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Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

Short-Baseline Neutrino Experiments

Minerba Betancourt (Fermilab) 20 September 2024

NuFact 2024

Introduction

- Three flavors ν_e, ν_μ and ν_τ have been observed
- The two mass differences and the three mixing angles have been measured by observing neutrino oscillation from solar, reactor, atmospheric and accelerator neutrino experiments

Atmospheric+Accelerator

$\Delta m^2_{32} \sim 2.5 \times 10^{-3} eV^2$

$\nu_\mu \rightarrow \nu_\mu$
$\nu_\mu \rightarrow \nu_\tau$

Reactor+Accelerator

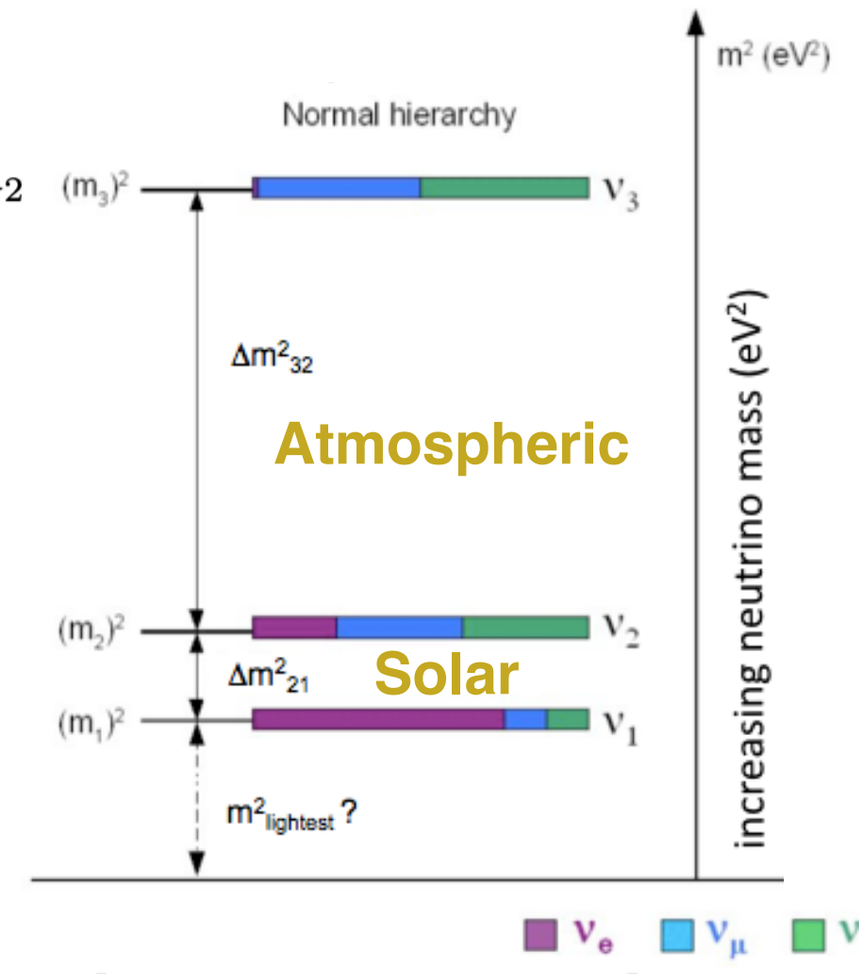
$\Delta m^2_{31} \simeq \Delta m^2_{32}$

$\nu_e \rightarrow \nu_e$
$\nu_\mu \rightarrow \nu_e$

Solar+Reactor

$\delta m^2_{21} \sim 8 \times 10^{-5} eV^2$

$\nu_e \rightarrow \nu_e$
$\nu_e \rightarrow \nu_\mu + \nu_\tau$



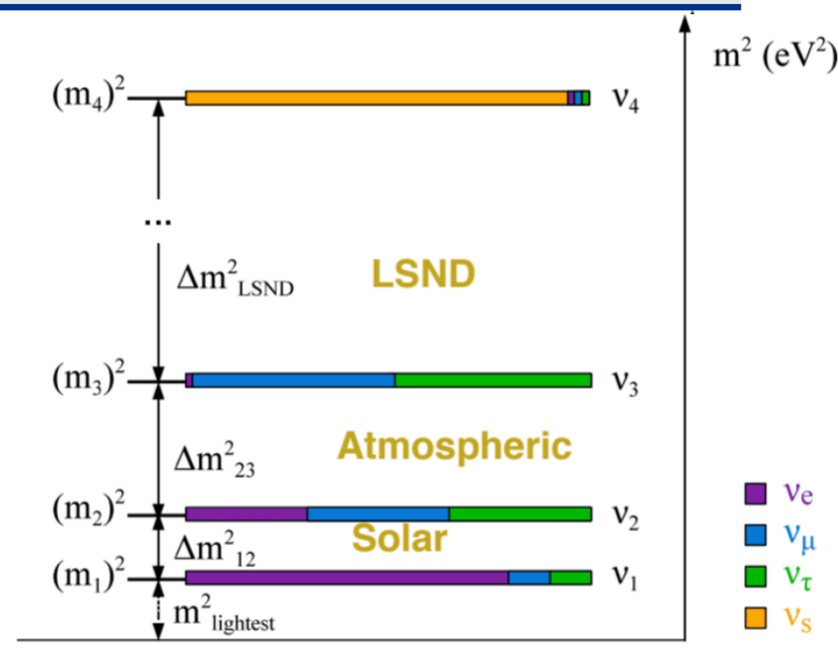
- Current and future experiments will address the remaining questions
  - The mass hierarchy, CP violation in the lepton sector precision measurements of three mixing angles
- Anomalous neutrino measurements
  - Neutrino oscillation experiment published results inconsistent with the 3-flavor framework
  - A sterile neutrino with mass ~0.1-100 eV^2 would explain the anomalous results

Is there a fourth neutrino?

- Several anomalies have been observed in neutrino experiments at short baseline in the last 20 years
- These anomalies provided hints to indicate there is a fourth and non-weakly interacting (sterile) type of neutrino

Experiment	Type	Channel	Significance
LSND anomaly	DAR accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8 σ
MiniBooNE anomaly	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8 σ
GALLEX/SAGE	Source – e	ν_e disappearance	2.8 σ
Reactors anomaly	β decay	$\bar{\nu}_e$ disappearance	3.0 σ

- Each possibly explained by non standard sterile neutrino states driving oscillations at $\Delta m^2_{new} \approx 1$ eV^2 and small $\sin^2(2\theta_{new})$
- Is there any additional physics beyond the 3- flavor mixing neutrino oscillation?



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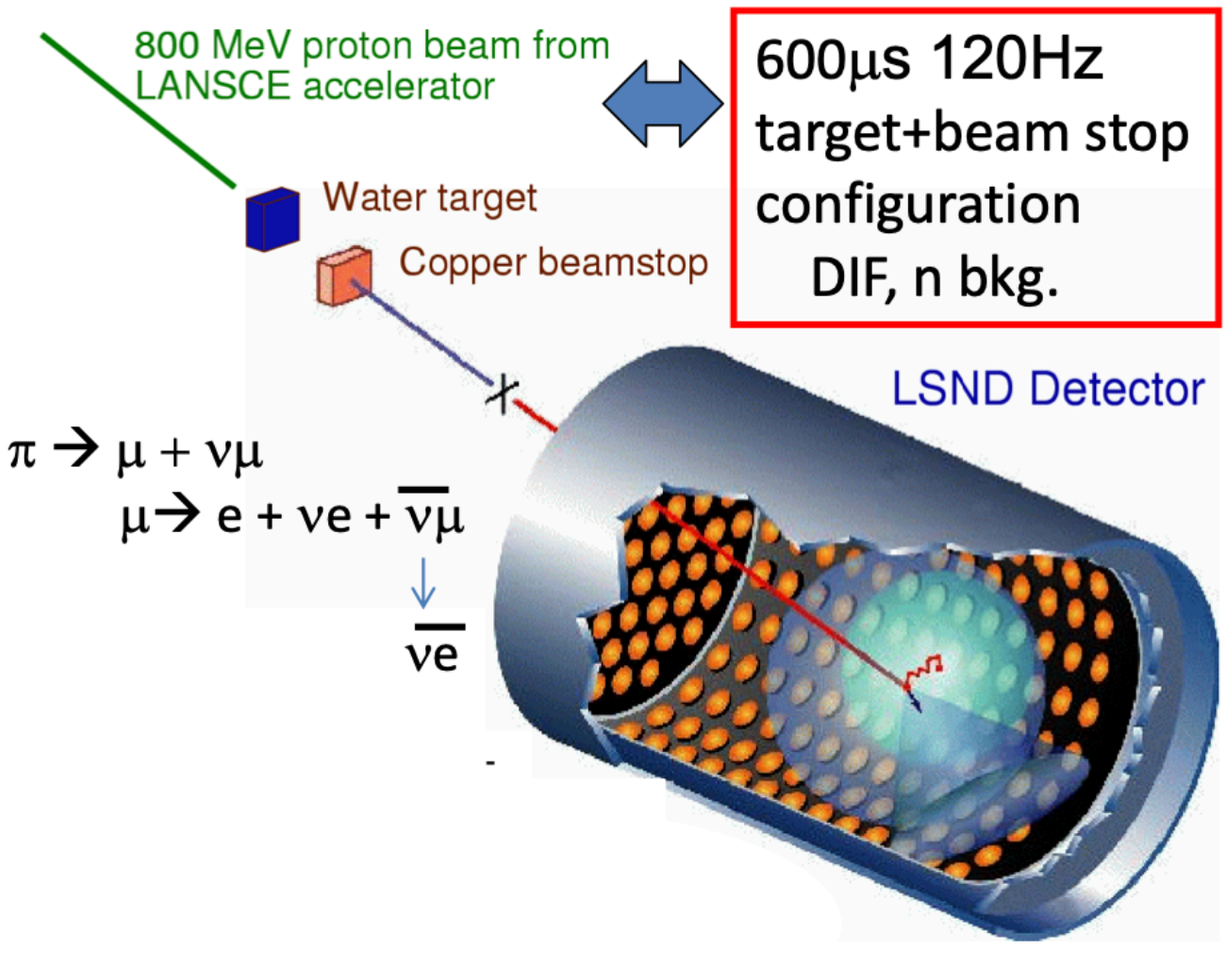
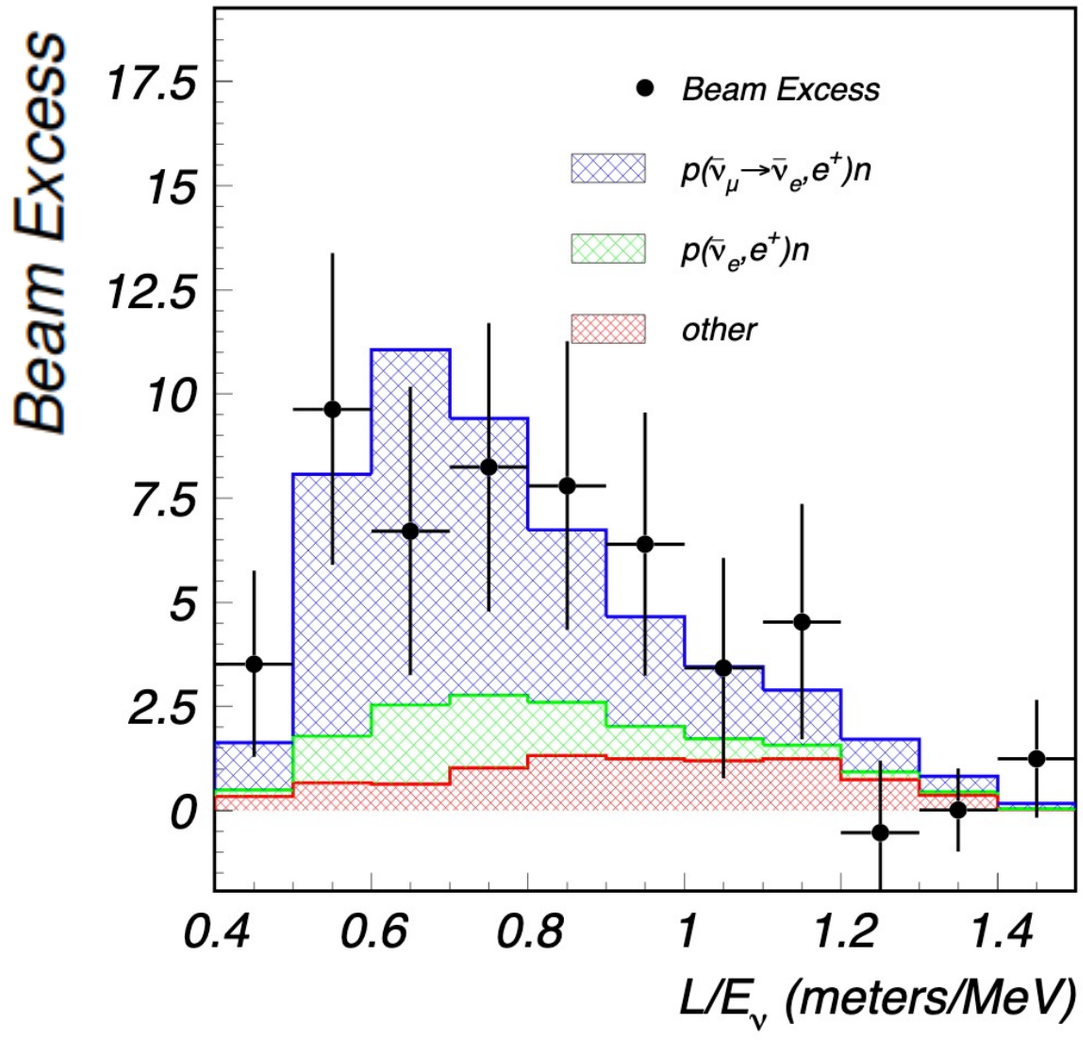
Short Baseline Oscillation Search

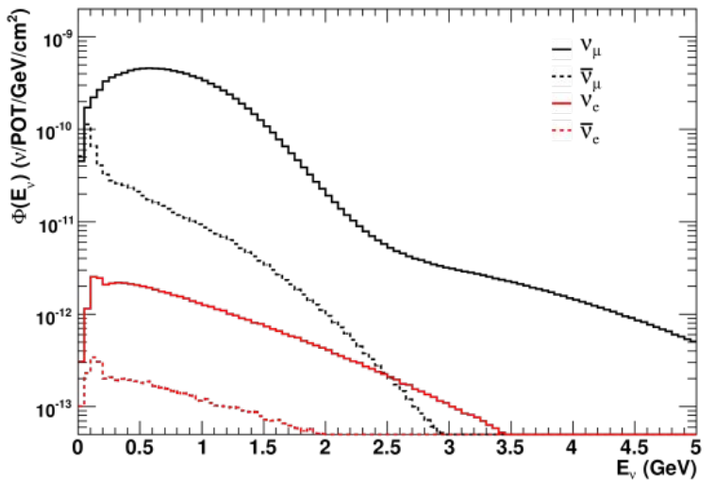
- Using neutrinos from π—>μ decay at rest
- LSND collaboration observed 3.8 sigma excess over SM prediction
- Saw an excess of: 87.9 ± 22.4 ± 6 events

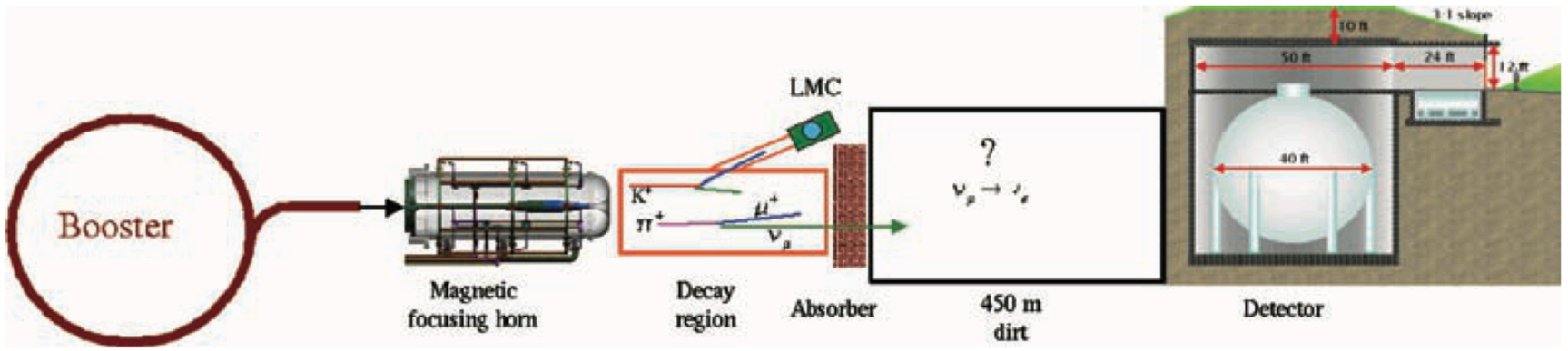


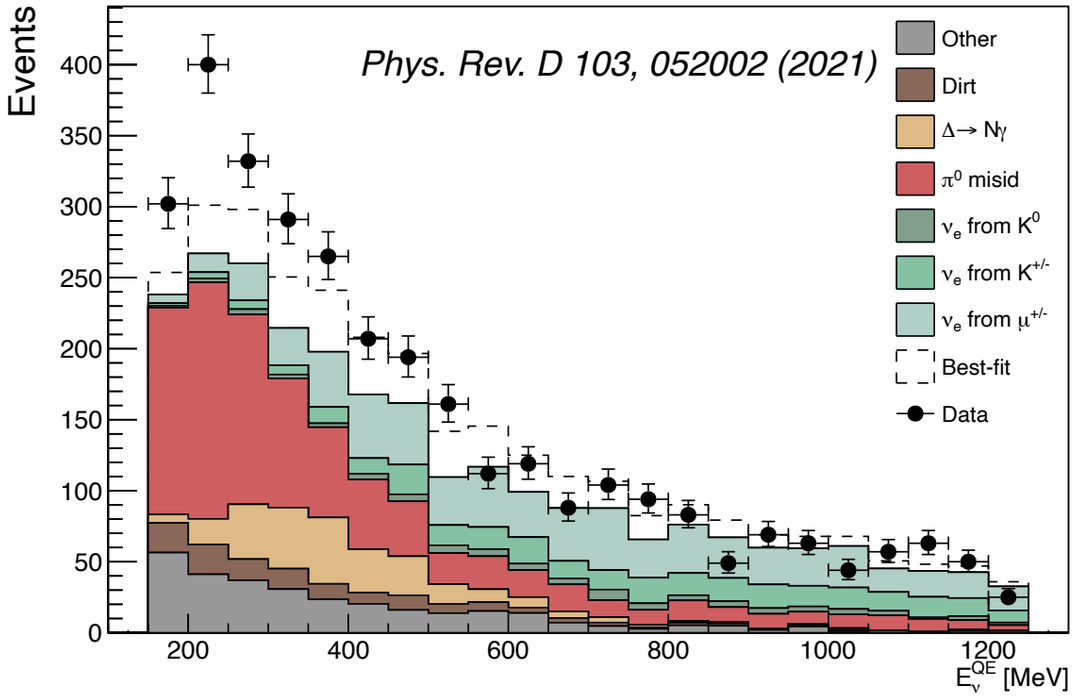


MiniBooNE Experiment

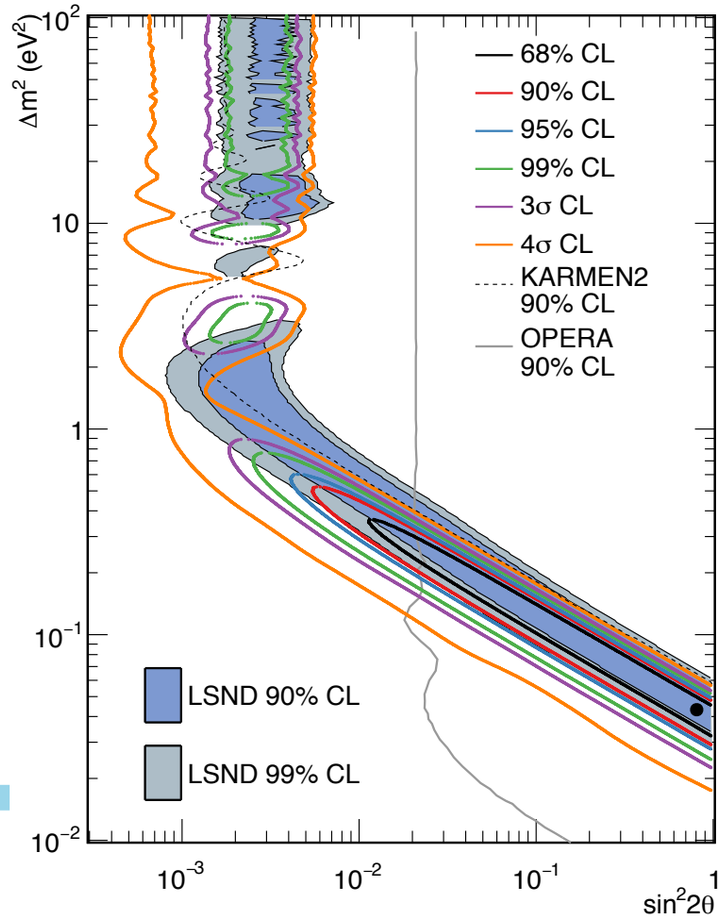
- Designed to test LSND signal: search for $\nu_\mu \rightarrow \nu_e$ appearance at L/E ~1
- MiniBooNE used neutrinos from Booster at Fermilab with a mineral oil Cherenkov detector







- 4.7 σ excess of electron neutrino events



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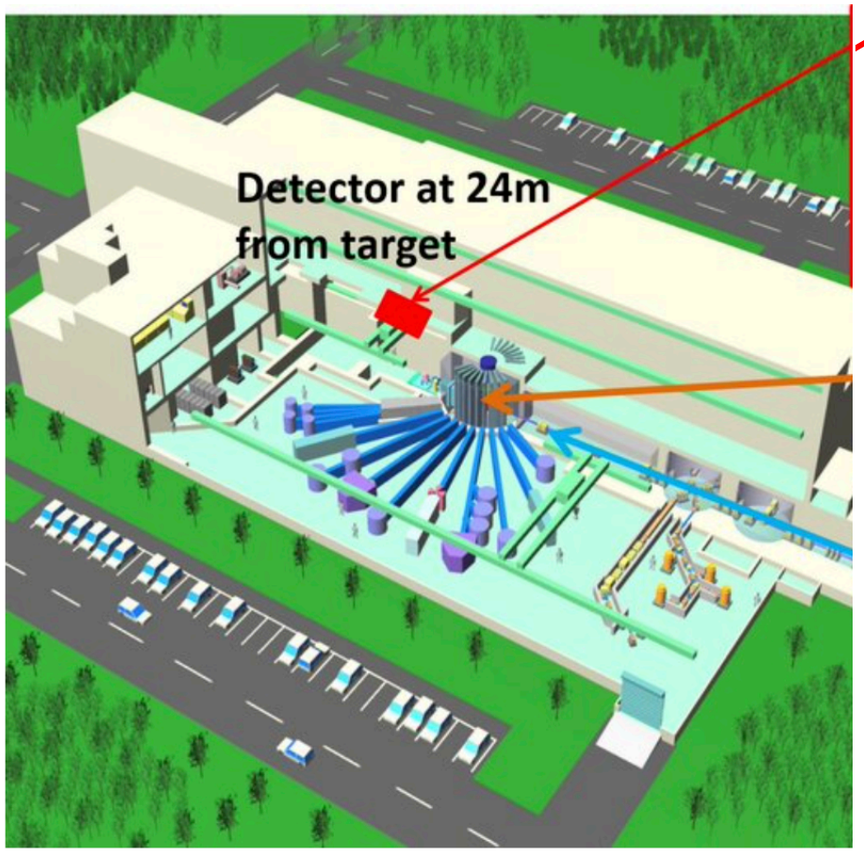
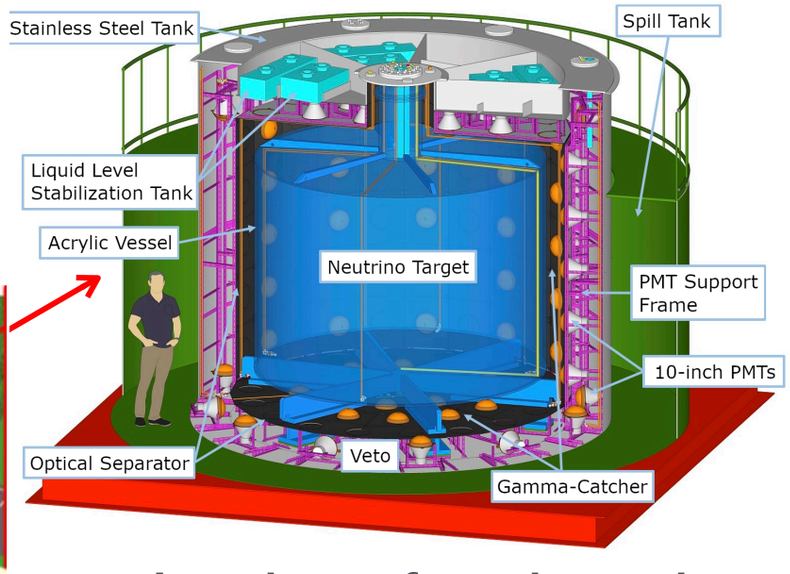
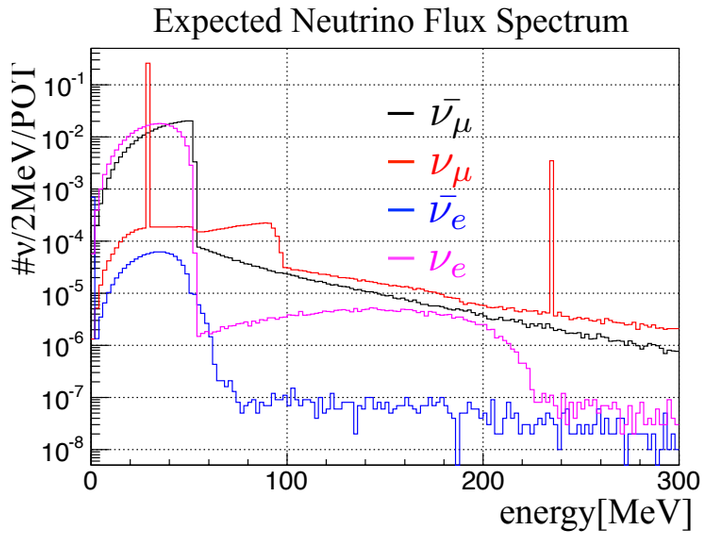
Searches with JSNS²

- Located at Materials and Life Science Facility at J-PARC
- A 1MW of 3 GeV protons incident on a spallation neutron target produces an intense and pulsed neutrino source from pion, muon and kaon at rest
- Data taking began in spring 2020 with commissioning, first physics runs were collected in 2021 and 2022

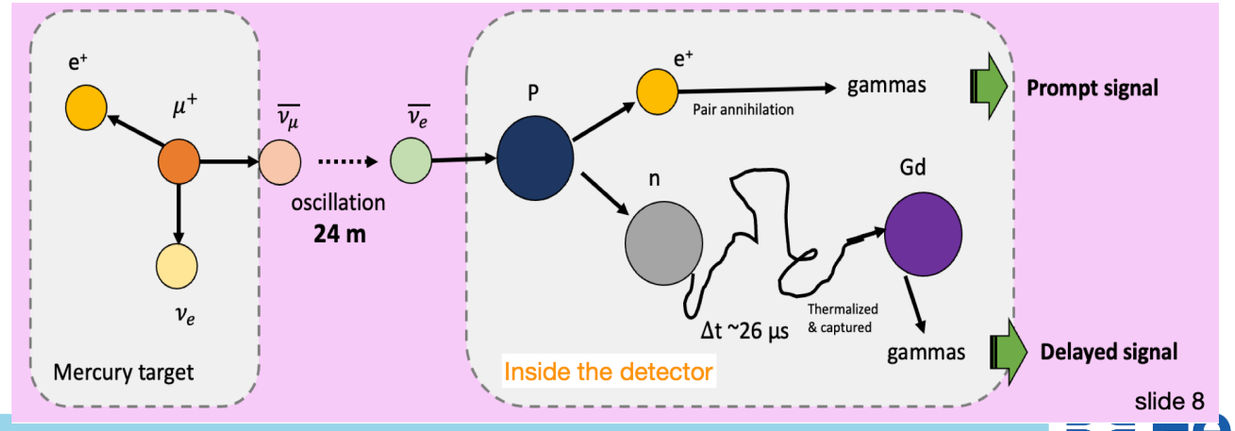
Detector is 17tons of gadolinium loaded liquid scintillator







- Looking for short baseline $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with neutrinos from muon decay



See more details in New Results and Status of JSNS² by Dongha Lee

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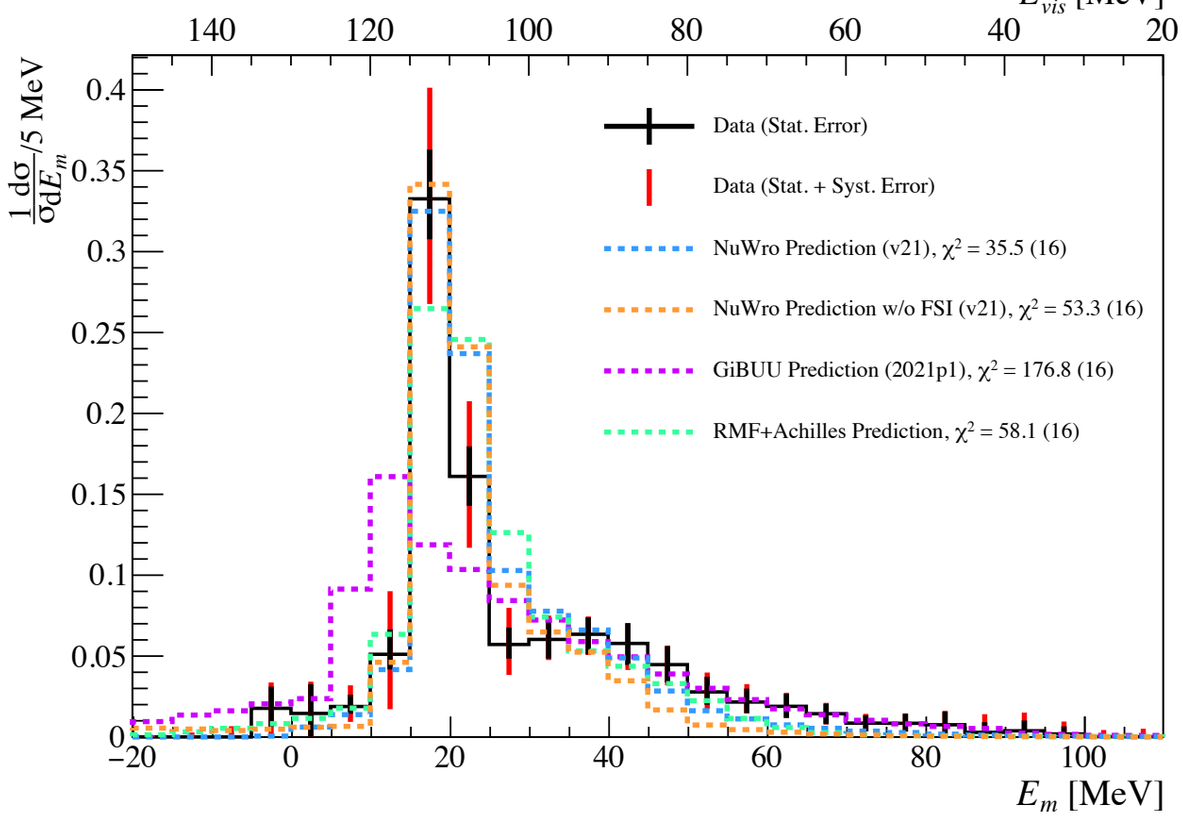
First KDAR Missing Energy Measurement

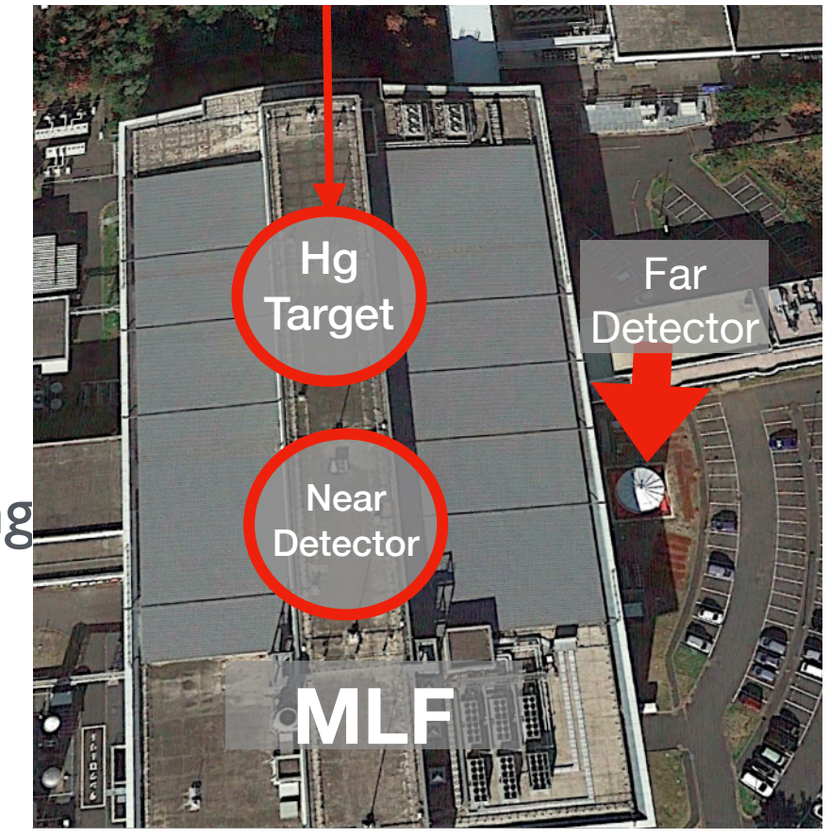
- JSNS^2 released the first measurement of the missing energy due to nuclear effects in mono energetic muon neutrino charged-current interactions on carbon
  - Neutrinos from $K^+ \rightarrow \mu^+ \nu_\mu$ decay-at-rest ($E_{\nu\mu}$=235.5 MeV)
- The missing energy is sensitive to nuclear effects (Fermi momenta, final-state interactions and nucleon separation energy)
- Differential cross section measurement compared to several neutrino event generators/model predictions

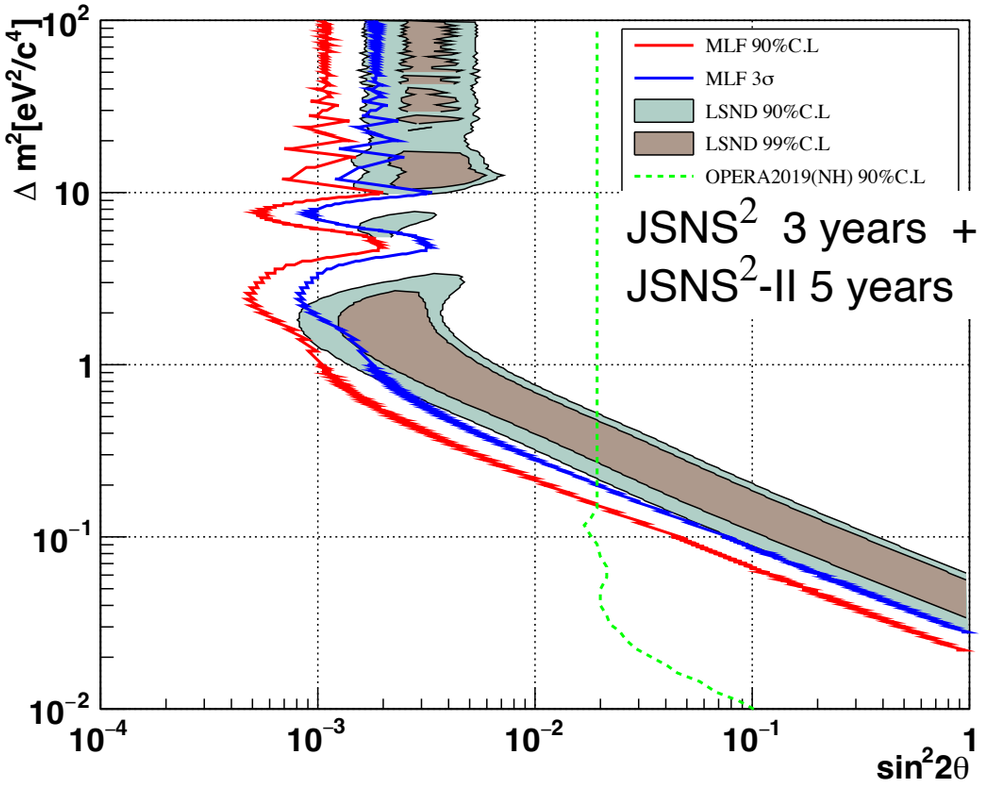


https://arxiv.org/abs/2409.01383

Searches with JSNS^2-II

- New far detector, design identical to the near detector
- Target volume 32-tonnes, baseline is 48 m
- A second baseline allows observation of oscillation signature
- Improves sensitivity across parameter space, especially at low Δm^2 values
- Construction began in 2021, expected to begin data taking in 2025

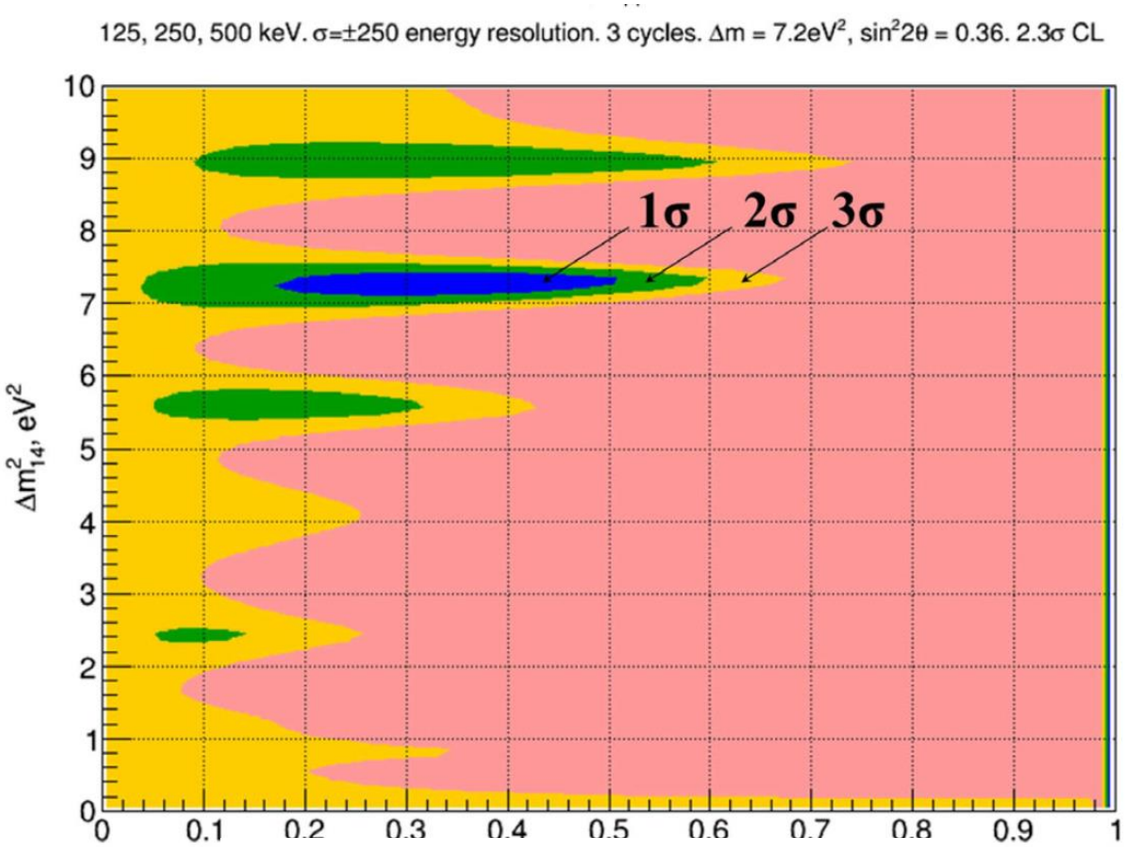


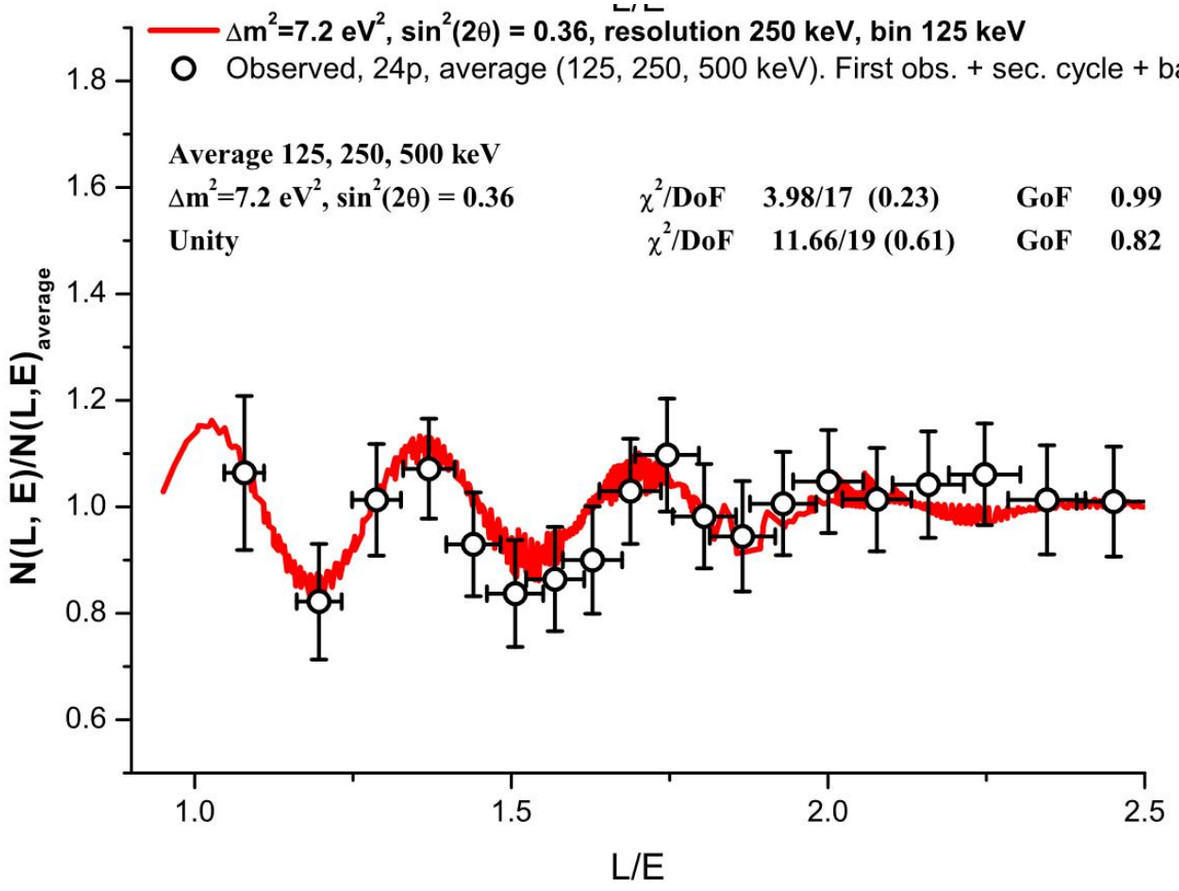


Searches with Neutrino-4

- Neutrino-4 experiment located close to SM-3 reactor in Dimitrovgrad (Russia)
  - The SM-3 is a 90 MW research reactor with a compact core 35x42x42 cm^3 using highly enriched U fuel
- Neutrino-4 published results in 2020: 2.9σ tension with the three flavor oscillation model

$$\Delta m^2_{14} = (7.3 \pm 1.17)\ \mathrm{eV}^2 \qquad \sin^2 2\theta = 0.36 \pm 0.12_{stat}(2.9\sigma)$$





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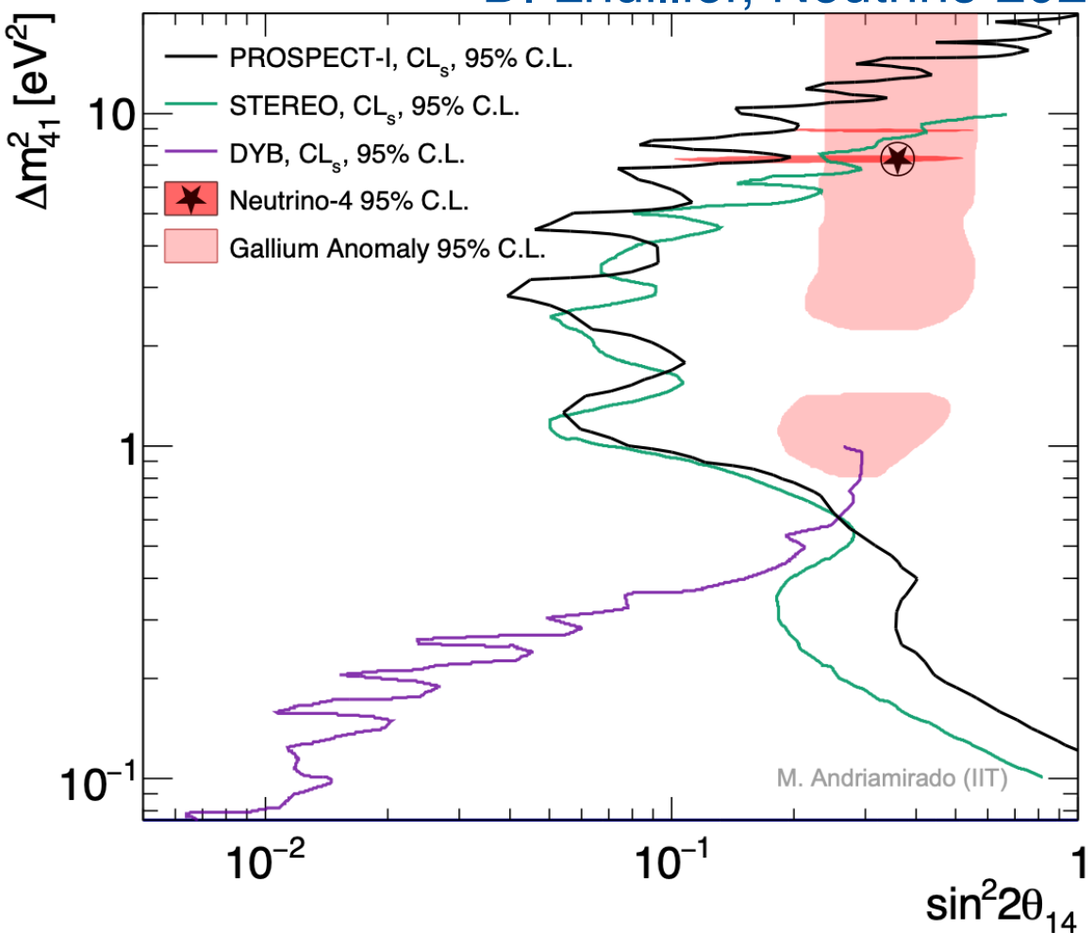
Several Experiments Searching for Sterile Oscillation

- Many reactor experiments at very short baselines!

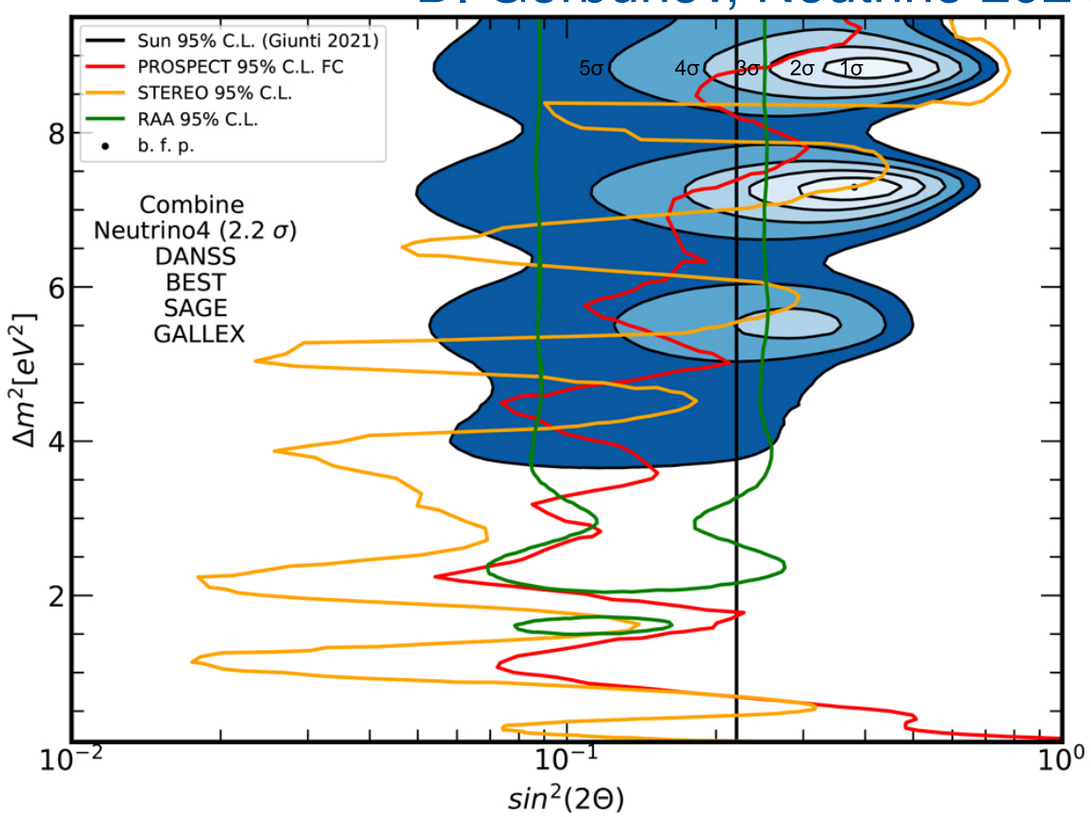
Joint analysis started late 2023 between DayaBay, Prospect and Stereo

D. Lhuillier, Neutrino 2024



BEST combined with others

D. Gorbunov, Neutrino 2024



- The Neutrino-4 best fit is rejected by STEREO and PROSPECT with >5σ CL, strong tension remains with the Gallium results

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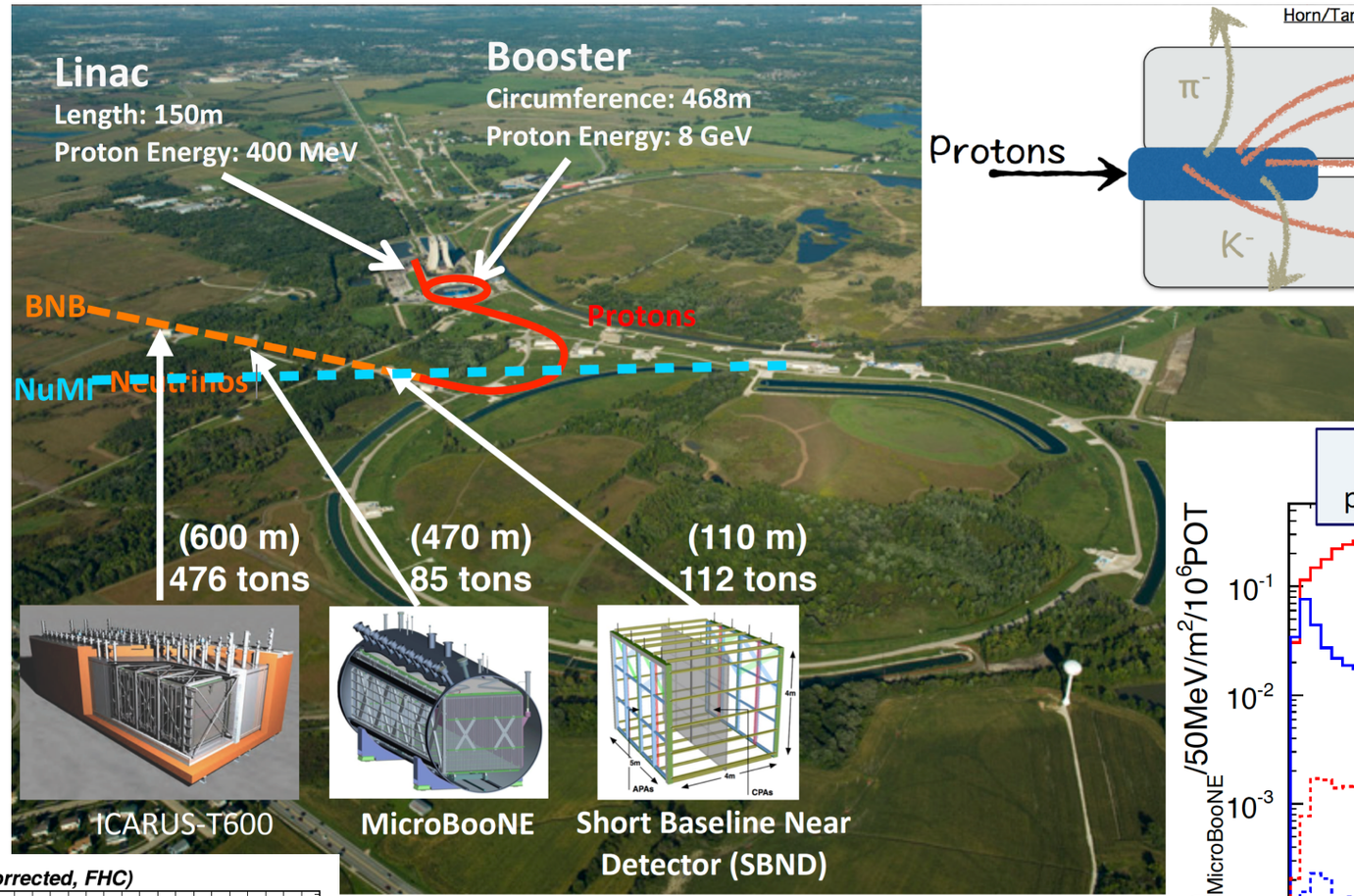
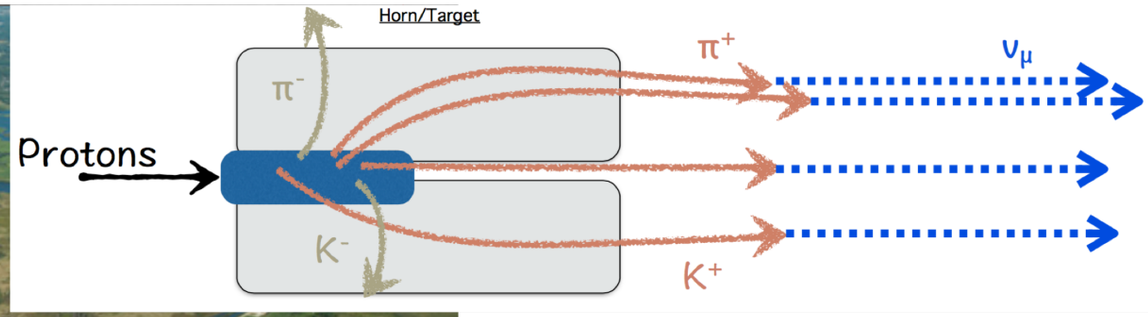
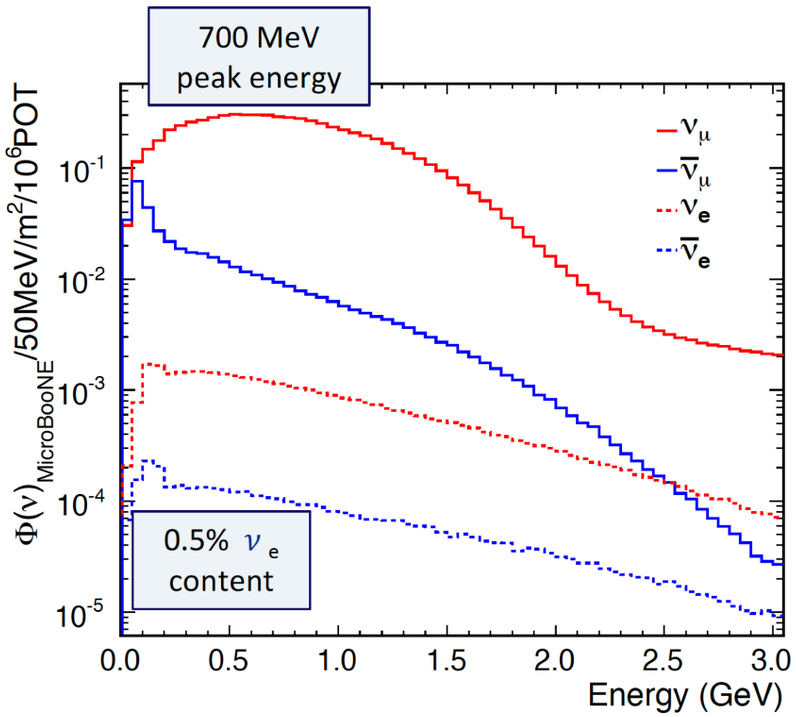
Short Baseline Program at Fermilab

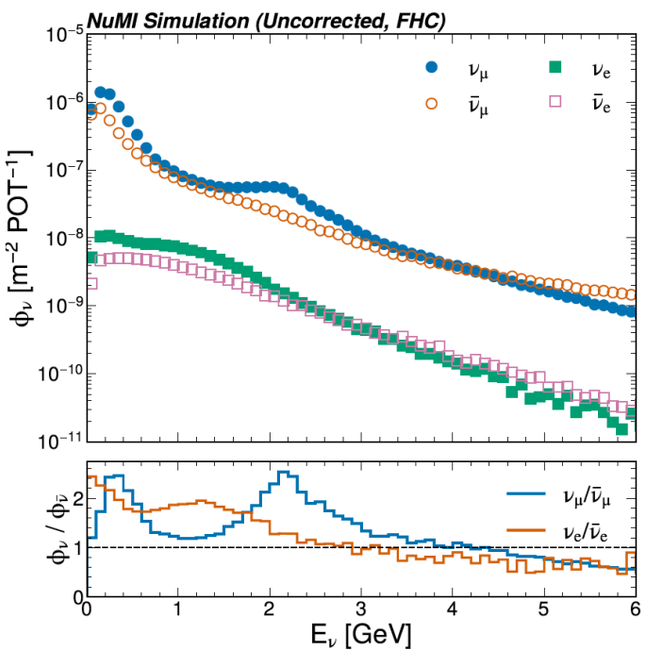
- Three liquid argon Time Projection Chambers (TPC) detectors at different baselines from Booster Neutrino Beam searching for sterile neutrino oscillations





Neutrinos from Booster





Neutrinos from NuMI

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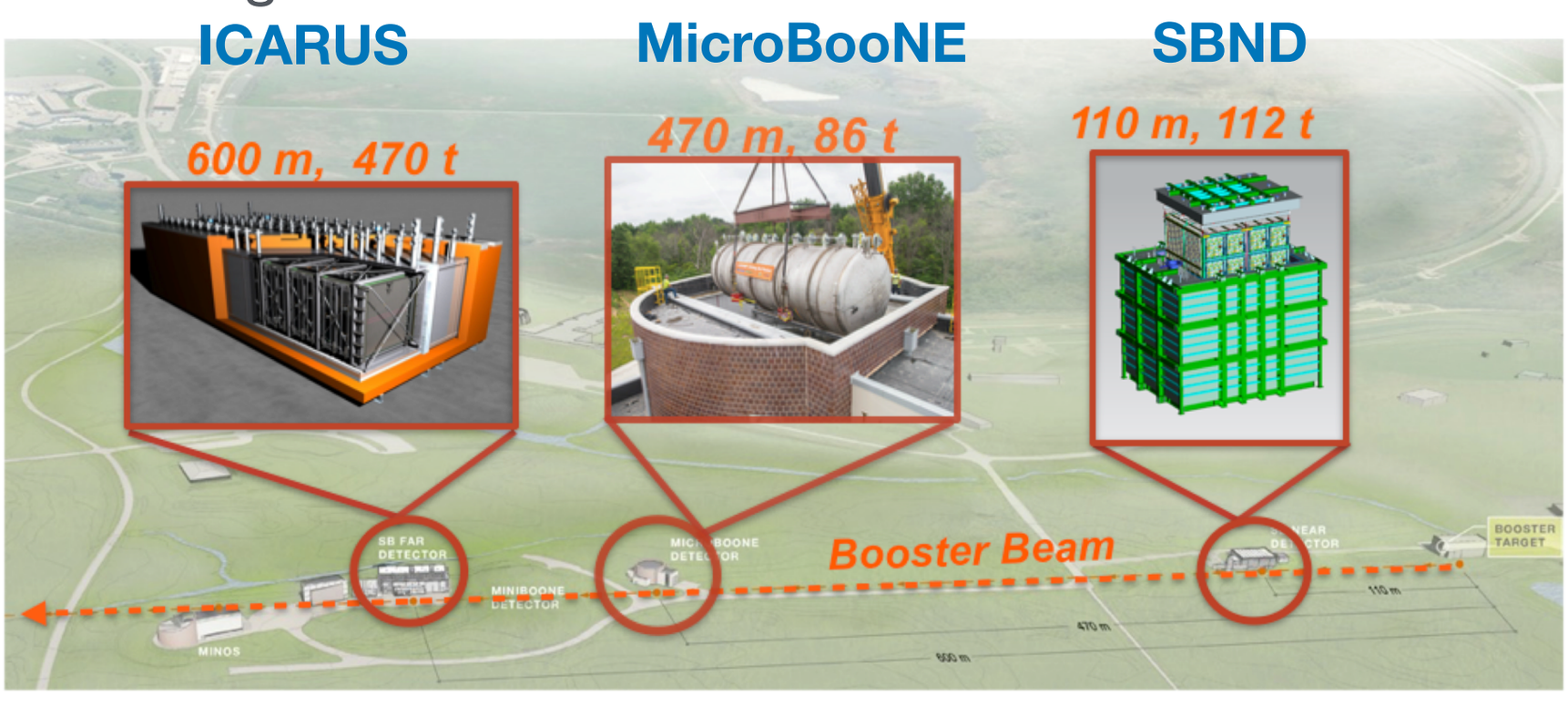
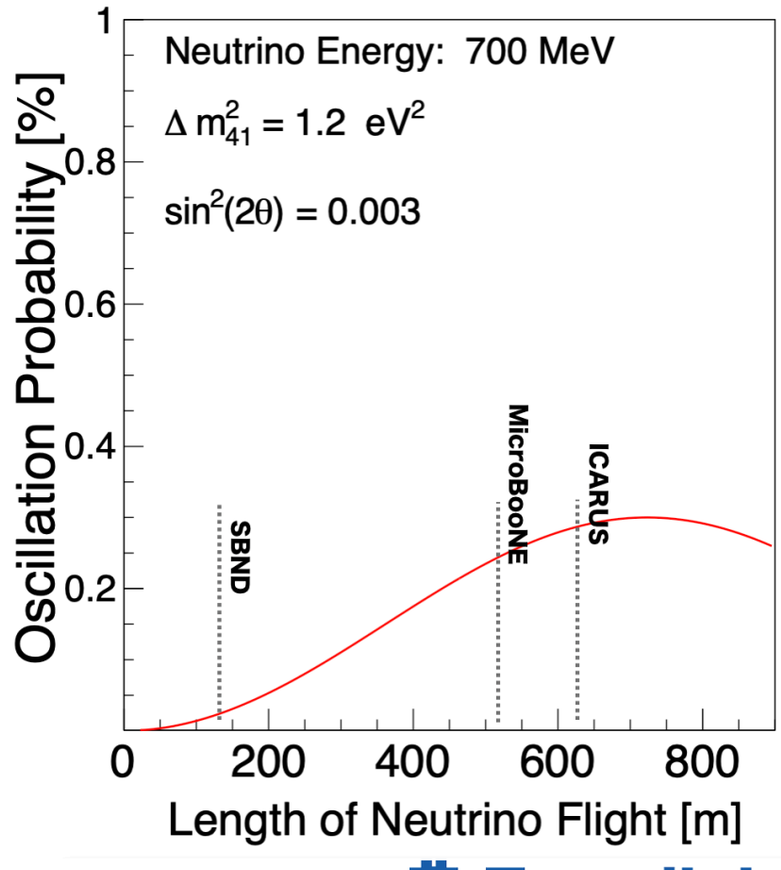
Short Baseline Program (SBN)

- Three LArTPC detectors at different baselines from Booster Neutrino Beam searching for sterile neutrino oscillations
  - Measuring both appearance and disappearance channels
- Measure neutrino cross sections on liquid argon
- Same detector technology and neutrino beamline: reducing systematic uncertainties to the % level
  - A detection technique providing an excellent neutrino identification to reduce the backgrounds





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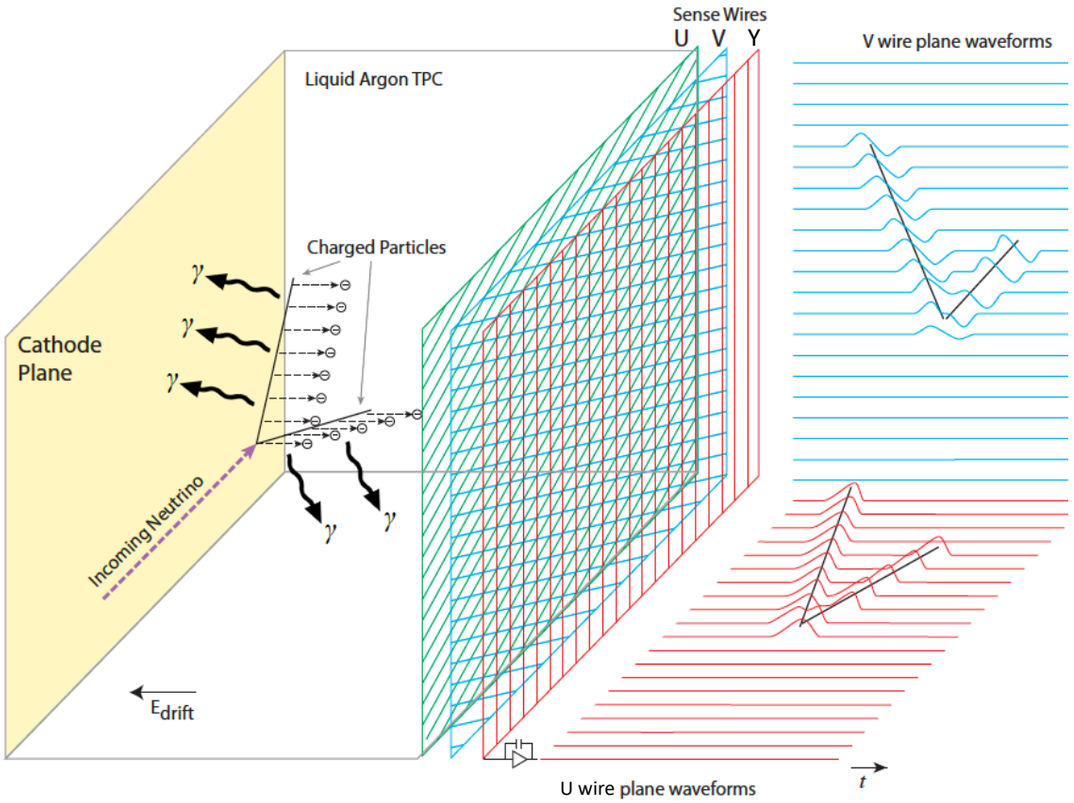
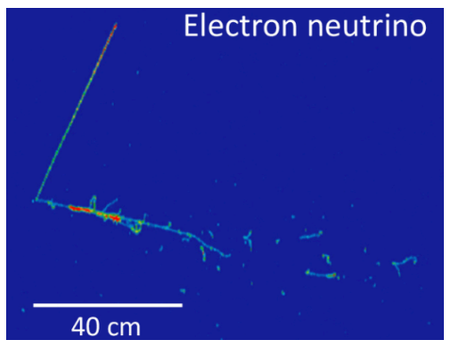
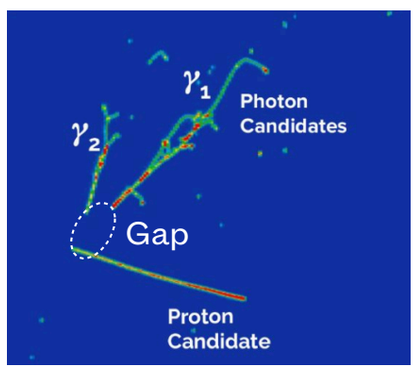
Liquid Argon TPC Detection Technique

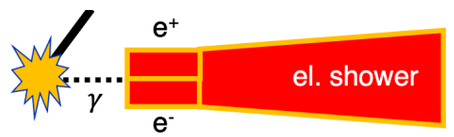
- Tracking device: precise 3D event topology with ~mm^3 resolution for ionizing particle
- Scintillation light detected by PMTs to provide event time and trigger
- Charged particles from neutrino interactions ionize the LAr, production ionization electrons drifting in 1 ms toward readout sense wires



- Powerful particle identification by dE/dx vs range
- Remarkable e/γ separation: calorimetric capabilities can distinguish e from γ at the shower start







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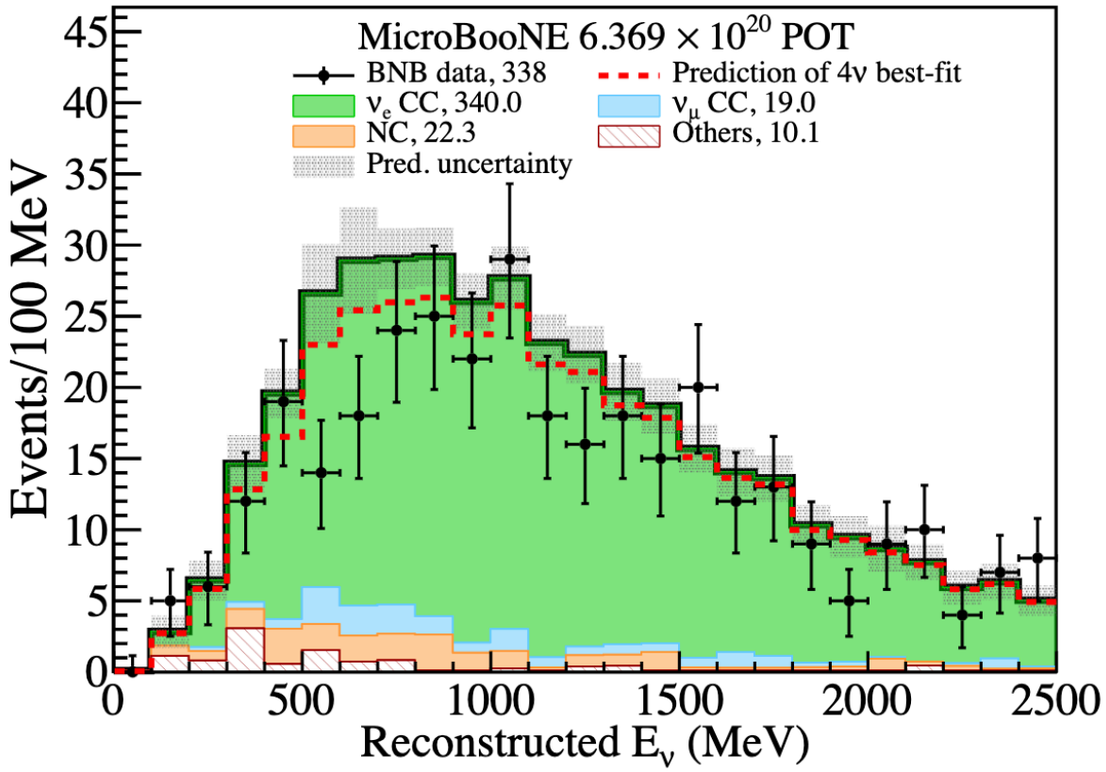
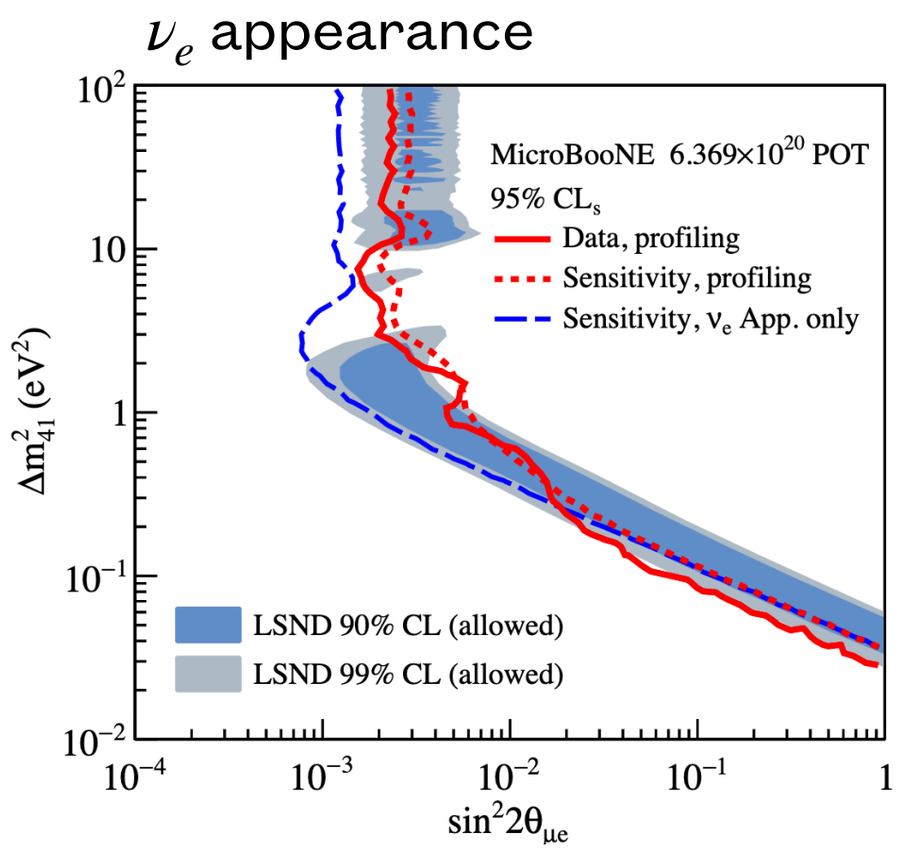
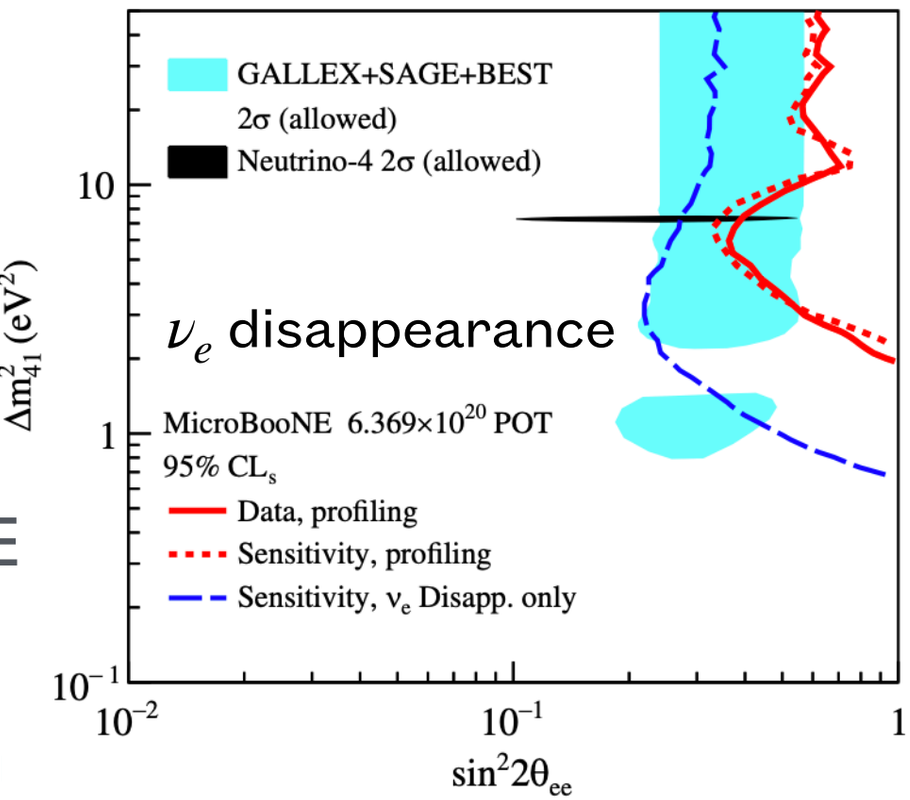
MicroBooNE

- 3+1 Sterile Neutrino Search: simultaneously analyze ν_e appearance and disappearance channels
- Low energy excess results rejecting ν_e -like interpretation at >99% CL







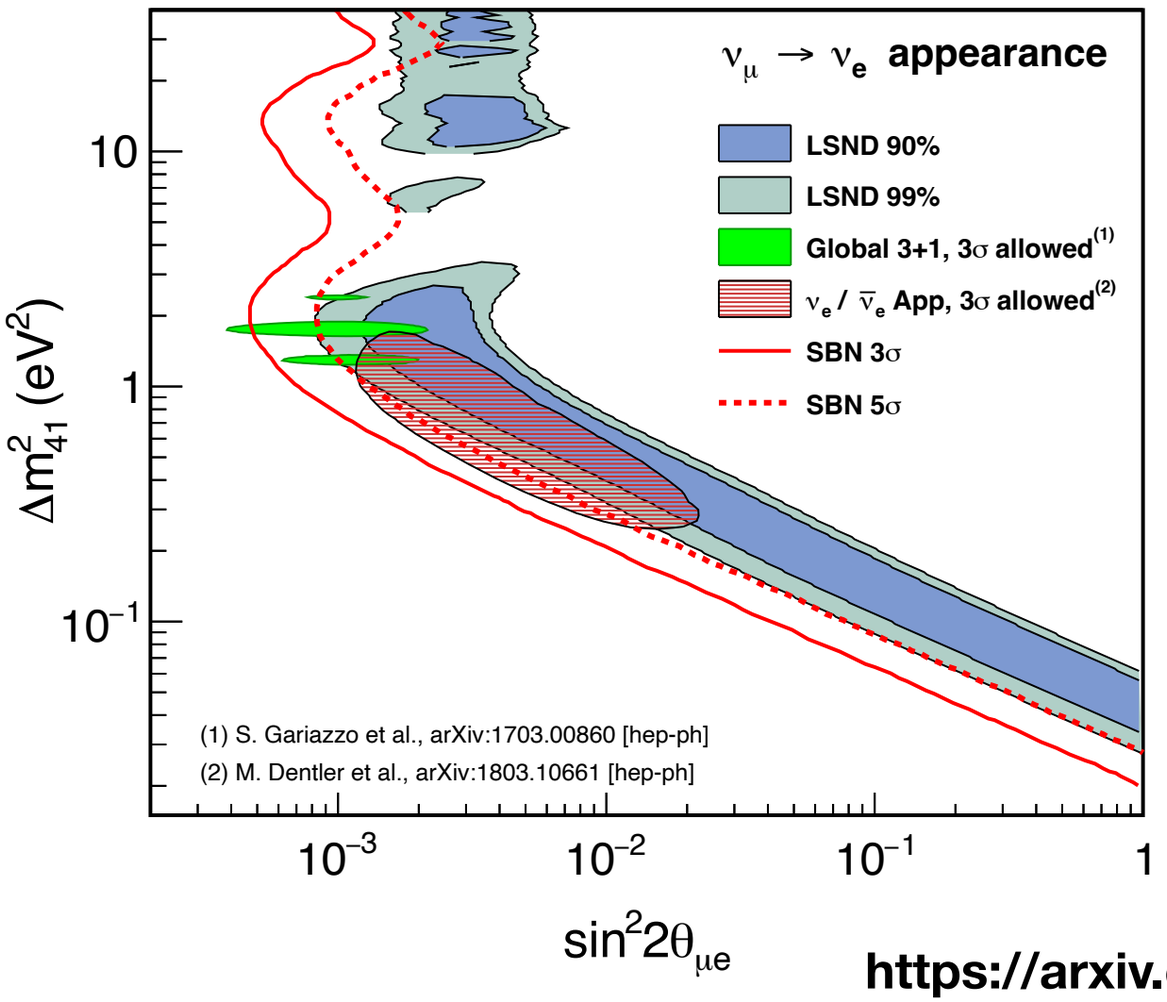
- See more details in Recent Results from MicroBooNE talks by Nitish Nayak, Erin Yandel's and Fan Gao

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

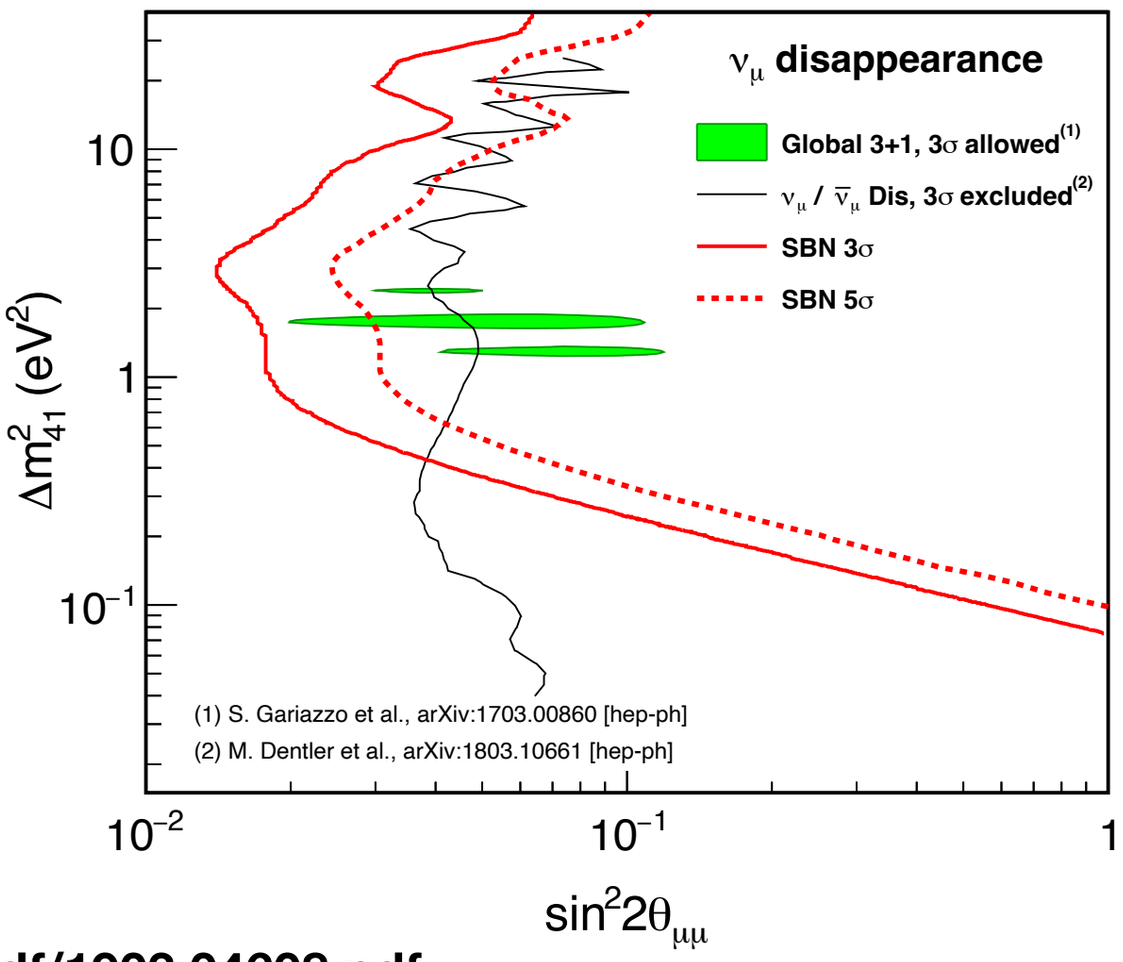
Sensitivity of SBN program

- Searches for both ν_e appearance and ν_μ disappearance

ν_e appearance



ν_μ disappearance



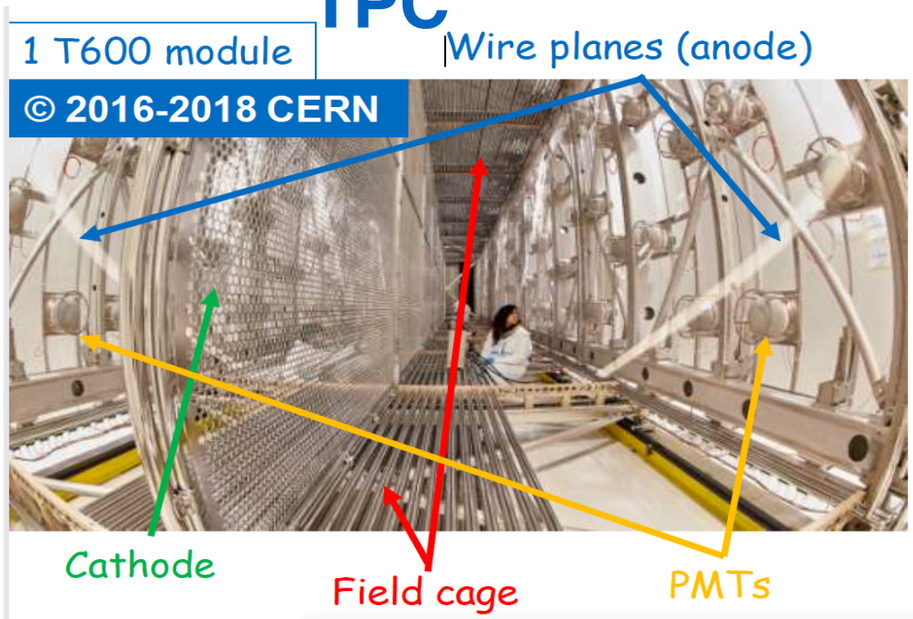
https://arxiv.org/pdf/1903.04608.pdf

- SBN covers much of the parameters allowed by past anomalies at >5σ significance

Far Detector (ICARUS)

- Several technology improvements were introduced, aiming to further improve the achieved performance of ICARUS previous runs: new cold vessels, improvement of the cathode planarity, higher performance read-out electronics and upgrade of the PMT system
- ICARUS is located on the surface, a cosmic ray tagger (CRT) and overburden has been installed to reduce and tag the abundant cosmic background events

TPC



PMT

Side CRT

Top CRT

3m concrete overburden

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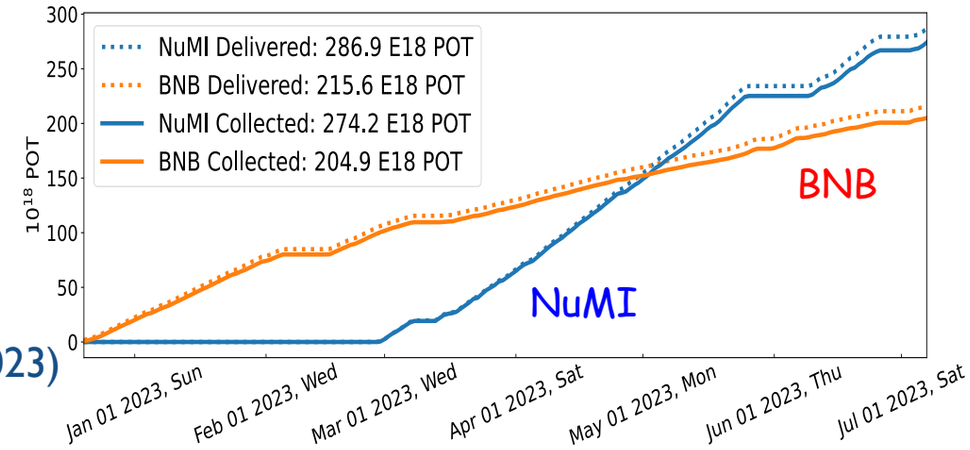
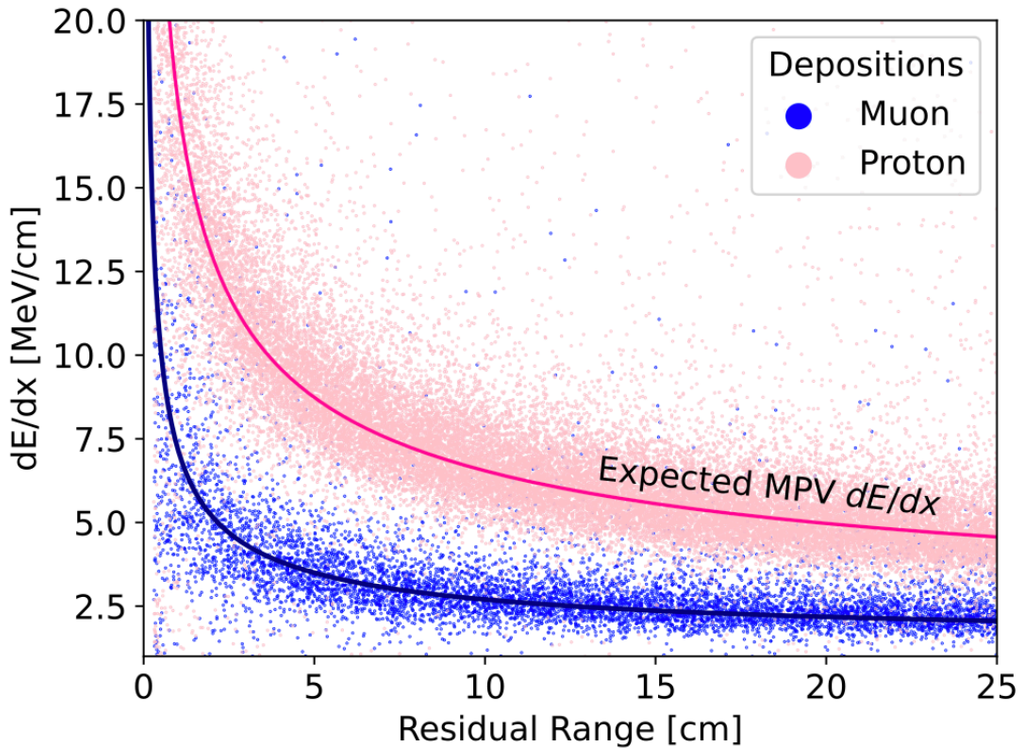
ICARUS at FNAL

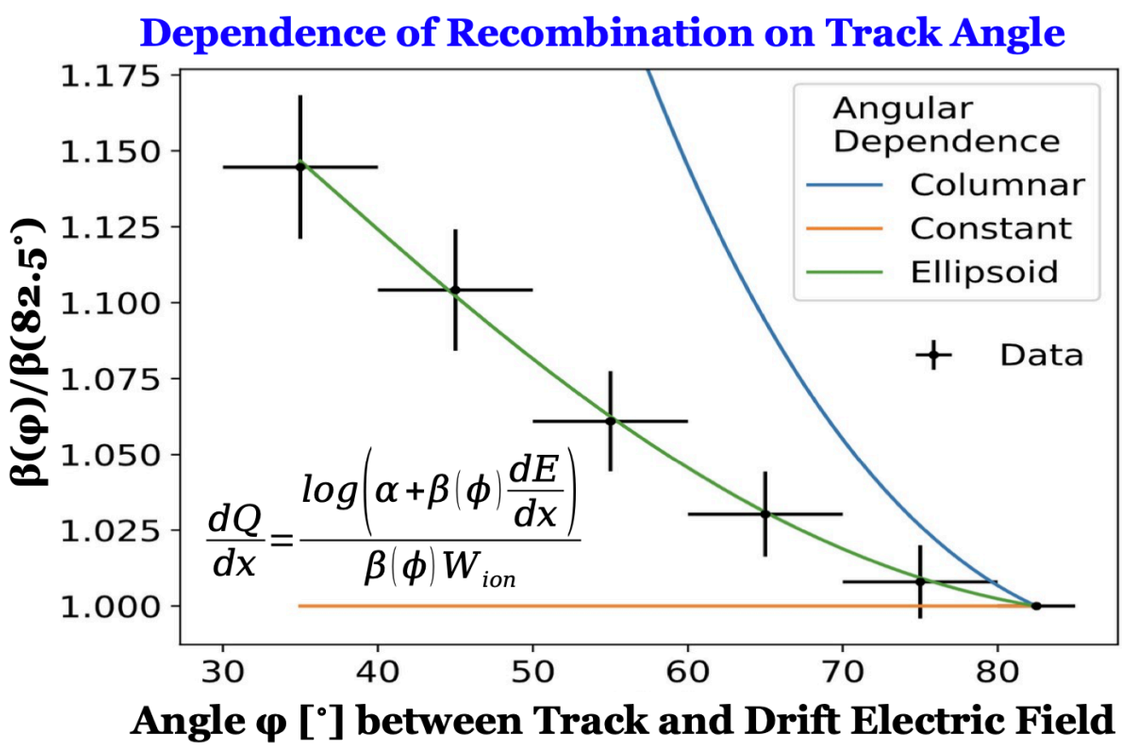
- ICARUS began commissioning in 2020 with cosmic data
- First ICARUS physics runs collected last June - December 2022 and spring 2023 from NuMI and Booster neutrino beams
- Commissioning and physics data have been used to perform the calibration, tune the reconstruction and start the first analyses with neutrino data, P.Abratenko et al, Eur. Phys. Journal C 83, 467 (2023)



Particle identification through calorimetric measurements



Measurement of the angular dependence of the liquid argon recombination model

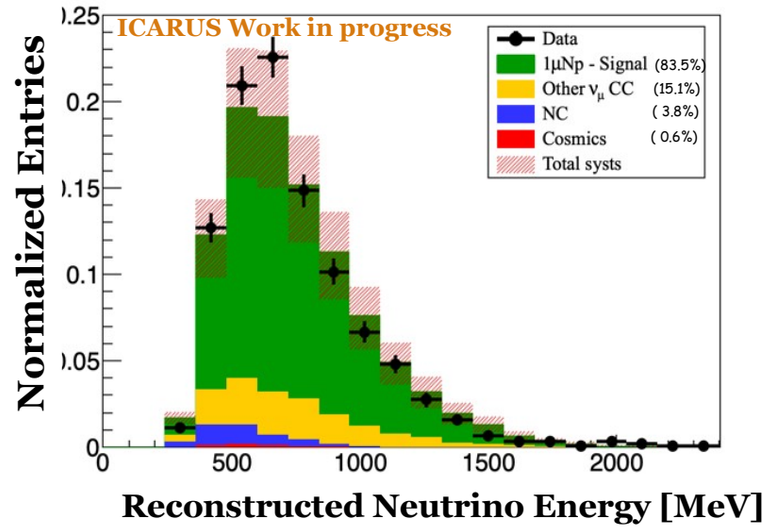


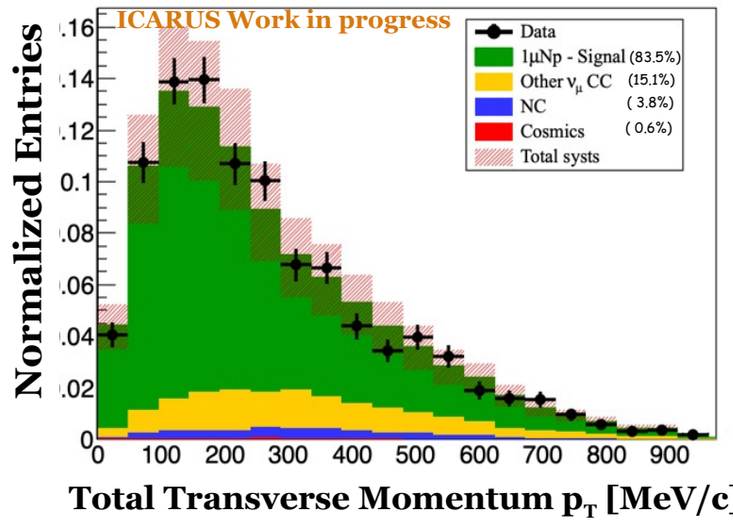
https://arxiv.org/pdf/2407.12969, submitted to JINST

Neutrino Oscillation Analysis

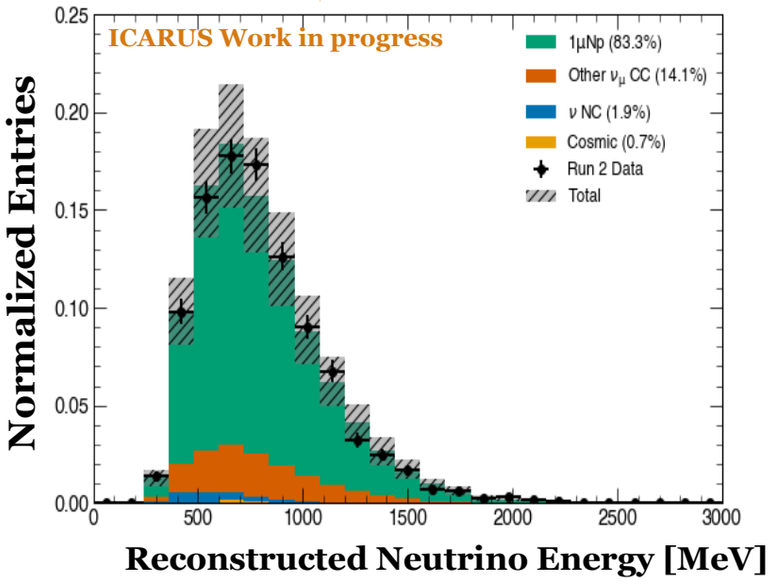
- ICARUS is pursuing single-detector neutrino oscillation measurement
- Studying events from BNB with 1μ Nproton and 0π, two approaches: pattern recognition (Pandora) and machine learning based reconstruction

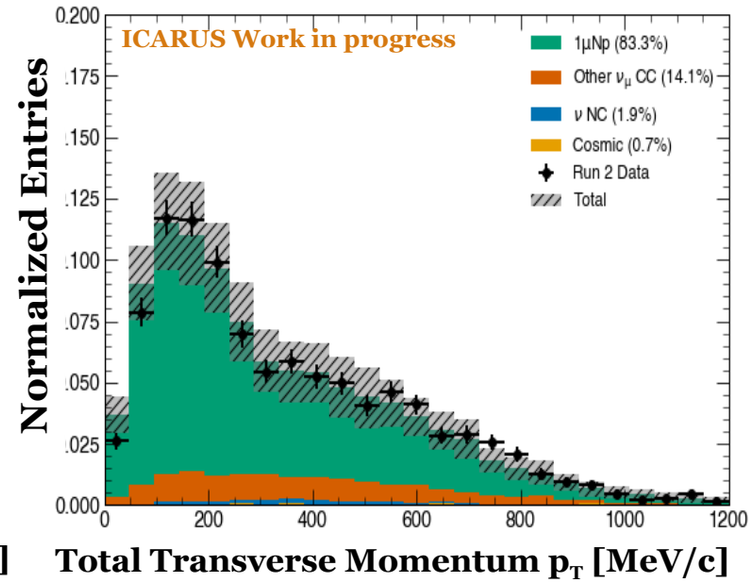
Pandora
1μNp0π Selection





ML (SPINE)
1μNp0π Selection





See more details in First Results from ICARUS by Jacob Zettlemoyer

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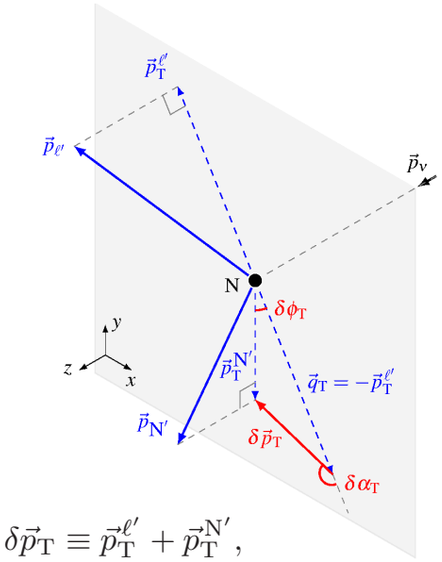
CC 0π Cross Section with Neutrinos from NuMI

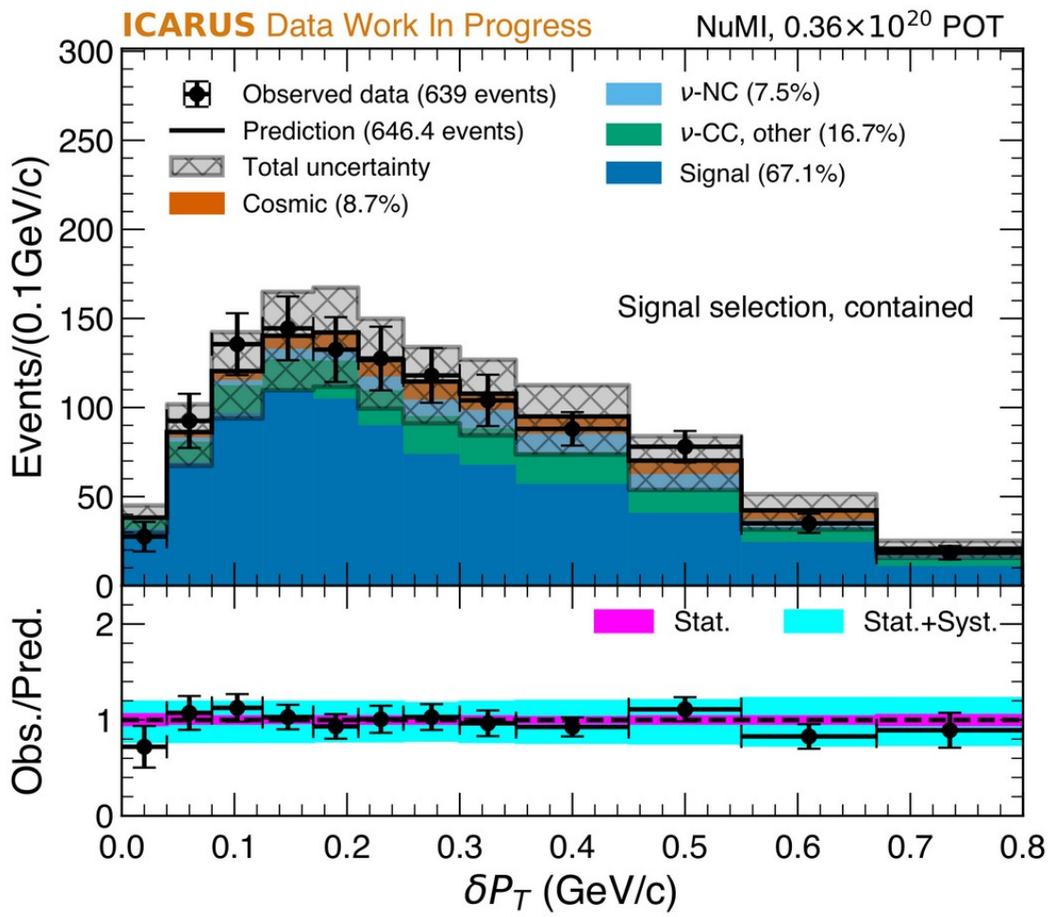
- First cross section measurement: 1μ+Nproton+0π
- Observables δP_T and $\delta\alpha_T$, sensitive to initial and final state effects
- Events with contained muons and protons
- Main background is events with pions



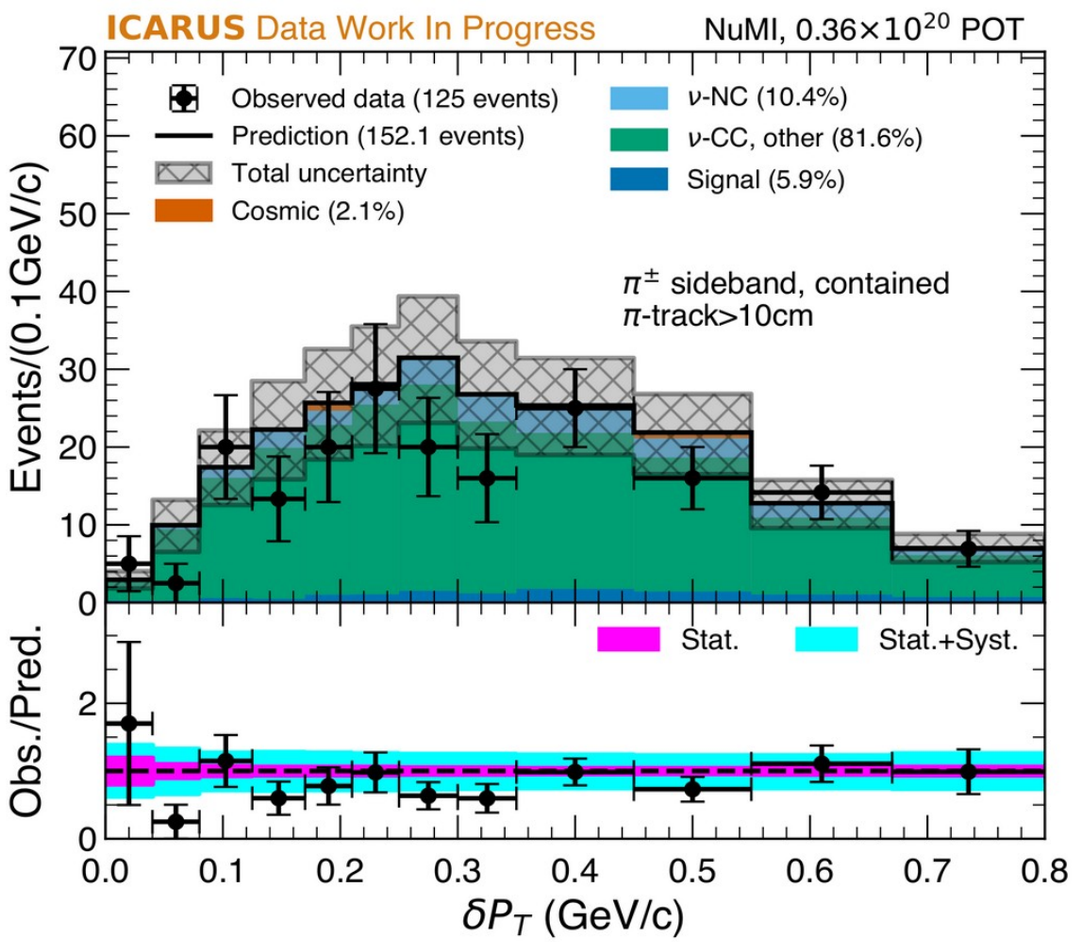
$$\delta\vec{p}_T \equiv \vec{p}_T^{\,\ell'} + \vec{p}_T^{\,N'},$$

$$\delta\alpha_T \equiv \arccos\frac{-\vec{p}_T^{\,\ell'}\cdot\delta\vec{p}_T}{p^{\ell'}\delta p_T},$$

Signal selection



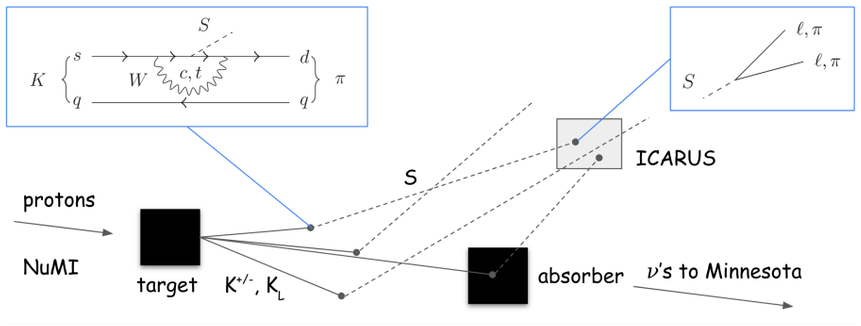
Pion Sideband

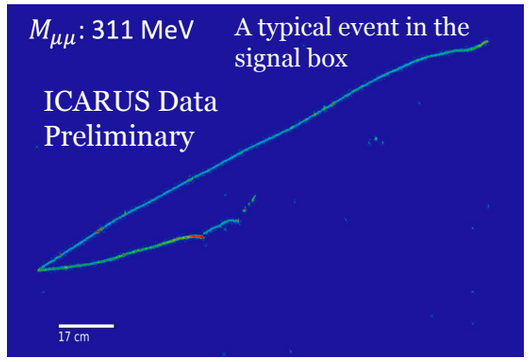


See more details in Neutrino Interaction Measurement by Jack Smedley

BSM Searches with NuMI

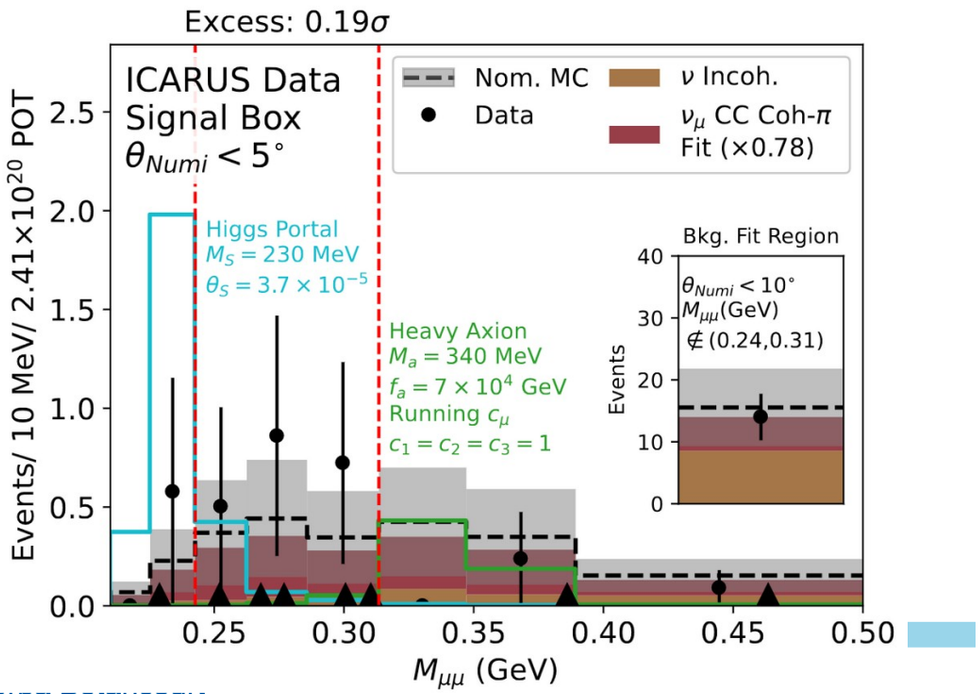
- Certain BSM searches benefit from sitting off-axis such as kaon coupled Higgs portal scalars
- Topology: events with two muons, search: look for resonance at specific value

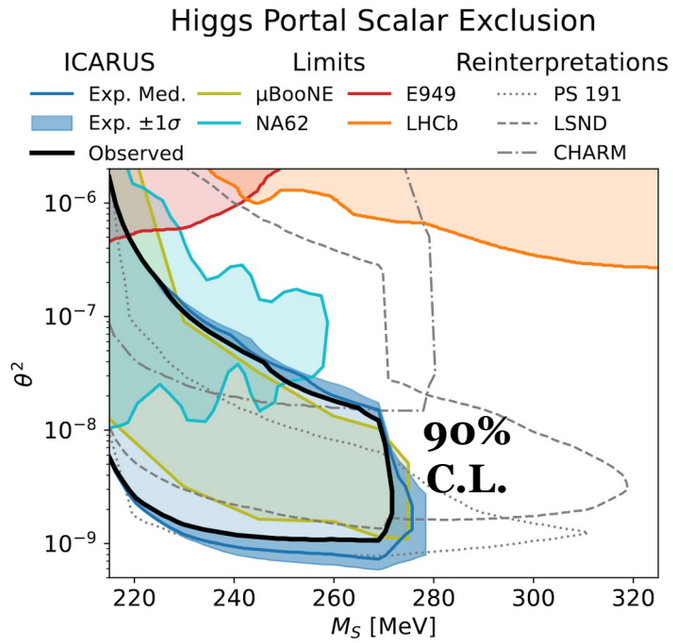


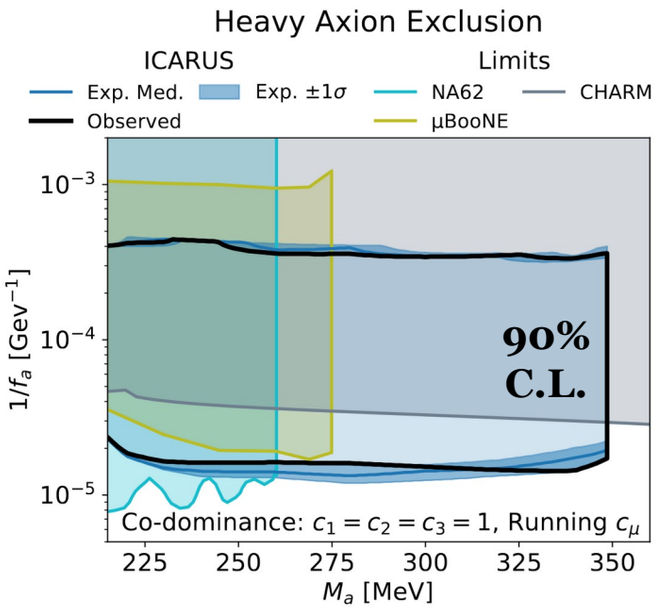


The event is consistent with neutrino background

- Collaboration opened the box, and found no new physics signal
- BSM models considered so far, both involving kaon decay and contained dimuon final states: Higgs Portal Scalar and Heavy QCD Axion





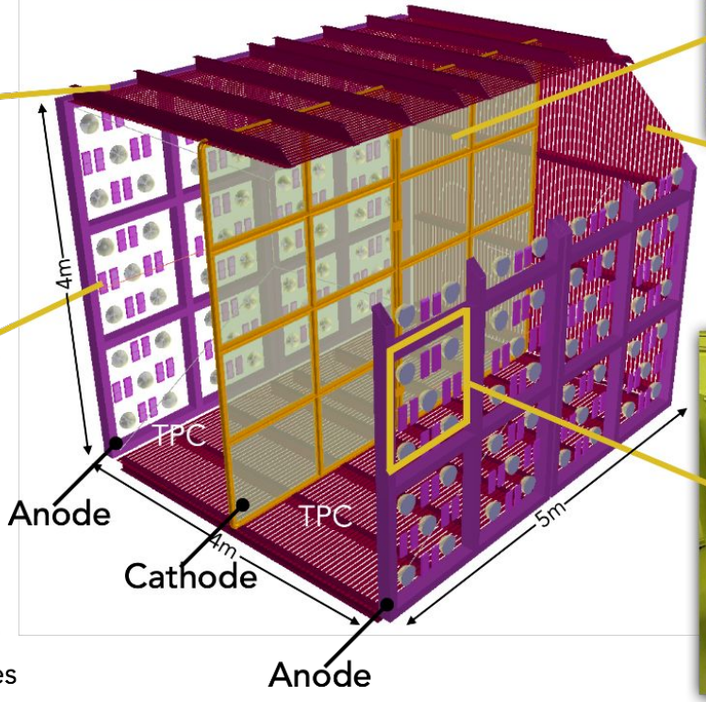


See more details in Search for a Long-Lived nu mu Resonance by Nathaniel Rowe

Near Detector (SBND)

TPC Cold electronics

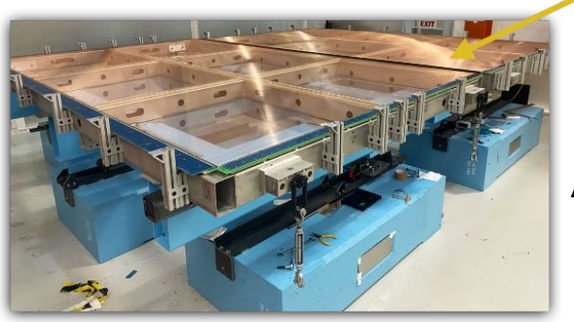
Two Time Projection Chambers
Total dimension: 4m x 4m x 5m
Total active argon mass: 112 ton



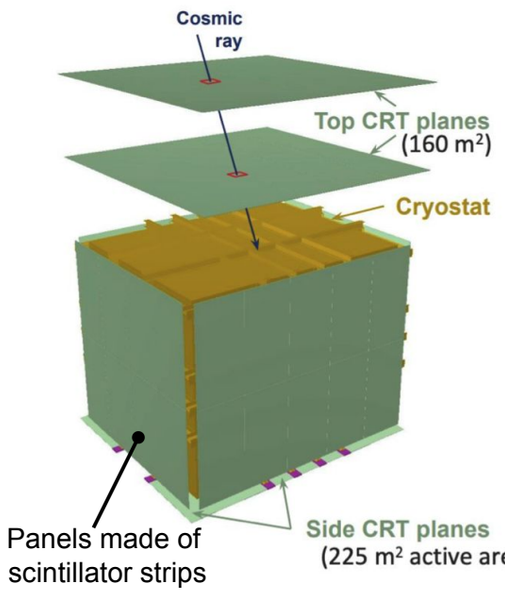
CPA-Cathode
covered with TPB
coated reflectors

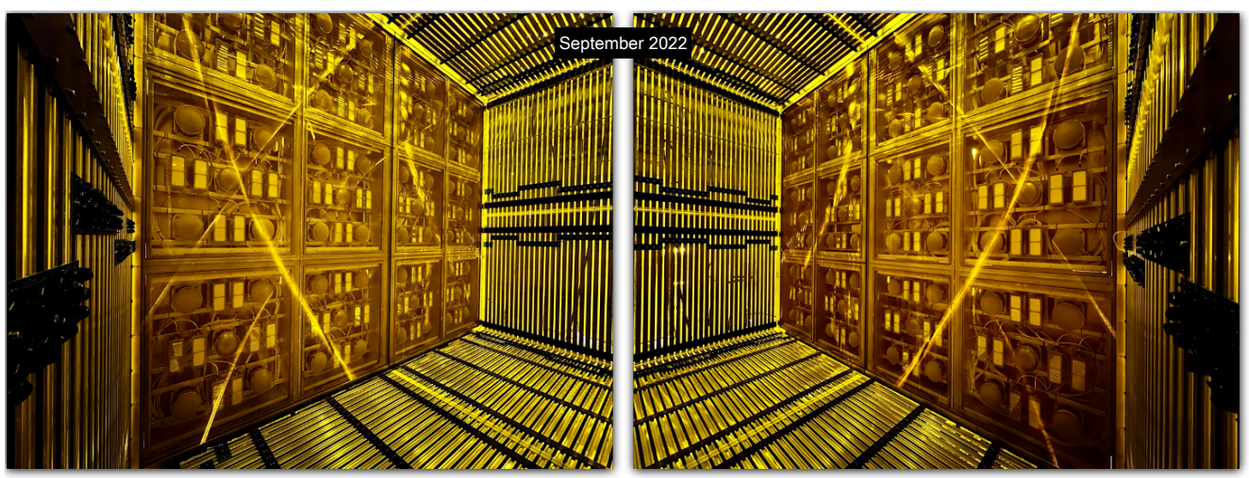
Field Cage

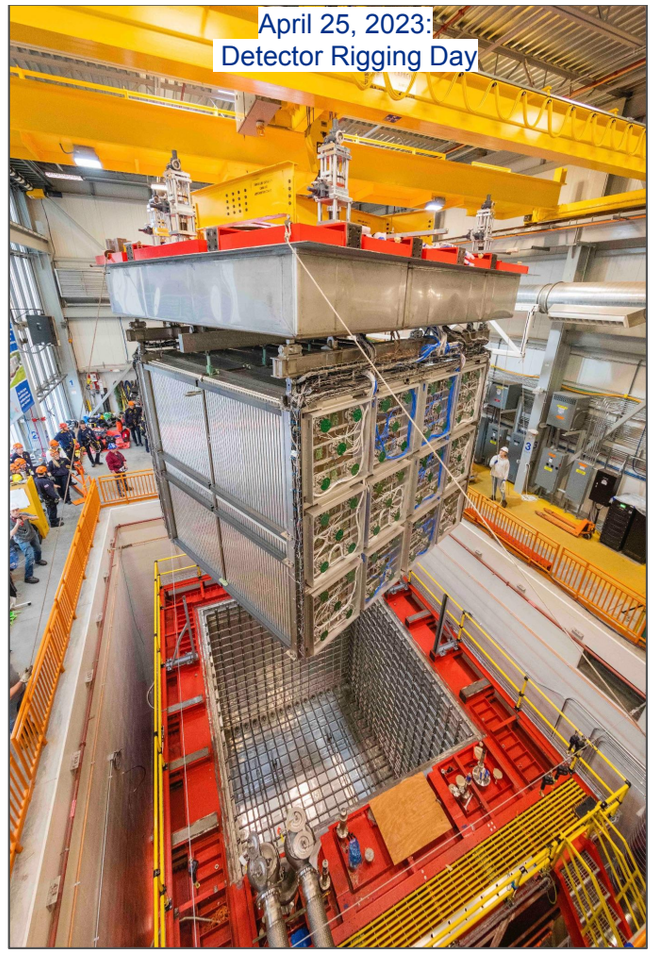
Photon Detection Systems: 120 PMTs, 192 X-Arapucas
SBND publication (arXiv:2406.07514)



APA-Wire Planes- 3 planes, ~11000 wires





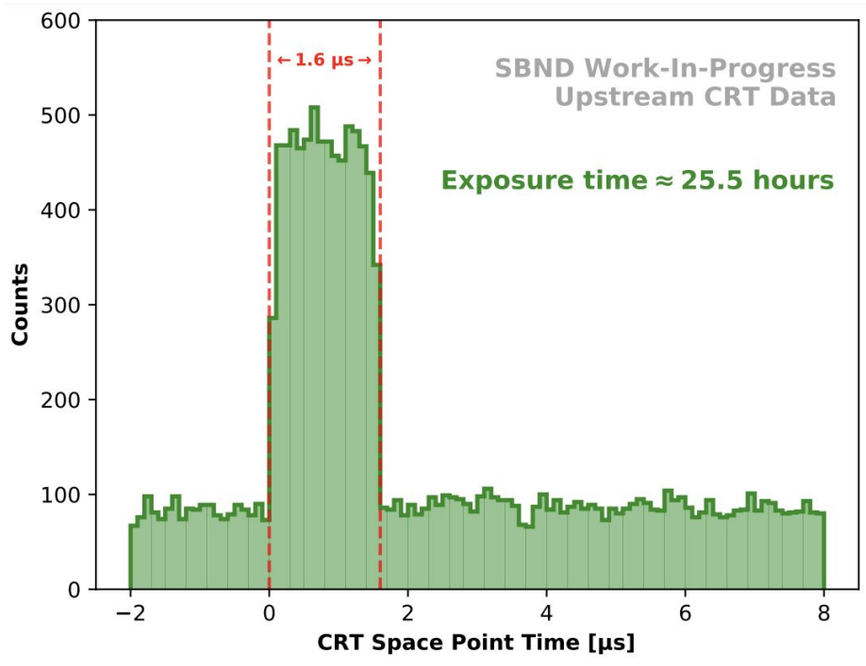


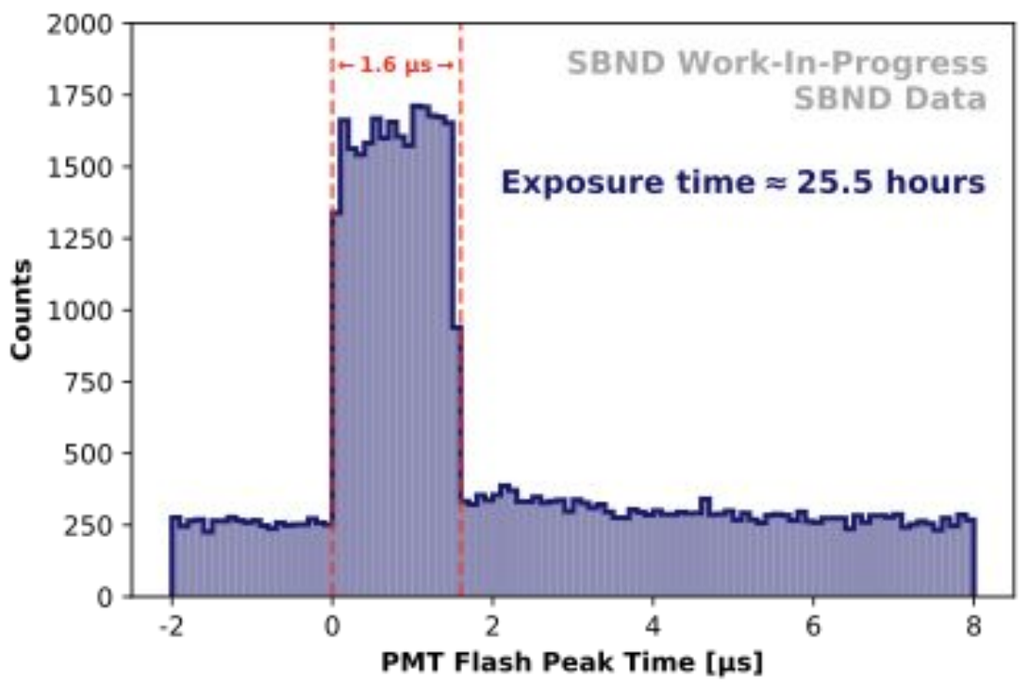
See more details in the SBND talk by Tereza Kroupova

Fermilab

SBND Detector Commissioning

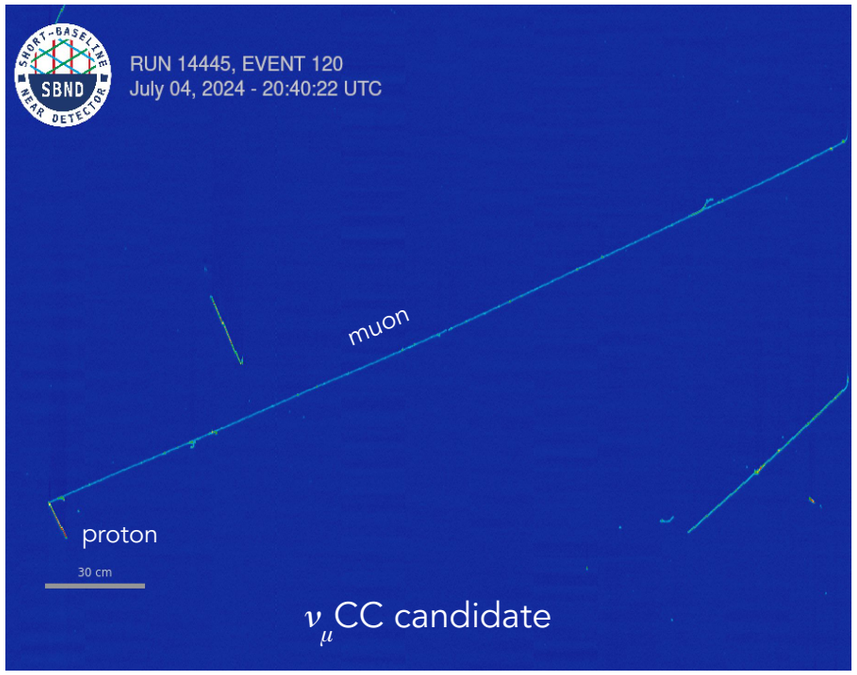
- Liquid argon fill was completed during February-March, 2024
- Observed drift electron lifetime meets design requirement of > 3ms
- PMTs commissioned and initial gain balancing completed
- All CRT walls installed as of August 2024
- TPC high voltage system has been operating stably since July
- Commissioning the different systems TPC, PMT and CRT is in progress
- 1.6 μs wide per reflecting the duration of the BNB spill

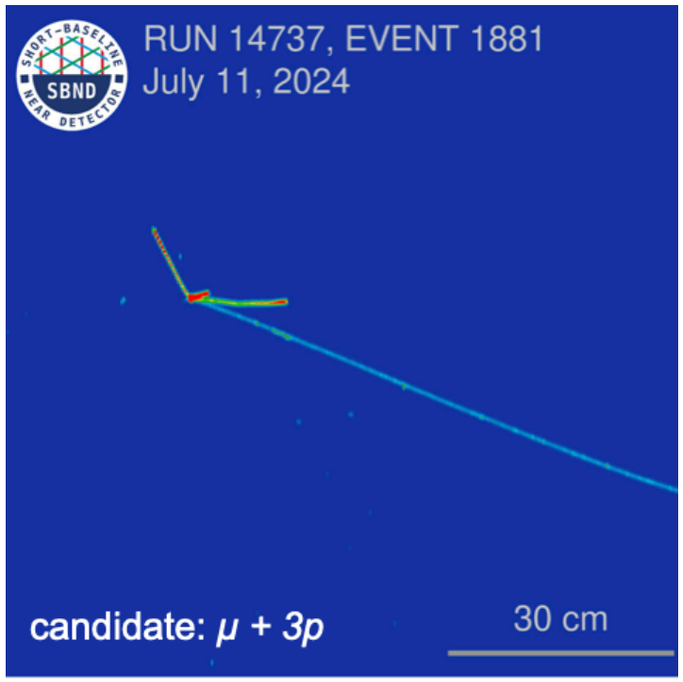


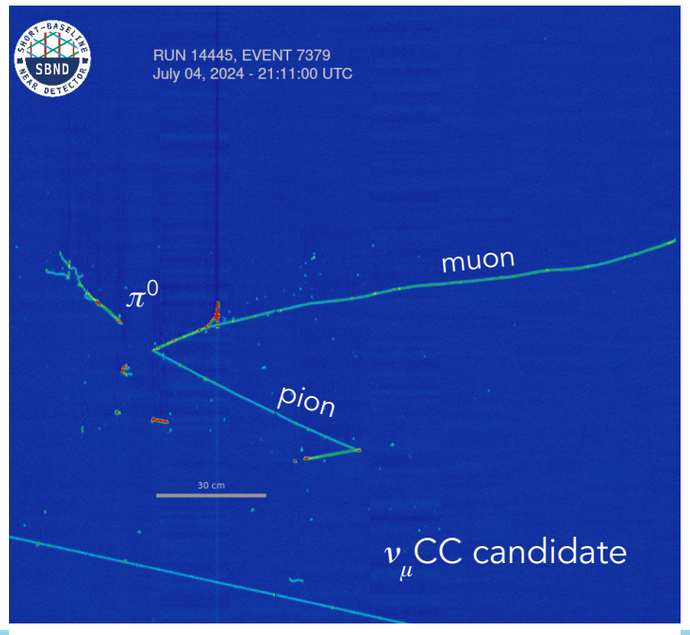


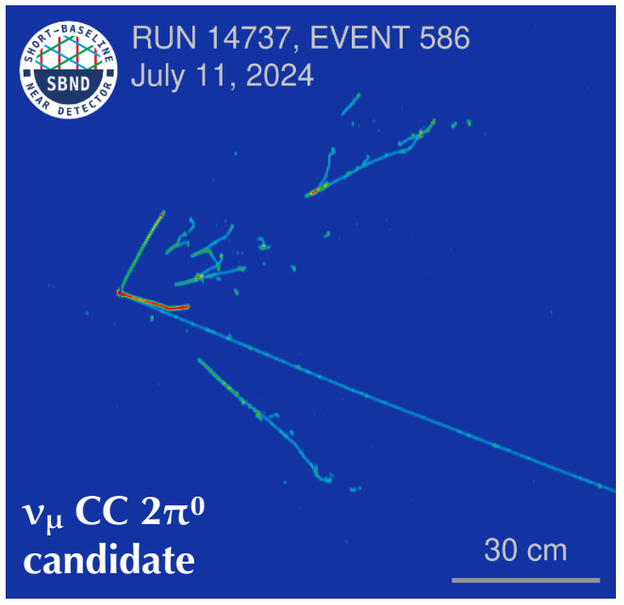
SBND First Neutrino Data

First neutrino interactions









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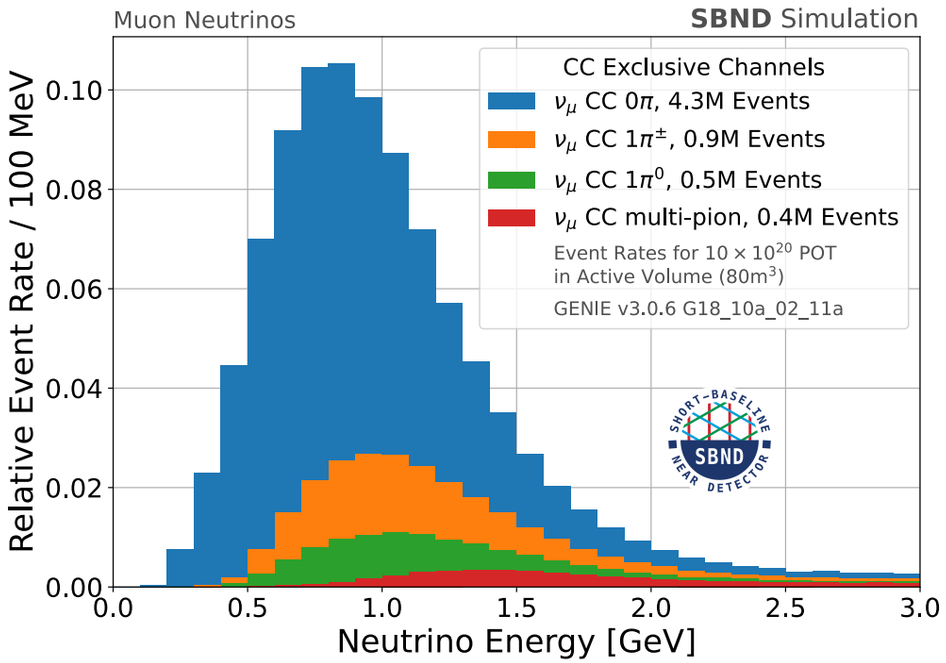
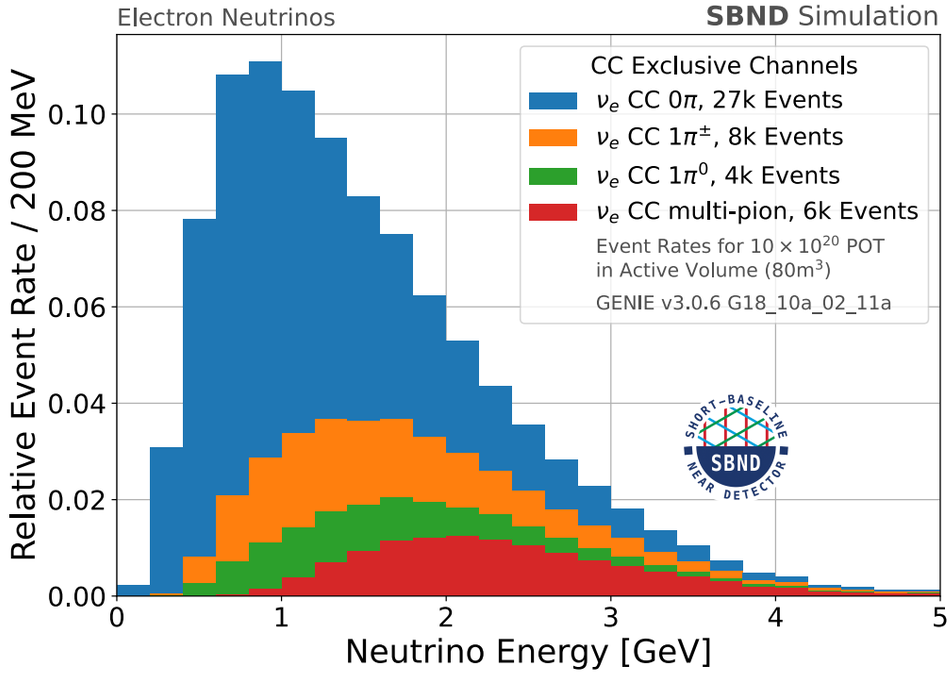
Neutrino Interactions at SBND

- New data sets will reach the order of millions of neutrino interactions for single channels

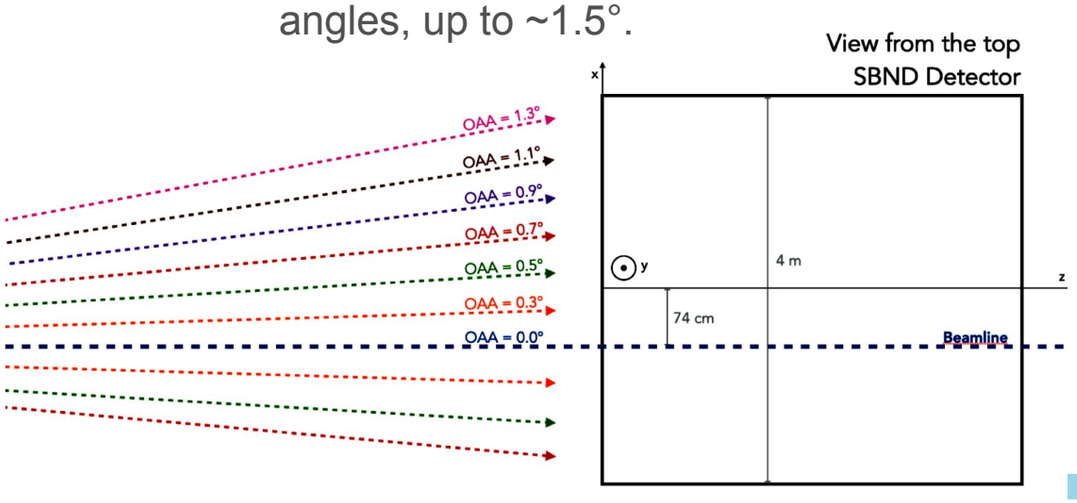


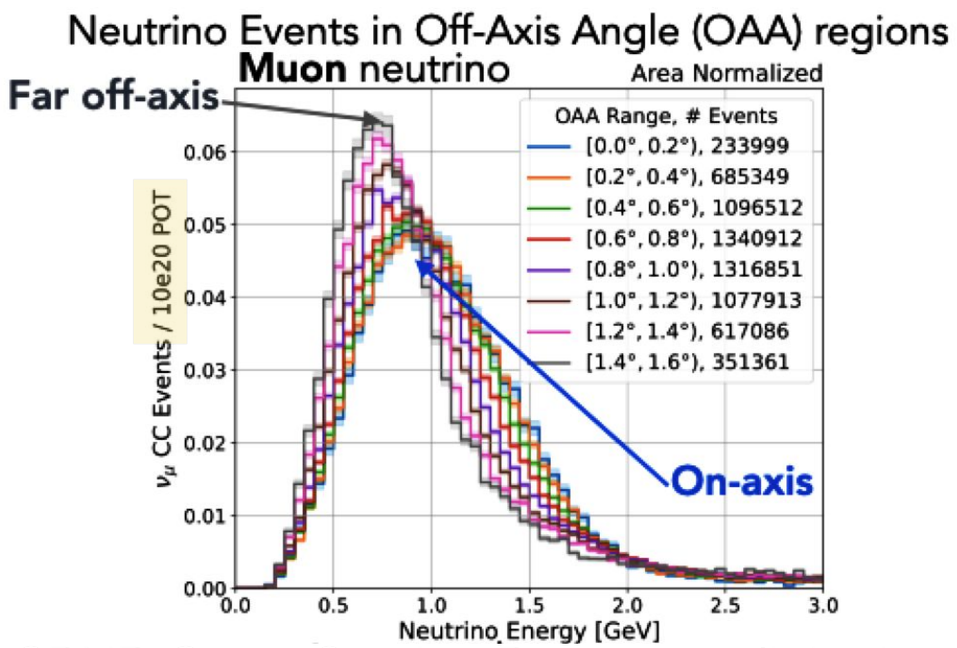
1.5M ν_μ CC events in 1 year



12k ν_e CC events in 1 year

SBND sees neutrinos from a range of off-axis angles, up to ~1.5°.





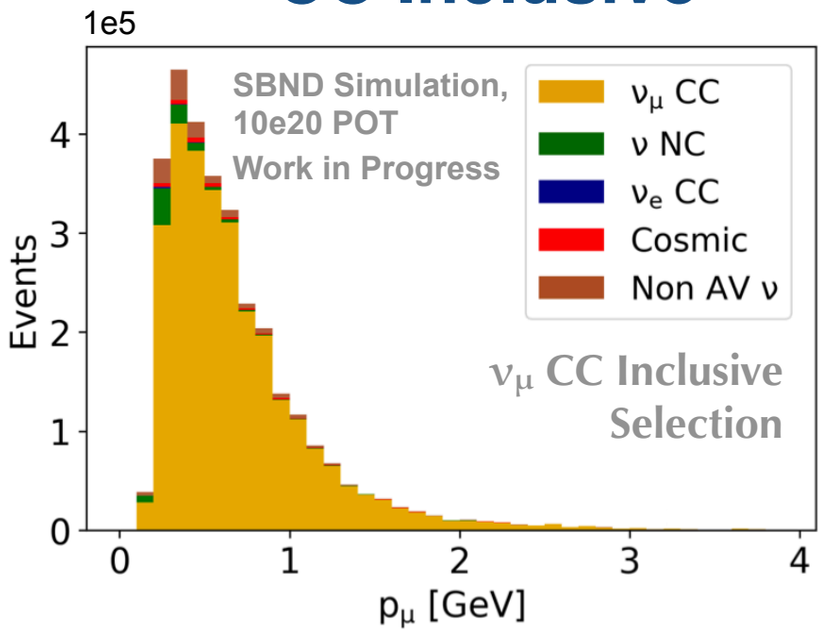
See more details in the SBND Cross-Section Program talk by Leo Aliaga

Fermilab

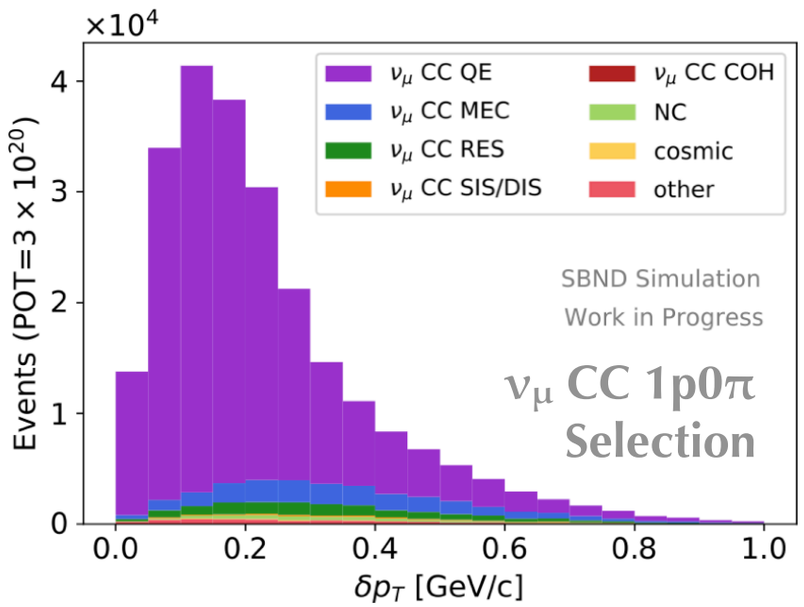
SBND Science Program Beyond the Oscillation Search

- Precision neutrino-nucleus interaction measurements
- Beyond standard model physics searches

CC Inclusive



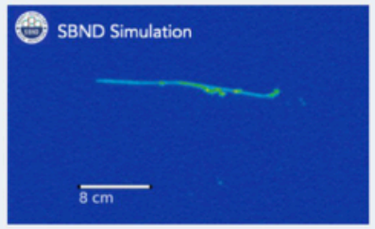
CC 1proton0π



See more details at SBND cross section program talk by Leo Aliaga and poster by Moon Jung

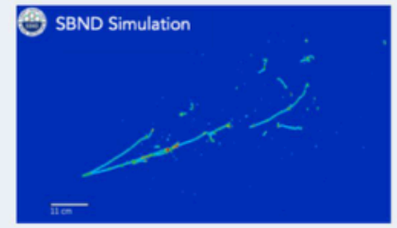
BSM Searches

Light Dark Matter



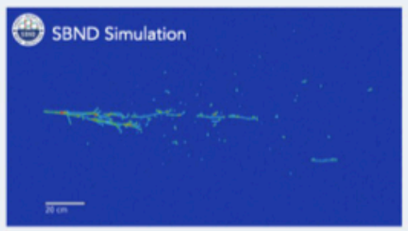
Single e^- scattering,
e^+e^- pair, $\gamma\gamma$
No hadronic activity

Dark Neutrinos



e^+e^-, $\mu^+\mu^-$ pair
w/ or w/o hadronic activity

Heavy Neutral Leptons

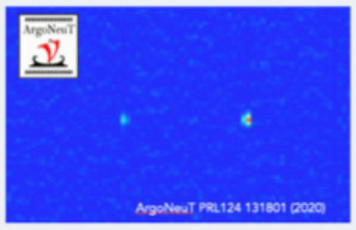


High energy e^+e^- or $\mu^+\mu^-$ pair , $\mu\pi$, $\gamma\gamma$
No hadronic activity

Higgs Portal Scalar

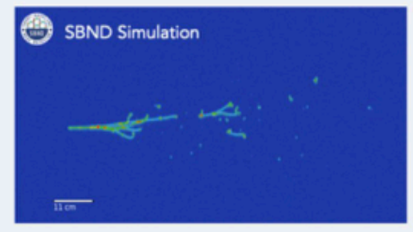
e^+e^-, $\mu^+\mu^-$ pair
No hadronic
activity

Millicharged Particles



blips/faint tracks

Axion-like Particles



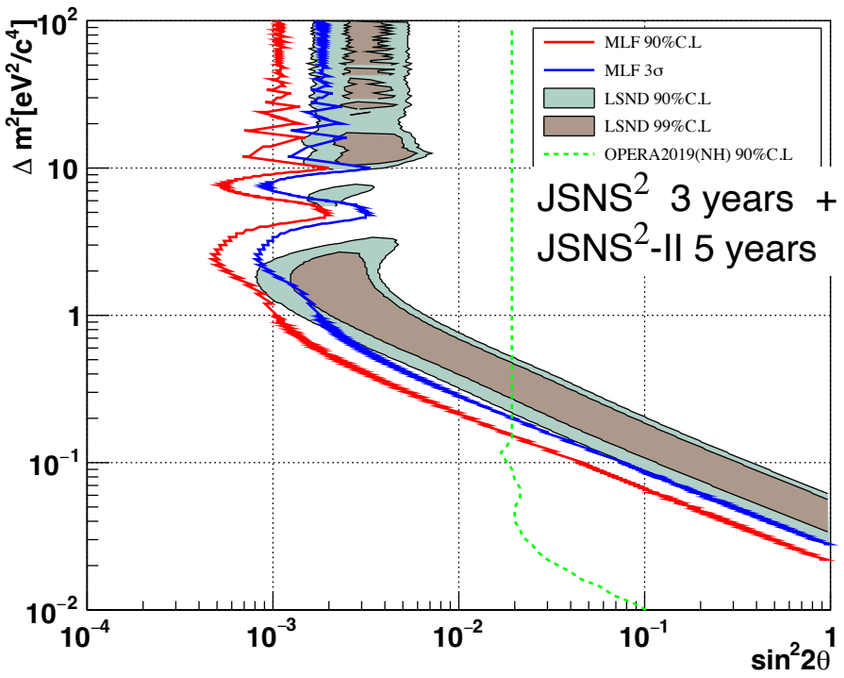
high-energy e^+e^-, $\mu^+\mu^-$ pair

Fermilab

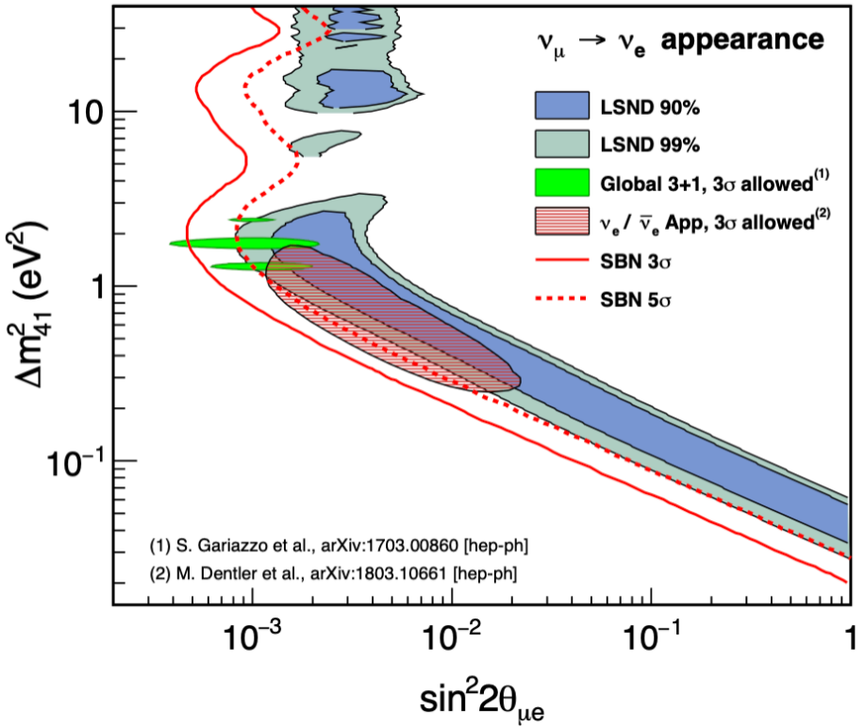
Summary

- Several measurements provided hints to indicate there is a fourth and non-weakly interacting (sterile) type of neutrino
  - LSND, MiniBooNE, reactor experiments, Neutrino-4
- New short baselines experiments with near and far detectors to search for sterile neutrinos
  - JSNS^2-II and SBN at Fermilab
- The SBN detectors will perform a world-leading search for eV-scale sterile neutrino by looking at both appearance and disappearance channels
- Rich physics program of neutrino-argon scattering measurements and BSM physics
- SBND completed the construction of the detector and commissioning is in progress
- ICARUS is collecting physics quality data with NuMI and Booster neutrino beams
- Exciting times for the community with commissioning and data analysis with short baseline experiments

JSNS^2-II



SBN



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