Astroparticle and Beyond the Standard Model Capabilities and Results from MicroBooNE

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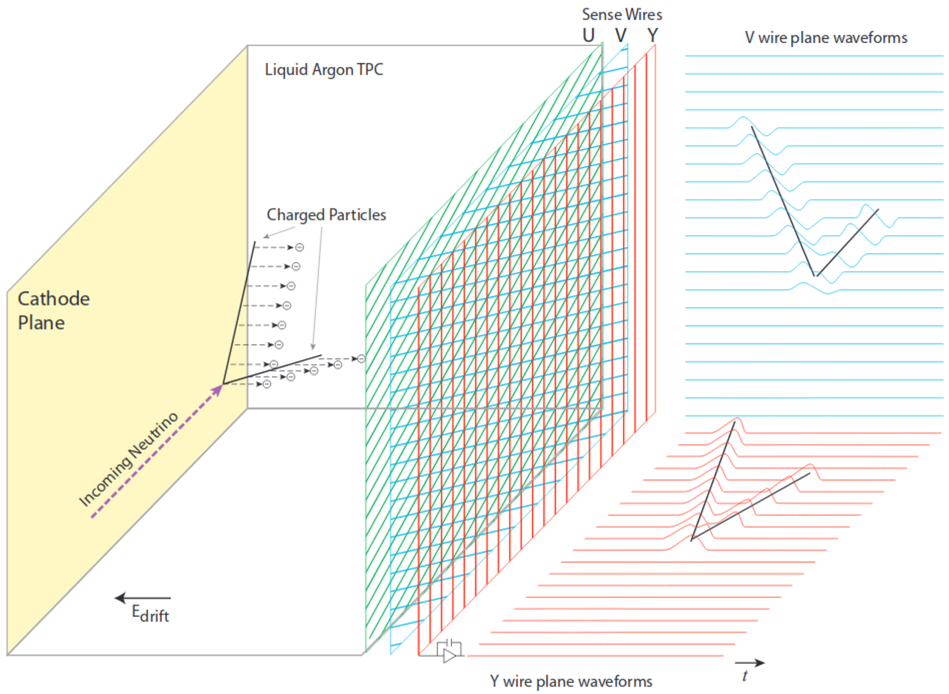
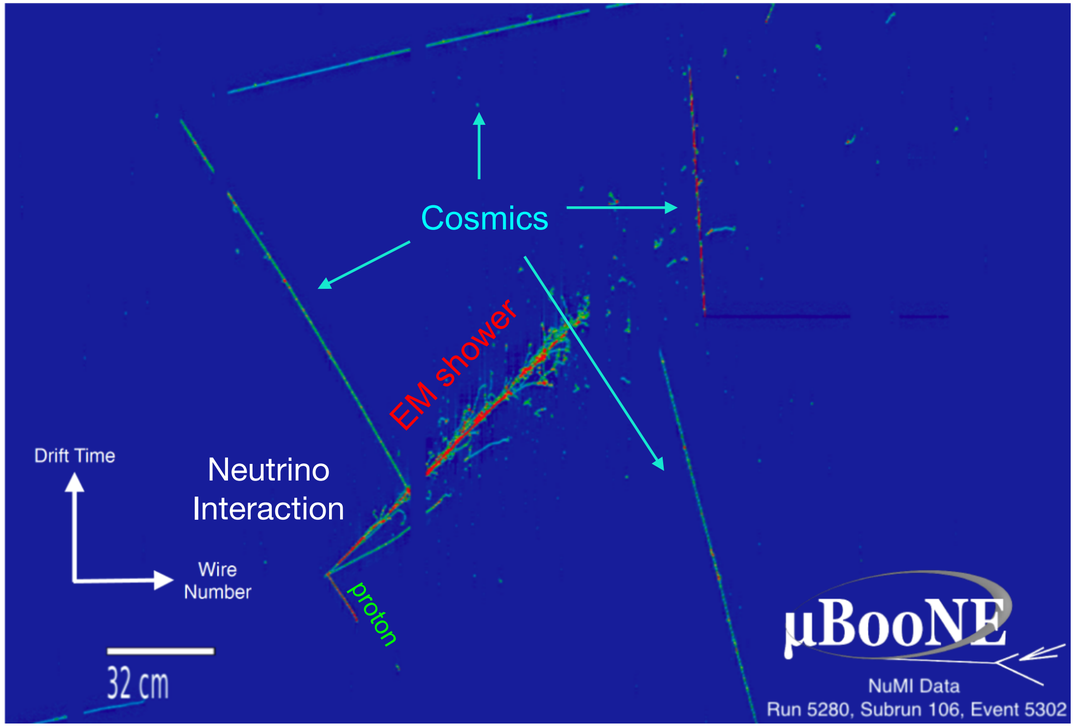
On behalf of the MicroBooNE Collaboration

30th International Symposium on Lepton Photon Interactions at High Energies - 12 January 2022

The MicroBooNE experiment

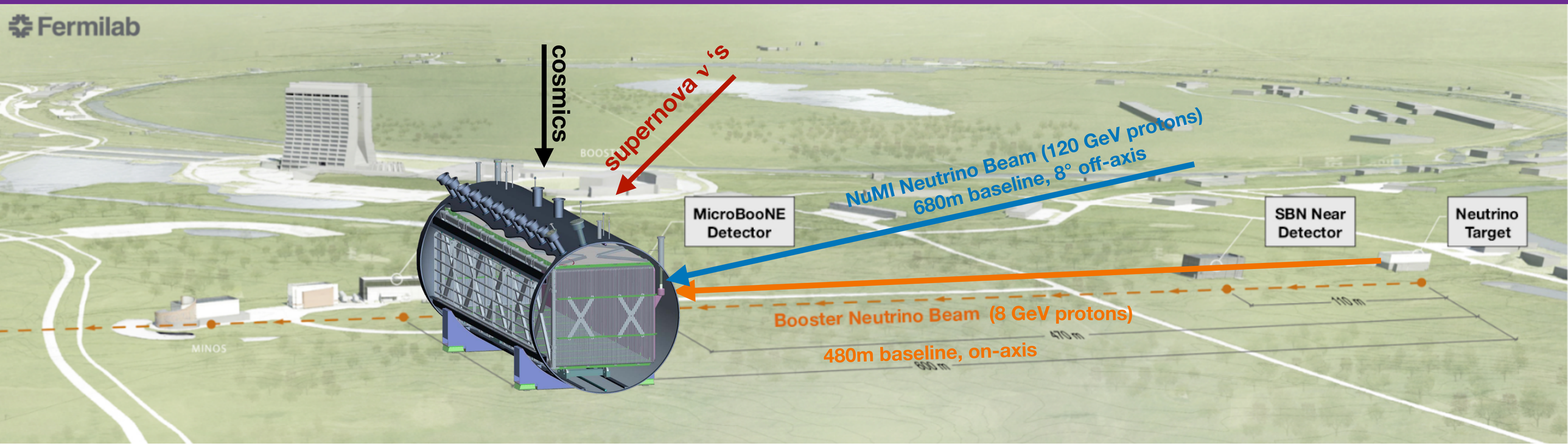




- MicroBooNE is an 85t Liquid Argon Time Projection Chamber (LArTPC)
- Exploit scintillation and ionisation signals from charged particles to produce bubble-chamber like images of events

- Advantages:
  - Excellent spatial resolution
  - Excellent calorimetry
  - Powerful particle identification

MicroBooNE's physics reach



Goals of the MicroBooNE Experiment

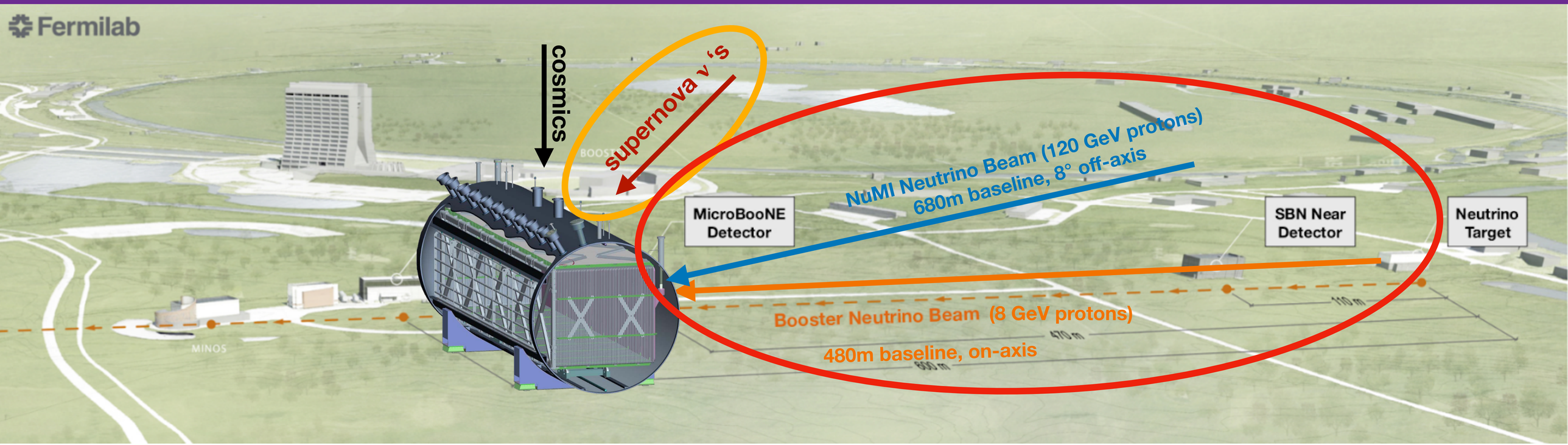
Investigate MiniBooNE Low Energy Excess
→ *See Nick Kamp's talk on Tuesday*

Cross-section measurements
→ *See Wenqiang Gu's talk on Tuesday*

LArTPCs detector physics, R&D

Many more capabilities in astroparticle and exotic physics, that we'll explore in this talk!

MicroBooNE's physics reach



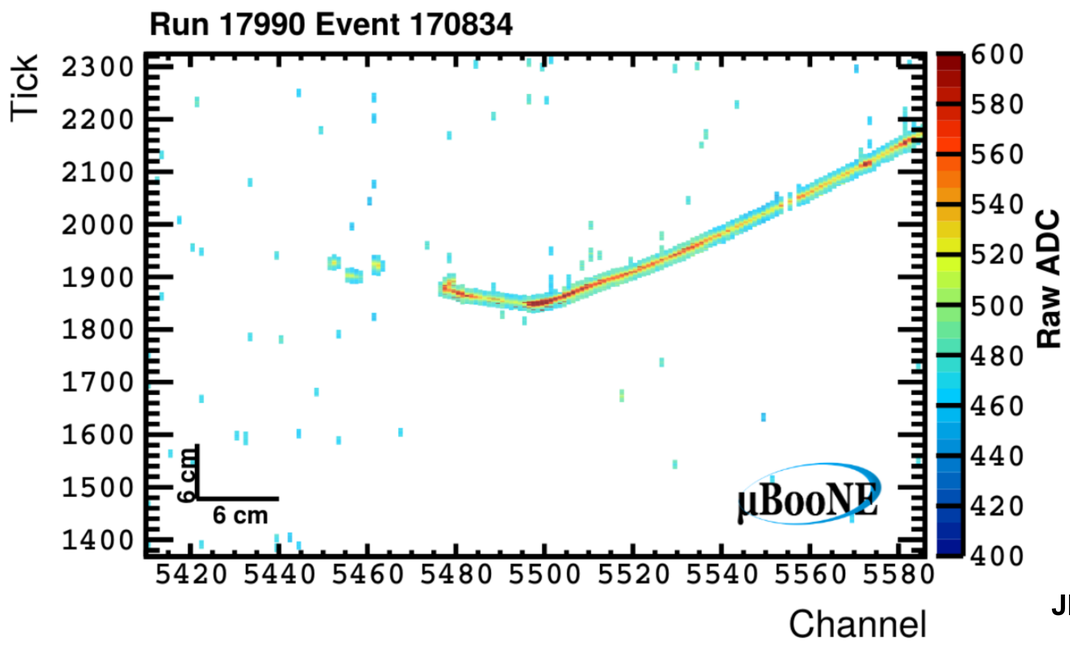
- Continuous readout for supernova detection
- MeV scale reconstruction

- Heavy Neutral Leptons (BNB)
- Higgs Portal Scalars (NuMI)

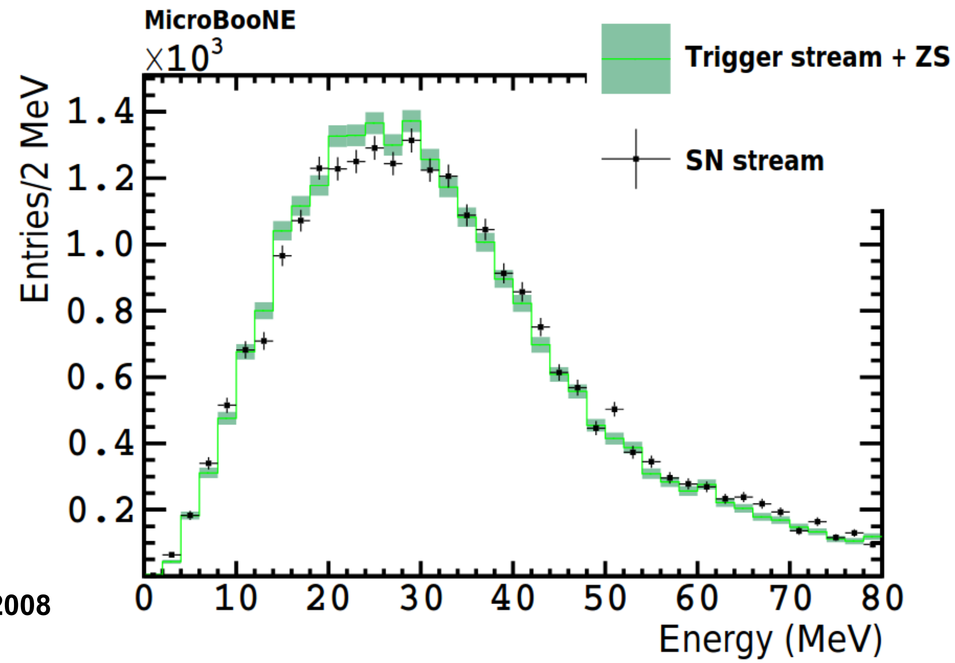
- Ongoing searches

Continuous readout for supernova neutrino detection

- Detecting a supernova neutrino burst requires continuous data readout (33GB/s raw data from MicroBooNE)
- Pioneered a system to zero-suppress and compress data
- Evaluated performance by looking at reconstruction of Michel electrons
- SN stream could be used for other off-beam physics
- Further work on reconstruction/selection



JINST 16 (2021) 02, P02008

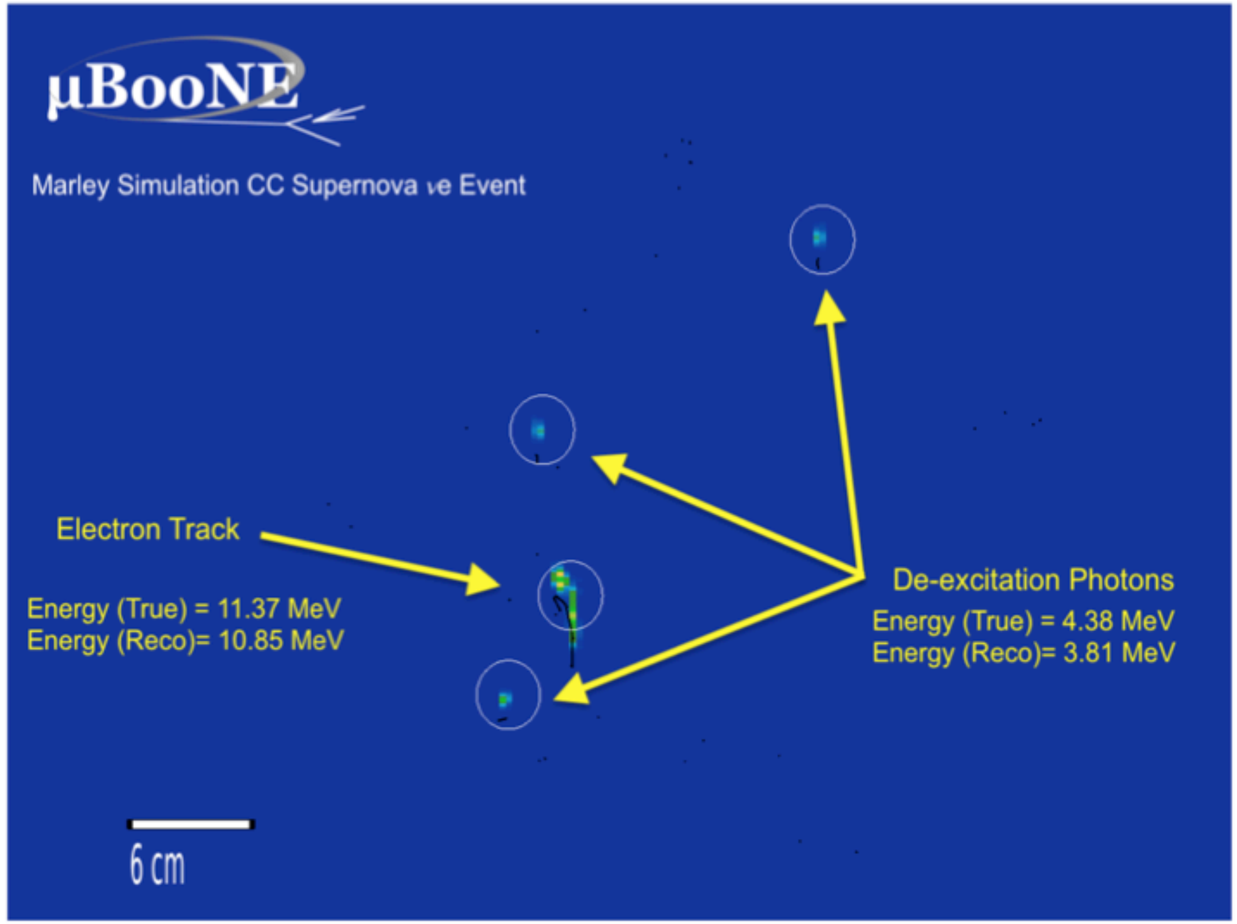


MeV scale reconstruction

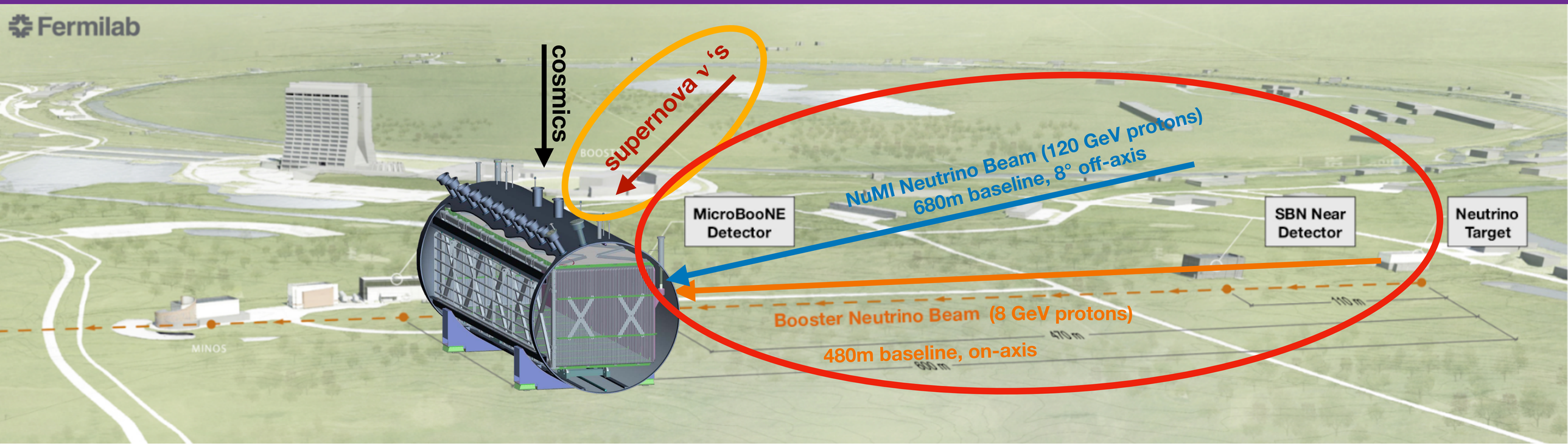
- Standard reconstruction algorithms designed for O(100 MeV) interactions
  - Not low enough for many low energy studies
  - Might miss part of the deposited energy
- Developed using “blips” of ionisation from low-energy gammas or neutrons (0-5 MeV)

Applications:
- Supernova neutrino reconstruction
- Muon/pion separation
- Some BSM searches e.g. millicharged particles

MICROBOONE-NOTE 1076-PUB



MicroBooNE's physics reach



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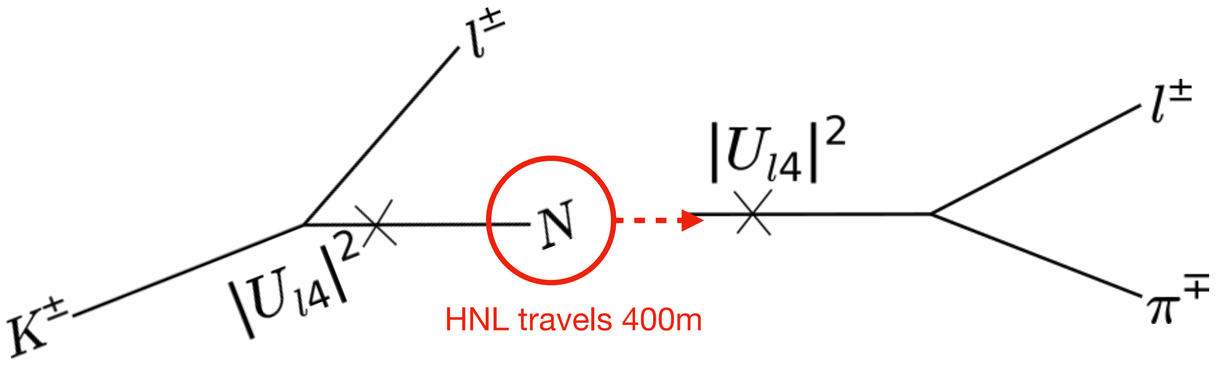
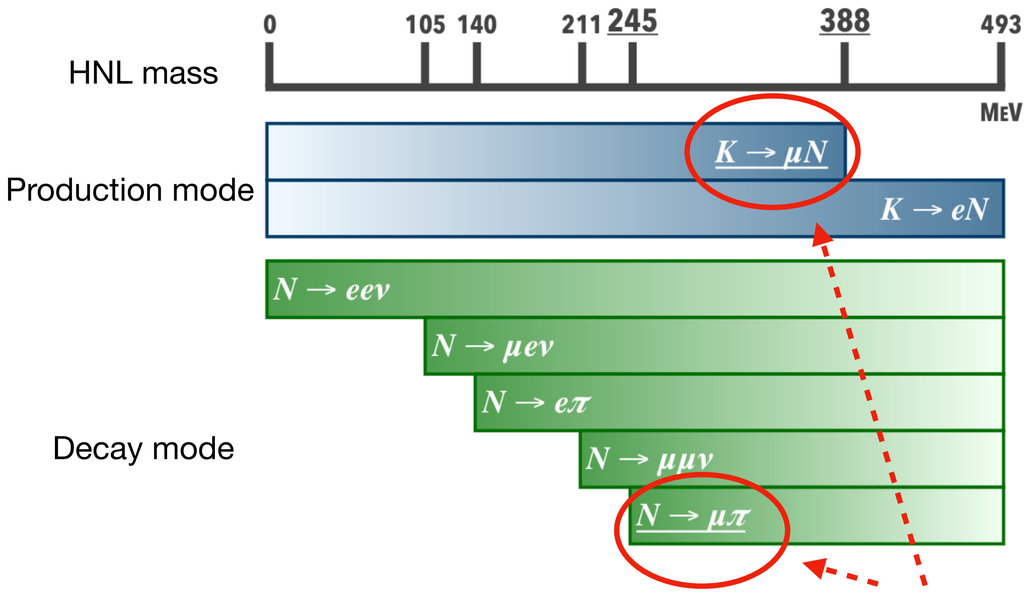
Heavy Neutral Leptons - Model

- Searches for neutral leptons in BNB with mass O(100 MeV)
- Produced via mass mixing with SM neutrinos with extended PMNS element $|U_{l4}|$
  - Used kaon decays as source for first search
- Decay via weak interaction
  - Chose muon + pion channel for this study
- Could decay inside MicroBooNE

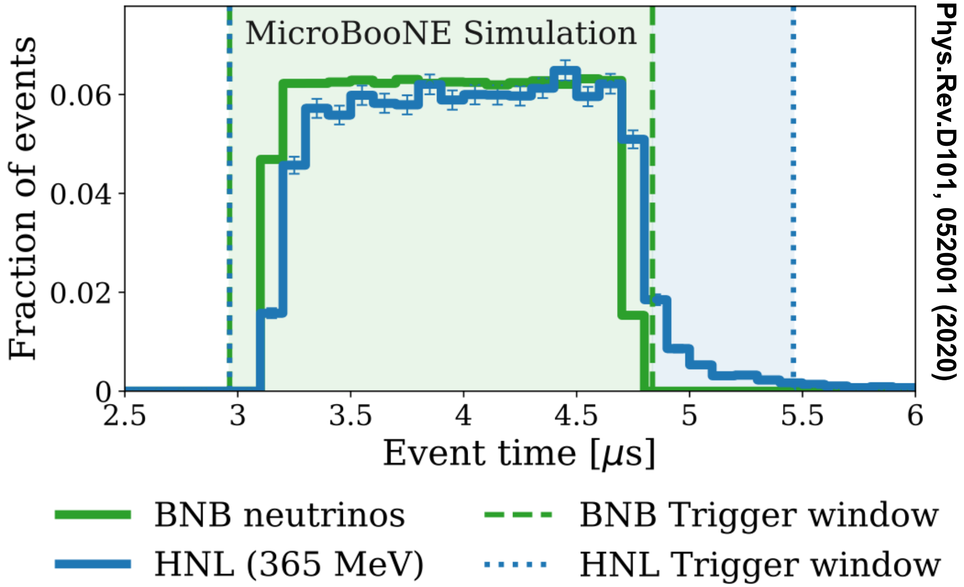




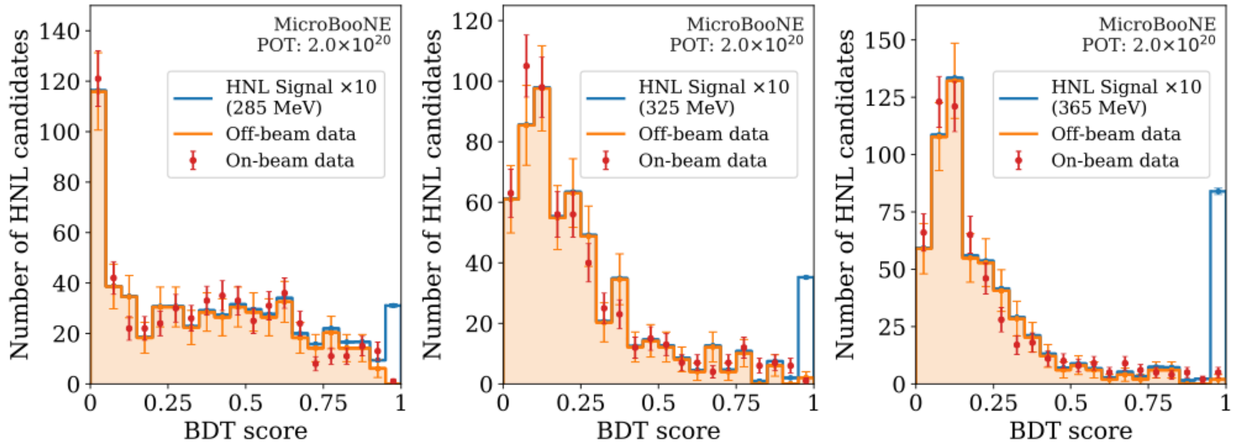
Consider only this production mode and this decay mode

Heavy Neutral Leptons - Analysis

- Developed a “late window” trigger specifically for this analysis
  - HNLs travel slower than neutrinos
  - Around ~10% of HNLs arrive after the neutrino spill
  - Late window trigger effectively eliminates in-beam neutrino events which would be background



Phys.Rev.D101, 052001 (2020)



Phys.Rev.D101, 052001 (2020)

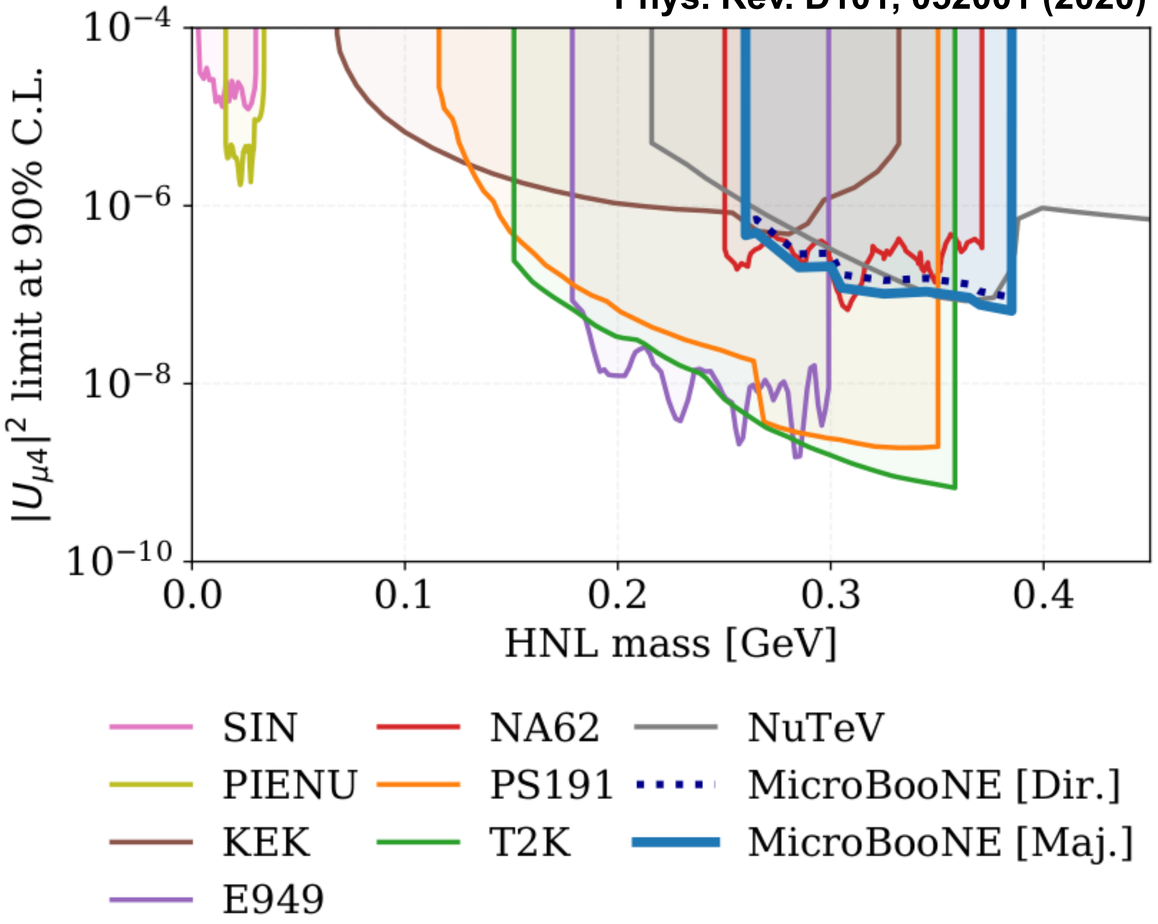
- BDT based analysis with 10 HNL mass points (260 - 385 MeV)
- Signal region defined as BDT score > 0.95

Heavy Neutral Leptons - Results

- Considered decay mode $K \to \mu N$, and production mode $N \to \mu\pi$
- No excess observed in signal region
- Set limits on $|U_{\mu 4}|^2$ as a function of HNL mass

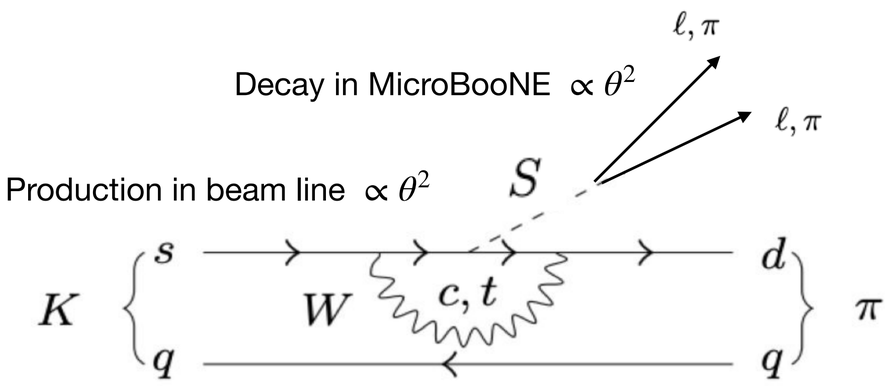
We will be using more production and decay modes, full trigger window and more data (including NuMI) in the future!

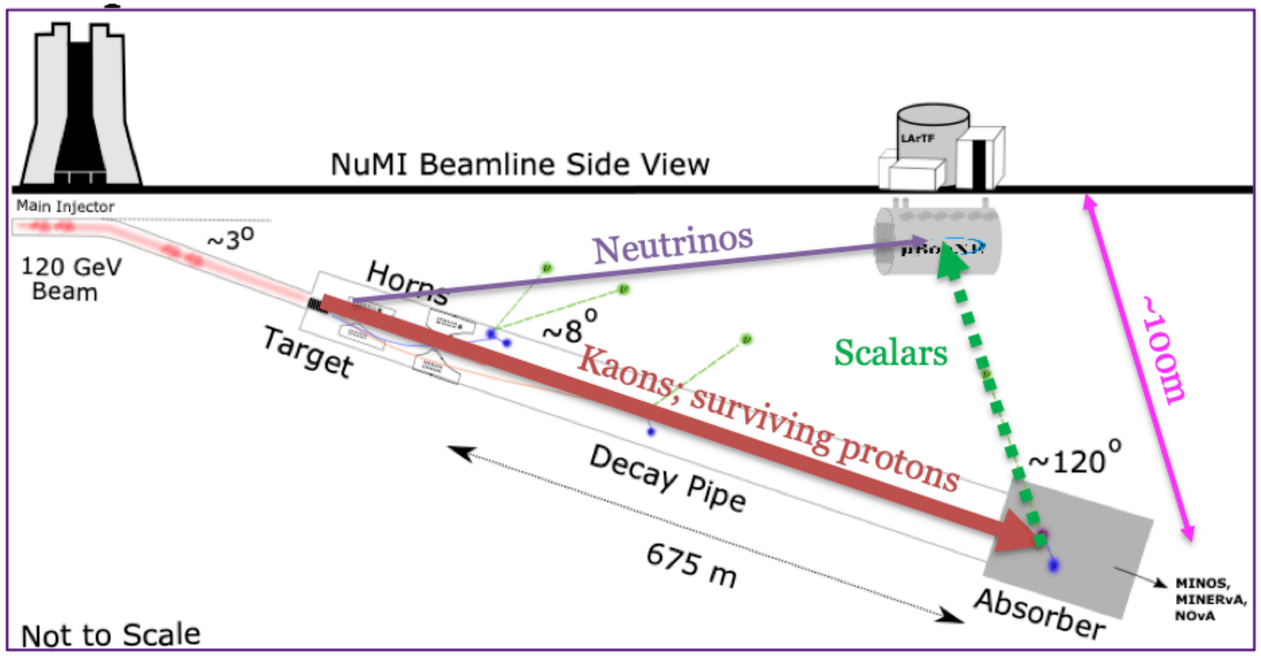
Phys. Rev. D101, 052001 (2020)



Higgs Portal scalars - Model

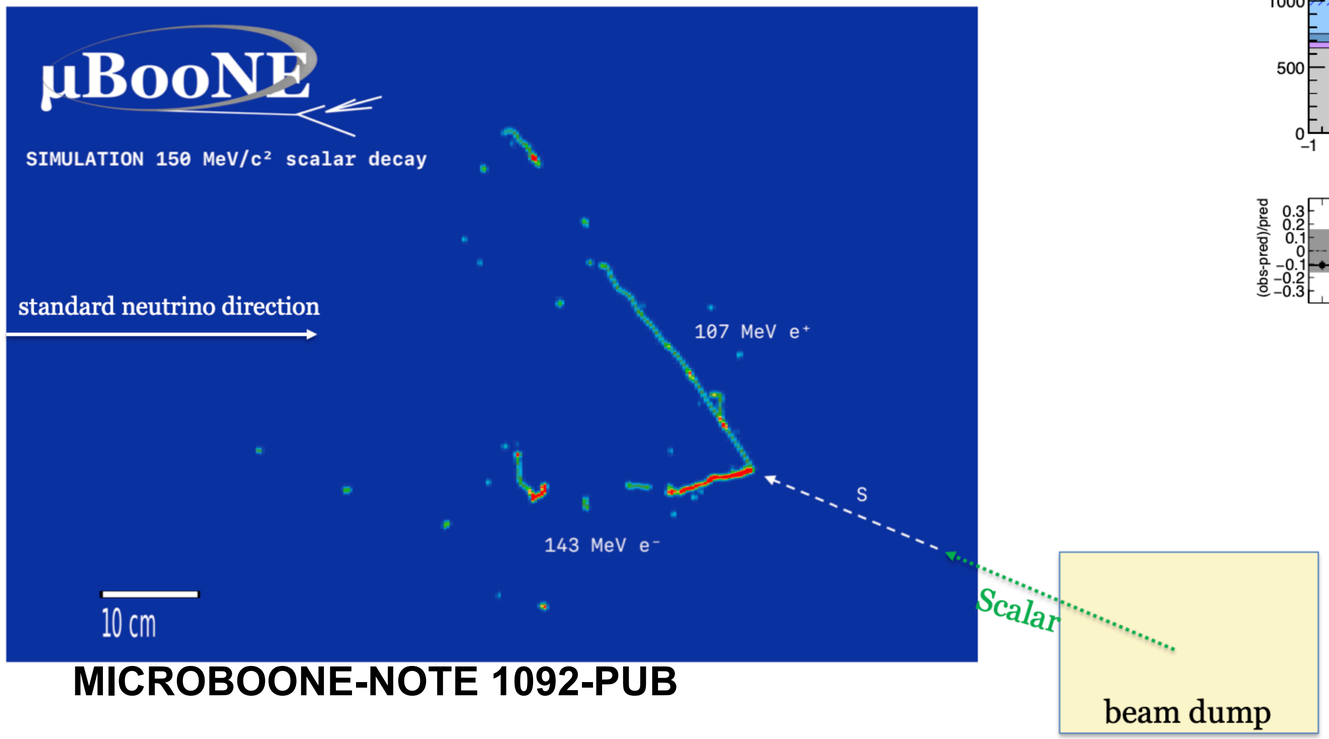
- "Portal" to the dark sector, via a dark scalar mixing with the Higgs (mixing angle θ)
- Similar phenomenology to HNLs
  - Search for kaons decaying to scalars in beam
  - Scalars decaying to fermions in detector
- First search uses kaons decaying at rest in the NuMI beam dump



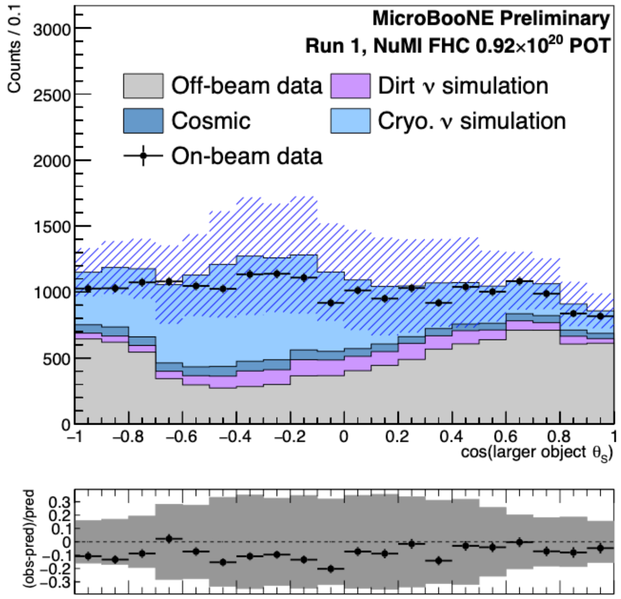


Higgs portal scalar - Analysis

- Search for e+e- pairs from the decay of a < 200 MeV scalar
- BDT based analysis



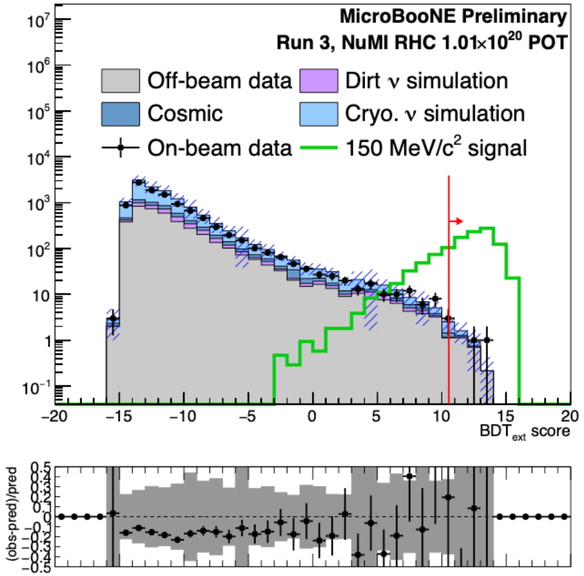
MICROBOONE-NOTE 1092-PUB



Angular distribution (one of the most important BDT variables)

Simulation is well-modelled with respect to the data

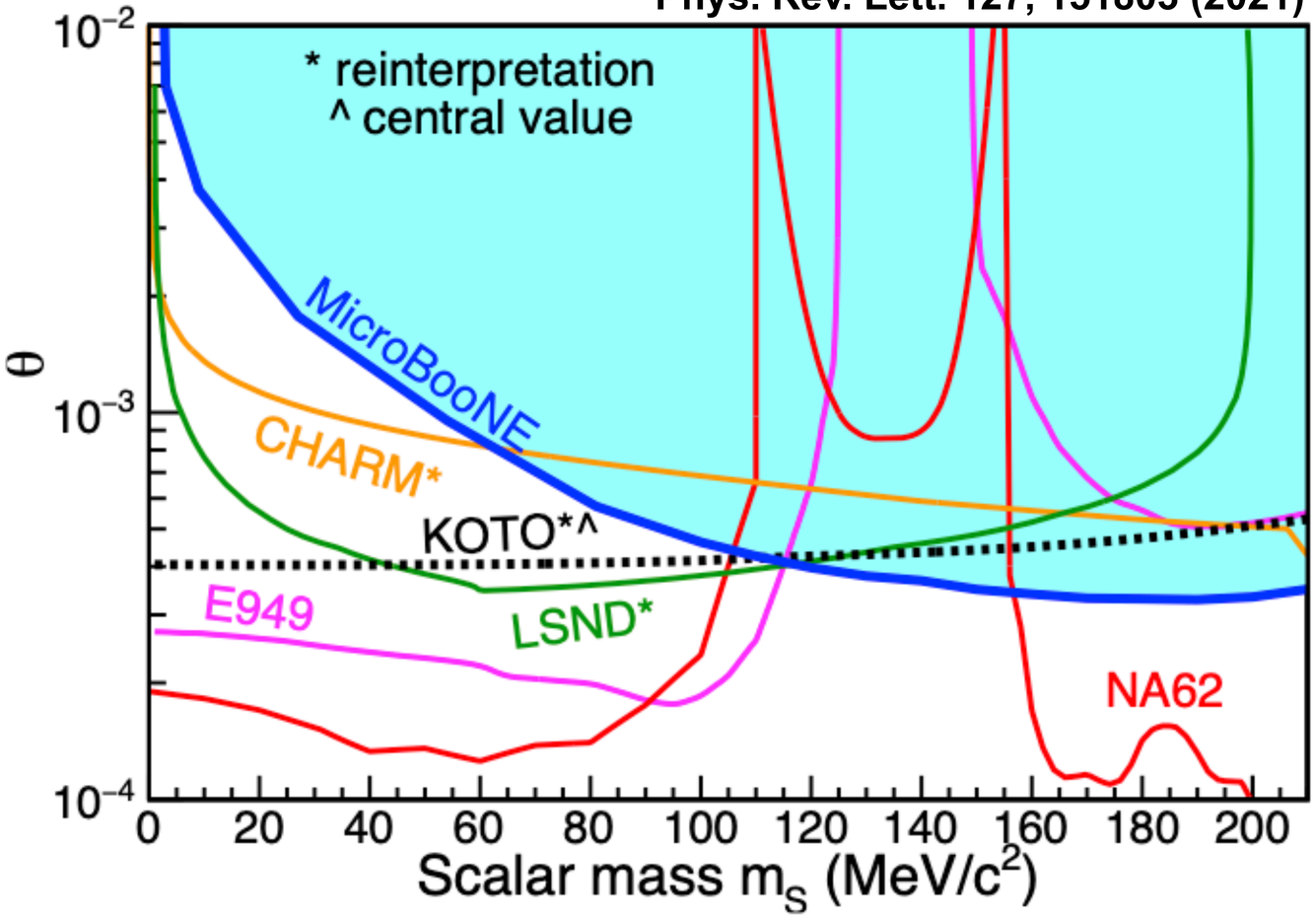
BDT distribution is well-modelled with background-only explanation



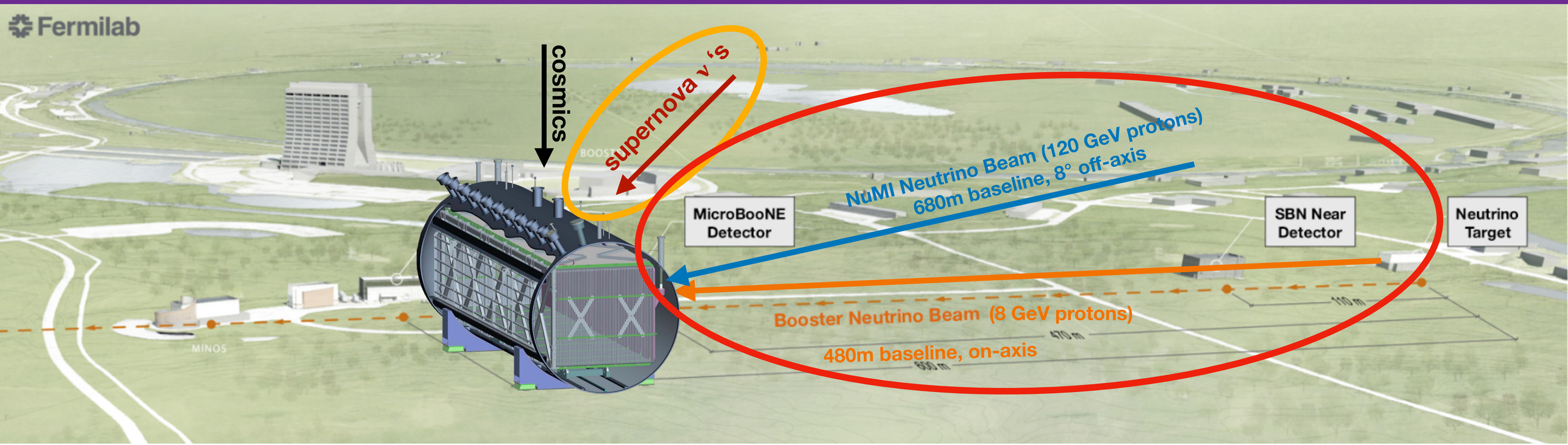
Higgs Portal scalars - Results

- Observed 1 event in signal region (consistent with 1.9 ± 0.8 background expectation)
  - Set limits on θ as a function of scalar mass
- Used only 10% of the NuMI dataset
- More results to come !

Phys. Rev. Lett. 127, 151803 (2021)



MicroBooNE's physics reach



- Continuous readout for supernova detection
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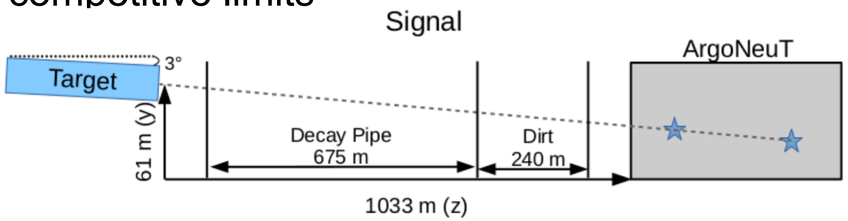
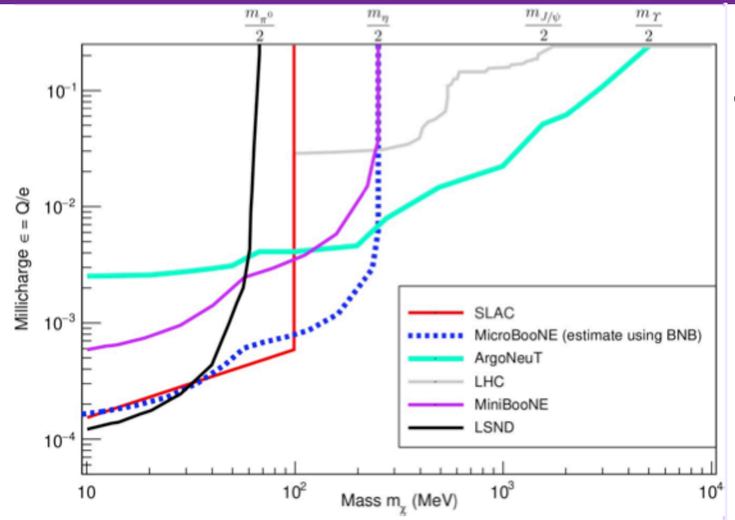
- Ongoing searches

Ongoing searches

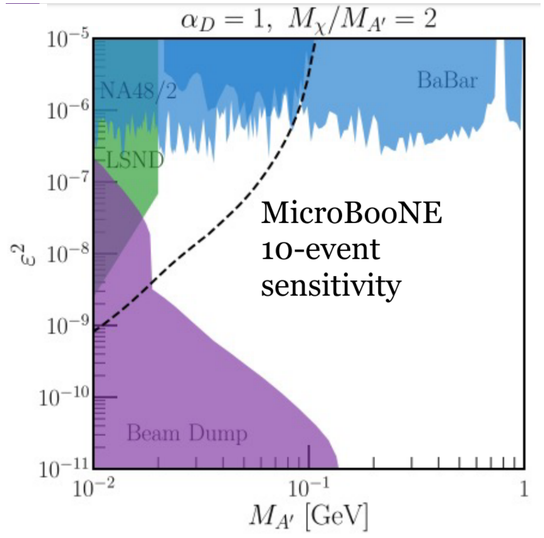
Millicharged particles

- Particles with a fraction of electric charge, potential dark matter candidates
- Could scatter off atomic electrons and cause “blips” of ionisation in LAr
  - MeV scale reconstruction useful
- MicroBooNE could provide competitive limits

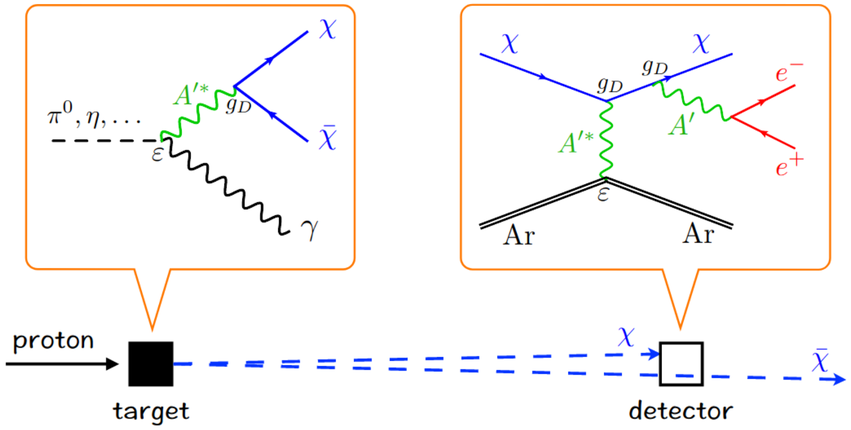




Phys. Rev. Lett. 122.071801



de Gouvêa et al, JHEP 01, 001 (2019)



Dark Tridents

- Dark matter produced from meson decays in the beam
- Leads to e^+e^- final states
- Could explain MiniBooNE Low Energy Excess if e^+e^- not resolved

See Luis Mora Lepin’s Poster

Summary

Stay tuned!

- MicroBooNE is a multi-faceted detector with access to a wide-range of signal sources and signatures
- Lots of R&D efforts to push our capabilities in new areas
- Recent exciting results include:
  - Supernova continuous readout
  - MeV Scale Physics
  - Searches for heavy neutral leptons
  - Higgs portal scalars
- We have only used a fraction of our data
- New BSM era for MicroBooNE!
  - More modes and signatures
  - More models (LEE explanations and more)

MiniBooNE LEE Theory Landscape

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

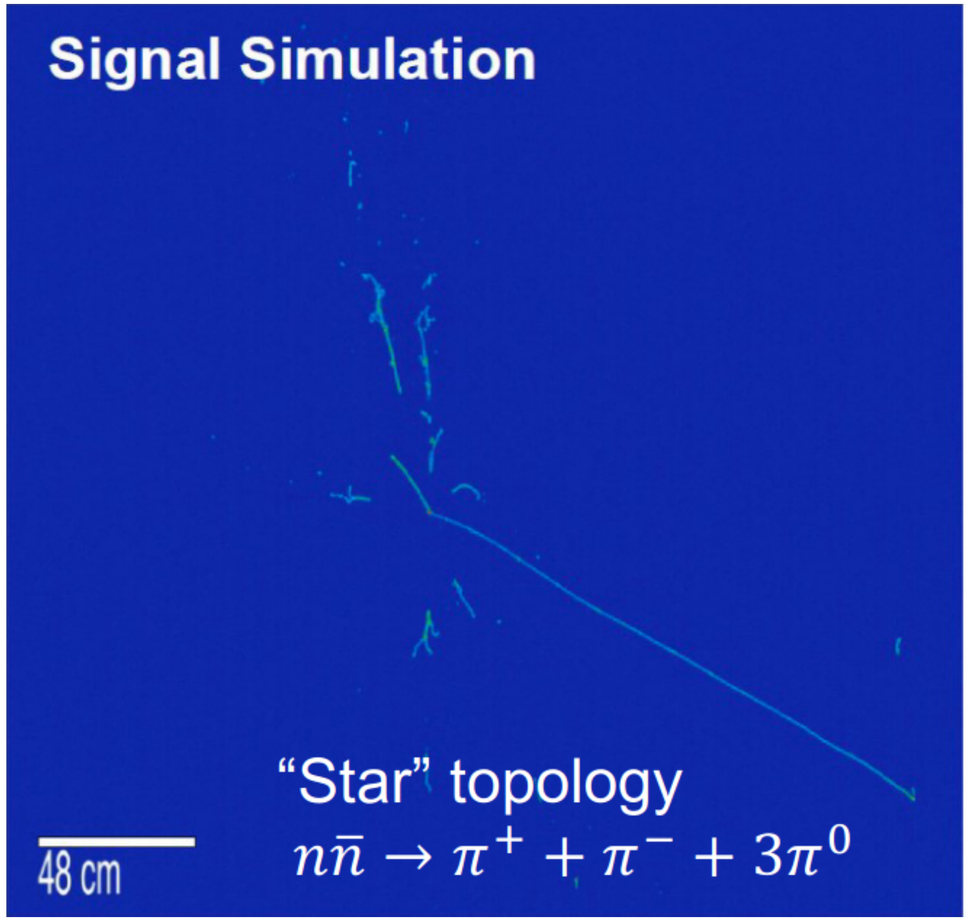
Models \ Reco topology	1e0p	1e1p	1eNp	1eX	e^+e^- + nothing	e^+e^-X	$1\gamma 0p$	$1\gamma 1p$	$1\gamma X$
eV Sterile ν Osc	✔	✔	✔	✔					
Mixed Osc + Sterile ν	✔ [7]	✔ [7]	✔ [7]	✔ [7]			✔ [7]		
Sterile ν Decay	✔ [13,14]	✔ [13,14]	✔ [13.14]	✔ [13,14]			✔ [4,11,12,15]	✔ [4]	✔ [4]
Dark Sector & Z' *	✔ [2,3]				✔ [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

Looking for exotic physics is also looking for MiniBooNE LEE explanations

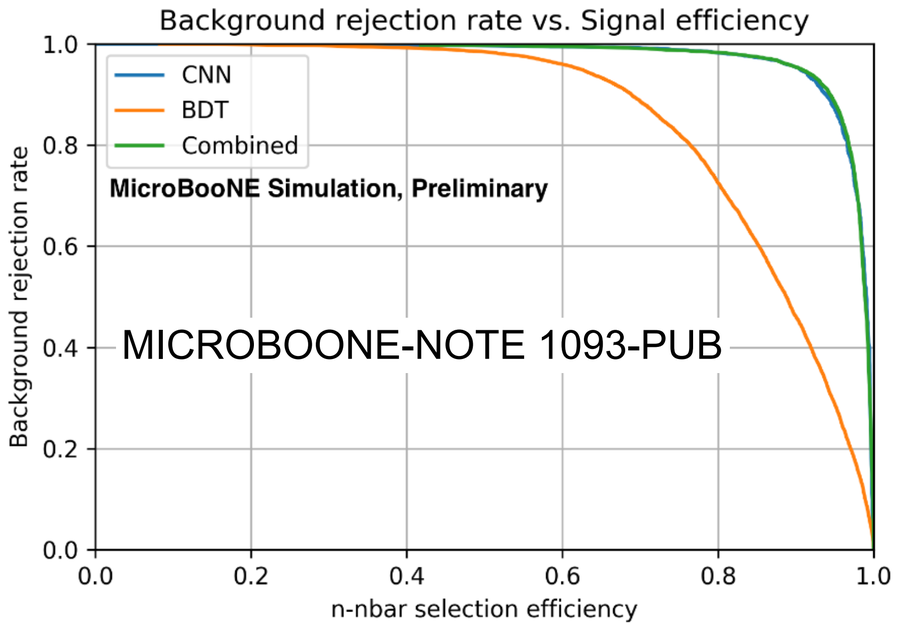
Backup

Neutron-antineutron oscillations

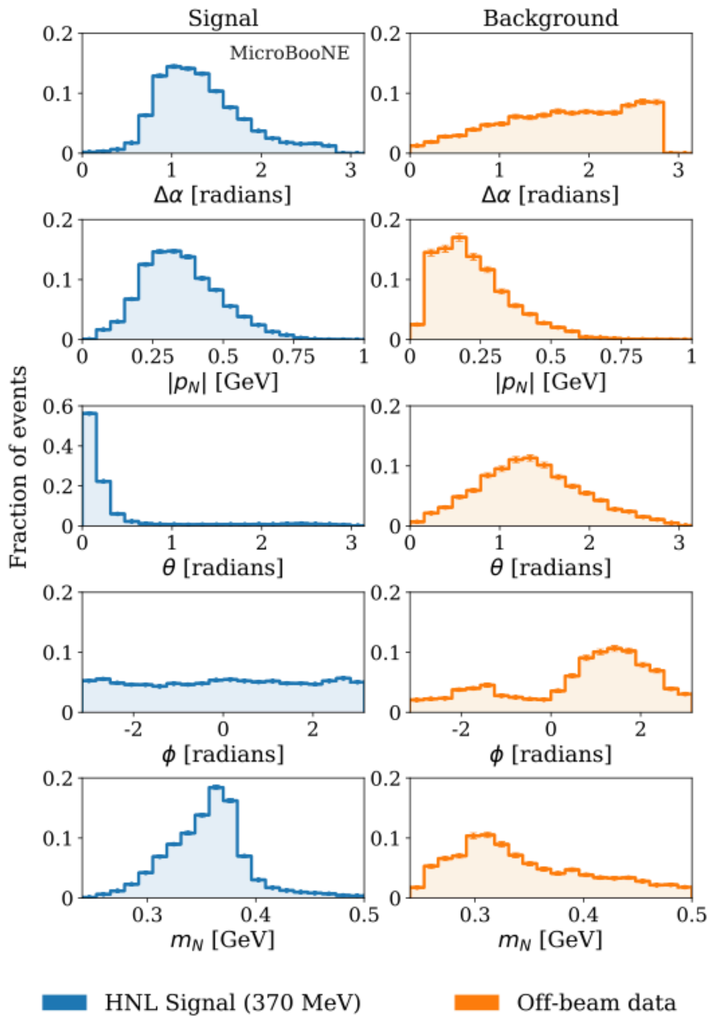


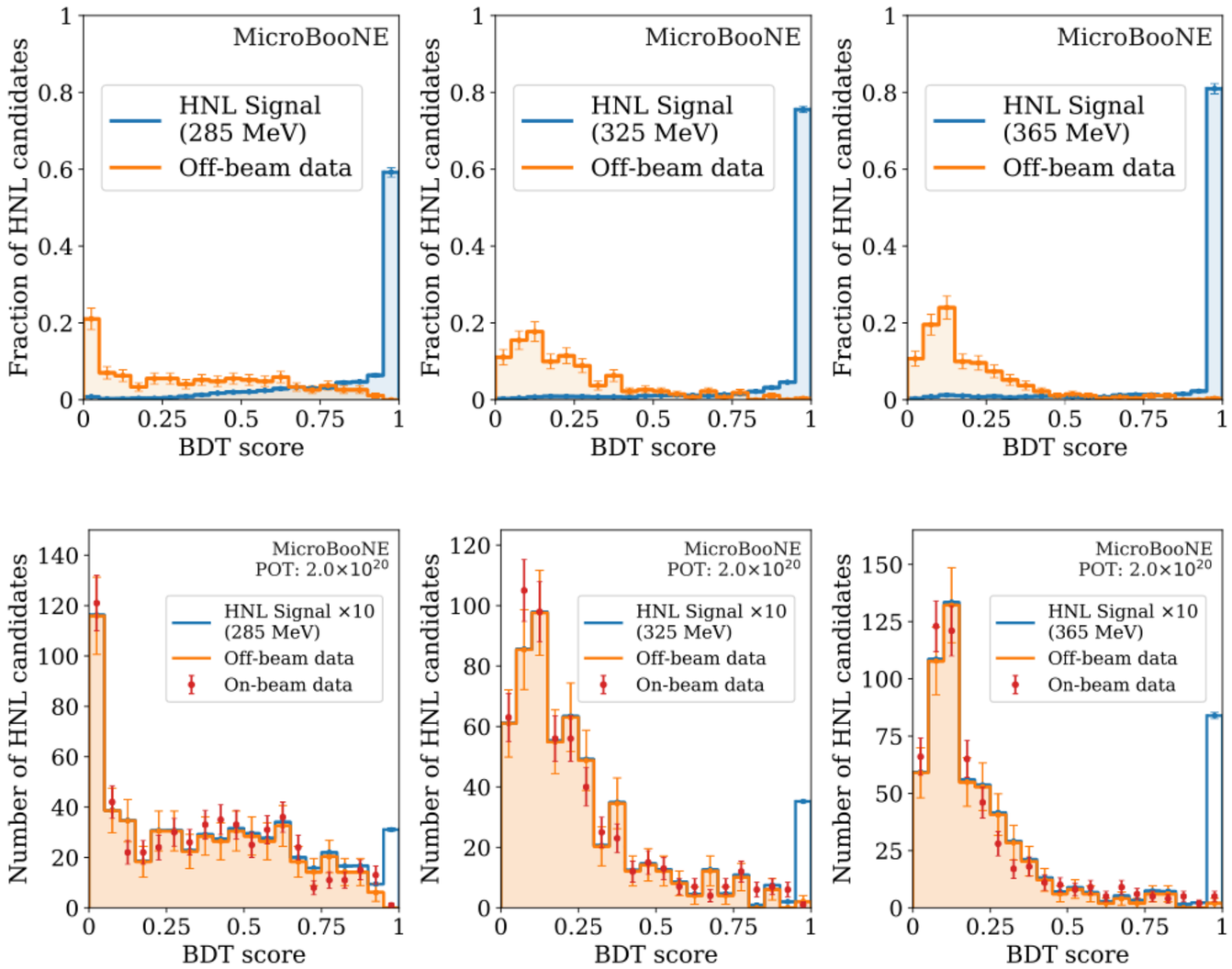
J. Jwa, ICHEP 2020

- Searched for this baryon-number violating process in argon
- Trained a Convolutional Neural Network (CNN) to identify signal over cosmic-induced background
- MicroBooNE pioneered techniques which may be used in DUNE



Heavy Neutral Leptons - BDT Training





MiniBooNE LEE Excess Theory Landscape

- 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

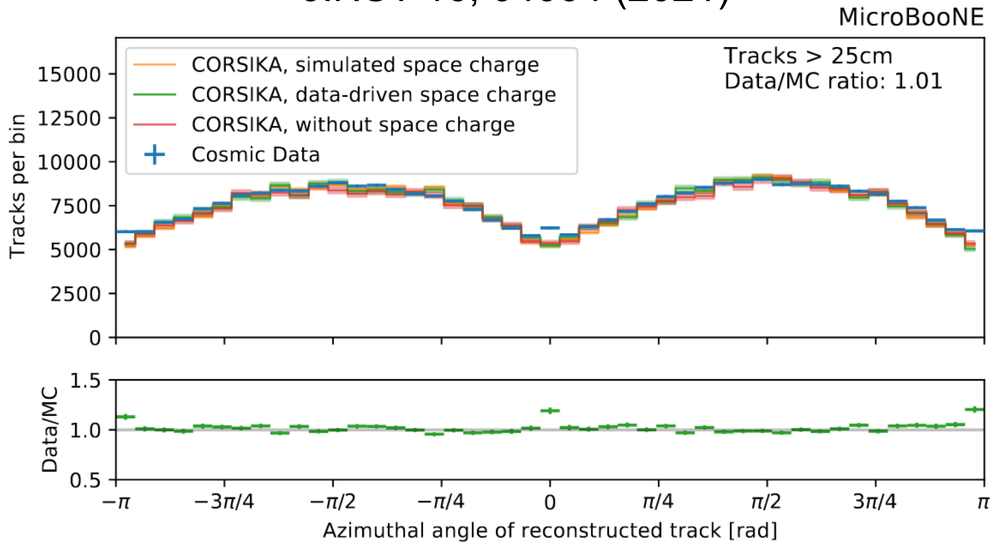
Produces true photons

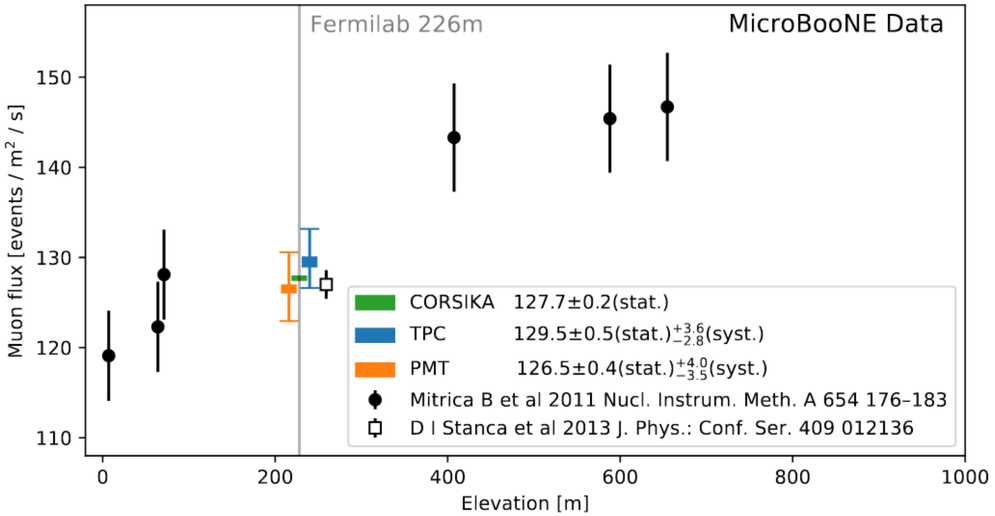
Produces e^+e^- pairs

Cosmic ray rates

- Used MicroBooNE data to measure the rate of cosmic ray muons at the surface at Fermilab
  - First measurement with a LArTPC
- Found good agreement with a CORSIKA simulation
- Useful for tuning cosmic simulation and as an input for future experiments at Fermilab, including SBN program and DUNE

JINST 16, 04004 (2021)





MiniBooNE LEE Models Score Card

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dmLEE

arxiv:2110.11944

- A novel, dark matter based model for the MiniBooNE LEE
- Model with two DM particles and two U(1) dark gauges
- Once DM reaches the detector, can upstater and decay
- e+e- signature
- Very early stages of search