MANCHESTER 1824
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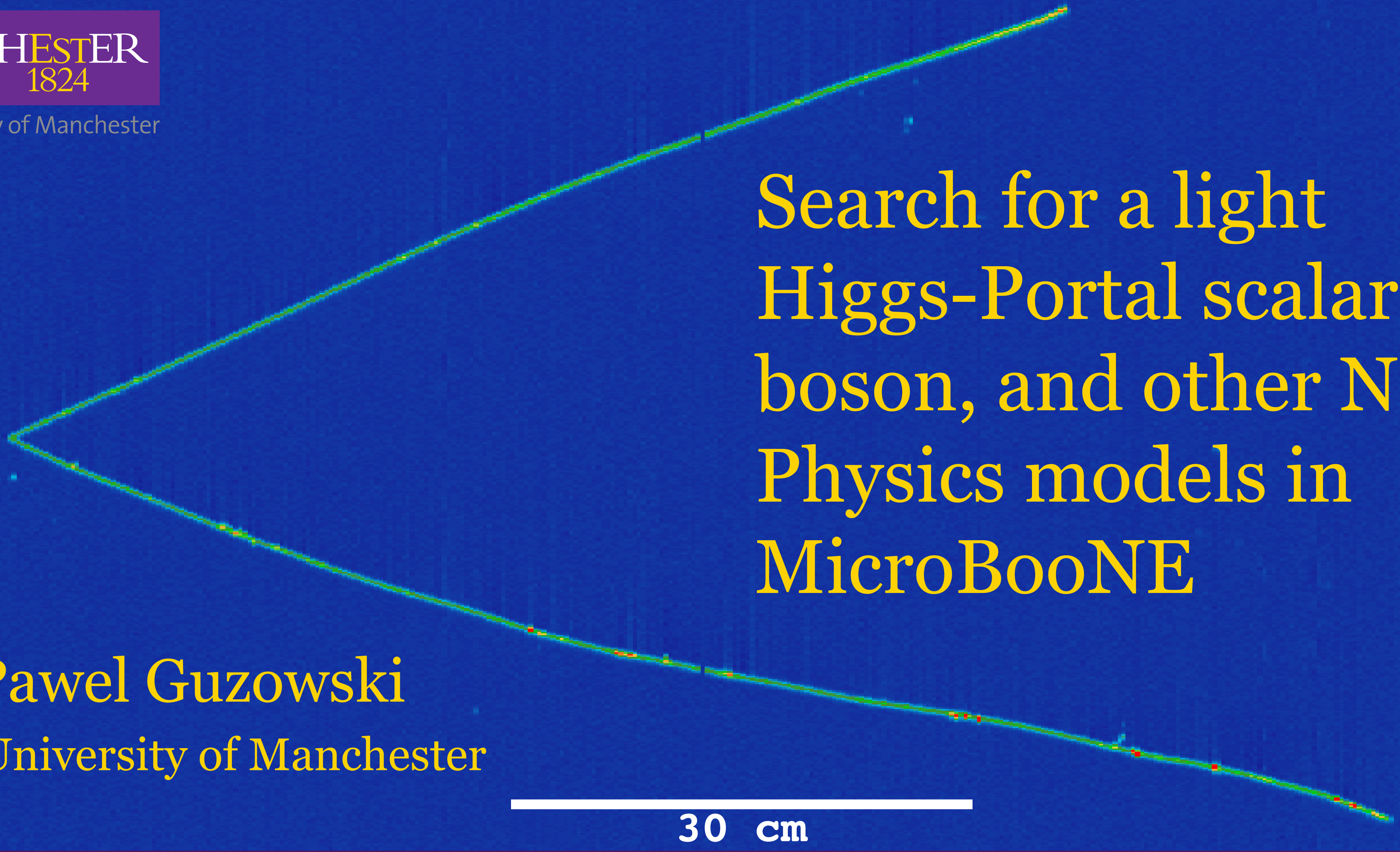
Search for a light Higgs-Portal scalar boson, and other New Physics models in MicroBooNE



Pawel Guzowski
The University of Manchester

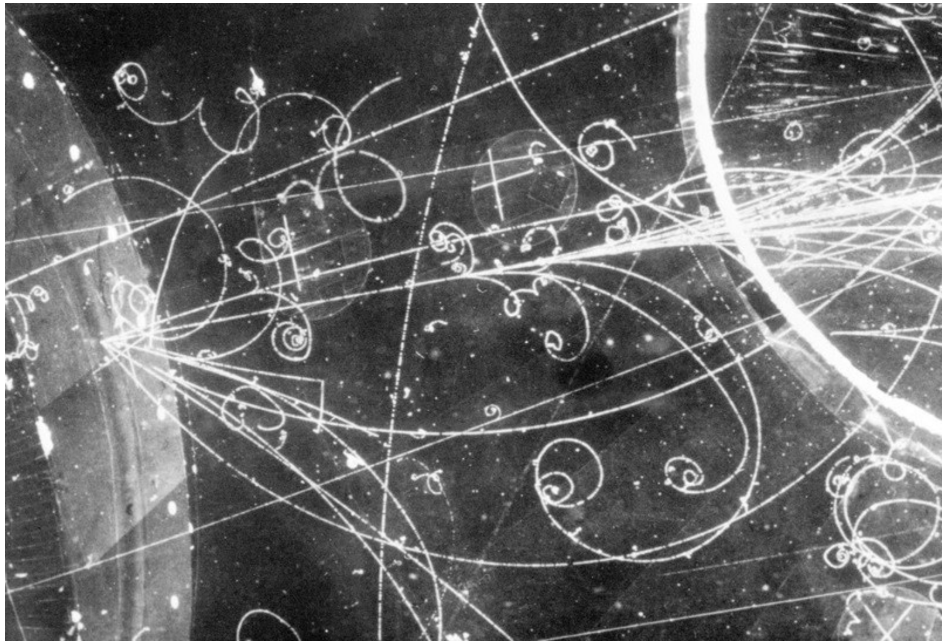
Outline

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

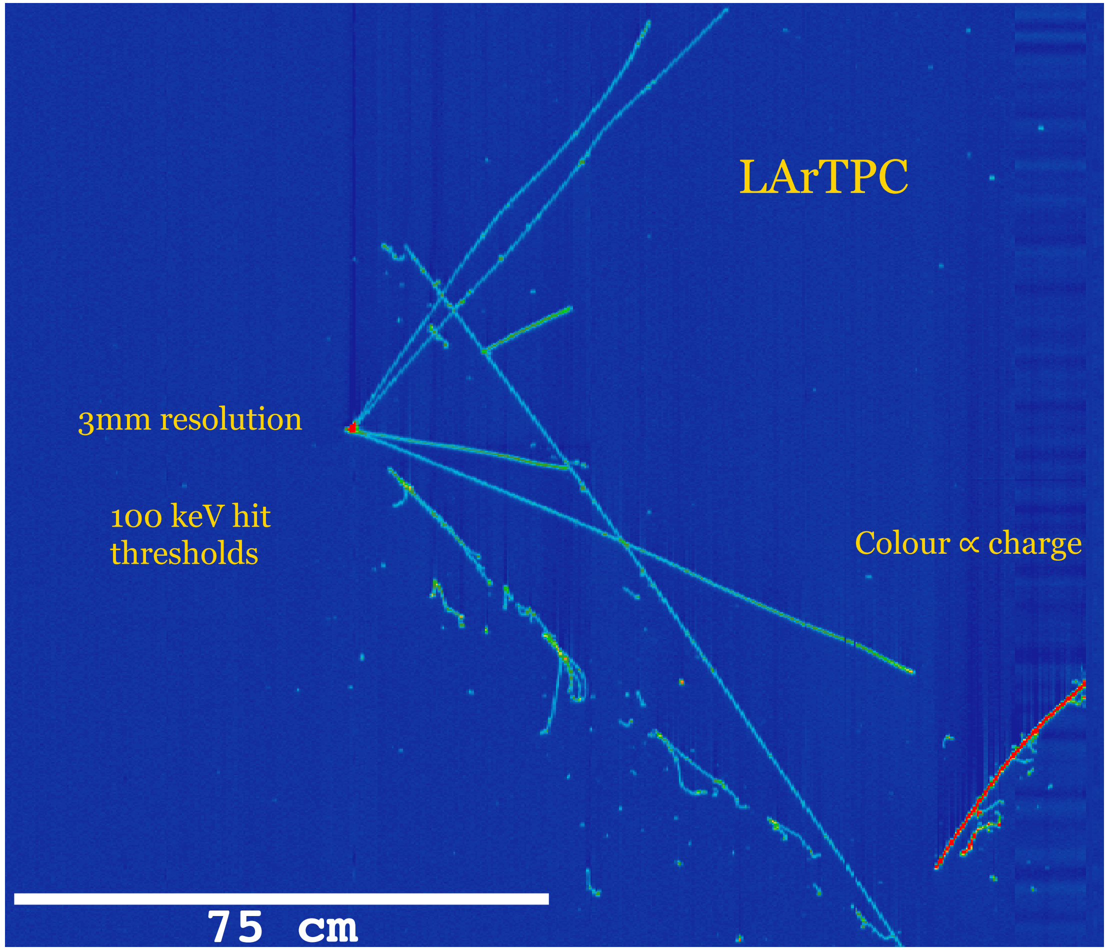
- Introduction to MicroBooNE
- The Higgs Portal to the dark sector
- New limits from MicroBooNE
- Other new physics models

Liquid argon time projection chambers

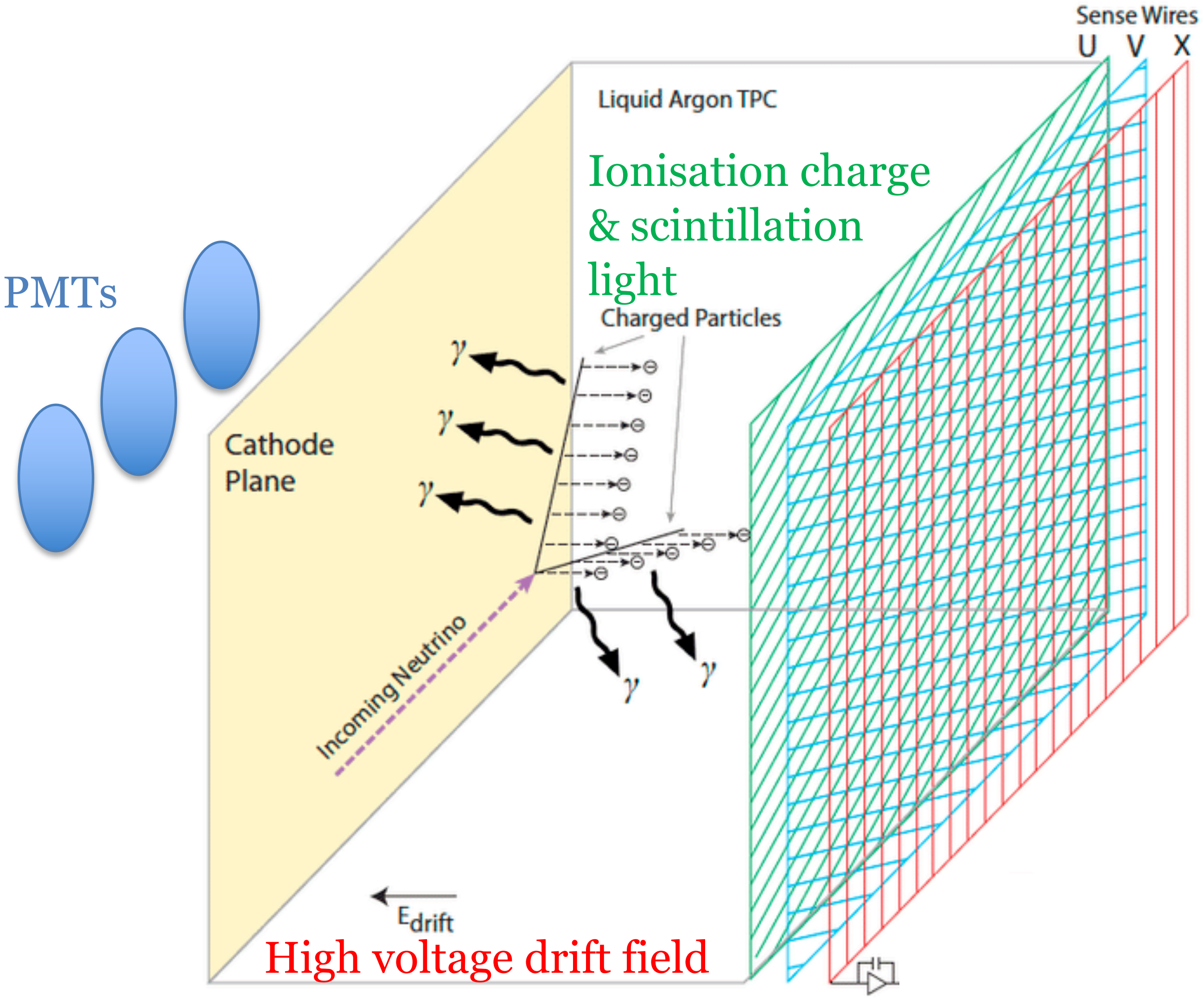
- Technology proposed by Carlo Rubbia in 1970s
- Bubble-chamber like images but with modern digitized charge readout



Bubble chamber

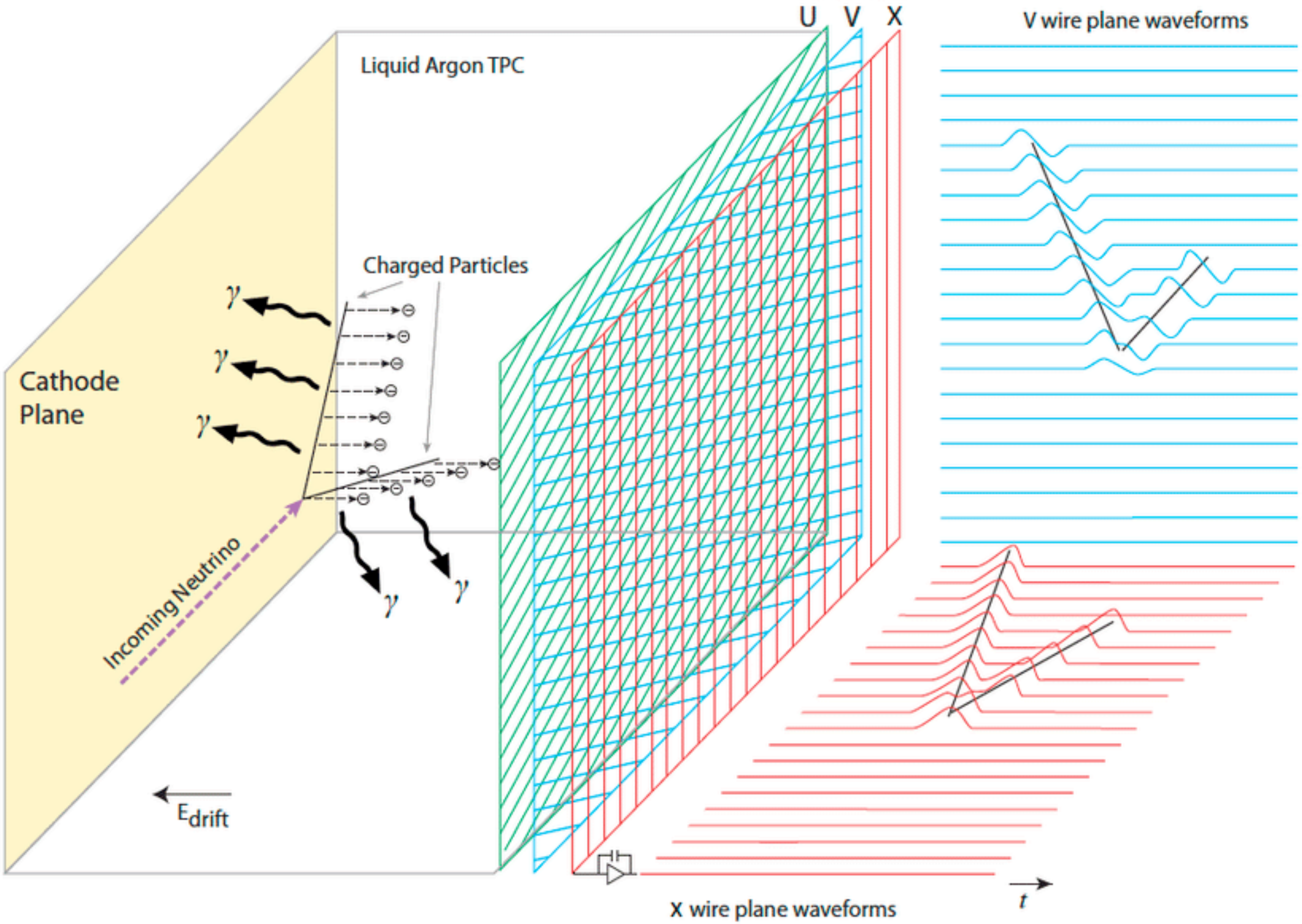


LArTPC operation principle



LArTPC operation principle

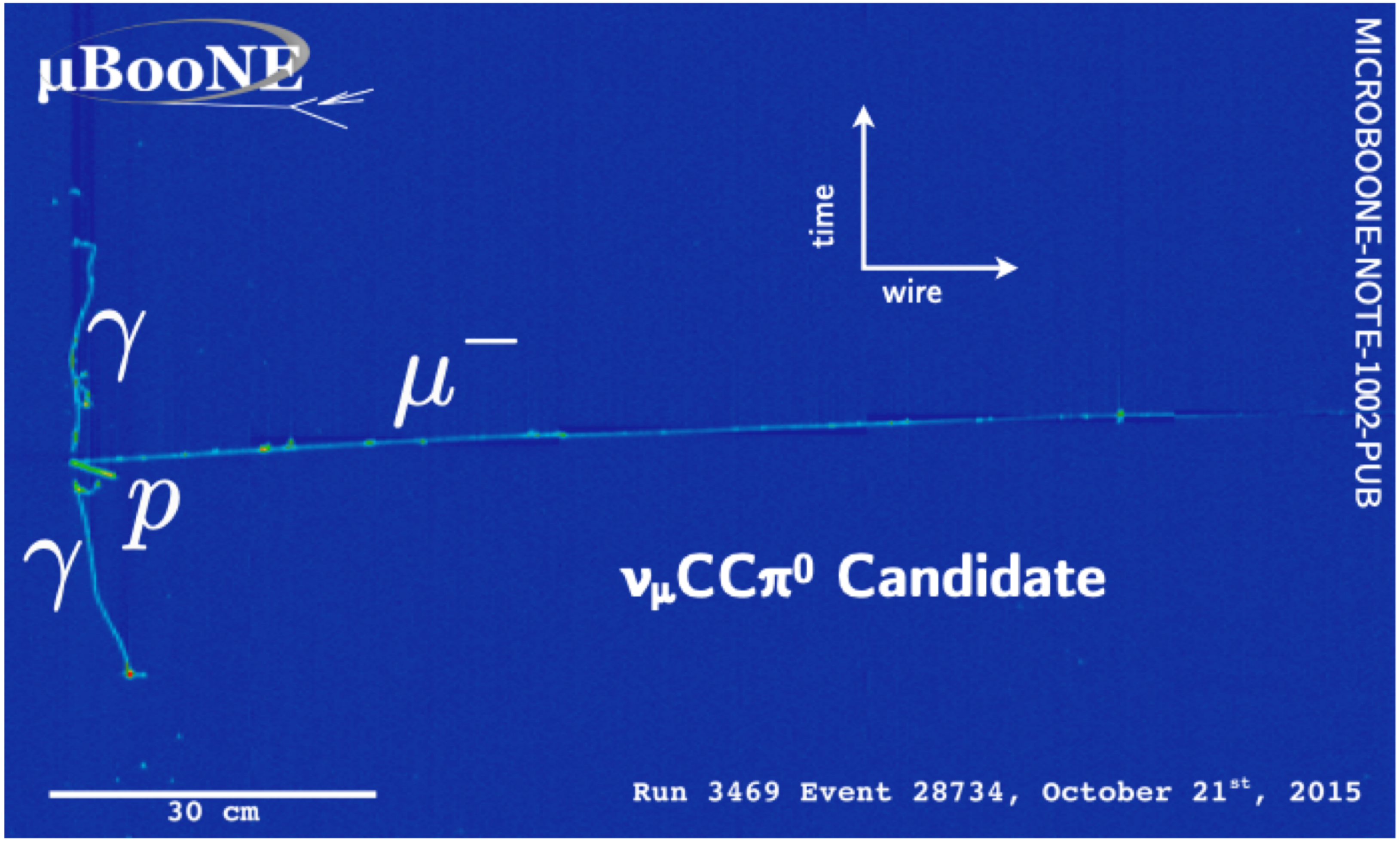
Multiple planes of readout sense wires



Charge vs time information on the wires allows 3D reconstruction

Particle identification

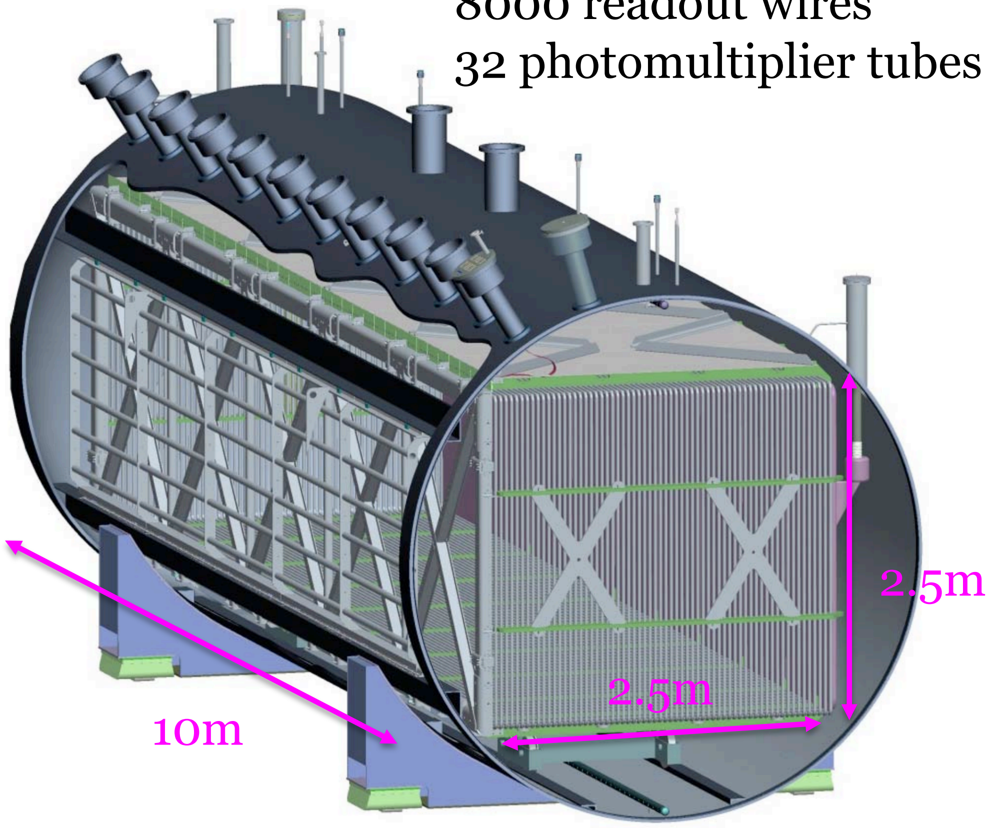
- Excellent spatial and charge resolution allows for PID



MicroBooNE

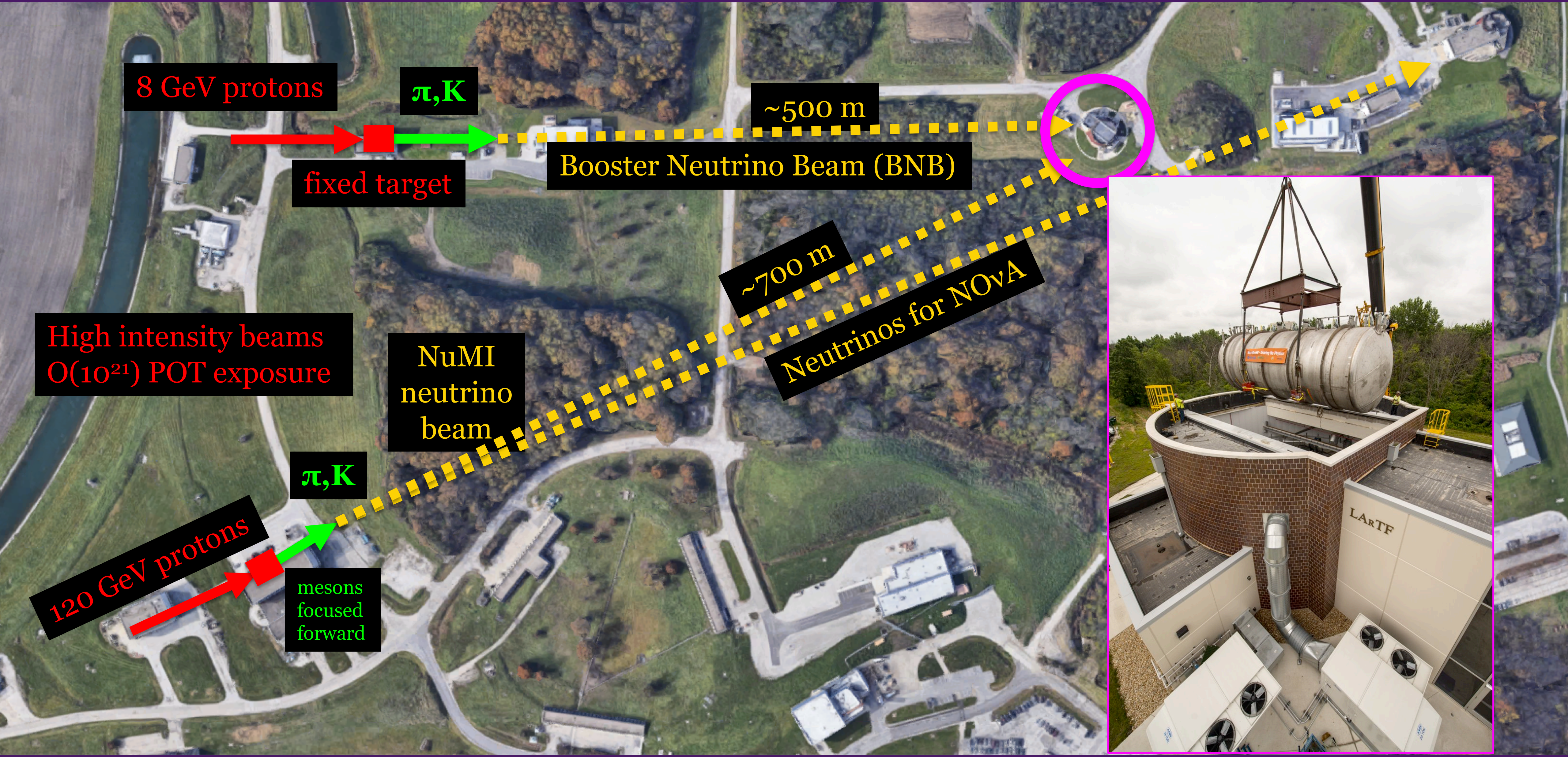
- Construction completed in 2014, and in operation since 2015

8000 readout wires
32 photomultiplier tubes



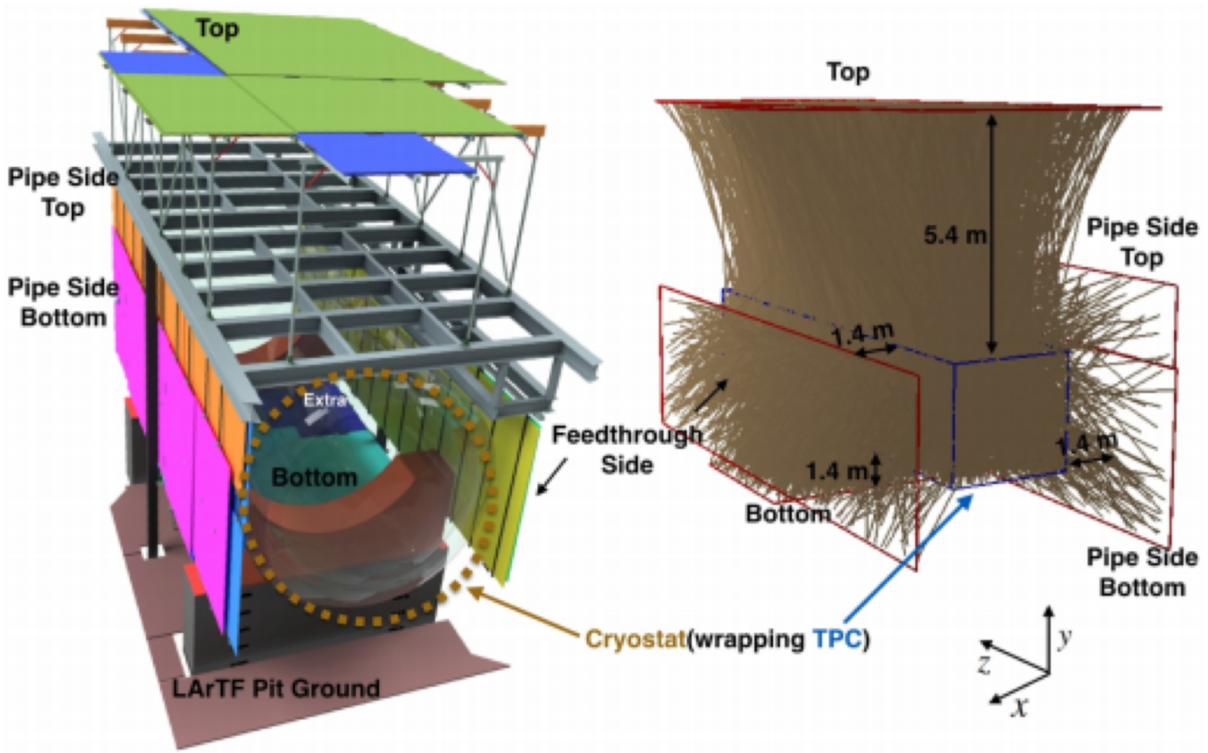
Cryostat

MicroBooNE and the Fermilab neutrino beamlines

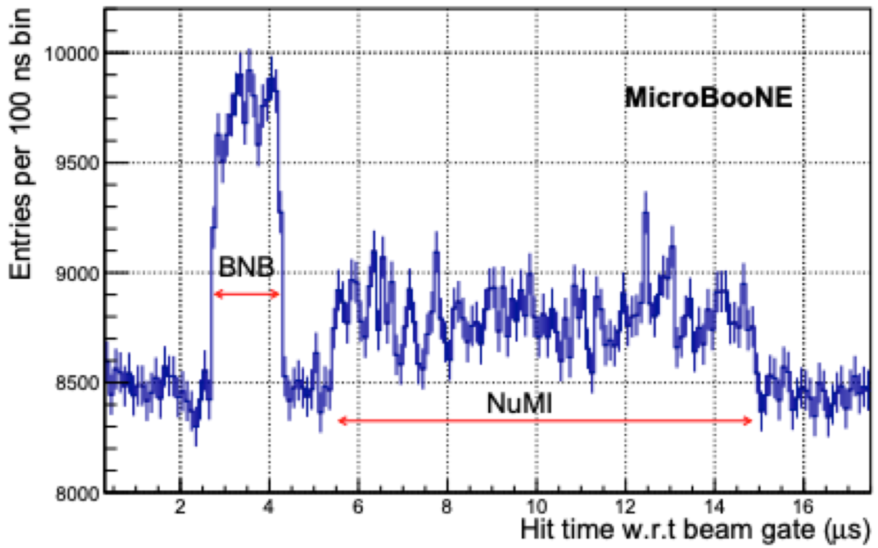


Cosmic Ray Tagger

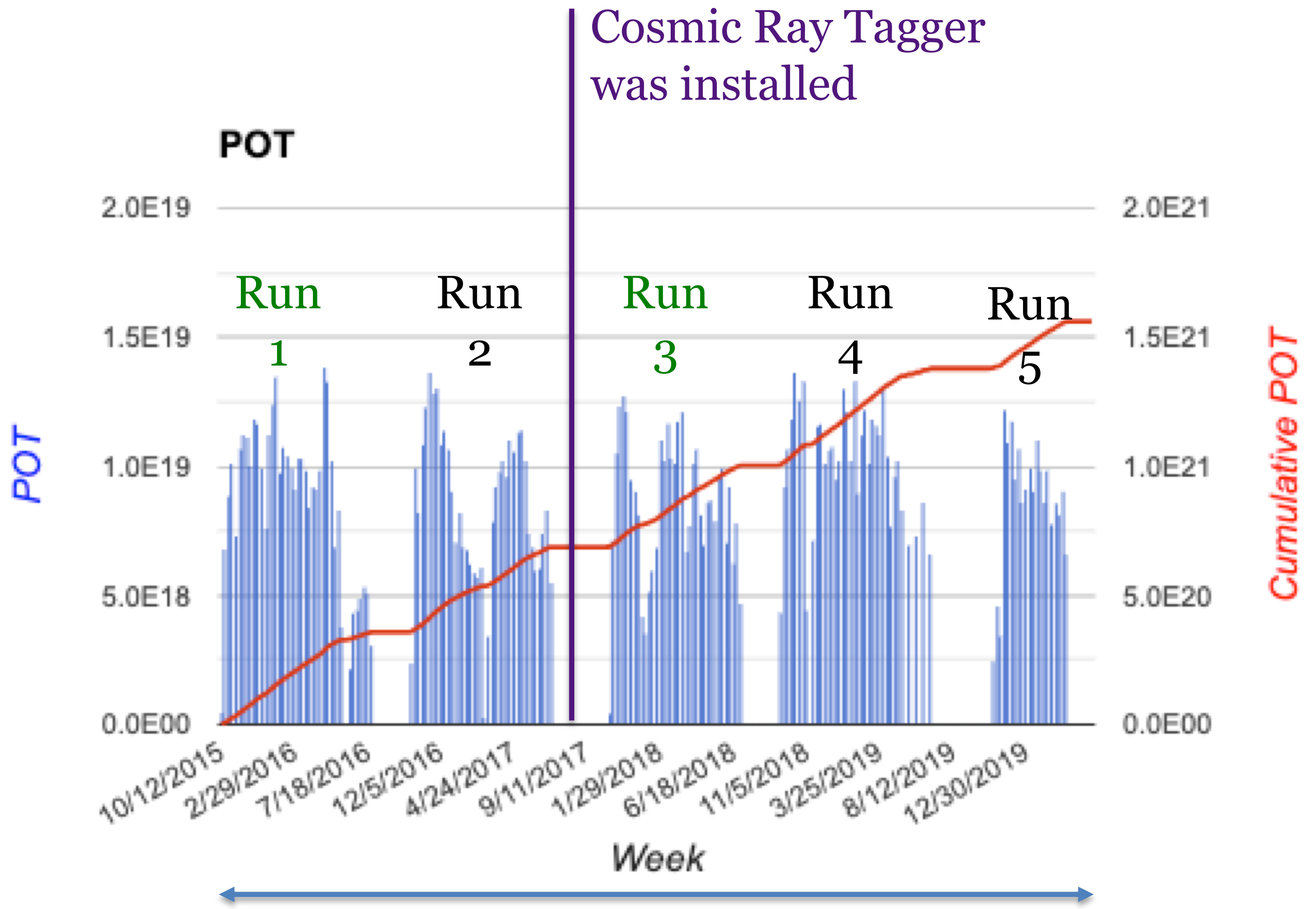
- A cosmic ray tagger was installed after two years
  - Plastic scintillator paddles surrounding the detector, to tag incoming muons with high-resolution timing
  - Can greatly reduce cosmic backgrounds



Timing of hits in CRT
Can see neutrino interaction excess



Data collected to date

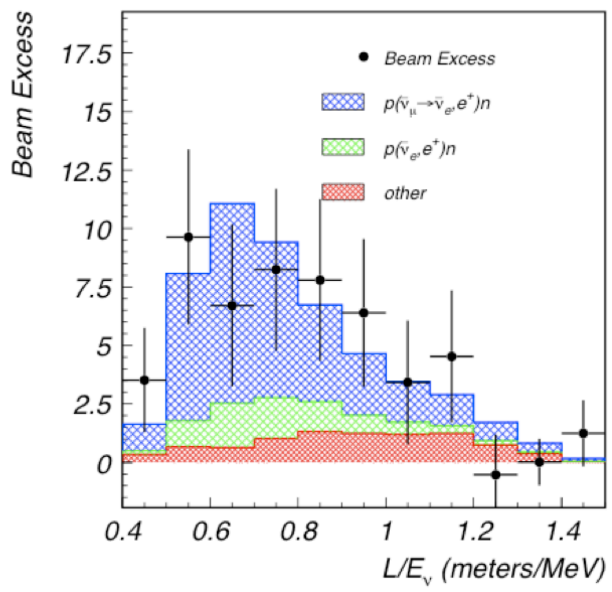


Operating for 5 years

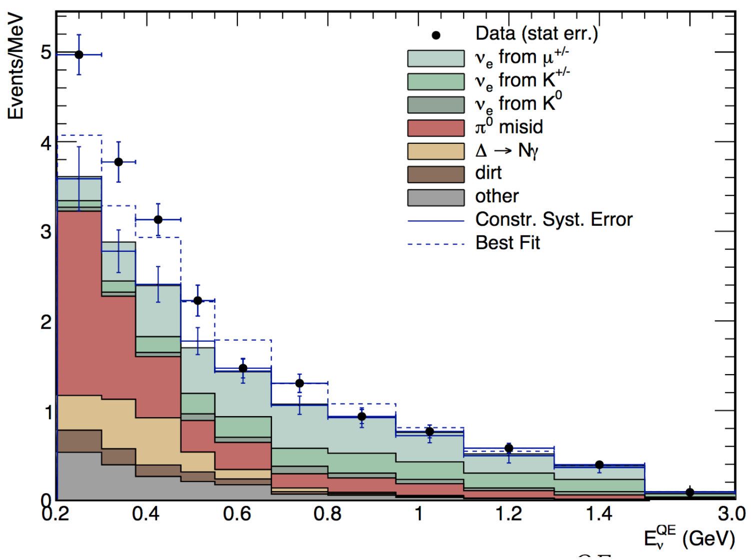
Data used in this result from Runs 1 & 3

Primary goal

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

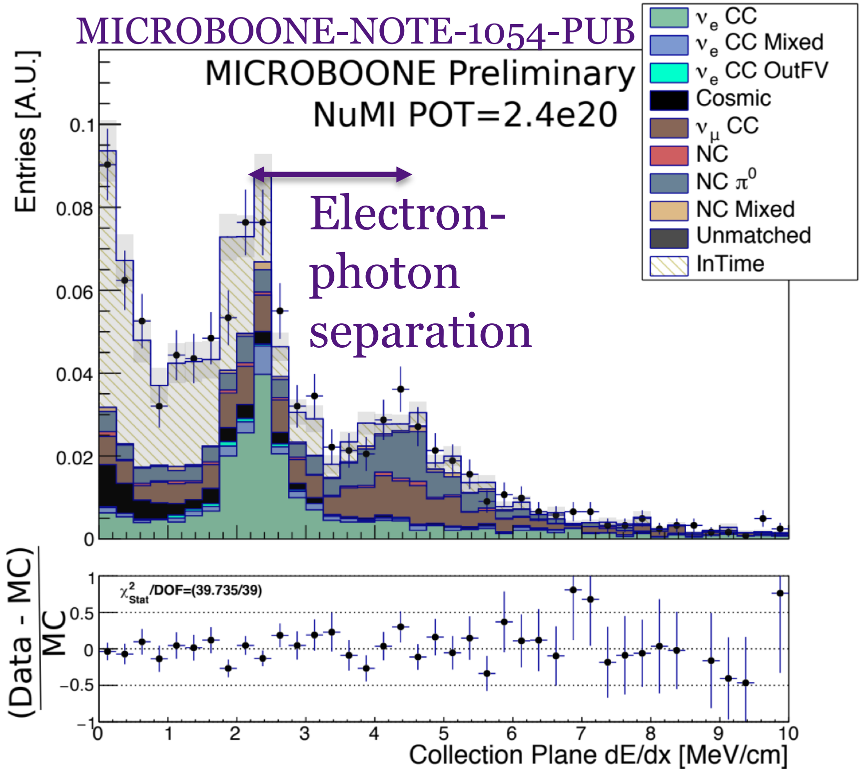


LSND: excess of positrons



MiniBooNE: excess of electron-like showers
(cannot distinguish electrons from photons)

MICROBOONE-NOTE-1054-PUB

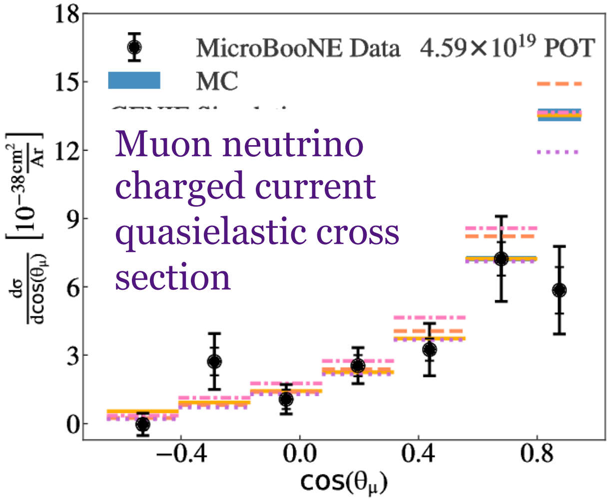


Measurement of electron neutrino interactions

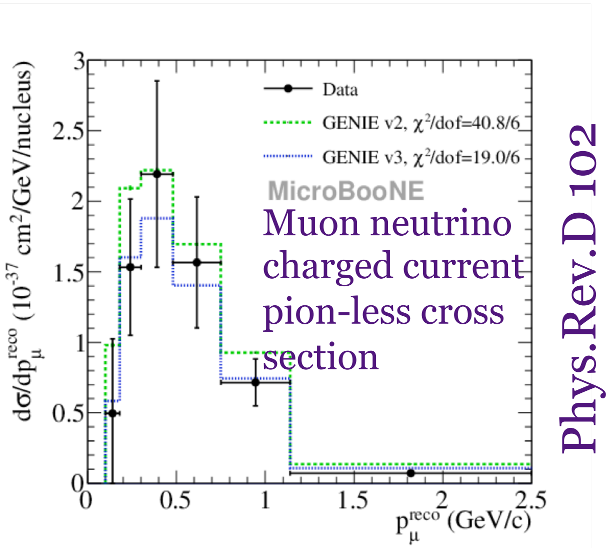
- MicroBooNE will be unblinding these searches soon!

Recent results

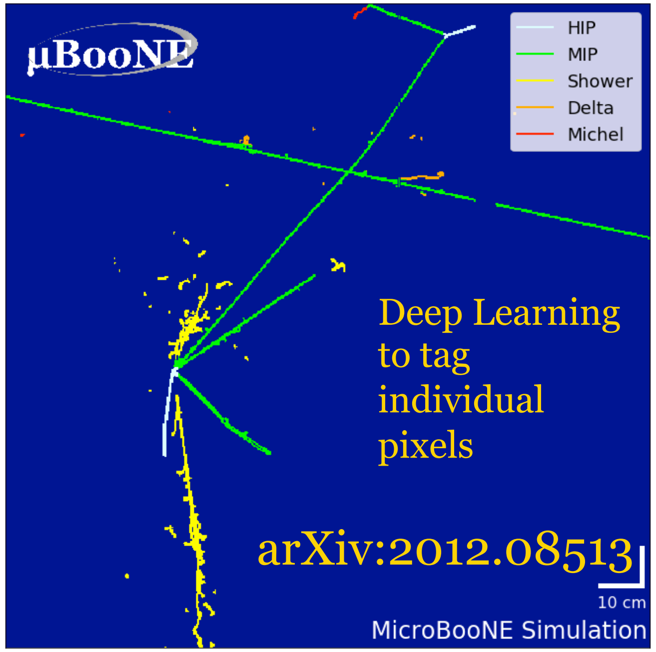
- MicroBooNE has also excellent capability of performing cross section measurements, detector physics and R&D for future experiments
- Only a small sample of our many results last year
  - 14 papers, 18 public notes

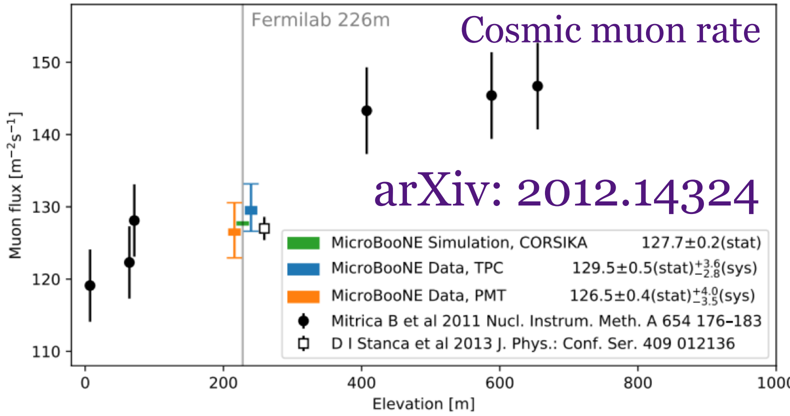


Phys.Rev.Lett. 125 (2020) 20, 201803



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



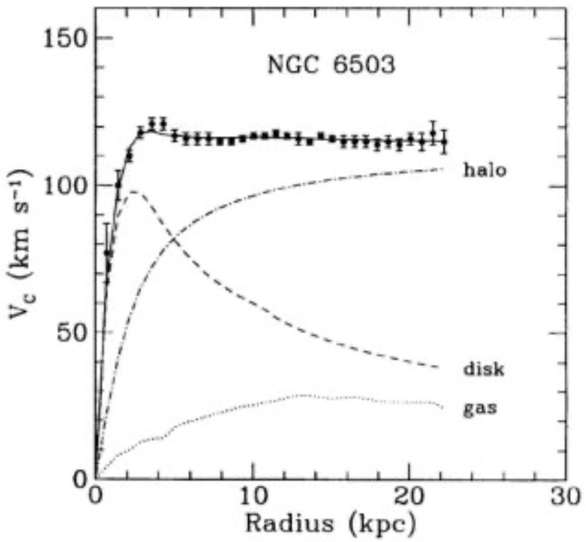


- However, these results are not what I have come to you to talk about

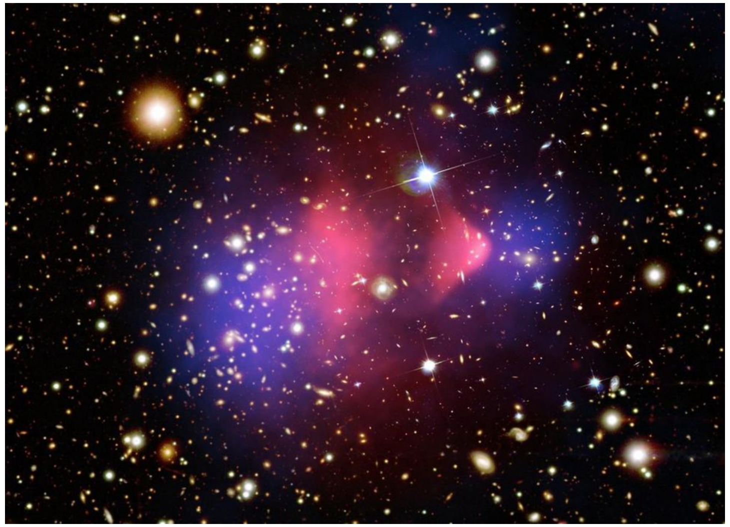
- MicroBooNE can also do a host of other interesting new physics searches …

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

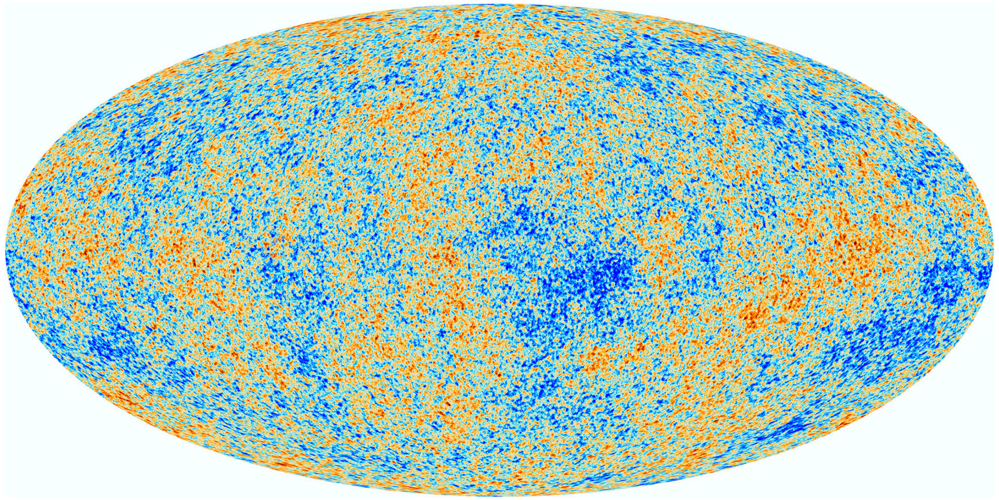
- Evidence for dark matter:



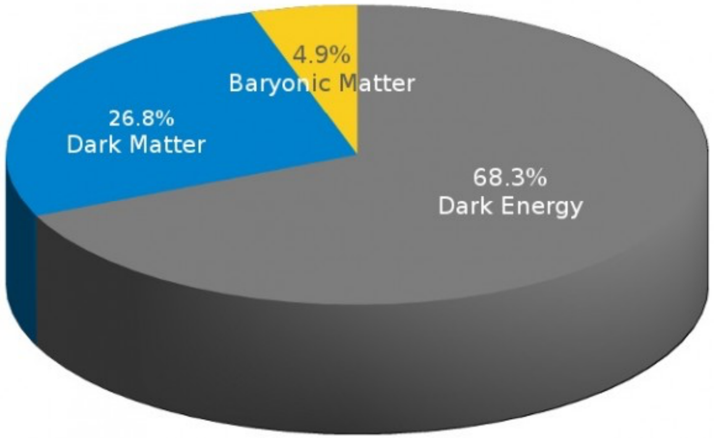
Galaxy rotation curves



Bullet cluster



Cosmic microwave background temperature fluctuations



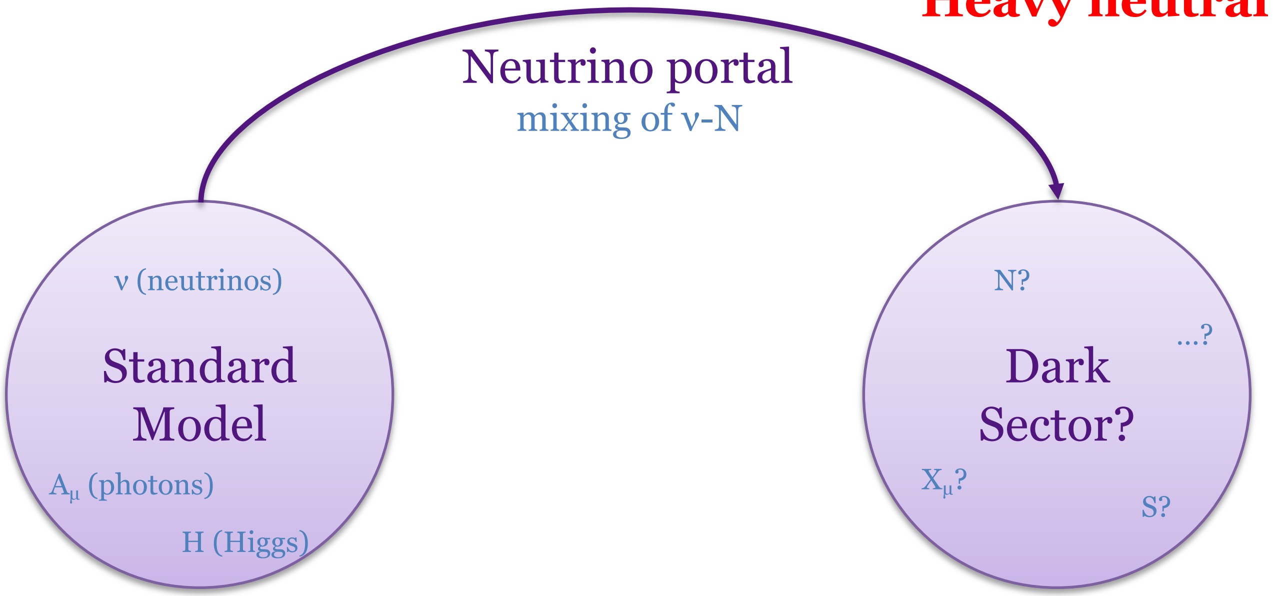
Could there be a dark sector of particles beyond the Standard Model?

How does our ordinary matter communicate with them?

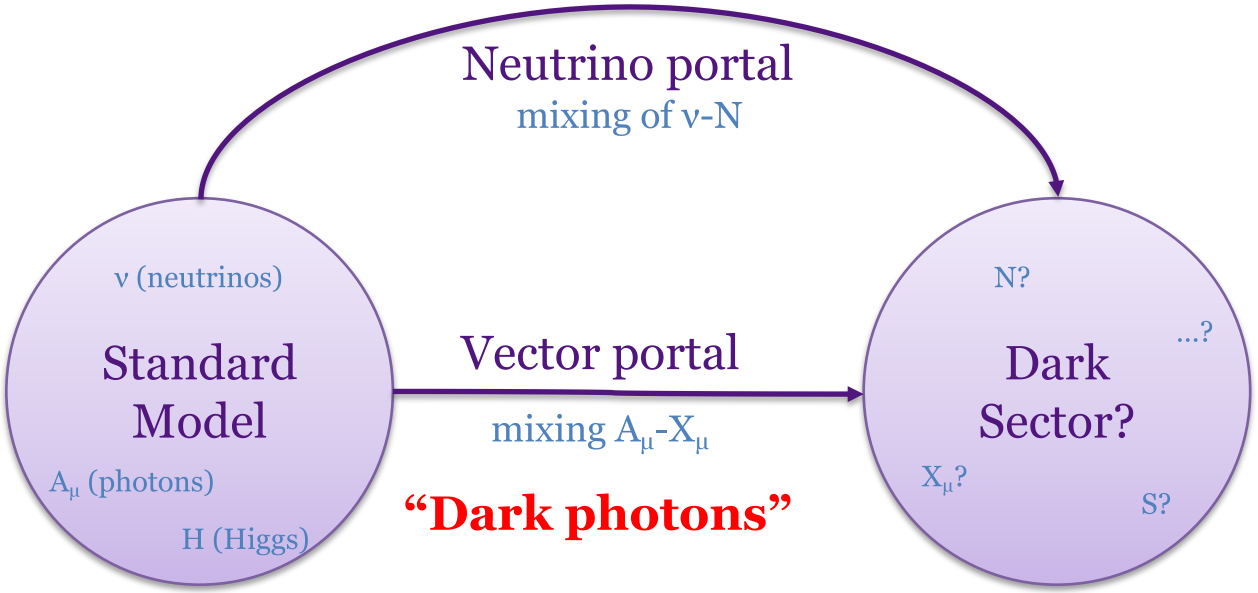
Portals to the dark sector

Portals to the dark sector

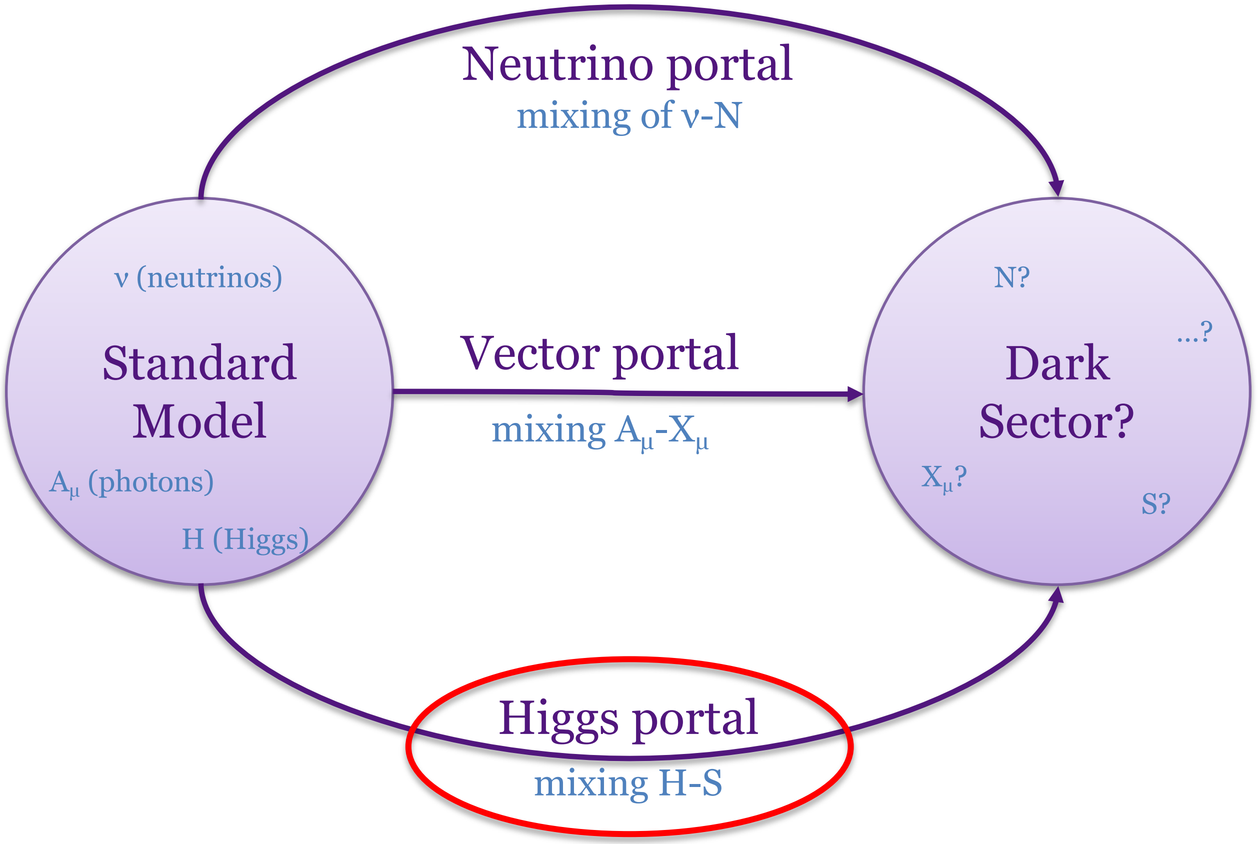
"Heavy neutral leptons"



Portals to the dark sector



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:

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

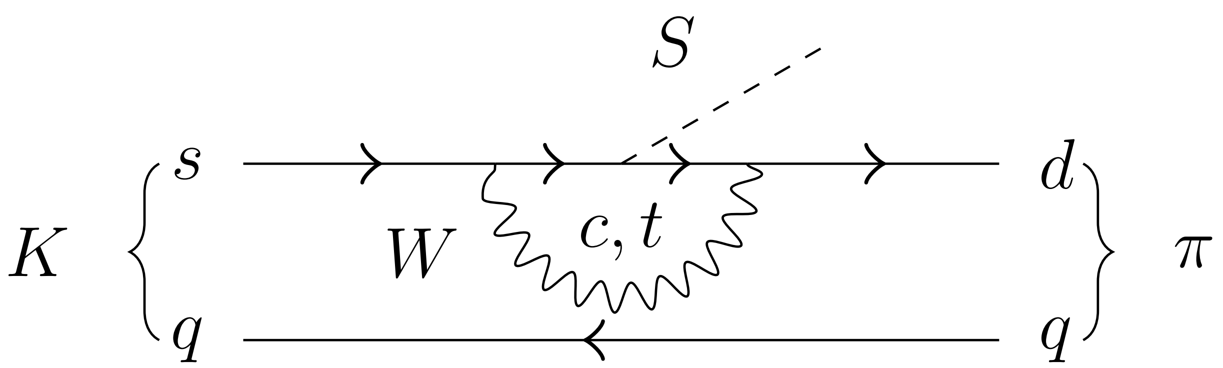
scalar mass

mixing angle

coupling to SM fermions

Kaon decays

- Light scalars can be produced in kaon decays, via a top quark in a penguin decay



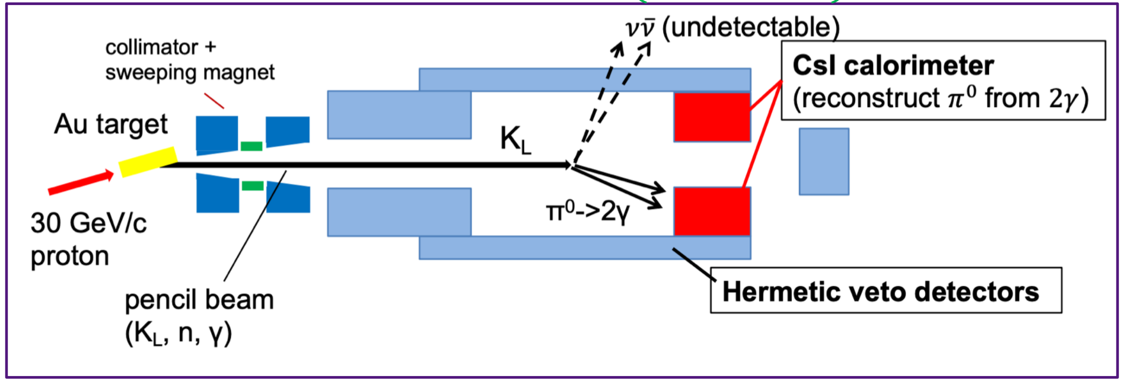
Decay rate

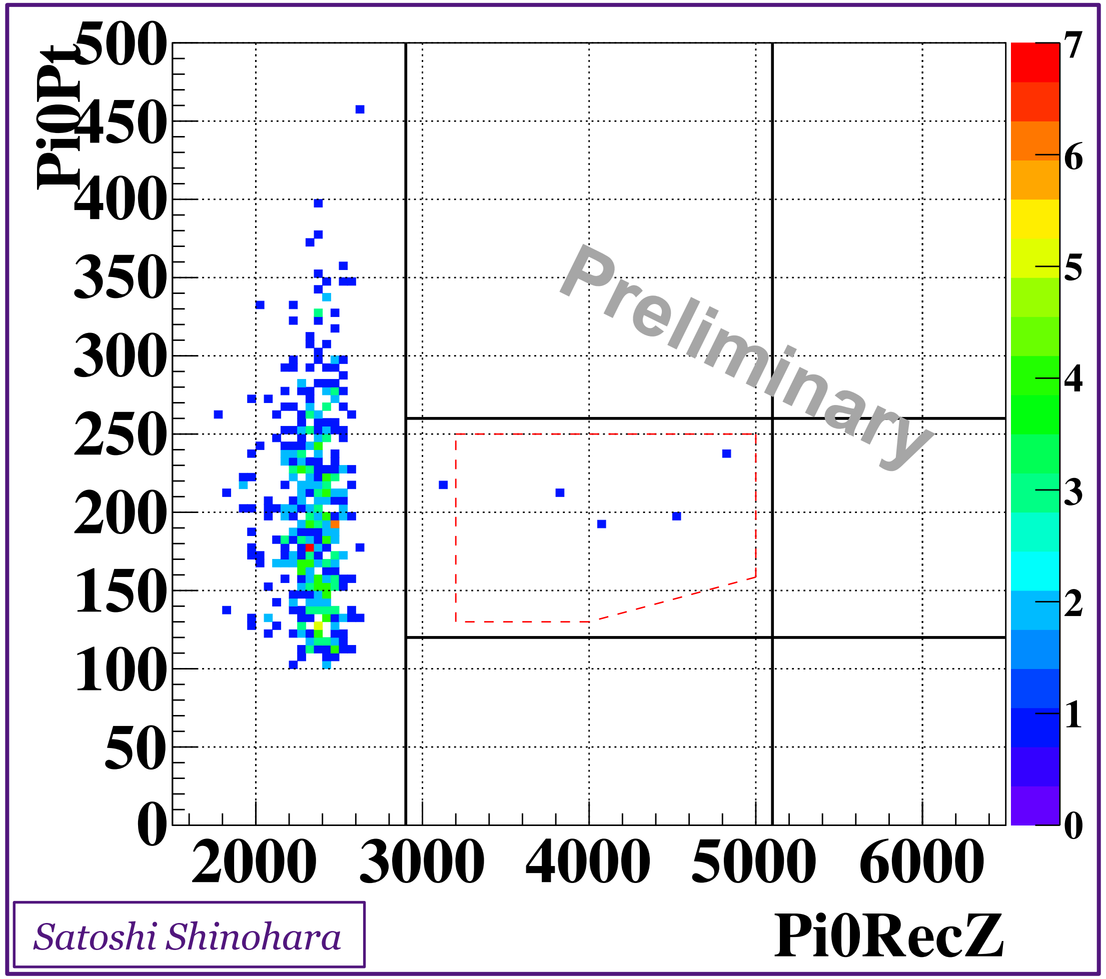
$$\Gamma(K^\pm \to \pi^\pm S) \simeq \frac{\theta^2}{16\pi m_K}\left|\frac{3V_{td}^* V_{ts} m_t^2 m_K^2}{32\pi^2 v^3}\right|^2 \lambda^{1/2}\left(1, \frac{m_S^2}{m_K^2}, \frac{m_\pi^2}{m_K^2}\right)$$

Aside: the KOTO anomaly

[Kaon 2019 talk]

(or scalar)



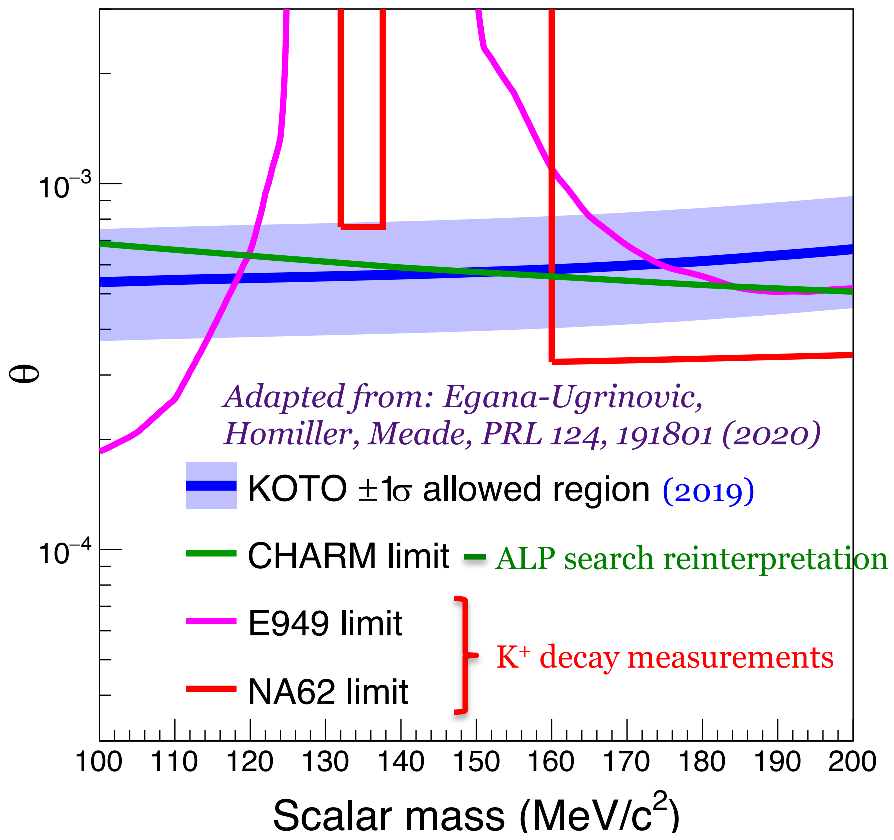


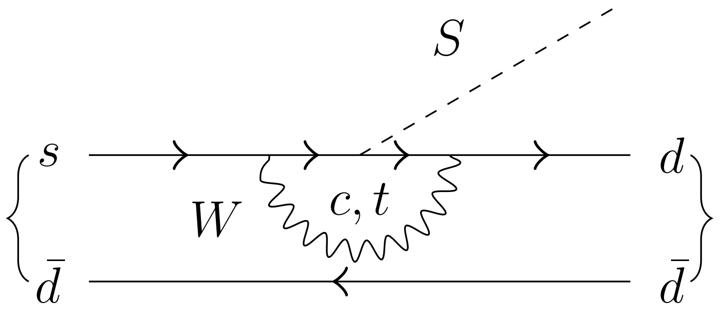
KOTO experiment at J-PARC is searching for rare neutral kaon decays

Observe 3 events
Branching ratio ~2 orders of magnitude larger than SM $K^0 \to \pi^0 \nu\nu$

This anomalous excess has weakened recently

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

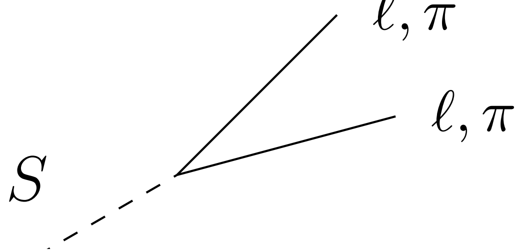
This is why we focused on this mass range for this first search

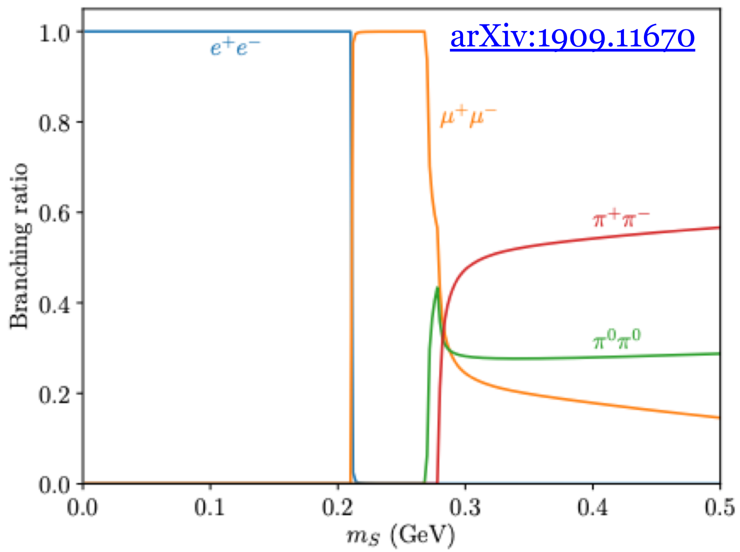
Scalar decays

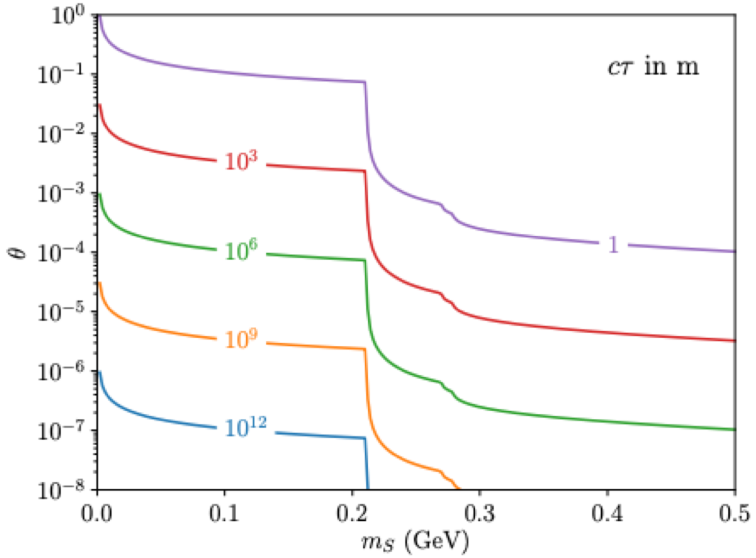
- Light scalars decay to electron-positron pairs, or di-muon or di-pion pairs if heavy enough

Decay rate

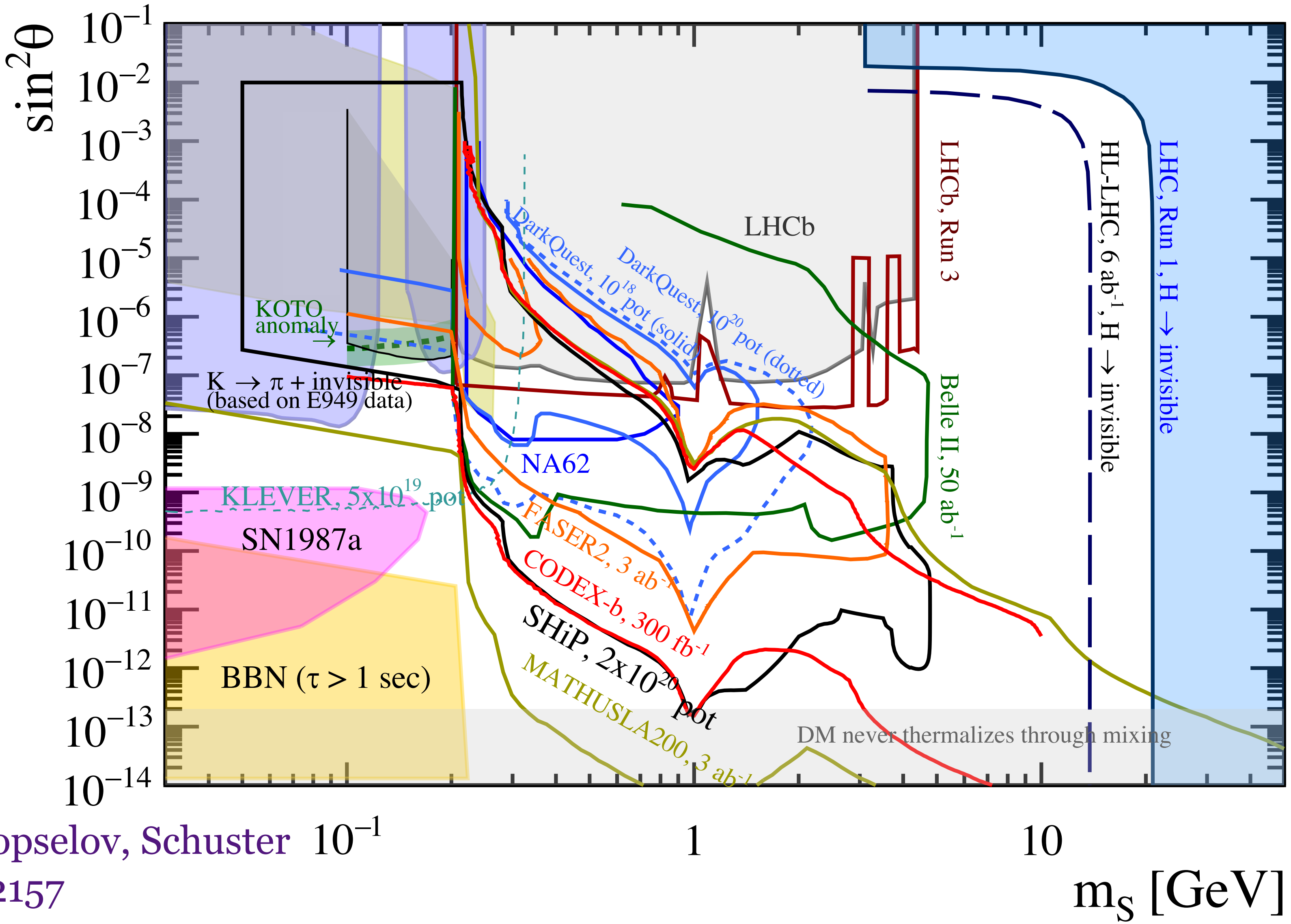
$$\Gamma(S \to \ell^+\ell^-) = \theta^2 \frac{m_\ell^2 m_S}{8\pi v^2}\left(1 - \frac{4m_\ell^2}{m_S^2}\right)^{3/2}$$







Current & Future experimental searches



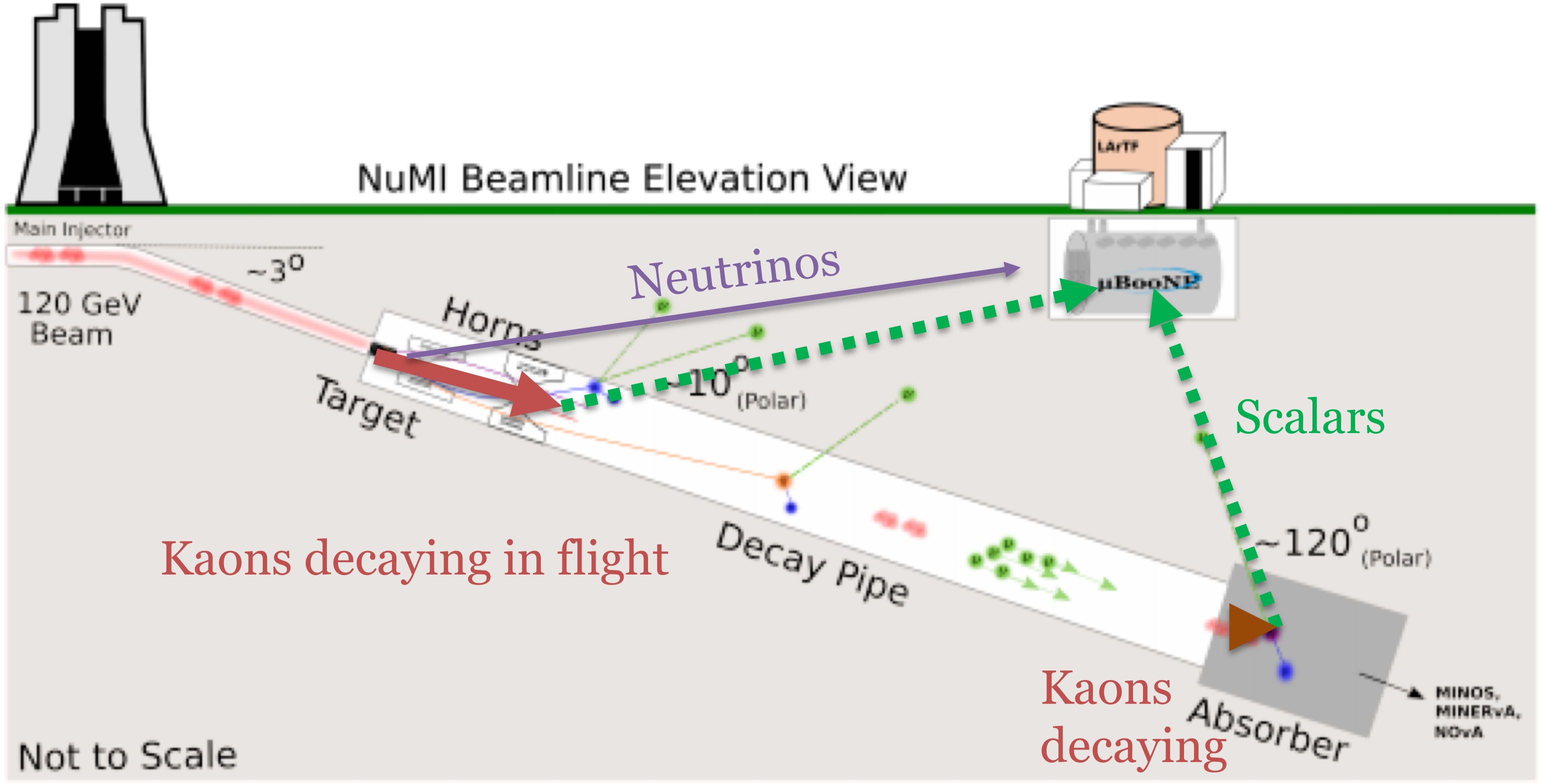
Lanfranchi, Popselov, Schuster
arXiv: 2011.02157

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

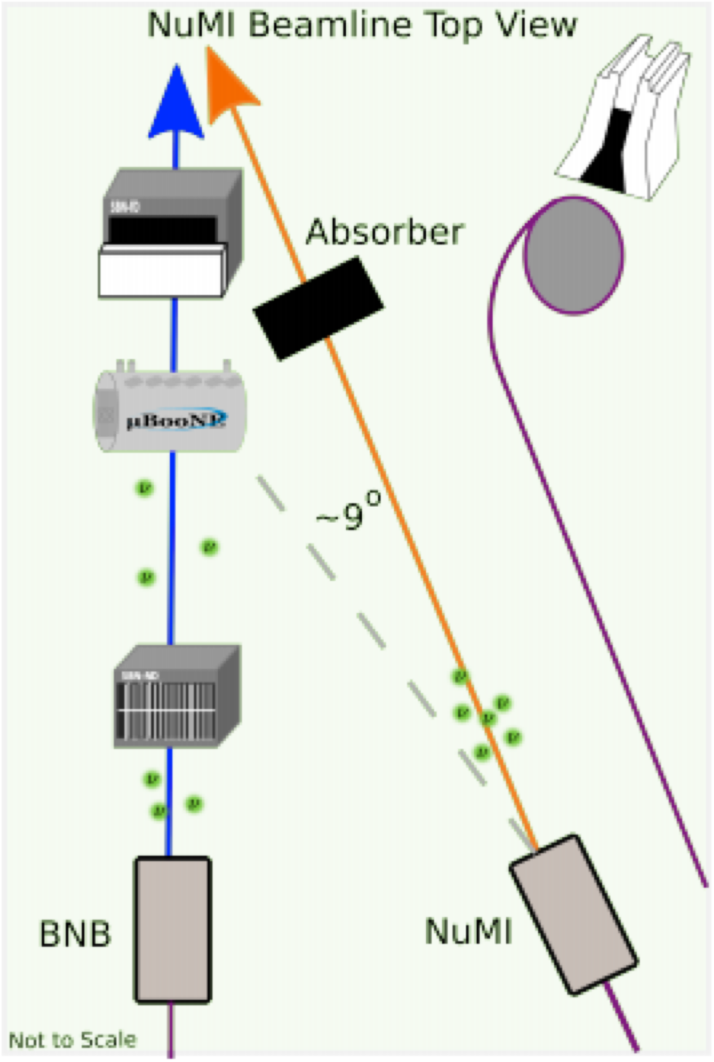
Production of the scalar in our experiment

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

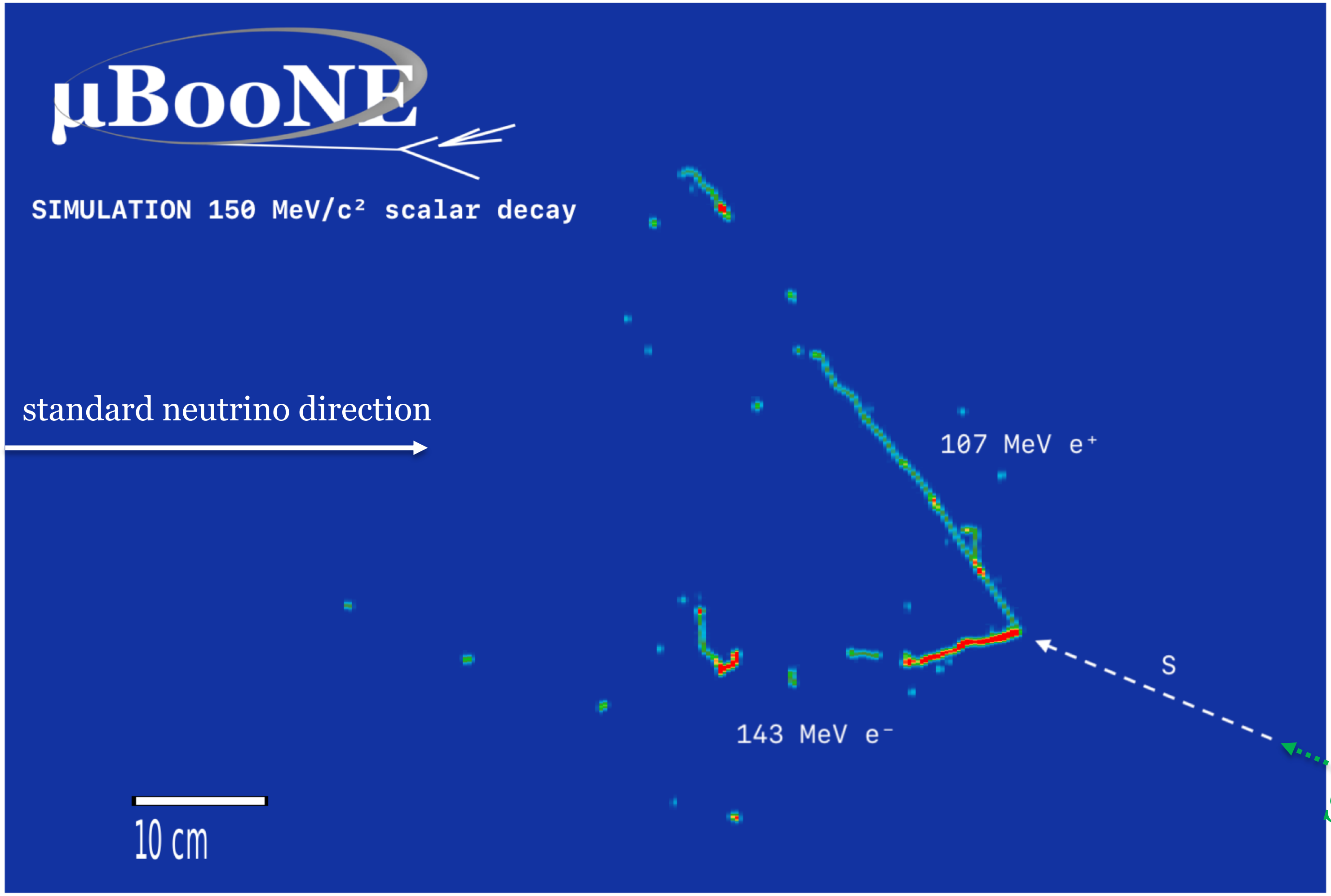
Kaons will decay at rest, producing monoenergetic scalars – a unique signature in the detector



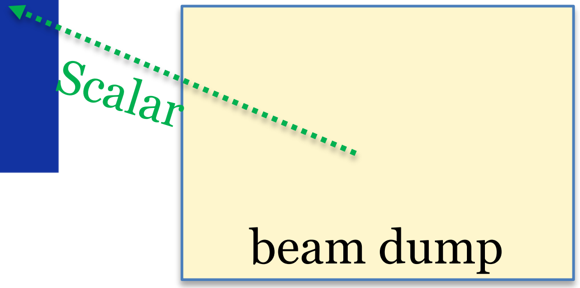
Kaons decaying at rest



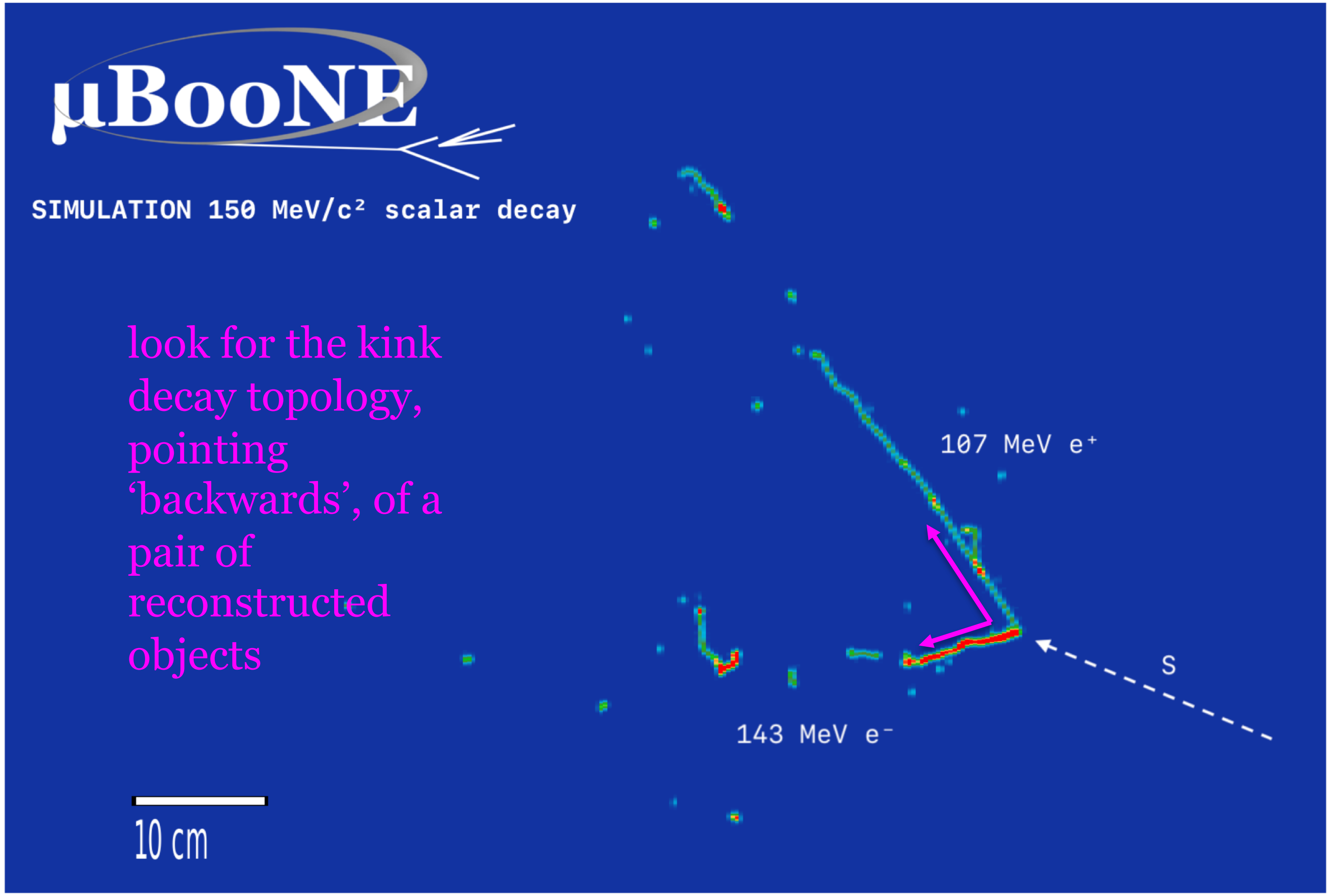
Example decay

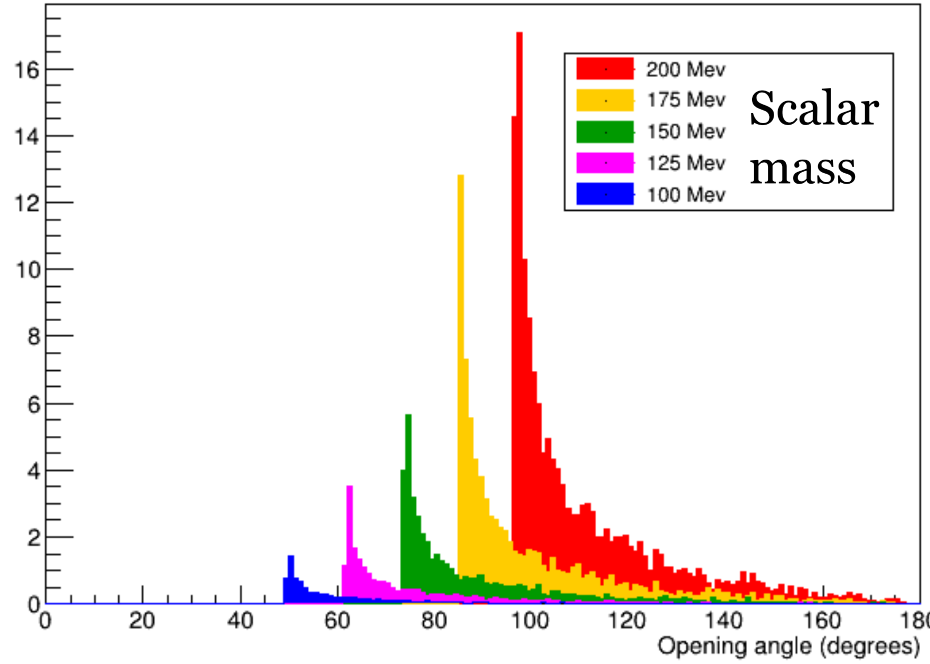


Simulation of a 150 MeV scalar decaying to e^+e^- inside MicroBooNE



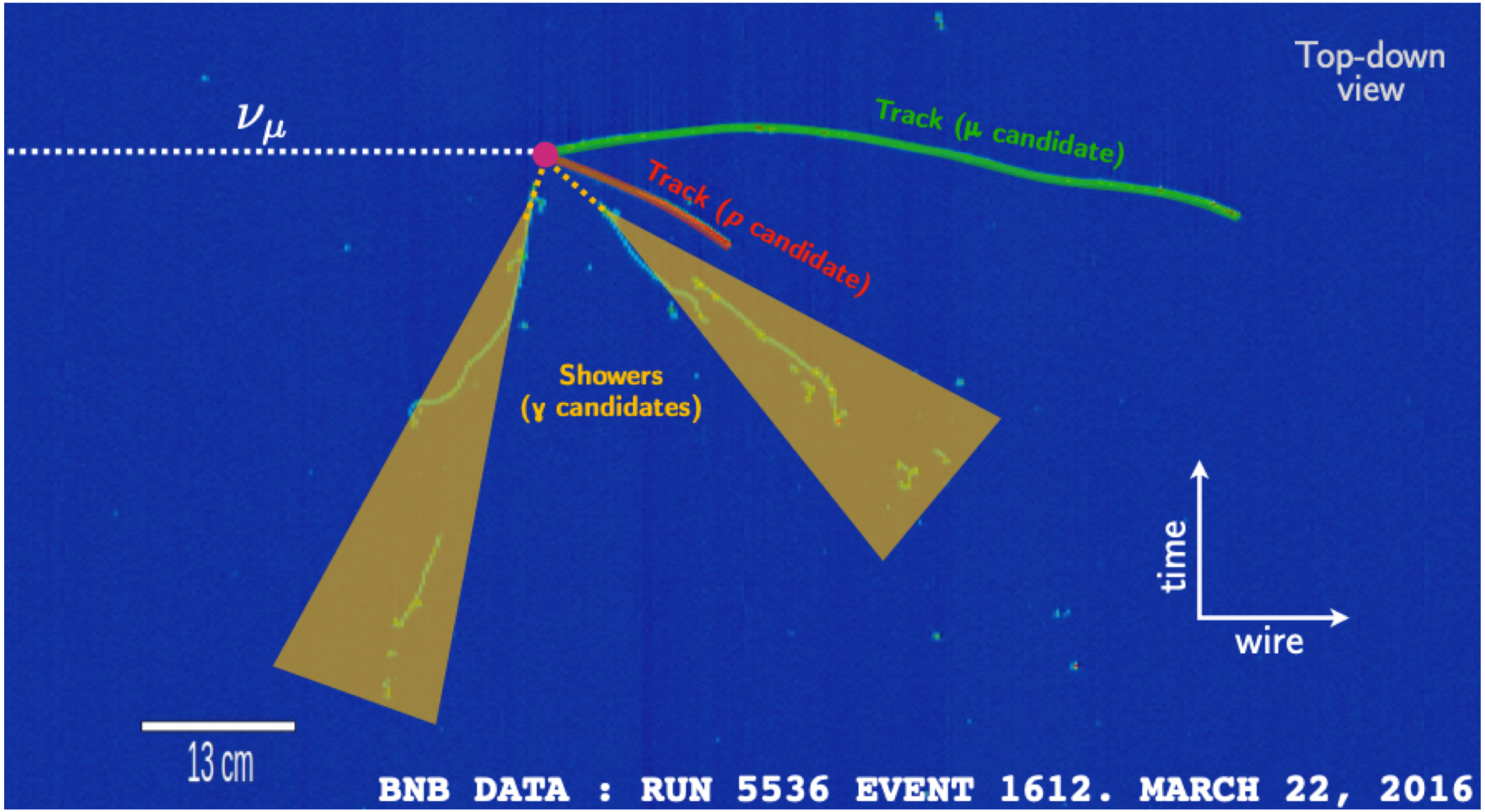
Selection philosophy





Opening angle strongly depends on mass

Pandora reconstruction



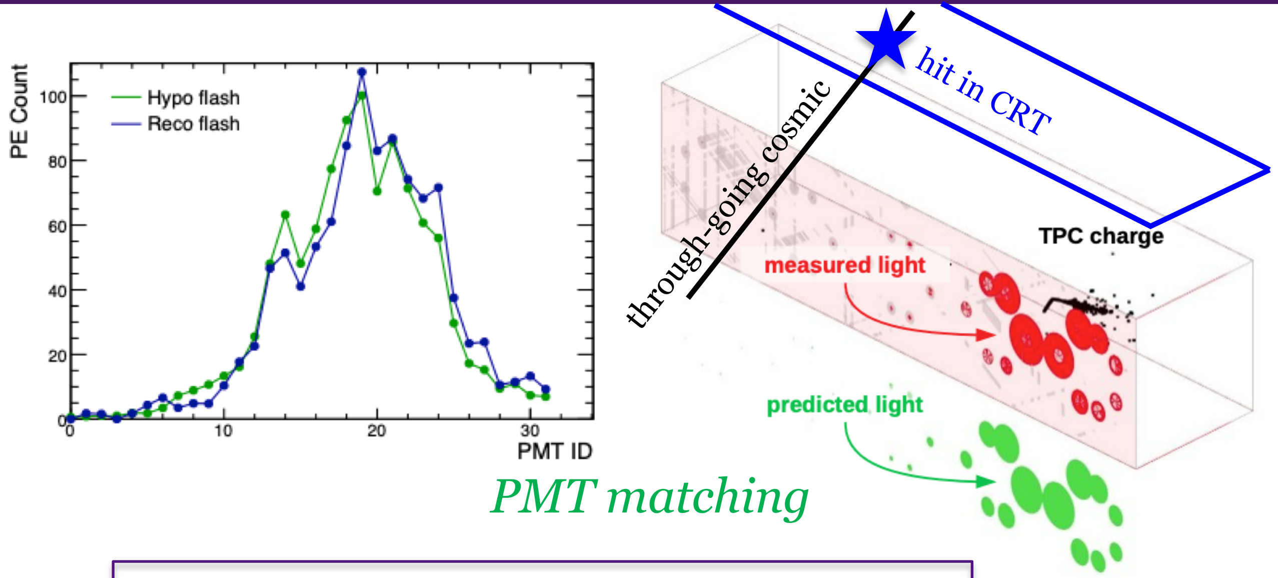
Pandora* is a toolkit to reconstruct LArTPC events, using particle flow algorithms based on ALICE experience

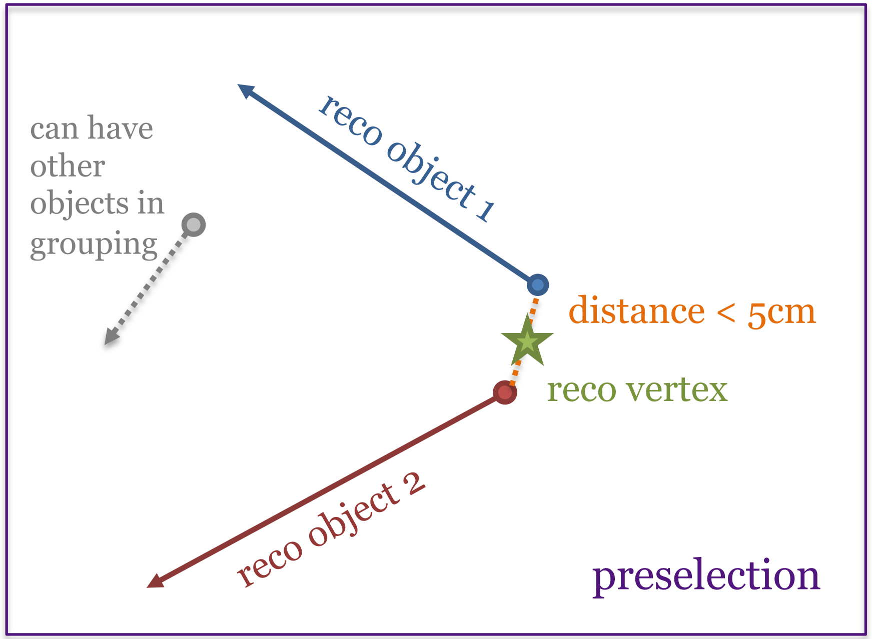
In our case, it produces “tracks” and “showers”

*https://github.com/PandoraPFA

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…



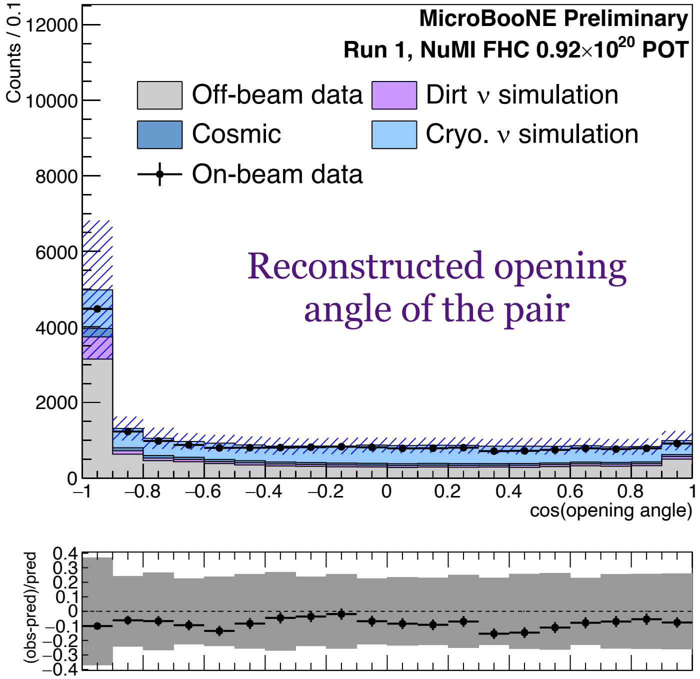


Boosted decision tree inputs

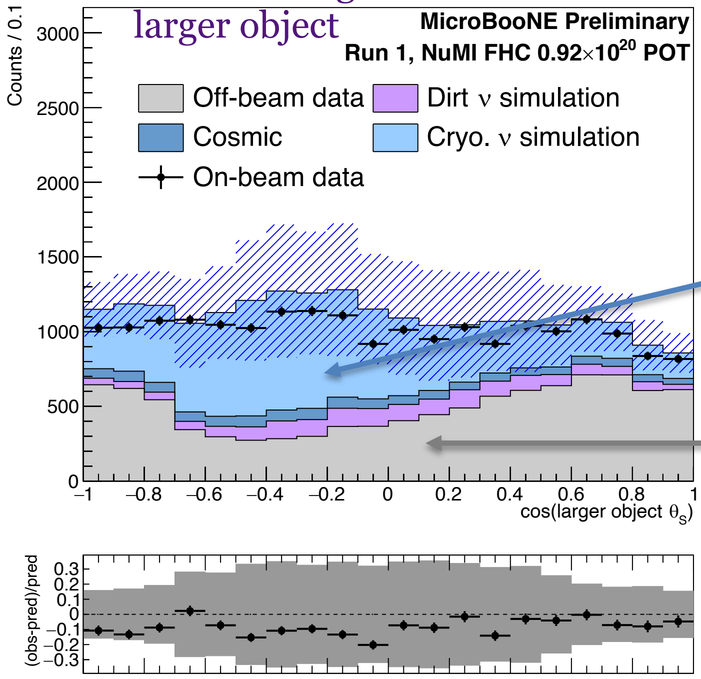
- BDT training variables:
  - Opening angle, transverse opening angle, angles of the two objects with respect to assumed incoming direction
  - Larger object's number of hits, length, pandora track/shower score
  - Number of tracks in the pandora slice
  - Maximum y-coordinate (height) and minimum z-coordinate (upstream) of any other object vertices in event, relative to candidate vertex
  - Number of hits in any other objects (not the electron-positron candidate) in the pandora slice
- BDTs are trained with a single "uniform mass" signal model (to be approximately mass agnostic)

BDT selection

- Trained BDTs against two types of background
  - Against pure cosmics, and against neutrinos
  - Final cuts are two-dimensional
- Performance of simulation verified using 600ns ‘prompt’ control region
  - Scalars from the beam dump arrive later in detector compared to neutrinos



Reconstructed angle of larger object



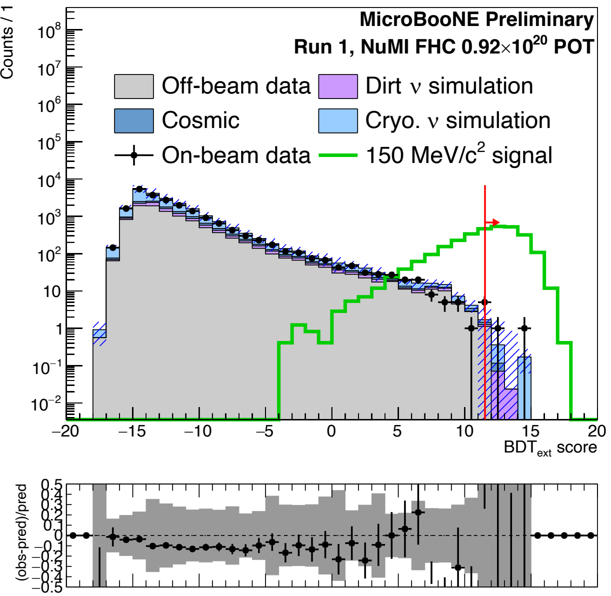
Neutrino interaction background (GENIE)

Pure cosmic background (data driven)

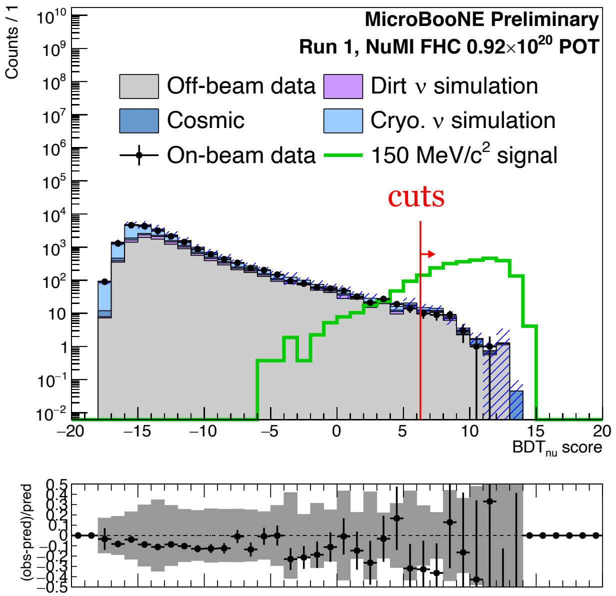
BDT Results

Run 1 (2016)
before CRT

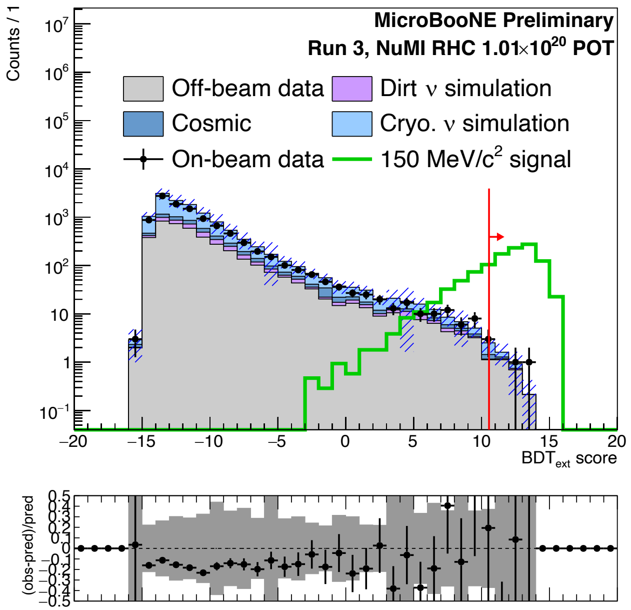
Run 3 (2018)
after CRT



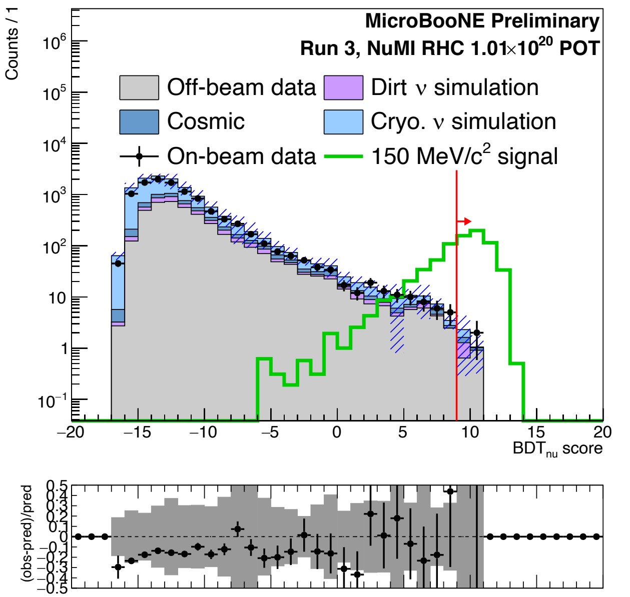
BDT vs cosmics



BDT vs neutrinos



BDT vs cosmics



BDT vs neutrinos

Systematic uncertainties

- For the preliminary result, several sources of uncertainty:
  - Flux
    - For signal, use the MiniBooNE estimated rate uncertainty, through a measurement of neutrinos from the beam dump
    - For neutrino background, use framework developed by the Minerva collaboration
  - Cross section
    - Use the neutrino generator framework for estimating these, through reweighting for different physics parameters in cross section models
- Detector uncertainties will be in the publication coming soon
- However, limit is statistics-dominated

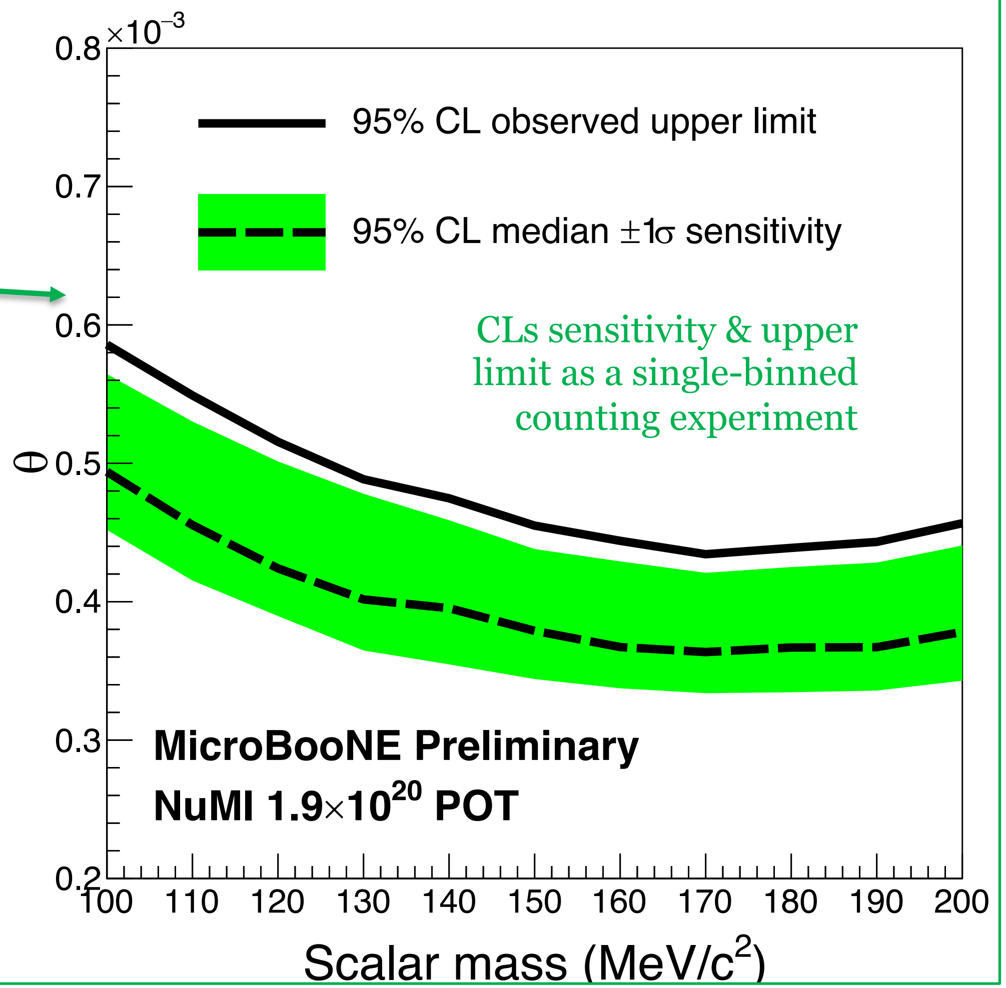
Results

- BDT cuts chosen to maximise sensitivity
- After unblinding, we observe 6 events
  - 1 is rejected as an obvious cosmic
    - PMT timing is before the beam spill window
- We have looked at these 5 events, and they are all consistent with background

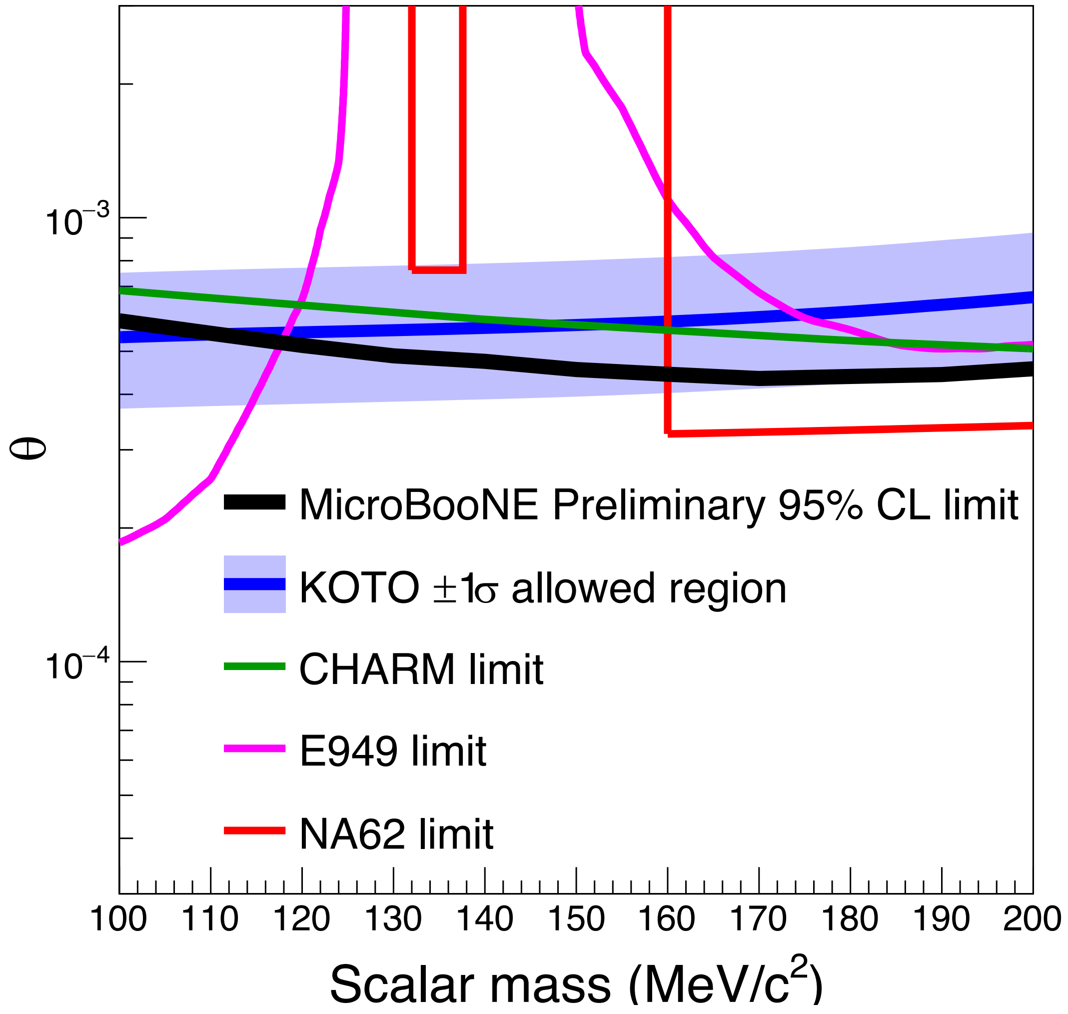
- 5 events, with background expectation of 2.0±0.8

Uncertainty	Background	Signal
Flux (hadron production)	34.0%	30.0%
Cross-section model	3.2%	–
Off-beam statistics	67.4%	–
Simulated statistics	24.3%	$< 2.2\%$

Systematic uncertainties



Preliminary limit & KOTO parameter space

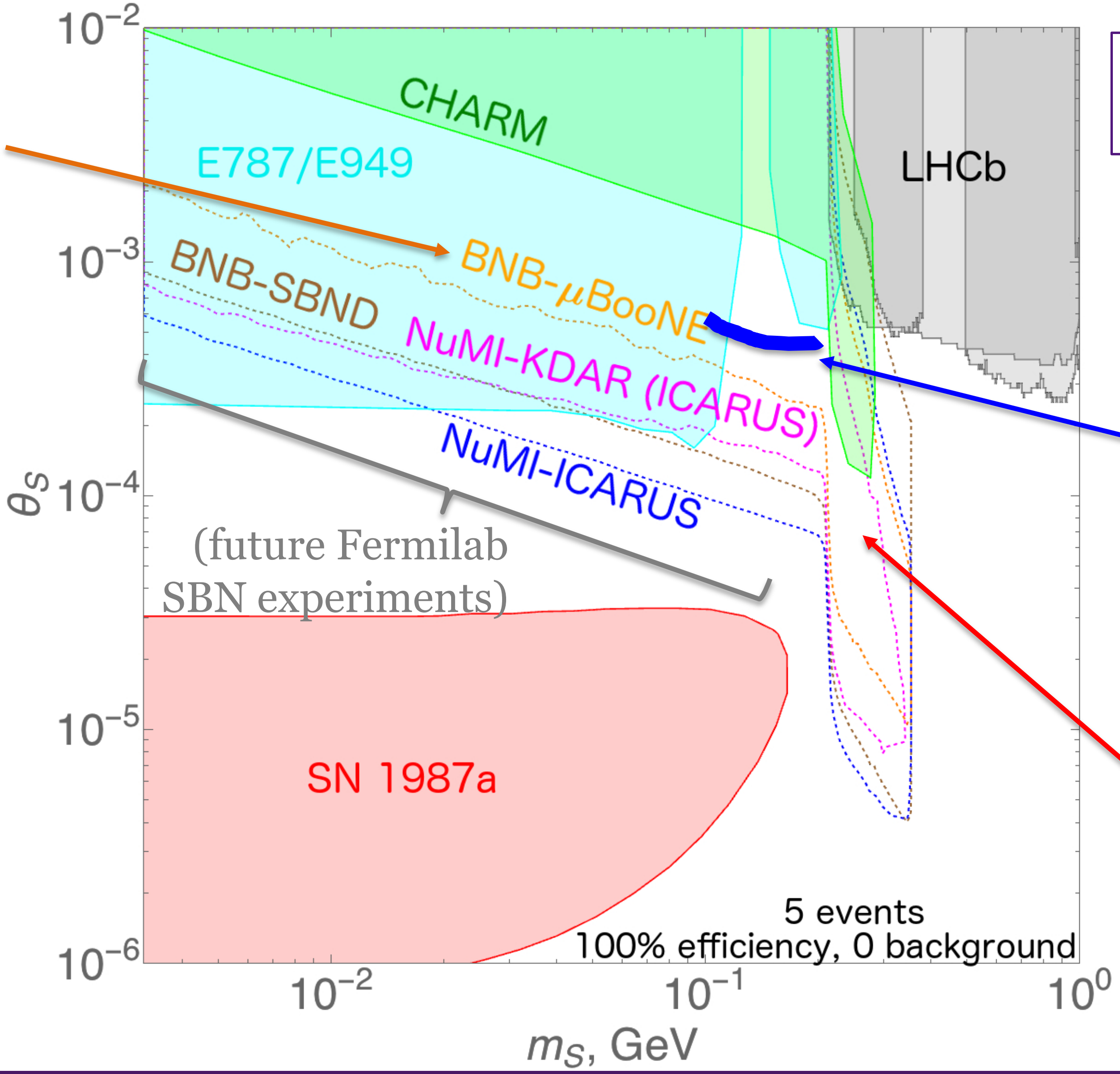


This is with ~10% of our NuMI dataset

Further details in our public note: MICROBOONE-NOTE-1092-PUB

Publication coming soon

Projected sensitivity (by phenomenologists)



MicroBooNE, using Booster Neutrino Beam

(future Fermilab SBN experiments)

Current limit (crudely drawn)

Di-muon, di-pion decay channels

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

- Introduction to MicroBooNE
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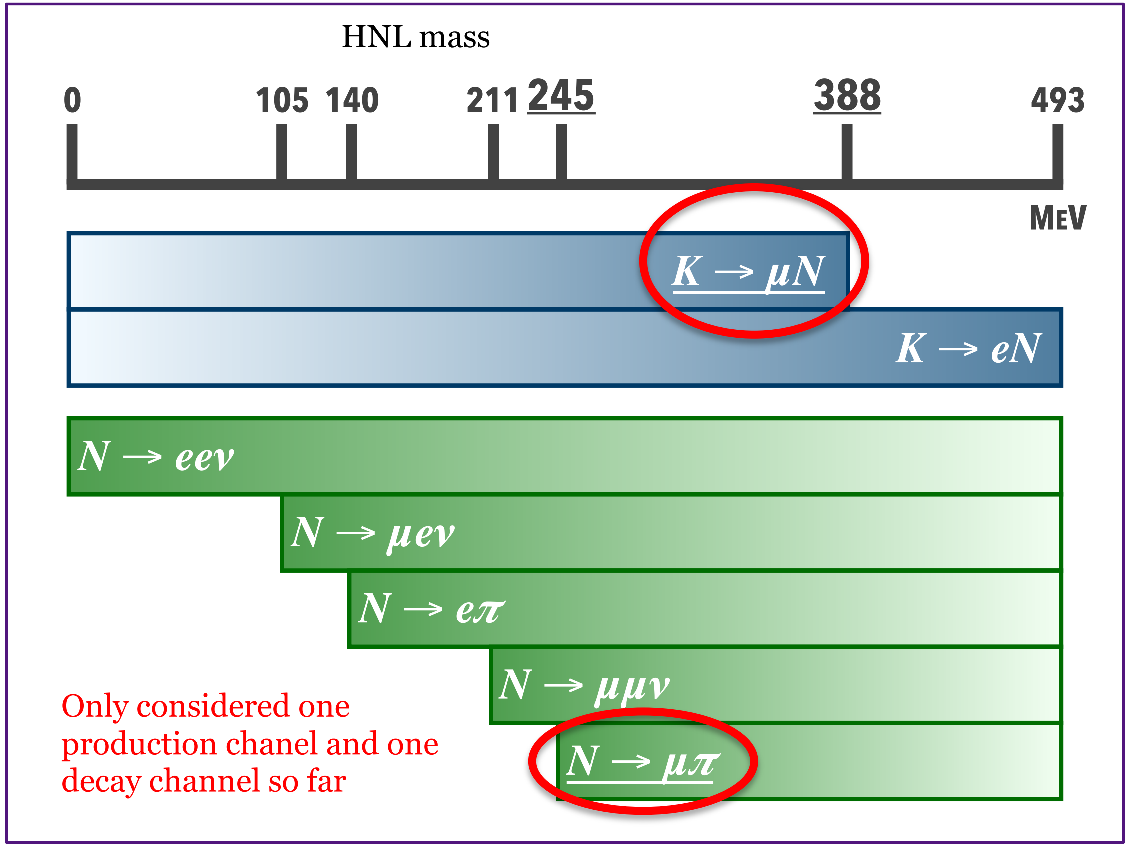
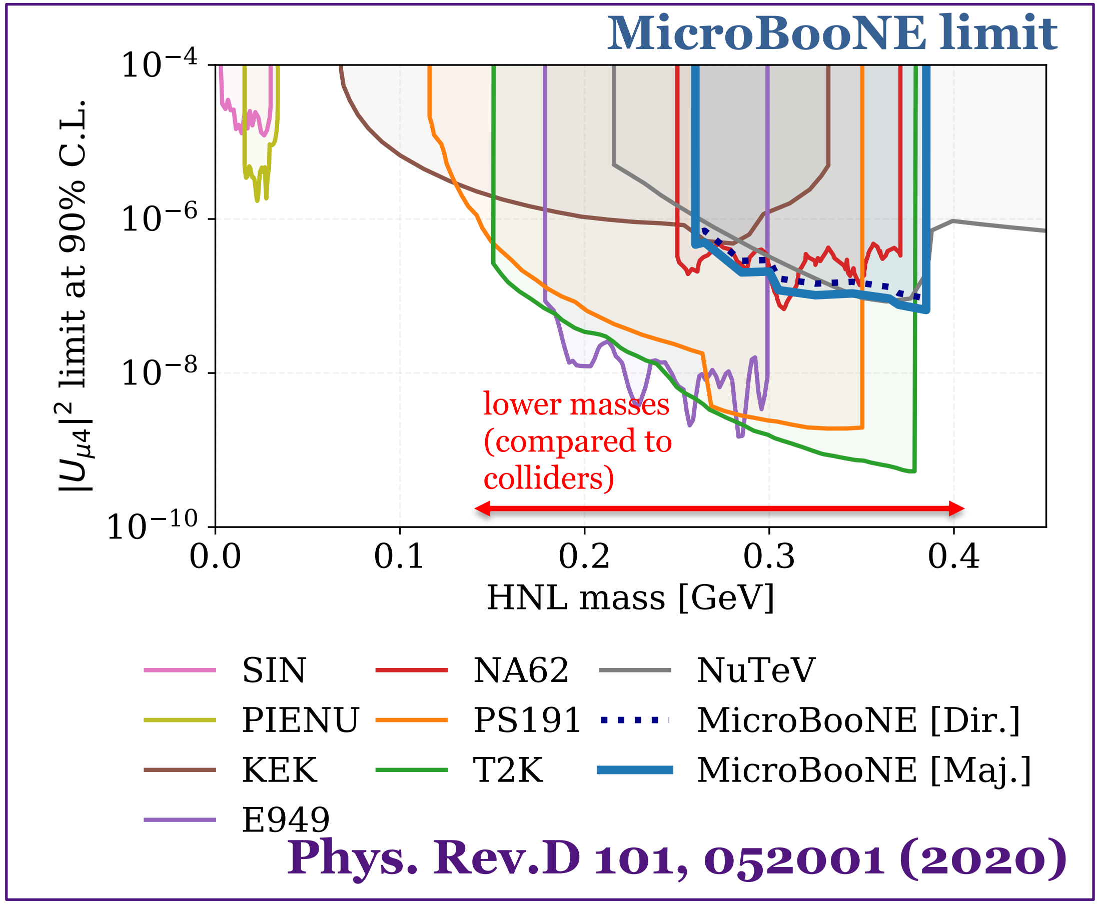
Heavy Neutral Leptons

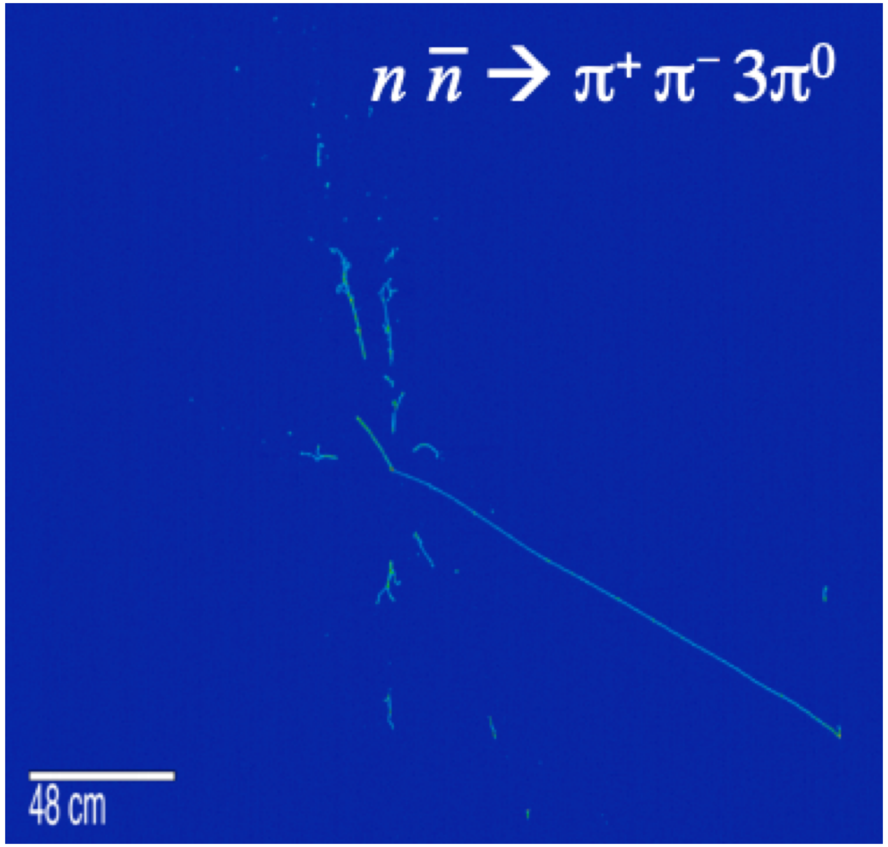
- Very similar phenomenology to the Higgs Portal scalar
  - Kaon decays to HNL; HNL decays to muon+pion
- Further strategies coming soon



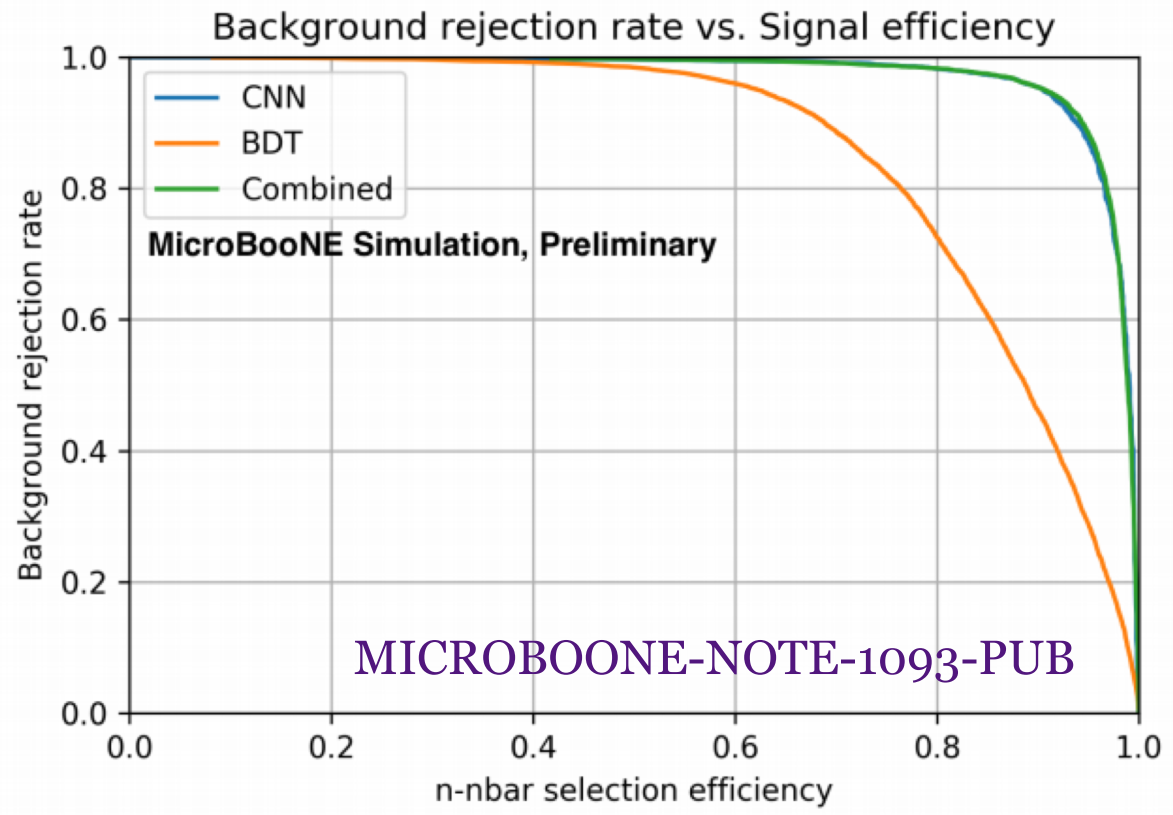


Neutron-antineutron oscillation

- Baryon number violation
- Neutrons oscillate into antineutrons and annihilate
- MicroBooNE will not have competitive sensitivity, but can be used for R&D for future, e.g. DUNE



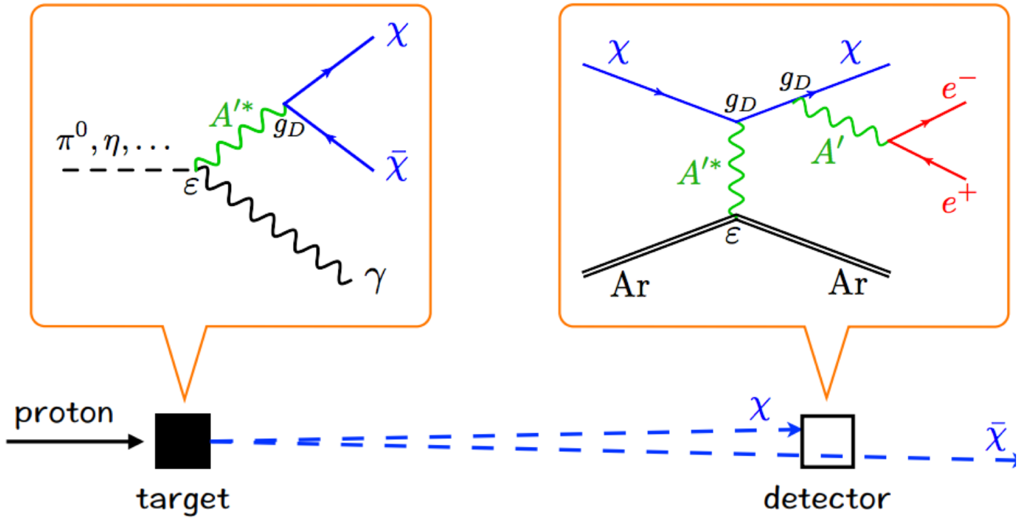
Developed convolutional neural networks to identify these

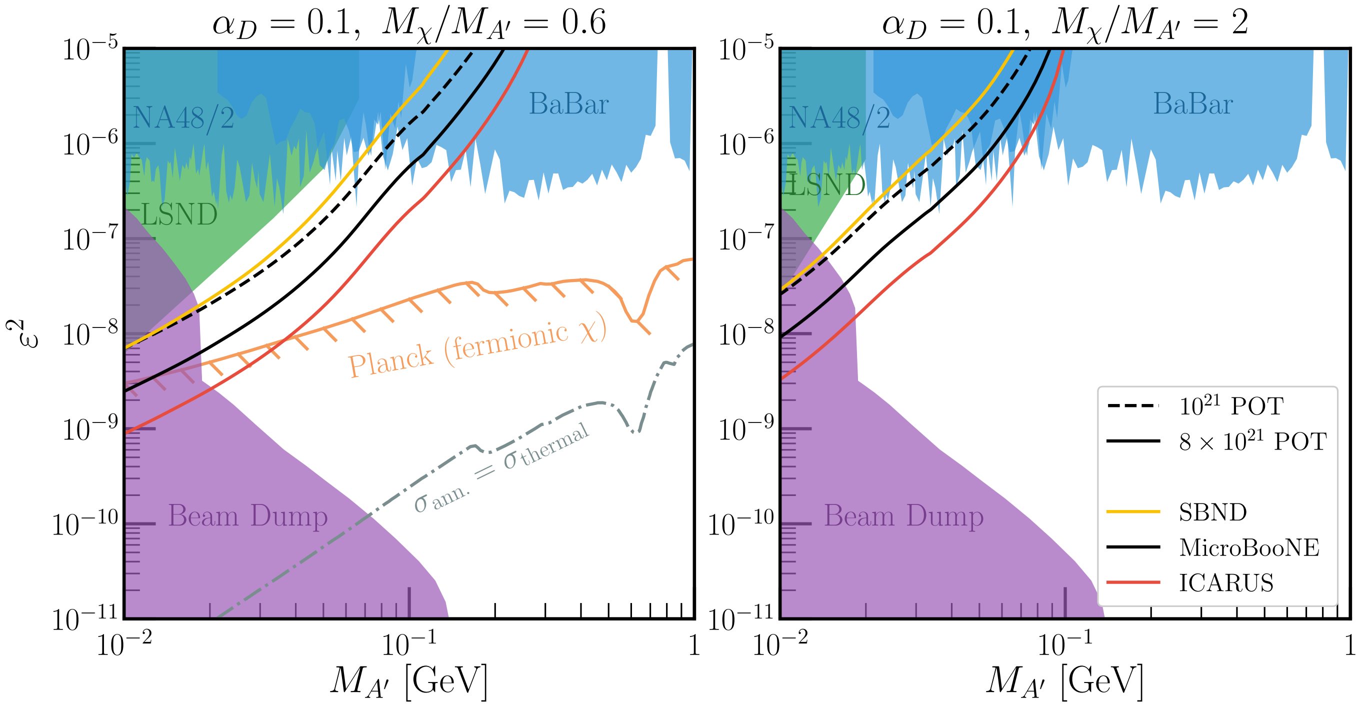


MICROBOONE-NOTE-1093-PUB

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



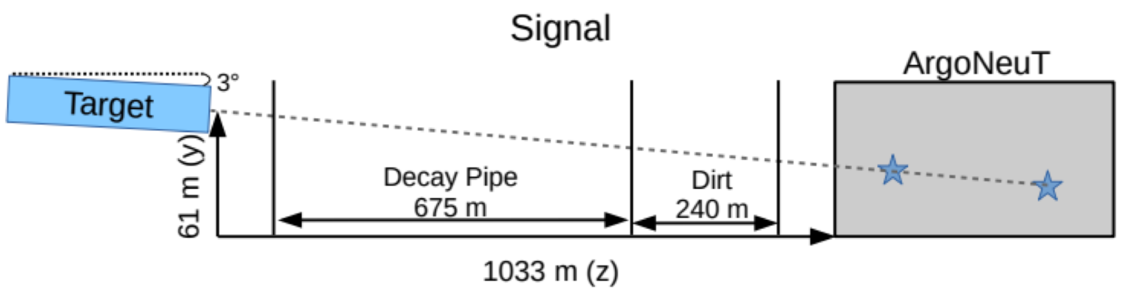


De Gouvea, Fox, Harnik, Kelly
JHEP 2019, 1 (2019)

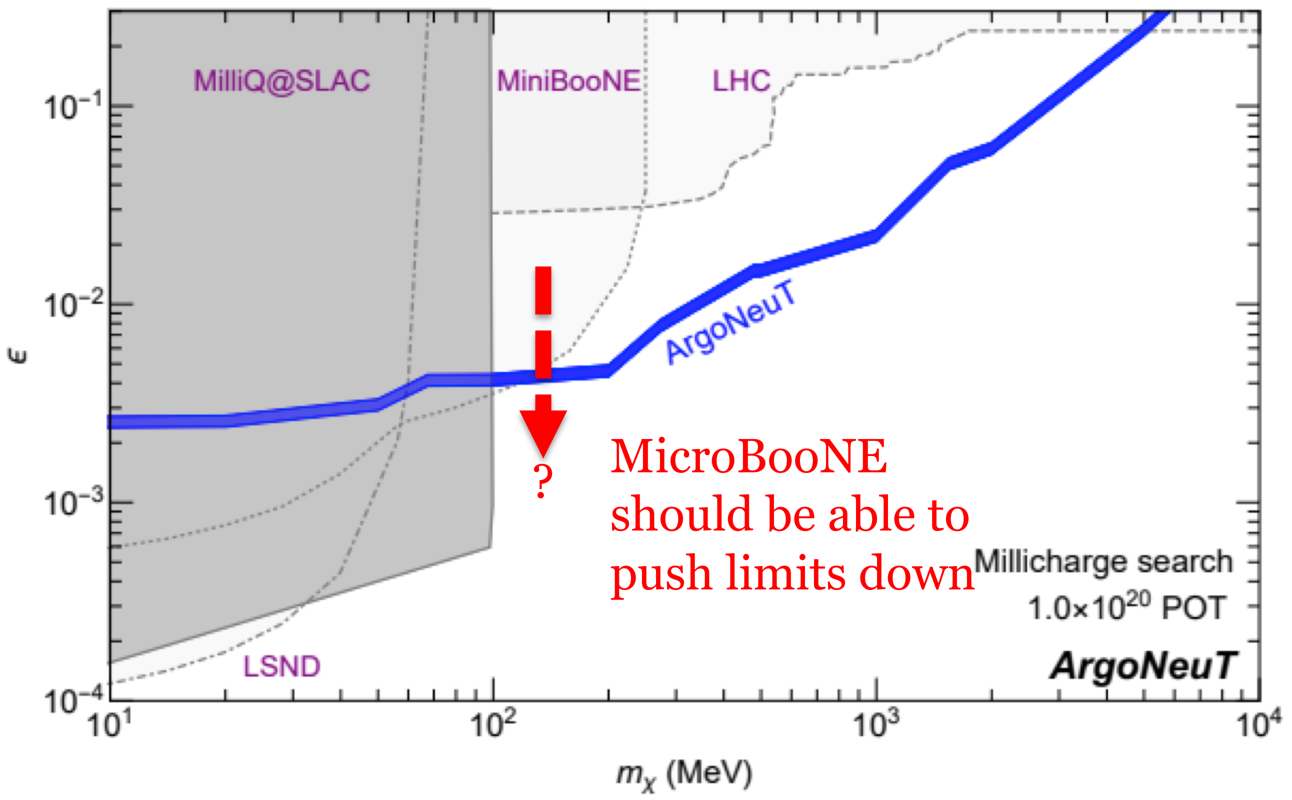
Millicharged Particles

- 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



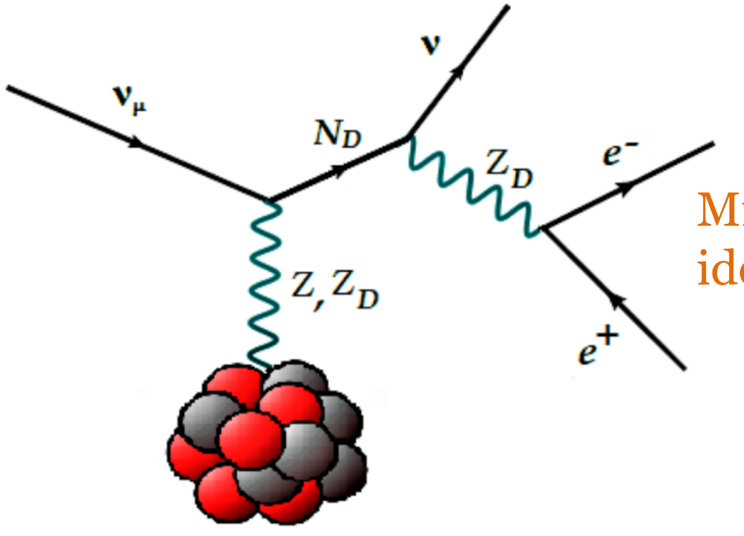
ArgoNeuT, Phys. Rev. Lett. 124, 131801 (2020)

Heavy/dark neutrino decay

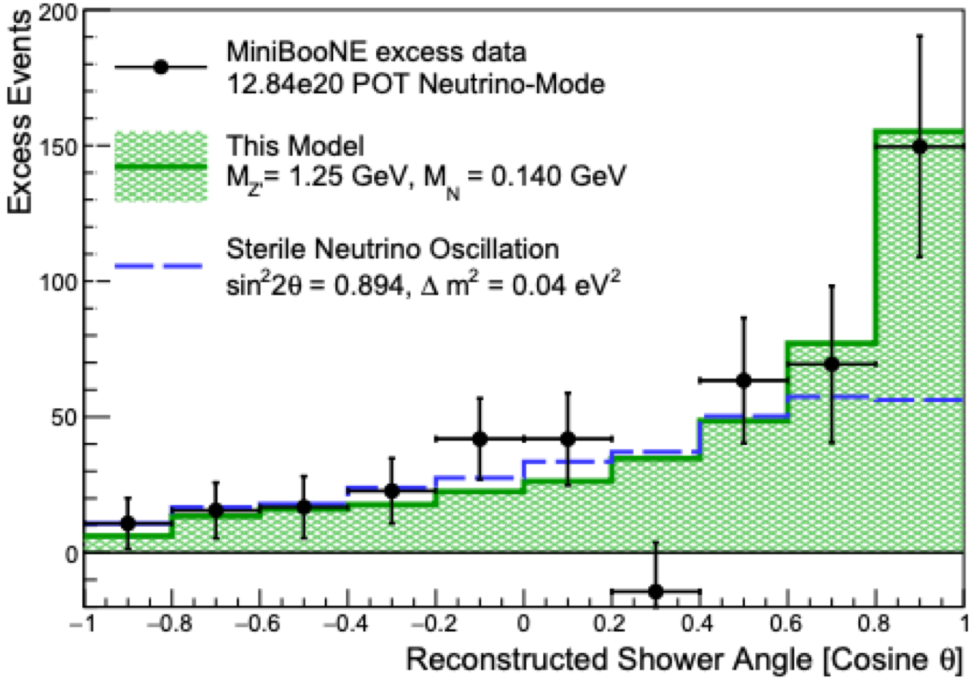
- Similar models to HNLs, however, produced in upscattering of standard neutrinos
- Can decay to dark photons → e^+e^- pairs
- Could explain MiniBooNE excess

Better fit for MiniBooNE

Sensitivity in MicroBooNE still to be evaluated



MicroBooNE can identify e^+e^- pairs



Ballett, Pascoli, Ross-Lonergan
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:
  - Magnetic monopoles
  - Micro black holes
  - Axion-like particles
  - Dark photons
- Many exciting physics models to explore in our five years of data!

SUMMARY

Summary

- MicroBooNE has been running for five years
  - many results on neutrino cross sections, detector physics and R&
  - 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 competitive limits on the Higgs-Portal scalar model in the ~100 MeV mass range
  - Can exclude the parameters required to explain the KOTO anomaly in this model
- Many more New Physics searches to come!