First demonstration of LArTPC-based search for intranuclear neutron-antineutron transitions & annihilation in Ar using the MicroBooNE detector

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CoSSURF-2024 (May 15, 2024)

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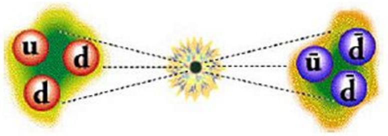
NSF

μBooNE

Intranuclear neutron antineutron transition

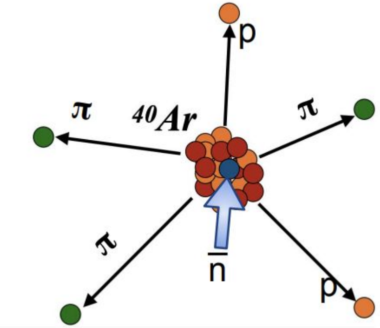
- A process where neutron transforms into an anti-neutron within a nucleus.
- The intranuclear transition followed by subsequent annihilation results in final state particles (mostly pions) with ~ zero net momentum and total energy ~ twice the nucleon mass.

Neutron antineutron transition



Credit:Y. Kamyshkov

Annihilation with a nucleon → unique star-like topology



$\bar{n}+p$		$\bar{n}+n$	
Channel	Branching ratio	Channel	Branching ratio
$\pi^+\pi^0$	1.2%	$\pi^+\pi^-$	2.0%
$\pi^+2\pi^0$	9.5%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	11.9%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	26.2%	$\pi^+\pi^-2\pi^0$	11.0%
$2\pi^+\pi^-2\pi^0$	42.8%	$\pi^+\pi^-3\pi^0$	28.0%
$2\pi^+\pi^-2\omega$	0.003%	$2\pi^+2\pi^-$	7.1%
$3\pi^+2\pi^-\pi^0$	8.4%	$2\pi^+2\pi^-\pi^0$	24.0%
		$\pi^+\pi^-\omega$	10.0%
		$2\pi^+2\pi^-2\pi^0$	10.0%

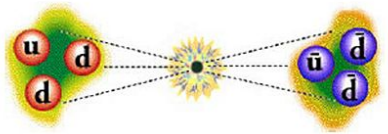
Phys.Rev.D 103 012008 Nucl.Phys. A720 357

Phys.Rep. 413 197

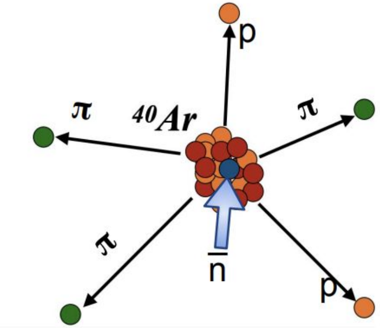
Intranuclear neutron antineutron transition

- ❑ A process where neutron transforms into an anti-neutron within a nucleus.
- ❑ The intranuclear transition followed by subsequent annihilation results in final state particles (mostly pions) with ~ zero net momentum and total energy ~ twice the nucleon mass.
- ❑ Intranuclear n → n̄ transition is suppressed due to nuclear potential.

Neutron antineutron transition



Annihilation with a nucleon → unique star-like topology



$$\tau_m = R\tau^2_{n-\bar{n}}.$$

Bound neutron lifetime

Free neutron lifetime

Suppression factor

The value of R depends on the type of nuclei e.g.
for ^{40}Ar, R is 5.6x10^{22} s^{-1}
for ^{16}O, R is 5.17x10^{22}s^{-1}

Credit:Y. Kamyshkov

Why is this process interesting?

- This baryon number violating (BNV) process is a high-priority objective of particle physics.
- If observed, would shed light on matter-antimatter asymmetry.
- If not discovered by future, more sensitive experiments like HyperK & DUNE, would tightly constrain the theories of baryogenesis
    - *Provides an important contribution to our understanding of baryon asymmetry of the Universe.

For further details on BNV, refer to talk by Linyan Wan

*Phys. Rev.D 87 115019
*Phys. Rev. D 87, 075004

Current best limit

- Current best limit on nucleus-bound neutron transition time is provided by the SuperKamiokande experiment (using ^{16}O). Phys.Rev.D 103 012008

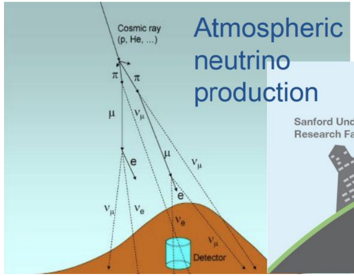
Experiment	Exposure	Signal selection efficiency	Observed events	Expected background	Limit on bound neutron lifetime at 90%CL
SuperKamiokande	**6050 days**	4.1%	11	9.3 ± 2.7	**3.6 x 10^{32} years**

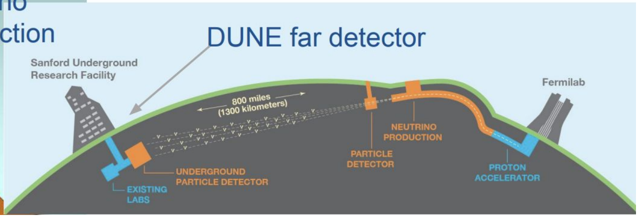
- The most stringent limit on free neutron transition time is provided by the ILL in Grenoble and is 0.86x10^8s with 90%CL. Z.Phys.C 63 409

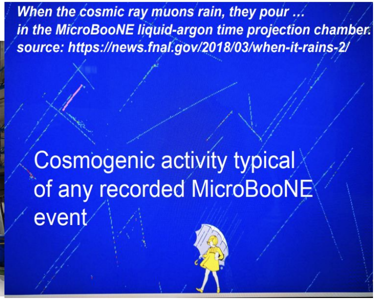
This search with the MicroBooNE detector

- This talk presents the first demonstration for the search of this process within an ^{40}Ar nucleus using a liquid argon time projection chamber (LArTPC) based detector.
  arXiv: 2308.03924 [submitted to JINST]
- Important proof-of-principle for next generation LArTPC detectors such as Deep Underground Neutrino Experiment (DUNE).

Same detector technology
Different mass (MicroBooNE is ~ x500 smaller than DUNE)
Different backgrounds







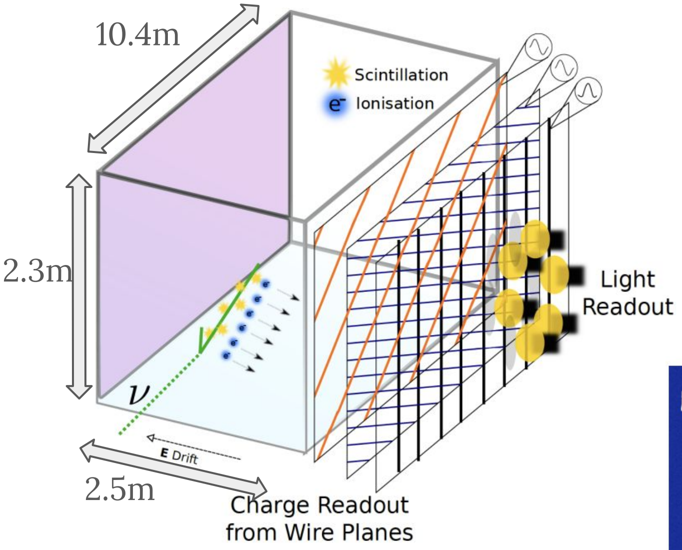
For further details on rare, BNV processes in DUNE, refer to talk by Josh Barrow

The MicroBooNE experiment

- The MicroBooNE detector (85 tonne active mass LArTPC) collected data from 2015–2021.
- The detector was operated on surface (subject to cosmic ray backgrounds).
- Exposed to pulsed neutrino beam from two different beamlines-
  - On-axis to Booster Neutrino Beamline (BNB).
  - Off-axis to Neutrinos at the Main Injector beamline (NuMI).
- **Recorded off-beam data collected using a random trigger anti-coincident to the neutrino beam (no neutrino interactions) → used for this analysis.**

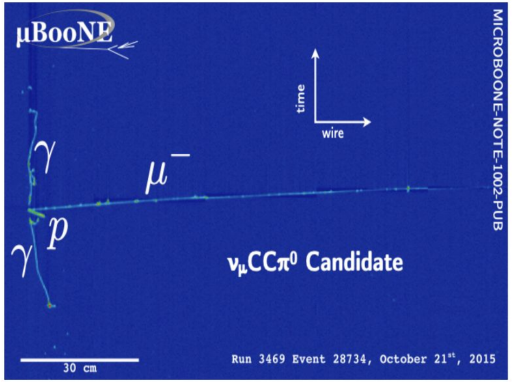
For further details on MicroBooNE and latest physics results, refer to talk by Brandon Eberly

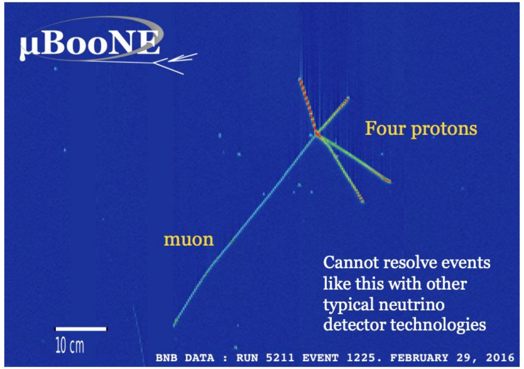
LArTPC detector technology



- Detection mechanism-
  - Ionization charge
  - Scintillation light
- Results in high resolution images of interaction with information of deposited ionization as a function of wire and time → **leverage this capability to develop image-based analysis using deep-learning (DL) techniques to search for n → n̄ signals.**

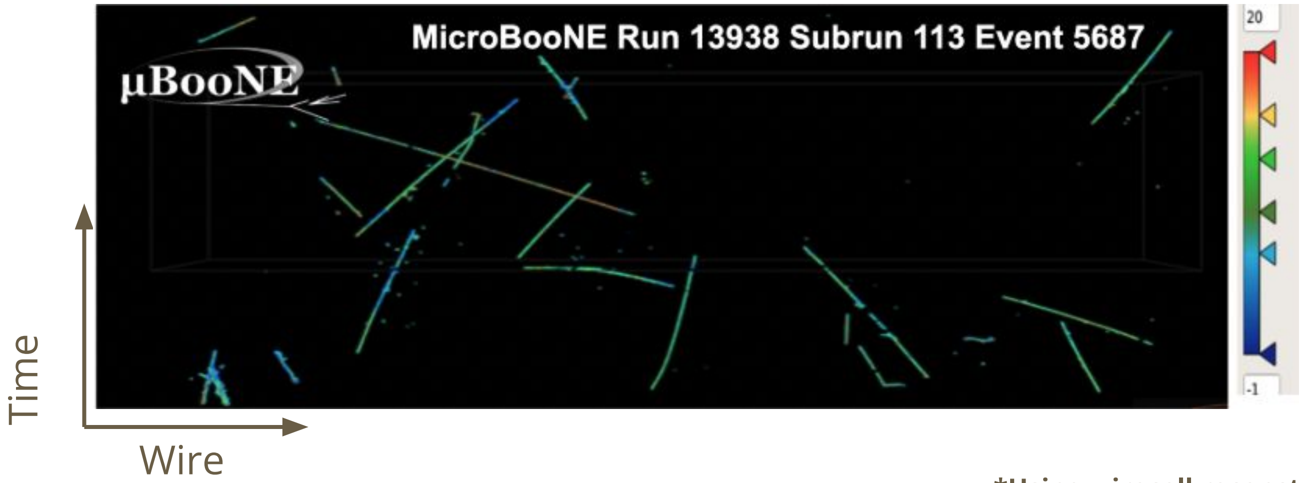
Beam direction





Analysis approach

Reconstructed clusters* over 2.3 ms exposure intervals → Image-based selection using machine-learning (ML) and deep-learning (DL) techniques → Limit on lifetime of $n \to \bar{n}$ process with 90% CL

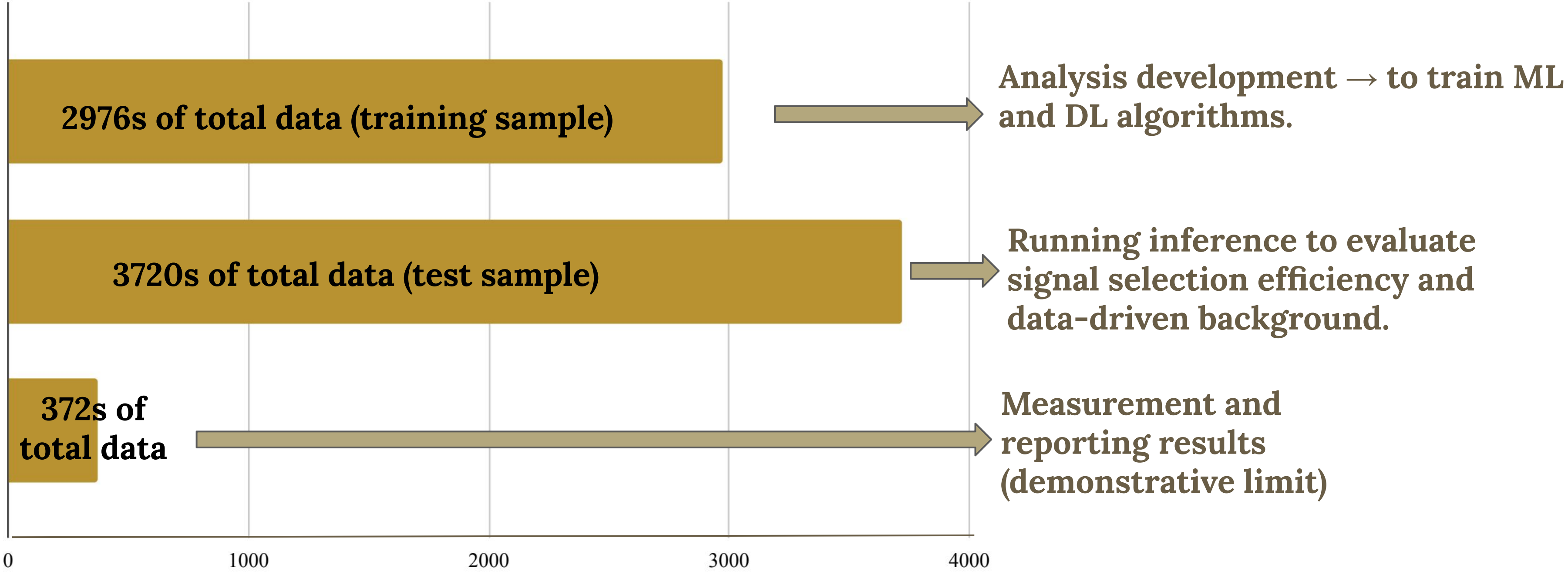


2.3 ms of readout window "an interaction"

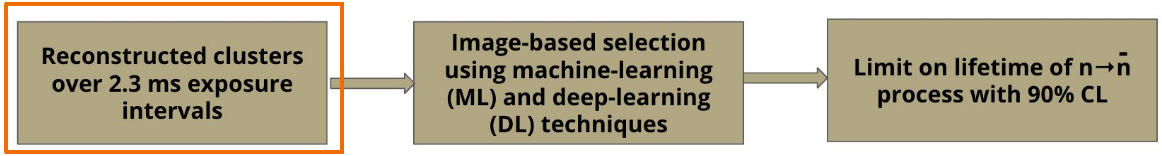
*Using wirecell reconstruction framework JINST 16 P06043

Exposure

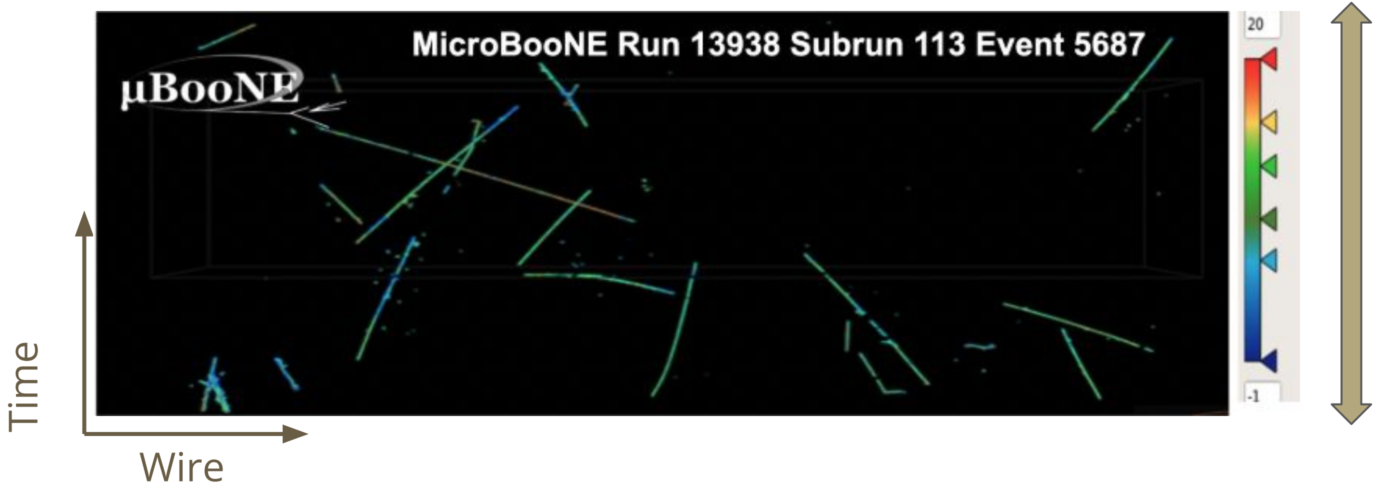
- The analysis used ~8000s of data.
  - Only a fraction of this data, corresponding to 372s, is used to report the measurement.



Background



- Real off-beam data (no neutrino interactions) is used to simulate a background sample, consisting predominantly cosmic ray muons and/or the induced electromagnetic and hadronic showers.
  - **Background interaction rate for this search is evaluated by direct measurement making use of the off-beam data (corresponding to 3720s of exposure).**



2.3 ms of readout window "an interaction"

Signal

Reconstructed clusters over 2.3 ms exposure intervals → Image-based selection using machine-learning (ML) and deep-learning (DL) techniques → Limit on lifetime of $n \rightarrow \bar{n}$ process with 90% CL

- Signal interactions are simulated using the GENIE event generator

GENIE (hA-Local Fermi Gas)
Simulates $n \rightarrow \bar{n}$ interactions

→

GEANT4
Accounts for hadron-Ar reinteractions

→

Detector simulation

Signal

Reconstructed clusters over 2.3 ms exposure intervals → **Image-based selection using machine-learning (ML) and deep-learning (DL) techniques** → **Limit on lifetime of $n \rightarrow \bar{n}$ process with 90% CL**

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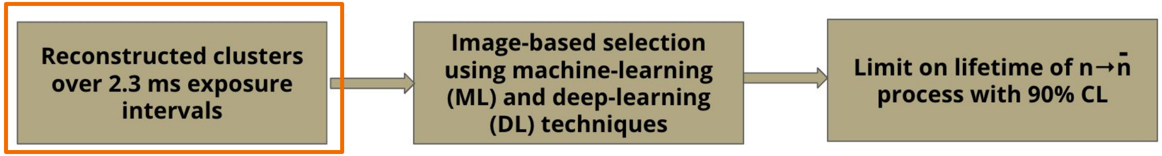
Signal overlay sample



- The GENIE simulated signal interactions are overlaid onto the background (real cosmic data)
  - Used to estimate the signal selection efficiency.
- This analysis assumed the presence of negligible signal in the off-beam data (consistent with the SuperKamiokande best limit) corresponding to 372s and 3720s of exposure.

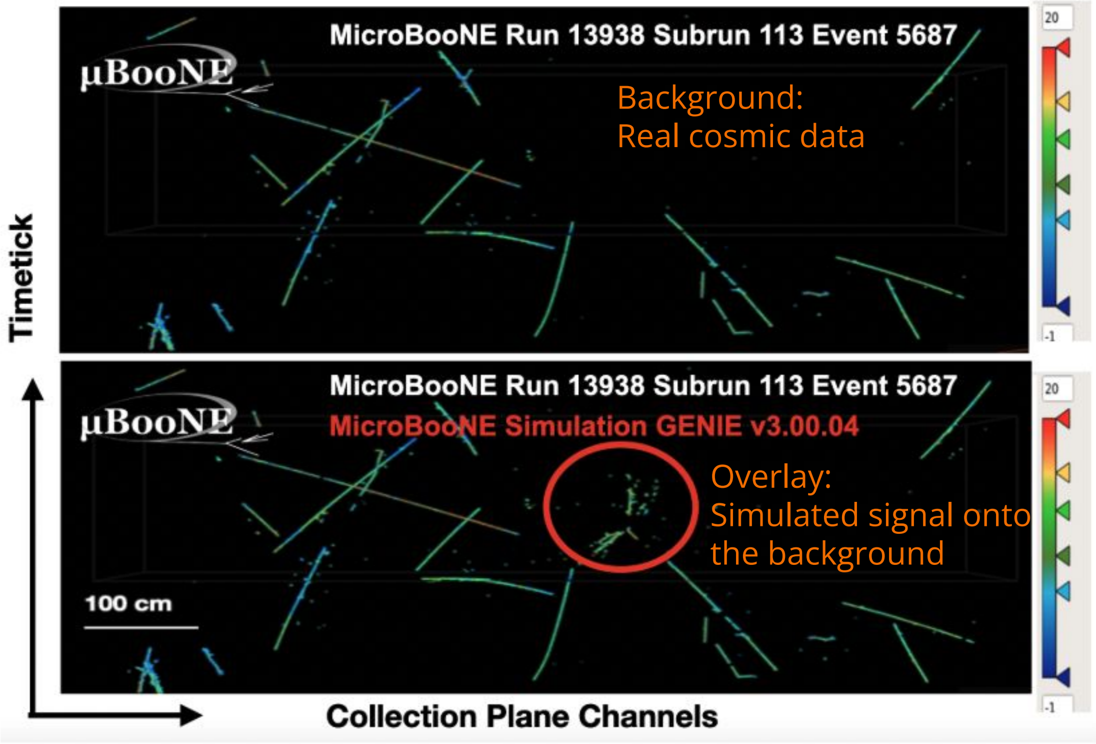
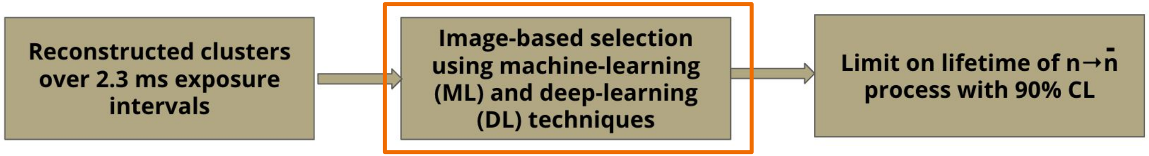
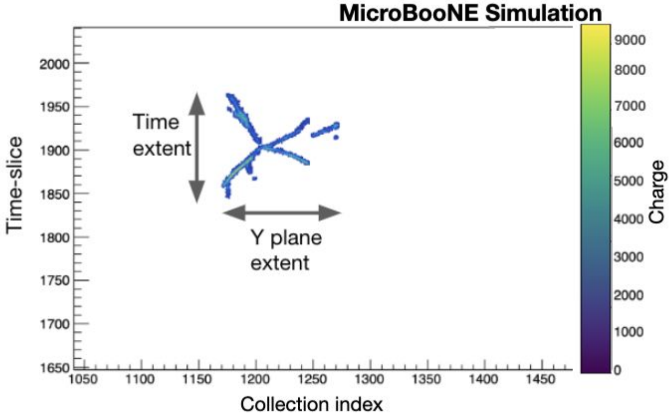
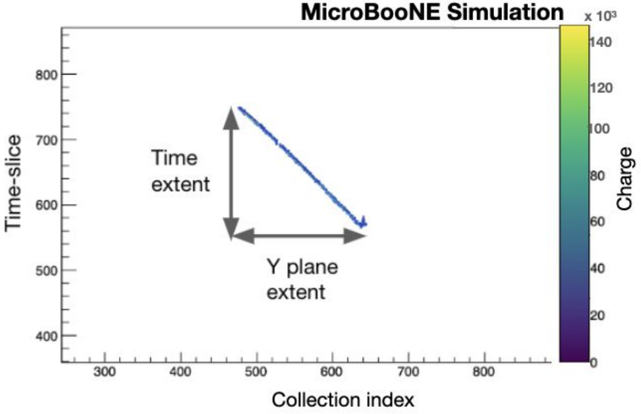


Image-based selection



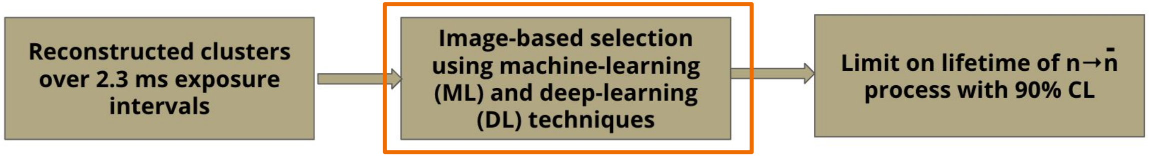
- This analysis utilized 2D topological features of signal and background interactions to train ML algorithm-
  - Signal has localized, semi-spherical star-like topology.
  - Typical cosmic ray background interactions have extended track-like topology (from cosmics)



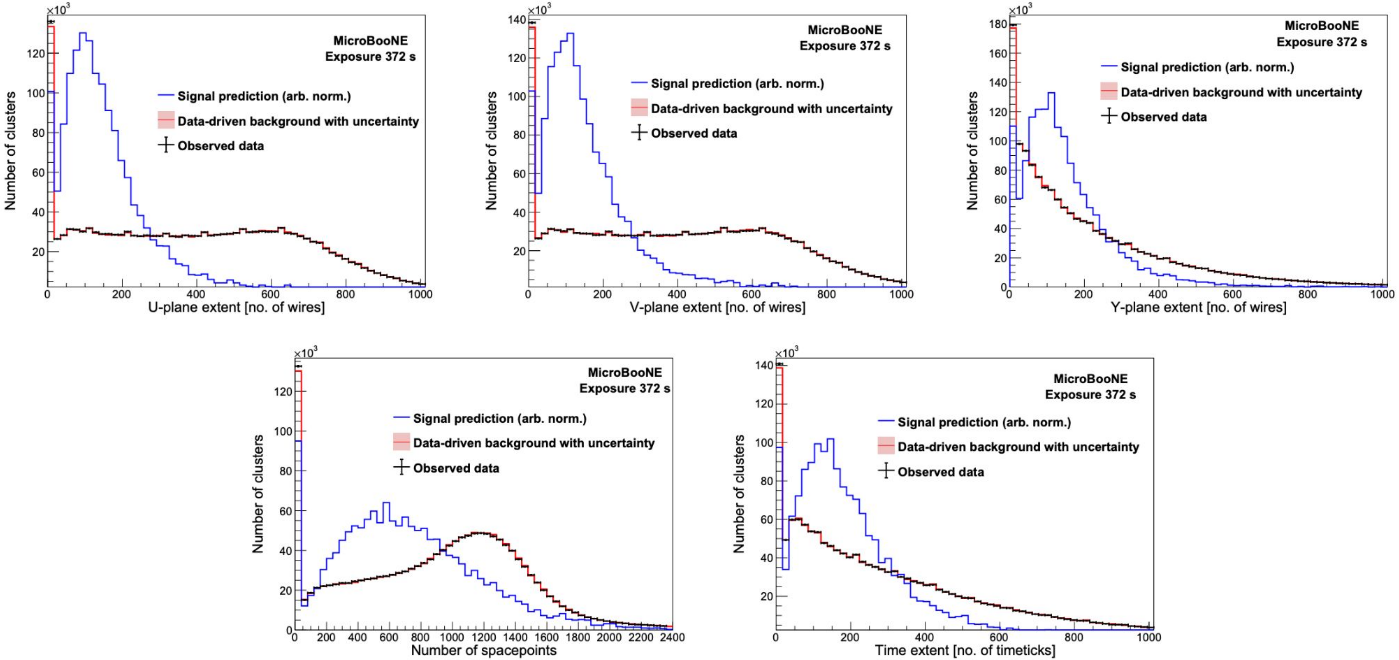


Different scale for two plots

Image-based selection

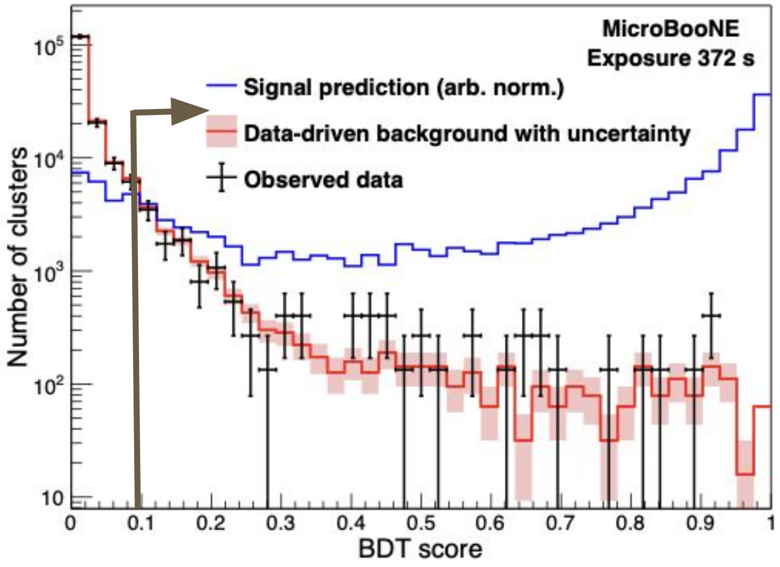


- The topological features are quantified using the extent in space and time and number of spacepoints in a cluster.



Boosted decision tree

Reconstructed clusters over 2.3 ms exposure intervals → **Image-based selection using machine-learning (ML) and deep-learning (DL) techniques** → Limit on lifetime of $n \to \bar{n}$ process with 90% CL



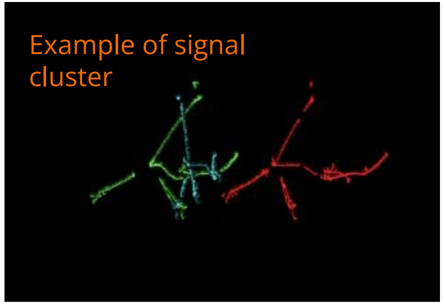
- Boosted decision tree (BDT) → reject cosmic background interactions.
- Remaining clusters are used to train a DL algorithm (a sparse Convolution Neural Network (CNN)*)

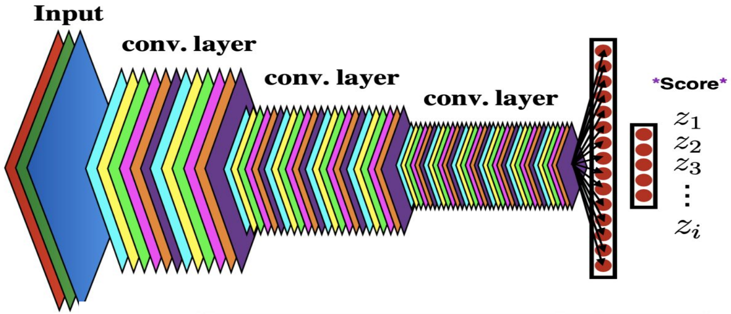
*[1]: arxiv:1711.10275
*[2]: arxiv:1706:01307
*[3]: Phys. Rev. D 103 052012

Convolution neural network

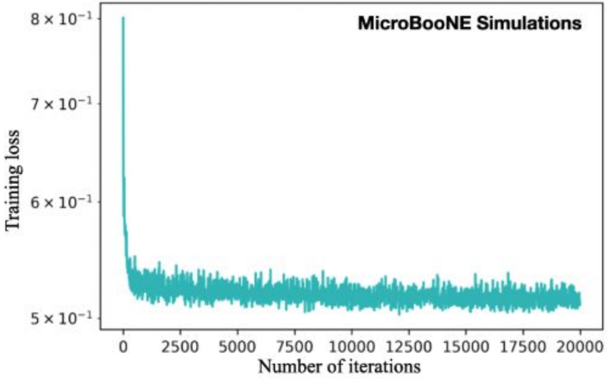
Reconstructed clusters over 2.3 ms exposure intervals → **Image-based selection using machine-learning (ML) and deep-learning (DL) techniques** → Limit on lifetime of n→n̄ process with 90% CL

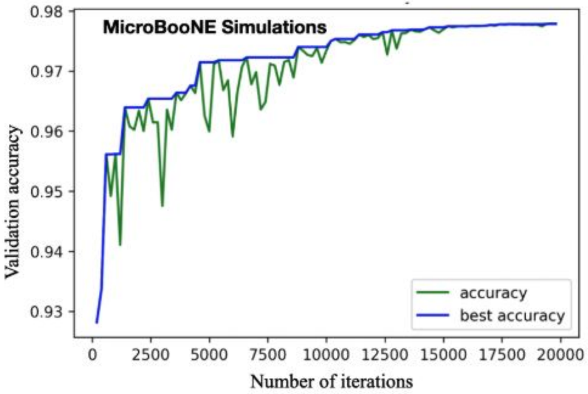
*A sparse CNN with VGG16 network architecture → trained using 1 million interactions as inputs.





Sparsified (Localized) input images of a given interaction (selected cluster), including only position, time, and hit value.





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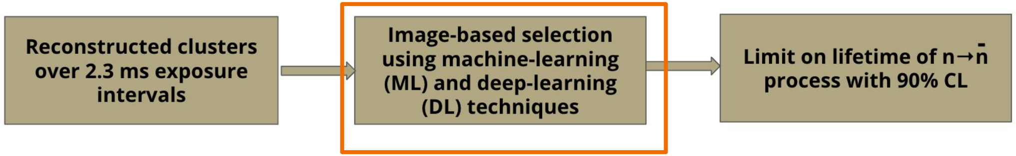
Convolution neural network



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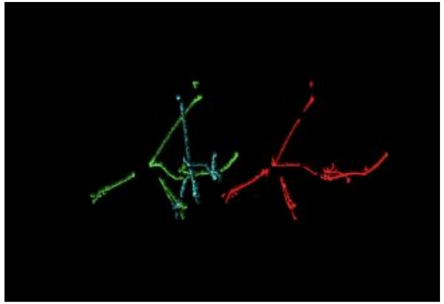

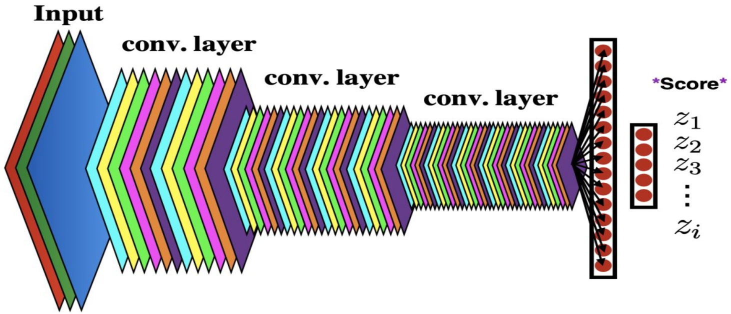

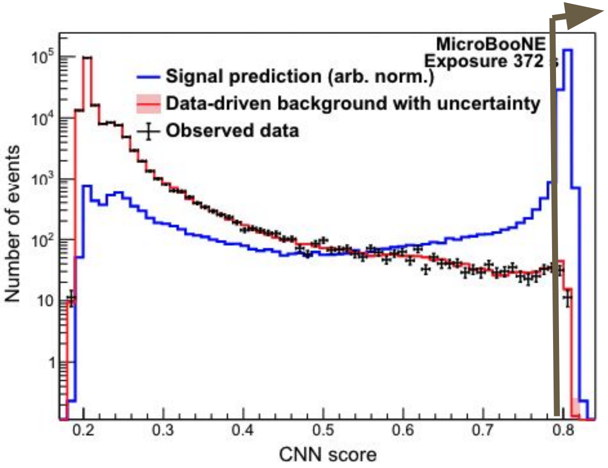

Sparsified (Localized) input images of a given interaction (selected cluster), including only position, time, and hit value.

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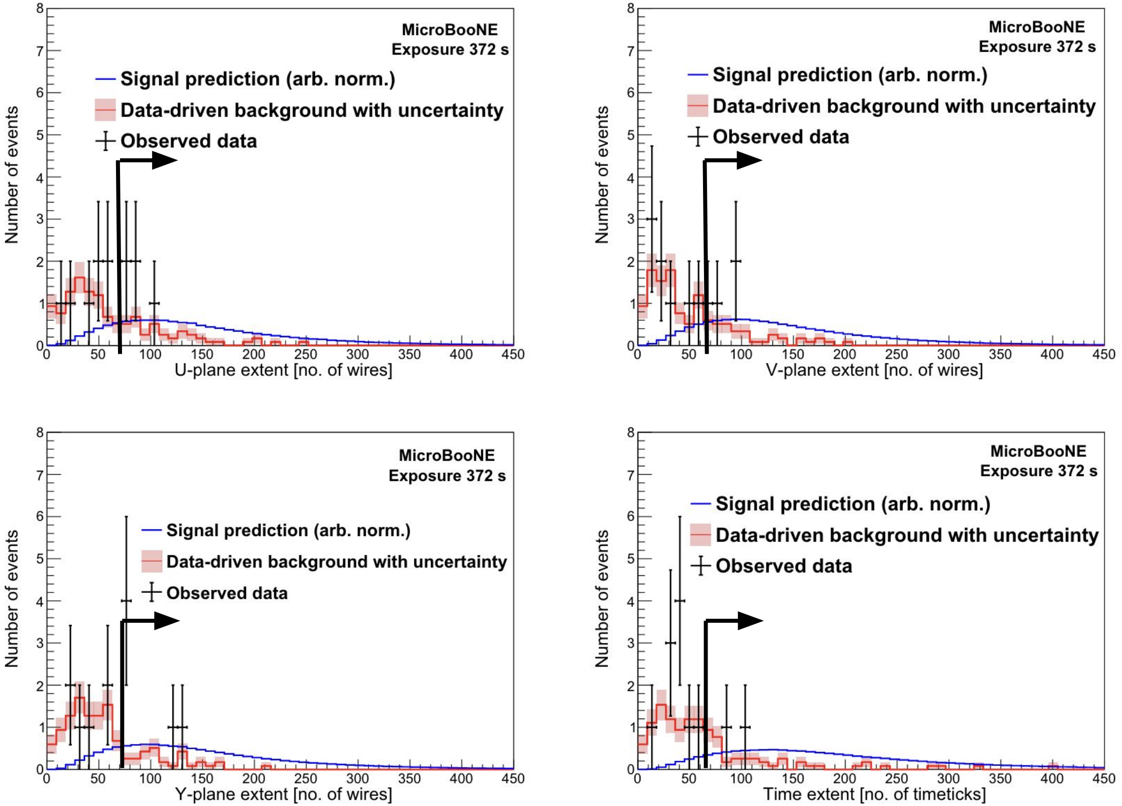
*[3]: Phys. Rev. D 103 052012

CNN>0.8 is selected (optimized based on statistical-only sensitivity as a figure of merit)

Topological cuts

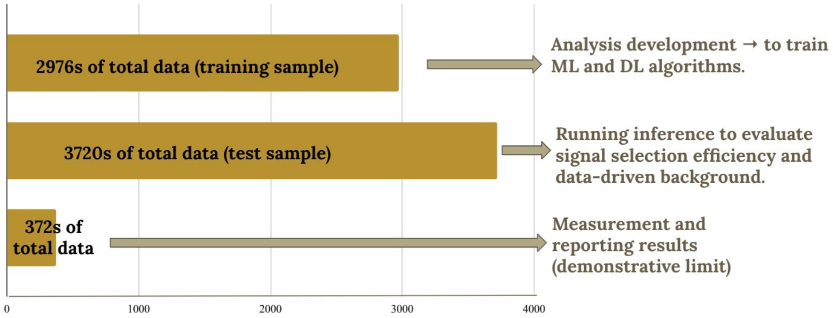
Topological cuts are applied in order to reject zero-extent and very low-extent clusters which can not represent signal topology



Number of interactions

Using test sample (3720s of exposure)	Signal	Background
No selection	1,633,525	1,618,827
Image-based selection	1,202,281	142
Topological cuts	1,147,57	32
Signal selection efficiency	70.2%	
Background efficiency		0.0020%

The expected background corresponding to 372 s of exposure is 3.20 ± 1.79 (stat.) ± 0.57 (syst.)



Systematic uncertainties - Signal

GENIE (hA-Local Fermi Gas (LFG))
Simulates $n \rightarrow \bar{n}$ interactions

→

GEANT4
Accounts for hadron-Ar reinteractions

→

Detector simulation

Generate different samples corresponding to different GENIE models (hN-LFG, hA-Bodek Ritchie(BR), and hN-BR)

↓

Apply Selection

↓

Signal selection efficiency (ε)

$$\eta_{\rm err} = \sqrt{\frac{\epsilon(1-\epsilon)}{N}},$$

Number of generated interactions for any given model

$$\eta_{\rm errnom} = \frac{\epsilon_{\rm nom} - \epsilon}{\epsilon_{\rm nom}},$$

Signal selection efficiency for MicroBooNE's default GENIE model (hA-LFG)

Systematic uncertainties - Signal

GENIE (hA-Local Fermi Gas (LFG))
Simulates n→ $\bar{n}$ interactions

→

GEANT4
Accounts for hadron-Ar reinteractions

→

Detector simulation

Generate different samples to account for differences in data and simulation for charge and light response

↓

Apply Selection

↓

Signal selection efficiency (ε)

$$\eta_{\text{err}} = \sqrt{\frac{\epsilon(1-\epsilon)}{N}},$$

Number of generated interactions for any given model

$$\eta_{\text{errnom}} = \frac{\epsilon_{\text{nom}} - \epsilon}{\epsilon_{\text{nom}}},$$

Signal selection efficiency for MicroBooNE's default GENIE model (hA-LFG)

Systematic uncertainties - Signal

GENIE (hA-Local Fermi Gas (LFG))
Simulates $n \rightarrow \bar{n}$ interactions

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GEANT4
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Detector simulation

Re-weighting scheme to account for hadron-Ar reinteractions due to charged hadrons (π^+, π^-, p)

$$\sigma = \frac{1}{N_w} \sum_{i=1}^{N_w} (W_i - N)^2,$$

i represents number of weights
W: weighted sample (takes weights generated for charged hadrons into account)
N: nominal sample

Systematic uncertainties - Signal

GENIE (hA-Local Fermi Gas (LFG))
Simulates $n \rightarrow \bar{n}$ interactions

→

GEANT4
Accounts for hadron-Ar reinteractions

→

Detector simulation

Systematic uncertainties on signal selection efficiency	
GENIE	4.85%
Detector	6.72%
GEANT4	2.32%
Total systematic uncertainty on signal	8.61% (quadrature sum)

Systematic uncertainties - Background

- Since, background is measured in-situ from the real cosmic data, the uncertainty comes from the statistical uncertainty on number of final selected background interactions in the test data sample which is 17.68%.

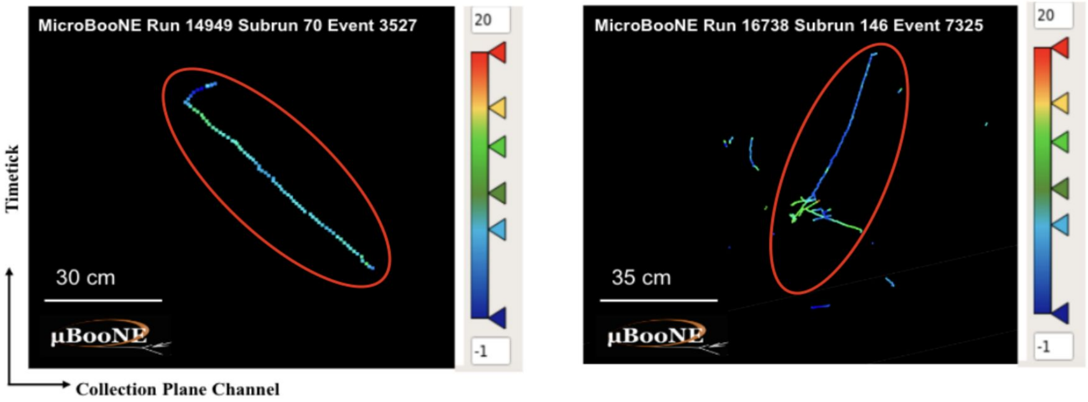
Results

Reconstructed clusters over 2.3 ms exposure intervals → Image-based selection using machine-learning (ML) and deep-learning (DL) techniques → **Limit on lifetime of n→n̄ process with 90% CL**

- Due to the absence of an excess of interactions above the expected background, a demonstrative lower limit on $n \rightarrow \bar{n}$ process is derived using *TRolke package in ROOT

Nucl.Instrum.Meth. A 458 745

	Exposure	Total interactions	Observed interactions	Expected background	Demonstrative limit 90%CL
MicroBooNE	372s	168636	2	3.2	1.1 x 10^{26} years



- The selected clusters in observed interactions are localized to few tens of wires and are therefore, selected as signal candidate interactions.

Comparison to SuperKamiokande

- Substantial **improvement in signal selection efficiency with MicroBooNE** using image-based analysis.
- Significantly lower exposure using randomly triggered off-beam data.
- Significantly higher background due to on-surface operation of detector.
- The obtained limits are lower than the current best limits from the SuperKamiokande because of the small-sized detector and low exposure.

	Nucleus	Exposure	**Signal selection efficiency**	Observed interactions (events)	Expected background	**Limit on nucleus-bound neutron lifetime 90%CL**
MicroBooNE	^{40}Ar	372s	**70.2%**	2	3.2	**1.1 x 10^{26} years**
SuperKamiokande Phys.Rev.D 103 012008	^{16}O	6050 days	**4.1%**	11	9.3	**3.6 x 10^{32} years**

Free neutron transition lifetime

$$\tau_m = R\tau^2_{n-\bar{n}}.$$

Bound neutron lifetime (τ_m)

Suppression factor (R)

Free neutron lifetime ($\tau_{n-\bar{n}}$)

Suppression factor (R) depends on the type of nuclei e.g.
for ^{40}Ar, R is 5.6×10^{22} s^{-1}
for ^{16}O, R is $5.17\times10^{22} s^{-1}$

Experiment	Nucleus	Suppression factor (R)	Free neutron lifetime (90%CL)
MicroBooNE	**^{40}Ar**	**5.6×10^{22} s^{-1}**	**2.6×10^{5} s**
SuperKamiokande Phys.Rev.D 103 012008	**^{16}O**	**5.17×10^{22} s^{-1}**	**4.7×10^{8} s**
ILL Z.Phys.C 63 409	-	-	**0.86×10^{8} s**

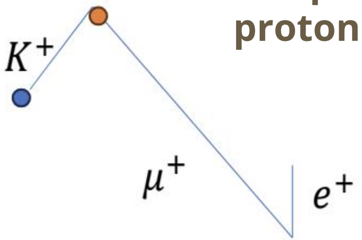
Proof-of-principle demonstration for DUNE

- The DUNE exposure is projected to be 10^9 larger than MicroBooNE.
- Achieving similar signal selection efficiency with DUNE as for MicroBooNE, while also achieving high atmospheric neutrino background rejection[1], would increase DUNE's statistical-only sensitivity by seven-fold compared to the MicroBooNE's[2] reported sensitivity.

(1) doi:10.2172/1426674
(2) arXiv: 2308.03924

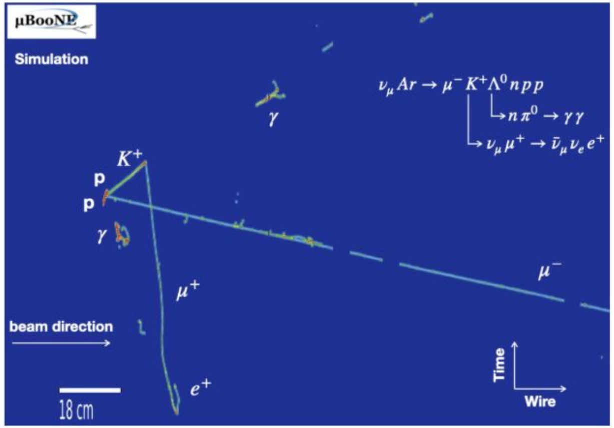
Real-time triggering for BNV searches in DUNE

- The developed analysis utilizing topological features presents a unique approach to select rare, BNV signatures e.g. as demonstrated by selecting n → n̄ signatures and could also be extended to select proton decay ($p \rightarrow \nu K^{+}$) signatures →**could potentially lend itself to online data selection for rare, BNV signatures for DUNE, if applied at raw waveform level information (without utilizing full reconstruction information).**



Unique kinked topology for proton decay channel

MicroBooNE Public Note - 1071



For further details on proton decay channels, refer to talk by Linyan Wan

Real-time triggering for BNV searches in DUNE

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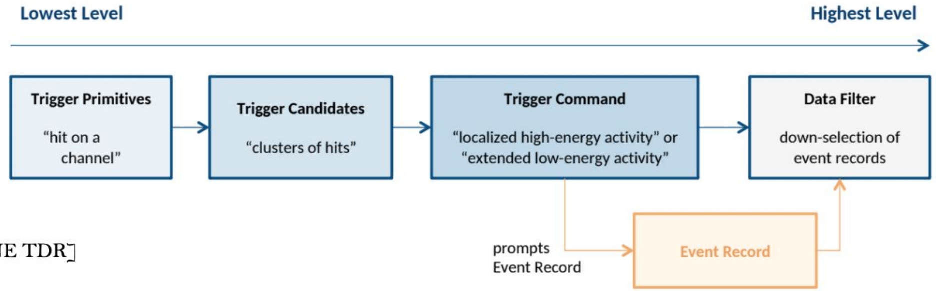
DUNE baseline trigger strategy is currently being demonstrated online in MicroBooNE (J.Phys.Conf.Ser 2374 (2022) 1,012163)

DUNE trigger strategy



[DUNE TDR]

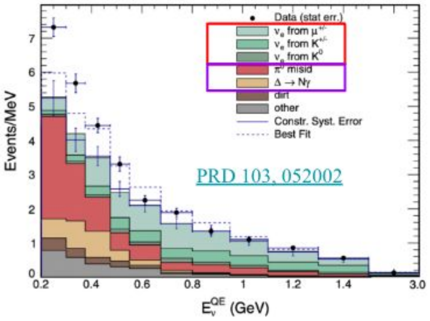
Conclusions

- The analysis demonstrates LArTPC's capability to search for this process with high signal selection efficiency and excellent background rejection.

- The developed analysis using real data from MicroBooNE holds great promise to search for this process in future large, well-shielded detectors like DUNE with enhanced sensitivity and to provide competitive limit on the lifetime of this process.

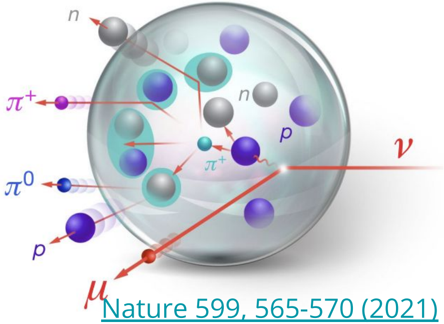
Thank you!

Physics goals of the MicroBooNE experiment

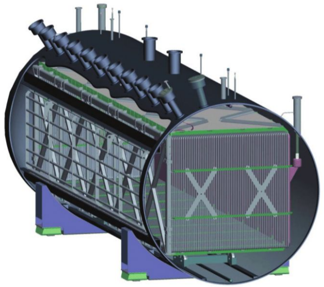


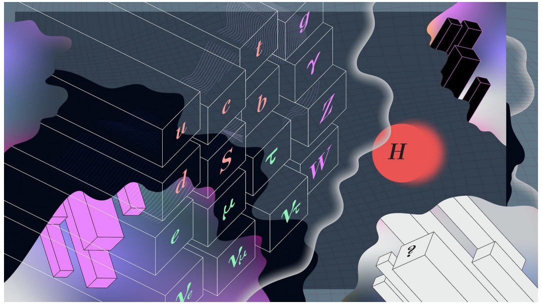
1. Resolve source of unexplained MiniBooNE Low Energy Excess

2. Understand neutrino-argon interactions



[Nature 599, 565-570 (2021)]





3. Searching for beyond-the-Standard Model (BSM) physics processes

4. R&D for the next-generation LArTPC-based experiments.

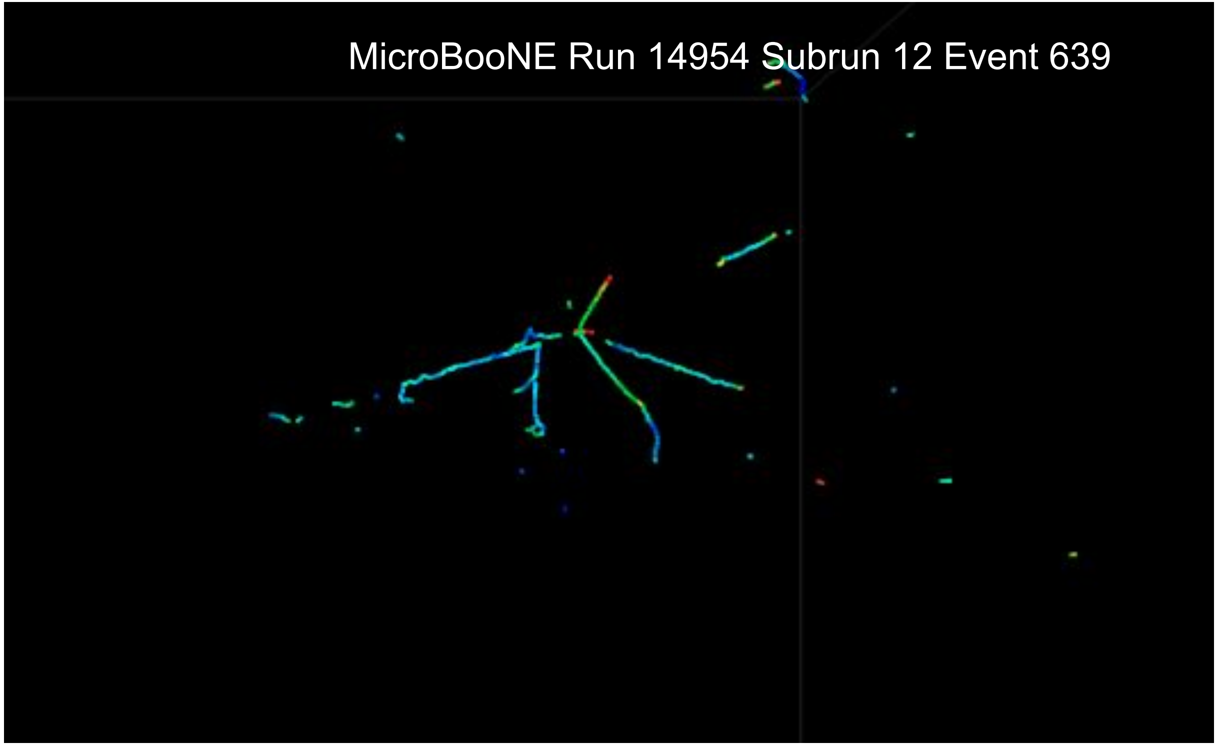
CNN score cut optimization

CNN criterion	Signal Efficiency	Background Efficiency (10^{-4})	Normalized Background Estimate	Sensitivity (10^{25} yrs)
0.797	0.8274 ± 0.0003	1.53 ± 0.10	24.8 ± 1.6	2.62
0.798	0.8222 ± 0.0003	1.27 ± 0.09	20.5 ± 1.4	2.83
0.799	0.8012 ± 0.0003	1.08 ± 0.08	17.5 ± 1.3	2.98
0.800	0.7360 ± 0.0003	0.88 ± 0.07	14.2 ± 1.2	2.99
0.801	0.6392 ± 0.0004	0.66 ± 0.06	10.7 ± 1.0	2.95
0.802	0.5081 ± 0.0004	0.50 ± 0.06	8.1 ± 0.9	2.65
0.803	0.3490 ± 0.0004	0.43 ± 0.05	6.9 ± 0.8	1.95

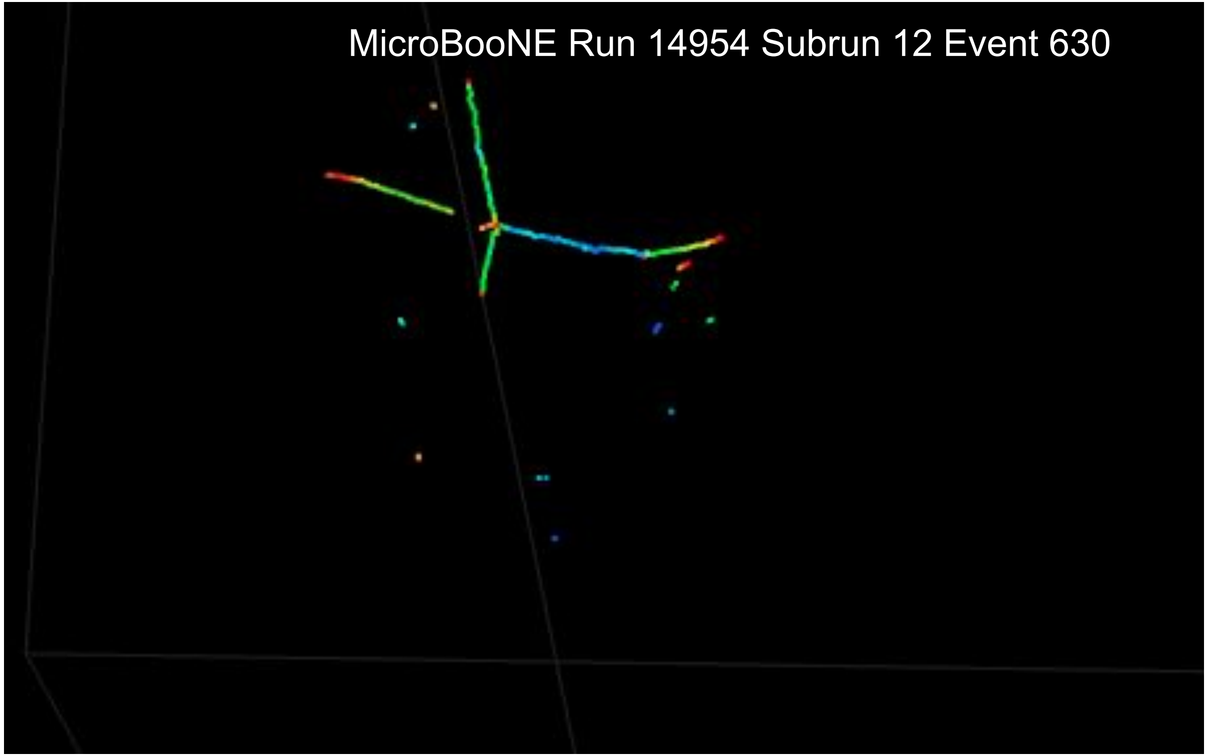
Detector systematics

Detector variation	η_{err} %	η_{errNom} %	η %
Recombination	0.13	0.53	0.54
Light yield	0.22	1.15	1.17
Space charge effect	0.12	0.13	0.18
TPC waveform modeling	0.24	6.59	6.59
Total			6.72

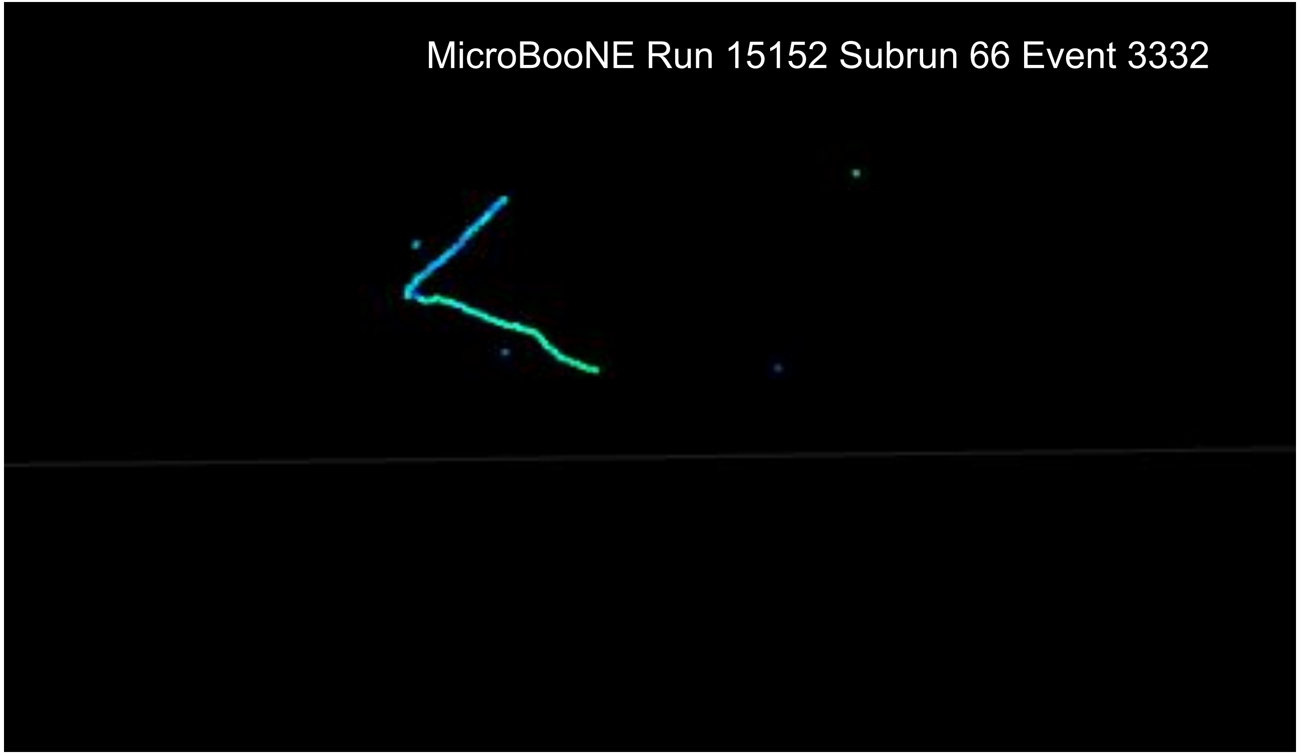
Selected simulated signal cluster



Selected simulated signal cluster



Selected background cluster



Selected background cluster