



Maximising MicroBooNE's sensitivity to Heavy Neutral Leptons produced in the NuMI beam

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UNIVERSITY OF CAMBRIDGE

ON BEHALF OF THE
MICROBOONE COLLABORATION

What is MicroBooNE?

85 tonne active-volume Liquid Argon Time Projection Chamber (LArTPC) at Fermilab, USA

Exposed to two different neutrino beams:

- On axis to the Booster Neutrino Beam (BNB) created from 8 GeV protons
- Off-axis to the Main Injector (NuMI) neutrino beam created from 120 GeV protons

~800k neutrino interactions recorded over five main runs from 2015-2020: extensive cross-section, short-baseline oscillation and Beyond the Standard Model (BSM) programmes (see [Joe Bateman's talk yesterday](#) for other recent BSM searches!)



Heavy Neutral Leptons (HNLs)



What is a Heavy Neutral Lepton (HNL)?

- Sterile Neutrinos, much heavier than Standard Model neutrinos

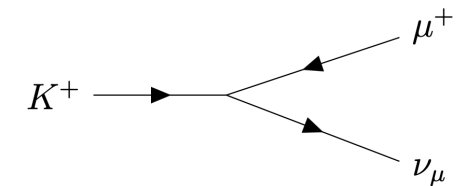
Why HNLs in general?

- Simple, testable, extension to Standard Model neutrino mixing
- Theoretically relevant to the origin of neutrino masses, provide lepton number violation, could provide leptogenesis mechanisms...

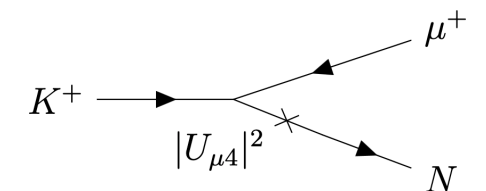
Why HNLs at MicroBooNE?

- The NuMI beam provides an **intense kaon source** and favourable geometry for separating HNLs from Standard Model neutrinos
- Liquid Argon Time Projection Chamber (LArTPC) technology provides **excellent imaging** of HNL decay products

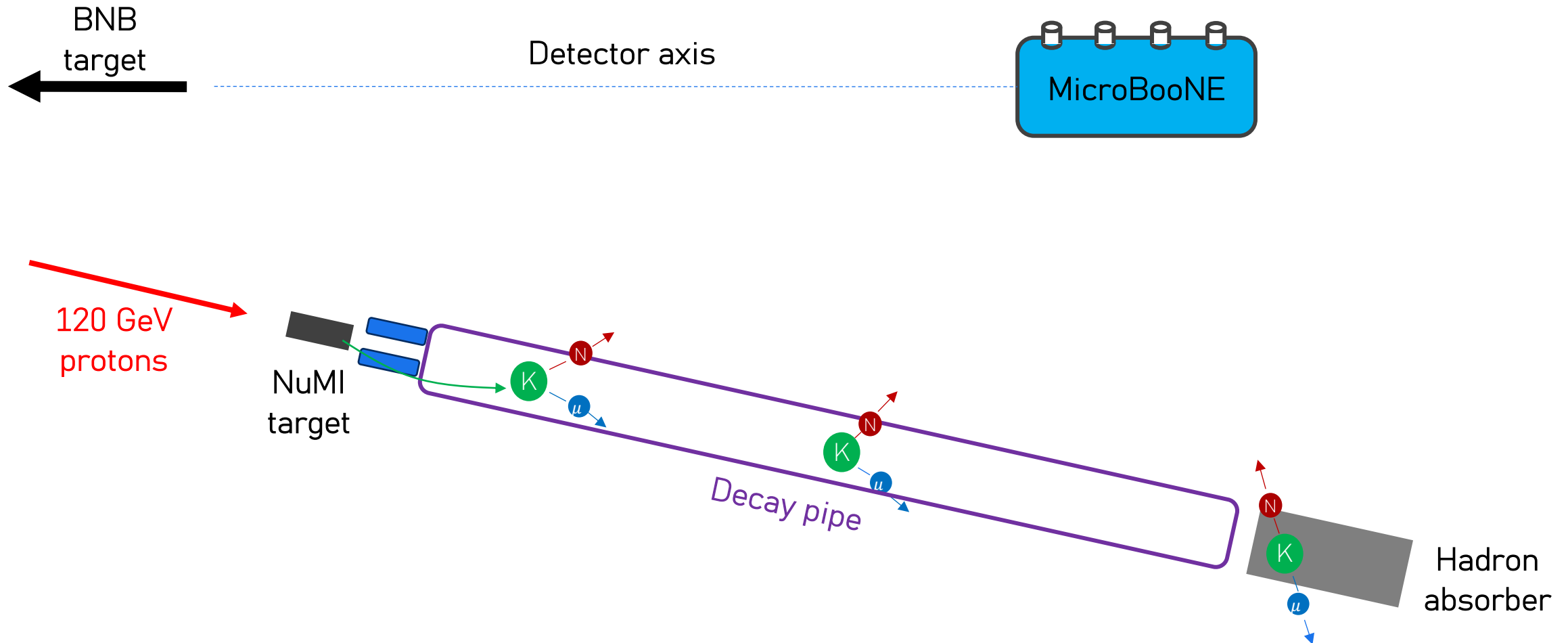
Standard Model
kaon decay



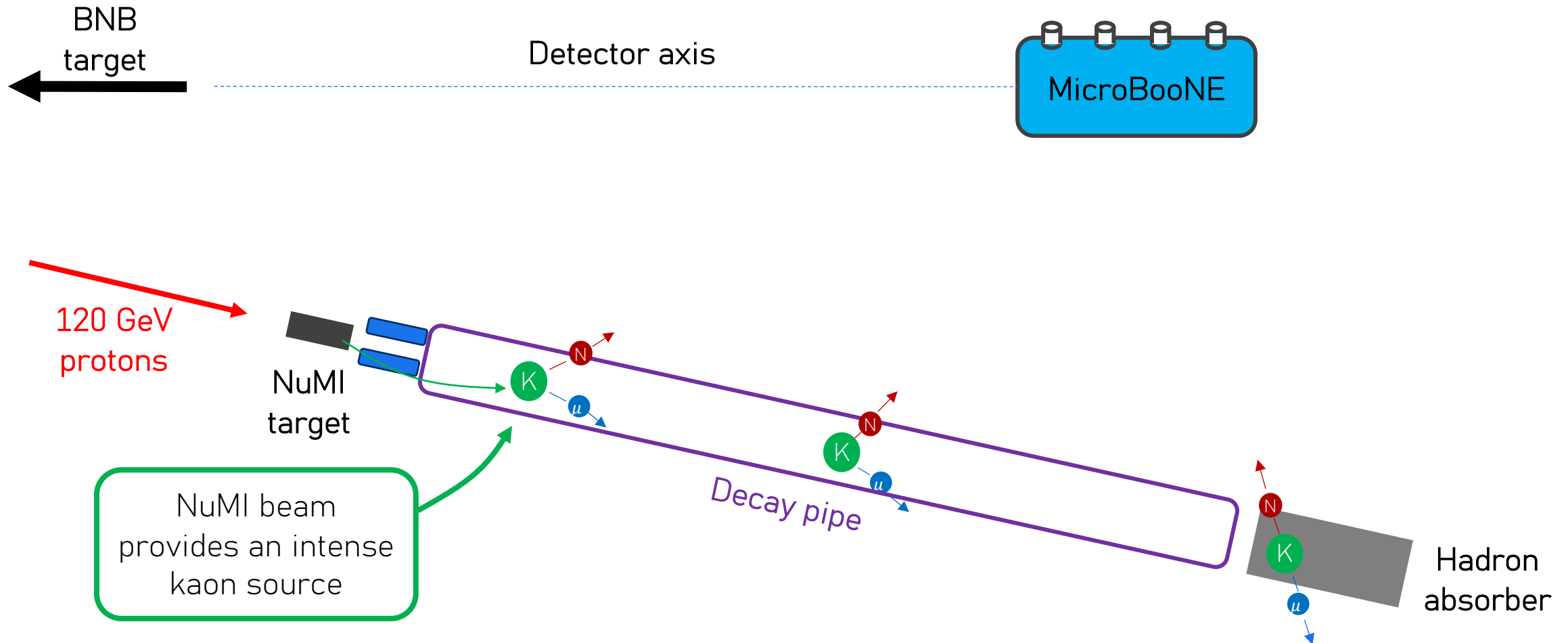
BSM kaon decay
to HNL



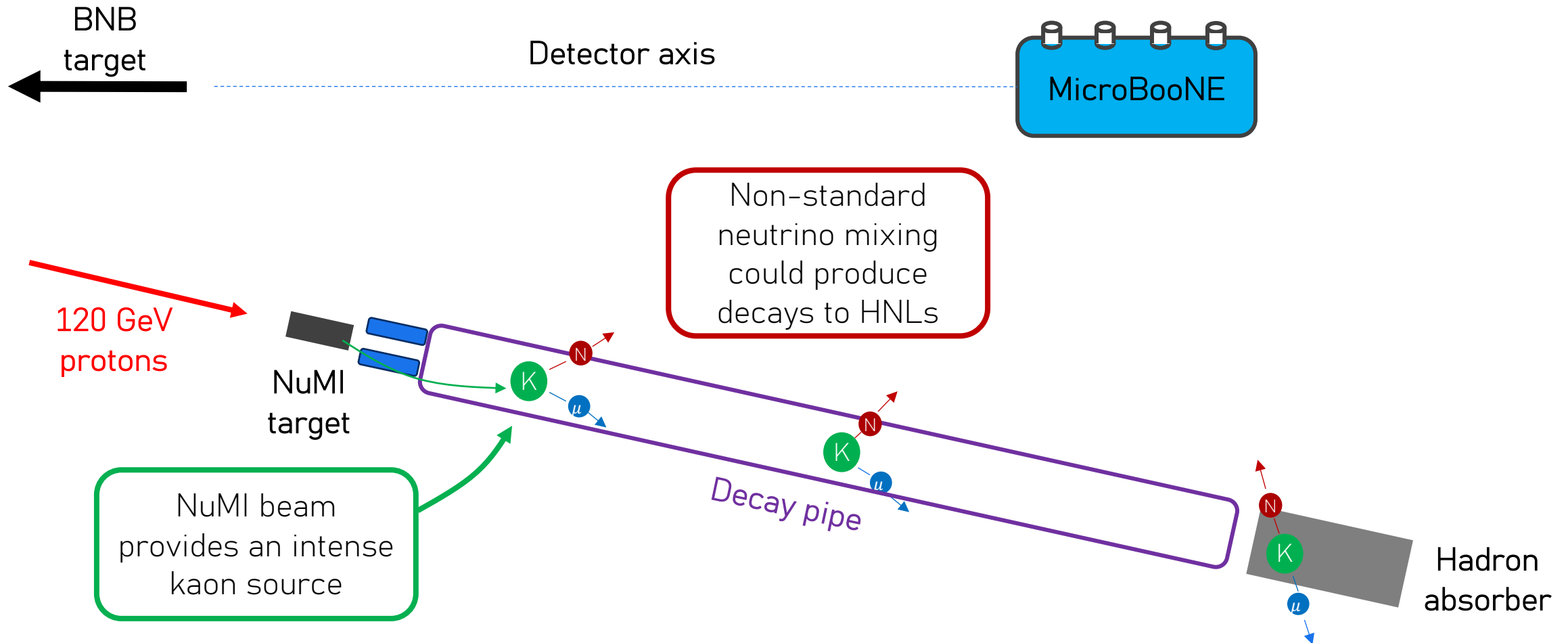
The Main Injector Neutrino Beam (NuMI)



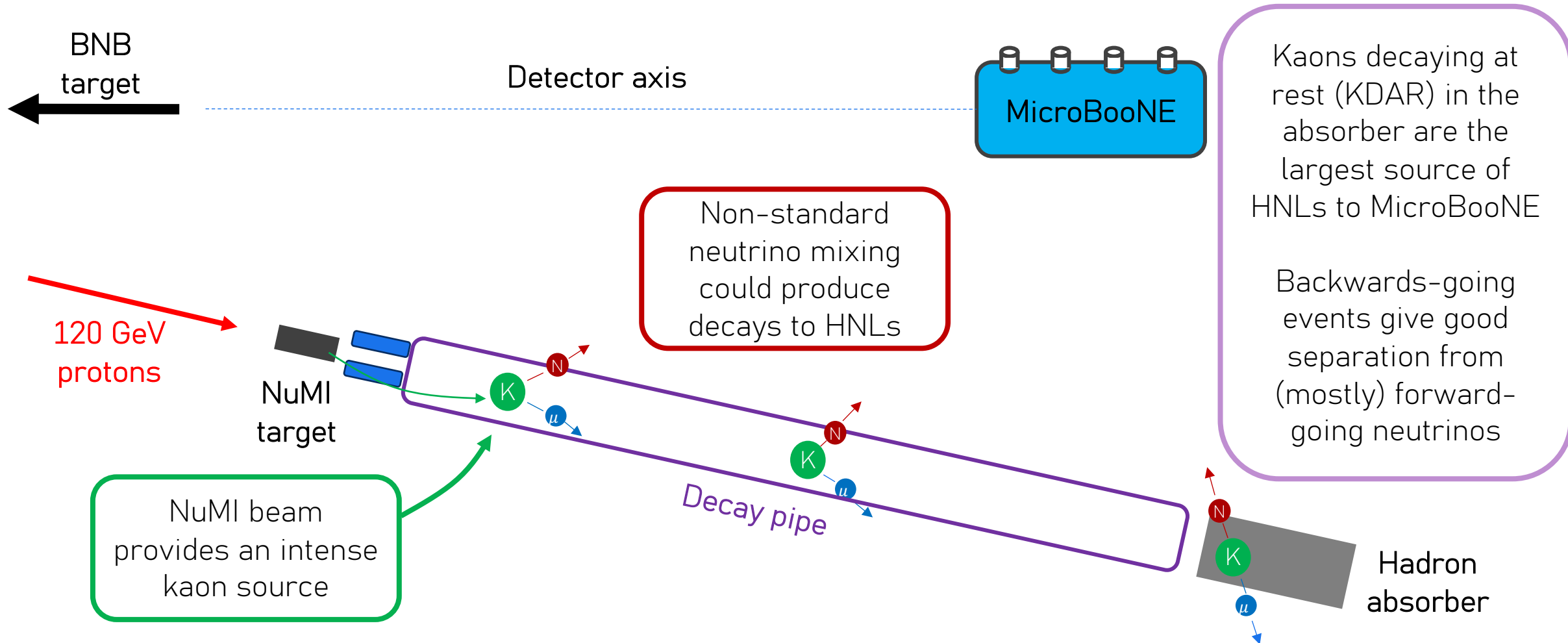
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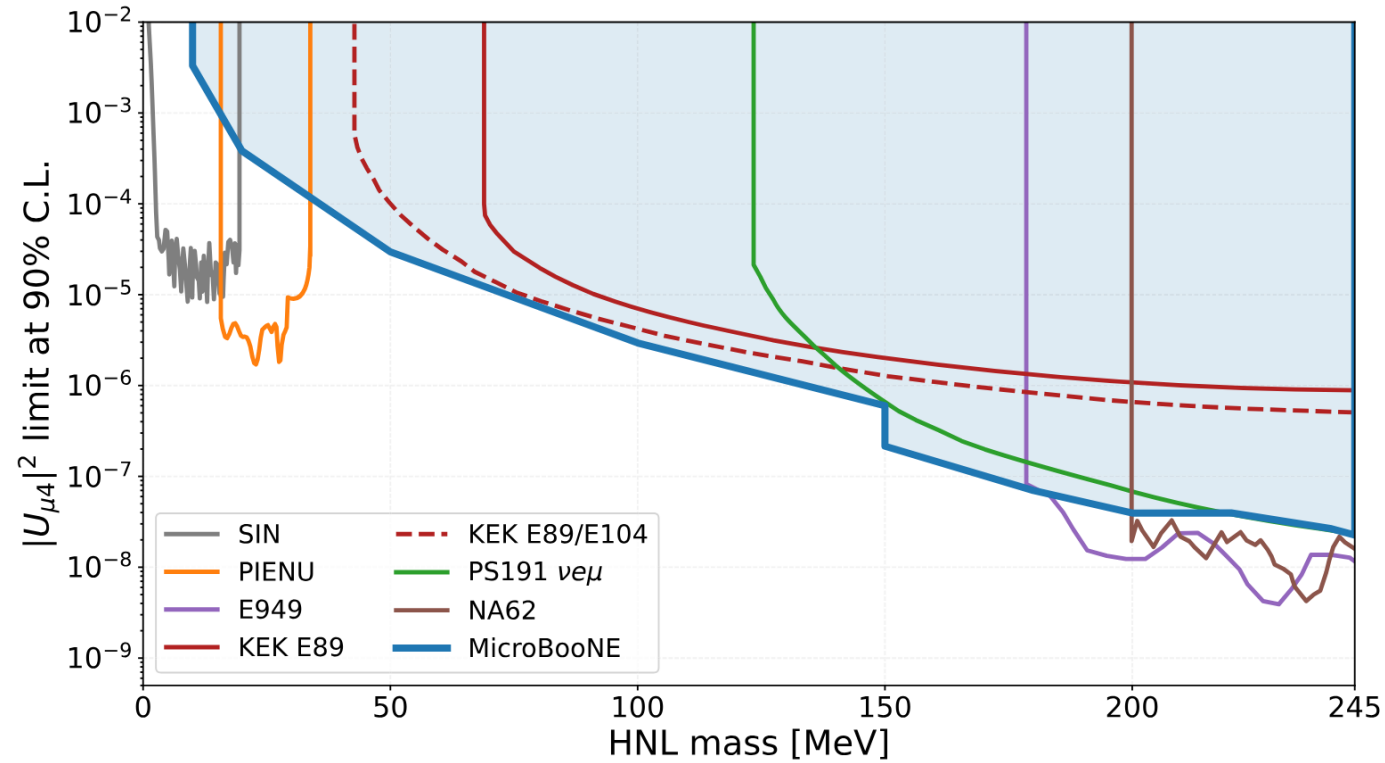
Decay channels

- Multiple previous generations of this analysis
- Searching for lower mass visible e^+e^- and π_0 states gave **world leading limits** between 35 and 175 MeV

Dominant visible states are:

1. $e^+e^- , m_N < m_{\pi_0}$
2. $\pi_0 , m_{\pi_0} < m_N < m_\pi + m_\mu$
3. $\mu\pi , m_N > m_\pi + m_\mu$

[Phys. Rev. D 106, 092006 \(2022\)](#)
[Phys. Rev. Lett. 132, 041801 \(2024\)](#)

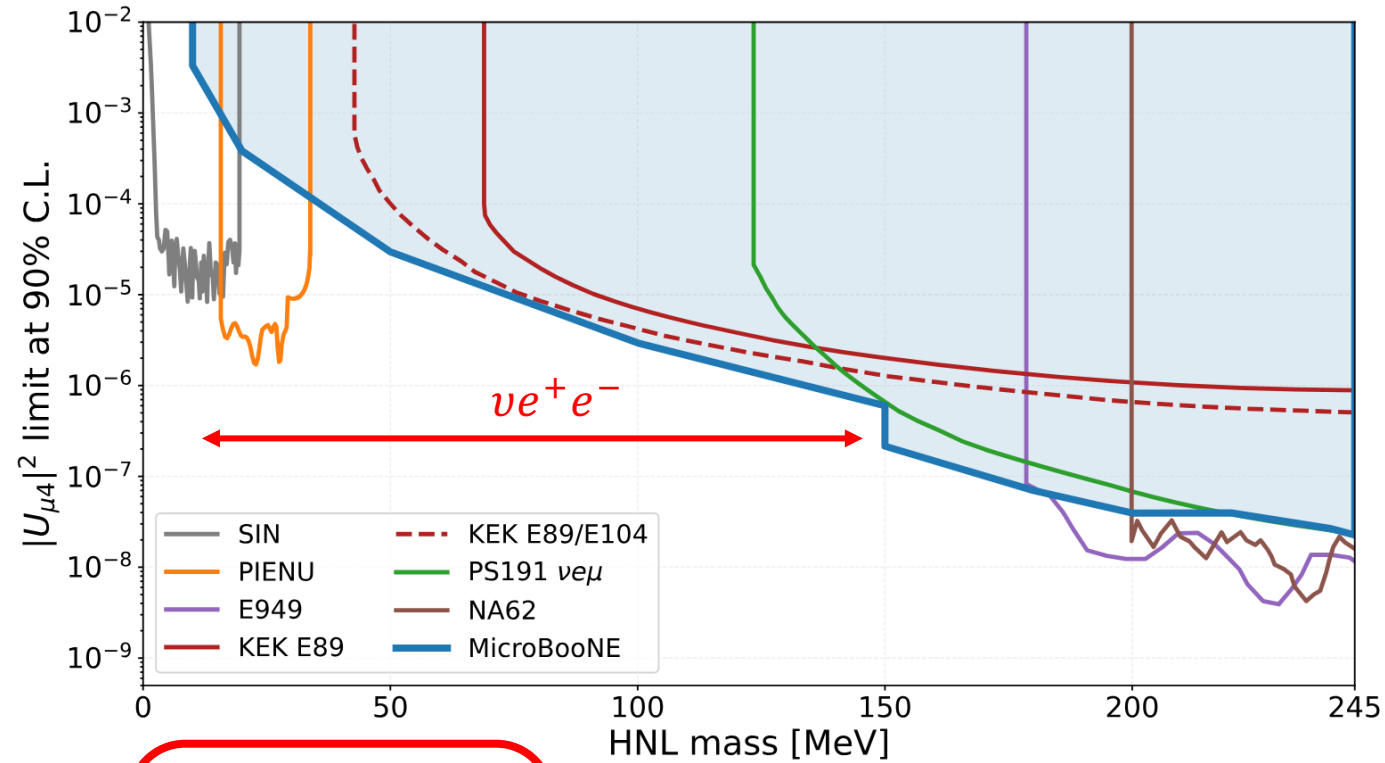


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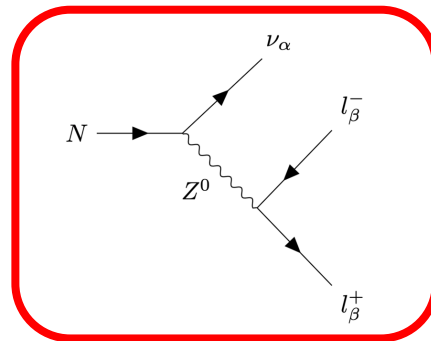


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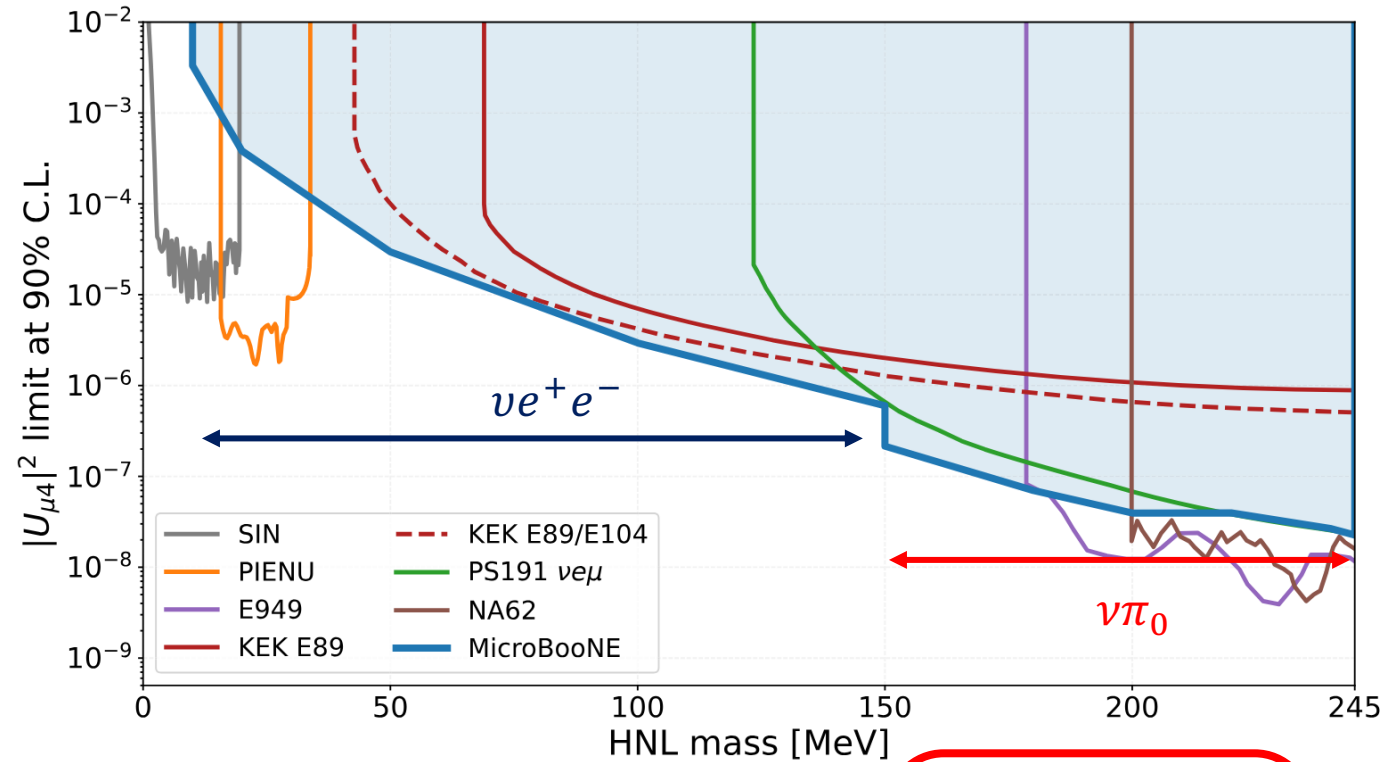


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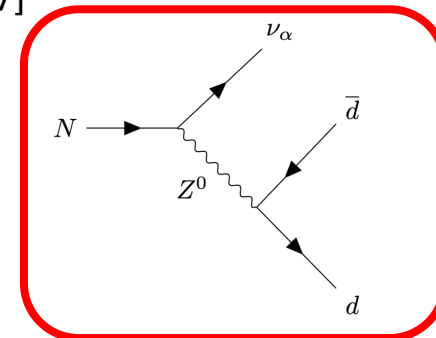
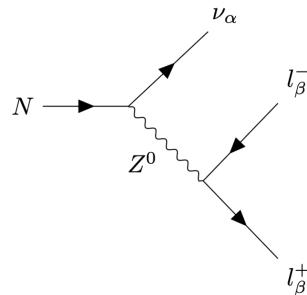


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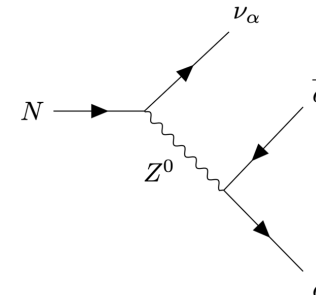
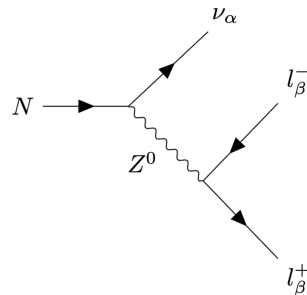
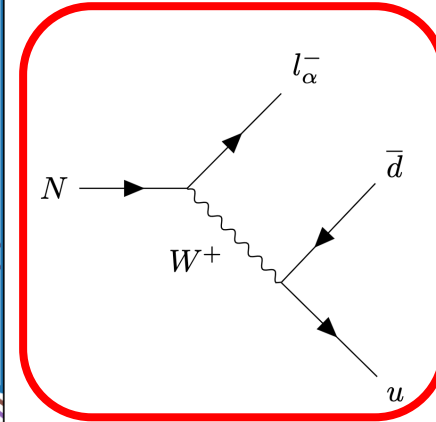
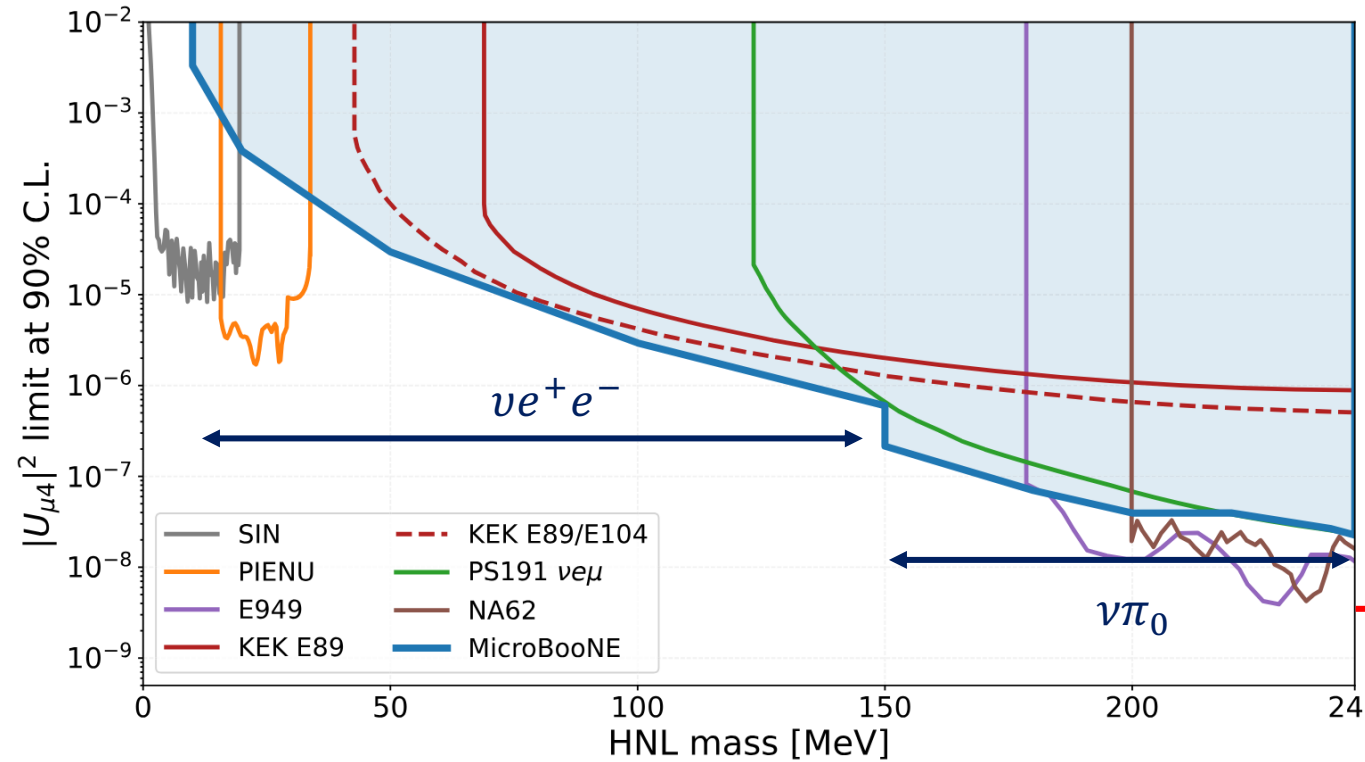
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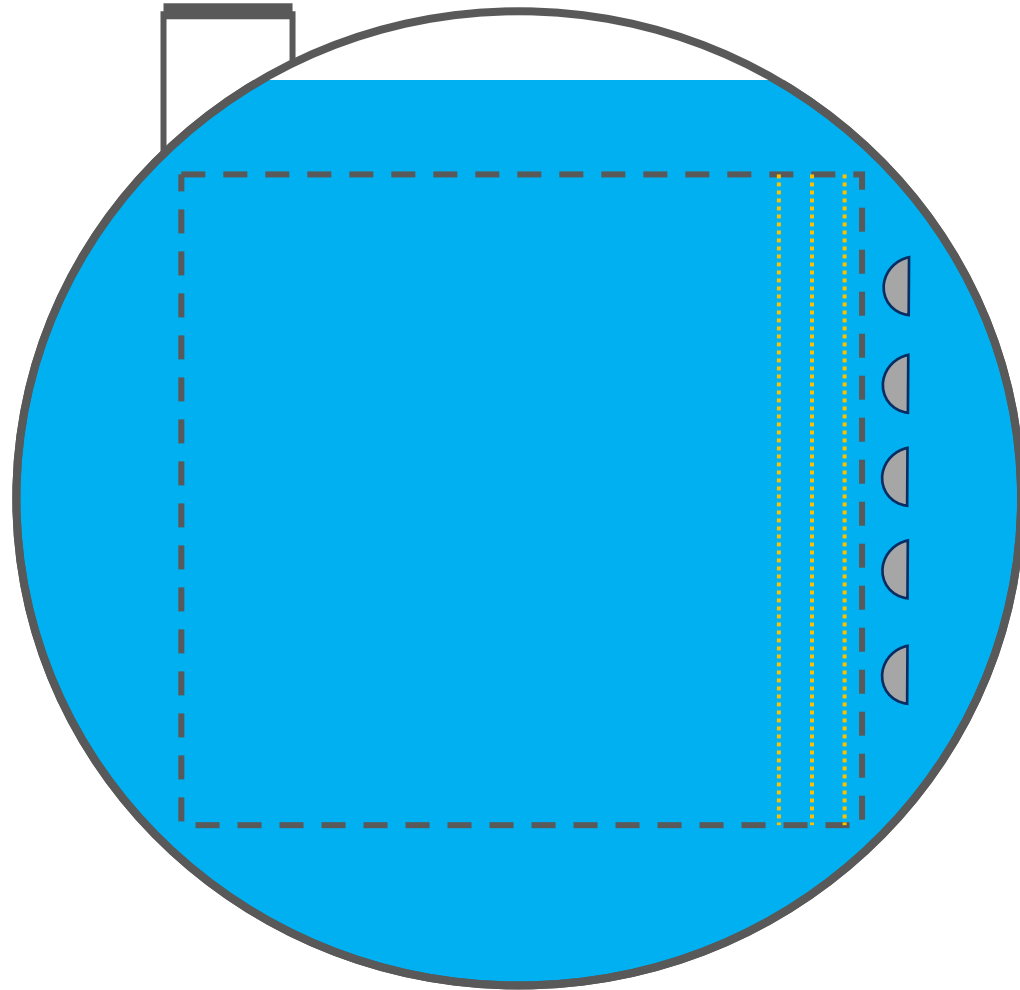
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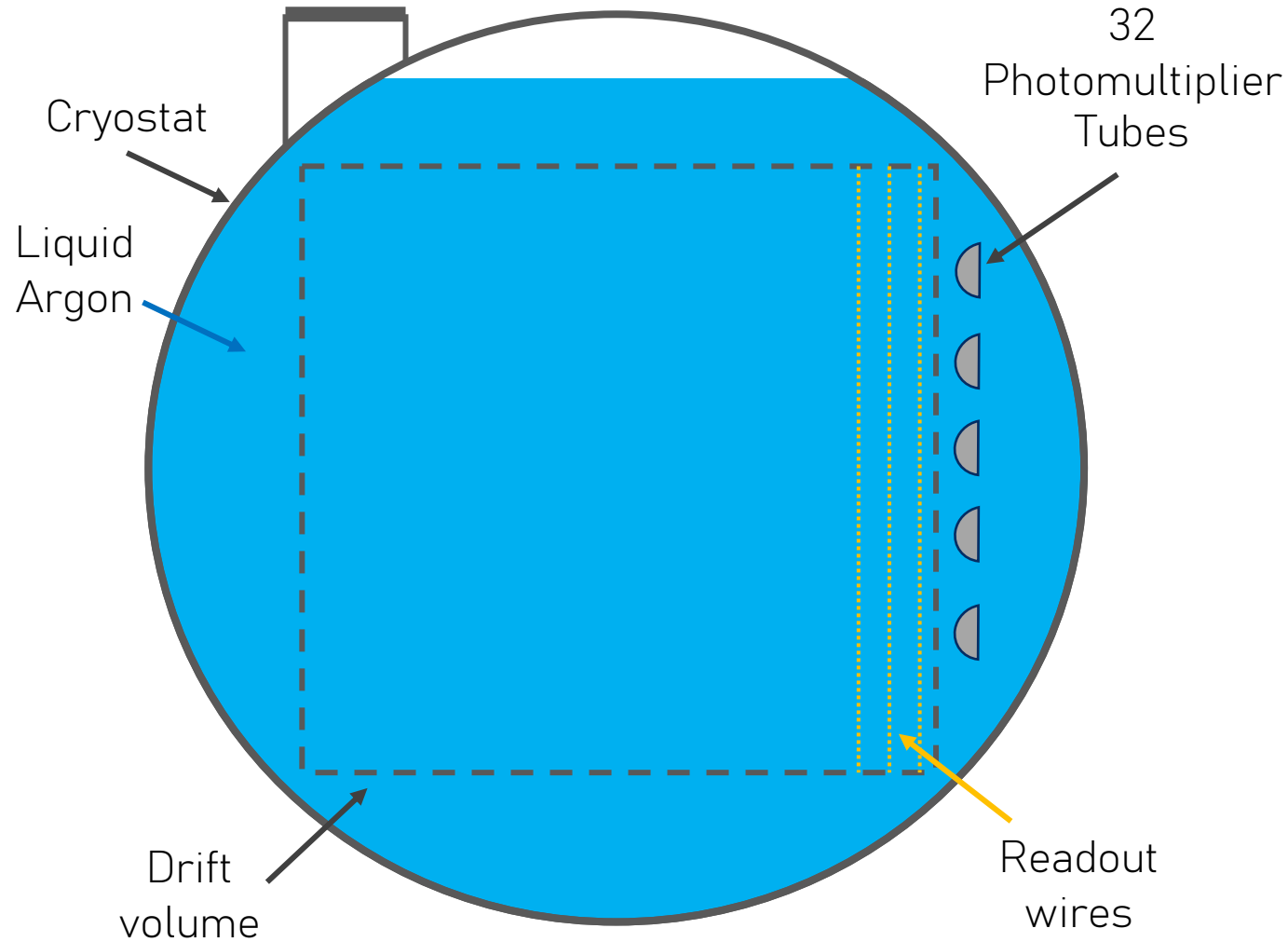
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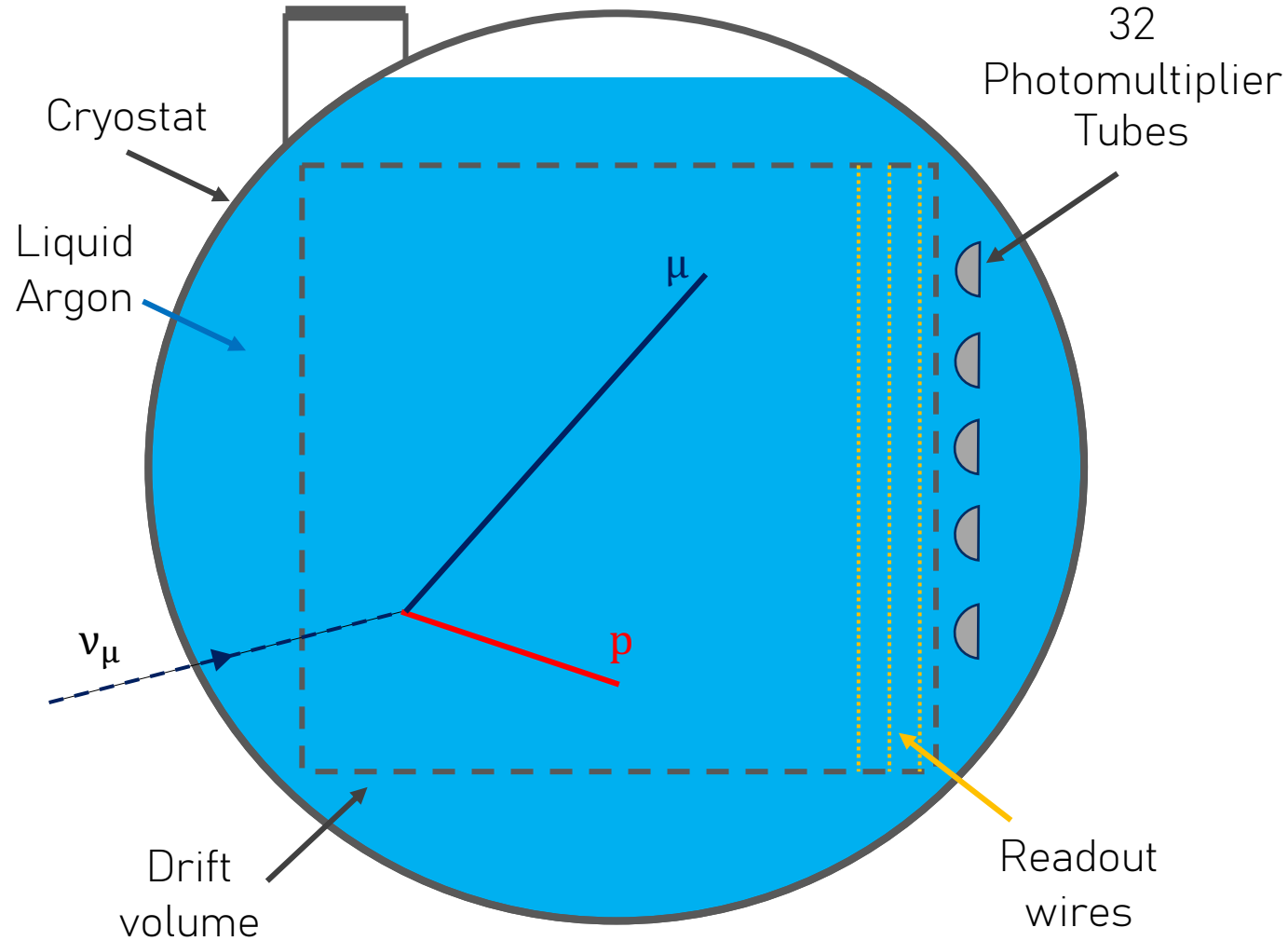
Detection: LArTPCs



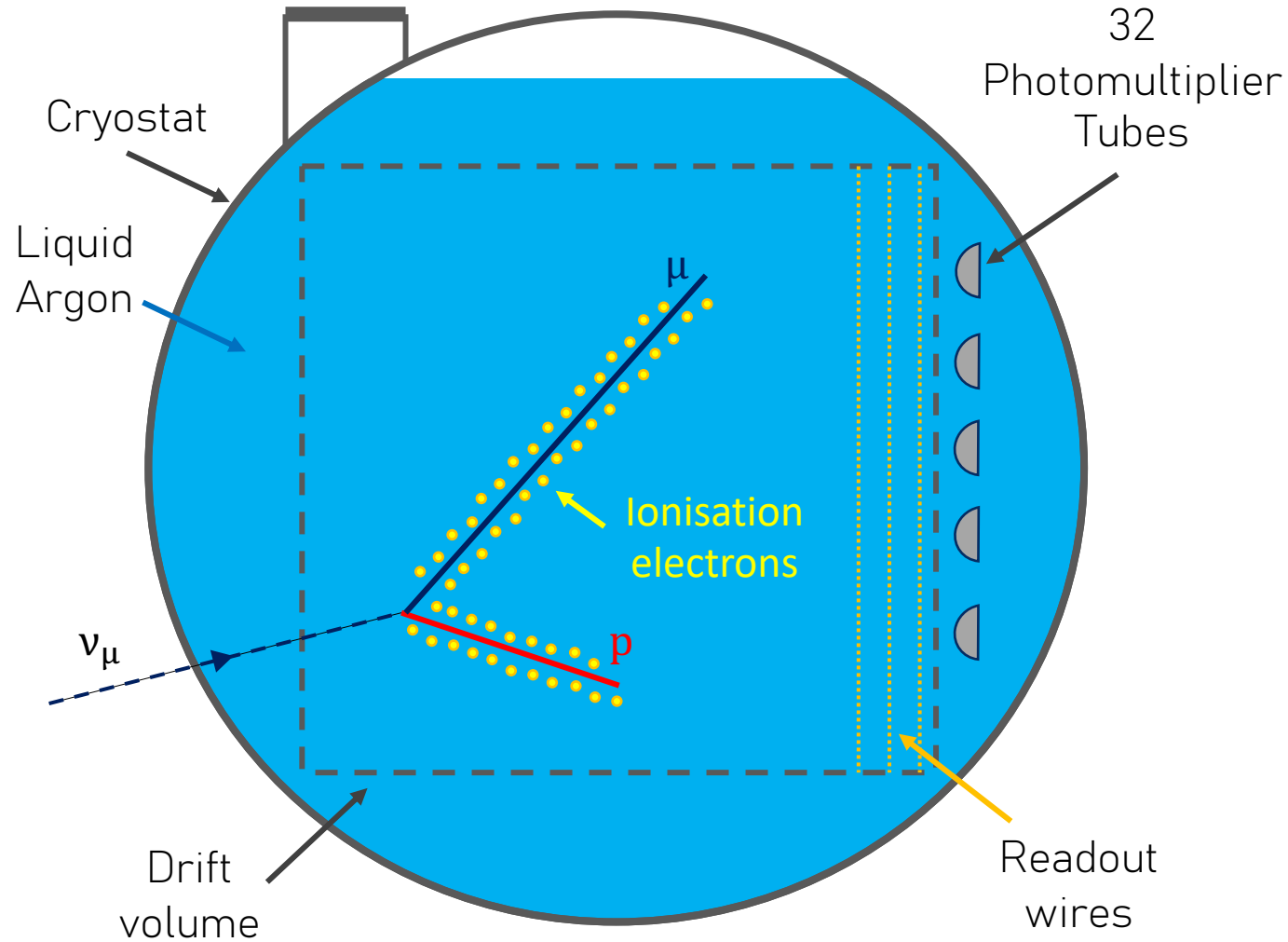
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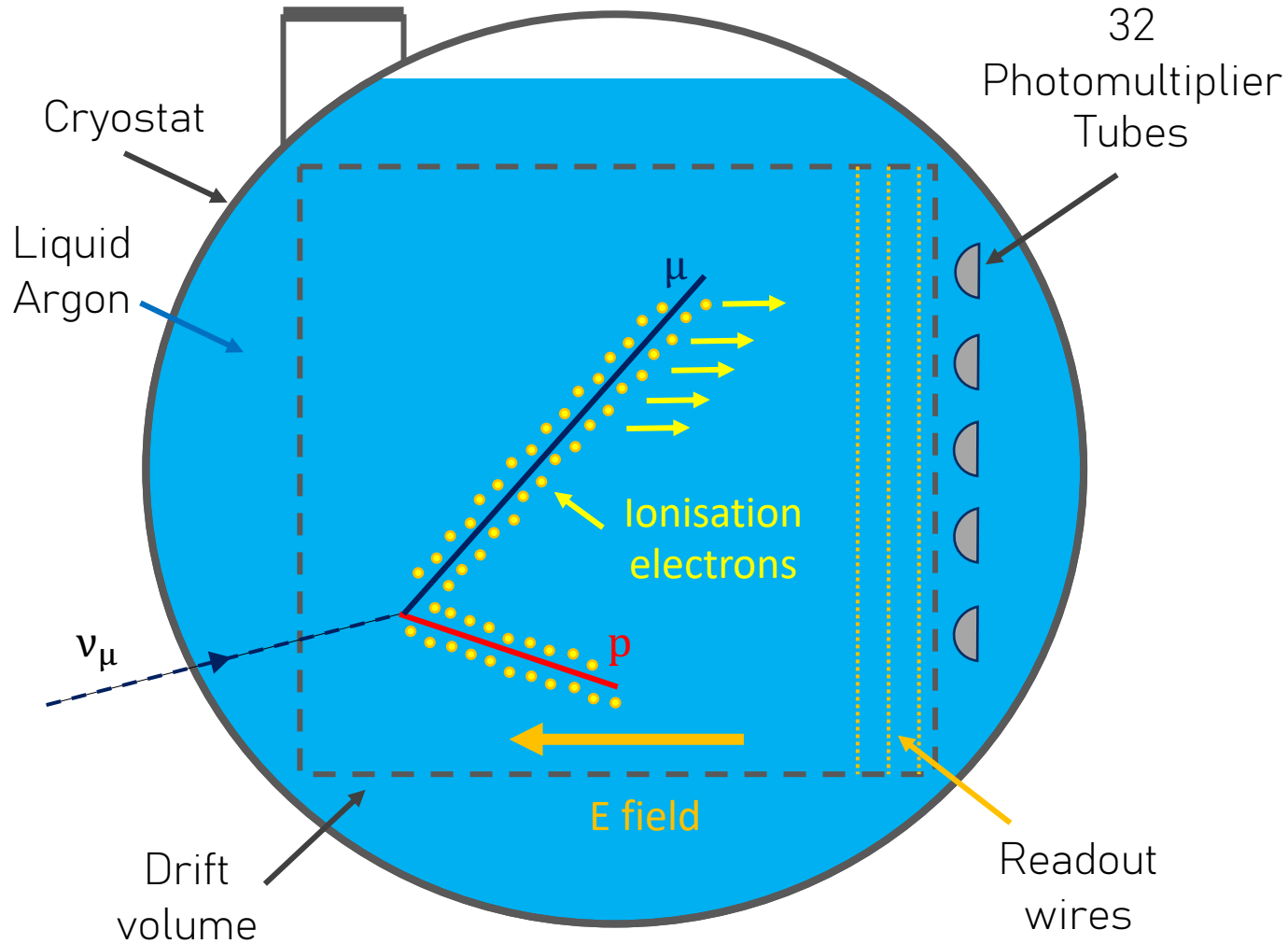
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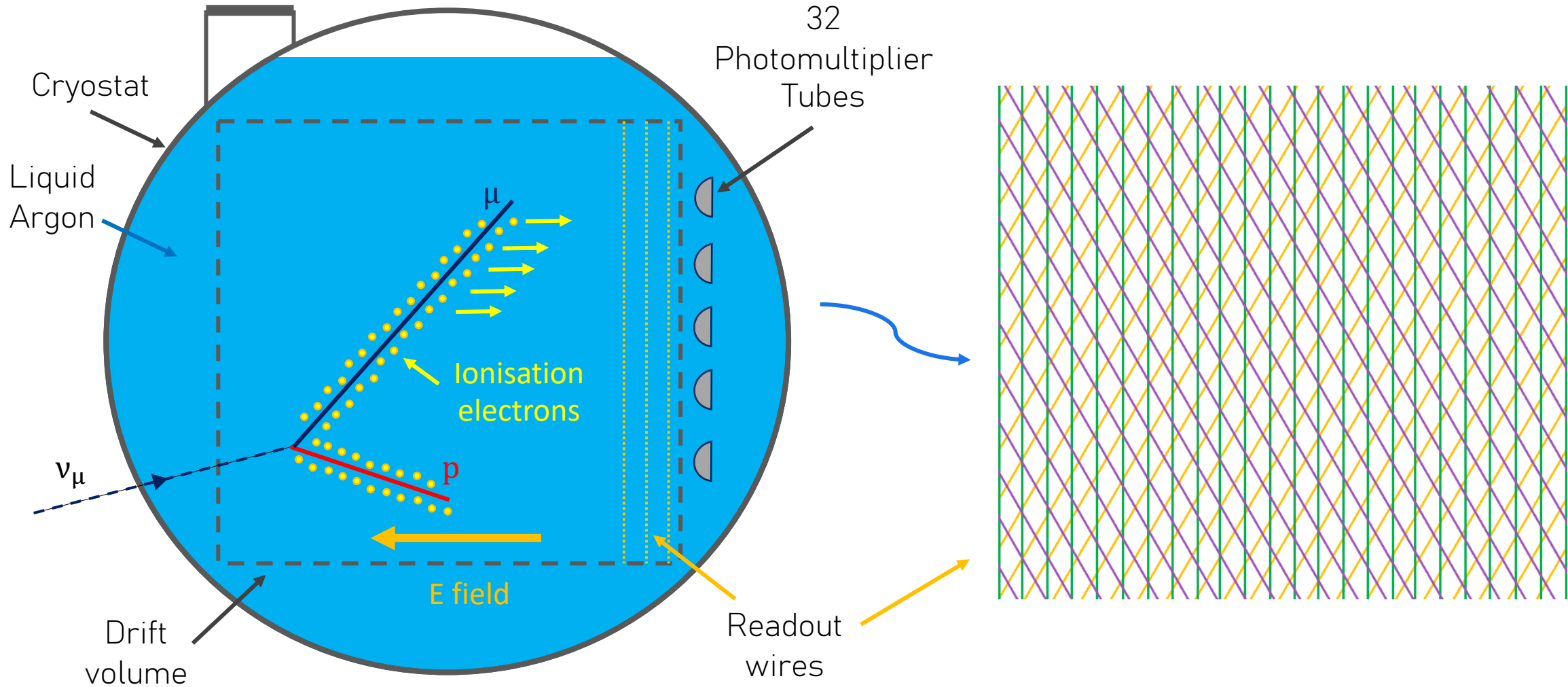
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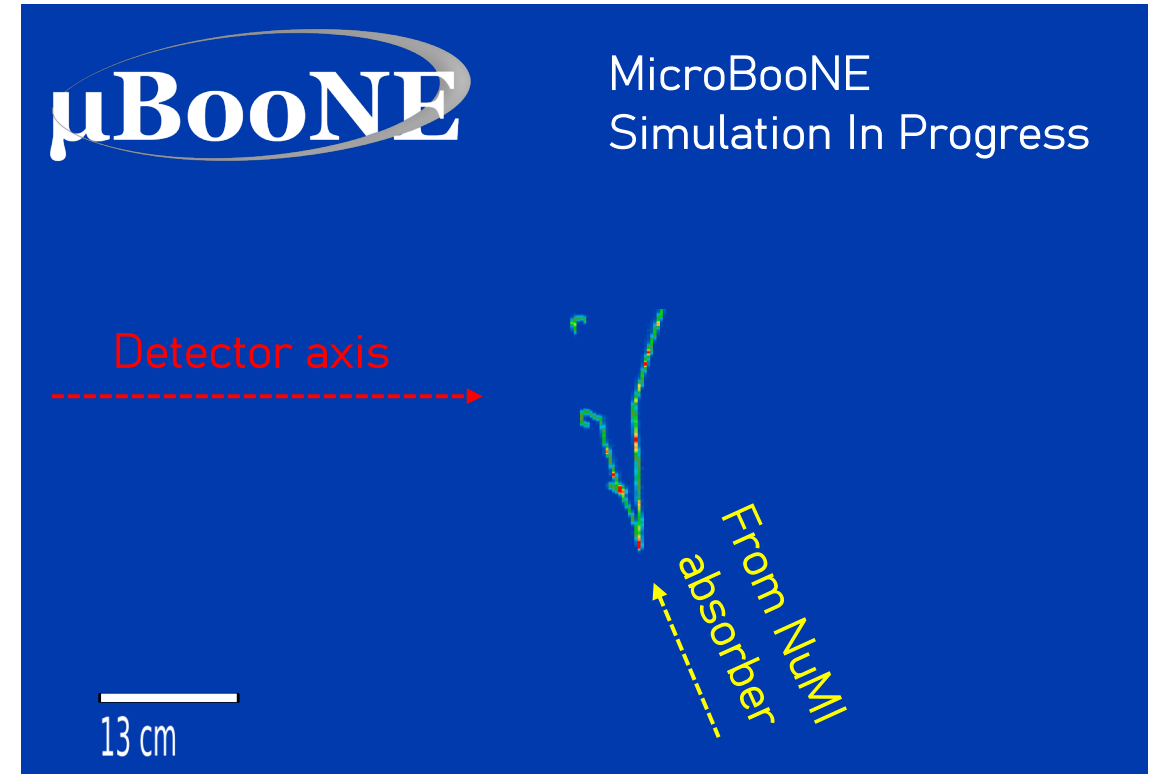
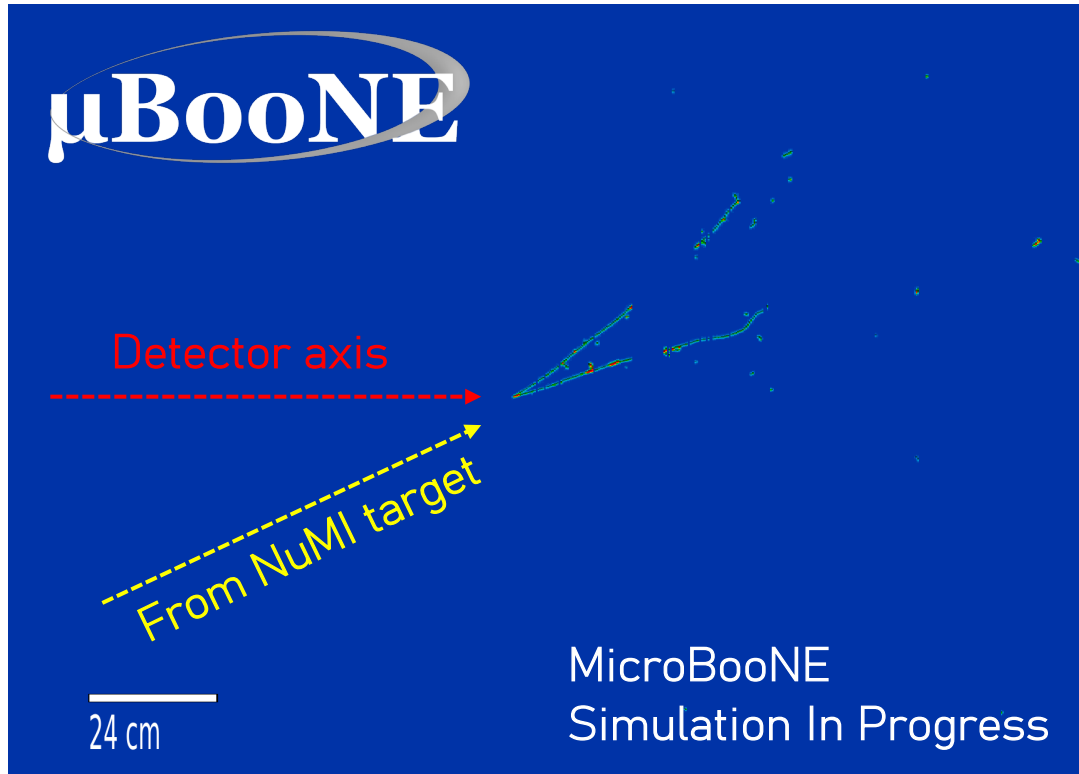
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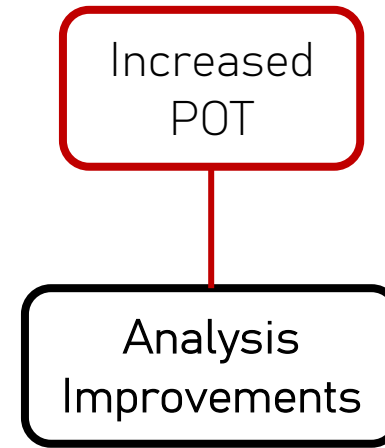
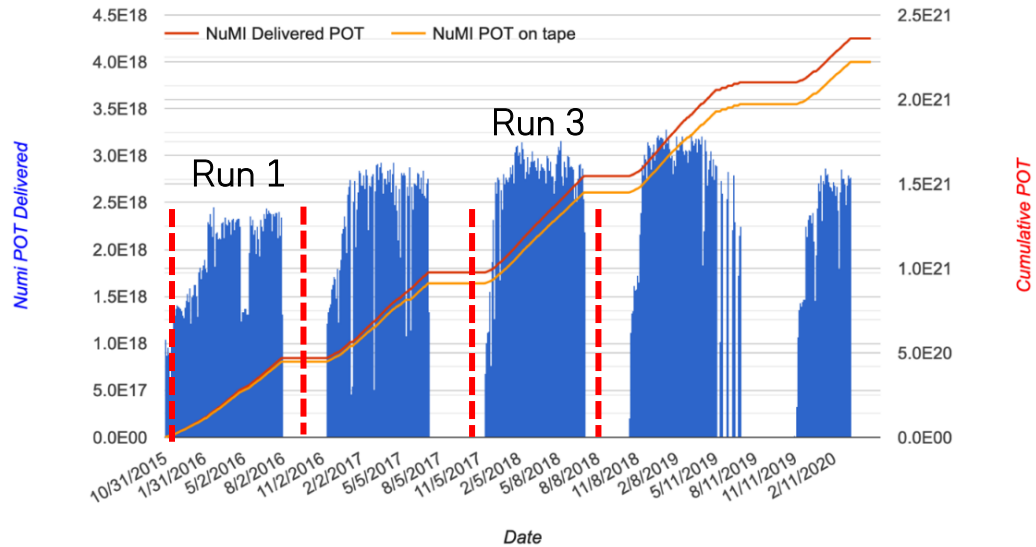


Simulated 100 MeV HNL decays in MicroBooNE



How do we improve?

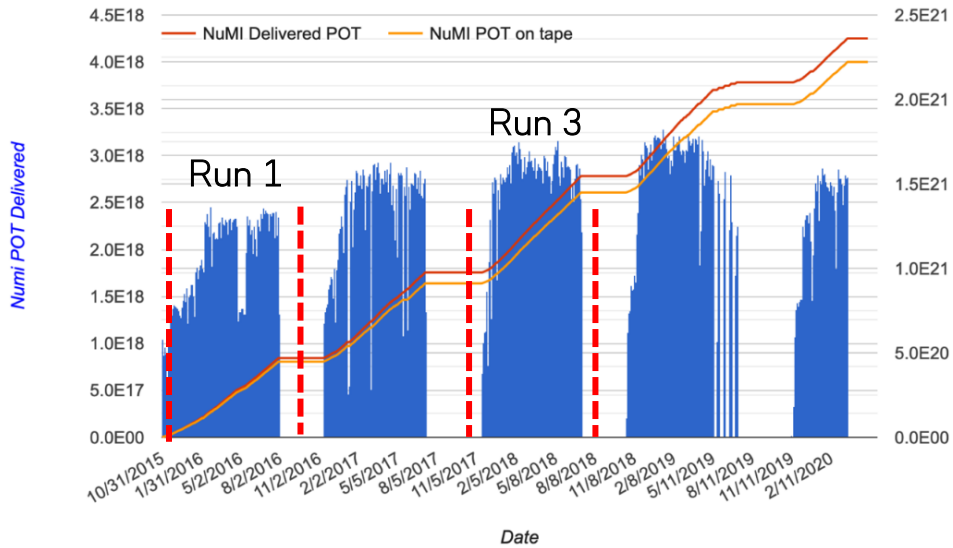
NuMI data collected by
MicroBooNE



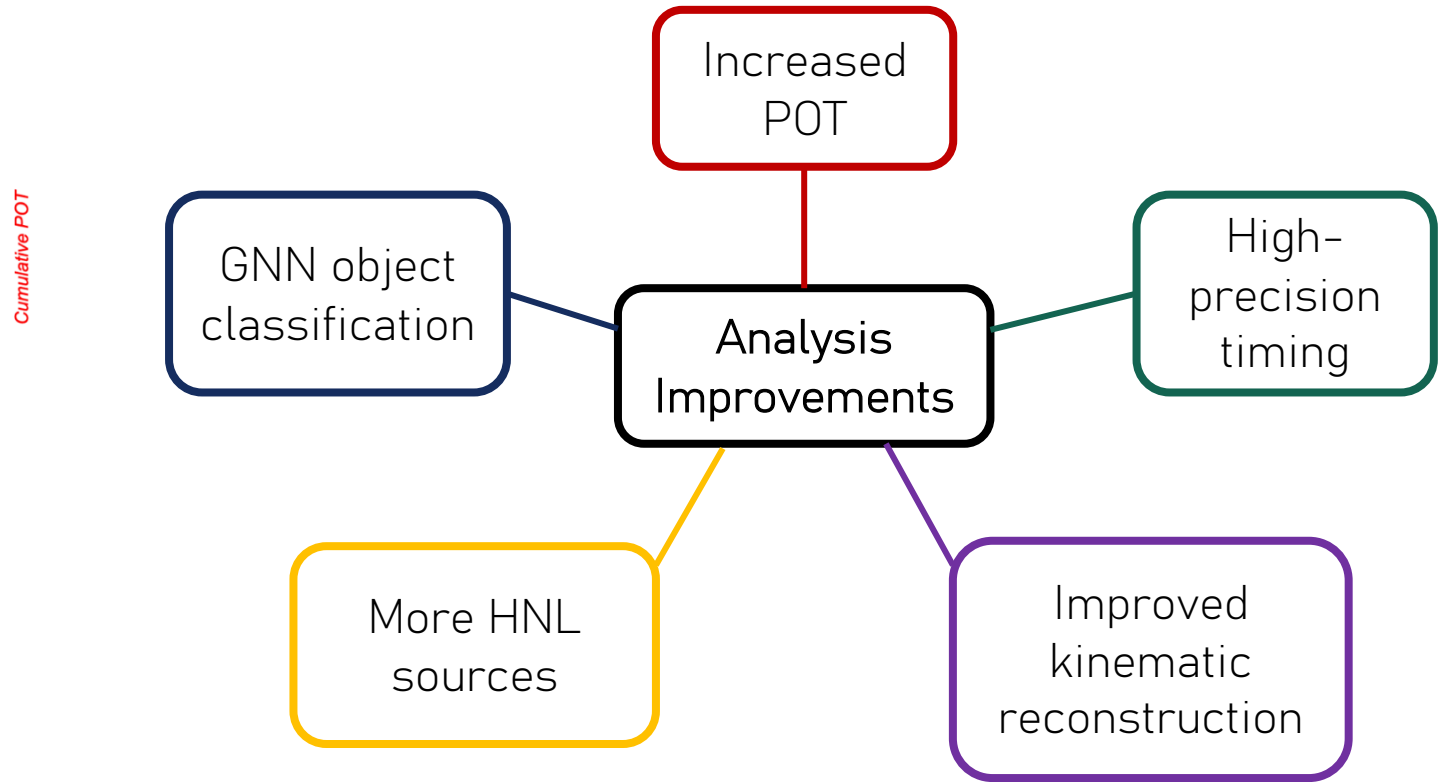
2024 analysis: runs 1+3, 7.0×10^{20} POT
New analysis: runs 1-5, 2.0×10^{21} POT

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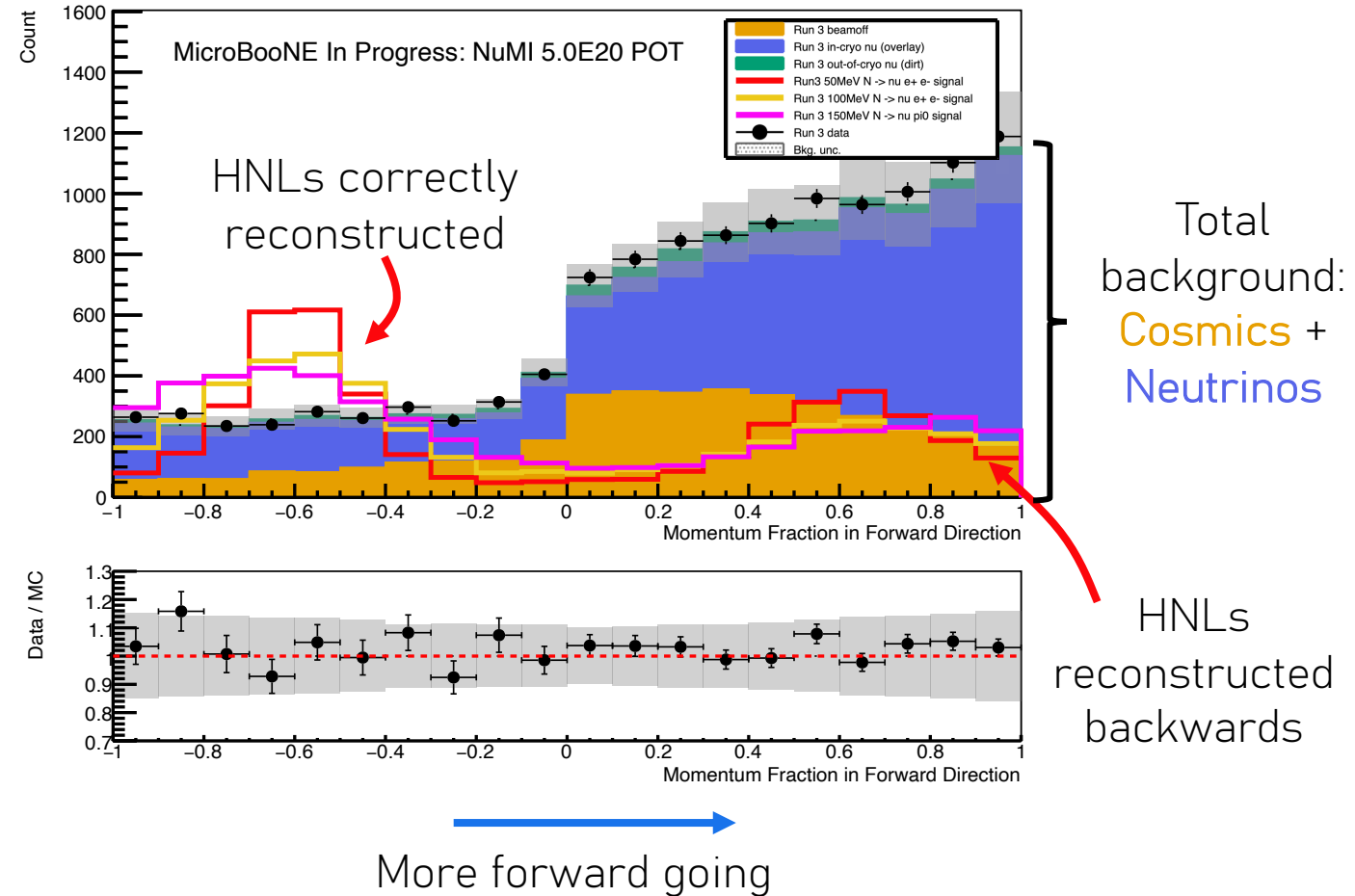
Shower clustering and vertexing improvements

In old reconstruction (right), some HNLs from the absorber are reconstructed as forward-going: reducing separating power

New reconstruction improves this with:

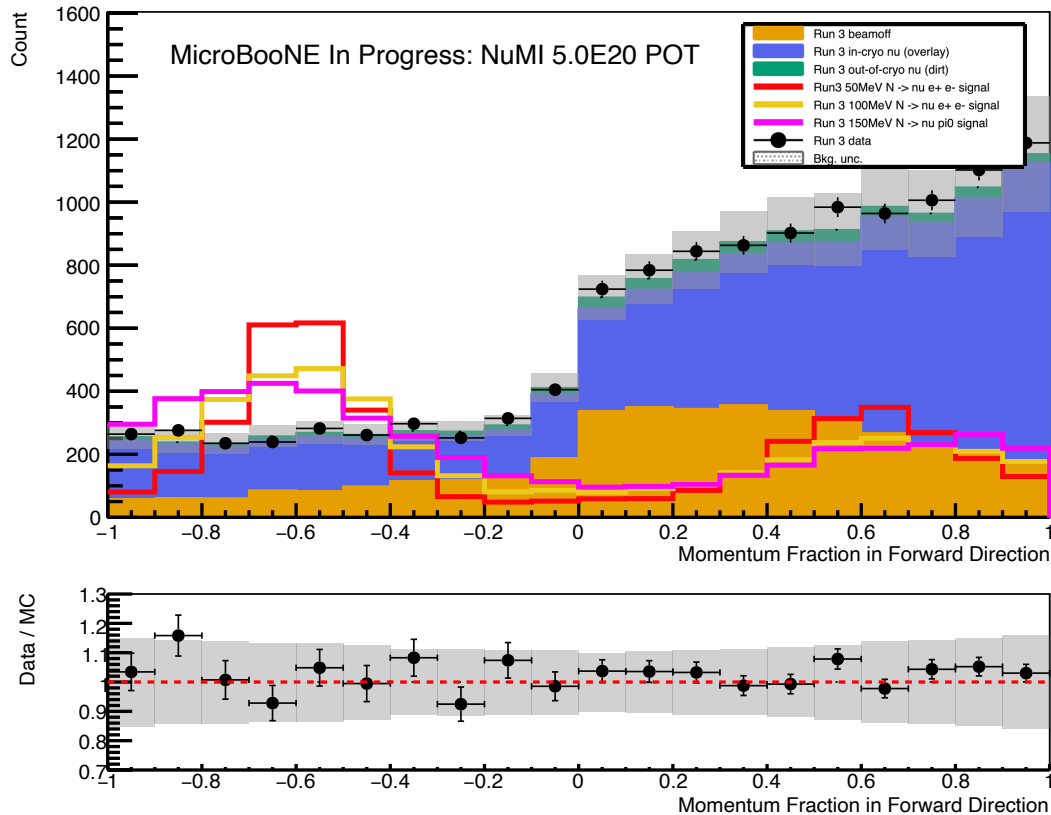
- New CNN-based vertexing algorithm (DUNE Paper: [arXiv:2502.06637](https://arxiv.org/abs/2502.06637))
- Improved reconstruction of shower-like clusters

Old reconstruction of HNLs from the absorber

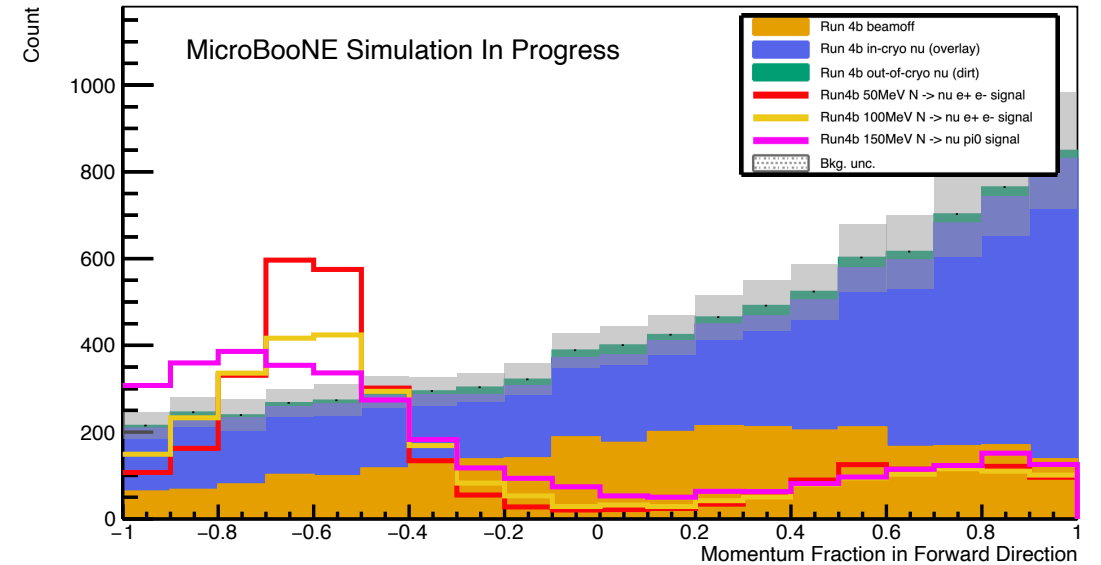


Improved direction reconstruction

Old reconstruction



New reconstruction

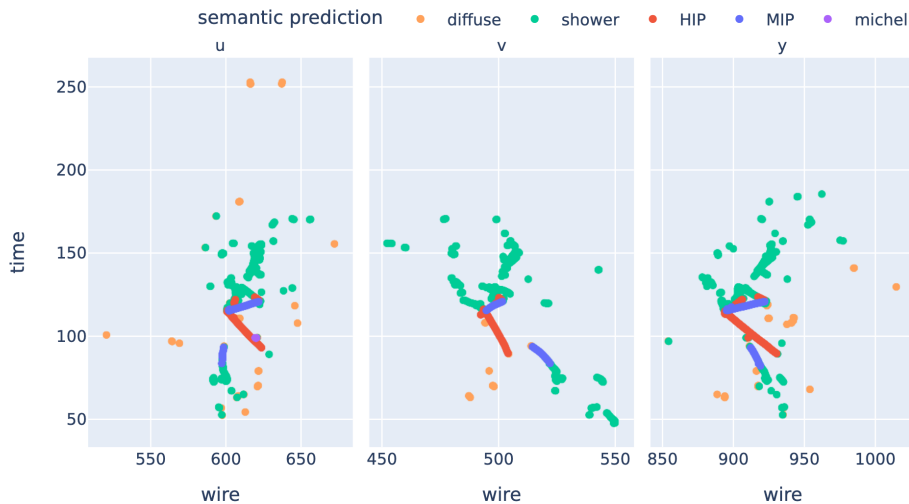


Fewer backwards-going events incorrectly reconstructed as going forward

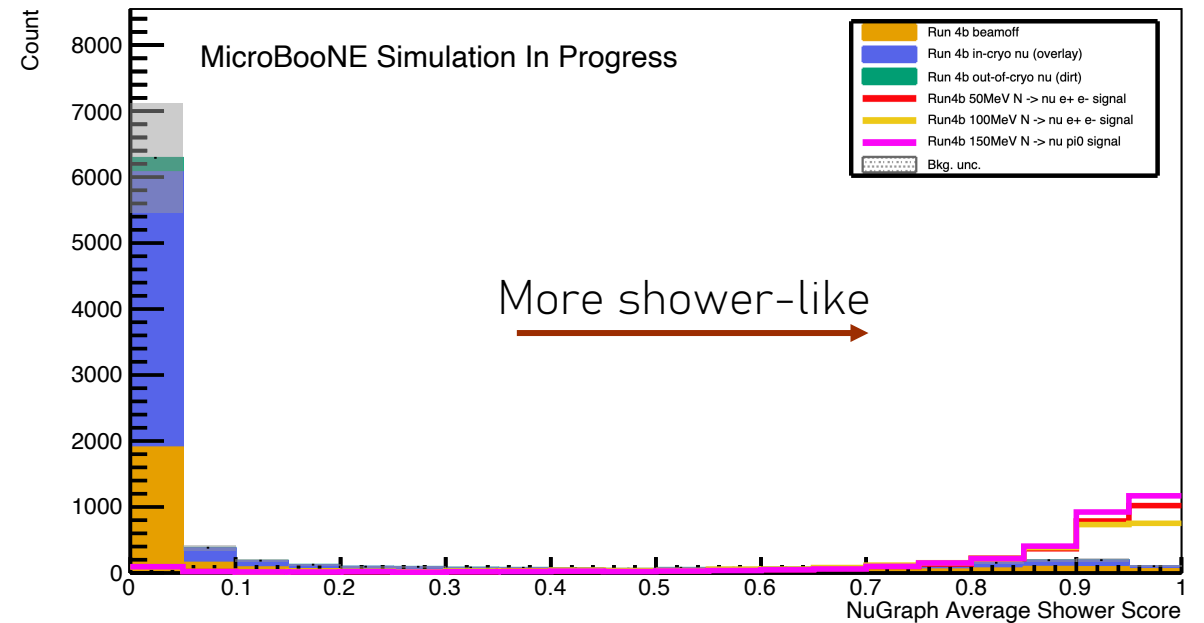
GNNs: NuGraph 2

- Graph Neural Network for neutrino event reconstruction
- Provides predictions for cosmic backgrounds and semantic classification of reconstructed particle types.
- Newly integrated into the MicroBooNE reconstruction workflow

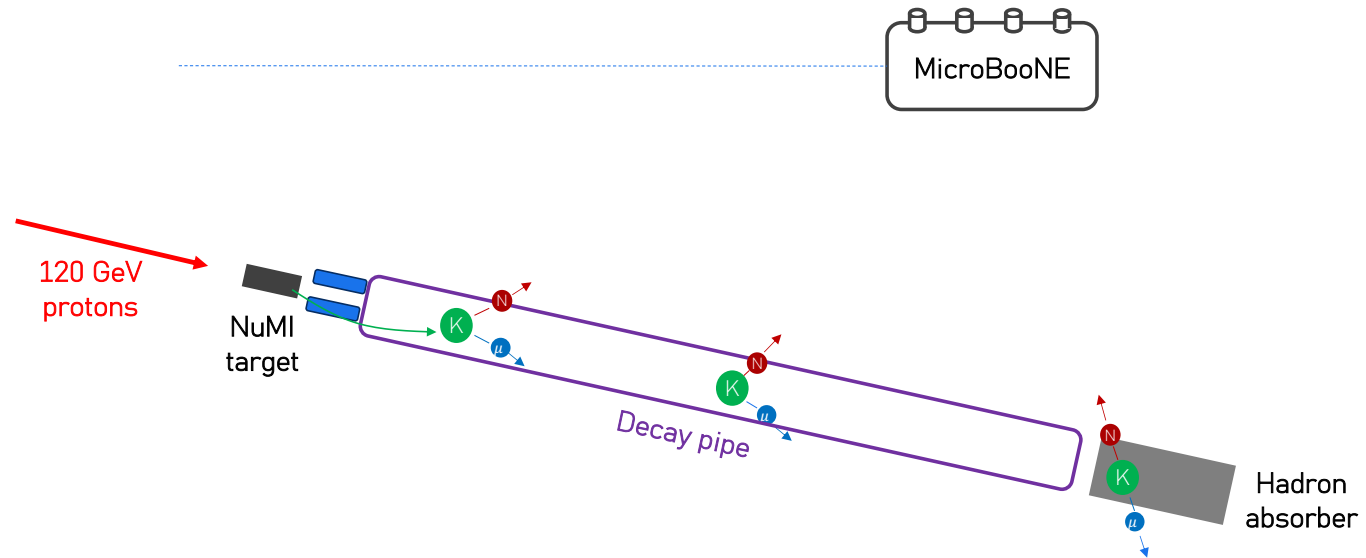
Low-mass HNL decays are shower-like, giving excellent background separation



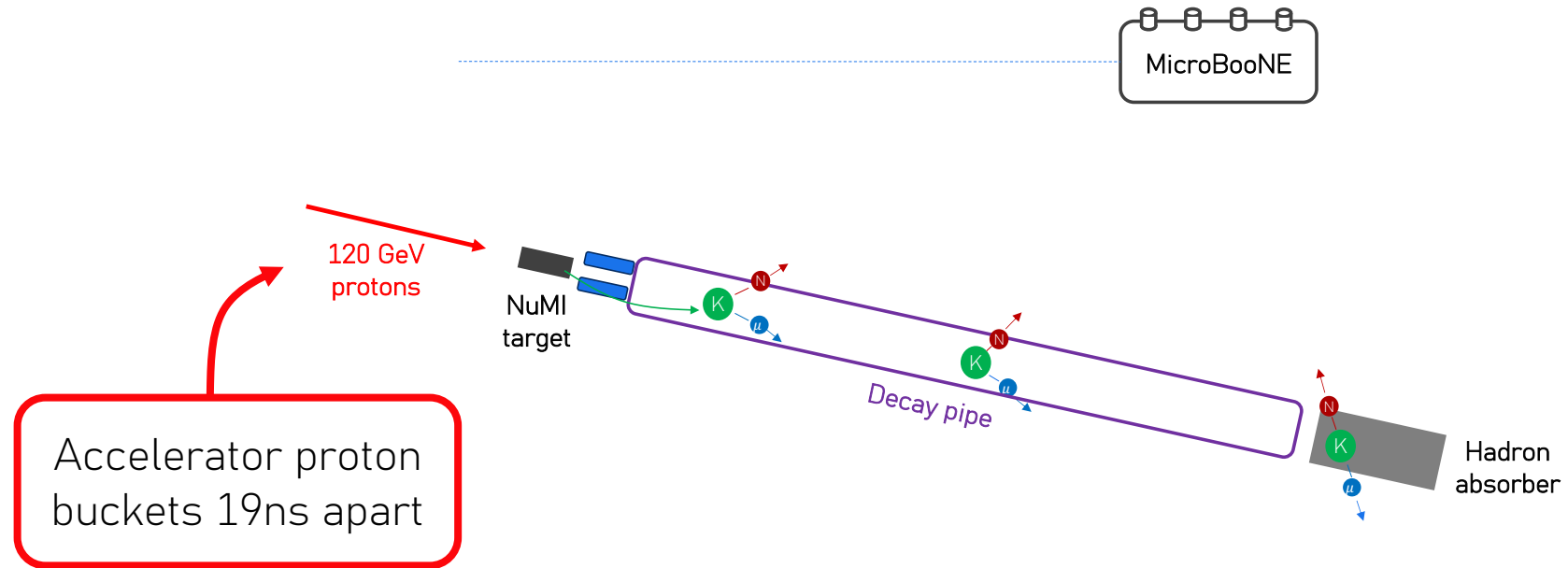
[Phys. Rev. D 110, 032008 \(2024\)](#)



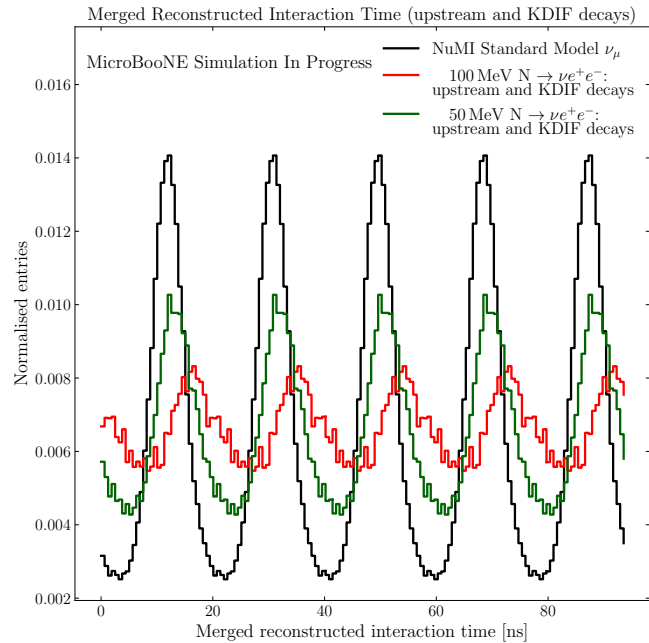
High-precision timing information



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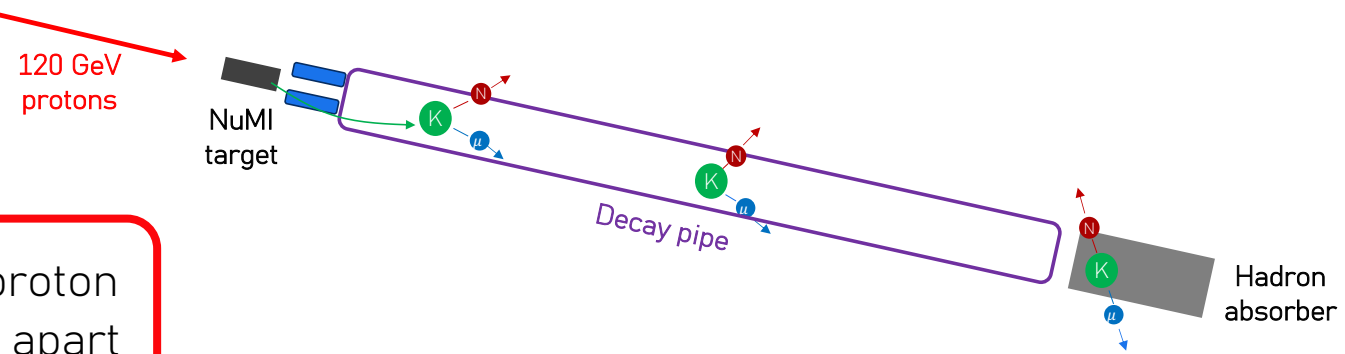
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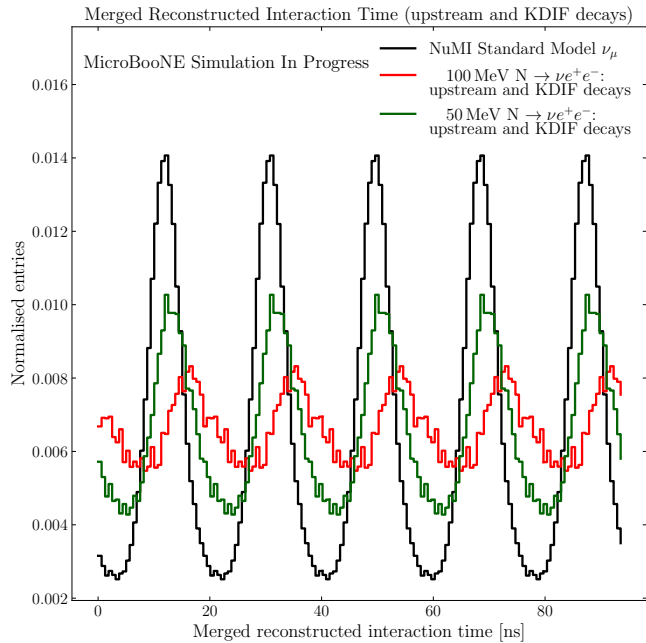
- Correlating light-flash times with information from the accelerator gives high-precision timing information
- Neutrinos have different timing structure to heavy, delayed, HNLs

MicroBooNE

Accelerator proton buckets 19ns apart



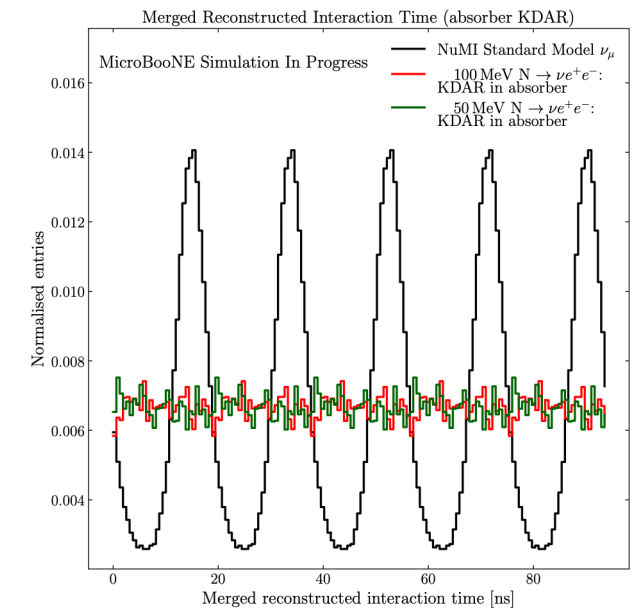
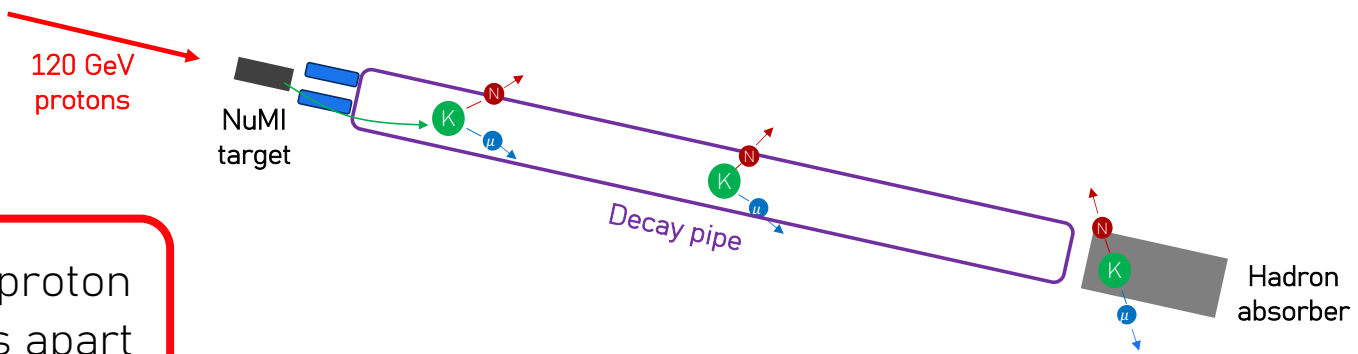
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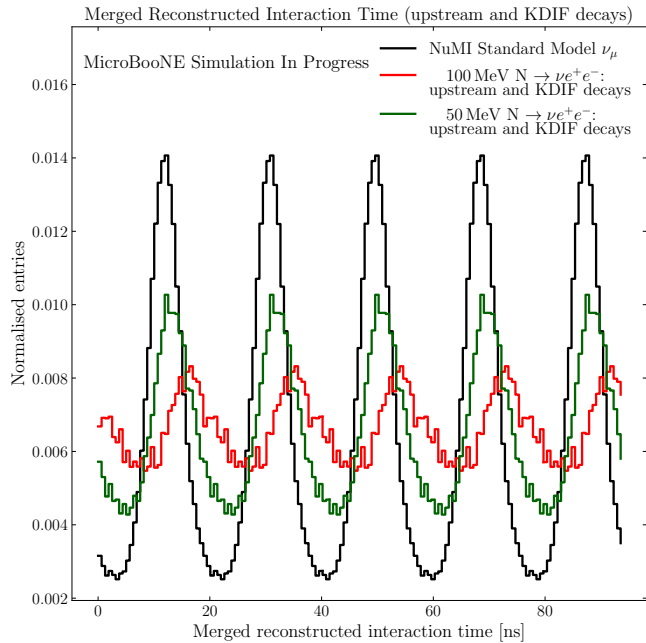
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MicroBooNE

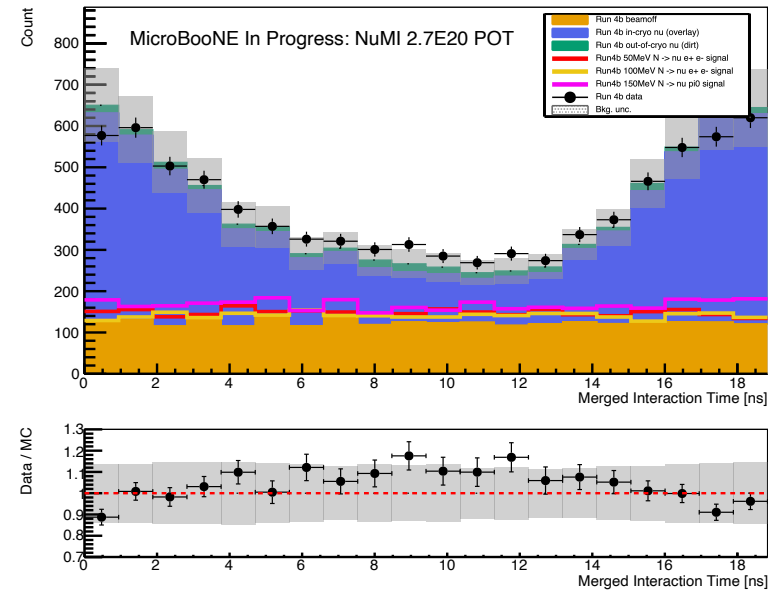
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High-precision timing information



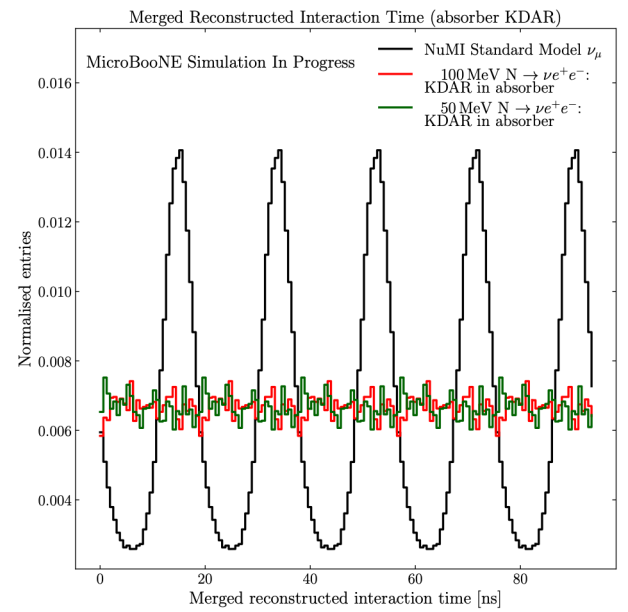
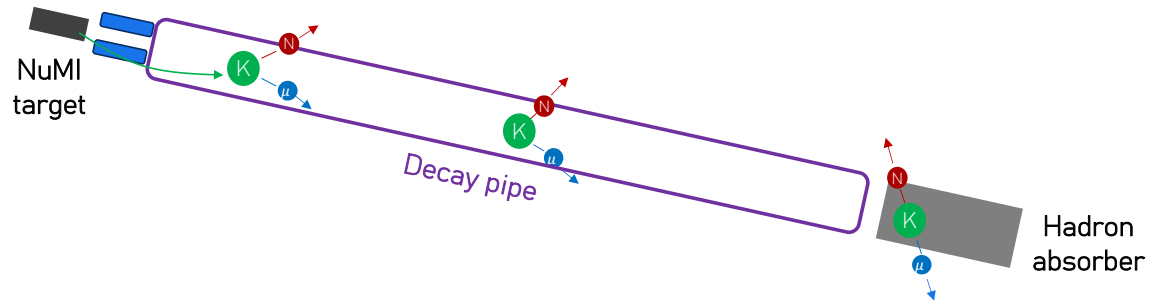
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MicroBooNE

Accelerator proton buckets 19ns apart

120 GeV protons



BDT distributions



BDT to identify HNLs trained on 22 variables describing:

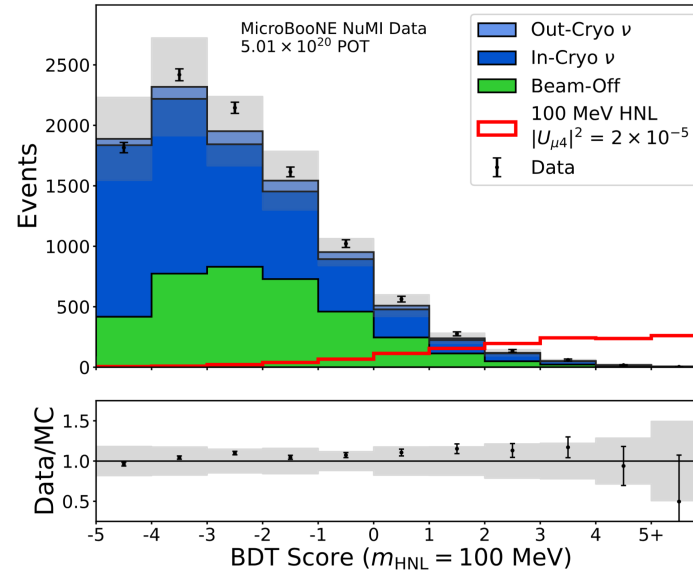
- Energy and kinematics (*improved!*)
- Track/shower object identification (*improved!*)

CLs (stat only) median limits improve!

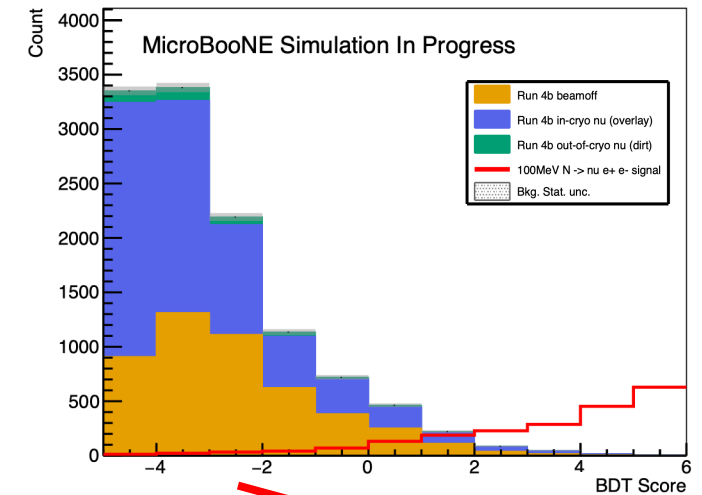
HNL Mass (MeV)	Final State	Reco-only improvement
50	$\nu e^+ e^-$	25%
100	$\nu e^+ e^-$	22%
150	$\nu \pi_0$	35%

- Timing structure (*new!*): Additional ~15% improvement in stat-only CLs sensitivity

Old reconstruction:
[Phys. Rev. Lett. 132, 041801](#)
 (2024)

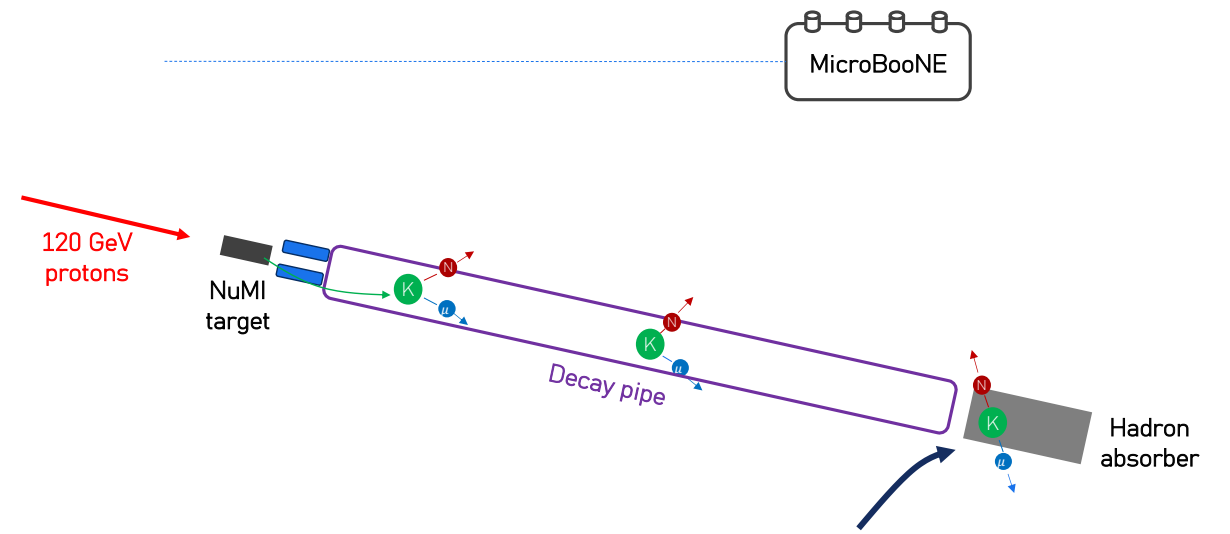


New reconstruction

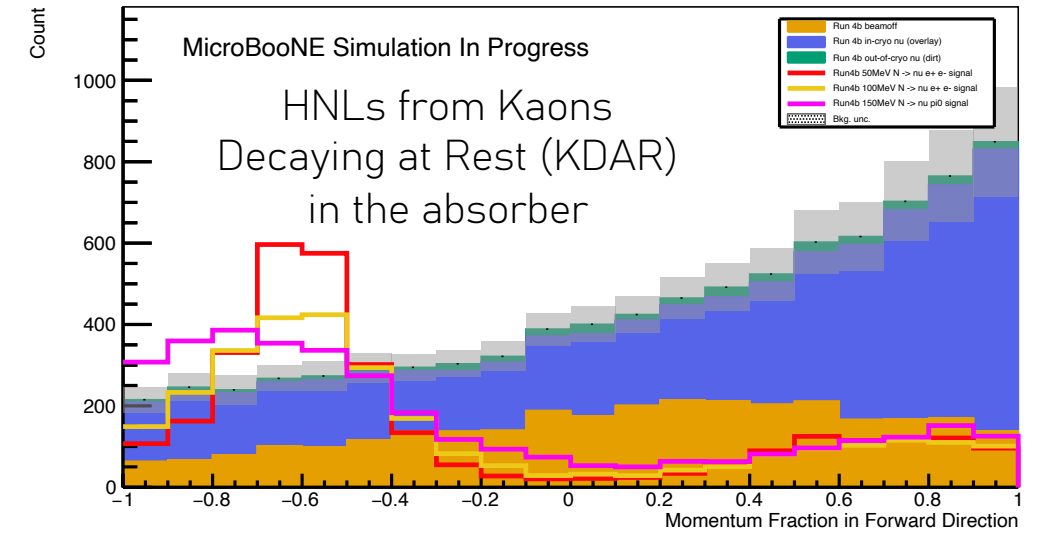


Separation of signal and background BDT distributions improves!

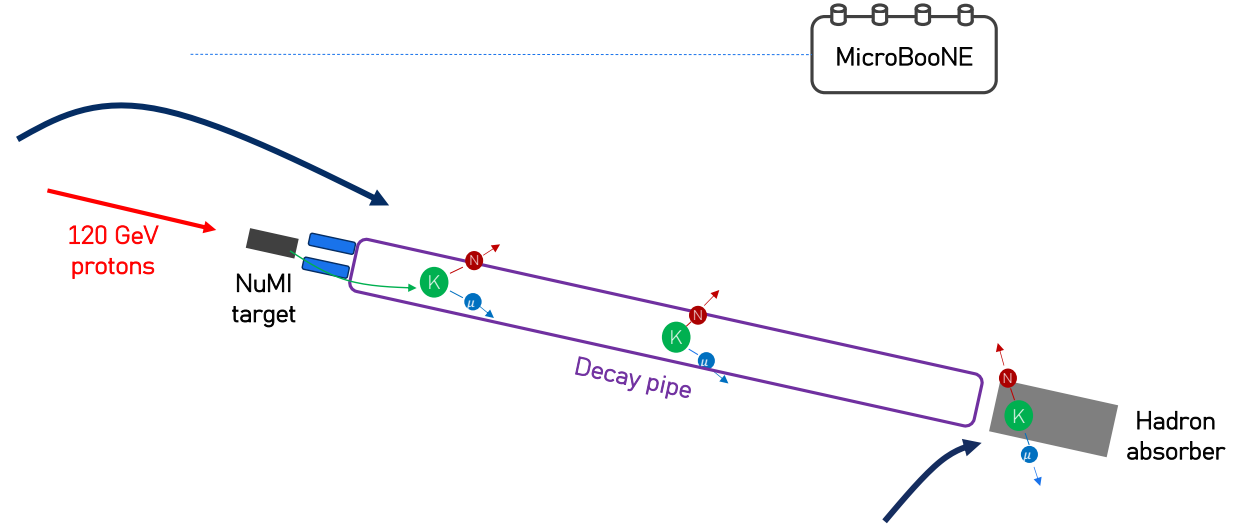
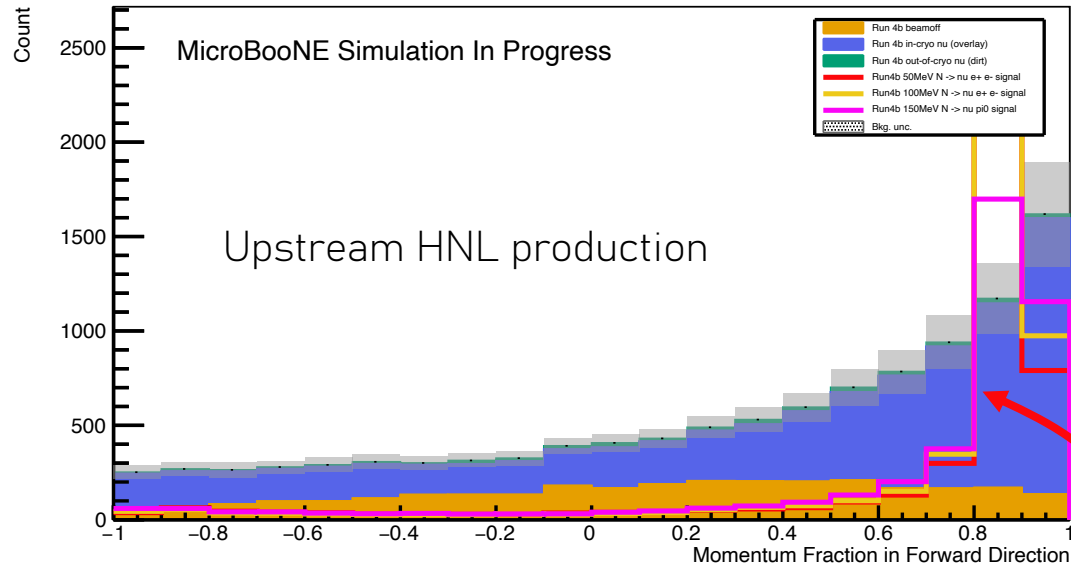
Adding in upstream HNL production



2024 analysis: Only KDAR
in absorber
New analysis: All HNLs
(~40% extra events)

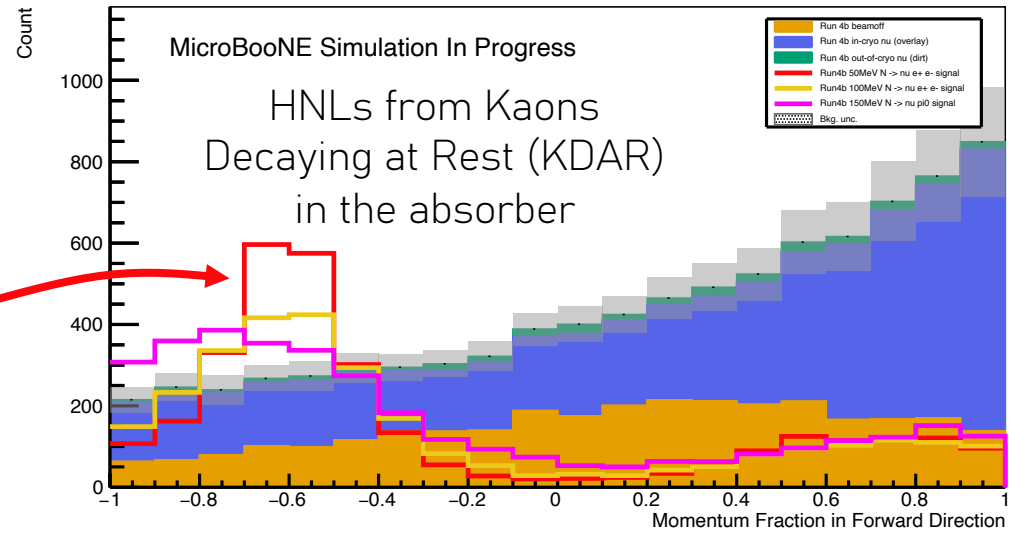


Adding in upstream HNL production



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Upstream HNL
signal kinematics
reversed and
more boosted



Summary

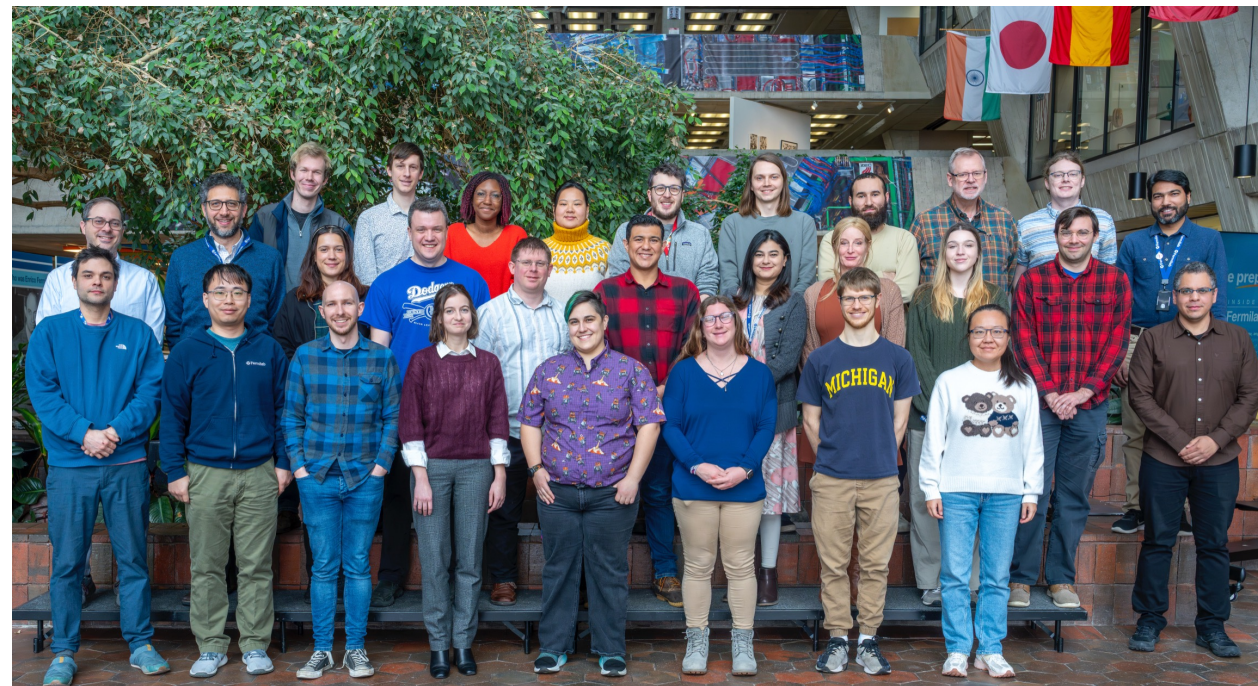
MicroBooNE has performed several successful searches for Heavy Neutral Leptons produced from the NuMI kaon flux, including a 2024 search which set world-leading limits

We aim to improve the 2024 analysis limits by:

- 1) **Increasing data** used from 7.0×10^{20} to 2.0×10^{21} POT
- 2) Including HNLs from **upstream kaon decays**
- 3) Leveraging improved reconstruction and including high-precision timing information

...so stay tuned!

MicroBooNE CM, Jan 2026



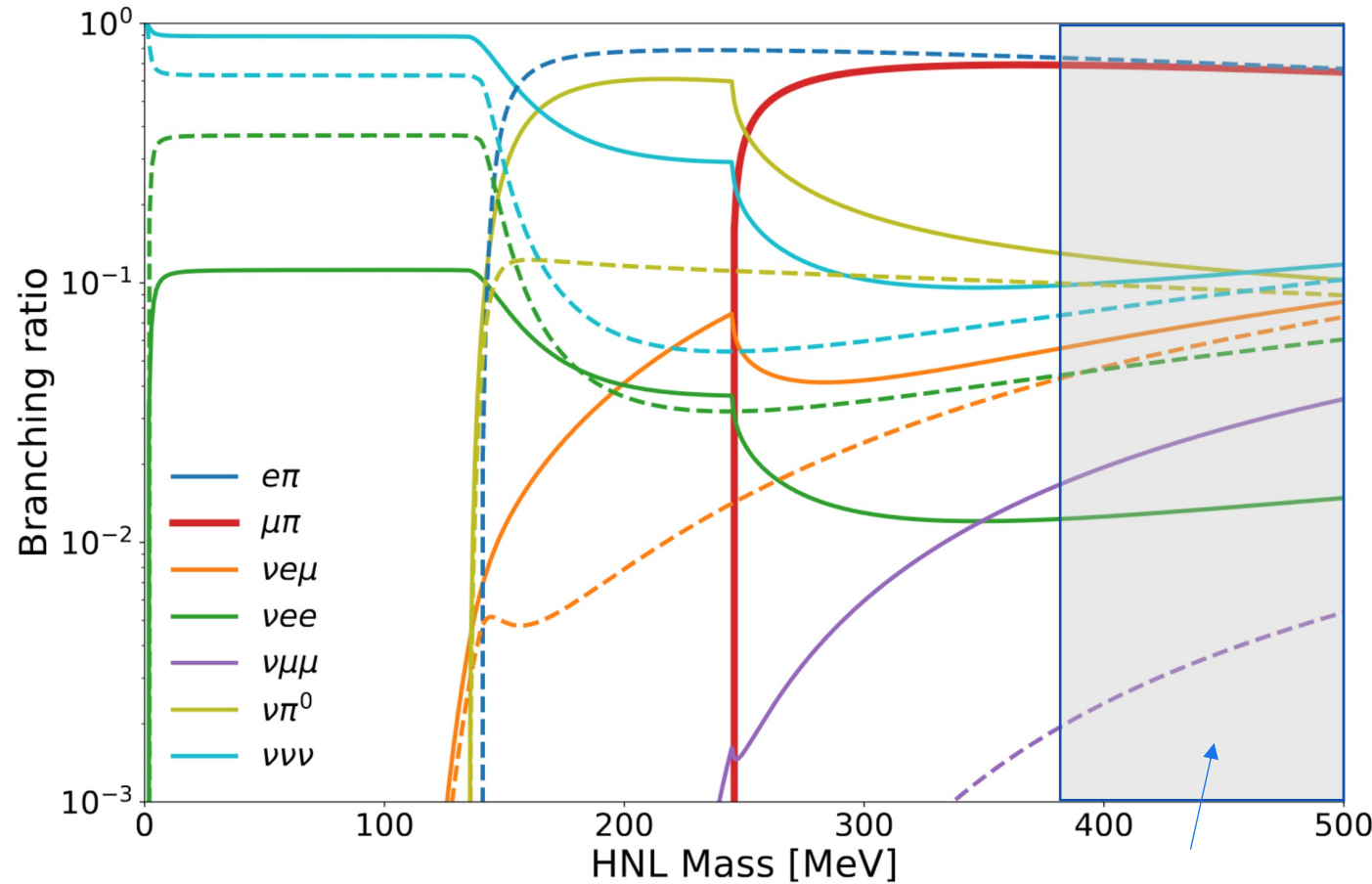
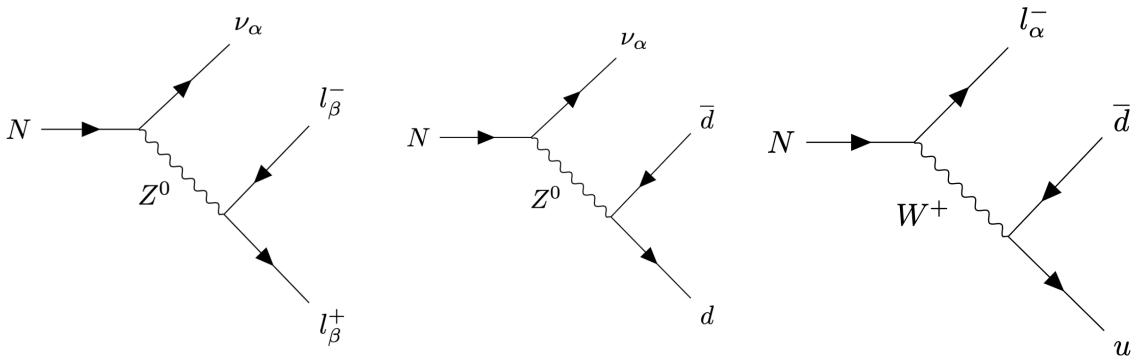


Backups

Heavy Neutral Leptons (HNLs)

- Kinematic upper bound of ~ 390 MeV to the HNL masses we can probe at uBooNE
- Dominant visible states below this are:

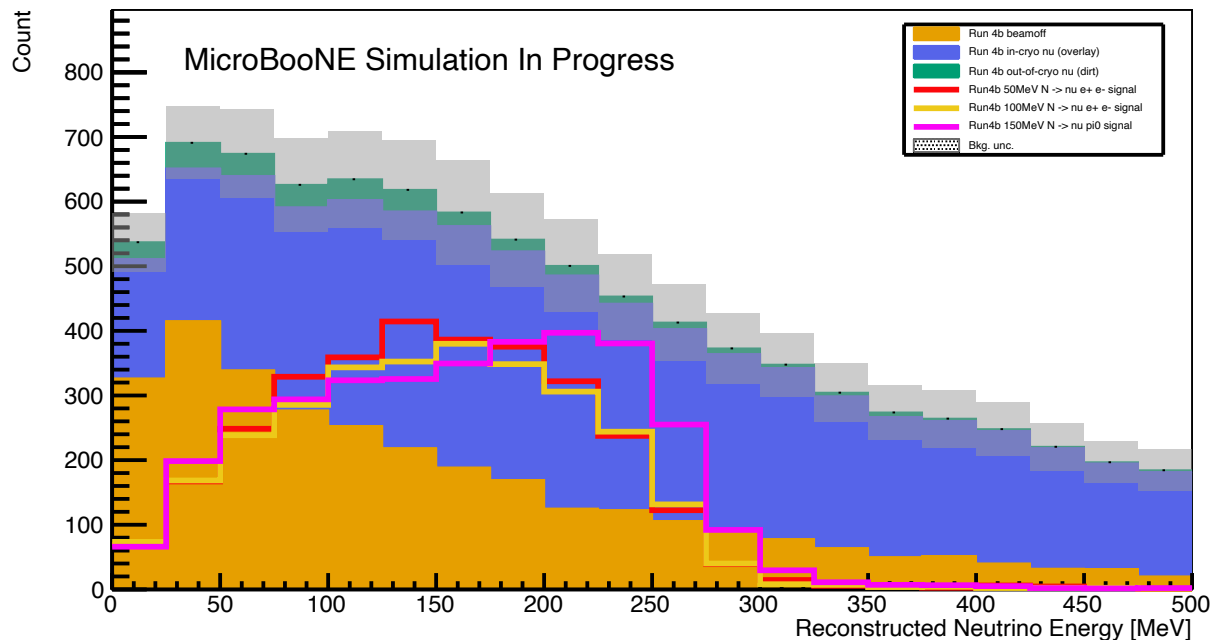
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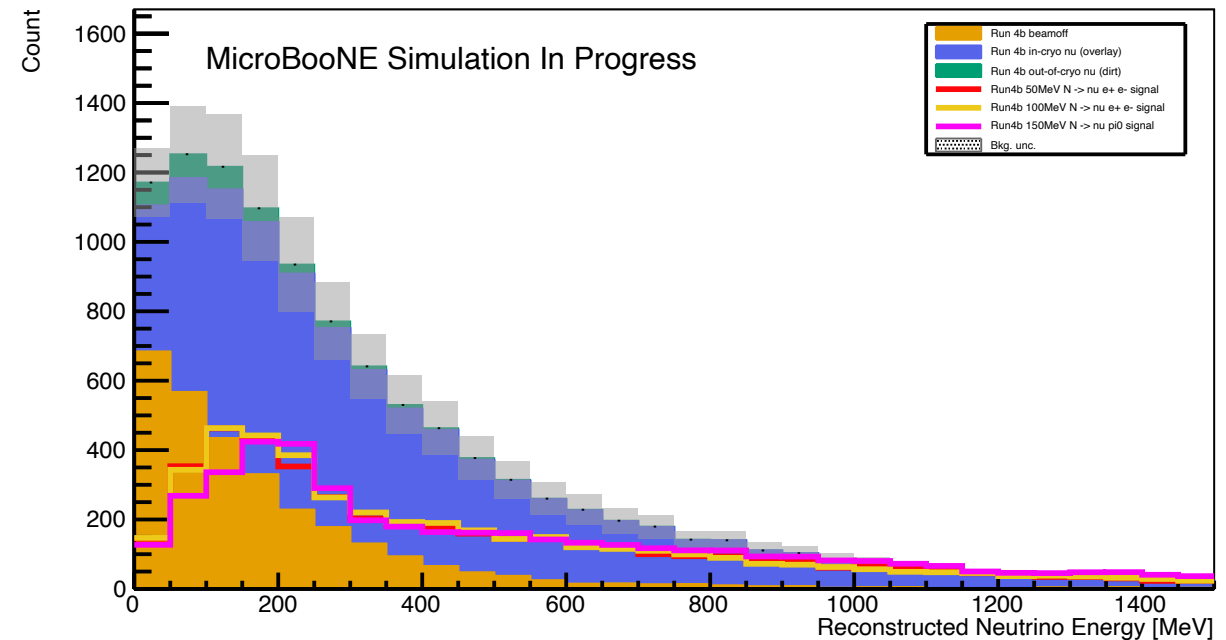
HNLs Not produced here if $|U_{e4}|=0$

Upstream vs absorber KDAR energy distributions

HNLs from Kaons Decaying at Rest (KDAR)
in the absorber

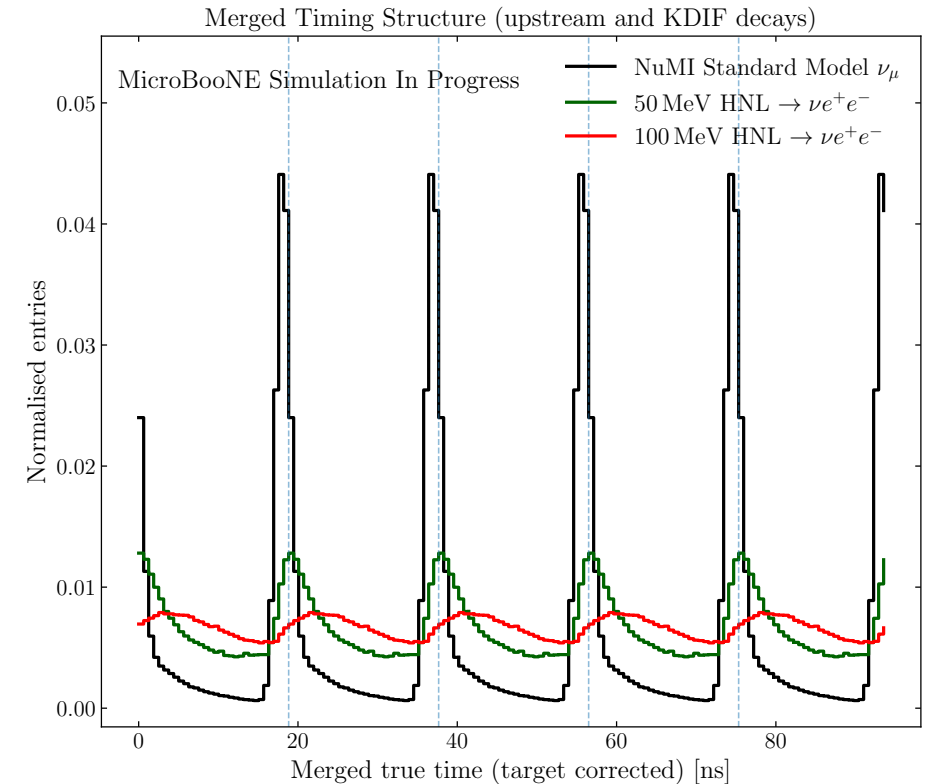
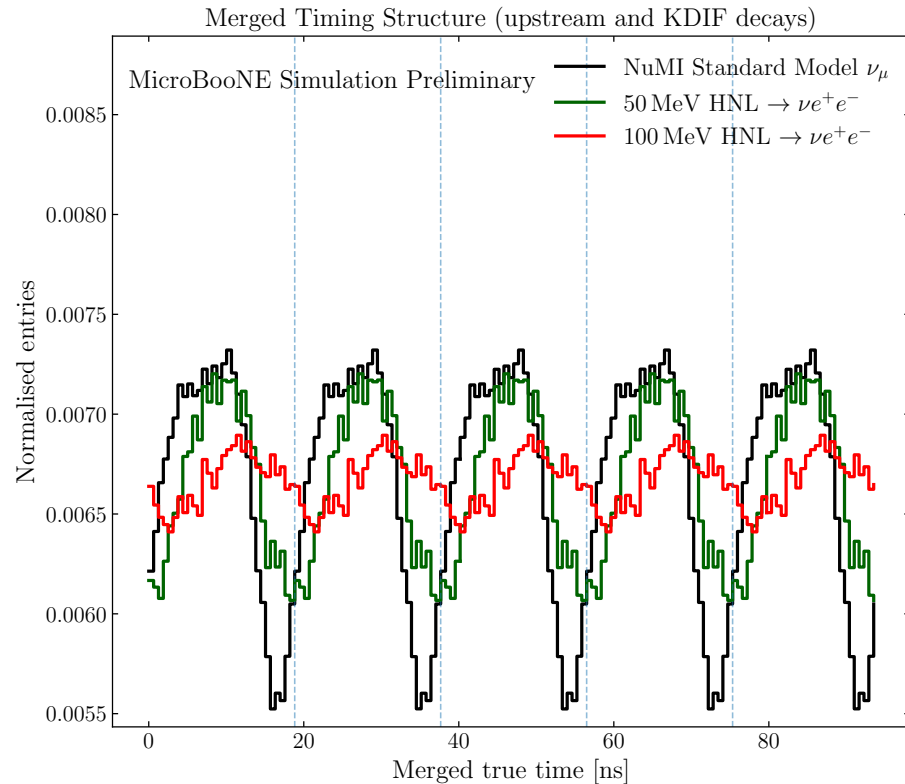


HNLs from upstream and in-flight kaon decays



Energy distribution of upstream decays
has a much longer tail

Upstream true and target-direction corrected time distributions



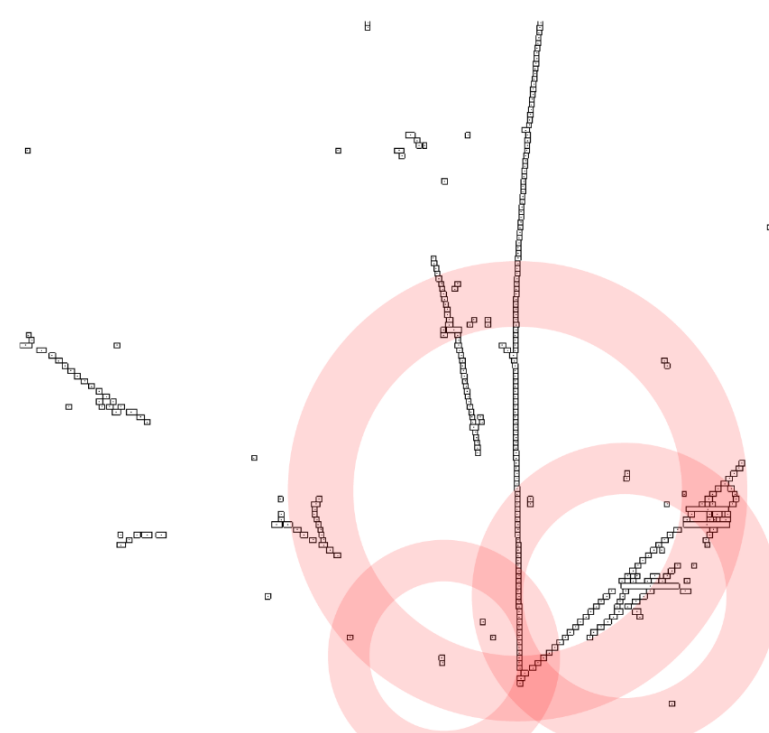
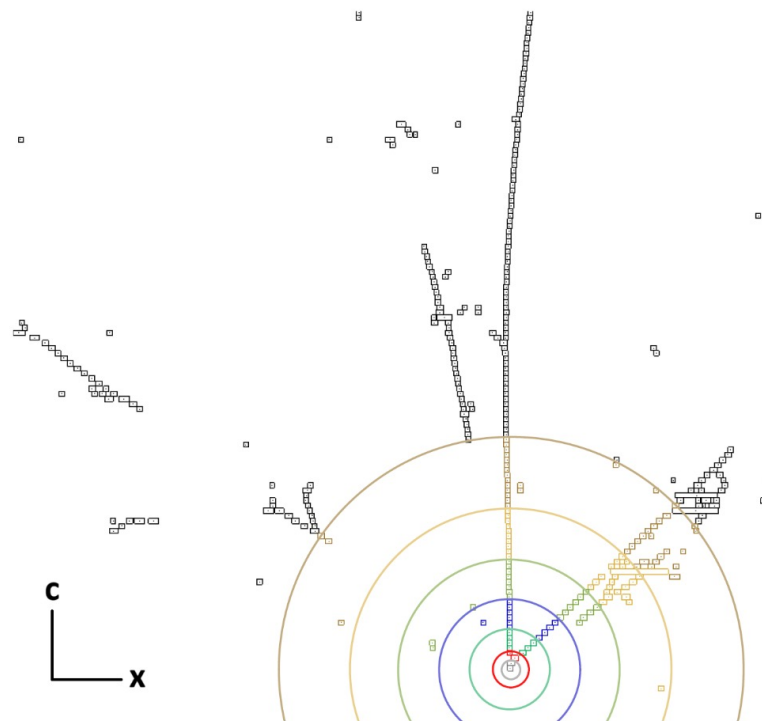
The position of interaction within the detector introduces a significant time-of-flight bias – we need to correct for this!

Deep Learning based Vertexing

- Pandora reconstruction development originally for DUNE, now implemented in MicroBooNE
- Vertexing important for all analyses, but particularly important for NuMI BSM searches with events originating far away from the target

- UResNet architecture learns distance of a hit from the vertex

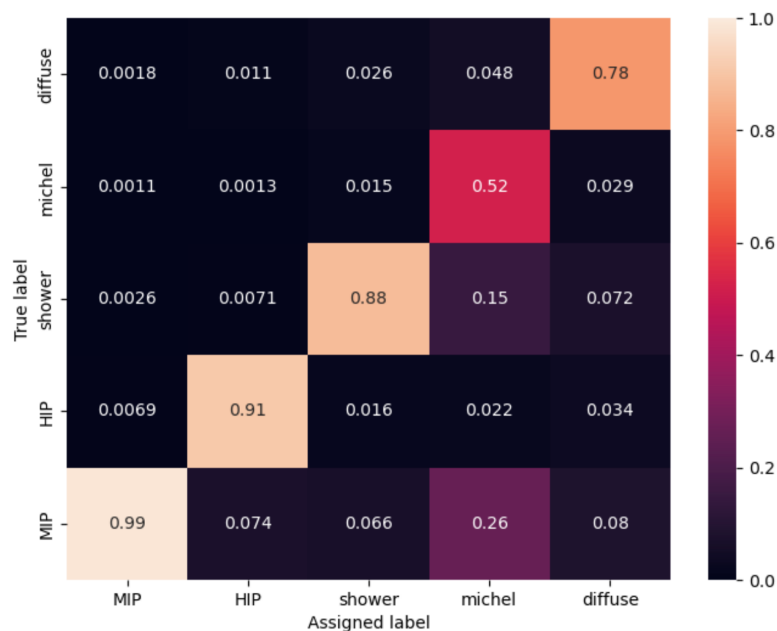
- Inference produces rings of estimated distance of hit from vertex: the intersection gives the likely vertex position



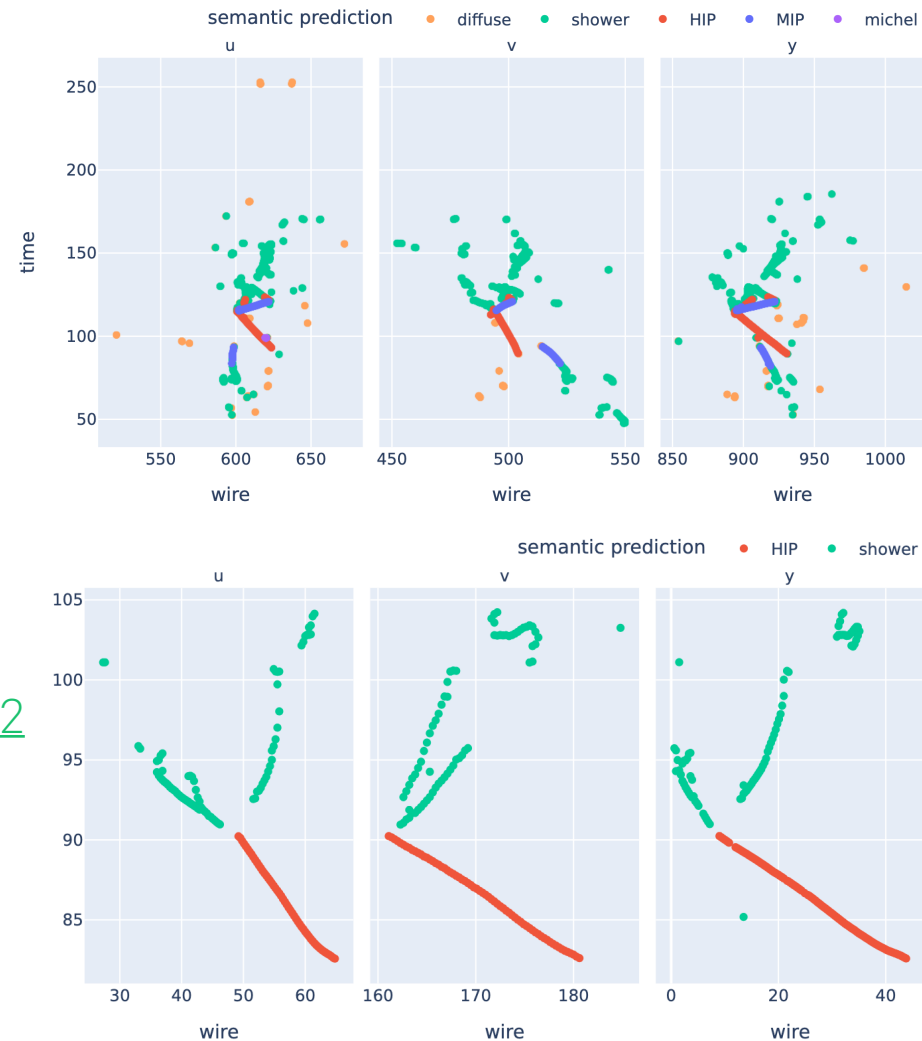
DUNE paper: [arXiv:2502.06637](https://arxiv.org/abs/2502.06637)

GNNs – NuGraph 2

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- Provides predictions for cosmic backgrounds and semantic classification of reconstructed particle types
- Now integrated into the MicroBooNE Pandora workflow



[arXiv:2403.11872](https://arxiv.org/abs/2403.11872)



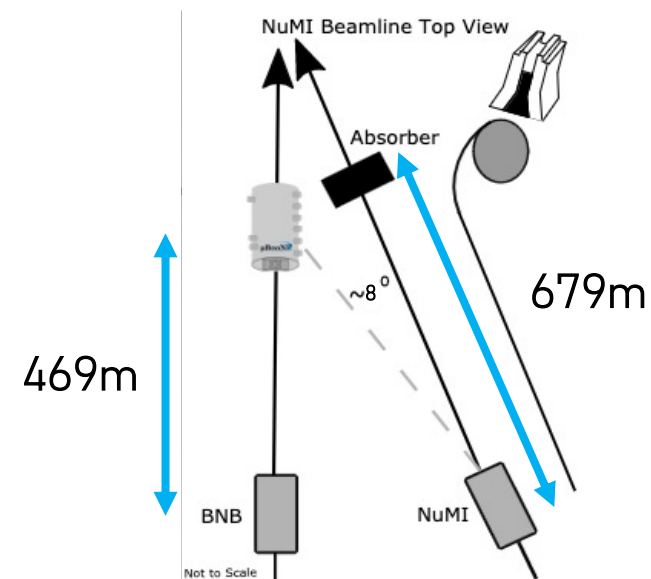
Where is MicroBooNE?

Fermilab, Illinois

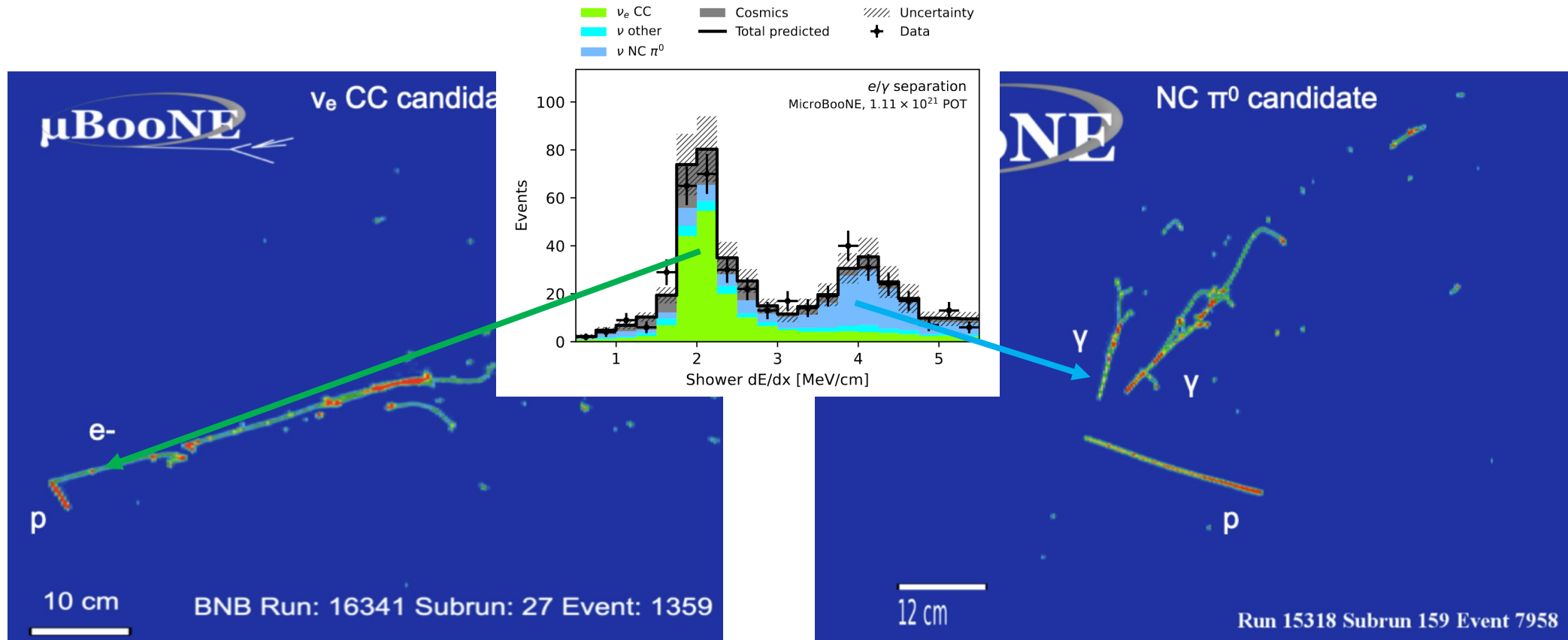


Neutrinos from two beams:

- 1) The Booster Neutrino Beam (BNB):
on-axis from 8GeV protons
- 2) The Main Injector (NuMI) beam:
8° off-axis from 120GeV protons

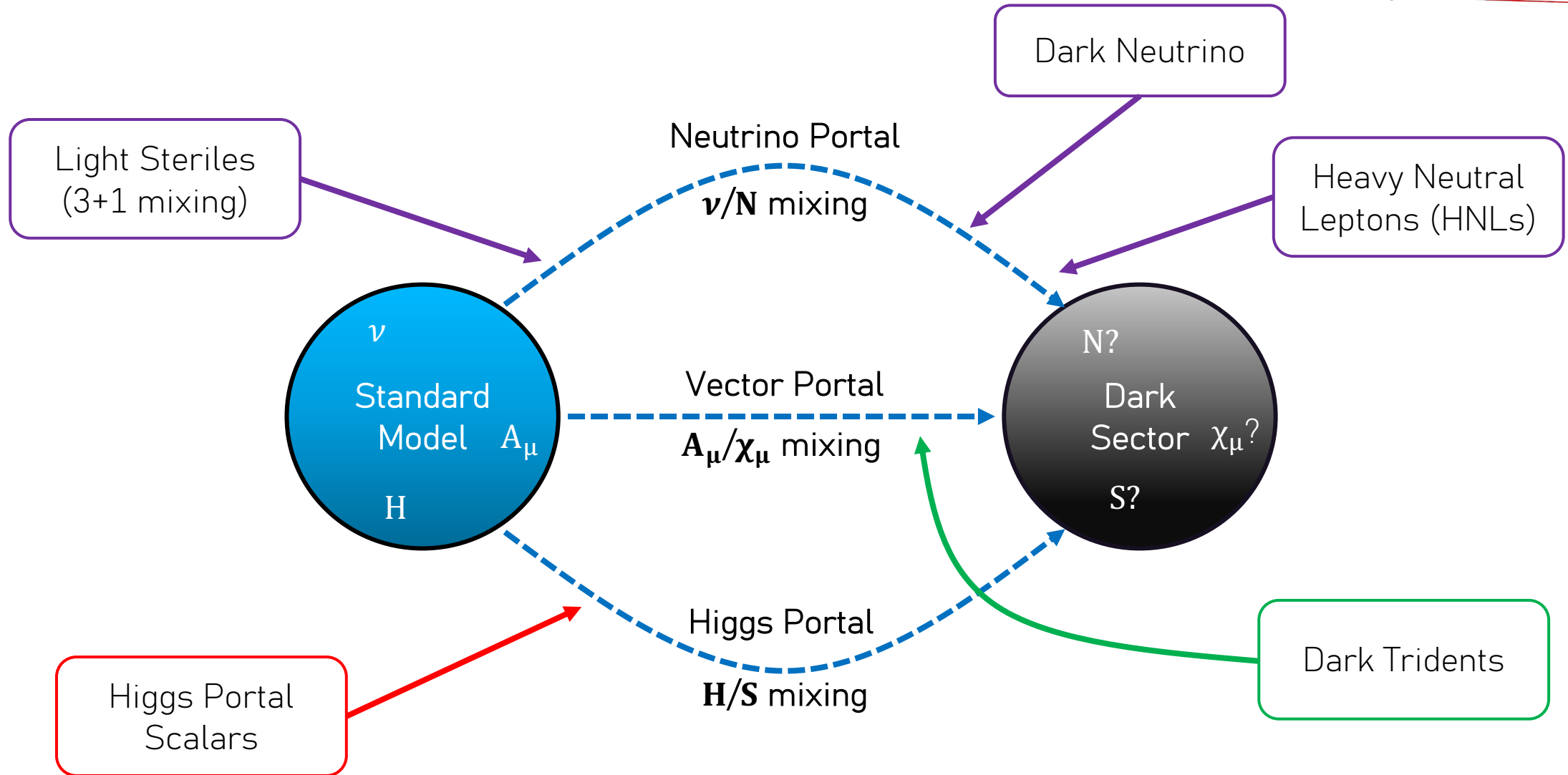


Electron/photon shower separation



Starting dE/dx is 2x higher for photon induced e+e- showers!

Some other uBooNE dark sector searches





MicroBooNE Collaboration

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