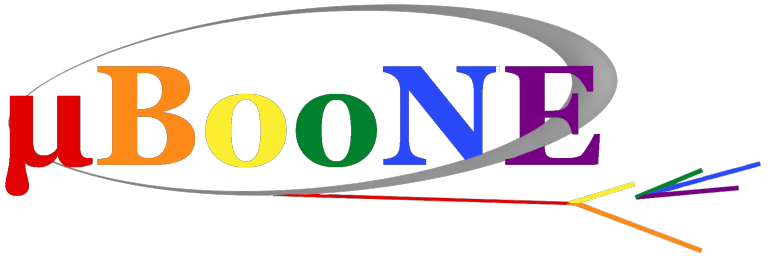
IMPERIAL



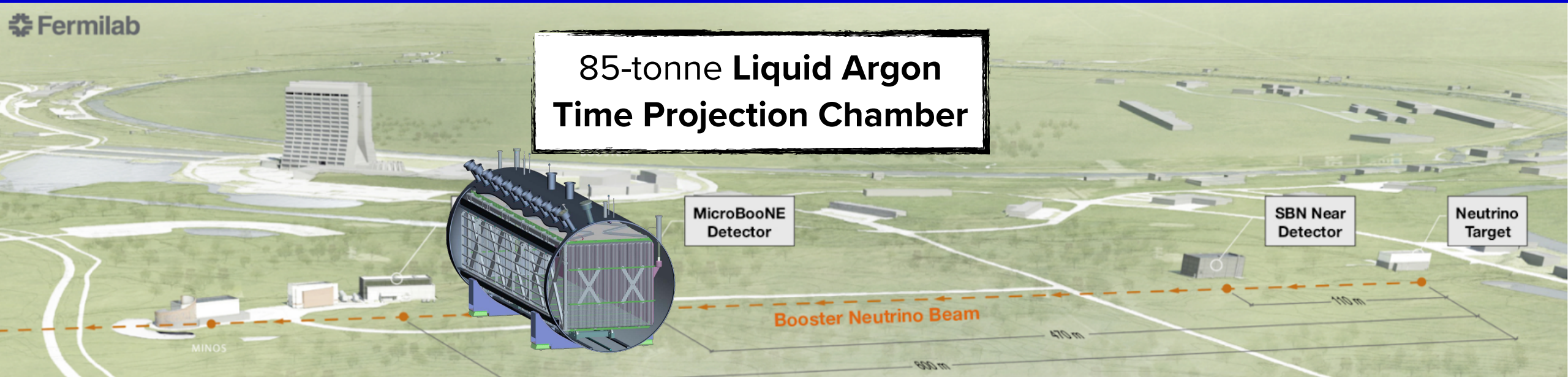
Searches for physics beyond the Standard Model with the MicroBooNE Experiment

Anyssa Navrer-Agasson,

On behalf of the MicroBooNE Collaboration

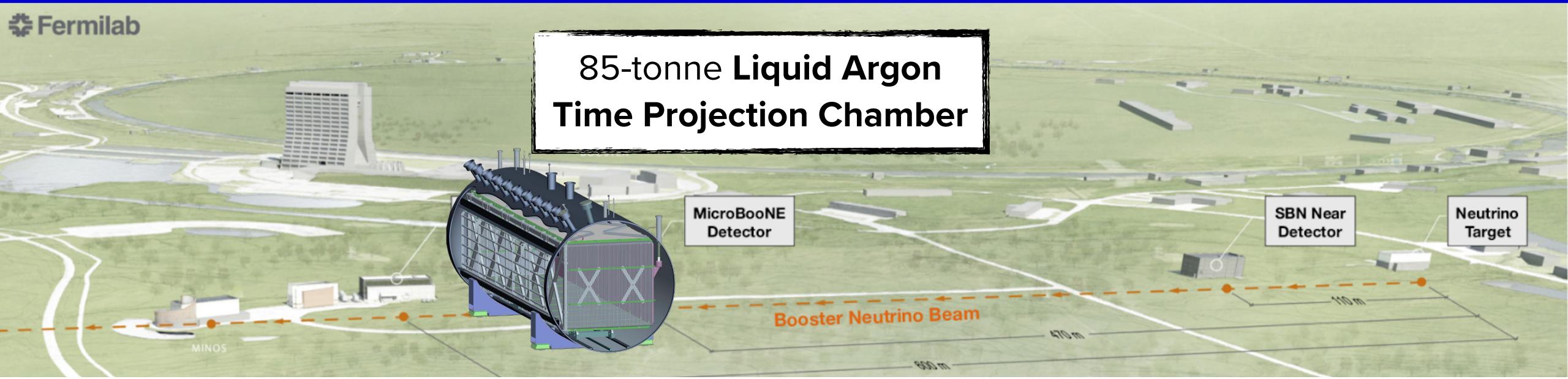
EPS-HEP - 9th July 2025

The MicroBooNE Detector



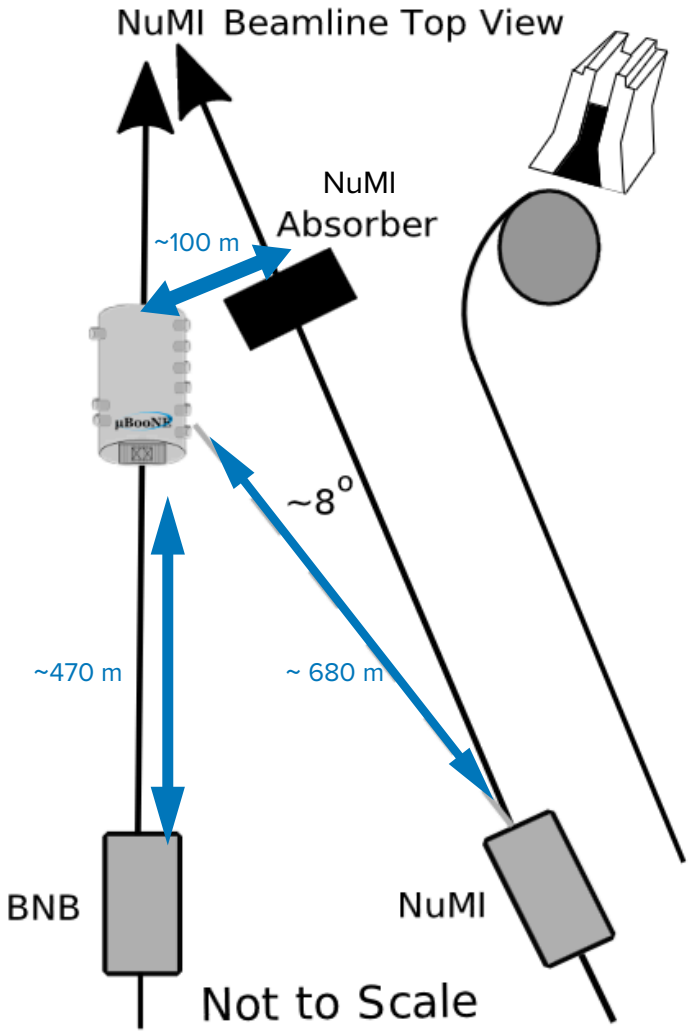
- Neutrino cross-section measurements
- Detector physics, R&D, tool development
- Beyond Standard Model physics ⟶ **This talk!**

The MicroBooNE Detector



- Neutrino cross-section measurements → **Holly Parkinson's talk**
- Detector physics, R&D, tool development
- Beyond Standard Model physics ⟶ **This talk!**

BSM Physics @ MicroBooNE: beamlines



MicroBooNE observes flux from two neutrino beams

Booster Neutrino Beam (BNB)

- **8 GeV** protons
- Target **~470 m** from MicroBooNE
- **On-axis**

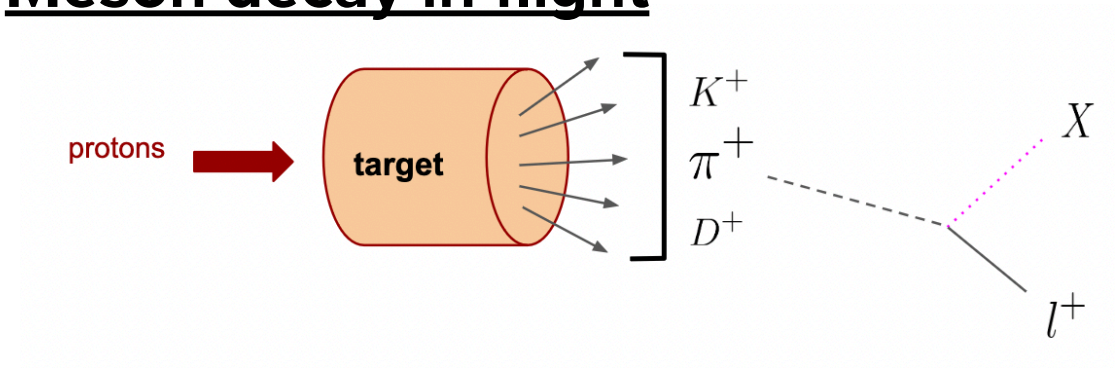
Neutrino at the Main Injector (NuMI)

- **120 GeV** protons
- **~680 m** away from target
- **~8° off-axis**
- **Absorber ~100 m** from MicroBooNE

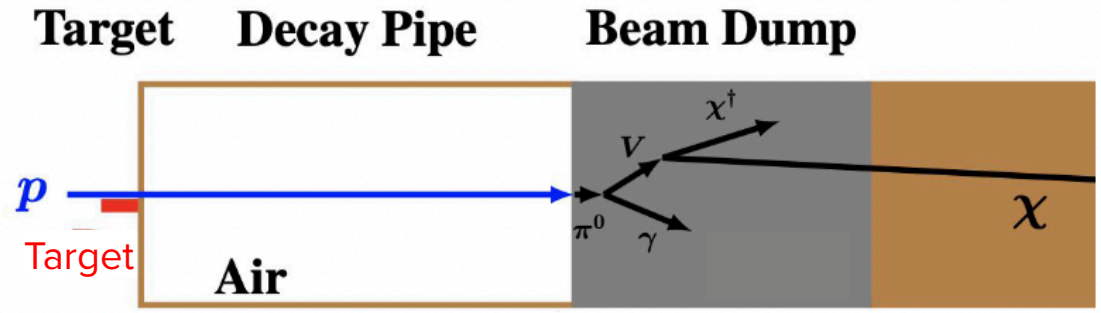
BSM Physics @ MicroBooNE: beamlines

- 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

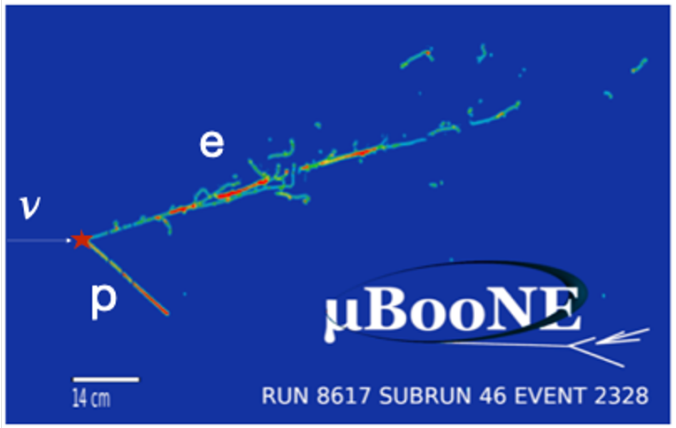
Meson decay in flight



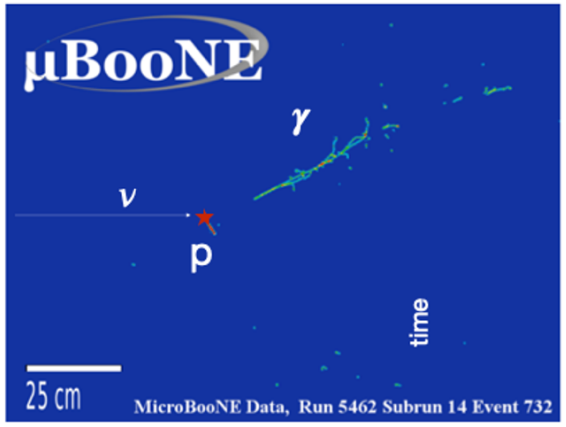
Beam dump



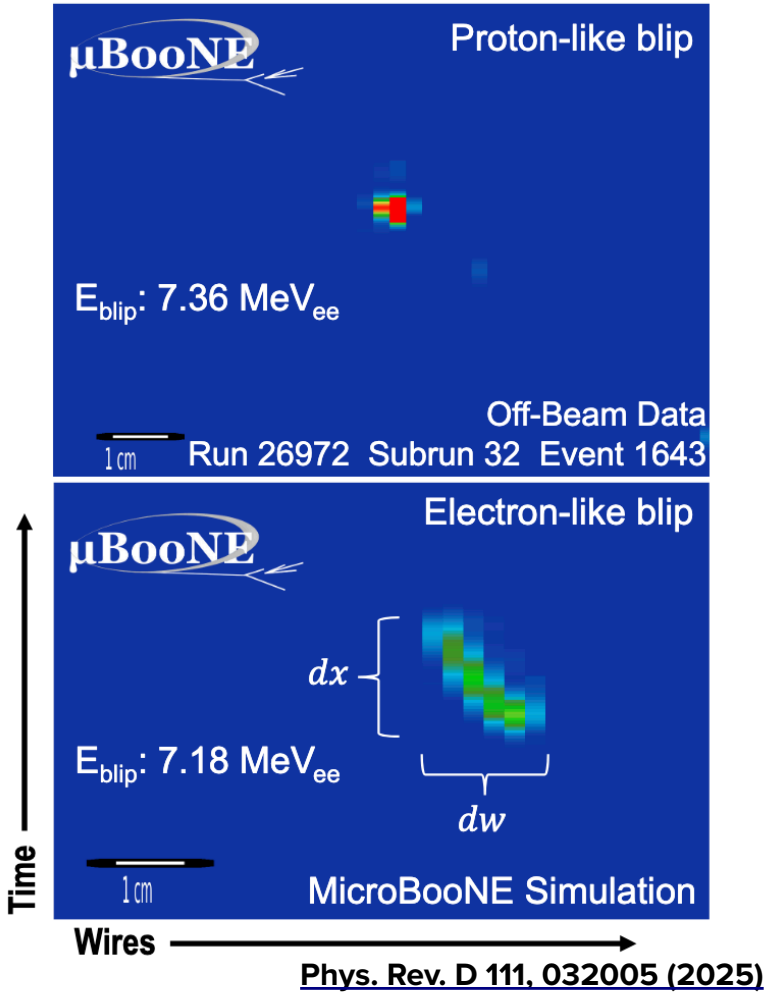
BSM Physics @ MicroBooNE: LArTPC



e^-/γ separation

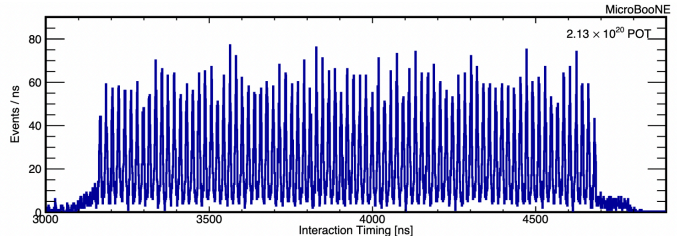


MeV-scale reconstruction

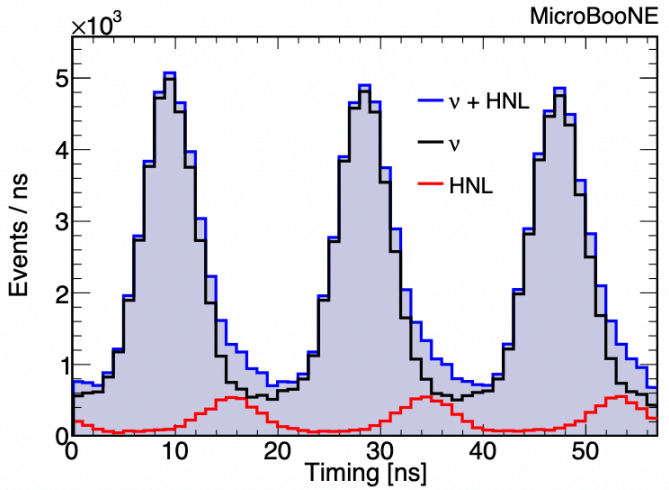


Phys. Rev. D 111, 032005 (2025)

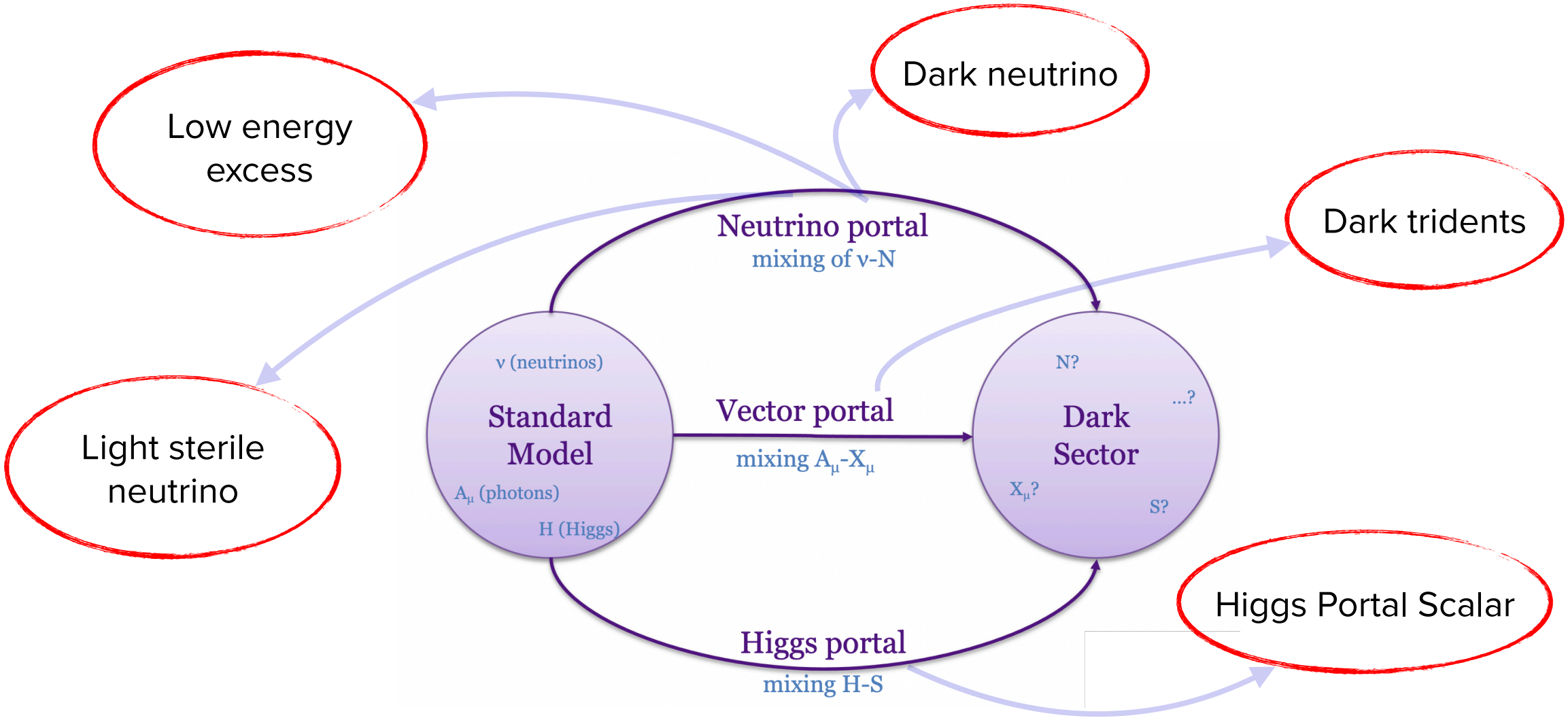
Phys. Rev. D 108, 052010



$\mathcal{O}$(ns) timing resolution



Exploring the dark sector



Exploring the dark sector

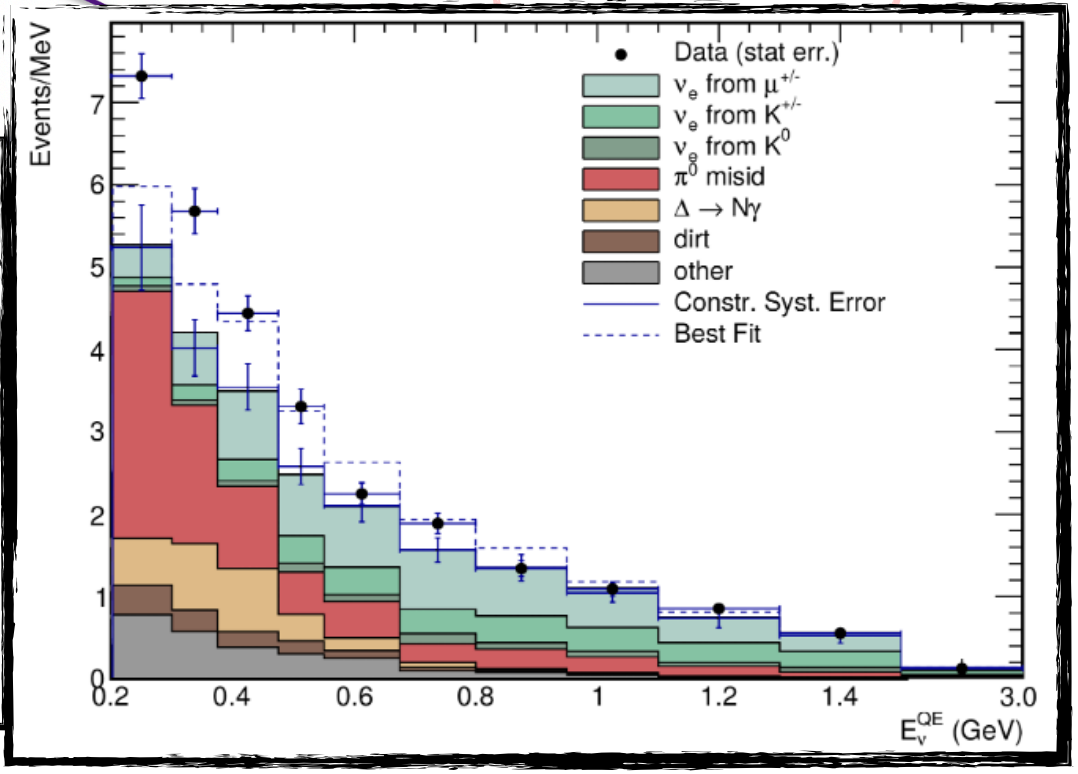
Low energy excess

Dark neutrino

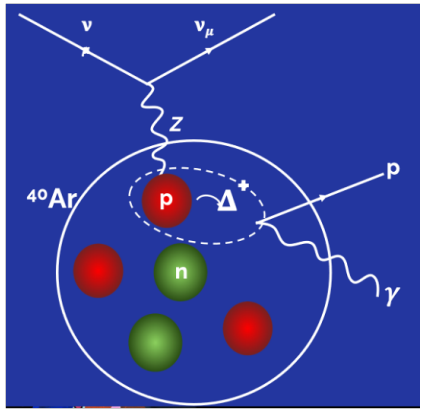
Neutrino portal
mixing of ν-N

Light sterile neutrino

- MiniBooNE observed an excess of low energy electron-like events
- No e^-/γ separation. Is the excess:
  - e^-: new physics with sterile neutrinos?
  - γ: unconstrained NC$\Delta \rightarrow$ Nγ process?
  - Something else??

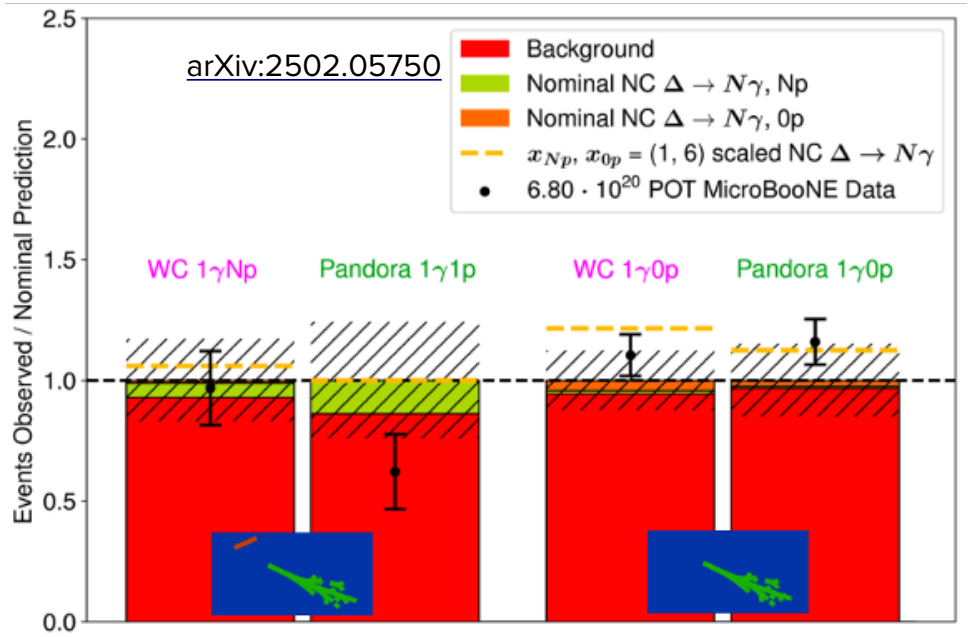


Low energy excess: photon-like



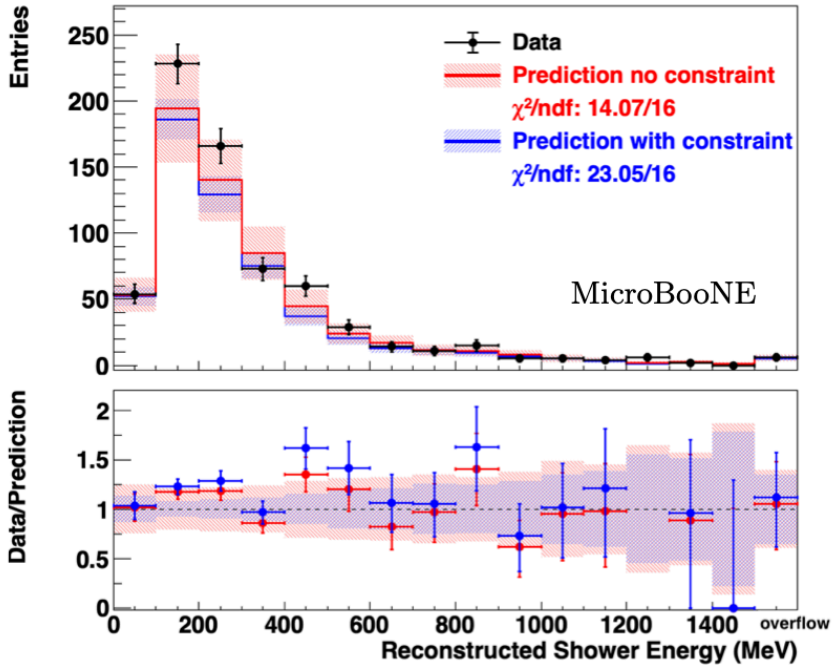
Exclusive

- Rejection of the NC$\Delta \rightarrow N\gamma$ process at 94.4% CL



Inclusive

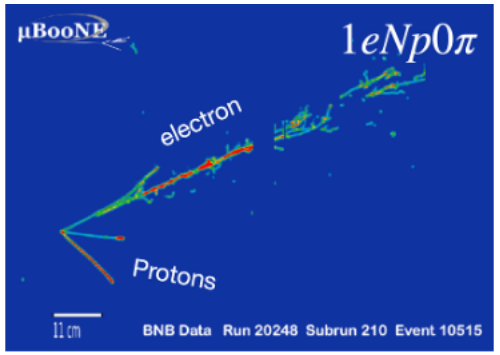
- Overall data/MC agreement across the board
- 2σ excess in the 0 proton final state

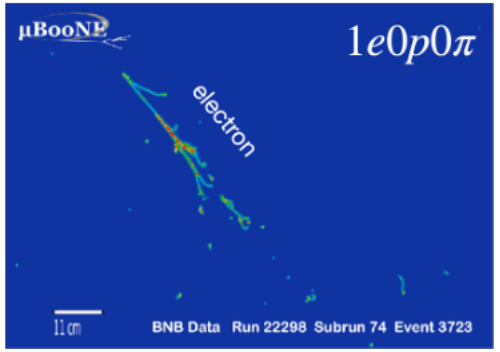


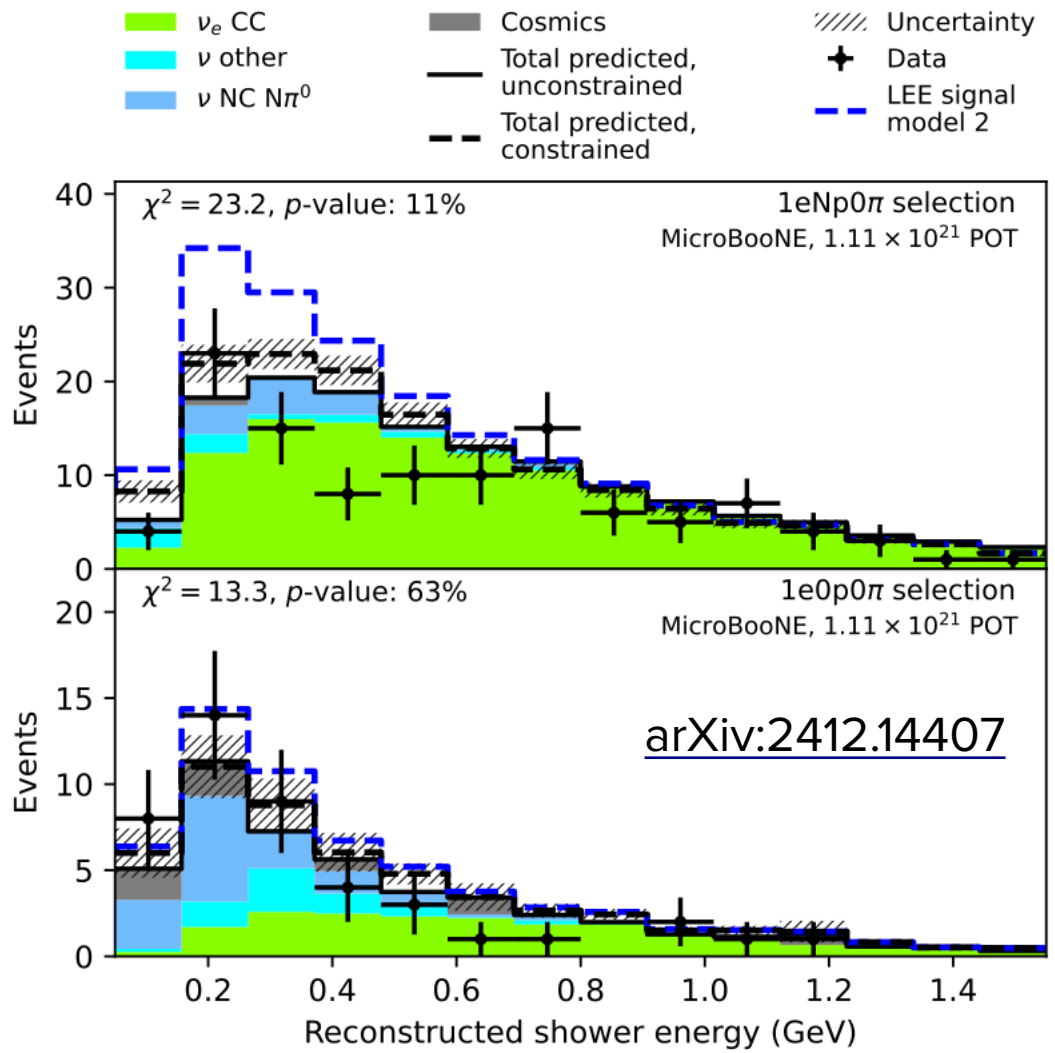
arXiv:2502.06064

Low energy excess: electron-like

- **No sign of excess** in analysed data
- Reject the electron-like hypothesis as explanation for the MiniBooNE result at > 99% CLs
- Accepted for publication in PRL



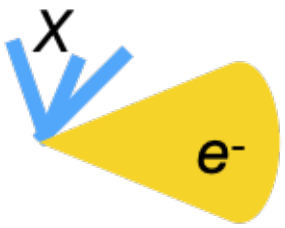




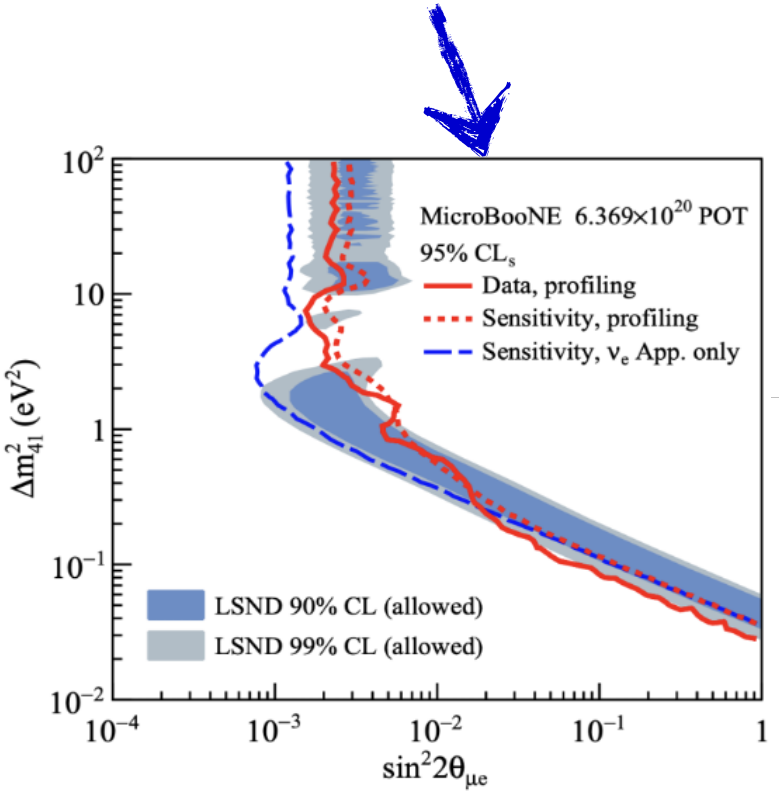
Sterile neutrino search

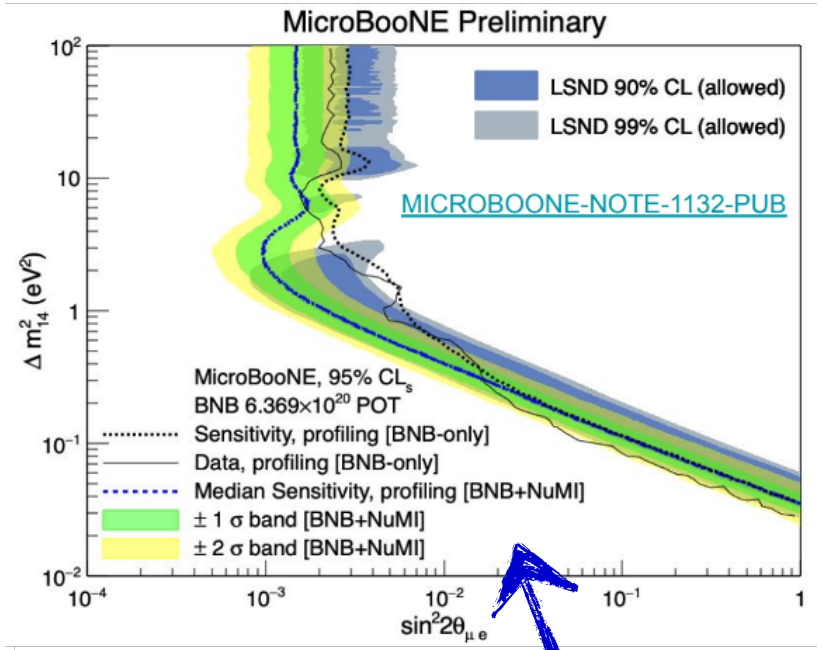
- **Inclusive search** for a light sterile neutrino
- Simplest 3 + 1 model

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \end{pmatrix}$$



Large phase space rejected at 95% CLs

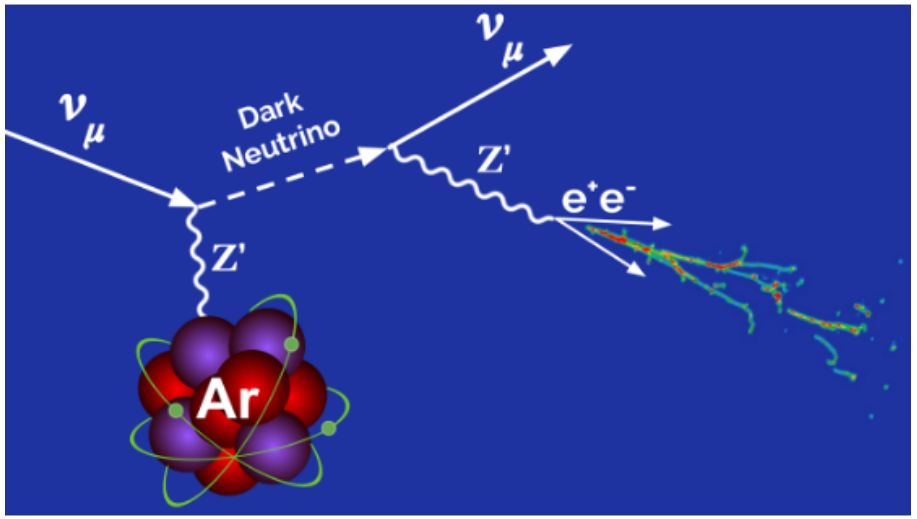


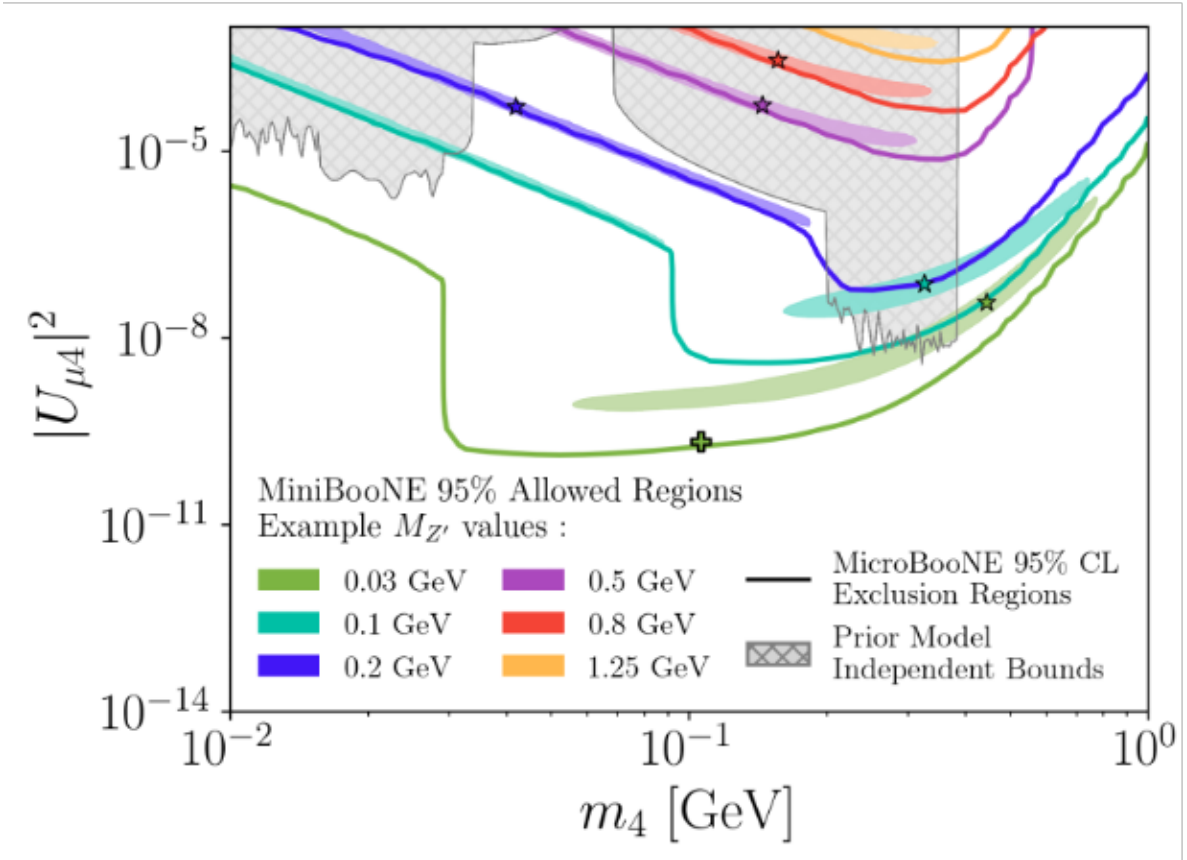


Sensitivity adding NuMI beam to break degeneracy.
Stay tuned for full result!

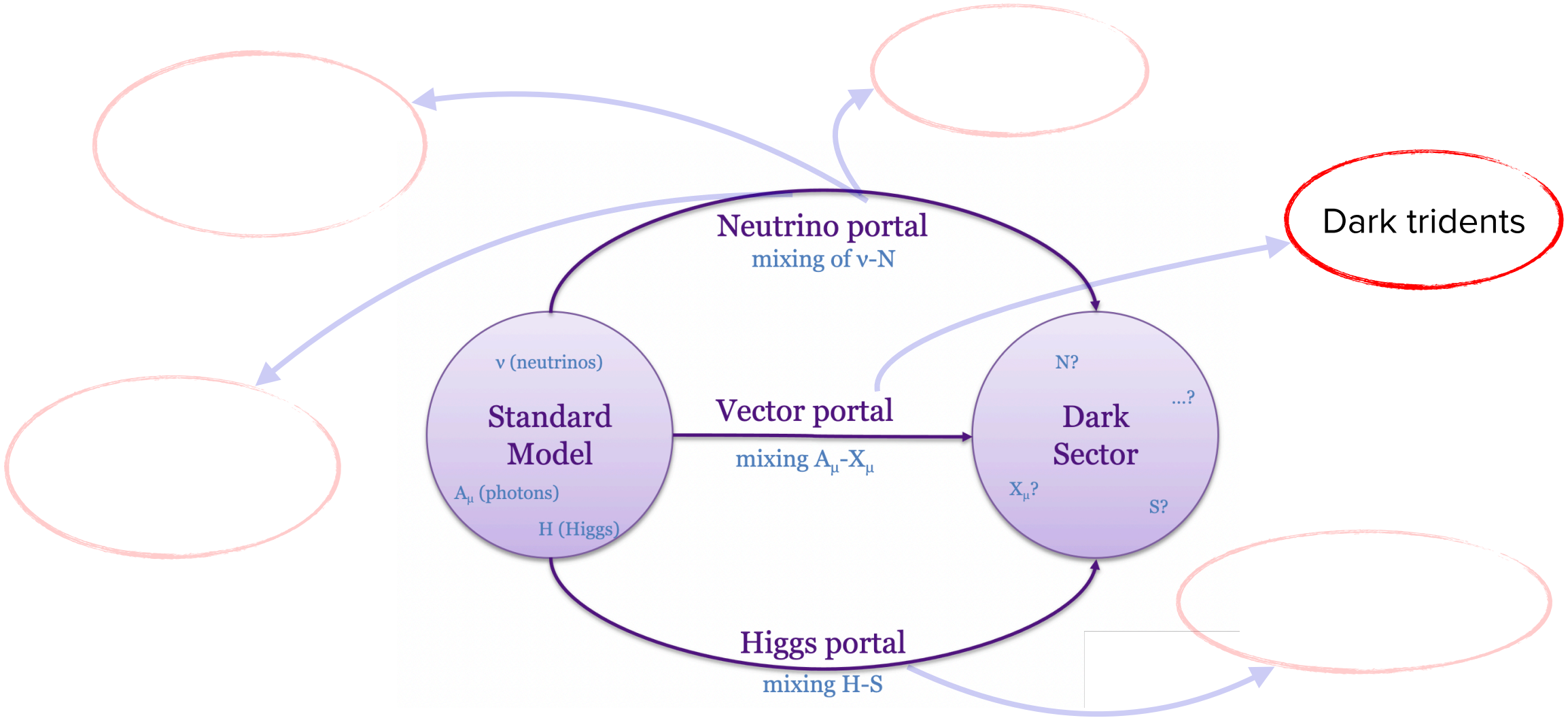
Dark neutrino

- Active neutrinos from the BNB scattering to produce a dark neutrino, ν_4
- Look for the $\nu_4 \rightarrow \nu_\mu(Z' \rightarrow e^+e^-)$ decay
- MiniBooNE excess as this model excluded at $\geq$ 95% CLs



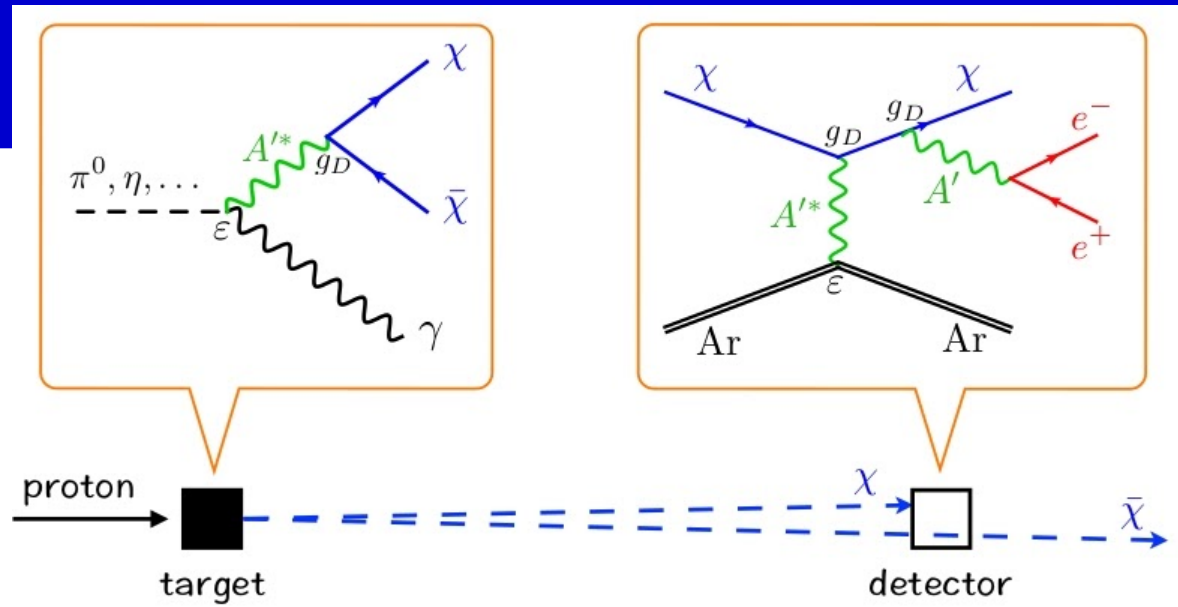


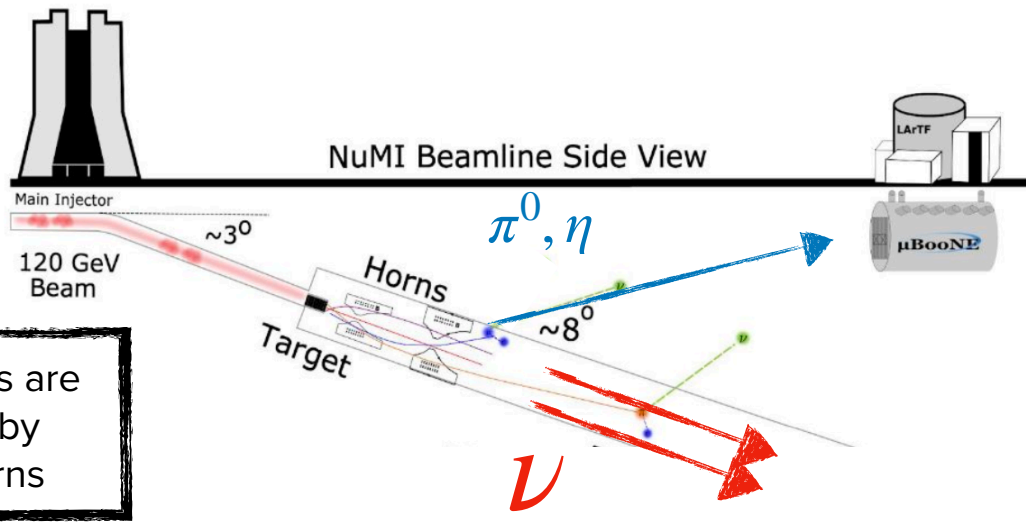
Exploring the dark sector



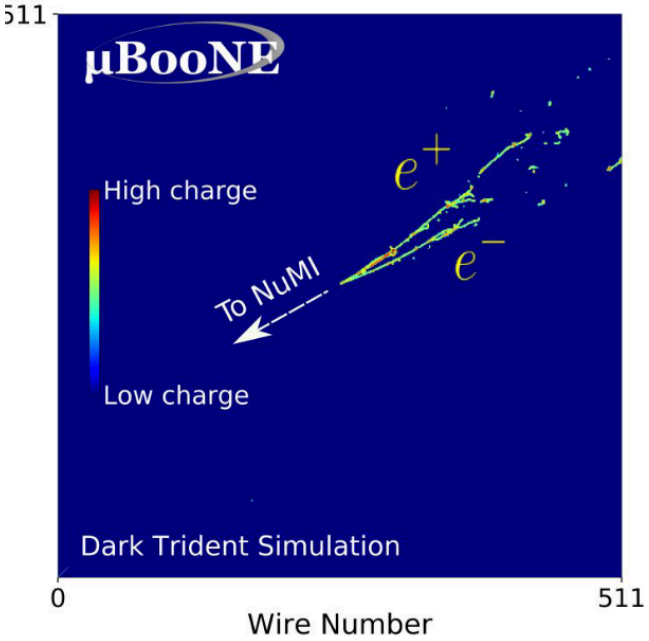
Dark tridents

- **Dark matter** produced in the beam via **dark photon mixing**
- **Scatter off argon nucleus,** accompanied by a dark photon radiation subsequently decaying to e^+e^-
- **NuMI off-axis search**: neutrino background reduction
- First search in a LArTPC!



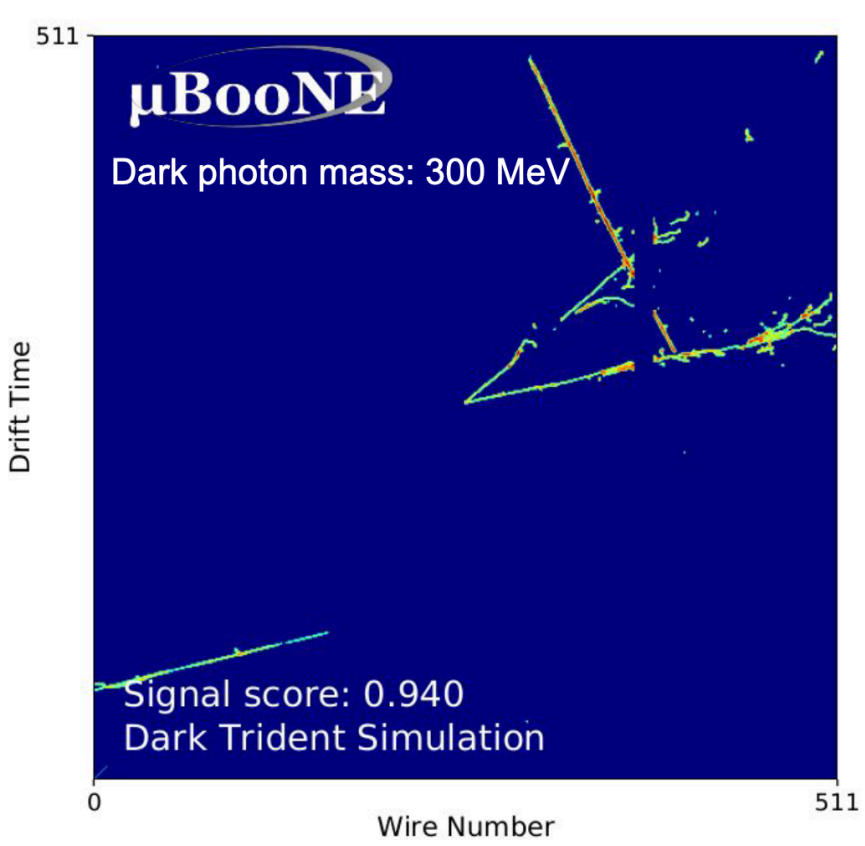


Neutral mesons are not focused by magnetic horns



Dark tridents

Selection done with a **Convolutional Neural Network**



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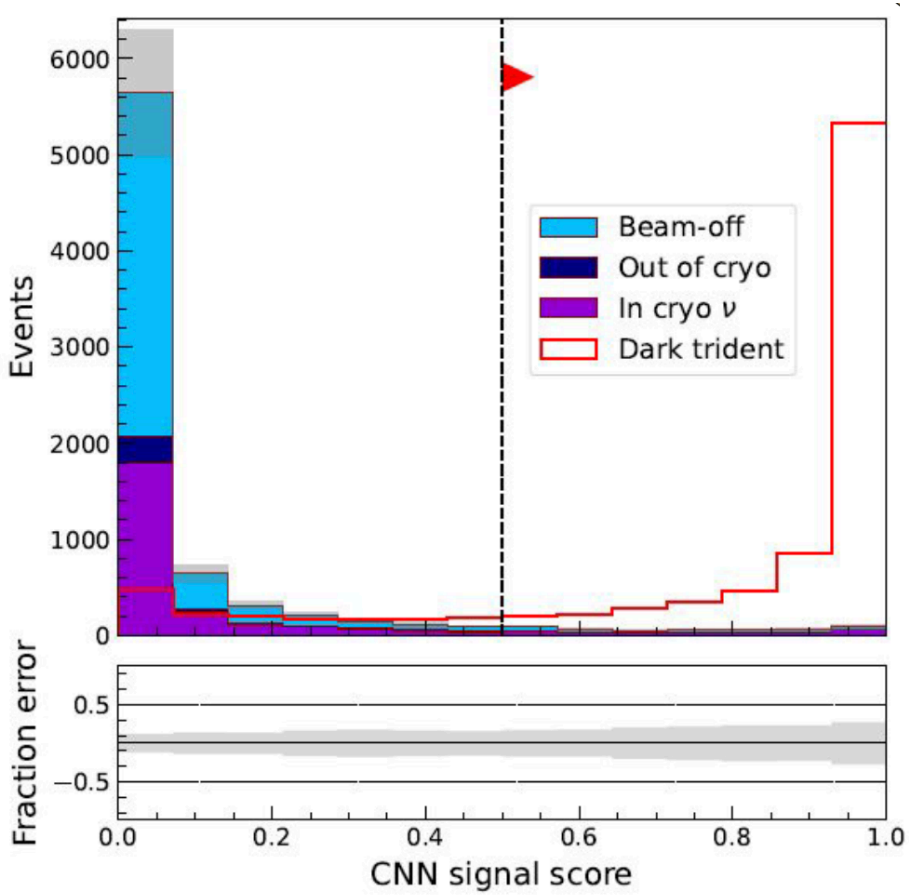

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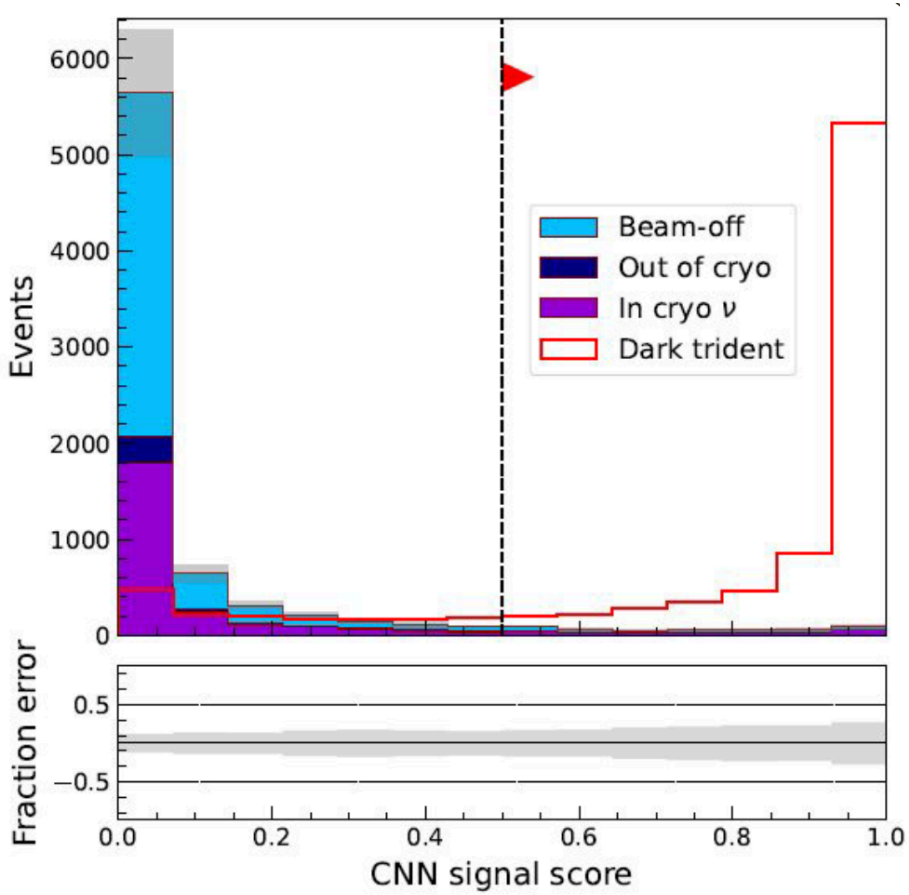
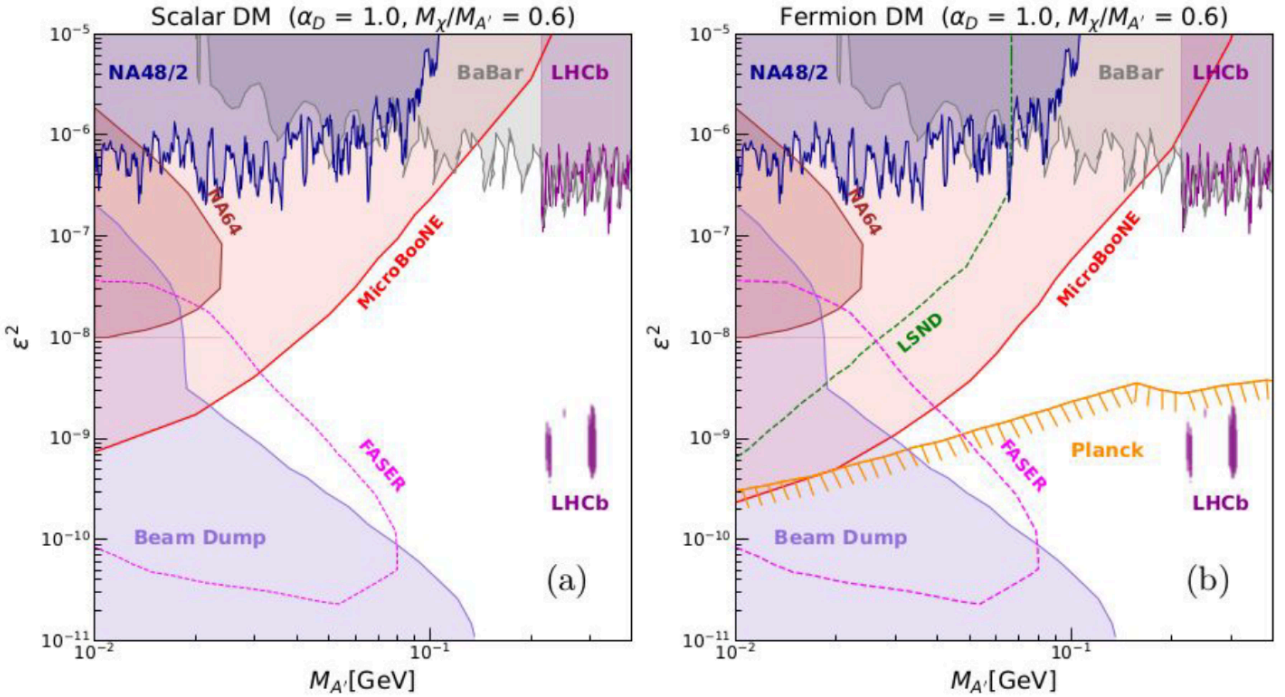
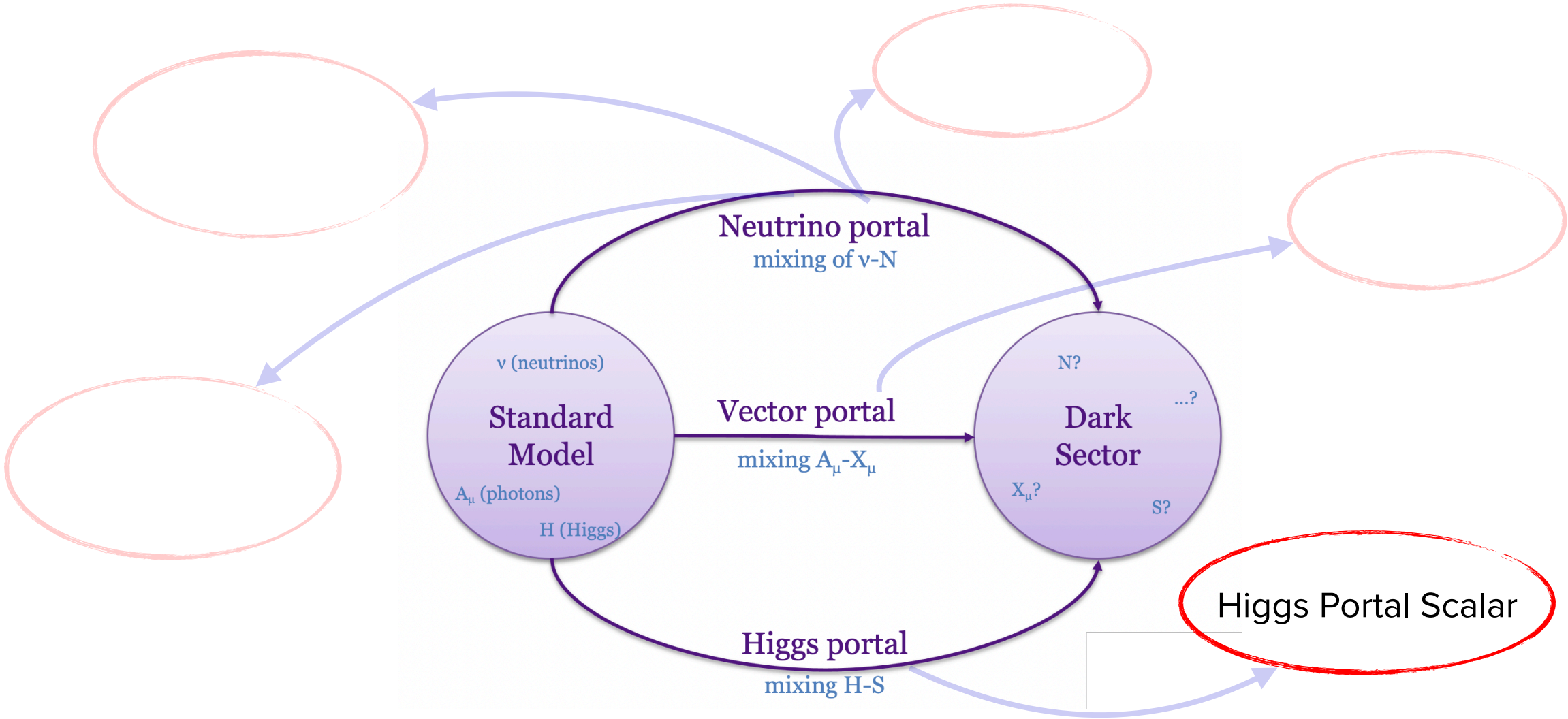


- Consider **both scalar and fermion** dark matter
- Several **couplings and mass ratios**



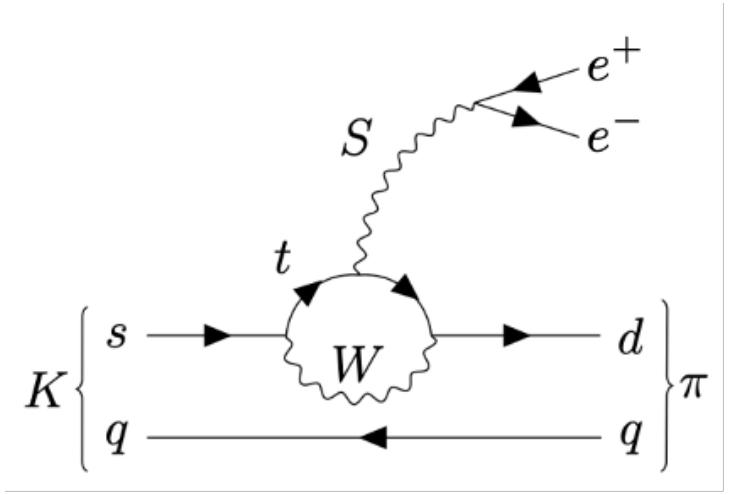
Phys. Rev. Lett. 132, 241801 (2024)

Exploring the dark sector



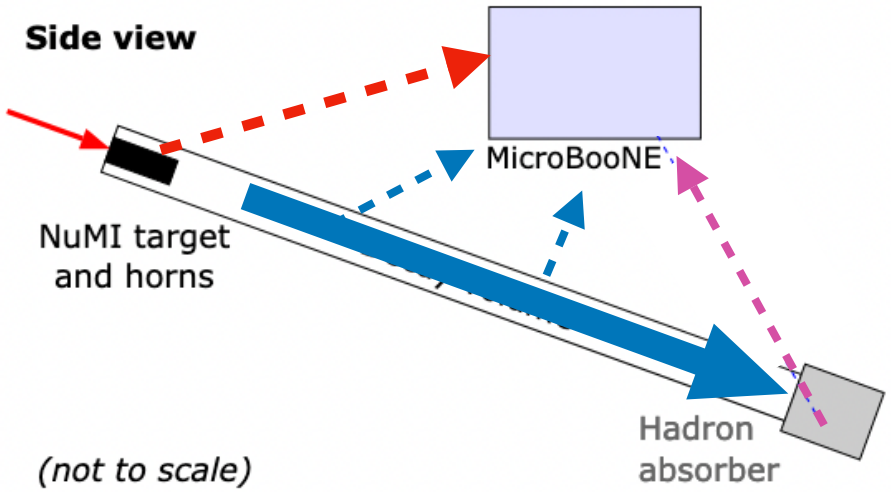
Higgs Portal scalars

- **Neutral scalar singlet S**, mixing angle θ with the Higgs boson
- Production from **kaon decays**
- **Signature:** e^+e^-



Kaons decaying

- at rest **in the NuMI target**
- at rest **in the NuMI absorber**
- **In flight**



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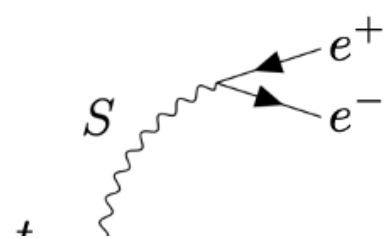
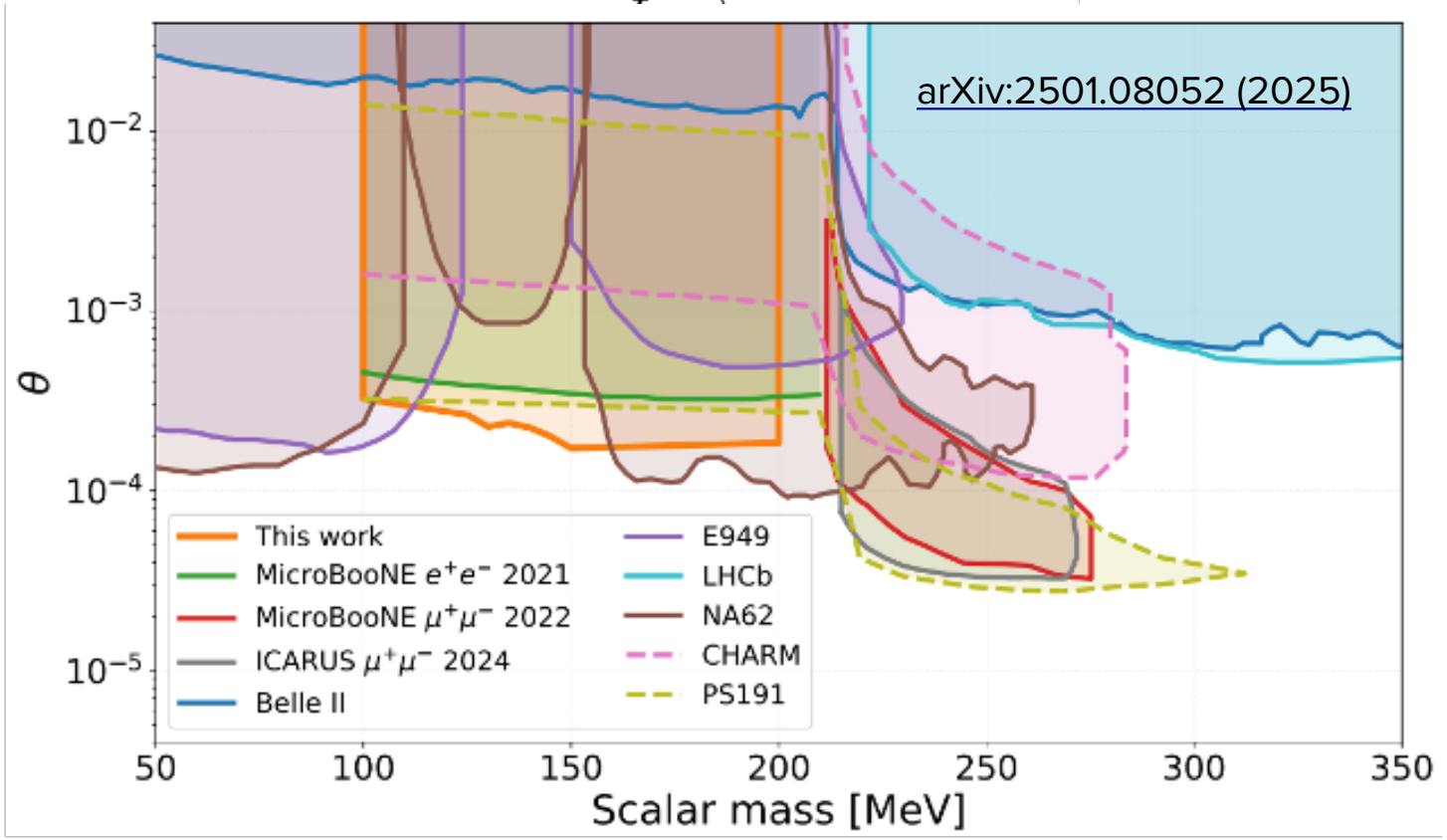
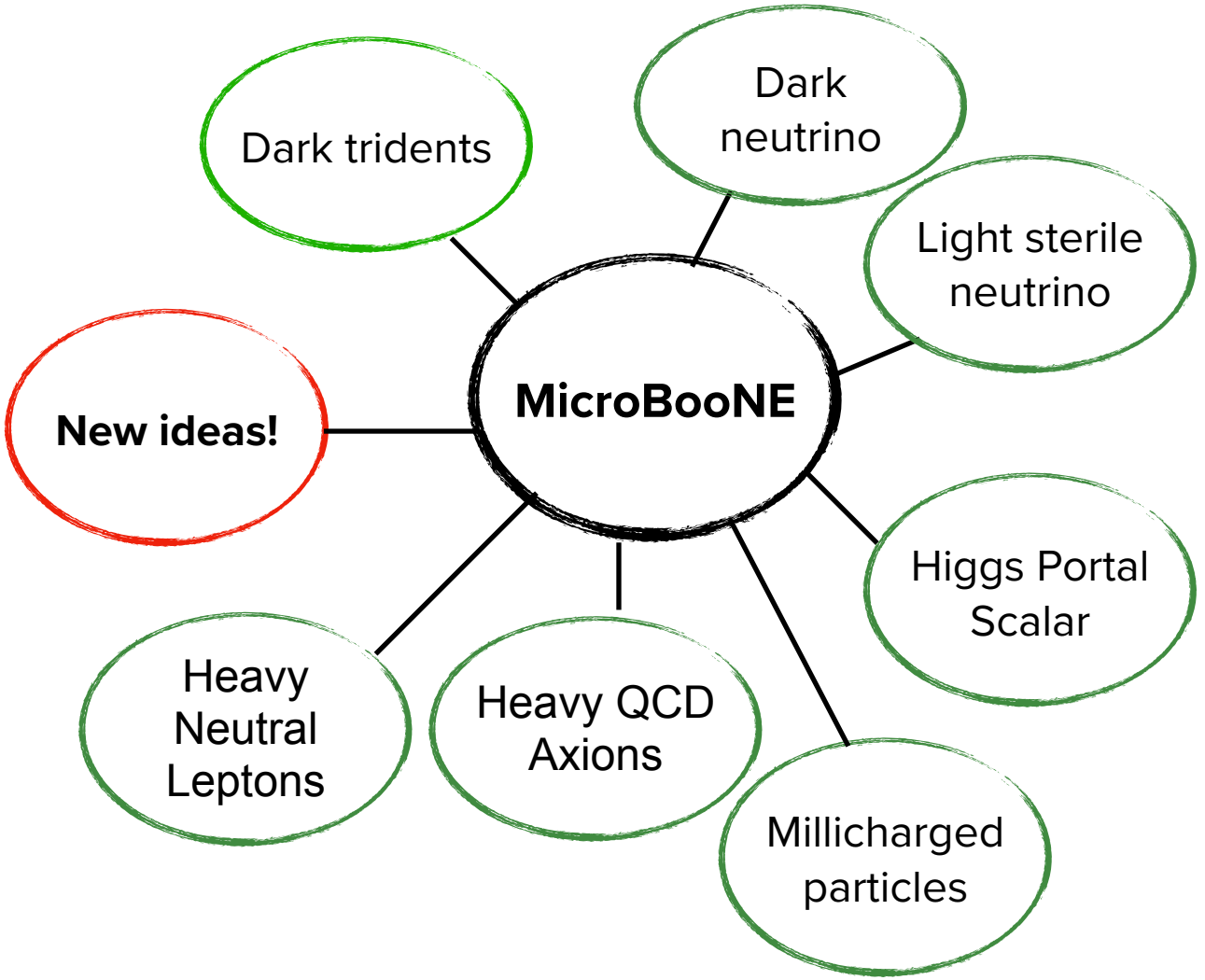




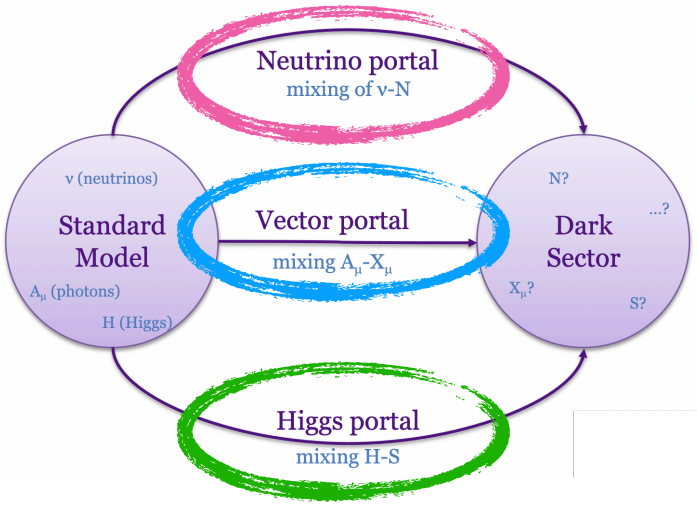
Summary

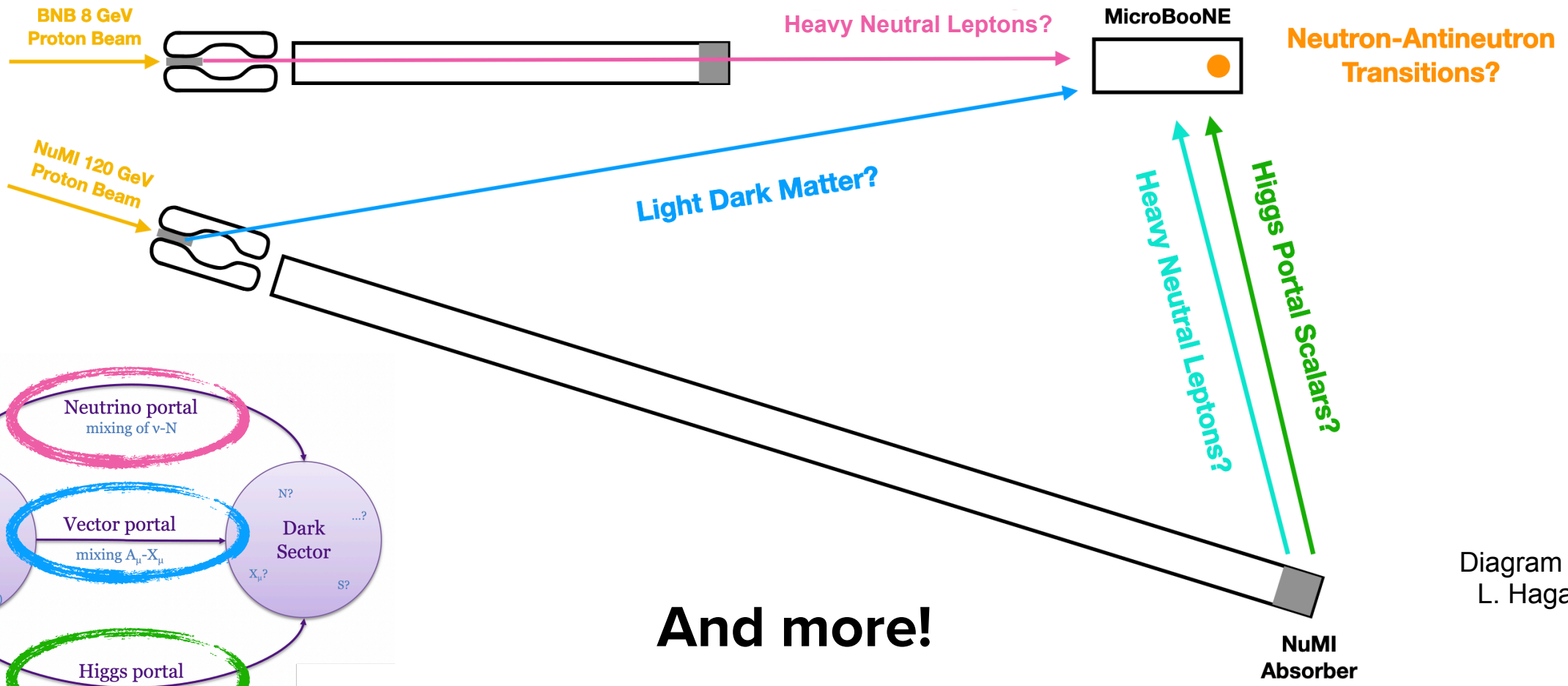
- MicroBooNE completed **5 years of data taking**
  - Extensive physics programme including cross-sections and BSM physics
  - Pioneering reconstruction techniques
- Exploits data from **two neutrino beams** (BNB and NuMI)
  - Access to a wide range of dark sector models
- Many **new full dataset analyses upcoming**!



Backup slides

BSM Physics @ MicroBooNE

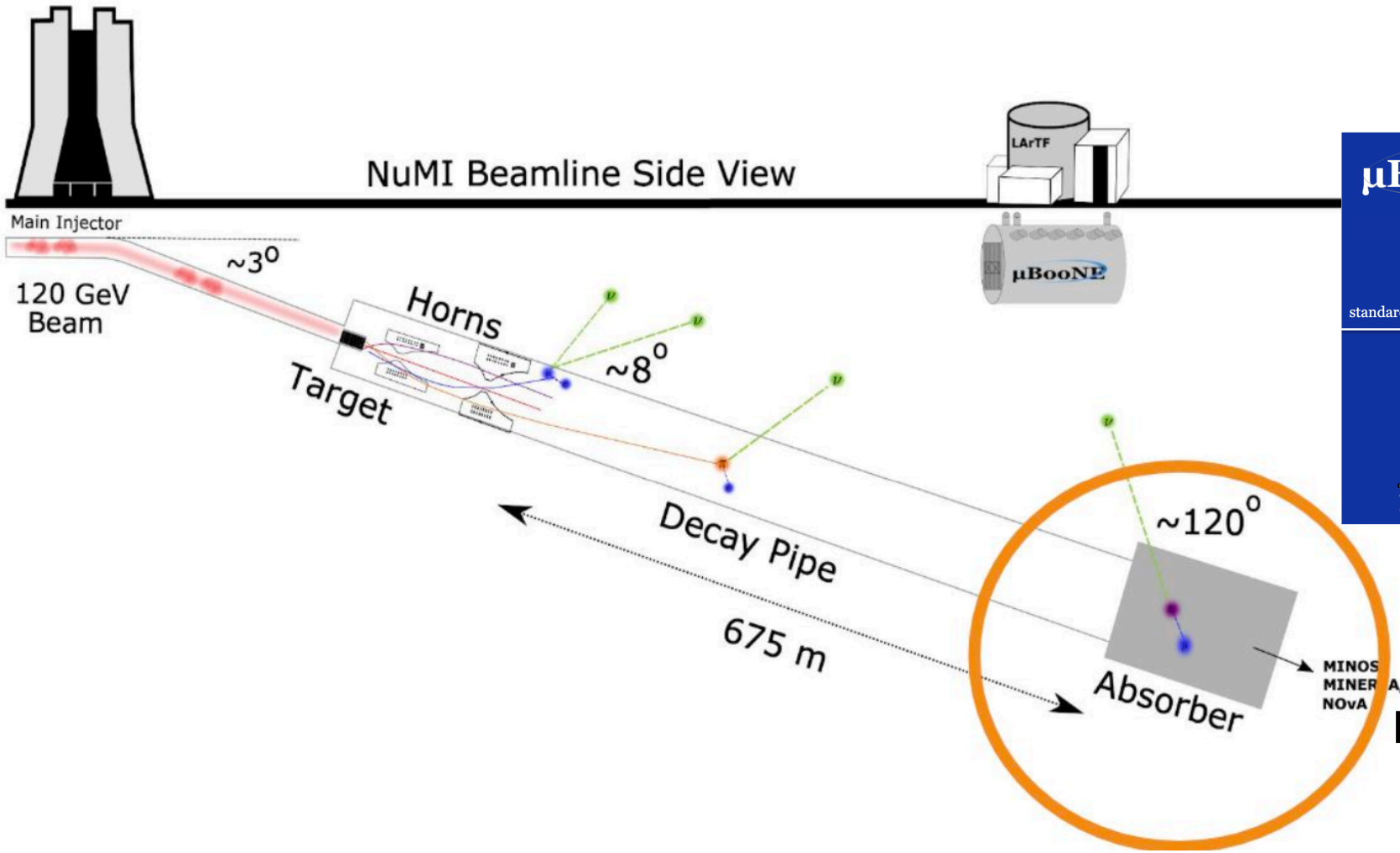


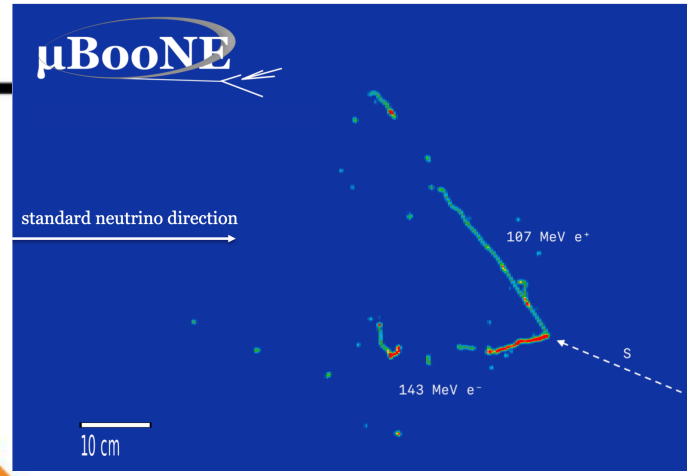


And more!

Diagram credit:
L. Hagaman

The NuMI beam absorber



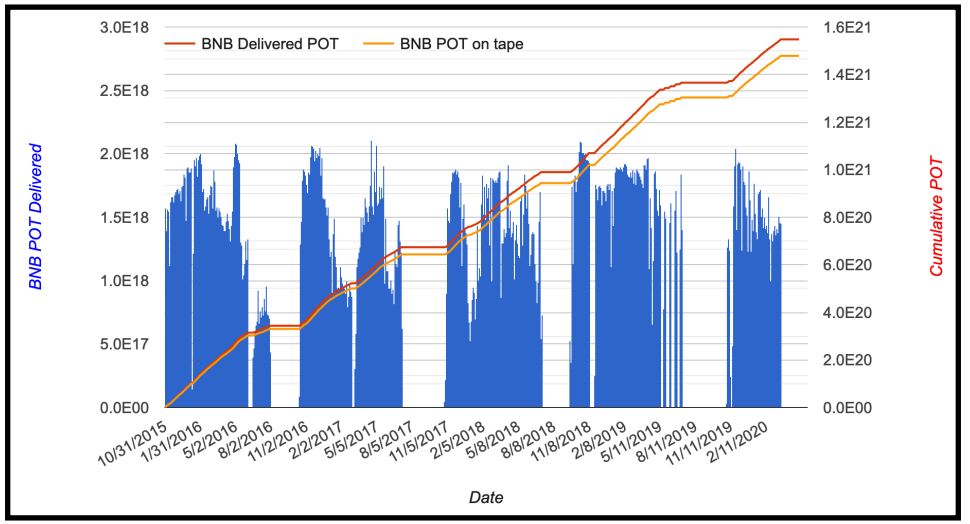


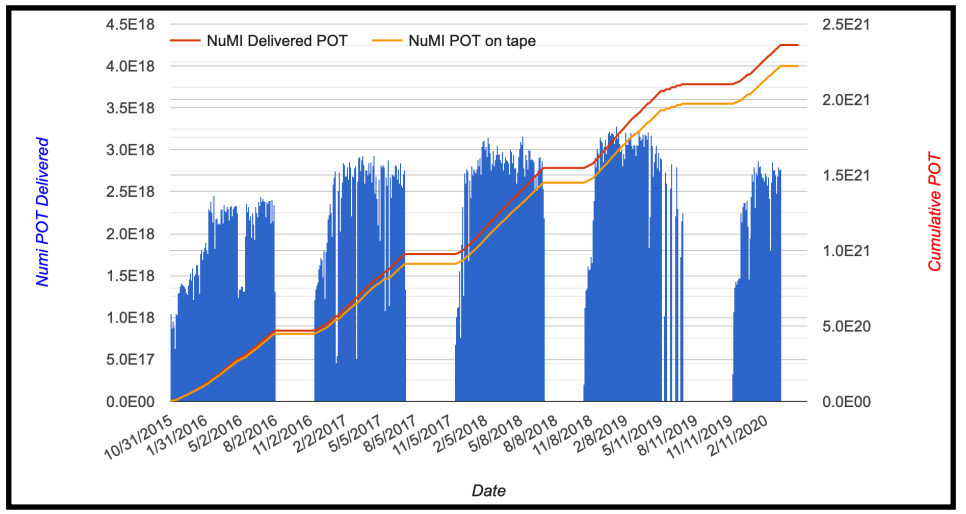
Events from the absorber will give a very specific "backwards" signature

Data collected by MicroBooNE

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

- Full dataset:
  - 1.1×10^{21} POT (BNB)
  - 2.37×10^{21} POT (NuMI)





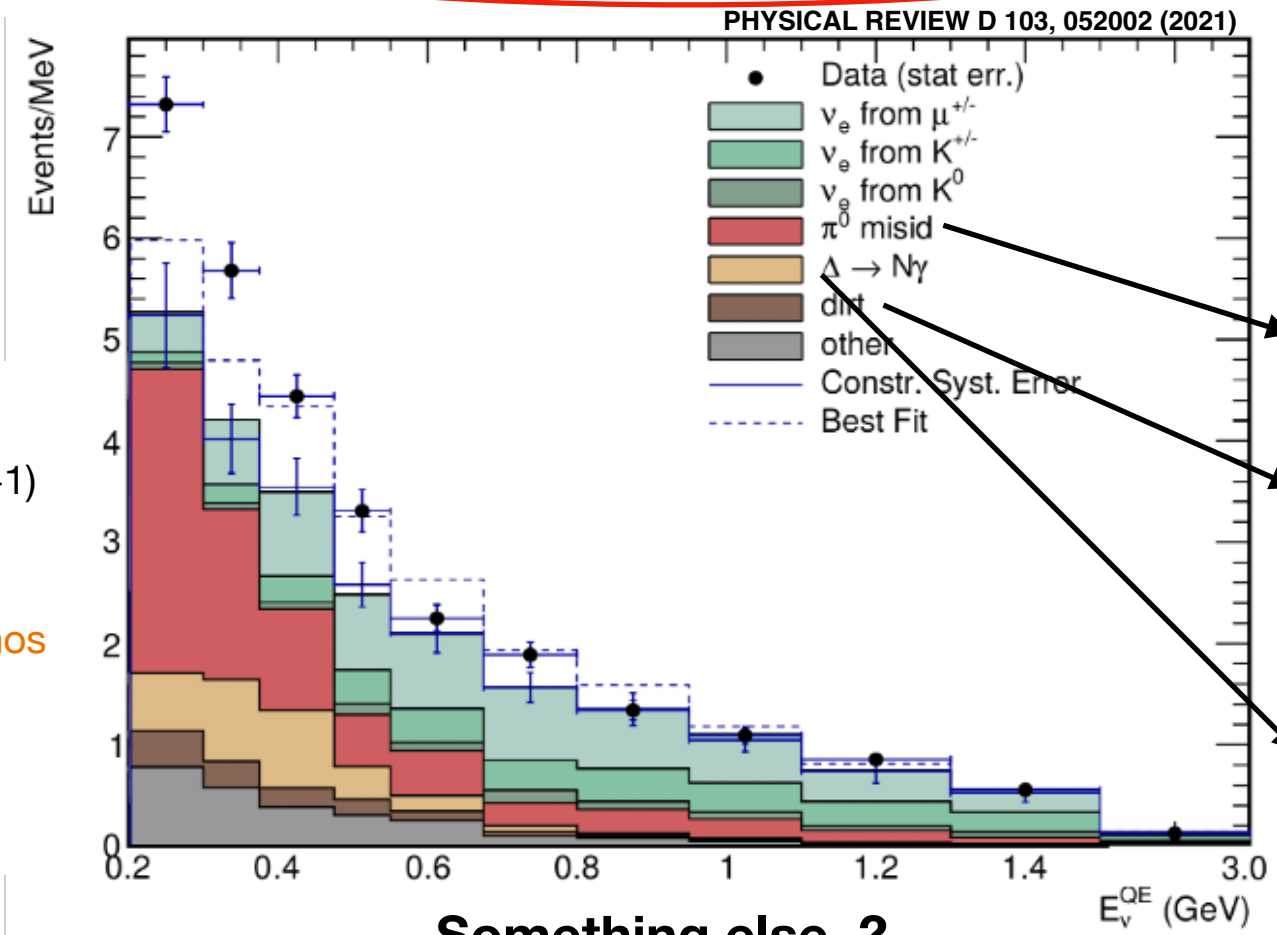
*POT: Protons on Target

Neutrino portal: low energy excess

No e^-/γ separation in MiniBooNE

Electrons?

- **Sterile neutrinos**
  - One sterile neutrino (3+1)
  - Other new physics involving sterile neutrinos possible



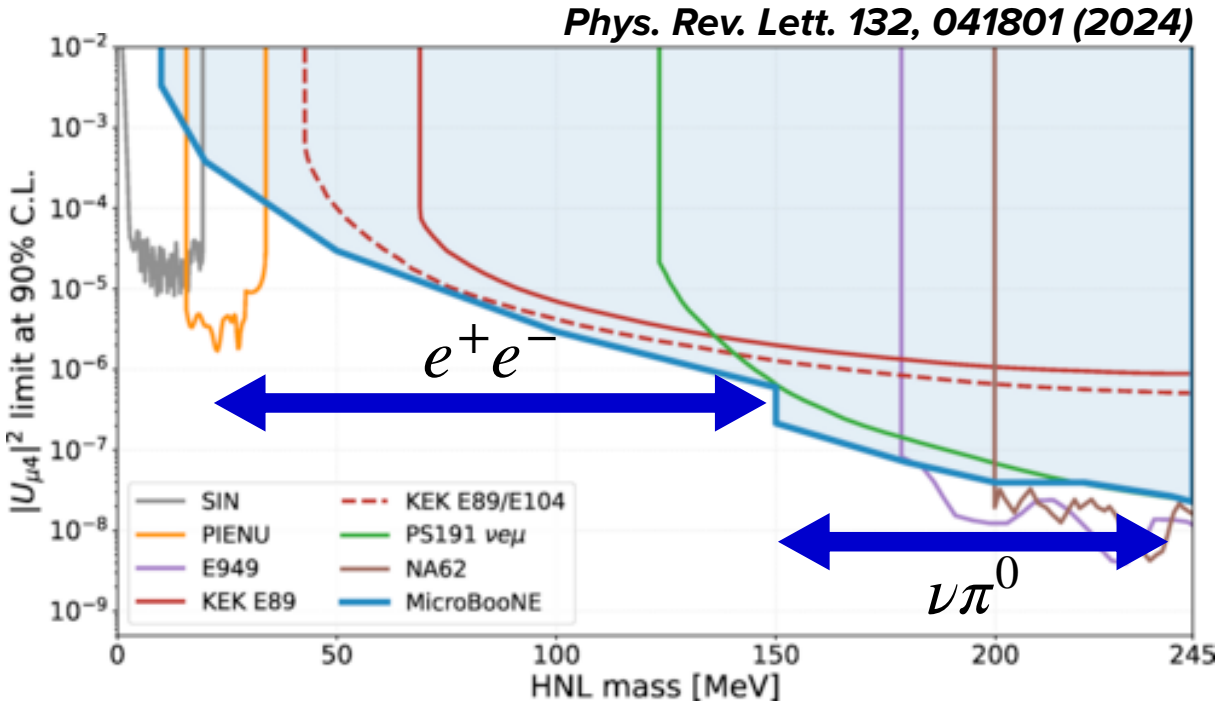
Something else..?

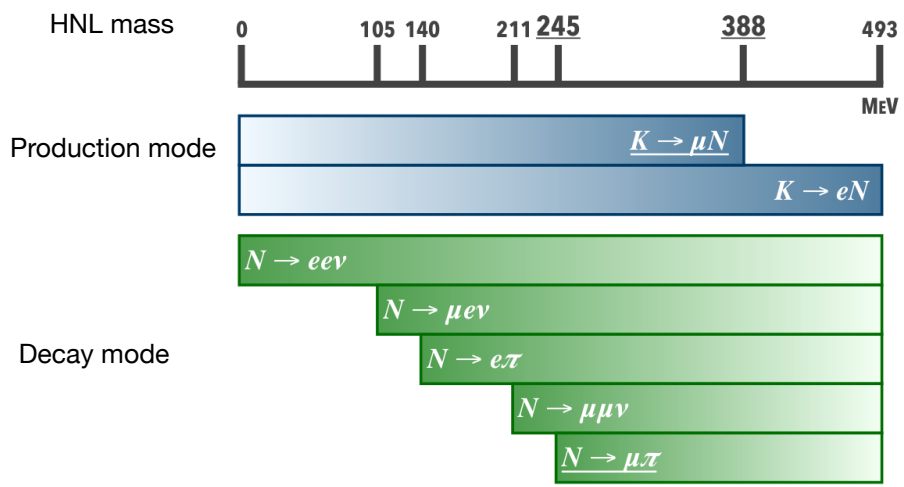
Photons?

- **Mis-identified NCπ^0**
  - Measured *in situ*
- **Dirt (interactions outside the detector)**
  - Eliminated with beam timing and radial cuts
- **NC$\Delta \rightarrow$ Nγ**
  - **Not directly constrained**

Heavy Neutral Leptons

- Search for **heavy neutral leptons in BNB with mass $\mathcal{O}$(100 MeV)**
- Produced by **kaon decays in the beam**, then travel and interact in the detector

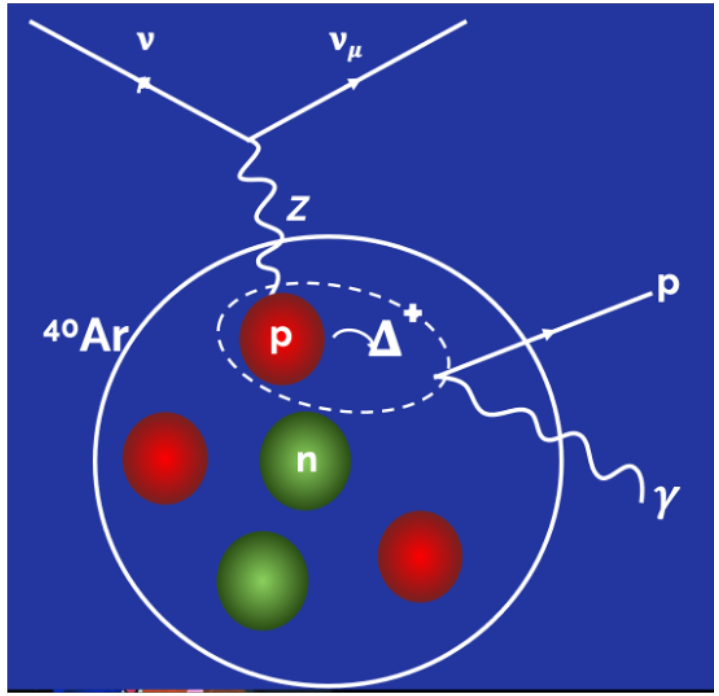




- BDT-based analysis
- **No excess** observed in signal region
- Set **limits on $|U_{\mu 4}|^2$** as a function of HNL mass

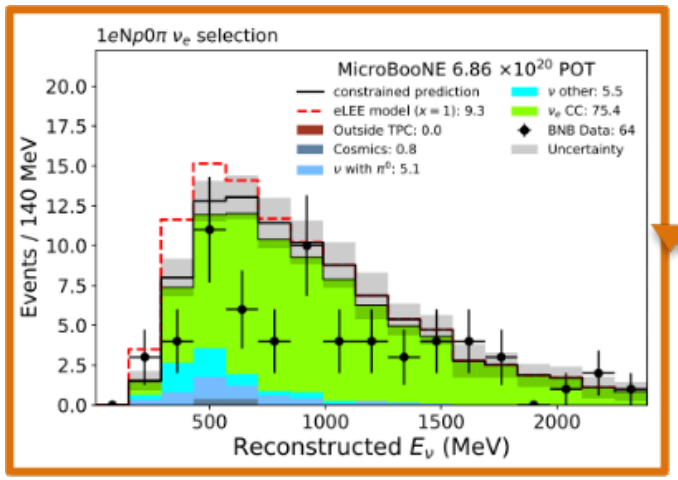
NC$\Delta \rightarrow N\gamma$

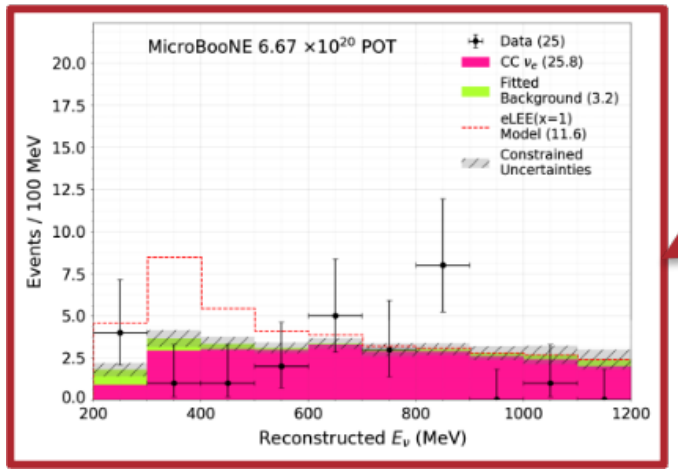
- Rare process: **never directly observed**
- Physics modelled with **GENIE**
- Needs **x3 scaling** to match MiniBooNE excess

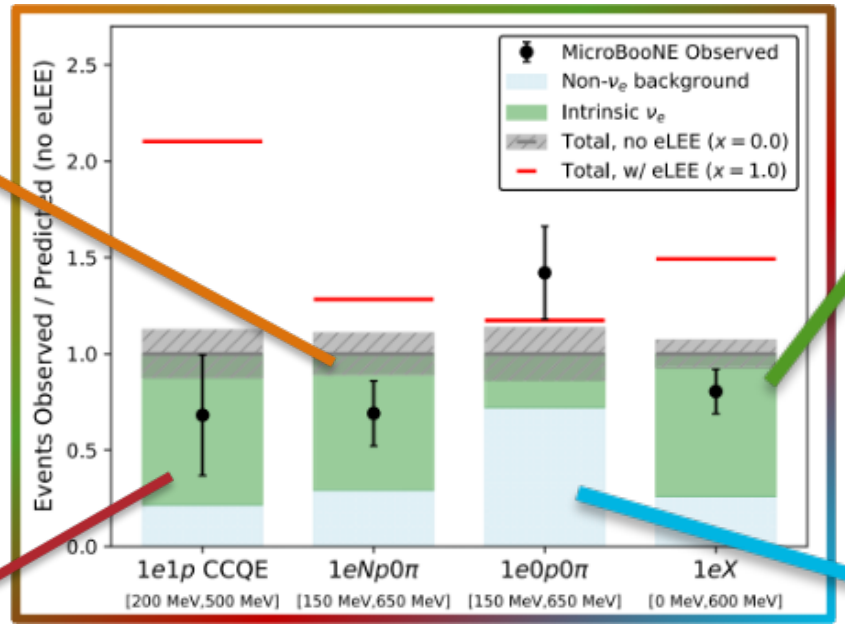


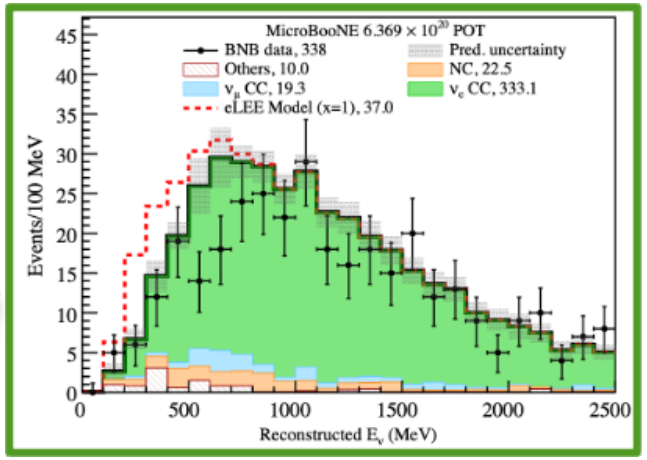
2021 results

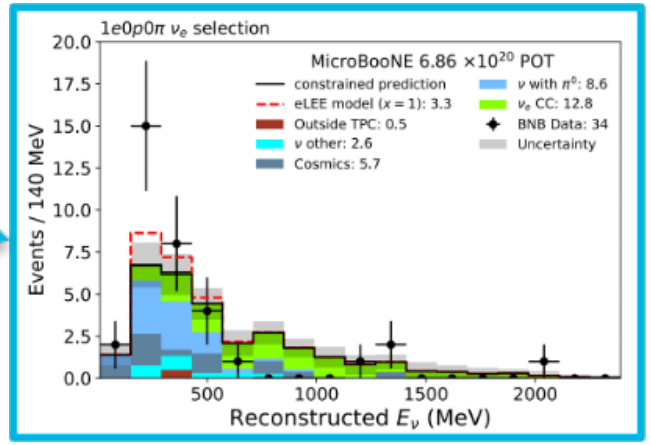
No sign of excess in the 2021 electron-like selections









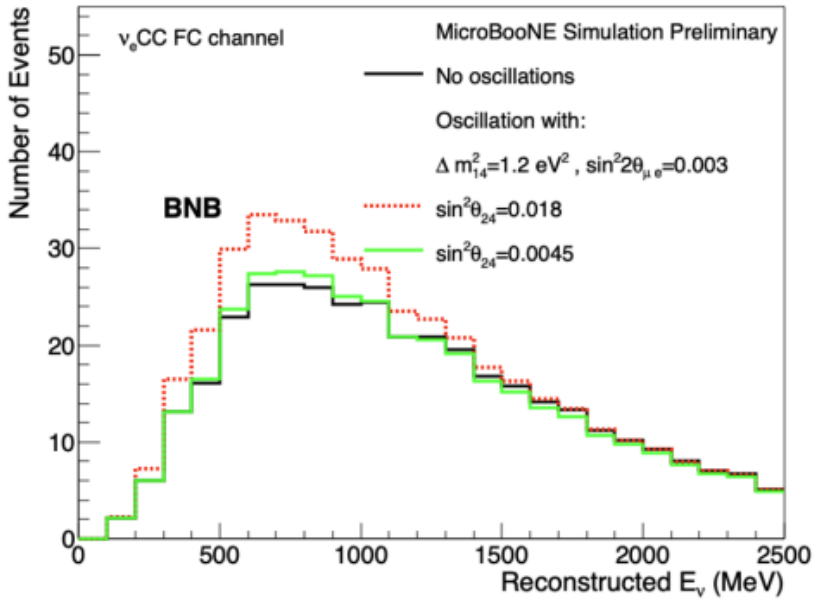


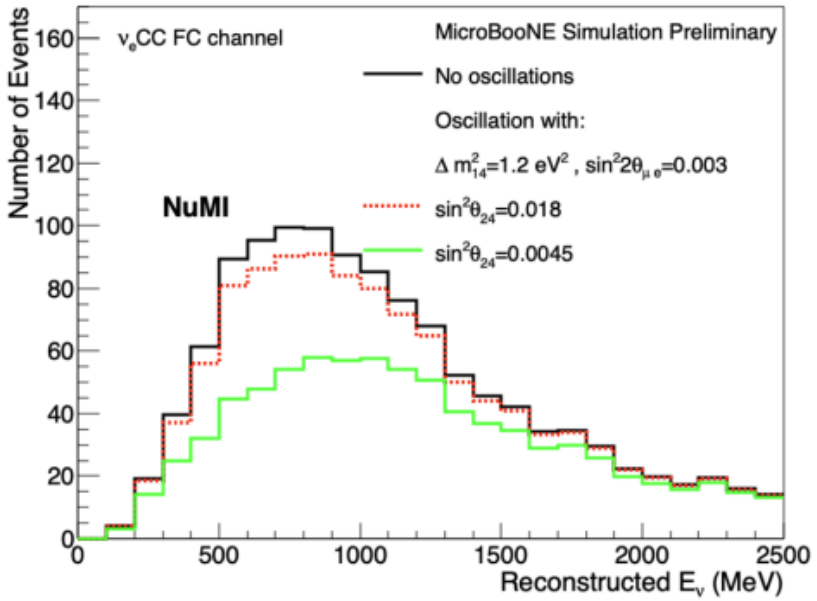
Phys. Rev. Lett. 128, 241801
Phys. Rev. D 105, 112003
Phys. Rev. D 105, 112004
Phys. Rev. D 105, 112005

Slide courtesy of V. Basque

Breaking the degeneracy with two beams

- Oscillation effect in 3+1 model can be hidden in appearance/disappearance degeneracy when using only one beam
  - BNB alone not sensitive to some values of θ_{24}
- Add NuMI data to break it:
  - For the same mixing angles, large effect in NuMI

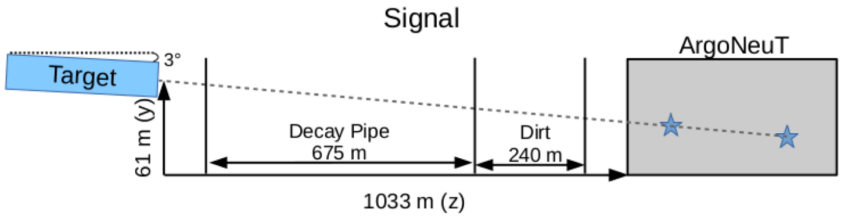




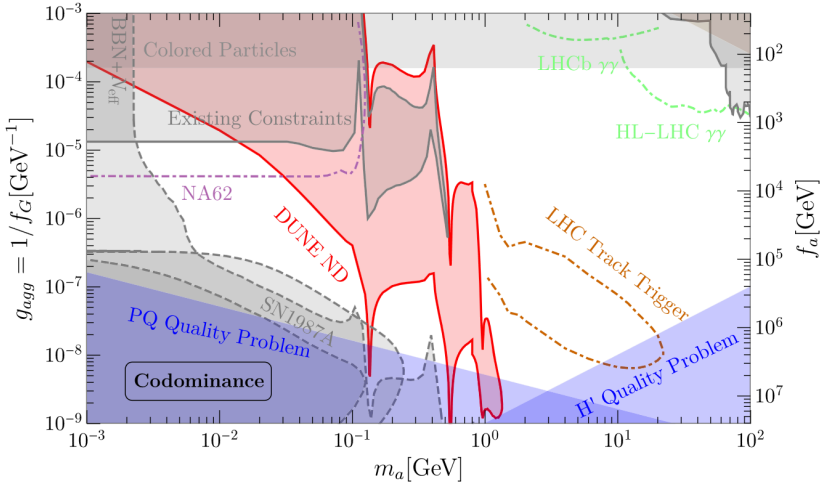
Ongoing searches

Millicharged particles

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

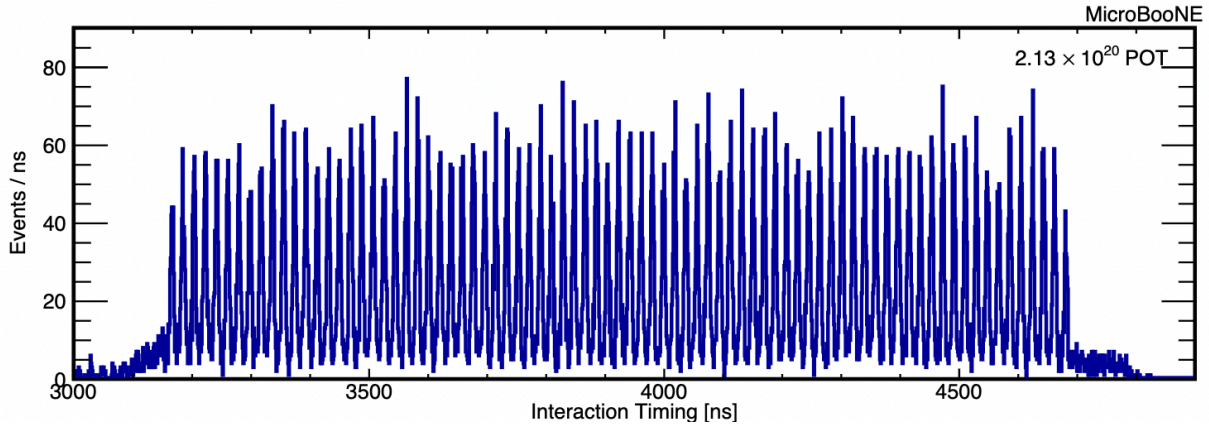


Heavy QCD Axions



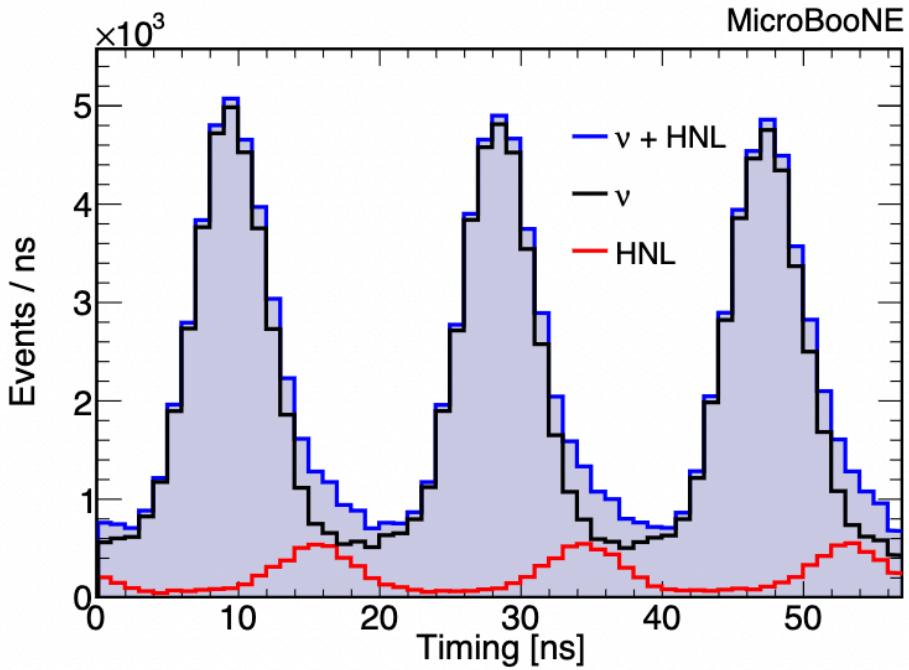
- Axions produced via **mixing with neutral mesons**
- Decay to **di-photon pairs** in MicroBooNE

$\mathcal{O}$(1 ns) timing resolution

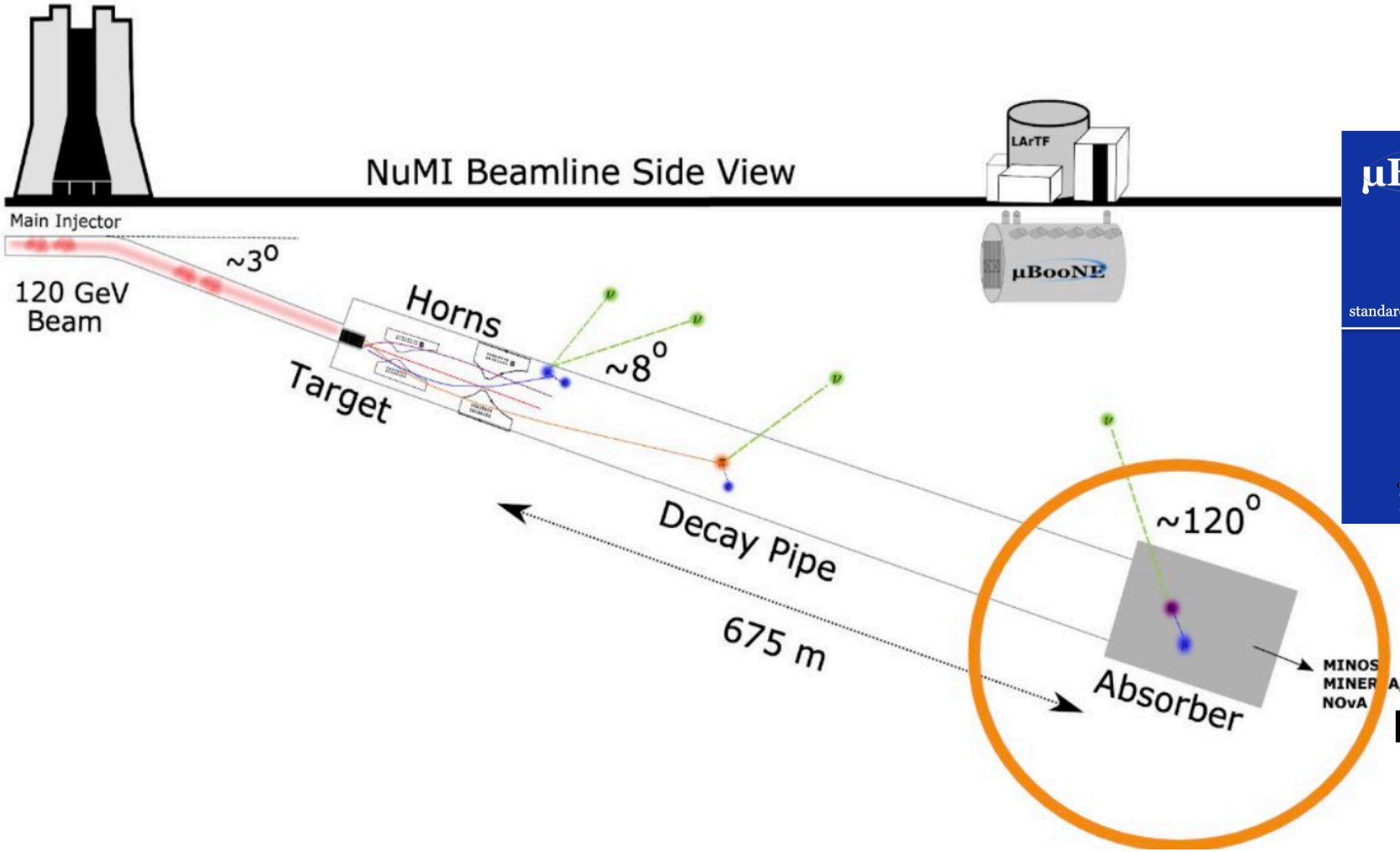


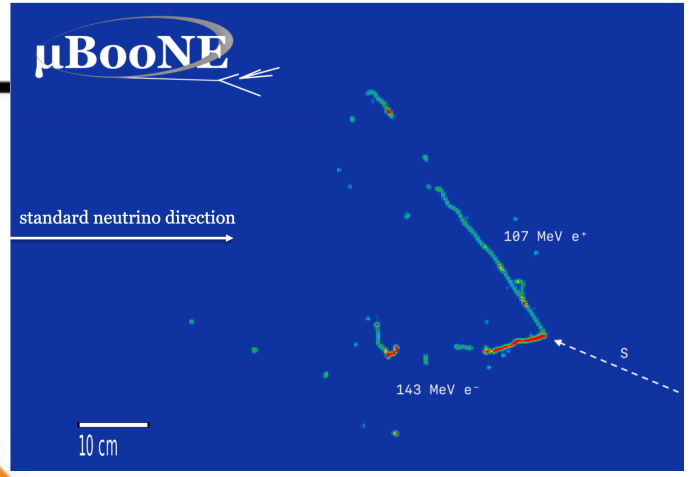
- Demonstrated **1.73 ± 0.05 ns resolution** on neutrino interaction time
- Allows to **probe beam structure!**

- In-bunch neutrino searches:
  - **Reduction of cosmic background**
- Out-of-bunch BSM searches
  - **Reduction of neutrino background**



The NuMI beam absorber





Events from the absorber will give a very specific "backwards" signature