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

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Owen Goodwin
on behalf the MicroBooNE collaboration

University of Manchester

The University of Manchester

Heavy Neutral Leptons

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Beyond Standard Model right-handed particles known as *sterile neutrinos* or *Heavy Neutral Leptons* ***(HNL)*** (shown as **N**)

- Can substitute an HNL into any SM neutrino process via extended PMNS matrix elements **(if kinematically allowed**).

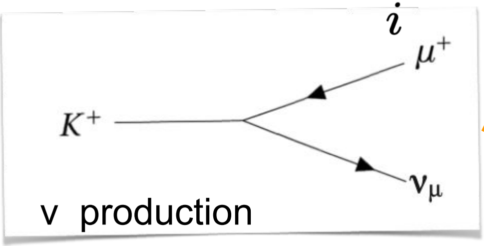
- O(100 MeV) mass HNL could be produced in high intensity neutrino beams, then decay to visible particles in detectors.

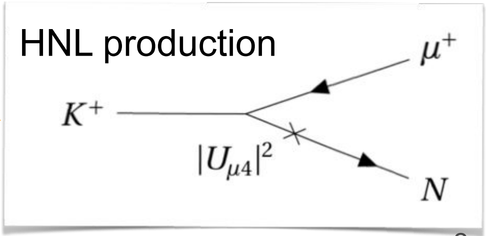
HNL enter SM physics through **mass mixing**.

Standard mixing (U^{3x3}_{PMNS}, green box); (Small) New physics (red box)

$$U^{\text{Extended}}_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots & U_{en} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots & U_{\mu n} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots & U_{\tau n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} & \cdots & U_{s_n n} \end{pmatrix}$$

$$\nu_\alpha = \sum_i U_{\alpha i} \nu_i + U_{\alpha 4} N$$





MicroBooNE

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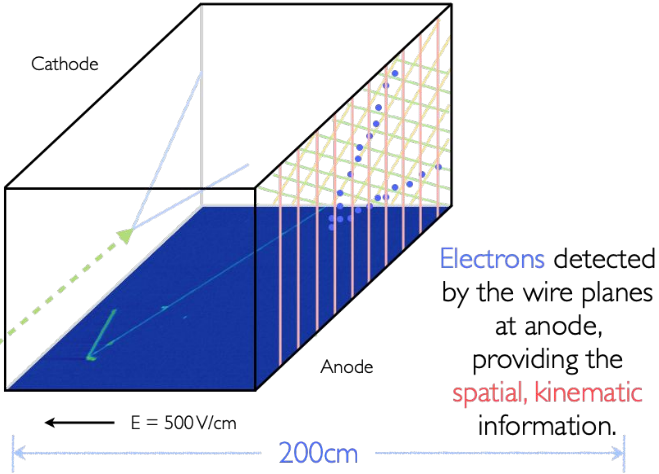
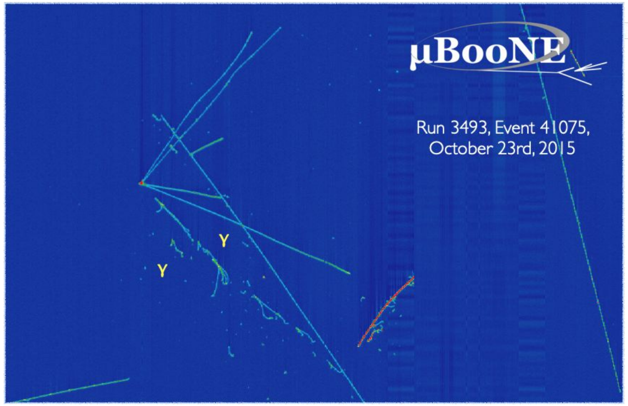
- Liquid Argon Time Projection Chamber (LArTPC) running in the Booster Neutrino Beam (BNB) **(470m from target)** at Fermilab since 2015 **(~1.5 x 10^21 POT of beam exposure)**
- Charged particles ionise the argon inside the TPC
- **3 sense-wire** planes detect ionisation electrons produced by charged particles traversing detector to create bubble-chamber like images.
- **32 PMTs** collect scintillation light used for triggering and neutrino event selection

See talk 757. The MicroBooNE Experiment by Ralitsa Sharankova for more details on the MicroBooNE LArTPC





HNL Production in BNB ν Beam

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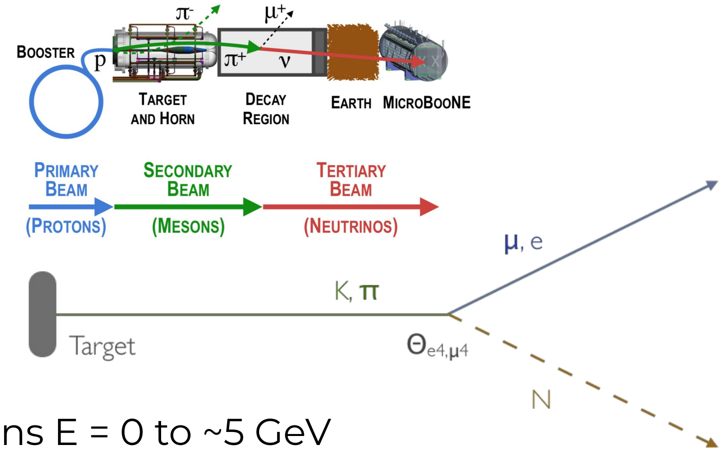
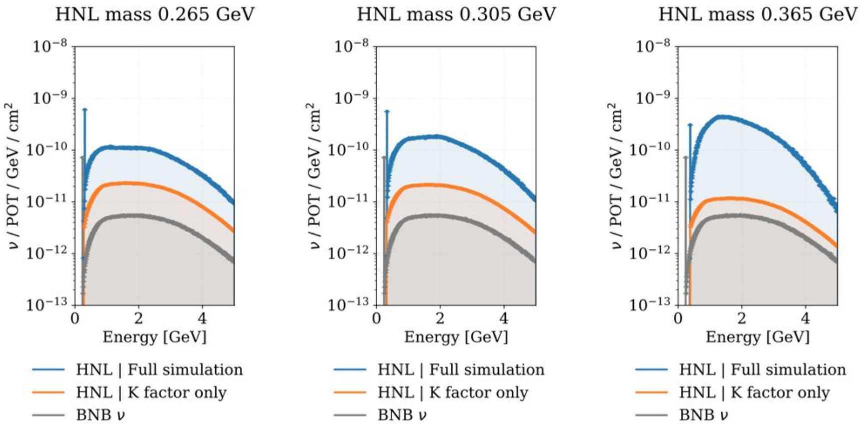
- Production rate ∝ $|U_{\alpha 4}|^2$
- **K⁺** are the heaviest meson produced in large quantities in BNB. **HNL mass < 495 MeV**
- Fully simulate **HNL flux** from parent information in SM neutrino simulation.
  - Phase space change
  - No helicity suppression
  - Kinematically enhanced **(more forward going)**



Mesons E = 0 to ~5 GeV



Decay to μπ Pairs

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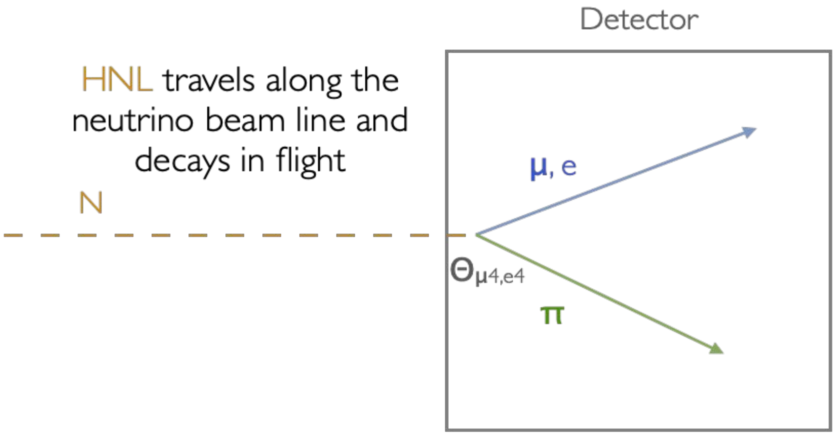
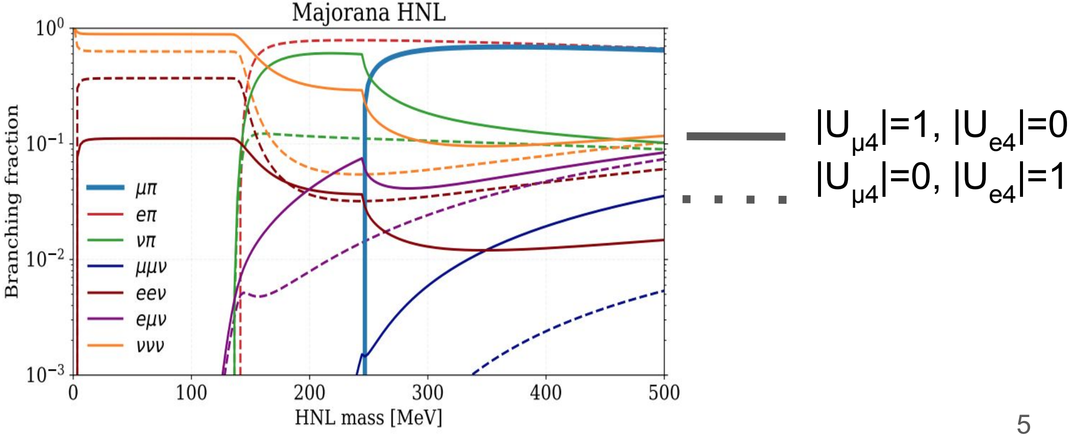
- This analysis searches for **$N \to \mu^{\pm}\pi^{\mp}$**
  - Two tracks from shared vertex with invariant mass of HNL
  - Decay rate **$\propto |U_{\mu4}|^2$**
- For **$|U_{\mu4}|^2 << 1$** decay length much longer than distance to MicroBooNE (470m)
- Consider non zero **$|U_{\mu4}|$, ($|U_{e4}|=0$)**
- Relevant HNL produced by **$K^+ \to \mu^+ N$**
  - 260 MeV < Mass < 385 MeV
  - Final event rate **$\propto |U_{\mu4}|^4$**



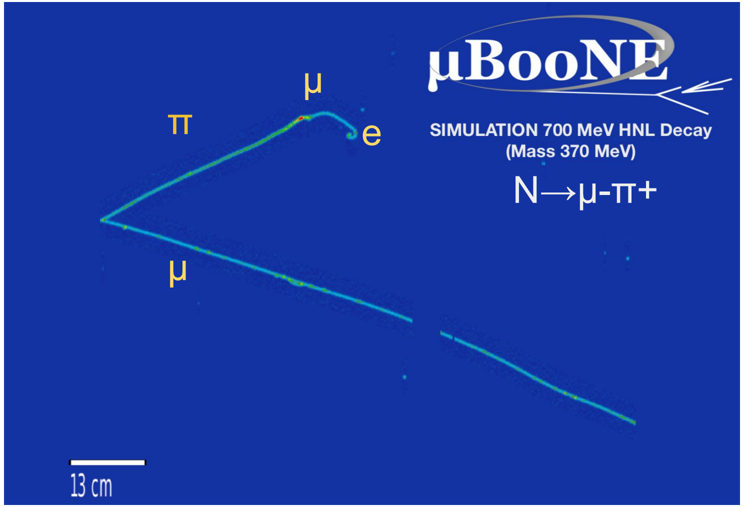
Example decay channels



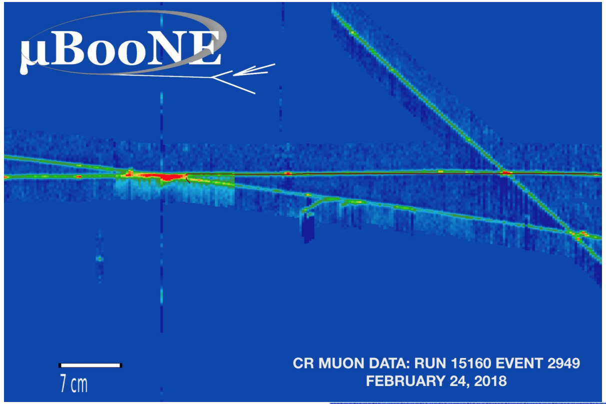
HNLs in MicroBooNE

Signal

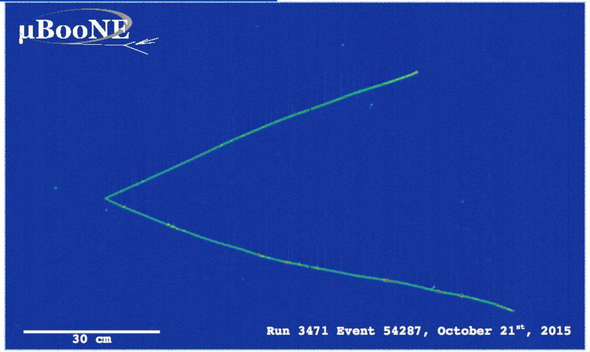
Simulated HNL decay



Backgrounds

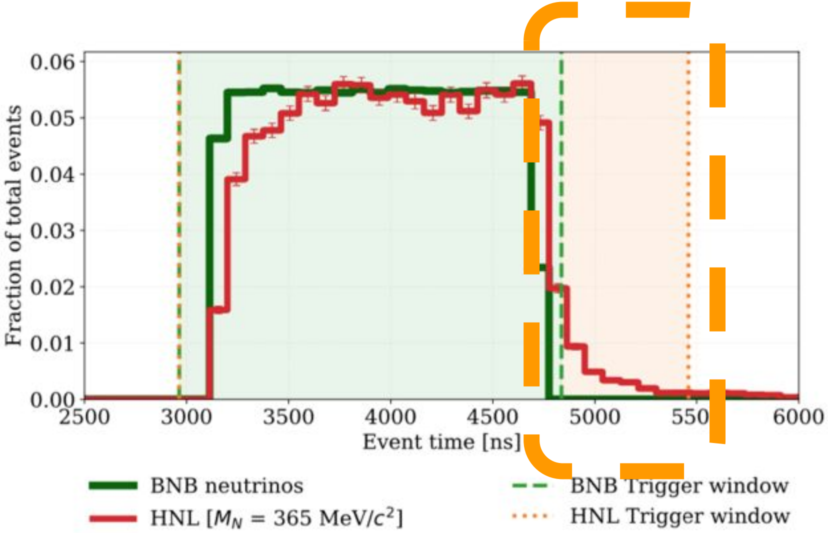


Data - cosmic ray (CR) muon event



Data - ν_μ charged current interaction

Timing



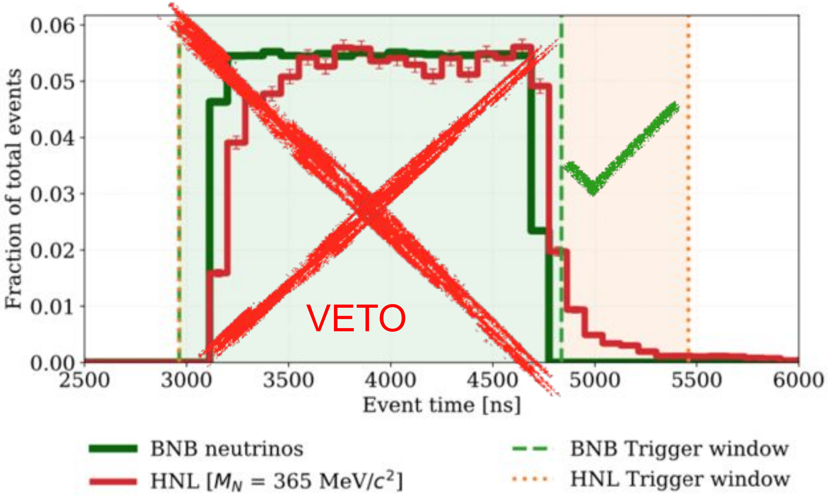
ν

N

- HNL travel slower than SM neutrinos
- Neutrinos arrive in well separated beam spills which last for **1.6 μs**
- Around ~10% of HNLs arrive "late", after the neutrino spill. Fraction is mass dependent.
- Analysis focuses on late HNLs, no neutrino background
- Expect cosmic-ray background only.

HNL Trigger

Trigger on optical flashes in time with beam window



- Special **HNL trigger** operating since **June 2017** with window extending 33% longer than neutrino trigger
- This analysis uses 2e20 POT (~ a third of data collected with trigger)
- Identical HNL trigger runs when there is no beam spill to collect cosmics for background subtraction for data driven analysis

Finding HNL

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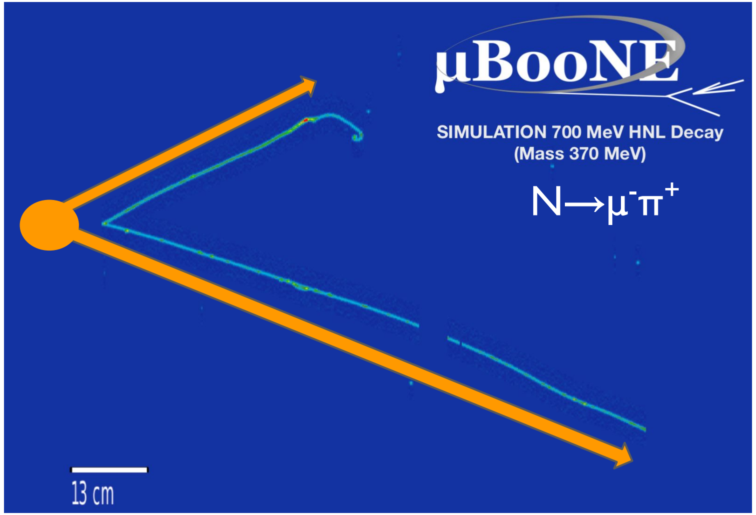
- Automatic event reconstruction uses Pandora pattern recognition* to create reconstructed particles.
    - Using same tools as many neutrino analyses in MicroBooNE
- Select events containing a reconstructed vertex associated with **exactly two** reconstructed tracks.

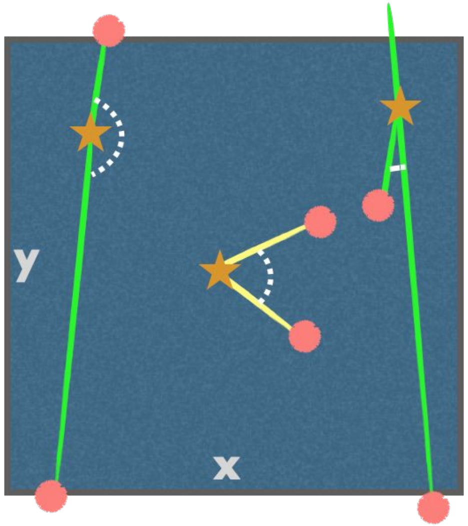


HNL efficiency: 50%
Cosmic rejection: 90%

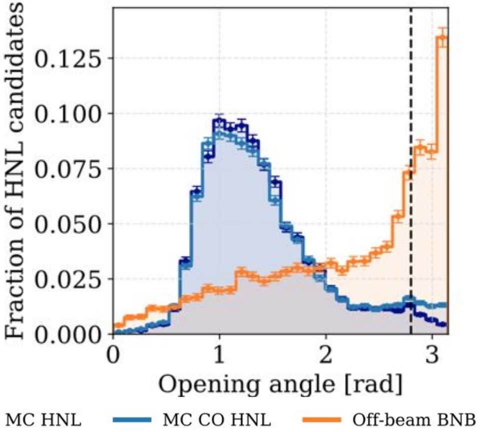
Eur. Phys. J. C 78, 82 (2018) *

Preselection & Cosmic Removal

- Preselection removes obvious cosmics and poorly reconstructed HNL
- Most effective cosmic removal cuts;
  - Containment cut: both tracks must end within the TPC
  - Angle cut: a cut on an **almost-flat opening angle** (160°)

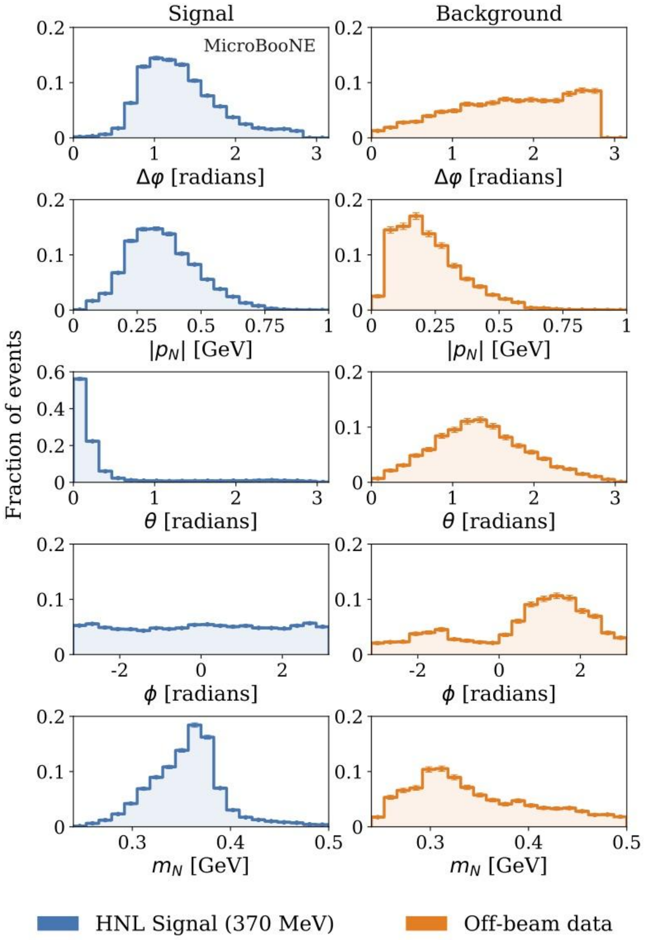


Cosmics typically mimic HNL via a broken track or delta ray causing a vertex to be found.



- Preselection designed to have limited mass dependency
  - HNL efficiency : 45-50%
  - Cosmic rejection: 98.4%

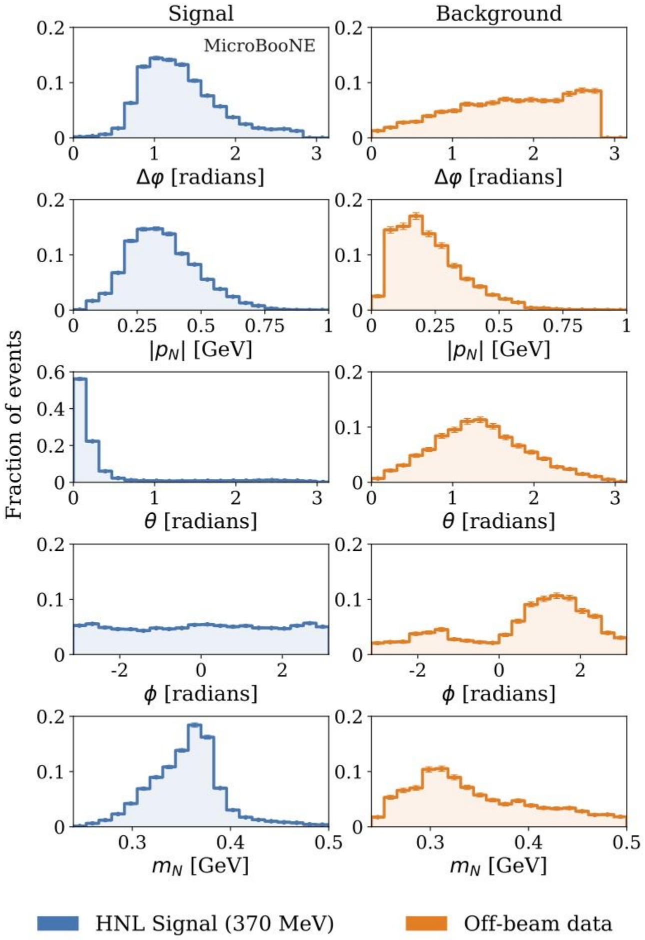
BDT Training



- Train BDT to discriminate between HNL and cosmics for 10 HNL masses in studied range (260 MeV to 385 MeV).

- 5 input variables for each candidate
  - Opening angle
  - Total momentum
  - Angle from the beamline
  - Azimuthal angle
  - Invariant mass

BDT Training



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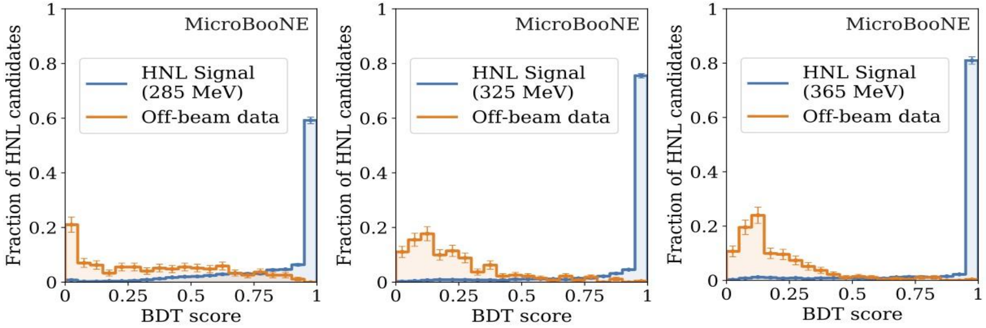
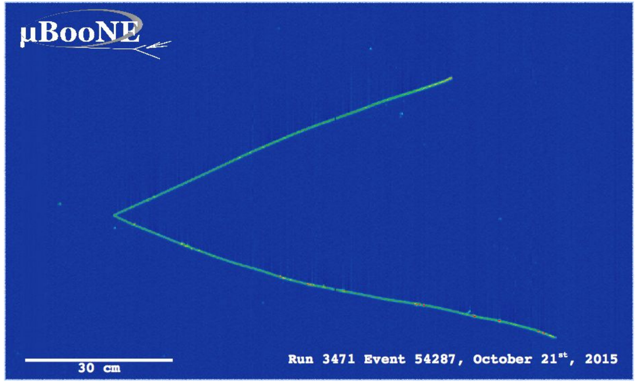
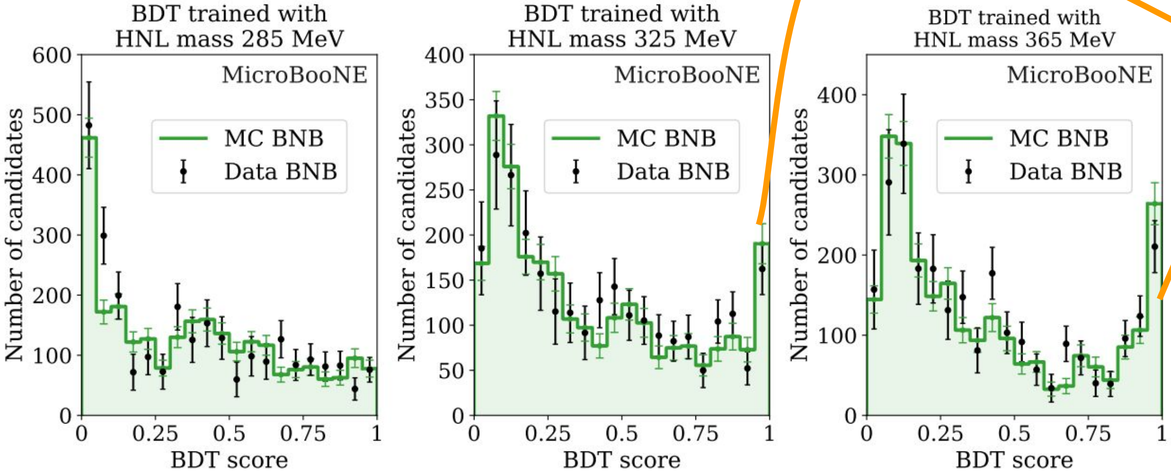


Control Sample

Validation of selection workflow is performed on **BNB ν interaction data** (and simulation) to ensure we are sensitive to data/MC differences.

- One single additional cut to reject non-signal like events containing highly ionising tracks (protons)





Contains **ν** events with similar topology to HNL (mainly **CC ν_μ 1 pion**)

Evidence that if HNL are present in data we would select them (at the rate we expect)

Looking at Data

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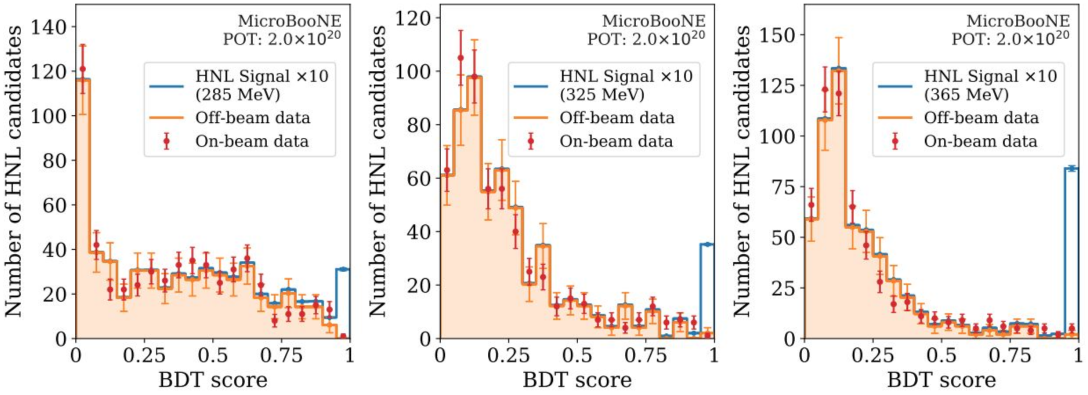
- Run BDT over data in beam correlated HNL window.
- Signal and background data samples show good agreement across BDT score
- No excess observed in signal like region (BDT score < 0.95)

$|U_{\mu 4}|^2 = 1.4 \times 10^{-7}$

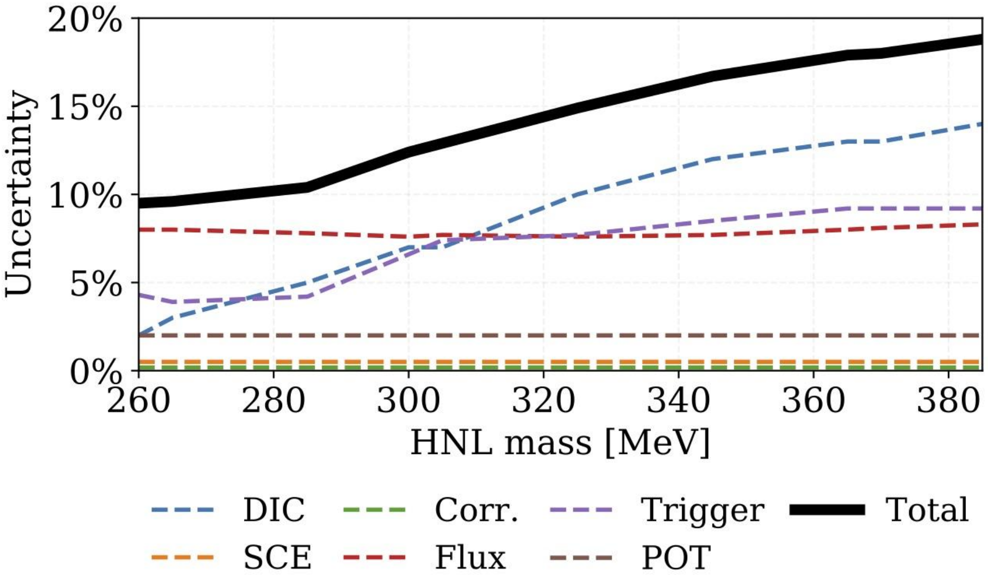


Mass (MeV)	BDT Score > 0.95 HNL	Bkg.	Data	BDT Score 0.5–0.95 HNL	Bkg.	Data
260	0.21 ± 0.03	< 3.7	1	0.43 ± 0.06	169 ± 19	170
265	0.42 ± 0.06	2 ± 2	1	0.6 ± 0.1	185 ± 19	205
285	1.6 ± 0.3	< 3.7	3	0.8 ± 0.1	175 ± 19	174
300	2 ± 0.3	2 ± 2	1	1.0 ± 0.2	126 ± 16	121
305	4 ± 0.6	2 ± 2	4	0.8 ± 0.1	61 ± 11	80
325	6 ± 1	2 ± 2	0	1.6 ± 0.3	57 ± 11	69
345	12 ± 2	2 ± 2	4	2 ± 0.3	59 ± 11	69
365	20 ± 3	2 ± 2	5	2 ± 0.3	35 ± 8	53
370	24 ± 4	2 ± 2	4	4 ± 0.6	37 ± 9	47
385	36 ± 6	< 3.7	4	4 ± 0.6	20 ± 6	28

- **Set limits on $|U_{\mu 4}|^2$ as a function of HNL mass (M_N)**

Systematic Error

- Uncertainties come predominantly from
  - Flux (kaon production at target, horn focusing uncertainty)
  - Trigger efficiency (PMT timing resolution)
  - Detector effects (Dynamically Induced Charge - DIC, Space Charge Effects - SCE)

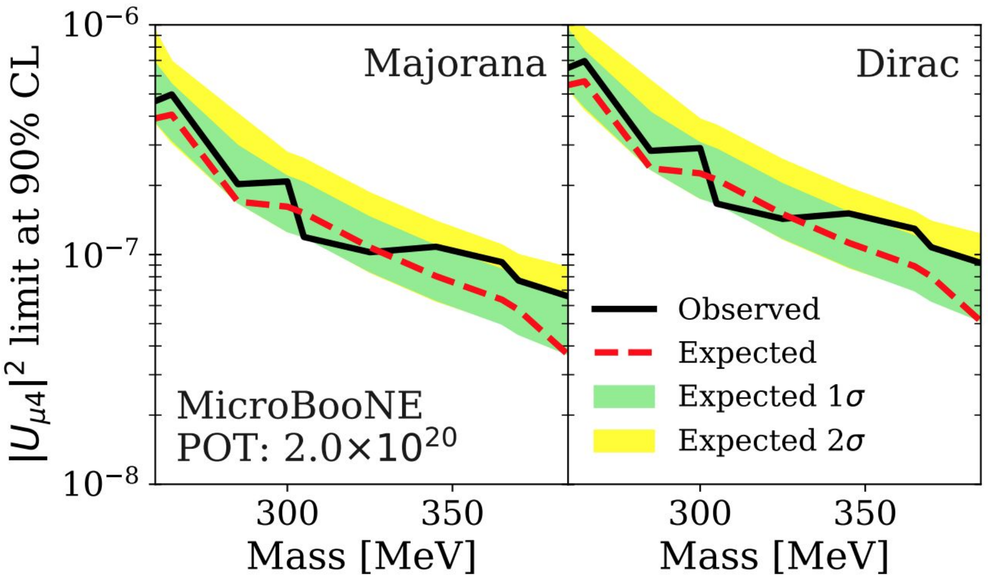


Limit Setting

- First search for HNLs in a LArTPC
- Observed and expected median **upper limits** at the 90% CL **agree within 1 standard deviation** over the entire mass range.
- Limits for Dirac case are identical but reduced by a factor of √2 as only **N→μ⁻π⁺** possible and $\mathbf{N_{events} \propto |U|^4}$

- Published in PRD DOI: [10.1103/PhysRevD.101.052001](https://doi.org/10.1103/PhysRevD.101.052001)

HNL Exclusion Limit



Limit in Context

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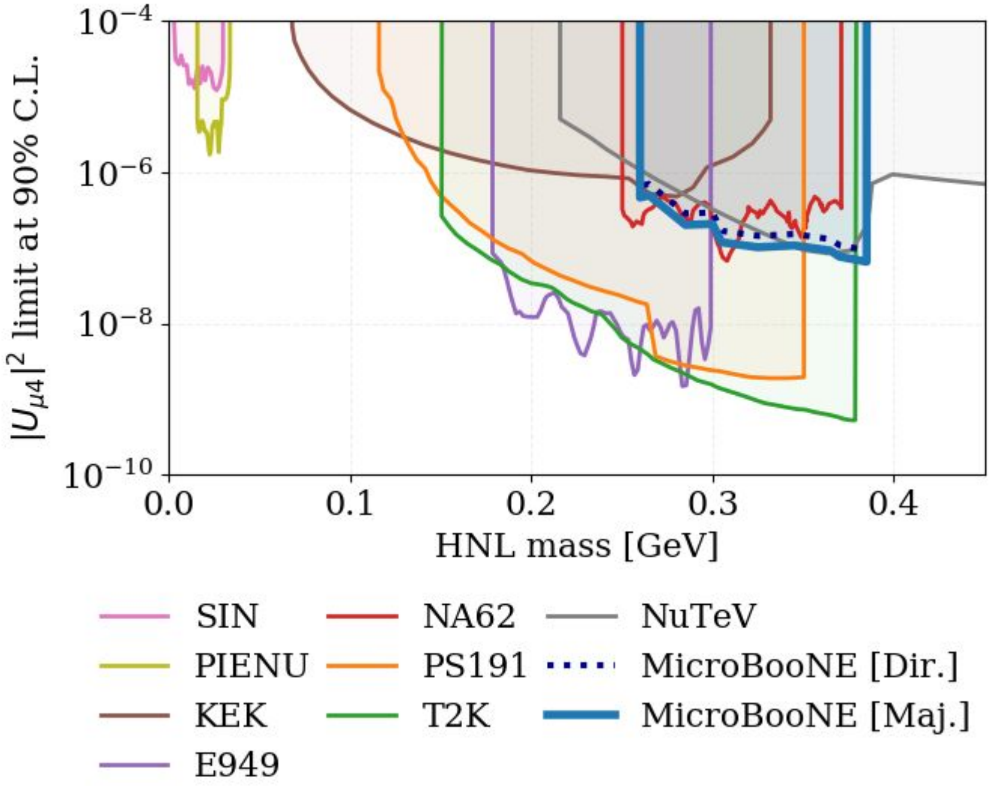
- Results similar sensitivity to NA62 and NuTeV for upper end of mass range
- PS191 and T2K currently set more constraining limits for most of mass range.
- MicroBooNE sets the most constraining limit at production threshold of 385 MeV



Summary & Outlook

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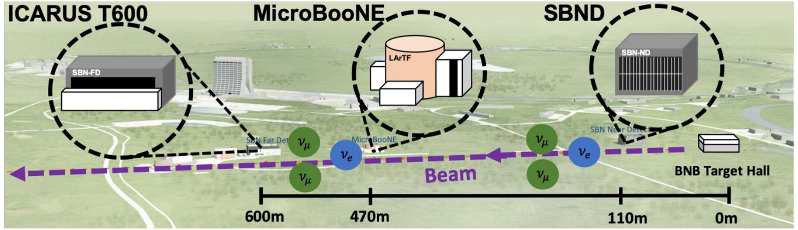
- This is the first search for HNLs in a LArTPC
- More searches in MicroBooNE ongoing.
  - Collected almost **3 times** more data in the late window than used in this analysis
  - Selections for different final states (**N→eπ, access to** $|U_{e4}|$)
  - Can also search within neutrino beam
- Full SBN program will extend sensitivities
  - SBND ~110m from beam, higher flux.
  - ICARUS significantly larger TPC volume



Detector	Baseline (m)	Active LAr mass (tonnes)
SBND	110	112
MicroBooNE	470	87
ICARUS T-600	600	476

Backup

Booster Neutrino Beam (BNB)

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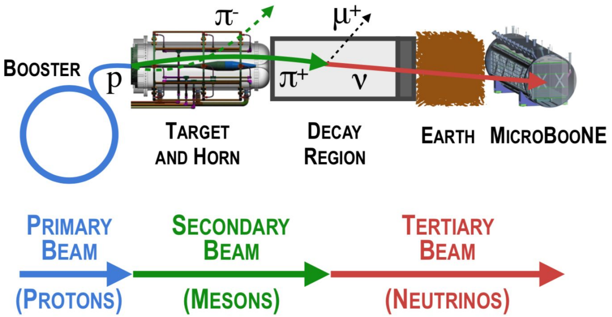
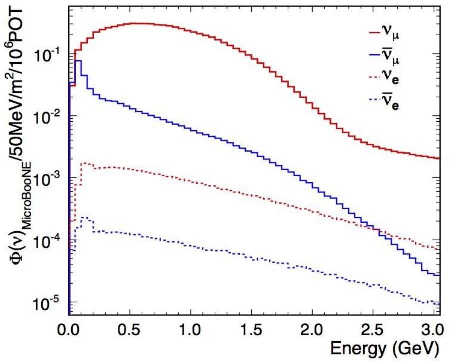
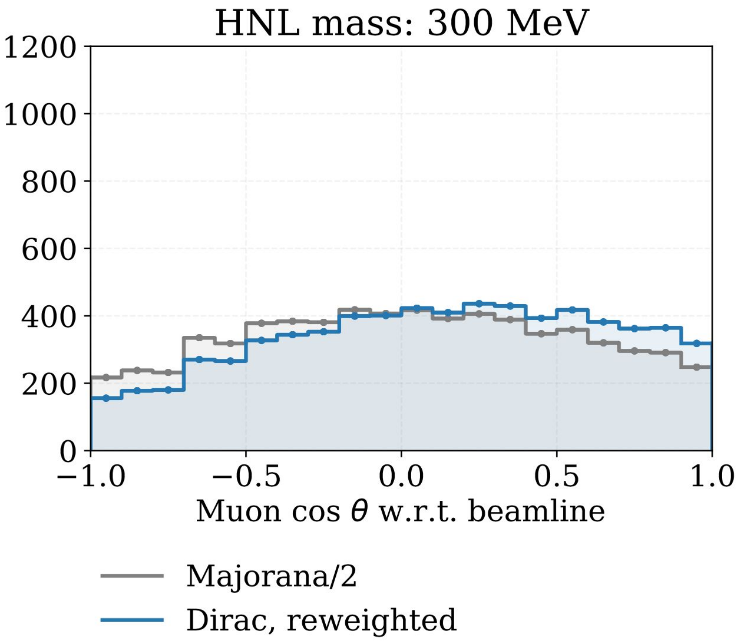
- Proton collisions with fixed target produce beam of predominantly $\pi^{+/-}$ (>96 %) and $K^{+/-}$ (<4%) which decay to neutrinos.
- Charge selection by focusing horn.
- Has been run in **neutrino mode** since 2015 when MicroBooNE came online





Majorana or Dirac

- HNLs could be a Majorana or Dirac particle
- Majorana HNL $\overline{N} = N$
  - **$N \to \mu^+\pi^-$** and **$N \to \mu^-\pi^+$** in equal number
  - Combination of $\mu^+\pi^-$ and $\mu^-\pi^+$ **isotropic** in HNL rest frame.
- Dirac HNL
  - **$N \to \mu^-\pi^+$** only
  - Decay rate half of Majorana
  - **Asymmetric** angles of decay in HNL rest frame (Muon more likely to be in direction of beam).



Work with Majorana assumption but reweight to Dirac distribution to produce results for both scenarios

Pre-selection Variables

- Pre-selection requirements serve the double purpose of **increasing S/B ratio** and **improving reconstruction quality** of HNL candidates for further discrimination via **BDT** application
- Variables chosen to have **minimum dependency on HNL mass**.
- Mass-dependent information is reserved for BDT, which is **trained for each HNL mass**.

Pre-selection requirements

Name	Variable Used	Requirement
Fiducial volume	HNL vertex x coordinate	>12 cm *and* < 244.35 cm
	HNL vertex y coordinate	> -80.5 cm *and* < 80.5 cm
	HNL vertex z coordinate	(> 25 cm *and* < 675 cm) *or* (> 775 cm *and* < 951.8 cm)
Vertex-track distance	Distance between vertex and farthest track start point	< 5 cm
Minimum number of hits	Number of hits of smallest track	> 30 hits on collection plane
Flash PE	PE of largest flash in event	> 0 PE
Vertex-flash distance	2-d distance between HNL and largest flash	< 150 cm
Track containment	x coordinate of end point farthest from centre	>12 cm *and* < 240 cm
	y coordinate of end point farthest from centre	> -98 cm *and* < 98 cm
	z coordinate of end point farthest from centre	> 15 cm *and* < 1010 cm
Opening angle	3-d angle between tracks	< 2.8 radians (160°)
Invariant mass	Range-calculated HNL candidate invariant mass	< 0.5 GeV

BNB HNL Flux

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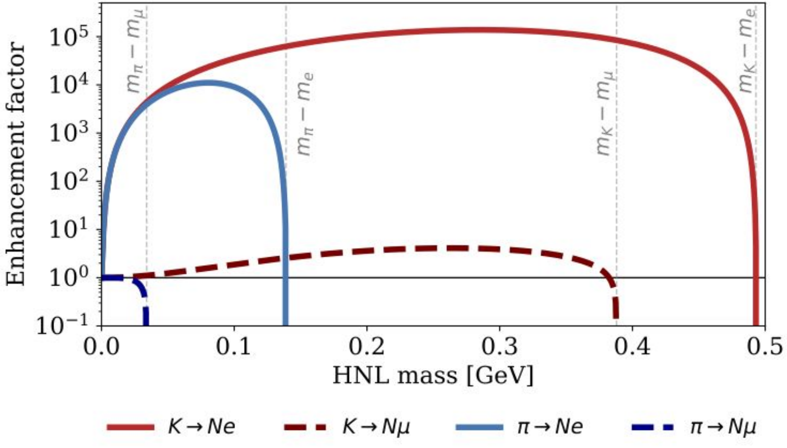
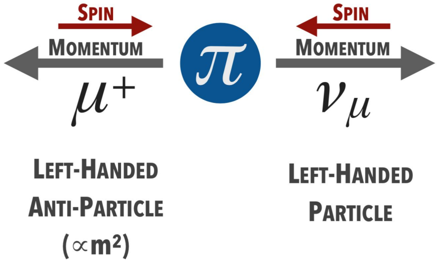
- Consider non zero $|U_{\mu 4}|$, $(|U_{e4}|=0)$
- HNL produced by $K^+ \to \mu^+ N$
- Flux calculated using parent meson (kaons) information from neutrino flux simulation for a mass M_N
  a. Calculate HNL kinematics for each kaon decay
  b. Weight by ratio of HNL and neutrino branching width
  c. Weight by probability of HNL intersecting TPC.



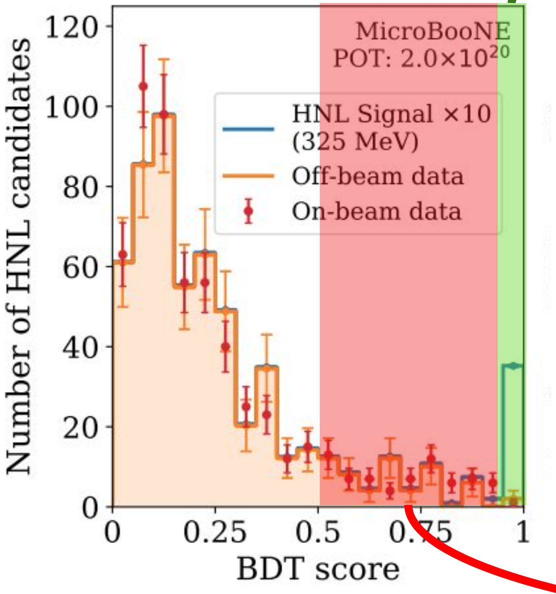
Adjusts for phase space change and enhancement due to helicity unsuppression



Limit Setting

Follow a two-bin approach, used for modified frequentist CLs method.

Signal Enriched



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Signal Depleted