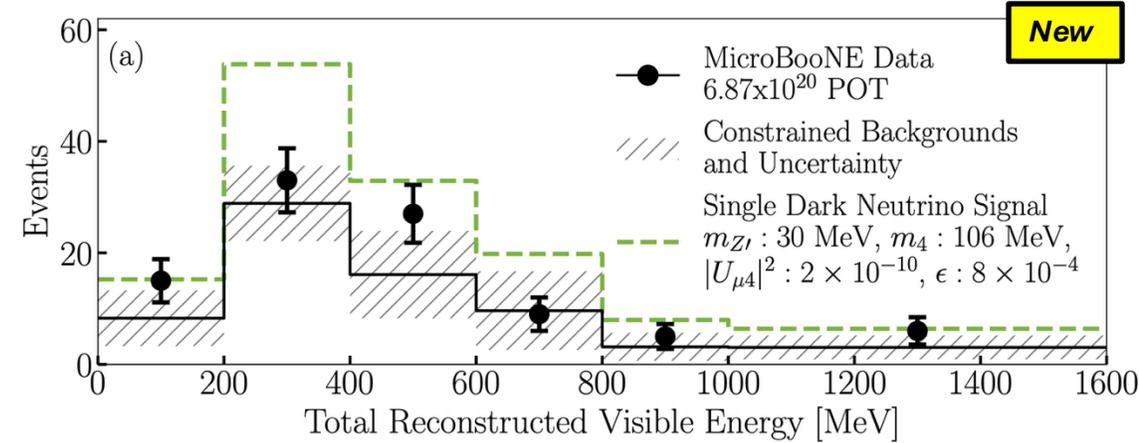
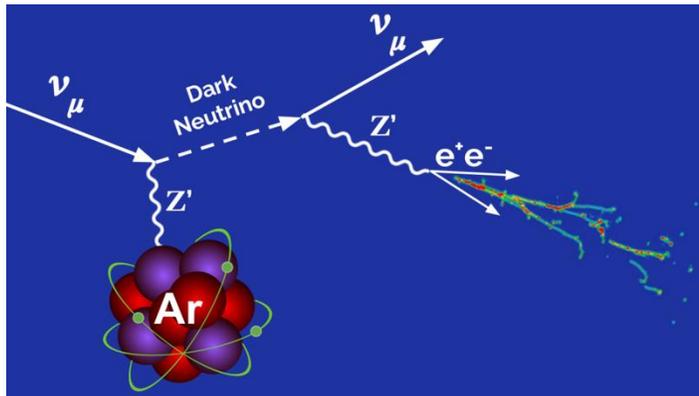
**$\nu \gamma$  Combined and Non-Minimal Portals**  
 Dark sector  $e^+e^-$

**Ongoing work!**

# Dark Neutrino $e^+e^-$ -like LEE search

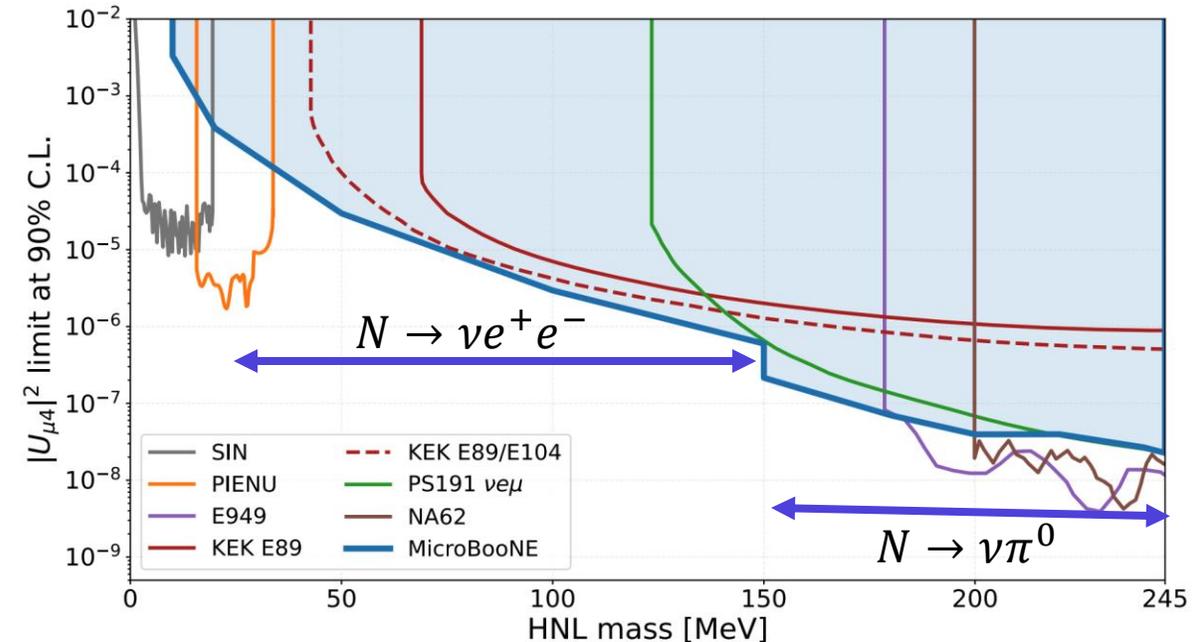
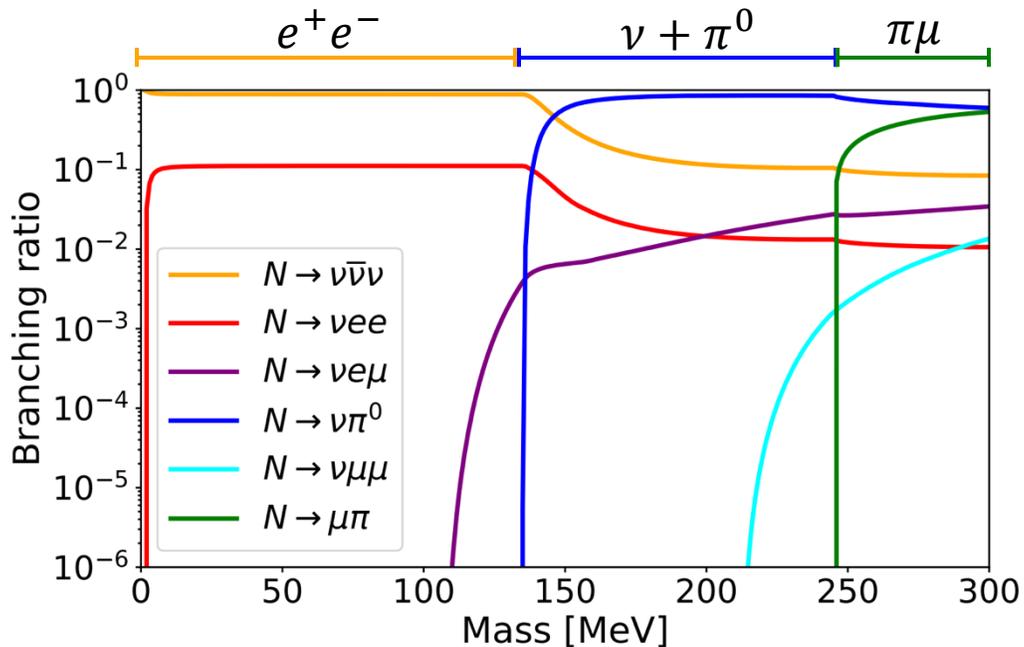
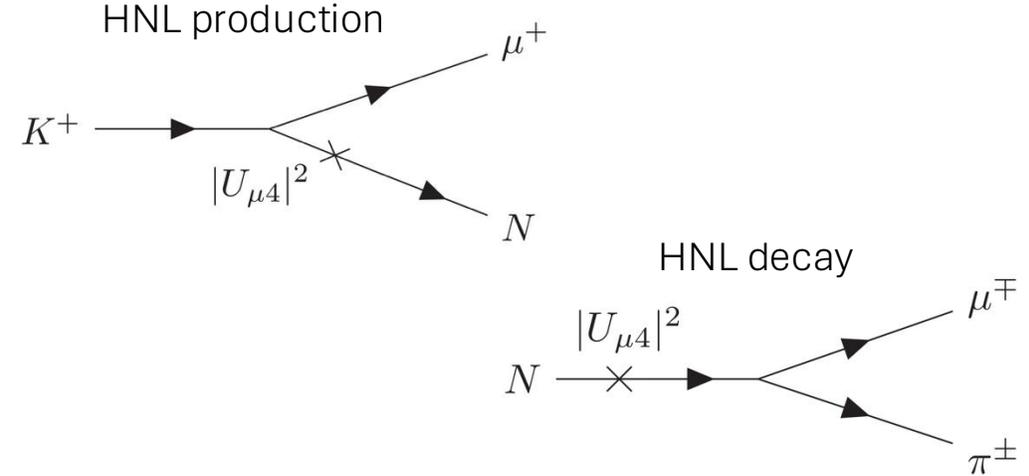
arXiv:2502.10900

- Non-minimal portal: neutrino and vector
- First search for an  $e^+e^-$ -like explanation to the LEE
  - Purely BSM hypothesis
- Dark neutrino decaying produced via a new dark  $Z'$ 
  - Decays to neutrino  $e^+e^-$  pair
- 95 events seen;  $69.7 \pm 17.3$  predicted
  - Agreement at  $1.5\sigma$
- Bounds placed on wide range of  $Z'$  mass values
  - Majority of MiniBooNE allowed phase space ruled out



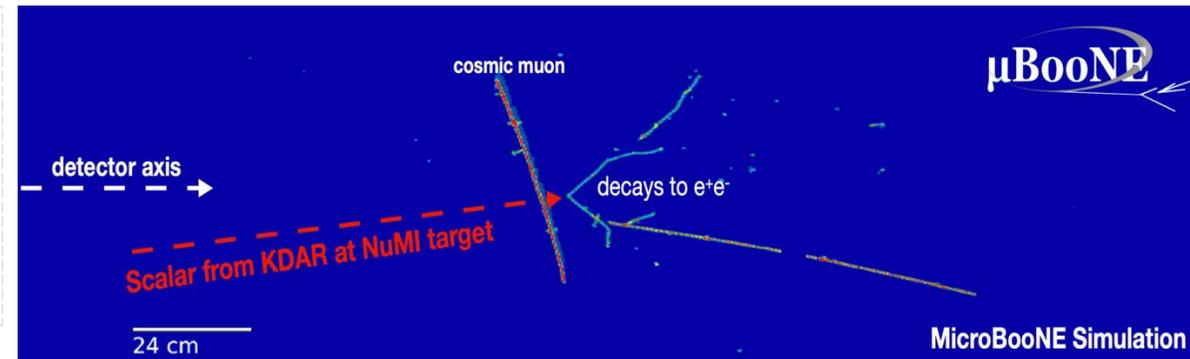
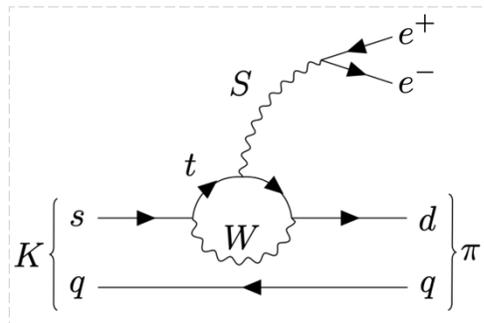
# Heavy Neutral Leptons (HNL)

- HNLs from  $K^+ \rightarrow \mu^+ N$  (At NuMI absorber)
- First search for  $N \rightarrow \nu e^+ e^-$  or  $N \rightarrow \nu \pi^0$  final states in a LArTPC
- Set limits on  $|U_{\mu 4}|^2$  as a function of HNL mass
  - $10 \leq m_{\text{HNL}} \leq 150$  MeV ( $\nu e^+ e^-$  channel)
  - $150 \leq m_{\text{HNL}} \leq 245$  MeV ( $\nu \pi^0$  channel)



# Higgs-portal scalar bosons

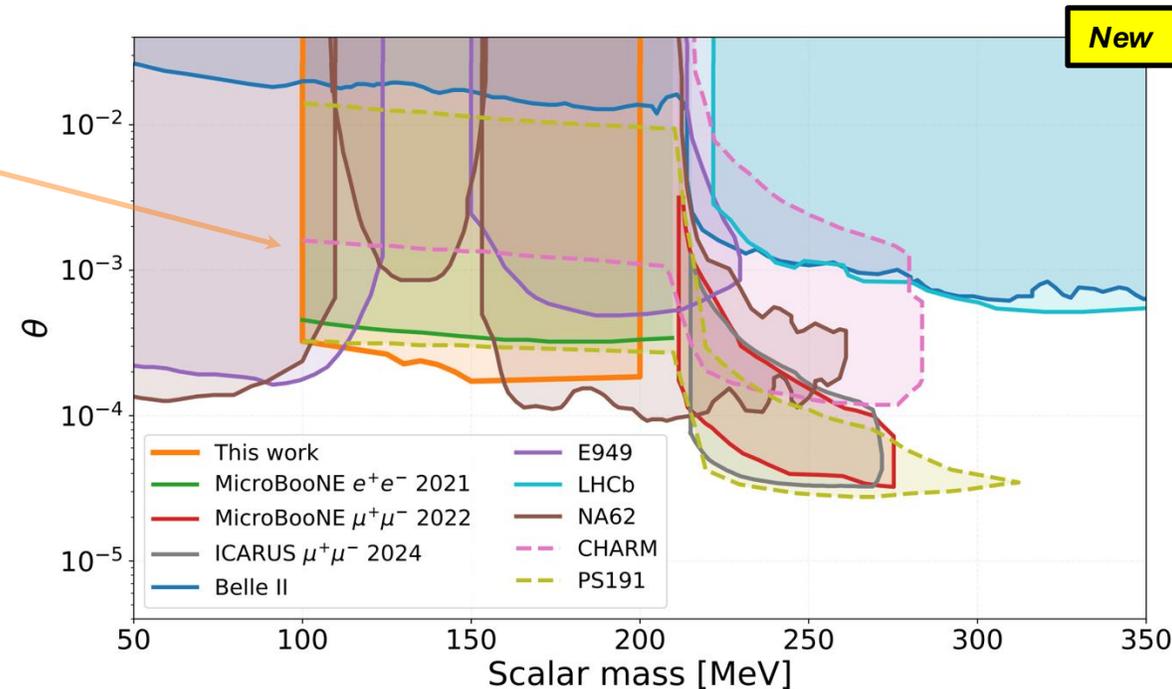
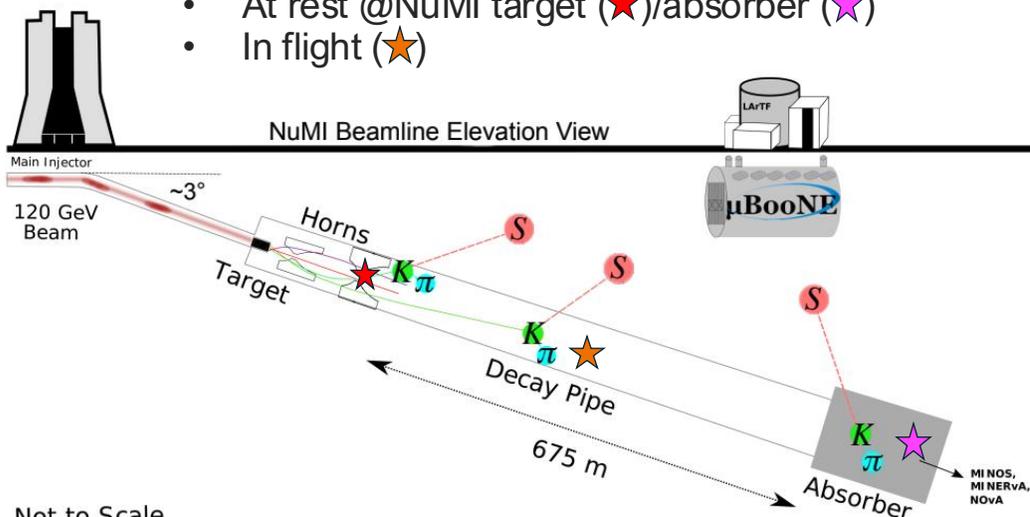
- Neutral scalar singlet  $S$ , mixing angle  $\theta$  with the Higgs boson
- Production from kaon decay
- Signature:  $S \rightarrow e^+e^-$



- Set strongest limits to date at 95% CL:
  - At  $m_S = 125$  MeV,  $\theta < 2.65 \times 10^{-4}$
  - At  $m_S = 150$  MeV,  $\theta < 1.72 \times 10^{-4}$

## Kaon decay

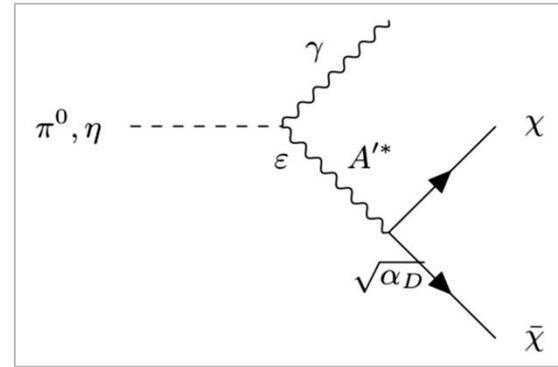
- At rest @NuMI target (★)/absorber (★)
- In flight (★)



Not to Scale

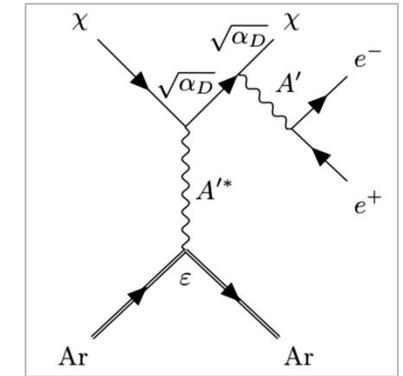
# Dark Tridents

- Light dark matter
- First search for dark-trident using a LArTPC
- Dark-Matter (DM) candidate can be produced at fixed-target facilities through neutral meson decays
- Mesons ( $\pi^0$  or  $\eta$ ) could decay into DM particles mediated via a dark photon  $A'$
- Parameters of the model:
  - dark photon ( $M_{A'}$ )
  - dark fermion (or scalar) ( $M_\chi$ )
- Set world-leading limits on this Light Dark Matter model



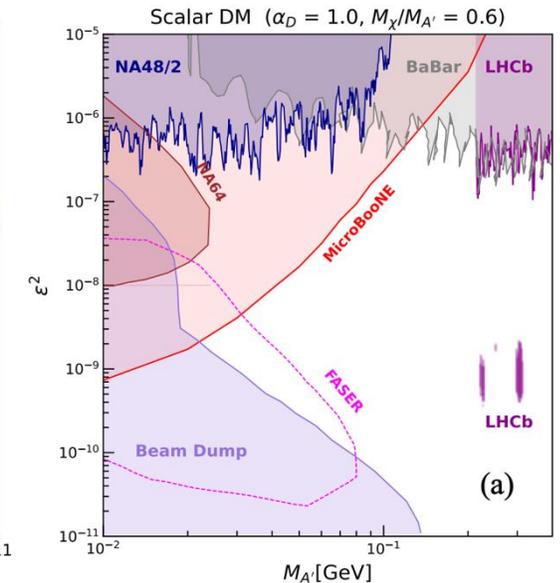
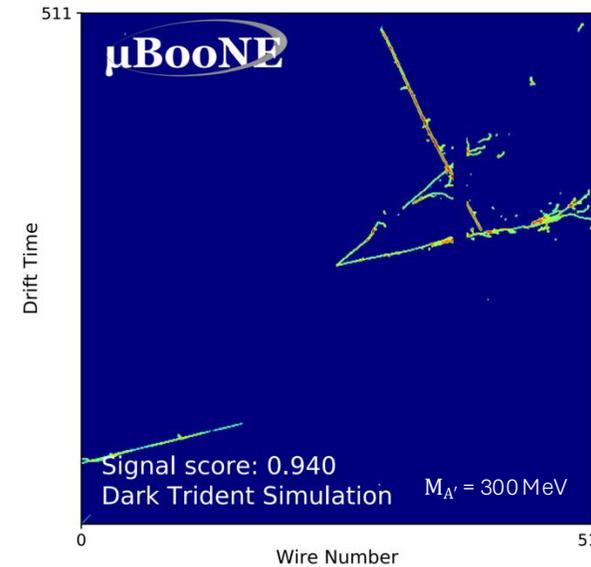
**Production**

DM particle produced in beam and interacts in MicroBooNE Dark photon mediator  $A'$



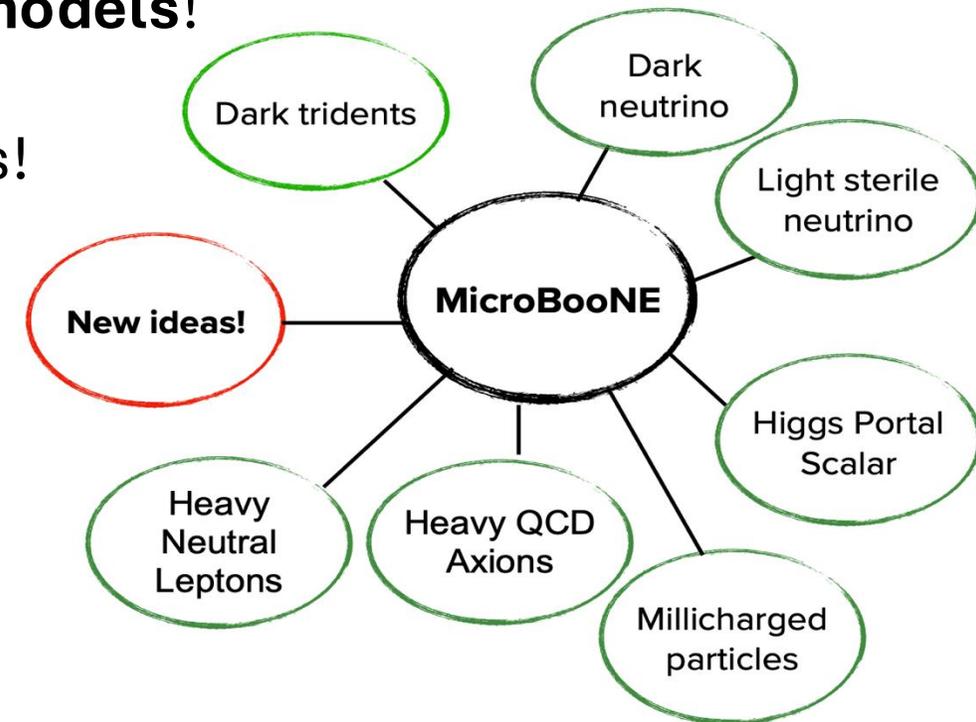
**Scatter**

Dark photon mediator  $A' \rightarrow e^+ e^-$



## ■ Summary

- MicroBooNE completed 5 years of data taking (**BNB** and **NuMI**)
- Extensive inclusive physics program:
  - *Pioneering BSM searches,  $\nu$ -Ar cross-sections and LArTPCs R&D*
- Looking at new signal topologies and **dark sector models!**
- Incorporation of new techniques into BSM searches!
  - *AI/ML based,  $N_s$  timing, MeV-scale reconstruction*
- New ideas to explore? Please reach out!





*Thank you!*

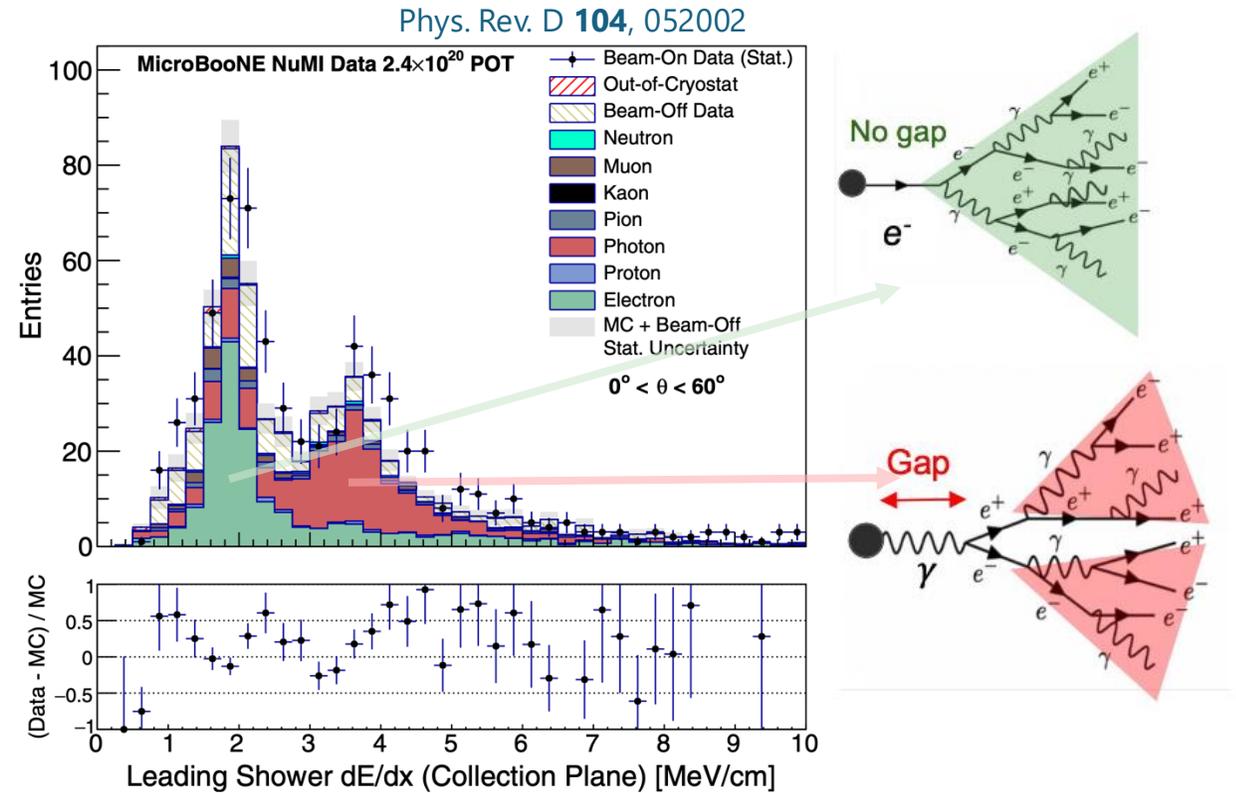
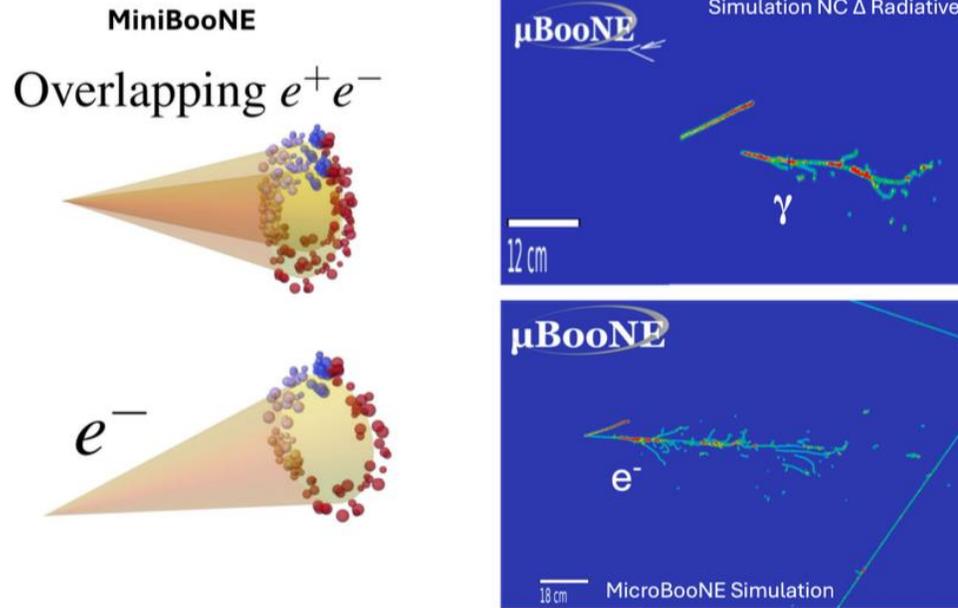
*MicroBooNE Collaboration Meeting  
Indiana University  
Bloomington, IN  
May 2025*

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# Backup slides

# ■ The MicroBooNE LArTPC

## EM shower separation



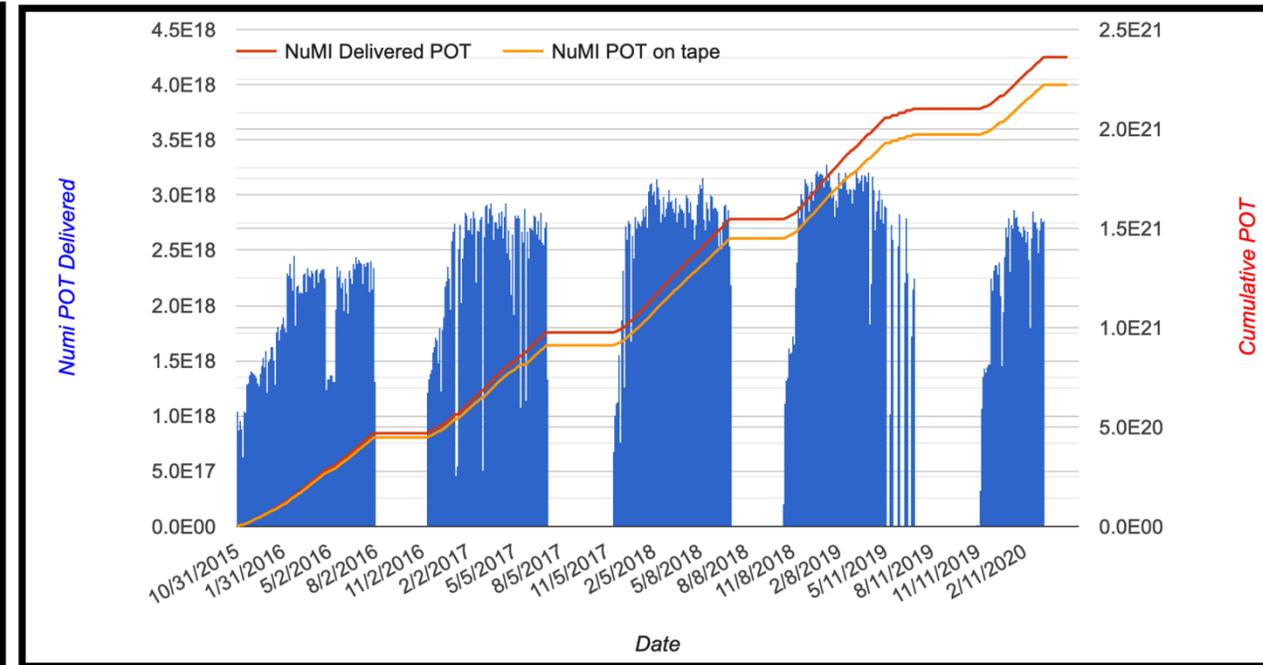
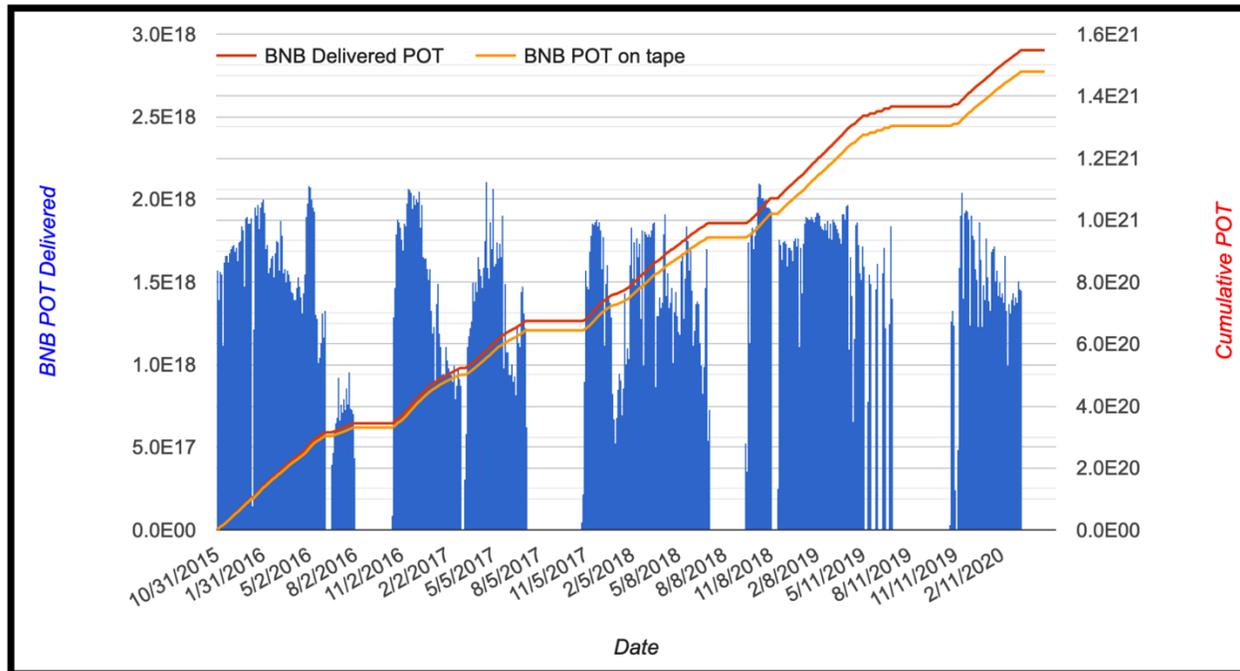
**Photons deposit twice as much energy per unit length at shower start (Shower  $dE/dx$ )**

- MicroBooNE's ability to separate electron- from photon-showers:
  - Electron showers attached to the reconstructed neutrino interaction vertex
  - Photons exhibit a gap w.r.t. reconstructed vertex

# Data taking

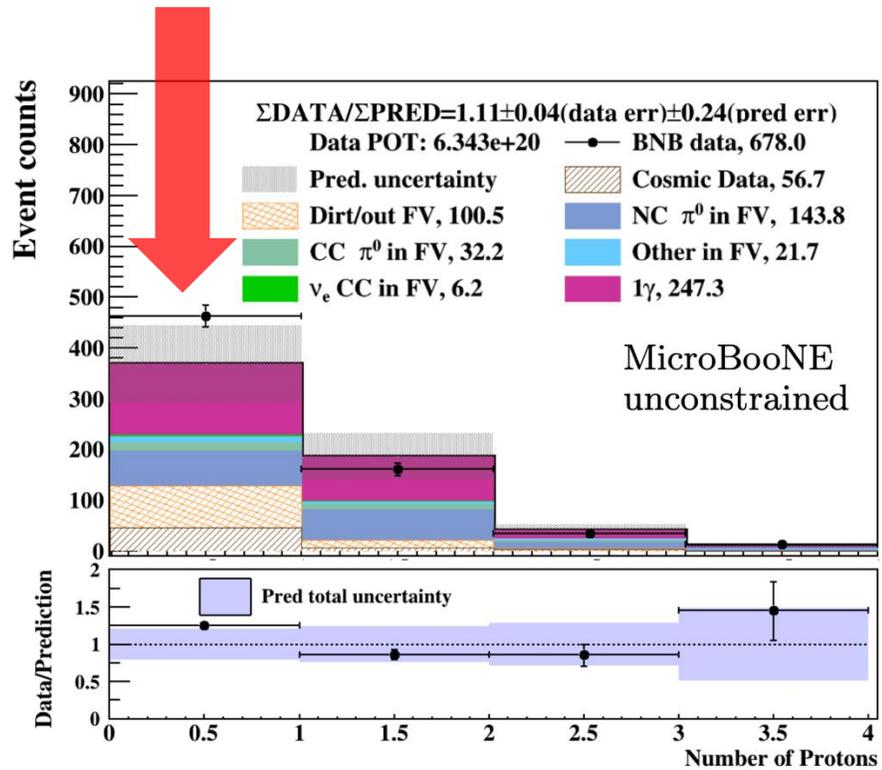
■ **BNB** Full Dataset:  $1.1 \times 10^{21}$  POT

■ **NuMI** Full Dataset:  $2.37 \times 10^{21}$  POT



- MicroBooNE collected BNB and NuMI data between 2015 and 2021 split into five runs

# ■ Inclusive single photon sample



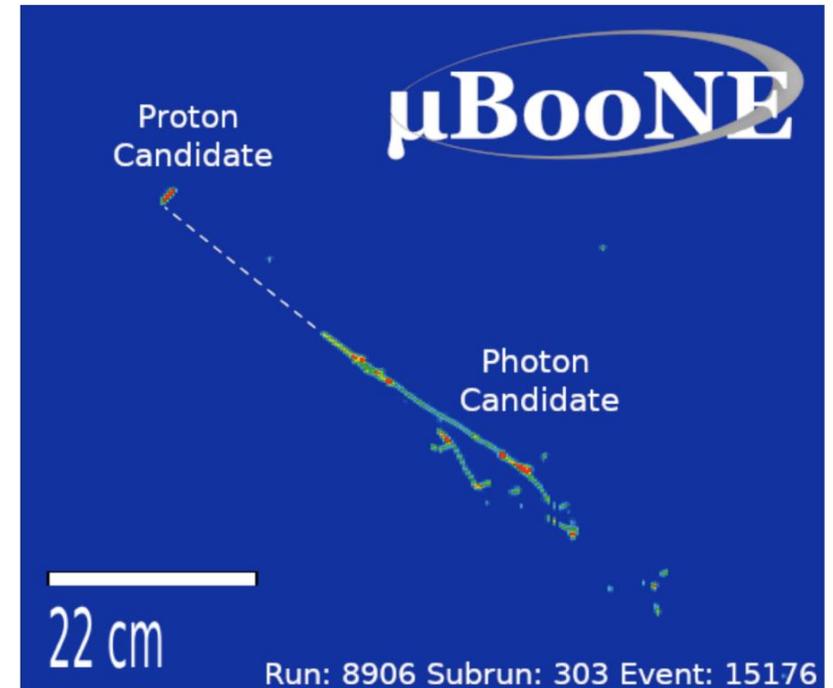
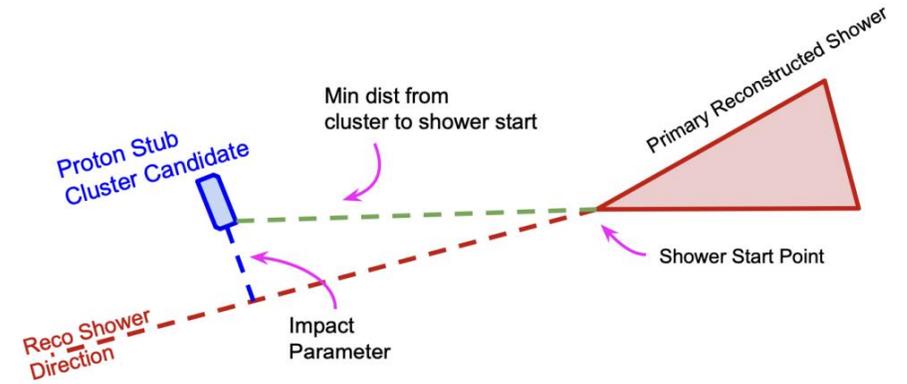
## Number of reconstructed protons

- *Interest in the inclusive single photon-single shower events with zero reconstructed proton*

FIG. 3. Numbers of reconstructed primary protons for inclusive single-photon selected events with no constraint applied. The horizontal axis is number of reconstructed protons with kinetic energy above the 35 MeV threshold.

# ■ Proton Stub Veto

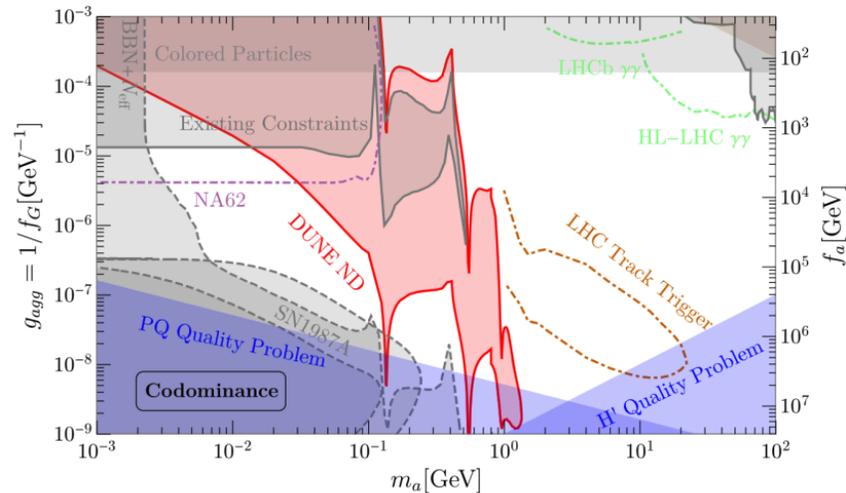
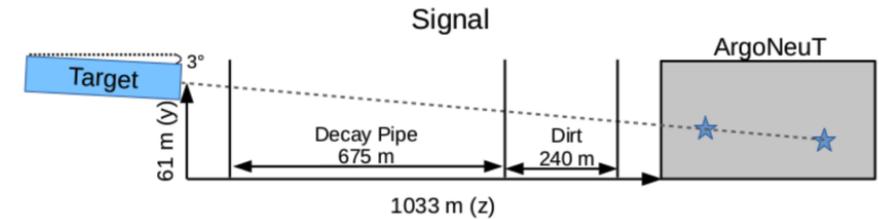
- True coherent single-photon events will never contain any visible hadronic activity at the neutrino interaction vertex
- Many NC  $\pi^0$  background events contain a low energy proton that was not reconstructed as part of the Pandora neutrino slice
  - Very hard to reconstruct this proton stub in all cases, but it is a lot easier to veto than to reconstruct
- We cluster nearby hits on each 2D view and use a BDT to determine if they are likely to correspond to an upstream proton
- Similar idea used in a Second Shower Veto for this analysis as well as the Pandora NC  $\Delta \rightarrow N\gamma$  selection



# ■ Ongoing BSM searches

## Millicharged particles

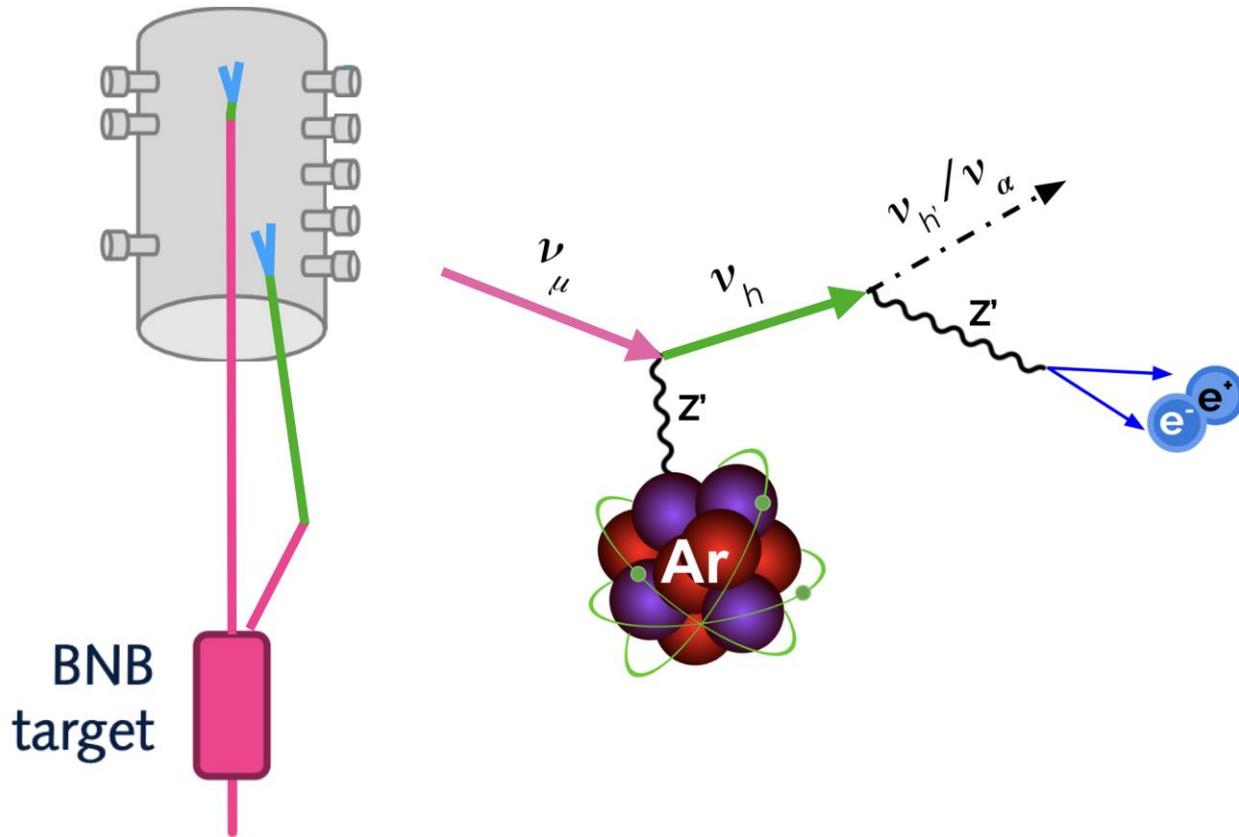
- Particles with a **fraction of electric charge**
- **Scatter off atomic electrons** and cause “blips” of ionisation in LAr
- Leverages MeV-scale reconstruction



## Heavy QCD Axions

- Axions produced via **mixing with neutral mesons**
- Decay to **di-photon pairs** in MicroBooNE

# ■ Dark Neutrino $e^+e^-$

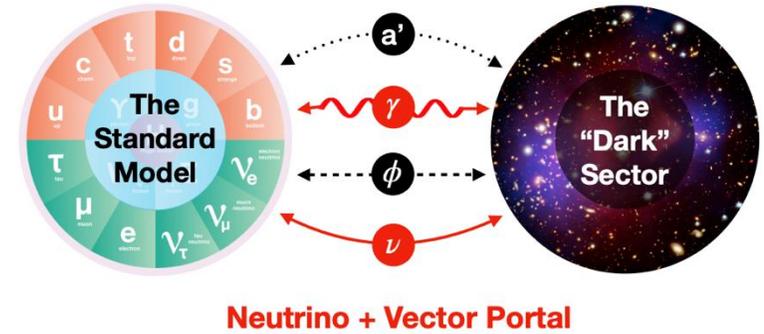


Asli M. Abdullahi, Jaime Hoefken Zink,  
Matheus Hostert, Daniele Massaro, Silvia Pascoli

[Phys. Rev. D 111, 035028 \(2025\)](#)  
[Comp. Phys. Comm. 297, 109075 \(2024\)](#)

Enrico Bertuzzo, Sudip Jana, Pedro A.N.  
Machado, Renata Zukanovich Funchal

[Phys. Rev. Lett. 121, 241801 \(2018\)](#)



- Non-minimal portal: neutrino and vector
- Neutrinos up-scatter to heavy sterile neutrinos (dark neutrinos or HNLs)
- These dark neutrinos can be:
  - Short-lived, produced inside MicroBooNE
  - Long-lived, produced in the dirt upstream of MicroBooNE
- The dark neutrino then decays to a normal or dark neutrino with an  $e^+e^-$  pair

# MicroBooNE Cross Section Analyses

- $\nu_\mu$  CC inclusive

- 3D  $\nu_\mu$  CC inclusive 0p/Np, BNB, [Phys. Rev. Lett. 133, 041801 \(2024\)](#), [Phys. Rev. D 110, 013006 \(2024\)](#)
- 3D  $\nu_\mu$  CC inclusive, BNB, [arXiv:2307.06413](#)
- 1D  $\nu_\mu$  CC inclusive  $E_\nu$ , BNB, [Phys. Rev. Lett. 128, 151801 \(2022\)](#)
- 2D  $\nu_\mu$  CC inclusive, BNB, [Phys. Rev. Lett. 123, 131801 \(2019\)](#)

- Pion production

- 2D NC  $\pi^0$  BNB, [Phys. Rev. Lett. 134, 161802 \(2025\)](#)
- 1D  $\nu_\mu$  CC  $\pi^0$  BNB, [Phys. Rev. D 110, 092014 \(2024\)](#)
- 1D NC  $\pi^0$ , BNB, [Phys. Rev. D 107, 012004 \(2023\)](#)
- $\nu_\mu$  CC  $\pi^0$ , BNB, [Phys. Rev. D 99, 091102\(R\) \(2019\)](#)

- $\nu_e$  CC

- $\nu_e$  CC N $\pi$ , NuMI, [arXiv:2503.23384](#)
- 1D  $\nu_e$  CC Np0 $\pi$ , BNB, [Phys. Rev. D 106, L051102 \(2022\)](#)
- 1D  $\nu_e$  CC inclusive, NuMI, [Phys. Rev. D105, L051102 \(2022\)](#)
- $\nu_e$  CC inclusive, NuMI, [Phys. Rev. D104, 052002 \(2021\)](#)

- Rare channels

- $\eta$  production, BNB, [Phys. Rev. Lett. 132, 151801 \(2024\)](#)
- $\Lambda$  production, NuMI, [Phys. Rev. Lett. 130, 231802 \(2023\)](#)
- $K^+$  production, NuMI, [arXiv:2503.00291](#)

- $\nu_\mu$  CC 0 $\pi$

- $\nu_\mu$  CC 0 $\pi$ , BNB, [arXiv:2507.00921](#)
- $\nu_\mu$  CC 1p0 $\pi$  angular reconstruction, BNB, [arXiv:2504.17758](#)
- $\nu_\mu$  CC Np0 $\pi$ , BNB, [arXiv:2403.19574](#)
- 1D & 2D  $\nu_\mu$  CC 1p0 $\pi$  Generalized Imbalance, BNB, [Phys. Rev. D 109, 092007 \(2024\)](#)
- 1D & 2D  $\nu_\mu$  CC 1p0 $\pi$  Transverse Imbalance, BNB, [Phys. Rev. Lett. 131, 101802 \(2023\)](#), [Phys. Rev. D 108, 053002 \(2023\)](#)
- 1D  $\nu_\mu$  CC 2p0 $\pi$ , BNB, [arXiv:2211.03734](#)
- 1D  $\nu_\mu$  CC Np0 $\pi$ , BNB, [Phys. Rev. D102, 112013 \(2020\)](#)
- 1D  $\nu_\mu$  CC 1p0 $\pi$ , BNB, [Phys. Rev. Lett. 125, 201803 \(2020\)](#)

