MicroBooNE's BSM Program

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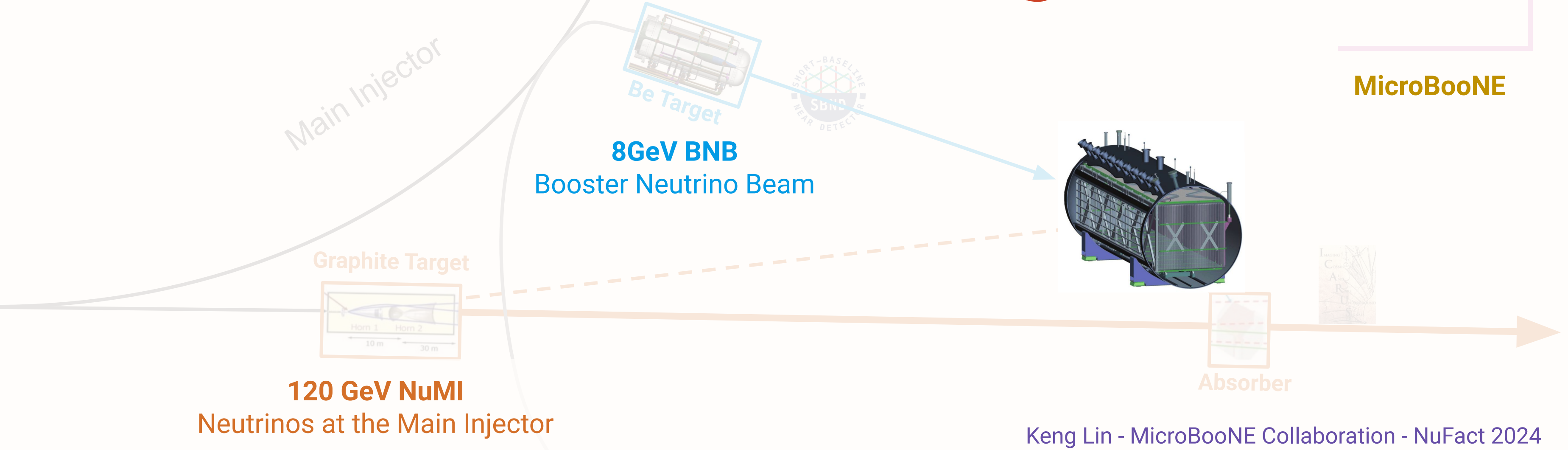
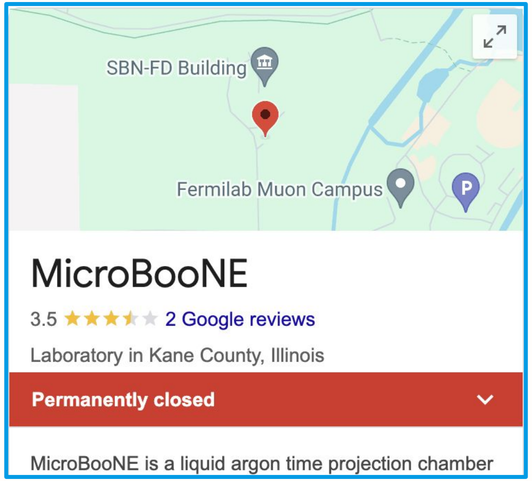
On Behalf of the MicroBooNE Collaboration

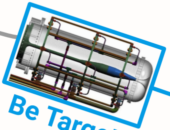
NuFact 2024
Sep. 2024

RUTGERS
THE STATE UNIVERSITY
OF NEW JERSEY

MicroBooNE With Dual Beam Configuration

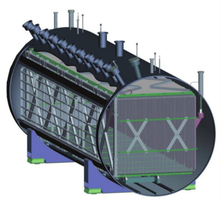






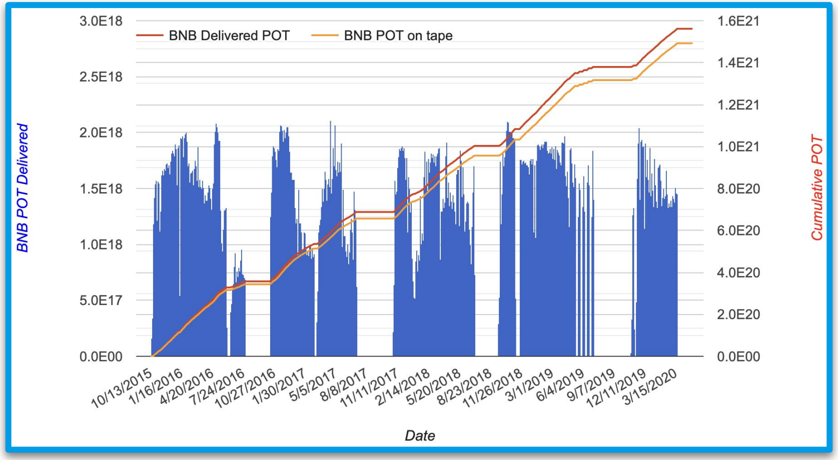
Be Target

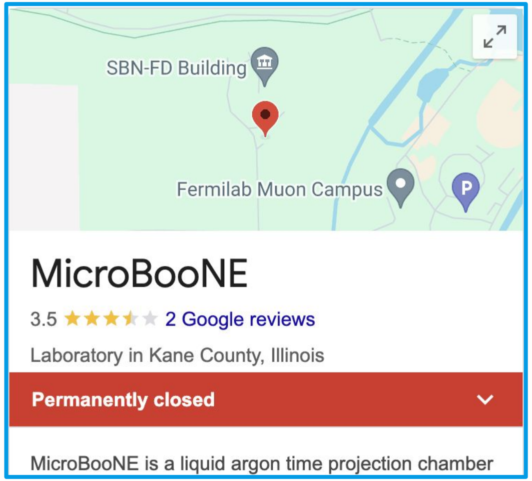
8GeV BNB
Booster Neutrino Beam

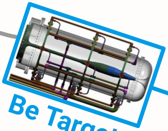


MicroBooNE
Data collection 2015 - 2020
470m

Booster Neutrino Beam
- On-axis beam line
- 470 meters away from target
- Data collected over 5 years of running: **1.5×10^{21} protons on target** (POT)







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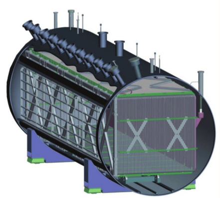

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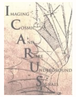
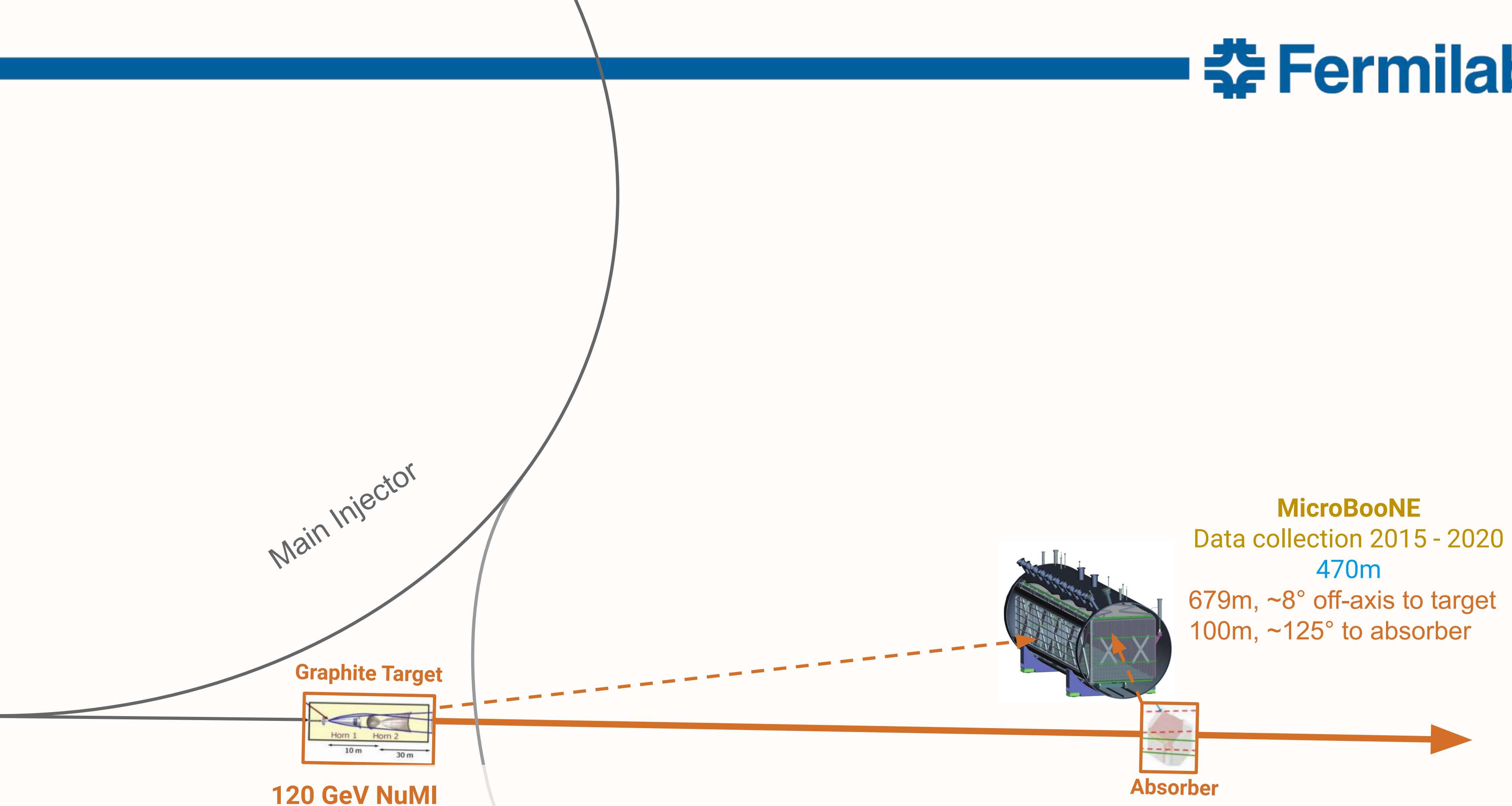
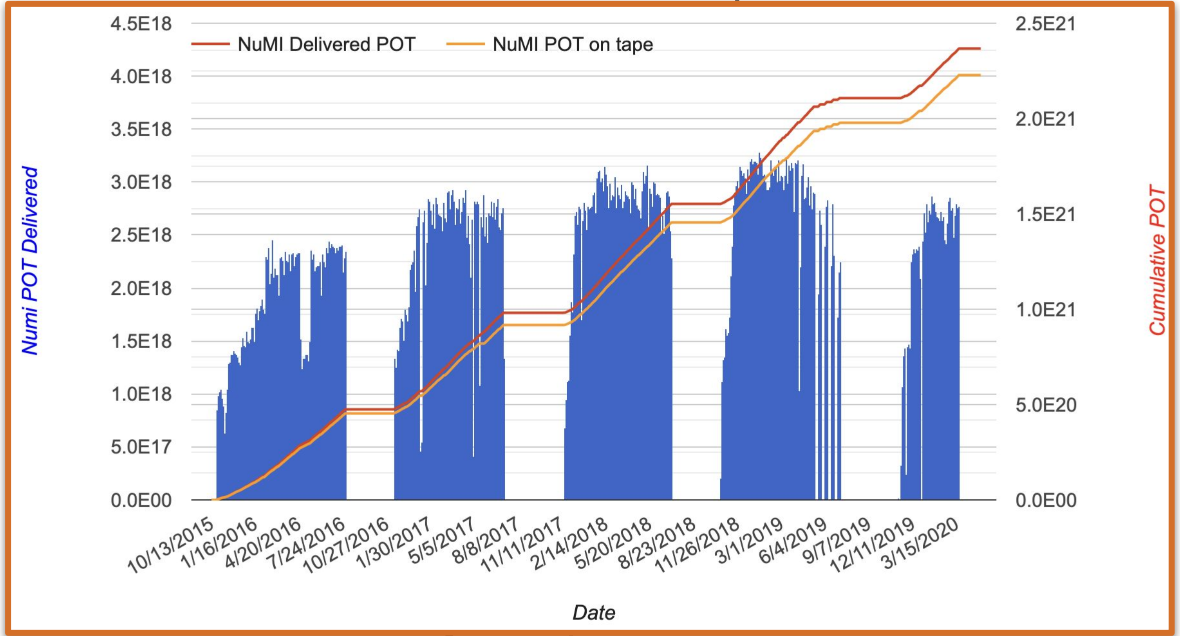




120 GeV NuMI
Neutrinos at the Main Injector



The NuMI Beam

- Off-axis beam
- 679 meters to target
- 100 meters to absorber
- Two modes:
  - Neutrino
  - Antineutrino
- Data collected over 5 years: **2.2×10^{21} POT**

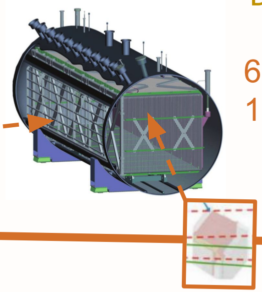
MicroBooNE

Data collection 2015 - 2020

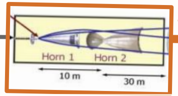
470m

679m, ~8° off-axis to target

100m, ~125° to absorber



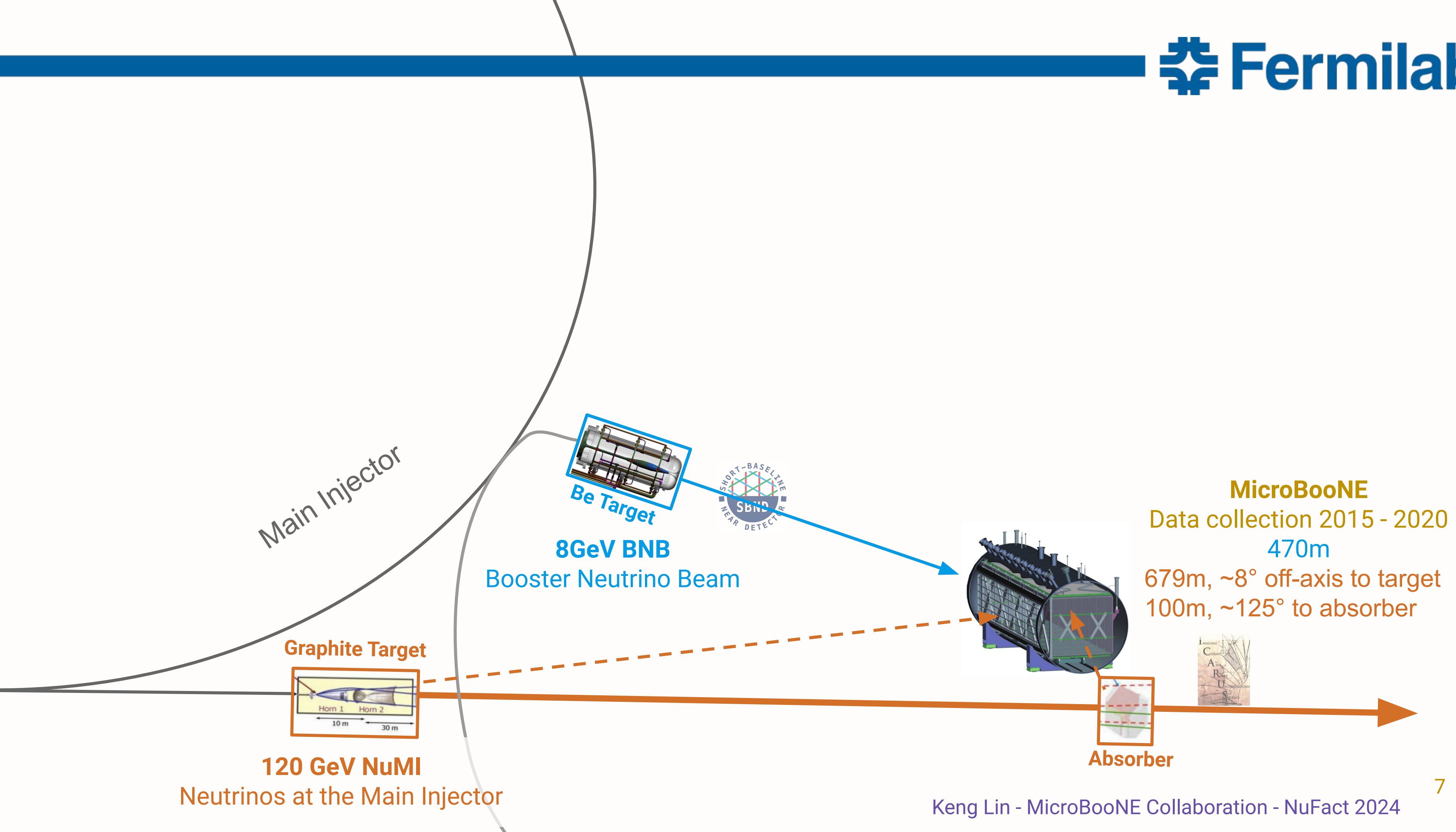
Graphite Target



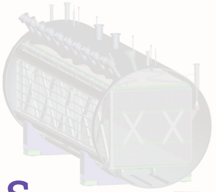
Absorber

120 GeV NuMI

Neutrinos at the Main Injector


Main Injector
Be Target
SHORT-BASELINE
SBND
NEAR DETECTOR
8GeV BNB
Booster Neutrino Beam
MicroBooNE
Data collection 2015 - 2020
470m
679m, ~8° off-axis to target
100m, ~125° to absorber
Graphite Target
Horn 1
Horn 2
10 m
30 m
120 GeV NuMI
Neutrinos at the Main Injector
Absorber

- ❖ The benefit of dual beam configuration:
  - ➢ Double the POT
  - ➢ Explore physics from different energy scale
    - ■ BNB: 8GeV proton beam at BE
    - ■ NuMI: 120GeV proton beam at Graphite
  - ➢ Strongly correlated detector systematics
  - ➢ Extra geometry-associated handles
    - ■ Off-axis reduces neutrino backgrounds

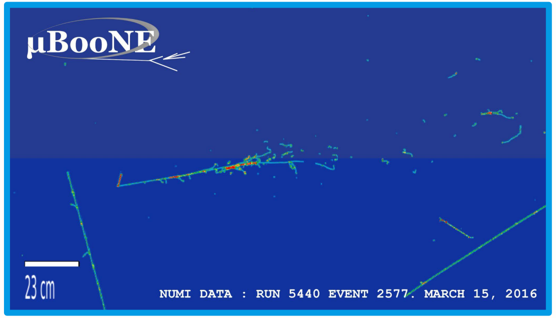


Plenary tomorrow: N. Nayak - Results from MicroBooNE

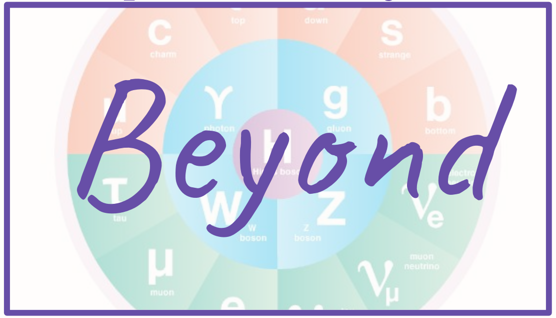
MicroBooNE Physics Goals

Detector R&D

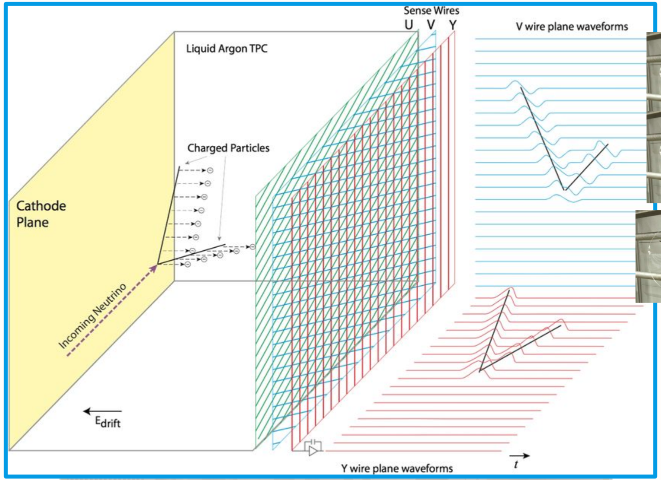
ν-Argon Interactions



Explore BSM Physics

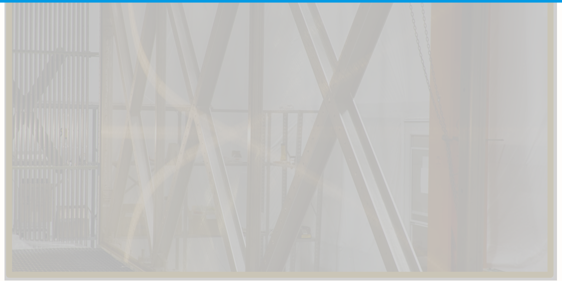


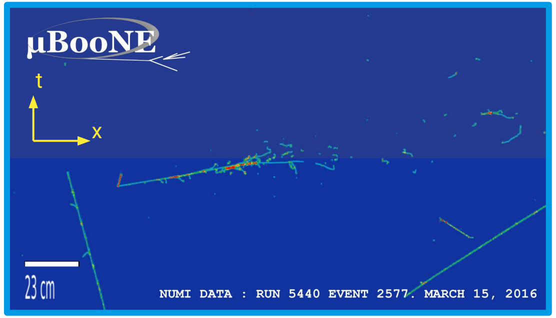
Neutrino-Argon Interactions



…
32 PMTs

- 85 tonne Liquid Argon Time Projection Chamber (LArTPC)
  - Passing charged particles induce ionization electrons, which drift toward wires
  - **Energy** deposition: low — high
  - **Timing** from PMTs & Wires





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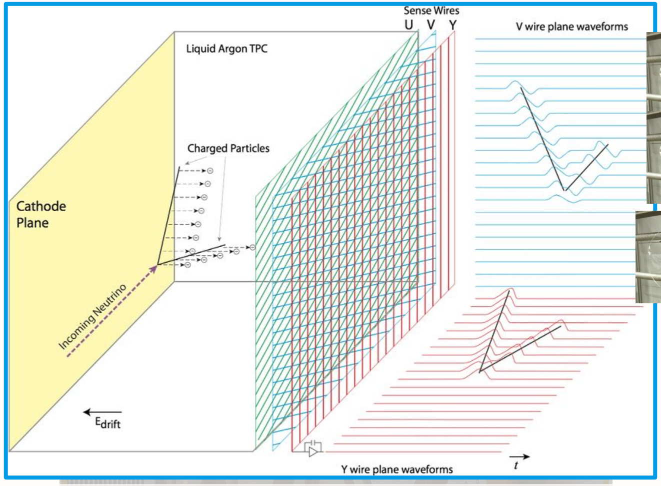

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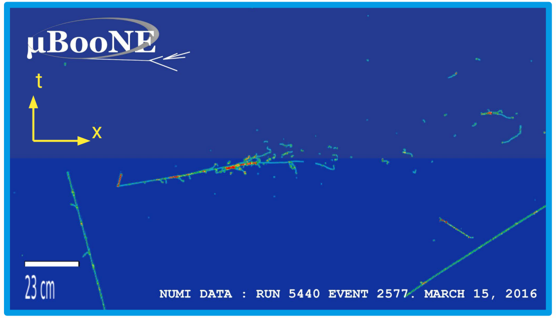
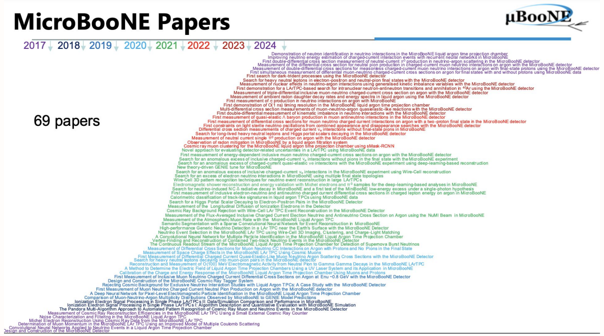




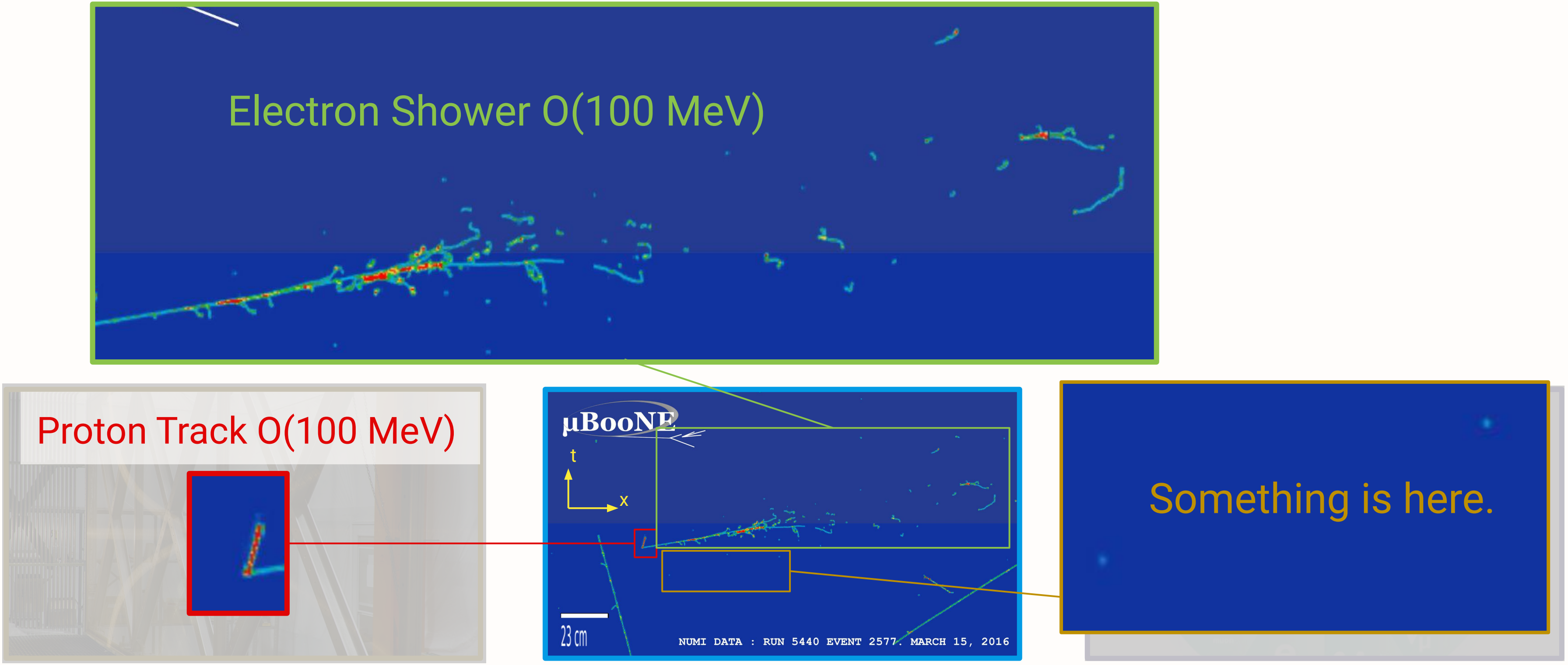
Talks:

- D. Barrow - Pionless XSec. (Thu.)
- P. Green - Pion XSec. (Thu.)

5 XSec. Posters:

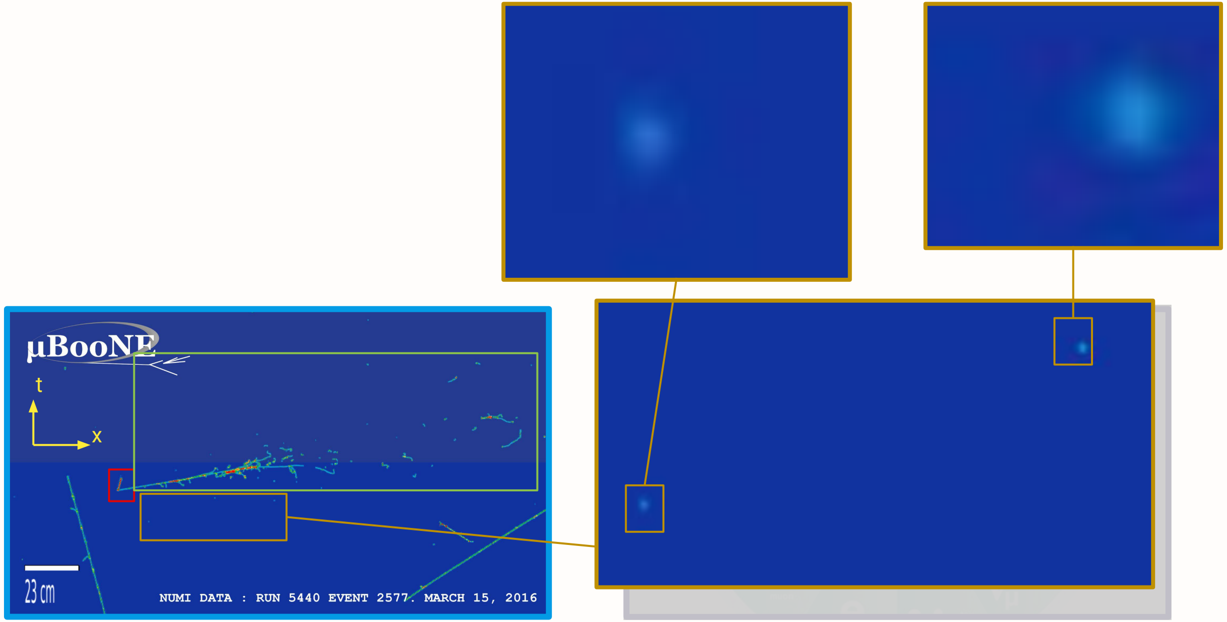
L Cooper-troendle 95
D Barrow 103
B Bogart 106
118 P Englezos
127 J Rondon

Neutrino-Argon Interactions



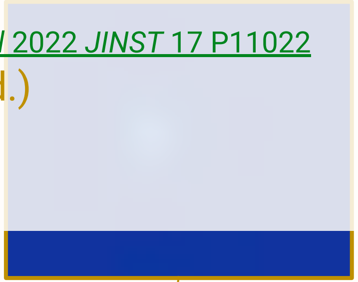
Neutrino-Argon Interactions

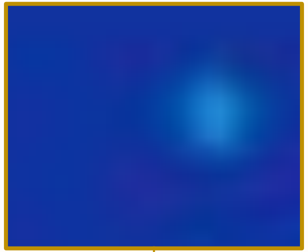
MeV scale “blips”

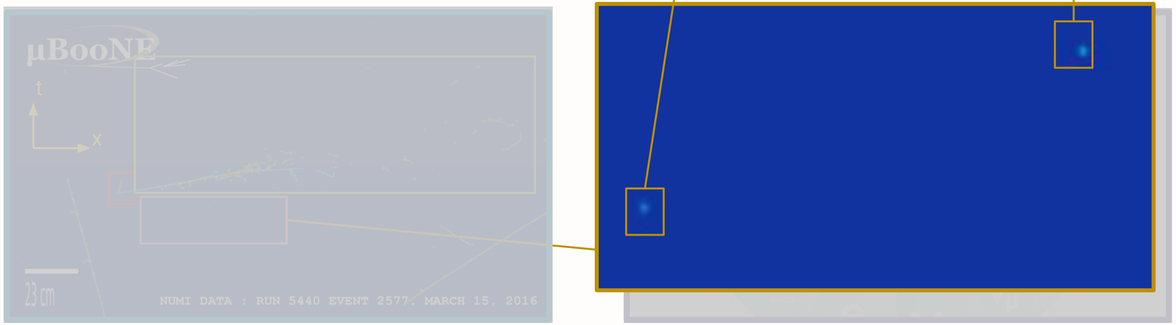


Detector R&D for Future LArTPCs

- Reconstructable energy threshold as low **as 100 keV**
  - Reveal MeV scale activities through “blips”. (Poster: D. Andrade 115)
  - Applications:
    - Radiological activity measurement P. Abratenko *et al* 2022 *JINST* 17 P11022
      W. Foreman’s talk on Radon Measurement (Wed.)
    - Neutron Identification
    - And more… e.g. millicharged particle search

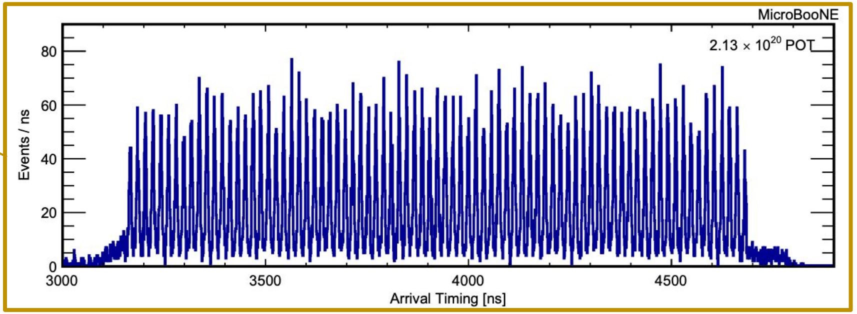




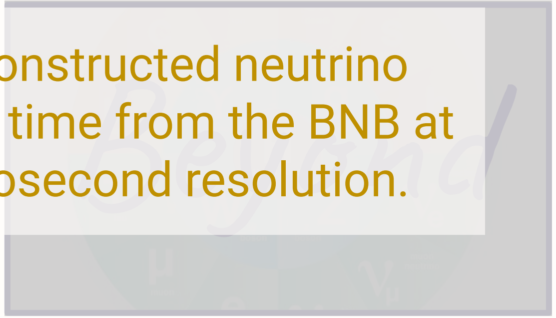


Detector R&D for Future LArTPCs

- Timing resolution as low as **O(1 ns)**
  - Reveal the beam pulse substructures.



Reconstructed neutrino arrival time from the BNB at nanosecond resolution.

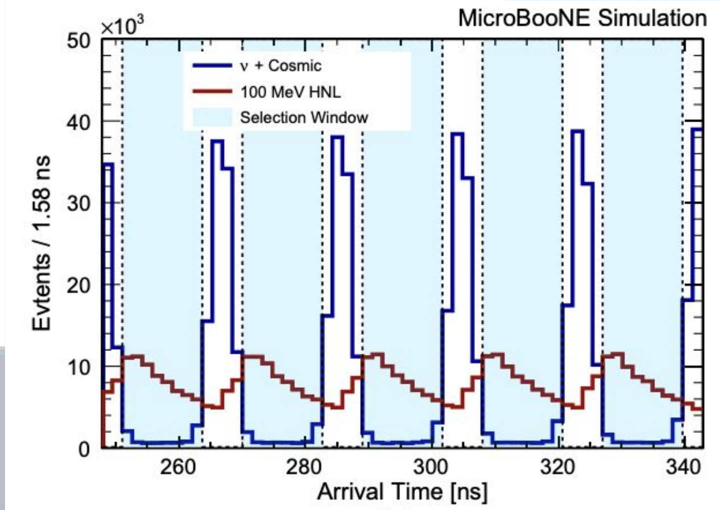


Detector R&D for Future LArTPCs

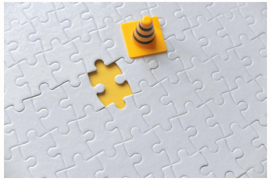
- Timing resolution as low as **O(1 ns)**
  - Reveal the beam pulse substructures.
  - Potential applications:
    - Heavy BSM particle searches
    - e.g. heavy neutral leptons

Neutrino arrival

HNL arrival

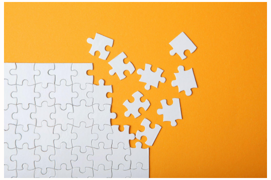


HNL sensitive region between beam pulses



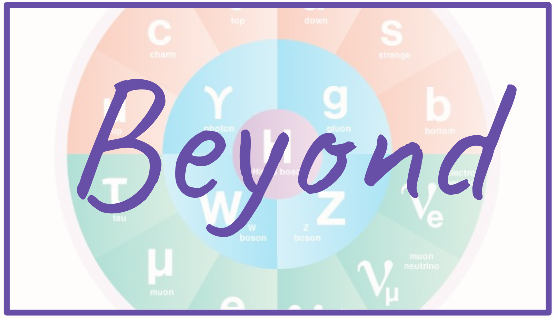
SBN Anomalies?

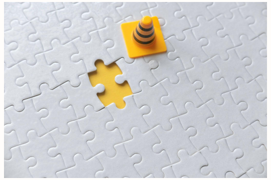
Explore the BSM Physics



Exotic Particles?

- Investigating hypotheses that explain why the SM isn't working:
  - Address the SBN Anomalies from LSND & MiniBooNE
    - SM approach from F. Gao (Thu.) & Poster: L. Hagaman: 104
    - BSM approach from E. Yandel (in 40 mins)
  - **Search for exotic particles from different sources**:





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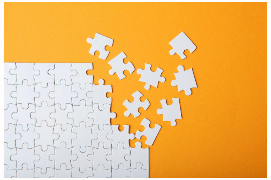

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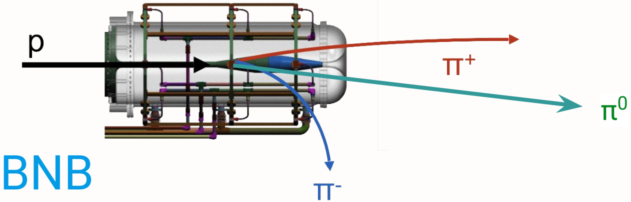

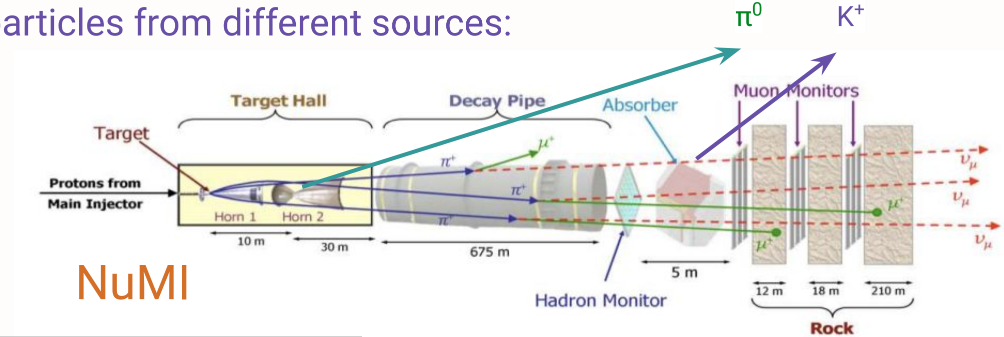

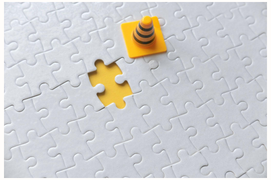

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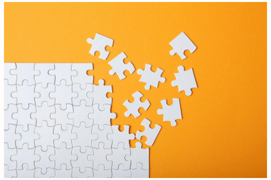

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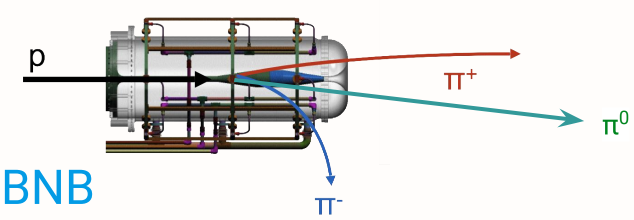
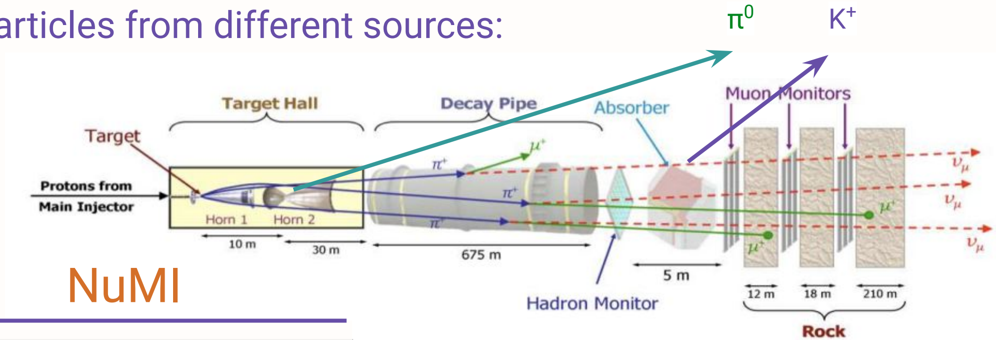


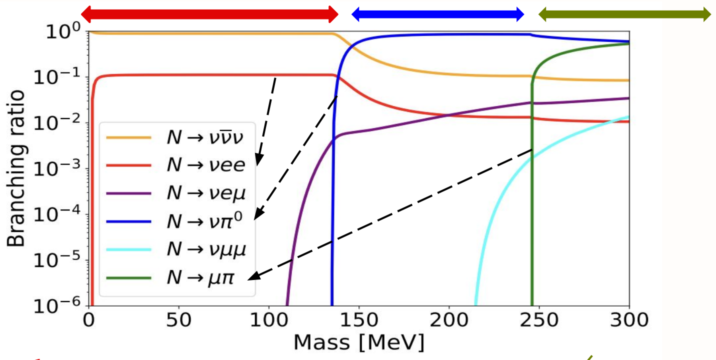


- From Charged Mesons:
  - **[NEW] Heavy Neutral Leptons (HNL, N)** — Phys. Rev. Lett. 132, 041801
  - [NEW] Higgs Portal Scalar (HPS, S) — Coming soon...
- From Neutral Mesons:
  - **[NEW] Light Dark Matter (χ), the Dark Trident Processes** — Phys. Rev. Lett. **132**, 241801
  - MilliCharged Particles (mCP, χ)
  - Heavy QCD Axions (a)
- From Random Rare Processes: — P. Abratenko *et al* 2024 *JINST* 19 P07032
  - **[NEW] Neutron-Antineutron Oscillation**

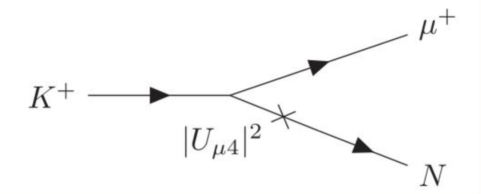
Heavy Neutral Leptons (HNL, N)

- HNL - Simple extension of the PMNS matrix, as Dirac or Majorana particle.
- Sources: charged meson decays
- Dominant decay channels are functions of mass.

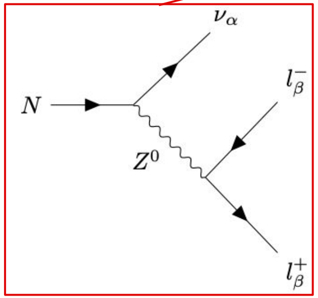
Final visible states: ee π^0 $\mu\pi$

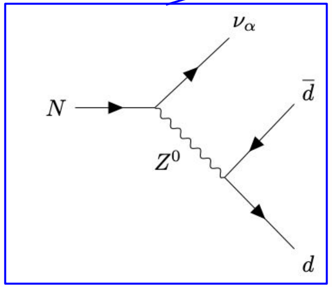


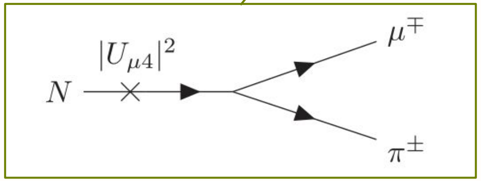
Production



Decays

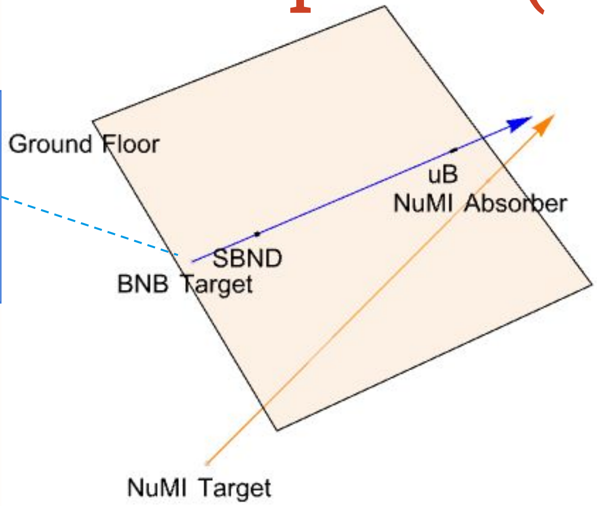






Heavy Neutral Leptons (HNL, N)

$N \rightarrow \mu^+\pi^-$ (Majorana)
$N \rightarrow \mu^-\pi^+$ (Majorana or Dirac)
Phys. Rev. D 101, 052001 (2020)
2e20 POT:



[NEW RESULTS]: [ONGOING SEARCHES]:

Heavy Neutral Leptons (H

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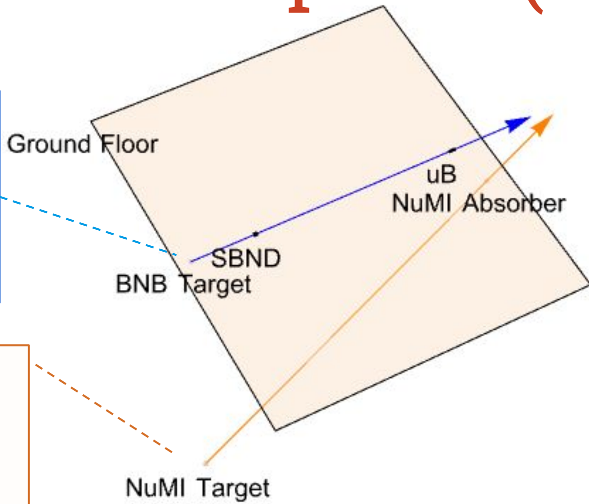
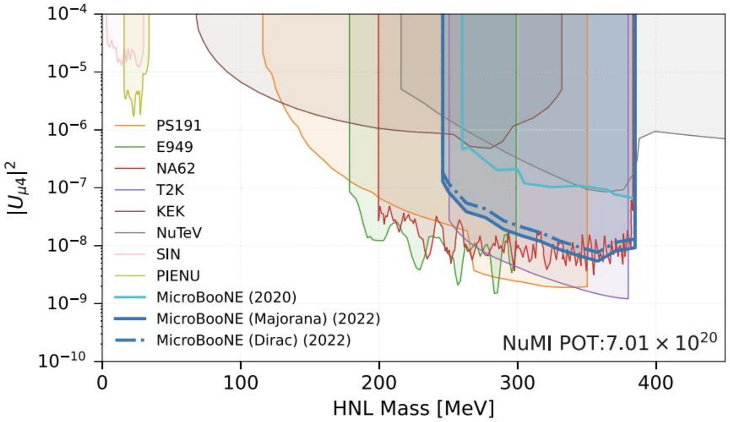
Phys. Rev. D 106 9, 092006 (2022)
7e20 POT:



μπ (2022)



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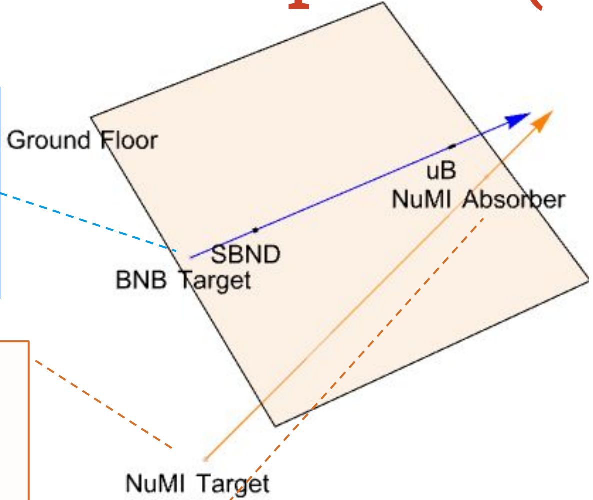
N→ νe⁺e⁻ (Majorana)
N→ νπ⁰ (Majorana)
Phys. Rev. Lett. 132, 041801 (2024)
7e20 POT:



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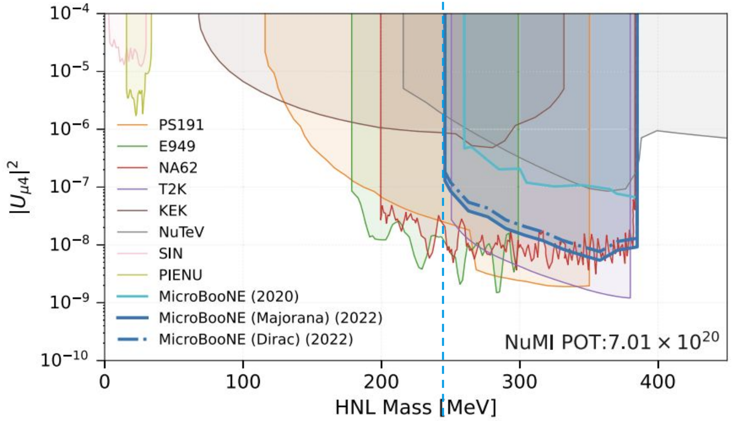

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$N \rightarrow \nu e^+e^-$ (Majorana)
$N \rightarrow \nu\pi^0$ (Majorana)
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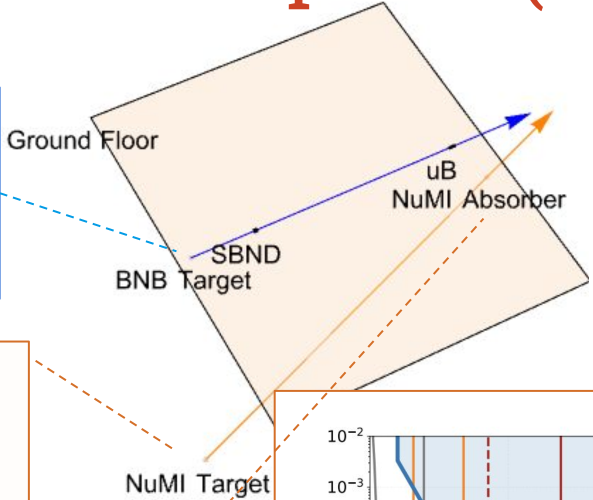

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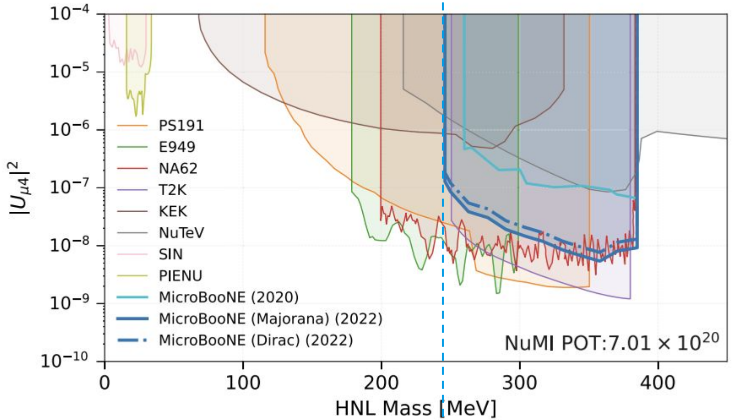
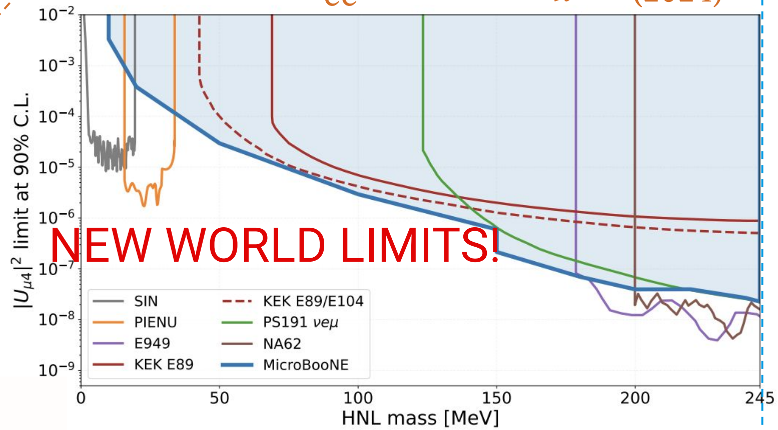


ee π⁰ (2024)



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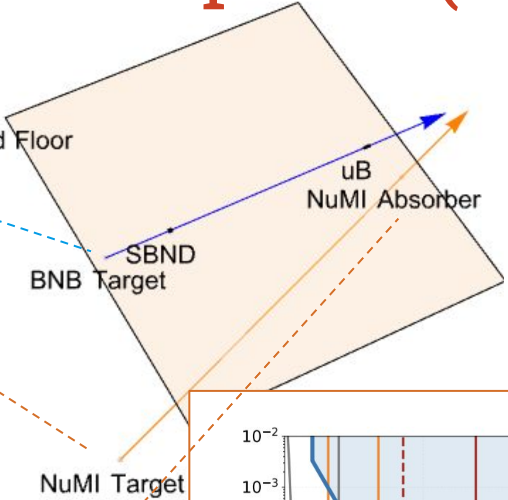
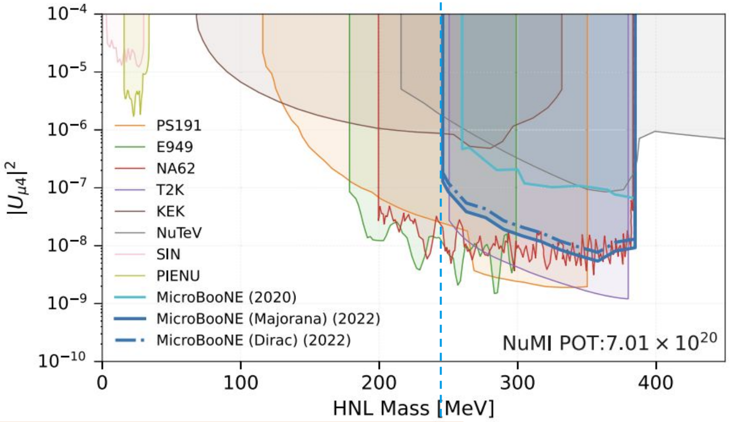
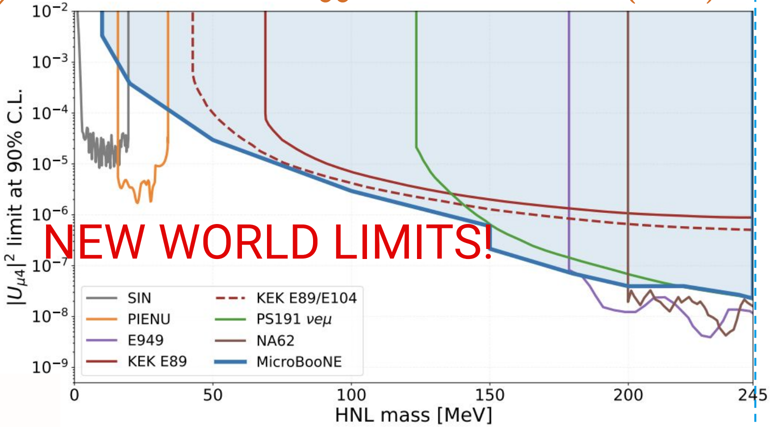
N→ νe^+e^- (Majorana)
N→ $\nu\pi^0$ (Majorana)
Phys. Rev. Lett. 132, 041801 (2024)
7e20 POT:

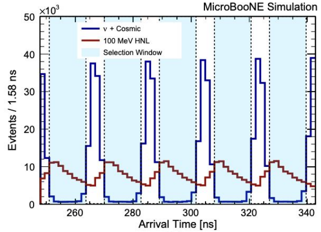


μπ (2022)



ee π⁰ (2024)



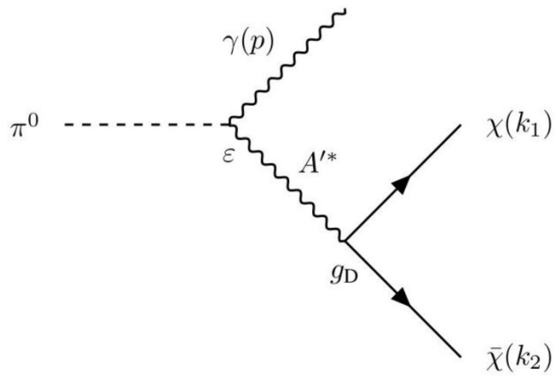


Potential use of ns timing.

Light Dark Matter (χ), the Dark Trident Processes

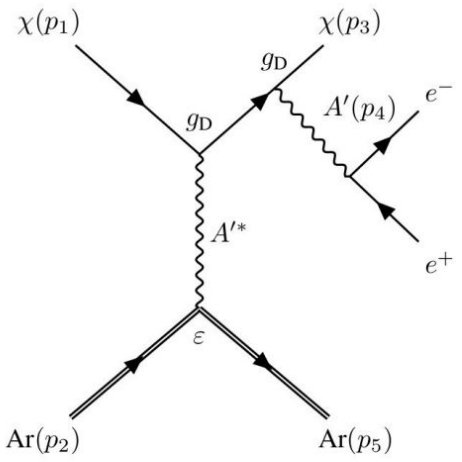
- Dark trident - new way to search χ in ν-beams
- Sources: neutral meson decays
- Decay products: emission of an on-shell dark photon after scattering

Production



Propagate to MicroBooNE

Interaction



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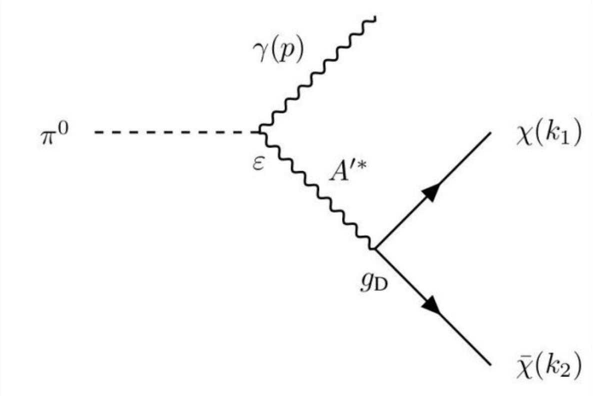

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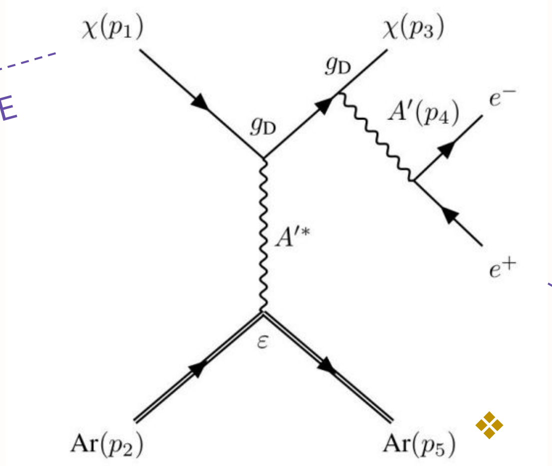
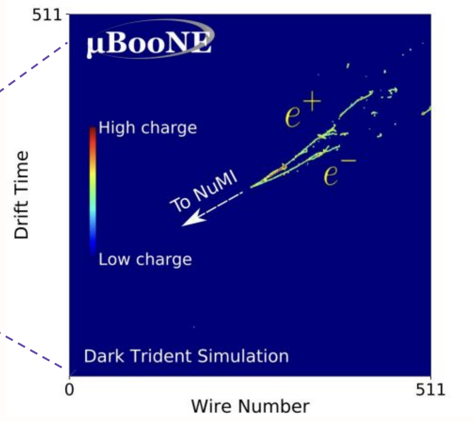
Interaction

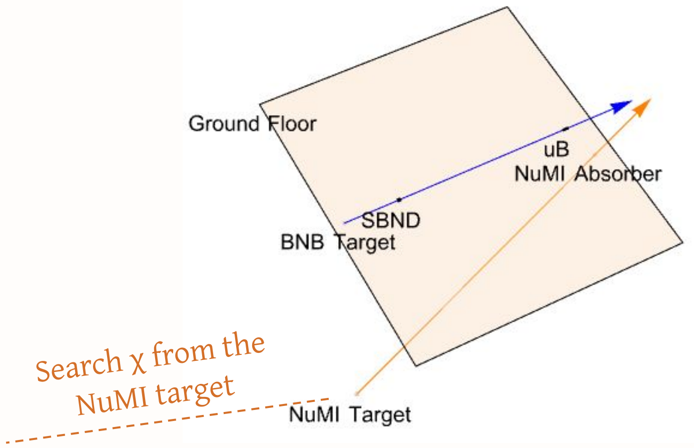


Final States



- ❖ Application of convolutional neural network (CNN)

Light Dark Matter (χ), the Dark Trident Processes



- NuMI may produce high energy dark matter.
- Off-axis beam reduces neutrino backgrounds

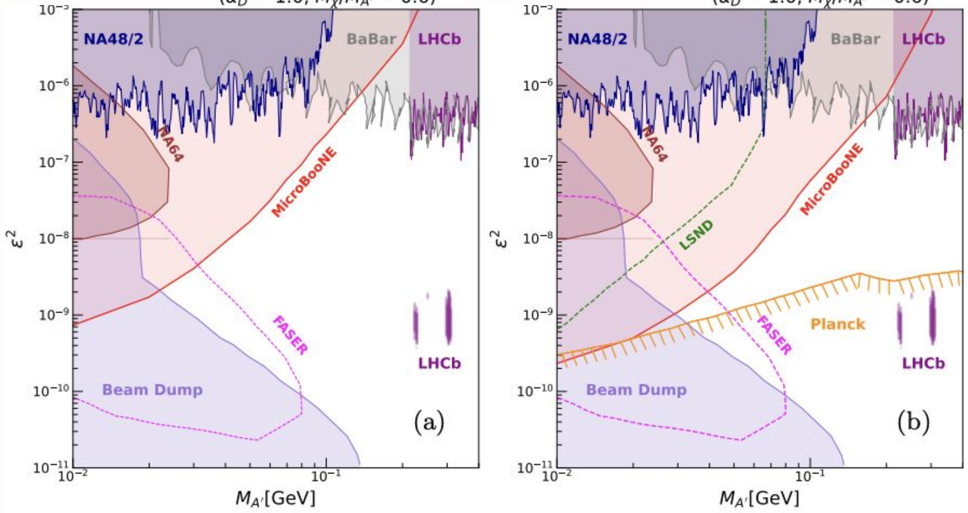
Phys. Rev. Lett. **132**, 241801 (2024)

7e20 POT:

Light Dark Matter (χ), the Dark Trident Processes

FIRST search using LArTPC

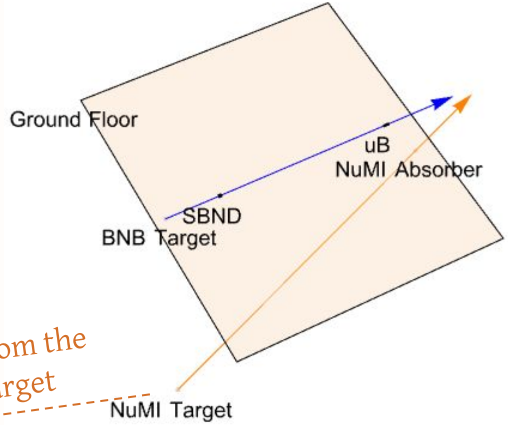
Scalar DM **Fermion DM**



Phys. Rev. Lett. **132**, 241801 (2024)

7e20 POT:

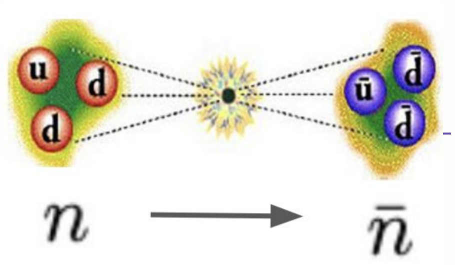
Search χ from the NuMI target



- NuMI may produce high energy dark matter.
- Off-axis beam reduces neutrino backgrounds

Neutron Antineutron Oscillation (n-nbar)

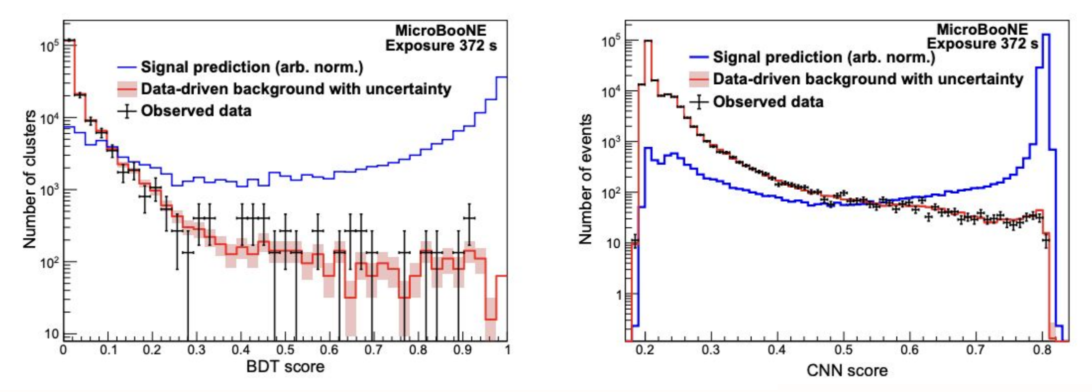
- Sources: neutron transforms itself to an antineutron and annihinate within the argon nucleus.
- Result in final state pions with star-like topology.



Neutron Antineutron Oscillation (n-nbar)

FIRST n-nbar study using Argon

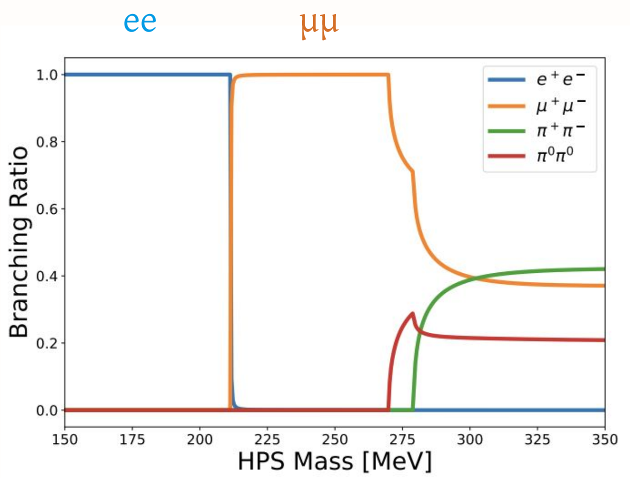
- Demonstrate the performance with:
  - selections using BDT and CNN
  - 70% signal efficiency
    - Improve DUNE's published efficiency by a factor of 7

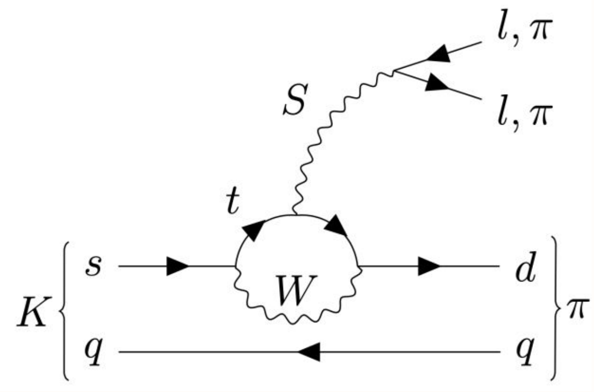


P. Abratenko *et al* 2024 *JINST* 19 P07032

Higgs Portal Scalars (HPS, S)

- Sources: charged meson decays
- Kaons can be decaying at rest (KDAR) or decaying in flight (KDIF)
- Dominant decay channels are functions of mass





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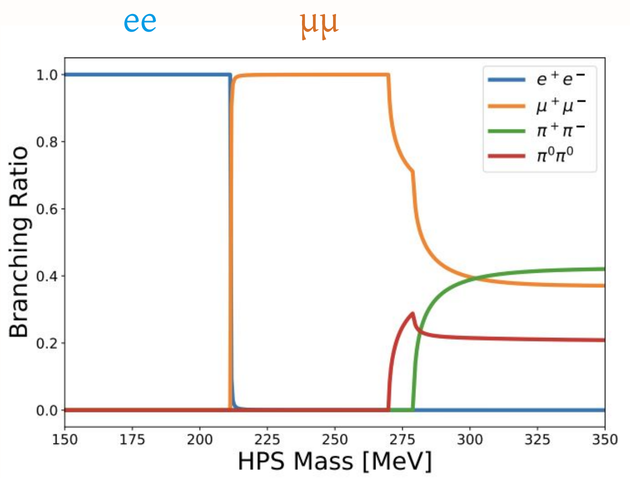
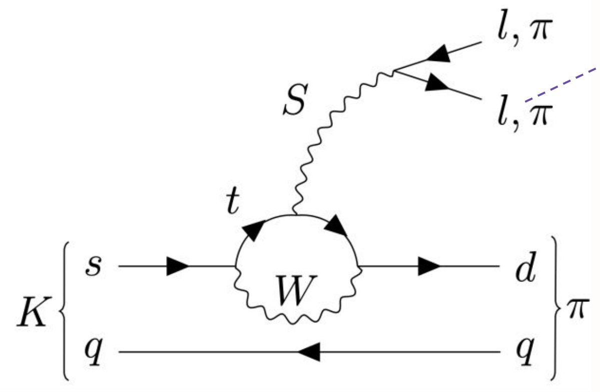
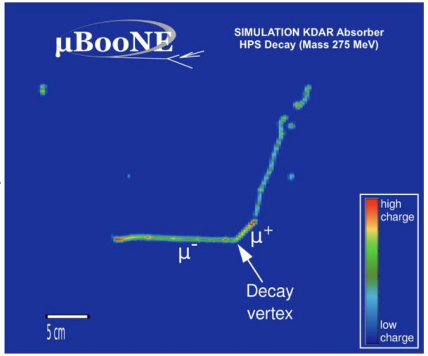
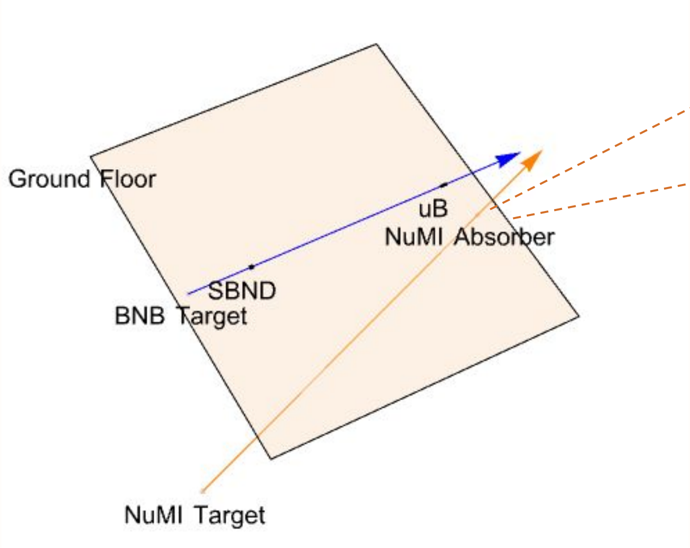






- The simulation shows HPS coming from the bottom right – the absorber!

Higgs Portal Scalars (HPS, S)

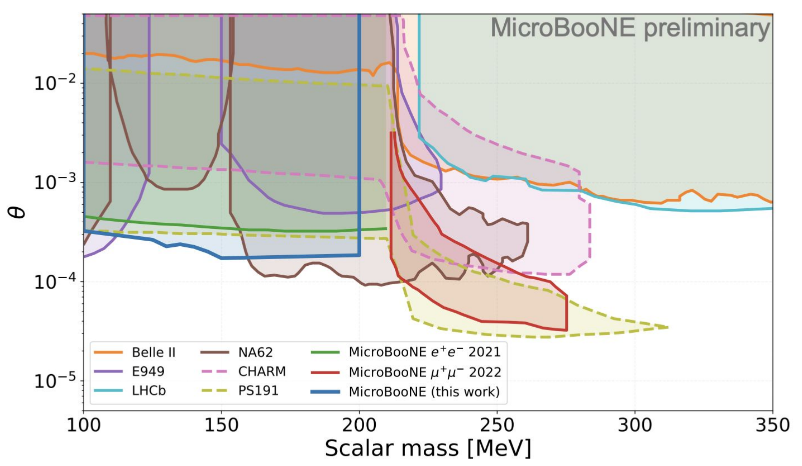


S→ e^+e^- (KDAR)
Phys. Rev. Lett. 127, 151803 (2021)
2e20 POT:

S→ $\mu^+\mu^-$ (KDAR)
Phys. Rev. D 106 9, 092006 (2022)
7e20 POT:

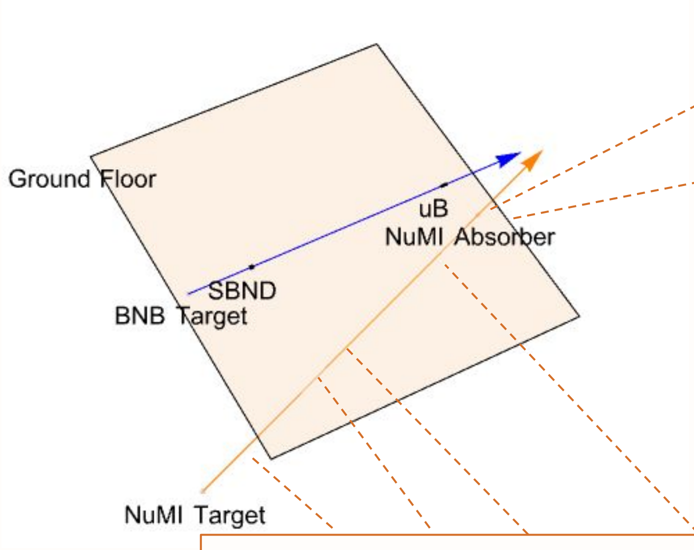
ee (2021)

μμ (2022)



[NEW RESULTS]: [ONGOING SEARCHES]:

Higgs Portal Scalars (HPS, S)

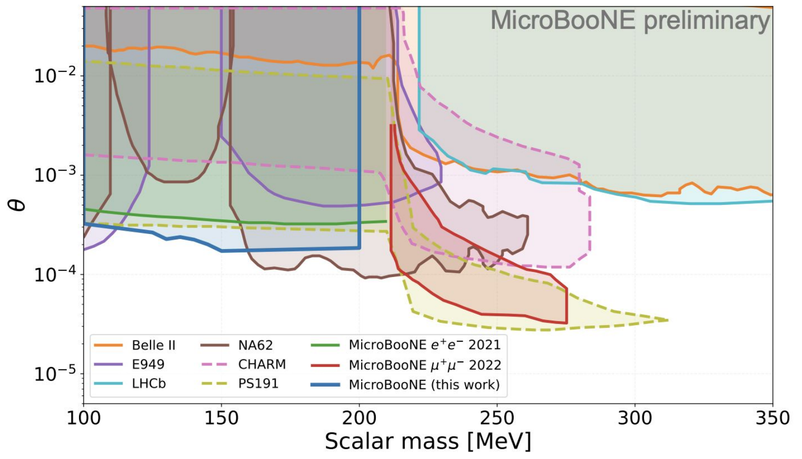


S→ e^+e^- (KDAR)
Phys. Rev. Lett. 127, 151803 (2021)
2e20 POT:

S→ $\mu^+\mu^-$ (KDAR)
Phys. Rev. D 106 9, 092006 (2022)
7e20 POT:

S→ e^+e^- (KDIF)
The publication comes soon! (Nu2024 Poster)
7e20 POT:

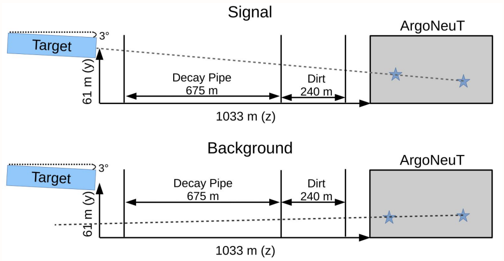
ee (2021)
ee (2024)
μμ (2022)



Millicharged Particles (mCP, χ)

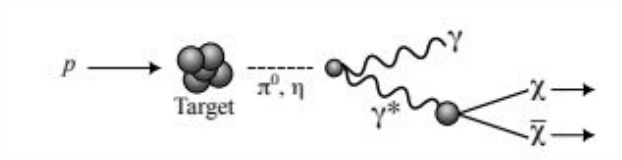
- Long-lived particles with fractional charge ($\varepsilon \sim 10^{-6} \sim 10^{-4}$ e)
- Sources: neutral meson decays
- mCP scatters with atomic electrons, creating low energy deposition.

ArgoNeuT search with NuMI



ArgoNeuT: Phys. Rev. Lett. 124, 131801

Production



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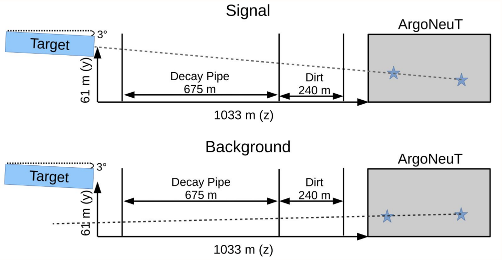
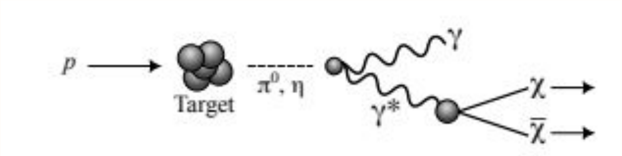
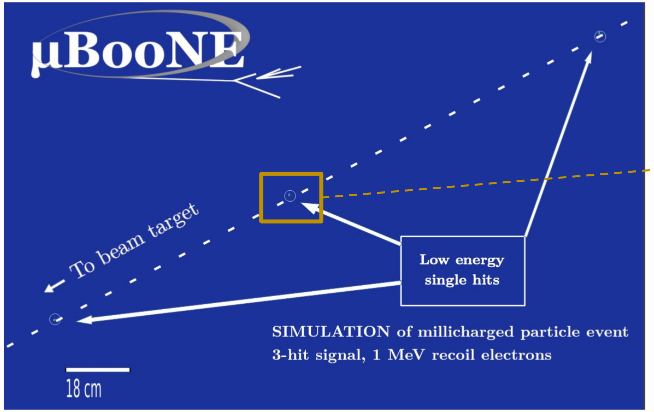


ArgoNeuT: Phys. Rev. Lett. 124, 131801

Production



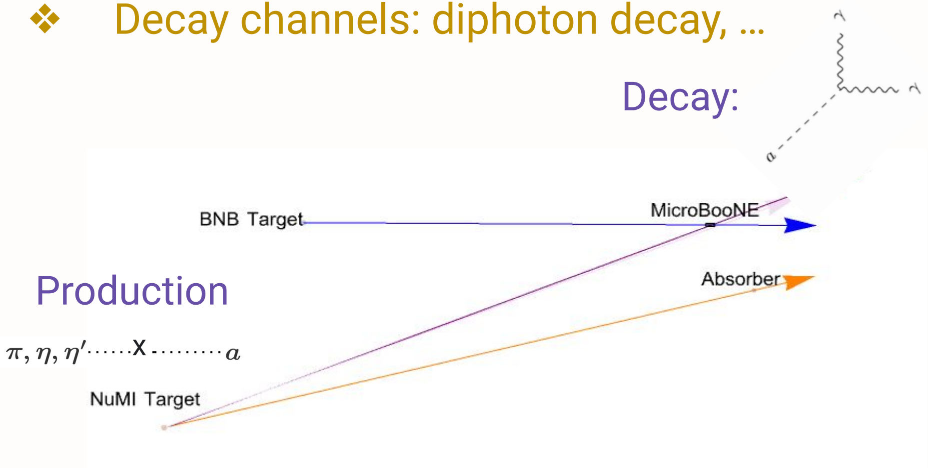
Interactions in MicroBooNE



Reconstructed as a MeV scale "blip"

Heavy QCD Axions (a)

- Solution to the Strong CP Problem & with mass upto 2 GeV [Phys. Rev. D 103, 095002]
- Sources: neutral meson mixing, …
- Decay channels: diphoton decay, …



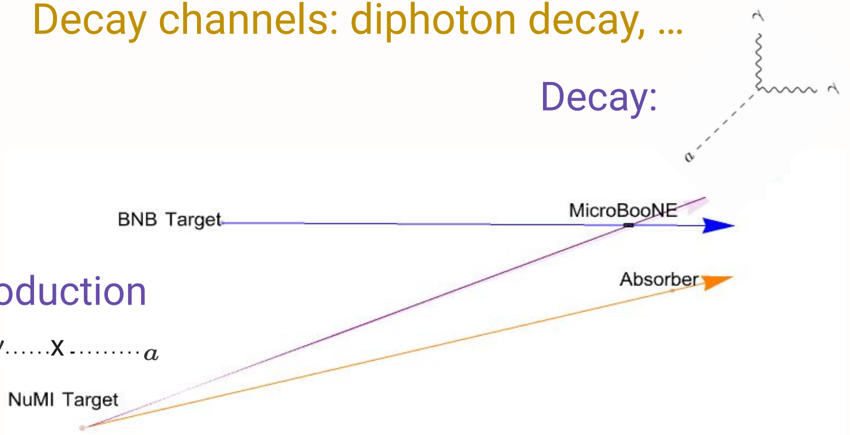
Heavy QCD Axions (a)

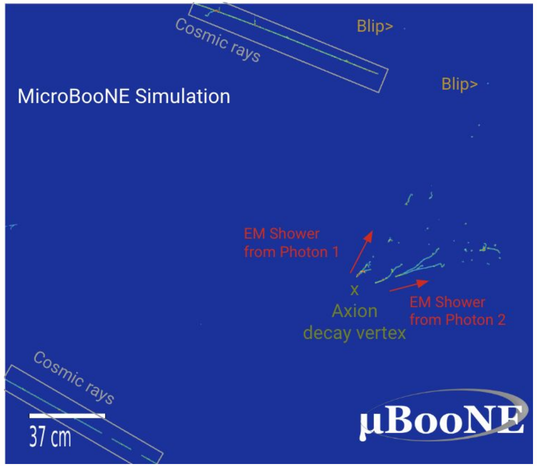
- Solution to the Strong CP Problem & with mass upto 2 GeV Phys. Rev. D 103, 095002
- Sources: neutral meson mixing, …
- Decay channels: diphoton decay, …

Decay:

Production

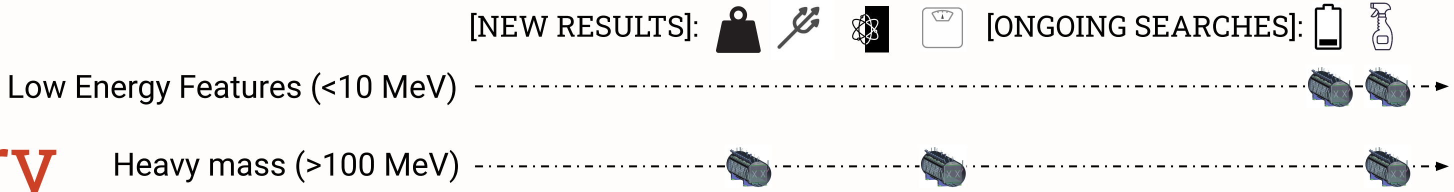
$\pi, \eta, \eta' \cdots\cdots X \cdots\cdots a$





- A clear event topology:
  - Two showers but with a clean vertex. ~~NCPi0~~, i.e. expected no vertex related "blips" from de-excitation photons in axion decay.
- Looking at those from the NuMI target with high POT & energetic beam.

And … !!!!



Summary

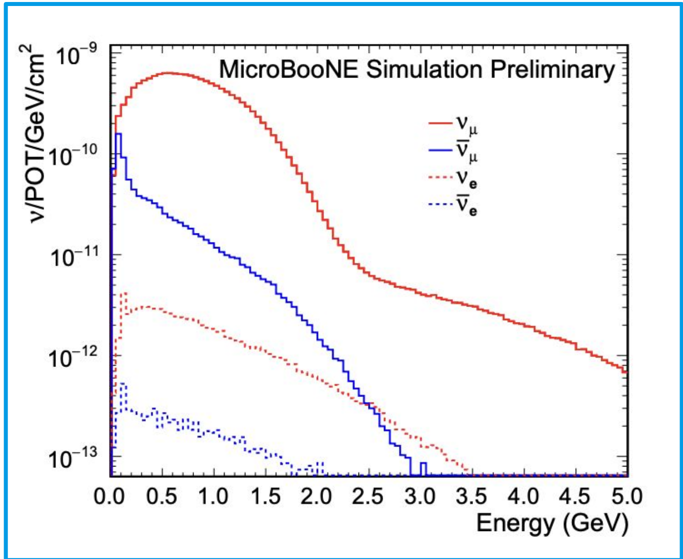
- ❖ MicroBooNE’s R&D provide handles for BSM searches
  - ➢ Low energy threshold
  - ➢ O(1ns) timing resolution

Summary

- MicroBooNE’s R&D provide handles for BSM searches
  - Low energy threshold
  - O(1ns) timing resolution
- MicroBooNE’s BSM program benefits from the **dual beam** configuration.
  - BNB (8 GeV proton) & NuMI (120 GeV proton)
  - Search for anomalies produced at rest or in-flight
- New results for **HNL**, **Light Dark Matter**, **N-nbar Oscillation, & HPS**
- Exciting new searches are on the horizon: **mCP** and **Axions**.

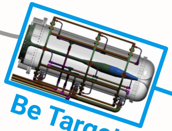
Thank you!

Extra



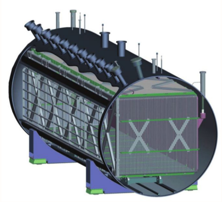
MICROBOONE-NOTE-1031-PUB

0.55% ν_e or $\bar{\nu}_e$

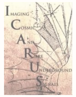


Be Target

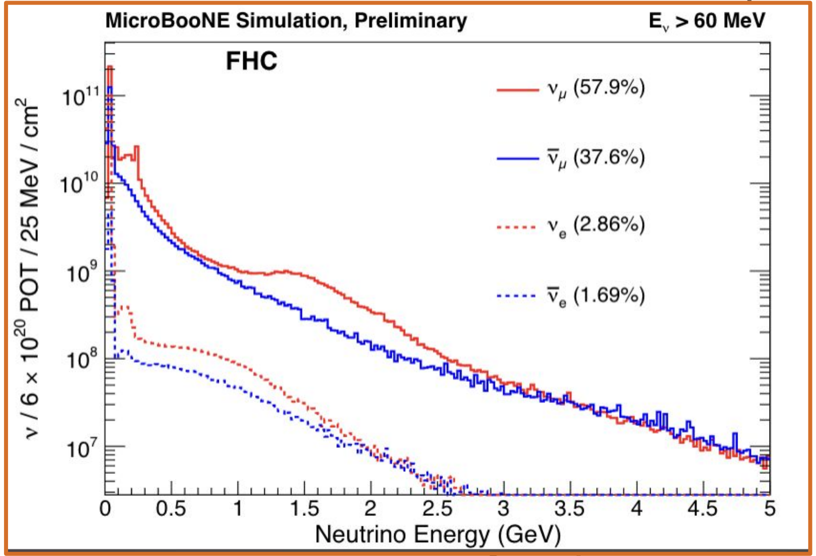
8GeV BNB
Booster Neutrino Beam



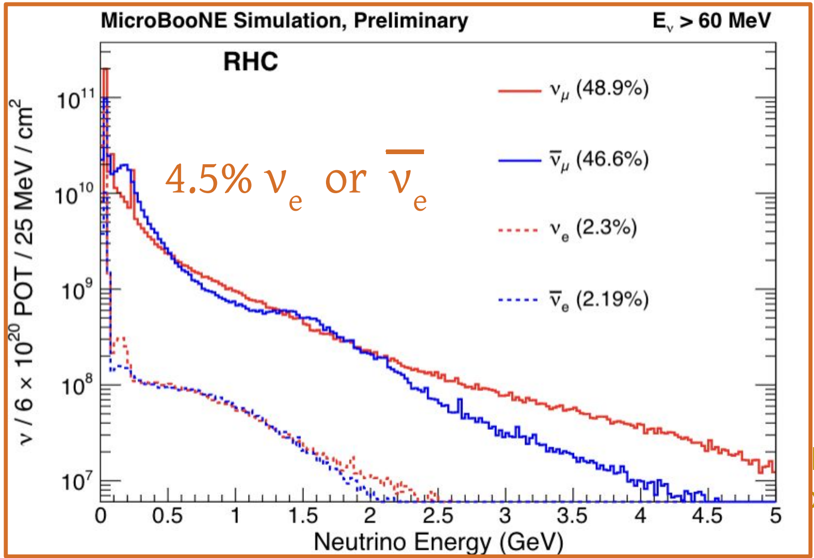
MicroBooNE
Data collection 2015 - 2020
470m



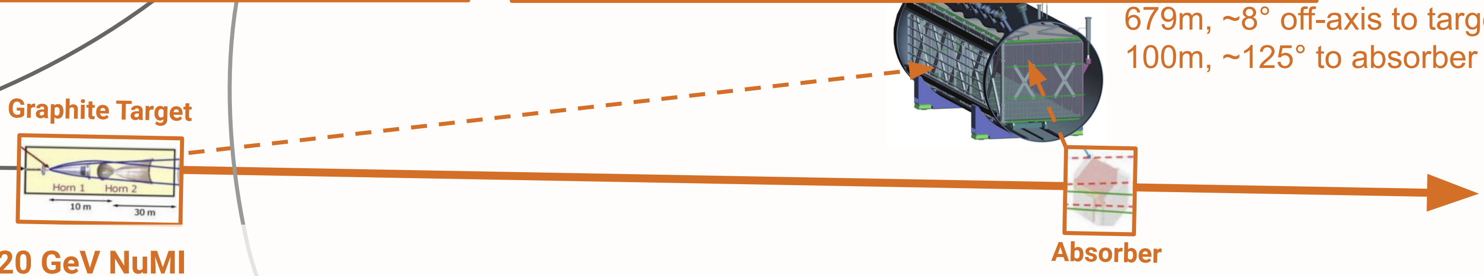
Front horn current - neutrino mode



Reverse horn current - antineutrino mode



BooNE
on 2015 - 2020
0m
679m, ~8° off-axis to target
100m, ~125° to absorber



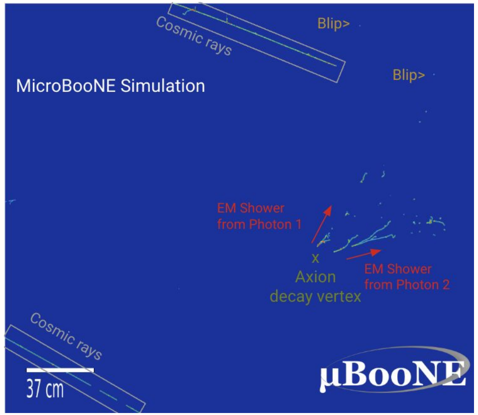
120 GeV NuMI
Neutrinos at the Main Injector

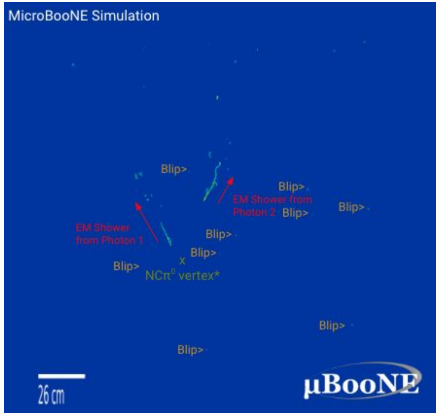
MicroBooNE R&D

[NEW RESULTS]: [ONGOING SEARCHES]:

Benefits of Reconstructing Low Energy Blips

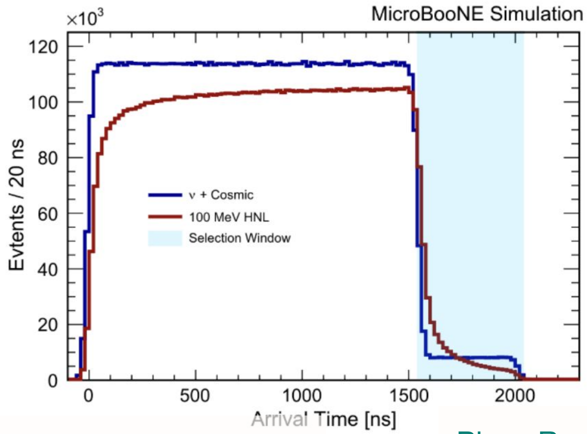
- In Millicharged particles search
  - It makes low-energy hits visible as event topology
- In Heavy QCD axions search
  - It provides extra handle to look at de-excitation photons to distinguish diphoton signal (via decay) from the NCPi0 backgrounds.(via scattering)

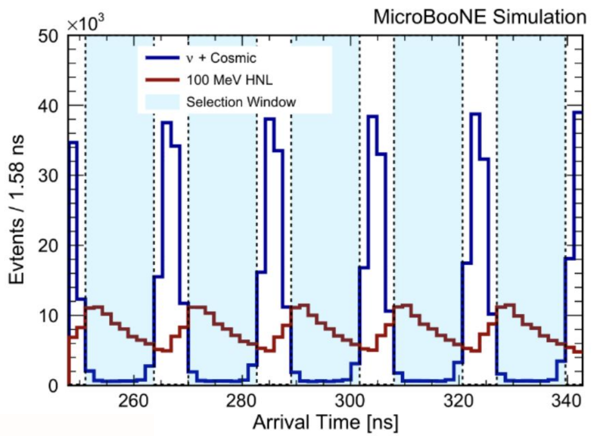




Benefits of the Nano-second Timing

- ❖ Neutrino is the background for exotic particle searches!
- ❖ Recent improvement resolves the BNB bunch substructure
  - ➢ It benefits the HNL searches with timing selections
- ❖ Future works are being done on the NuMI bunch substructure
  - ➢ HPS and axions with heavy masses are expected to survived the timing elections.





Phys. Rev. D 108, 052010

Heavy Neutral Leptons

Heavy Neutral Lepton

- Motivation: Neutrino oscillation measurement suggests new neutrinos: sterile neutrinos or heavy neutral leptons (NHL)
- Production: HNL is mixed with a extended PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

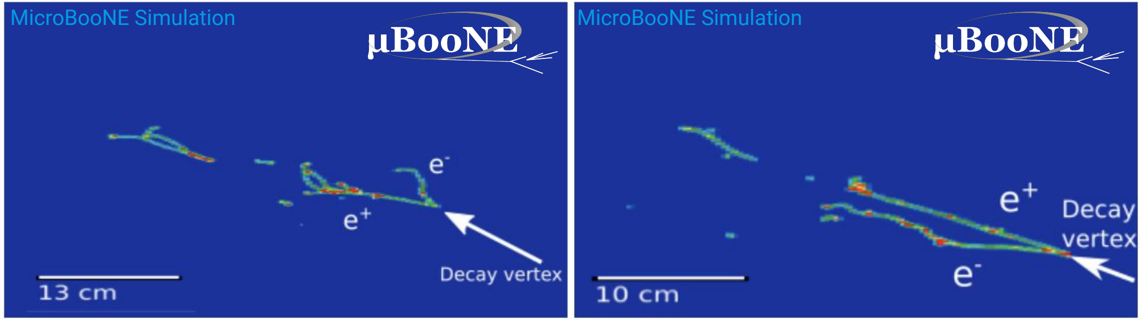
Standard mixing

$$U_{\text{PMNS}}^{\text{Extended}} = \begin{pmatrix} \overbrace{\begin{matrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{matrix}}^{U_{\text{PMNS}}^{\text{3x3}}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

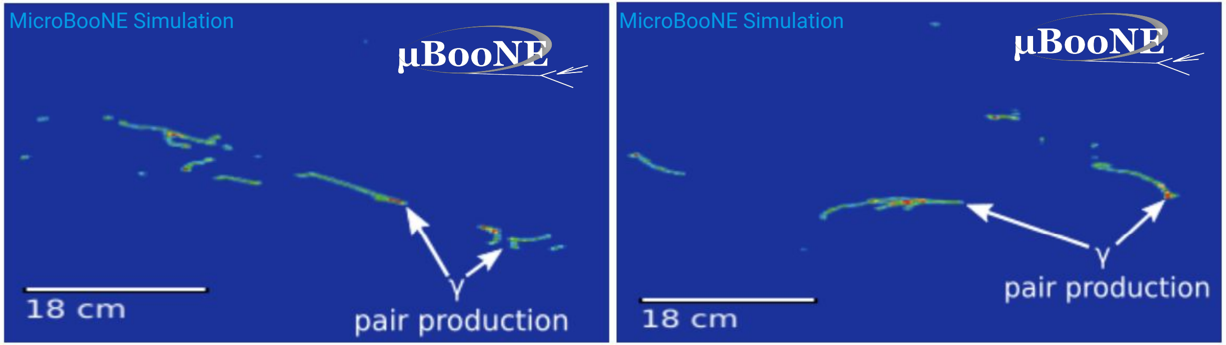
New physics

Event Display

100 MeV HNL→ e+e- from absorber

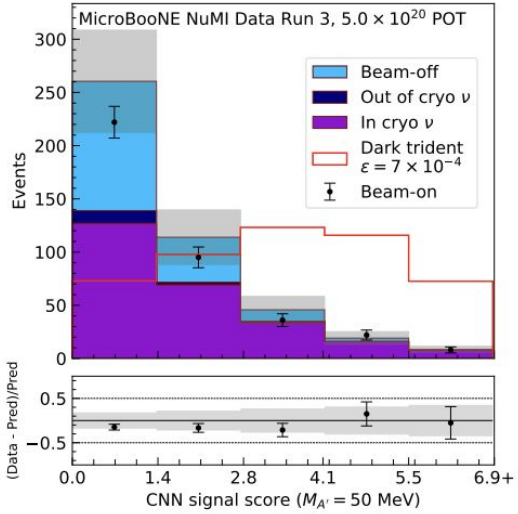


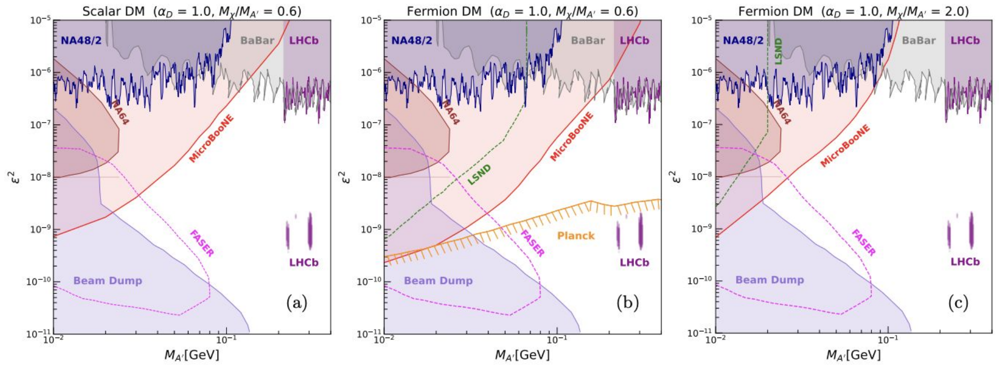
180 MeV HNL→ nuPi0 from absorber



Light Dark Matter

Plots from the recent paper (2024)





Example CNN score for one set of αD, MA’, Mχ.

90% CL contour

N-Nbar Oscillation

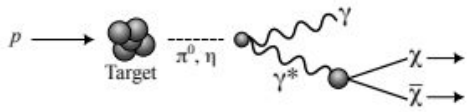
Neutron Antineutron Oscillation (n-nbar)

- Demonstration was performed with:
  - a data set equivalent to 3e26 neutron-years
- Set demonstrative bounds on n-nbar oscillation lifetime > 1e26 years.
- Tools are developed for DUNE with 1e35 neutron-years worth of data.

Millicharged Particles

Millicharged Particles (mCPs, x)

https://arxiv.org/pdf/2305.04964.pdf



- Motivation: EDGES anomaly (https://arxiv.org/pdf/2102.11284.pdf / https://arxiv.org/pdf/1803.02804.pdf)
  - The Experiment to Detect the Global Epoch of Reionization Signature (EDGES) found a stronger than expected absorption of the 21-cm transition of atomic hydrogen.
  - Reasons:
    - 1) The Dark Ages gas is much colder than expected,
    - or 2) the background radiation is much hotter.
  - This could be explained via dark matter cooling down baryon fluid, and they need to be:
    - Light mass (<O(1)GeV) – light dark matter
    - Mediator has to be light with mass m<10E-3 eV – couples to photons
    - Has contribution to high radiation energy density – responsible of a small fraction of dark matters, f_DM
  - mCPs is the candidate.
- Definition: Long-lived particles with fractional charge (ε~10E-6~10E-4 e)
- Production: χ are produced via dark photons.
  - At beam target, these dark photons can come from neutral mesons decay.
  - Dark photons can be also produced by high energy cosmic rays collision.
- Detection Process: Elastic scattering with atomic electrons.
- Signature: Create isolated hits in a straight line, mostly low-energy hits.

Heavy QCD Axions

The Strong CP Problem and the QCD Axion

- QCD describes neutron electric dipole moment (EDM) as
a function of a physical CP violating angle θ-bar at O(1) order

$$d_n = 5.2 \times 10^{-16} \bar{\theta} e \cdot cm$$

- Small measured neutron EDM [the Paul Scherrer Institute (Phys. Rev. Lett. 124, 081803)]

$$d_n < 1.3 \times 10^{-26} e \cdot cm$$

$$|\bar{\theta}| < 10^{-10}$$

- Why the angle favors a small value?
A scalar field equipped with a global axial U(1) symmetry,
the QCD axion, could be the answer.

Heavy QCD Axions Ingredient

- Heavy Mass
  - The boundary of mass is limited by $\mathbf{m_a f_a \approx \Lambda^2}$, where Λ is the SM cosmological constant.
  - Assume Z_2 symmetric mirror sector (dark sector) existed [arXiv: 1911.12364], then we have an updated cosmological constant, such that
  - $\mathbf{m_a f_a \approx \Lambda_D^2 >> \Lambda^2}$ would allow a larger mass than QCD axions.

- High Quality
  - PQ symmetry holds at the renormalizable level, i,e. suppress PQ symmetry-breaking operators at energy above planck scale
  - Vacuum expectation value of the axion field has maximum allowed value

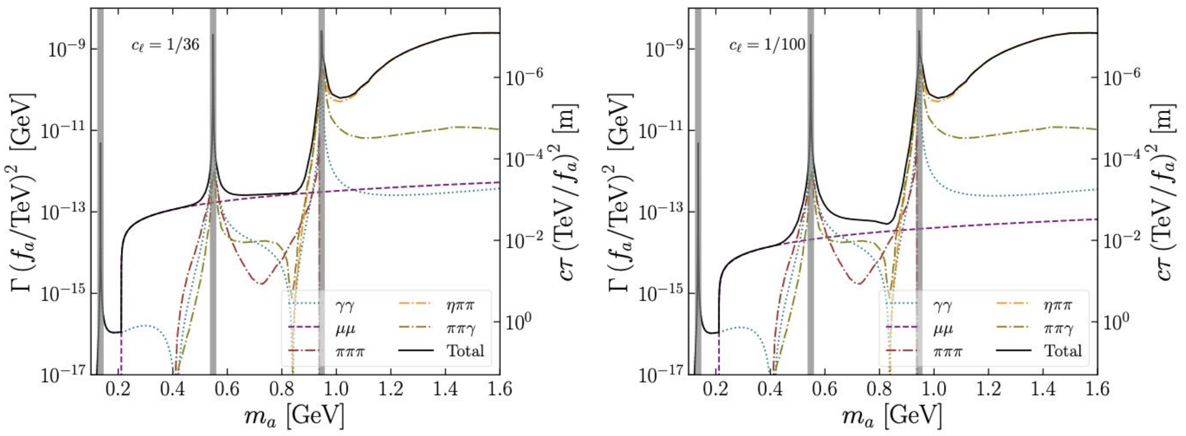
- Production Models
  - Meson-mixing from the flux (dominated at mass < GeV)
  - Gluon-gluon fusion at the beam target (dominated at mass ~ GeV)

Heavy QCD Axion Lagrangian

$$\mathcal{L}_{\text{gauge}} = c_3 \frac{\alpha_s}{8\pi f_a} aG\tilde{G} + c_2 \frac{\alpha_2}{8\pi f_a} aW\tilde{W} + c_1 \frac{\alpha_1}{8\pi f_a} aB\tilde{B}.$$

$$\mathcal{L}_{\text{lepton}} = \sum_{\ell=e,\mu,\tau} c_\ell \frac{\partial_\mu a}{2 f_a} \bar{\ell}\gamma^\mu \gamma_5 \ell.$$

G for gluon interaction
W for electroweak interaction (leptons)
B for strong interaction (hypercharge)



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