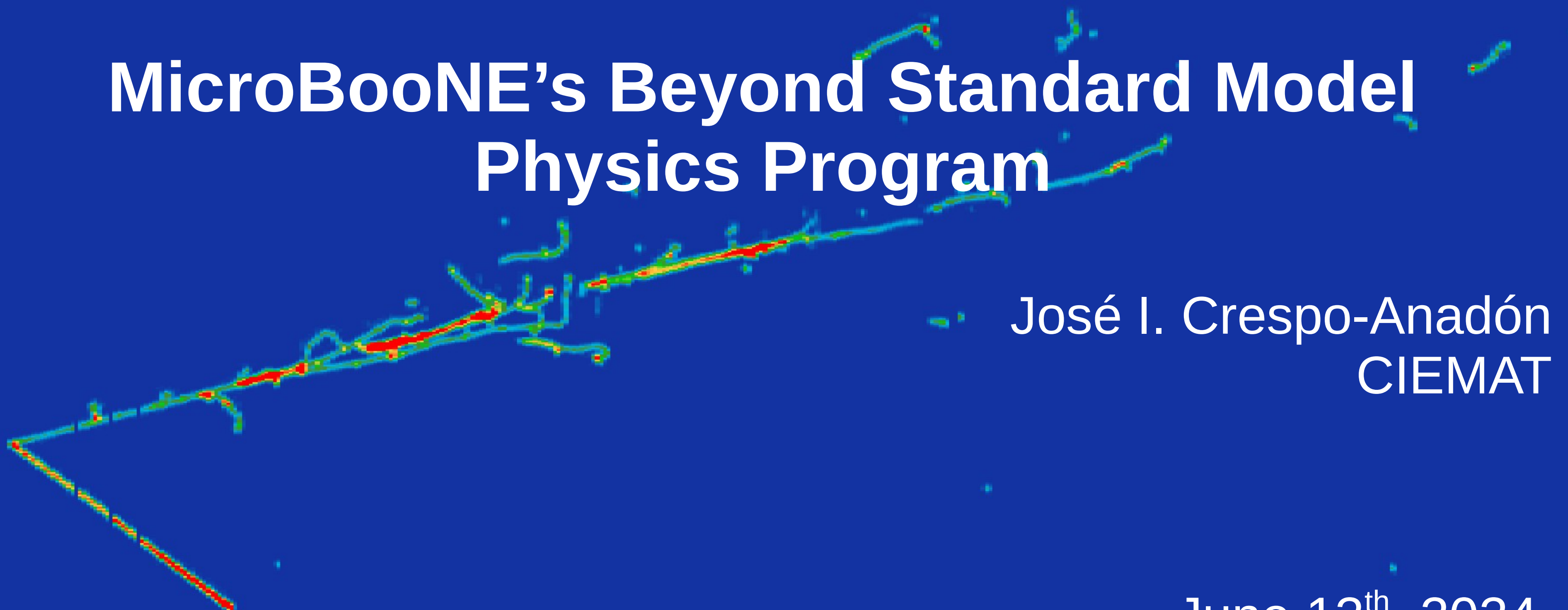
µBooNE

MicroBooNE’s Beyond Standard Model Physics Program



José I. Crespo-Anadón
CIEMAT

June 13th, 2024
31st International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY 2024)

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
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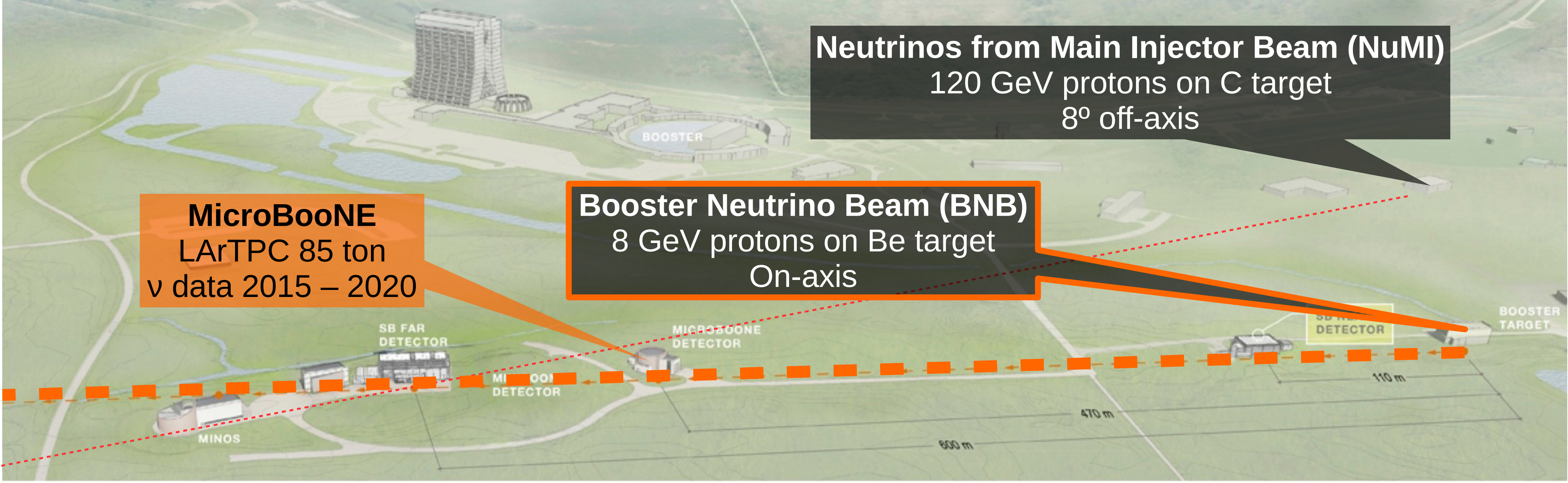
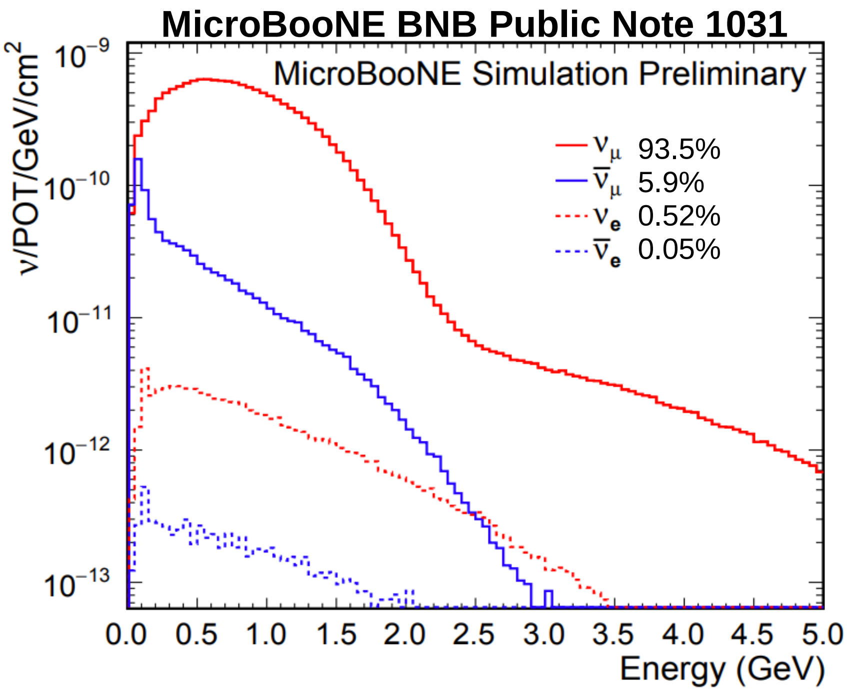
SUSY 2024
Theory meets Experiment

The MicroBooNE experiment at Fermilab





One experiment. Two neutrino beams:

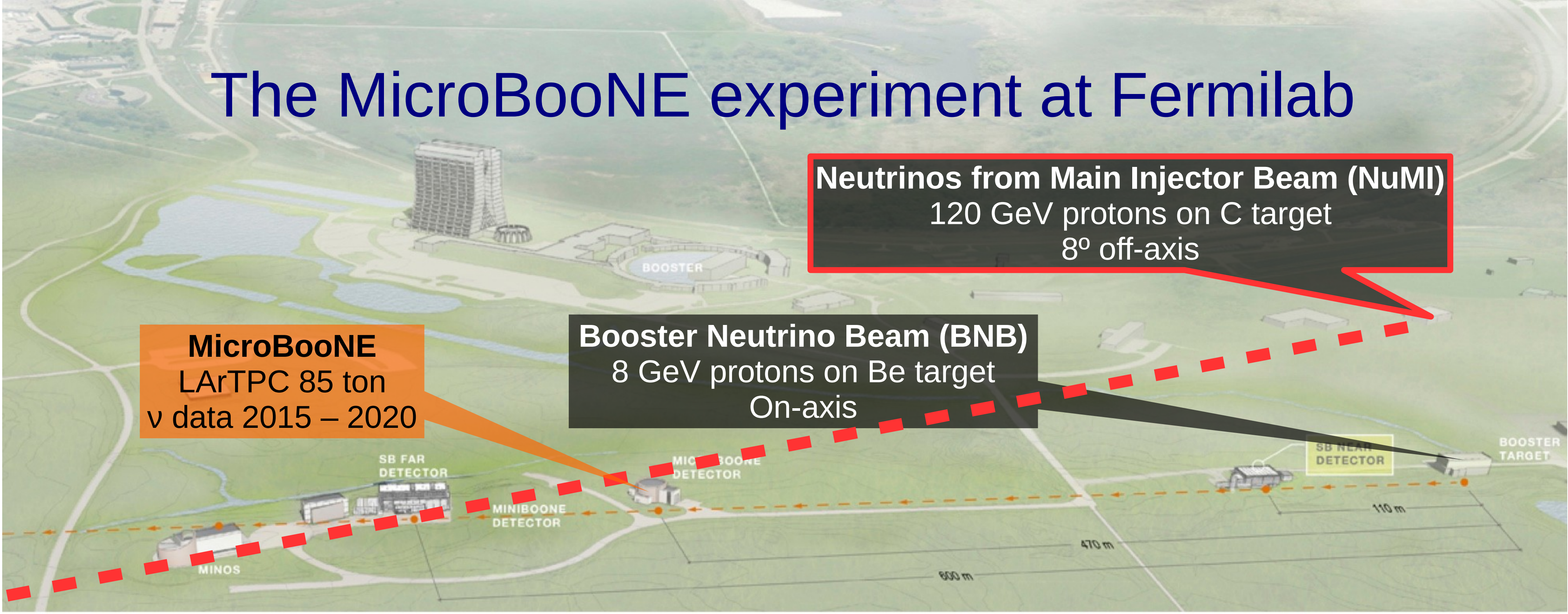
Booster Neutrino Beam (BNB) from pion decay-in-flight mostly, plus kaon and muon decays.

Single horn for focusing charged mesons. MicroBooNE BNB dataset is only **neutrino-mode** (positive mesons focused).

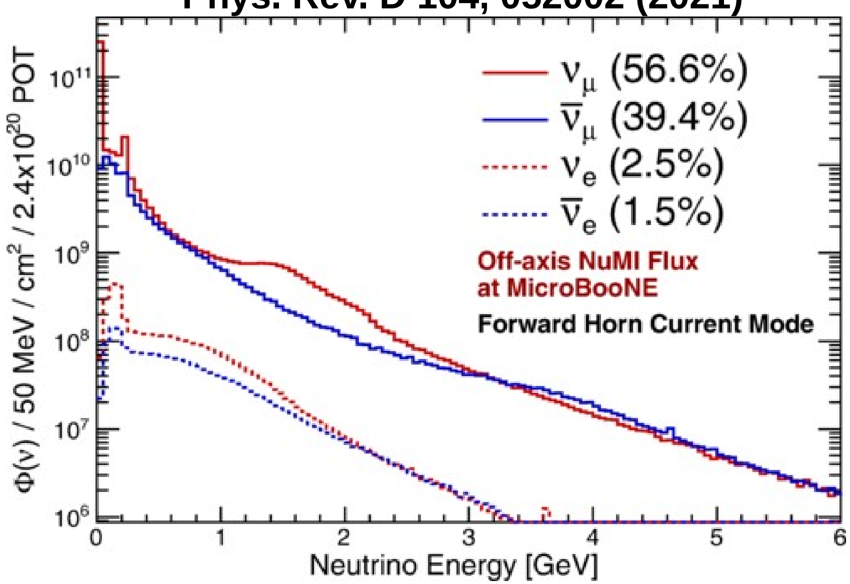
Neutrinos from the Main Injector (NuMI) from a high-energy beam off-axis.

Two horns. MicroBooNE NuMI dataset has both **neutrino and antineutrino modes**.

The MicroBooNE experiment at Fermilab



Phys. Rev. D 104, 052002 (2021)



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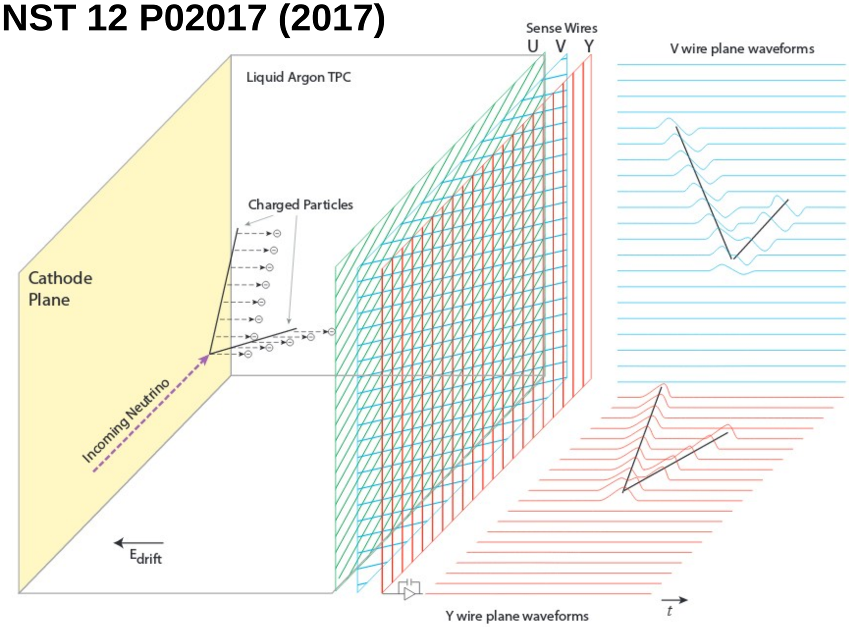
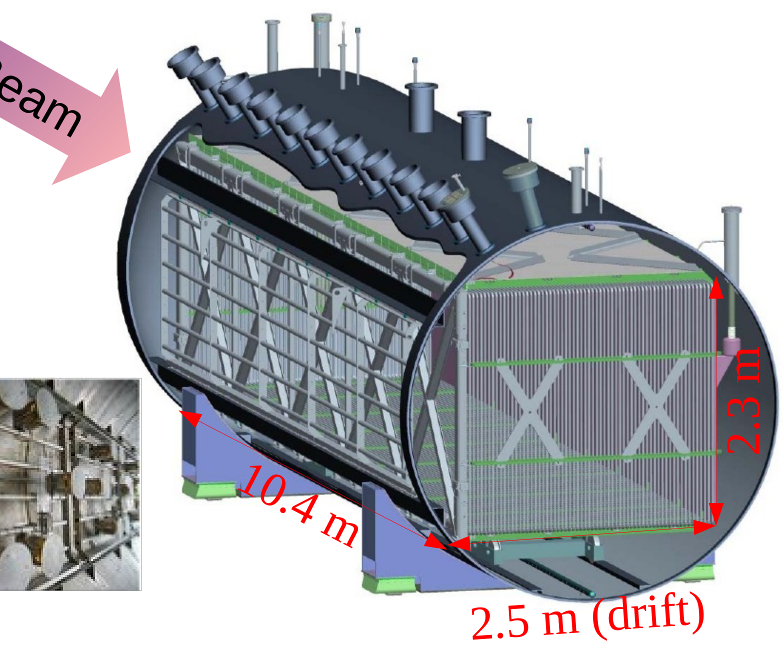
MicroBooNE detector

JINST 12 P02017 (2017)





85 ton active liquid argon TPC.

Maximum drift length: 2.5 m. Drift time: 2.3 ms.

3 wire planes to reconstruct 3D interaction. **3 mm wire pitch.**

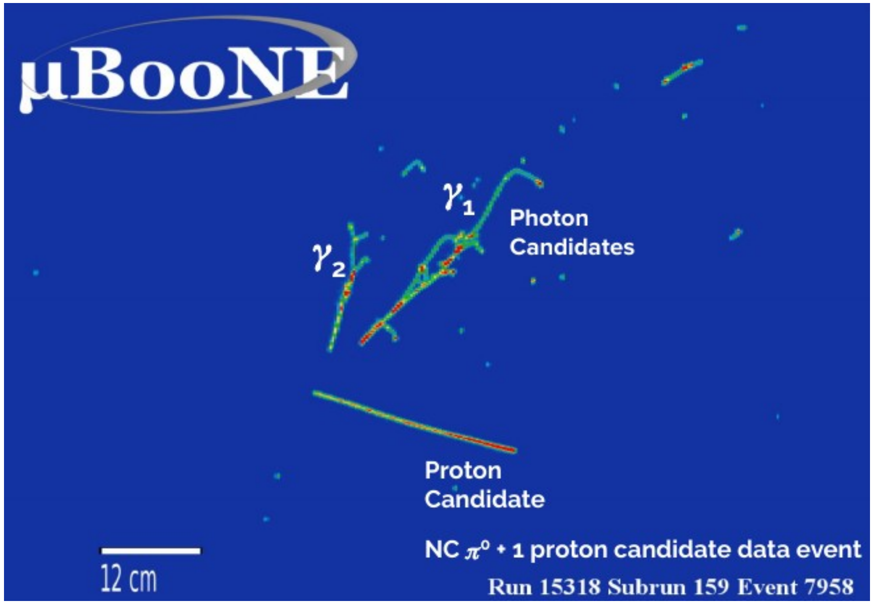
Low-noise cold front-end electronics.

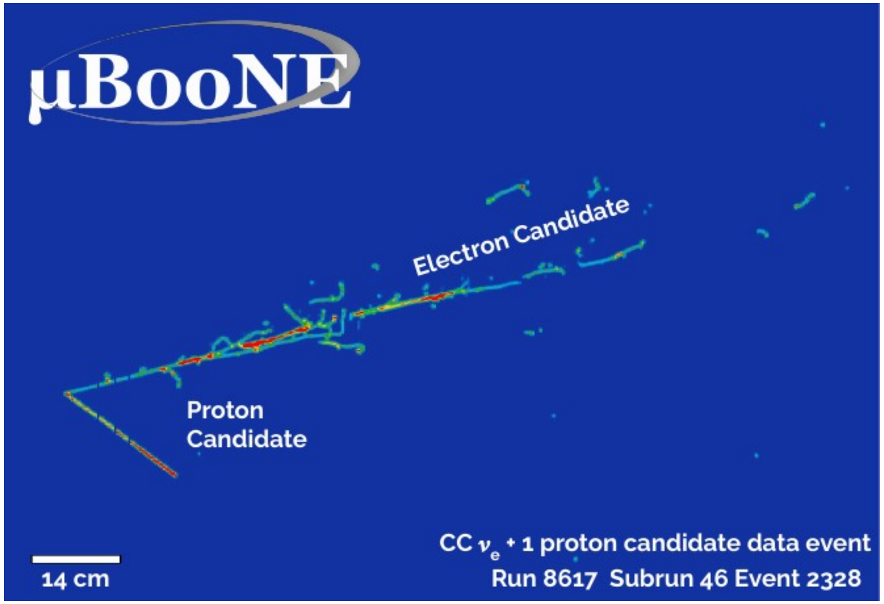
32 8” Hamamatsu R5912 Cryogenic **PMTs** mounted behind the wire planes with TPB-coated acrylic plates.

Near surface. External **cosmic-ray tagger** system.

Operations 2015 – 2021.

Liquid Argon TPC (LArTPC) technology





Imaging like a "**digital bubble chamber**".

mm-level spatial resolution.

High resolution calorimetry.

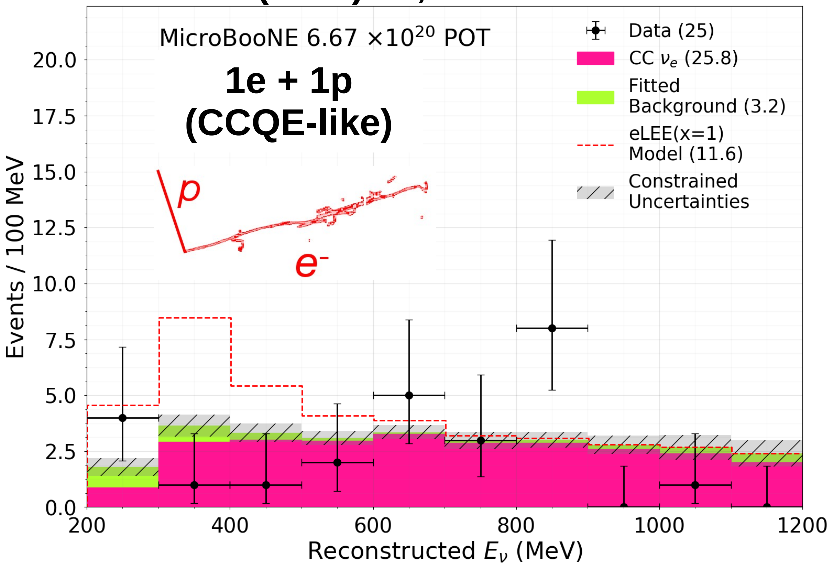
3-D reconstruction.

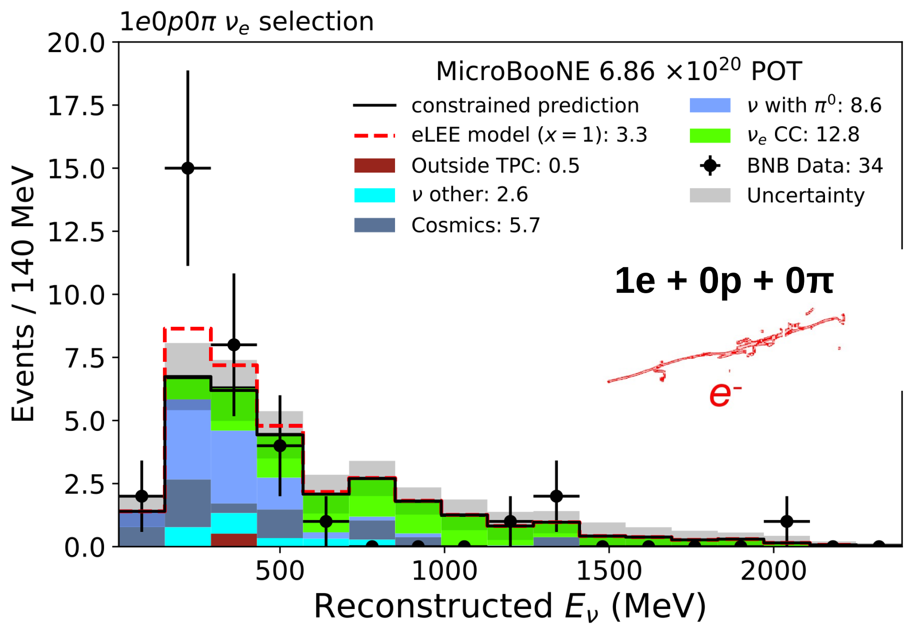
Scintillation light for triggering and cosmic background rejection.

Exclusive final-state kinematics and particle identification.

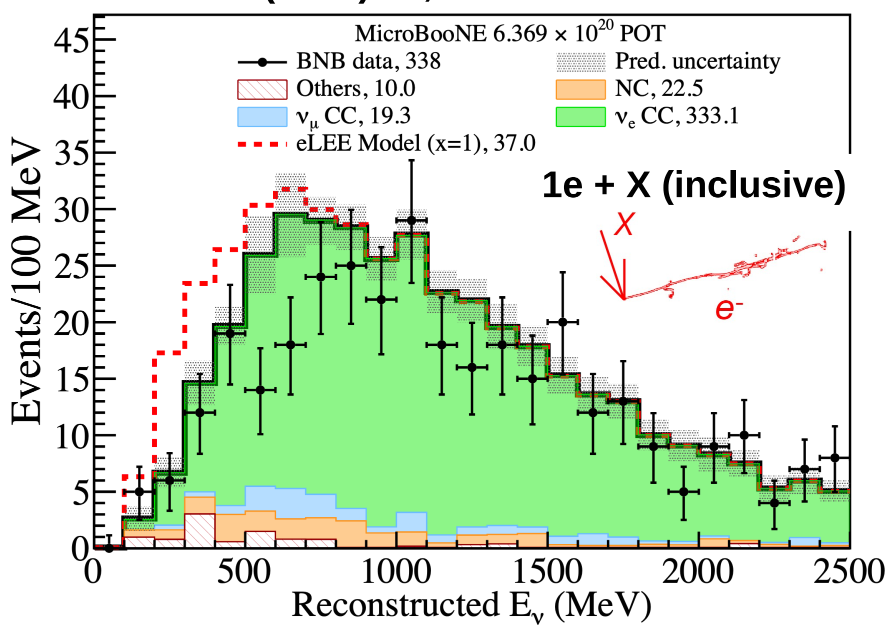
Search for anomalous ν_e appearance

PRD 105 (2022) 11, 112003

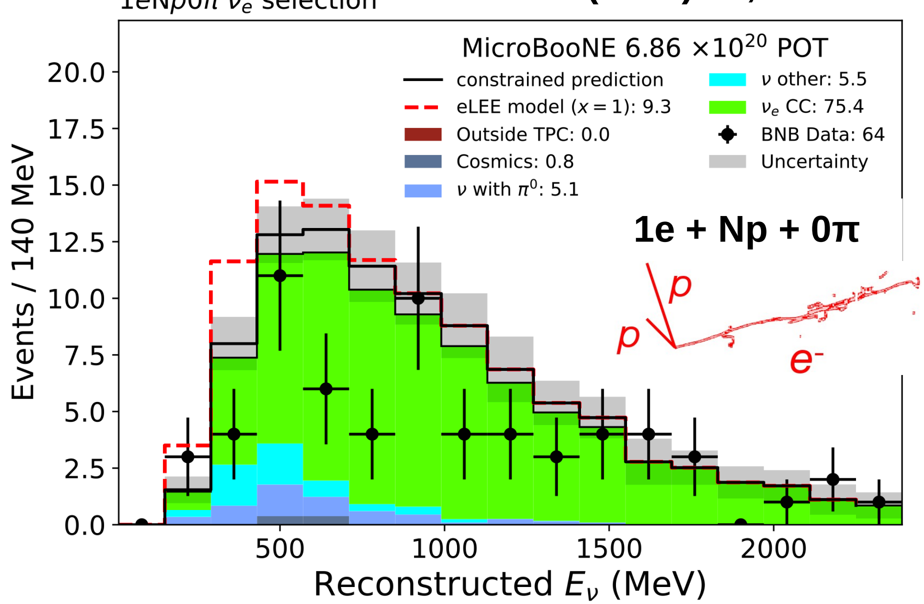




PRD 105 (2022) 11, 112005

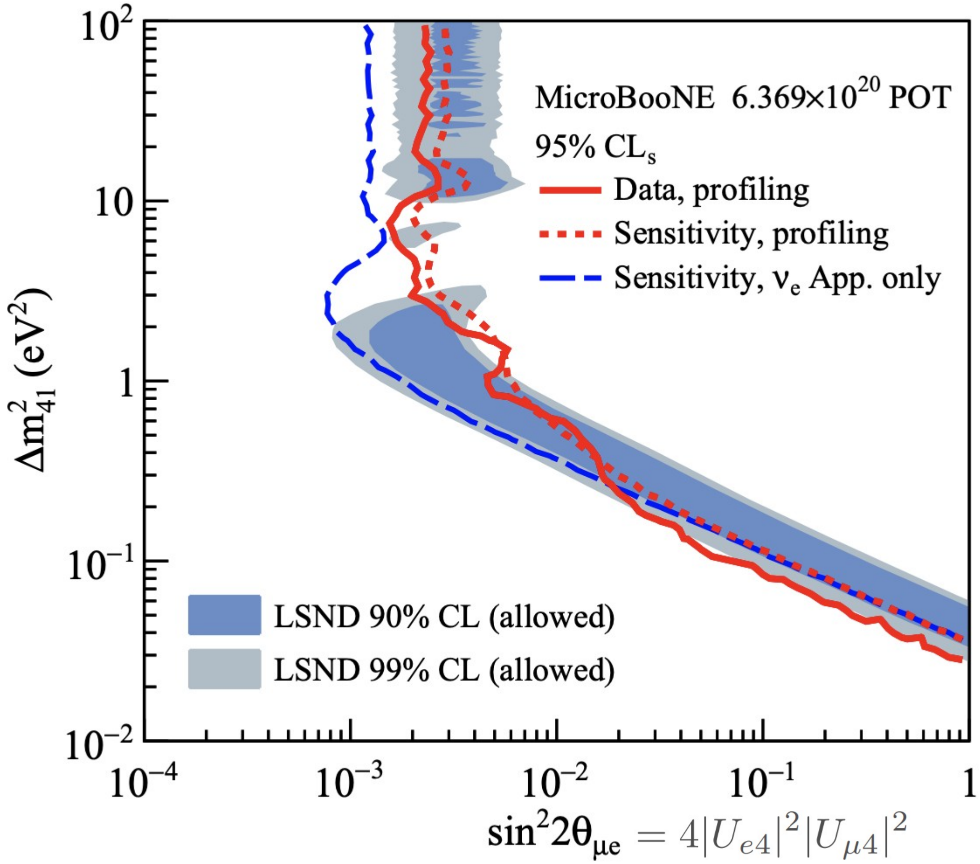


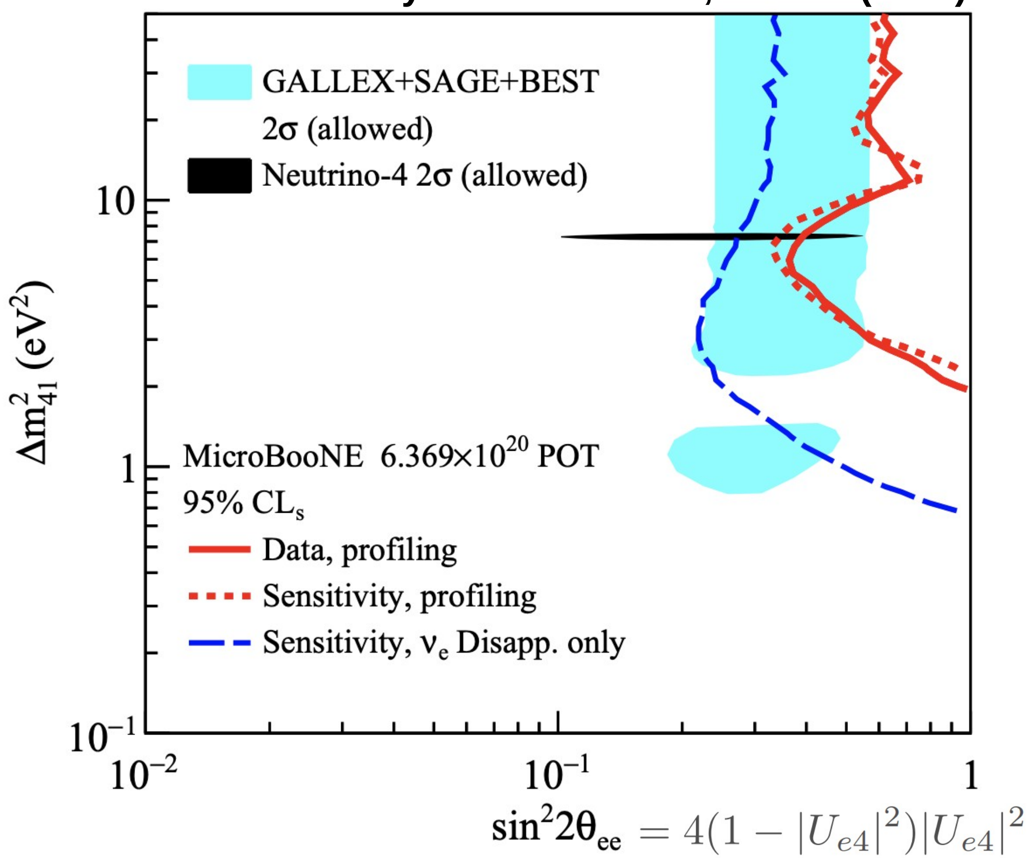
PRD 105 (2022) 11, 112004



Oscillation analysis

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





MicroBooNE has set **constraints on the eV-sterile neutrino parameter space**, excluding part of the LSND-allowed region at 95% CL.

New searches for excesses and oscillation analyses coming soon!

Neutrino beams as portals to BSM physics

Neutrino experiments compete in the **intensity frontier** (exploring smaller couplings).

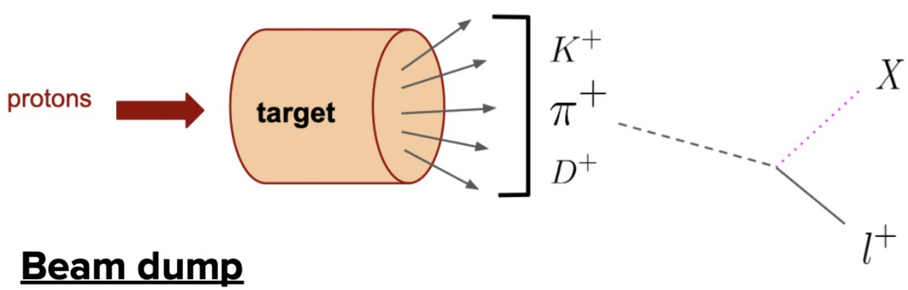
Neutrino beams are made from intense secondary **meson beams created by the high-intensity proton beams.**

Remaining protons are dump into beam stoppers

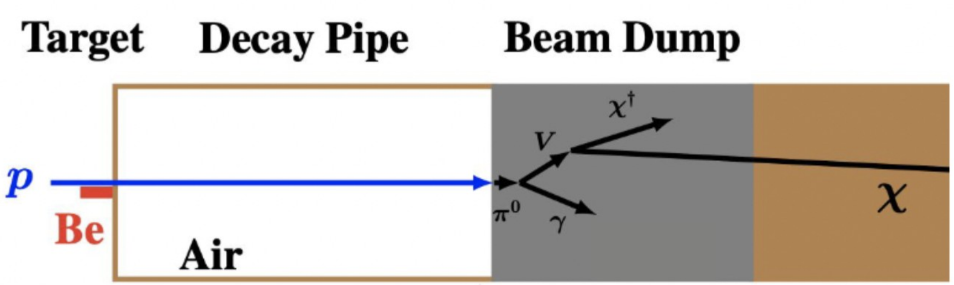
New particles may be produced in the decay of **both charged and neutral mesons**.

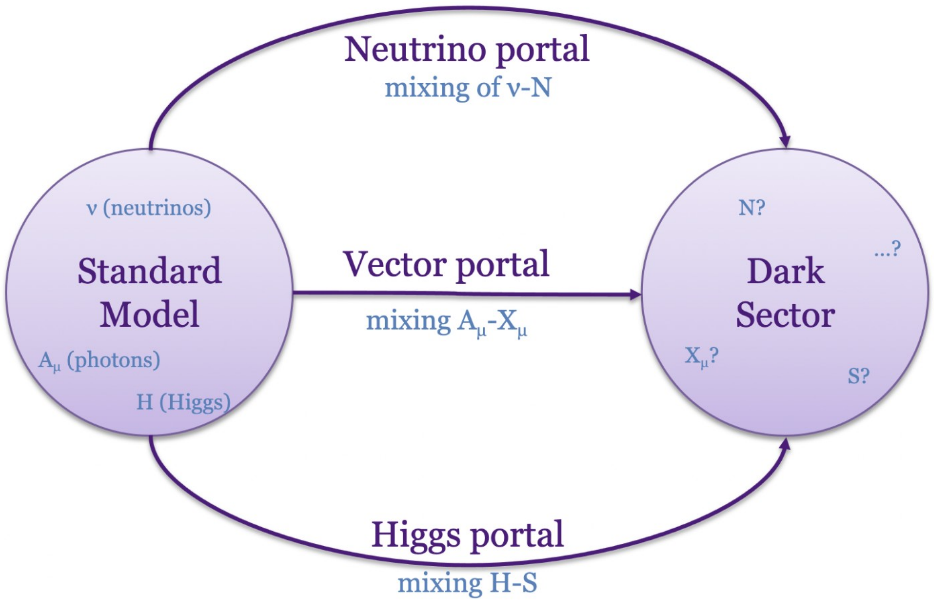
Long-lived massive particles may avoid helicity suppression due to their mass or from production in 3-body decays.

Meson decay in flight



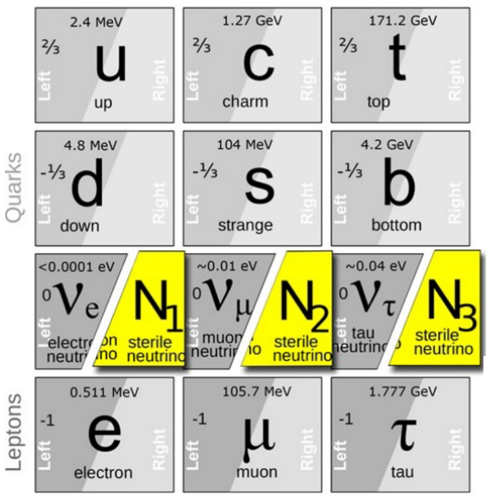
Beam dump





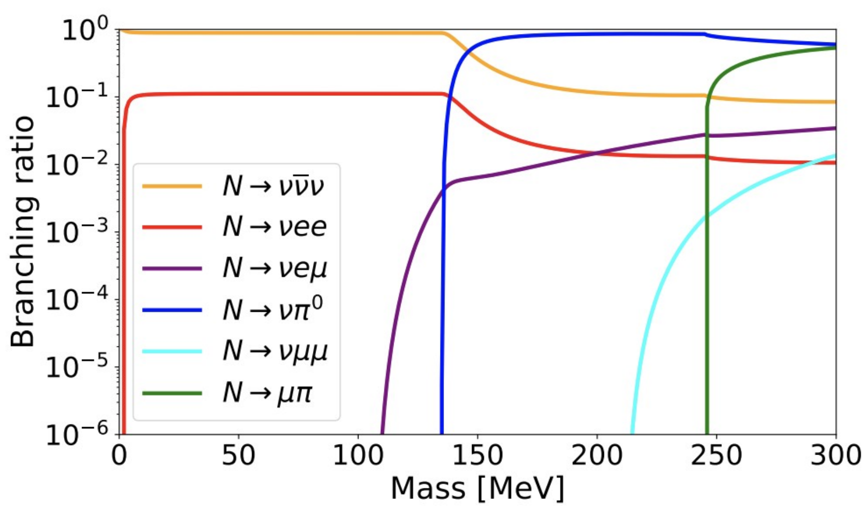
Neutrino portal: Heavy Neutral Leptons (HNL)

From arXiv:1504.04855



Extended PMNS matrix

$$\begin{bmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ \vdots & & \vdots & U_{\mu 4} \\ \vdots & & \vdots & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{bmatrix}$$



Extension of SM by adding **right-handed** counterparts to left-handed neutrinos.

Singlets under SM interactions → a.k.a. **Heavy sterile neutrinos.**

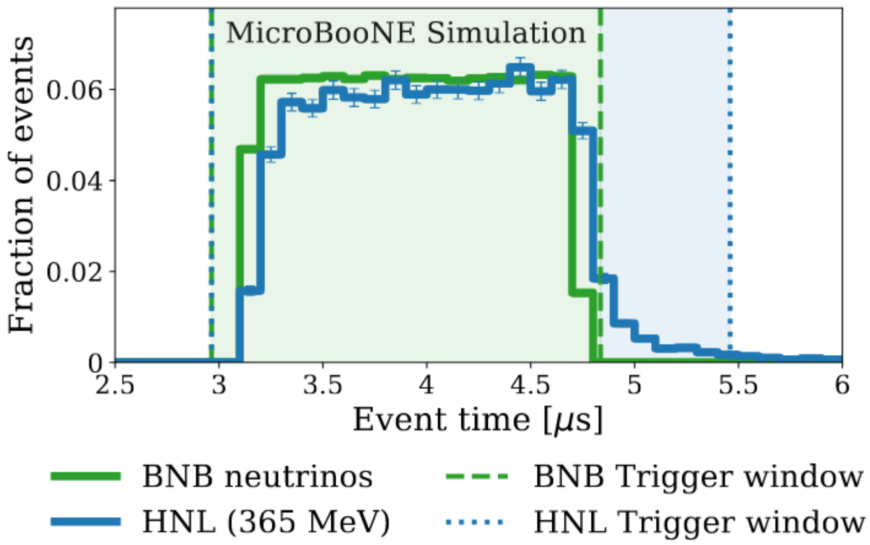
Can have both **Dirac** (Yukawa) and **Majorana** masses. **Mass scale unconstrained.**

Produced in meson decays through mixing with SM neutrinos via **extended PMNS mixing matrix elements: U_{e4}, $U_{\mu 4}$ (no significant τ production).**

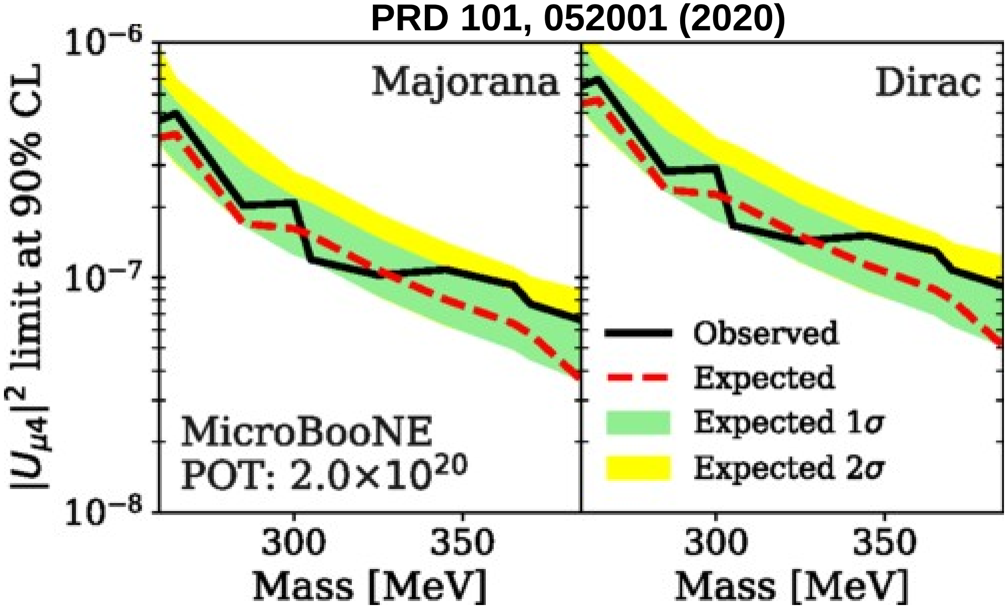
No oscillation due to large mass – loss of coherence.

HNL **decay in flight**. No interaction with Ar nucleus.

Heavy neutral leptons: BNB search



PRD 101, 052001 (2020)



MicroBooNE exploited their baseline (470 m) to search for delayed HNL from the BNB in a neutrino-free window.

Dedicated trigger window after the BNB SM neutrino trigger.

Assume **$|U_{e4}| = |U_{\tau4}| = 0$** and **production via $K \rightarrow \mu N$**

Search between kinematic limits for ***$K \rightarrow \mu N$* production and *$N \rightarrow \mu\pi$* decay.**

Majorana HNL decays

$N \rightarrow \mu^+\pi^-$ and $N \rightarrow \mu^-\pi^+$

Isotropic decays (summed over both channels, no charge discrimination).

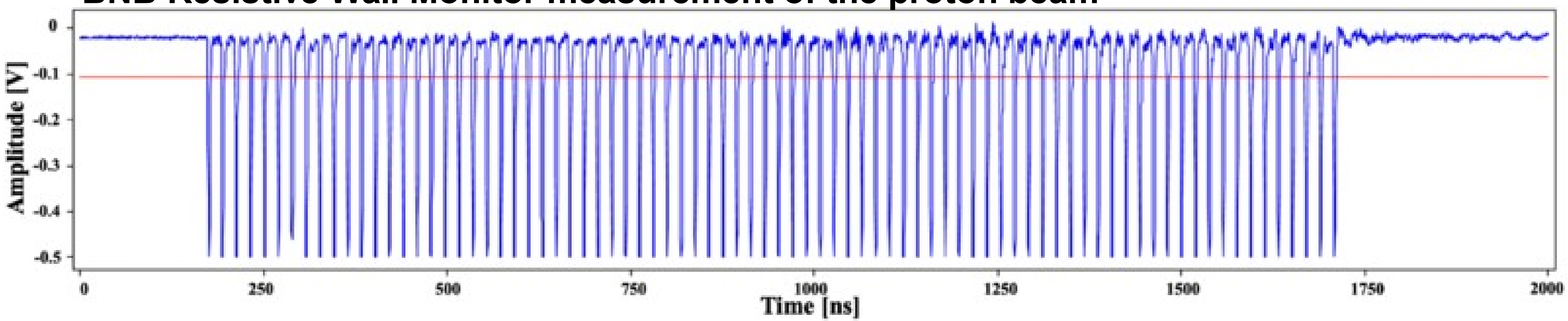
Dirac HNL decays

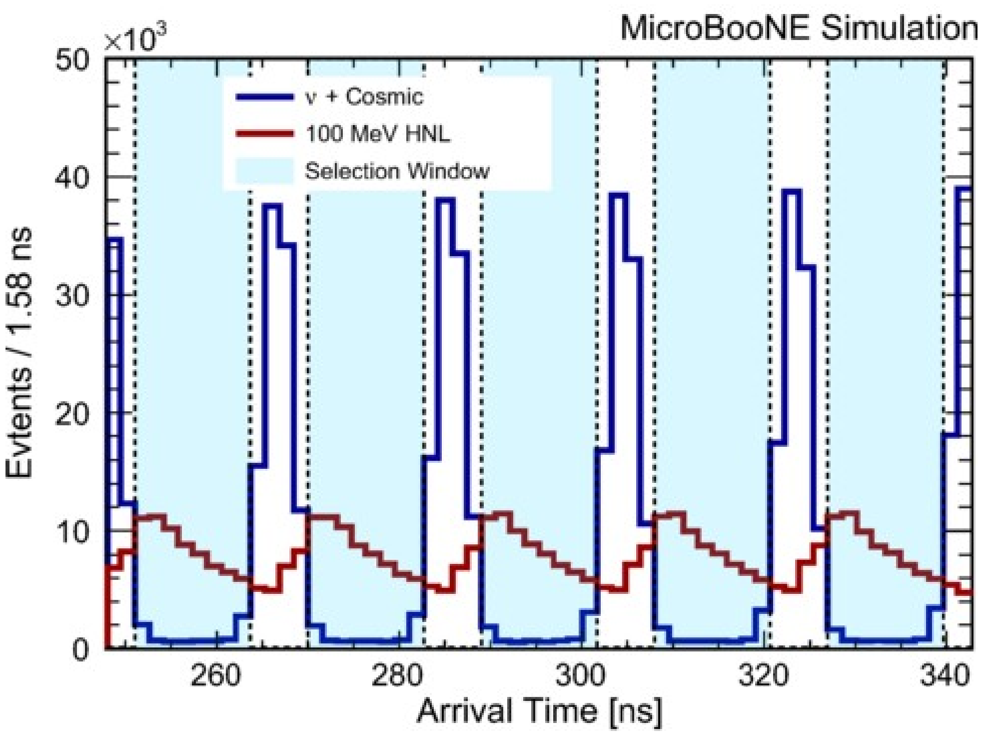
$N \rightarrow \mu^-\pi^+$ only: factor of two lower rate.

Non-isotropic decays (negligible effect).

Prospects for ns-timing searches

BNB Resistive Wall Monitor measurement of the proton beam





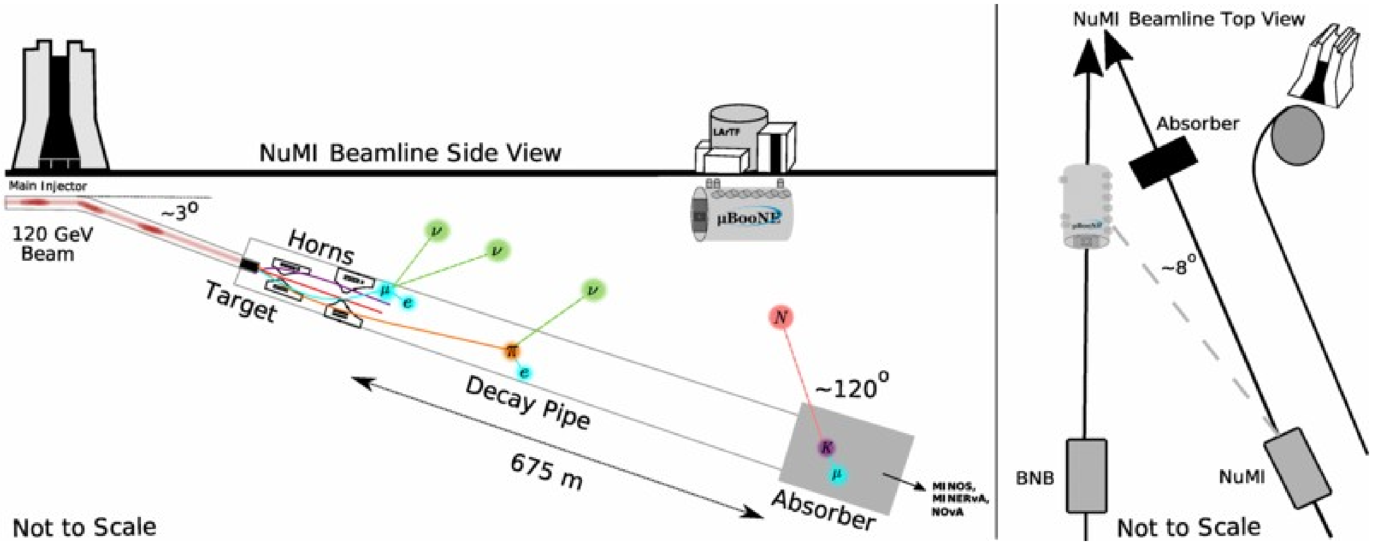
Previous search discarded the full 1.6 μs BNB spill window to suppress the neutrino background.

Neutrinos inherit the RF structure of the proton beam. Appear in **bunches 1.3 ns wide, spaced by 19 ns**.

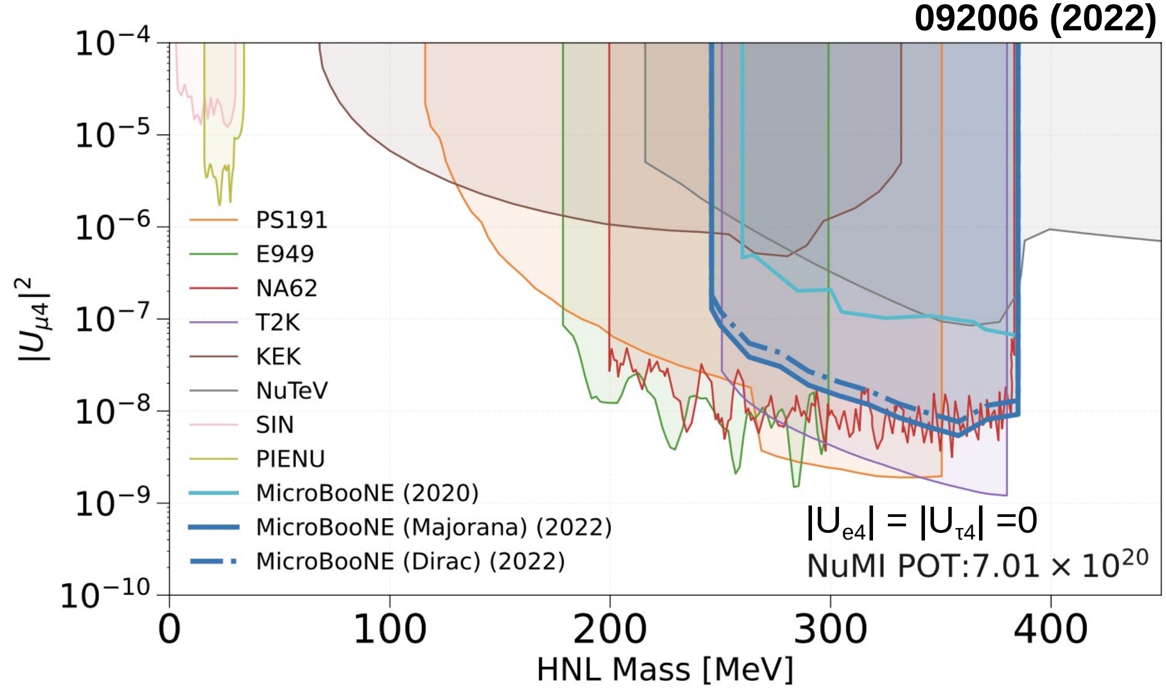
Enhanced scintillation light reconstruction techniques allow us to recover the RF structure of the spill, enabling **searching in-between bunches for long-lived massive particles.**

Phys.Rev.D 108 (2023) 5, 052010

Heavy neutral leptons: NuMI search



Phys. Rev. D 106, 092006 (2022)



Protons surviving the target are dumped into the **NuMI absorber.**

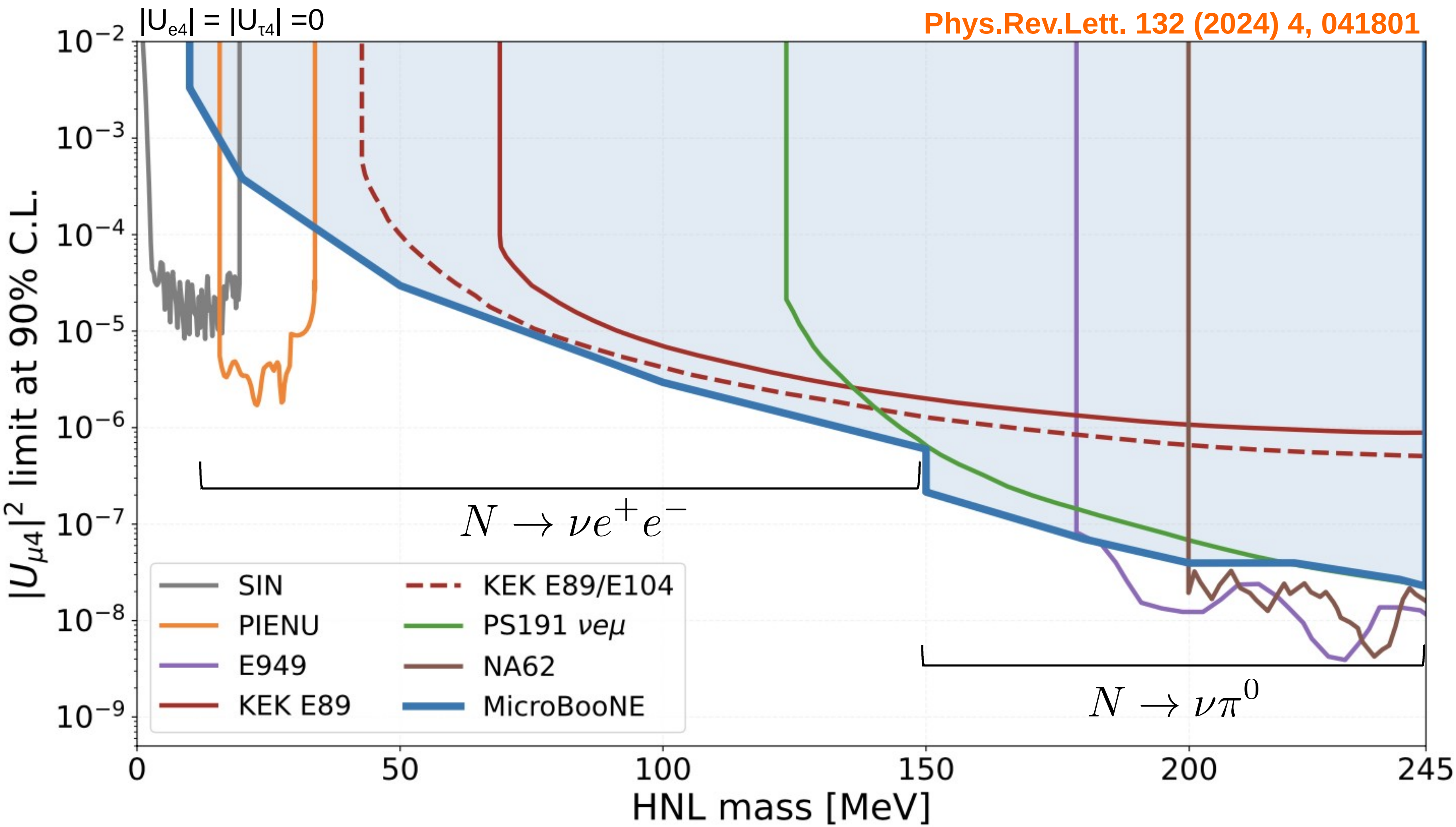
Located **~ 100 m from MicroBooNE → A near detector!**

Exploit the production of BSM particles form **decay-at-rest kaons in the absorber**.

SM neutrino background is **suppressed using the incoming direction** of the particle.

Improvement over previous BNB search.

Heavy neutral leptons: new NuMI search



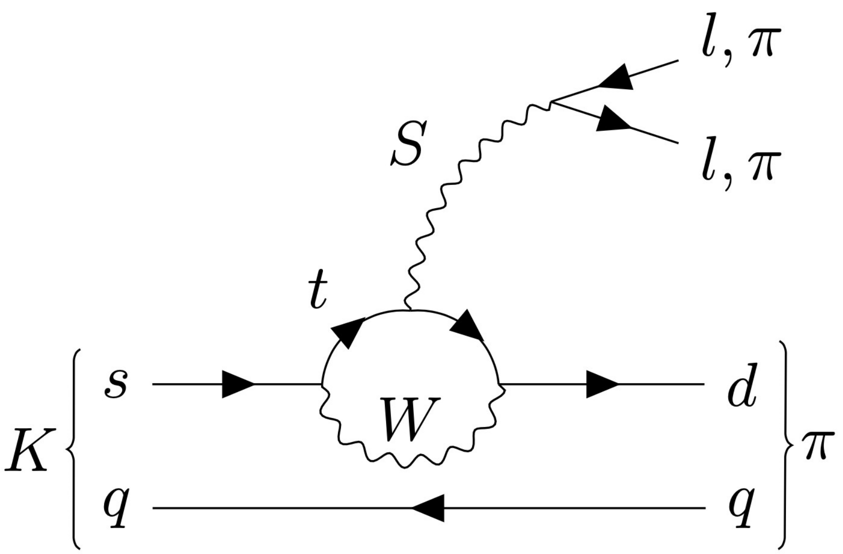
New NuMI search targeting **lower HNL masses** and focused on **EM final states** has set **world-leading limits on HNL via $|U_{\mu 4}|$ mixing.**

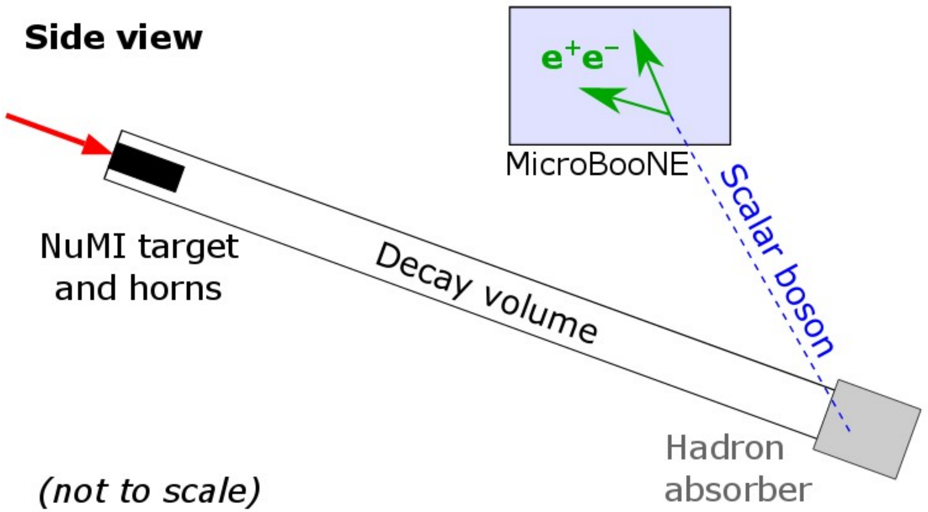
Higgs portal: light scalar

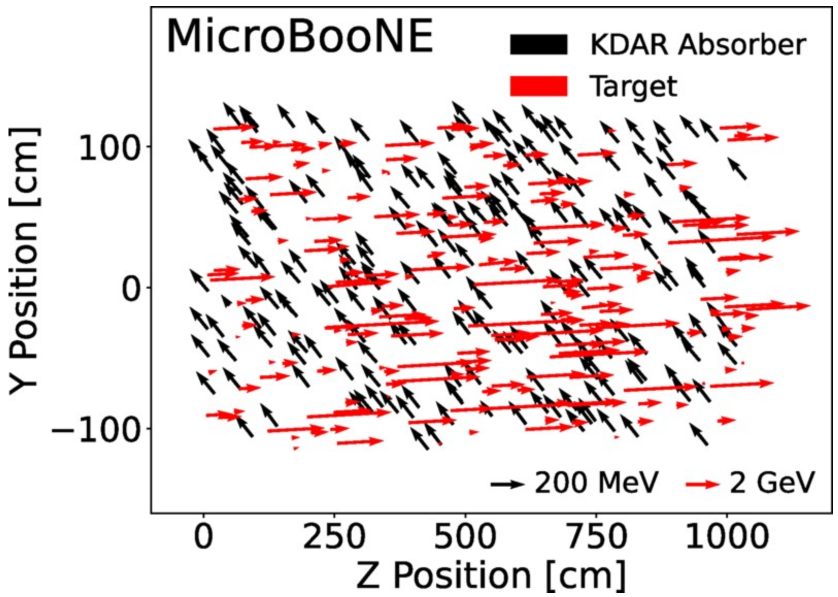
New dark boson that mixes with the SM Higgs boson, parameterized by an angle θ.

May be produced in kaon decays via a Penguin diagram [Proposed in **Phys. Rev. D 100, 115039 (2019)**].

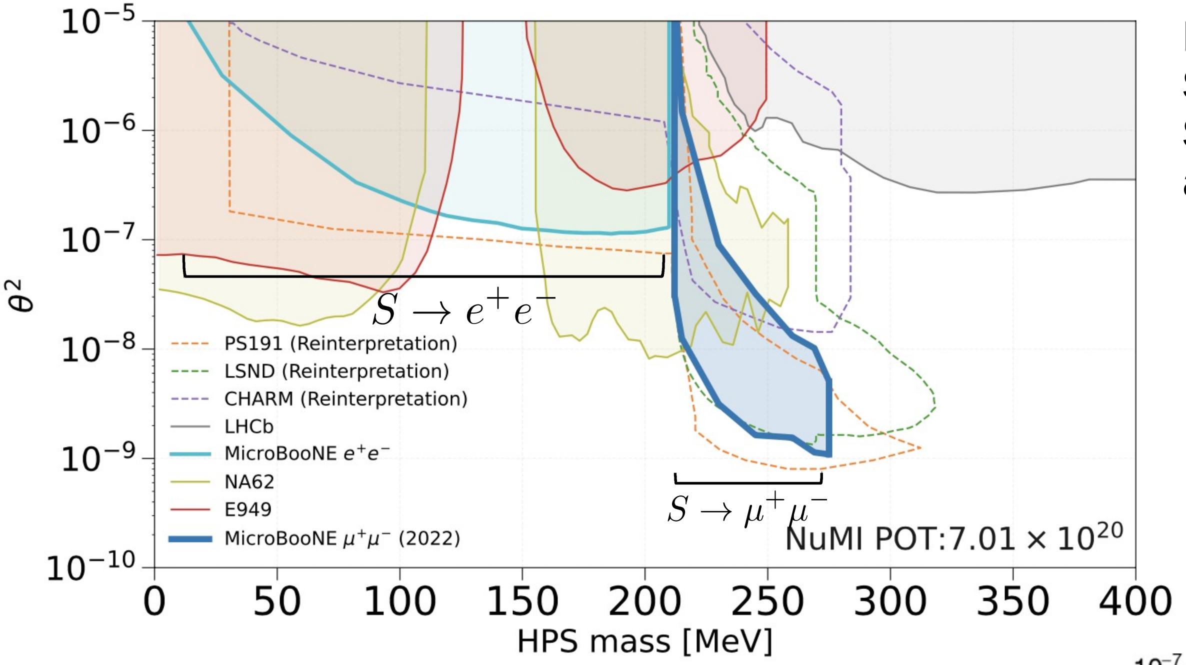
Exploit directionality of signal produced from decay-at-rest kaons in the NuMI absorber vs neutrino background from decay-in-flight mesons in the NuMI beam.







Higgs-portal scalar NuMI searches

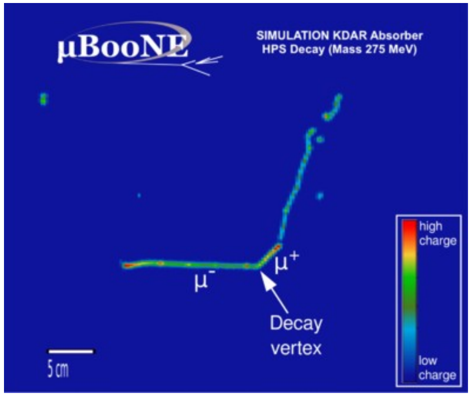


MicroBooNE searched for

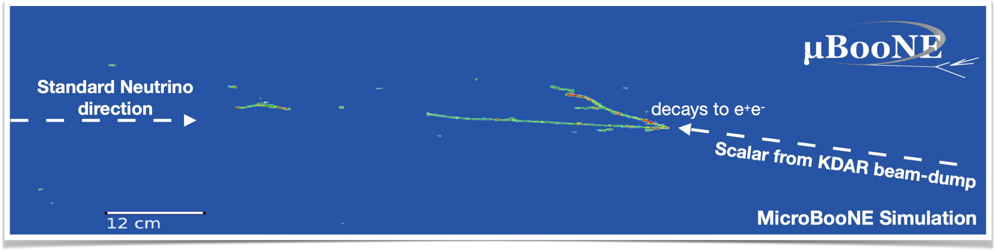
S → e^+ e^- [Phys. Rev. Lett. 127, 151803 (2021)]

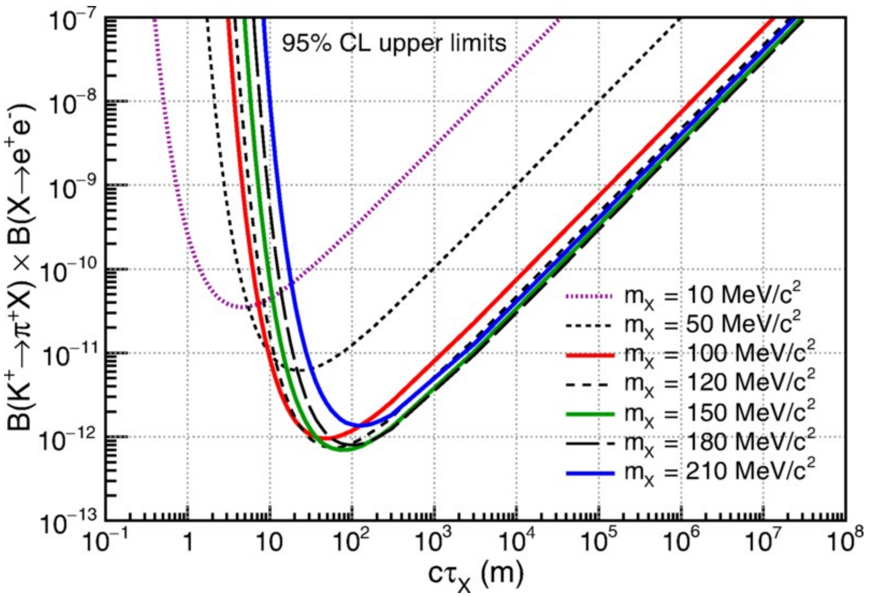
S → μ^+ μ^- [Phys. Rev. D 106, 092006 (2022)]

and **set limits at 90% CL.**

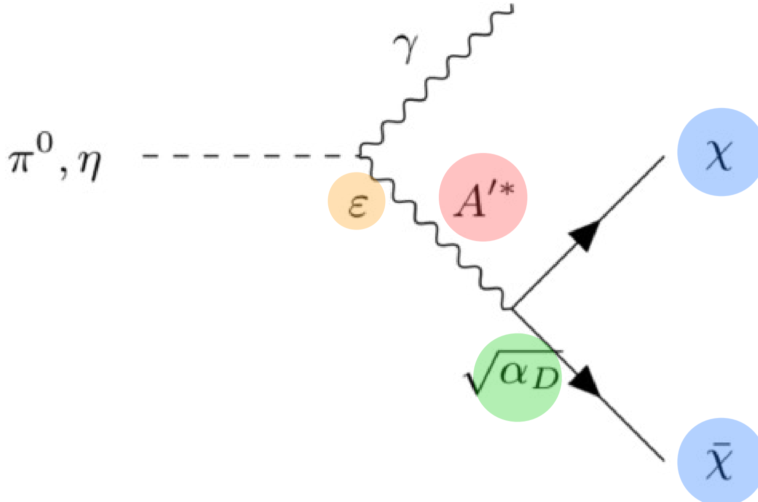


S → e^+ e results also reported as a **model-inpendent search.**





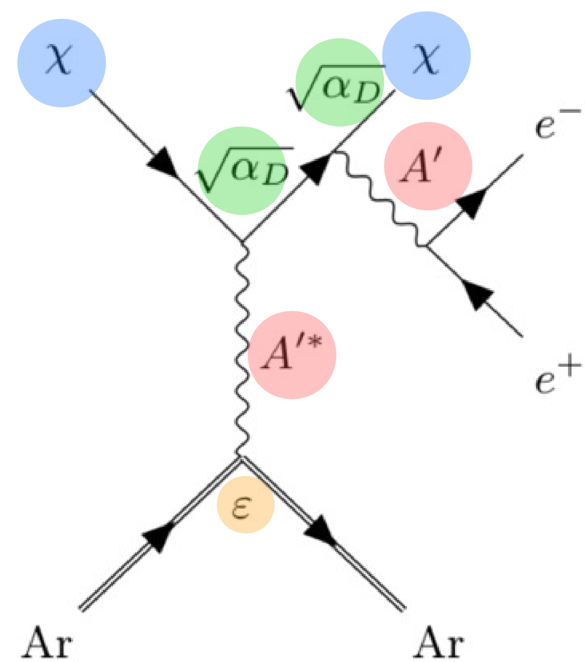
Vector portal: dark photons and dark matter



Proposed in **JHEP 01 (2019) 001.**

Off-shell **dark photon A'** produced in decays of neutral mesons via **kinematic mixing with SM photon (ε)**.

Dark photon (mass M_A) subsequently decays (**α_D coupling**) into **dark matter (DM) particles (mass M_χ)**, either fermions or bosons.



Dark trident: **DM** travels to detector and scatters off an Ar nucleus, radiating another **dark photon that decays into an e^+e^- pair**.

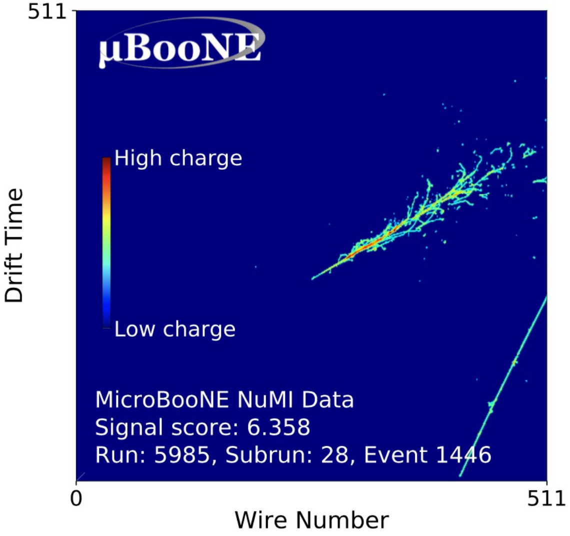
Large off-axis DM flux compared to beam neutrinos due to **neutral mesons not being focused and decaying into 3 bodies.**

Dark trident NuMI search

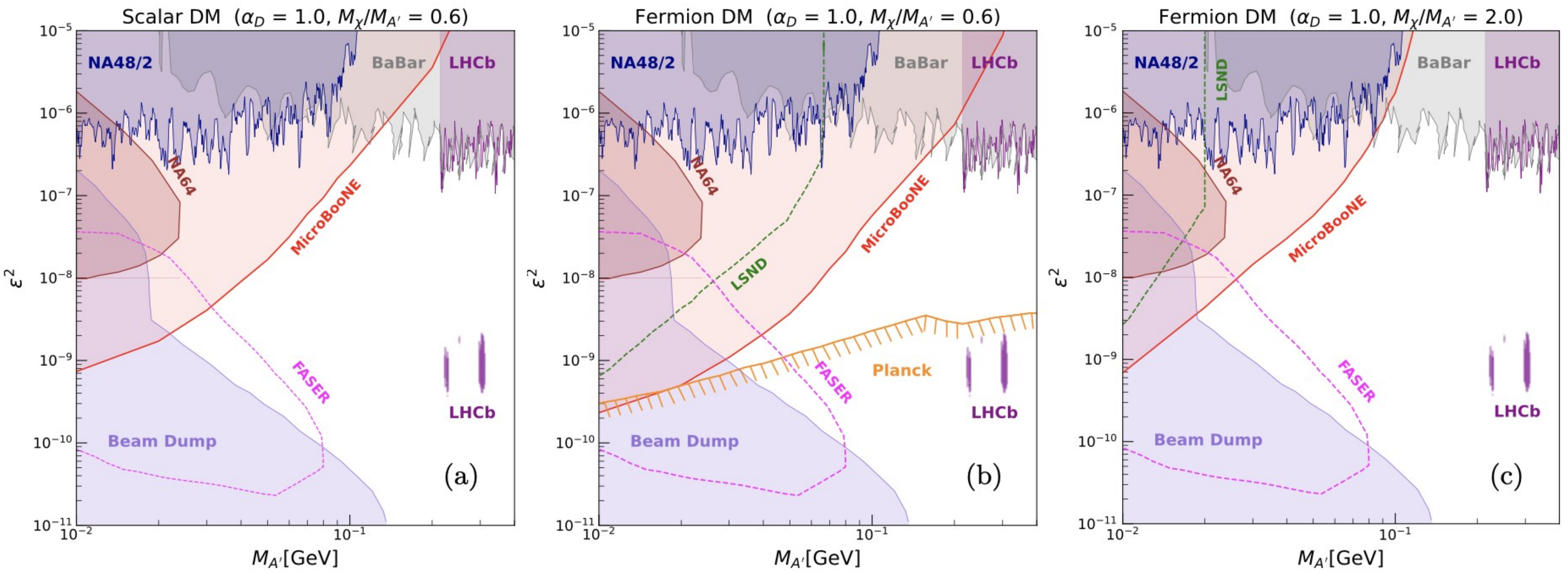
NuMI neutrino **background suppressed due to off-axis location**.

Signal selection using **deep learning methods** (convolutional neural network).

Exclude previously unexplored space for dark photons with mass between 10 and 400 MeV at 90% CL.



Just published! Phys.Rev.Lett. 132 (2024) 24, 241801



Neutron-antineutron oscillation search

Neutron-antineutron oscillation predicted by BSM theories with **baryon number violation**.

Antineutron annihilates with a neutron within the Ar nucleus, producing a charateristic topology of pions.

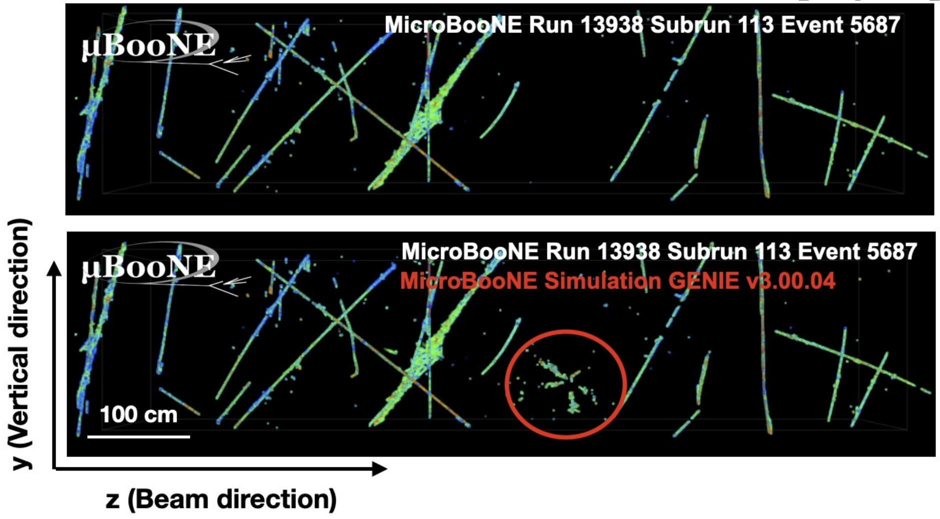
MicroBooNE search uses **non-beam triggers.**

MicroBooNE's exposure cannot compete with large detectors (e.g. Super-Kamiokande) but serves as **demonstrator for the future DUNE Far Detector** (same LArTPC technology).

We use **deep learning techniques** to identify the topology and achieve 70% signal efficiency.

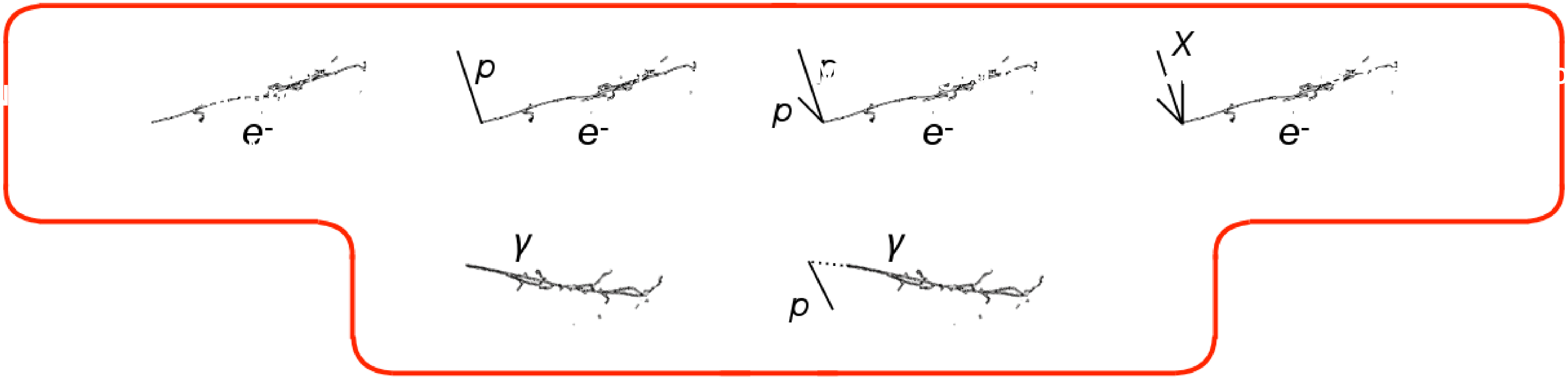
Our techniques can **improve DUNE's** TDR **efficiency** (assumed to be 8%) for neutron-antineutron searches [arXiv:2002.03005 [hep-ex]].

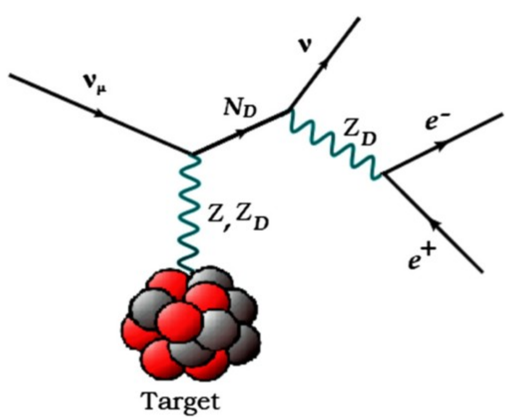
arXiv:2308.03924 [hep-ex]



Probing the MiniBooNE anomaly

MicroBooNE's first series of LEE search results





First searches for the origin of the MiniBooNE low-energy excess (LEE) did not find an excess.

Work in progress to **search for new topologies**. Stay tuned!

Phys.Rev.Lett. 121 (2018) 24, 241801
Phys.Rev.D 99 (2019) 071701

Conclusion

MicroBooNE has:

light sterile-neutrino oscillation searches (more coming soon),

a **comprehensive neutrino cross-section program** (not covered today),

a **blooming BSM physics program**: heavy neutral leptons, Higgs-portal scalars, dark tridents, neutron-antineutron oscillation.

Exciting analyses are in progress: e^+e^- production from Z'/Z_D decays, axion-like particles, millicharged particles...

The full **Short-Baseline Neutrino Program** at Fermilab, and the future **DUNE Near Detector** complex and the powerful LBNF beam, will be able to push beyond the current limits.

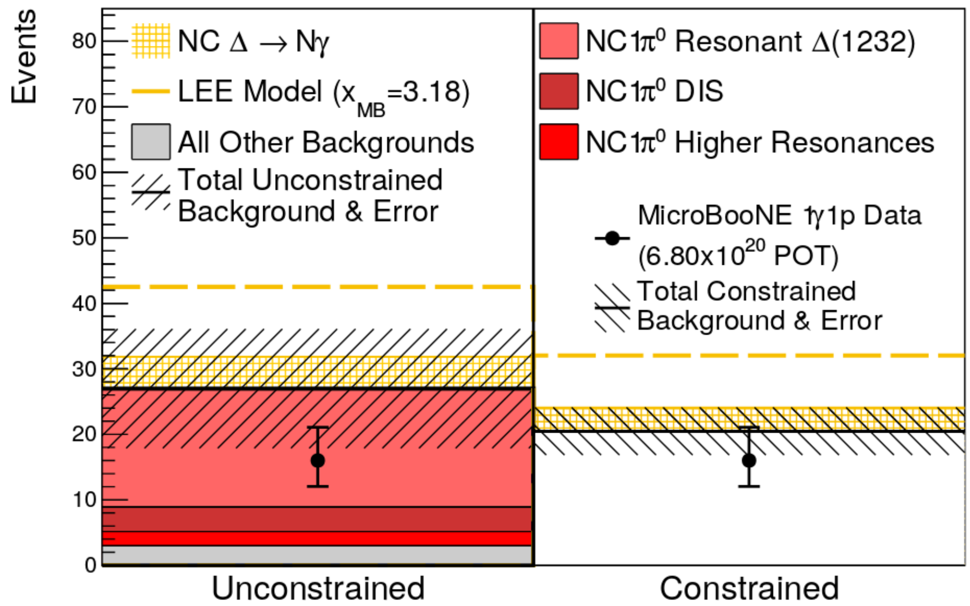
New ideas to test with our data are most welcomed!

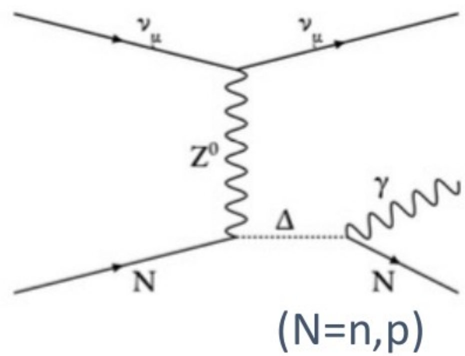
Thank you for your attention!

jcrespo@ciemat.es

Backup

Search for anomalous production of single photons





A × 3.18 enhancement of the effective branching ratio of NC Δ → Nγ describes well the MiniBooNE excess.

Two search topologies: 1γ1p and 1γ0p.

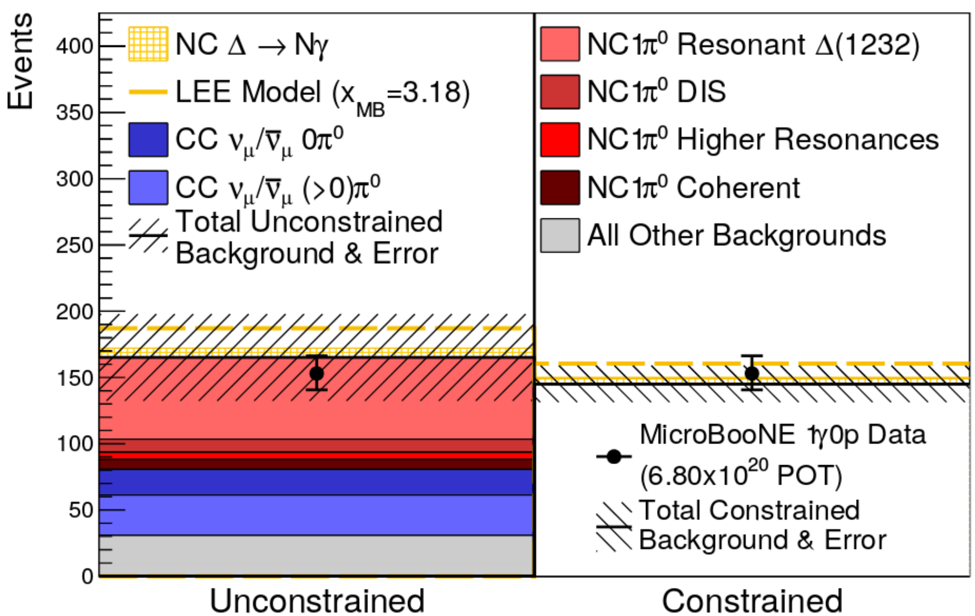
Backgrounds constrained from dedicated in-situ high-purity NC π^0 measurement (both 2γ1p and 2γ0p).

Result shows no excess with respect to SM.

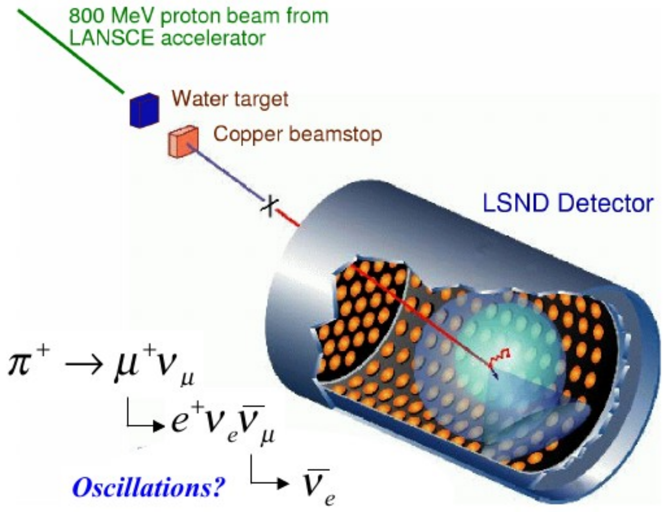
NC Δ → Nγ explanation of the excess is disfavored at 94.8% CL.

PRL. 128 (2022) 11, 111801

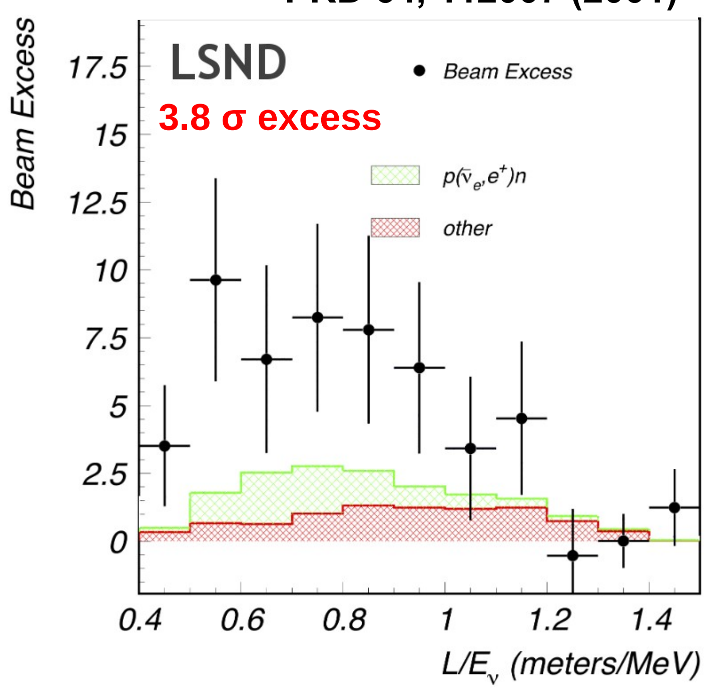
More single photon analyses soon!



LSND experiment



PRD 64, 112007 (2001)



Antineutrinos from π^+ & μ^+ decay at rest source.

Very low intrinsic $\overline{\nu}_e$ contamination.

Liquid scintillator detector.

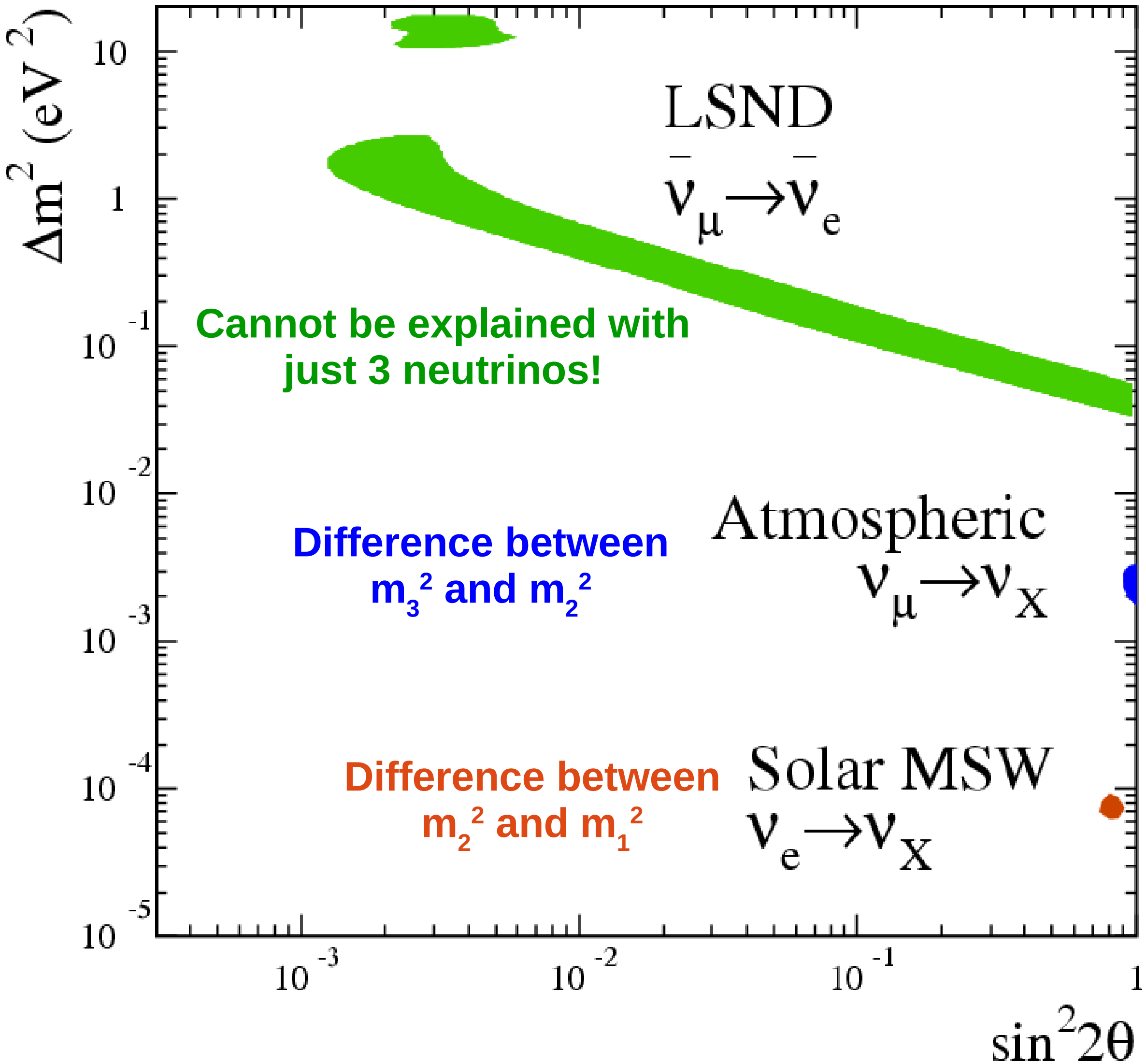
Low background & well-understood cross-section: inverse β-decay detection.

$$\overline{\nu}_e + p \rightarrow e^+ + n$$

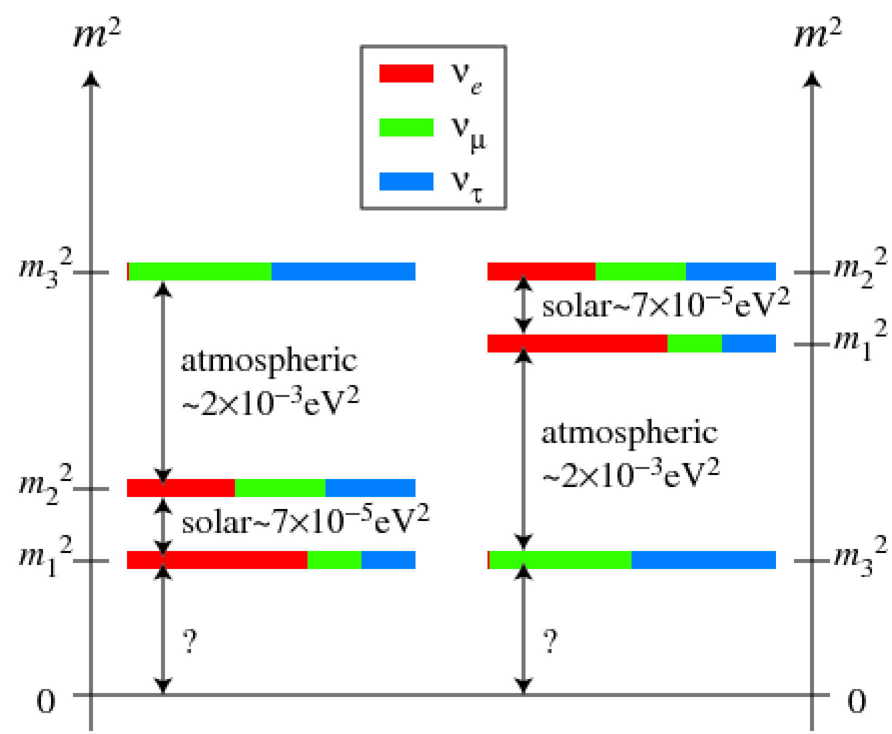
$\overline{\nu}_e$ excess observed.

LSND anomaly

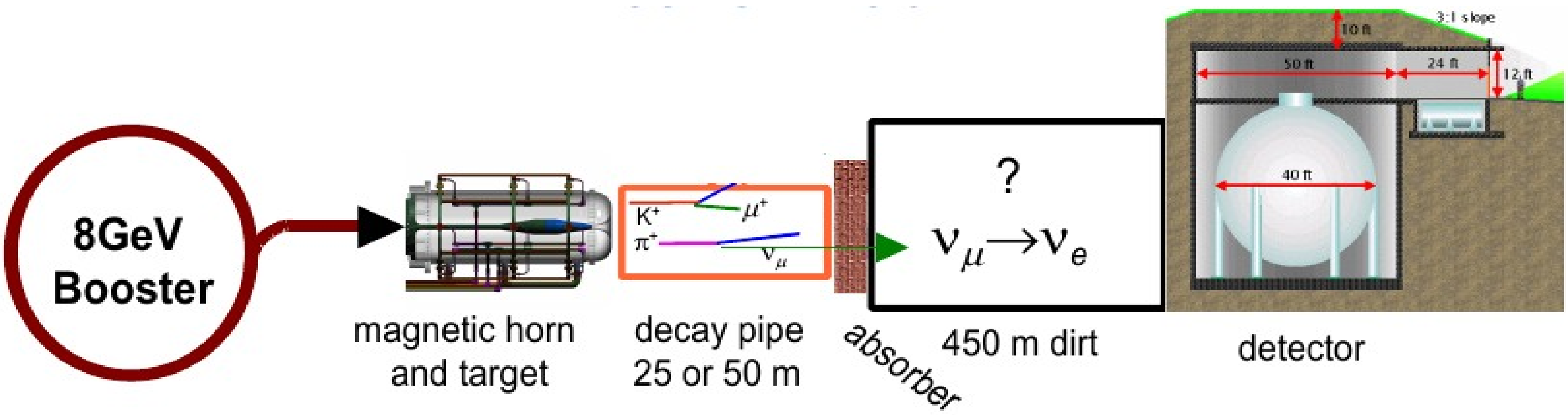
If the excess is interpreted as **oscillations**:



$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$



MiniBooNE experiment



Different beam: mostly pion decay-in-flight experiment.

Magnetic horn enhances neutrino/antineutrino.

Higher energy and longer baseline.

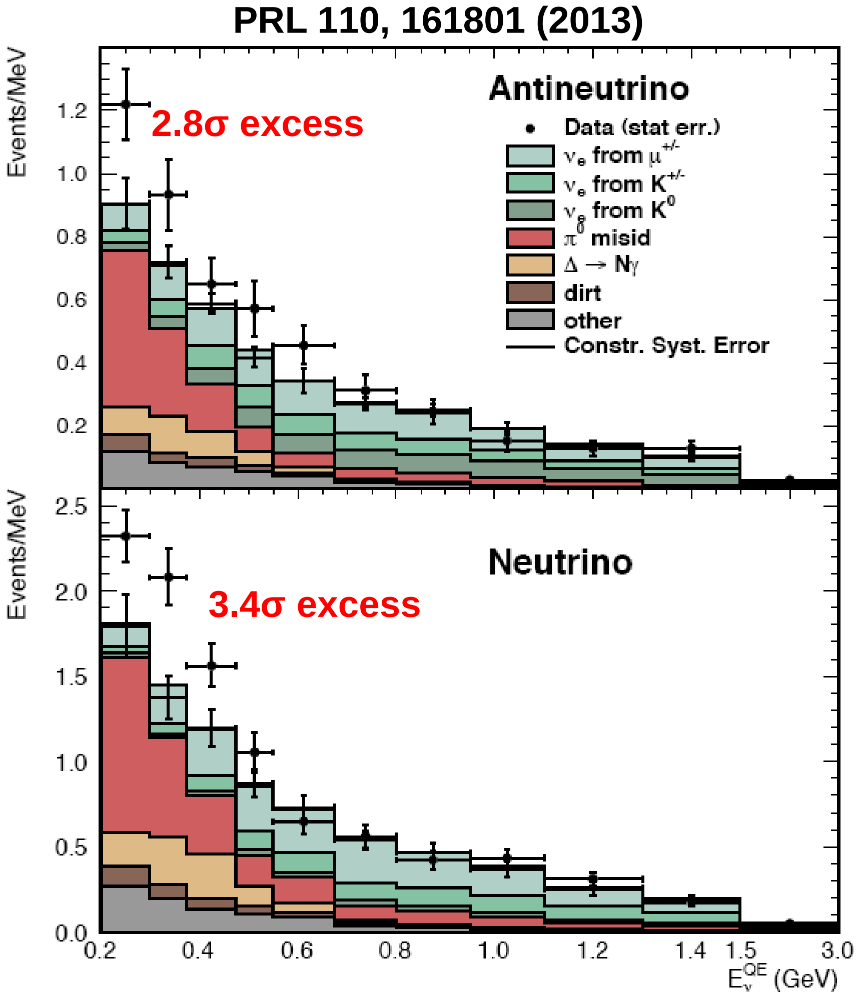
Different detector: Cherenkov detector.

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Different event selection and systematic uncertainties.

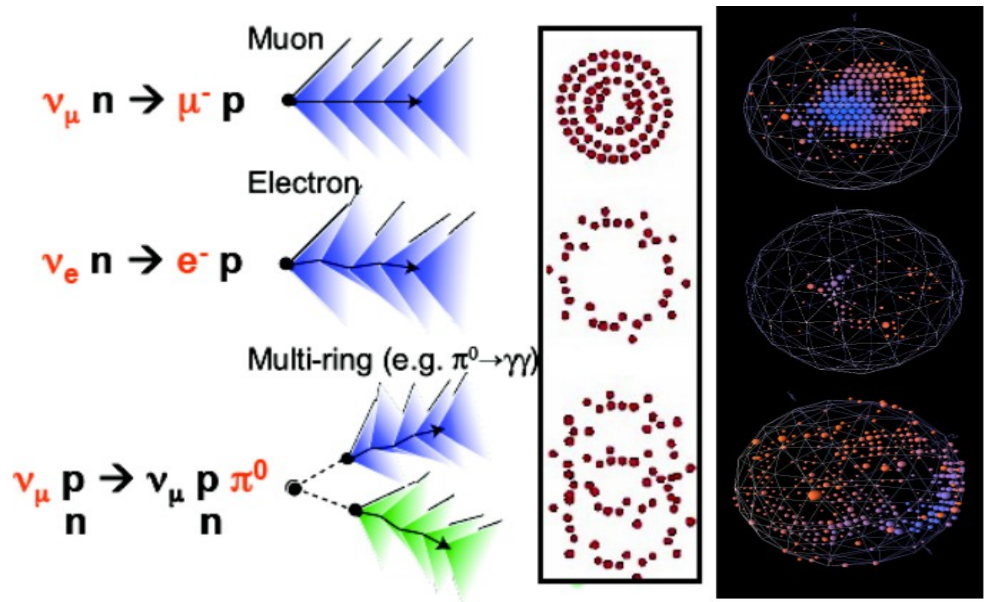
Similar L/E to explore the same oscillation region.

MiniBooNE anomaly



Excess of events observed.

Cherenkov detector. Could **not distinguish between electron and gamma.**



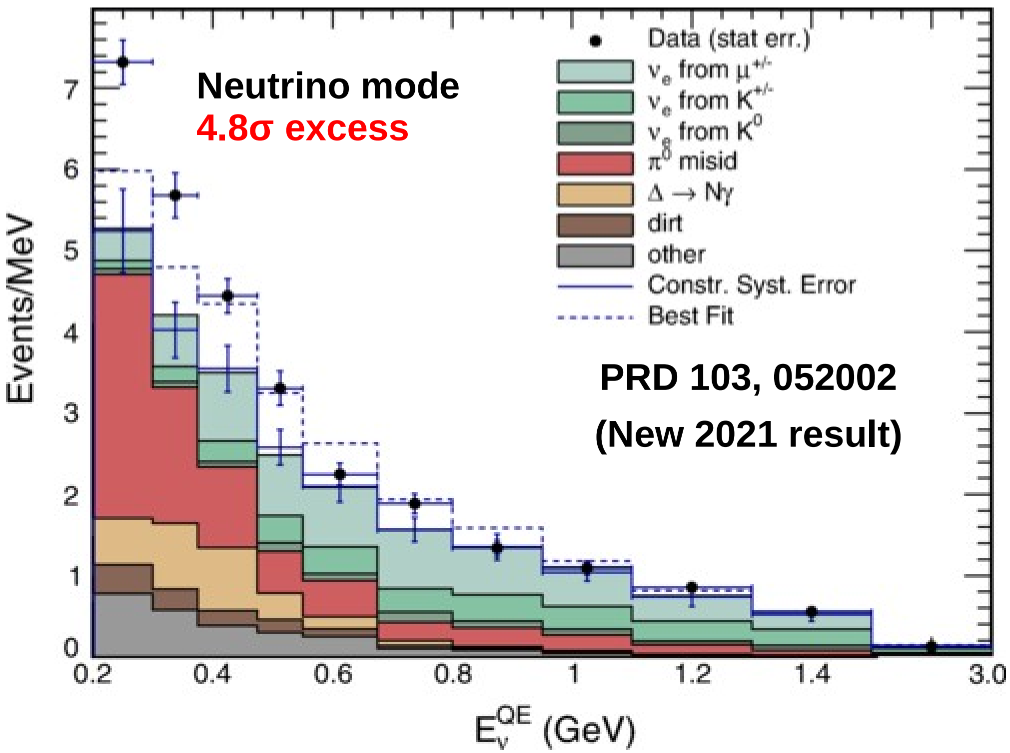
New MiniBooNE results

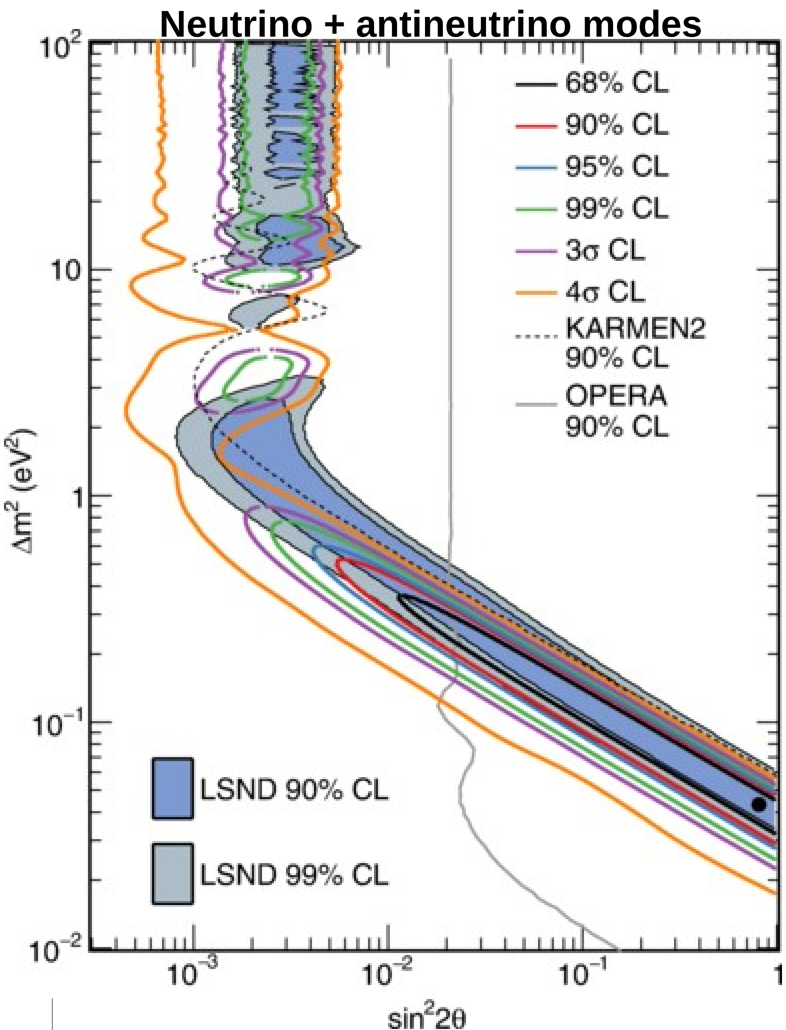
Latest MiniBooNE results (2018, 2021) more than **doubled statistics** in neutrino mode.

Old and new datasets are **consistent** with each other.

Same analysis. Improved background constrains with the additional statistics.

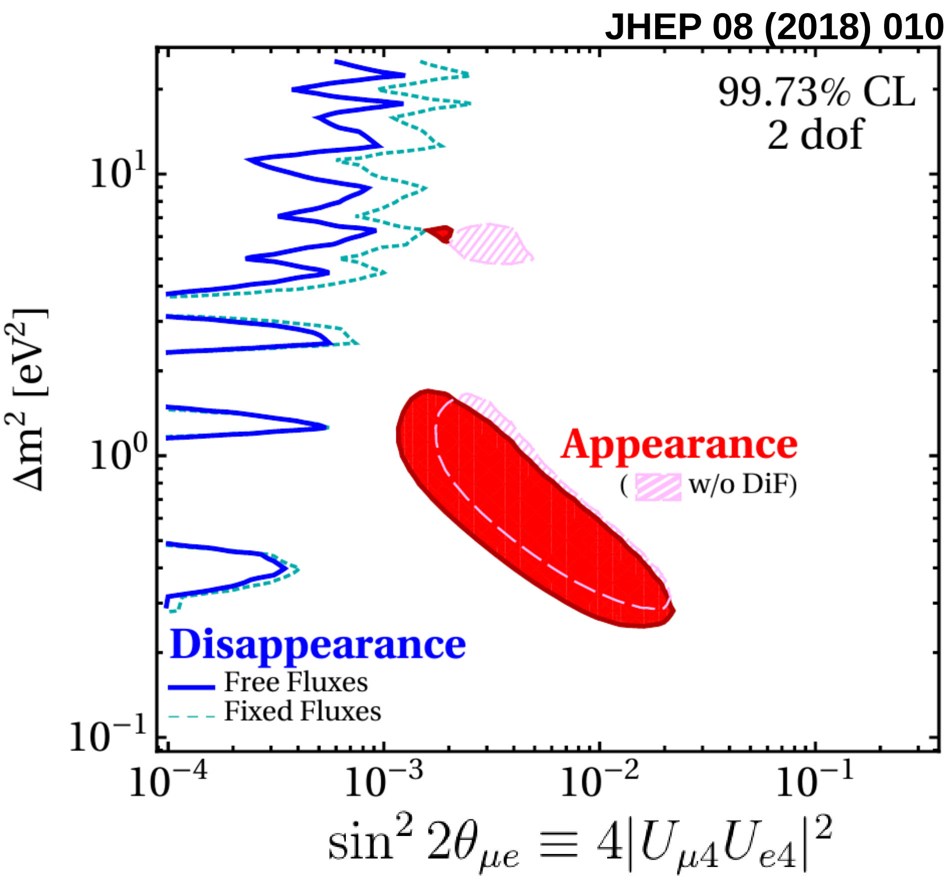
Consistent results with **LSND**.





SM neutrinos have Δm^2 of $O(10^{-3})$ and $O(10^{-5})$ eV^2.

Short-Baseline Neutrino Anomalies



Other anomalies in reactor and **radioactive source experiments** also interpreted as neutrino oscillations point to **$\Delta m^2 \sim 1$ eV^2.**

Cannot be explained with the 3 Standard Model neutrinos.

Minimal model (3 + 1) requires an **additional heavier neutrino mass eigenstate, m_4, mostly sterile.**

Most of the very short-baseline reactor new experiments do not see an oscillation signal.

Cosmology observations consistent with 3 ν.

Tension between appearance and disappearance experiments. (3 + 2) or (3 + 3) models do not improve much.

Is the MiniBooNE excess really caused by appearance of electron neutrinos?

If not, what is it?