First Search for Heavy Neutral Leptons with a Liquid-Argon Detector

Warwick Elementary Particle Physics Seminar - 14/05/2020

Owen Goodwin
University of Manchester

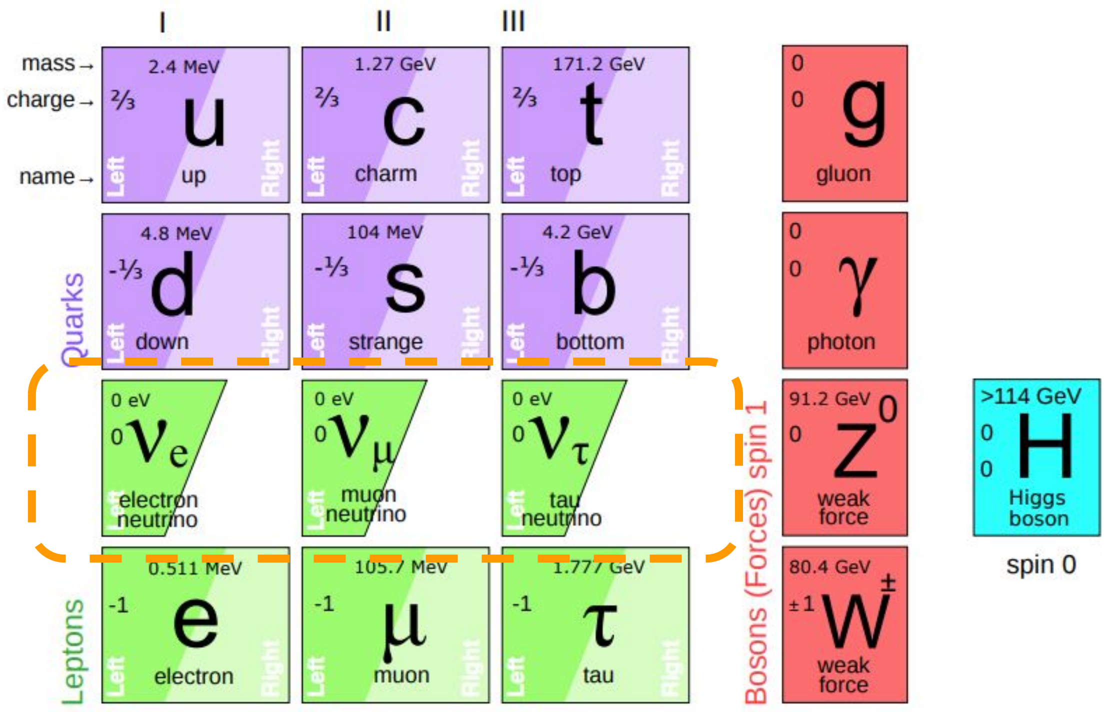
MANCHESTER 1824
The University of Manchester

Outline

- Standard Model Neutrinos, what we know and don't know?
- What are Heavy Neutral Leptons (HNL)?
- The Short Baseline Neutrino program at Fermilab
    - MicroBooNE data taking

- Heavy Neutral Leptons at MicroBooNE
    - Production in neutrino beams
    - Visible final state decays
    - Using MicroBooNE LarTPC to perform first search for HNL
    - Outlook

Neutrinos in the SM



- Neutrinos are one of the least understood particles in the Standard Model (SM)
- Neutral leptons with tiny mass & very small interaction cross section
- Only Left Handed versions in the SM

Oscillations

- **Super-Kamiokande** and **SNO** established that neutrinos oscillate and therefore have mass
- Three-neutrino picture well established
- Mixing angles well measured by oscillation experiments
- Next generation long baseline experiments (**DUNE** & **Hyper-K**) will complete picture.

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27 \Delta m_{ij}^2 \frac{L}{E}\right)$$

$\delta_{cp} = ?$

$\Delta m_{23} > 0$ or $\Delta m_{23} < 0$?

Open Questions

Which neutrino is the lightest?

Is there CP violation in neutrino oscillation?

Are there extra neutrinos (sterile)?

How is the neutrino mass generated (Dirac or Majorana)?

Can CP violation in leptons lead to the matter-antimatter asymmetry of the Universe today?

Heavy Neutral Leptons

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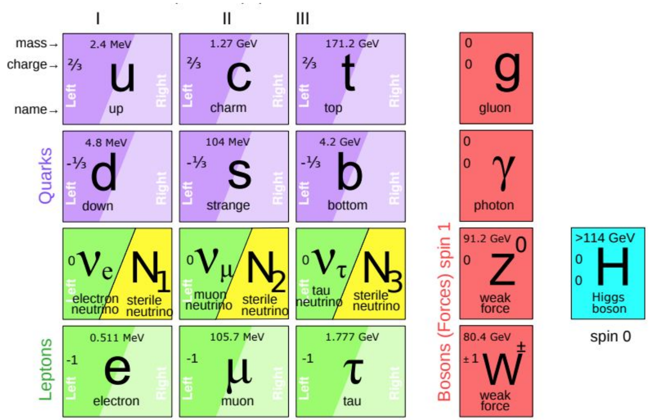
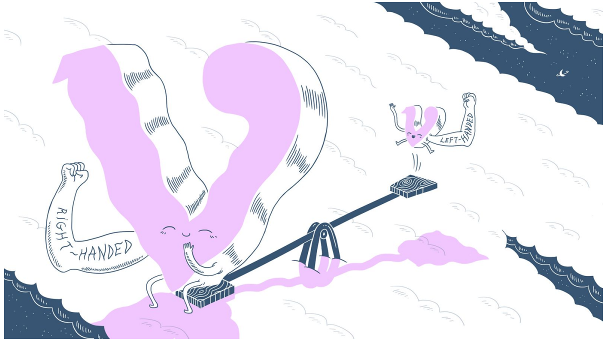
νMSM: T.Asaka, M.Shaposhnikov PL B620 (2005) 17

Beyond Standard Model right-handed neutral leptons, known as *sterile neutrinos* or *Heavy Neutral Leptons* ***(HNL)***

Their inclusion provides possible mechanisms for neutrino mass generation

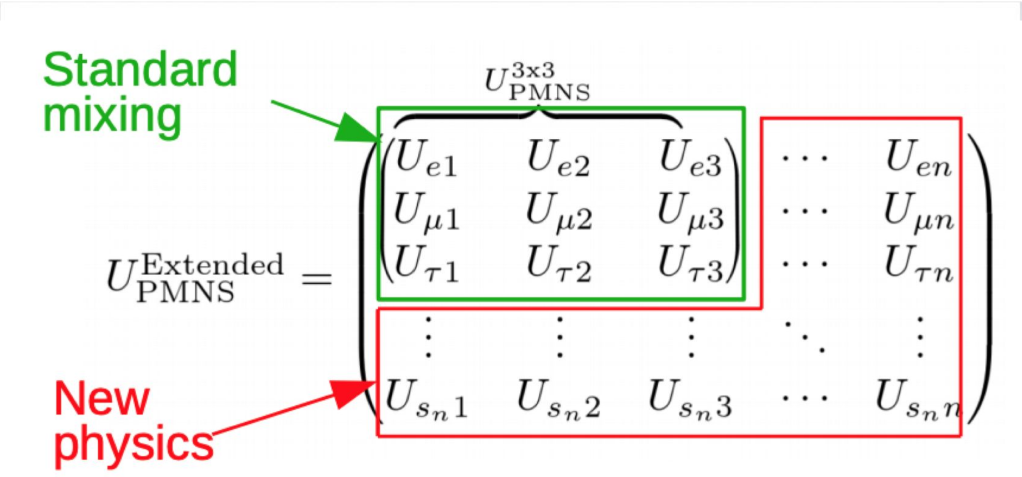
Could play a role in Leptogenesis in the early universe to explain current matter-antimatter asymmetry



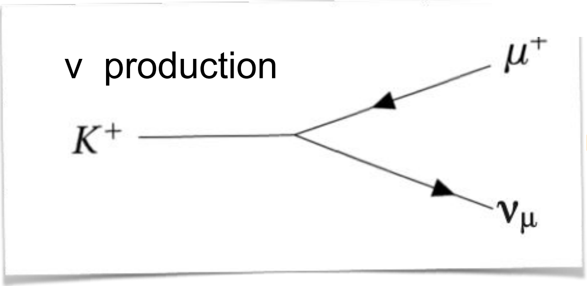


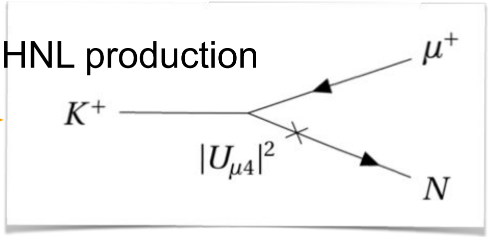
HNLs

- HNL (shown as **N**) enter SM physics through **mass mixing**.
- Can substitute an HNL into any SM neutrino process via mass mixing through extended PMNS matrix element (if kinematically allowed).



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



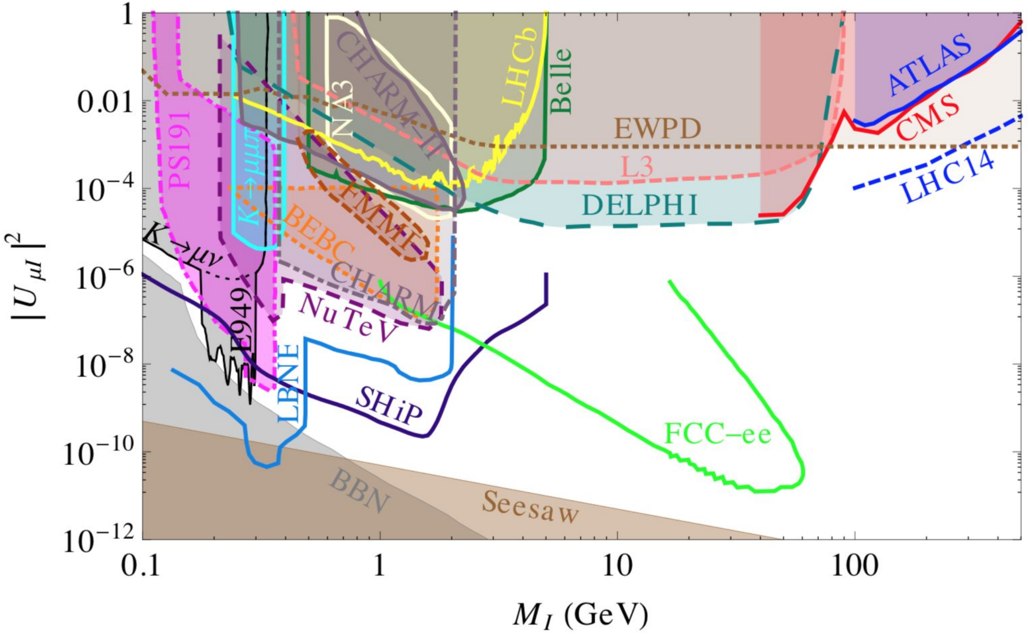


HNLs

Possible mass of HNL spans many orders of magnitude

The mass mixing elements are known to be very small

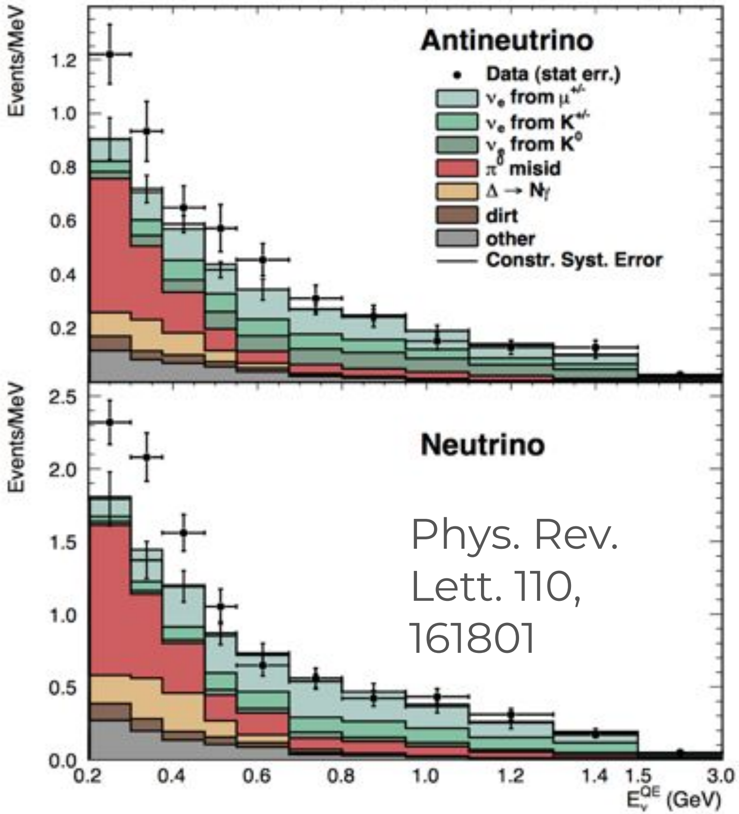
O(100 MeV) mass HNL could be produced in high intensity neutrino beams, then decay to visible particles in detectors.



The Short Baseline Neutrino program at Fermilab

1eV oscillation anomaly

- Anomalies measured at short baseline (< 1km) neutrino experiments.
- LSND: measured a **3.8σ** excess in **ν_μ-> ν_e** appearance channel
- Follow up experiment MiniBooNE measured a **4.7σ** combined excess of electron neutrino like events at low energy.
- Can be interpreted as a “fast” oscillation not consistent with 3-flavour oscillation pattern.
  - → New fourth “sterile” neutrino
  - $\Delta m^2_{41} \approx 1$ eV^2



Phys. Rev. Lett. 110, 161801

SBN program

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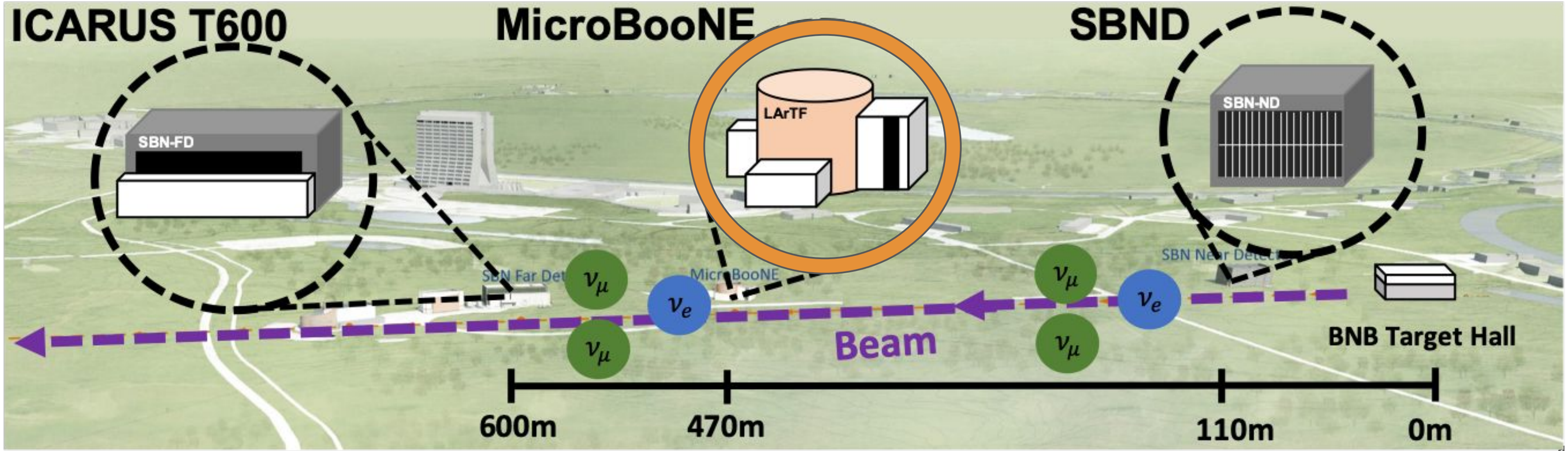
3 detectors in ~800 MeV Neutrino Beam

All Liquid Argon Time Projection Chambers (LArTPC)

Measure flavour composition at different baselines

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



SBN program Physics Goals

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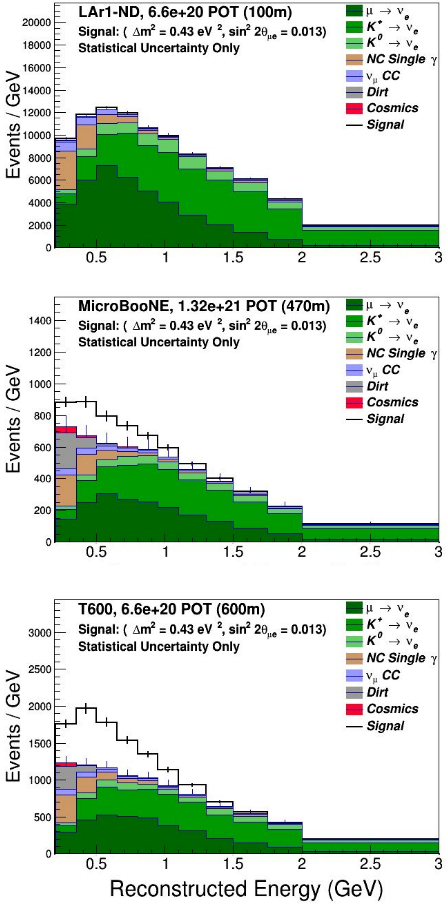
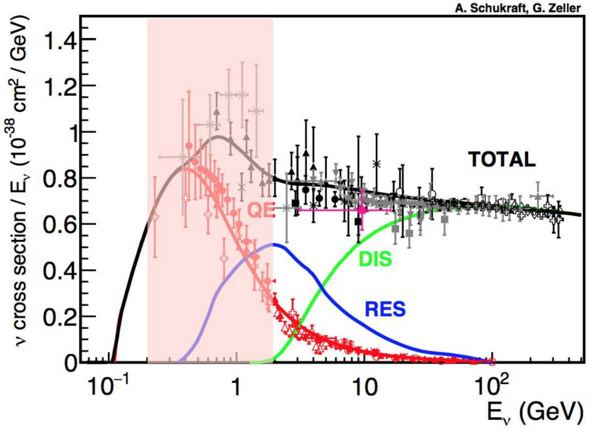


- Designed to comprehensively investigate the Miniboone low energy excess.
- Precise **ν**-LAr cross sections, pioneered in MicroBooNE, followed up with more stats in SBND. Feed into DUNE long-baseline oscillation experiment
- ***Search for astroparticle and rare exotic events***



Booster Neutrino Beam (BNB)

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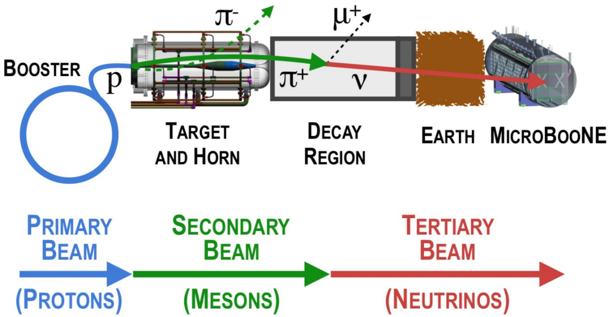
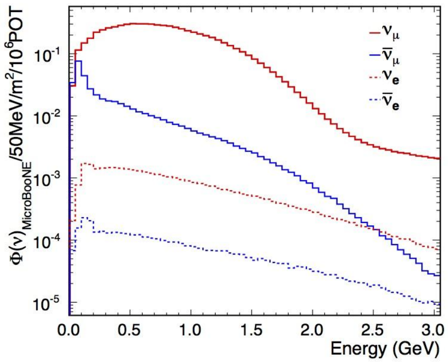
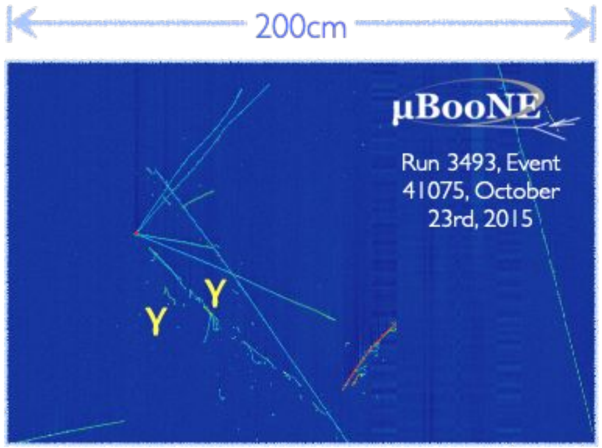
- Protons accelerated to **8 GeV** onto a fixed target
- Focused beam of predominantly **$\pi^{+/-}$** (>96 %) and **$K^{+/-}$** (<4%) decays to neutrinos.
- Charge selection by focusing horn.
- Has been run in **neutrino mode** since 2015 when MicroBooNE came online

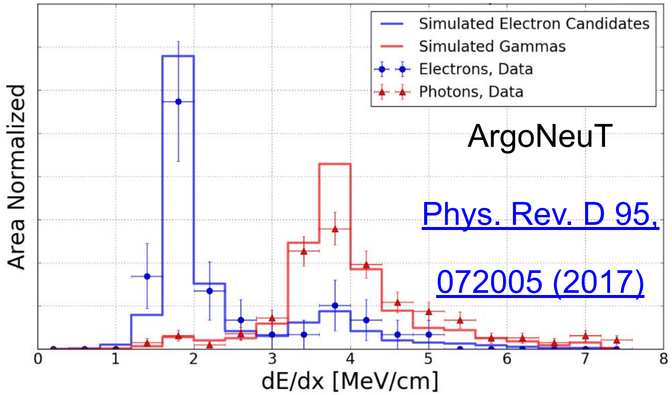




LArTPCs

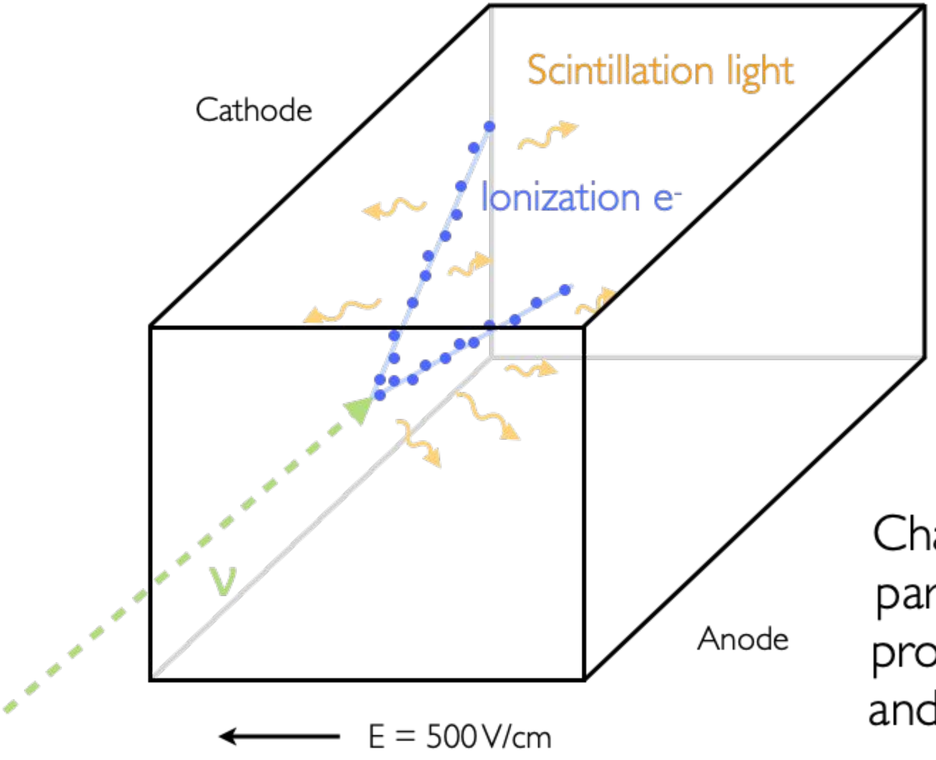
- LAr - inexpensive and dense, excellent neutrino target
- Bubble-chamber like images with excellent spatial resolution (~3mm)
- Digital format images with automated reconstruction algorithms for large-scale analysis.
- Excellent calorimetric response and energy resolution





[Phys. Rev. D 95, 072005 (2017)]

LArTPC

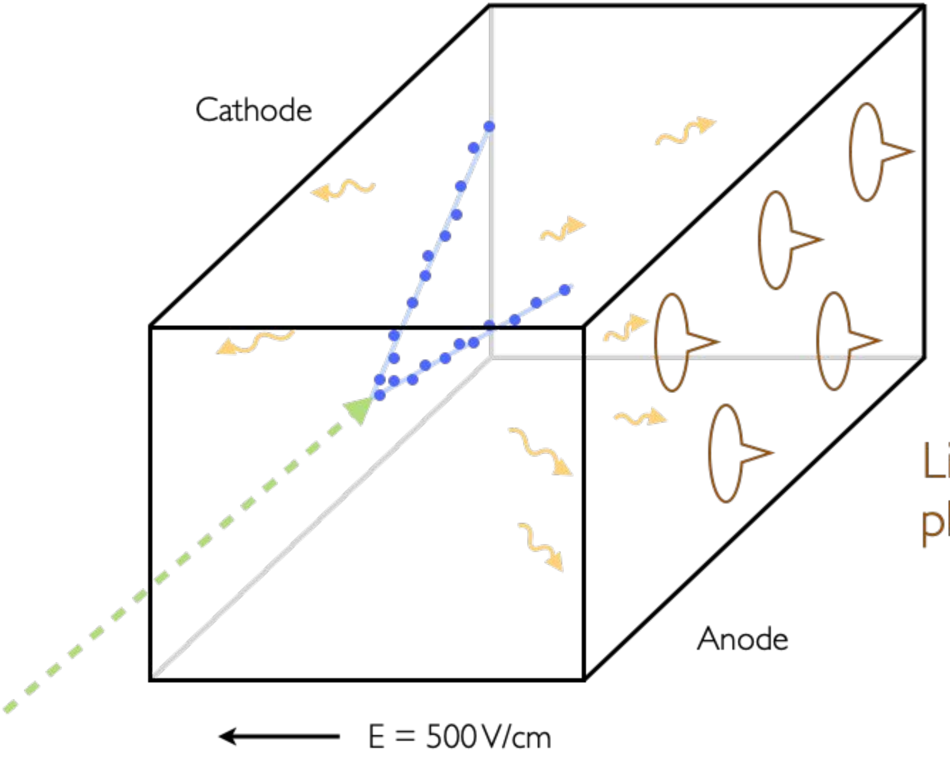


Incoming neutrino interacting with LAr

Charged secondary particles ionize LAr, producing electrons and scintillation light

Graphics from Yun-Tse Tsai

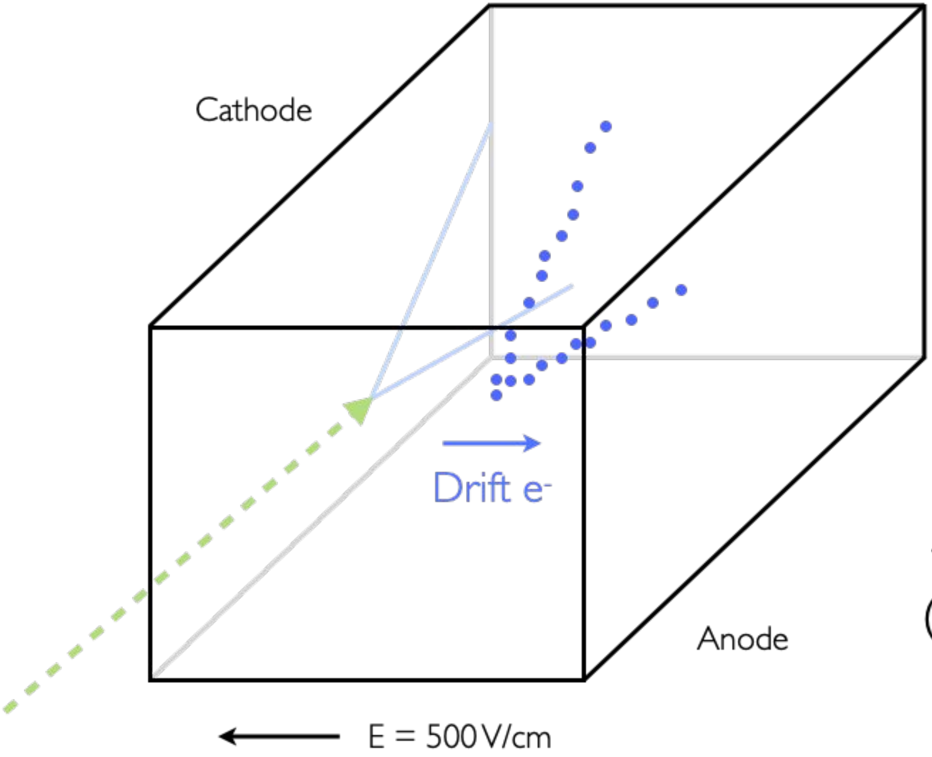
LArTPC



Light collected by photon detectors (10-100ns), determining event time t_0

Graphics from Yun-Tse Tsai

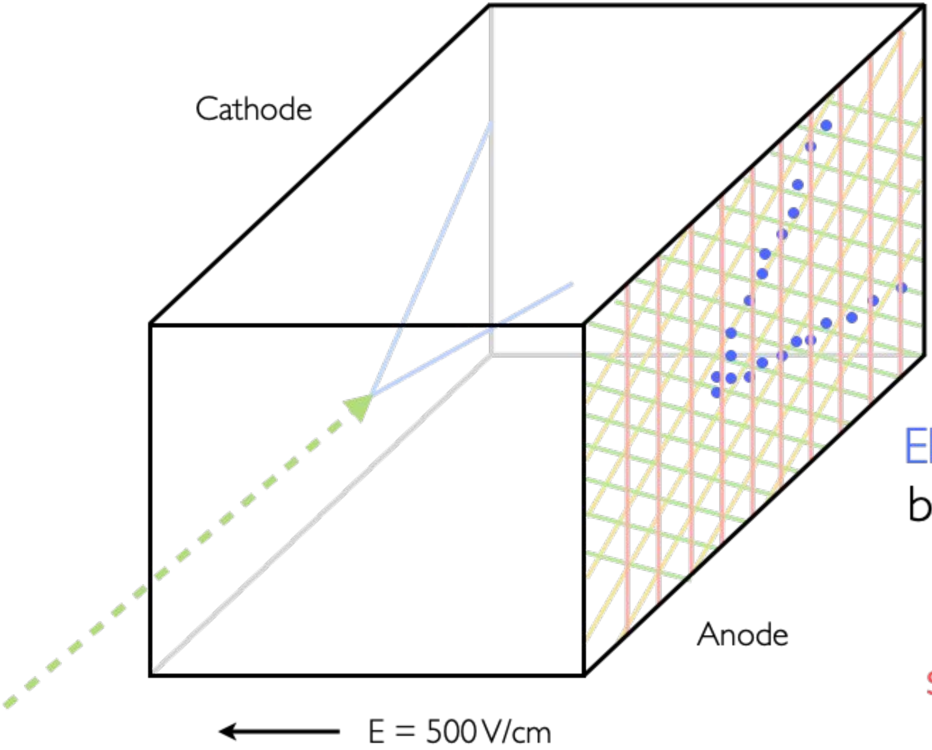
LArTPC



Electrons drift towards anode (drift time at ms scale)

Graphics from Yun-Tse Tsai

LArTPC

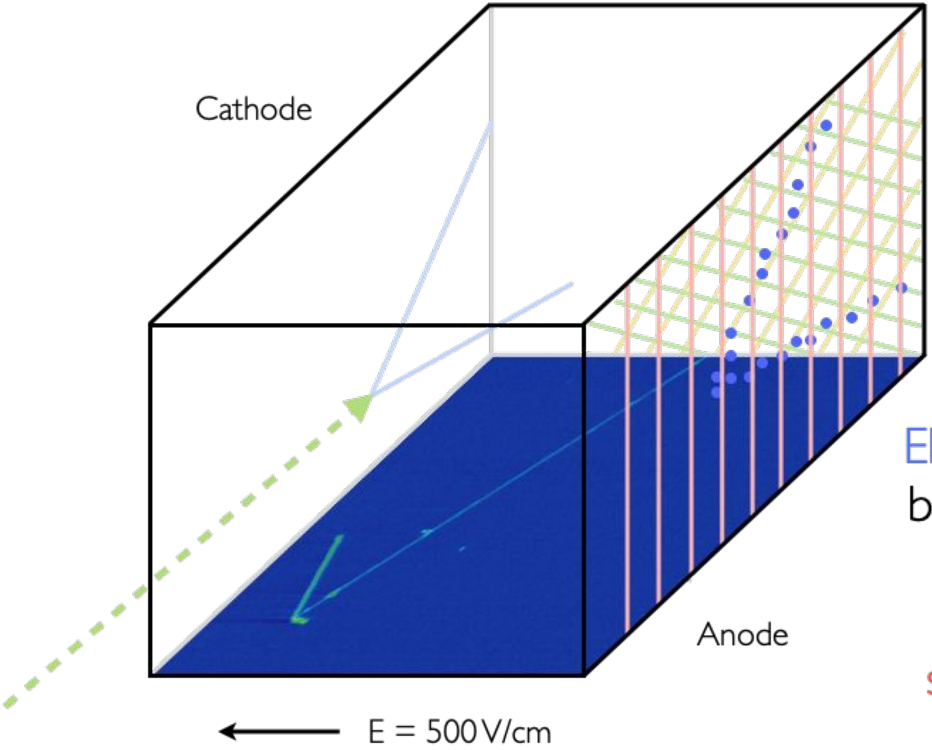


2 induction planes
1 collection plane

Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

Graphics from Yun-Tse Tsai

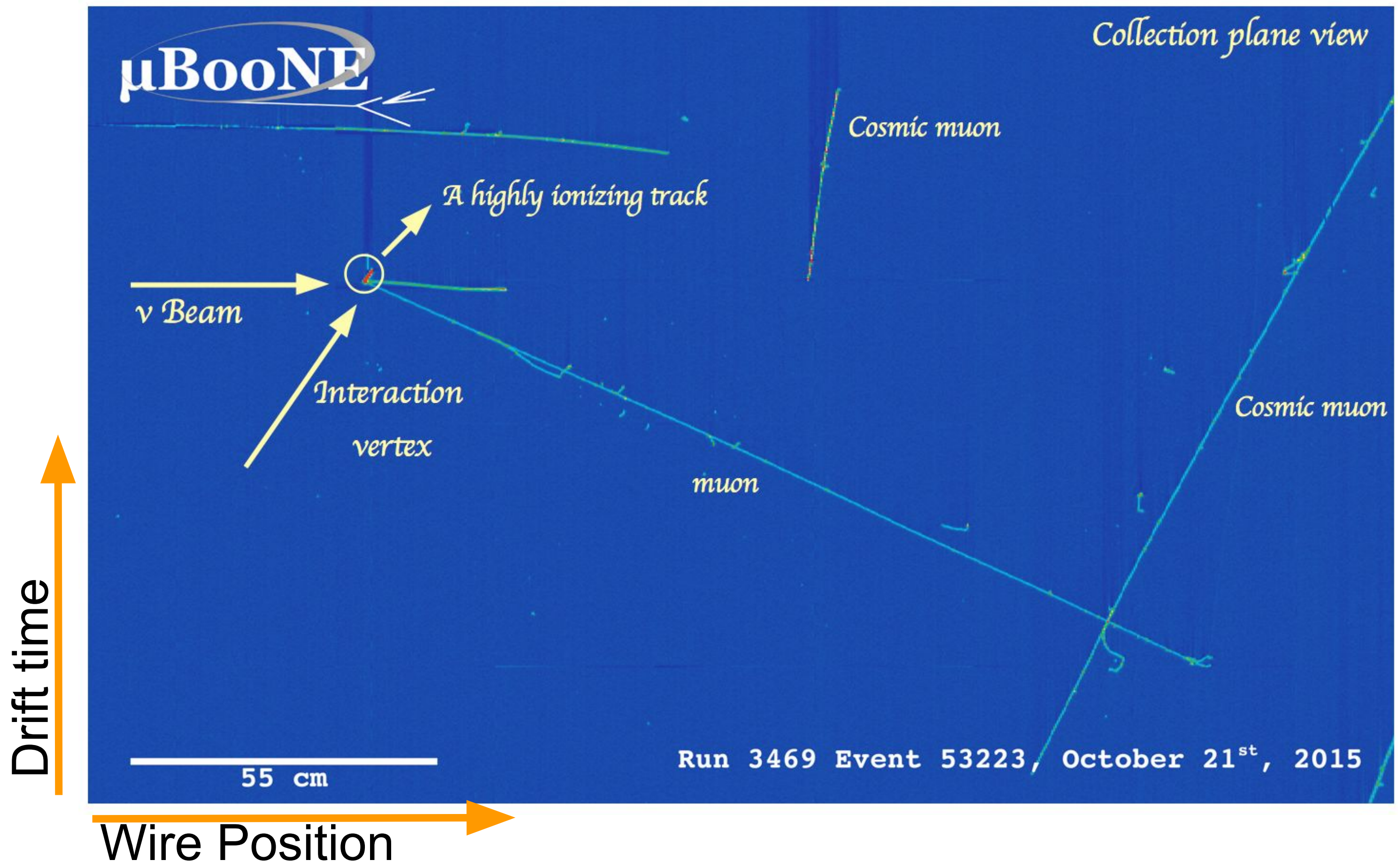
LArTPC



Electrons detected by the wire planes at anode, providing the spatial, kinematic information.

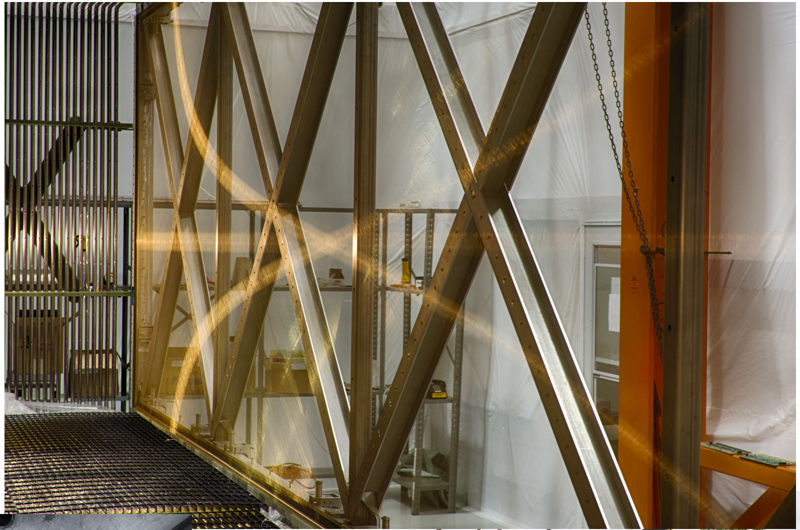
Graphics from Yun-Tse Tsai

Interaction in LArTPC



MicroBooNE

- Collecting neutrino data since 2015
- Longest running LAr neutrino experiment (~1.5 x 10^21 POT of beam exposure)



Cosmic Rays

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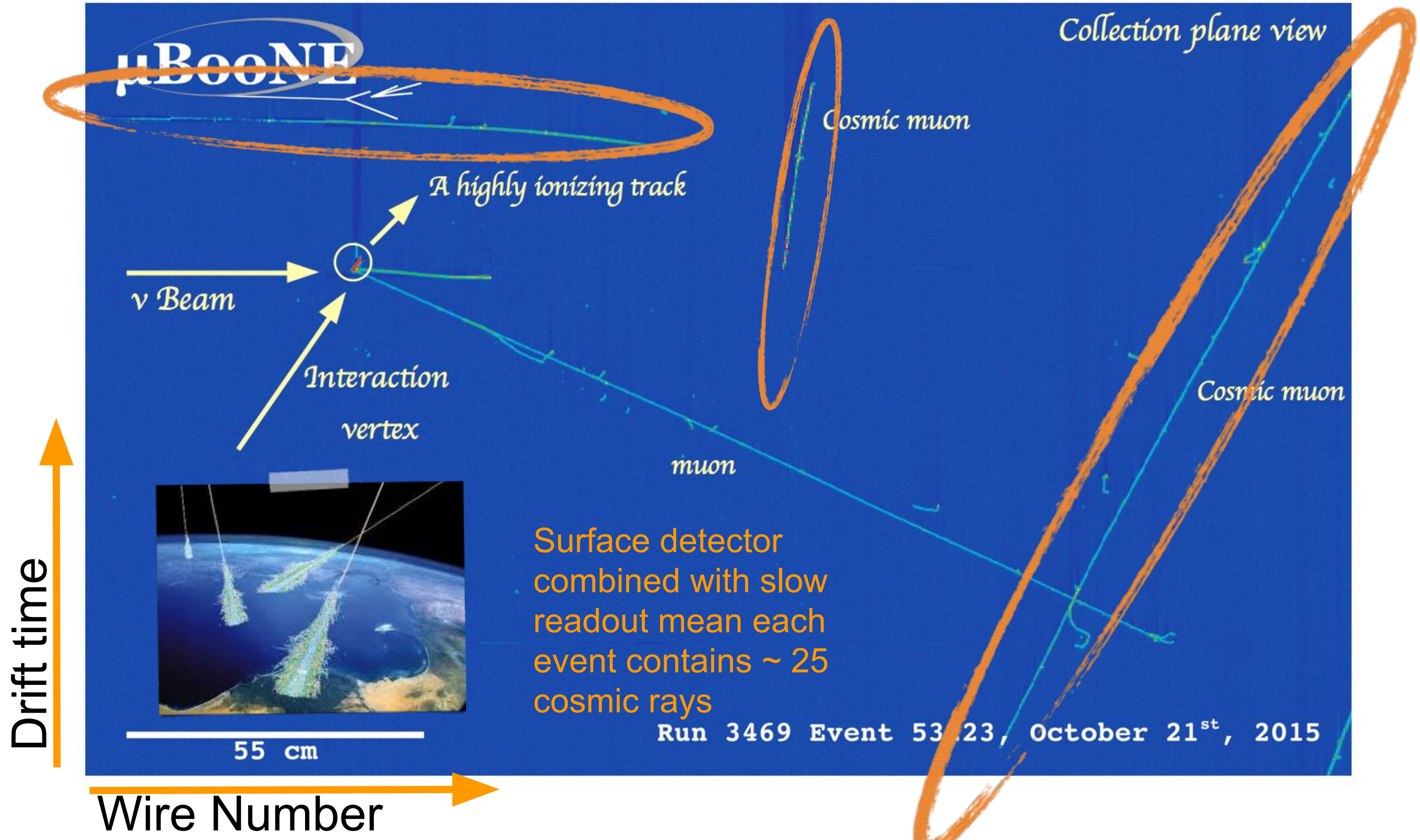
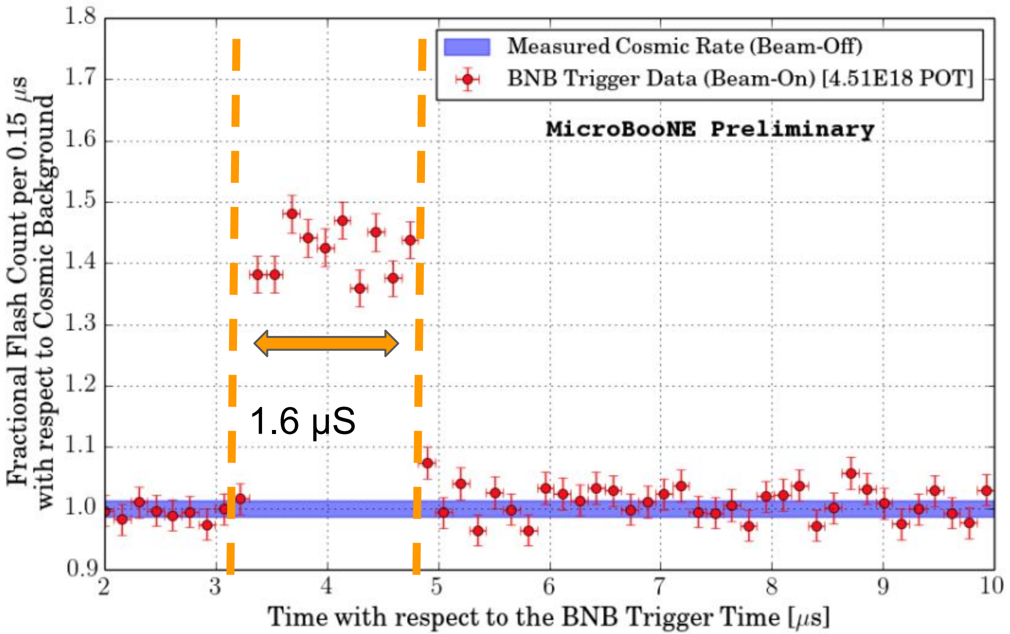
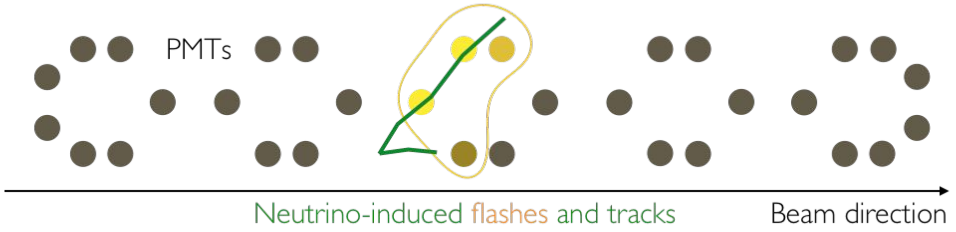


Surface detector combined with slow readout mean each event contains ~ 25 cosmic rays

Event timing and triggering

- Neutrinos arrive in a beam spill which lasts for **1.6 μS**
- Only ~1/600 beam spills produces a neutrino interaction in MicroBooNE
- Trigger on optical flashes occurring in coincidence with the arrival time of neutrinos.
- Drifted charge matched to these flashes is likely to be beam-induced

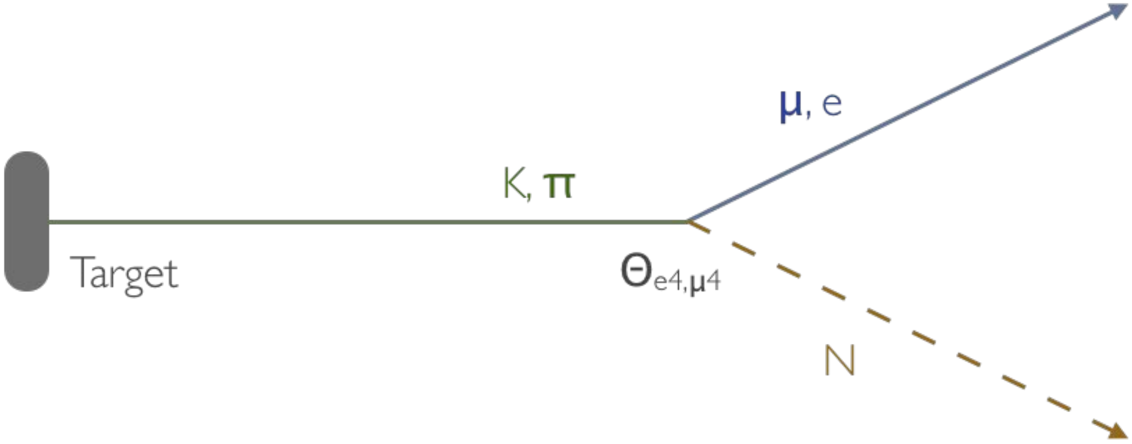




MeV Scale Heavy Neutral Leptons in MicroBooNE

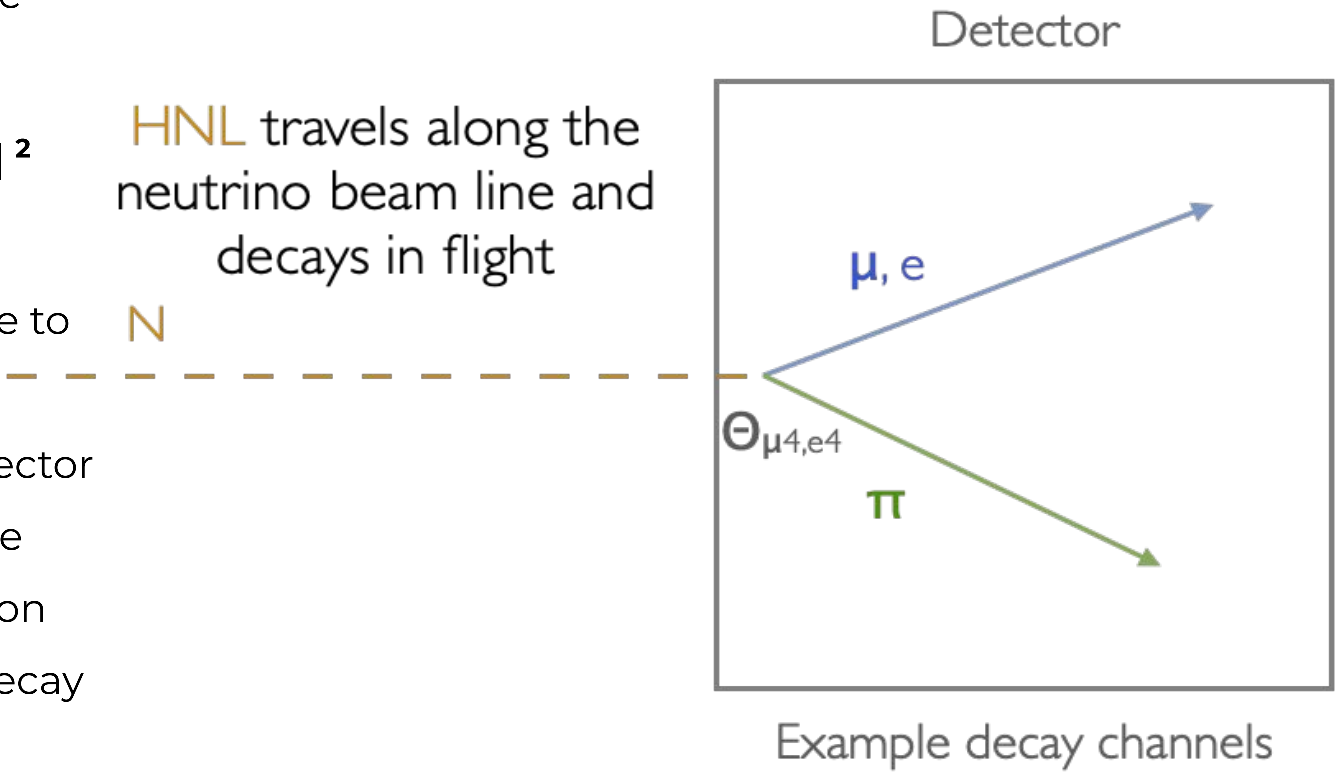
Production in BNB ν beam

- HNLs are produced in meson decays in the beam line via mixing
- Production rate ∝ $|U_{\alpha 4}|^2$
- Kaons heaviest meson produced in large quantities in BNB
- HNL with **mass < 495 MeV** could be produced in BNB

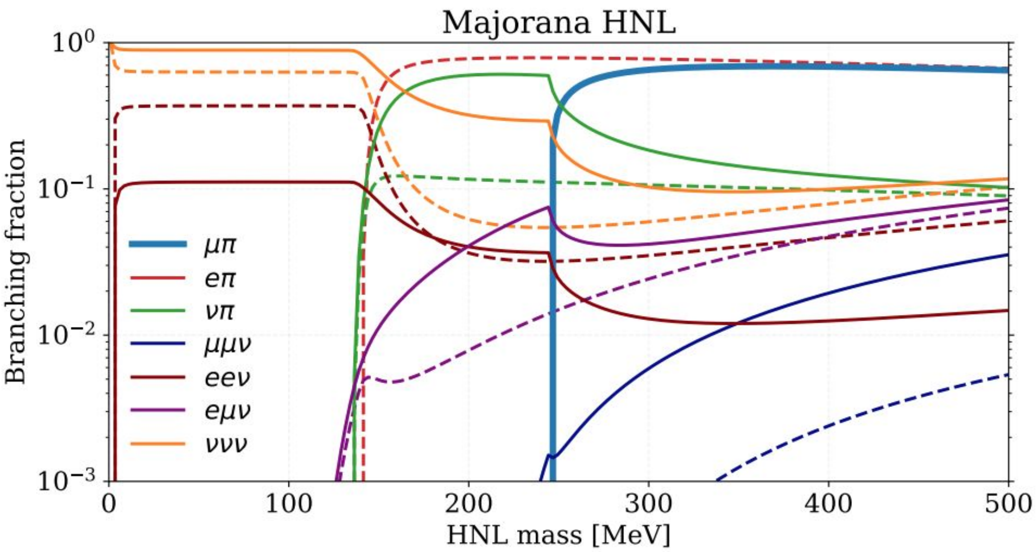


HNL Detection

- Decay in flight inside detector
- Decay Rate $\propto |U_{\alpha 4}|^2$
- Decay length much longer than distance to MicroBooNE
- So event rate in detector is proportional to the product of production mixing angle and decay mixing angle



Possible Decay Channels



$|U_{\mu4}|=1$

$|U_{e4}|=1$

Two-body decays $N \rightarrow l^{\pm}\pi^{\mp}$ dominate when $M_N > 250$ MeV

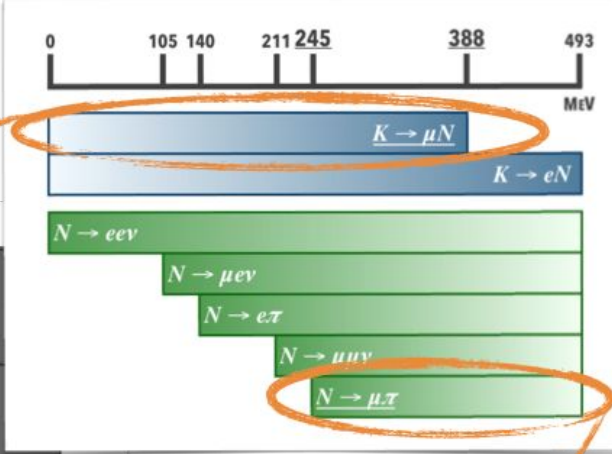
- Charged current: N→γν, N→μeν, **N→eπ, N→μπ**
- Charged and neutral current: N→3ν, N→eeν, N→$\nu\pi^0$, N→μμν

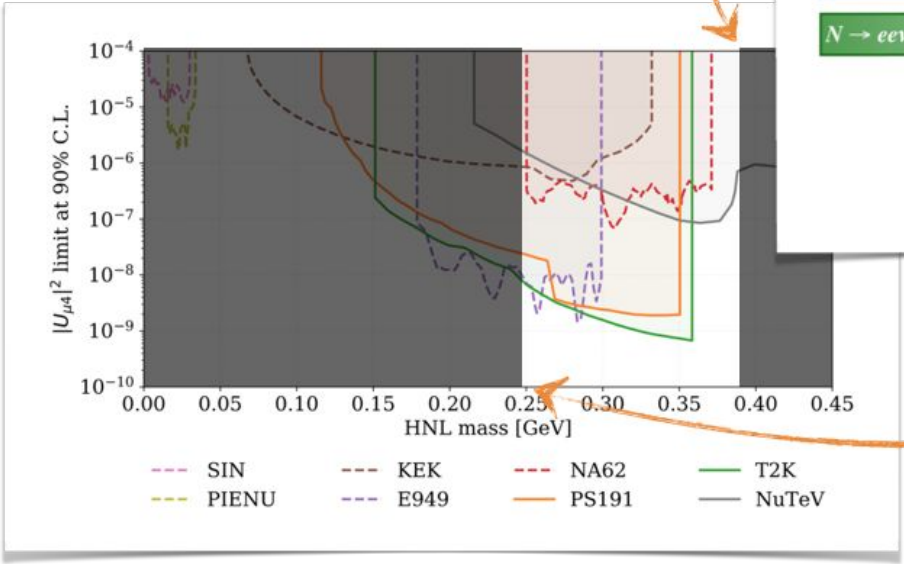
Decay to μπ pairs

This analysis searches for $N \rightarrow \mu^{\pm}\pi^{\mp}$

Two tracks from shared vertex with invariant mass of HNL

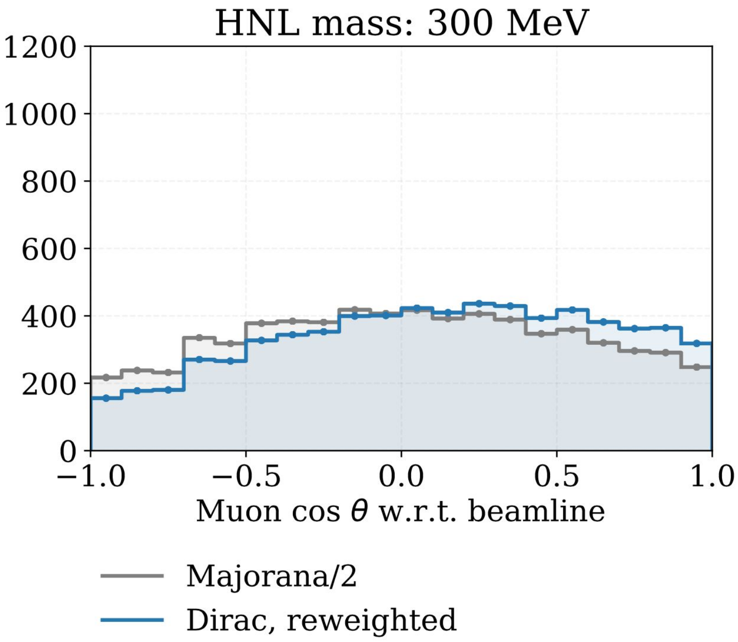
Decay rate probes $|U_{\mu 4}|$ mixing.





Majorana or Dirac

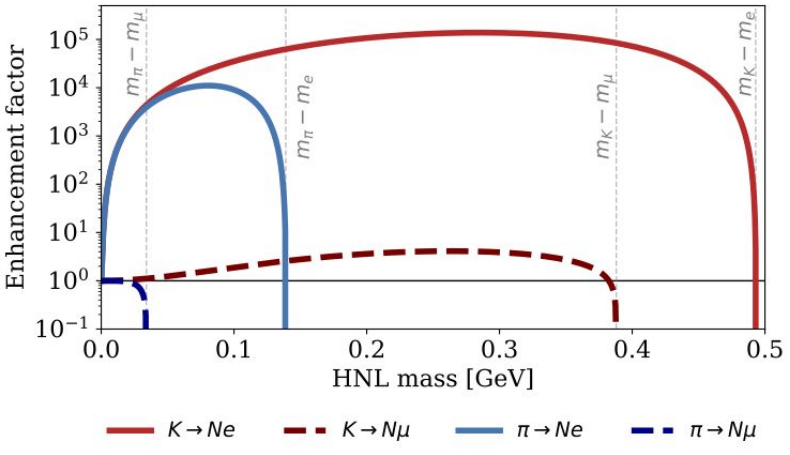
- HNLs could be a Majorana or Dirac particle
- Majorana HNL $\overline{N} = N$
  - **N→μ⁺π⁻** and **N→μ⁻π⁺** in equal number
  - Combination of $\mu^+\pi^-$ and $\mu^-\pi^+$ **isotropic** in HNL rest frame.
- Dirac HNL
  - **N→μ⁻π⁺** only
  - Decay rate half of Majorana
  - **Asymmetric** angles of decay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



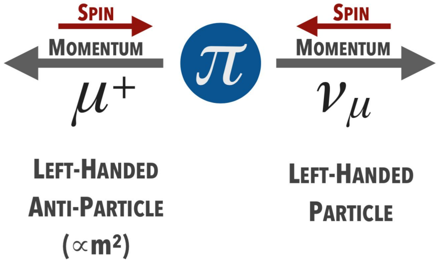
Work with Majorana assumption but reweight to Dirac distribution to produce results for both scenarios

BNB HNL Flux

- Consider non zero **$|U_{\mu4}|$** , **($|U_{e4}|=0$)**
- HNL produced by $K^+ \rightarrow \mu^+ N$
- 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



Collimation of HNL

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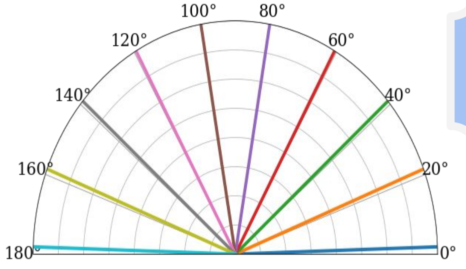
Meson decays to both **HNL** and **ν** are **isotropic** in **rest frame**

To MicroBooNE

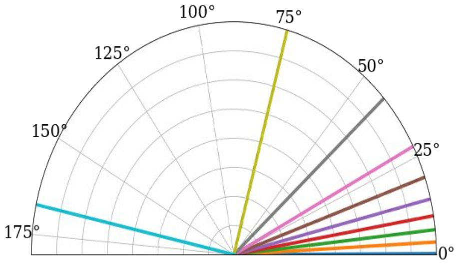
1.75 GeV kaon
$K^+ \rightarrow \mu^+$ + (ν or N)



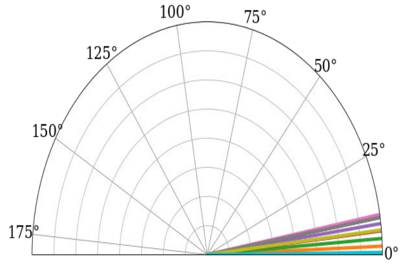
Isotropic Rest Frame Angle

Boost

Boost



ν Lab Frame Angle

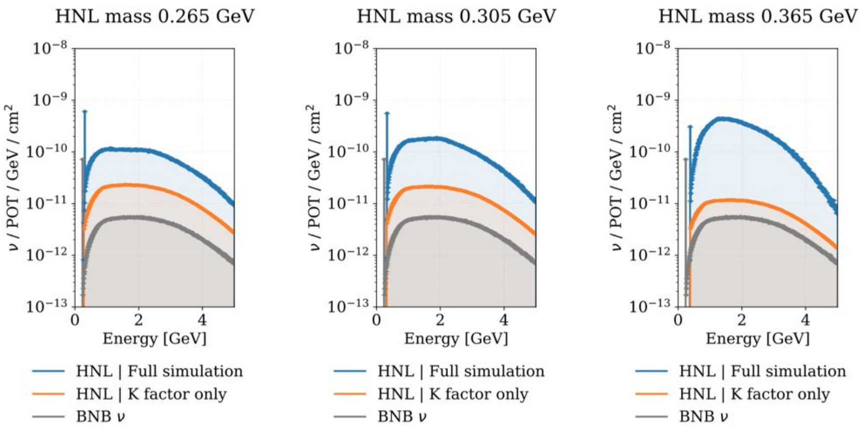


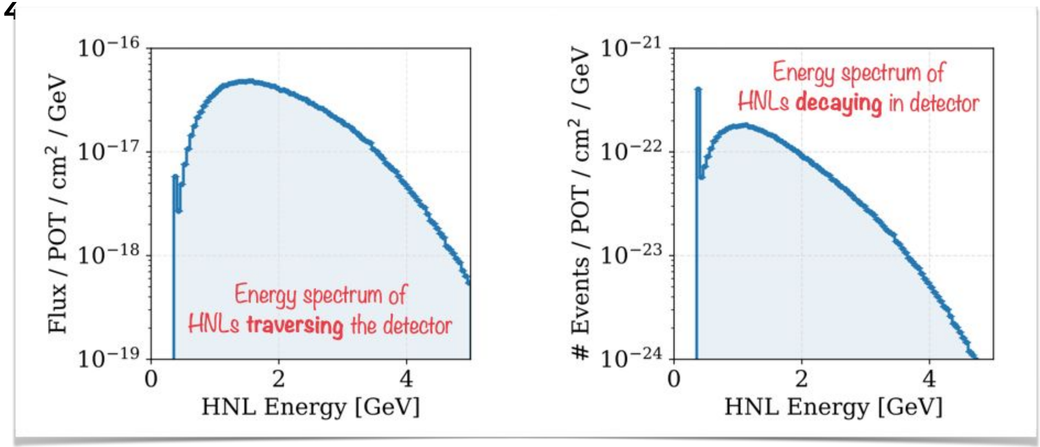
HNL (Mass 265 MeV) Lab Frame Angle

HNL significantly more **collimated** towards detector than neutrinos

Event Rate

- Event spectrum = flux x decay spectrum
- Decay rate $\propto$ 1/(HNL Momentum)
- Enhances low momentum HNL
- Event rate in MicroBooNE $\propto$ $|U_{\mu 4}|^4$

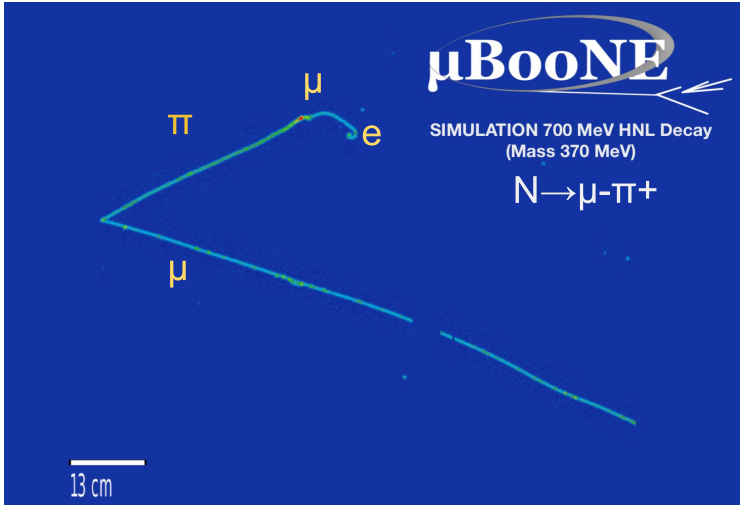




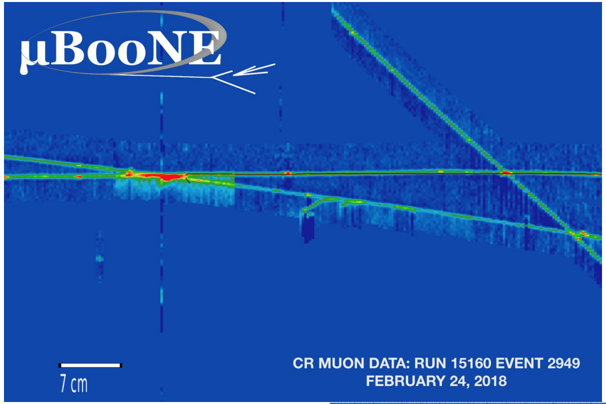
HNLs in MicroBooNE

Signal

Simulated HNL decay

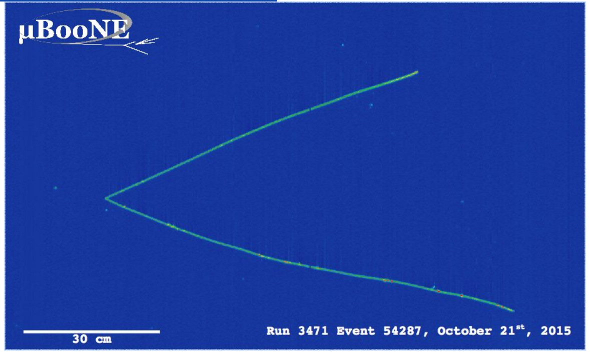


Backgrounds

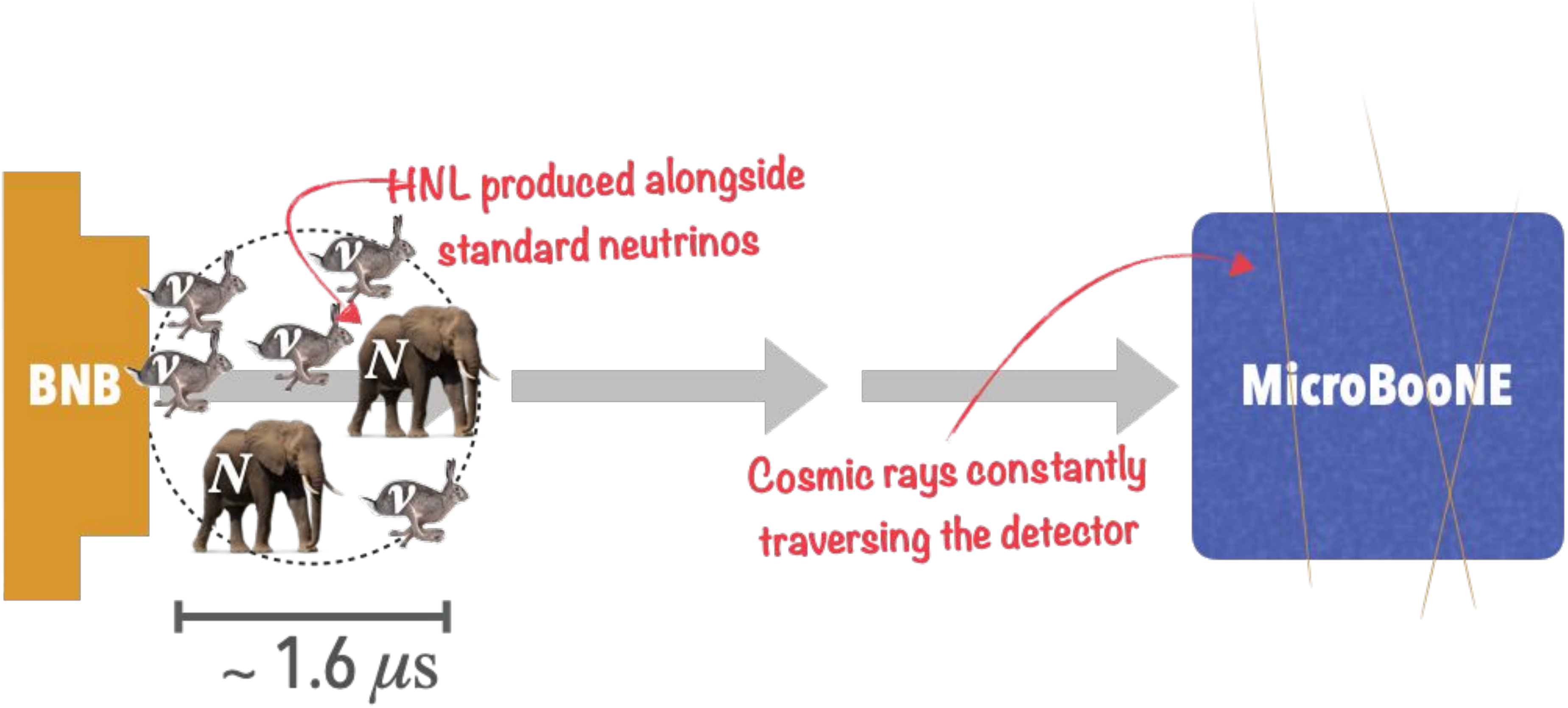


Data - Cosmic muon event

Data - ν_μ charged current interaction

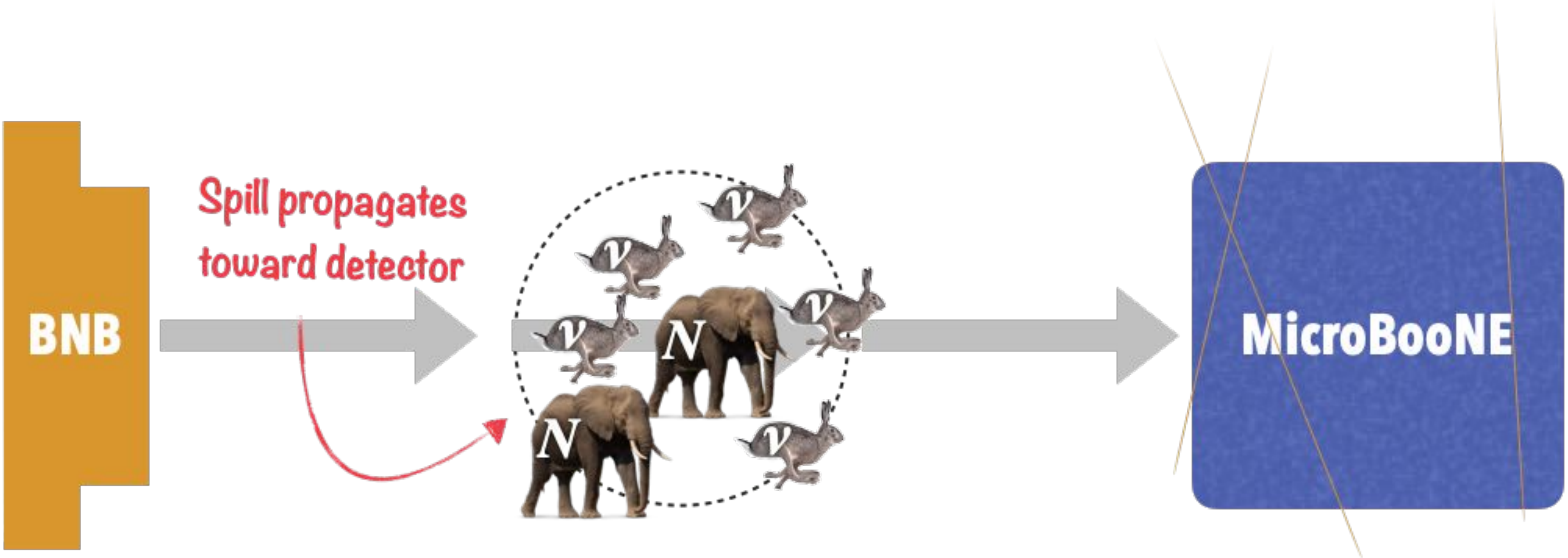


Timing



Courtesy of Davide Porzio

Timing



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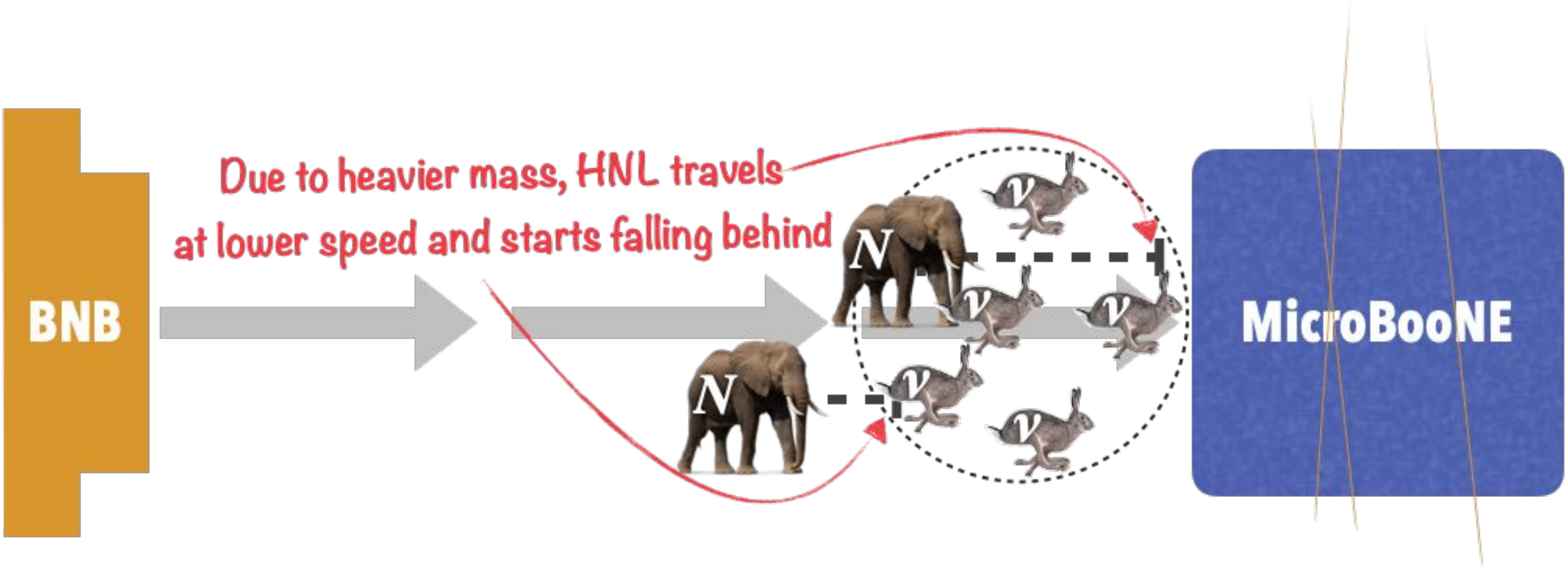
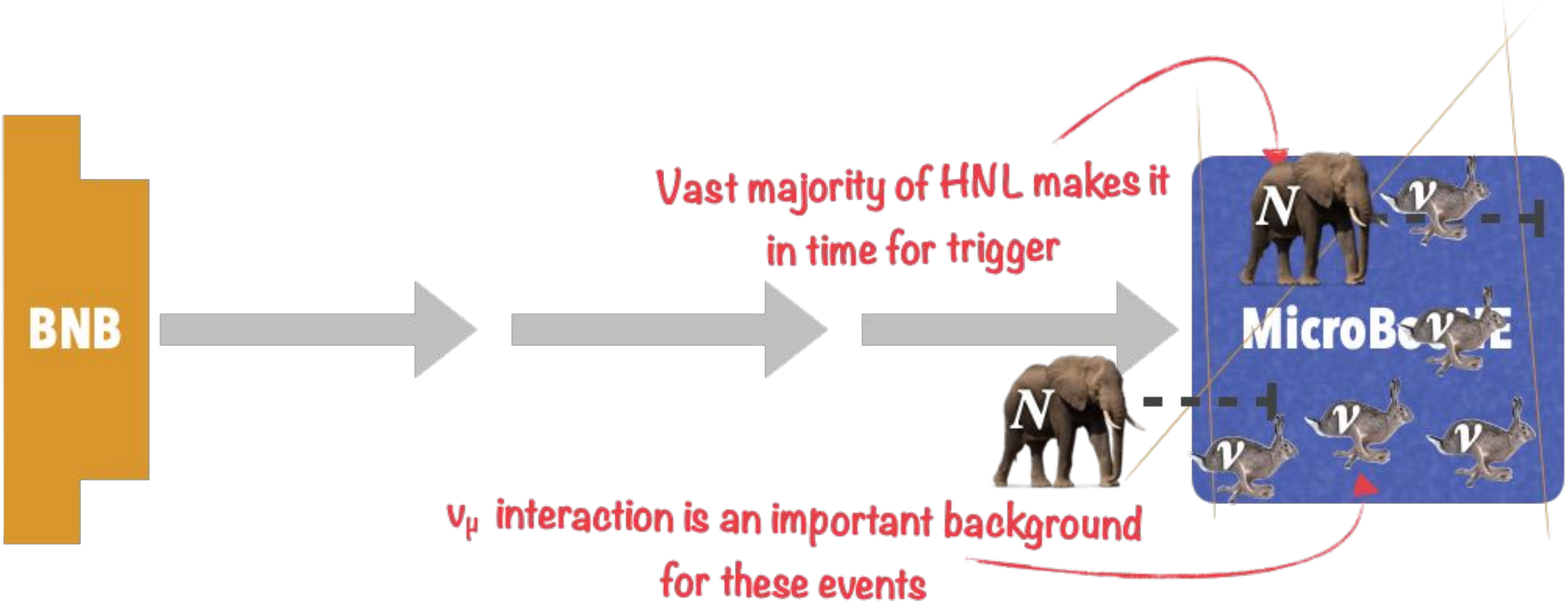


Courtesy of Davide Porzio

Timing



Courtesy of Davide Porzio

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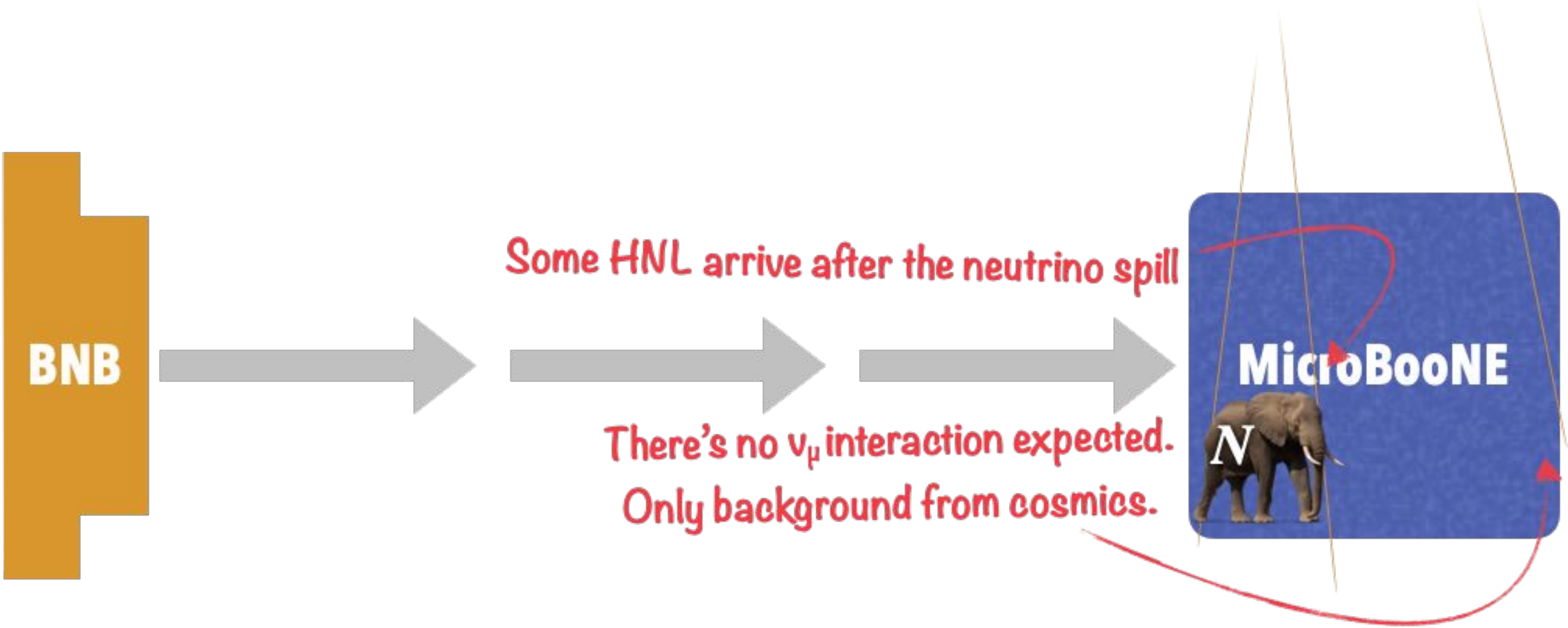
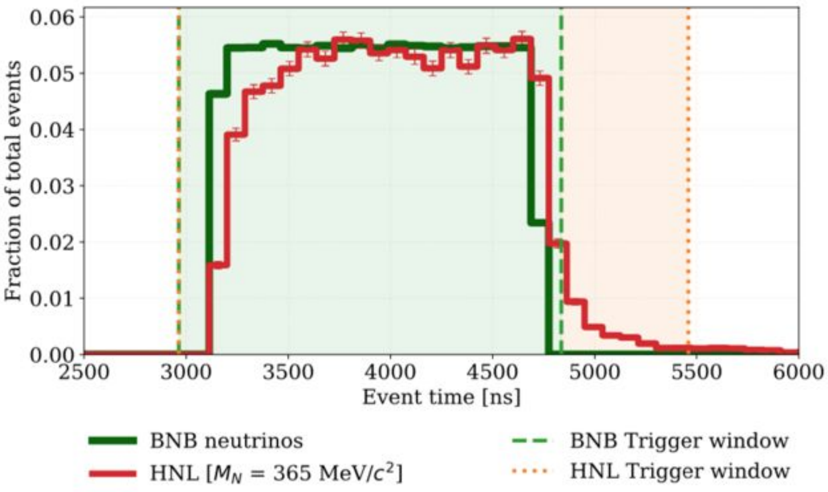
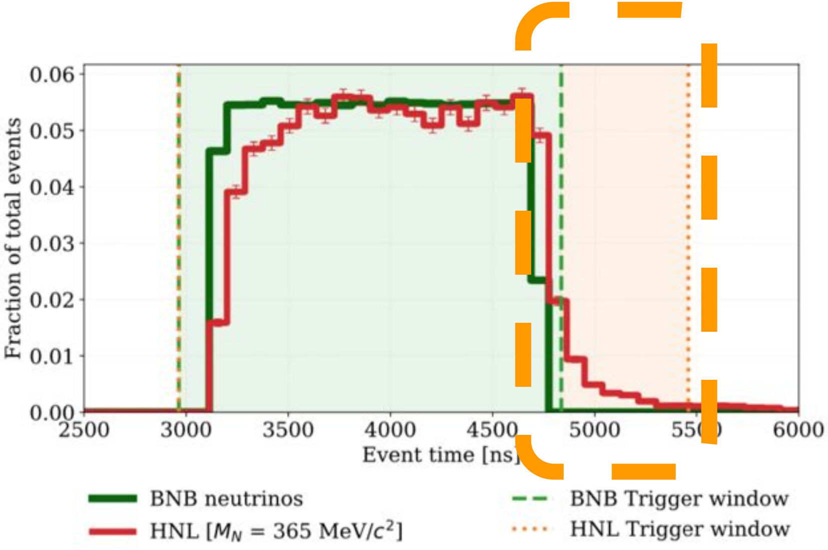


Courtesy of Davide Porzio

Timing

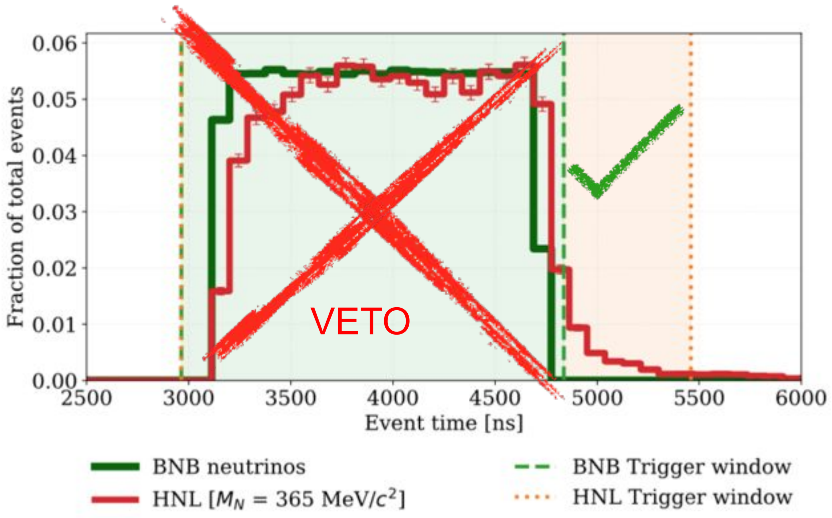

Fraction of total events
0.06
0.05
0.04
0.03
0.02
0.01
0.00
2500
3000
3500
4000
4500
5000
5500
6000
Event time [ns]
BNB neutrinos
HNL [M_N = 365 MeV/c^2]
BNB Trigger window
HNL Trigger window

Timing



- ~10% of HNLs arrive “late”, fraction is mass dependent.
- Analysis focuses on late HNLs, no neutrino background
- Expect cosmic-ray background only.

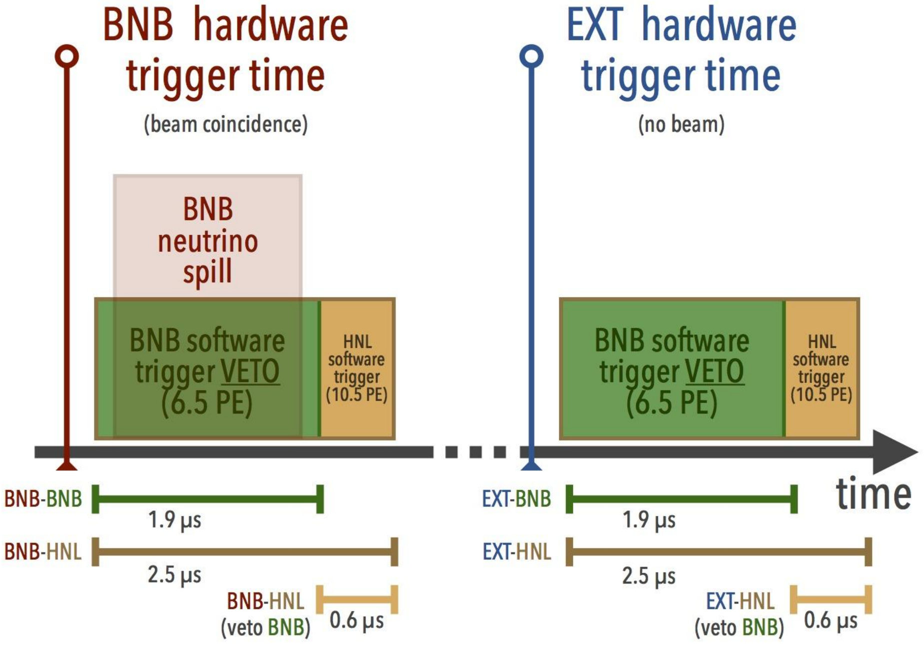
HNL Trigger



- Special **HNL trigger** operating since **June 2017**.
- Collected more than **4e20 POT** of data to date.
- This analysis uses the almost entire **Run 3 data** (1.97e20 POT)
- Trigger window extends 33% longer than **BNB** with **higher PE threshold** (+60%)
- HNL trigger collects data in the extended window and **VETOES the BNB trigger** (to reject BNB interaction background)

Data Driven Analysis

Identical HNL trigger runs when there is no beam spill to collect cosmics for background subtraction

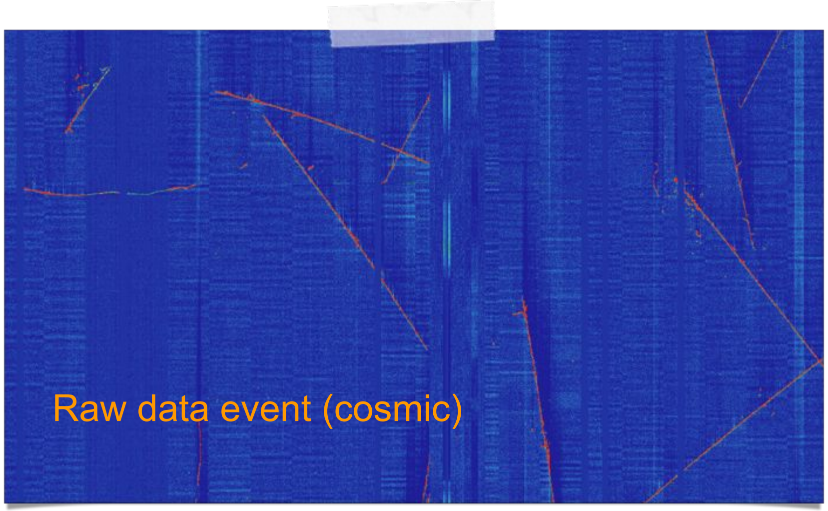


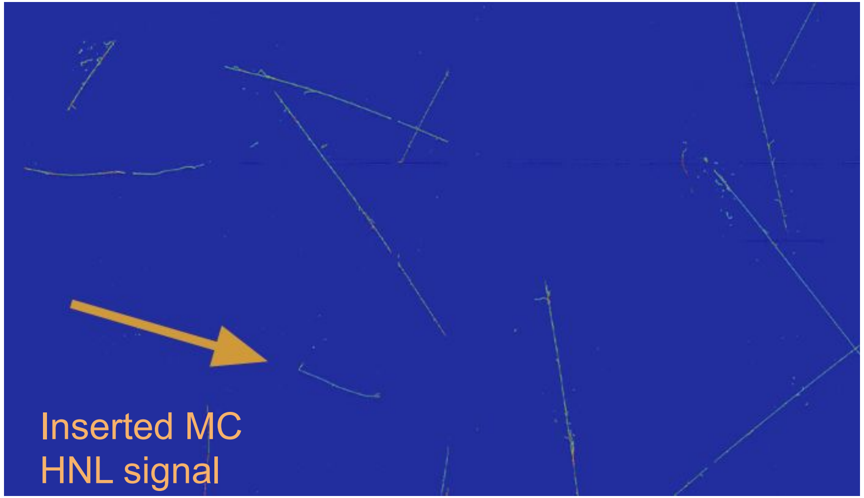
Beam correlated activity
potential HNLs

Beam uncorrelated
only cosmics

HNL simulation

- The HNL Monte Carlo simulation makes use of a novel LArTPC MC approach: **MC Overlay**
- **MC** signal only simulation is combined with **real Comic Ray** (beam off data) to create a single event, signal processed and reconstructed together.



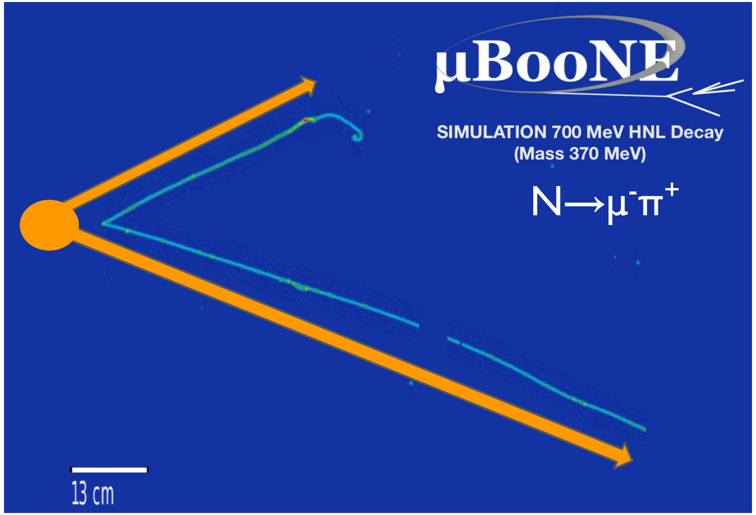


Event Selection

- The core of the HNL analysis is the search for an **excess of two-track** (μ and π) objects amongst a large number of **cosmic-ray muon tracks**, which constitutes the dominating background.

Finding HNL

- Pandora pattern recognition* used to create reconstructed particles.
  - Using same tools as for neutrinos
- Select events containing a reconstructed vertex associated with **exactly two** reconstructed tracks.



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

Event Kinematics

- Use track lengths to reconstruct event kinematics
    - Continuous Slowing Down Approximation
    - Pion mass close to muon mass; at relevant energies they appear very similar in LArTPC
- Assume longer track of pair is the muon (correct ~70% of the time)
    - Relevant kinetic variables largely insensitive to incorrect labeling

Muon

Pion

Event Kinematics

- Use track lengths to reconstruct event kinematics
  - Continuous Slowing Down Approximation
  - Pion mass close to muon mass; at relevant energies they appear very similar in LArTPC
- Assume longer track of pair is the muon (correct ~70% of the time)
  - Relevant kinetic variables largely insensitive to incorrect labeling

Selection Variables

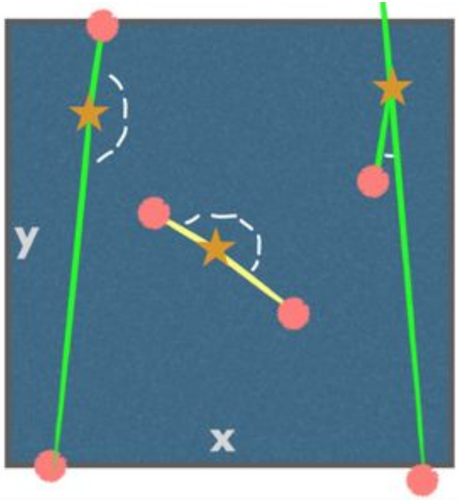
- Pre-selection requirements serve the double purpose of **increasing S/B ratio** and **improving reconstruction quality** of HNL candidates for further discrimination via **BDT** application
- Variables chosen to have **minimum dependency on HNL mass**.
- Mass-dependent information is reserved for BDT,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

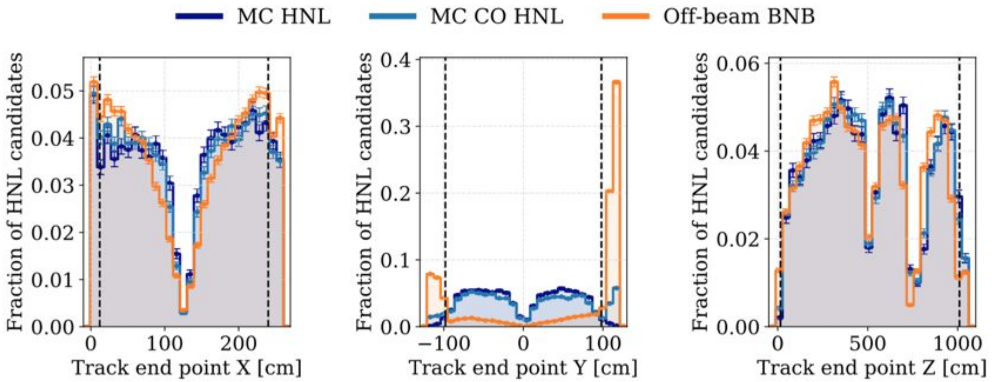
Pre-selection requirements

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

Cosmic Removal

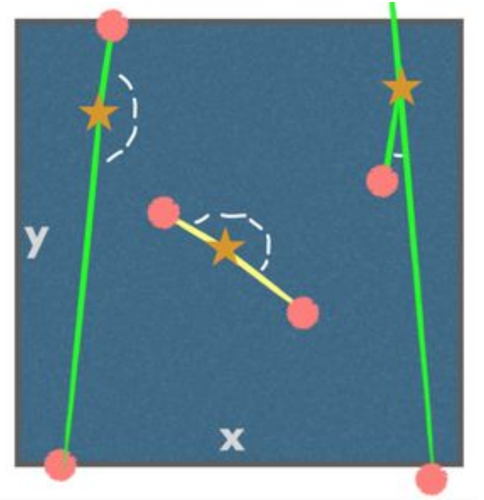
- Cosmics typically mimic HNL via a broken track or delta ray causing a vertex to be found.
- Containment cuts:
    - Since many CR muons are **through-going** and enter/exit the detector through the top/bottom panel, the Y-cut **reduces background** by a **factor of 6**.

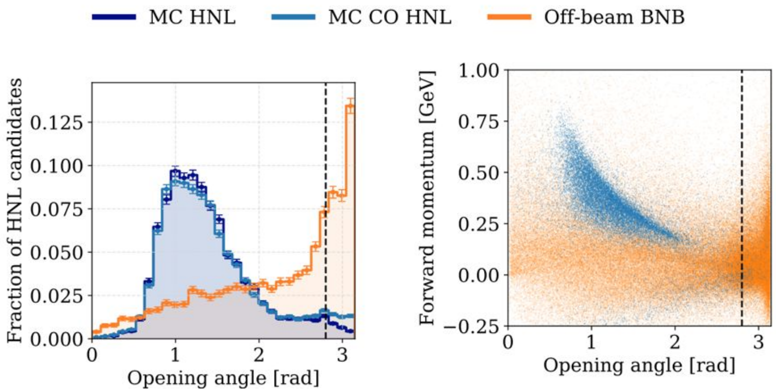




Cosmic Removal

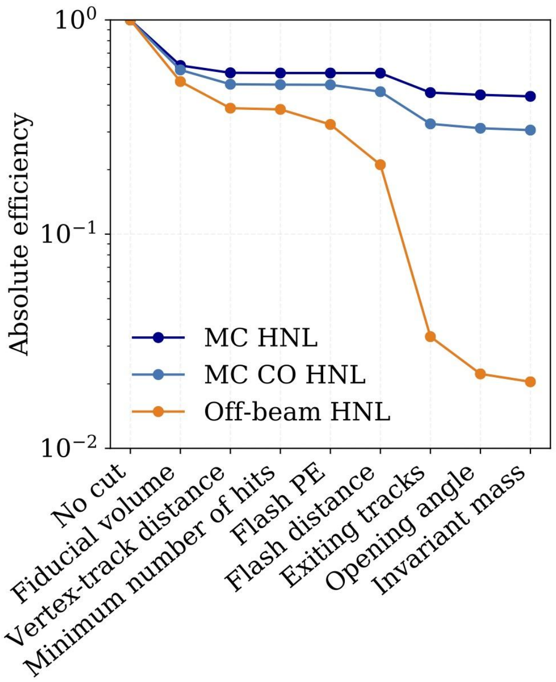
- Cosmics typically mimic HNL via a broken track or delta ray causing a vertex to be found.
- Angle Cut:
    - **Broken tracks** constitute most of the background (single CR muon track fragmented by the reconstruction).
    - A **cut** on an **almost-flat opening angle** (160°) is effective in removing CR background.



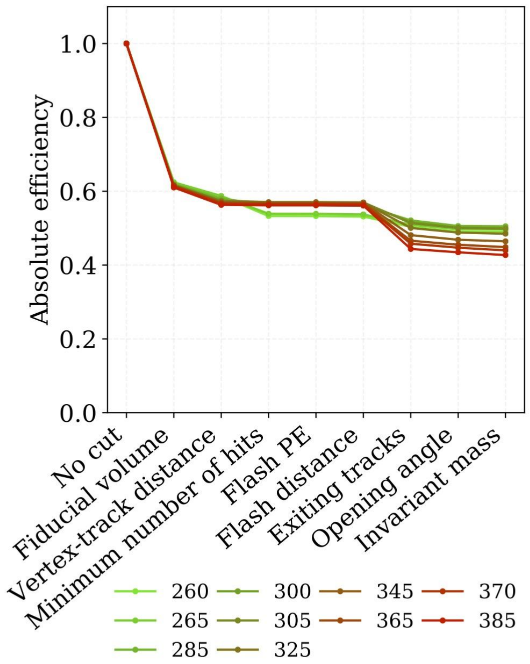


Selection efficiency

Combined pre-selection improves signal/background ratio by 25

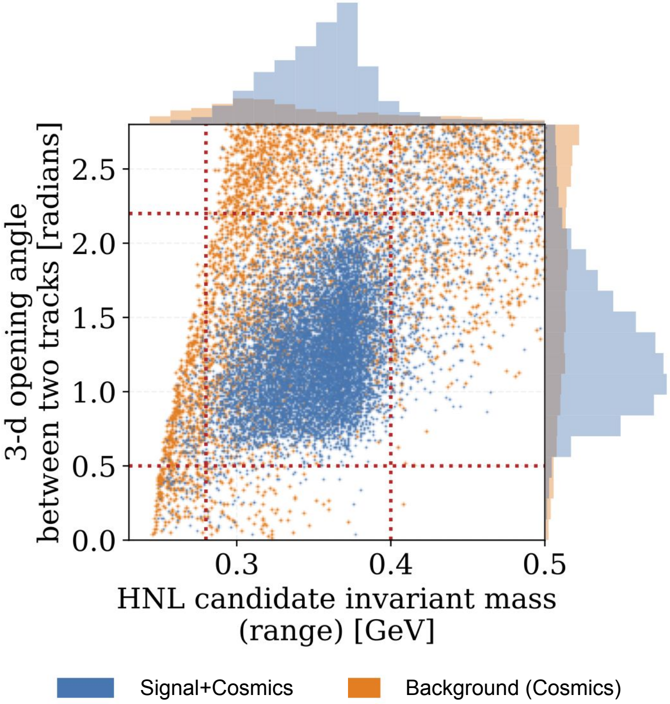


The efficiency is comparable across all the studied HNL masses.

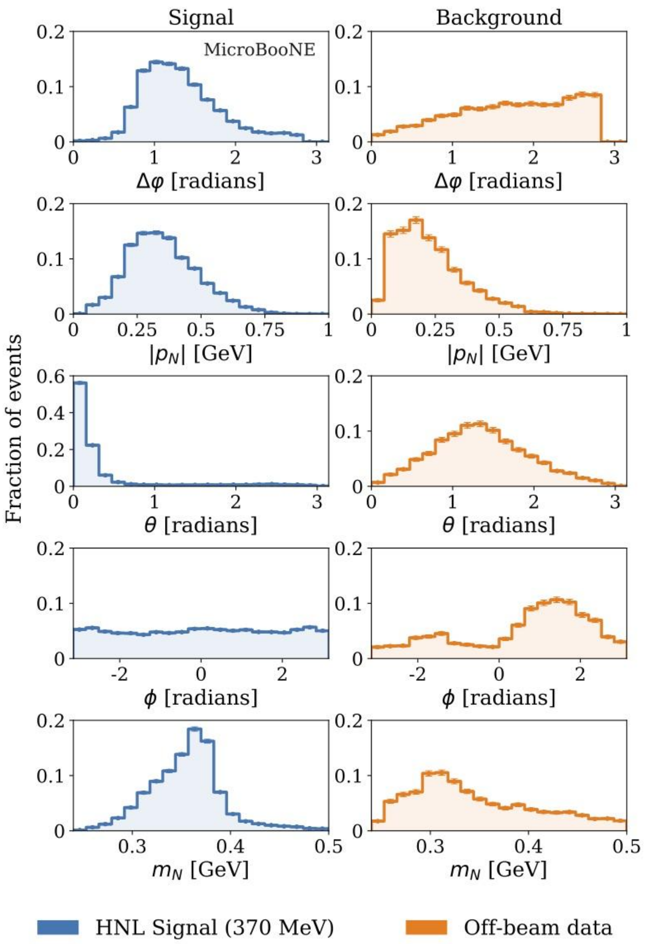


Boosted Decision Tree

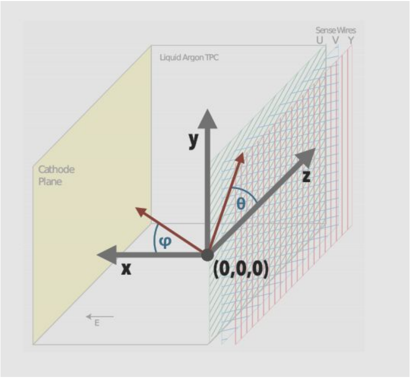
- Can harness correlations between kinematic variables as well as HNL mass dependent variables to further separate HNL and cosmics
- Train a Boosted Decision Tree (BDT) for each of the HNL masses studied.



BDT Training

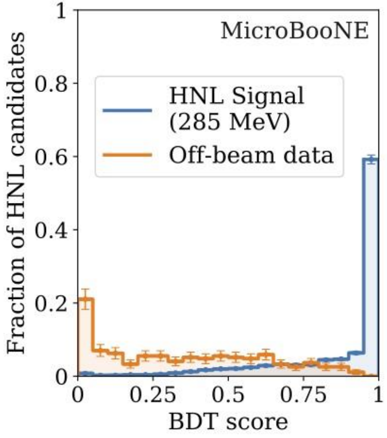


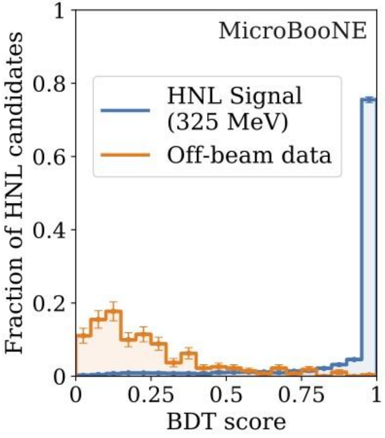
- Train BDT to discriminate between HNL and Cosmics.
- 5 input variables for each candidate
    - Opening Angle
    - Total Momentum
    - Angle from the beamline
    - Azimuthal Angle
    - Invariant mass

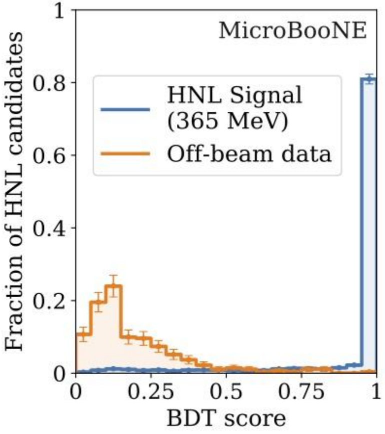


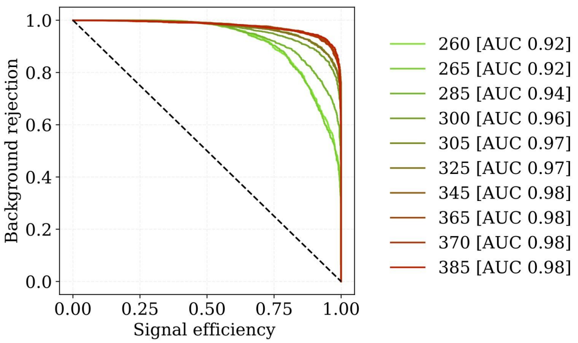
BDT Discriminant

- BDT output score separates HNL and background well
- Better separation for higher HNL masses









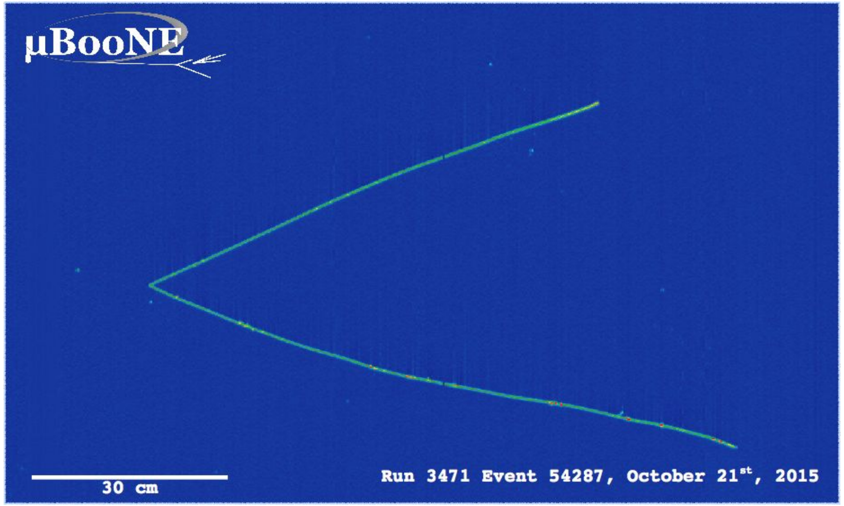
Validation

Control Sample

Validation of selection workflow is performed in data.

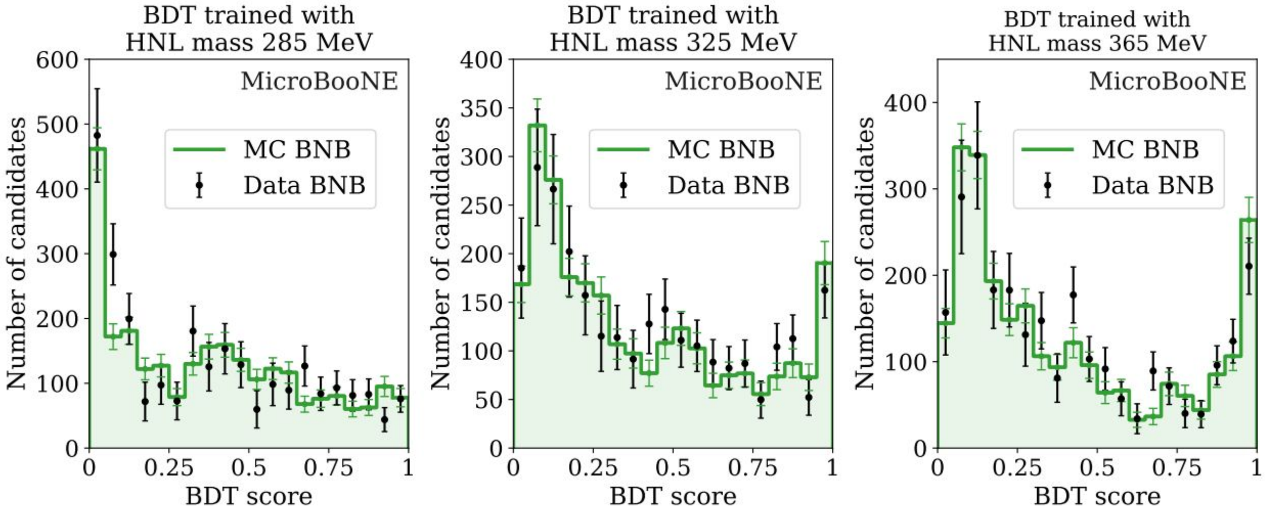
A “control sample” of BNB ν interaction data (and simulation) is used to verify that the candidate identification, pre-selection efficiency and BDT work in data and are not sensitive to data/MC differences.

- Will contain CC ν_μ events with similar topology to our events
- Additional cut to reject non-signal like events containing highly ionising tracks (protons)



Control Sample

- Good agreement between data and MC
    - Validates workflow
    - Signal-like events appear at high BDT for trained with higher HNL mass.
        - ν_μ CC 1 pion events
    - Evidence that if HNL are present in data we would select them (at the rate we expect)



Results

Looking at the HNL Data

Looking at data

Owen Goodwin 14/05/2020

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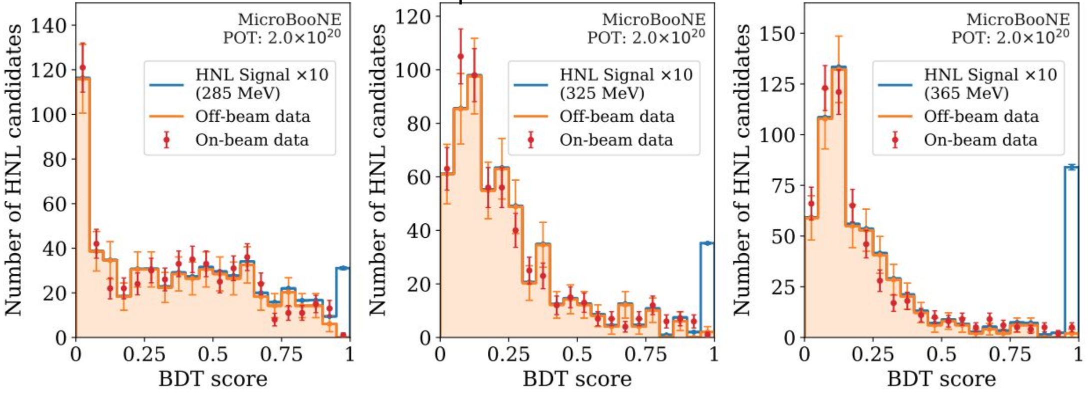
- Run BDT over data in beam correlated HNL window.
- Signal and background data samples show good agreement across BDT score
- No excess observed in signal like region (BDT score < 0.95)

- **Set limits on $|U_{\mu4}|^2$ as a function of HNL mass (M_N)**

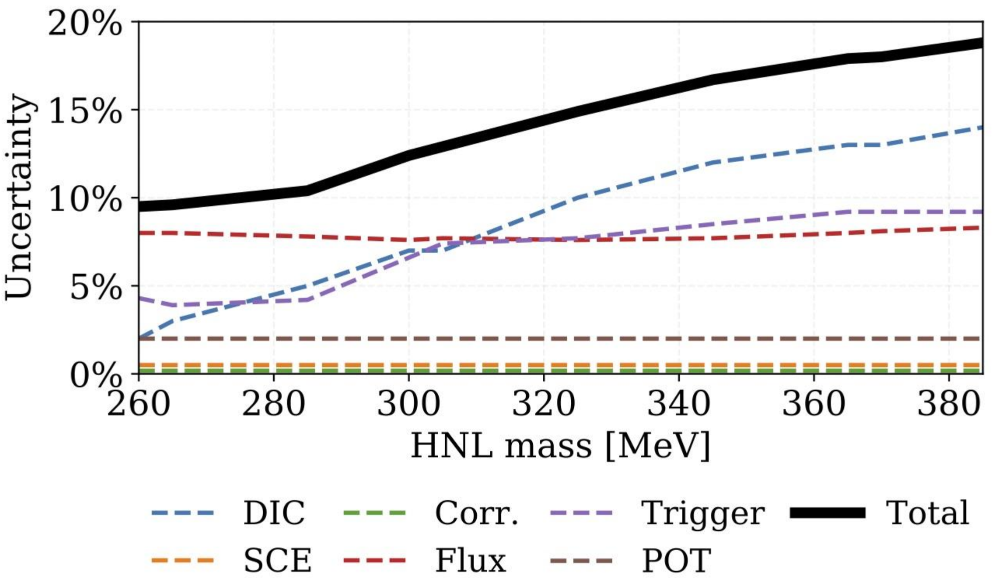
$|U_{\mu4}|^2 = 1.4 \times 10^{-7}$



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

Systematic Error

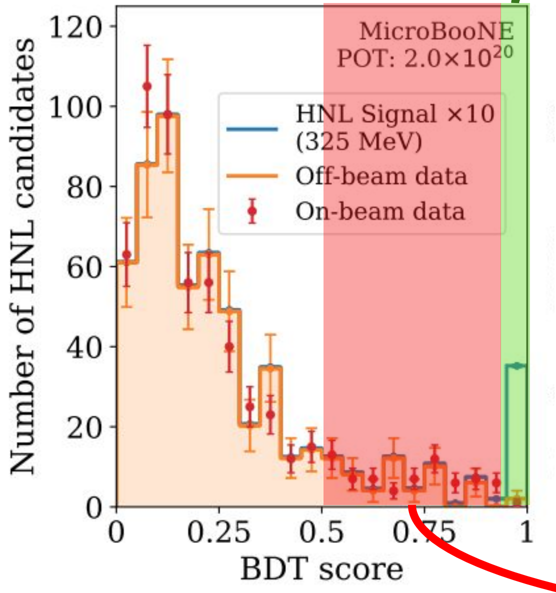
- Uncertainties come predominantly from
  - Flux (kaon production at target, horn focusing uncertainty)
  - Trigger efficiency (PMT timing resolution)
  - Detector effects (Dynamically Induced Charge - DIC, Space Charge Effects - SCE)



Limit Setting

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

Signal Enriched



Mass	BDT Score > 0.95			BDT Score 0.5–0.95		
(MeV)	HNL	Bckg.	Data	HNL	Bckg.	Data
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385	36 ± 6	< 3.7	4	4 ± 0.6	20 ± 6	28

Signal Depleted

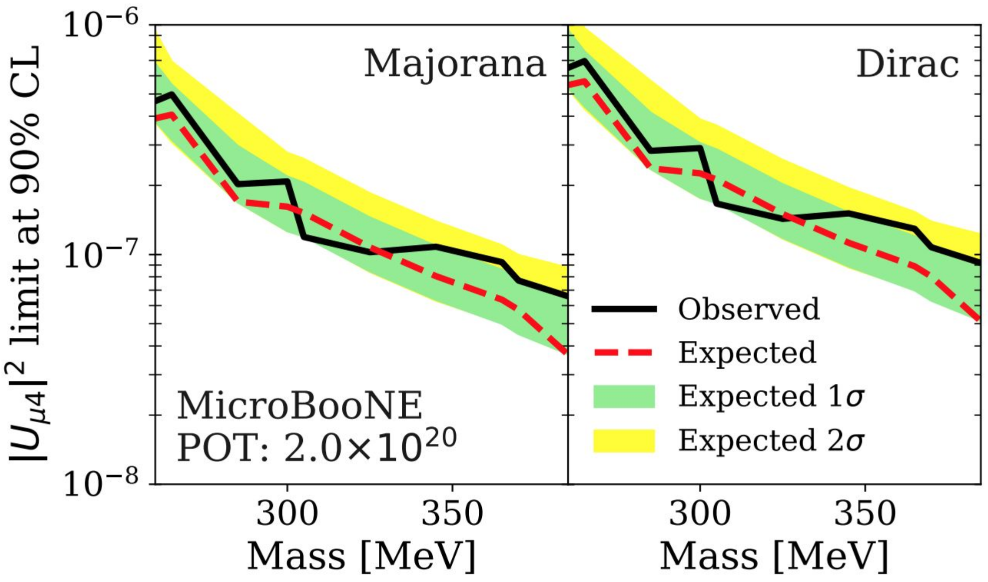
Limit Setting

Observed and expected median **upper limits** at the 90% CL **agree within 1 standard deviation** over the entire mass range.

- Constraints on the **extended PMNS mass-mixing elements** are obtained in the range (5–0.8) x 10^{-7} (for Majorana).
- Limits for Dirac case are identical but reduced by a factor of √2 as $N_{events} \propto |U|^4$

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

HNL Exclusion Limit

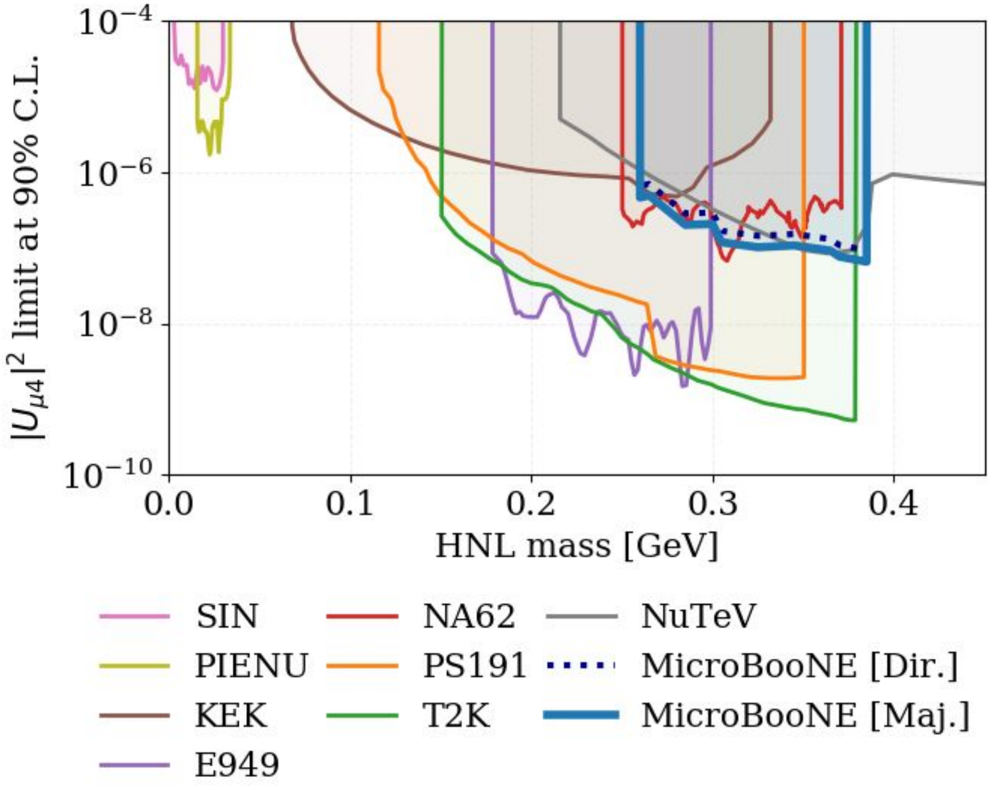


Limit Setting

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 up to 385 MeV

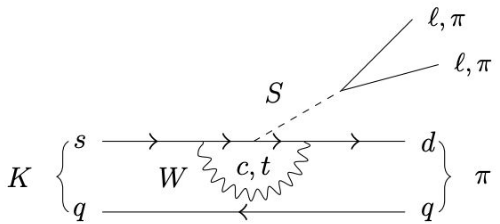


HNL Outlook @ MicroBooNE

Owen Goodwin 14/05/2020

- This was the first search, more searches for HNL 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** $|U_{e4}|$)

Late Window useful for other models. Eg Higgs Portal Scalars

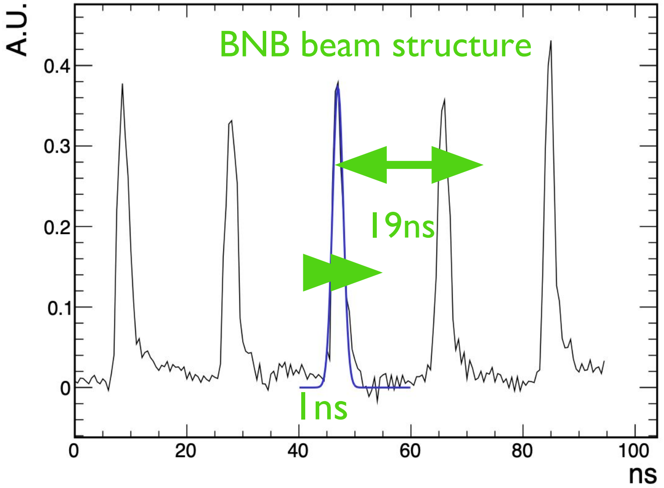


  - More MicroBooNE BSM search results coming.

https://arxiv.org/pdf/1909.11670.pdf

Full SBN Outlook

- Full SBN program will extend sensitivities
  - SBND ~110m from beam, higher flux.
  - ICARUS significantly larger TPC volume
  - Higher photon detector sampling rate, can potentially resolve beam bucket structure



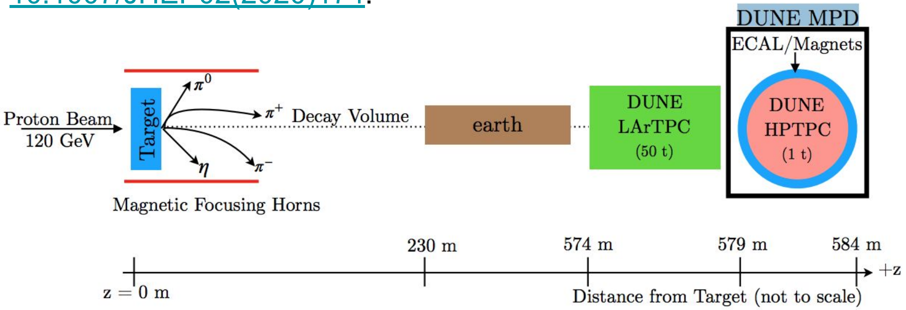
Courtesy of En-Chuan Huang

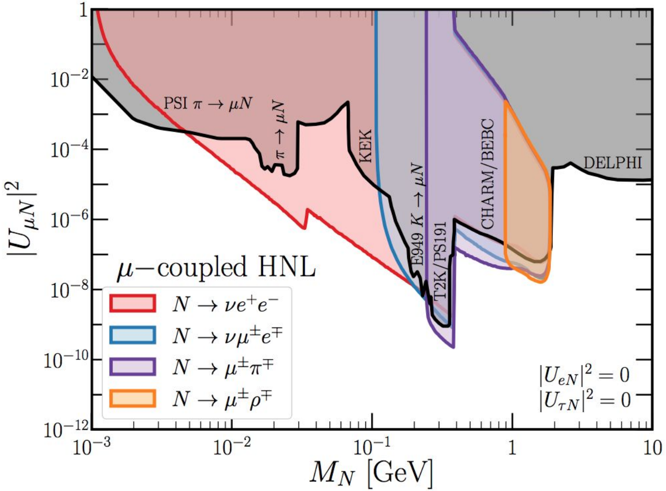
DUNE Near Detector

Owen Goodwin 14/05/2020

- Very well suited to a HNL search
  - Charmed Mesons produced in beam giving greater mass reach
  - Gas TPC has lower density
    - *> decay/interaction ratio*
  - Magnet for sign selection and precise momentum determination.

10.1007/JHEP02(2020)174.





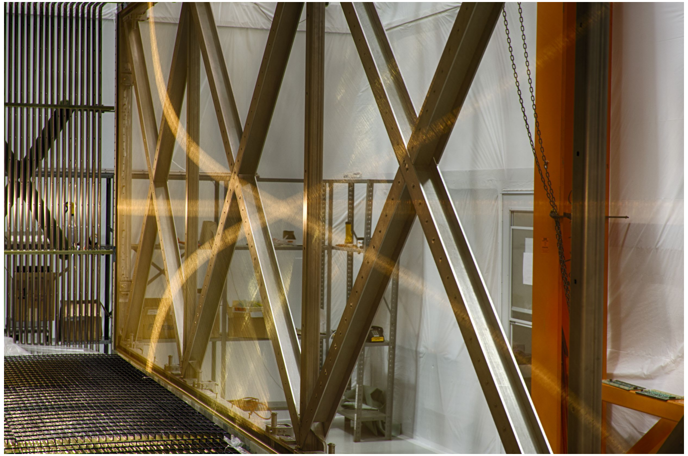
Summary

- As well as neutrino measurements, LArTPCs provide sensitivity to unexplored parameter space for interesting beyond standard model scenarios.
- First search for HNLs in a LArTPC has been performed at MicroBooNE, results published in PRD DOI: 10.1103/PhysRevD.101.052001
- Additional searches in progress with MicroBooNE
- Full SBN and DUNE offer excellent opportunities to extend searches for HNL and other BSM physics.

Backup

MicroBooNE

- Collecting neutrino data since 2015
- 89 tonnes LAr (active volume)
- Longest running LAr neutrino experiment (~1.5 x 10^21 POT of beam exposure)
- 8192 wires with 3mm pitch (2 x Induction - 2468 + Collection - 3456)
- 32 PMTs + 4 paddle PMTs



MicroBooNE data taking

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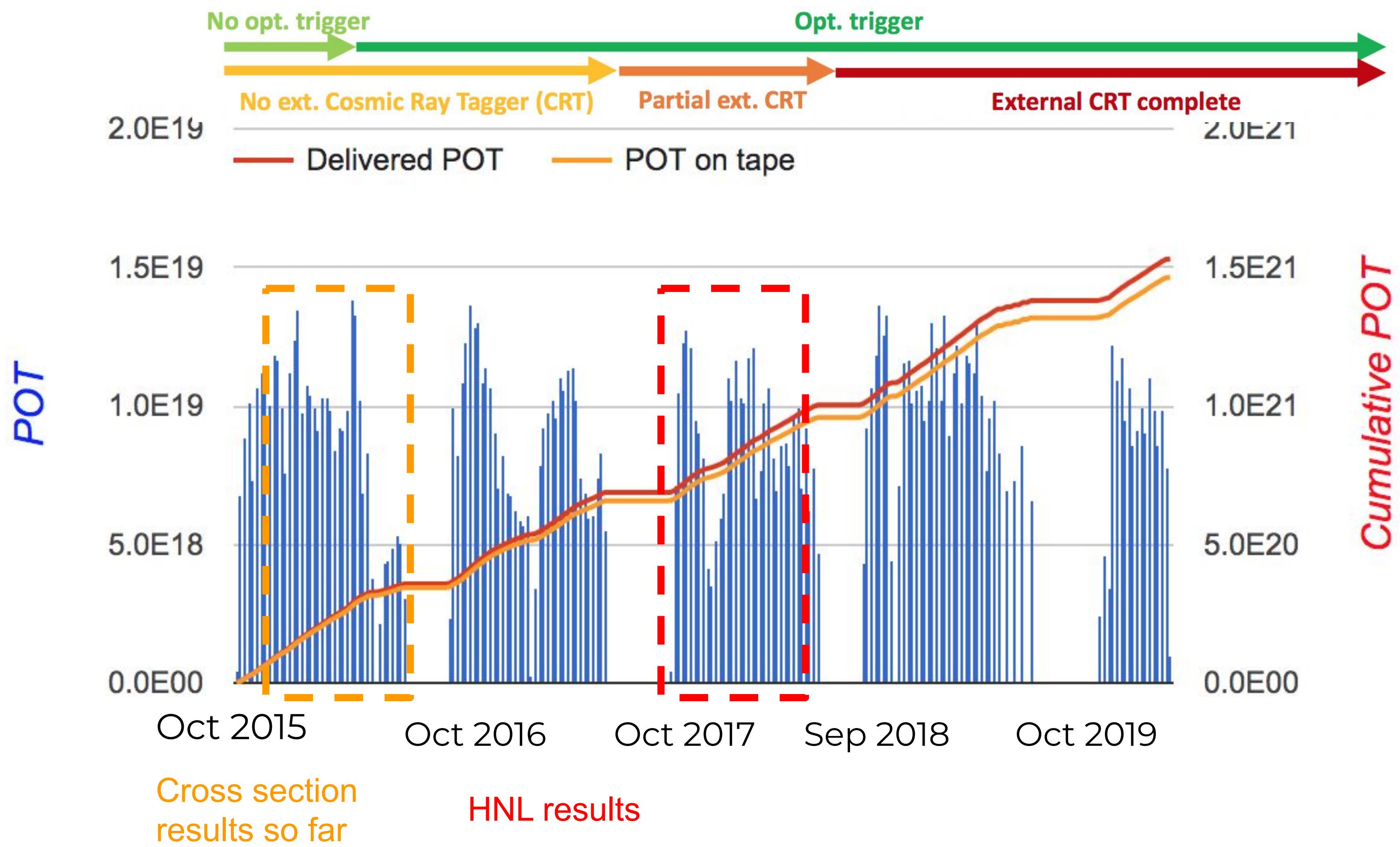
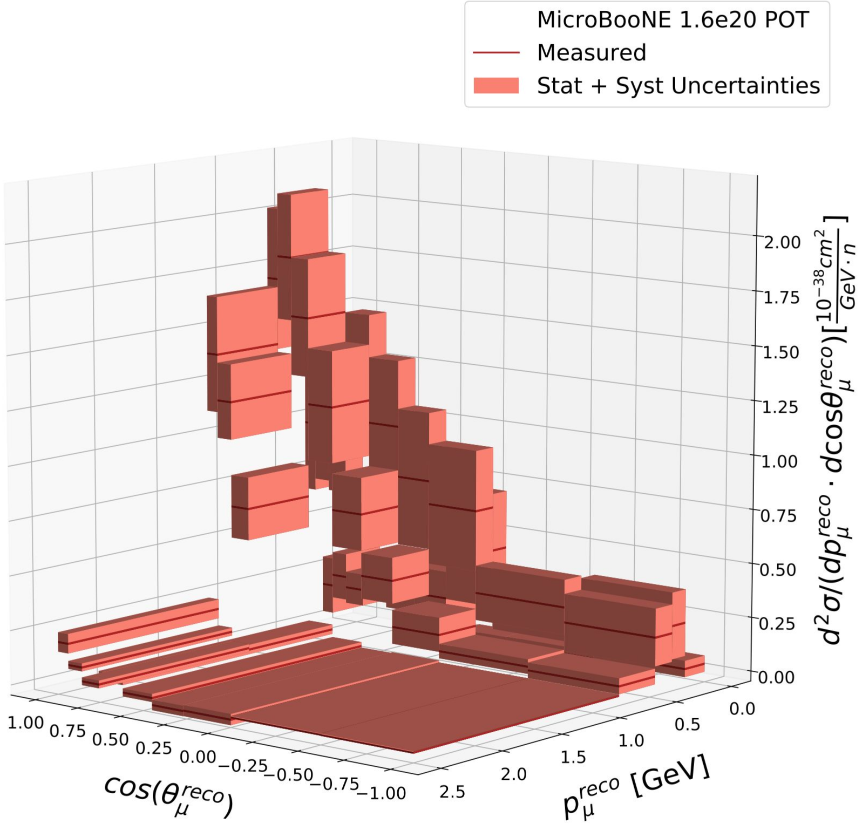


CC Inclusive ν_μ cross section

- Main background: cosmic rays (CRs)
- Eliminate CRs: timing (optical flash matching) and topology (through-going tracks)
- Track length and calorimetry to identify muons
- First double differential ν_μ cross section measurement in argon, with full angular and momentum coverage
- Allow tests of event generators and ν_e constraints



Phys.Rev.Lett. 123 (2019) 13, 131801

Double Differential ν_μ-Ar σ

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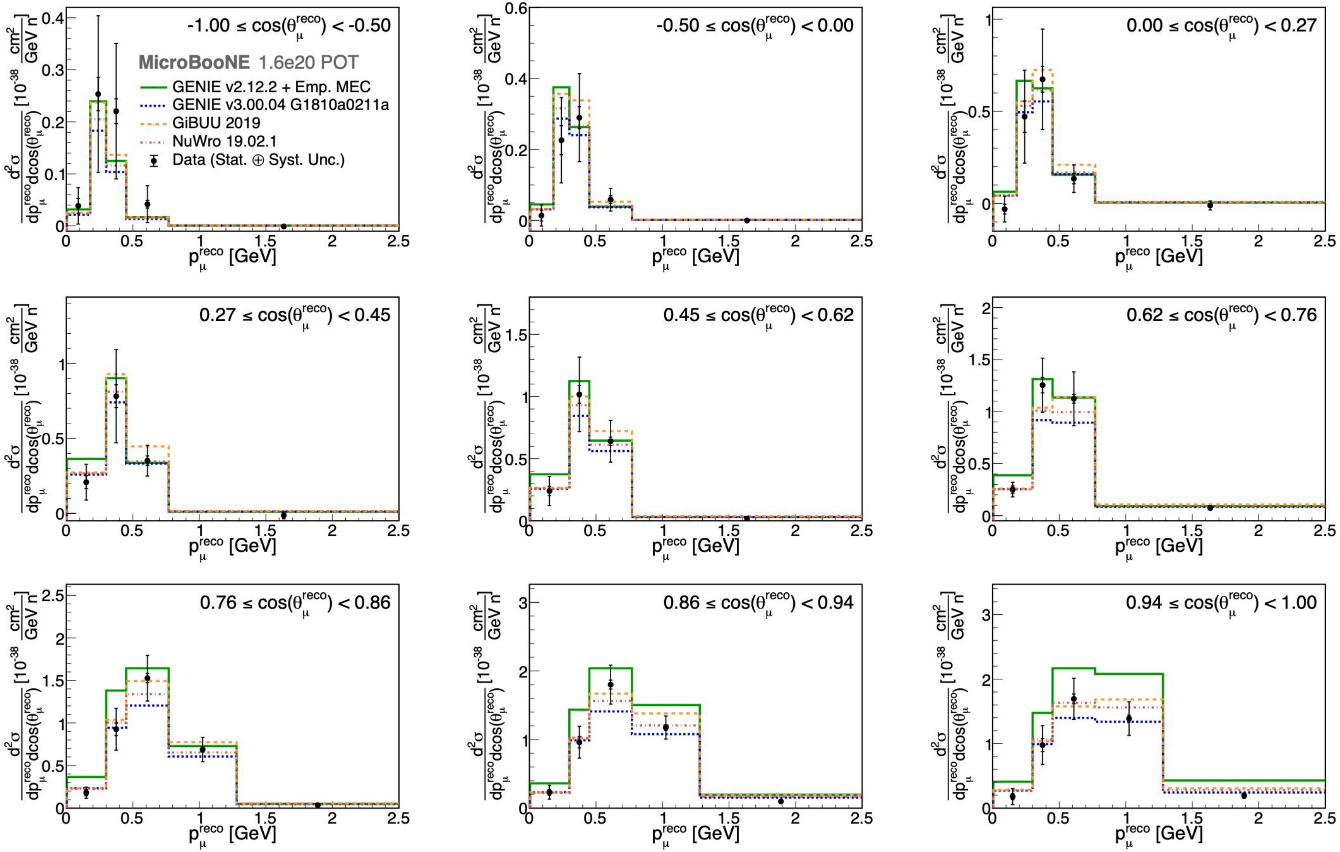
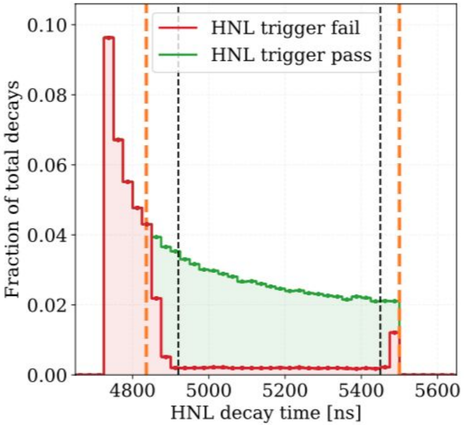
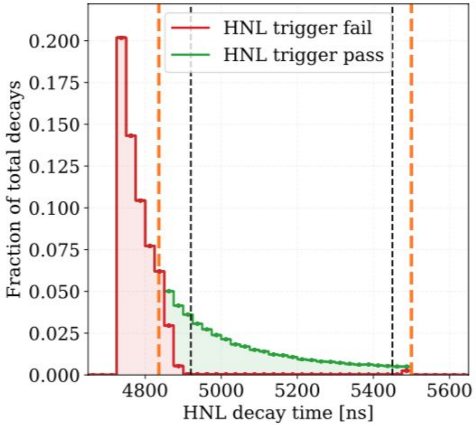


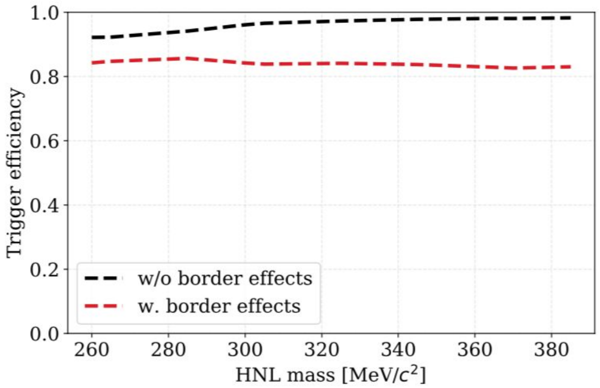
Phys.Rev.Lett. 123 (2019) 13, 131801

Trigger

- MC input to simulate trigger
  - >95% of HNLs fire trigger
- Trigger pass rate has little dependence on **HNL mass**

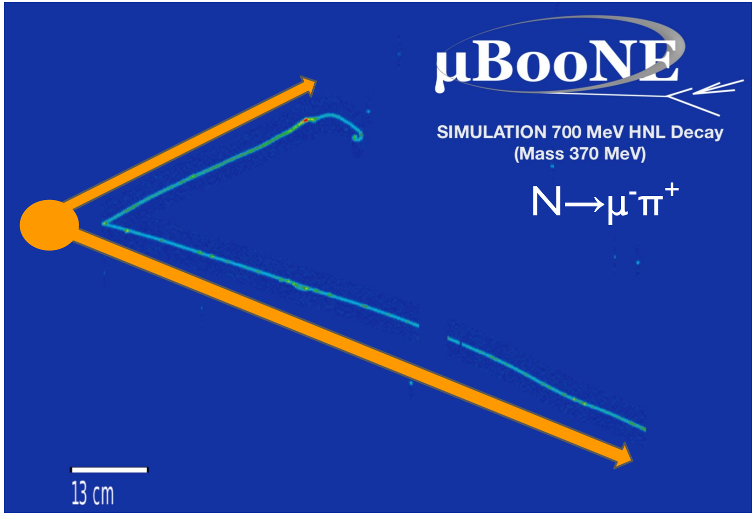






Finding HNL

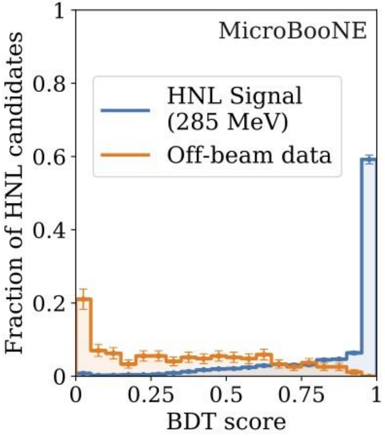
- Reconstruction quality cuts;
  - Vertex in fiducial volume
  - Vertex location matches optical flash
  - Distance between start of track and vertex **< 5cm**
  - Each track has **>30 hits** on collection plane **(~20 MeV/c)**

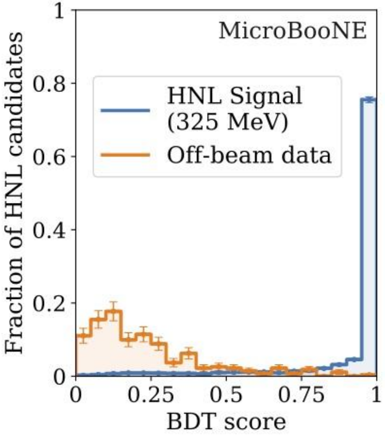


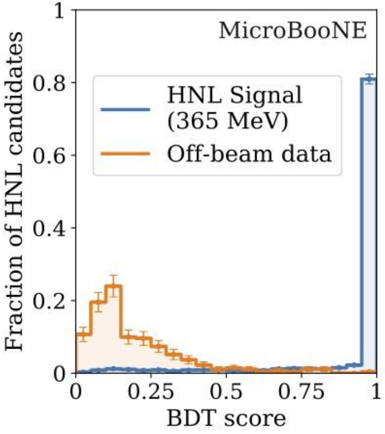
BDT Discriminant

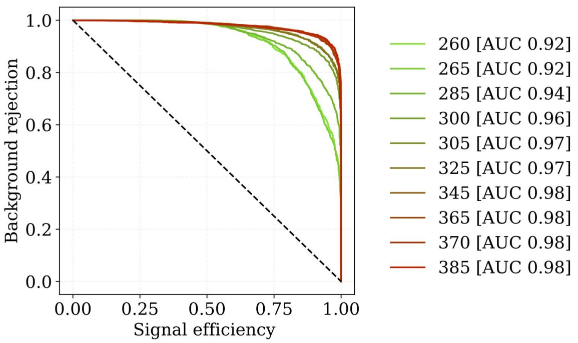
- BDT trained on HNL overlay and off-beam **BNB** data
- After pre-selections off-beam **HNL** and off-beam **BNB** samples have **same distributions**.
- Save smaller stats “off-beam HNL” testing.

BDT output score separates HNL and background well



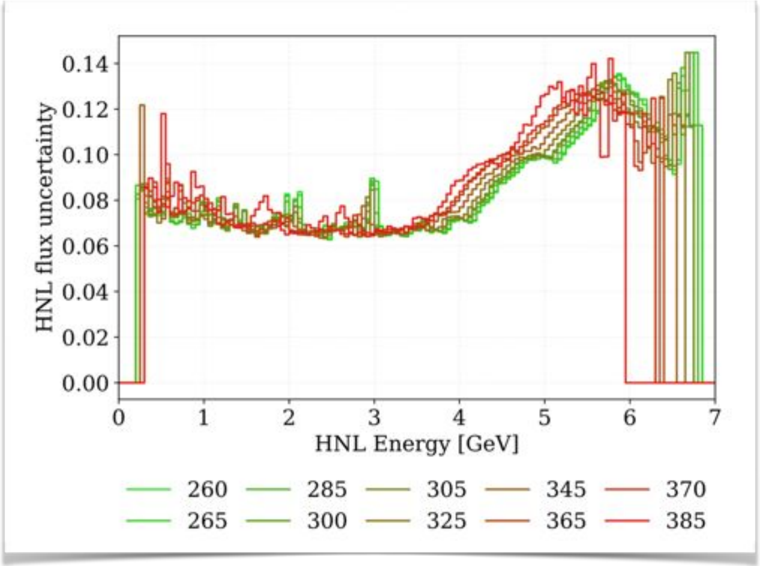






Flux Systematics

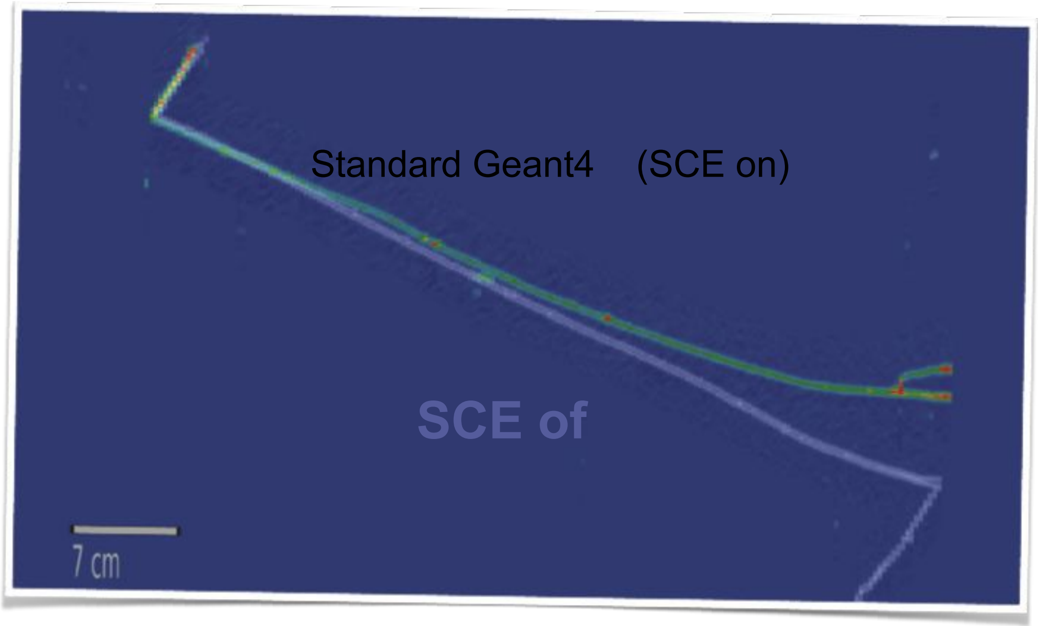
- Assessed using same multi-sim infrastructure as MicroBooNE neutrino analysis.
- Approximately an 8% flat uncertainty
- Predominantly due to uncertainties in the kaon production rate and horn current.



Detector Effect Systematics

Assessed using uni-sims

Dynamically Induced Charged (DIC) and Space charge effect on and off to assess impact



HNL from NuMI

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- MicroBooNE and ICARUS exposed to extreme off-axis flux from NuMI beam.
- Higher Energy
- Greater Kaon content in beam
- HNL flux dominated by Kaon decays at rest in the absorber

HNL Delay

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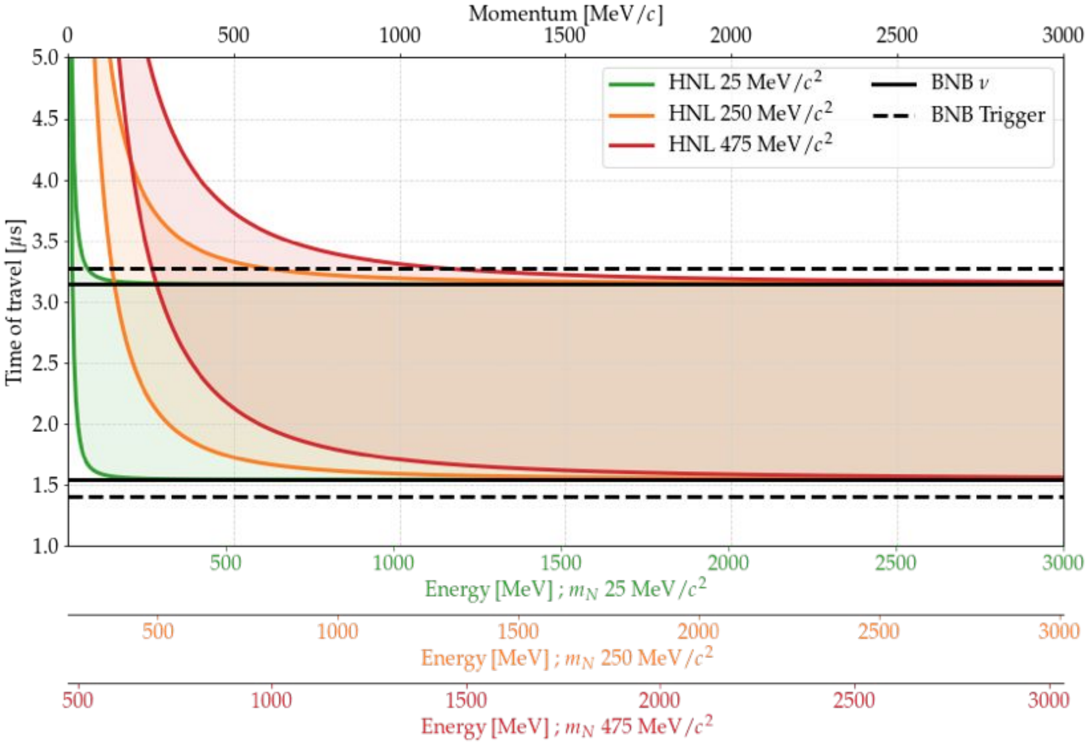
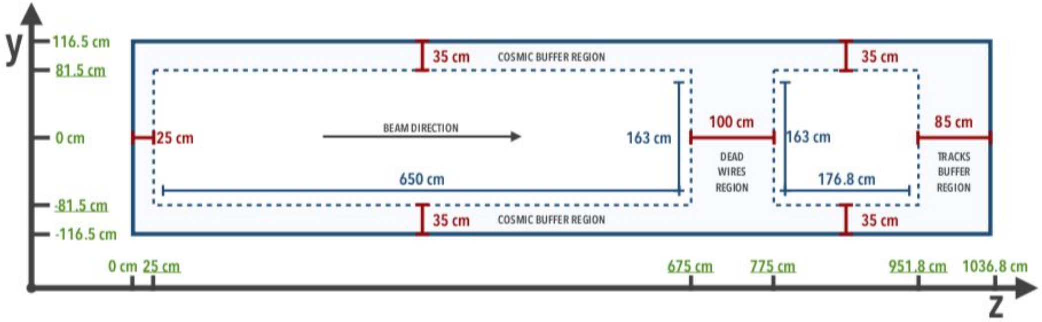
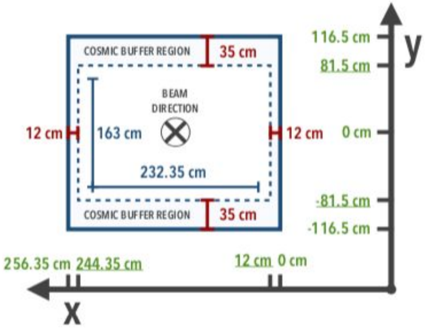
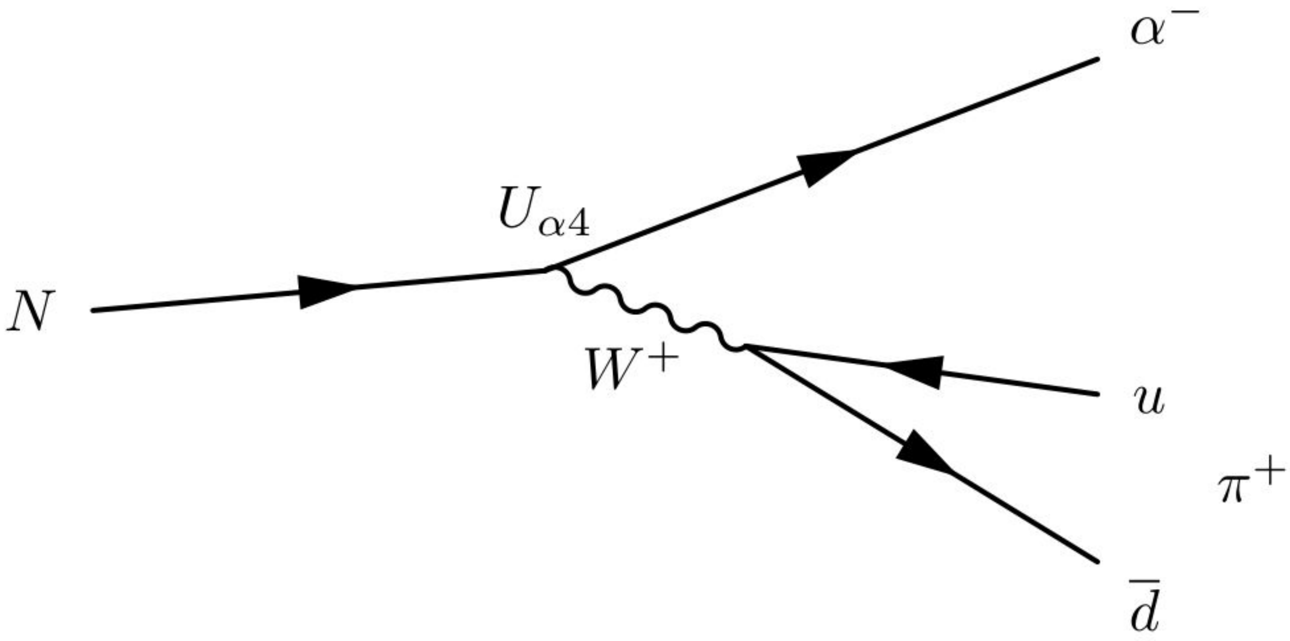


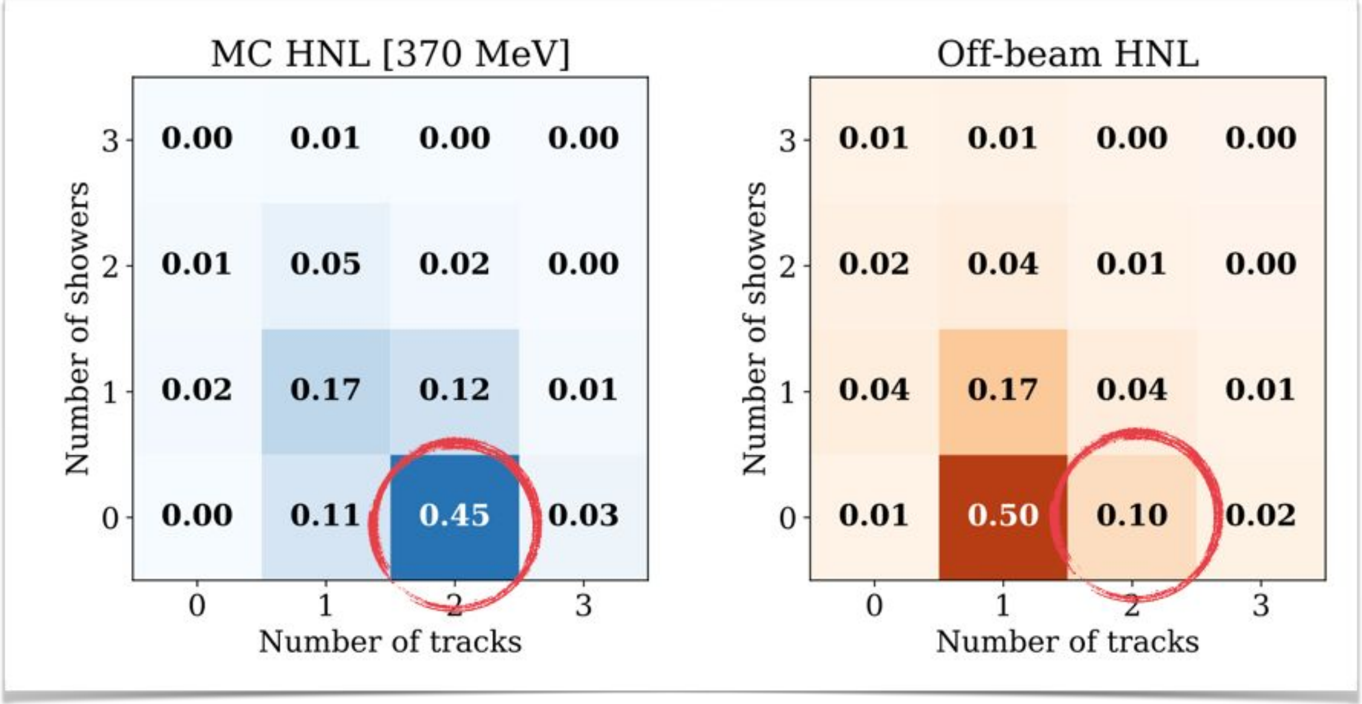
Fiducial Volume



(a) Side view.




α^-
$U_{\alpha 4}$
N
W^+
u
π^+
$\bar{d}$


MC HNL [370 MeV]
Number of showers
Number of tracks
0.00 0.01 0.00 0.00
0.01 0.05 0.02 0.00
0.02 0.17 0.12 0.01
0.00 0.11 0.45 0.03
Off-beam HNL
Number of showers
Number of tracks
0.01 0.01 0.00 0.00
0.02 0.04 0.01 0.00
0.04 0.17 0.04 0.01
0.01 0.50 0.10 0.02