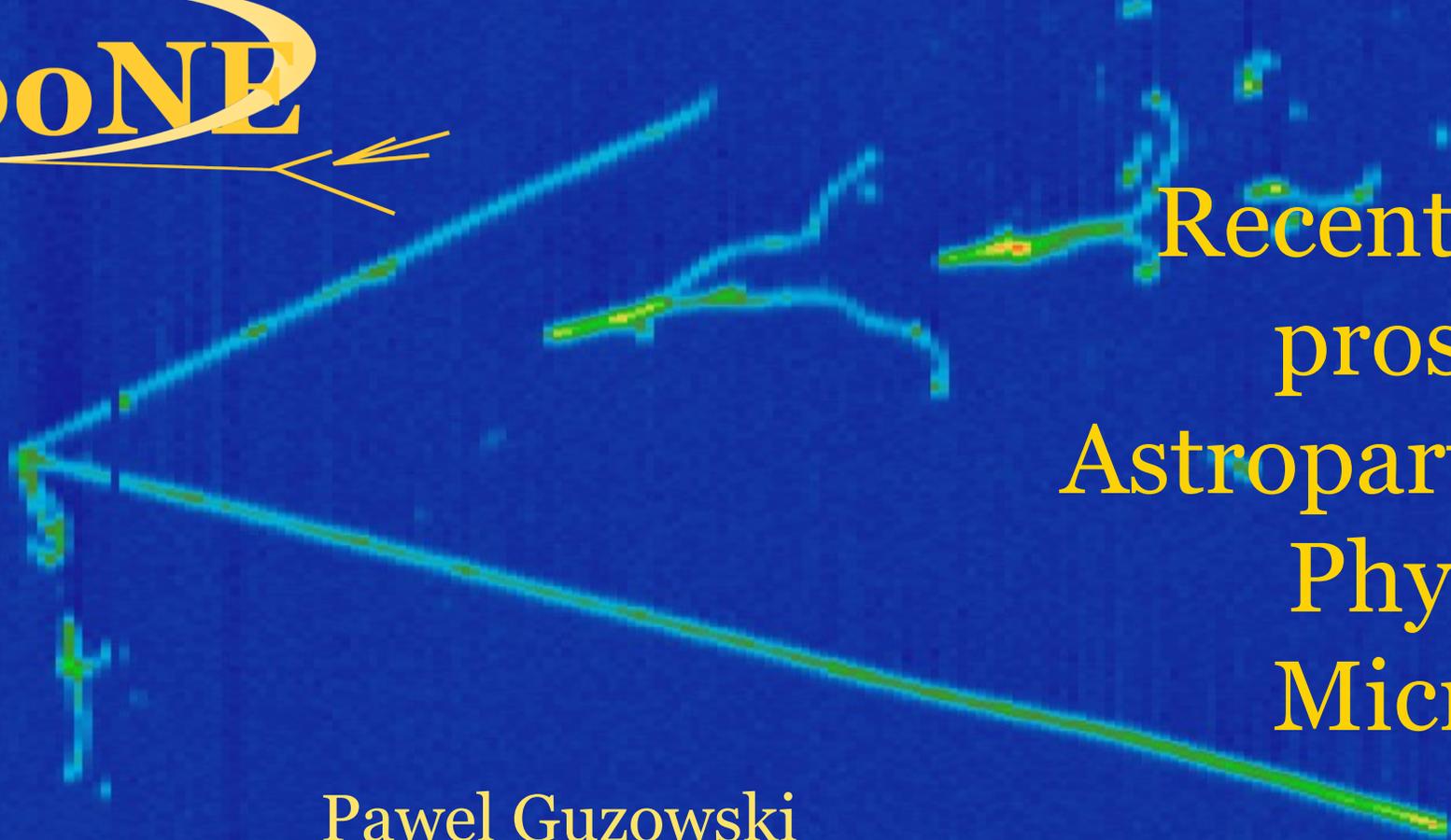


The logo for MicroBooNE, featuring the Greek letter mu followed by 'BooNE' in a stylized font, with a yellow oval and three arrows pointing to the right.

μ BooNE

A visualization of particle tracks within a detector, showing a central vertex from which several tracks emerge and interact with other particles, depicted as glowing green and blue lines against a dark blue background.

Recent results and
prospects for
Astroparticle and BSM
Physics with
MicroBooNE

Pawel Guzowski

The University of Manchester

On behalf of the MicroBooNE Collaboration

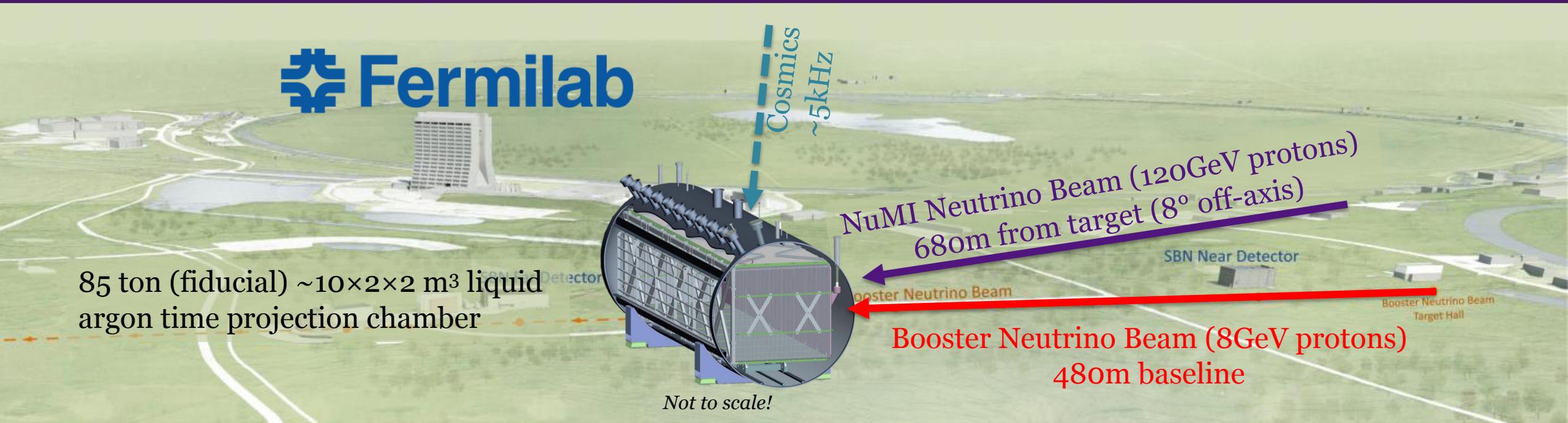
NeuTel 2021 – 23 Feb 2021

The University of Manchester logo, consisting of the word 'MANCHESTER' in white capital letters above the year '1824' in a smaller font, all set against a purple rectangular background.

MANCHESTER
1824

The University of Manchester

Introduction



Goals of the experiment:

Investigate the MiniBooNE anomalous excess

- Mark Ross-Lonergan – Tue sterile parallel
- Hanyu Wei – Tue sterile parallel
- Andrew Mogan – Fri sterile flash

Cross-section measurements

- Marina Reggiani Guzzo – Fri cross-section flash
- Wenqiang Gu – Fri cross-section flash
- Krishan Mistry – Fri cross-section parallel

LArTPC detector physics, research and development

- Maya Wospakrik – Wed detector parallel

Diverse variety of other topics in astroparticle and exotic physics, that MicroBooNE is capable of (this talk)

Liquid argon time projection chamber capabilities

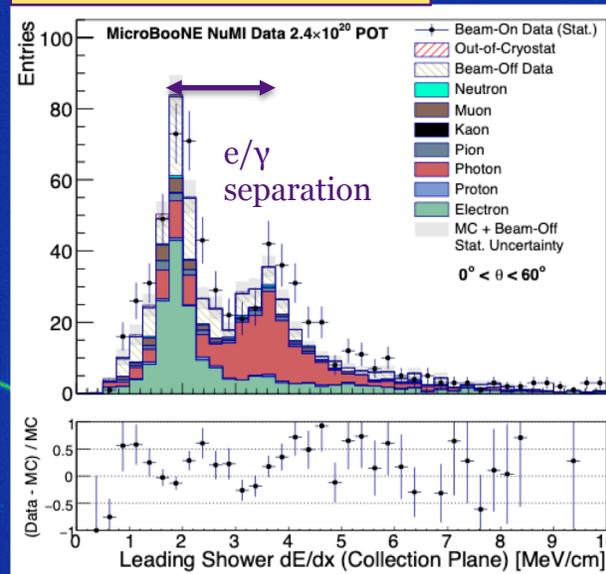
For more details on the detector principles: please see talks by Krishan Mistry and Maya Wospakrik

Liquid Argon Time Projection Chamber
“digital bubble chamber”

μ BooNE

arXiv:2101.04228

Particle ID by dE/dx



100 keV hit thresholds

75 cm

10 cm

Four protons resolved

3mm spatial resolution

BNB DATA : RUN 5211 EVENT 1225. FEBRUARY 29, 2016

Excellent spatial and charge resolution allows for unprecedented PID, and interesting *new physics searches via anomalous final state topologies*

Astroparticle and exotic physics with MicroBooNE

- Results released in 2020

- Informing and developing for future experiments

- Supernova neutrino R&D
- Cosmic rate measurement
- Baryon number violation

- Pushing reconstruction capabilities

- MeV-scale physics

- Searches for new physics

- Heavy neutral leptons
- ‘Higgs Portal’ dark scalars

- Some prospects for future results

Journal of Instrumentation

The continuous readout stream of the MicroBooNE liquid argon time projection chamber for detection of supernova burst neutrinos

To cite this article: P. Abratenko et al 2021, JINST 16 P03008

View the article

Progress Toward the First Search for Bound Neutron Oscillation into Antineutrino in a Liquid Argon TPC

MICROBOONE-NOTE-1093-PUB

The MicroBooNE Collaboration

August 3, 2020

PHYSICAL REVIEW D 101, 052001 (2020)

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

P. Abratenko,¹⁰ M. Alrashed,¹³ R. An,¹⁴ J. Anthony,⁴ J. Asadi,¹⁴ A. Ashkenazi,¹⁰ S. Balasubramanian,¹⁰ C. Barnes,² G. Barr,² V. Basque,¹ S. Berkman,¹ A. Bhandari,¹ A. Bhat,¹ M. Bishai,¹ A. Blake,¹ L. Camilleri,¹ D. Caratelli,¹ I. Caro Terrazas,¹ R. Castillo Fernandez,¹ F. Cavanna,¹ G. Cerati,¹ Y. C. D. Cianci,¹ E. O. Cohen,² J. M. Conrad,¹⁰ M. Convery,¹⁰ L. Cooper-Treondle,¹⁰ J. I. Crespo-Anadón,⁹ D. Devin,¹ L. Dominge,² K. Duffy,¹ S. Dyman,²⁰ B. Eberly,¹ A. Ereditato,¹ L. Escudero Sanchez,¹ R. S. Fitzpatrick,² B. T. Fleming,²⁰ N. Fogliani,¹ D. Franco,¹⁴ A. P. Furusawa,^{10,21} D. Garcia-Gonzalez,¹ V. Getty,¹ D. Goeldi,¹ S. Gollaputti,^{10,17} O. Goodwin,¹⁸ E. Granelini,¹¹ P. Green,¹⁸ H. Greenlee,¹¹ R. Gugena,¹ P. Guzowski,¹ P. Hamilton,¹ O. Hen,¹ C. Hill,¹ G. A. Horton-Smith,¹ A. Hourigan,¹ R. Iley,² C. James,¹¹ J. Jan de Vries,²⁰ X. Ji,¹ L. Jiang,²⁰ J. H. Kim,¹ R. A. Johnson,¹ J. Joshi,¹ Y. J. Joo,¹ W. Ketchum,¹ B. Kirby,¹ M. Kirby,¹ T. Kobharlikar,¹ I. Kreslo,¹ R. LaZar,¹ L. Lepetit,¹⁴ Y. Li,¹ B. R. Littlejohn,¹ S. Lockwitz,² D. Lorea,¹ W. C. Louis,¹ M. Lucchi,¹ B. Lundberg,¹ X. Luo,¹⁰ S. Marocco,¹¹ C. Mariani,²⁰ J. Marshall,¹ J. Martin-Albo,¹⁰ D. A. Martinis-Calcio,¹⁰ K. Mason,¹⁰ N. McCloskey,¹⁴ V. Medjaga,¹¹ T. Mettler,¹ K. Miller,¹ J. Mills,¹⁰ K. Mistry,¹ A. Morgan,²¹ T. Mohr,¹ M. Mooney,¹ C. D. Moore,¹ J. Mousseau,²⁰ R. Murrells,¹⁰ D. Naples,²⁰ R. K. Neely,¹⁰ P. Nienabe,¹ O. Palamara,¹ V. Pandey,² V. Paolone,¹ A. Papadopoulos,¹ V. Papavasiliou,¹ S. F. Paté,¹ A. Paule,¹ E. Pascazzy,¹⁰ D. Porziani,¹ S. Ponce,¹ G. Pulliam,¹⁰ X. Qian,¹ H. L. Raaf,¹ V. Rajkovic,¹ A. Raff,¹ L. Rochester,¹ H. E. Rogers,¹⁰ M. Ross-Lonsinger,¹ C. Radloff von Rohr,¹ B. Russell,¹⁰ G. Scavani,¹ A. Schukraft,¹ W. Seligman,¹ M. H. Shaevitz,¹ R. Sharankov,¹ J. Sinclair,¹ A. Smith,¹ E. L. Snider,¹ S. Soltesz-Rembold,¹⁰ S. R. Soletki,^{10,11} P. Spentzos,¹⁰ J. J. Spin,²⁰ M. Stancari,¹¹ J. St. John,¹¹ T. Sme,¹ S. Sword-Fehlberg,²² A. M. Szelc,¹⁸ N. Tapp,²¹ W. Tang,¹⁰ K. Terao,²⁰ R. T. Thornton,¹⁰ M. Toups,¹ S. Tufanli,¹ M. A. Uchida,¹ T. Usher,²⁰ W. Van De Pottsele,^{10,11} R. G. Van De Water,¹ B. Viren,¹ M. D. A. Wickremasinghe,²² Z. Williams,¹⁰ S. Wolthers,¹ T. Wongjittakul,¹ K. Woodruff,¹ M. Wosycki,¹¹ W. G. Yarbrough,¹¹ L. E. Yates,¹⁰ G. P. Zeller,¹¹ J. Zennaro,¹¹ and C. Zhang²

(The MicroBooNE Collaboration)

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PREPARED FOR SUBMISSION TO JINST

Measurement of the Atmospheric Muon Rate with the MicroBooNE Liquid Argon TPC

P. Abratenko¹⁰, M. Alrashed¹³, R. An¹⁴, J. Anthony⁴, J. Asadi¹⁴, A. Ashkenazi¹⁰, S. Balasubramanian¹⁰, C. Barnes², G. Barr², V. Basque¹, M. Bhat¹, M. Bishai¹, A. Blake¹, L. Camilleri¹, D. Caratelli¹, I. Caro Terrazas¹, R. Castillo Fernandez¹, F. Cavanna¹, G. Cerati¹, Y. C. D. Cianci¹, E. O. Cohen², J. M. Conrad¹⁰, M. Convery¹⁰, L. Cooper-Treondle¹⁰, J. I. Crespo-Anadón⁹, D. Devin¹, L. Dominge², K. Duffy¹, S. Dyman²⁰, B. Eberly¹, A. Ereditato¹, L. Escudero Sanchez¹, R. S. Fitzpatrick², B. T. Fleming²⁰, N. Fogliani¹, D. Franco¹⁴, A. P. Furusawa^{10,21}, D. Garcia-Gonzalez¹, V. Getty¹, D. Goeldi¹, S. Gollaputti^{10,17}, O. Goodwin¹⁸, E. Granelini¹¹, P. Green¹⁸, H. Greenlee¹¹, R. Gugena¹, P. Guzowski¹, P. Hamilton¹, O. Hen¹, C. Hill¹, G. A. Horton-Smith¹, A. Hourigan¹, R. Iley², C. James¹¹, J. Jan de Vries²⁰, X. Ji¹, L. Jiang²⁰, J. H. Kim¹, R. A. Johnson¹, J. Joshi¹, Y. J. Joo¹, W. Ketchum¹, B. Kirby¹, M. Kirby¹, T. Kobharlikar¹, I. Kreslo¹, R. LaZar¹, L. Lepetit¹⁴, Y. Li¹, B. R. Littlejohn¹, S. Lockwitz², D. Lorea¹, W. C. Louis¹, M. Lucchi¹, B. Lundberg¹, X. Luo¹⁰, S. Marocco¹¹, C. Mariani²⁰, J. Marshall¹, J. Martin-Albo¹⁰, D. A. Martinis-Calcio¹⁰, K. Mason¹⁰, N. McCloskey¹⁴, V. Medjaga¹¹, T. Mettler¹, K. Miller¹, J. Mills¹⁰, K. Mistry¹, A. Morgan²¹, T. Mohr¹, M. Mooney¹, C. D. Moore¹, J. Mousseau²⁰, R. Murrells¹⁰, D. Naples²⁰, R. K. Neely¹⁰, P. Nienabe¹, O. Palamara¹, V. Pandey², V. Paolone¹, A. Papadopoulos¹, V. Papavasiliou¹, S. F. Paté¹, A. Paule¹, E. Pascazzy¹⁰, D. Porziani¹, S. Ponce¹, G. Pulliam¹⁰, X. Qian¹, H. L. Raaf¹, V. Rajkovic¹, A. Raff¹, L. Rochester¹, H. E. Rogers¹⁰, M. Ross-Lonsinger¹, C. Radloff von Rohr¹, B. Russell¹⁰, G. Scavani¹, A. Schukraft¹, W. Seligman¹, M. H. Shaevitz¹, R. Sharankov¹, J. Sinclair¹, A. Smith¹, E. L. Snider¹, S. Soltesz-Rembold¹⁰, S. R. Soletki^{10,11}, P. Spentzos¹⁰, J. J. Spin²⁰, M. Stancari¹¹, J. St. John¹¹, T. Sme¹, S. Sword-Fehlberg²², A. M. Szelc¹⁸, N. Tapp²¹, W. Tang¹⁰, K. Terao²⁰, R. T. Thornton¹⁰, M. Toups¹, S. Tufanli¹, M. A. Uchida¹, T. Usher²⁰, W. Van De Pottsele^{10,11}, R. G. Van De Water¹, B. Viren¹, M. D. A. Wickremasinghe²², Z. Williams¹⁰, S. Wolthers¹, T. Wongjittakul¹, K. Woodruff¹, M. Wosycki¹¹, W. G. Yarbrough¹¹, L. E. Yates¹⁰, G. P. Zeller¹¹, J. Zennaro¹¹, and C. Zhang²

July 2020

MeV-scale Physics in MicroBooNE

MICROBOONE-NOTE 1076-PUB

The MicroBooNE Collaboration

Abstract: The scope of this public note is to present preliminary measurements of MeV energy signatures and relevant backgrounds for beam neutrino interactions using a dedicated reconstruction using this model.

Search for a Higgs Portal scalar decaying to electron-positron pairs in MicroBooNE

MICROBOONE-NOTE-1092-PUB

The MicroBooNE Collaboration

July 2020

We present a search for the decays of a neutral scalar boson produced by kaons decaying at rest, in the context of the Higgs Portal model, using the MicroBooNE detector. We analyze data triggered in time with the Fermilab NuMI neutrino beam spill, with an exposure of 1.93×10^{10} protons on target. We look for monoenergetic scalars coming from the direction of the NuMI hadron absorber, 100 m away from the detector, and decaying to electron-positron pairs. We observe 5 candidate events, with a Standard Model background prediction of 2.0 ± 0.8 . We set an upper limit on the scalar-Higgs mixing angle α of $(4.1 - 5.8) \times 10^{-4}$ at the 90% confidence level, for scalar masses in the range (100 – 200) MeV/c². We exclude at the 90% confidence level the remaining model parameters required to explain the central value of the KOTO anomalous excess of $K_L^0 \rightarrow \pi^0 \pi^0$ invisible decays using this model.

I. INTRODUCTION

The Higgs Portal model [1] is an extension to the Standard Model, where an electrically-neutral real singlet scalar boson (S) mixes with the Higgs boson with mixing angle θ . Through this mixing, it acquires a coupling to Standard Model fermions via their Yukawa couplings with the Higgs boson, and proportional to $\sin\theta$. For the scalar mass in the range (100 – 200) MeV/c², and assuming that there are no new dark sector particles lighter than half its mass, S will decay to electron-positron pairs with partial width [2]

$$\Gamma = \theta^2 \frac{m_e^2 m_S}{32\pi^2} \left(1 - \frac{4m_e^2}{m_S^2}\right), \quad (1)$$

where m_S is the scalar mass, m_e the electron mass, and v the Higgs field vacuum expectation value. For these masses, S can be produced from kaon two-body decays in association with pions, with the dominant production process being a penguin diagram with a top quark running in the loop. The partial width of the production process is [2]

$$\Gamma \approx \frac{\theta^2}{16\pi m_K} \left| \frac{3V_{cb}^* V_{cs} m_K^2 m_S^2}{32\pi^2 m_b^2} \right|^2 \lambda^{1/2} \left(1, \frac{m_S^2}{m_K^2}, \frac{m_S^2}{m_K^2}\right), \quad (2)$$

where m_K is the kaon mass, m_b the pion mass, m_t the top quark mass, V_{ij} and V_{ij}^* the elements of the CKM matrix, and λ the Källen Lambda function.

Recently, the KOTO collaboration has reported [3] the anomalous excess of $K_L^0 \rightarrow \pi^0 \pi^0$ invisible decays, two orders of magnitude more frequent than the Standard Model prediction for $K_L^0 \rightarrow \pi^0 \pi^0$ decays. The Higgs Portal model could explain the high rate of these decays, with the required model parameter θ value $\sim (5 - 7) \times 10^{-4}$ over the scalar mass range (100 – 200) MeV/c² to agree with KOTO central value branching ratio [4]. There are experimental limits that exclude this central value for $m_S < 118$ MeV/c² by the E989 experiment [5] and $m_S > 160$ MeV/c² by the NA62 experiment [6]. Data from the CHARM [7] experiment is also sensitive to this model, however this requires reinterpretation of the experiment's search for axon-like particles decaying to electron-positron pairs, and different phenomenology groups [4, 8, 9] have different estimates of the kaon fluxes and scalar acceptances observed by CHARM. Taking the most sensitive of these estimates [4], the KOTO central value can be excluded for $m_S > 150$ MeV/c².

This note presents the first search for Beyond the Standard Model electron-positron pair production in a liquid argon time projection chamber, using the MicroBooNE detector. We can use this search to exclude at 90% confidence the remaining parameter space of the Higgs Portal model required to explain the central value of the KOTO excess.

II. EXPERIMENTAL SETUP

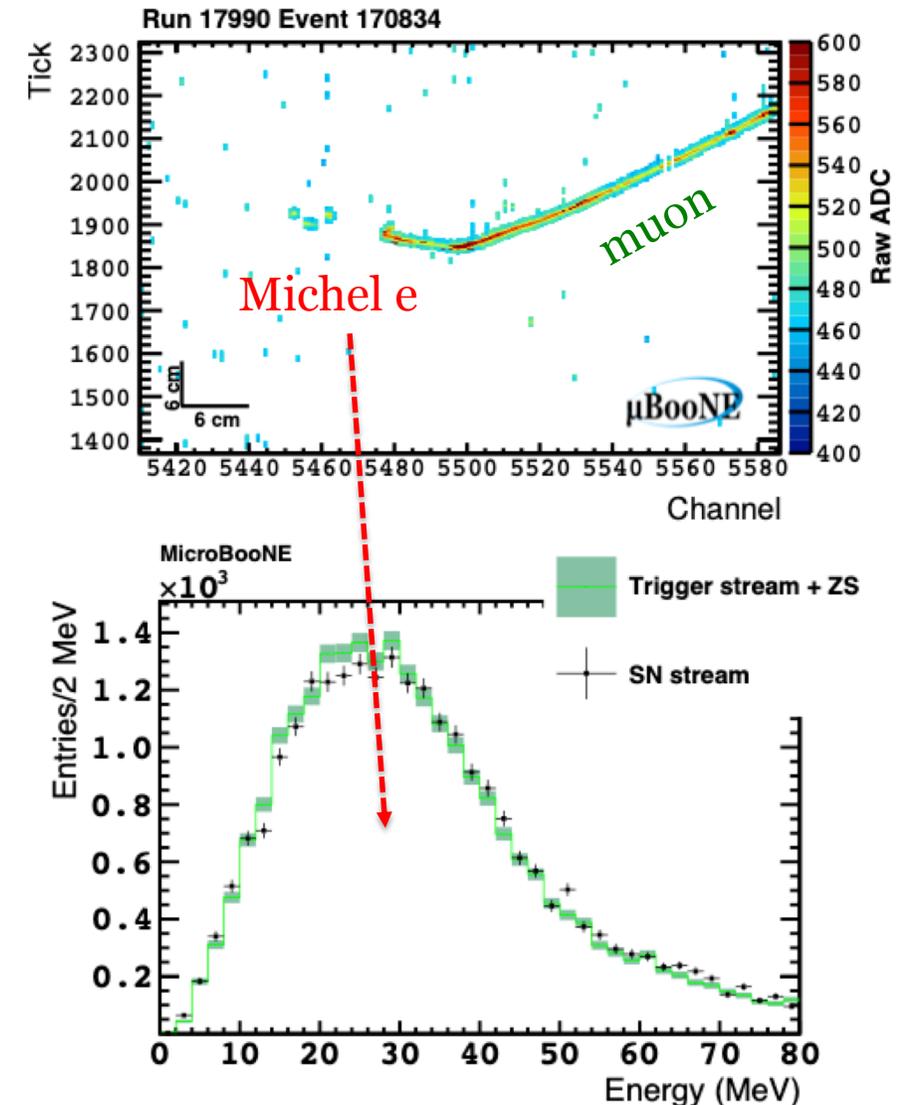
The MicroBooNE experiment is primarily designed for neutrino scattering measurements in Fermilab's Booster Neutrino Beam (BNB). The detector sits just below surface, and comprises an 85 ton liquid argon time projection

* email: MICROBOONE.NE@fnal.gov

R&D for supernova neutrino detection

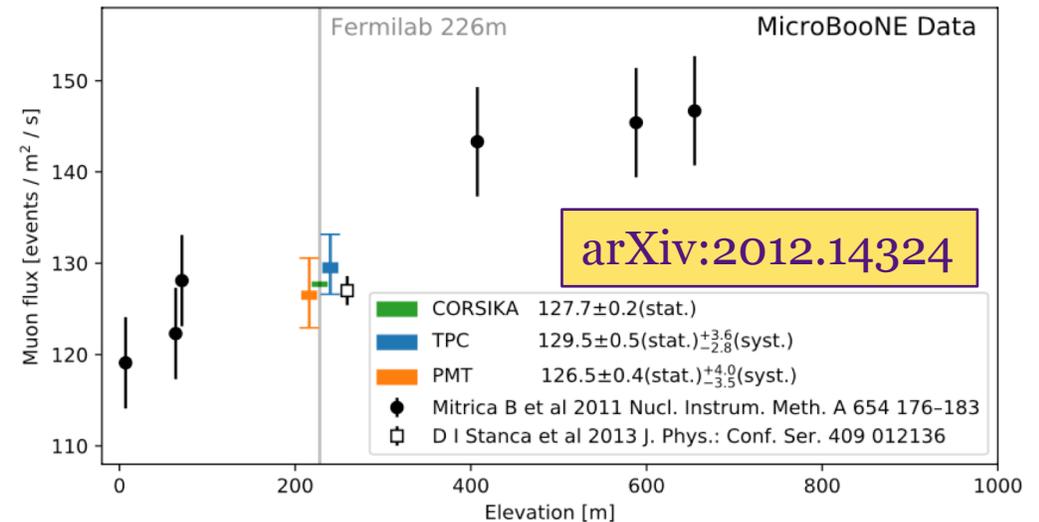
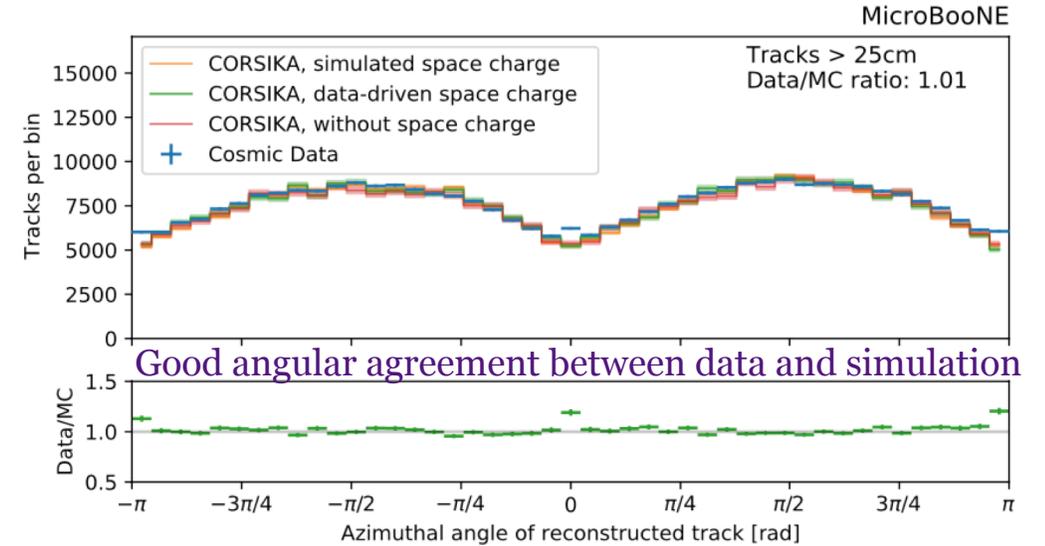
- A lot of data is produced by MicroBooNE – **33 GB/s**
 - Orders of magnitude more expected in DUNE
- To observe supernova neutrino burst, would need **continuous readout**
- **Pioneered** a system to zero-suppress and compress the TPC data
 - Reduction of rates by over $80\times$
 - Prototype for DUNE
- Performance evaluated by reconstruction of Michel electrons
 - Comparable to full datastream

JINST 16, 02, P02008 (2021)



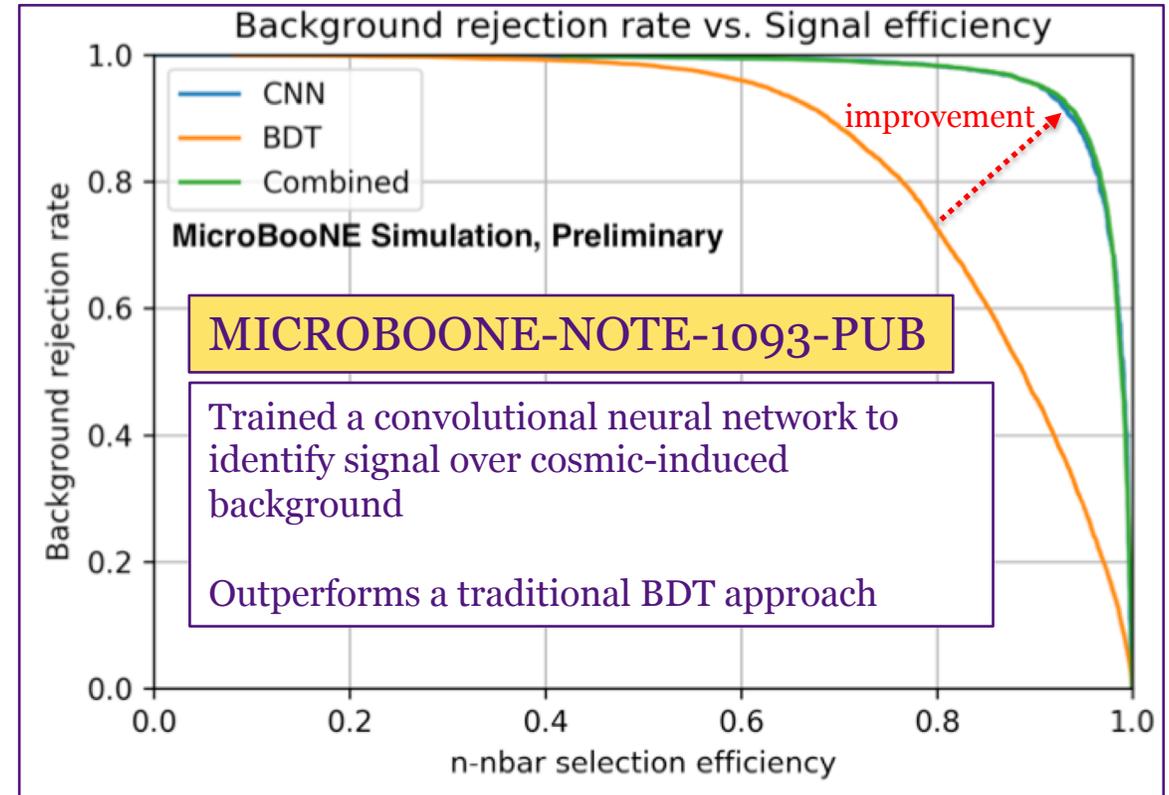
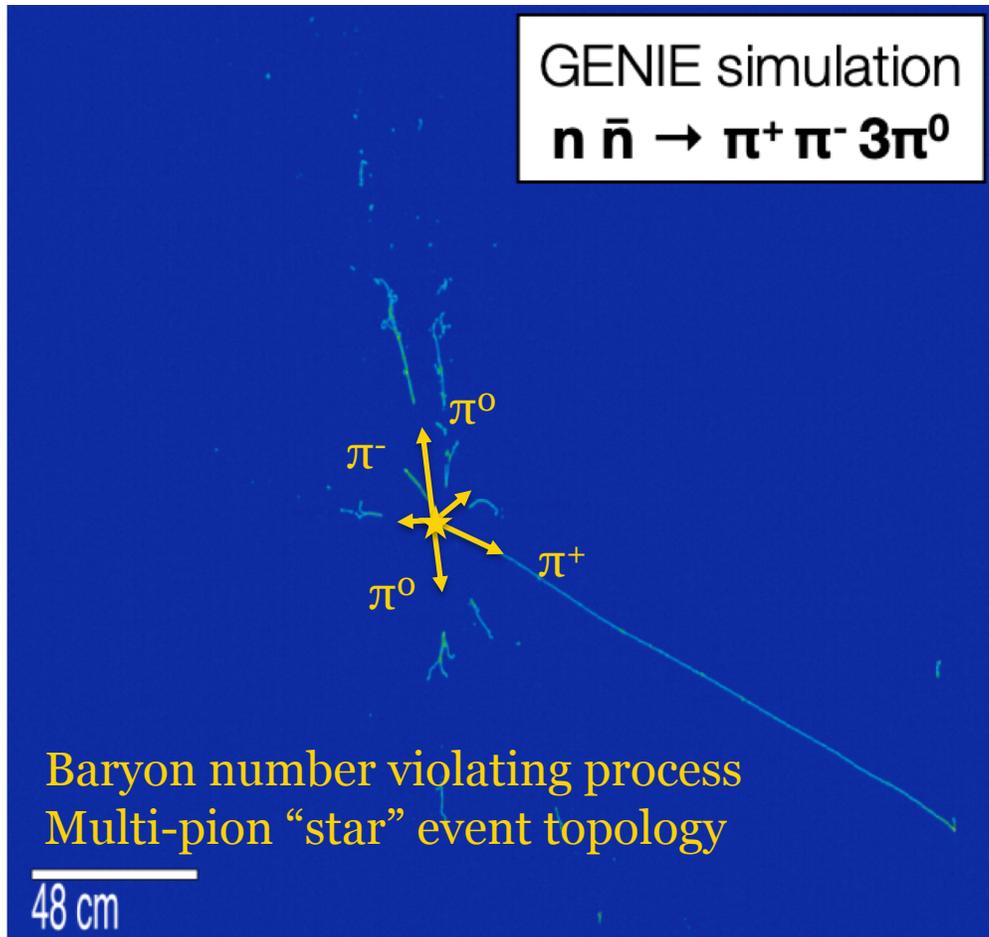
Cosmic ray rates

- Used our data to measure rate of cosmic rays on surface at Fermilab
 - **First** such measurement with a liquid argon TPC
- Allows tuning the cosmic simulation
 - Measurement agrees with ‘out-of-the-box’ CORSIKA simulation
 - **Incompatible** with ‘constant mass composition’ extension* of the simulation
- Useful input to simulations of future experiments at Fermilab, including SBN program and DUNE



* Alternative spectral composition of light and heavy ion cosmic rays impacting atmosphere

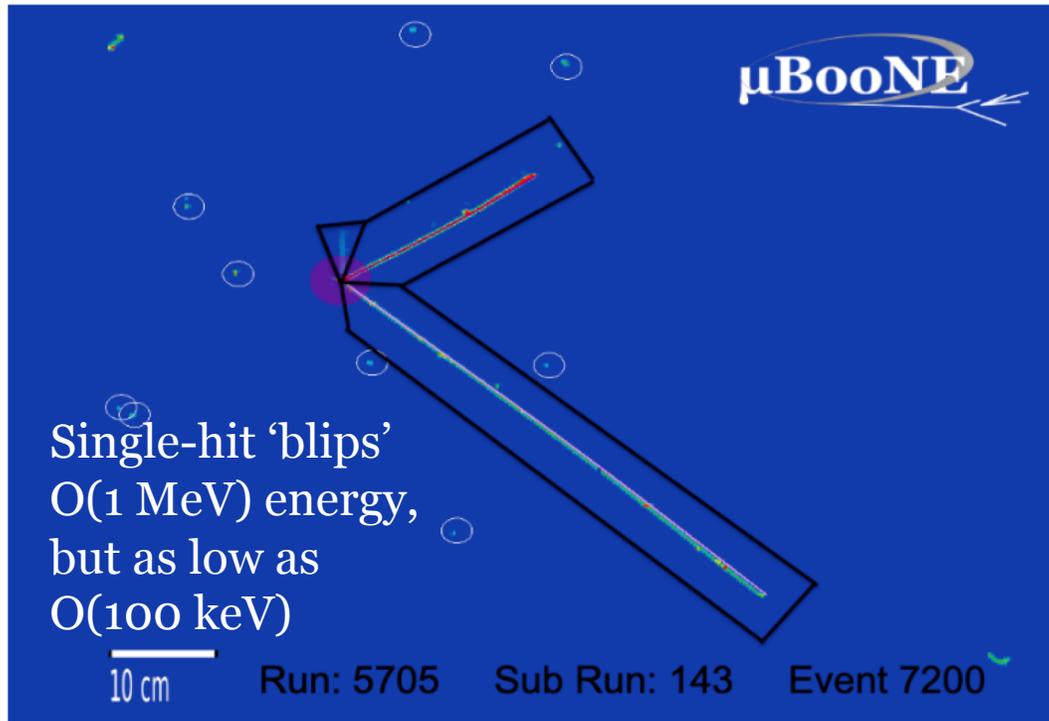
Neutron-antineutron oscillation



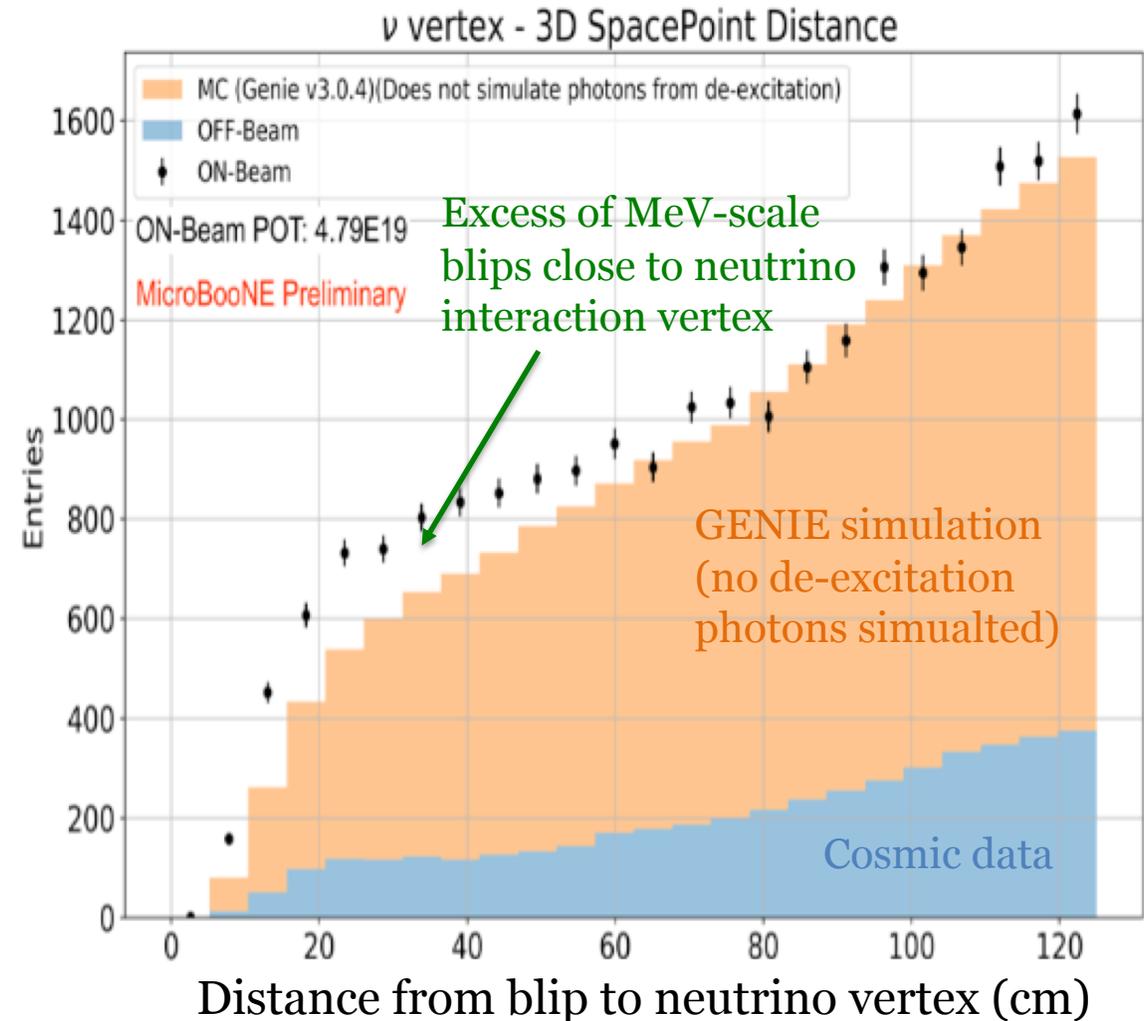
- MicroBooNE is pioneering techniques to be used in DUNE
- Convolutional neural network based search

MeV-scale reconstruction

- Standard reconstruction algorithms designed for $O(100 \text{ MeV})$ interaction
- ‘Blips’ of ionization produced by low-energy gammas or neutrons
- We are **pushing down the thresholds** for reconstructing this information

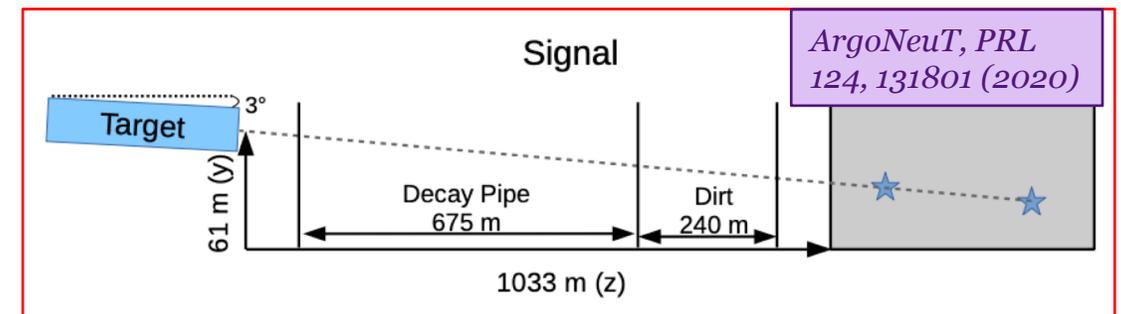
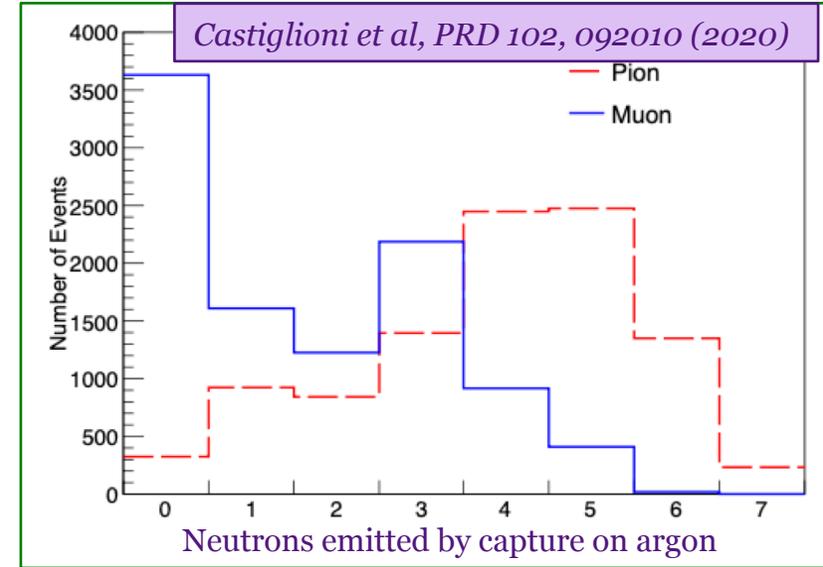
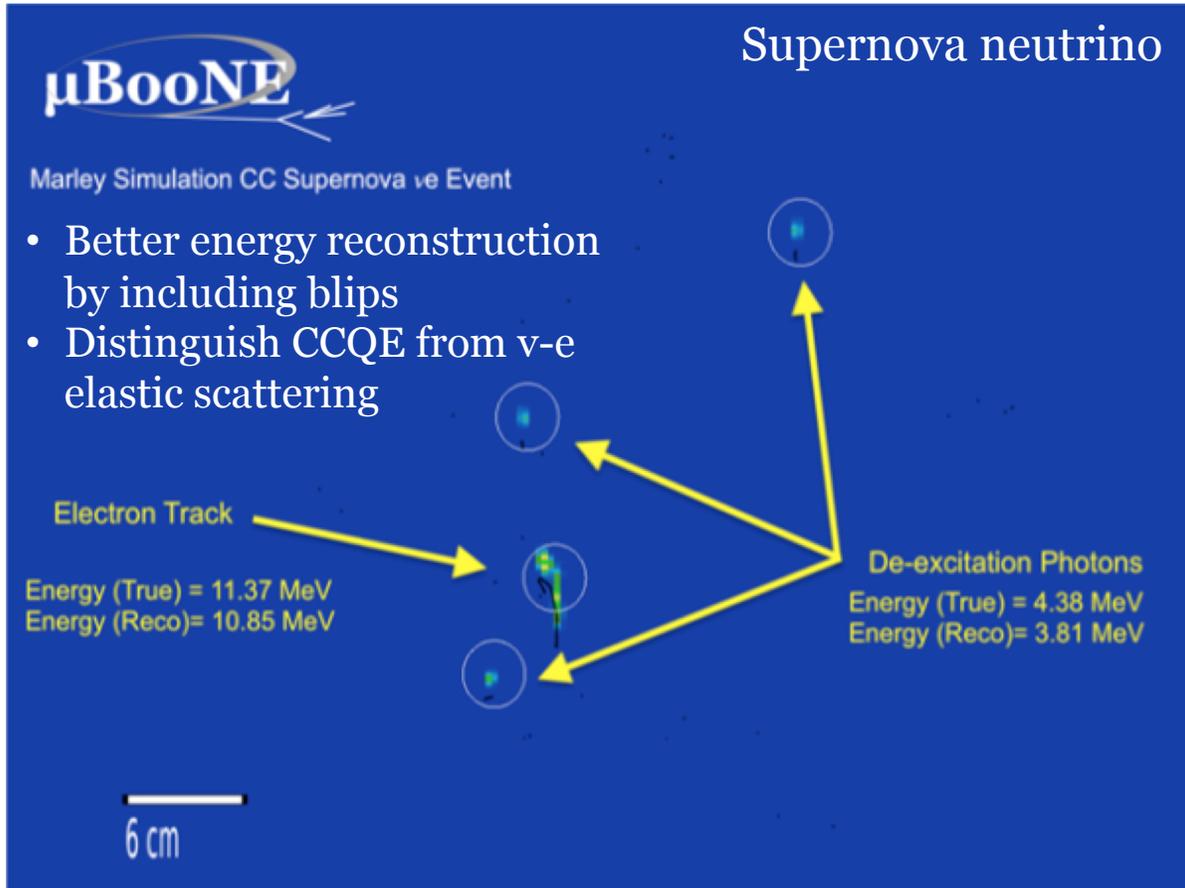


MICROBOONE-NOTE-1076-PUB



MeV-scale applications

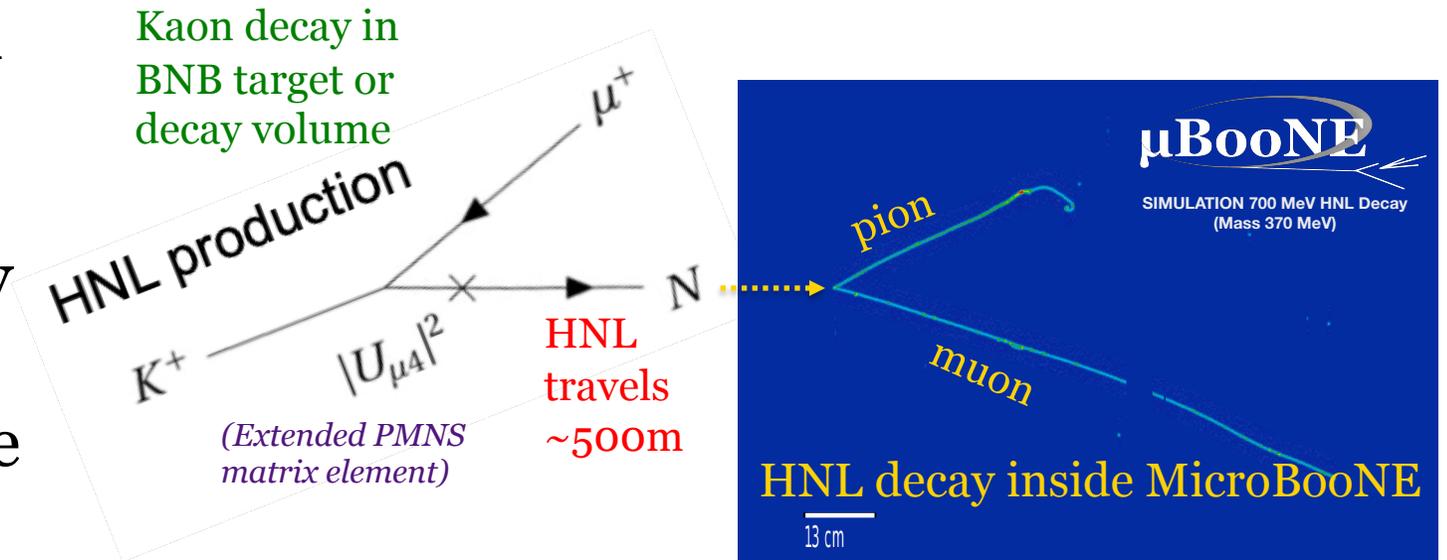
Muon-pion separation, allowing e.g. distinguishing BSM di-muon signals from SM muon-pion backgrounds



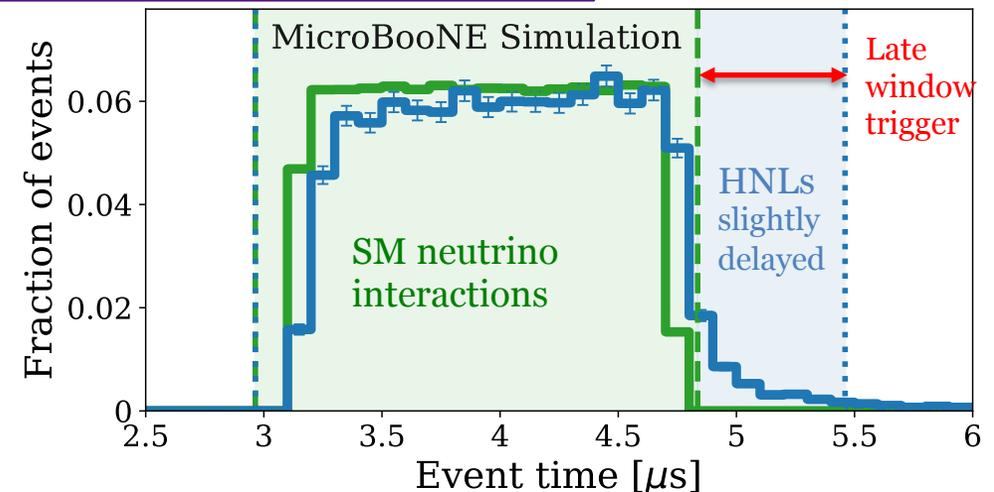
Searches for millicharged particles
(blips along a straight line, pointing back to target)

Heavy neutral leptons

- $O(100 \text{ MeV})$ mass neutral leptons; mixing with SM neutrinos
- Produced in the same way as standard neutrinos
 - We used kaon decays as the source, for this first search
- Decay via weak interaction
 - Muon+pion in our case
- “Late window” trigger **developed** for this analysis
 - Negligible neutrino backgrounds

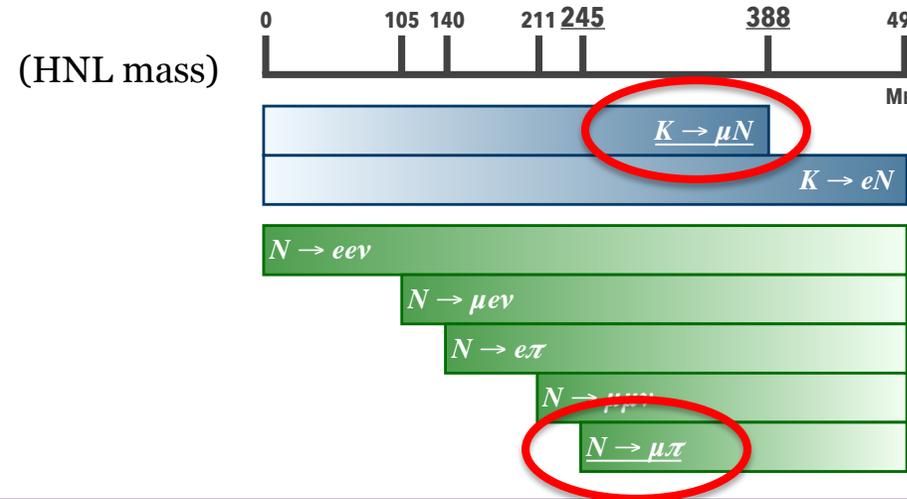
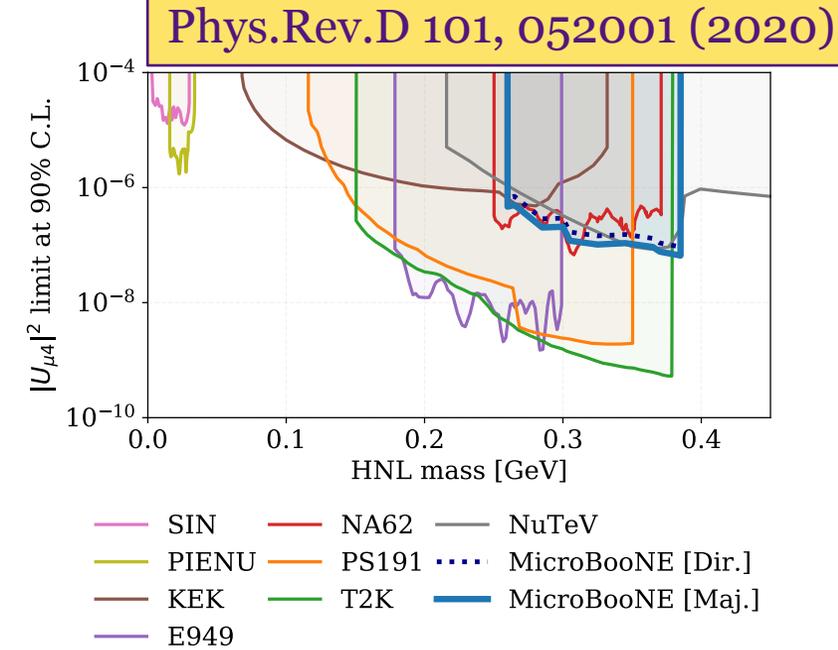
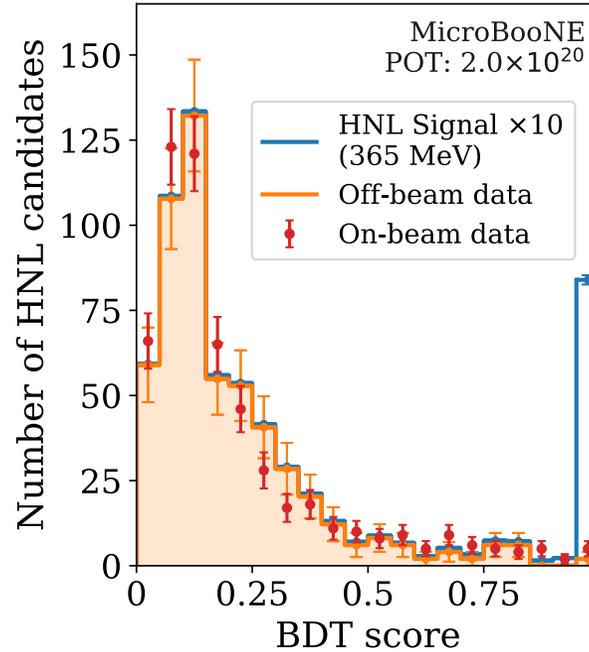


Phys.Rev.D 101, 052001 (2020)



Heavy neutral leptons

- BDT based analysis with 10 HNL mass points (245-388 MeV)
- **No excess observed**
- **Competitive limits**, with only small fraction of our dataset
- We will be using more production and decay modes, full trigger window, and NuMI data, in the near future
 - Stay tuned

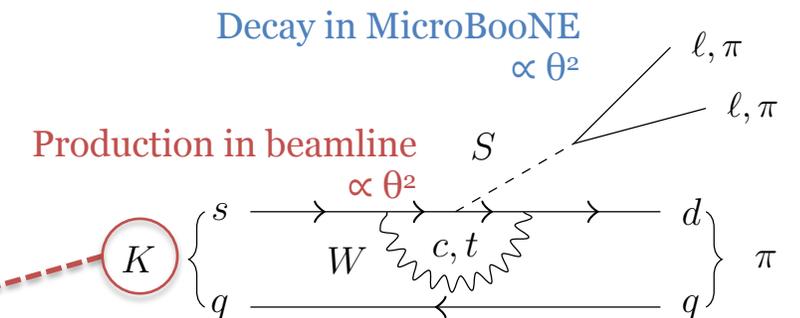
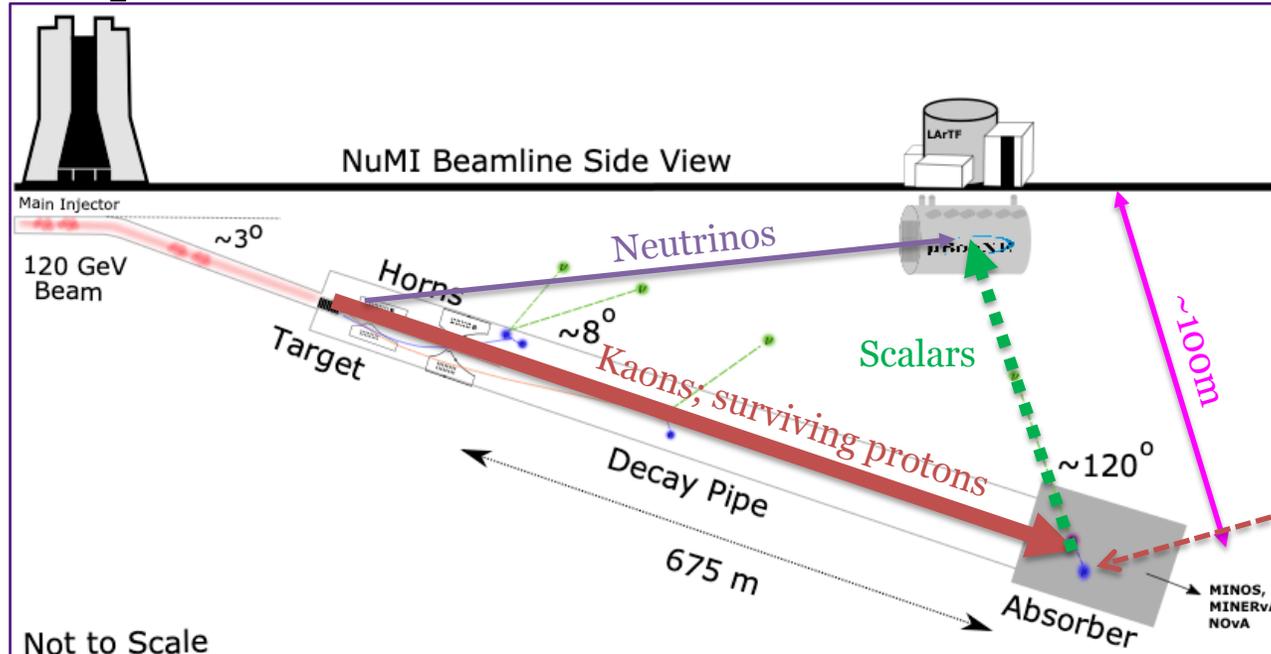
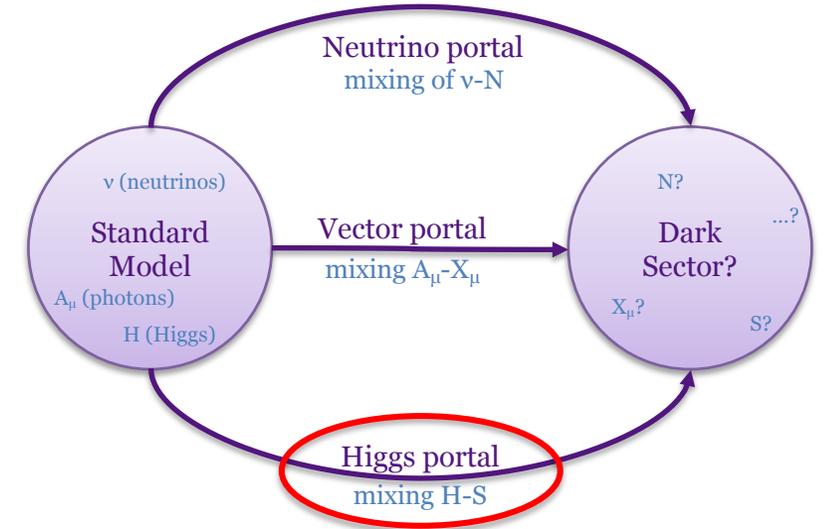


Only searched for this production mode

Only searched for this decay mode

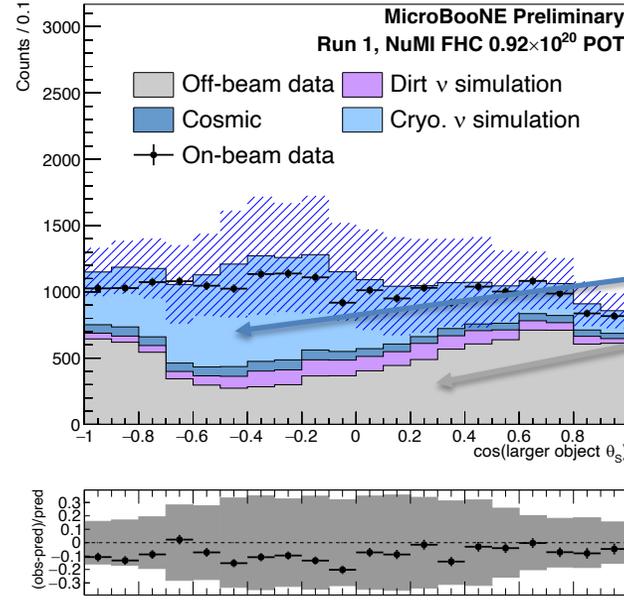
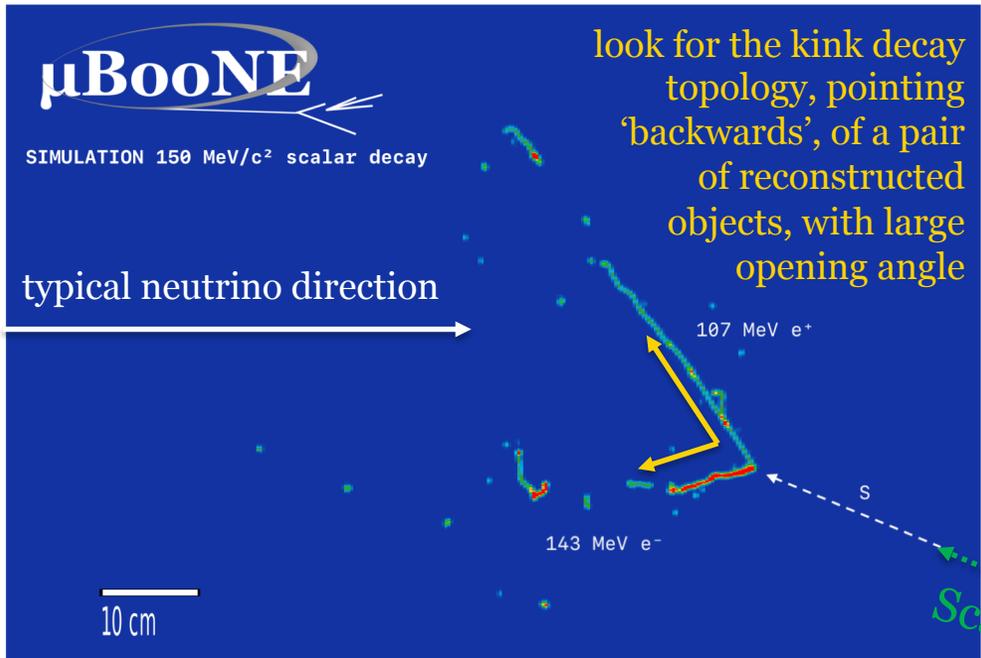
Higgs Portal scalars

- “Portal” to the dark sector, via a dark scalar mixing with the Higgs (mixing angle θ)
 - Couples to SM fermions via Yukawa couplings $\propto \theta^2 m^2$
- Very similar phenomenology as HNLs
 - Kaons decaying to scalars in beamline
 - Scalar decays to fermions in detector
- Our first search uses kaons decaying at rest in the NuMI beam dump



Higgs Portal scalars

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



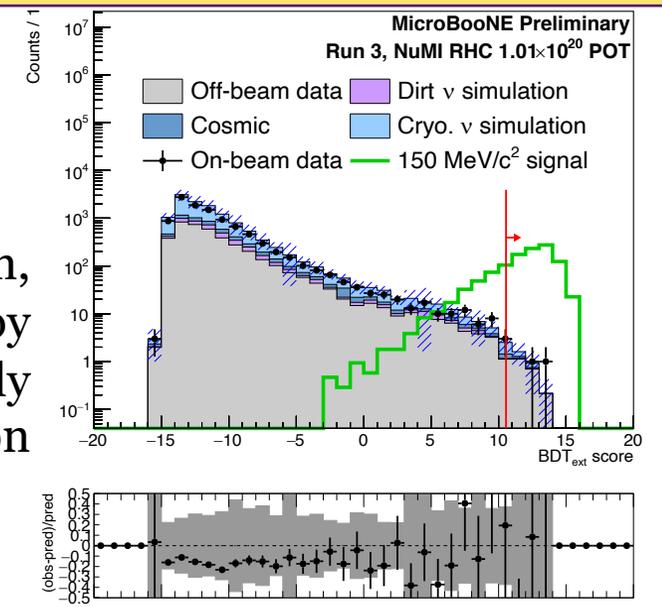
Angular variable (one of the most important for BDT); Simulation is well modelled with respect to the data

Neutrino simulation (GENIE)
Data-driven cosmic background

MICROBOONE-NOTE-1092-PUB

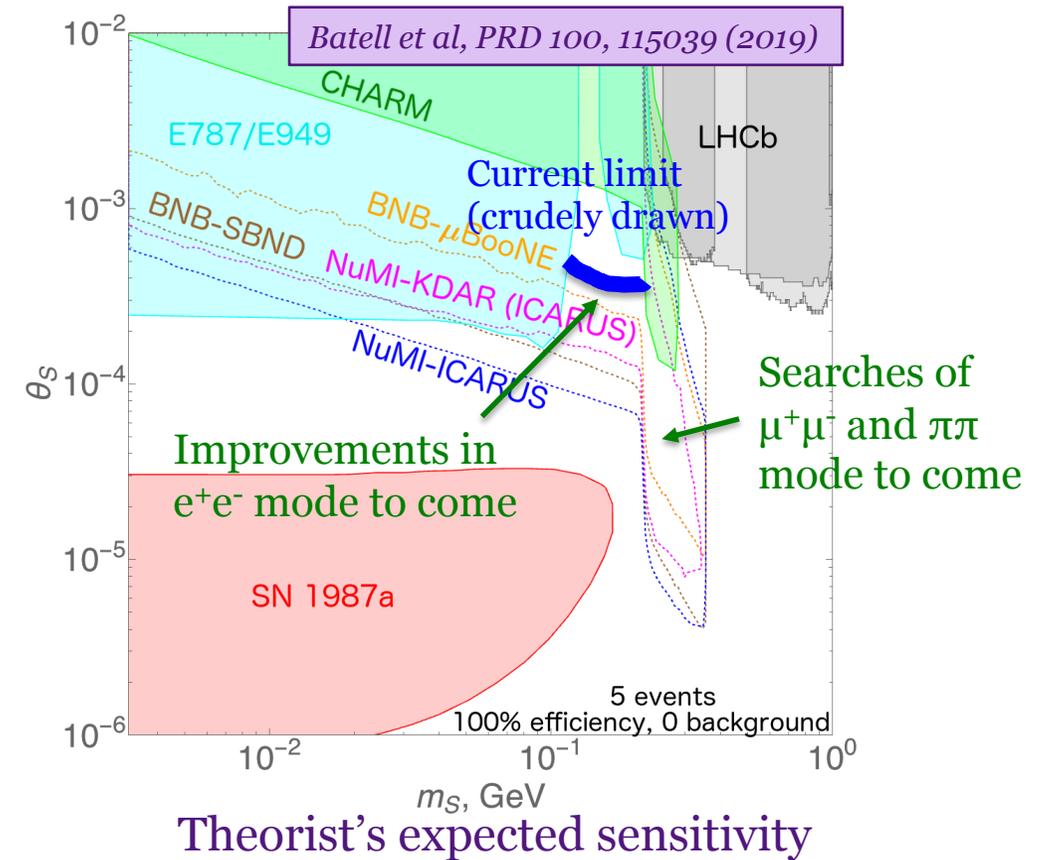
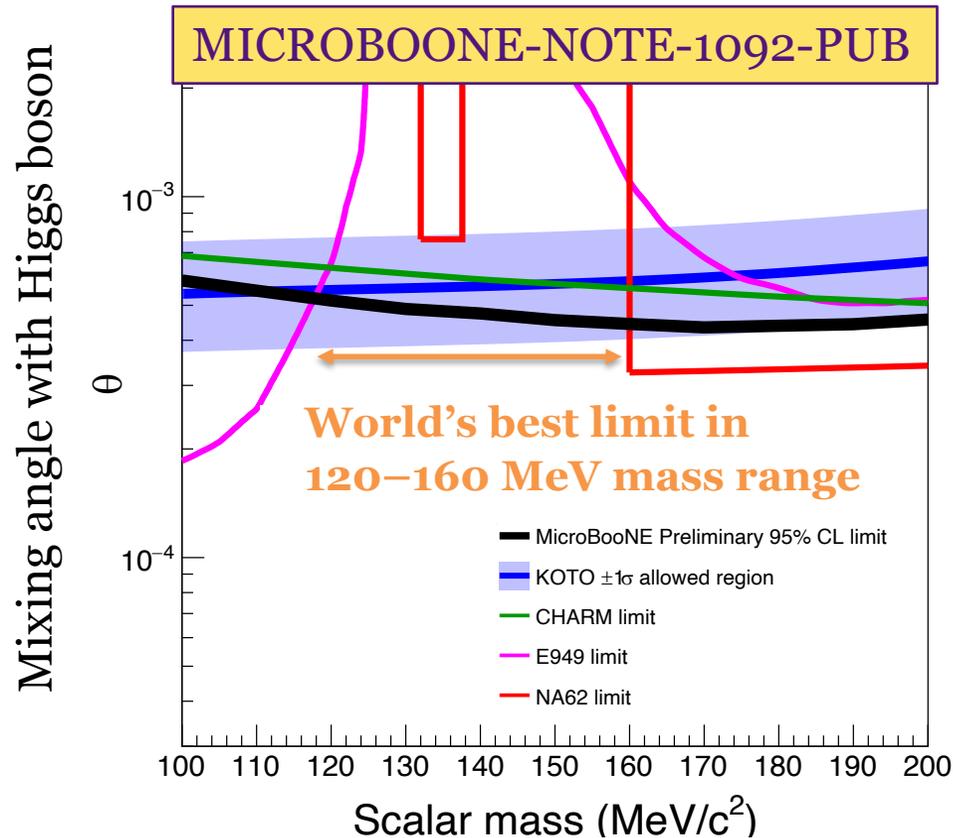
NuMI beam dump

BDT distribution, well modelled by background-only expectation



Higgs Portal scalars

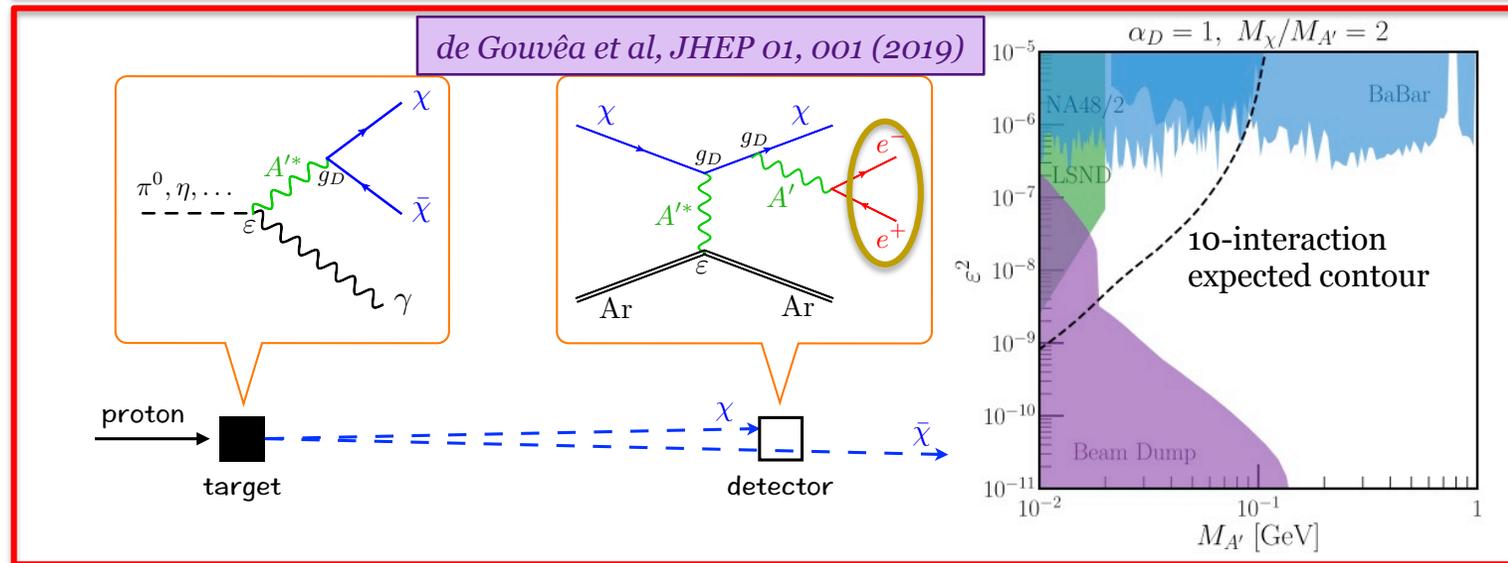
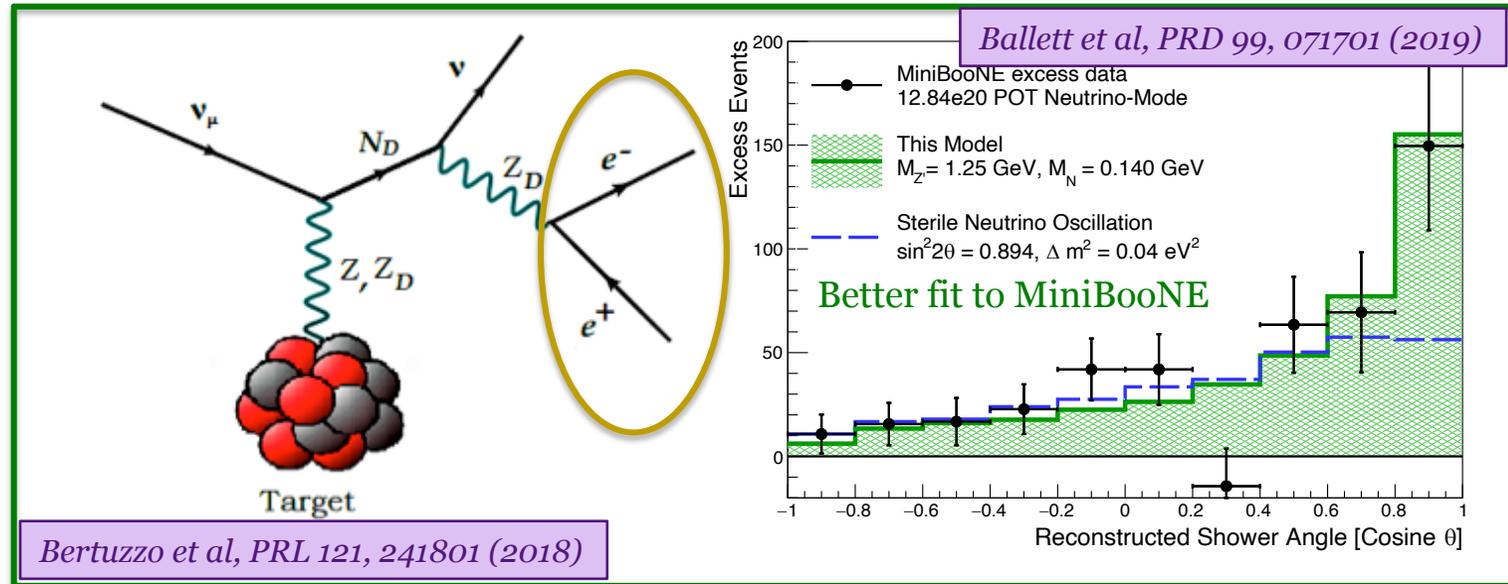
- We observe 5 events in signal region, with 2.0 ± 0.8 expected
- Can **exclude** central value model parameters required to explain KOTO anomaly*
- This was with 10% of our NuMI dataset; further search results to come!



*In 2019, KOTO [reported](#) anomalous excess of $K^0 \rightarrow \pi^0 + \text{invisible}$ decays, although significance has decreased in recent reporting

Dark prospects

- Further BSM models being explored with e^+e^- final states
- Dark neutrino portal, with dark Z' decay
 - could explain MiniBooNE: if e^+e^- resolved as single shower
- Dark matter produced in beamline; inelastic scattering off argon
 - MicroBooNE has excellent sensitivity



Summary

- MicroBooNE is not only **excellent** for investigating MiniBooNE or measuring cross sections, but can also perform a **diverse variety** of astrophysical or exotic measurements
- We have produced some **exciting results** in the past year
 - Supernova continuous readout ([JINST 16, 02, P02008 \(2021\)](#))
 - MeV-scale physics ([MICROBOONE-NOTE-1076-PUB](#))
 - Cosmic ray rate measurement ([arXiv:2012.14324](#))
 - Neutron-antineutron oscillation analysis development ([MICROBOONE-NOTE-1093-PUB](#))
 - Searches for heavy neutral leptons ([Phys.Rev.D 101, 052001 \(2020\)](#)), and dark sector scalars ([MICROBOONE-NOTE-1092-PUB](#))
- We do have a lot more results to come in the near future
 - **watch this space!**

