MicroBooNE's beyond the Standard Model physics program

M. Nebot-Guinot
for the
MicrooBooNE
Collaboration

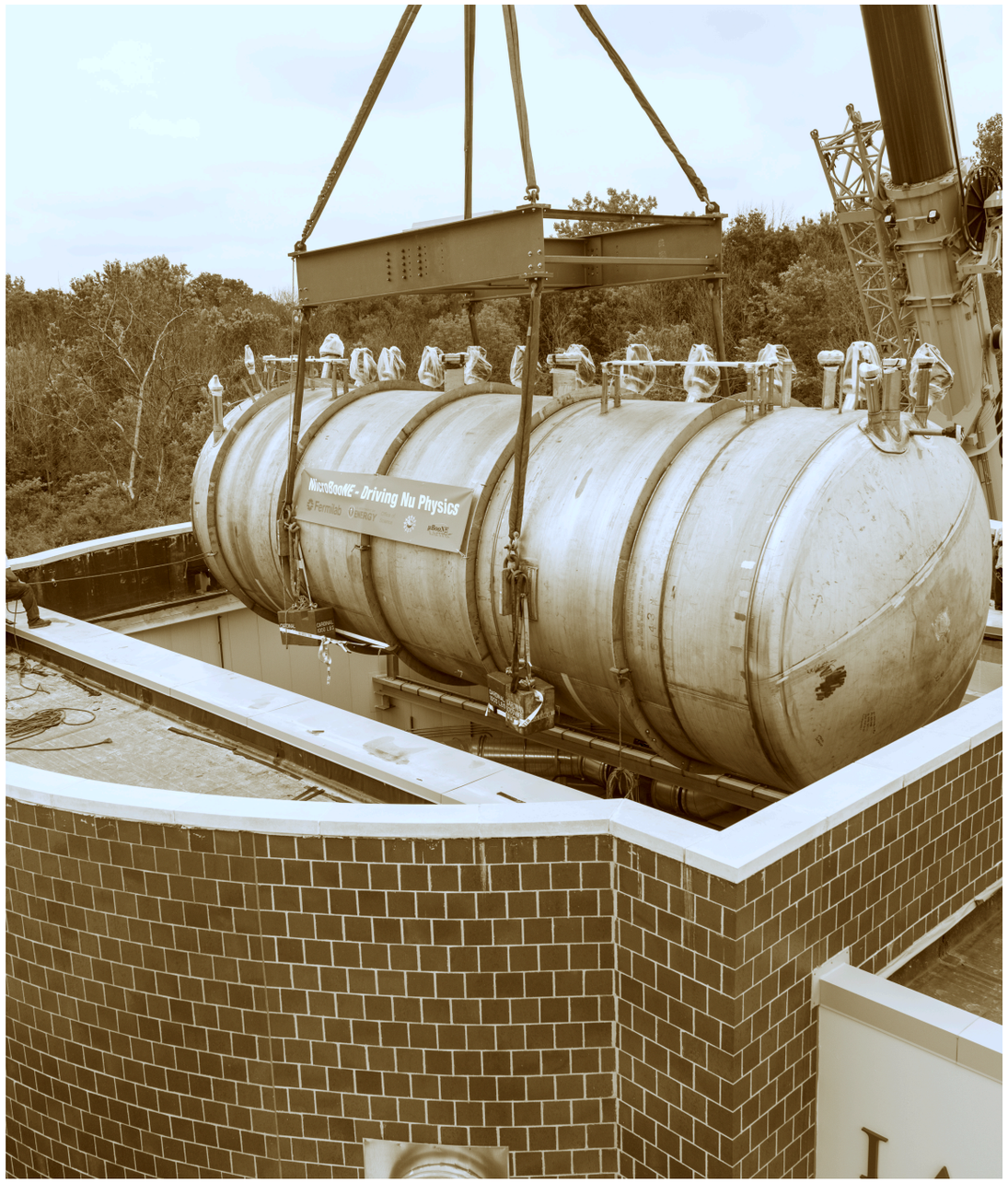
THE UNIVERSITY of EDINBURGH

XXI Workshop on Neutrino Telescopes

Outline

- The MicroBooNE experiment

- BSM searches in MicroBooNE



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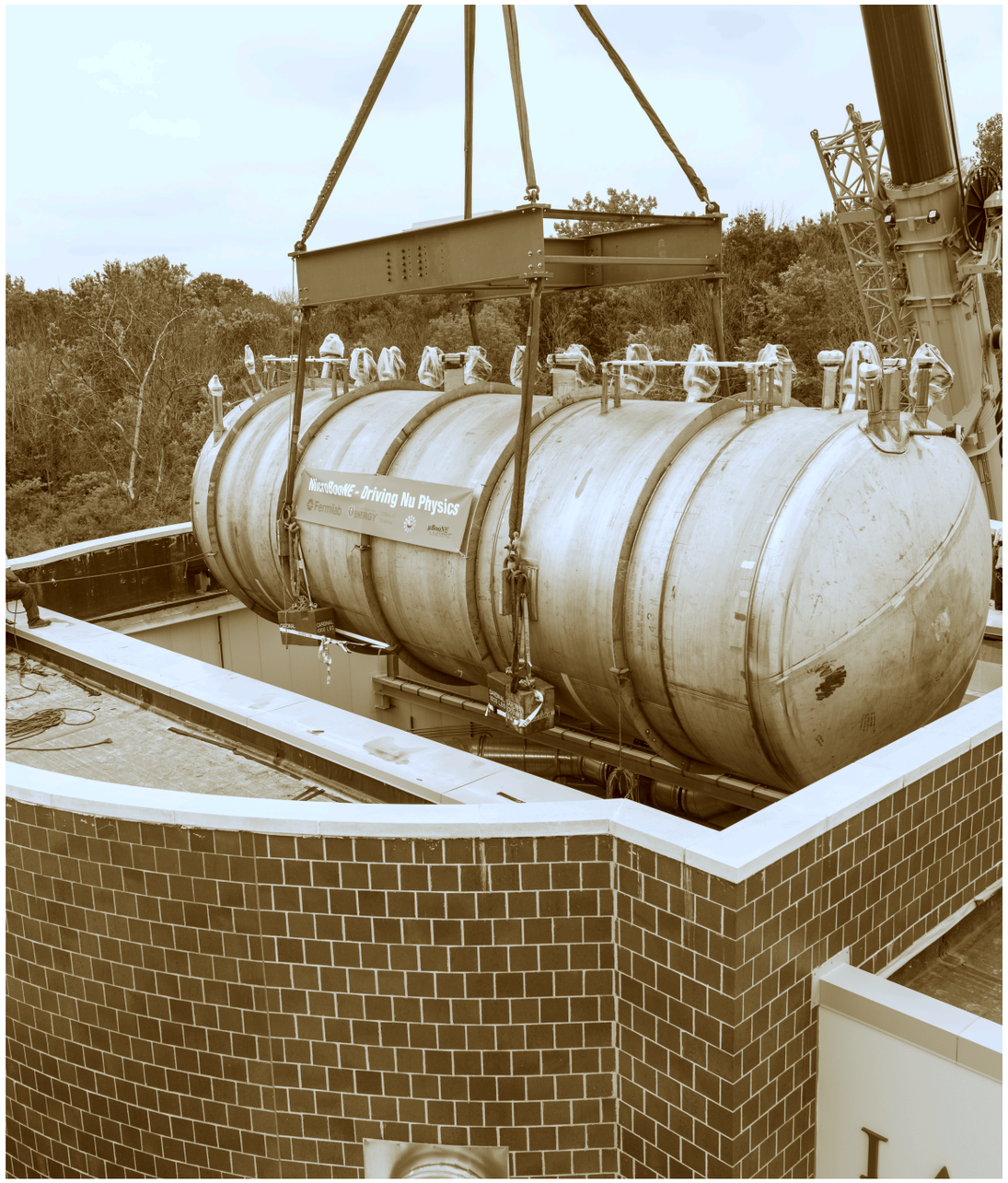


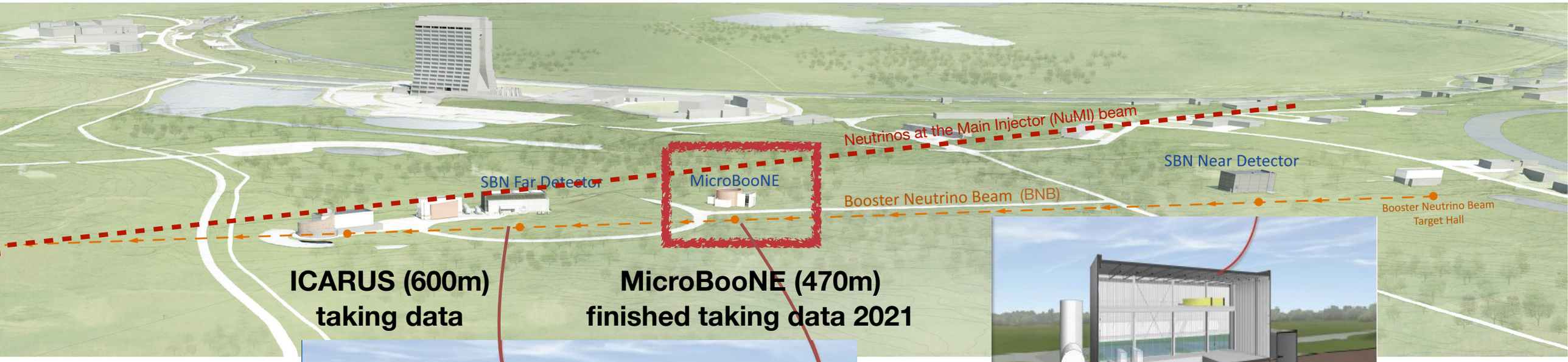
The MicroBooNE experiment

The Short Baseline Neutrino (SBN) program at Fermilab

A multi-detector and multi-beam facility on the Booster Neutrino Beam (& Neutrinos at the Main Injector beam) at Fermilab to test MiniBooNE's anomaly.
It uses the same neutrino beam, nuclear target, detector technology to reduce systematic uncertainties.

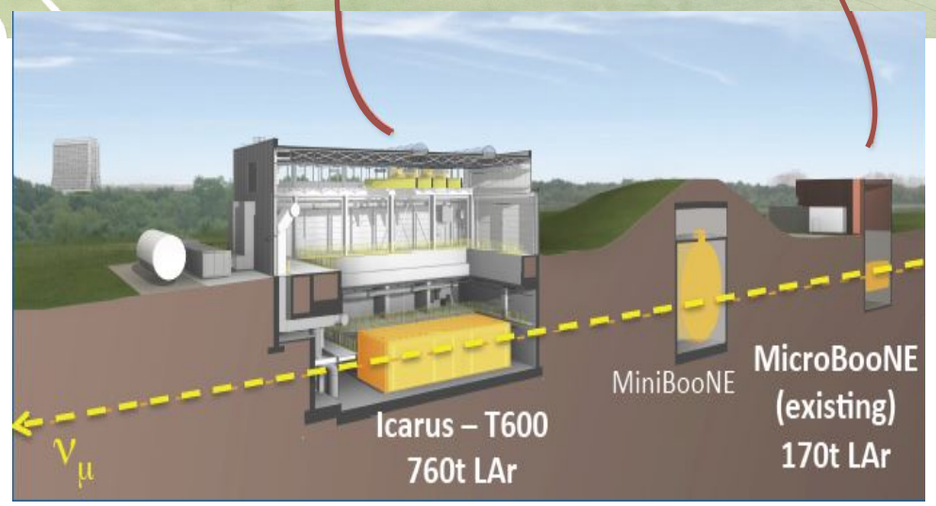
- Neutrino beam from pion decay-in-flight mostly. Well-known beam, same as MiniBooNE (PRD 79, 072002).
  The same mechanisms that produce neutrinos are great sources of potential BSM particles.

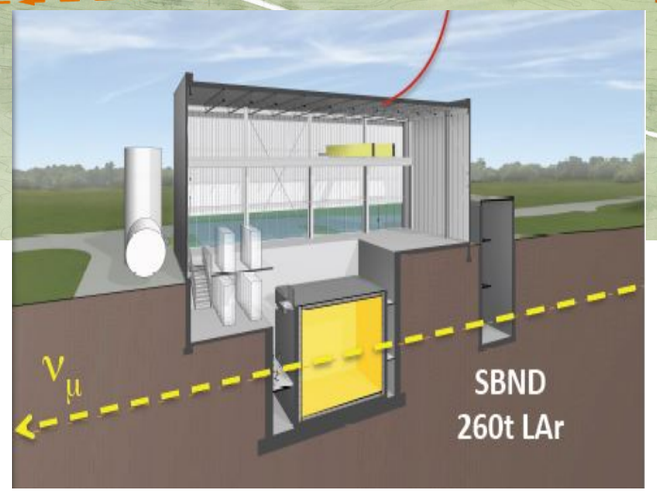
- 3 Liquid Argon Time Projection Chamber (LArTPC) detectors.



ICARUS (600m)
taking data

MicroBooNE (470m)
finished taking data 2021





SBND (110m)
taking data

For more details see my other talk

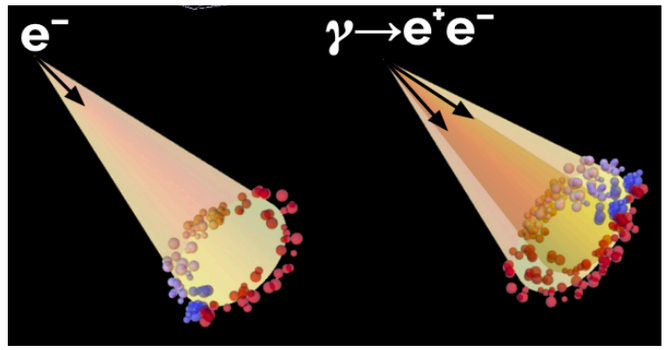
For more details see Christian Farnese's talk

For more details see London's, Jairo's, Fan's talks

Why LArTPCs?

- MiniBooNE: 600t active volume mineral oil Cherenkov detector
  → poor e/γ separation and most hadronic activity missed.

- LArTPCs are capable of identifying different species of particles reconstructing 3D images with fine-grained information.
  Neutrino vertex, particle flow, track vs. shower…



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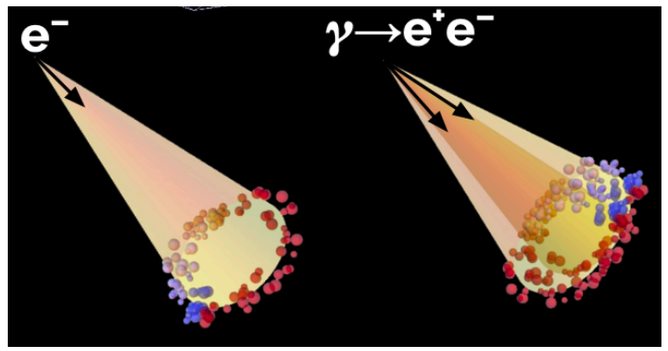

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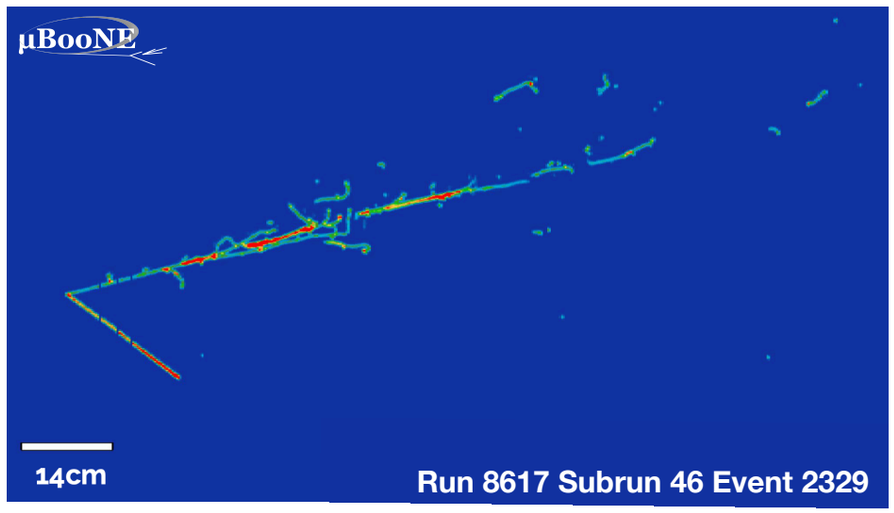
- Tracks: Simple line segments → single higher-mass particle
  (p, $\pi^{\pm}$, $\mu^{\pm}$, etc.)

- Showers: Branching clusters of line segments
  $e^{\pm}$ or $\gamma \rightarrow e^{+}e^{-}$ pair leads to a cascade of electromagnetic activity (γ, e^{+}, e^{-})



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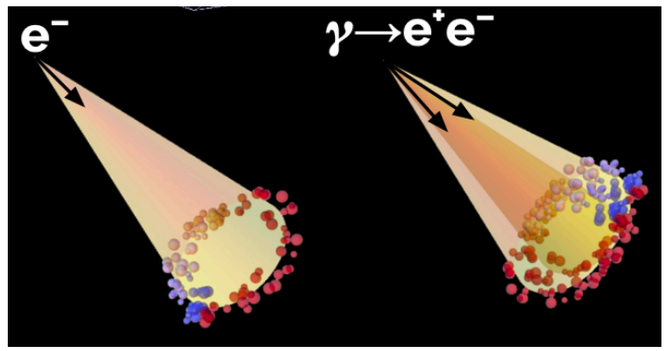
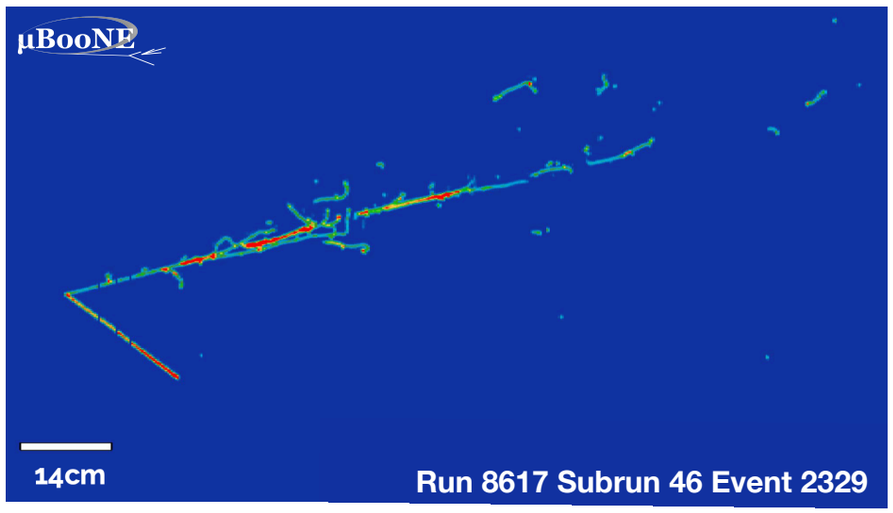


Electron vs gamma discrimination:

- Conversion gap
- dE/dx at start of shower



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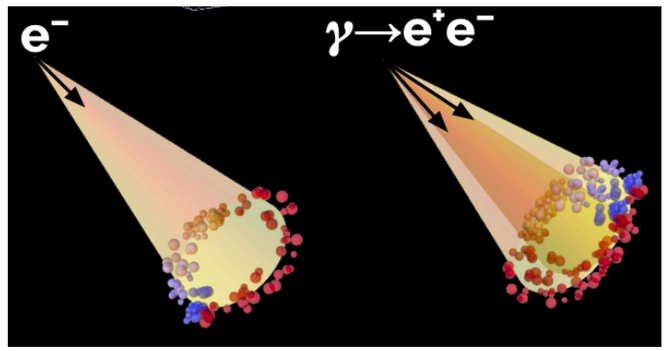

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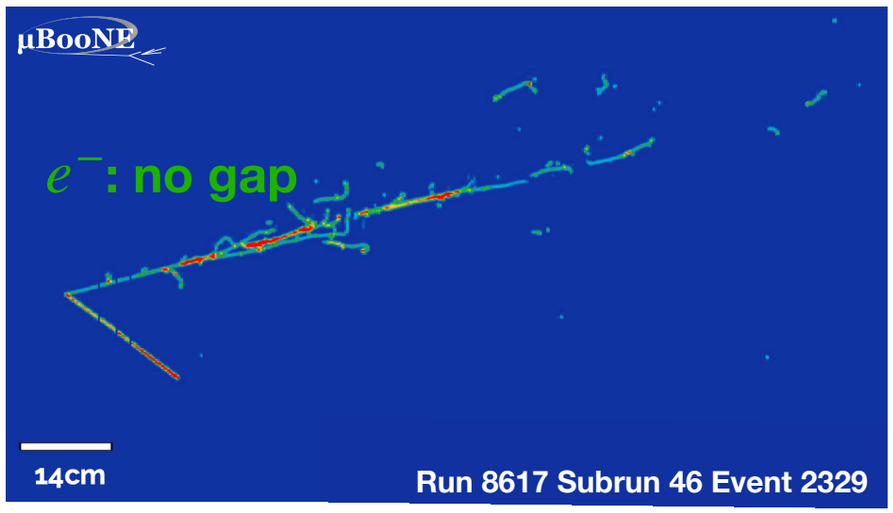

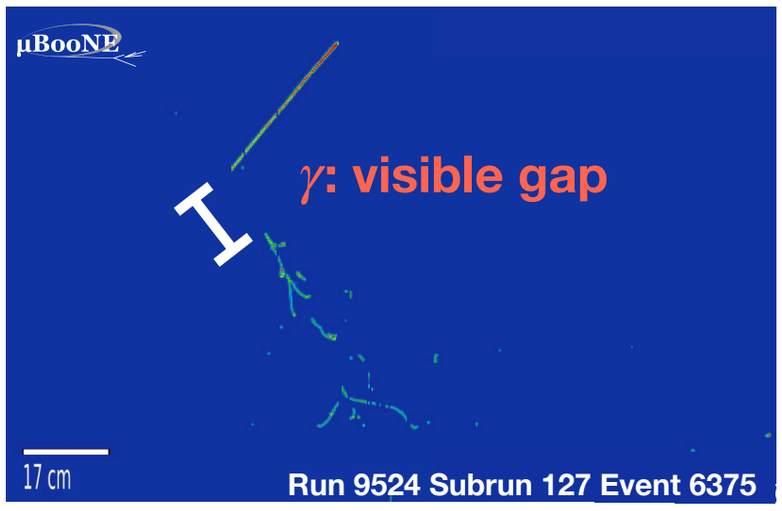

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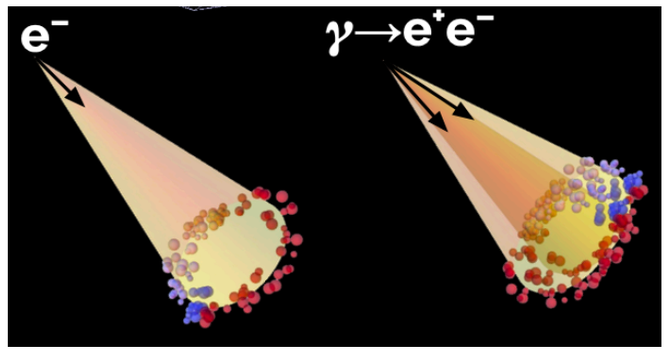

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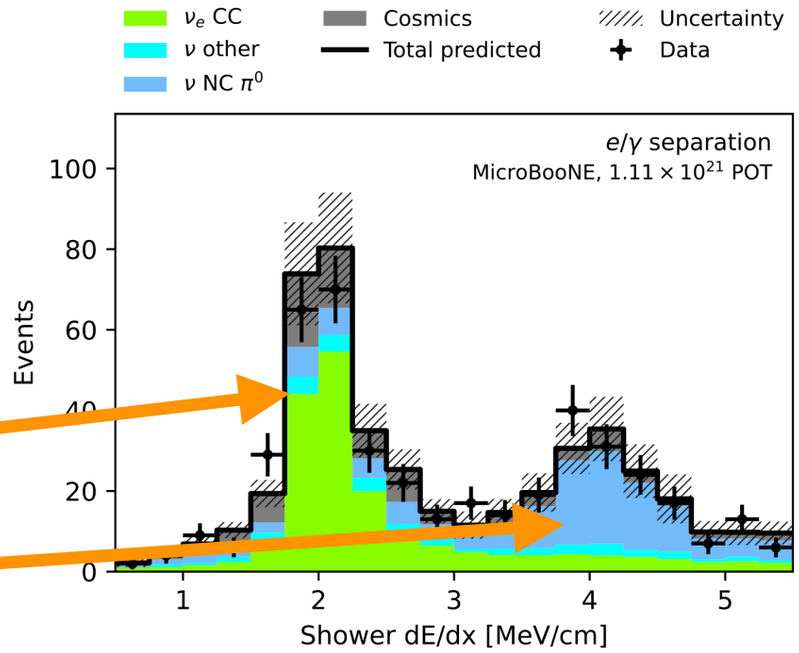
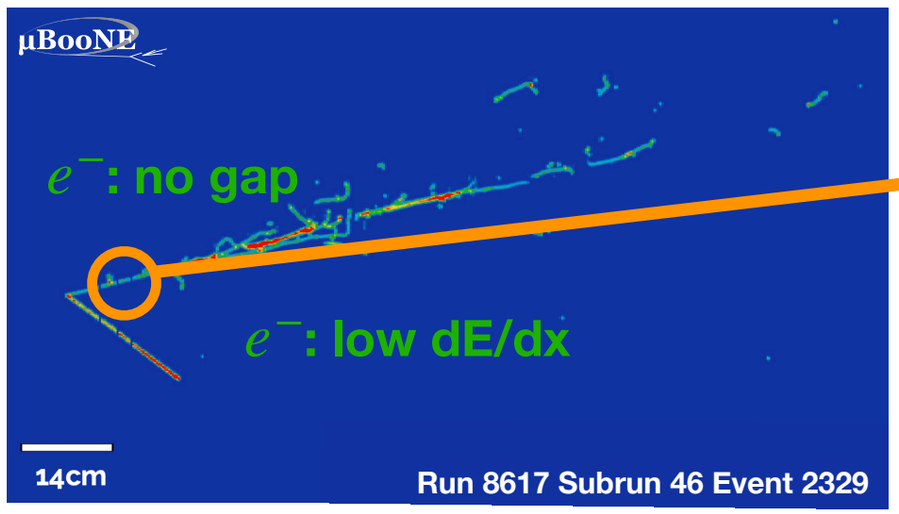
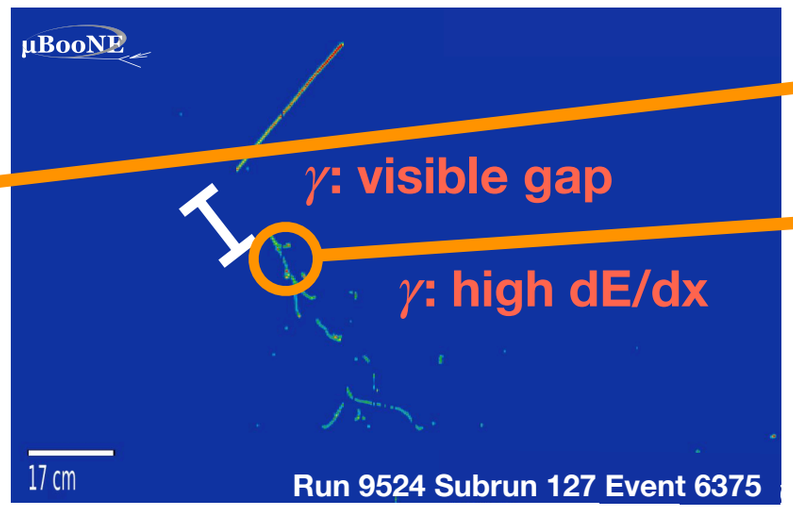


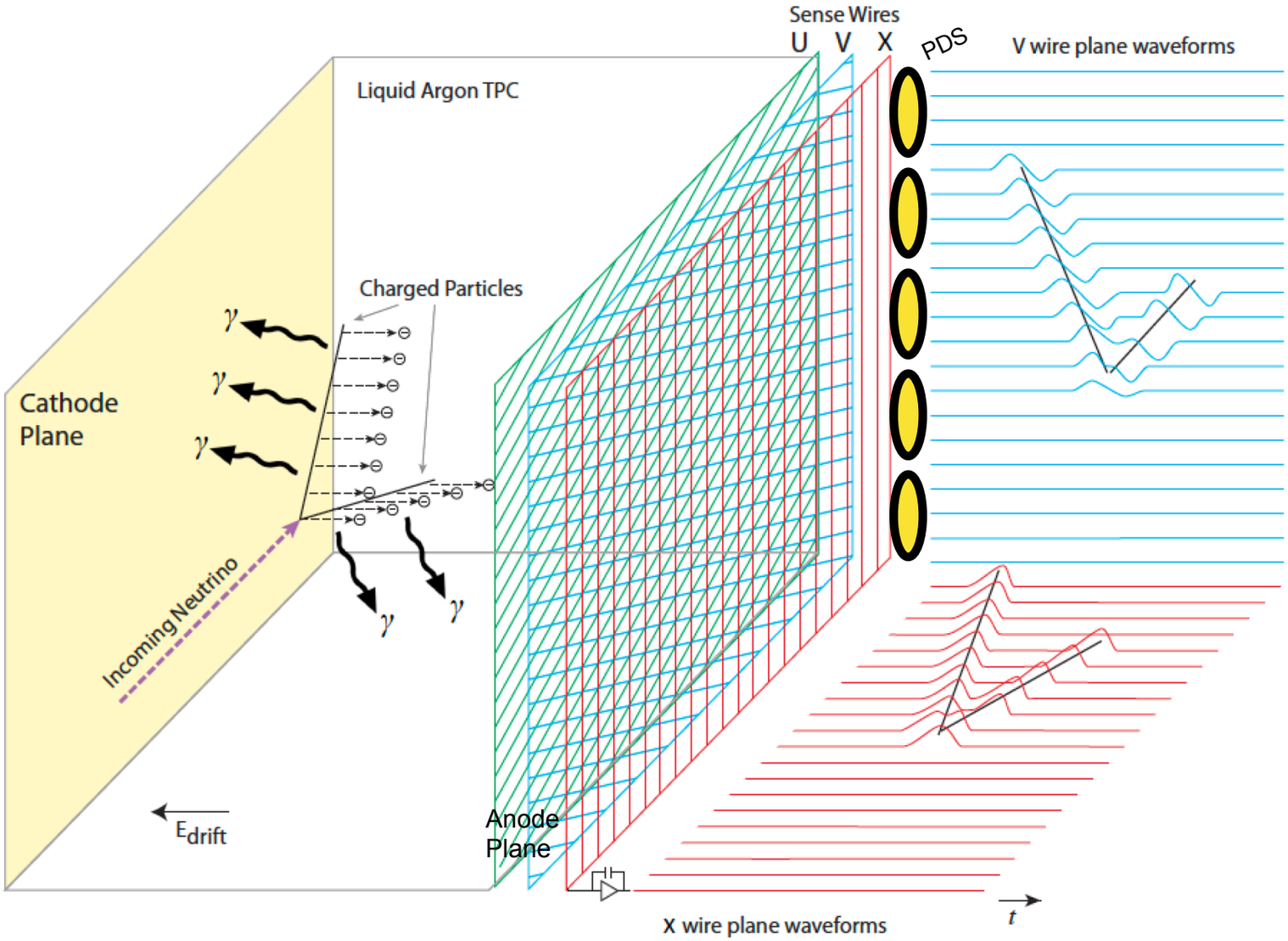
Aux. material Phys.Rev.Lett. 135 (2025) 8, 081802





Operation of LArTPC

Homogeneous target that combines large mass with accurate spatial and calorimetric reconstruction.



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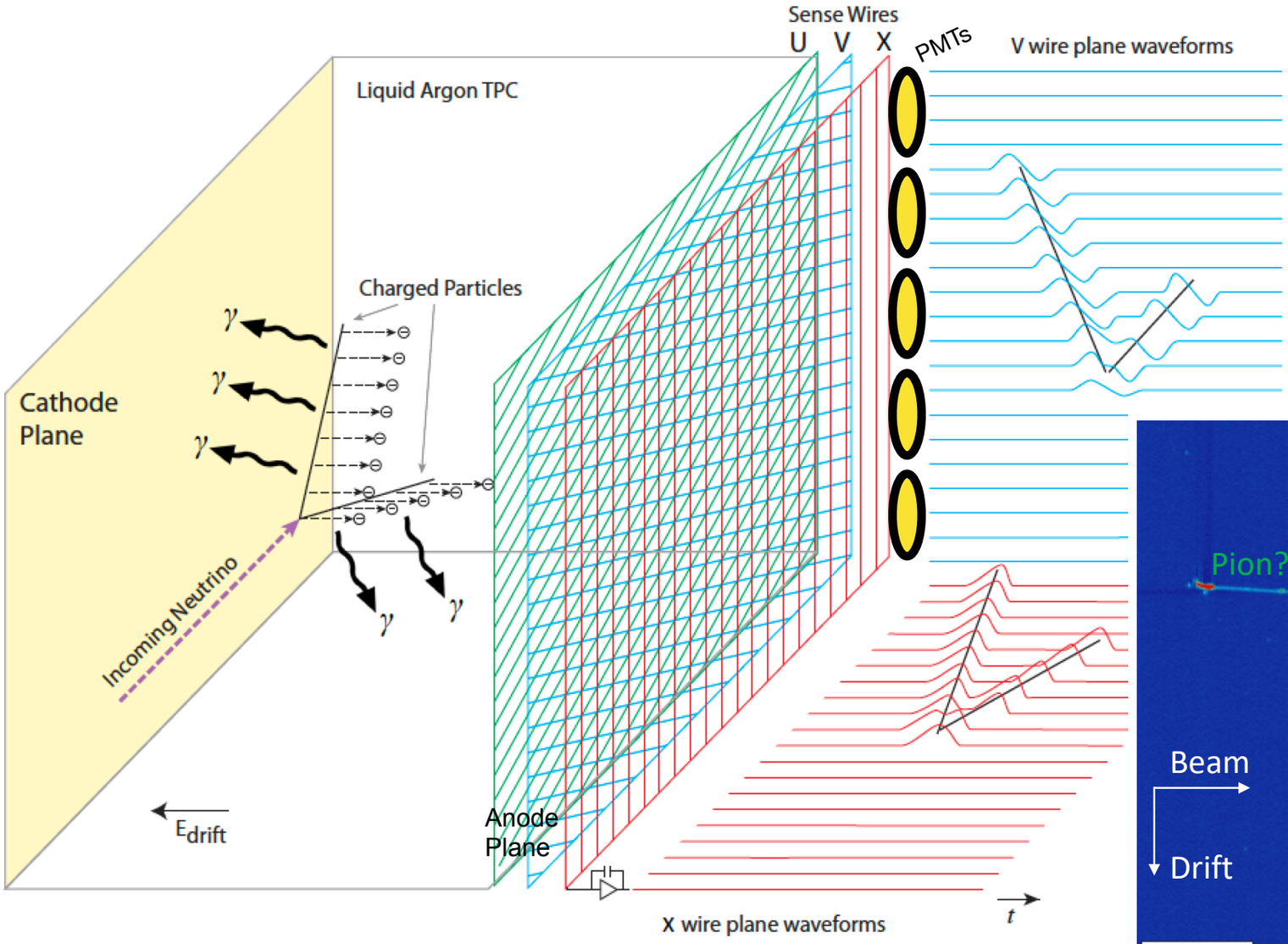
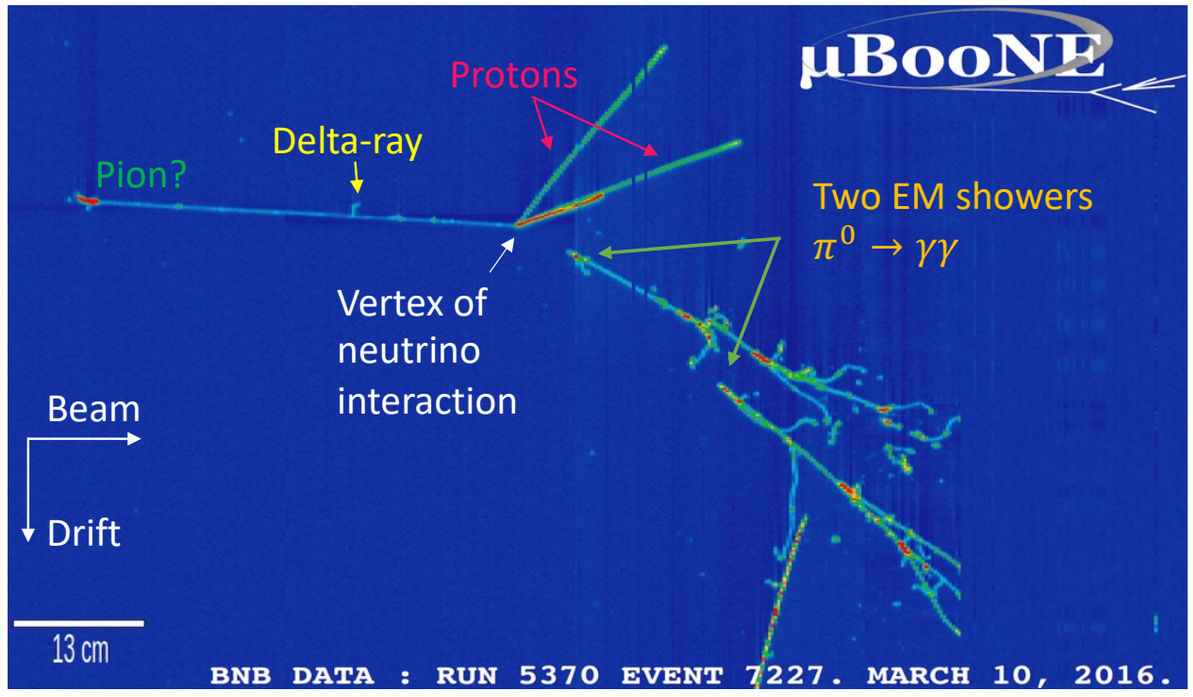
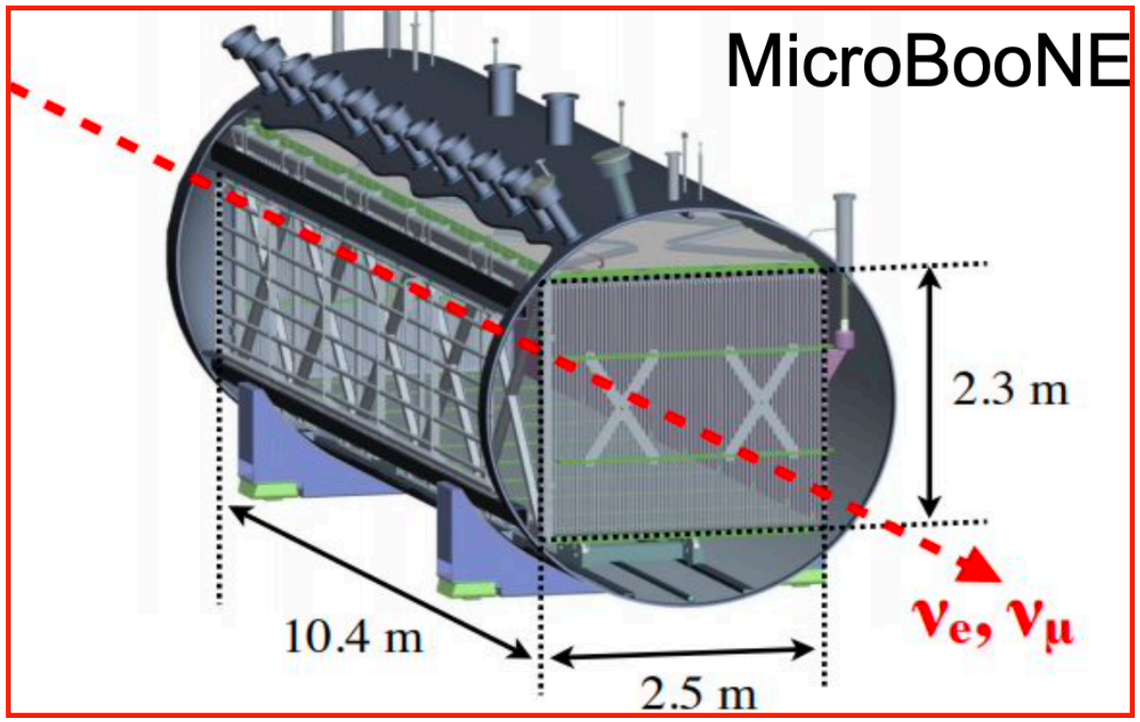


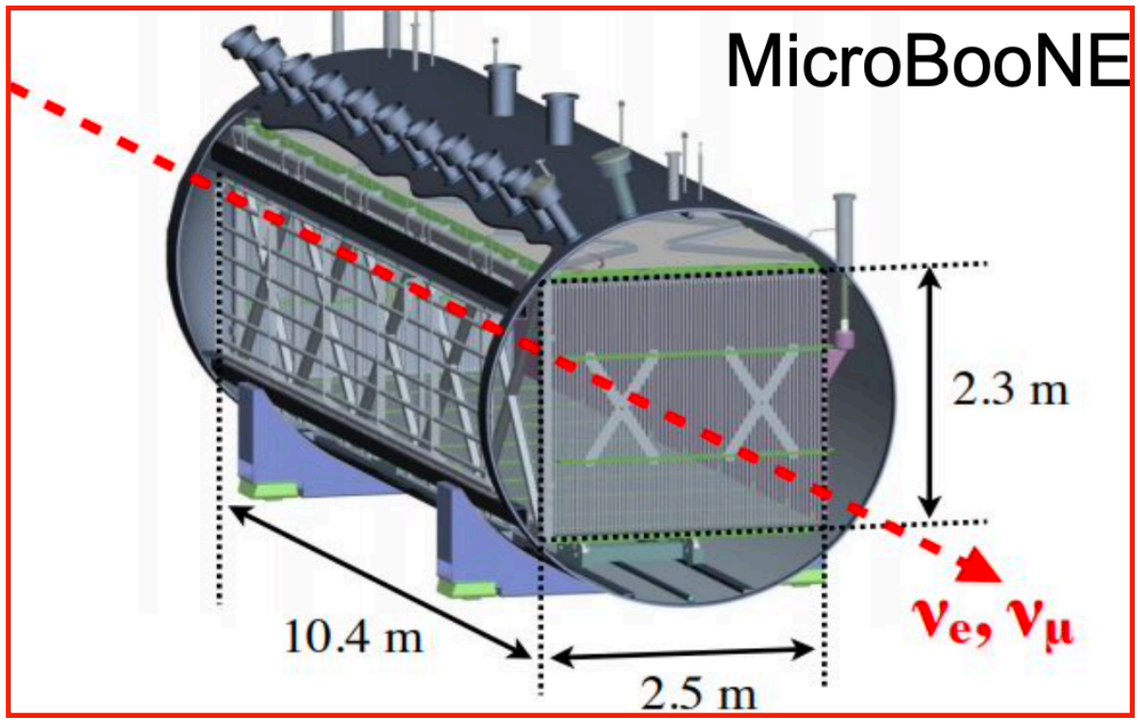


MicroBooNE detector



- MicroBooNE is a surface-level, 85 active LAr tonne (10×2.5×2.5 m3) LArTPC neutrino experiment.
- Scintillation light collected by 32 PMTS and ionization charge by 3 wire planes.

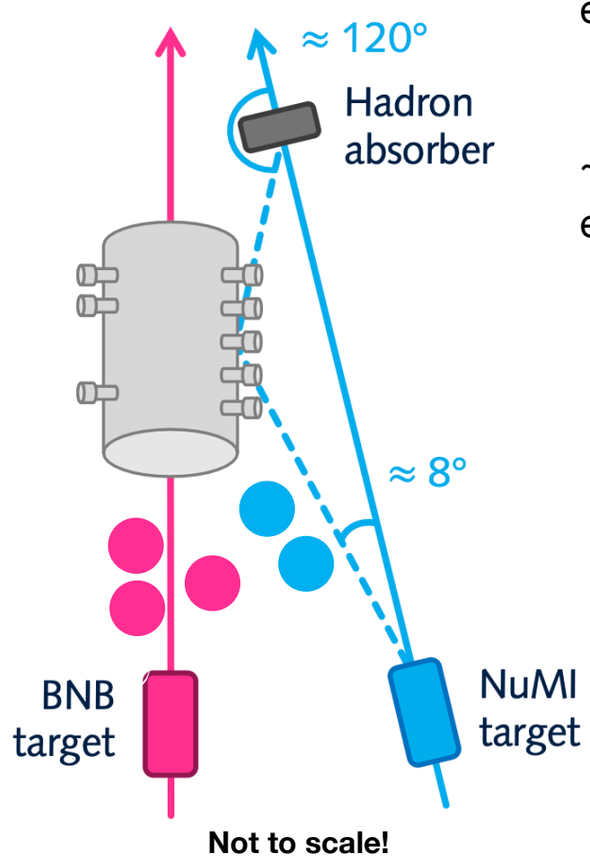
MicroBooNE detector



- ~6 years of data @ Fermilab ’15 - ’21
- Large and well-understood sample of neutrino interactions on argon.

~500,000 BNB neutrino events ($1.11 \cdot 10^{21}$ POT)

~300,000 NuMI neutrino events ($2.0 \cdot 10^{21}$ POT)



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MicroBooNE goals

- Investigate the MiniBooNE Low Energy Excess and search for BSM physics
- Improve our understanding of ν-Ar interactions
- LArTPC hardware and software R&D

Investigations of the MiniBooNE anomaly and sterile neutrinos with MicroBooNE

Oct 2, 2025, 9:10 AM
20m
Spazio 35 (Centro Culturale Altinate San Gaetano)

Contributed Talk | Neutrino Properties | Neutrino Physics

Speaker

Fan Gao

MicroBooNE's cross-section program for future long-baseline oscillations

Oct 1, 2025, 9:10 AM
20m
Main Auditorium (Centro culturale Altinate San Gaetano)

Contributed Talk | Neutrino Properties | Neutrino Physics

Speaker

London Cooper Troendle

Recent cross-section results from MicroBooNE

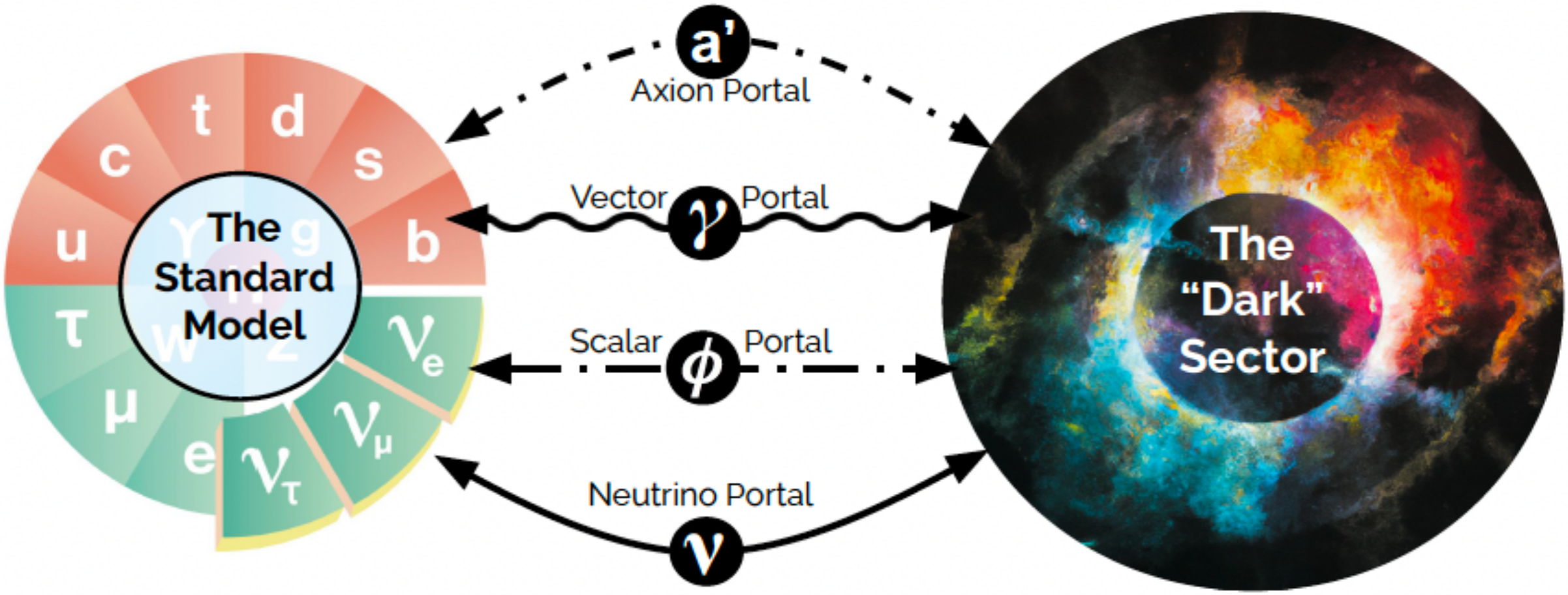
Oct 1, 2025, 9:30 AM
20m
Main Auditorium (Centro culturale Altinate San Gaetano)

Contributed Talk | Neutrino Properties | Neutrino Physics

Speaker

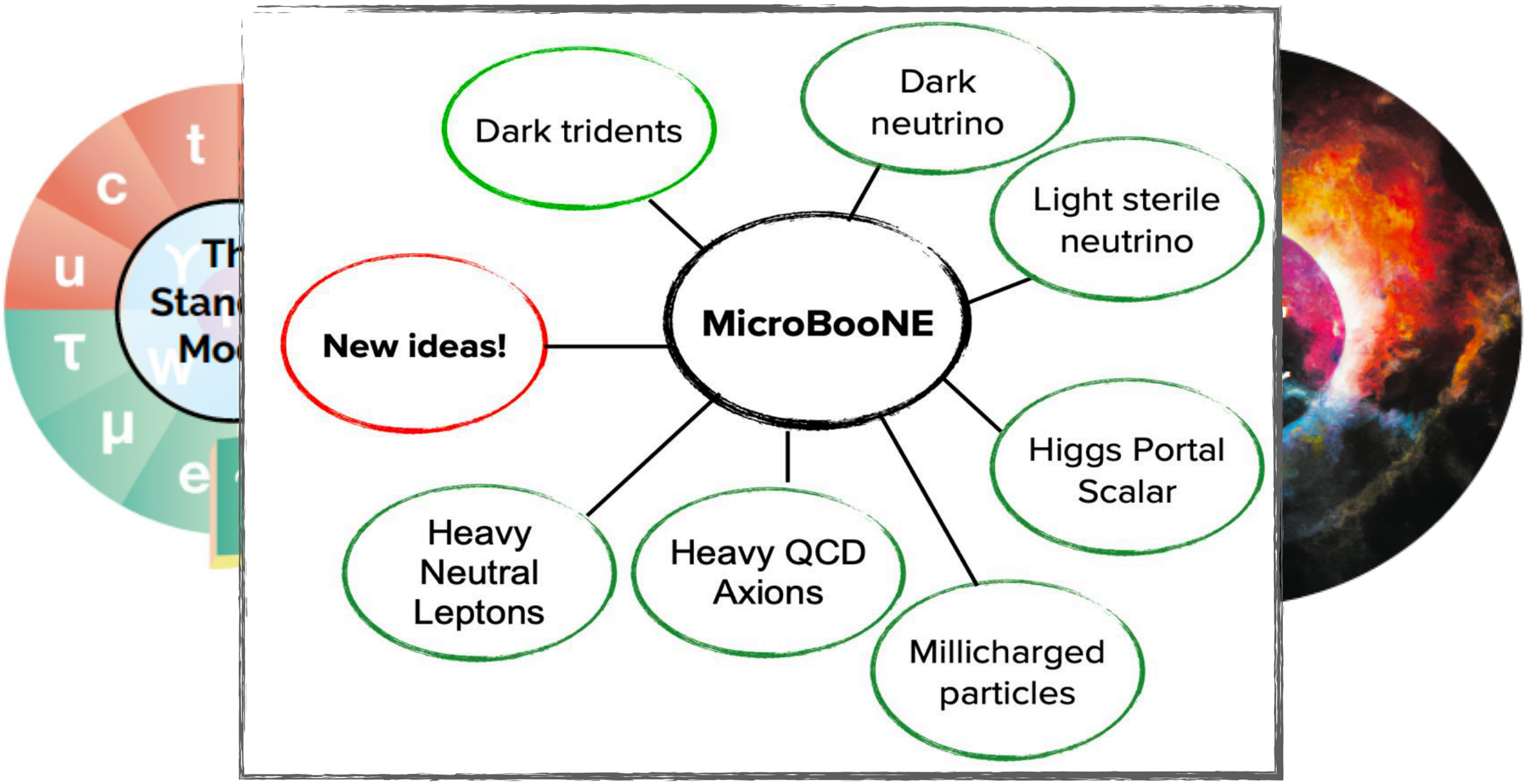
Jairo Rodriguez Rondon

MicroBooNE BSM program



Minimal extensions of the Standard Model (SM) featuring a single new light mediator particle coupled through one of these portals. This implies that both the production of the mediator and its visible decay to SM particles occur due to the portal interaction.

MicroBooNE BSM program



Outline

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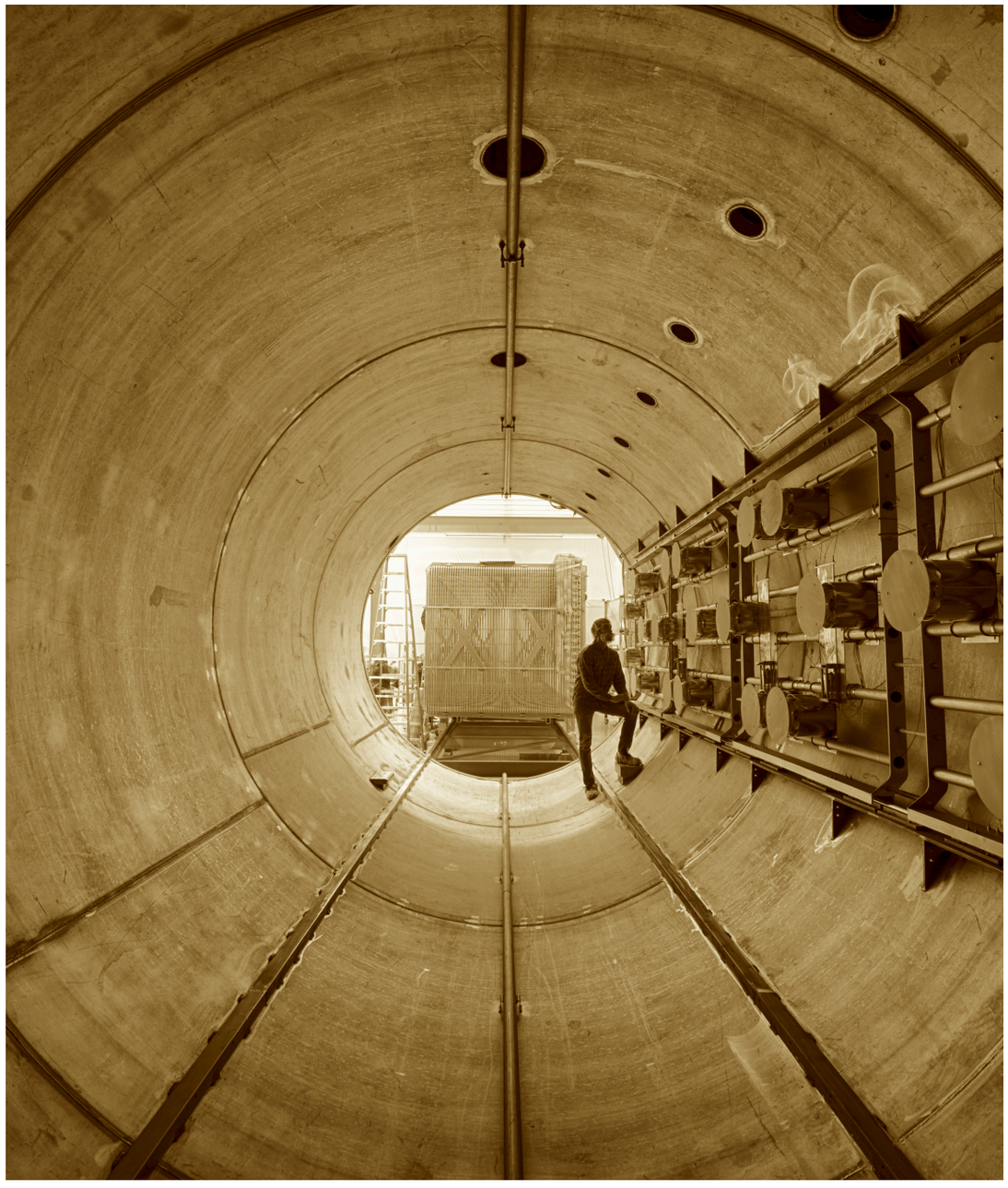
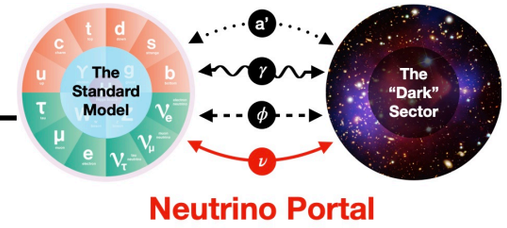
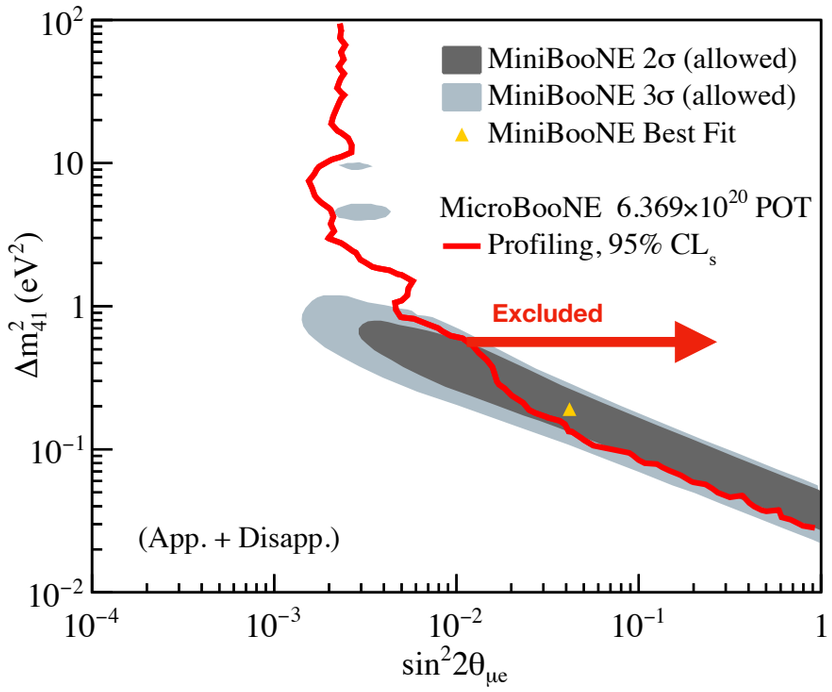
- BSM searches in MicroBooNE



Light sterile neutrino



- Search for 3+1 (eV) sterile neutrino oscillation.
  - Using BNB ν_e inclusive search to look at 3+1 model, large phase space rejected at 95% CLs
  - Degeneracy when $\sin^2 \theta_{24} \approx 0.005$ given (BNB) $R_{\nu_\mu/\nu_e} \approx 185$



Phys. Rev. Lett. 130, 011801 (2023)

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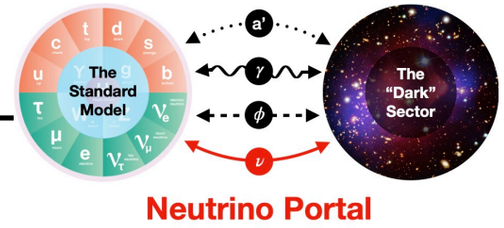

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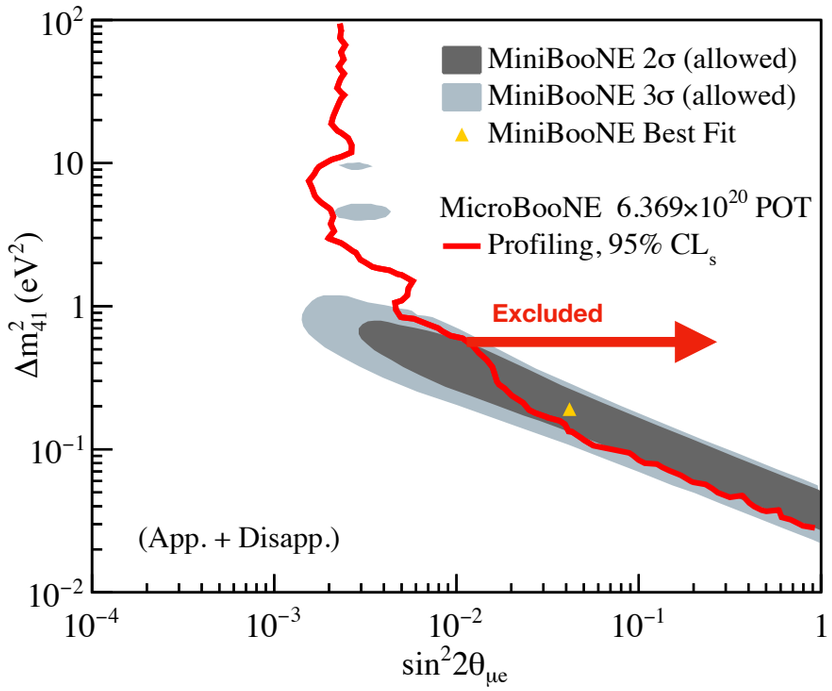
  - Degeneracy when $\sin^2\theta_{24} \approx 0.005$ given (BNB) $R_{\nu_\mu/\nu_e} \approx 185$
  - Degeneracy mitigated by adding data from NuMI beamline $R_{\nu_\mu/\nu_e} \approx 21$



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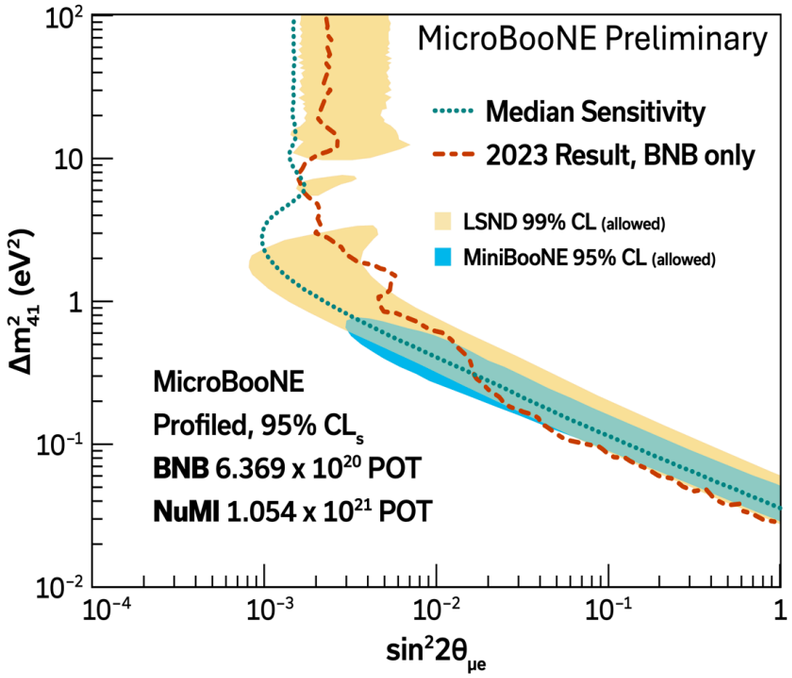
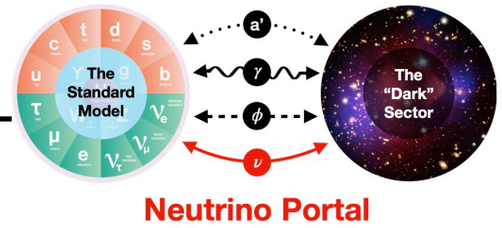


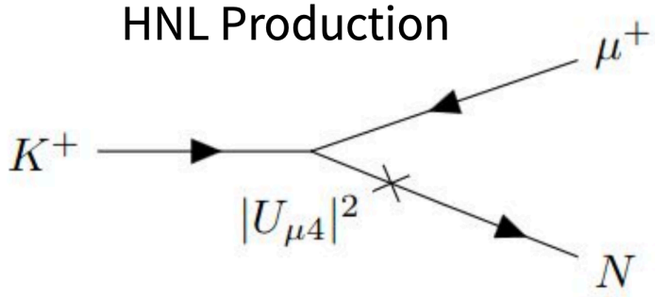
MICROBOONE-NOTE-1132-PUB

Stay tuned for the full result!

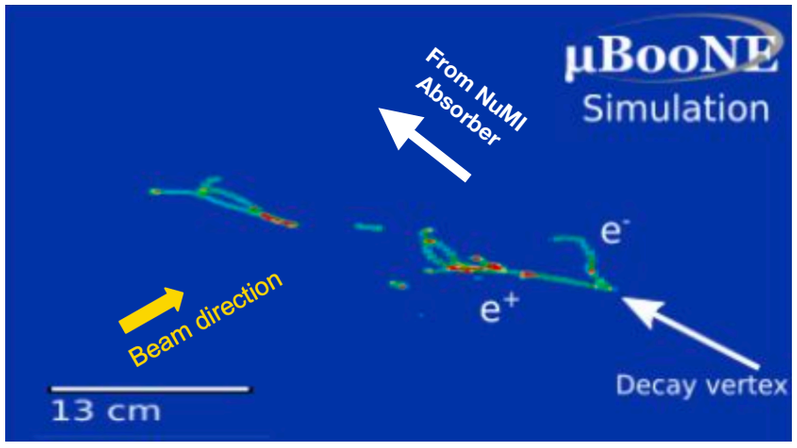
Heavy Neutral Leptons (HNL)

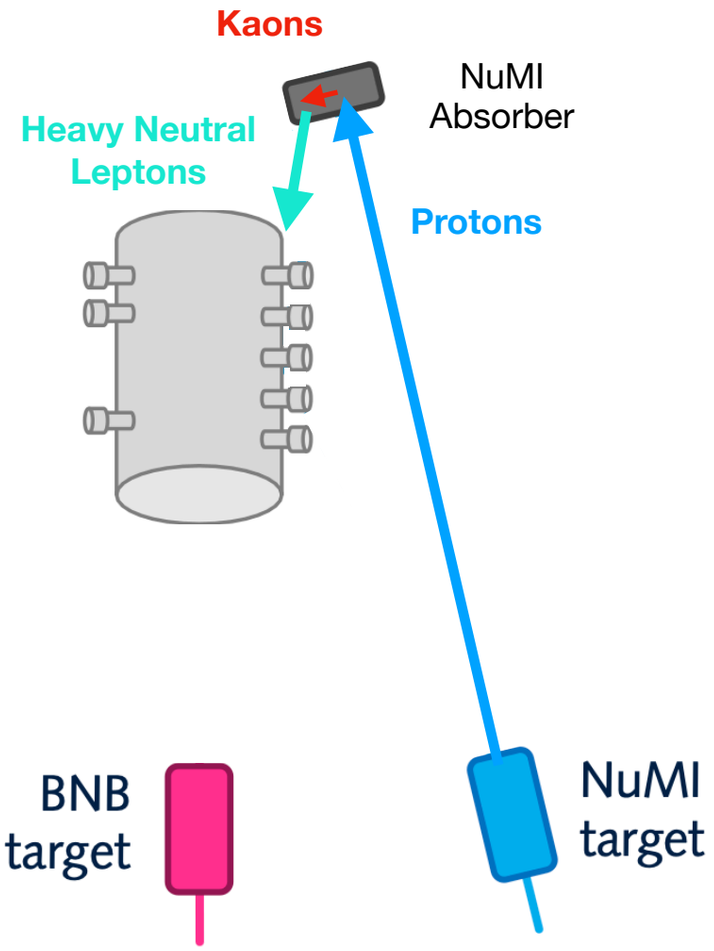


HNL Production



- First search for $N \rightarrow \nu\, e^+e^-$ or $N \rightarrow \nu\, \pi^0$ final states in a LArTPC





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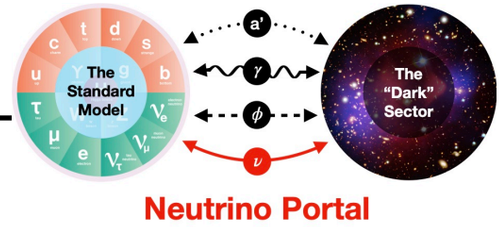

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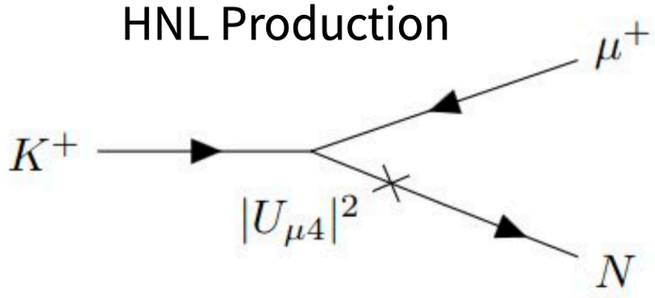

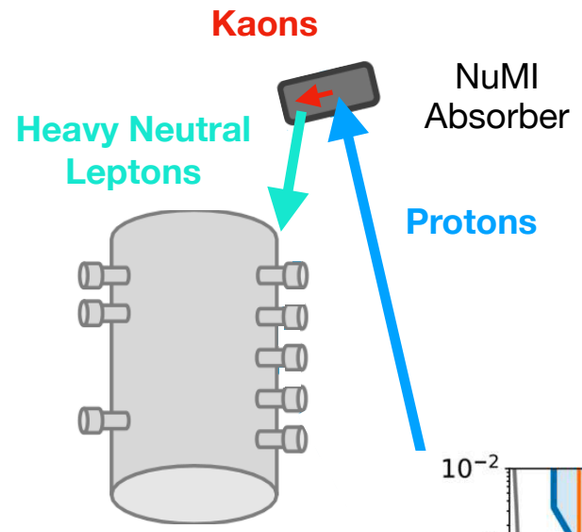

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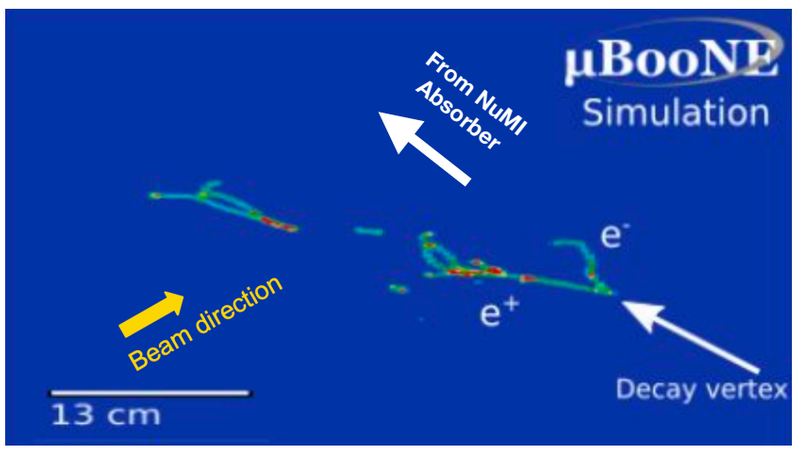

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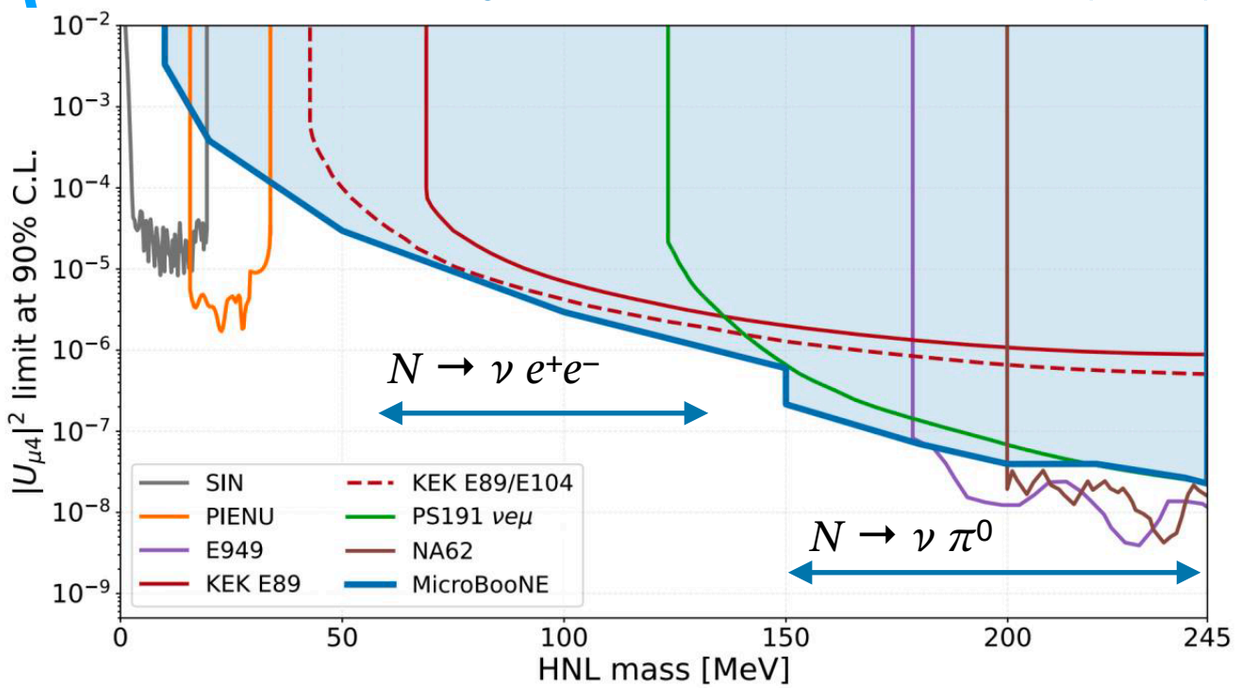
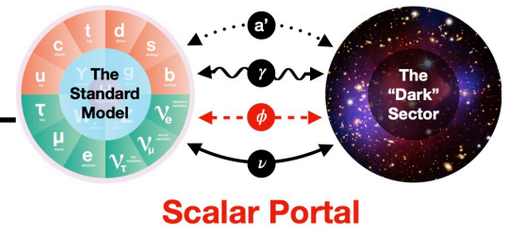
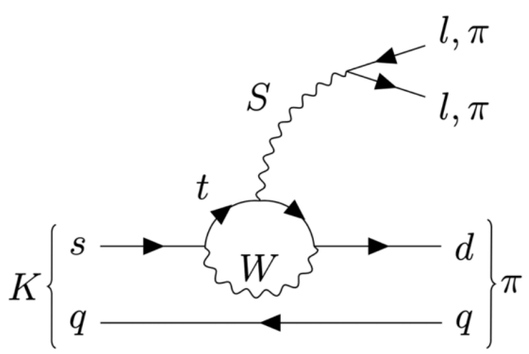


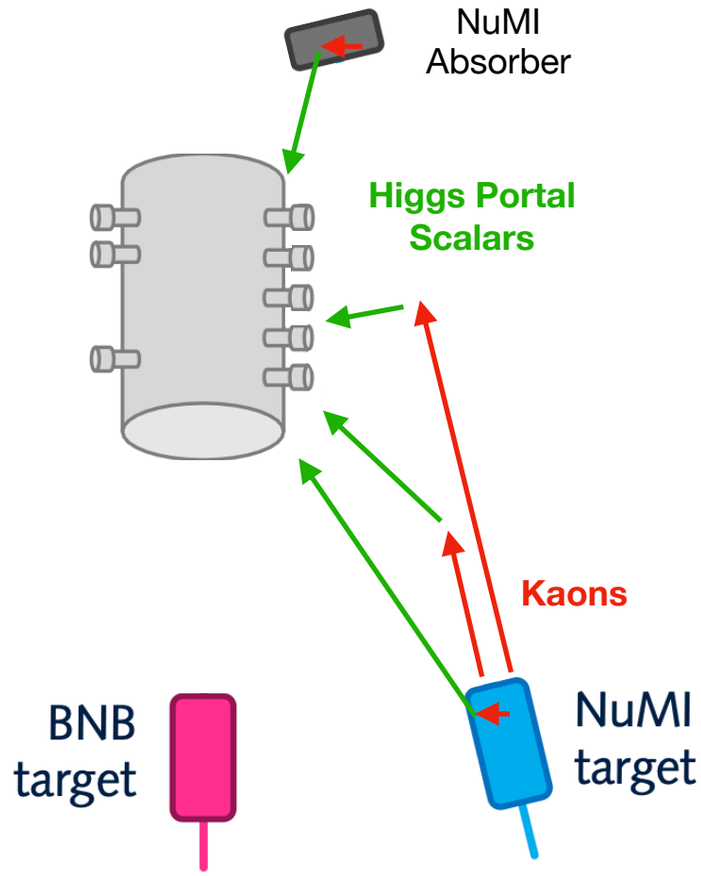
- Set limits on $|U_{\mu 4}|^2$ as a function of HNL mass
  $10 \leq$ mHNL ≤ 150 MeV (νe^+e^- channel)
  $150 \leq$ mHNL ≤ 245 MeV ($\nu\pi^0$ channel)

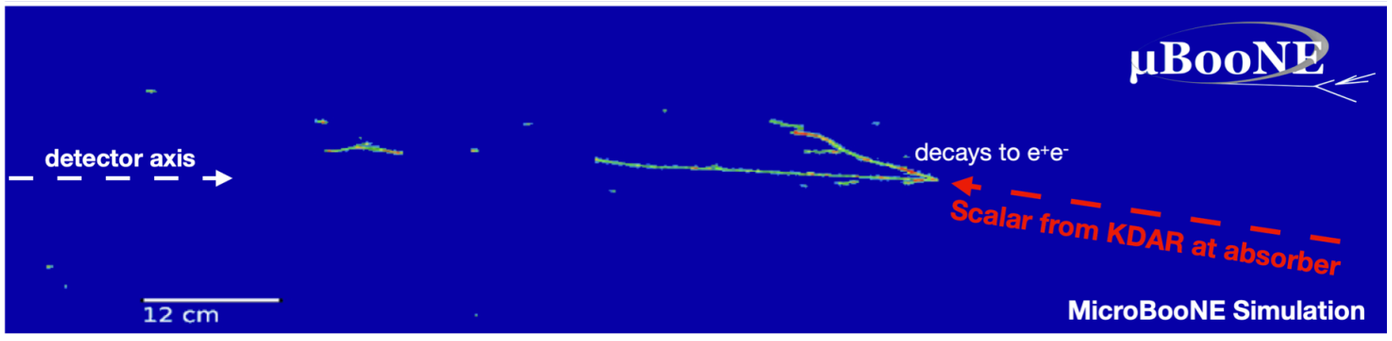
Higgs Portal Scalars



- Neutral scalar singlet S, mixing angle θ with the Higgs boson
- Production from kaon decay
- Signature: $S \rightarrow e^+e^-$







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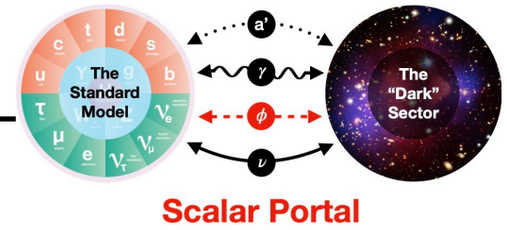

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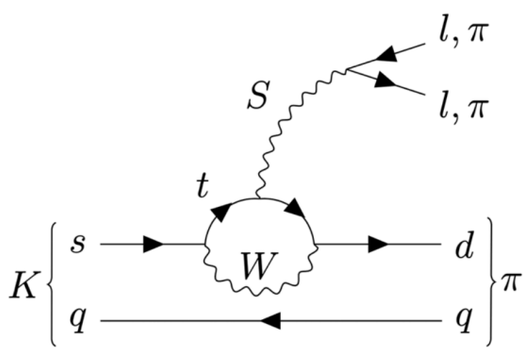
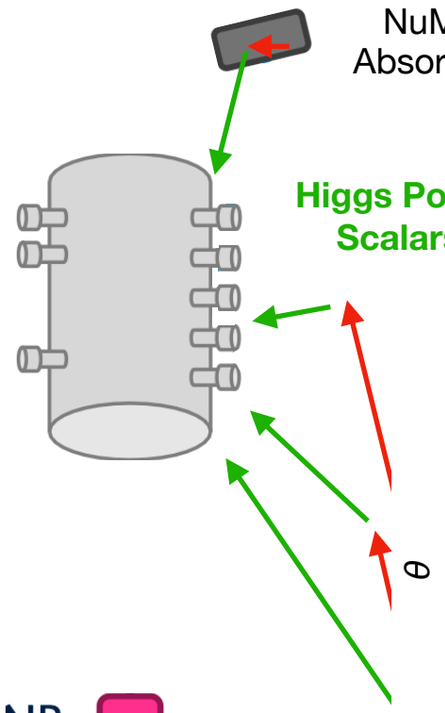
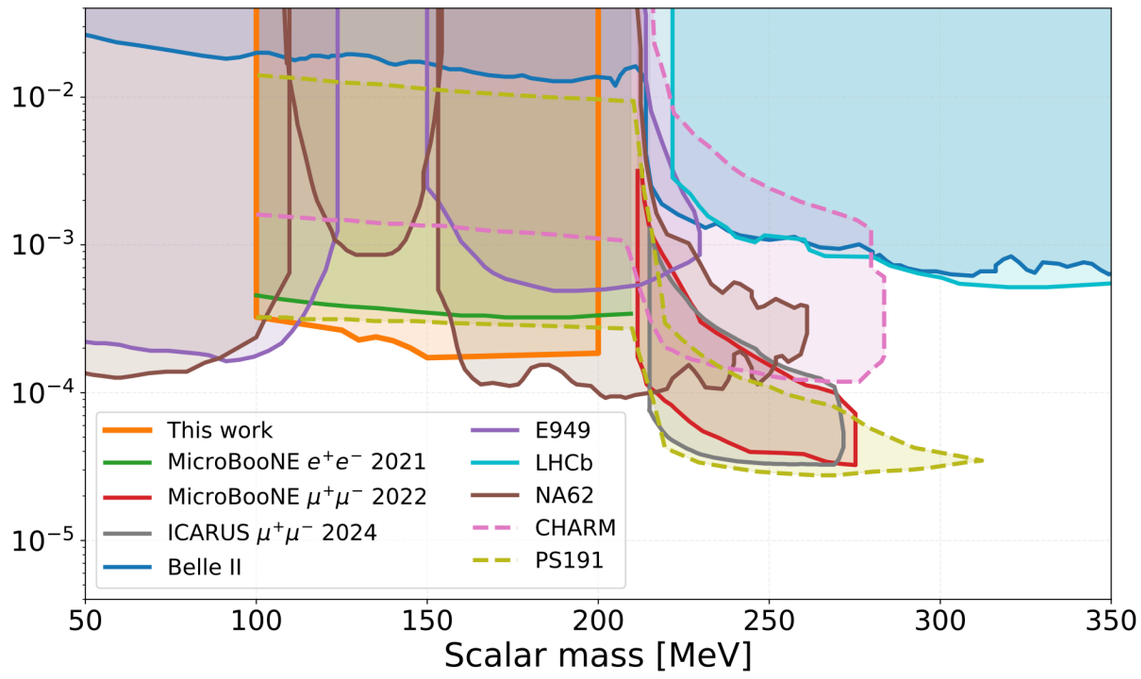
- Production from kaon decay
- Signature: $S \rightarrow e^+e^-$

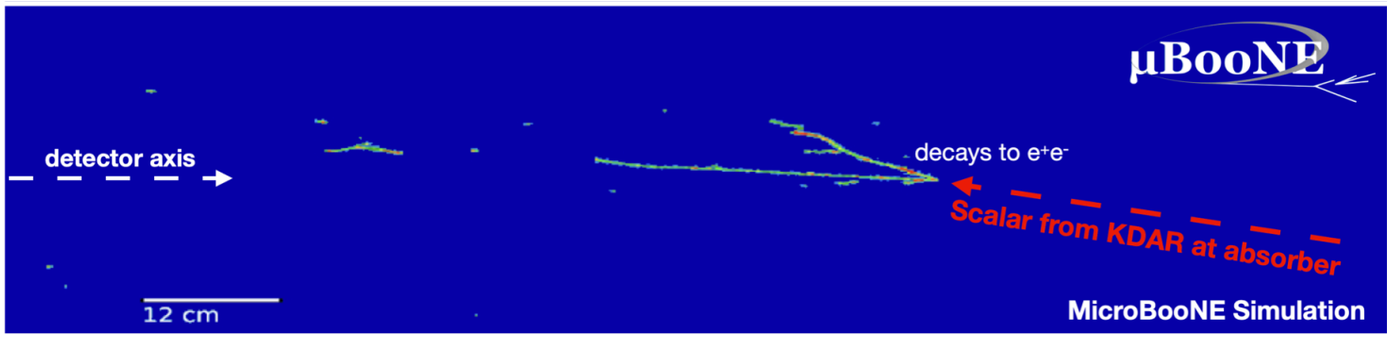




New!

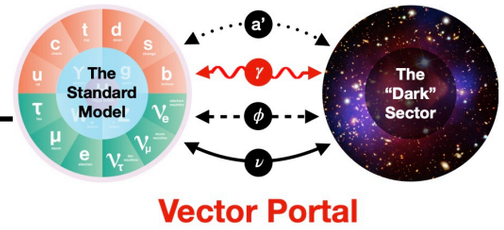
arXiv:2501.08052





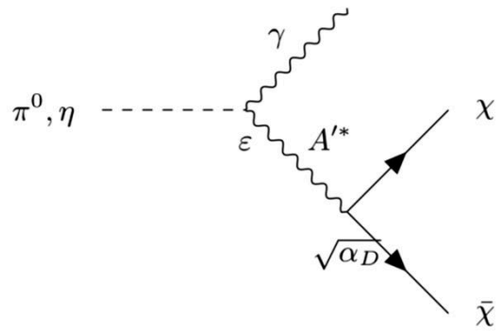
- Set strongest limits to date at 95% CL:
  At mS = 125 MeV, θ < 2.65 × 10–4
  At mS = 150 MeV, θ < 1.72 × 10–4

Light dark matter

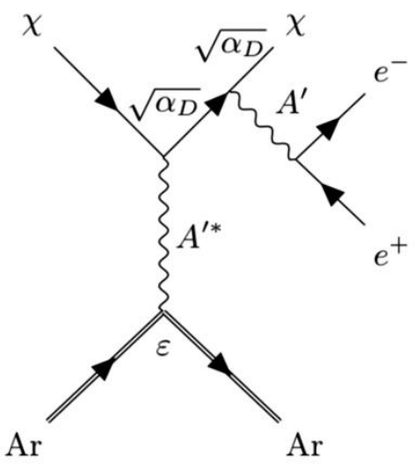


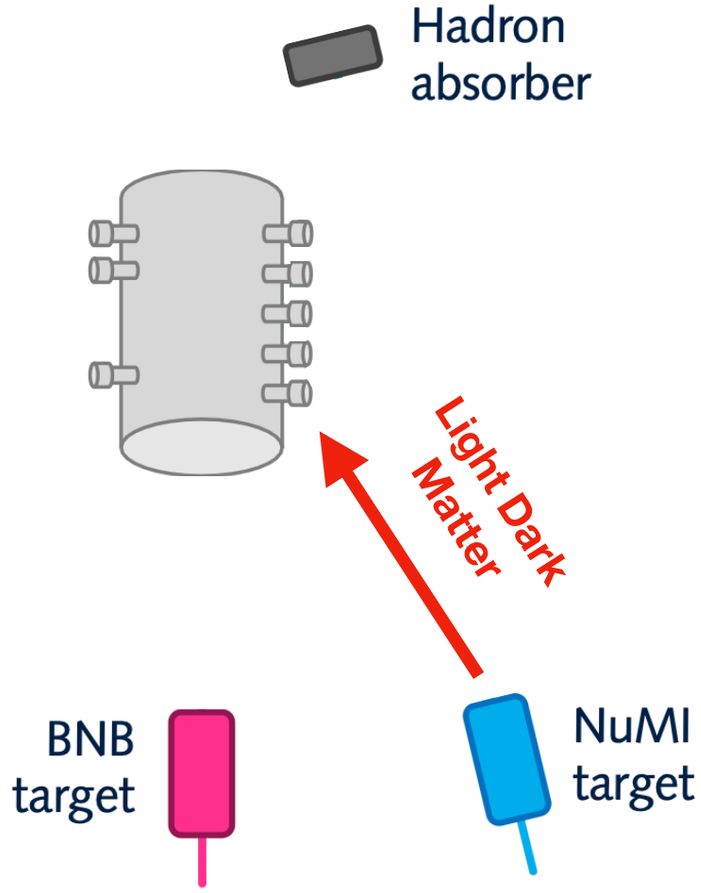
- First search for dark-trident using a LArTPC

Production
DM particle produced in beam and interacts in MicroBooNE Dark photon mediator A'



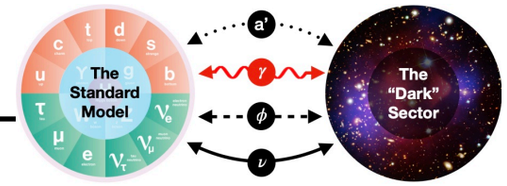
Scatter
Dark photon mediator $A' \rightarrow e^+e^-$





BSM searches in MicroBooNE

Light dark matter



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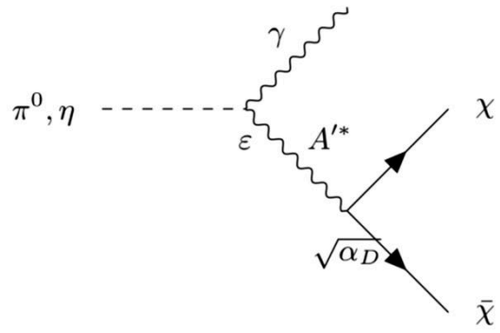
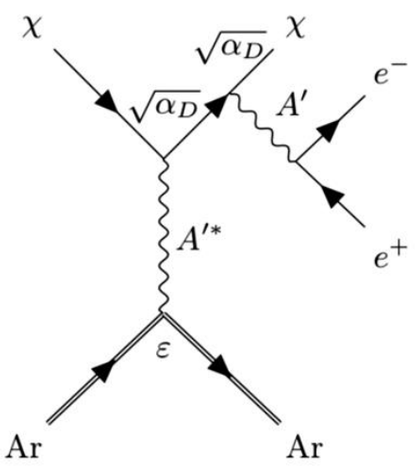
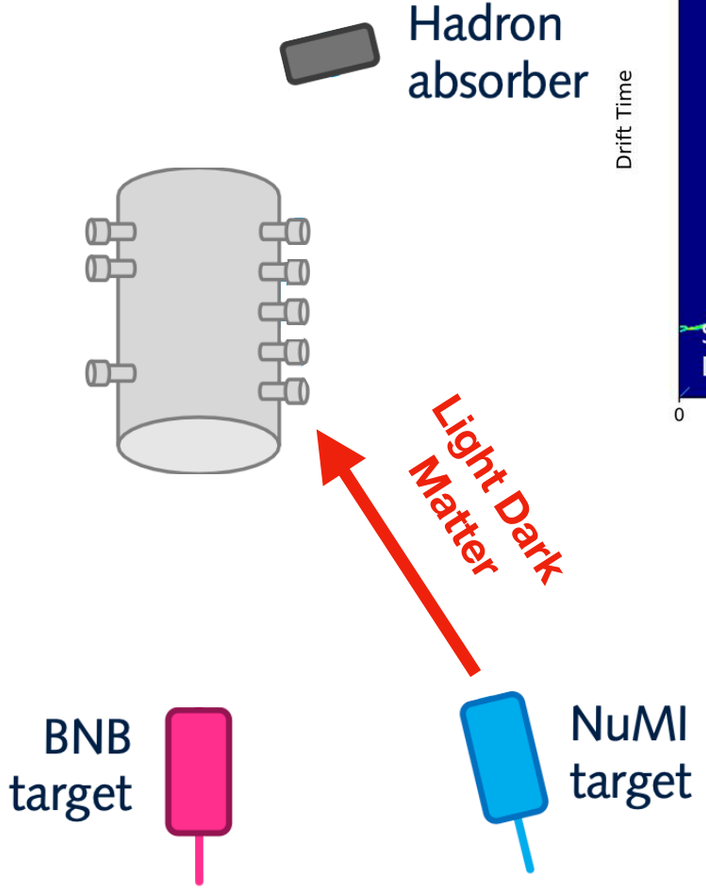
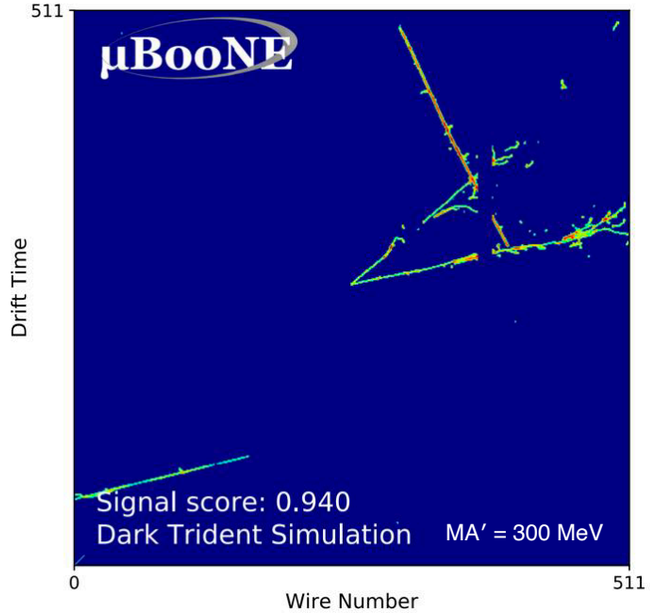


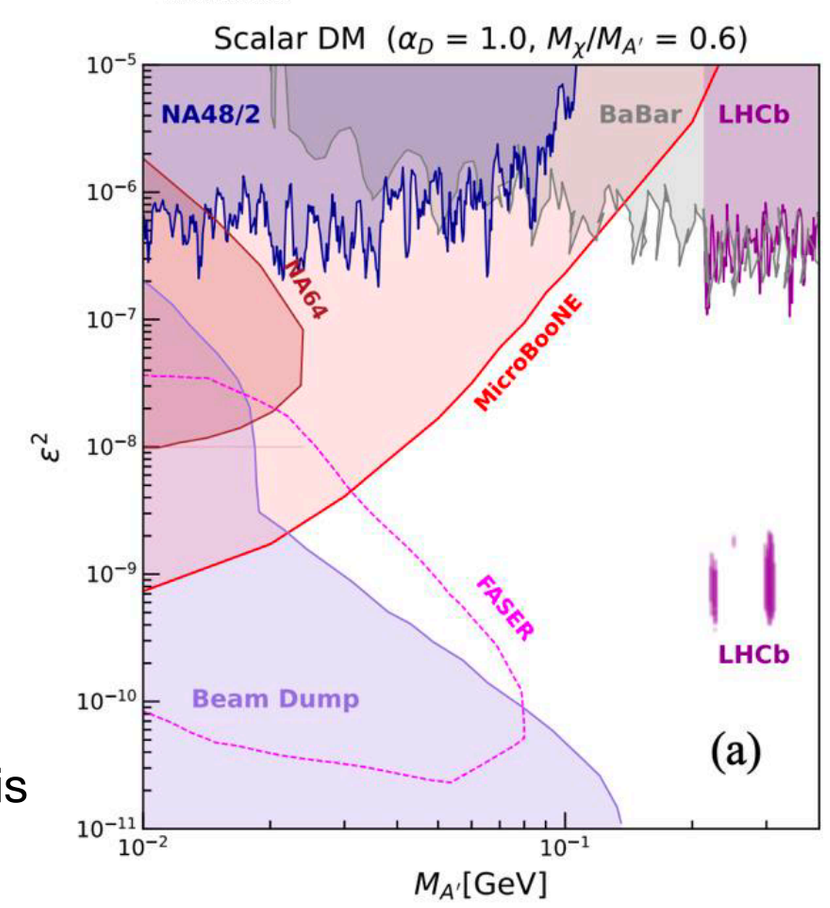
Scatter
Dark photon mediator $A' \rightarrow e^+e^-$





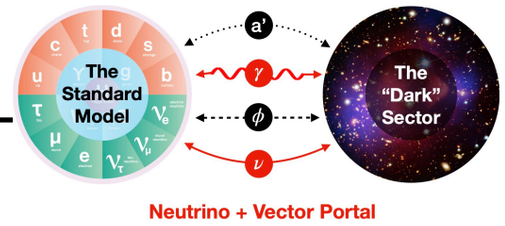


- Parameters of the model:
  - dark photon (MA')
  - dark scalar (or fermion) (Mχ)
- Set world-leading limits on this Light Dark Matter model



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

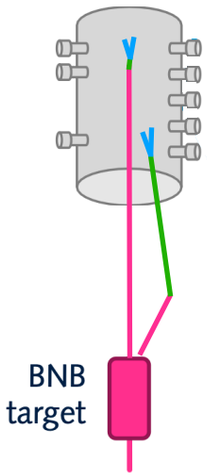
BSM searches in MicroBooNE



Dark Neutrino e^+e^- -like LEE signal

Non-minimal portal: neutrino and vector

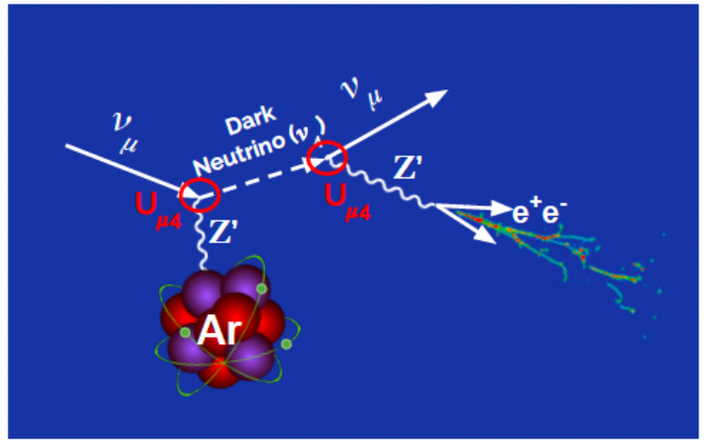
- Two main possibilities for the MiniBooNE LEE:
  - Single electron
  - Single photon, pair-converting to e^+e^-



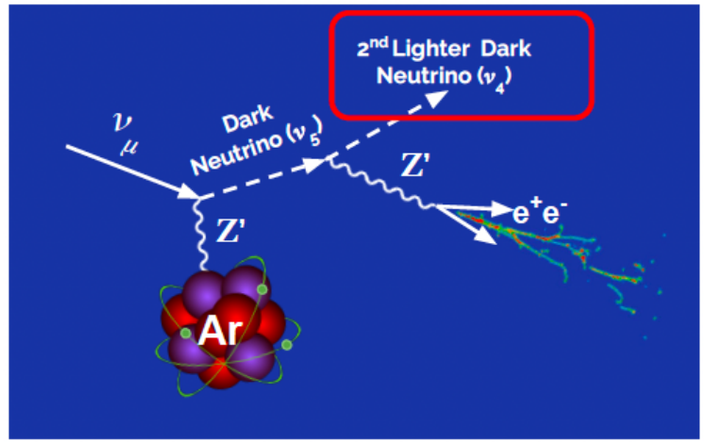
- Possible e+e- solutions to the MiniBooNE excess
  - *Dark Neutrino Portal to Explain MiniBooNE excess*
  10.1103/PhysRevLett.121.241801 Light Z' regime $m_{z'} < m_4$
  - *U(1)' mediated decays of heavy sterile neutrinos in MiniBooNE*
  10.1103/PhysRevD.99.071701 Heavy Z' regime $m_{z'} > m_4$

- Neutrinos up-scatter to a heavy dark neutrino ν_4 via a new dark gauge boson Z'.
  - ν_4 is unstable and decays $\nu_4 \rightarrow \nu_\alpha\, e^+e^-$
  (or to a 2nd lighter dark neutrino, dual dark neutrino model)

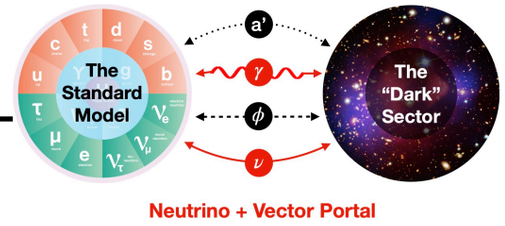
Single Dark Neutrino Model



Dual Dark Neutrino Model



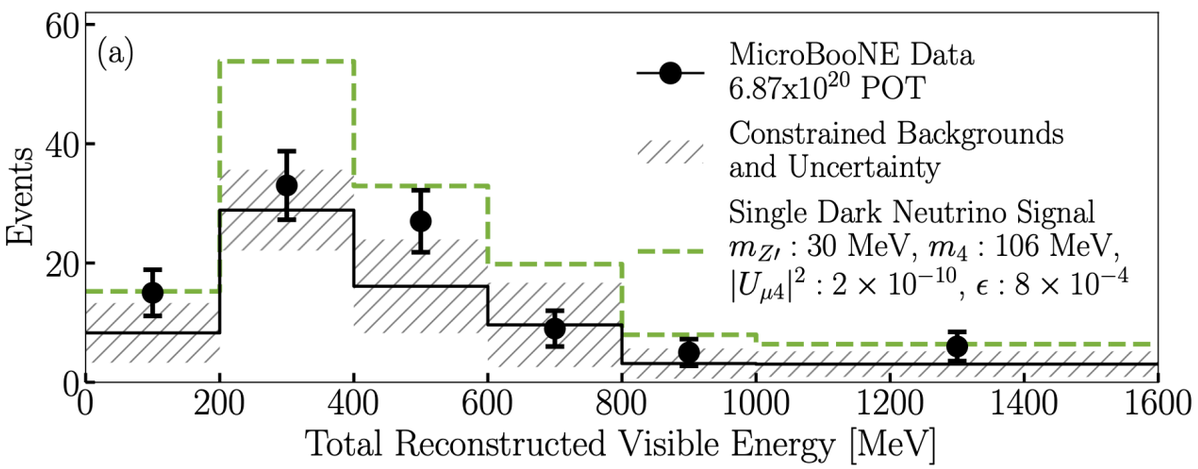
BSM searches in MicroBooNE

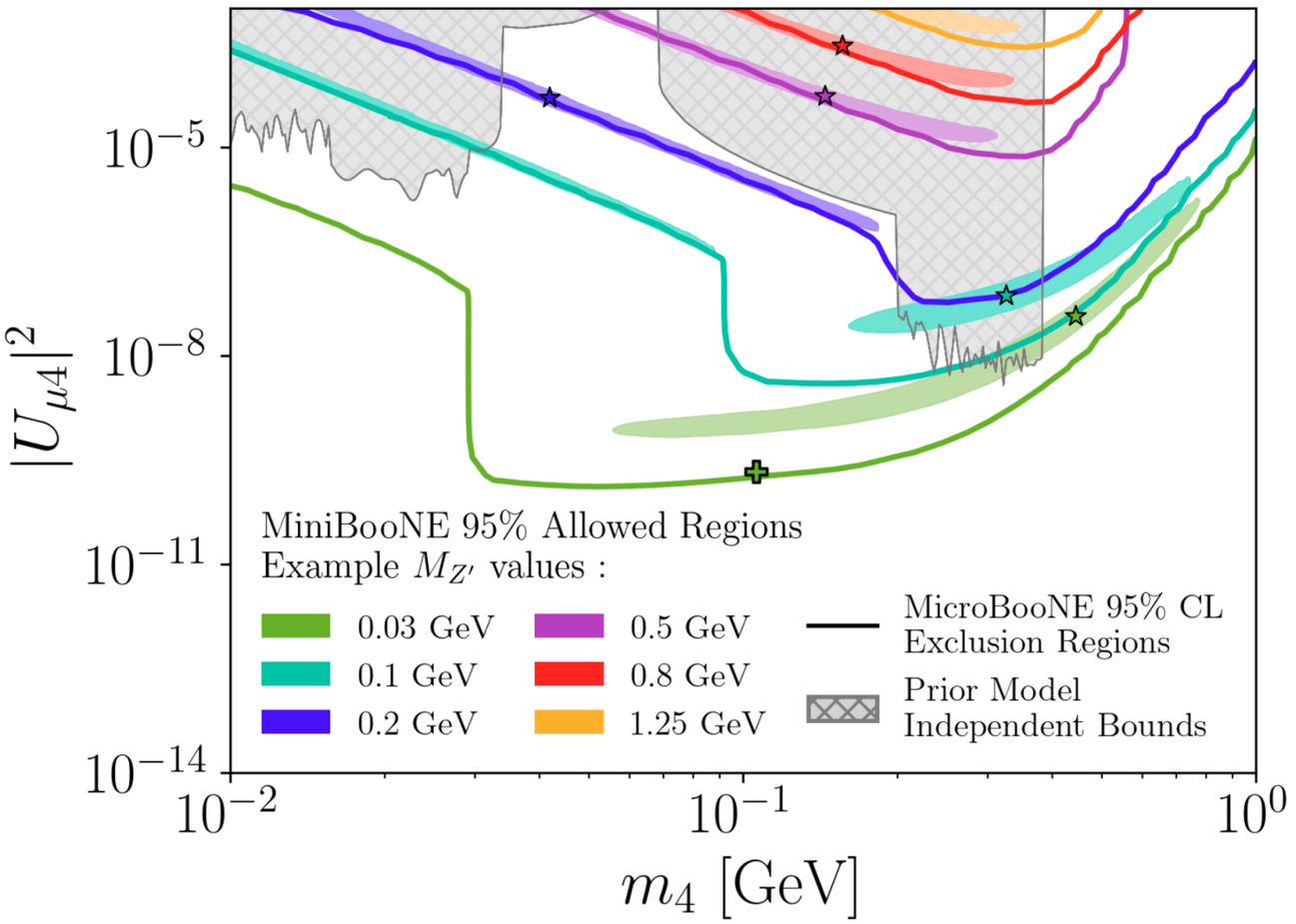


Dark Neutrino e^+e^- -like LEE signal

Non-minimal portal: neutrino and vector

- 95 events seen; 69.7 ±17.3 predicted. Agreement at 1.5σ
- We exclude almost all of the MiniBooNE-allowed phase space of this model
- In general, we expect small changes to assumptions in this model to affect MiniBooNE and MicroBooNE in similar ways

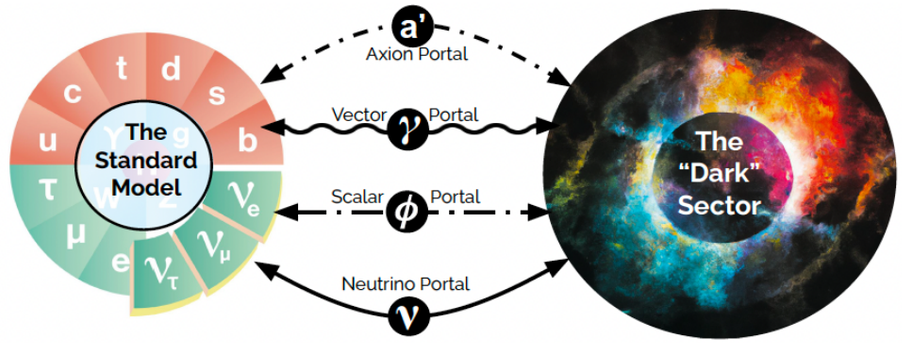




arXiv:2502.10900

BSM summary

MicroBooNE is powerful probe of minimal dark sector portals

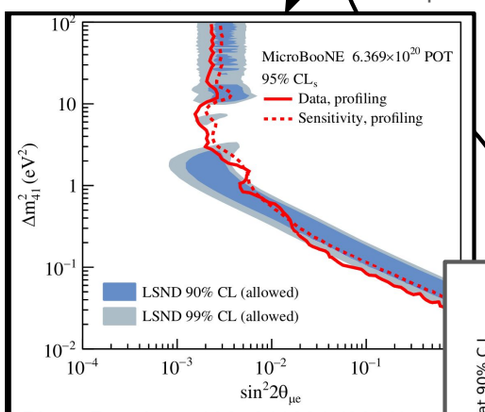


Neutrino Portal

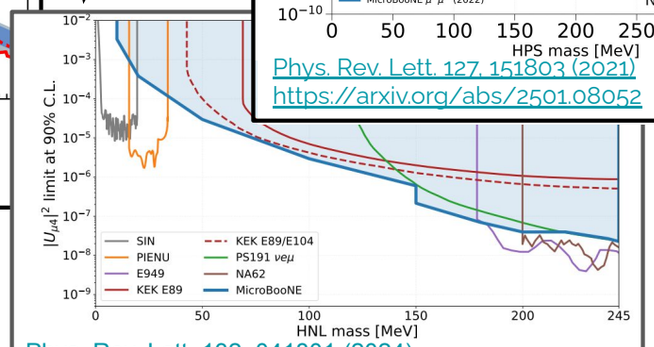
$\mathcal{L} \supset -y^{\alpha} L_{\alpha} H N + \text{h.c.}$

Light 3+1 sterile Neutrino

Heavy Neutral Leptons



Phys. Rev. Lett. 130, 011801 (2023)

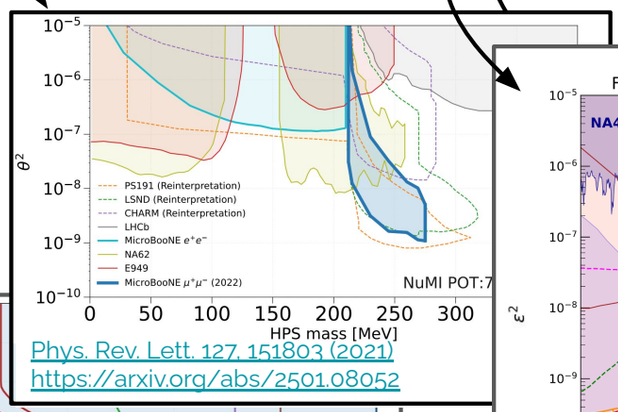


Phys. Rev. Lett. 132, 041801 (2024)
Phys. Rev. D 106, 092006 (2022)

Scalar Portal

$\mathcal{L} \supset (A\,S + \lambda\,S^2)\,H^{\dagger}H$

Higgs Portal Scalars



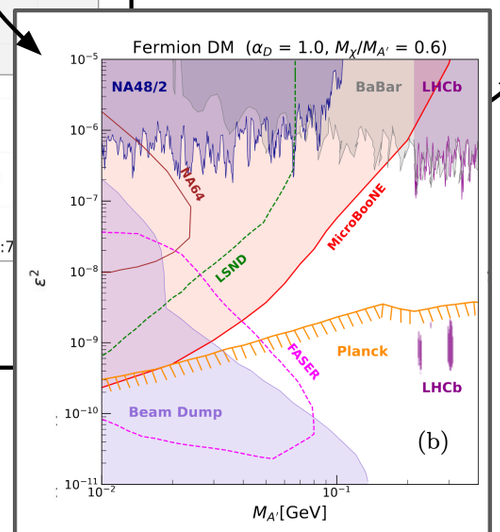
Phys. Rev. Lett. 127, 151803 (2021)
https://arxiv.org/abs/2501.08052

Vector Portal

$\mathcal{L} \supset \epsilon F'_{\mu\nu} B^{\mu\nu}$

Light Dark Matter

Millicharged Particles



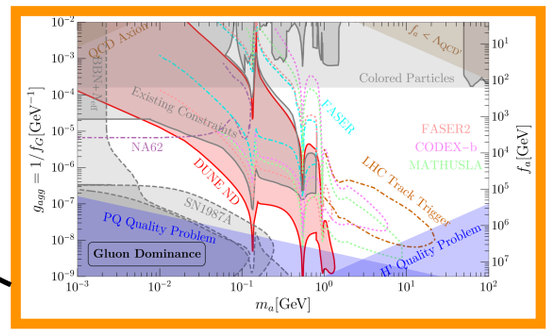
Phys. Rev. Lett. 132, 241801 (2024)

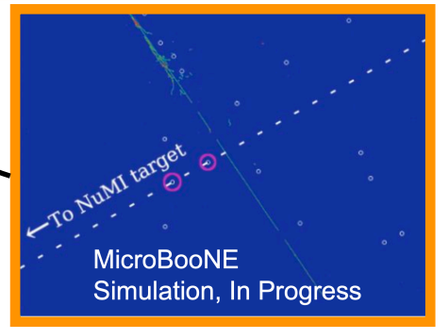
Axion Portal

$\mathcal{L} \supset c_{GG} \dfrac{\alpha_s}{4\pi} \dfrac{a}{f} G^{a}_{\mu\nu} \widetilde{G}^{a,\mu\nu}$

Heavy QCD Axions

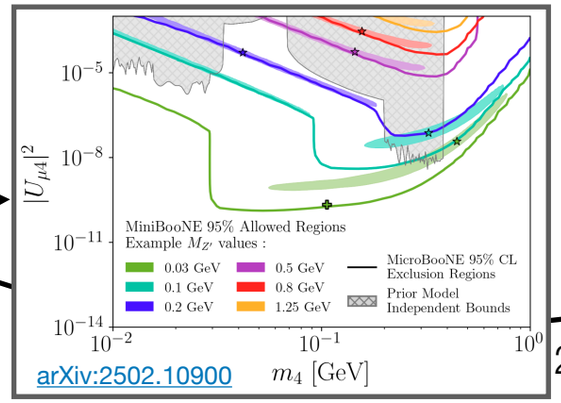
QCD axion and milli-charged particle analyses ongoing!





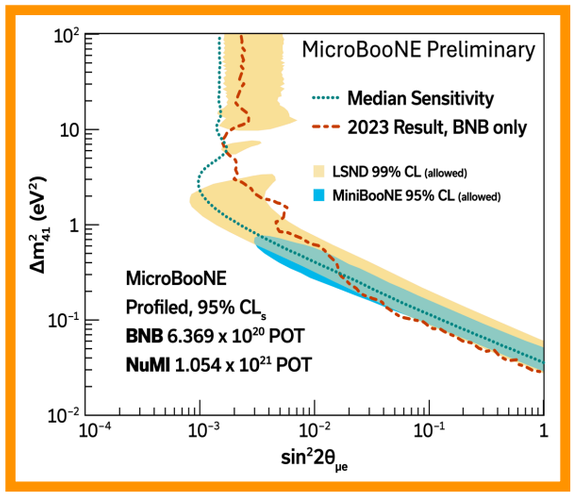
Combined and Non-Minimal Portals

Dark Neutrino



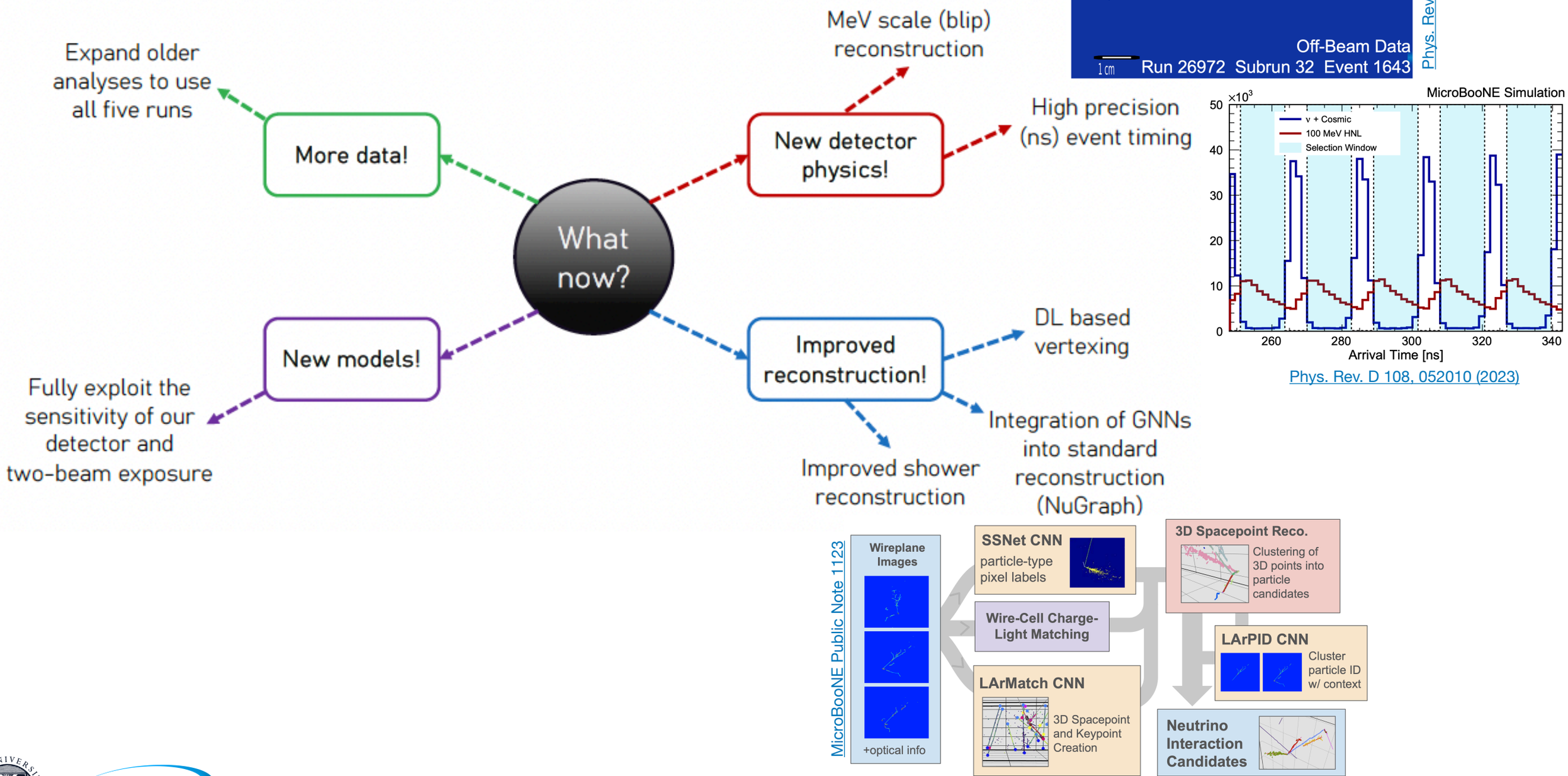
arXiv:2502.10900

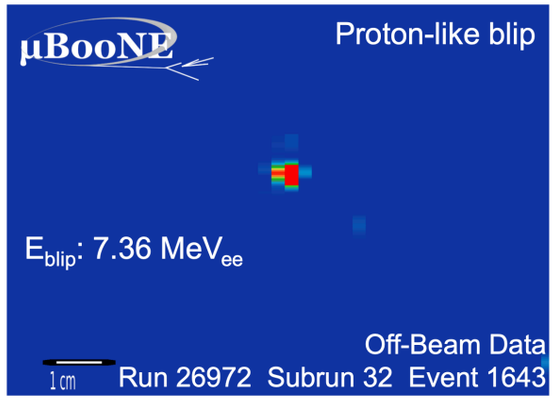
sterile neutrino oscillations comming soon!



MicroBooNE Public Note 1132

Future of MicroBooNE BSM Searches





Phys. Rev. D 111, 032005 (2025)

Phys. Rev. D 108, 052010 (2023)

Summary

- MicroBooNE collected BNB and NuMI neutrino beams data for ~6 years producing >80 papers.

- Extensive inclusive physics program:
  Pioneering BSM searches, ν-Ar cross-sections (see London's and Jairo's xsec talks tomorrow) and LArTPCs R&D
  Many BSM explanations of prior anomalies ruled out (see Fan's talk on Thursday for more discussion of the MiniBooNE anomaly)

- Strong constraints placed on many other models! (HNLs, HPSs, Dark Tridents, Dark Neutrinos...)

- Incorporation of new techniques into BSM searches! AI/ML based, Ns timing, MeV-scale reconstruction …
  Lots of exciting results to come!

MicroBooNE Collaboration Meeting - Oxford, Sept.25

Backup

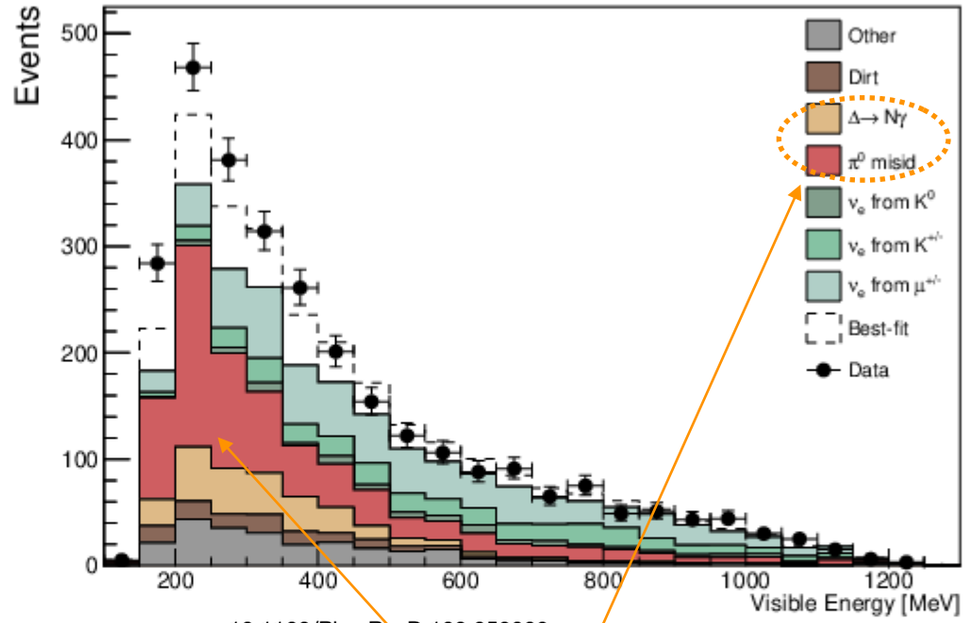
Short-Baseline neutrino anomalies

- MiniBooNE was built to test LSND anomaly.
- With data collected from 2002 to 2019, sees a 4.8σ excess of ν_e candidate events
- Neutrino and anti-neutrino final fits consistent with LSND allowed regions.

If excess is truly electron neutrinos from oscillation then could be evidence of a 3+N sterile neutrino theory

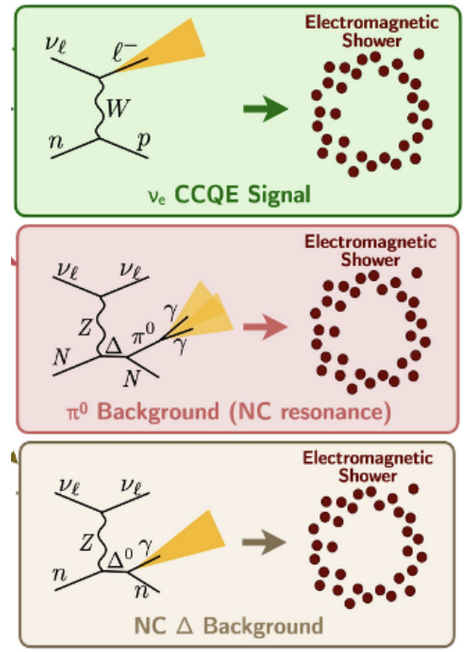
- MicroBooNE main physics goal:
  Investigate the MiniBooNE "Low Energy Excess"
  - Same BNB beam, baseline but new detector!
- Additional physics program:
  BSM, ν-Ar interactions, LArTPC R&D

MiniBooNE ν_e



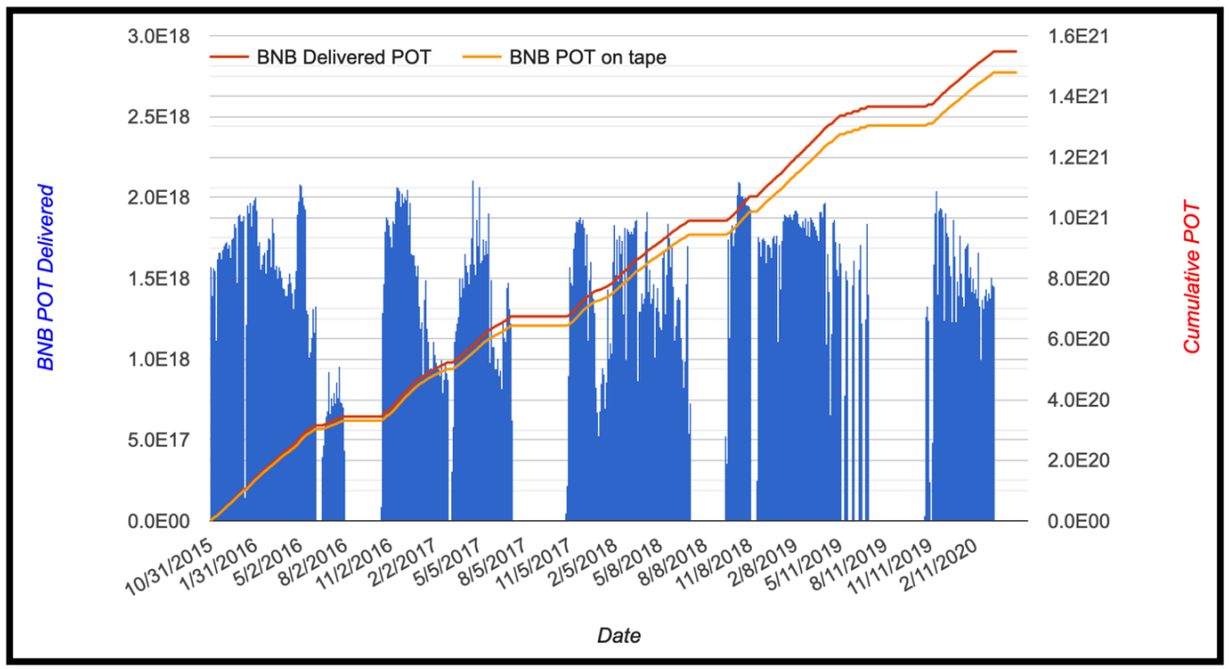
10.1103/PhysRevD.103.052002

Main backgrounds:

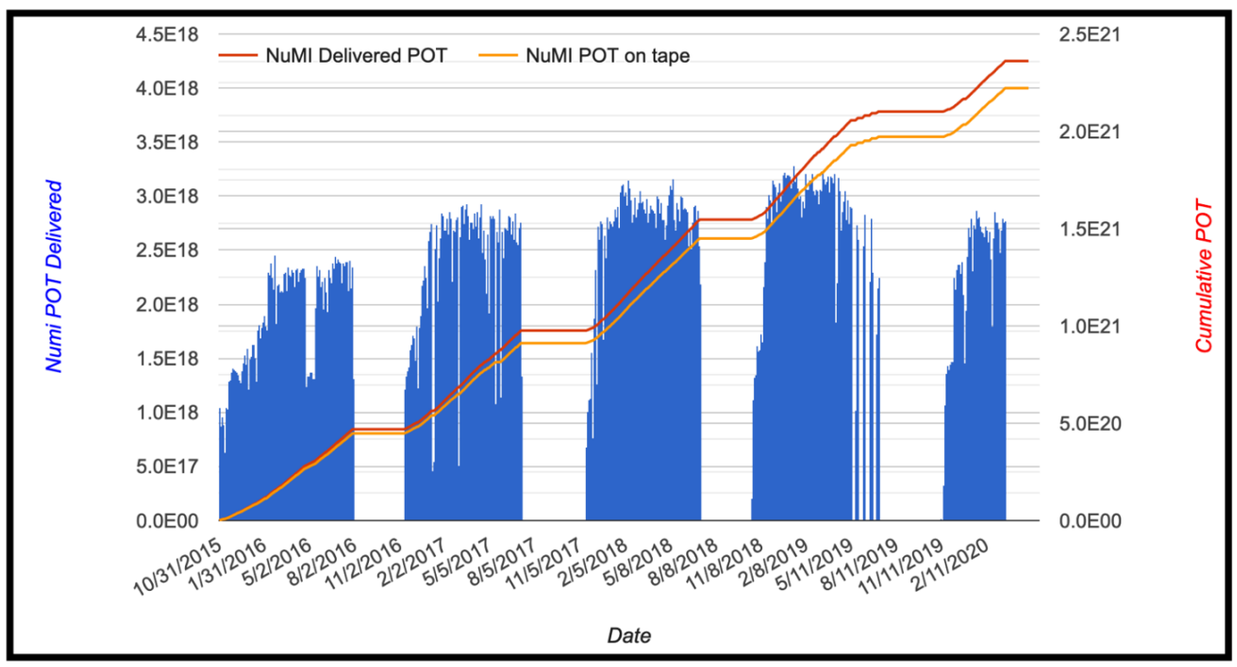


Data taking

- BNB Full Dataset: 1.1 X 10^{21} POT



- NuMI Full Dataset: 2.37 X 10^{21} POT



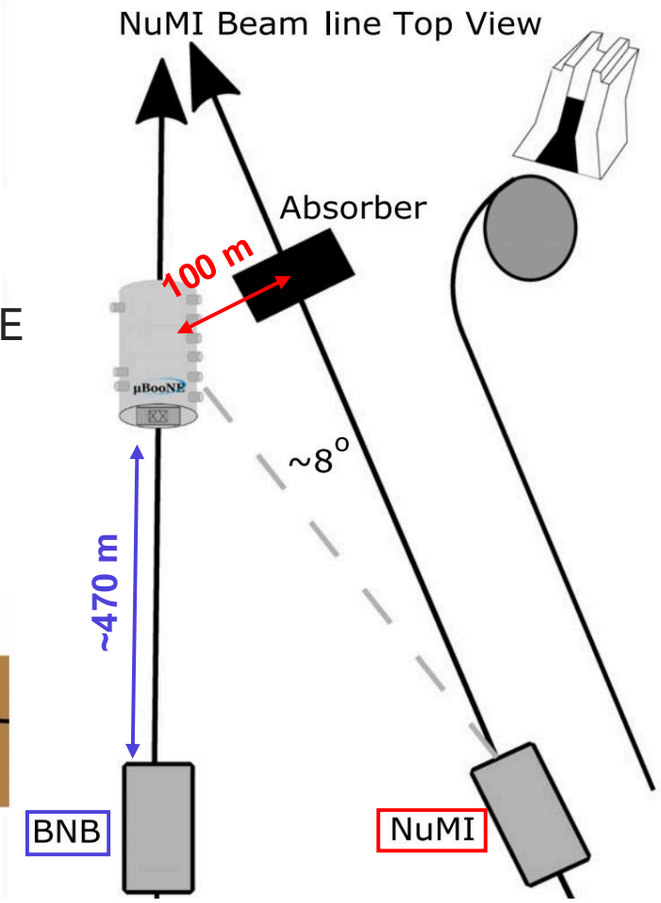
- MicroBooNE collected BNB and NuMI data between 2015 and 2021 split into five runs

Neutrino Beamlines at Fermilab

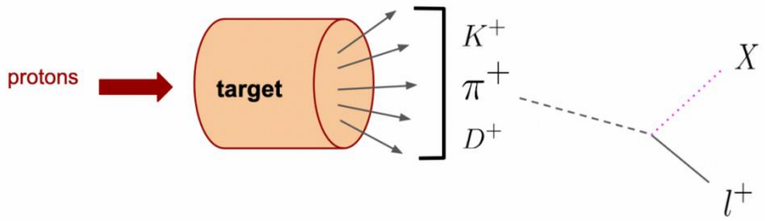
Beamlines

- Large flux of **charged/neutral mesons** from high intensity proton beams
- New particles can be produced from meson decays
- Proximity to the **NuMI absorber**

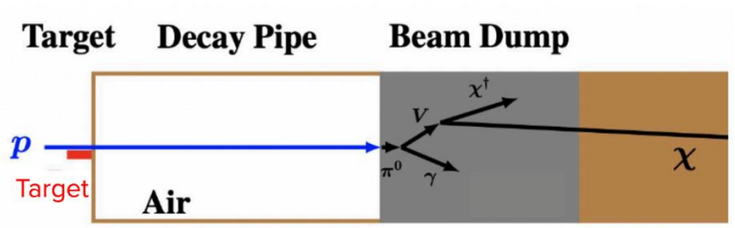
→ Particles survive long enough to reach MicroBooNE

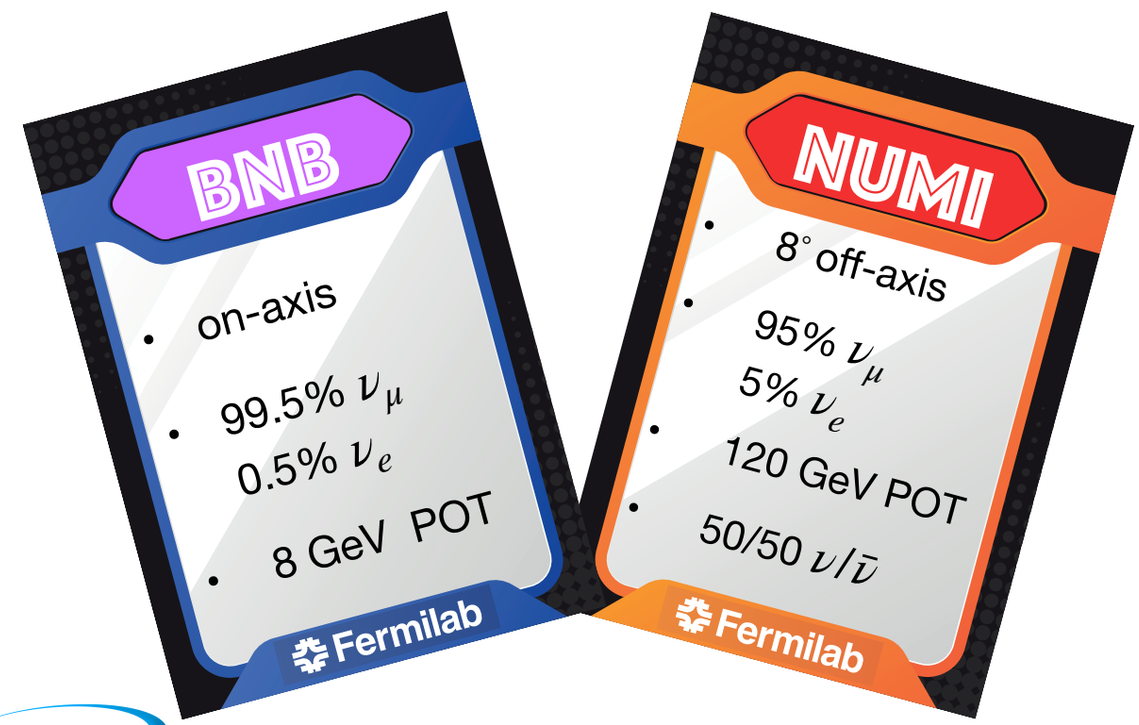


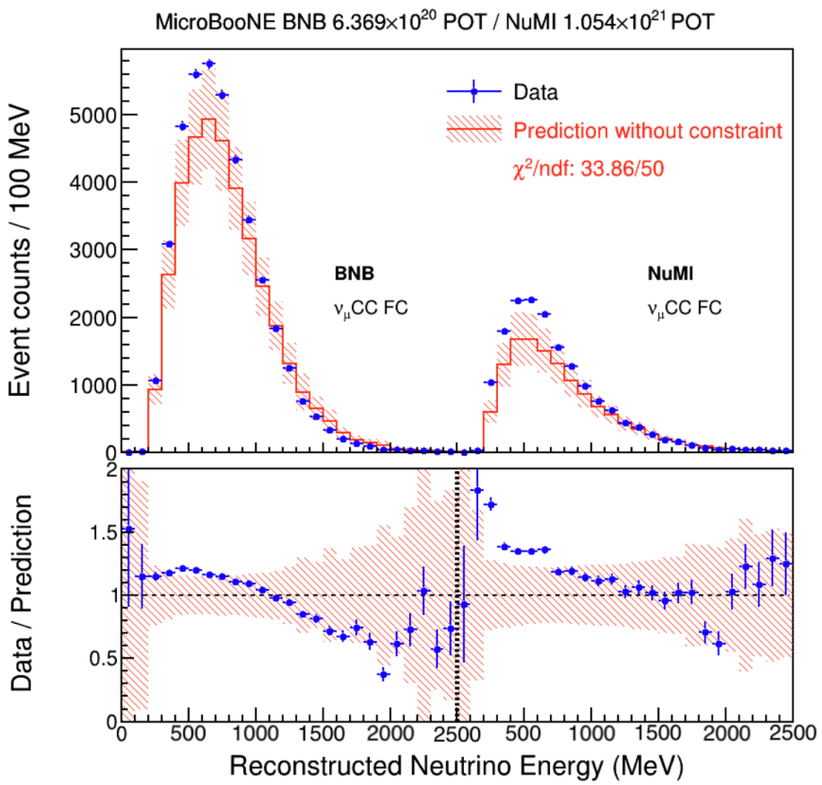
Meson decay in flight



Beam dump



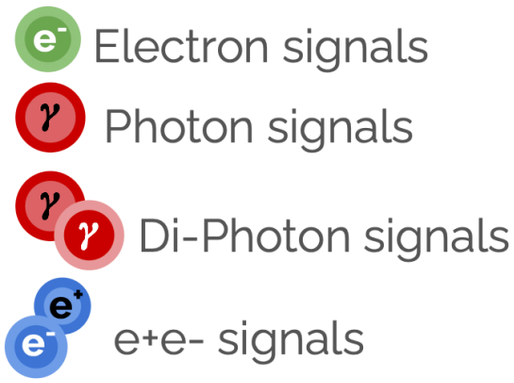




BSM Possibilities for the LEE

Category	Model	Signature	Anomalies			References
			LSND	MiniBooNE	Sources	
Flavor transitions Secs. 3.1.1-3.1.3, 3.1.5	(3+1) oscillations	oscillations	✓	✓	✓	Reviews and global fits [93, 103, 105, 106]
	(3+1) w/ invisible sterile decay	oscillations w/ ν_4 in decay	✓	✓	✓	[151, 155]
	(3+1) w/ sterile decay	$\nu_\mu \to$	✓	✓	✓	[159–162, 270]
Matter effects Secs. 3.1.4, 3.1.7	(3+1) w/ anomalous matter effects	$\nu_\mu \to \nu_e$ via matter effects	✓	✓	✗	[143, 147, 271–273]
	(3+1) w/ quasi-sterile neutrinos	$\nu_\mu \to \nu_e$ w/ resonant ν_s matter effects	✓	✓	✓	[148]
Flavor violation Sec. 3.1.6	Lepton-flavor-violating μ decays	$\mu \to e \nu_\alpha \overline{\nu_e}$	✓	✗	✗	[174, 175, 274]
	neutrino-flavor-changing bremsstrahlung	$\nu_\mu A \to$	✓	✓	✗	[275]
Decays in flight Sec. 3.2.3	Transition magnetic mom., heavy ν decay	$N \to \nu\gamma$	✗	✓	✗	[207]
	Dark sector heavy neutrino decay	$N \to \nu(X \to e^- e^+)$	✗	✓	✗	[208]
Neutrino Scattering Secs. 3.2.1, 3.2.2	neutrino-induced upscattering	$\nu N \to \nu e$ $N \to \nu\gamma$	✓	✓	✗	[205, 206, 209–216]
	neutrino dipole upscattering	$\nu \to$	✓	✓	✗	[40, 185, 187, 188, 190, 193, 233, 276]
Dark Matter Scattering Sec. 3.2.4	dark particle-induced upscattering	$\chi e \to$	✗	✓	✗	[217]
	dark particle-induced inverse Primakoff		✓	✓	✗	[217]

- The MiniBooNE LEE has often been interpreted as an excess of e^- events, potentially from sterile neutrino short baseline $\nu_\mu \to \nu_e$ oscillations
- But there are lots of well motivated beyond-standard-model possibilities for γ and e^+e^- events as well



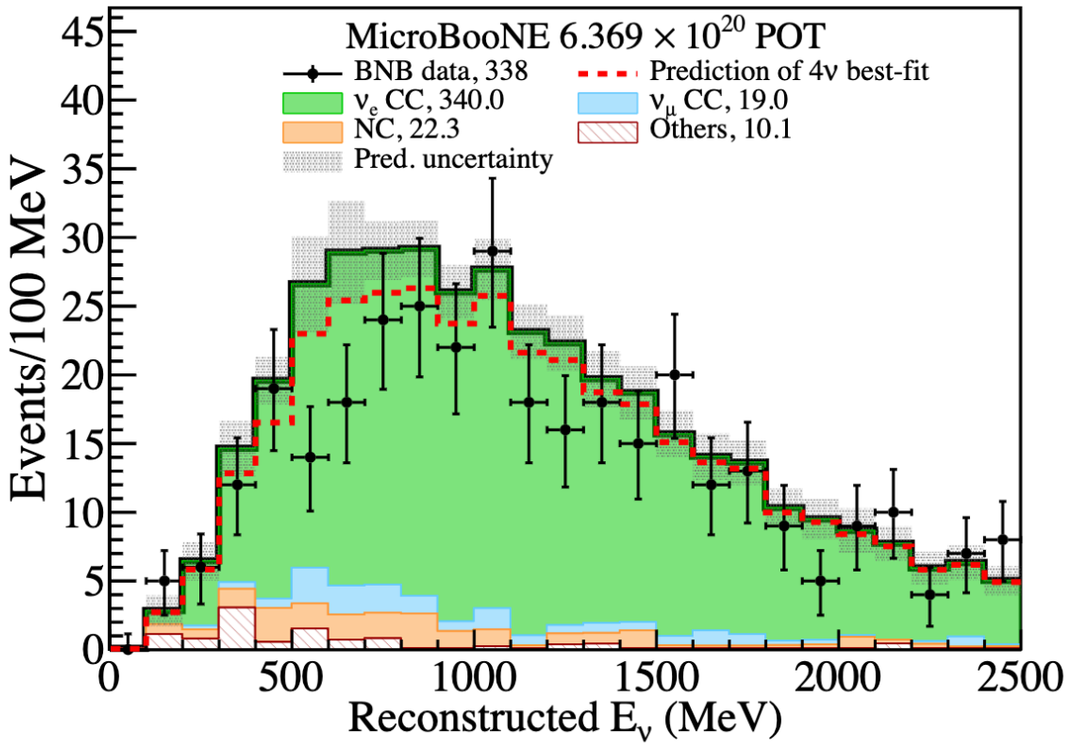
Snowmass White Paper on Light Sterile Neutrinos
J. Phys. G: Nucl. Part. Phys. 51 120501 (2024)

Title Text

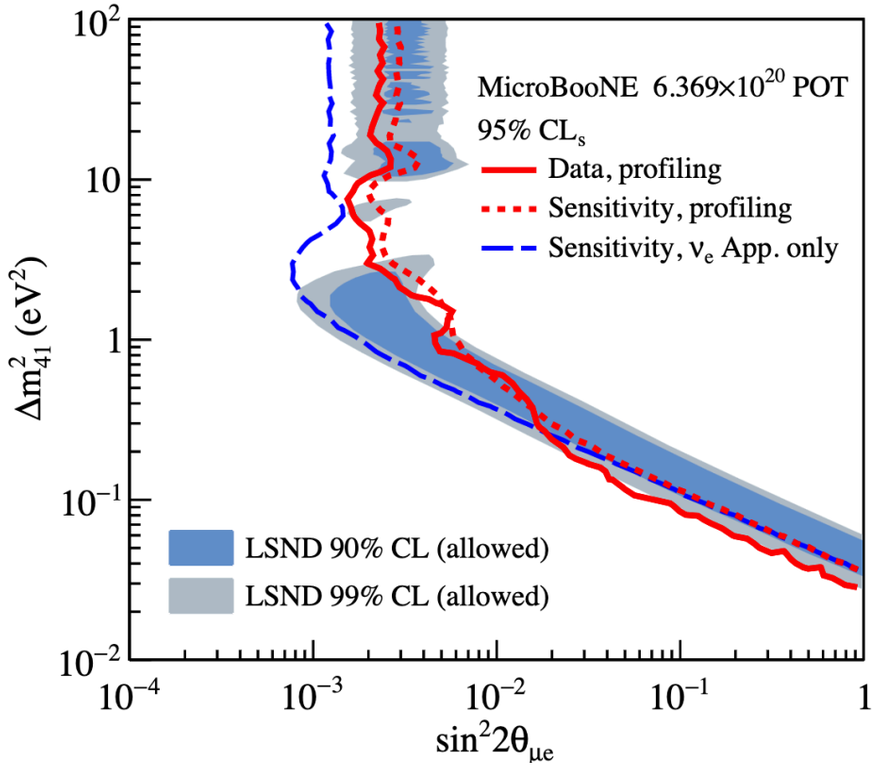
MicroBooNE's '22 analyis: 3+1 with BNB

- Reinterpret LEE ν_e analysis under 3+1 sterile neutrino oscillation framework

inclusive ν_e analysis. performed with BNB data.



Sensitivity *not* statistics limited!



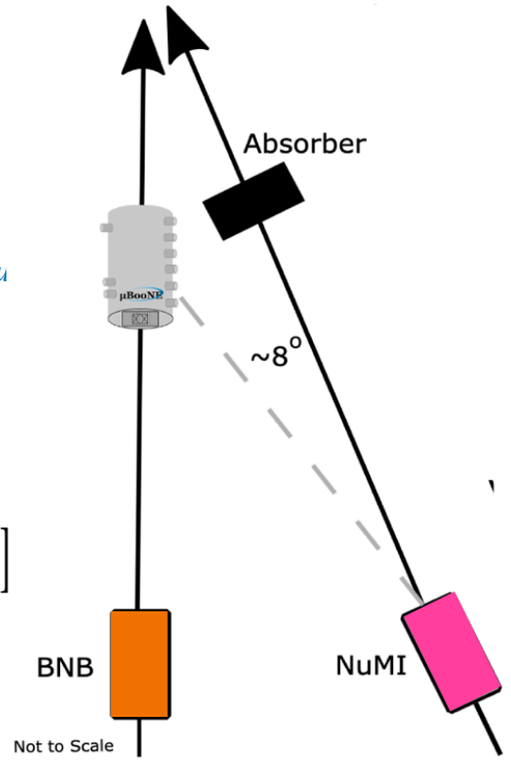
PRL 130 (2023) 1, 01180

eV-scale sterile neutrino searches

BNB + NuMI

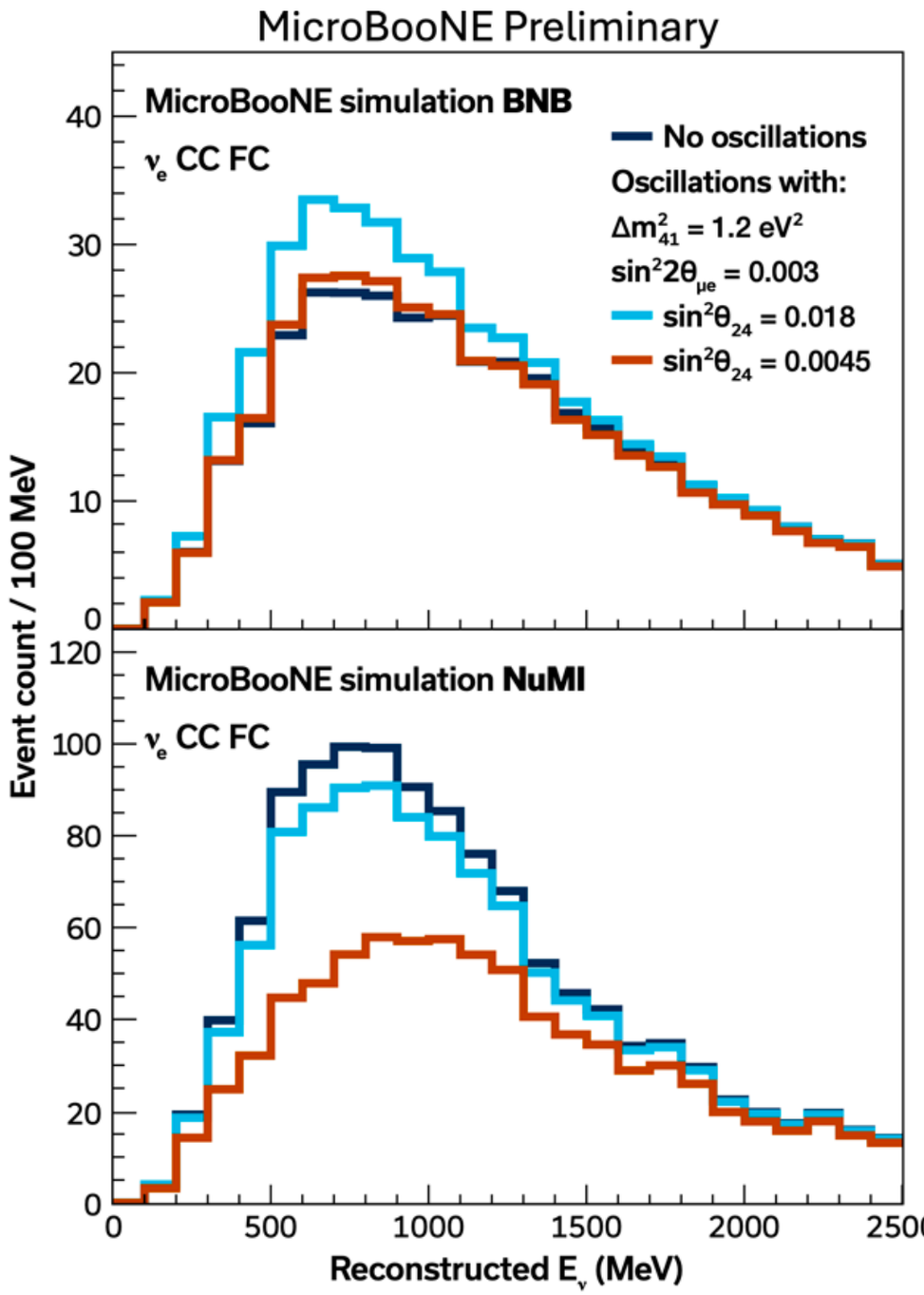
- 3+1 degeneracy:
  $\nu_e$appearance cancels out $\nu_e$disappearance
- Degeneracy depends on intrinsic rate of ν_e vs. ν_μ
  For BNB $\frac{N_{\nu_\mu}}{N_{\nu_e}} \sim 200$

$$N_{\nu_e} = N_{\text{intrinsic } \nu_e} \cdot P_{\nu_e \to \nu_e} + N_{\text{intrinsic } \nu_\mu} \cdot P_{\nu_\mu \to \nu_e}$$
$$= N_{\text{intrinsic } \nu_e} \cdot \left[1 + (R_{\nu_\mu/\nu_e} \cdot \sin^2\theta_{24} - 1) \cdot \sin^2 2\theta_{14} \cdot \sin^2 \Delta_{41}\right]$$



- Impact on NuMI ν_e spectrum is large due to the different $\frac{N_{\nu_\mu}}{N_{\nu_e}} \sim 25$
- NuMI beam allows us to break the degeneracy

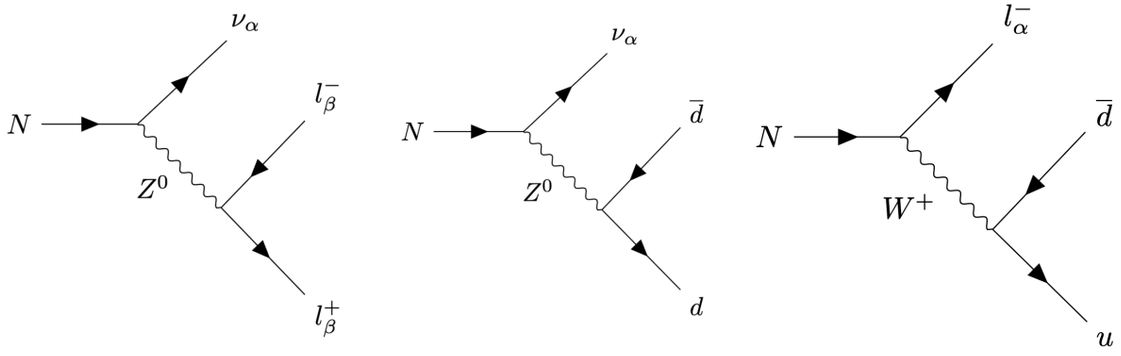
Updated NuMI flux at MicroBooNE
MICROBOONE-NOTE-1129-PUB

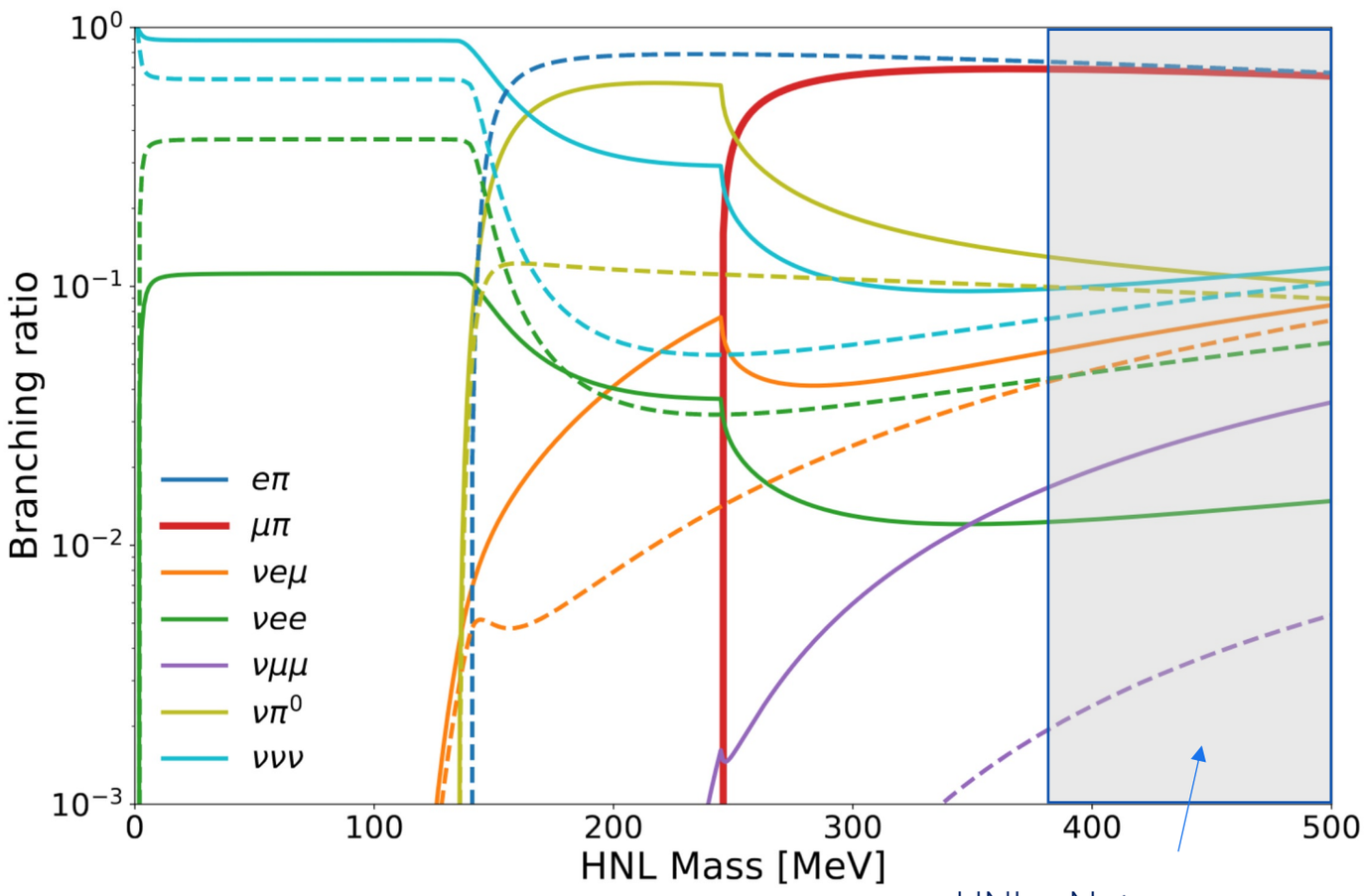


Heavy Neutral Leptons (HNLs)

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

1. e^+e^- , $m_N < m_{\pi 0}$
2. π_0 , $m_{\pi 0} < m_N < m_{\pi\mu}$
3. $\mu\pi$, $m_N > m_{\pi\mu}$



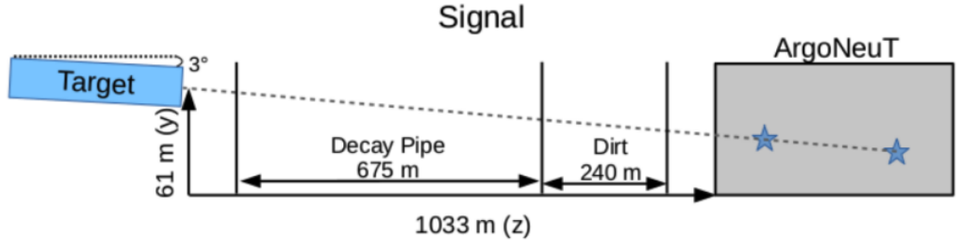


HNLs Not produced here if $|U_{e4}|=0$

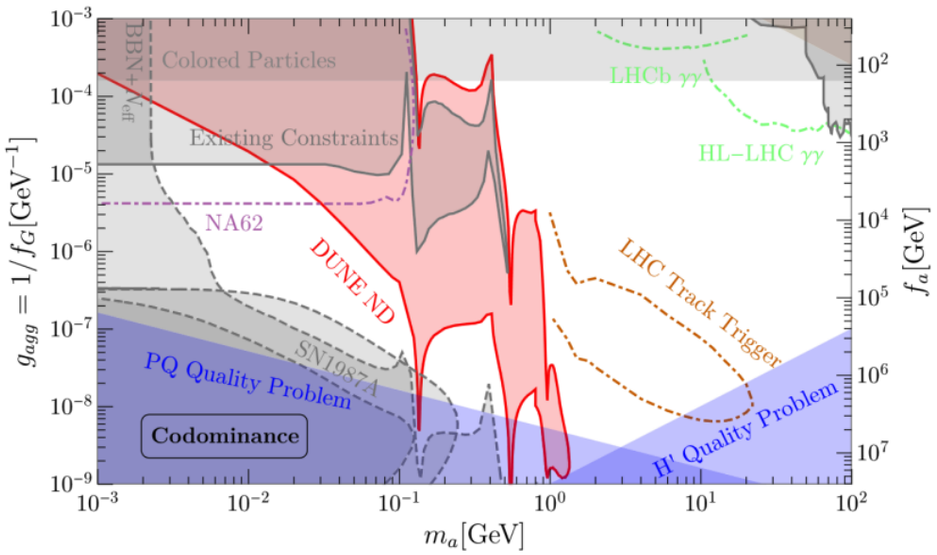
Ongoing BSM searches

Millicharged particles

- Particles with a **fraction of electric charge**
- **Scatter off atomic electrons** and cause “blips” of ionisation in LAr
- Leverages MeV-scale reconstruction



Heavy QCD Axions



- Axions produced via **mixing with neutral mesons**
- Decay to **di-photon pairs** in MicroBooNE

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note: also includes Masters, post-bacc

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MicroBooNE papers

82 papers