Lessons learned from BSM searches in LArTPCs

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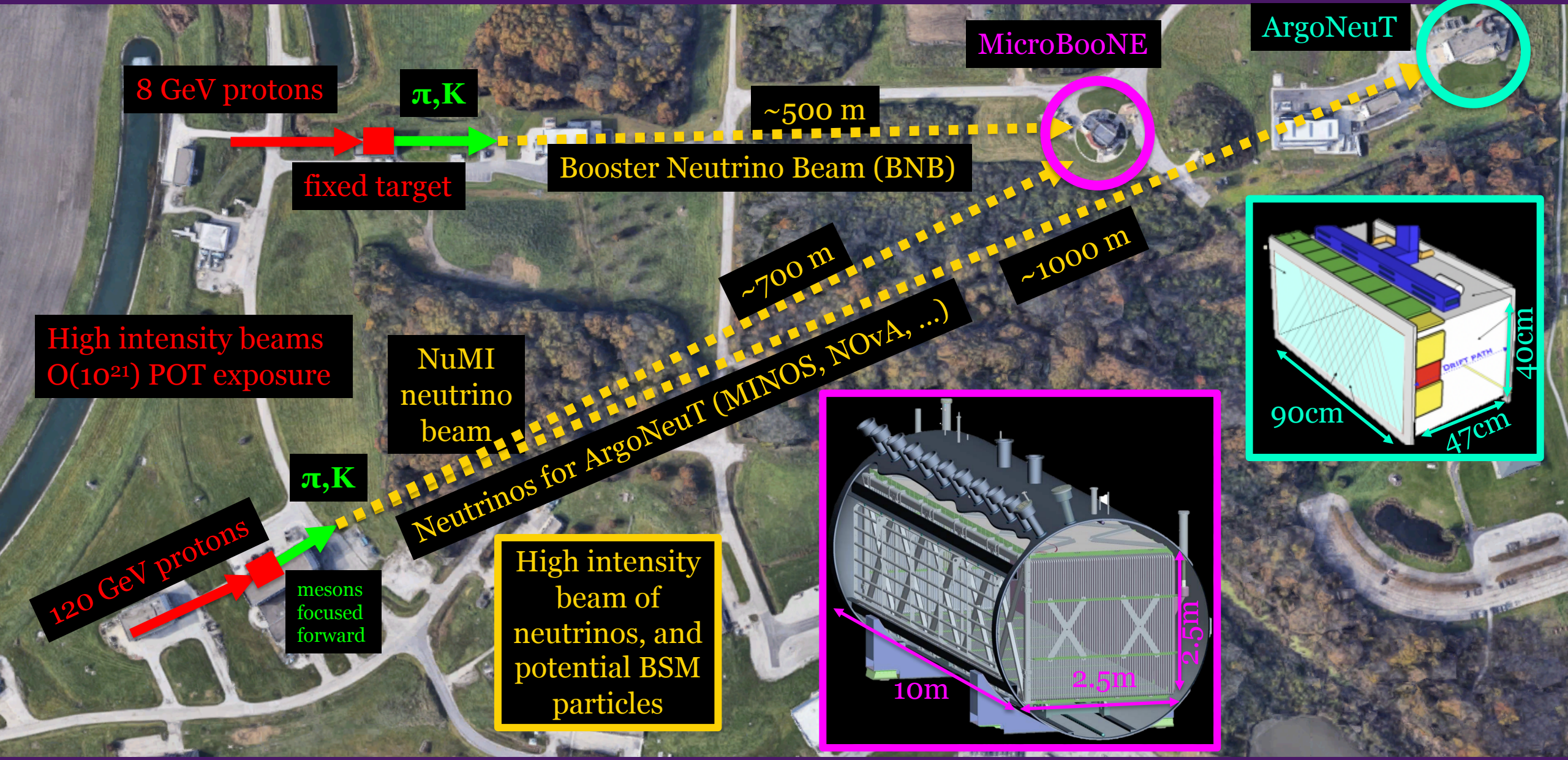
Outline

- ArgoNeuT BSM searches
  - Millicharged particles
  - Heavy neutral leptons
- MicroBooNE BSM searches
  - n-nbar oscillations
  - MeV-scale physics
  - Heavy neutral leptons
  - Higgs-portal scalars
  - Dark matter & dark sector prospects
- Wishlist
  - Personal opinions
  - Wishlist for the theory community
  - Hopefully some discussion points for later today

ArgoNeuT & MicroBooNE in FNAL ν beamlines



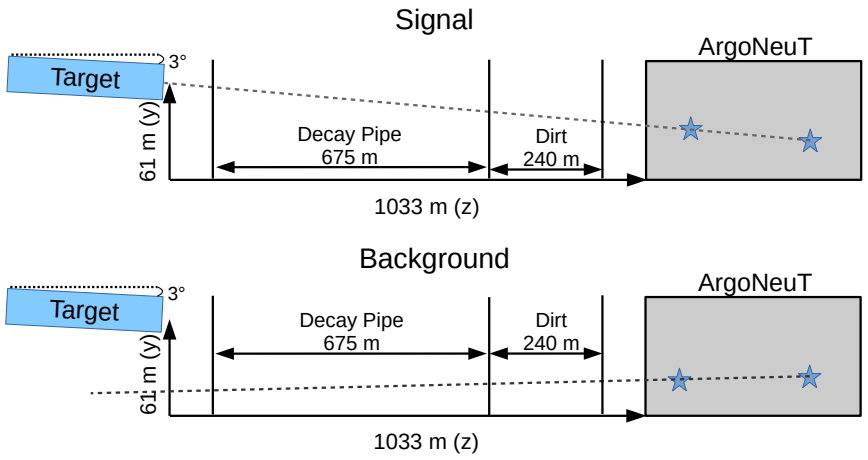
ArgoNeuT's search for Millicharged particles

Millicharged particles have electric charge $Q = \varepsilon \cdot e$ ($\varepsilon << 1$):

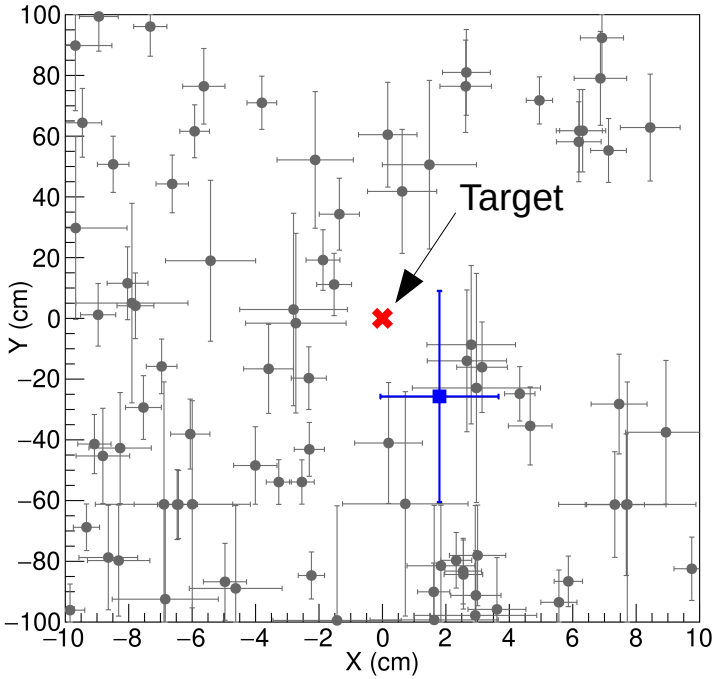
- can be produced from meson decays in the NuMI beam
- interact via elastic scattering, mostly below detector threshold but see occasional individual hits above threshold

Search for multiple low energy hits in line pointing to beam target

- low energy threshold is key, 300 keV in ArgoNeuT



Intersection with beam target position

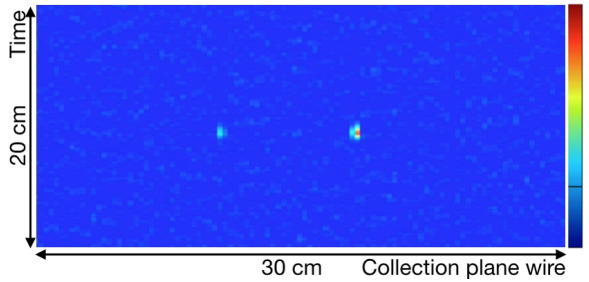


ArgoNeuT's search for Millicharged particles

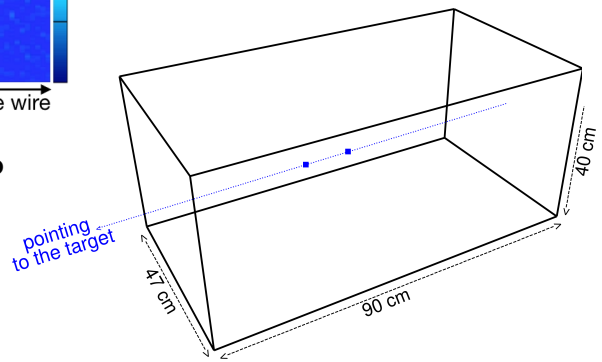
One candidate event identified, consistent with background expectation

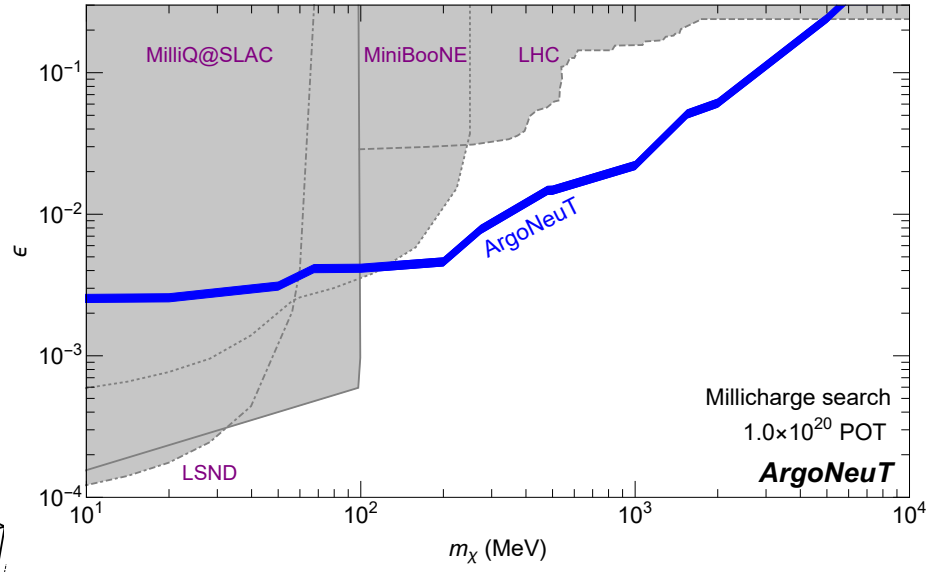
New exclusion limit at 95% CL in large region of unexplored parameter space

SBN could improve on this, but since they are surface detectors cosmic related background more challenging



ArgoNeuT candidate mCP





Phys. Rev. Lett. 124, 131801 (2020) [1911.07996]

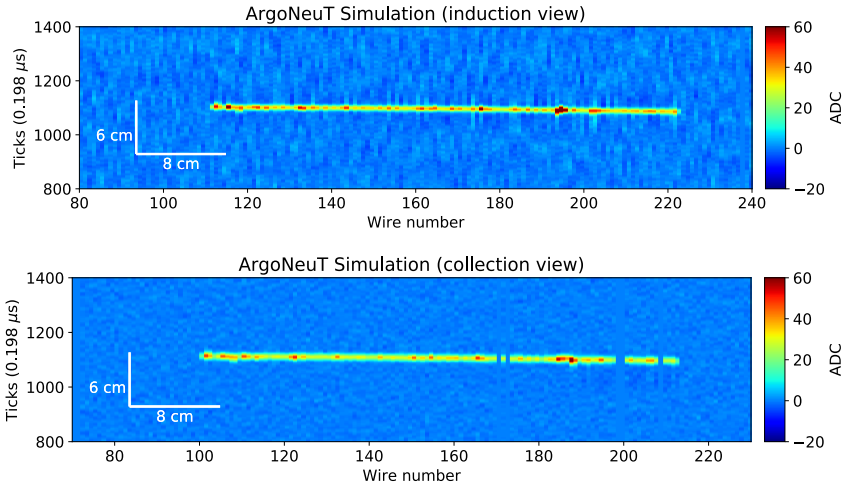
ArgoNeuT's search for Heavy Neutral Leptons

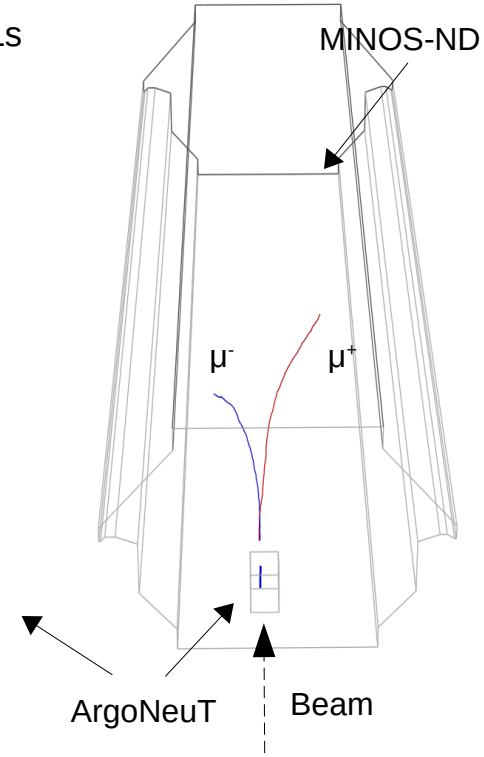
Search for τ-coupled HNLs produced in NuMI beam:

- D / D_s mesons produced by beam, decay to τ particles, that subsequently decay to HNLs
- require high energy beam to produce flux of τ particles, ~1e-7 per POT in NuMI
- search for di-muon decay signature: $N \rightarrow \nu_\tau + \mu^+ + \mu^-$

Highly boosted muon pair:

- overlap in ArgoNeuT, select via dE/dx
- matched to muon pair in MINOS-ND
- magnetised detector allows muon charge to be identified: very powerful for reducing background





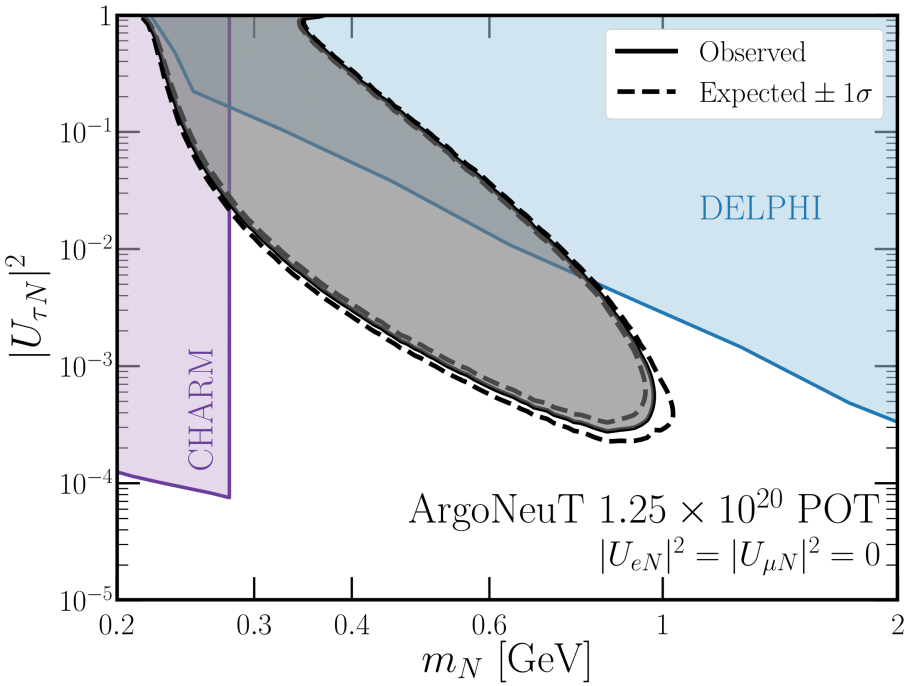
ArgoNeuT's search for Heavy Neutral Leptons

Selection applied to ArgoNeuT data-set:

- 1.25e20 POT, anti-neutrino mode beam
- **0 events observed in data**, consistent with background expectation (0.4 ± 0.2 events)

New exclusion limit at 90% CL for τ-coupled HNLs with mass 280-970 MeV

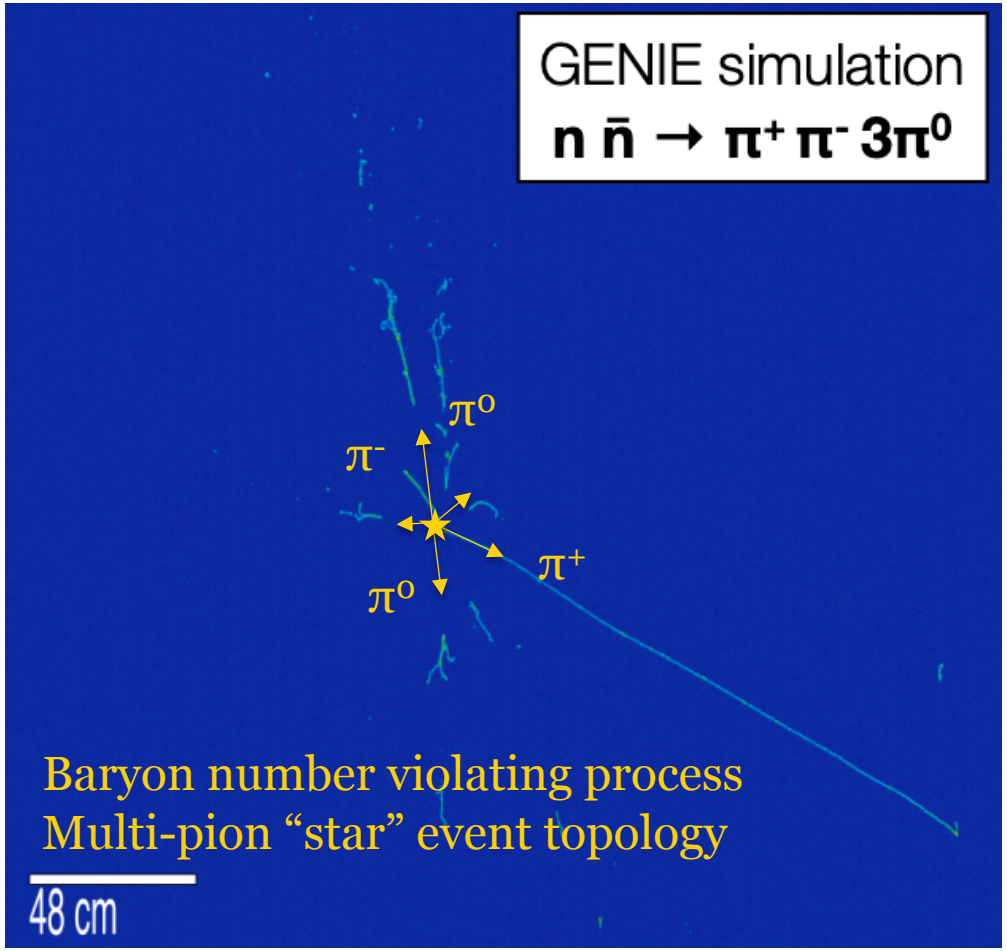
Limited by ArgoNeuT's small exposure – SBN detectors could potentially improve on this (using off-axis NuMI beam)

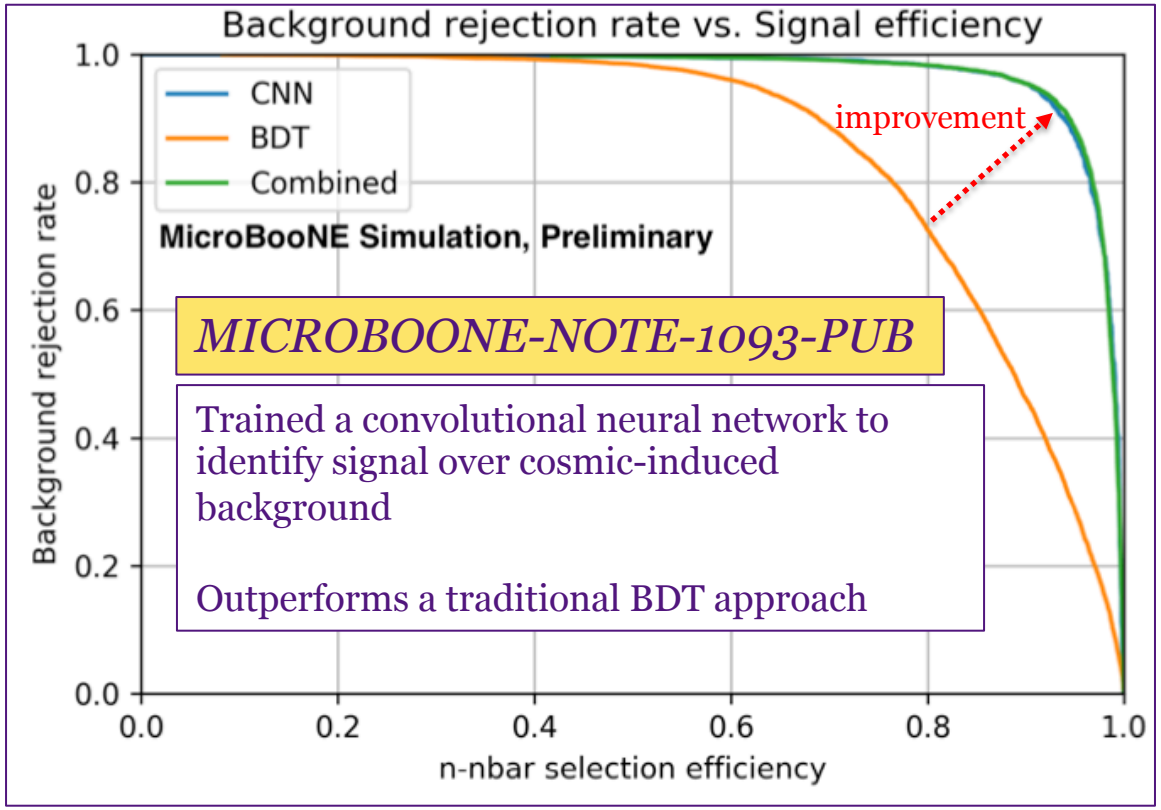


Phys. Rev. Lett. 127, 121801 (2021) [2106.13684]

MicroBooNE: n-nbar oscillation

(Beam-independent)





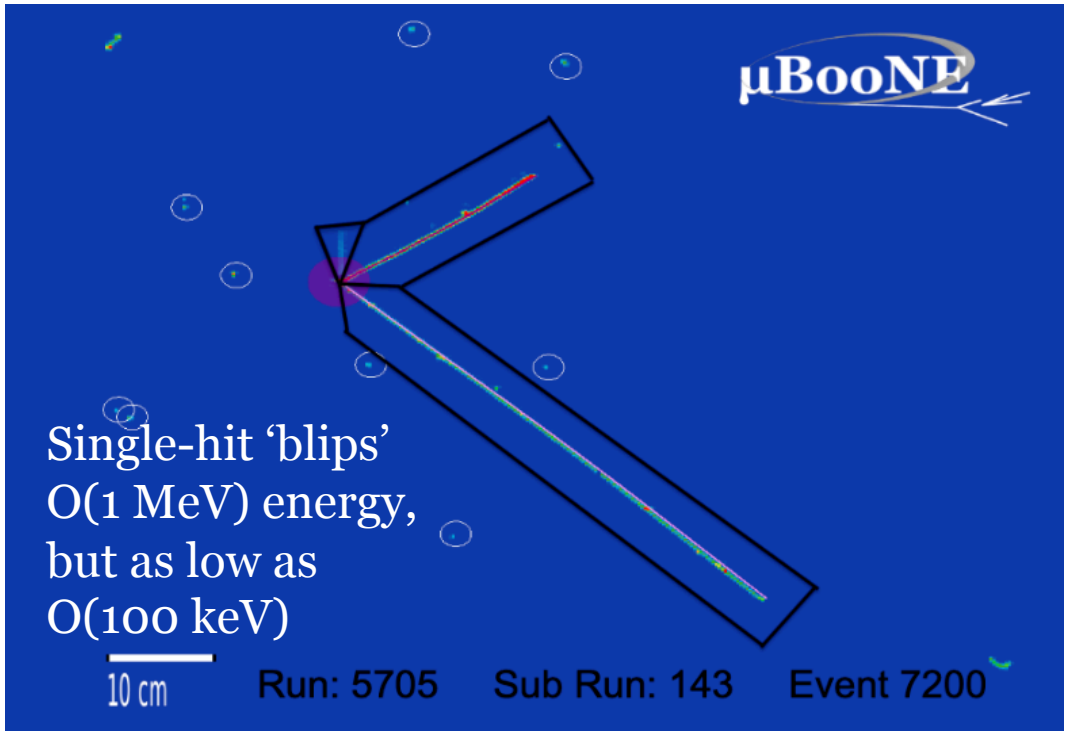
MicroBooNE is pioneering techniques to be used in DUNE

- No sensitivity beyond current experimental limits

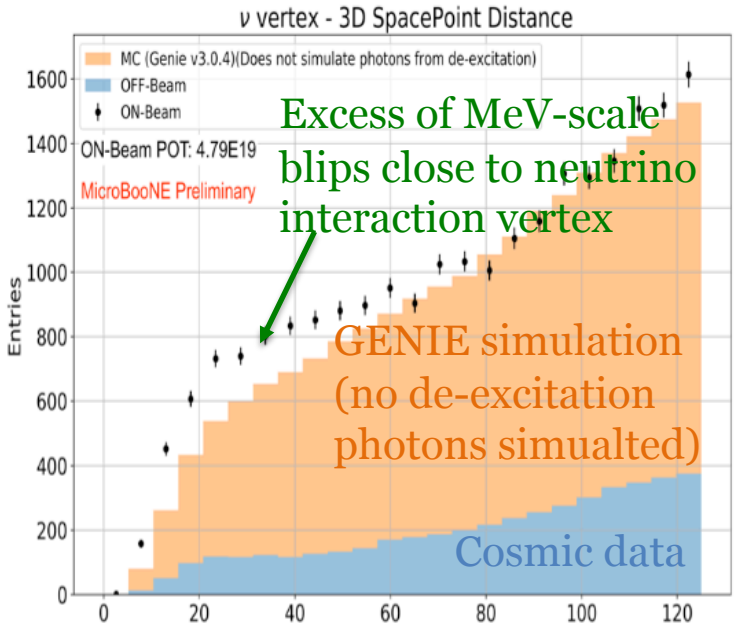
Could potentially investigate other BNV modes

MicroBooNE: MeV-scale reconstruction

- Standard reconstruction algorithms designed for O(100 MeV) interaction
- 'Blips' of ionization produced by low-energy gammas or neutrons
- MicroBooNE is pushing down the thresholds for reconstructing this information



MICROBOONE-NOTE-1076-PUB

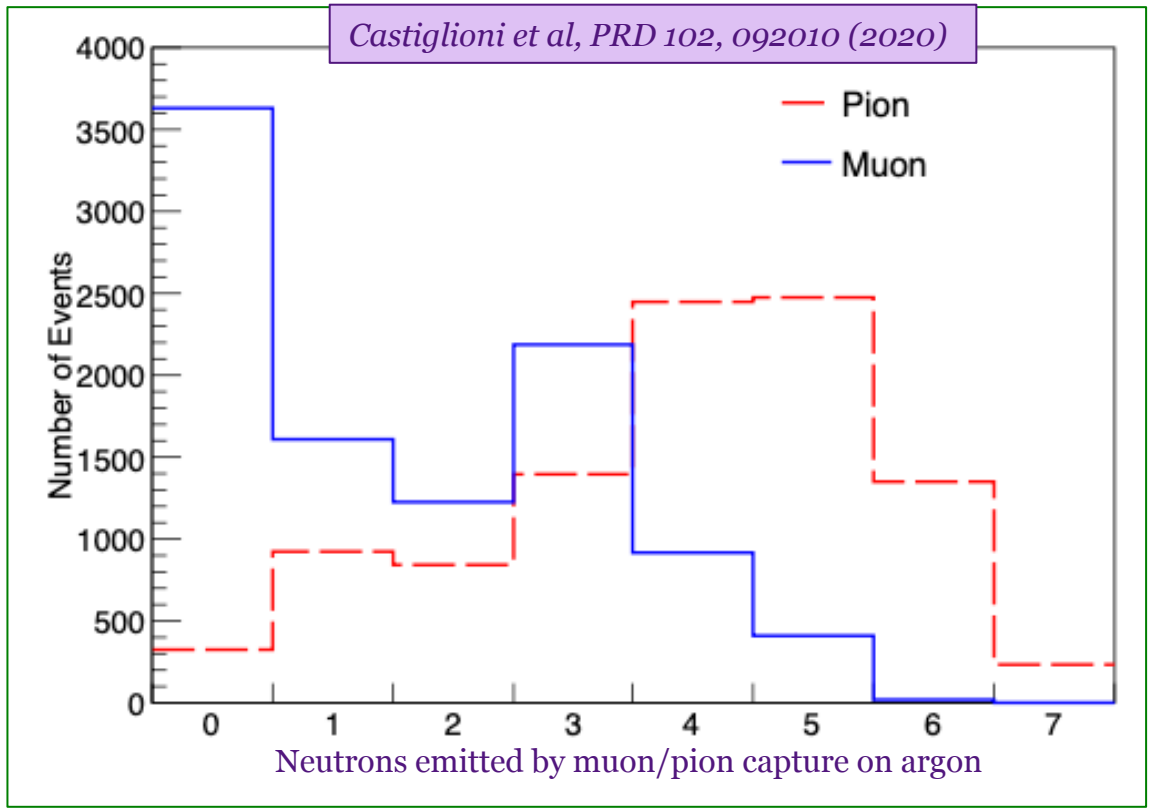


Distance from blip to neutrino vertex (cm)

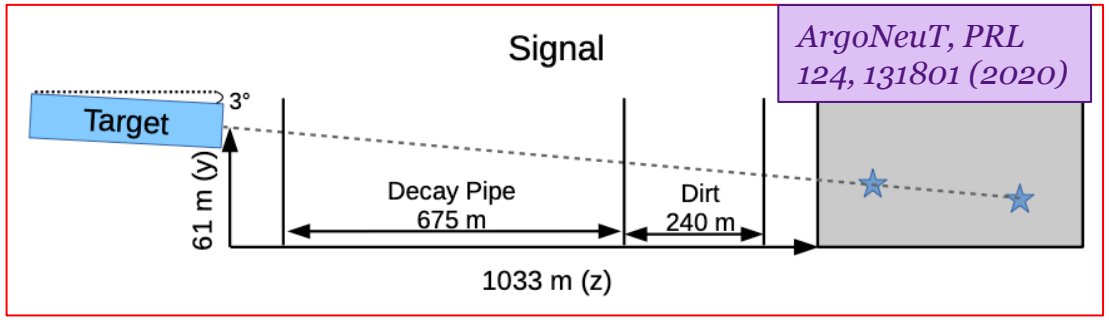
MeV-scale applications for BSM

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

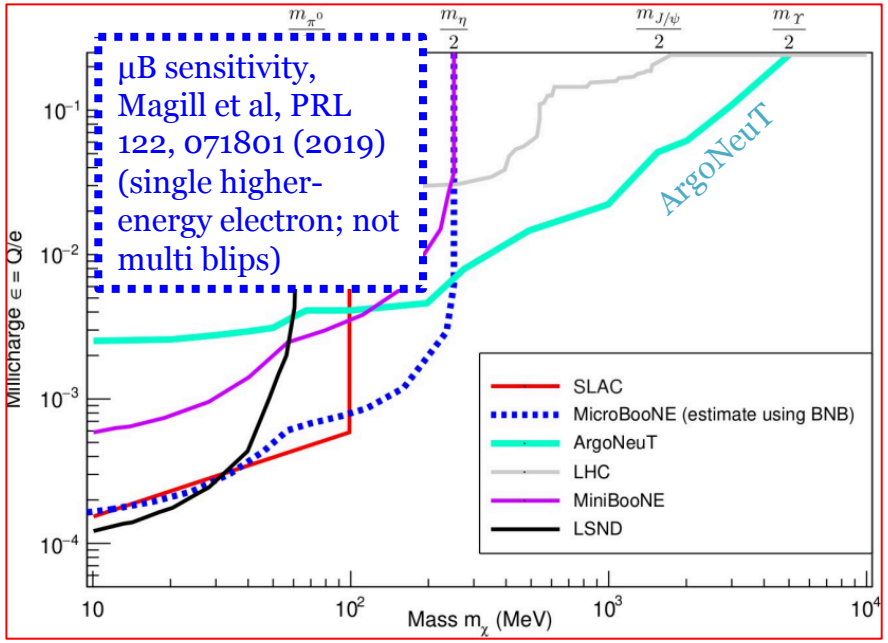
- E.g. Z' (L_μ-L_τ models)



Should also aid with nuclear-scattering vs pure BSM-decay signatures



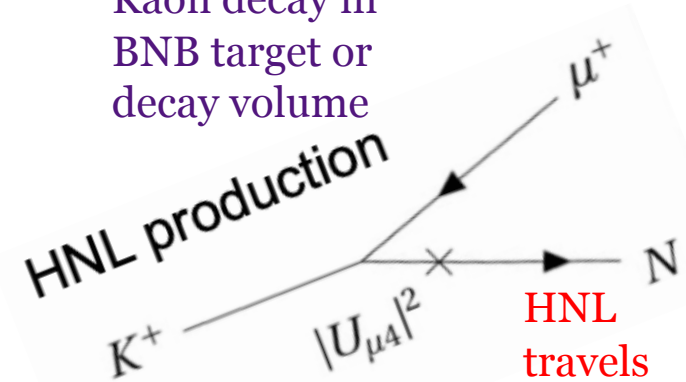
Searches for millicharged particles (blips along a straight line, pointing back to target)



MicroBooNE: Heavy neutral leptons

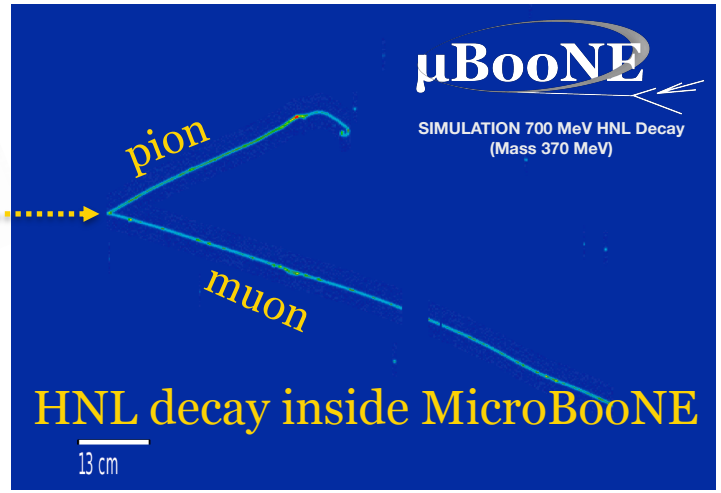
- O(100 MeV) mass neutral leptons; mixing with SM neutrinos
- Produced in the same way as standard neutrinos
  - From kaon decays, in MicroBooNE's first search
- "Late window" trigger was developed for this analysis
  - Negligible neutrino backgrounds

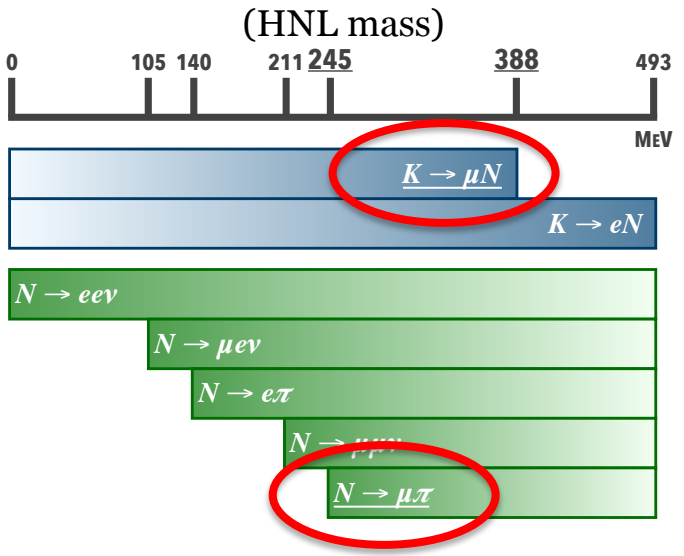
Kaon decay in BNB target or decay volume



(Extended PMNS matrix element)

HNL travels ~500m



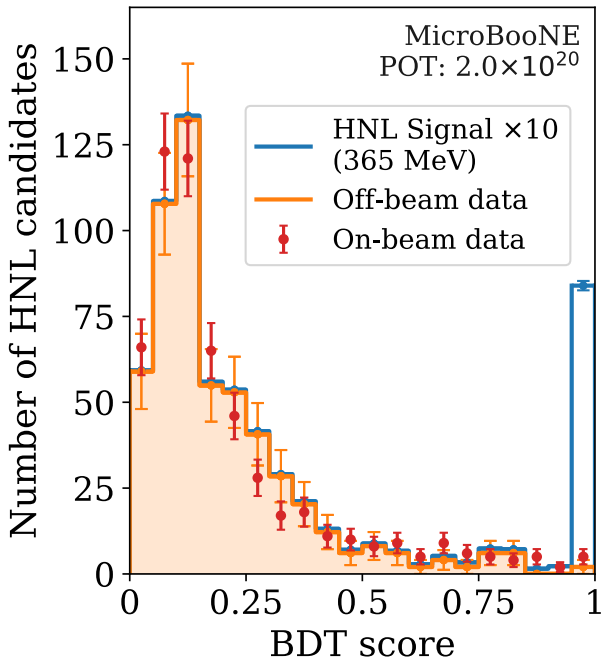


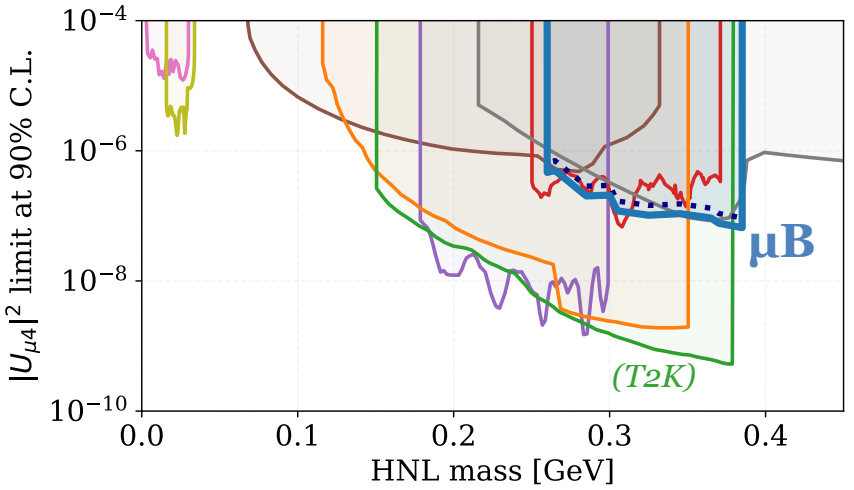
First result: one production mode & one decay mode

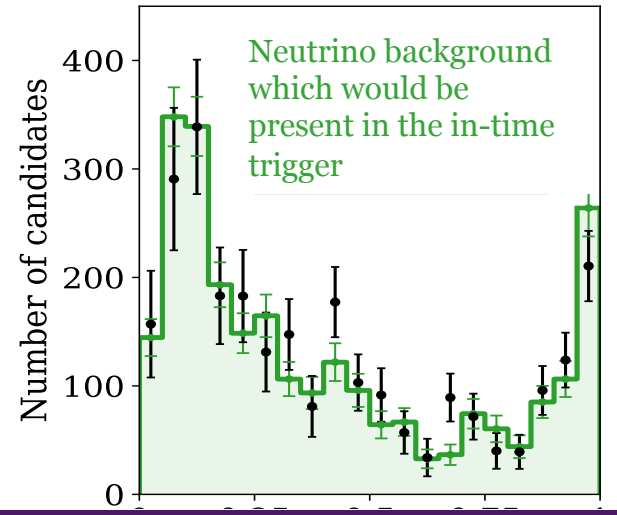
MicroBooNE: Heavy neutral leptons

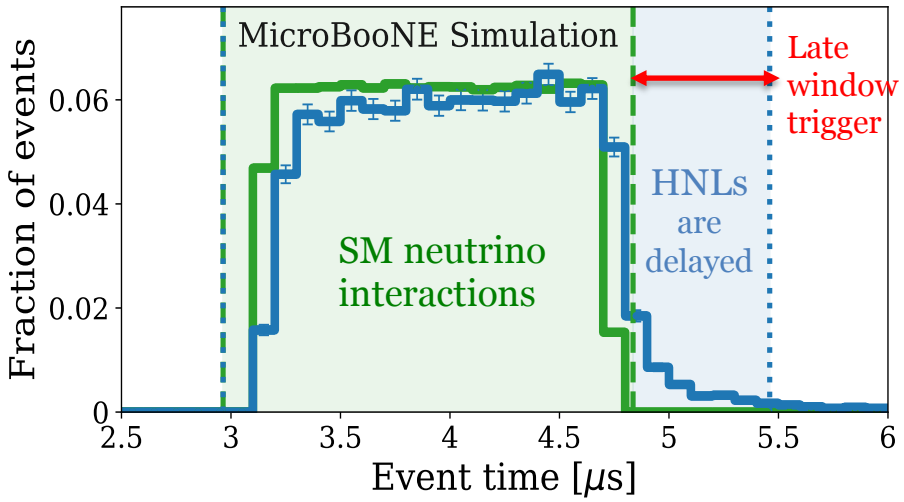
MicroBooNE, Phys.Rev.D 101, 052001 (2020)

- BDT based analysis with 10 HNL mass points
- No excess observed
- Competitive limits, with only small fraction of dataset
- Further decay modes in the near future

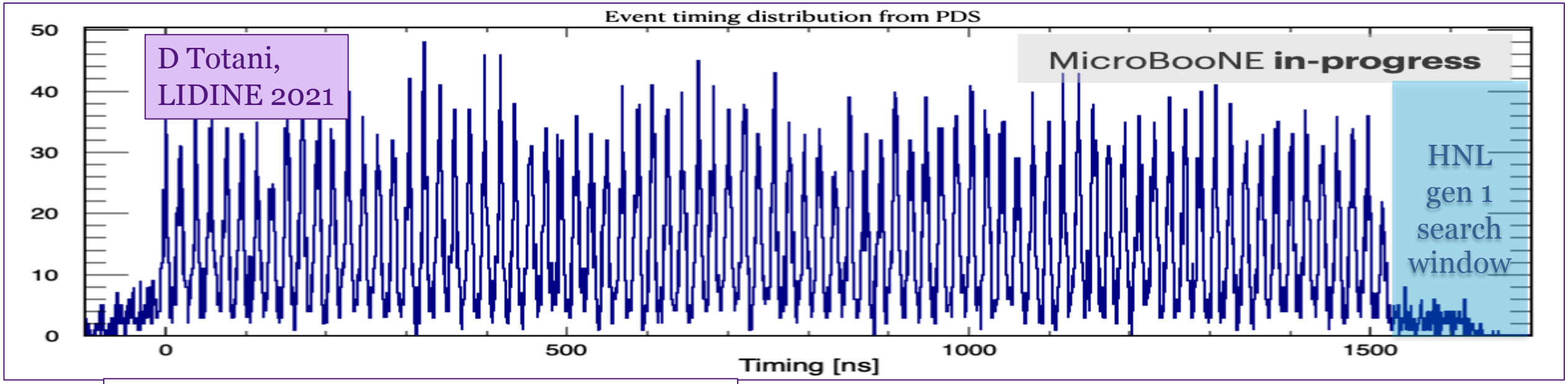


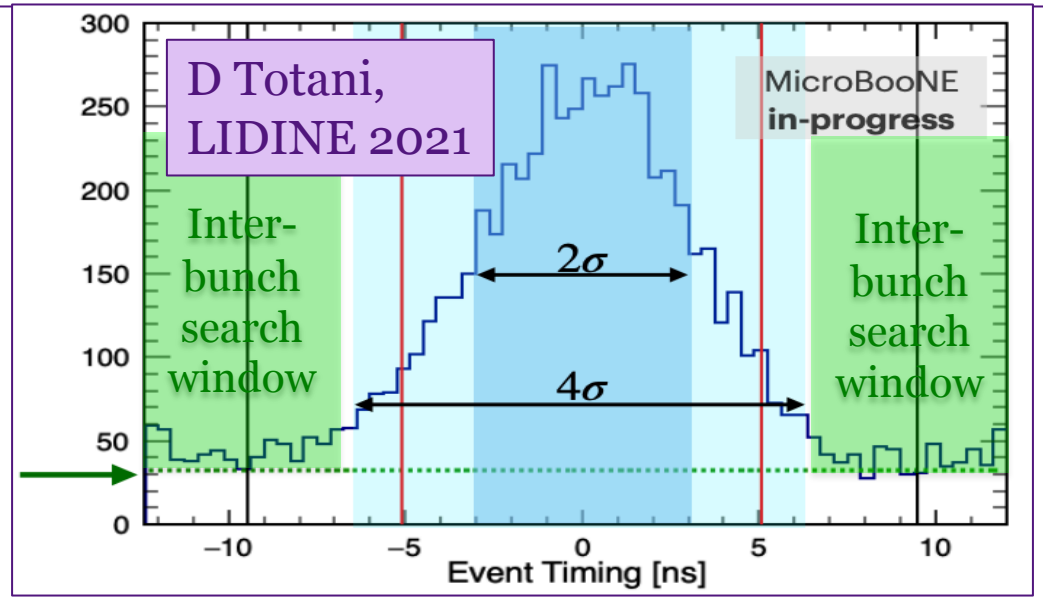






Inter-bunch searches

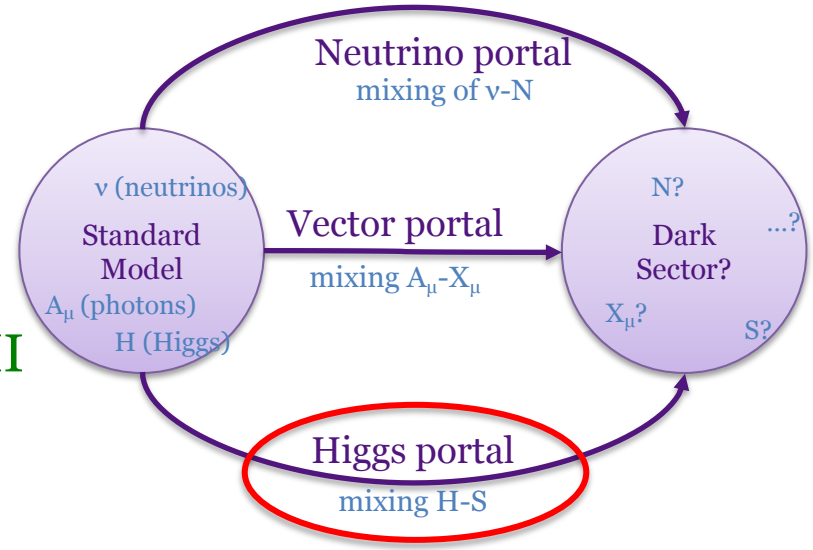




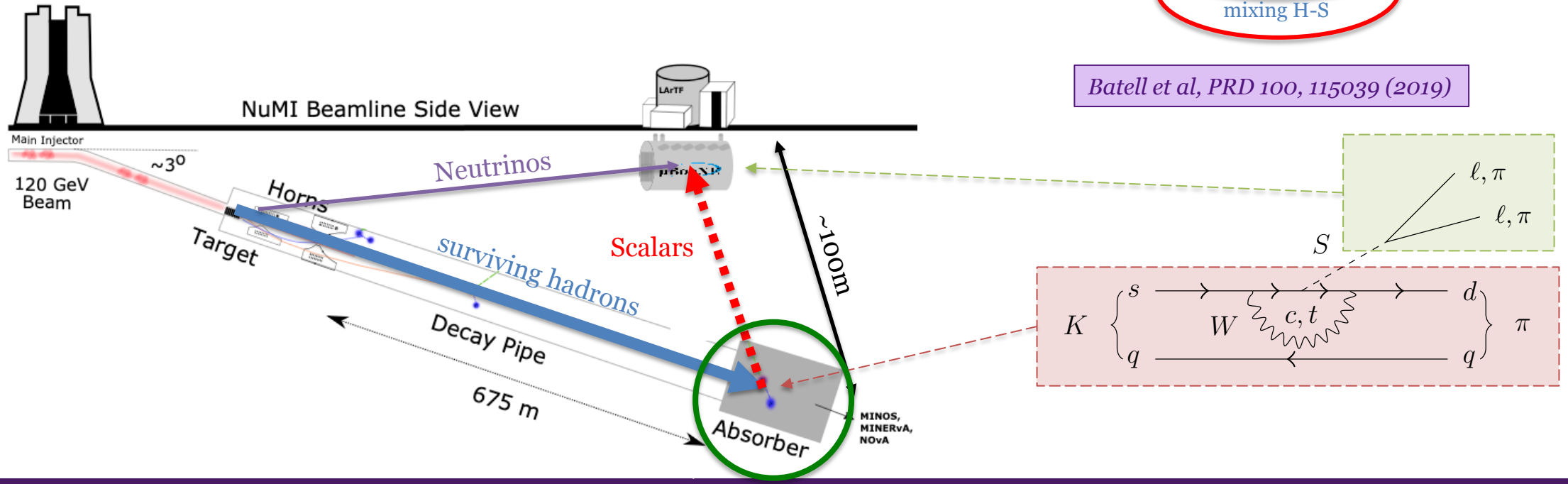
Can search for heavy new physics in between the beam bunches

MicroBooNE: 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 ∝ $\theta^2 m^2$
- Very similar phenomenology as HNLs
  - Search for kaons decaying to scalar in beam
  - Scalar decays to fermions in detector
- MicroBooNE's first search used kaons decaying at rest in the NuMI beam dump

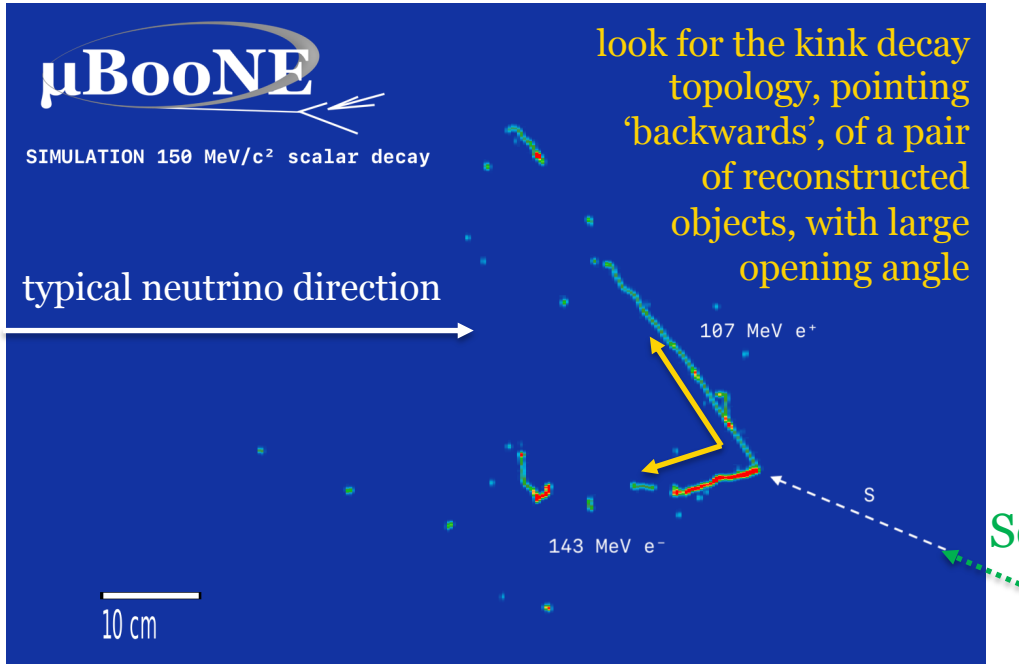


Batell et al, PRD 100, 115039 (2019)

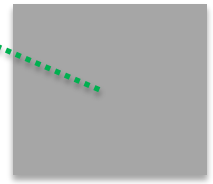


MicroBooNE: Higgs portal scalars

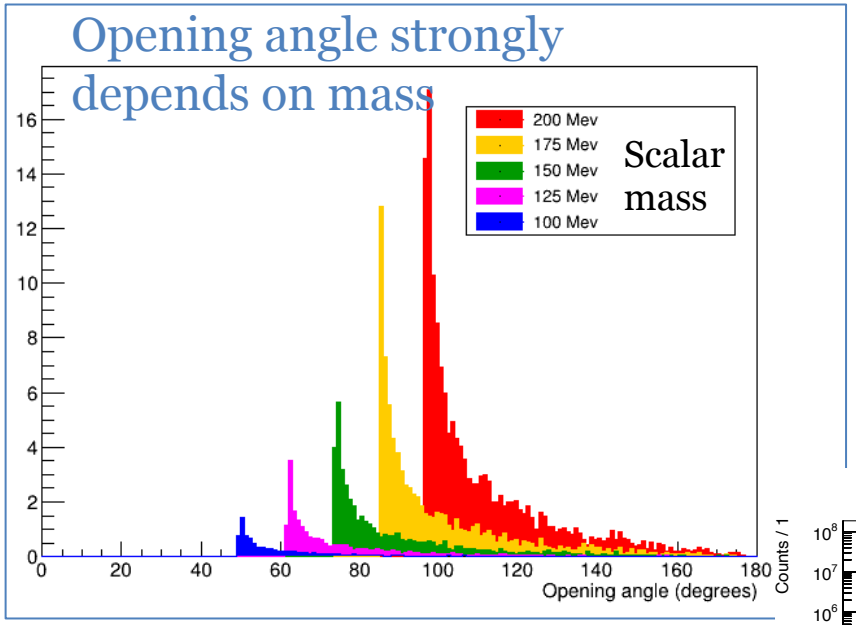
- Searching for e^+e^- pairs from the decay of a <200 MeV scalar boson
- Using a BDT-based analysis



Scalar boson

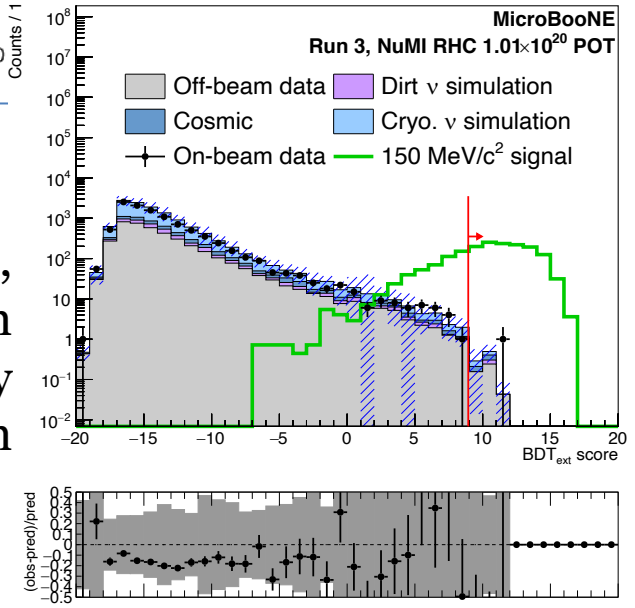


NuMI beam dump



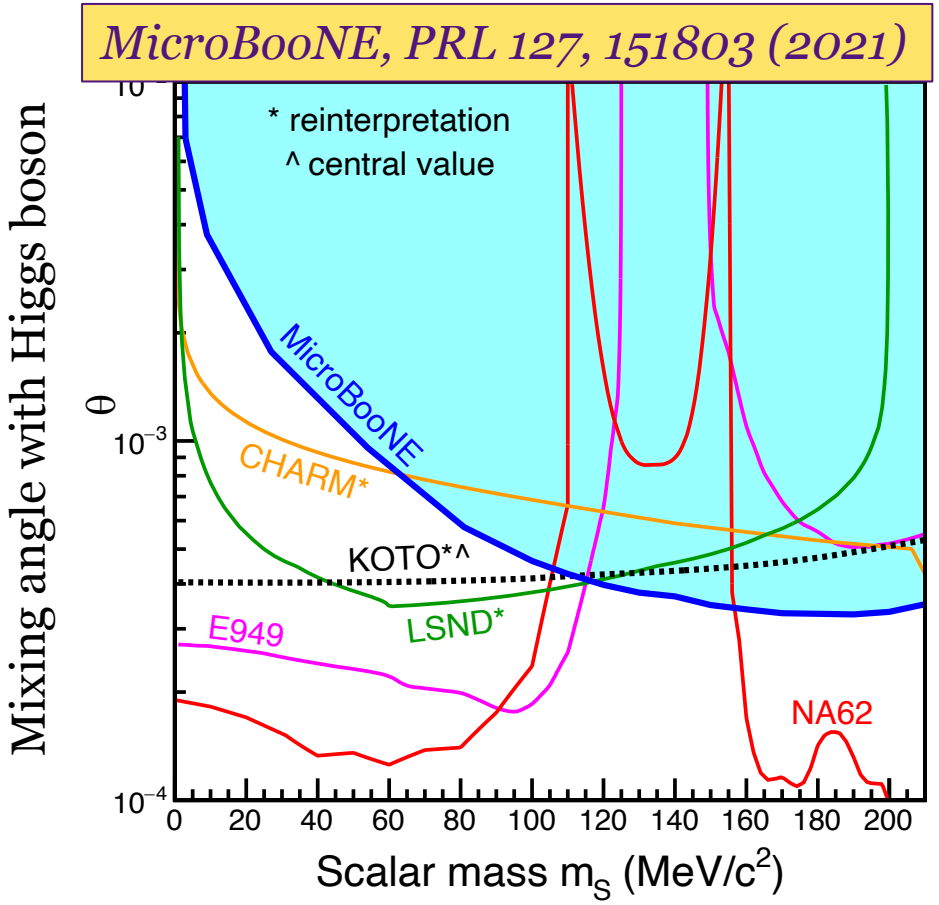
(analysis focused on the 100-200 MeV scalar masses, where MicroBooNE had competitive sensitivity)

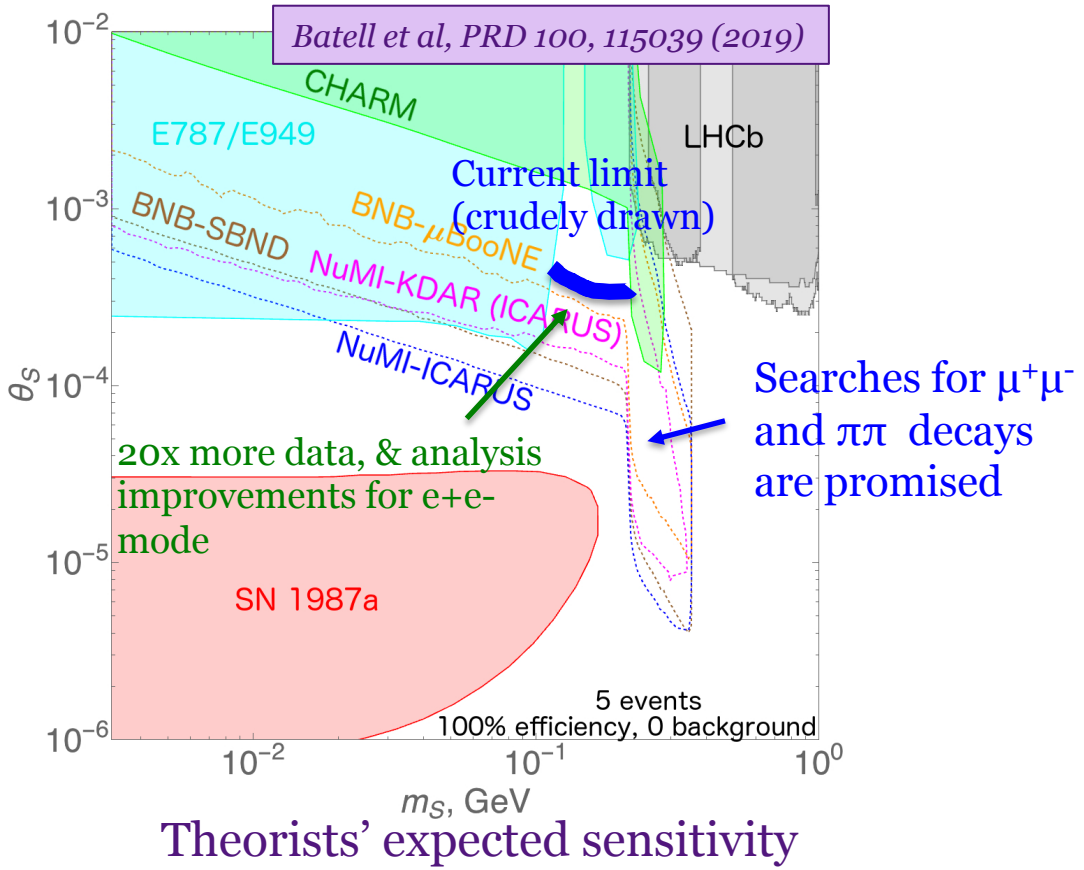
BDT distribution, well modelled with background-only expectation



MicroBooNE: Higgs portal scalars

- MicroBooNE observed 5 events in signal region, with 2.0±0.8 expected
  - This was with 10% of their NuMI dataset
- Could exclude model central value parameters required to explain KOTO anomaly*





Theorists' expected sensitivity

*In 2019, KOTO reported anomalous excess of $K^0 \to \pi^0$+invisible decays, although significance of the excess has decreased in 2021 publication

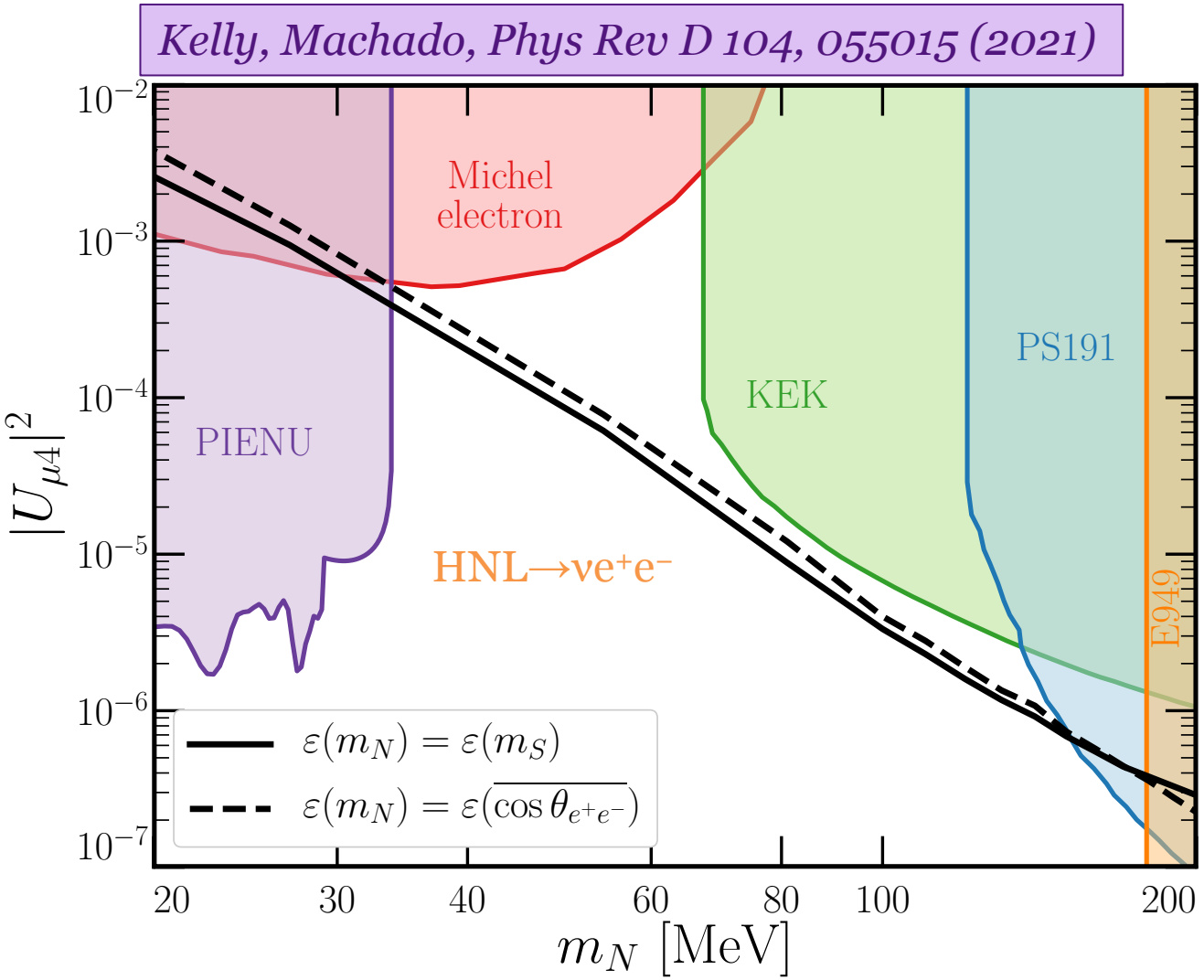
HNL reinterpretation

- Theorists are reinterpreting these first results, for other models
  - Heavy neutral leptons →

https://arxiv.org/abs/2106.06548

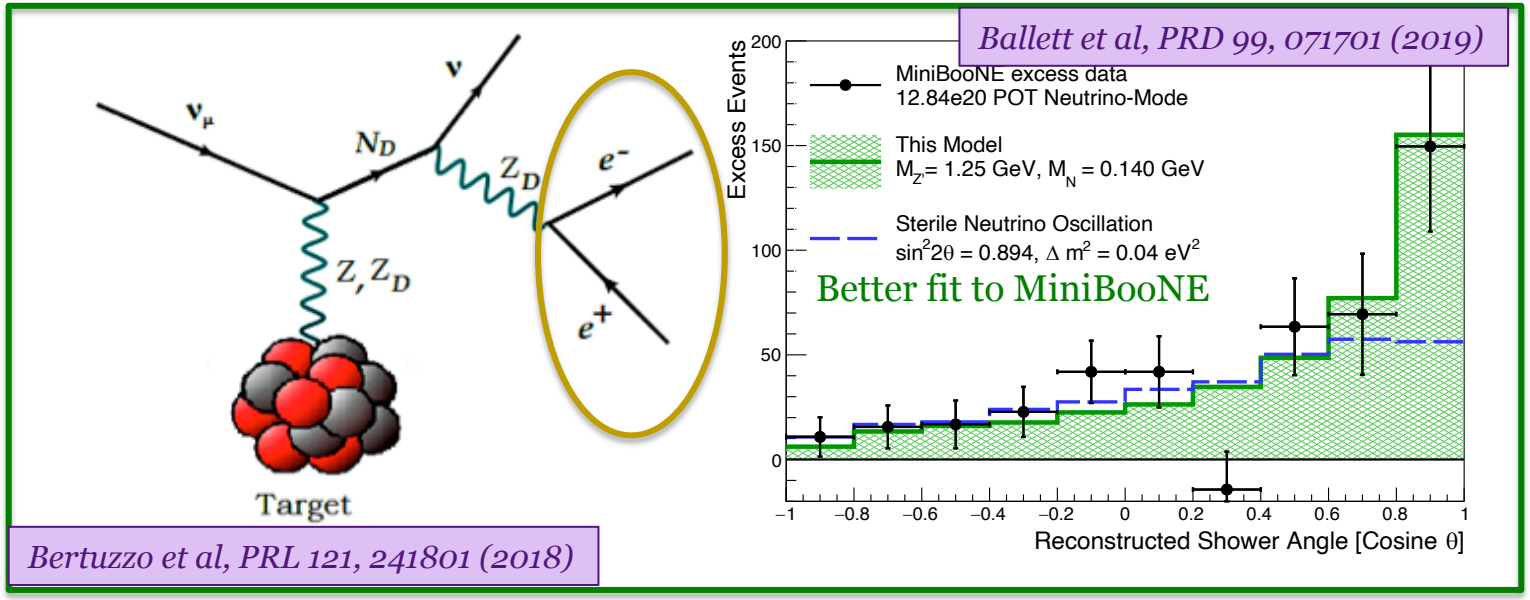
K→πS(→ee) (μB search)
K→μN(→νee) (reinterp.)

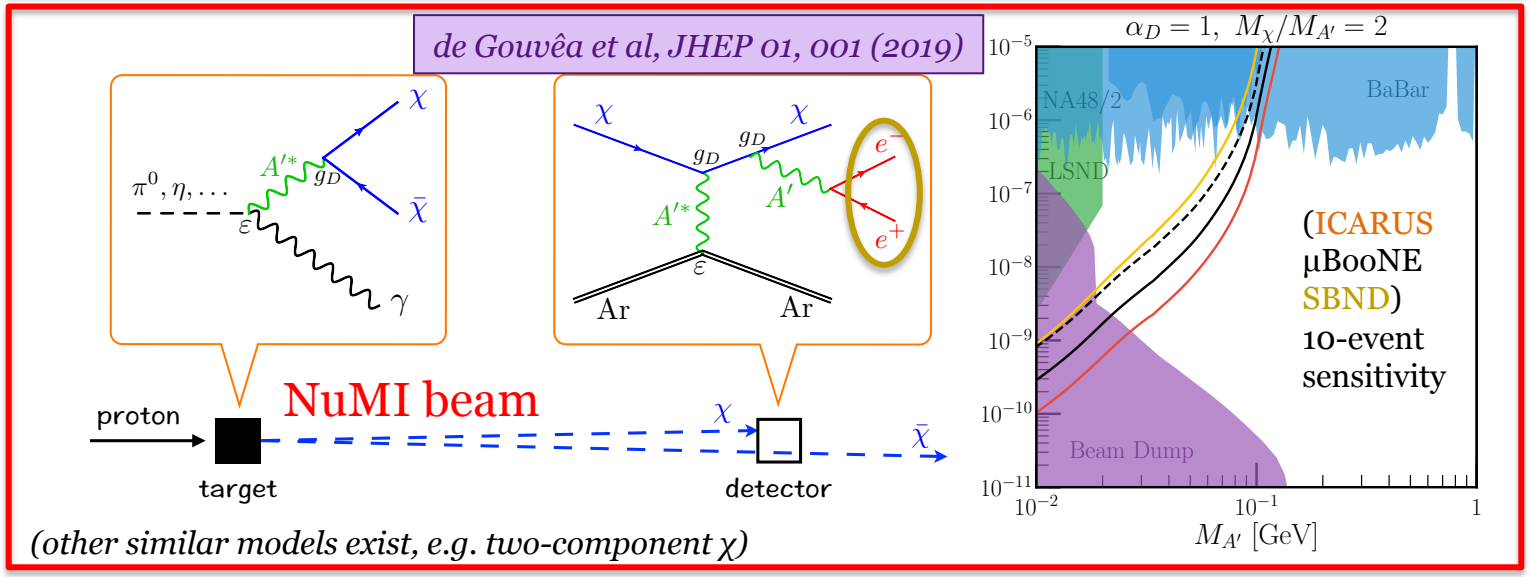
They have also provided an event generator for this model, **which is very valuable, thank you!**



MicroBooNE: Dark sector searches

- Further BSM models being explored with e^+e^- final states
- Dark neutrino portal, with dark Z' decay
  - MicroBooNE-Durham collaborative analysis
- Dark matter produced in beamline; inelastic scattering off argon
  - SBN has excellent sensitivity





(MY PERSONAL) WISHLIST FOR THE THEORY COMMUNITY

Something to consider as part of the discussion later on

Event generators

- **Event generators**
- *In an ideal world*, we could just search for a model-independent excess of some BSM final state (e.g. e^+e^-) over a *naturally-small* SM-expectation
- However, we are very background-dominated, and need to apply harsh cuts
  - O(10,000):1 cosmic background to neutrinos
  - O(10,000):1 neutrino background to potential BSM
- Need signal models to evaluate efficiencies & optimise cuts
- Need signal models to train machine learning algos

Event generators

- **Event generators** are our biggest stumbling block, in my opinion

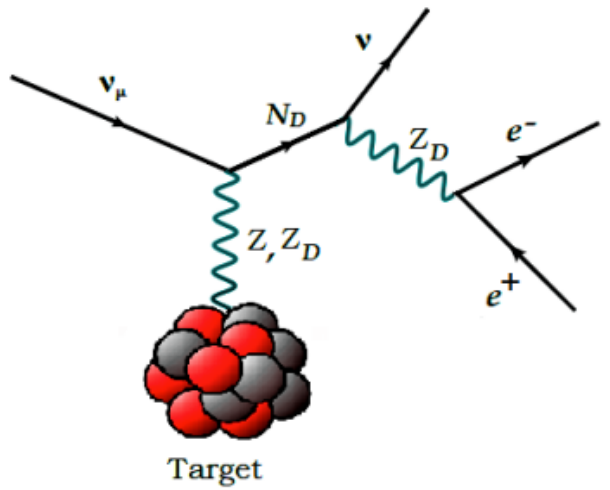
- The experimental limits I have presented today, are for relatively simple models*, e.g.
  - 2-body decays of BSM particles
  - 2→2 elastic scattering of millicharged particles
  - We could easily implement them in our experimental simulations

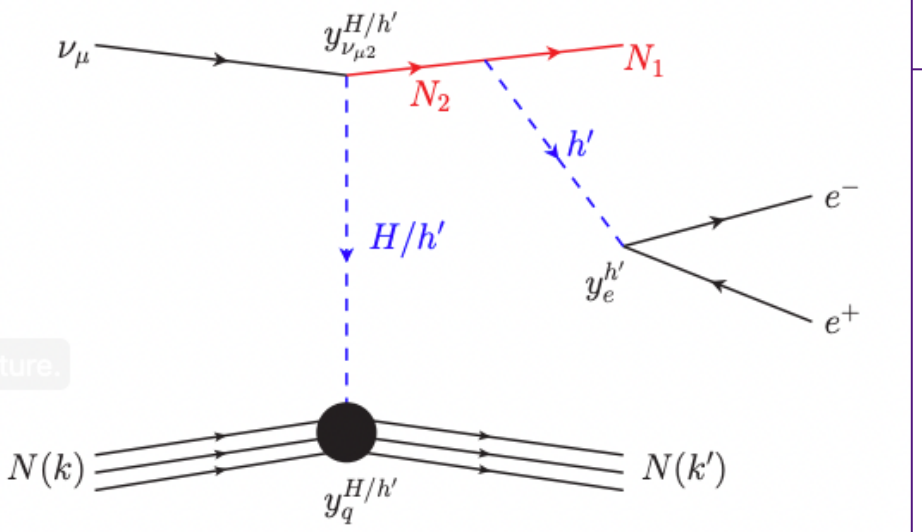
- For more complicated models, we are almost always stuck

** except n-nbar, but that is in GENIE*

Event generators

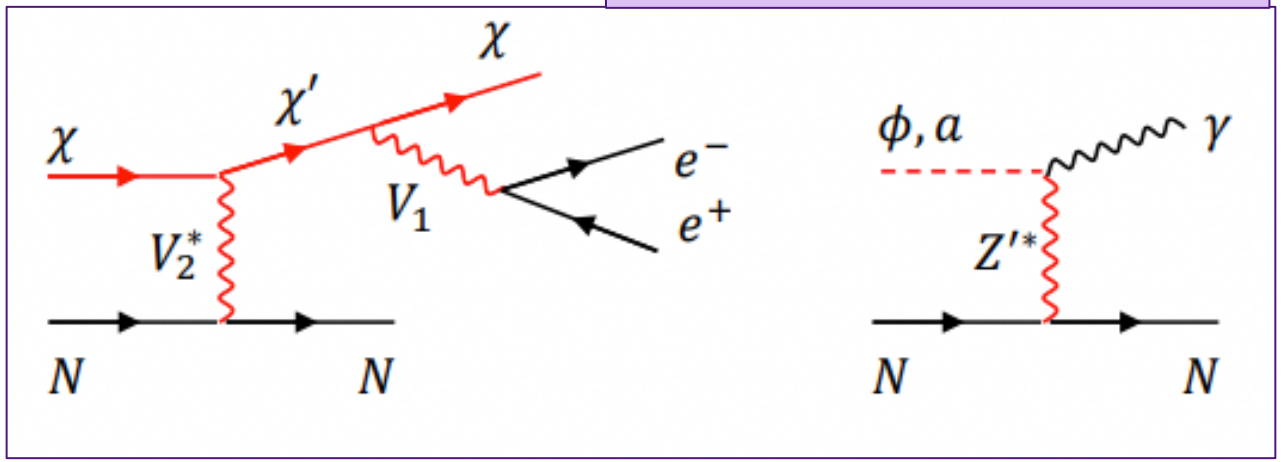
Bertuzzo et al, PRL 121, 241801 (2018)
Ballett et al, PRD 99, 071701 (2019)
Abdullahi et al, Phys.Lett.B 820, 136531 (2021)





Dutta et al, PRD 102, 055017 (2020)
Abdallah et al, Phys. Rev. D 104, 055028 (2021)

de Gouvêa et al, JHEP 01, 001 (2019)
Dutta et al, arXiv:2110.11944



It would be great to simulate these ourselves

Event generators

- For simple exploratory studies, we can use HEPEVT files
  - Text files containing final state particle info
  - Cumbersome to work with for large-scale production, or parameter scans

- We could also implement hepmc3 handling within larsoft
  - Doesn't exist yet, but shouldn't be difficult

- However, ideally *(in my opinion)* we would like to implement generators directly into our software framework
  - Don't have time to go into much detail exactly why, but –
  - Large parallel jobs, makeup of failed jobs, bookkeeping, metadata, cosmic 'overlay', systematics; all a lot easier to handle with internal generator

Event generators

- Let us handle the flux* and geometry part
  - This is essentially a solved problem, shared between all models & SM; no need for each theory group to implement their own system
- Essentially, all we need from you, is
  - On an event by event basis:
  - For a provided incoming particle type & energy, and scattering target
    - The total cross section, (or total width, for decays) and
    - An unweighted final state (optional – sometimes e.g. in burn-in mode, or accept-reject sampling, we only care about the cross section)
  - Some global configuration & metadata handling, bookkeeping, etc
  - Don't worry too much about CPU efficiency (up to reasonable limit)
    - Can take tens of minutes to do detector simulation & reconstruction per event
    - Hard process event generation isn't the bottleneck

* *some aspect of the flux production (e.g. BSM in proton collisions or hadron decays) might also need to be done externally, but don't worry about propagation, geometry etc*

Event generators

- Wishlist:

- It would be great to have these as part of a library based server-client system
  - We run your library directly from our own software modules
  - Pull model: ask and receive a single event (& total cross section)

- Alternatively some kind of forked process & intermediate file format (& inter-process communication: more difficult technologically to implement)
  - Again using a client-server model where we ask & receive the information event-by-event
  - Maybe hepmc3 for the format?

Bonus

- Bonus wishlist:

- Theorists to investigate (exploratory) studies of BSM sensitivity of a MicroBooNE-sized gas TPC at the MicroBooNE location
  - Quite a few studies have been done for DUNE ND-GAr
    - Maybe also consider similar studies for the μB location
    - Using both BNB and NuMI.
  - May provide some motivation to implement in near future?

Summary

- ArgoNeuT & MicroBooNE have been producing world-leading BSM searches
- Lessons learned:
  - These LArTPCs that were primarily designed for neutrino interaction measurements are also excellent for various other BSM analyses you can throw at them
  - Beam timing is important for signal/BG separation
  - Need to exploit all possible beam modes (pions, kaons, NuMI, BNB, in-flight or at-rest decays, targets, beam dumps, …)
  - Some neutrino-dominated channels would benefit from a gas tpc
- We would be a lot more productive with other models, if we had event generators