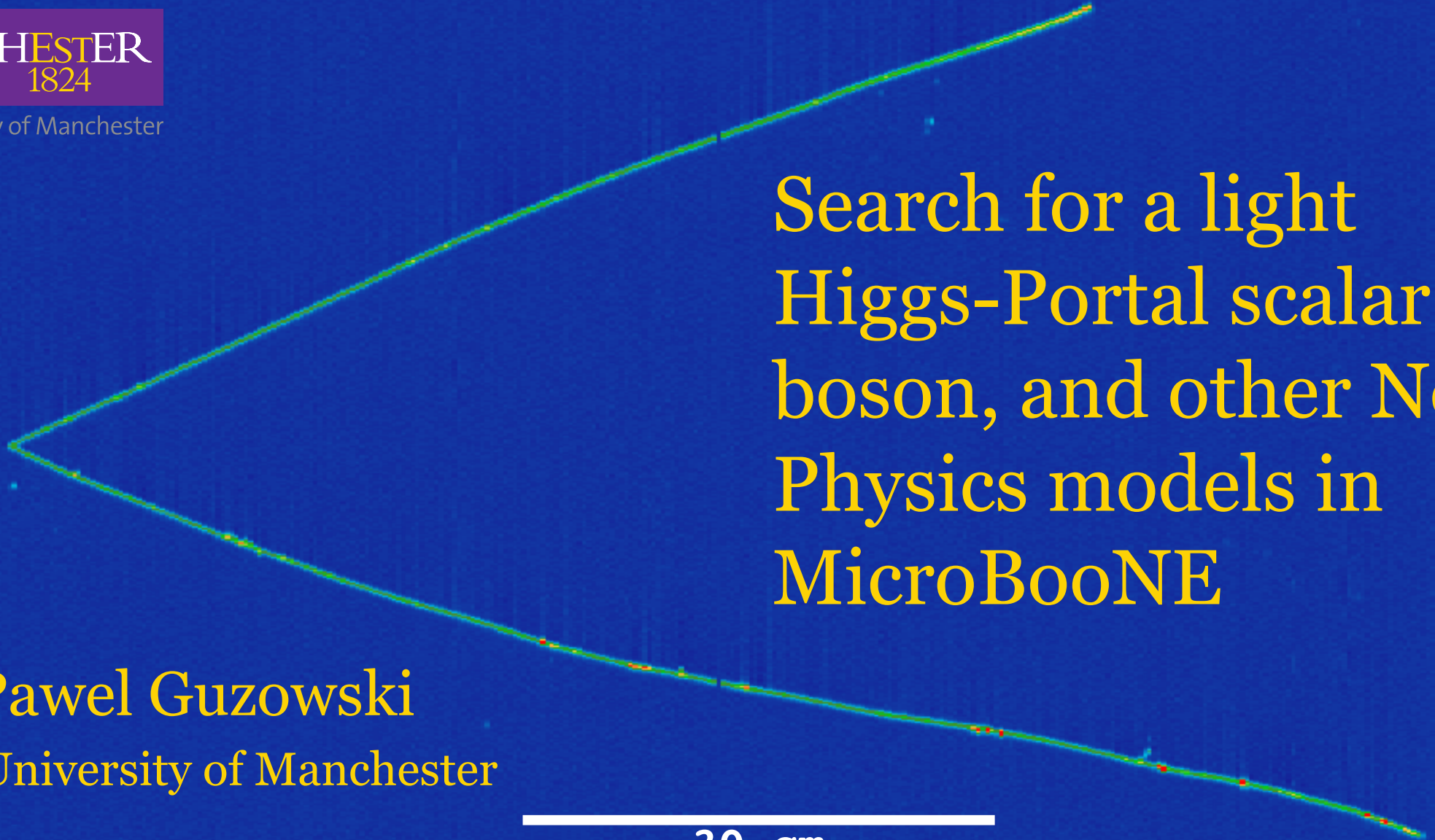


Search for a light Higgs-Portal scalar boson, and other New Physics models in MicroBooNE

Pawel Guzowski

The University of Manchester

30 cm



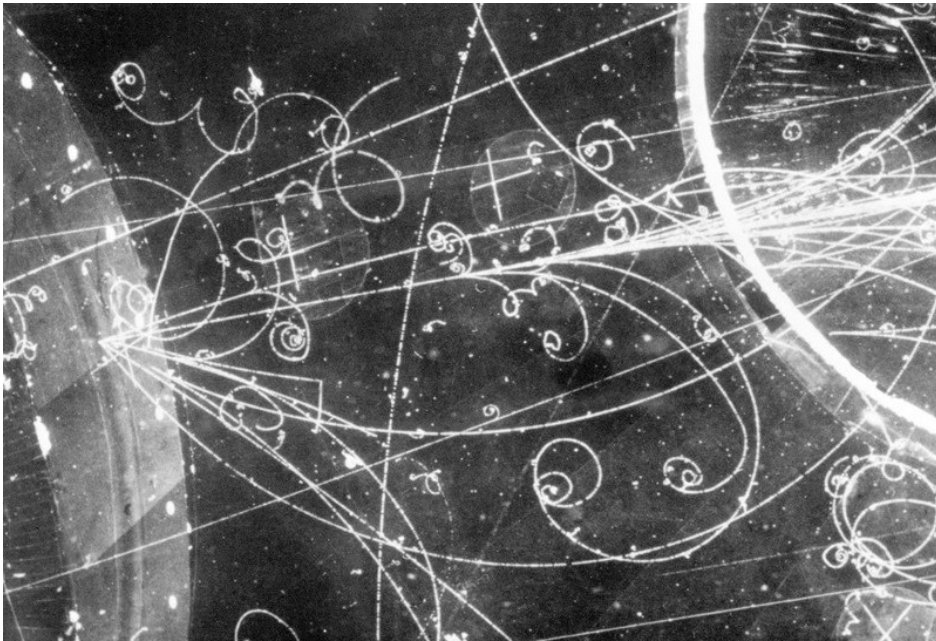
Outline

- Introduction to MicroBooNE
- The Higgs Portal to the dark sector
- New limits from MicroBooNE
- Other new physics models

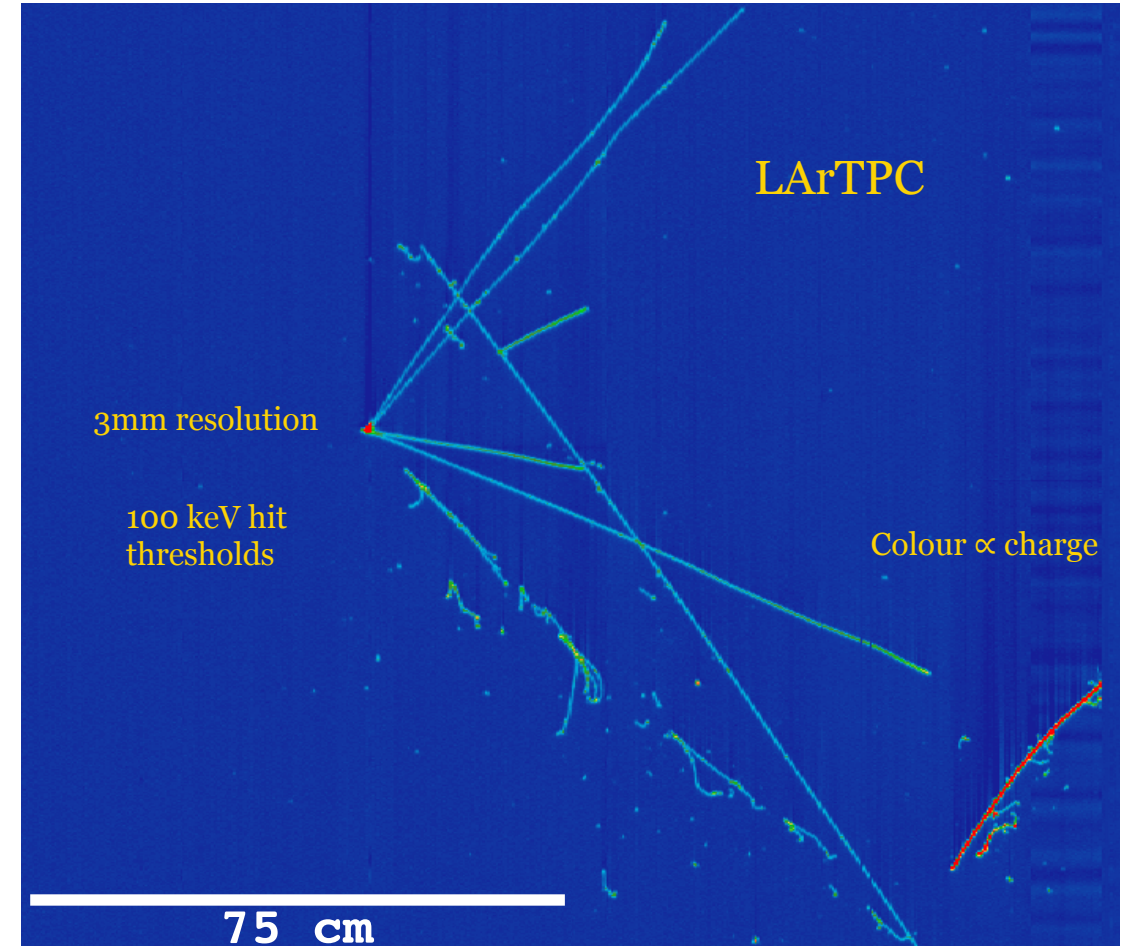
- Introduction to MicroBooNE
- The Higgs Portal to the dark sector
- New limits from MicroBooNE
- Other new physics models

Liquid argon time projection chambers

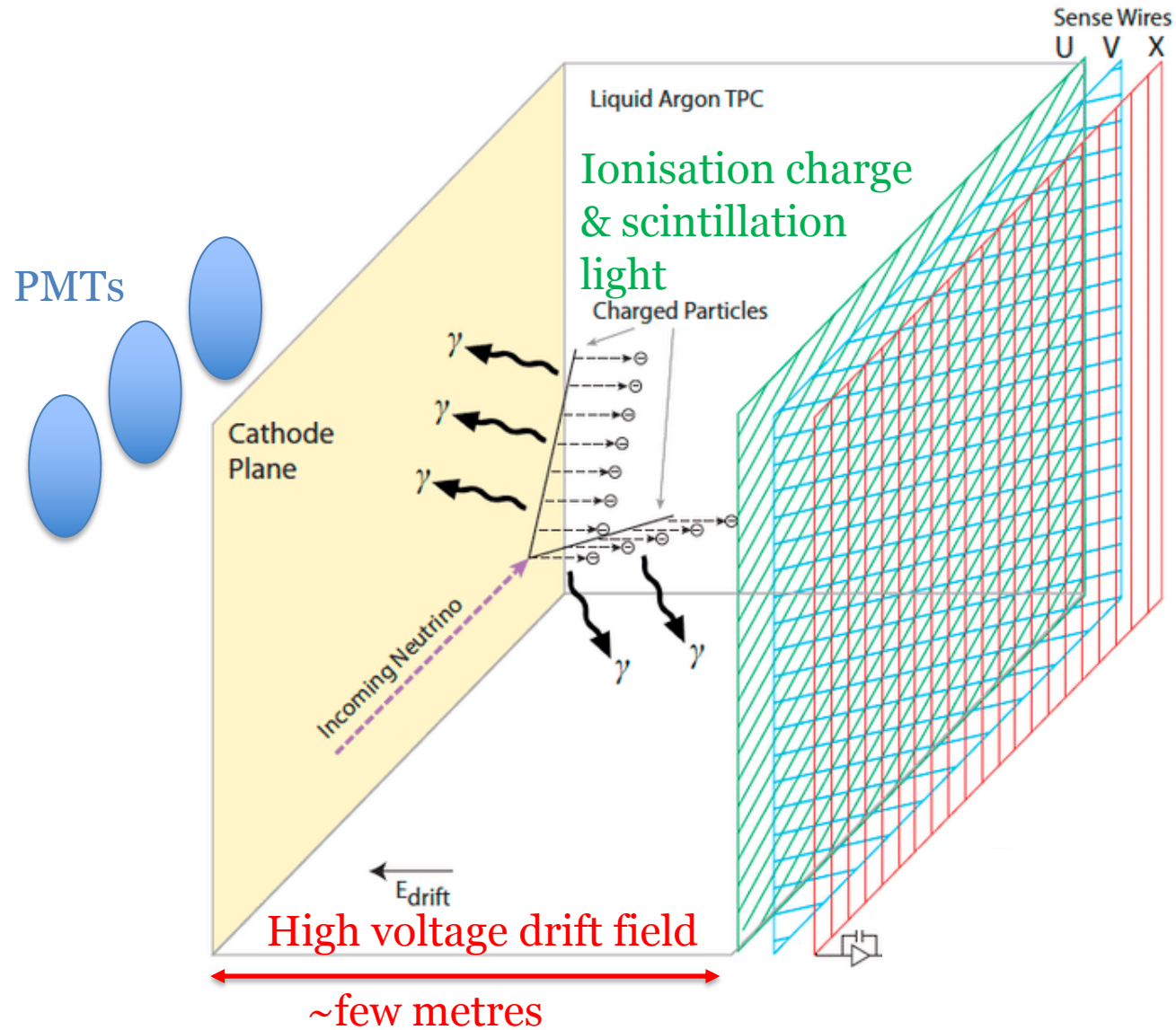
- Technology proposed by Carlo Rubbia in 1970s
- Bubble-chamber like images but with modern digitized charge readout



Bubble chamber

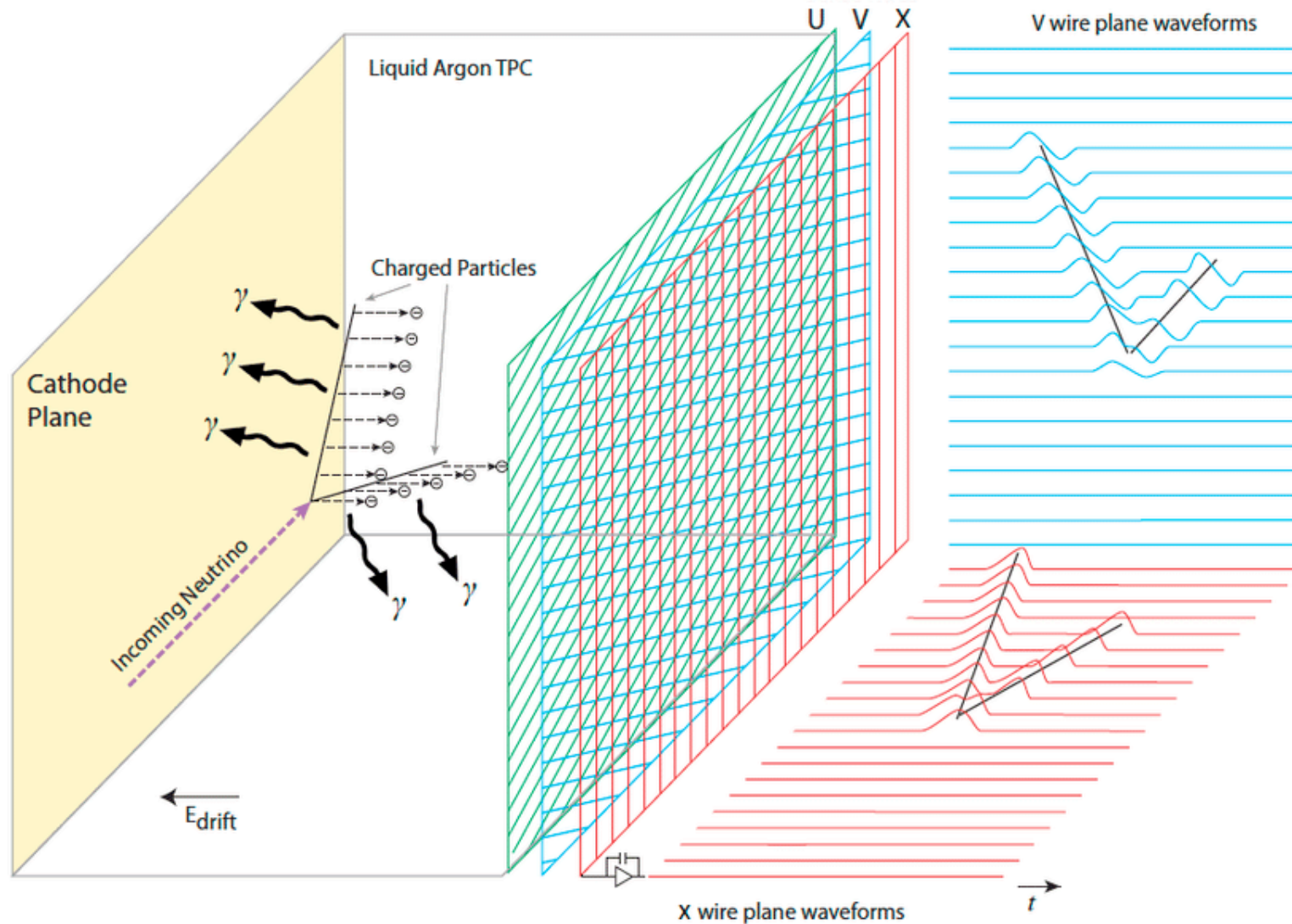


LArTPC operation principle



LArTPC operation principle

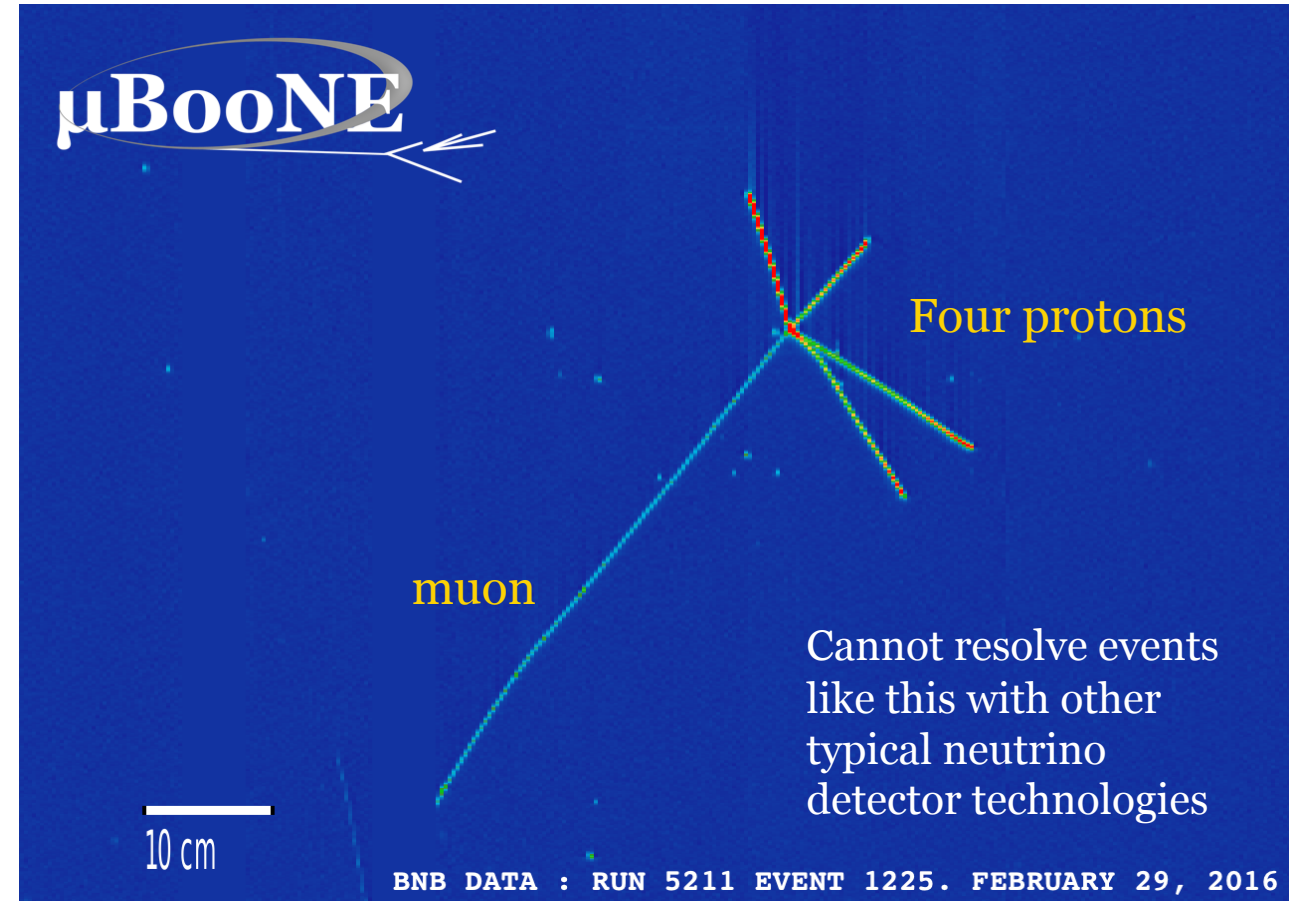
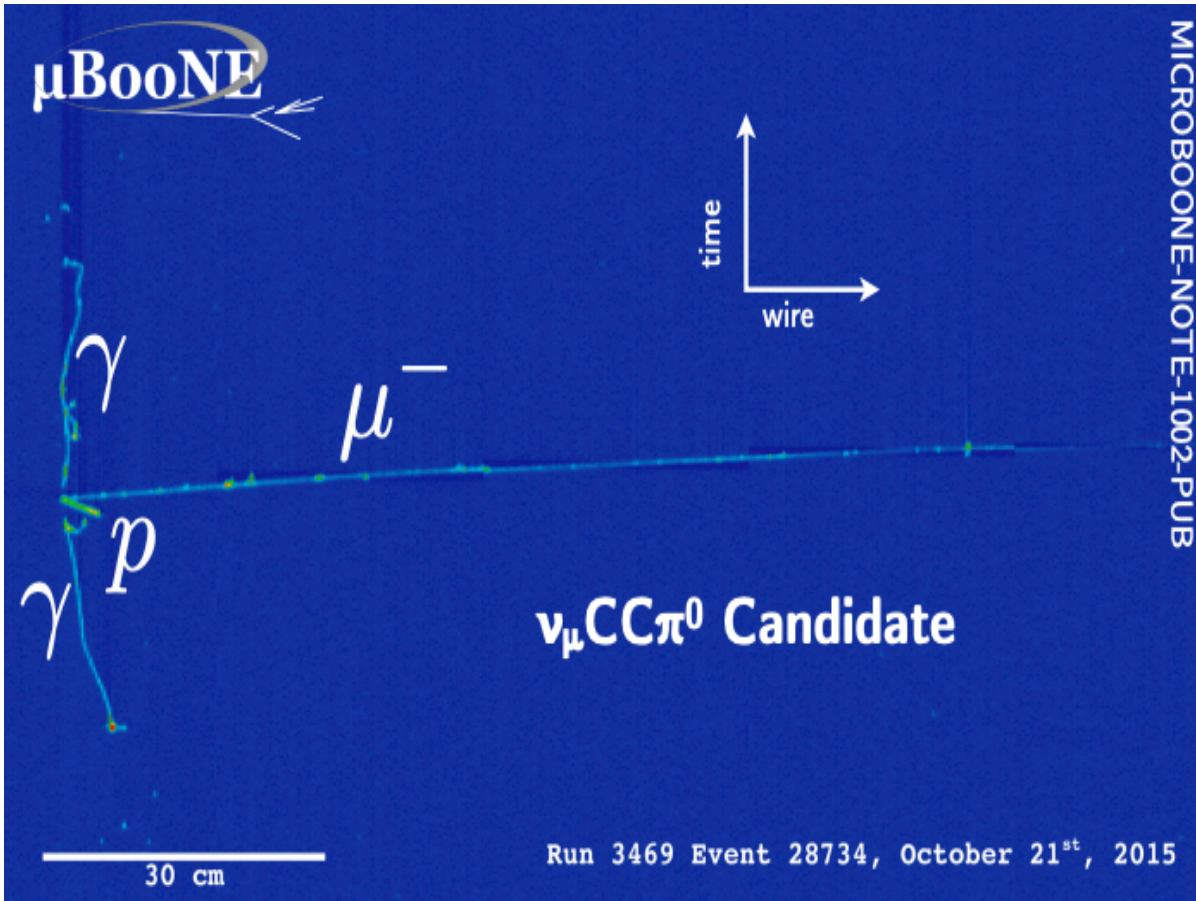
Multiple planes of readout sense wires



Charge vs time information on the wires allows 3D reconstruction

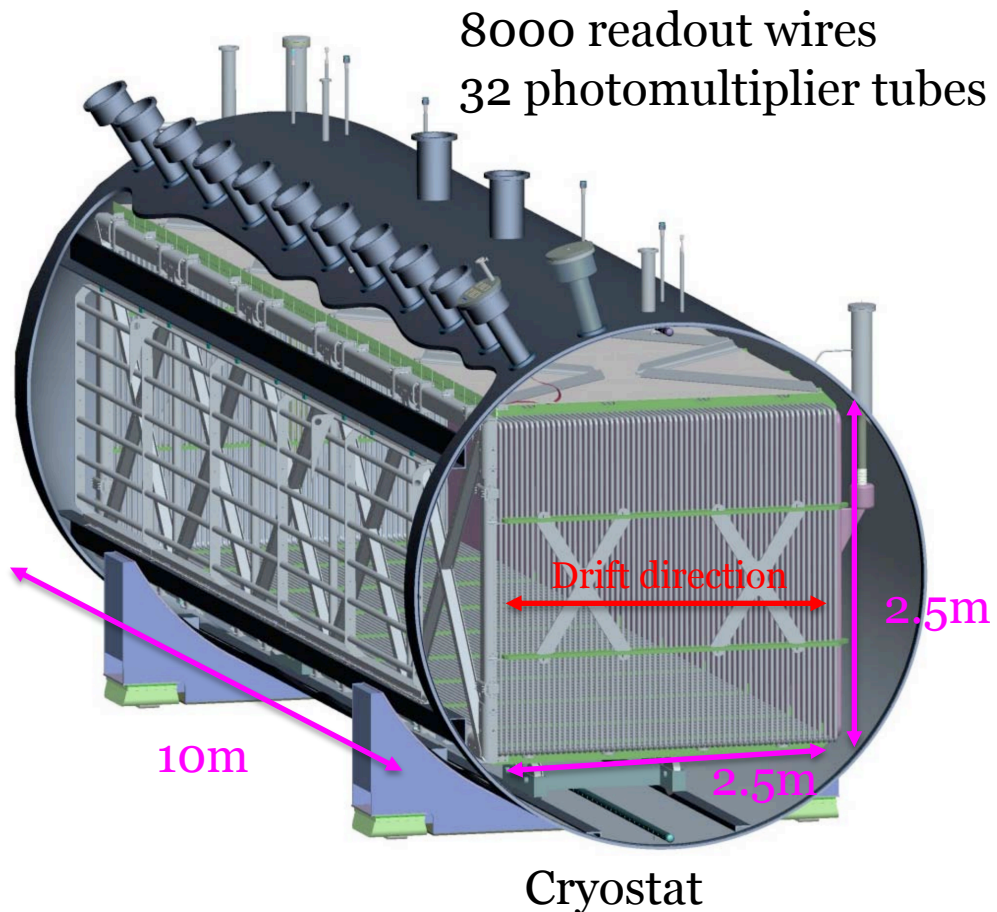
Particle identification

- Excellent spatial and charge resolution allows for unprecedented PID

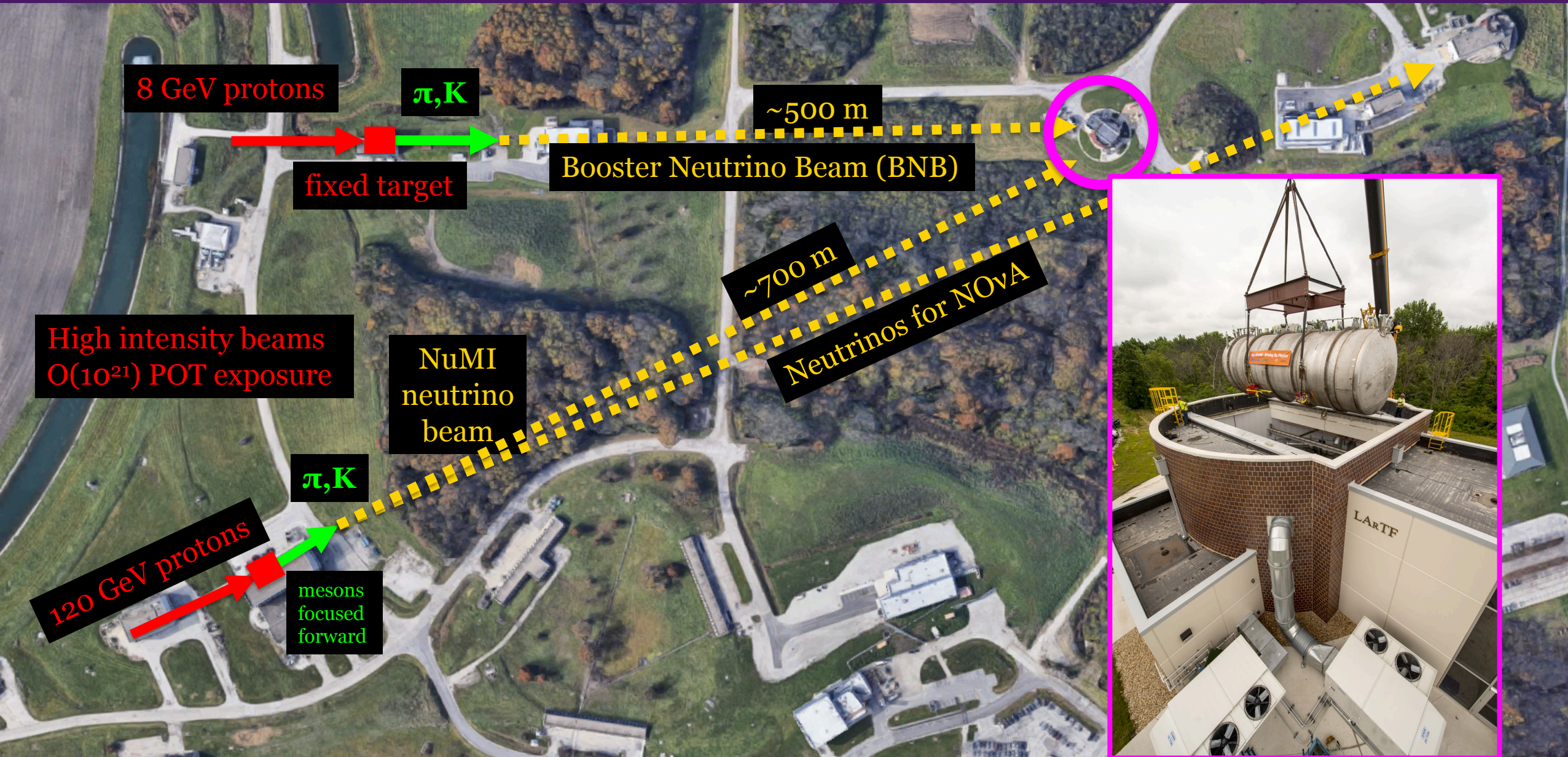


MicroBooNE

- Construction completed in 2014, and in operation since 2015

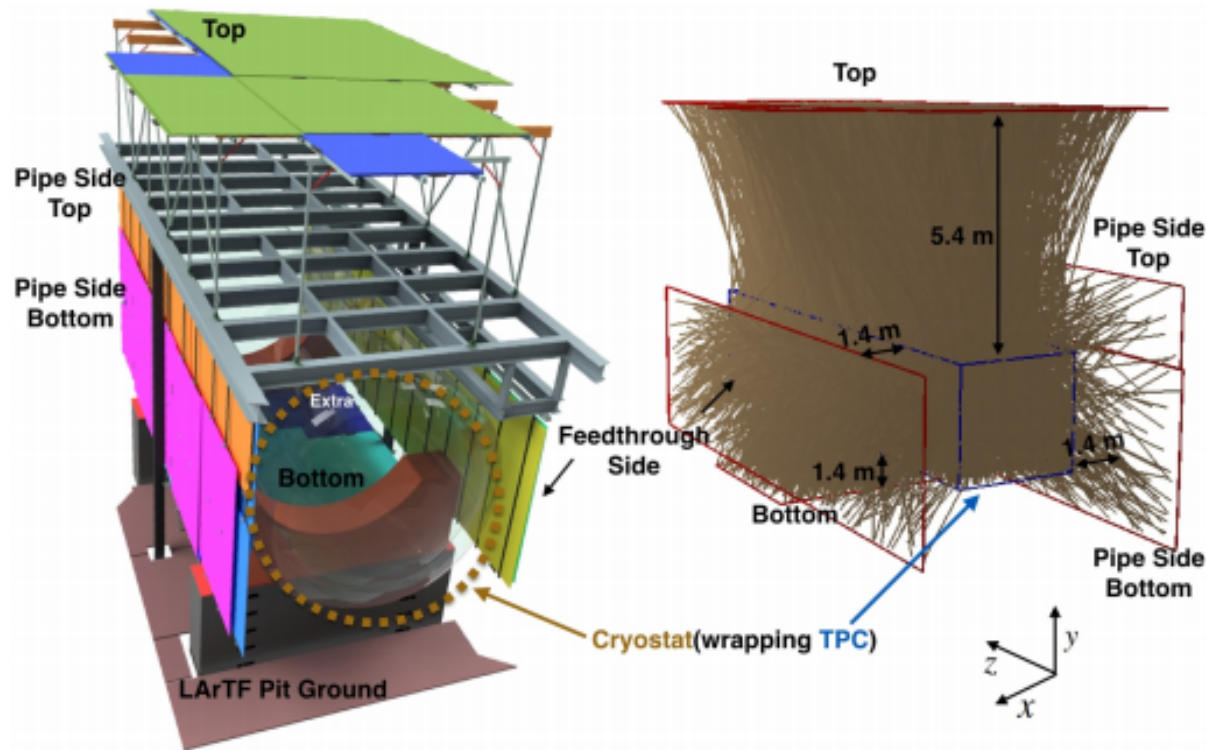


MicroBooNE and the Fermilab neutrino beamlines

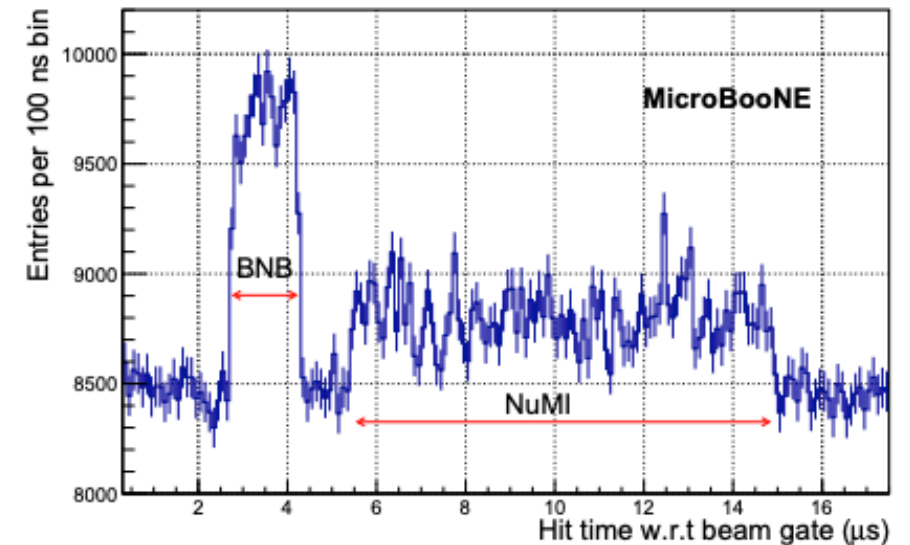


Cosmic Ray Tagger

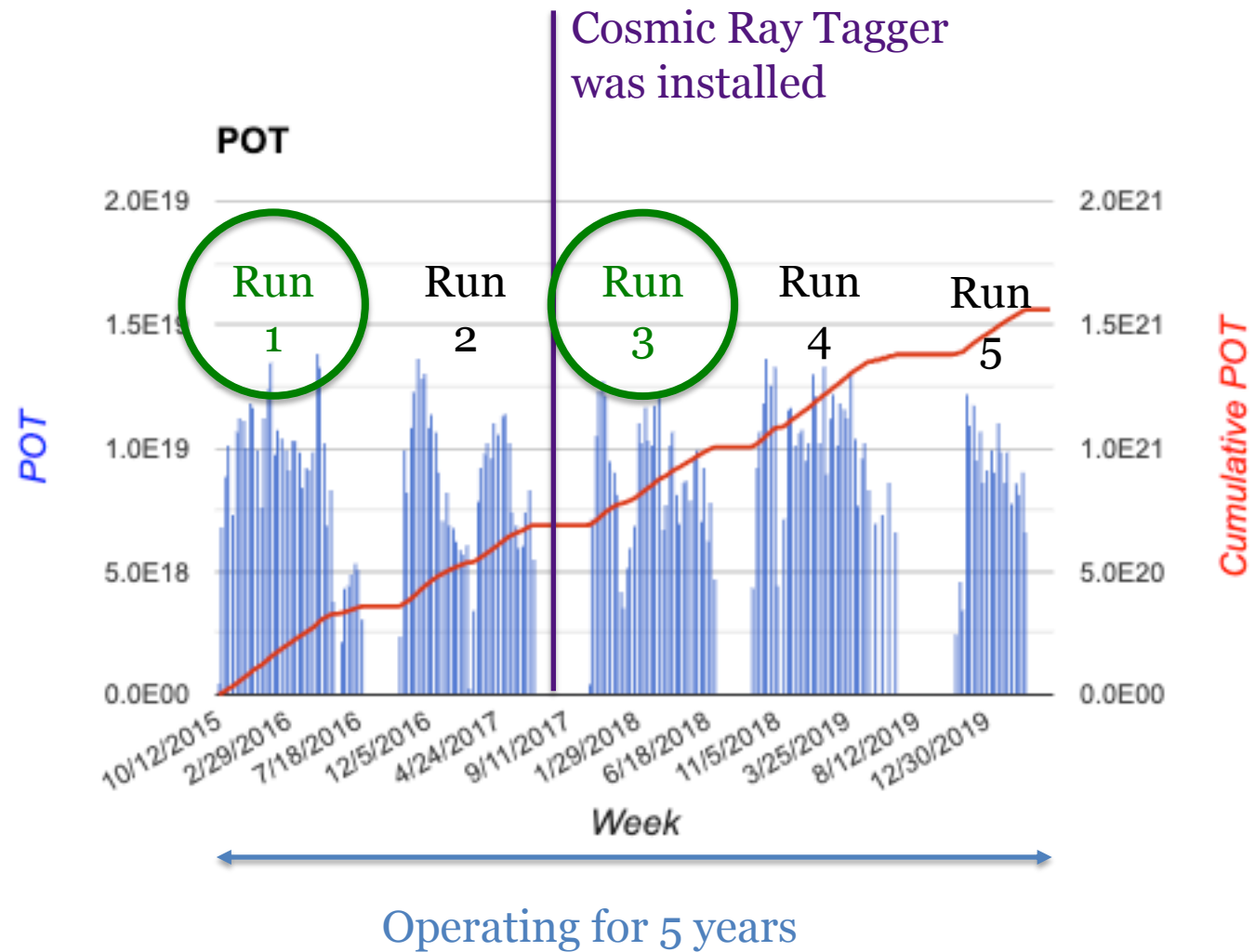
- A cosmic ray tagger was installed after two years
 - Plastic scintillator paddles surrounding the detector, to tag incoming muons with high-resolution timing
 - Can greatly reduce cosmic backgrounds



Timing of hits in CRT
Can see neutrino interaction excess



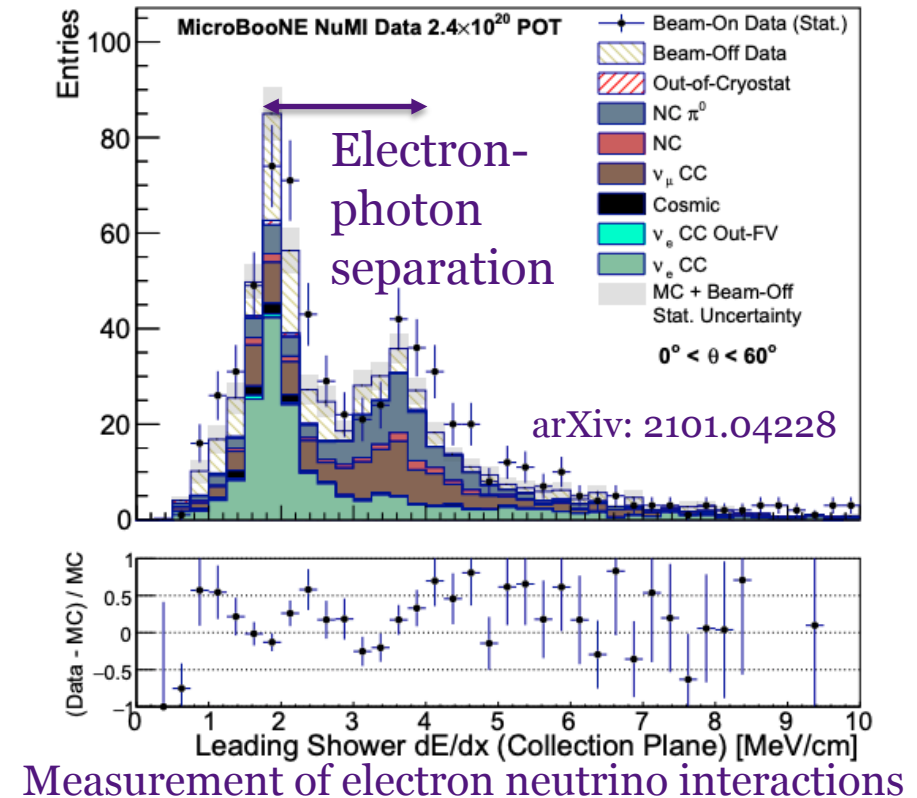
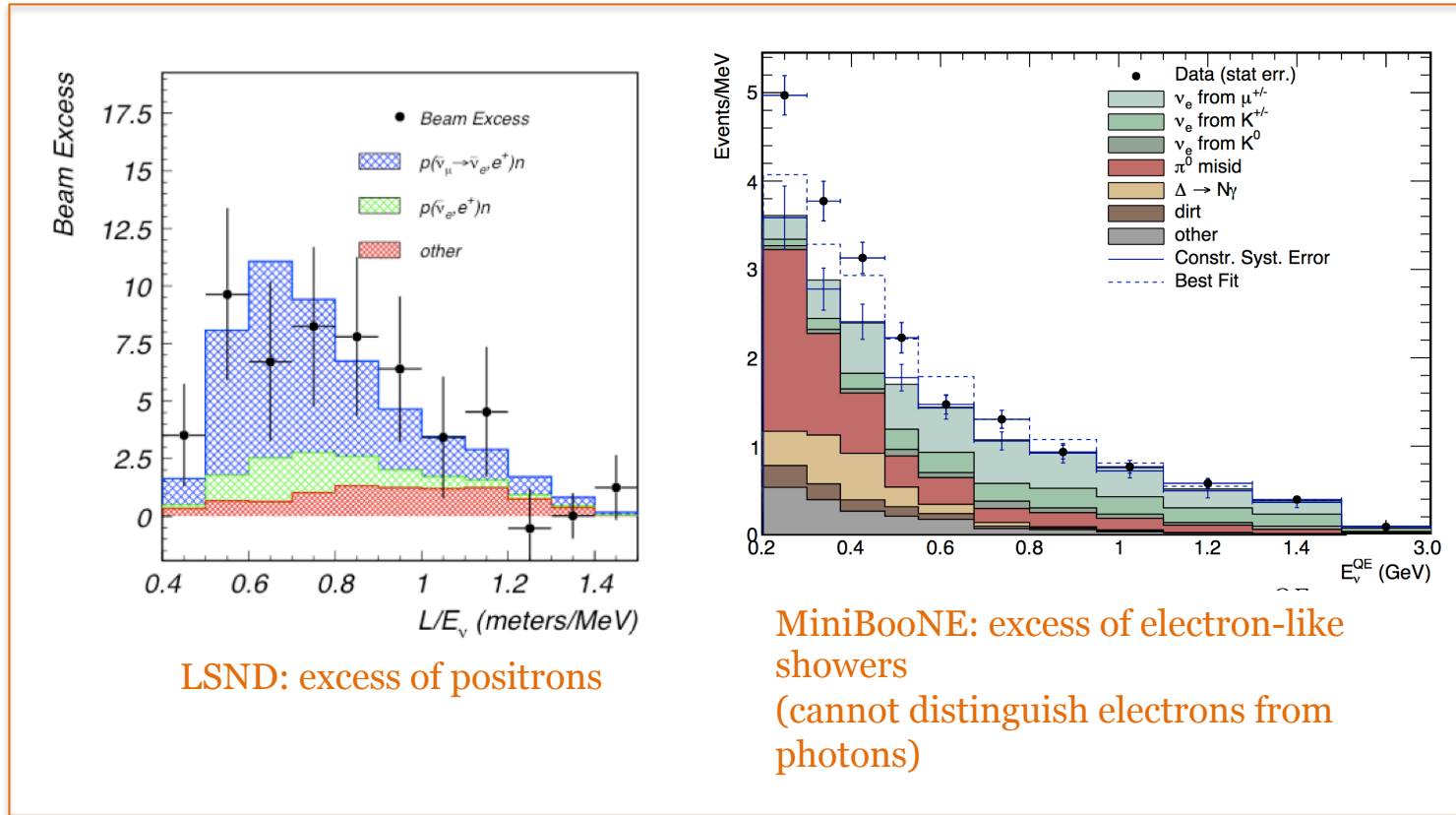
Data collected to date



Data used in this seminar's result from Runs 1 & 3

Primary goal

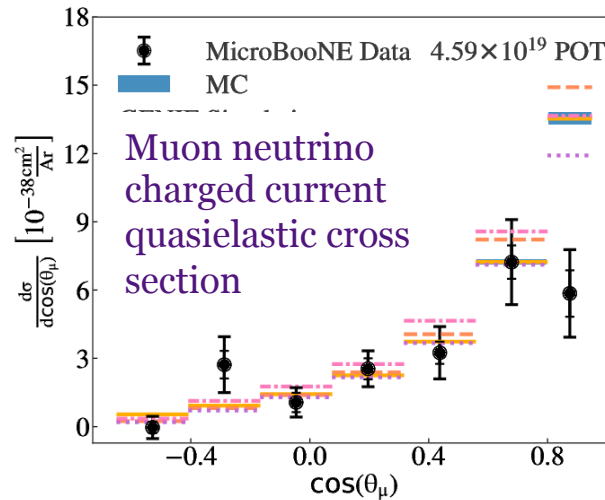
- The experiment was originally proposed to investigate the electron-like excesses observed in short-baseline muon neutrino beams



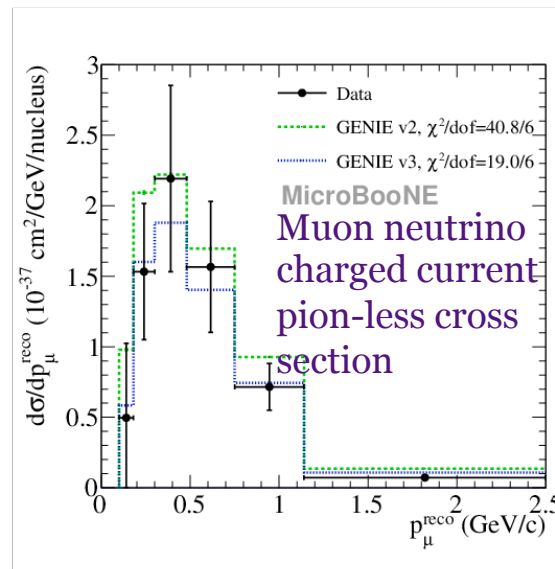
- MicroBooNE will be unblinding these searches very soon!

Recent results

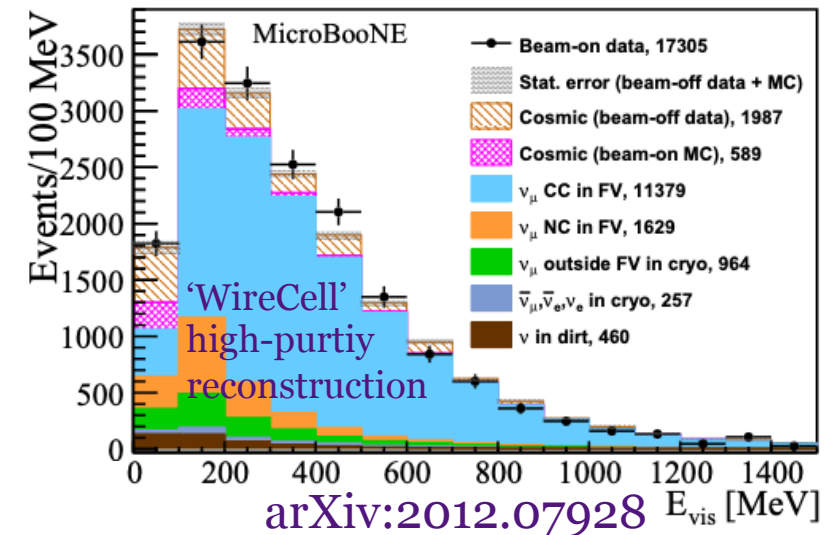
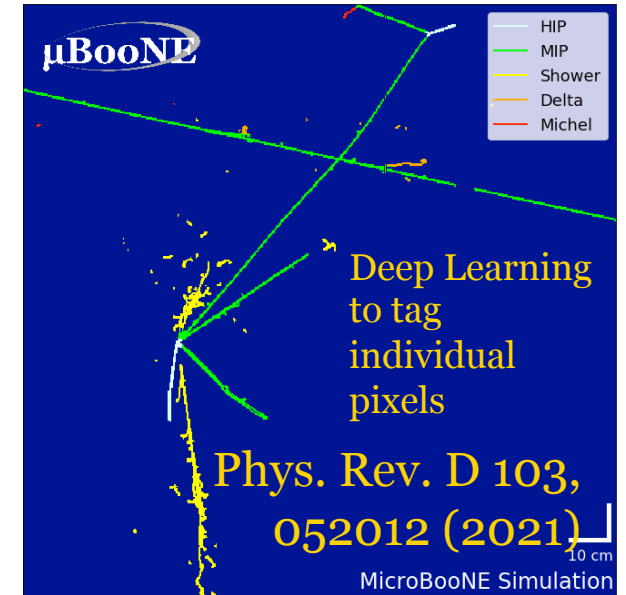
- MicroBooNE has also excellent capability of performing cross section measurements, detector physics and R&D for future experiments
- Only a small sample of our many results last year
 - 17 papers, 19 public notes



Phys.Rev.Lett. 125
(2020) 20, 201803



Phys.Rev.D 102
(2020) 11, 112013



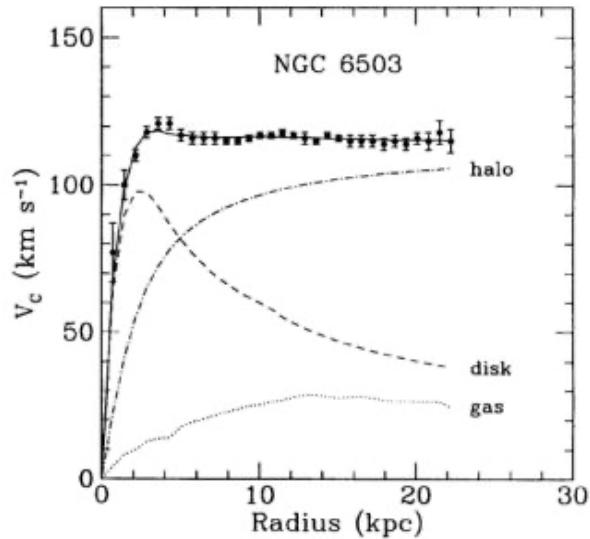
- However, these results are not the focus of my talk today

- However, these results are not the focus of my talk today
- MicroBooNE can also do a host of other interesting new physics searches ...

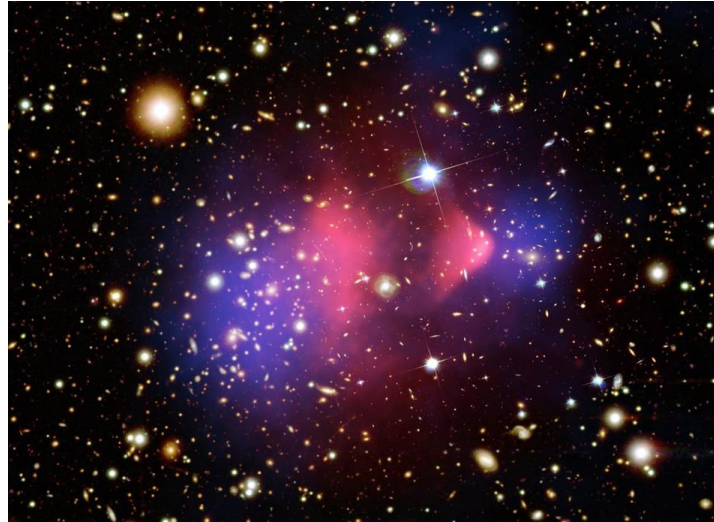
- Introduction to MicroBooNE
- **The Higgs Portal to the dark sector**
- New limits from MicroBooNE
- Other new physics models

Dark matter

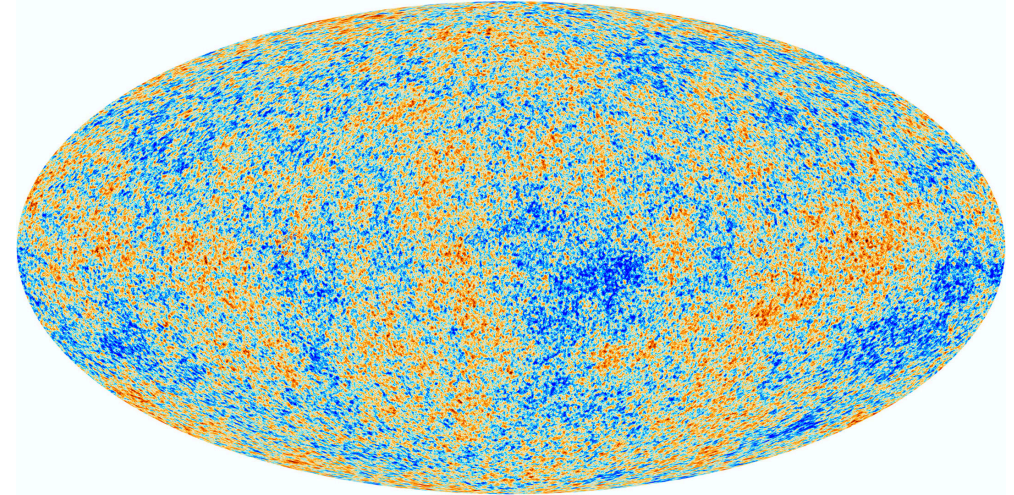
- Evidence for dark matter, including:



Galaxy rotation curves



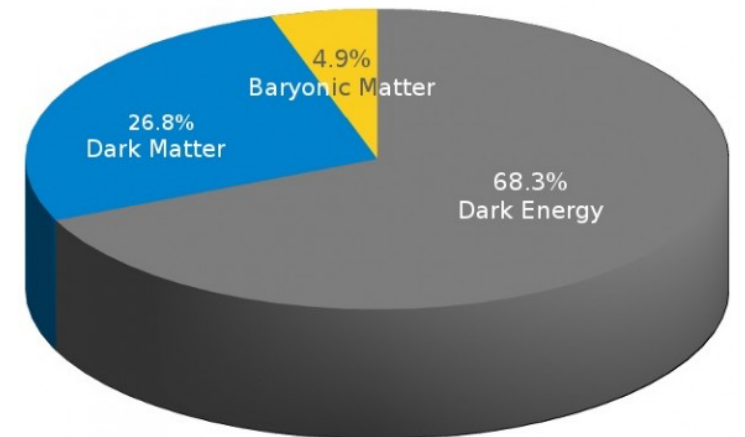
Bullet cluster



Cosmic microwave background temperature fluctuations

Could there be a dark sector of particles beyond the Standard Model?

How does our ordinary matter communicate with them?



Portals to the dark sector



Portals to the dark sector



Portals to the dark sector



Can you bridge
the two sides?

Portals to the dark sector

Searches at colliders, beam dumps, neutrino facilities



PUBLISHED FOR SISSA BY SPRINGER

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ACCEPTED: September 22, 2019
PUBLISHED: October 30, 2019

Search for heavy neutral leptons in decays of W bosons produced in 13 TeV pp collisions using prompt and displaced signatures with the ATLAS detector



The ATLAS collaboration

E-mail: atlas_publications@cern.ch

ABSTRACT: The problem of neutrino masses, matter-antimatter asymmetry, and dark matter could be successfully addressed by postulating right-handed neutrinos with Majorana masses below the electroweak scale. In this work, leptonic decays of W bosons extracted from 20.1fb^{-1} to 36.1fb^{-1} of 13 TeV proton-proton collisions at the LHC are used to search for heavy neutral leptons (HNLs) that are produced through mixing with muon or electron neutrinos. The search is conducted using the ATLAS detector in both prompt and displaced leptonic decay signatures. The prompt signature requires three leptons produced at the interaction point (either pup or epu) with a veto on same-flavour opposite-charge topologies. The displaced signature comprises a prompt muon from the W boson decay and the requirement of a dilepton vertex (either pup or epu) displaced in the transverse plane by ≥ 300 mm from the interaction point. The search sets constraints on the HNL mixing to muon and electron neutrinos for HNL masses in the range 45–50 GeV.

KEYWORDS: Hadron-Hadron scattering (experiments)

ARXIV EPRINT: [1906.09787](https://arxiv.org/abs/1906.09787)

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Article funded by SCOAP³.

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



Search for heavy neutral lepton
in $W^+ \rightarrow \mu^+ \mu^\pm$ jet decays

LHCb collaboration¹

Abstract

A search is performed for heavy neutrinos in the decay of a W boson into two muons and a jet. The data set corresponds to an integrated luminosity of approximately 3.0fb^{-1} of proton-proton collision data at centre-of-mass energies of 7 and 8 TeV collected with the LHCb experiment. Both same-sign and opposite-sign muons in the final state are considered. Data are found to be consistent with the expected background. Upper limits on the coupling of a heavy neutrino with the Standard Model neutrinos are set at 95% confidence level in the heavy-neutrino mass range from 5 to 50 GeV/ c^2 . These are of the order of 10^{-3} for lepton-number-conserving decays and of the order of 10^{-4} for lepton-number-violating heavy-neutrino decays.

Submitted to Eur. Phys. J. C

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¹Authors are listed at the end of this paper.

ν (neutrinos)

Standard
Model

A_μ (photons)

H (Higgs)

PHYSICAL REVIEW D **100**, 052006 (2019)

Search for heavy neutrinos with the T2K near detector ND280

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052006-1

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PHYSICAL REVIEW D **101**, 052001 (2020)

Search for heavy neutral lepton decaying into muon-pion pairs in the MicroBoNE detector

...?
N?
Dark Sector?
 X_μ ?
S?

(The MicroBoNE Collaboration)

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052001-1

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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ERN-EP-2021-018

28 January 2021

Search for K^+ decays to a muon and invisible particles

The NA62 Collaboration

Abstract

The NA62 experiment at CERN reports searches for $K^+ \rightarrow \mu^+ N$ and $K^+ \rightarrow \mu^+ X$ decays, where N and X are massive invisible particles, using the 2016–2018 data set. The N particle is assumed to be a heavy neutral lepton, and the results are expressed in upper limits of $\mathcal{O}(10^{-5})$ for the neutrino mixing parameters $|V_{\mu N}|^2$ for N masses in the range 200–384 MeV/ c^2 and lifetime exceeding 50 ns. The X particle is considered a scalar or vector hidden sector mediator decaying to an invisible final state, and upper limits of the decay branching fraction for X masses in the range 10–270 MeV/ c^2 are reported for the first time, ranging from $\mathcal{O}(10^{-5})$ to $\mathcal{O}(10^{-7})$. An improved upper limit of 1.0×10^{-6} is established at 90% CL on the $K^+ \rightarrow \mu^+ \nu$ branching fraction.

To be submitted to Physics Letters B

arXiv:2101.12304v1 [hep-ex] 28 Jan 2021

arXiv:2011.06263v1 [hep-ex] 10 Nov 2020

JHEP10(2019)265

Portals to the dark sector



Higgs Portal

Lagrangian

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

Extension to the Standard Model

After electroweak symmetry breaking:

$$\mathcal{L} \supset -\frac{1}{2}m_S^2 S^2 + \sin\theta S \left(\frac{2m_W^2}{v} W_\mu^+ W^{\mu+} + \frac{m_Z^2}{v} Z_\mu Z^\mu - \sum_f \frac{m_f}{v} \bar{f} f \right)$$

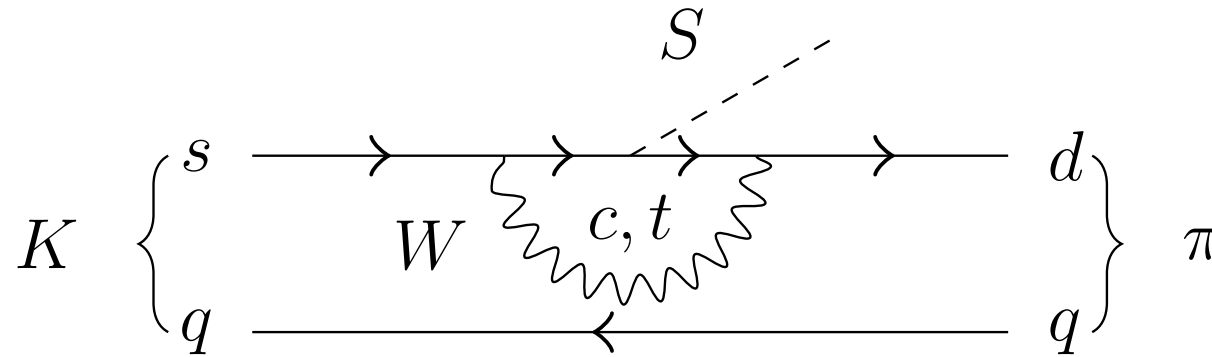
scalar mass

mixing angle

coupling to SM fermions

Kaon decays

- Light scalars ($< \sim 240 \text{ MeV}$) can be produced in kaon decays, via a top quark in a penguin decay

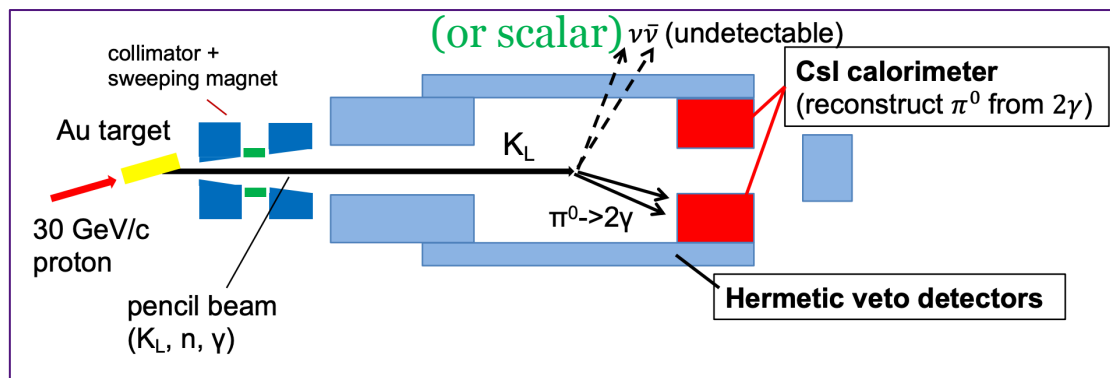


Decay rate

$$\Gamma(K^\pm \rightarrow \pi^\pm S) \simeq \frac{\theta^2}{16\pi m_K} \left| \frac{3V_{td}^* V_{ts} m_t^2 m_K^2}{32\pi^2 v^3} \right|^2 \lambda^{1/2} \left(1, \frac{m_S^2}{m_K^2}, \frac{m_\pi^2}{m_K^2} \right)$$

Aside: the KOTO anomaly

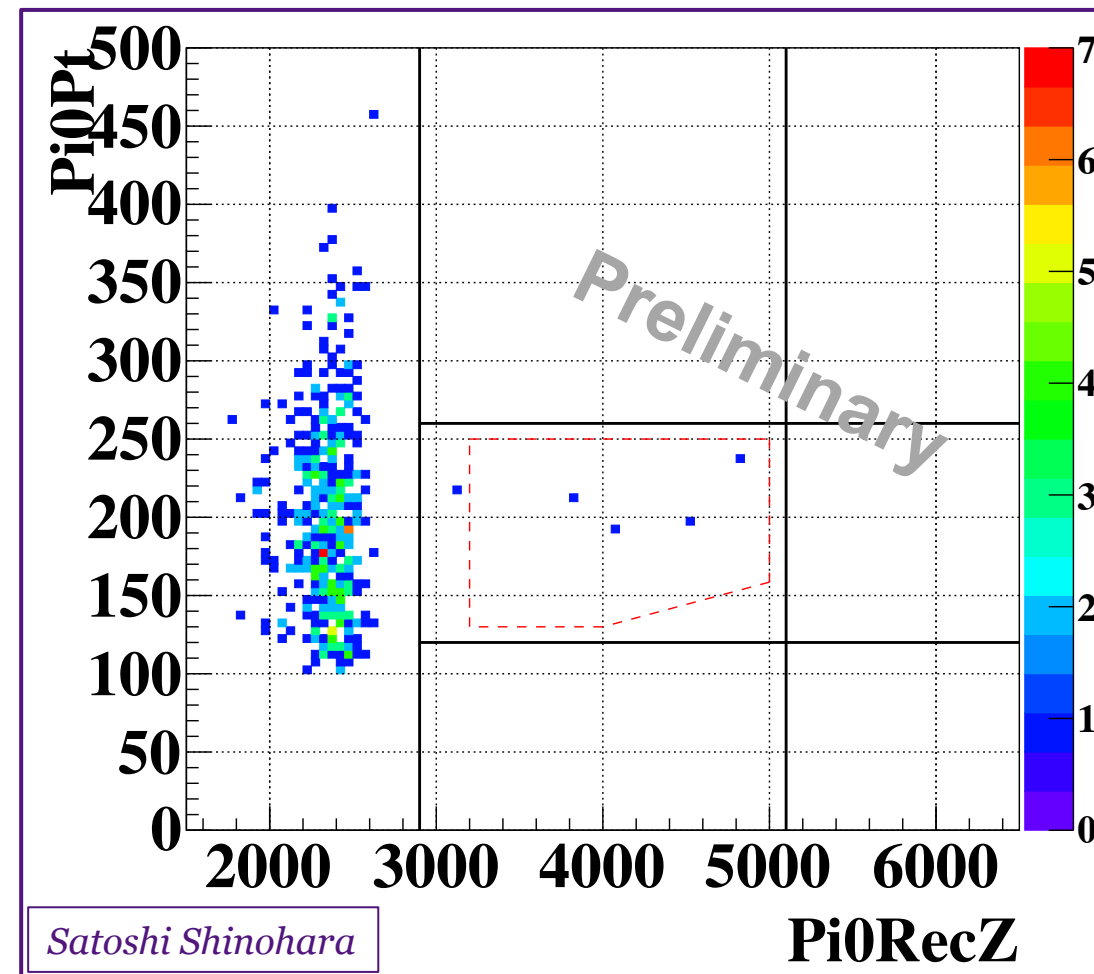
[Kaon 2019 talk](#)



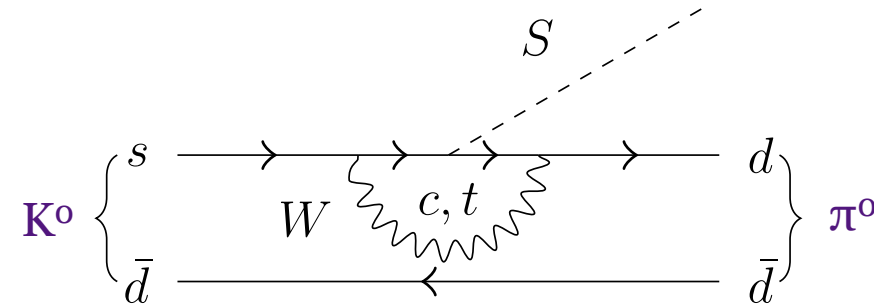
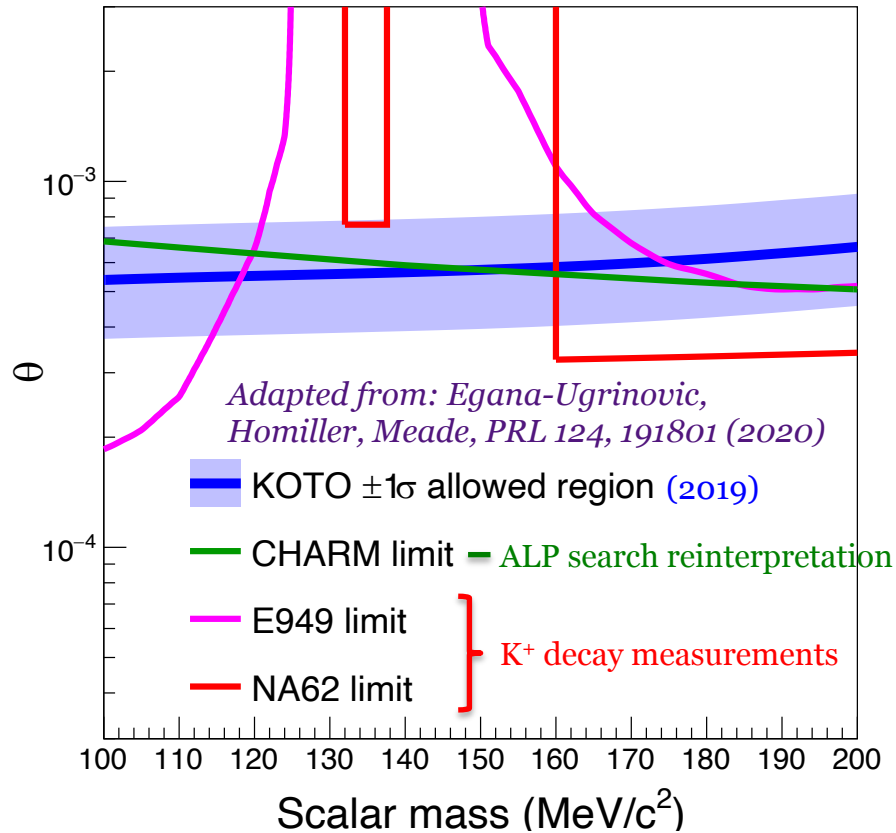
KOTO experiment at J-PARC is searching for rare neutral kaon decays

Observe 3 events (0.05 expected background)
Branching ratio ~ 2 orders of magnitude larger than SM $K^0 \rightarrow \pi^0 \nu\bar{\nu}$

The size of this excess has weakened recently
 $\Rightarrow 1.22$ expected background counts



Aside: the KOTO anomaly



You can explain this anomaly with a Higgs-portal scalar

Only a narrow window of allowed parameter range remains, in the 100-200 MeV window

This is why we focused on this mass range for this first search

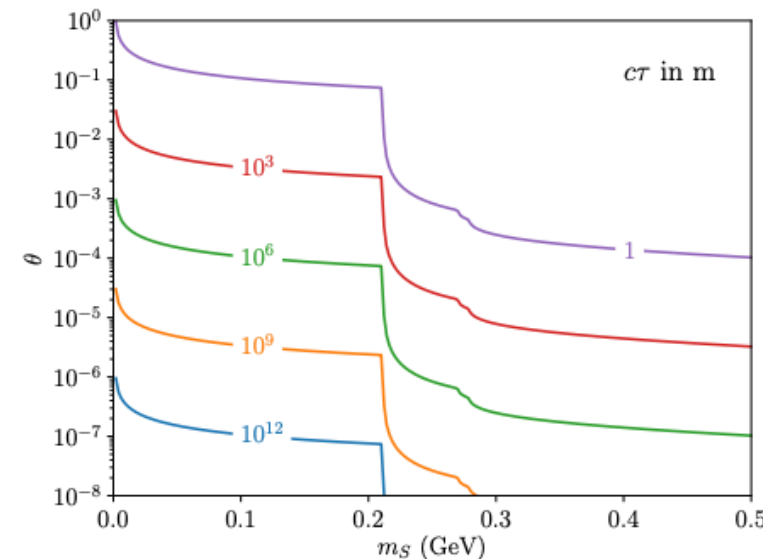
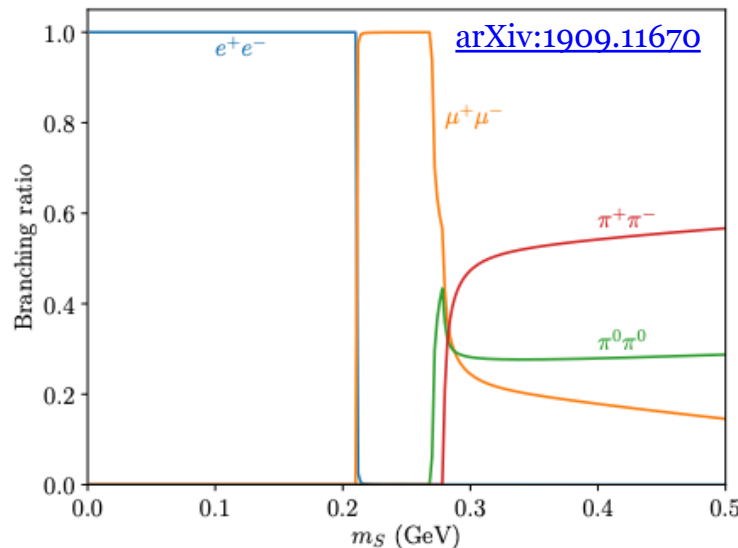
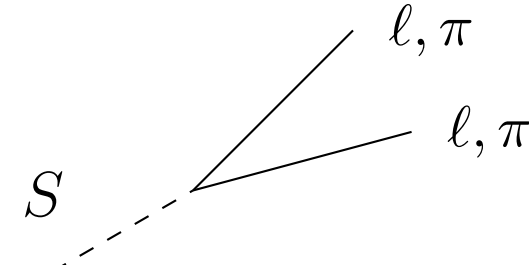
KOTO has now released updated results a few months ago, and the significance of the excess has decreased ($p=0.13$)

Scalar decays

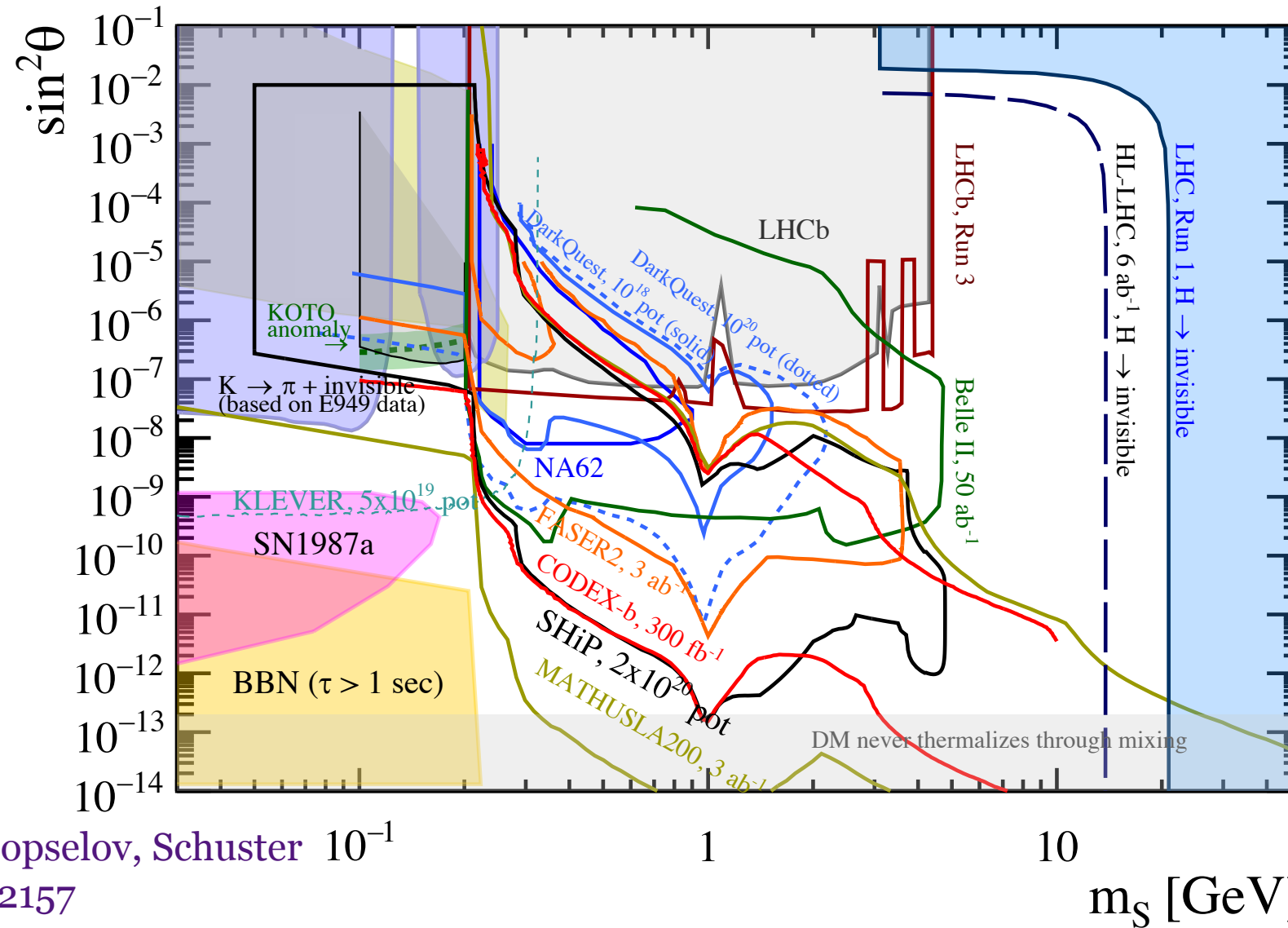
- Light scalars decay to electron-positron pairs, or di-muon or di-pion pairs if heavy enough

Decay rate

$$\Gamma(S \rightarrow \ell^+ \ell^-) = \theta^2 \frac{m_\ell^2 m_S}{8\pi v^2} \left(1 - \frac{4m_\ell^2}{m_S^2}\right)^{3/2}$$



Current & Future experimental searches



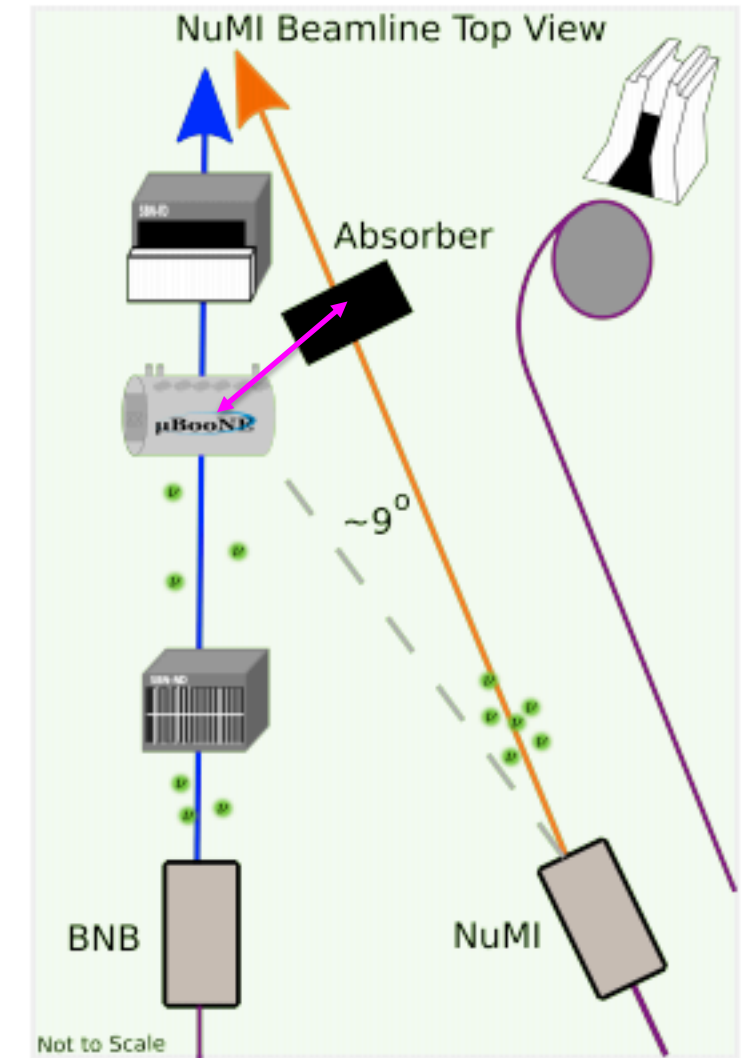
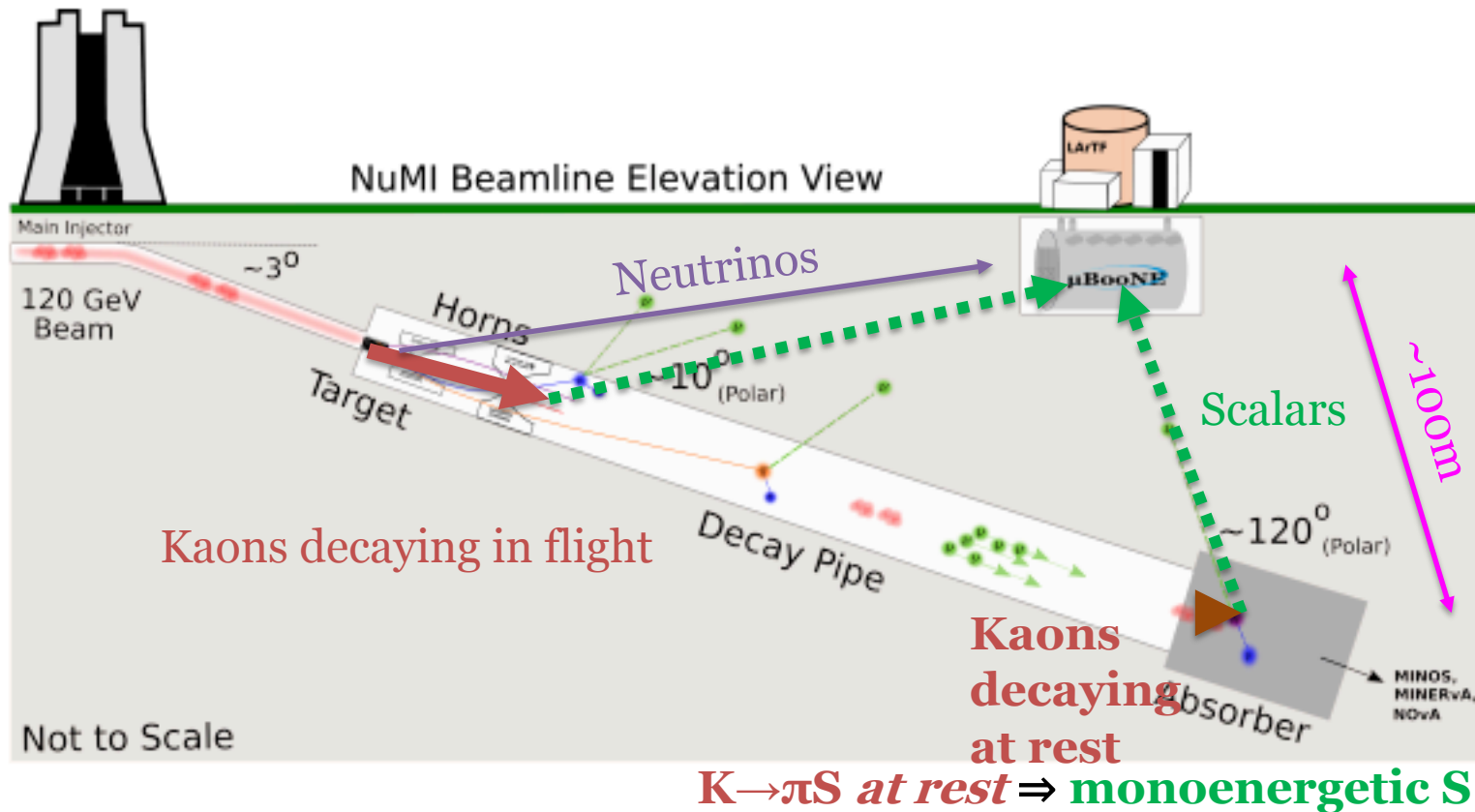
Lanfranchi, Popselov, Schuster
arXiv: 2011.02157

- Introduction to MicroBooNE
- The Higgs Portal to the dark sector
- **New limits from MicroBooNE**
- Other new physics models

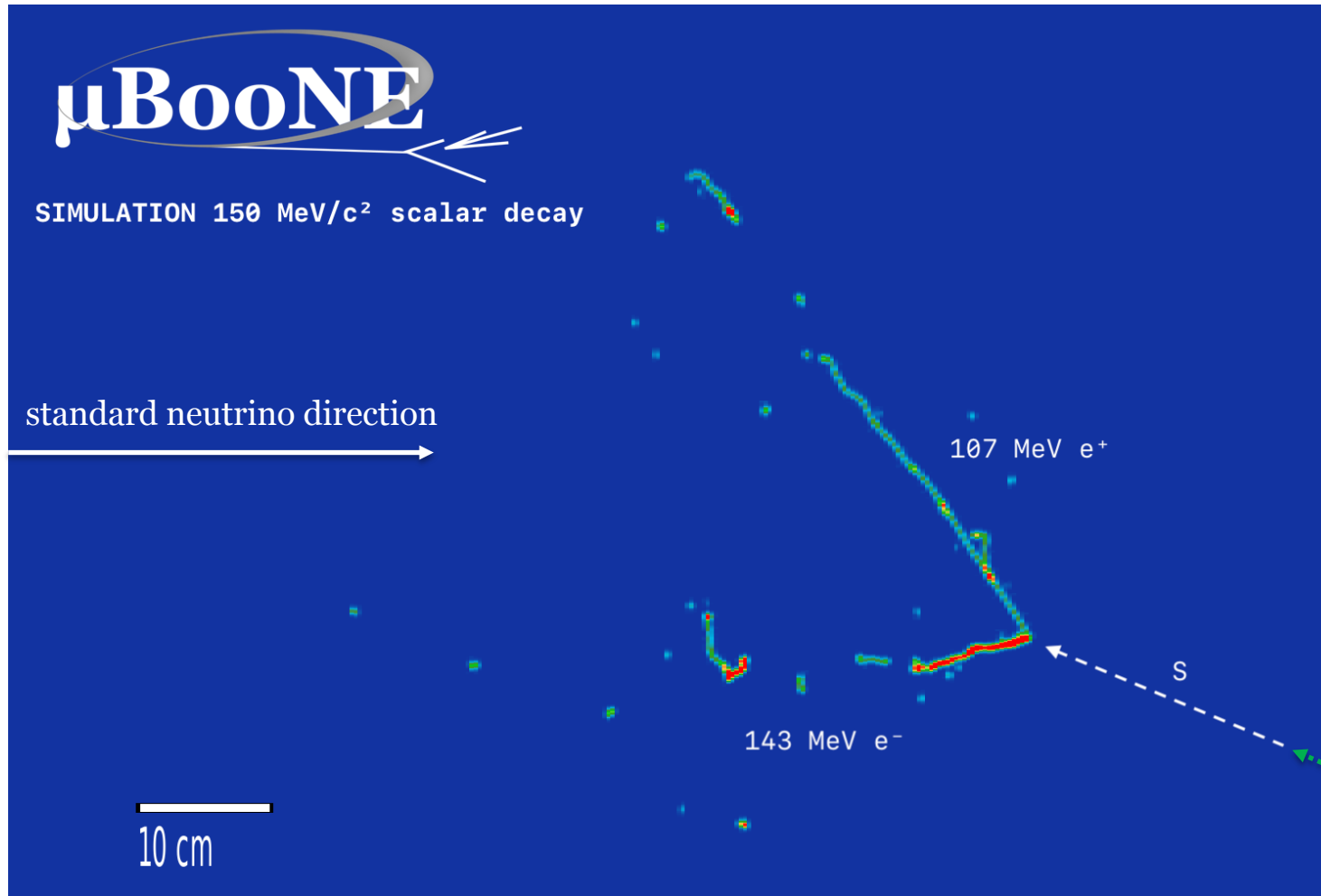
Production of the scalar in our experiment

For this first result, we are interested in scalars produced in the beam dump (hadron absorber) of the NuMI beam

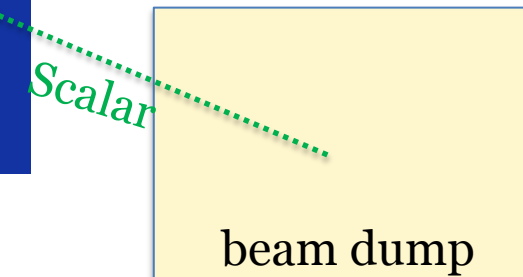
Kaons will decay at rest, producing monoenergetic scalars – a unique signature in the detector



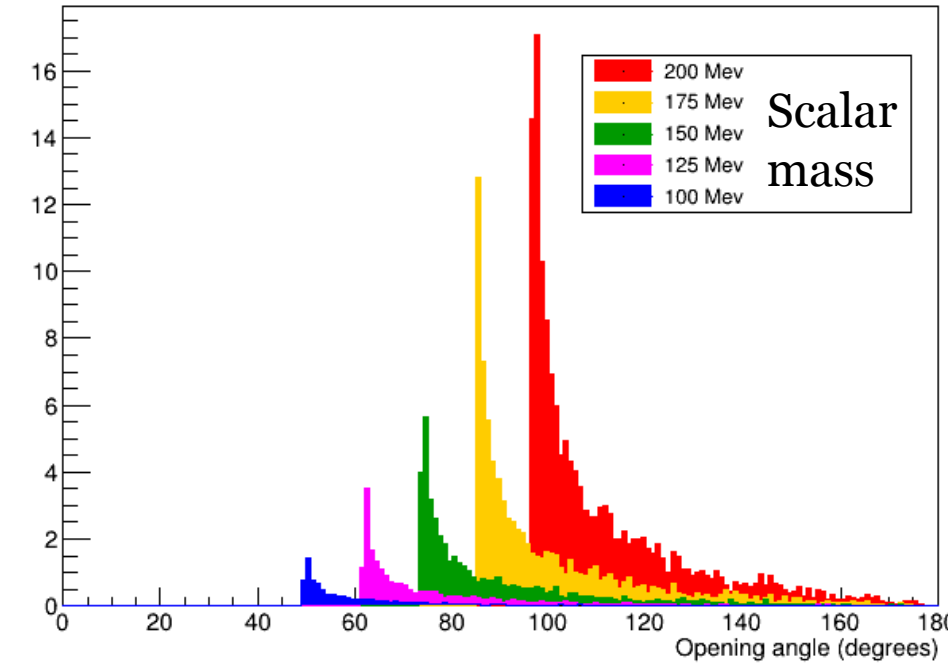
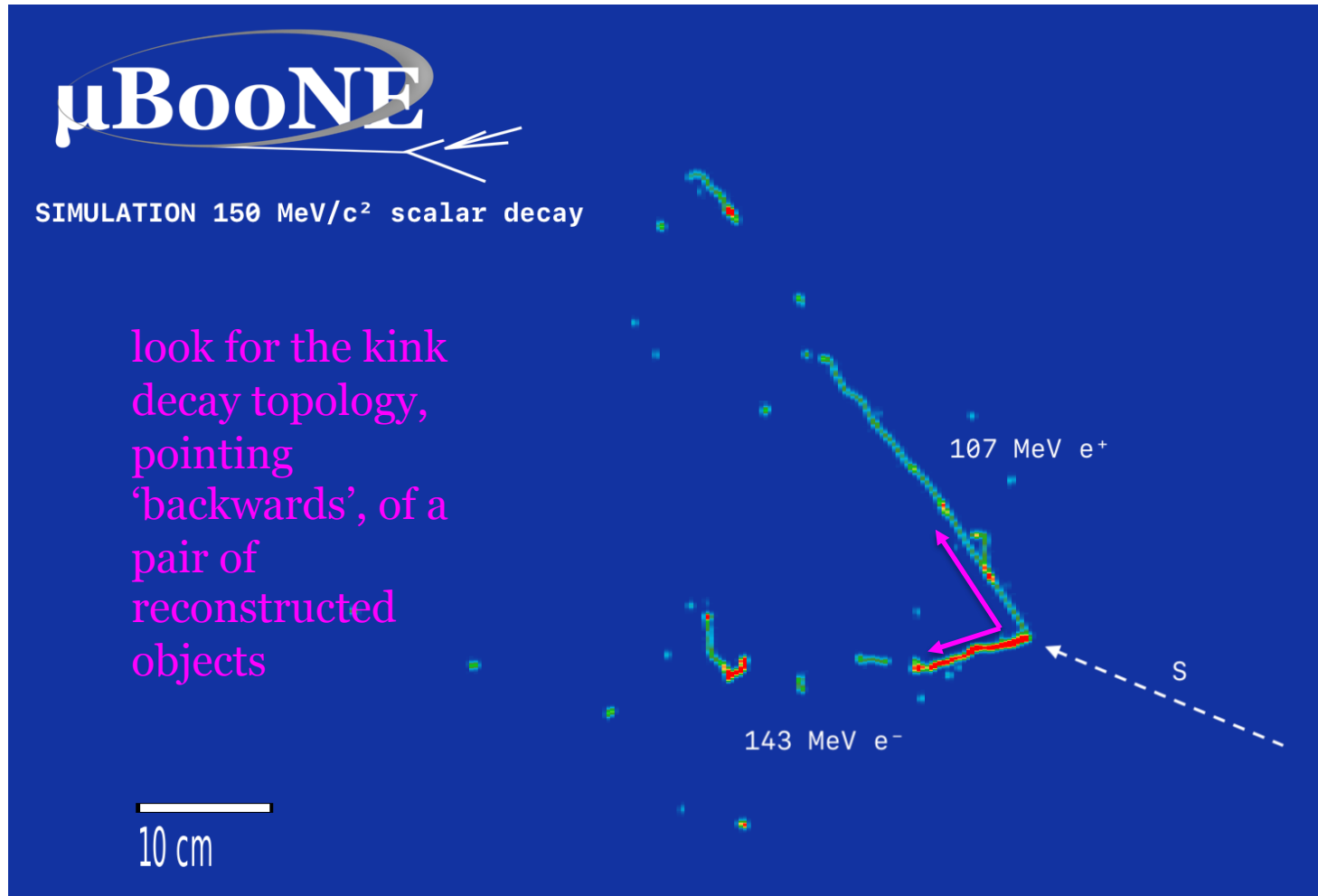
Example decay



Simulation of a 150 MeV scalar decaying to e⁺e⁻ inside MicroBooNE

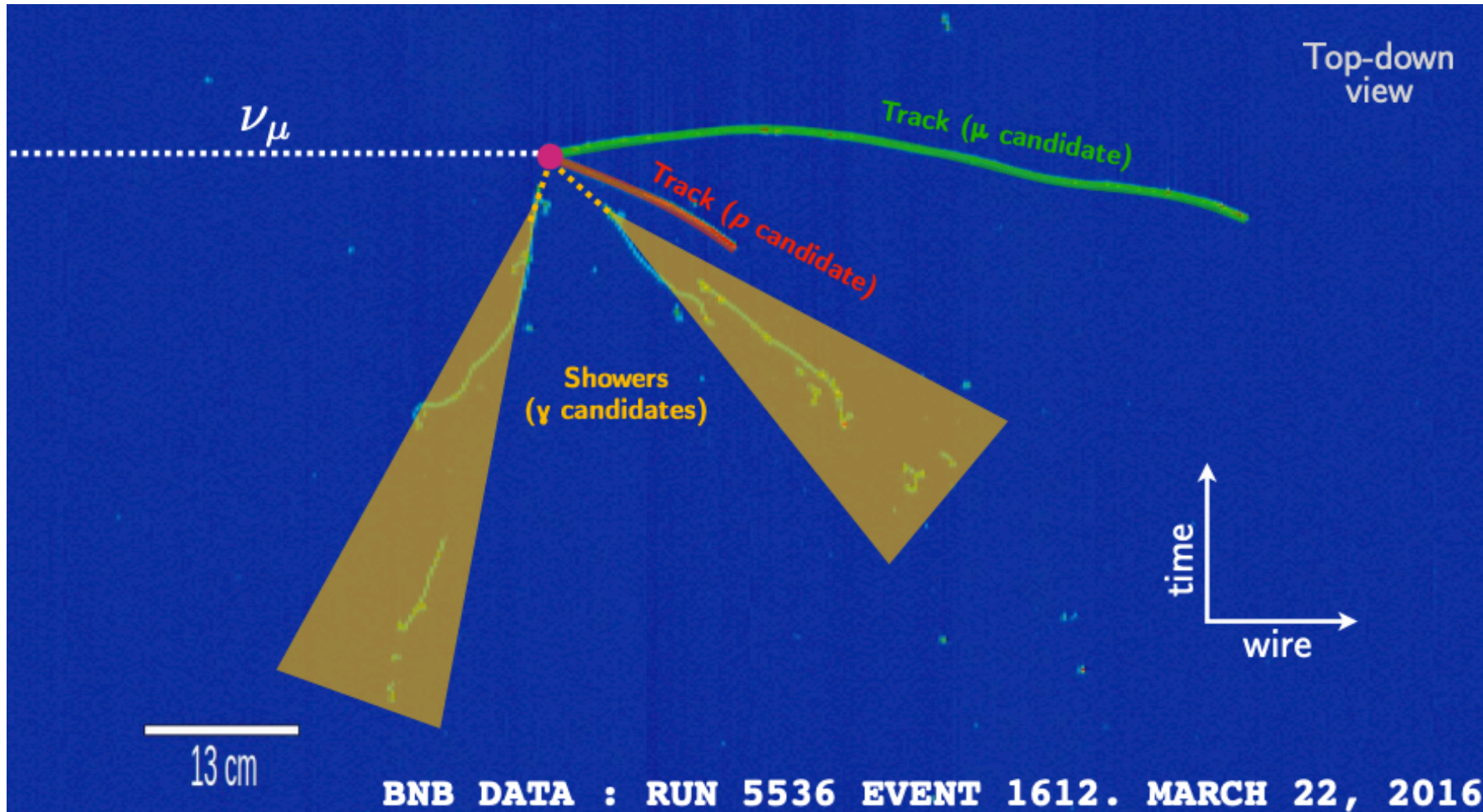


Selection philosophy



Opening angle strongly
depends on mass

Pandora reconstruction



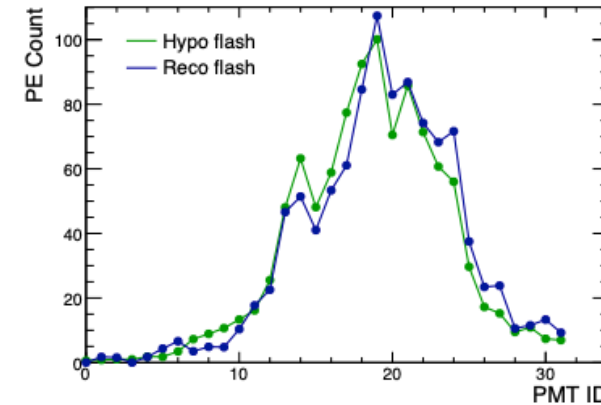
Pandora* is a toolkit to reconstruct LArTPC events, using particle flow algorithms based on ALICE experience

In our case, it produces “tracks” and “showers”

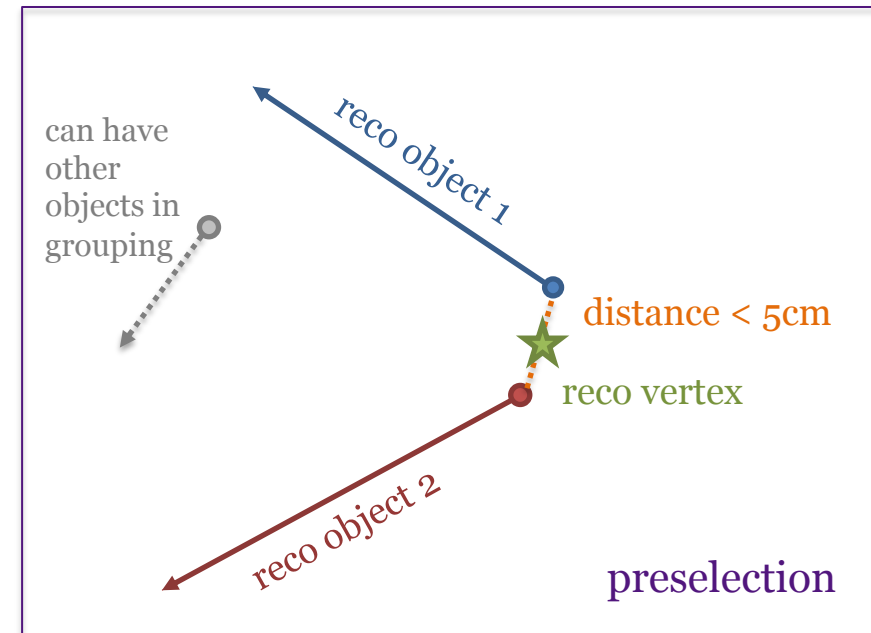
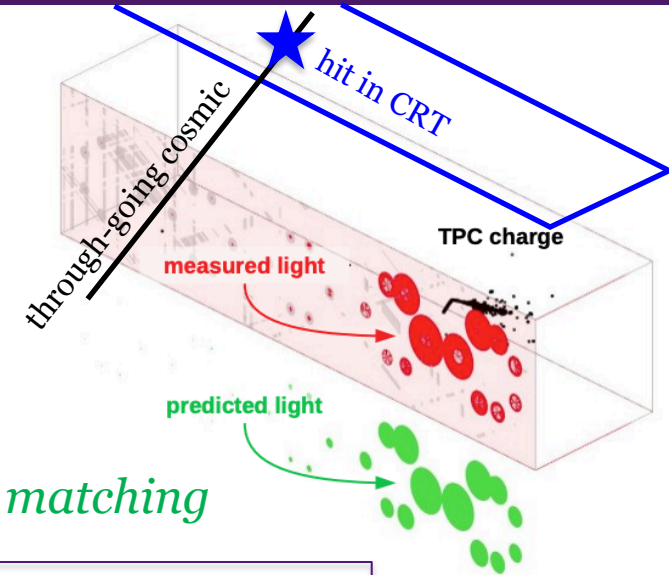
[*https://github.com/PandoraPFA](https://github.com/PandoraPFA)

Signal preselection

- *Pandora* groups reconstructed objects together – “slice”
 - **matching** to PMT signals, for event timing
 - **Cosmic ray tagger veto** in Run 3
- Take all pairs of objects in the grouping
 - Require **distance between object ends** less than 5 cm
 - **Reconstructed vertex** inside TPC active volume
- Consider all possible passing pairs of objects at this stage
 - Boosted Decision Tree to filter out backgrounds...

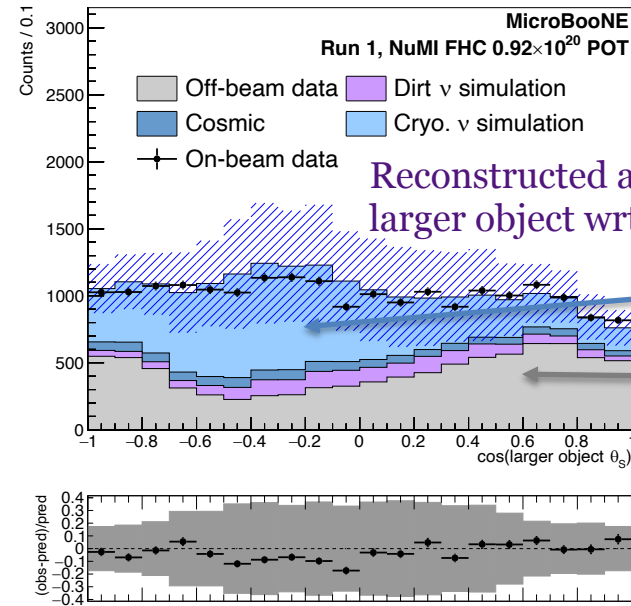


PMT matching



Boosted decision tree inputs

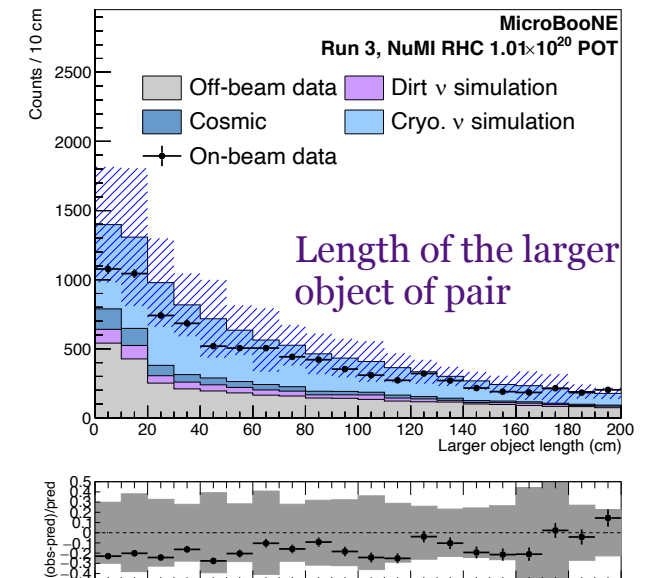
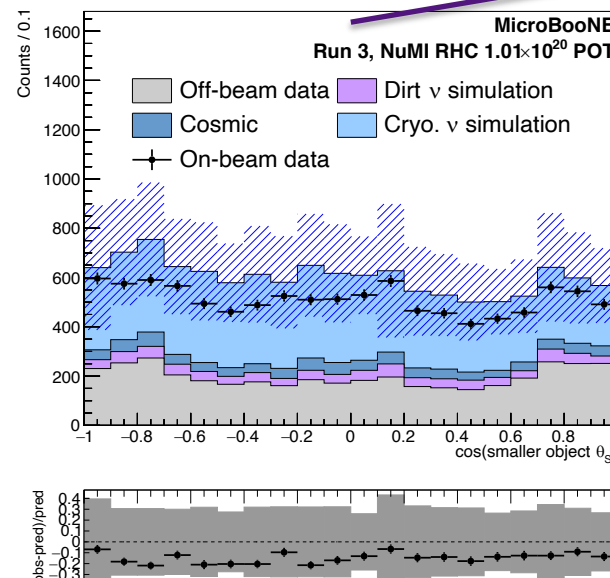
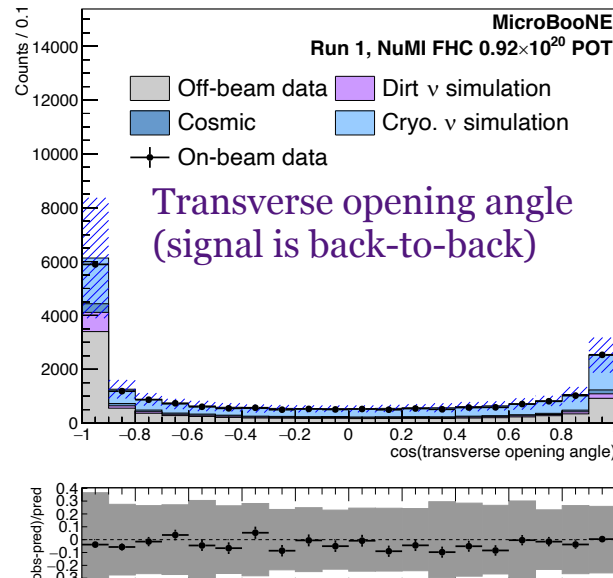
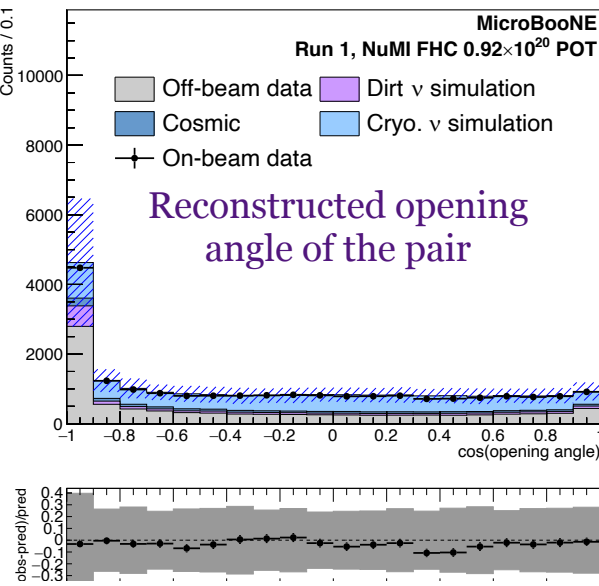
- BDTs are trained with a “uniform” mass signal model between 100–200 MeV
- 10 input variables
 - Data/MC agreement for some of the most important shown here
- Trained using only geometrical quantities (e.g. no calorimetry used)



(“Dirt”: Neutrino interactions outside cryostat)
(“Cosmic”: beam-related event, but cosmic is reconstructed)

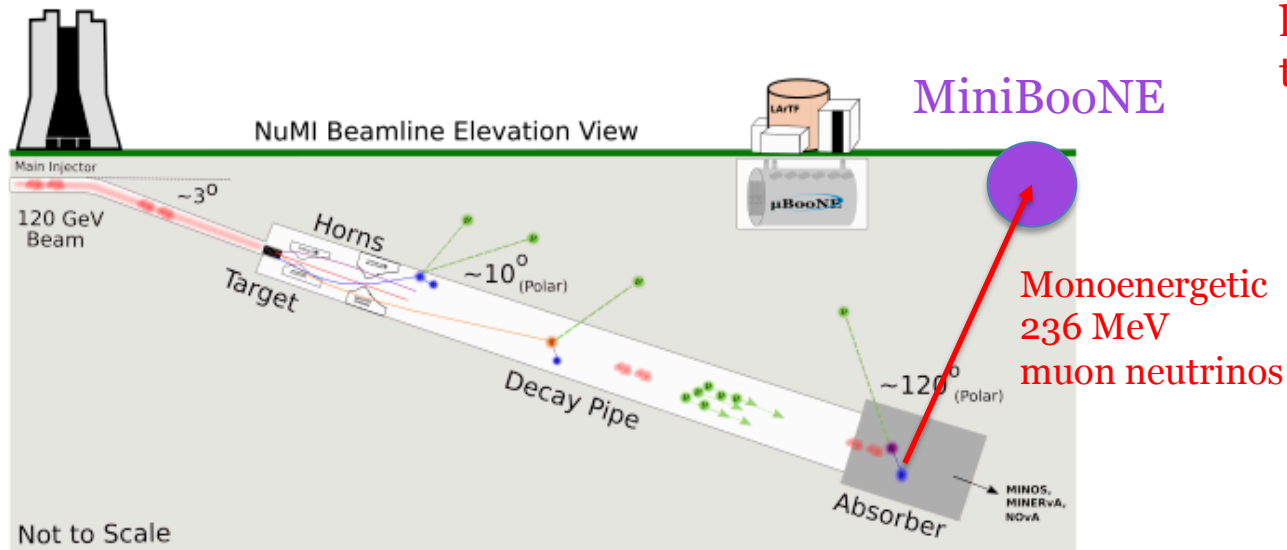
Neutrino interaction background (simulation)

Pure beam-unrelated cosmic background (data driven measurement)

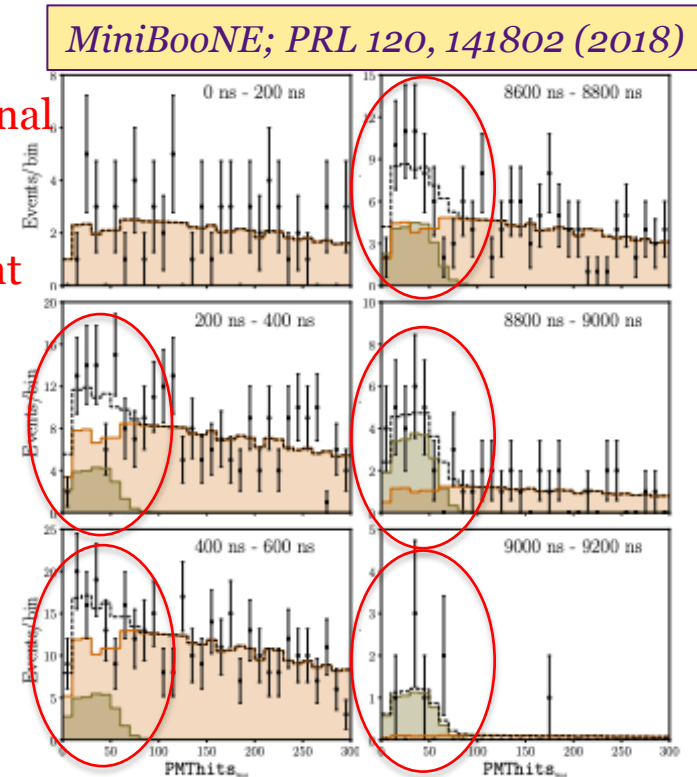


Signal model uncertainty

- Largest uncertainty on the signal model is due to flux normalisation
- MiniBooNE measured the rate of KDAR neutrinos from the beam dump $\Rightarrow$ 30% uncertainty

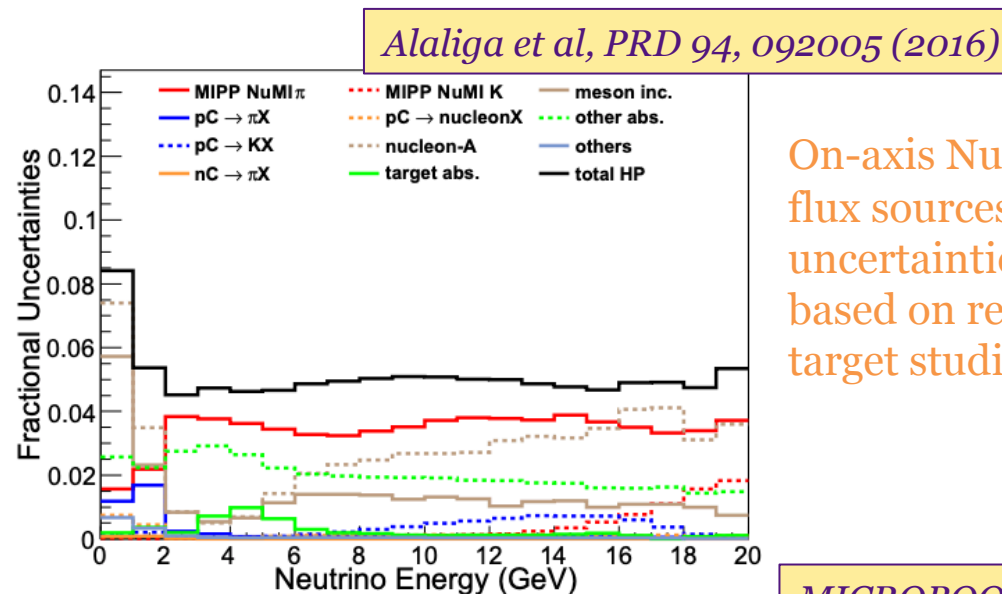


Delayed signal
due to kaon
lifetime &
time of flight



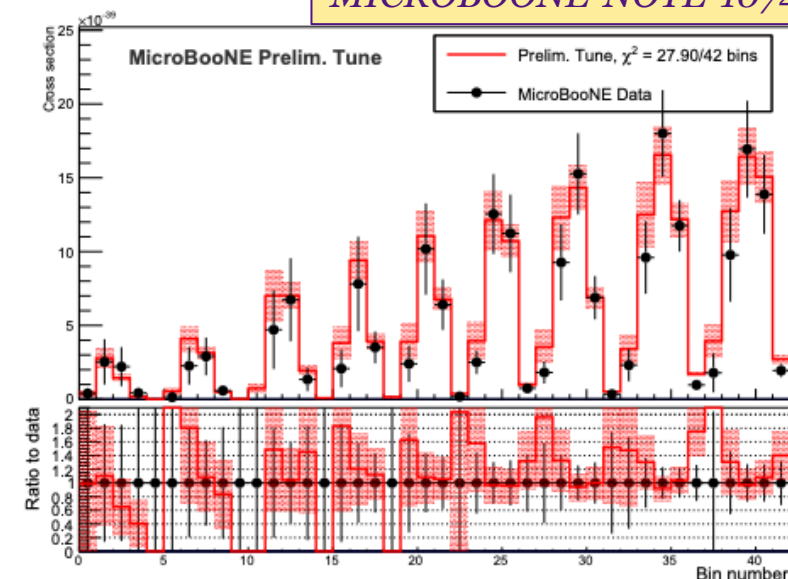
Background model uncertainty

- In the signal region, we are **stats dominated**
 - 2.0 expected events
- Largest uncertainties are due to flux, detector systematics, off-beam data statistics
 - **Flux uncertainties** evaluated with “PPFX” framework used by Minerva and NoVA
 - **Cross-section uncertainties** evaluated with GENIE reweighting framework
 - **Detector uncertainties**; resimulation with modified detector model



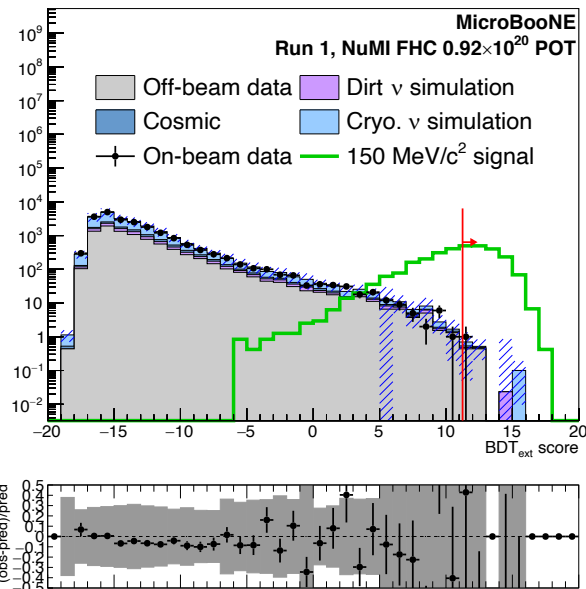
On-axis NuMI
flux sources of
uncertainties,
based on replica
target studies

Tuning the
neutrino
interaction
cross sections
+ model
uncertainties
with BNB data

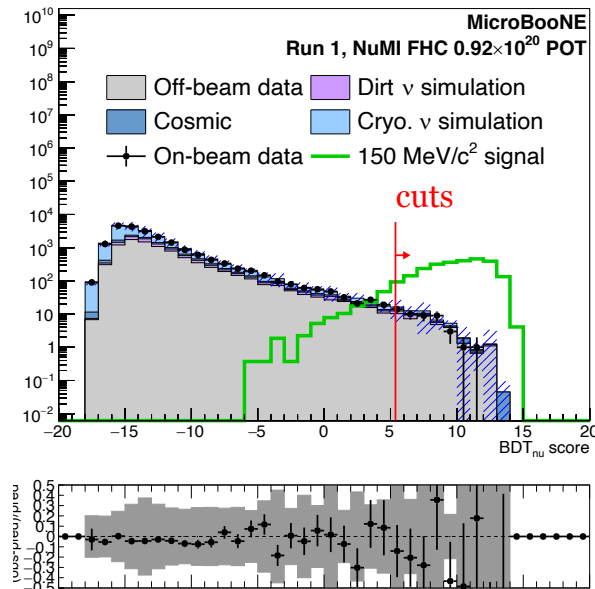


BDT Results

- Trained BDTs against two types of background
 - Against pure cosmics (data driven), and against neutrinos (simulated)
 - Final cuts are two-dimensional; optimised for maximum sensitivity

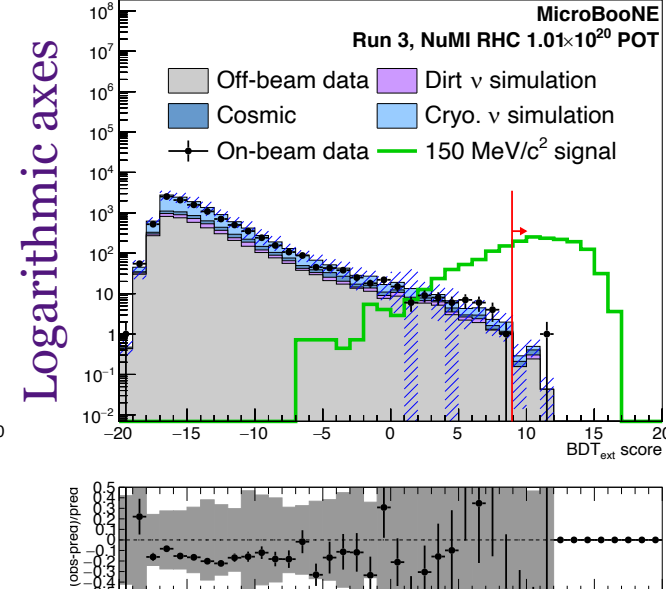


BDT vs cosmics

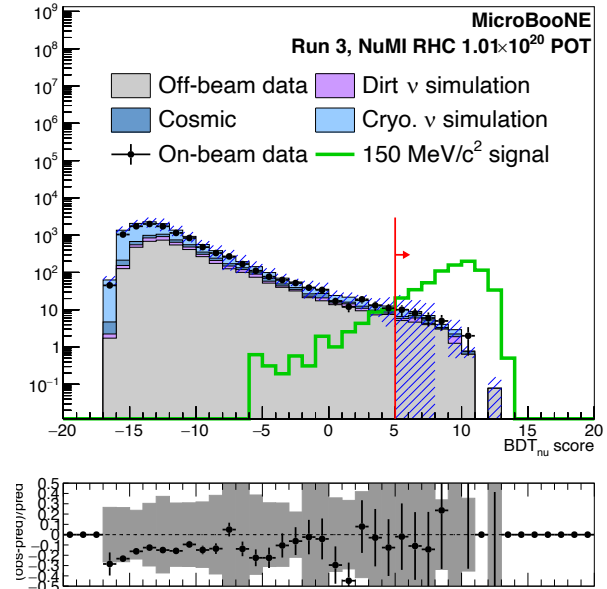


BDT vs neutrinos

Run 1 (2016)
before CRT



BDT vs cosmics



BDT vs neutrinos

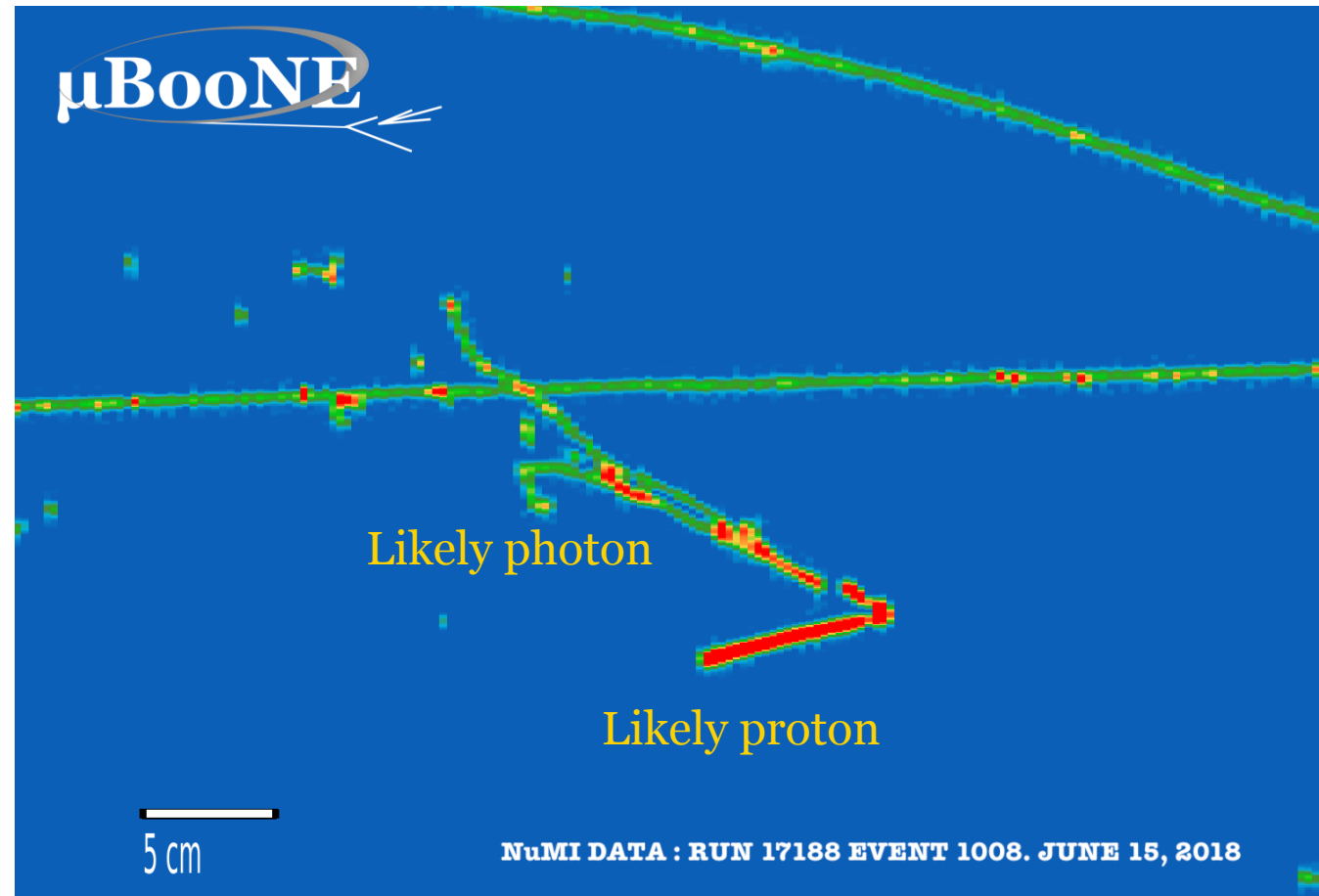
Run 3 (2018)
after CRT

Results

- Looking in the signal region, we **observed 2 events**
 - **1 is rejected** as an obvious cosmic
 - PMT timing is before the beam spill window
- We have looked at the surviving event, and it is consistent with background

Results

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 - **1 is rejected** as an obvious cosmic
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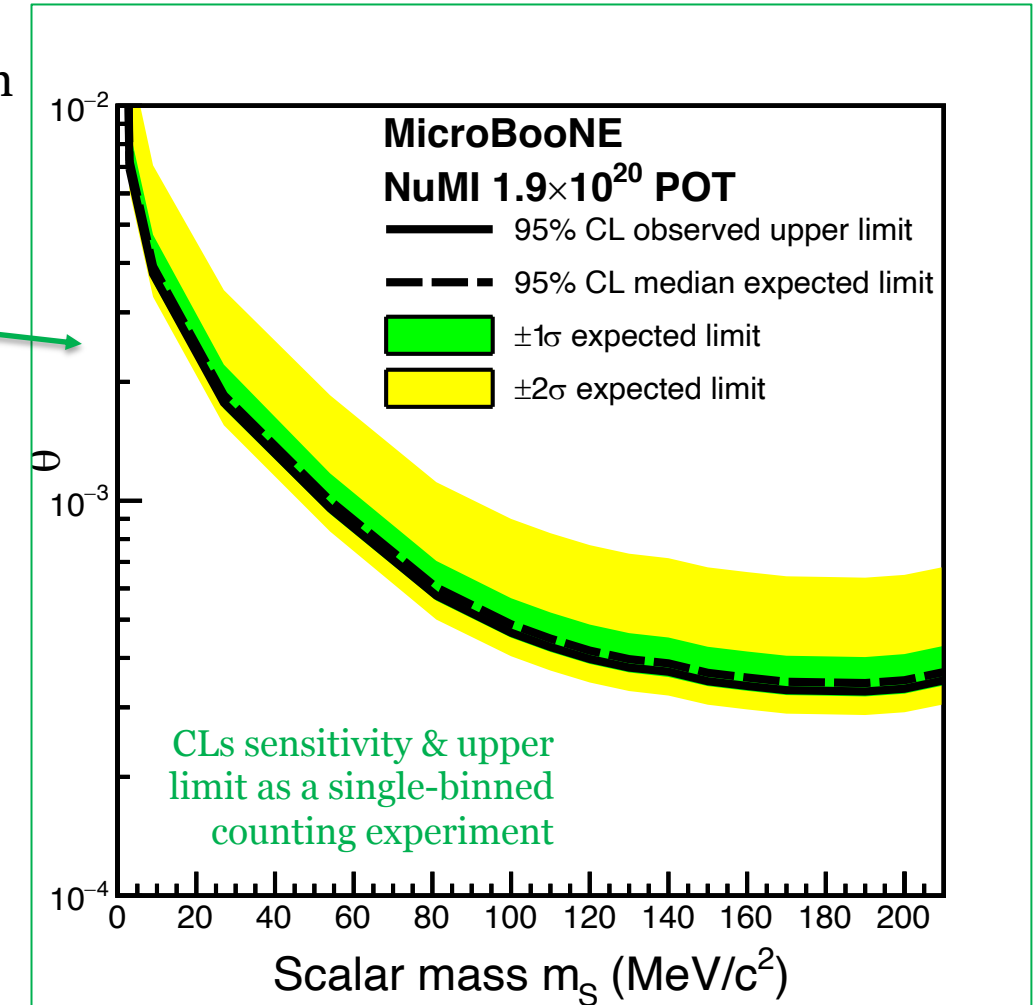
Results

- Looking in the signal region, we **observed 2 events**
 - 1 is rejected** as an obvious cosmic
 - PMT timing is before the beam spill window
- We have looked at the surviving event, and it is consistent with background
- Limit with 1 observed event, with a background expectation of 1.9 ± 0.8

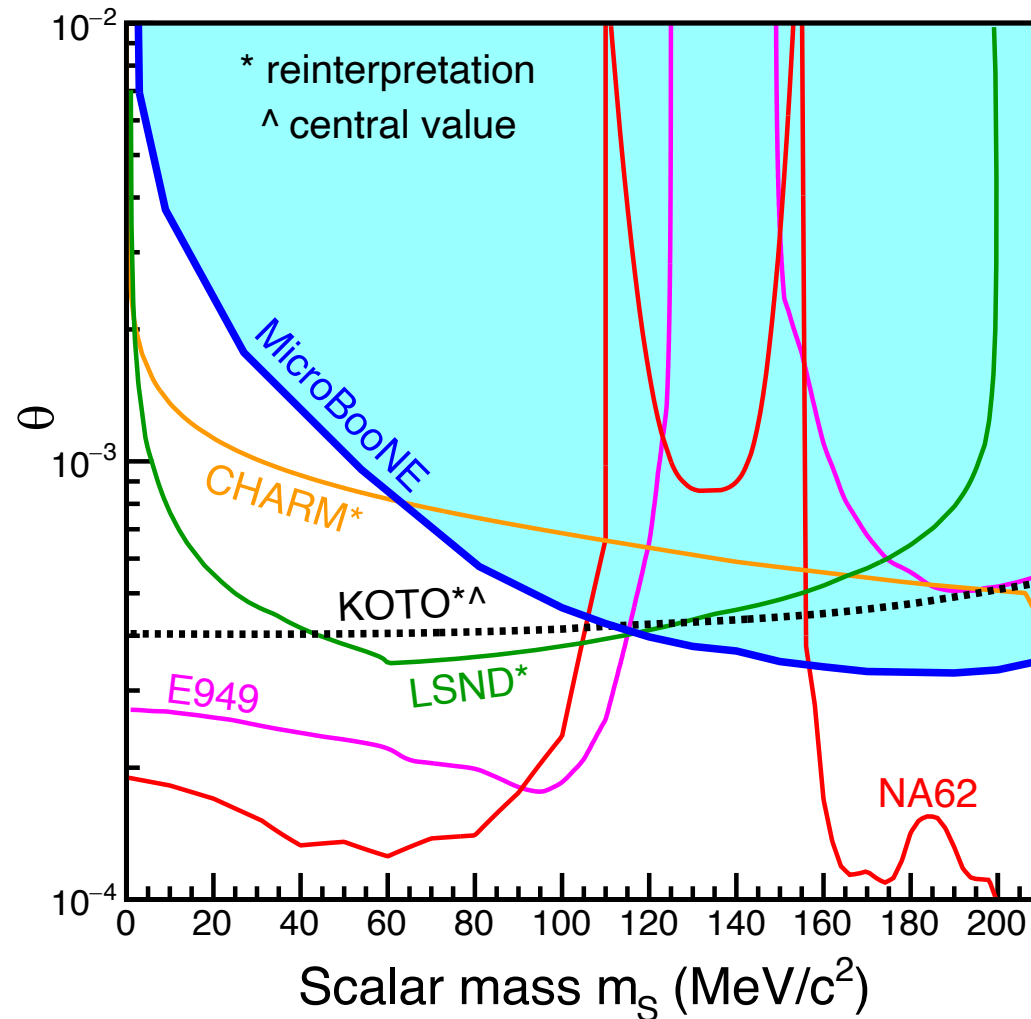
Uncertainty	Background	Signal
Flux (hadron production)	26.6%	30.0%
Cross section model	1.7%	—
Detector model	70.0%	5.0%
Beam-off statistics	38.0%	—
Simulation statistics	28.2%	< 2.0%

Systematic uncertainties

The most important



Preliminary limit & KOTO parameter space



This is with
~10% of our
NuMI dataset

Can exclude the KOTO (2019)
allowed model parameters at 95% CL

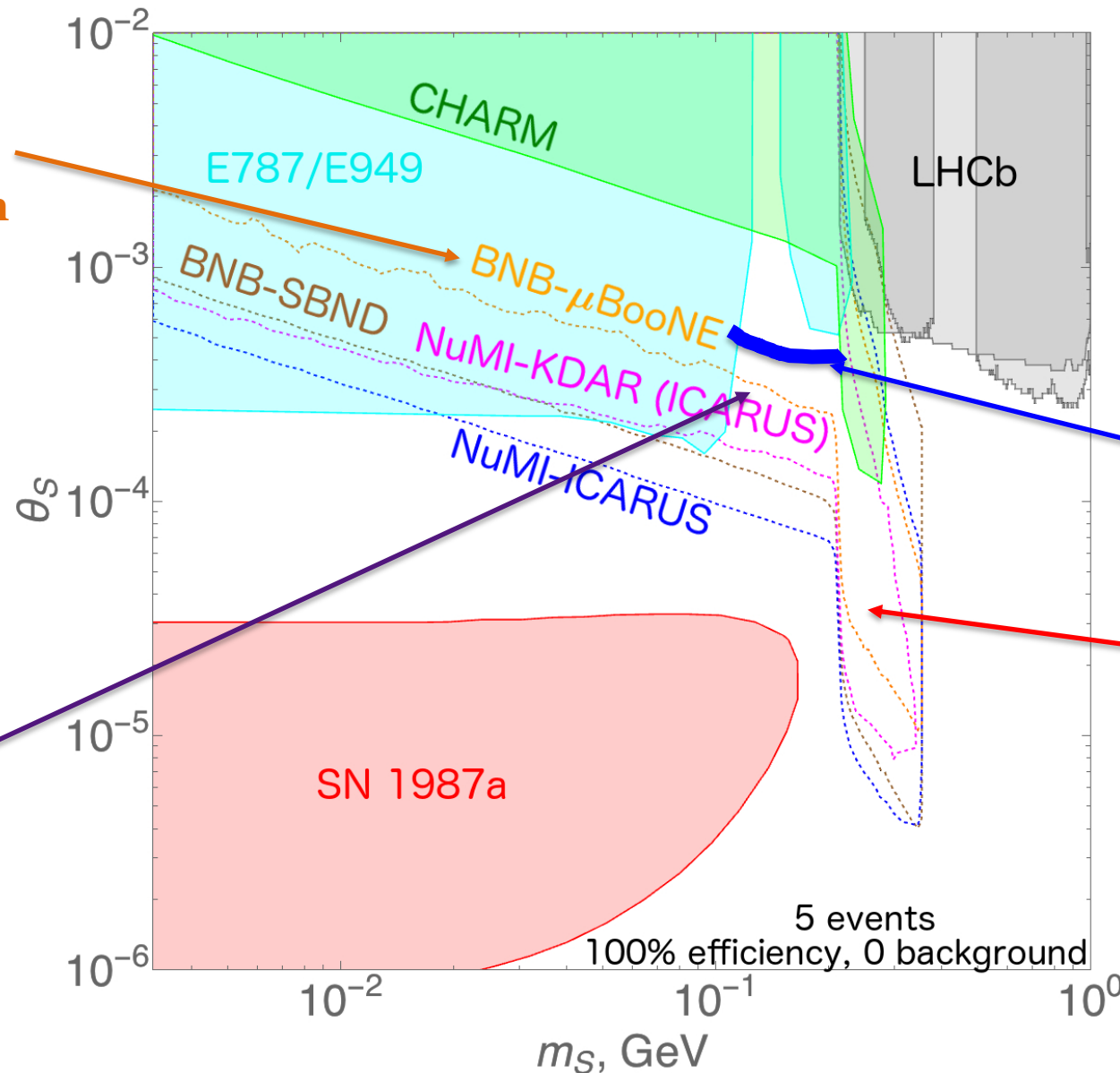
Further details in our publication:
arXiv:2106.00568

Projected sensitivity (by phenomenologists)

MicroBooNE,
using Booster
Neutrino Beam

Batell, Berger, Ismail
PRD 100, 115039 (2019)

Kaon decay-
in-flight
based search



Current limit
(crudely drawn)

Di-muon, di-pion
decay channels

Reinterpretation

The MicroBooNE Experiment, the NuMI Absorber, and Heavy Neutral Leptons

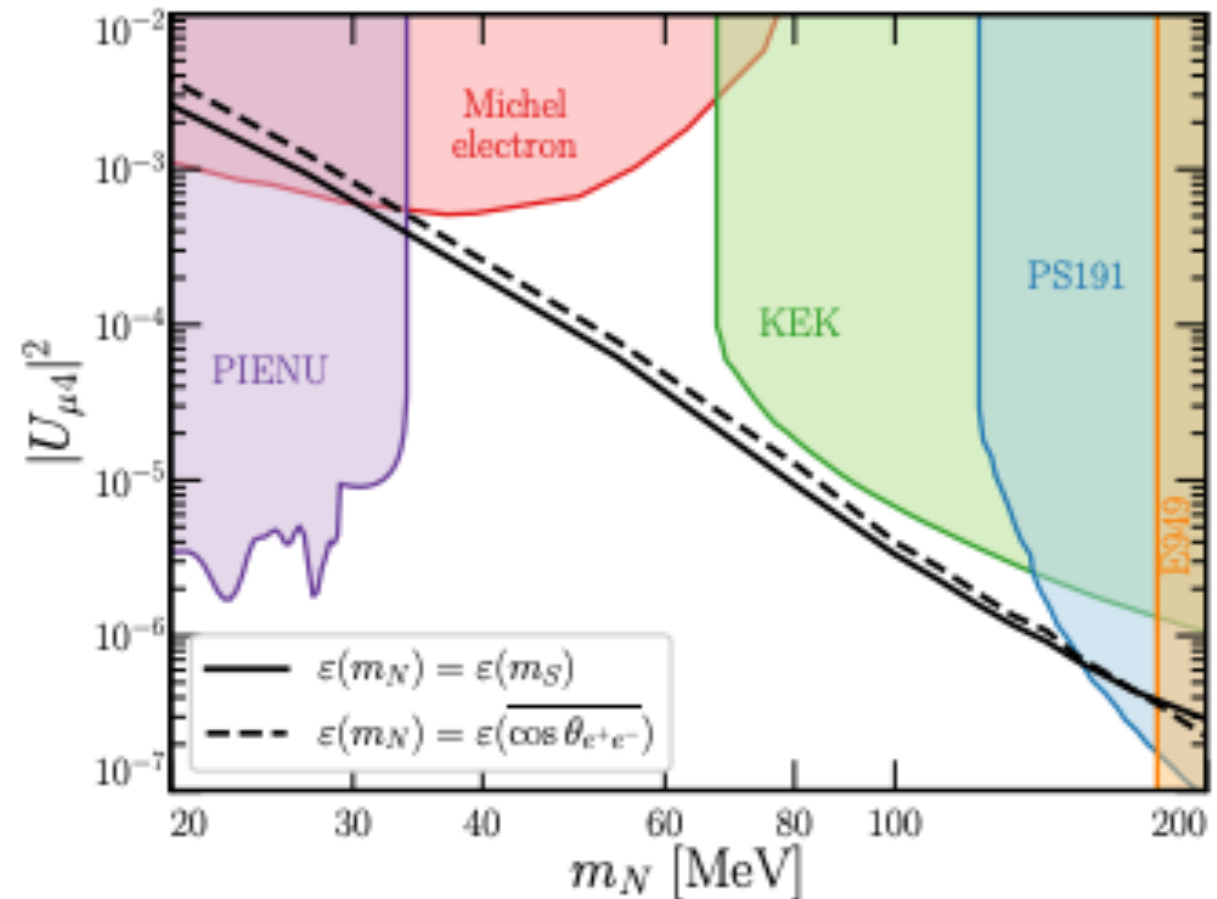


Kevin J. Kelly and Pedro A.N. Machado

Theory Department, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

(Dated: June 15, 2021)

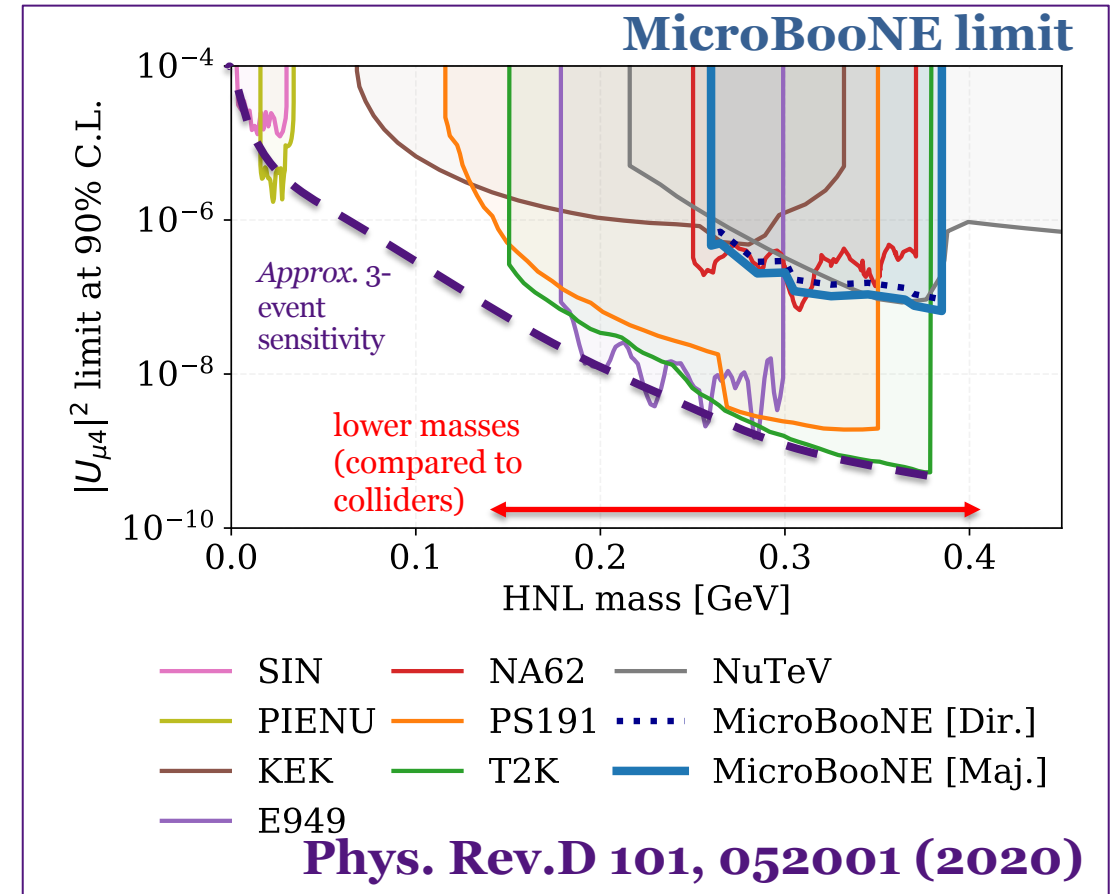
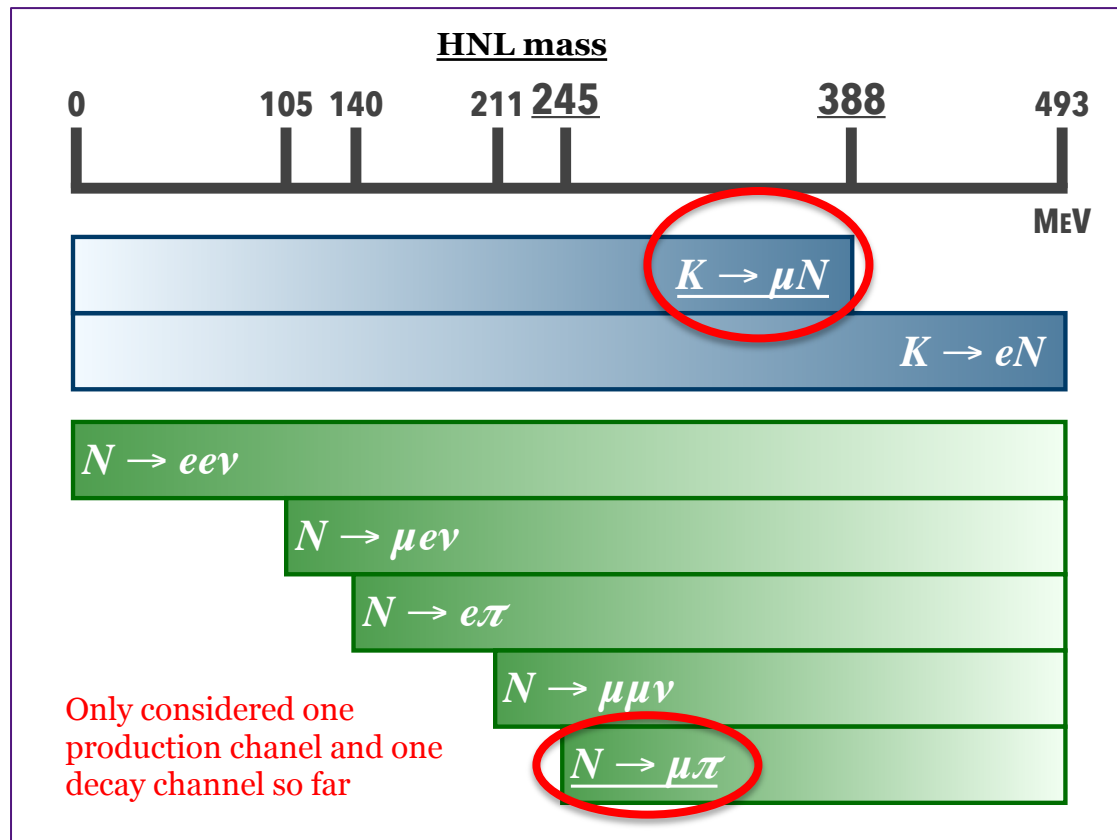
- Within weeks, we already have theorists reinterpreting our results, for other models
 - Heavy neutral leptons → <https://arxiv.org/abs/2106.06548>



- Introduction to MicroBooNE
- The Higgs Portal to the dark sector
- New limits from MicroBooNE
- Other new physics models

Heavy Neutral Leptons

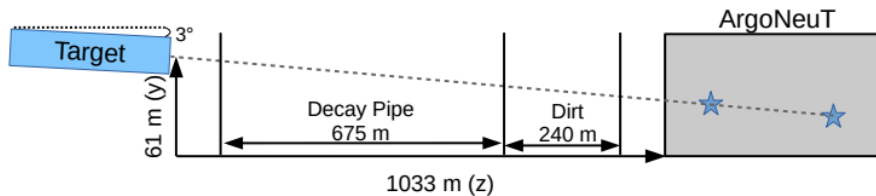
- Very similar phenomenology to the Higgs Portal scalar
 - Kaon decays to HNL; HNL decays to muon+pion
- Further strategies coming soon



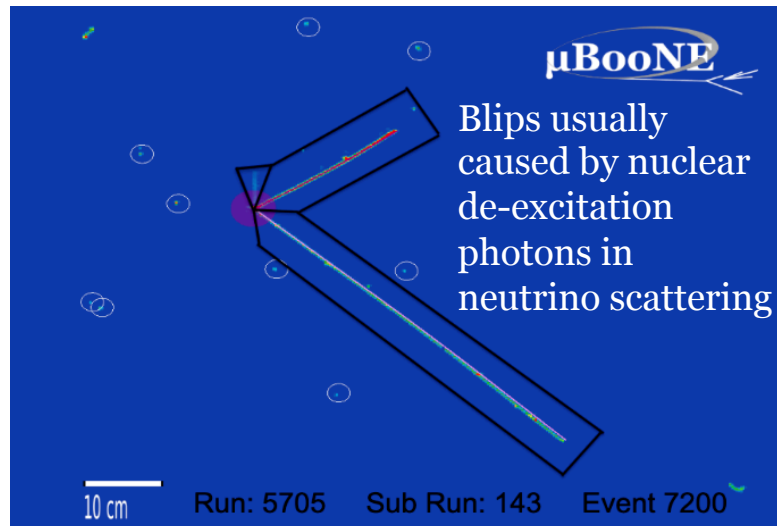
Millicharged Particles

- A measurement performed by ArgoNeuT (another LArTPC experiment); student is now a PDRA on MicroBooNE

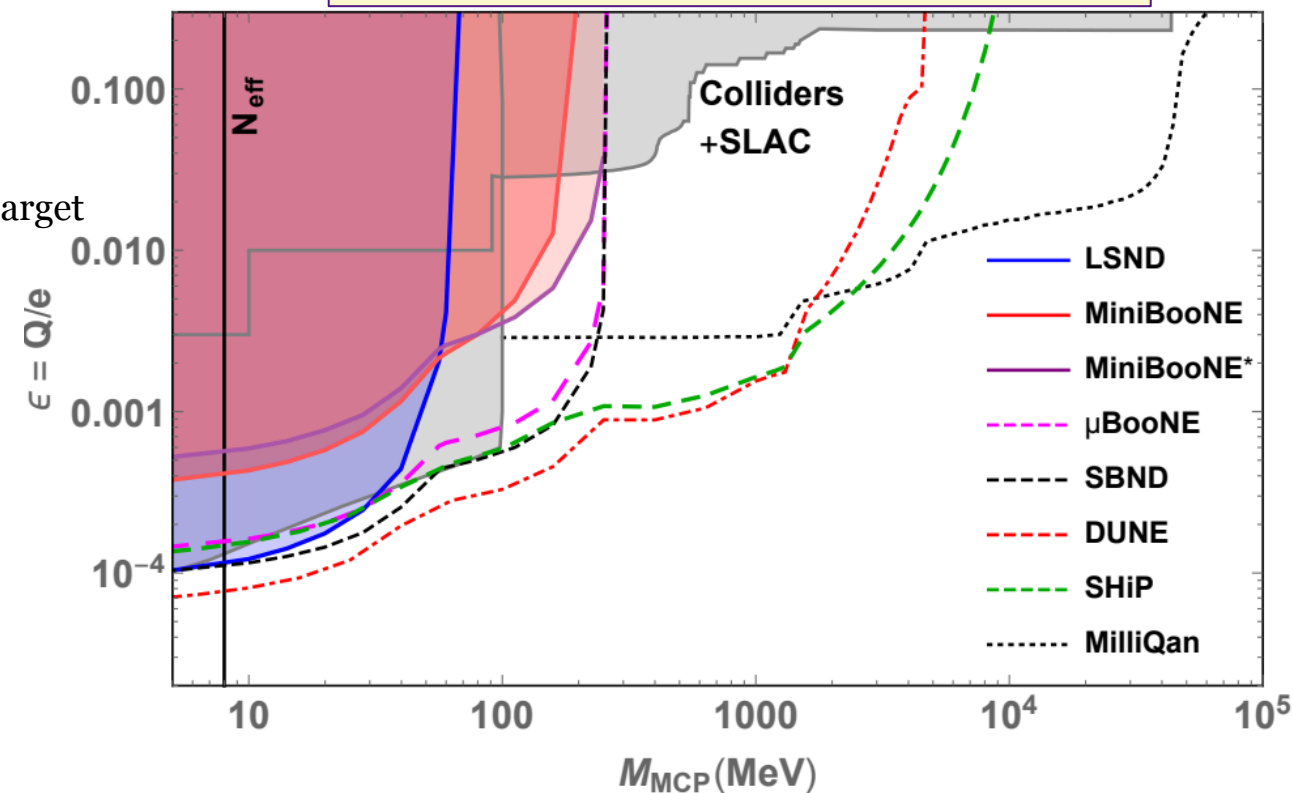
MCPs produced in neutral pion decays



Search for collinear “blips” of charge deposit, in line with the production target

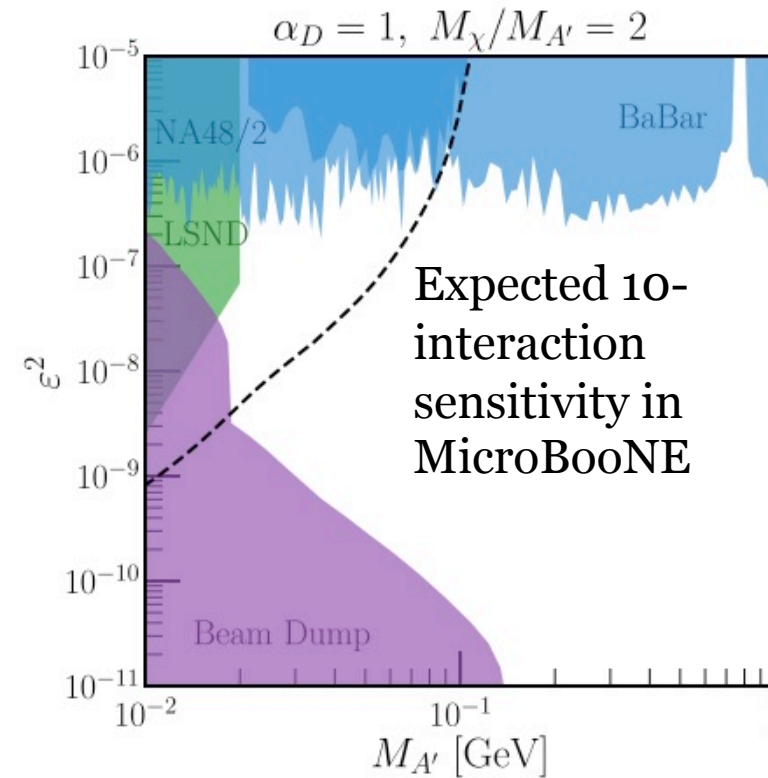
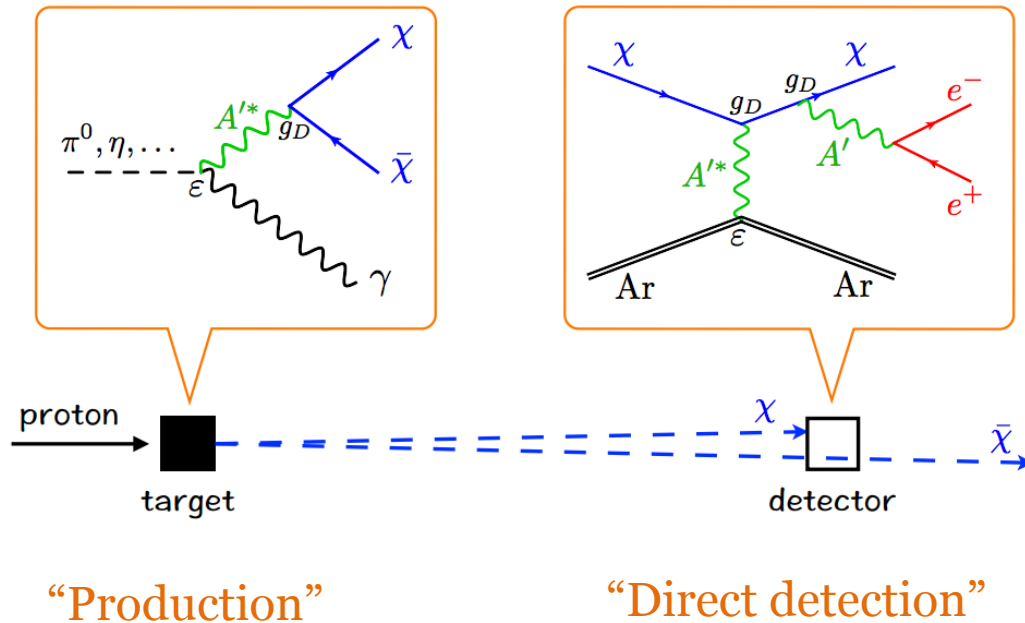


Magill et al, PRL 122, 071801 (2019)



Dark Tridents

- Dark matter could be produced in the beams, from neutral pion or eta decays
 - Via photon – dark photon mixing
- DM can scatter inside MicroBooNE, either elastically off electrons and nuclei, or inelastically to produce “trident” electron-positron signatures



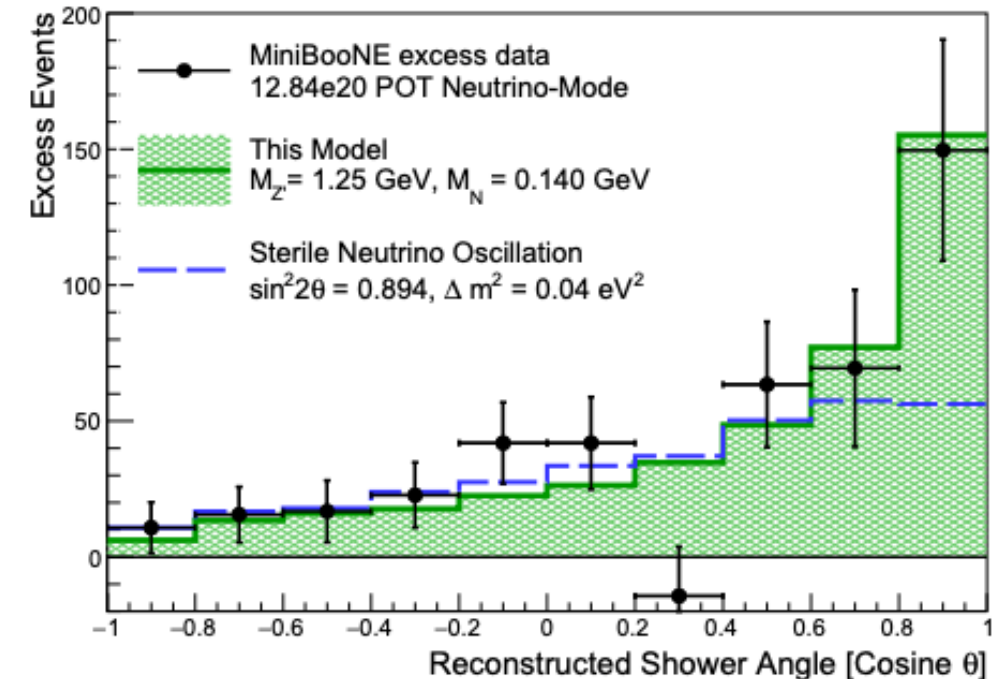
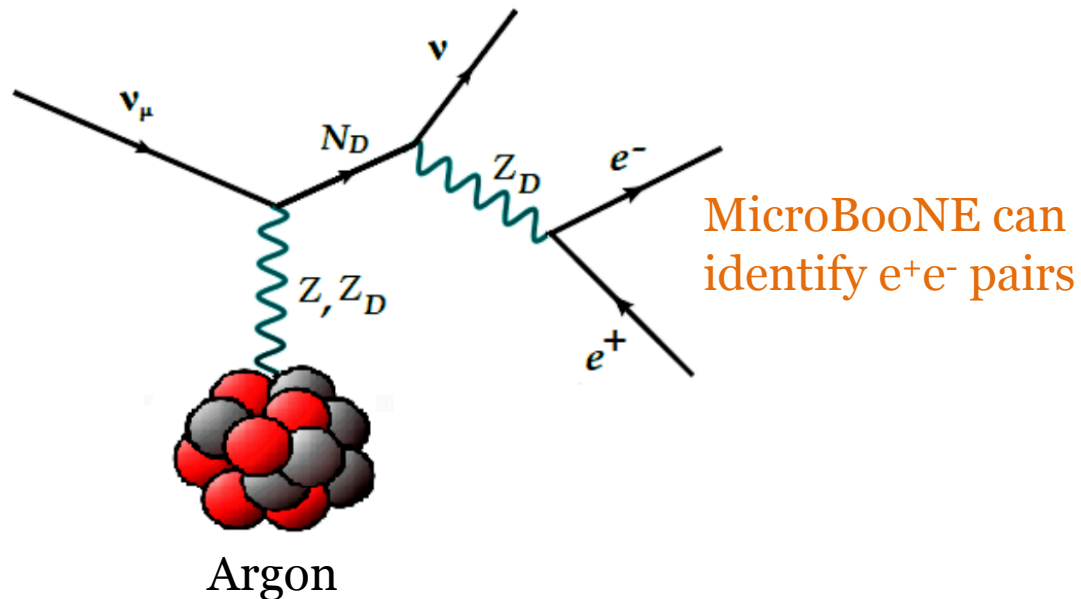
De Gouvea, Fox, Harnik, Kelly
JHEP 2019, 1 (2019)

Heavy/dark neutrino decay

- “Bi-portal” model, combining Vector & Neutrino portals to dark sector
- Upscattering of neutrino to HNL
- Can decay to dark photons $\rightarrow e^+e^-$ pairs
- Could explain MiniBooNE excess

Better fit for MiniBooNE angular distribution

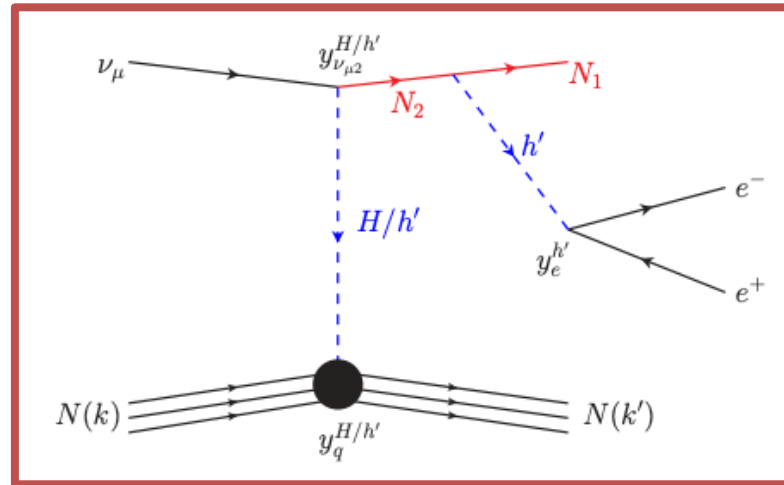
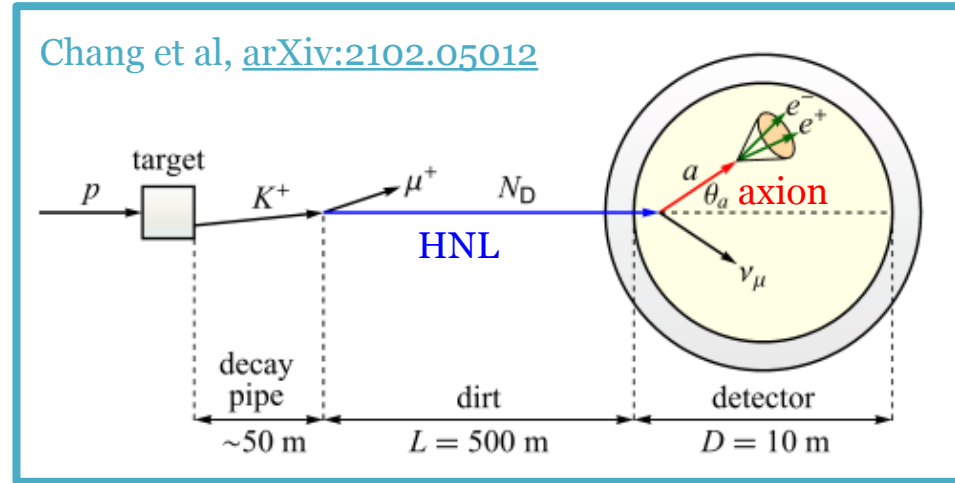
Sensitivity in MicroBooNE still to be evaluated



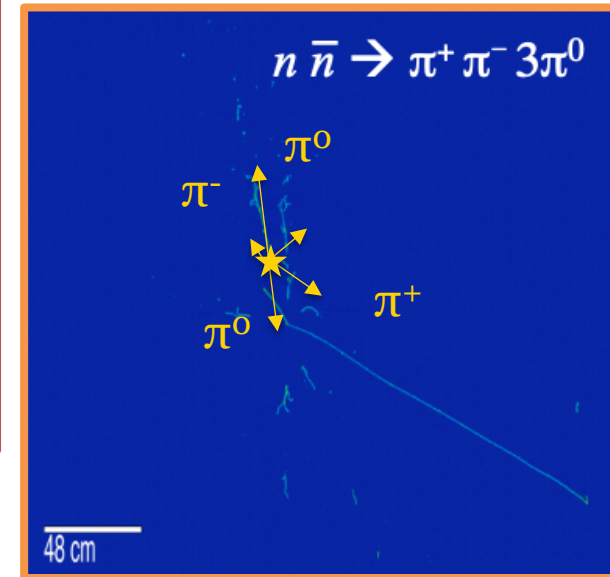
Ballett, Pascoli, Ross-Loneragan
Phys. Rev. D 99, 071701 (2019)

Further models

- There are also other interesting ideas we could investigate in the future
 - Although we haven't yet performed studies to see if there is sensitivity
- Example searches:
 - Light Two-Higgs-Doublet BSM models
 - Magnetic monopoles & Micro black holes
 - Axion-like particles
 - Dark photons
 - Neutron-antineutron oscillation
- Many exciting physics models to explore in our five years of data!



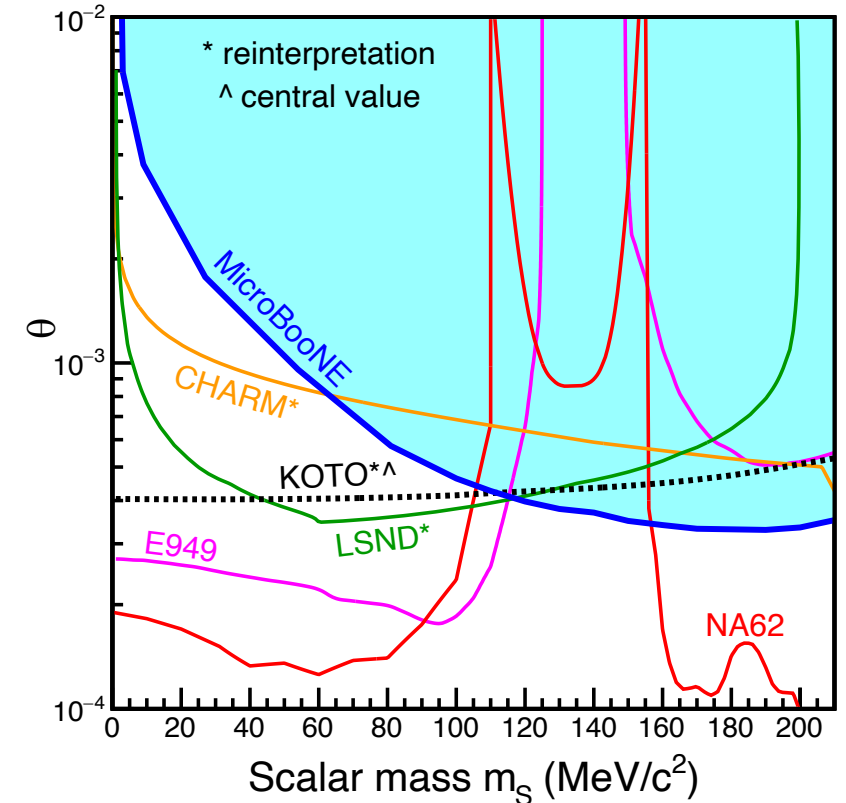
Abdallah et al, [arXiv:2010.06159](https://arxiv.org/abs/2010.06159)



SUMMARY

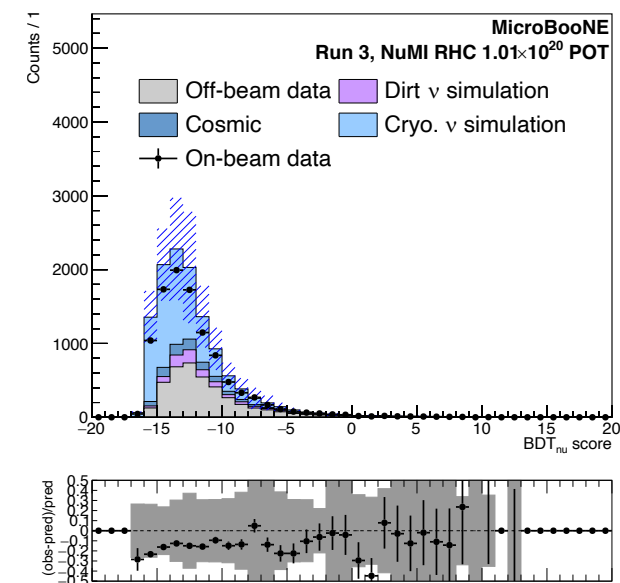
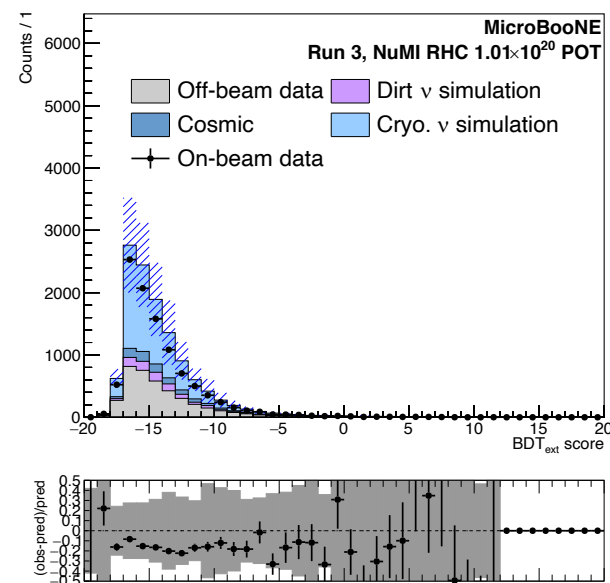
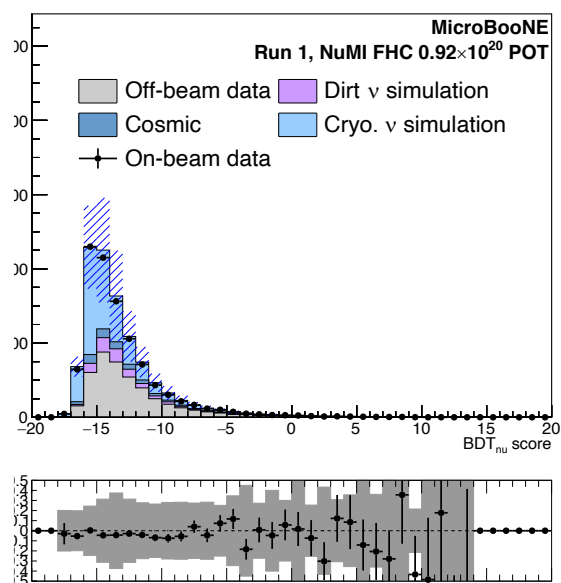
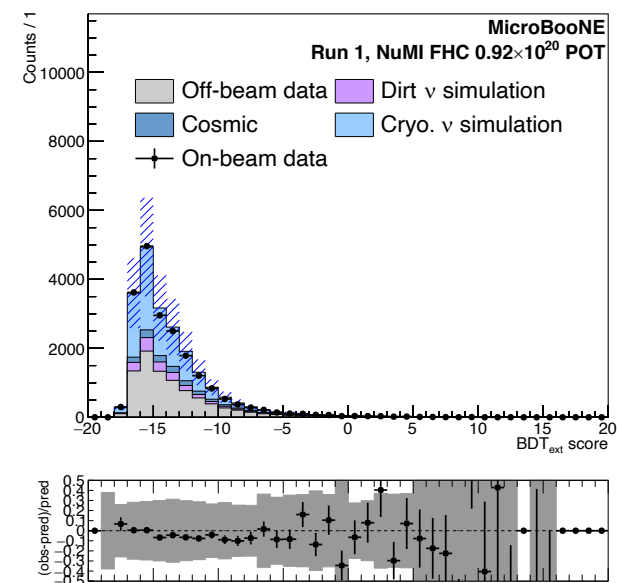
Summary

- MicroBooNE has been running for five years
 - many results on neutrino cross sections, detector physics and R&D
 - on the way to examining the reported MiniBooNE low energy excess
- We can also search for many new physics models beyond the original goals of the experiment
- Have recently announced **world-leading limits** on the Higgs-Portal scalar model in the $O(100 \text{ MeV})$ mass range
 - Can **exclude** the parameters required to explain the KOTO mild anomaly in this model
- Many more New Physics searches to come!



[arXiv:2106.00568](https://arxiv.org/abs/2106.00568)

ADDITIONAL SLIDES



BDT vs cosemics

BDT vs neutrinos

BDT vs cosemics

BDT vs neutrinos

Run 1 (2016)
before CRT

Run 3 (2018)
after CRT