Nevis Laboratories
Columbia University

Exploring Physics Beyond the Standard Model with MicroBooNE

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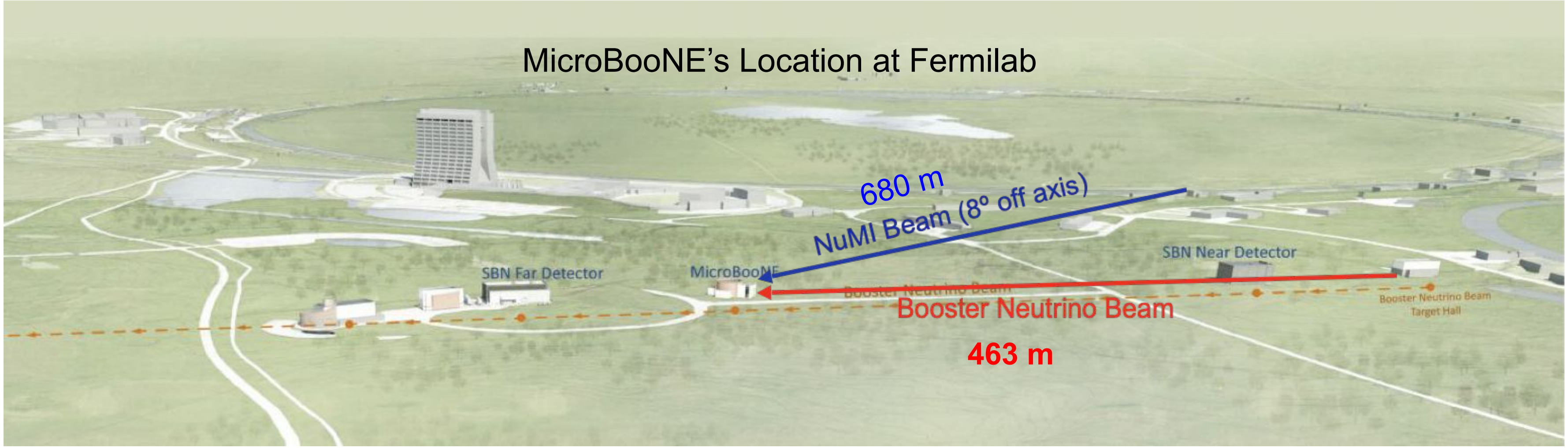
on behalf of MicroBooNE Collaboration

FPCP 2022 (May 25th, 2022)

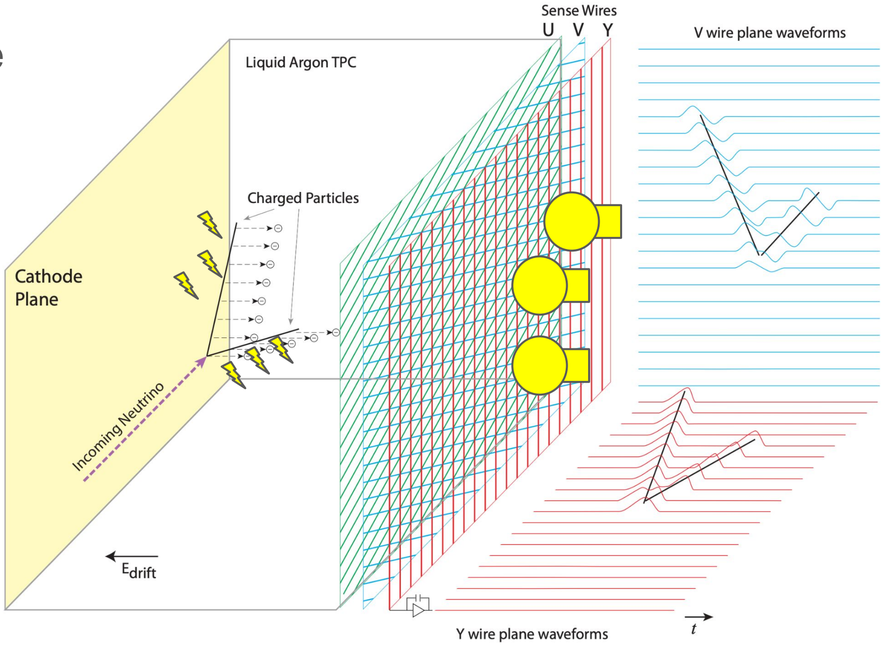
MicroBooNE

- MicroBooNE is an 85 tonne active mass Liquid Argon Time Projection Chamber
- On-axis to Booster Neutrino Beamline (BNB) with 8 GeV proton on target
- Off-axis to Neutrinos at Main Injector (NuMI) beam with 120 GeV proton on target



Liquid Argon Time Projection Chamber (LArTPC)

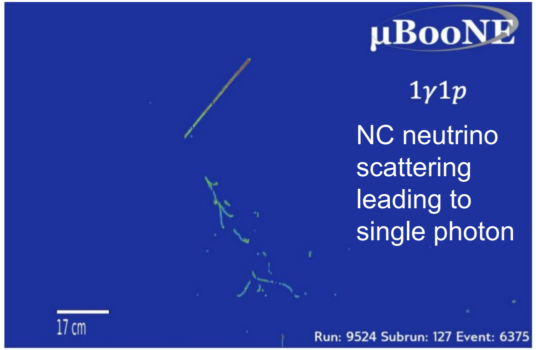
- Particle interactions in the LAr volume can generate charged particles.
  - Charged particles produce ionization electrons and scintillation light.
- Anode plane wires receive ionization electrons and generate signal waveforms.
- Photomultiplier tubes (32 PMTs) lie behind the wires to capture scintillation light.



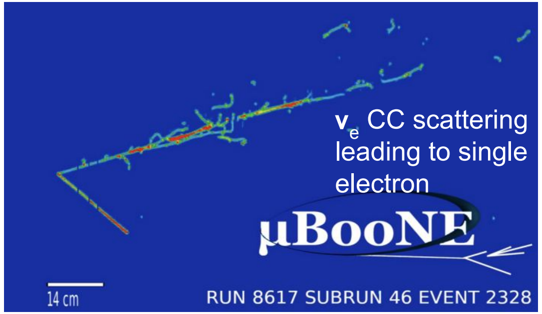
JINST 12(2017)09, P09014

Physics in MicroBooNE

- Primary goal is to investigate MiniBooNE anomalous low energy excess (LEE) (See talk by Giuseppe Cerati)
  - Photon-like
  - Electron-like
- Cross-section measurements
- **BSM searches ← focus of this talk**
  - Neutron-antineutron oscillation (MICROBOONE-NOTE-1113-PUB)
  - Heavy neutral leptons (Phys.Rev.D 101, 052001 (2020))
  - Higgs portal scalars (Phys.Rev.Lett. 127, 151803 (2021))
  - MeV-Scale physics (MICROBOONE-NOTE-1076-PUB)



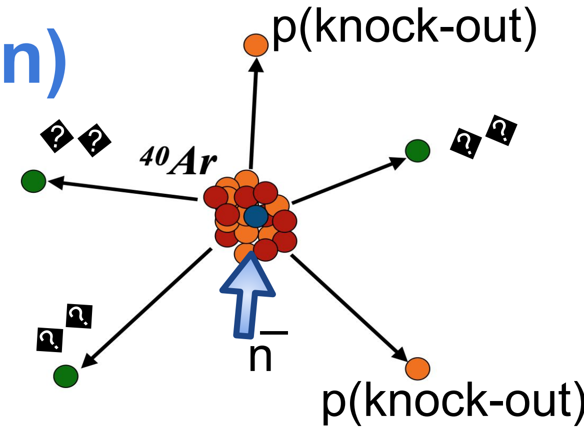
Phys. Rev. Lett. **128**, 111801

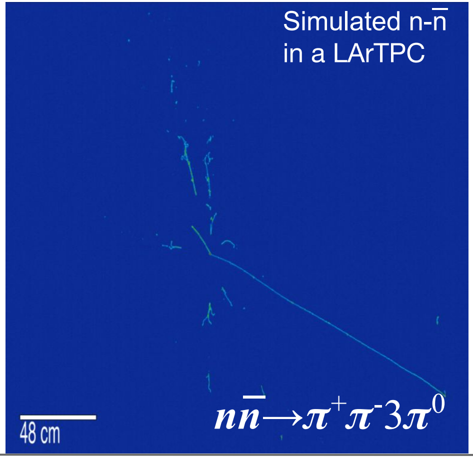


arXiv:2110.14080v2, arXiv:2110.14065 and arXiv:2110.13978 accepted to PRD
arXiv:2110.14054, submitted to PRL

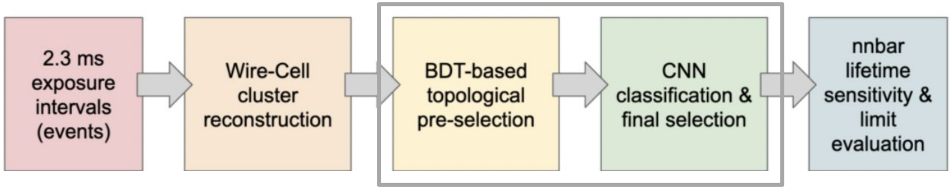
Neutron-Antineutron Oscillation ($\bar{n}$-n)

- n spontaneously transforms itself into $\bar{n}$
  - Baryon number violation ($|\Delta B|=2$)
- $\bar{n}$ annihilates with nearby nucleon
  - ($\bar{n}$, n), ($\bar{n}$, p) annihilation generates multiple pions.
    ⇒ a unique **star-like** topology
- Currently, Super-Kamiokande holds the world's best limit for bound neutrons [Phys. Rev. D **103**, 012008].
  - n-$\bar{n}$ lifetime limit: 3.6×10^{32} years (90% C.L.) for oxygen-bound neutrons.
- **First-ever n-$\bar{n}$ search demonstration using argon-bound neutrons in MicroBooNE.** [MICROBOONE-NOTE-1113-PUB]
  - Proof-of-principle demonstration for future LArTPC: Deep Underground Neutrino Experiment (DUNE).

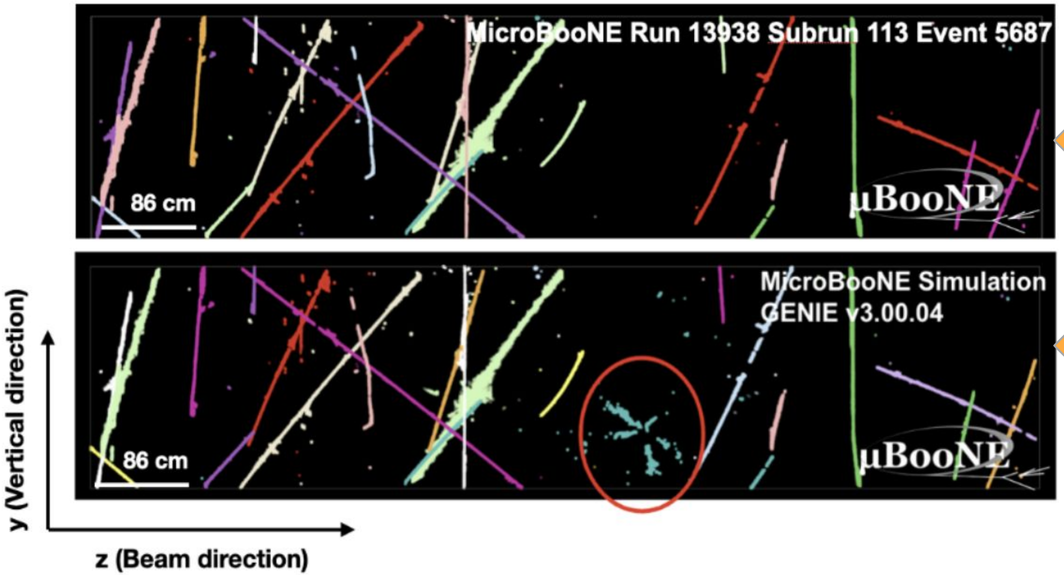




Neutron-Antineutron Oscillation ($\bar{n}$-n)



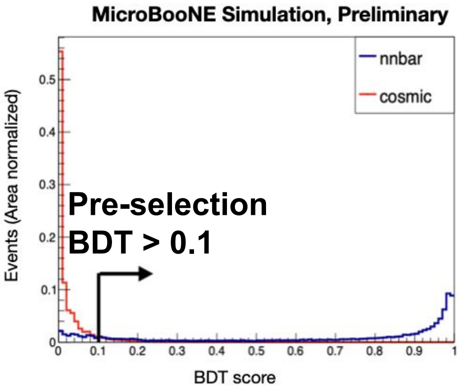
- Reconstructed “clusters” in each interaction are selected by a two-stage selection (see next slide).

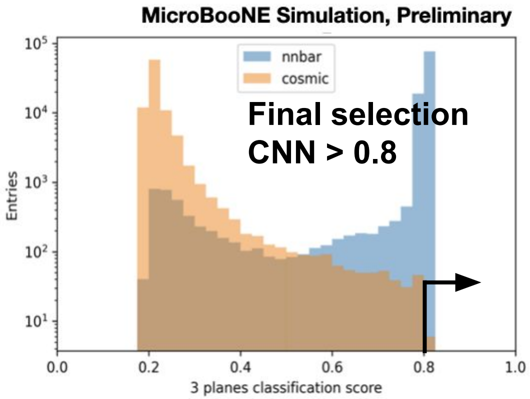


Background “simulation”: off-beam data

Signal simulation: signal interaction simulation overlaid on the background

Neutron-Antineutron Oscillation ($\bar{n}$-n)



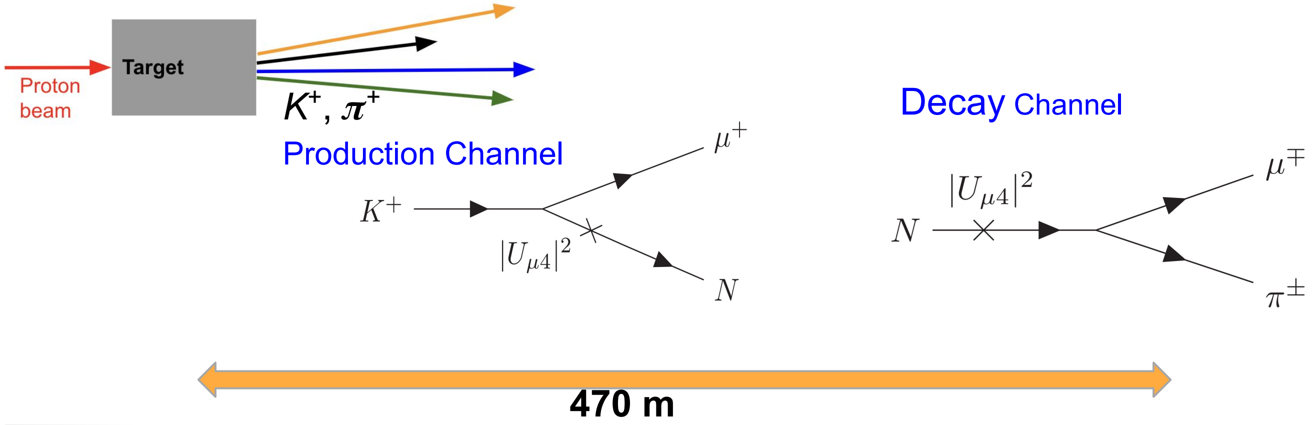


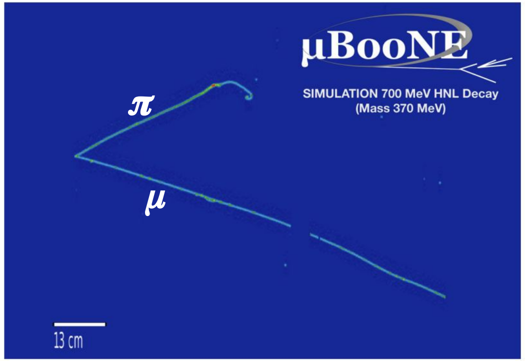
- Boosted decision tree (BDT)-based pre-selection uses shape and size information of clusters.
- Convolutional neural network (CNN)-based final-selection uses image classification.
- **73.6% signal efficiency, 0.0088% background efficiency** is achieved after the final selection.

90% C.L. sensitivity with finite-MC stat. uncertainty is obtained at **3.09×10^{25} years.** Systematic uncertainty evaluation and final validation of the analysis are in progress, aiming for a publication as early as this summer. (for more details: MICROBOONE-NOTE-1113-PUB)

Heavy Neutral Leptons (HNLs)

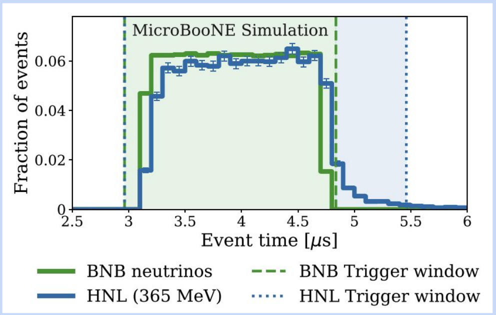
- Heavy right-handed neutral leptons are theoretically motivated within the context of the Standard Model left-handed neutrinos.
- HNLs with mass scale *O*(100) MeV can be searched in MicroBooNE.
  - HNL production in the beam ($K^+ \rightarrow N\mu^+$)
  - HNL decay in the MicroBooNE detector ($N \rightarrow \mu^\mp \pi^\pm$)



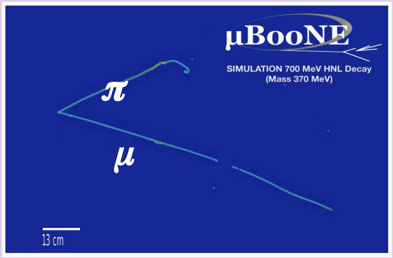


Phys.Rev.D 101, 052001 (2020)

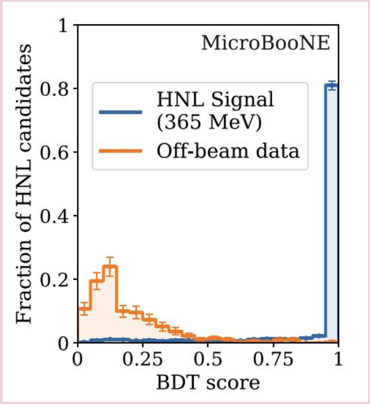
Heavy Neutral Leptons (HNLs)



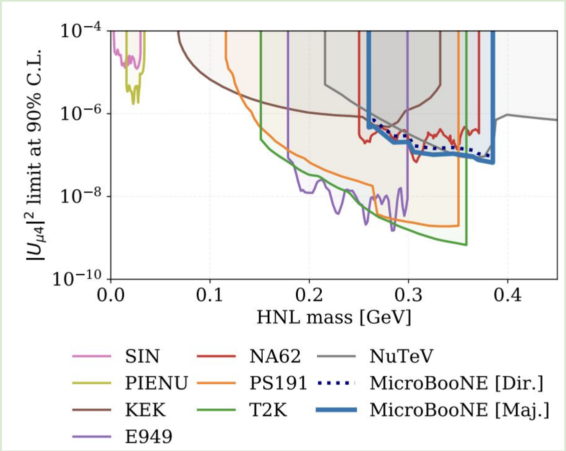
HNL signal is delayed due to the heavier mass than the SM neutrinos:
HNL trigger window is selected to reject neutrino background.



Cuts are applied to select $\mu\pi$ signal with a shared vertex.



BDT is further used to select signal.



No data excess is observed. Limits are set on HNL production rate at 90 C.L.

[Phys.Rev.D 101, 052001 (2020)]

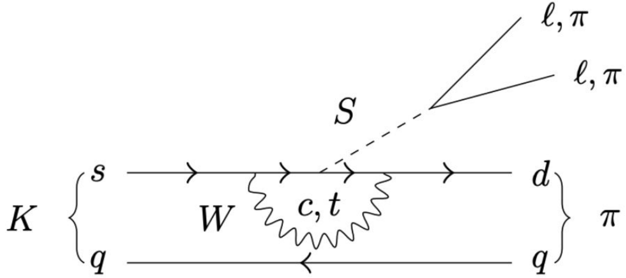
- **Currently, more production channels (kaons from NuMI beam) and decay modes ($e^{\mp}$+ $\pi^{\pm}$) are being explored.**

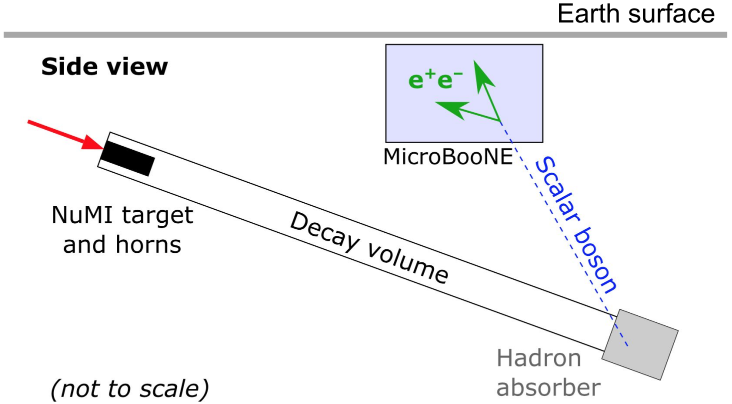
Higgs Portal Scalars

- Theoretically motivated dark scalars (S) in the context of the Higgs portal model that couple with Higgs boson with angle θ.

- Light scalars (<~240 MeV) can be produced from kaons decaying at rest and decays into a pair of leptons.
    - *K→πS at rest ⇒ monoenergetic S*

- This decay at the NuMI hadron absorber can be detected in MicroBooNE.

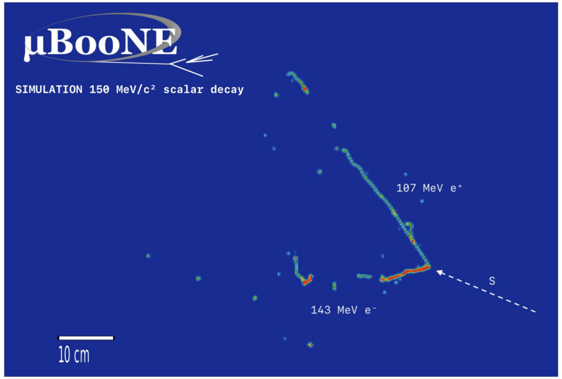


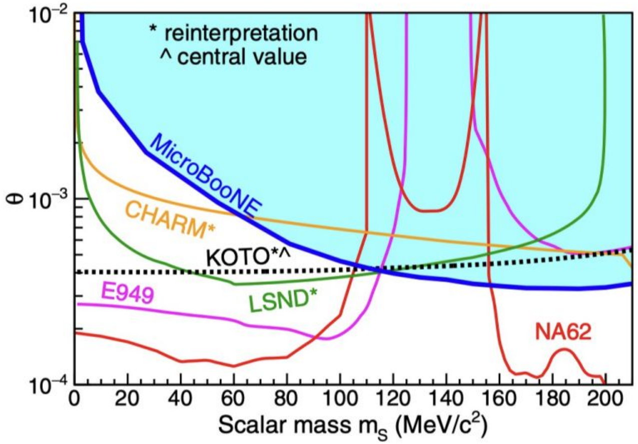


Phys.Rev.Lett. 127, 151803 (2021)

Higgs Portal Scalars

- Preselection requires small vertex distance between two electrons in $S \to e^+e^-$.
- BDTs reject the backgrounds.
- One candidate passes the selection, consistent with expected background 1.9 ±0.8 using an exposure of 1.9×10^{20} POT.
- Upper limit is set on scalar mixing angle θ at 95% CL.
- Current efforts include expanding the search to di-muon pairs and using more statistics.



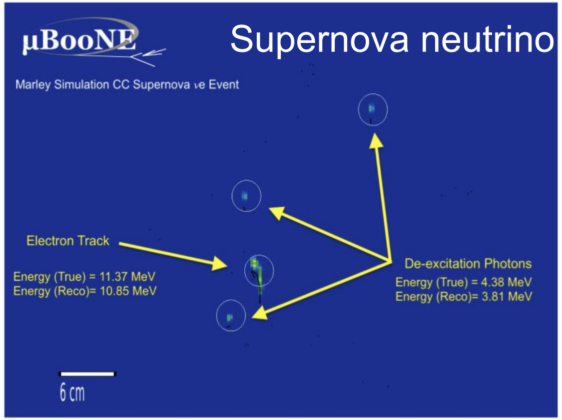


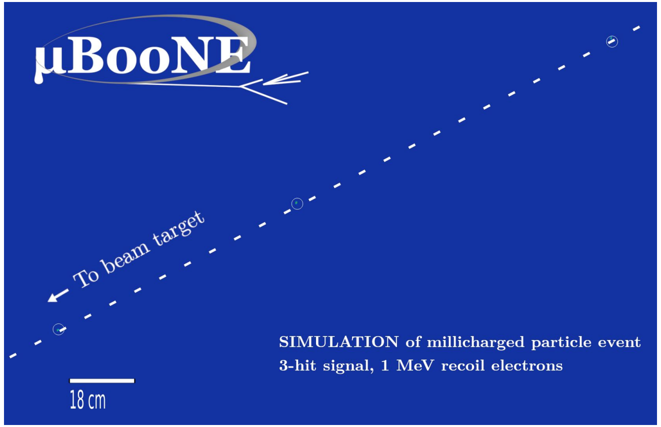
Phys.Rev.Lett. 127, 151803 (2021)

MeV-Scale Physics

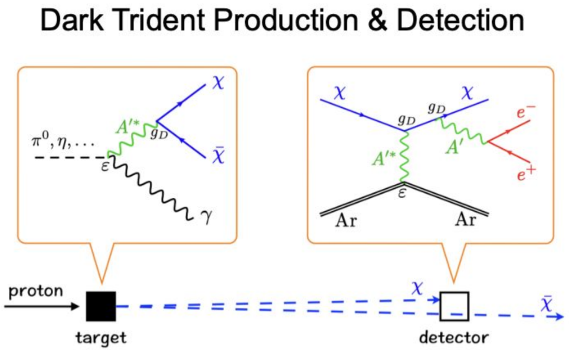
- A dedicated reconstruction technique for low energy (sub-MeV to MeV) ionization and blips is developed
  - based upon the original study in ArgoNeuT [Phys.Rev.D 99, 012002 (2019)].
  - MeV-scale reconstruction is crucial to investigate supernova neutrinos and solar neutrinos in LArTPCs. (for more details, see snowmass White Paper Low Energy Physics in Neutrino LArTPCs [arxiv:2203:00740])
- Search for millicharge particles:
  - Simple extension to the SM with fractional charge (e.g. 0.001e) would violate charge quantisation.
  - Pusing down the reconstruction threshold in LArTPC will allow the search for millicharge particles.

MICROBOONE-NOTE-1076-PUB

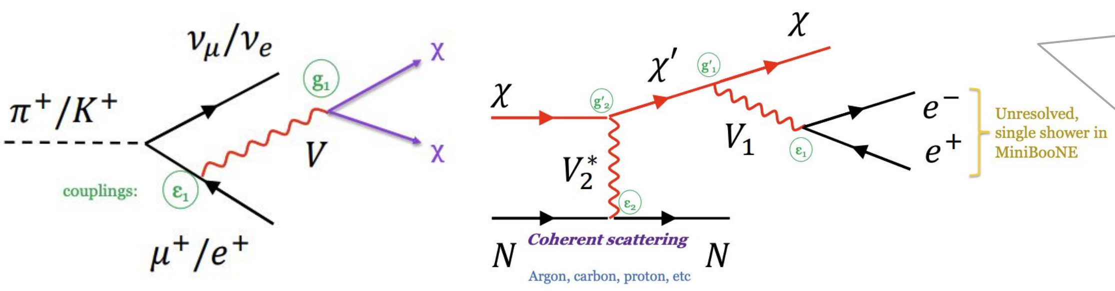




Other BSM searches



Dark Tridents model:
dark matter production with
e^+e^- final states. [JHEP 01(2019) 001]



Dark matter LEE:
dark matter production with e^+e^- final states, aims to explain MiniBooNE low energy excess.
[arxiv:2110.11944]

Summary

- MicroBooNE has demonstrated LArTPC's capability to perform world leading BSM physics searches.
- Exciting publications include:
  - Search for heavy neutral leptons ([Phys.Rev.D 101, 052001 (2020)])
  - Search for Higgs portal scalars ([Phys.Rev.Lett. 127, 151803 (2021)])
- Aiming for publication based on search for neutron-antineutron oscillation [MICROBOONE-NOTE-1113-PUB], this summer.

Stay tuned!

Search for a Higgs Portal Scalar Decaying to Electron-Positron Pairs in the MicroBooNE Detector

P. Abratenko,[35] R. An,[15] J. Anthony,[4] J. Asaadi,[34] A. Ashkenazi,[20,32] S. Balasubramanian,[12] B. Baller,[12] C. Barnes,[21] G. Barr,[25] V. Basque,[19] L. Bathe-Peters,[14] O. Benevides Rodrigues,[31] S. Berkman,[12] A. Bhanderi,[19] A. Bhat,[31] M. Bishai,[2] A. Blake,[17] T. Bolton,[16] J. Y. Book,[14] L. Camilleri,[10] D. Caratelli,[12] I. Caro Terrazas,[9] R. Castillo Fernandez,[12] F. Cavanna,[12] G. Cerati,[12] Y. Chen,[1] D. Cianci,[10] J. M. Conrad,[20] M. Convery,[28] L. Cooper-Troendle,[38] J. I. Crespo-Anadón,[6] M. Del Tutto,[12] S. R. Dennis,[4] D. Devitt,[17] R. Diurba,[22] R. Dorrill,[15] K. Duffy,[12] S. Dytman,[26] B. Eberly,[30] A. Ereditato,[1] J. J. Evans,[19] R. Fine,[18] G. A. Fiorentini Aguirre,[29] R. S. Fitzpatrick,[21] B. T. Fleming,[38] N. Foppiani,[14] D. Franco,[38] A. P. Furmanski,[22] D. Garcia-Gamez,[13] S. Gardiner,[12] G. Ge,[10] S. Gollapinni,[33,18] O. Goodwin,[19] E. Gramellini,[12] P. Green,[19] H. Greenlee,[12] W. Gu,[2]

arXiv:2106.00568v2 [hep-ex] 29 Sep 2021

Search for heavy neutral leptons decaying into muon-pion pairs in the MicroBooNE detector

P. Abratenko,[35] M. Alrashed,[15] R. An,[14] J. Anthony,[4] J. Asaadi,[34] A. Ashkenazi,[19] S. Balasubramanian,[38] B. Baller,[11] C. Barnes,[20] G. Barr,[24] V. Basque,[18] S. Berkman,[11] A. Bhanderi,[18] A. Bhat,[31] M. Bishai,[2] A. Blake,[16] T. Bolton,[15] L. Camilleri,[9] D. Caratelli,[11] I. Caro Terrazas,[8] R. Castillo Fernandez,[11] F. Cavanna,[11] G. Cerati,[11] Y. Chen,[1] E. Church,[25] D. Cianci,[9] E. O. Cohen,[32] J. M. Conrad,[19] M. Convery,[29] L. Cooper-Troendle,[38] J. I. Crespo-Anadón,[9] M. Del Tutto,[13,11] D. Devitt,[16] L. Domine,[29] K. Duffy,[11] S. Dytman,[26] B. Eberly,[10] A. Ereditato,[1] L. Escudero Sanchez,[4] J. J. Evans,[18] R. S. Fitzpatrick,[20] B. T. Fleming,[38] N. Foppiani,[13] D. Franco,[38] A. P. Furmanski,[18,21] D. Garcia-Gamez,[12] S. Gardiner,[11] V. Genty,[9] D. Goeldi,[1] S. Gollapinni,[33,17] O. Goodwin,[18] E. Gramellini,[11] P. Green,[18] H. Greenlee,[11] L. Gu,[36] W. Gu,[2] R. Guenette,[13] P. Guzowski,[18] P. Hamilton,[31] O. Hen,[19] C. Hill,[18] G. A. Horton-Smith,[15] A. Hourlier,[19] E.-C. Huang,[17] R. Itay,[29] C. James,[11] J. Jan de Vries,[4] X. Ji,[2] L. Jiang,[26,36] J. H. Jo,[38] R. A. Johnson,[7] J. Joshi,[2] Y.-J. Jwa,[9] G. Karagiorgi,[9] W. Ketchum,[11] B. Kirby,[2] M. Kirby,[11] T. Kobilarcik,[11] I. Kreslo,[1] R. LaZur,[8] I. Lepetic,[14] Y. Li,[2] A. Lister,[16] B. R. Littlejohn,[14] S. Lockwitz,[11] D. Lorca,[1] W. C. Louis,[17] M. Luethi,[1] B. Lundberg,[11] X. Luo,[38,3] A. Marchionni,[11] S. Marcocci,[11] C. Mariani,[36] J. Marshall,[37] J. Martin-Albo,[13] D. A. Martinez Caicedo,[30] K. Mason,[35] A. Mastbaum,[6,27] N. McConkey,[18] V. Meddage,[15] T. Mettler,[1] K. Miller,[6] J. Mills,[35] K. Mistry,[18] A. Mogan,[33] T. Mohayai,[11] J. Moon,[19] M. Mooney,[8] C. D. Moore,[11] J. Mousseau,[20] R. Murrells,[18] D. Naples,[26] R. K. Neely,[15] P. Nienaber,[28] J. Nowak,[16] O. Palamara,[11] V. Pandey,[36] V. Paolone,[26] A. Papadopoulou,[19] V. Papavassiliou,[22] S. F. Pate,[22] A. Paudel,[15] Z. Pavlovic,[11] E. Piasetzky,[32] D. Porzio,[18] S. Prince,[13] G. Pulliam,[31] X. Qian,[2] J. L. Raaf,[11] V. Radeka,[2] A. Rafique,[15] L. Ren,[22] L. Rochester,[29] H. E. Rogers,[8,5] M. Ross-Lonergan,[9] C. Rudolf von Rohr,[1] B. Russell,[38] G. Scanavini,[38] D. W. Schmitz,[6] A. Schukraft,[11] W. Seligman,[9] M. H. Shaevitz,[9] R. Sharankova,[35] J. Sinclair,[1] A. Smith,[4] E. L. Snider,[11] M. Soderberg,[31] S. Söldner-Rembold,[18] S. R. Soleti,[24,13] P. Spentzouris,[11] J. Spitz,[20] M. Stancari,[11] J. St. John,[11] T. Strauss,[11] K. Sutton,[9] S. Sword-Fehlberg,[22] A. M. Szelc,[18] N. Tagg,[23] W. Tang,[33] K. Terao,[29] R. T. Thornton,[17] M. Toups,[11] Y.-T. Tsai,[29] S. Tufanli,[38] M. A. Uchida,[4] T. Usher,[29] W. Van De Pontseele,[24,13] R. G. Van de Water,[17] B. Viren,[2] M. Weber,[1] H. Wei,[2] D. A. Wickremasinghe,[26] Z. Williams,[34] S. Wolbers,[11] T. Wongjirad,[35] K. Woodruff,[22] M. Wospakrik,[11] W. Wu,[11] T. Yang,[11] G. Yarbrough,[33] L. E. Yates,[19] G. P. Zeller,[11] J. Zennamo,[11] and C. Zhang[2]

(The MicroBooNE Collaboration)*

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Thank you!