MicroBooNE in 10 minutes

Natsumi Taniuchi on behalf of the MicroBooNE Collaboration

New Perspectives Conference
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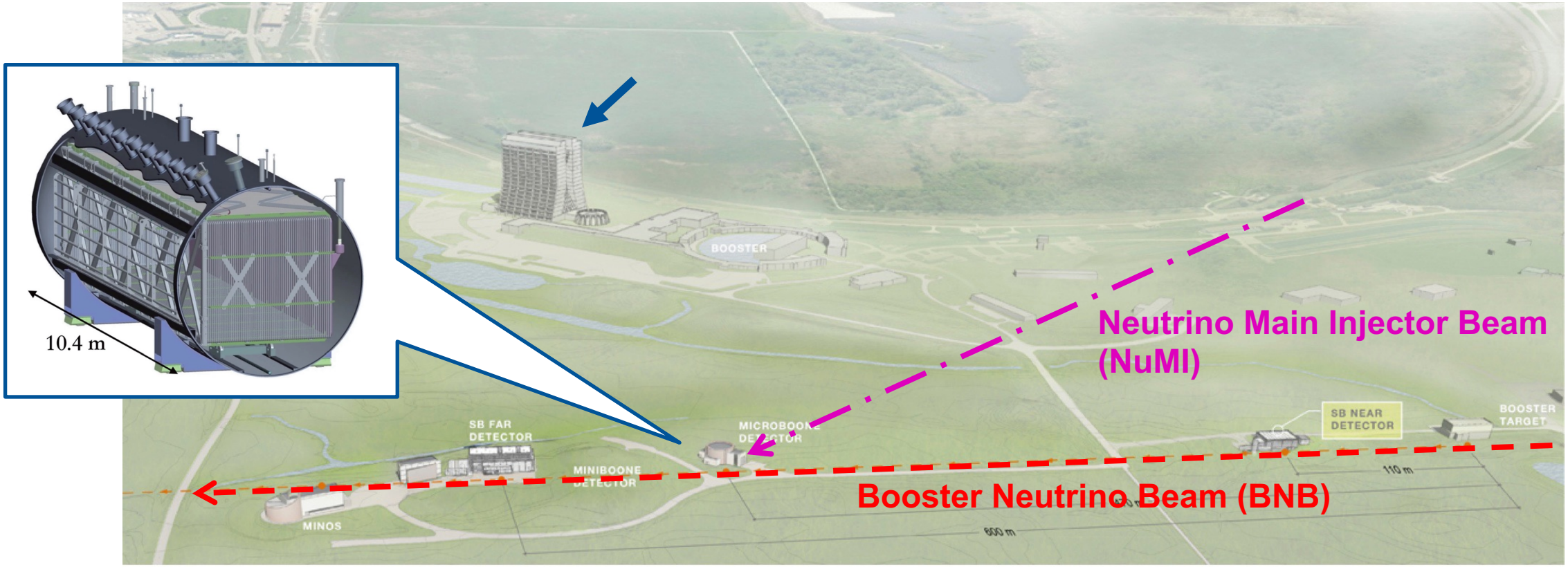
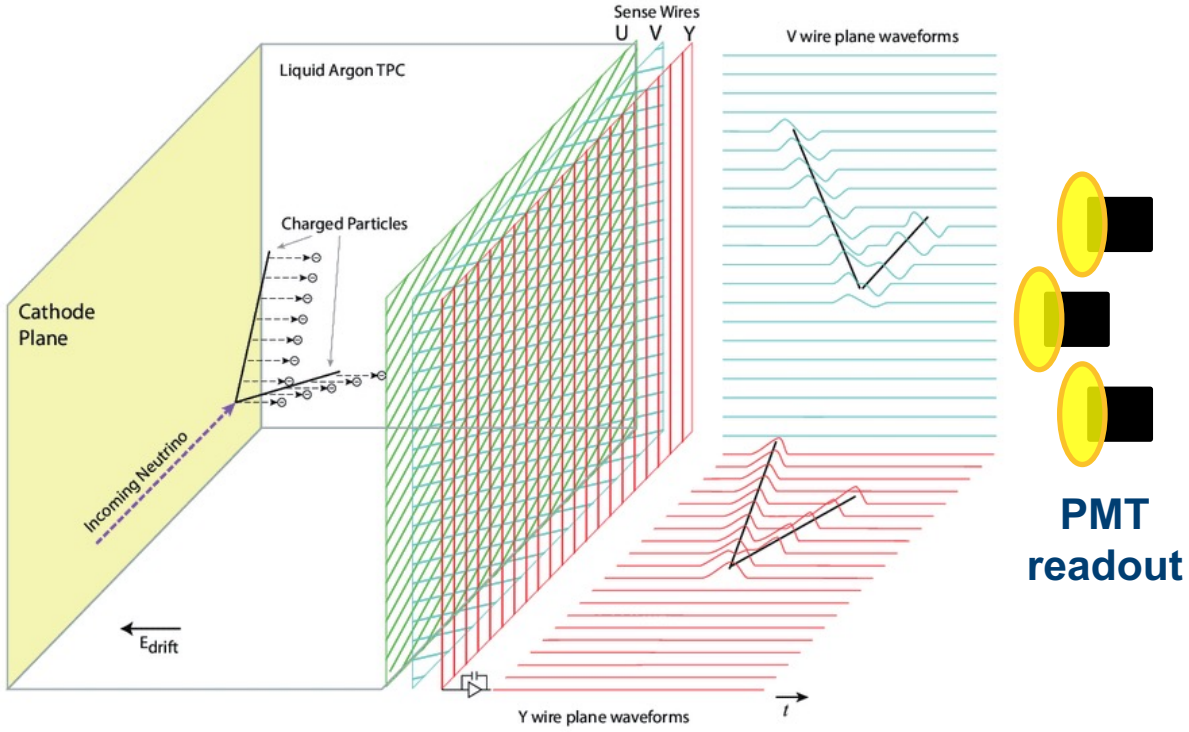
DOE Report Number: FERMILAB-SLIDES-23-128

What is MicroBooNE?

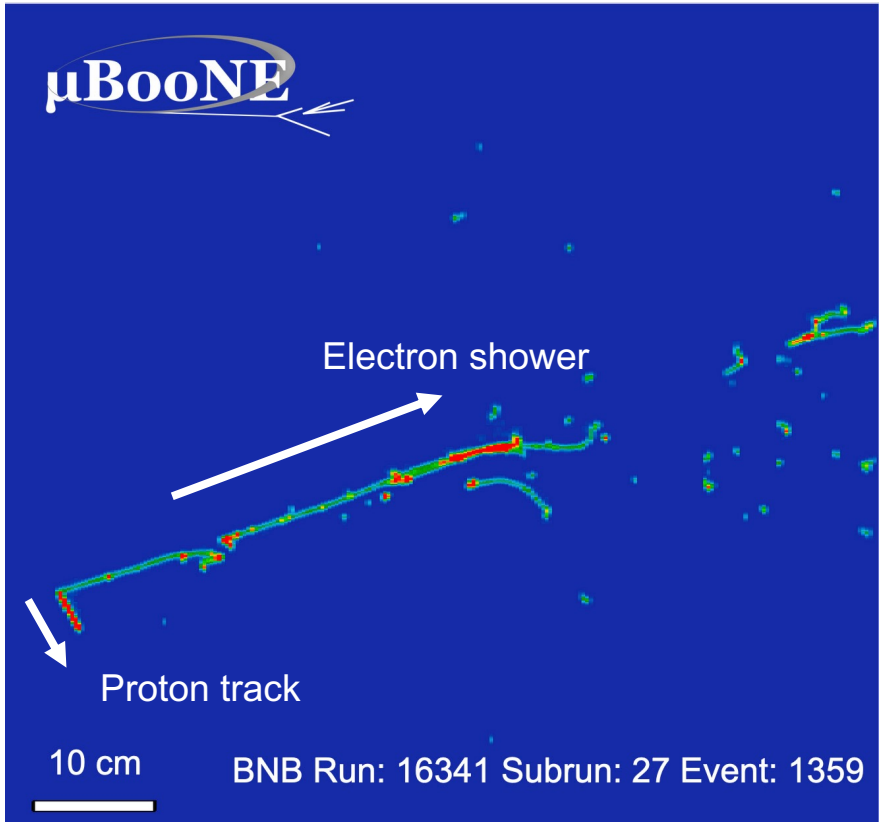
- Part of the Fermilab Short-Baseline Neutrino (SBN) program
- 85-tonne **Liquid Argon Time Projection Chamber (LArTPC)** which ran 2015 - 2021



MicroBooNE LArTPC



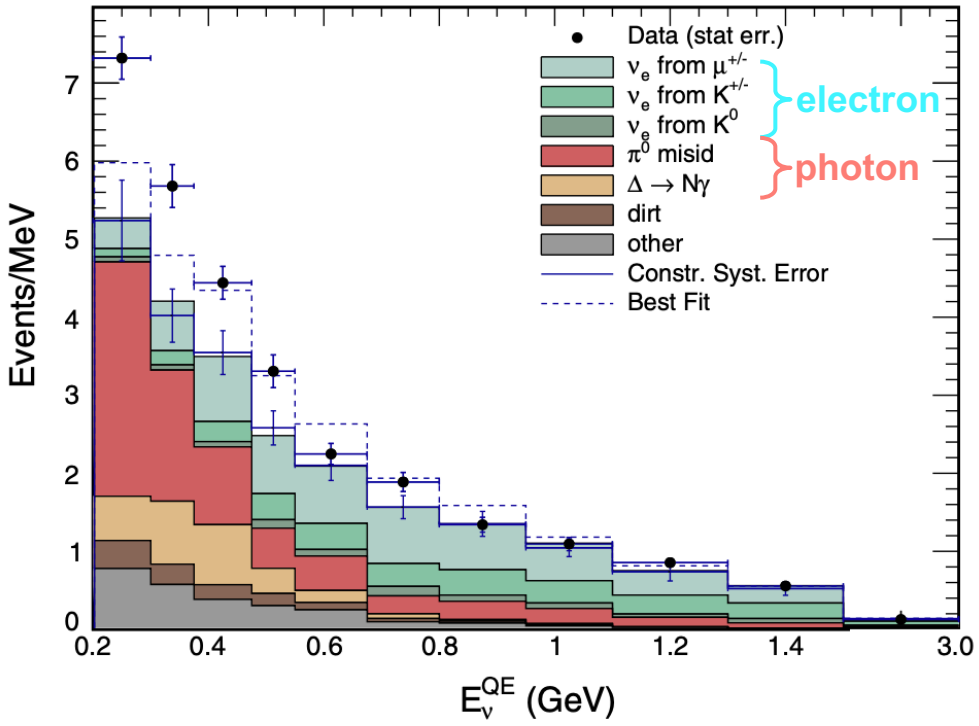
PMT readout



From Fermilab MicroBooNE Galleries

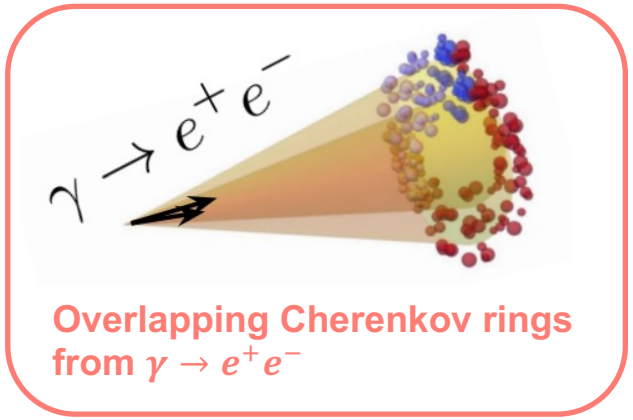
- Uniform electric field
- Fine-grained wire readouts record ionisation charge
- PMTs collect scintillation light

What is MicroBooNE looking for?

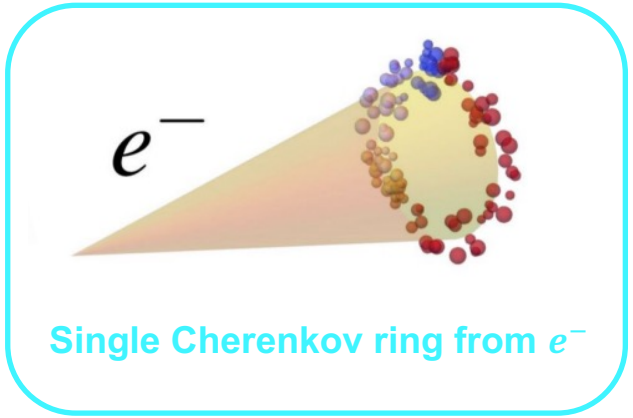


Phys. Rev. D 103, 052002 (2021)

- ✓ MiniBooNE (2002-2019) measured $\nu_\mu \rightarrow \nu_e$ & $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$ **appearance**
- ✓ It observed **an excess of ν_e and $\overline{\nu_e}$ -like events** at low energy with 4.8σ significance: **Low Energy Excess (LEE)**
- ✓ Similar anomaly observed by LSND (1993-1998) from $\overline{\nu_\mu} \rightarrow \overline{\nu_e}$
- ✓ As a mineral oil Cherenkov detector, it was **unable to distinguish photons and electrons**



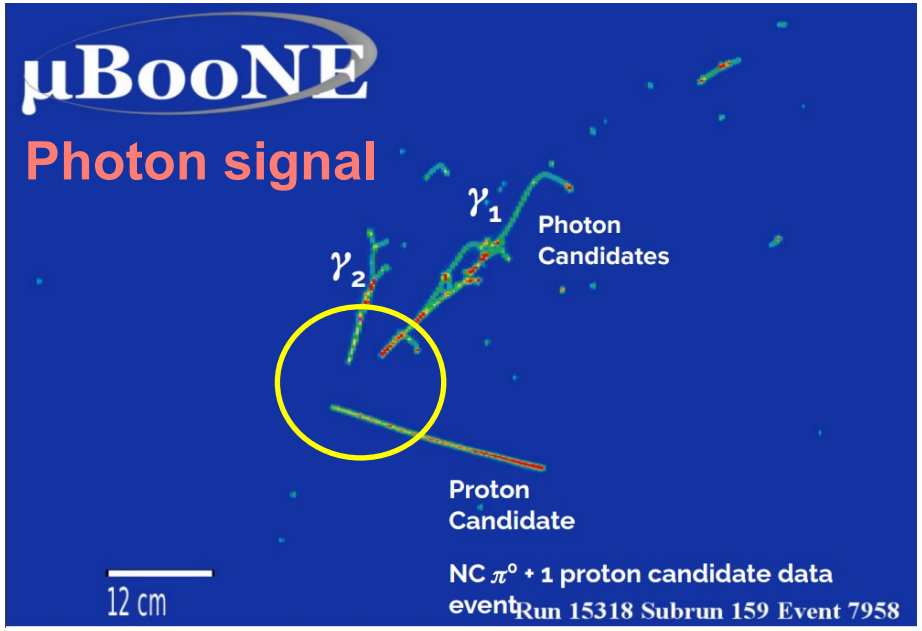
Overlapping Cherenkov rings from $\gamma \rightarrow e^+e^-$



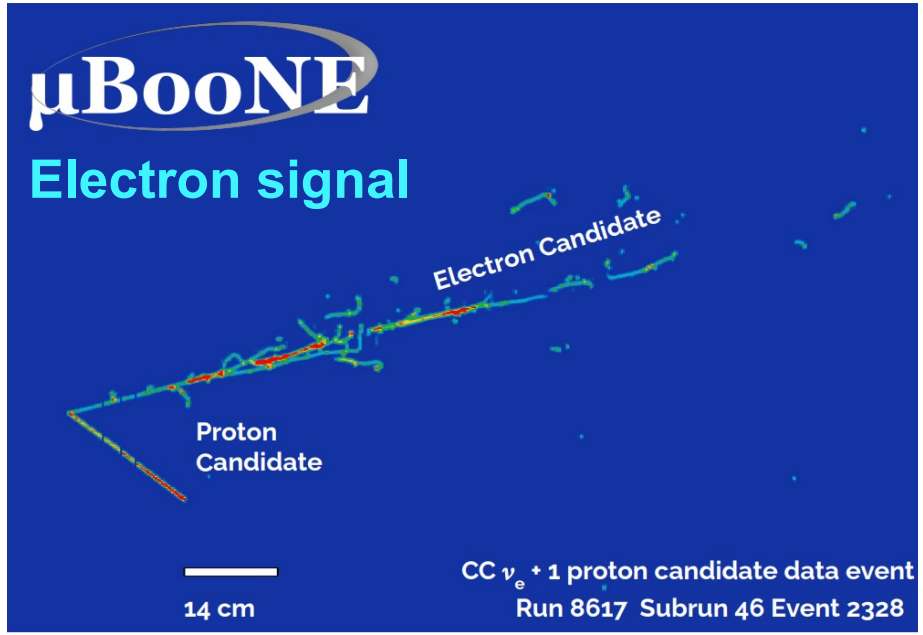
Single Cherenkov ring from e^-

We can separate e/γ with LArTPC!

MicroBooNE can distinguish e/γ by shower conversion distance and energy loss (dE/dx).



If the excess is **photons…**
it could come from **mismodeled background** processes or BSM physics producing photons.



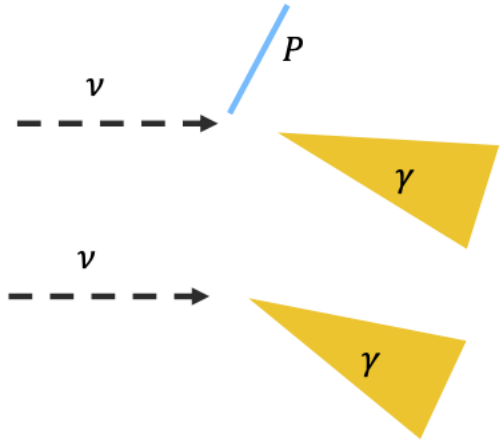
If the excess is **electrons…**
it could be **an oscillation involving additional neutrinos** or other exciting exotic physics.

MicroBooNE's Low Energy Excess Search

MicroBooNE investigated the MiniBooNE LEE using two interpretations.

Photon Search

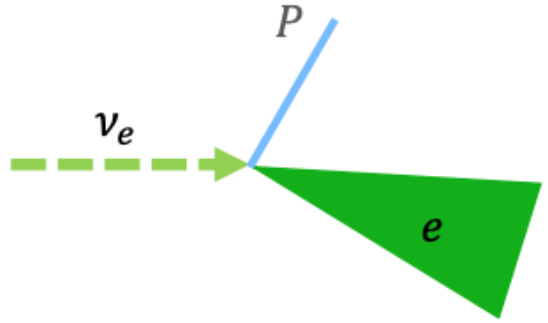
- $1\gamma 0p, 1\gamma 1p$ search:
  targeting NC $\Delta \rightarrow \mathrm{N}\gamma$ hypothesis
  PhysRevLett.128.111801 (2022)

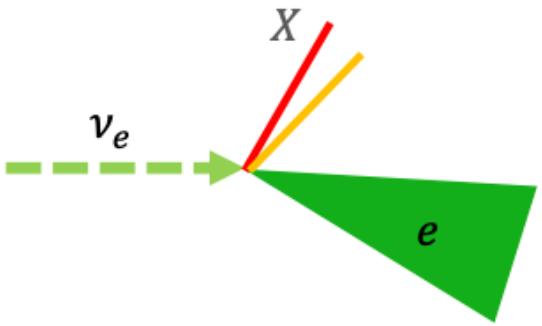


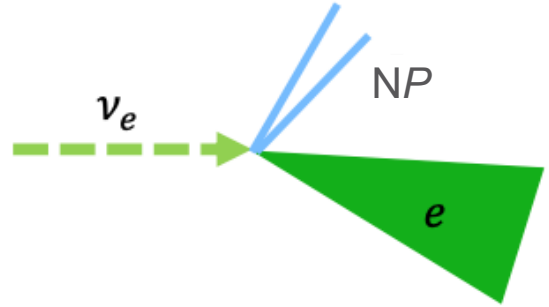
Electron Search

3 different reconstruction frameworks:

- $1e1p0\pi$ search with Deep Learning
  PhysRevD.105.112003 (2022)
- $1e0p0\pi, 1eNp0\pi$ search with Pandora
  PhysRevD.105.112004 (2022)
- $1eX$ search with Wire-Cell
  PhysRevD.105.112005 (2022)





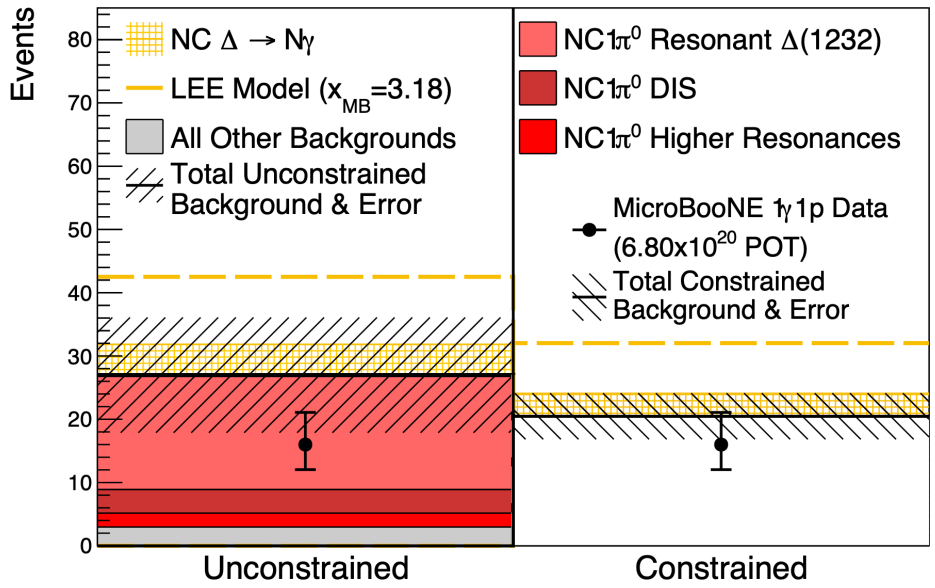


Results of Low Energy Excess Search

Photon Search

PhysRevLett.128.111801 (2022)

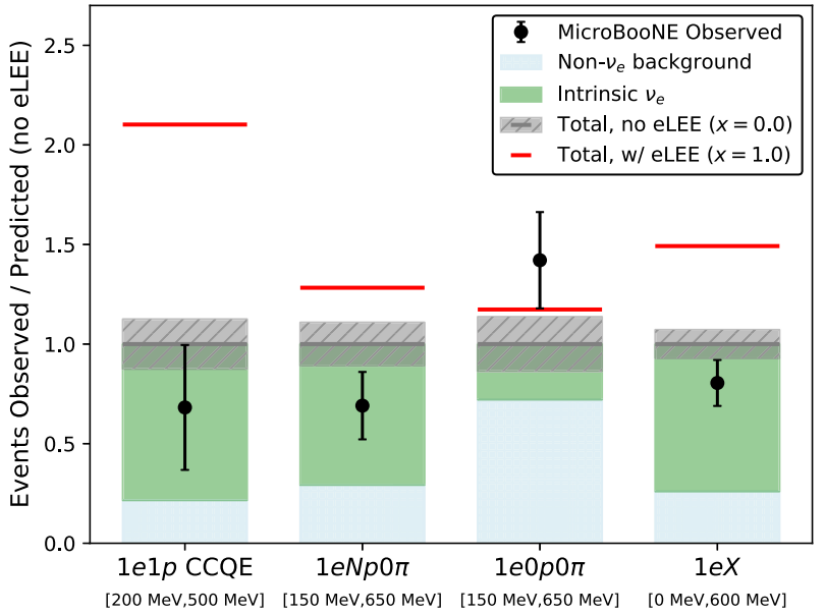
$1\gamma 0p$ search



✓ **Disfavor** enhanced NC $\Delta \rightarrow N\gamma$ rate prediction derived from MiniBooNE.

Electron Search

PhysRevLett.128.241801 (2022)

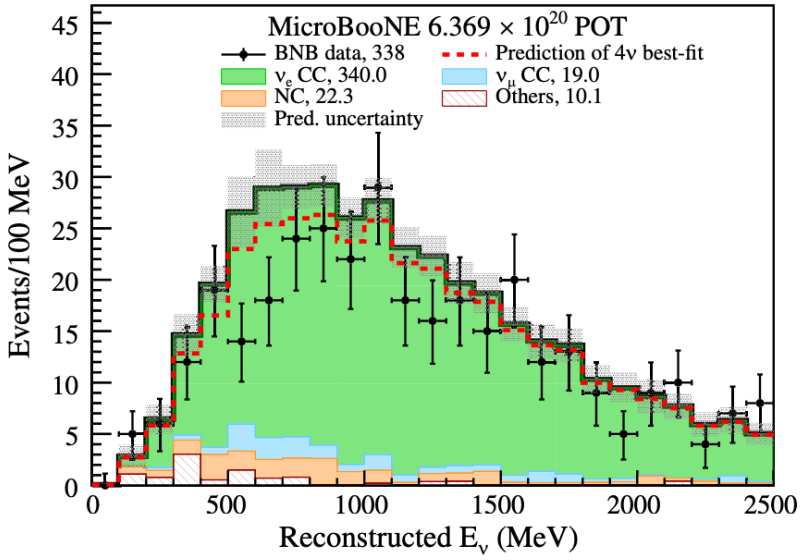


✓ Observed ν_e candidates are statistically **consistent with no LEE ν_e rate expectations**.

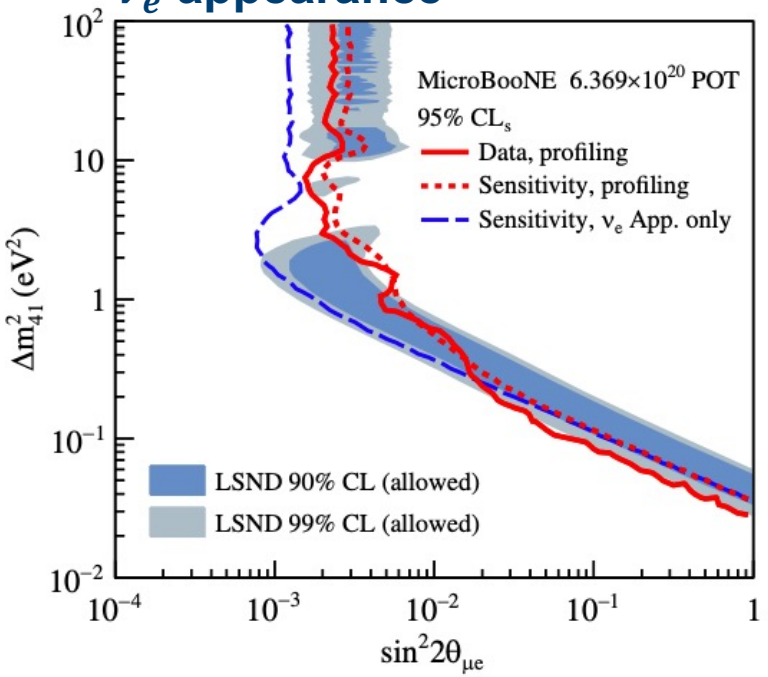
No evidence of excessive ν_e or NC Δ radiative decay to explain the MiniBooNE excess.

Sterile Neutrino Search

Fully contained ν_eCC



ν_e appearance



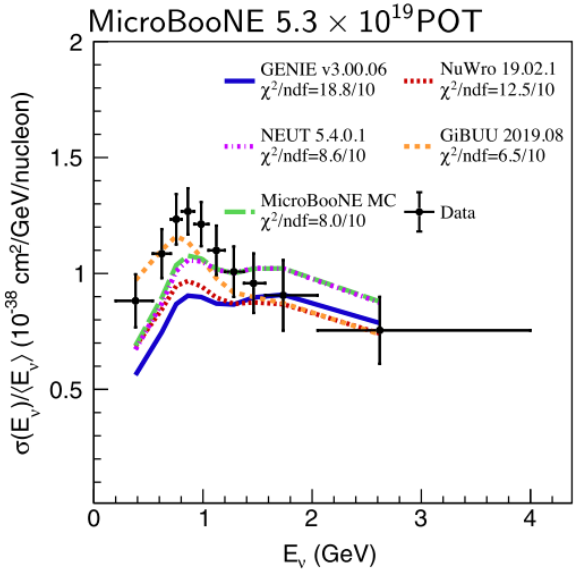
[PhysRevLett.130.011801 (2023)]

- MicroBooNE searched for oscillations caused by **sterile neutrinos as source of the LEE**
- **(3+1) model**: 3 standard neutrinos + 1 additional sterile neutrino
- **Data was consistent with a 3ν hypothesis within 1σ significance**
- **95% CL limits exclude part of LSND allowed region**

Cross Section Physics

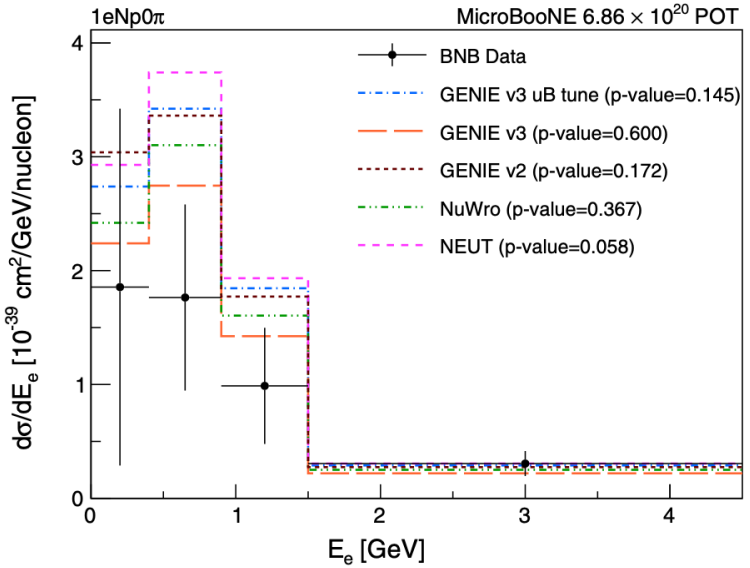
- ✓ Understanding ν **interactions on** $\mathbf{Ar}$ **is crucial in reducing systematic uncertainties and improving background models** for LArTPC experiments
- ✓ MicroBooNE enables **high-statistics** $\nu - \mathbf{Ar}$ **cross-section measurements** with BNB and NuMI

Inclusive cross sections:
ν_μCC cross sections with BNB



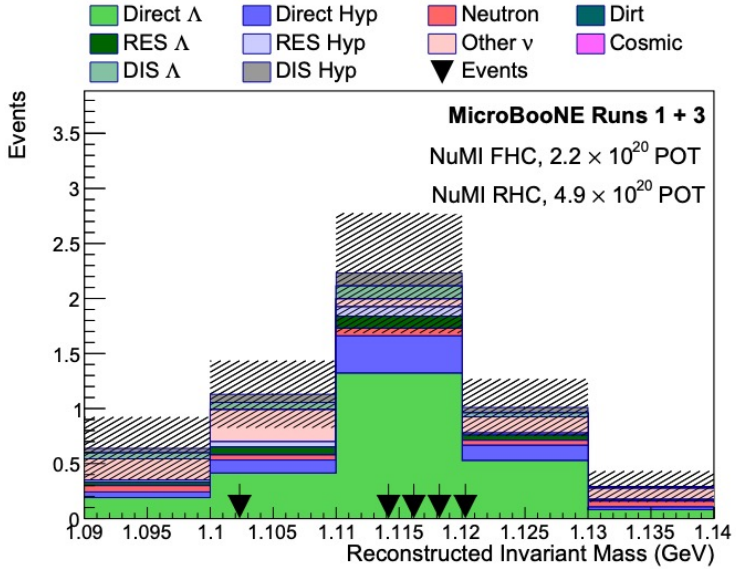
PhysRevLett.128.151801 (2022)

Exclusive cross sections:
ν_e differential cross section with BNB



PhysRevD.106.L051102 (2022)

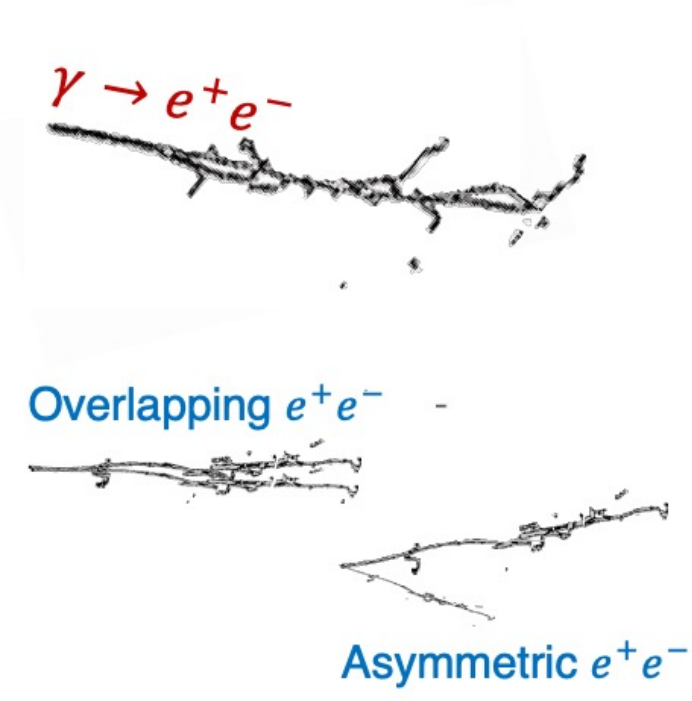
Rare process cross sections:
Λ hyperon production with NuMI



arXiv: 2212.07888 (Accepted by PRL)

Future Prospects

- First searches of the LEE found **no evidence for excessive ν_e or photons from NC Δ radiative decay** to explain the MiniBooNE/LSND excess
- A multitude of **further investigations are ongoing**:
  - ✓ Expanded scope of sterile neutrino oscillations
  - ✓ Extended photon-like event searches & exotic **e^+e^- pair** search from BSM particles/processes
    → See **Leon Tong's** talk!
- **Full dataset results are expected soon**, which will approximately double the statistics



Credit: Matt Toups

Summary

- ✓ **MicroBooNE is a LArTPC detector** based at Fermilab and has completed its 5 years physics run.
- ✓ It has **a wealth of different physics projects**, too much to introduce in 10 minutes!
- ✓ **Various techniques and tools have been developed** to perform precision physics analyses in LArTPCs.
- ✓ MicroBooNE laid the groundwork for the **other SBN LArTPC detectors and the future DUNE** experiment.

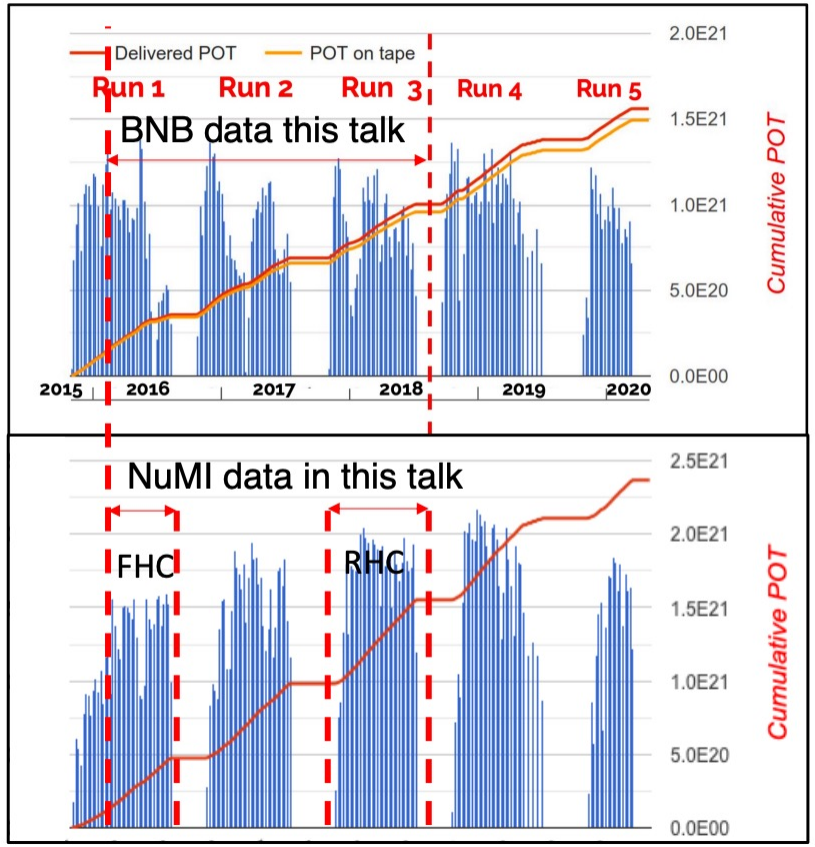
Thank You!

MicroBooNE Collaboration Meeting, May 2023

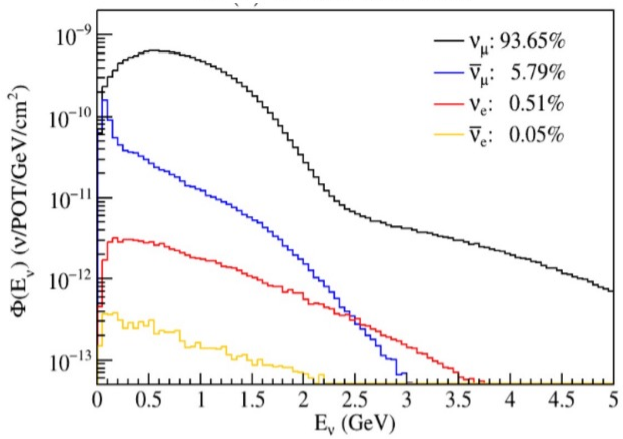
µBooNE
Fermilab
U.S. DEPARTMENT OF ENERGY | Office of Science
NSF
FNSNF
SWISS NATIONAL SCIENCE FOUNDATION
Science & Technology Facilities Council
THE ROYAL SOCIETY
European Commission
Horizon 2020
European Union funding
for Research & Innovation

Data taking from BNB and NuMI

Since turning on in 2015, MicroBooNE has amassed the **largest sample of neutrino interactions on argon in the world**



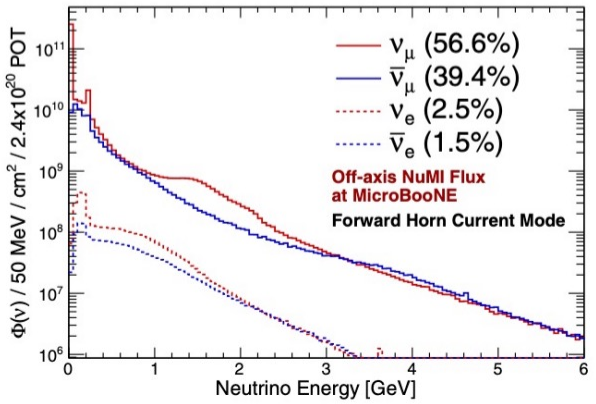
BNB neutrino flux



Credit: Hanyu Wei

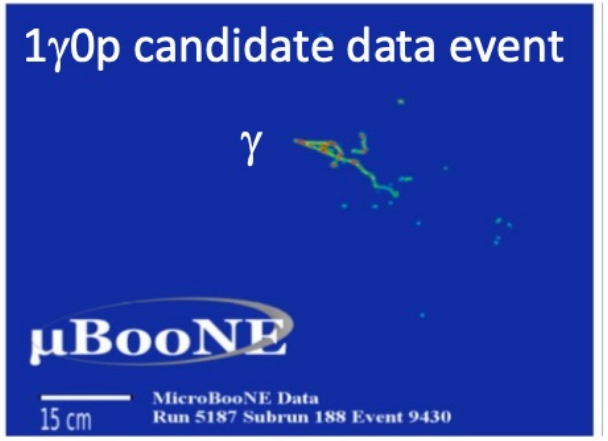
Intrinsic ν_e ~0.6%

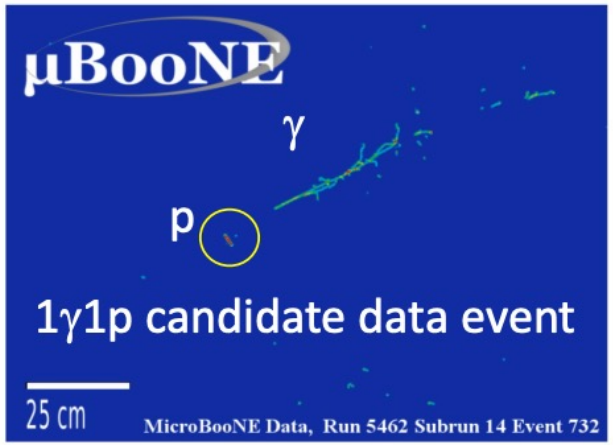
NuMI neutrino flux [FHC, neutrino mode]

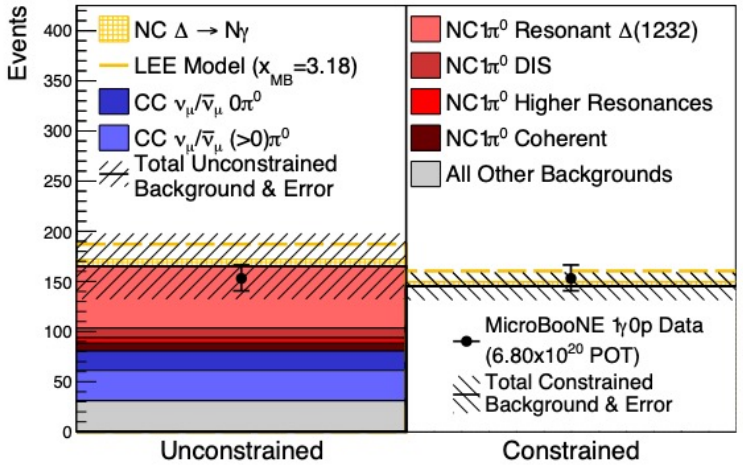


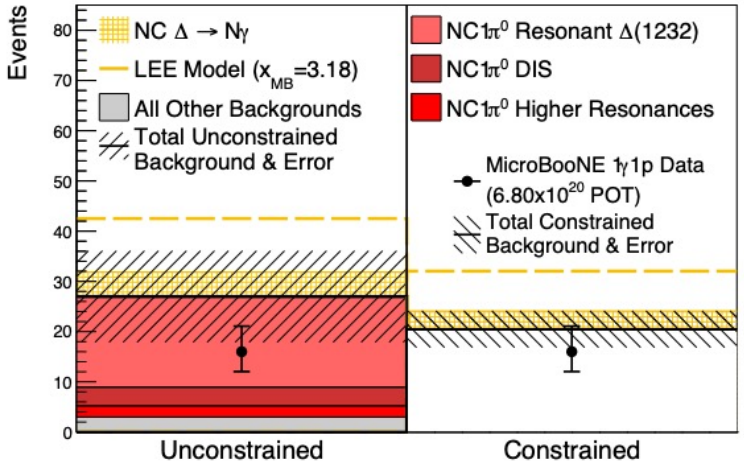
Intrinsic ν_e ~4.0%

Photon-like LEE Search









PhysRevLett.128.111801 (2022)

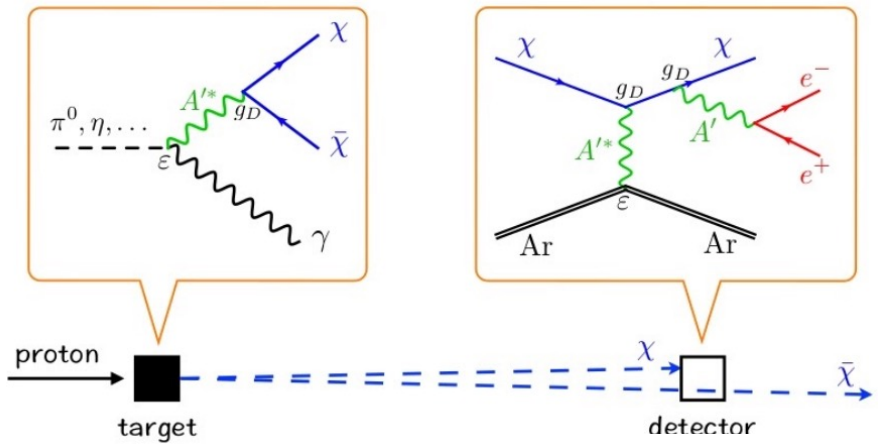
This analysis uses boosted decision trees (BDT)'s to target the key backgrounds to the NC **Δ**→Nγ signal.

Other BSM Models

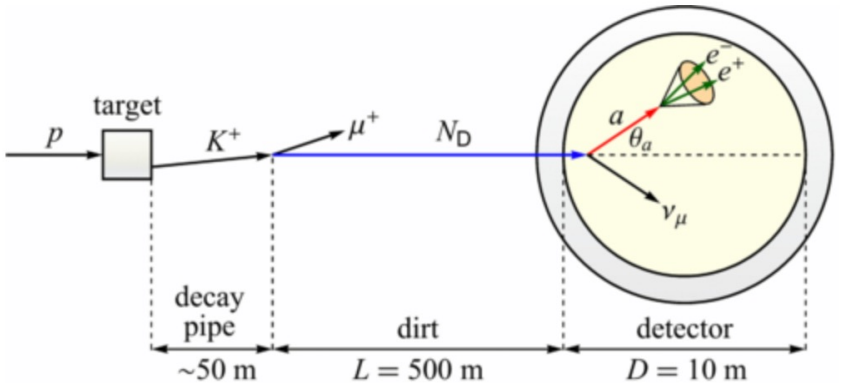
- **Dark Tridents**: Beam produced dark matter scatters and produces an e+e- trident.

- **Dark Neutrino Portal**:
  Dark neutrinos decay to the dark gauge boson, which in turn gives rise to electron-like events.

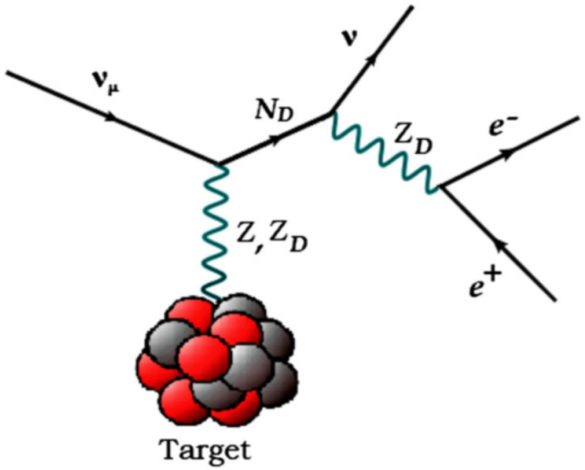
- Decay of **axion-like particles**



JHEP01(2019)001



PhysRevD.104.015030 (2021)



PhysRevLett.121.241801 (2021)

MicroBooNE Next Steps

First series of results (1/2 the MicroBooNE data set)

Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔[7]	✔[7]	✔[7]	✔[7]			✔[7]		
Sterile ν Decay	✔[13,14]	✔[13,14]	✔[13.14]	✔[13,14]			✔[4,11,12,15]	✔[4]	✔[4]
Dark Sector & Z' *	✔[2,3]				✔[2,3]	✔[2,3]	✔[1,2,3]	✔[1,2,3]	✔[1,2,3]
More complex higgs *					✔[10]	✔[10]	✔[6,10]	✔[6,10]	✔[6,10]
Axion-like particle *					✔[8]		✔[8]		
Res matter effects	✔[5]	✔[5]	✔[5]	✔[5]					
SM γ production							✔	✔	✔

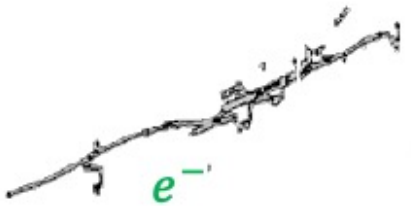
* Requires heavy sterile/other new particles also

More exploration of MiniBooNE excess

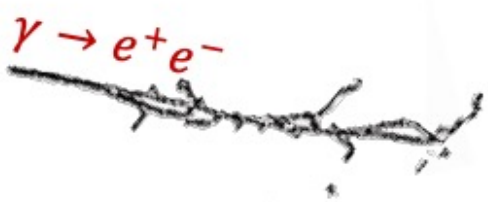
Credit:
Mark Ross-Lonergan

- 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)*
  - *[16] Alves, Louis, deNiverville, [hep-ph]2201.00876 (2022)*
- 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)*
  - *[17] Dutta, Kim, Thompson, Thornton, Van de Water [hep-ph]2110.11944*
- 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)*

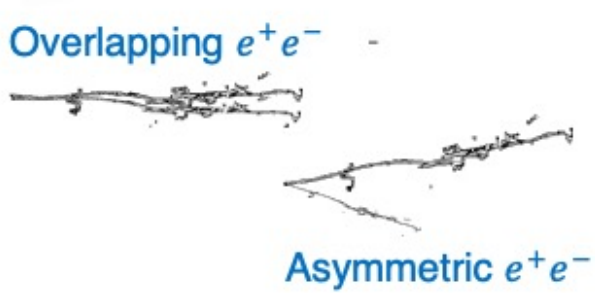
Produces True Electrons e^-



Produces True Photons γ



Produces e^+e^- pairs



Evolving theory landscape …
(not an exhaustive list)