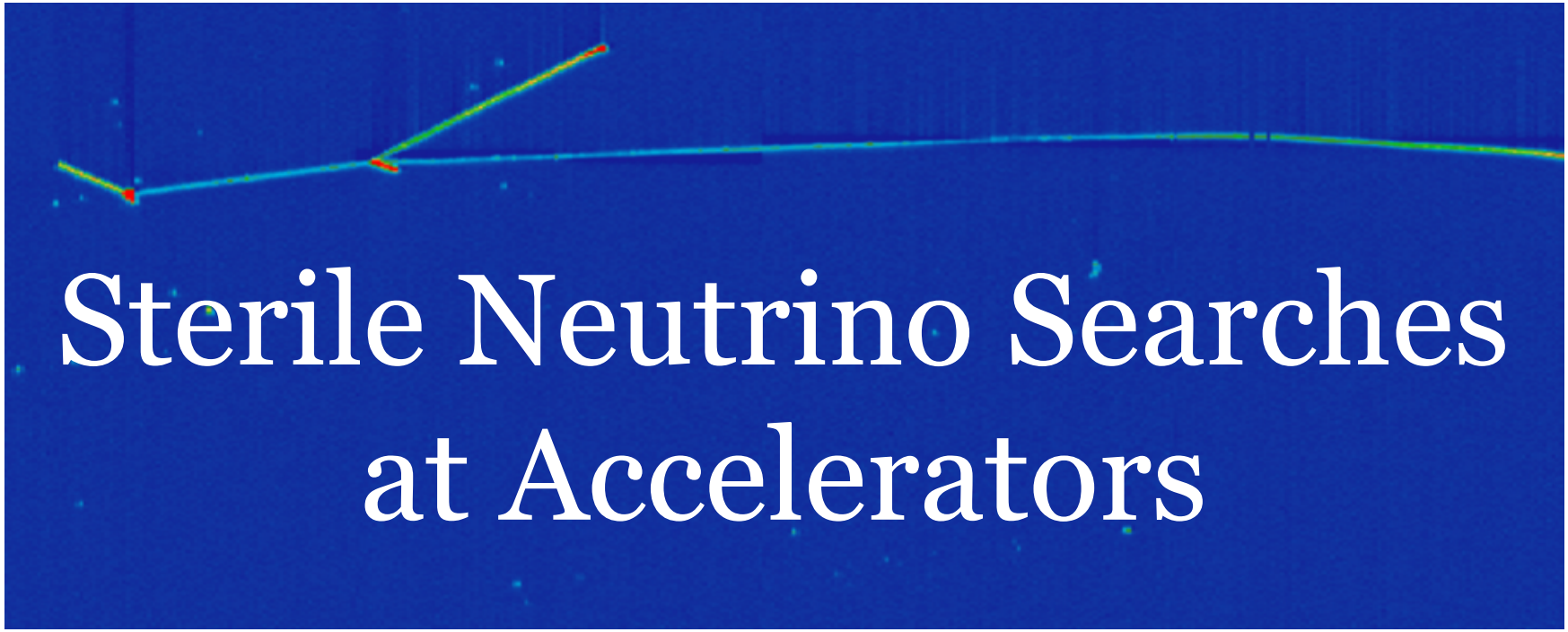


Sterile Neutrino Searches at Accelerators

Michael Mooney

Colorado State University

The XV International Conference on Heavy Quarks and Leptons, University of Warwick, UK

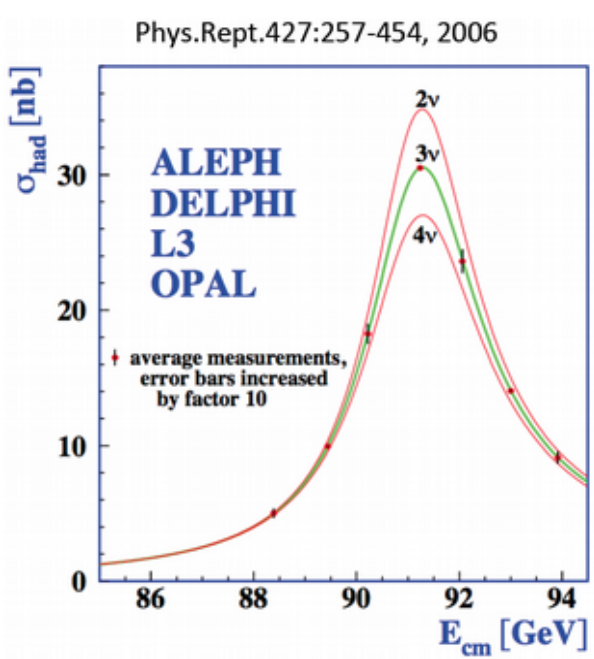
September 17th, 2021

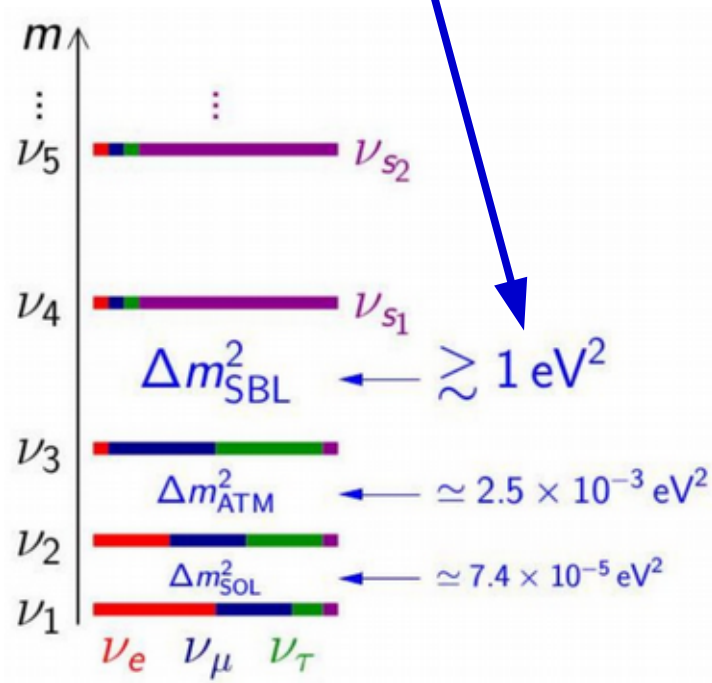
Sterile Neutrinos?

- Are there other neutrinos aside from the three SM neutrinos?
  - Probe of sterile neutrinos at accelerators: $\nu_\mu \rightarrow \nu_e$

Two-Flavor Approximation:

$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

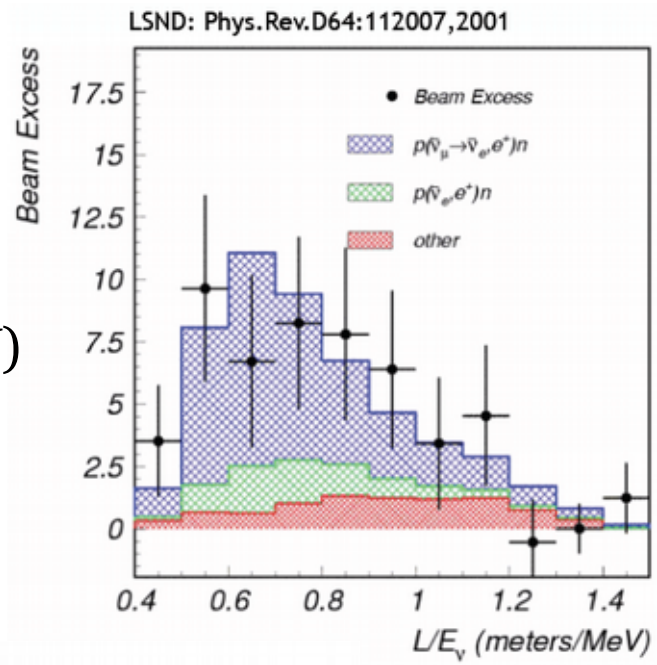


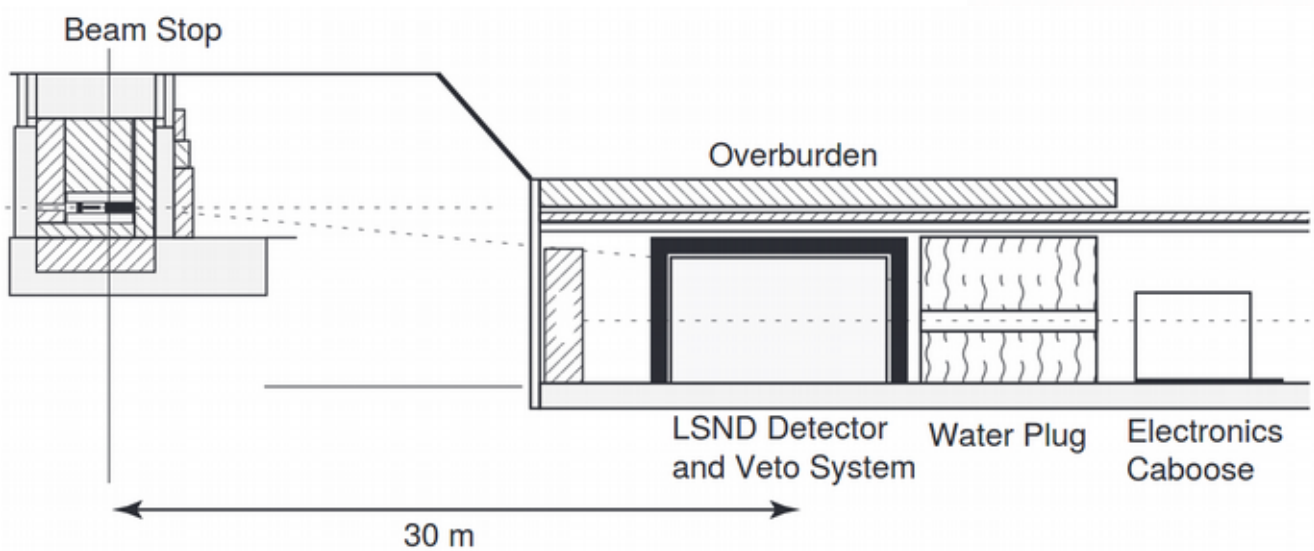


Motivation: LSND and MiniBooNE

The LSND Anomaly

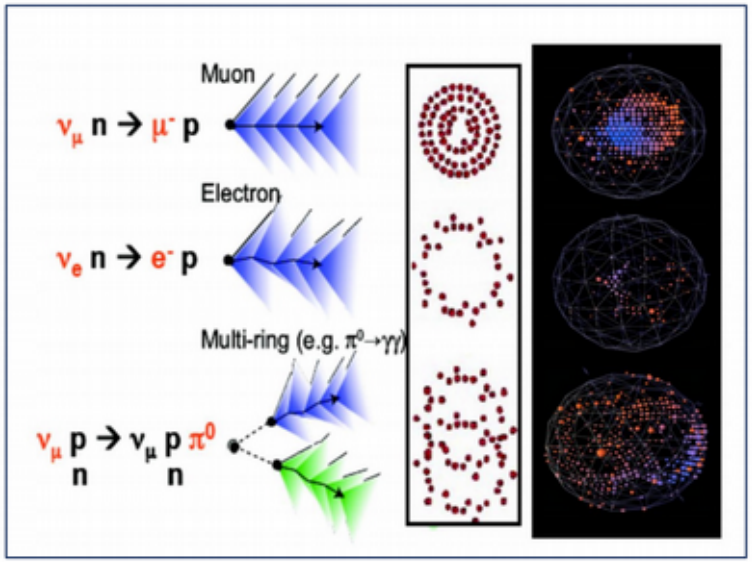
- LSND: Liquid Scintillator Near Detector (Los Alamos National Lab)
  - Mainly $\bar{\nu}_\mu$ from stopped μ^+ decay at rest
  - **L/E ~ 1 m/MeV** (L ~ 30 m, E ~ 30 MeV)
- Excess of $\bar{\nu}_e$-like events observed
  - **3.8 σ** excess; Δm^2 in [0.2, 10] eV^2 range

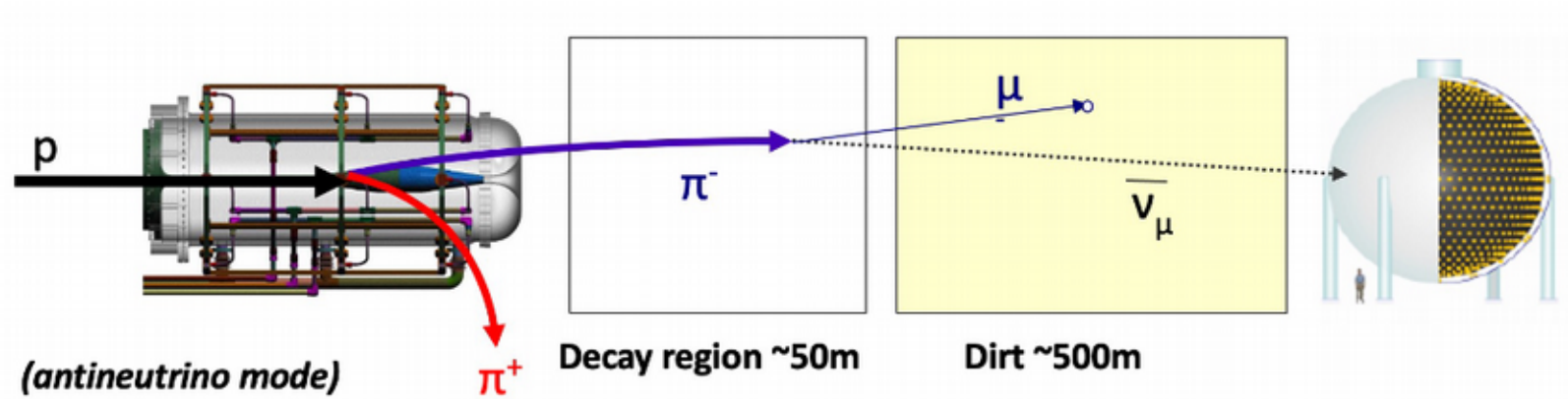




Follow-up w/ MiniBooNE

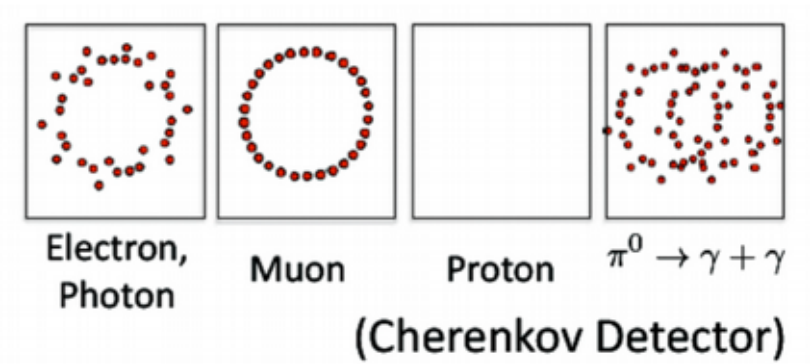
- MiniBooNE: ~800 t mineral oil Cherenkov detector on FNAL Booster Neutrino Beamline (BNB)
  - Mainly $\nu_\mu/\bar{\nu}_\mu$ from π/μ decay in flight
  - **L/E ~ 1** (L ~ 500 m, E ~ 500 MeV)
- 17 years of operation in total
  - **3×10^{21} POT** (protons on target)



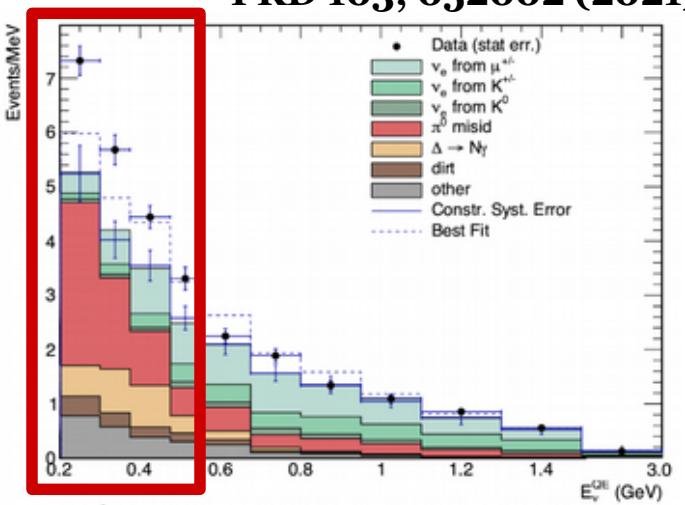


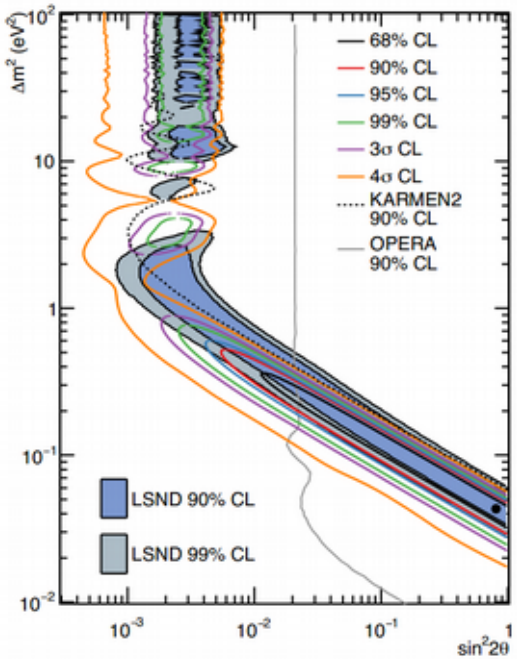
The MiniBooNE Anomaly

- Low-energy ν_e / $\bar{\nu}_e$ candidate excess (LEE) also seen at MiniBooNE
  - Baseline too short (L = 541 m) for 3-flavor $\nu_\mu \rightarrow \nu_e$ oscillation
  - **4.8 σ** excess → **6.1 σ** when combined with LSND (consistent results)
- No $e^{\pm}/\gamma$ separation… is excess misunderstood background, sterile neutrino, or… ?



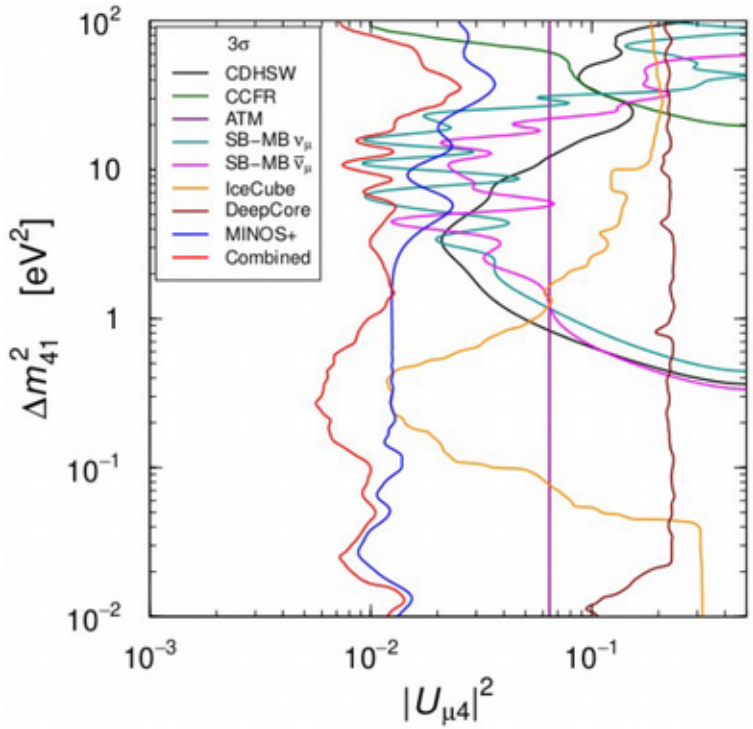
PRD 103, 052002 (2021)

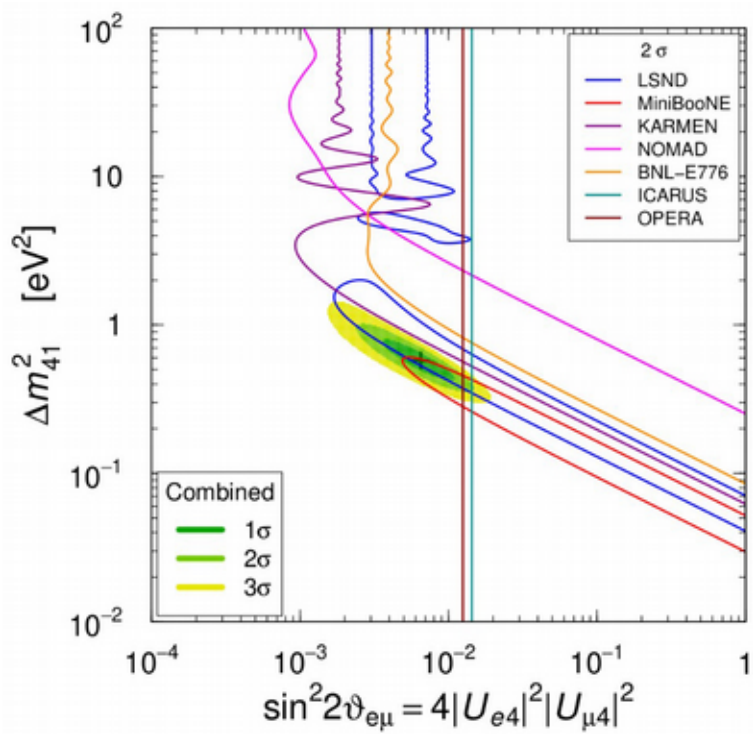




Some Tension

C. Ternes (Yesterday's Talk)





- Tension between ν_μ disappearance (left) and ν_e appearance (right) results, which show incompatibility
- Important to clarify this issue, e.g. by measuring ν_μ disappearance and ν_e appearance at same experiment (SBN)

Some Tension

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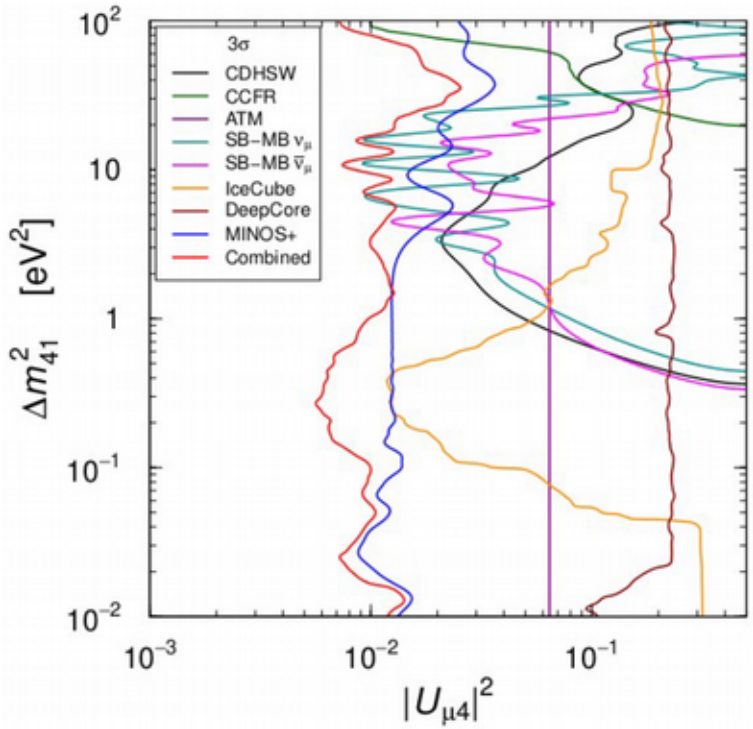
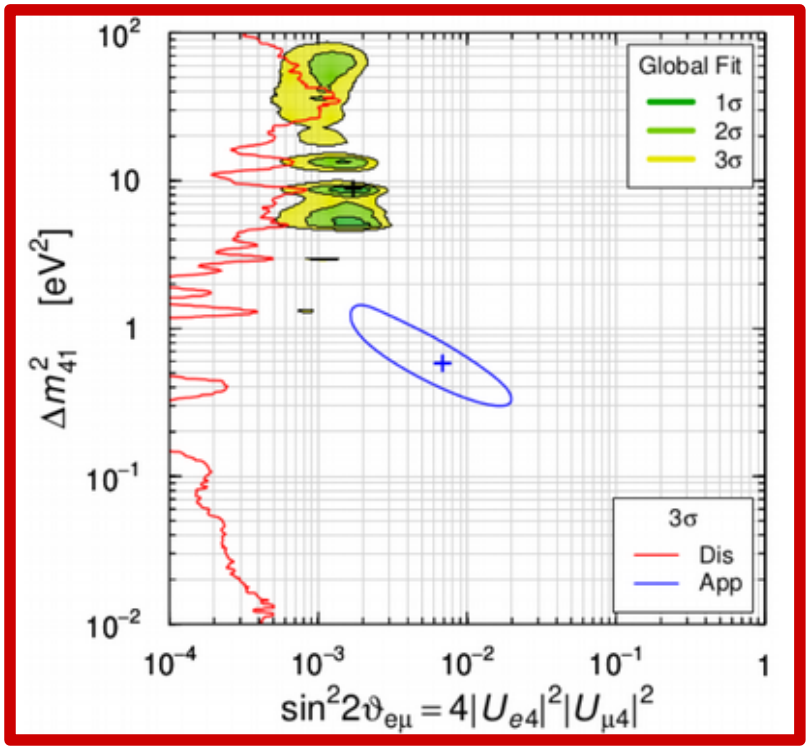


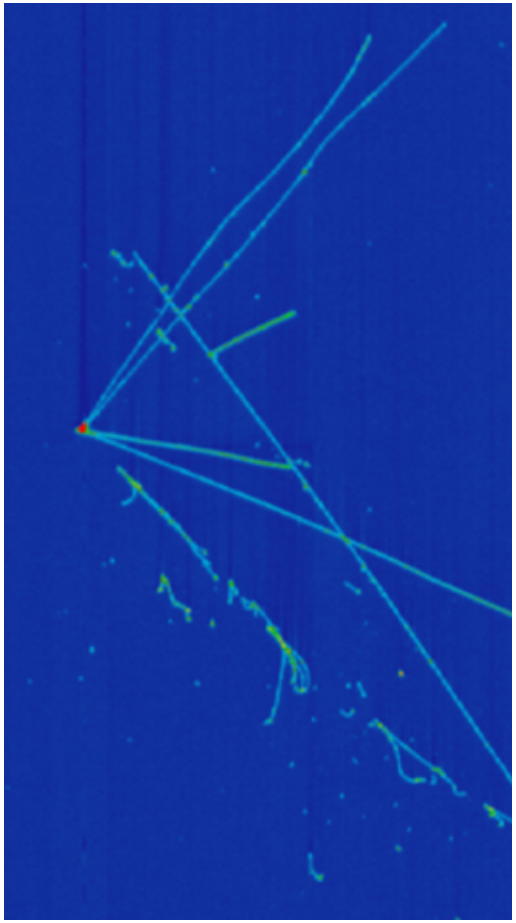


- Tension between ν_μ disappearance (left) and ν_e appearance (right) results, which show **incompatibility**
- Important to clarify this issue, e.g. by measuring ν_μ disappearance and ν_e appearance at same experiment (SBN)

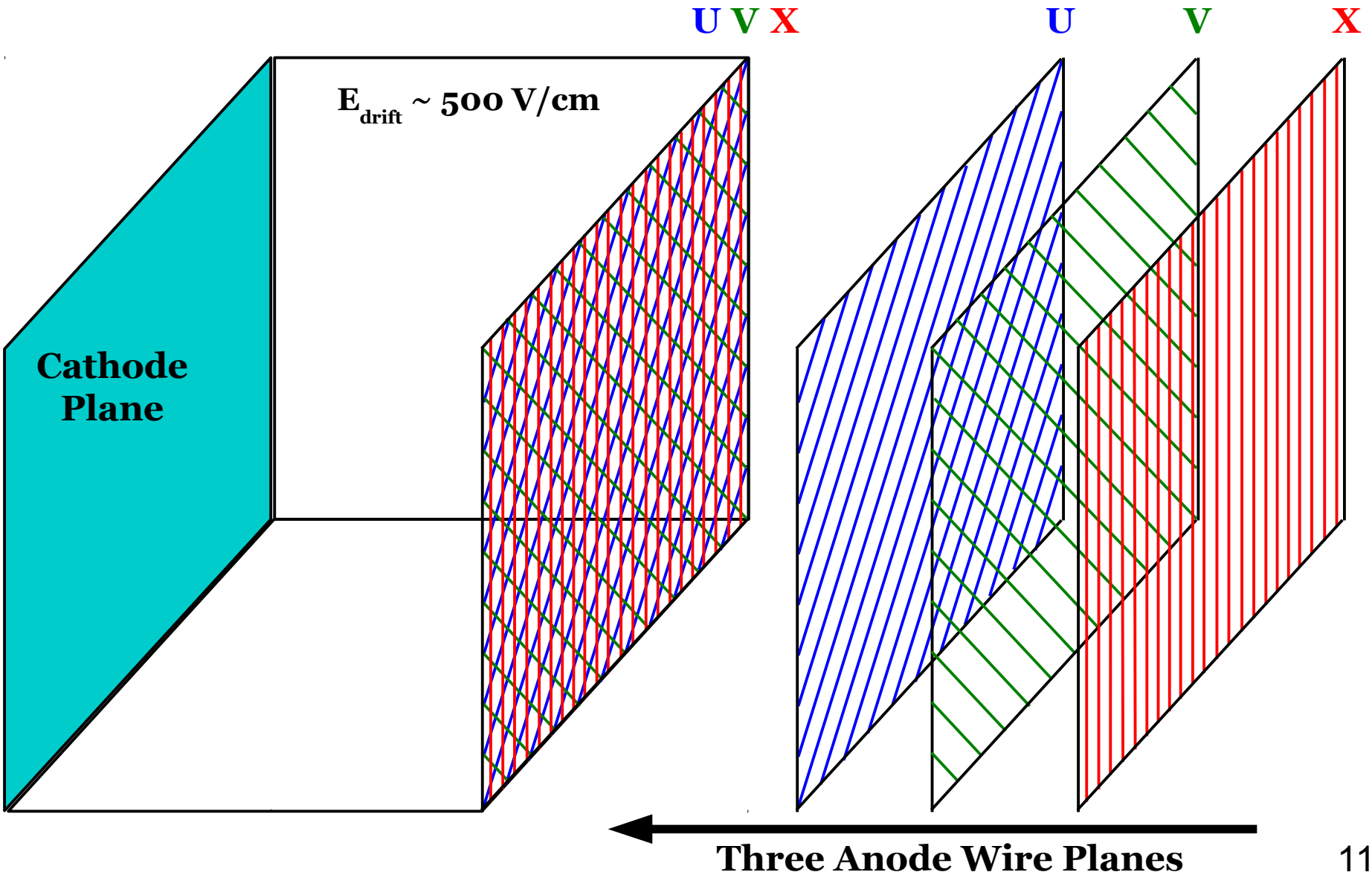
Liquid Argon Time Projection Chambers (LArTPCs)

Introducing… the LArTPC

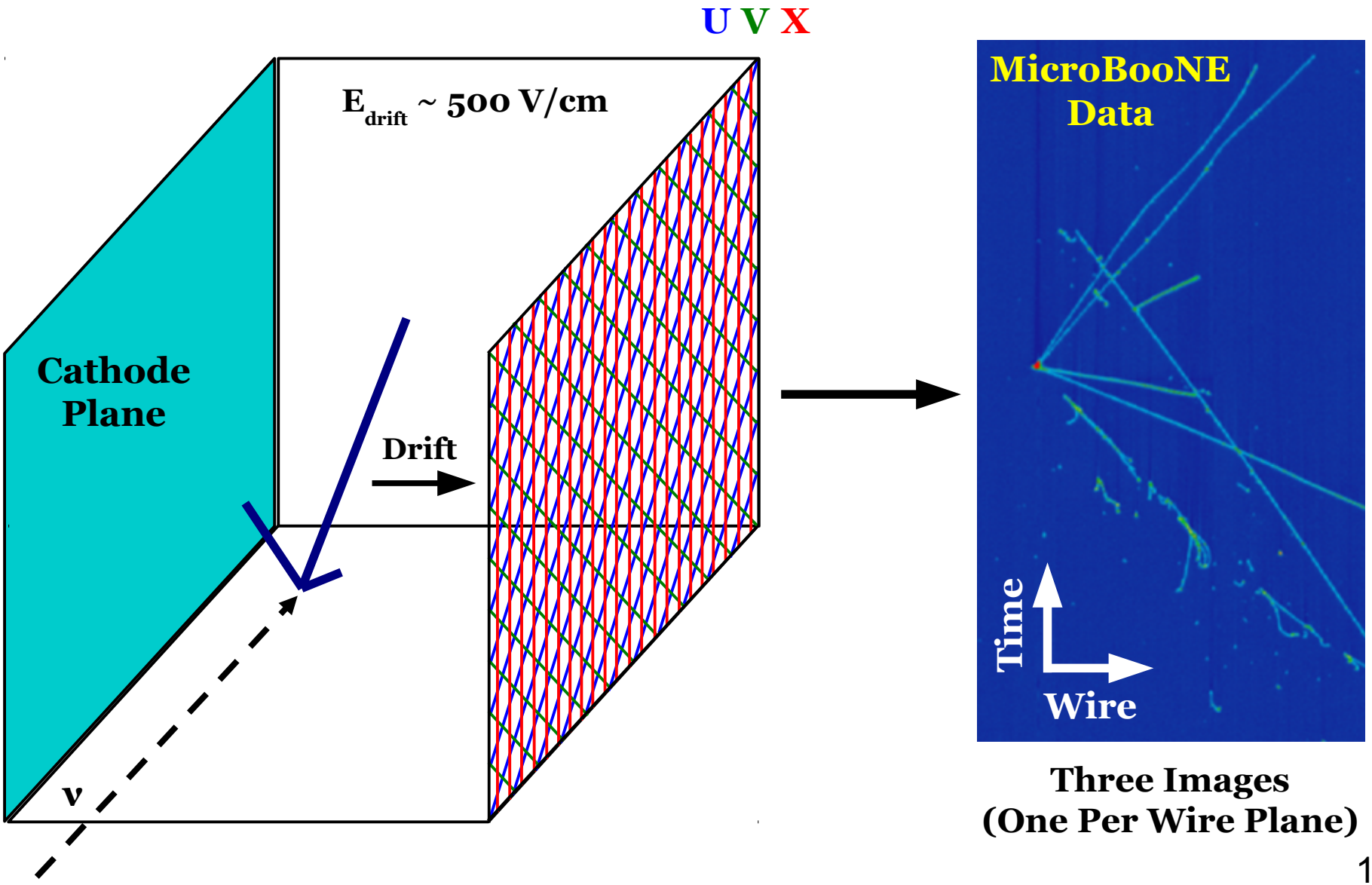
- **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber
- Advantages of LArTPC detectors
  - ***Low Thresholds*** – important for detecting low-energy particles (e.g. protons from hadronic part of neutrino interactions)
  - ***Excellent Calorimetry*** – important for precise estimation of neutrino energy, particle ID with dE/dx
  - ***High Spatial Resolution*** – allows for background rejection and particle ID
  - ***Scalability*** – large detectors yielding high event rates for precision physics
- LArTPCs can help with e/γ separation
  - Addresses limitation at MiniBooNE



Signal Formation



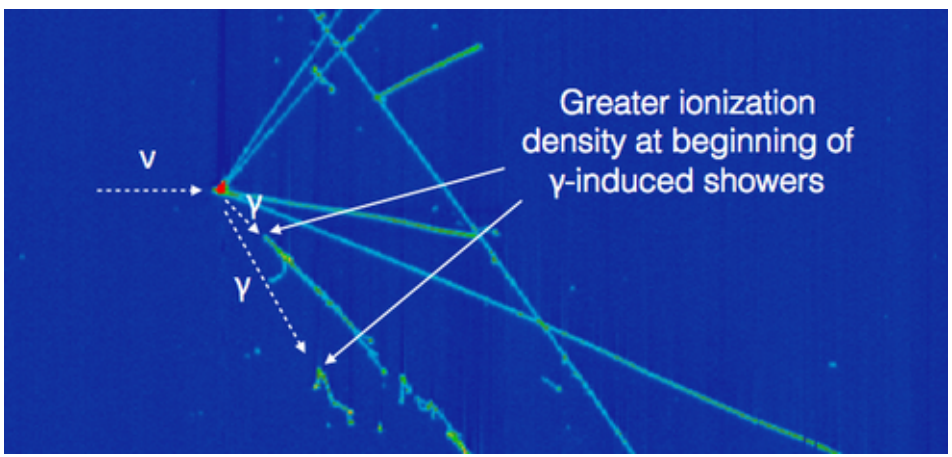
Signal Formation

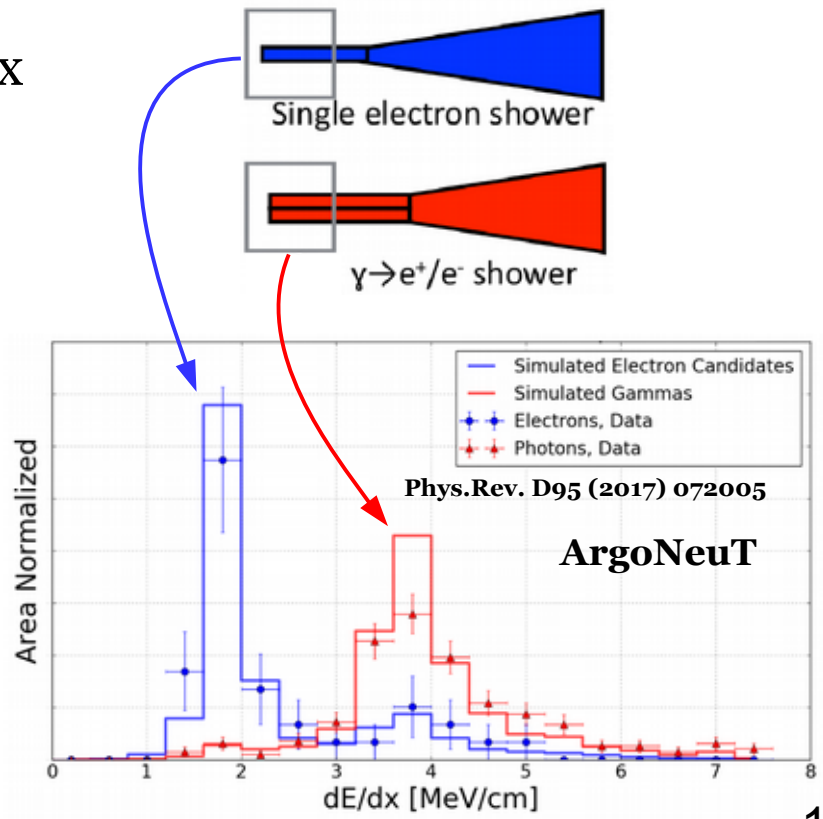


Three Images
(One Per Wire Plane)

Separating e, γ w/ LArTPCs

- Two ways to discriminate e/γ with LArTPCs:
  - Shower displacement from vertex ("gap") for γ (none for e)
  - Factor of two difference in dE/dx (γ double that of e)

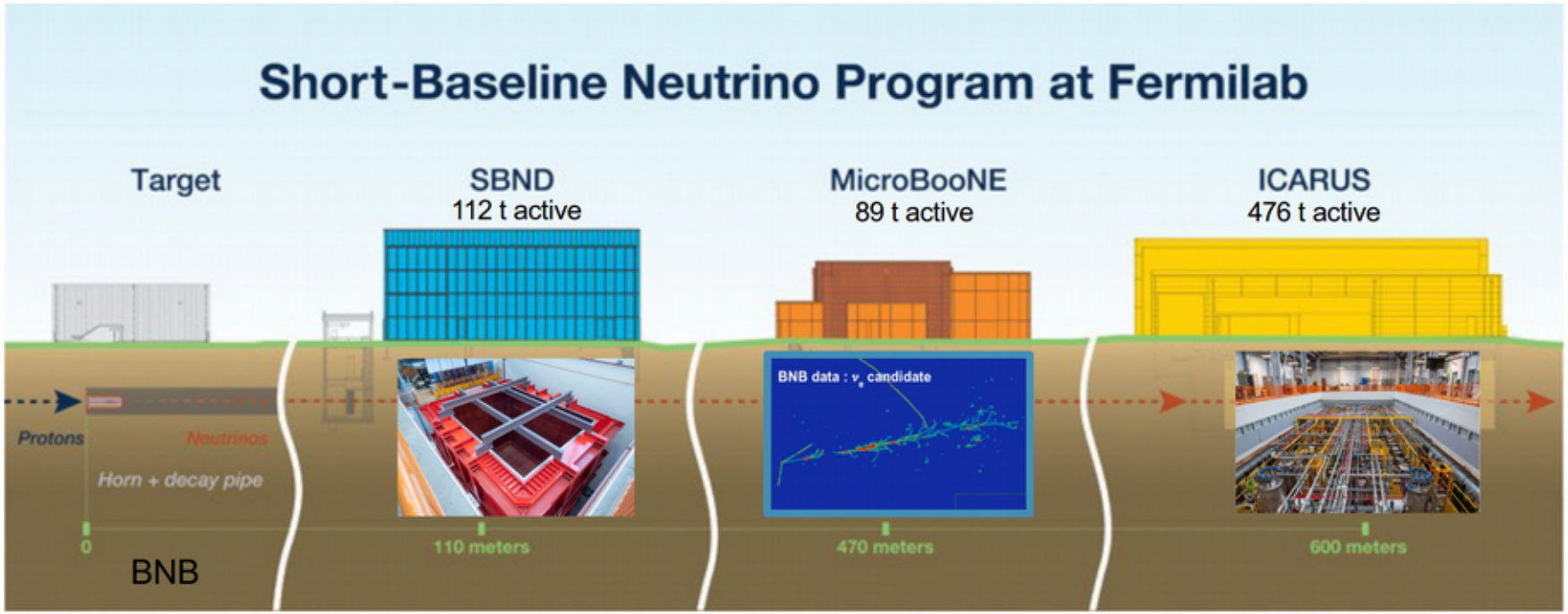




Short Baseline Neutrino (SBN) Program

SBN Program

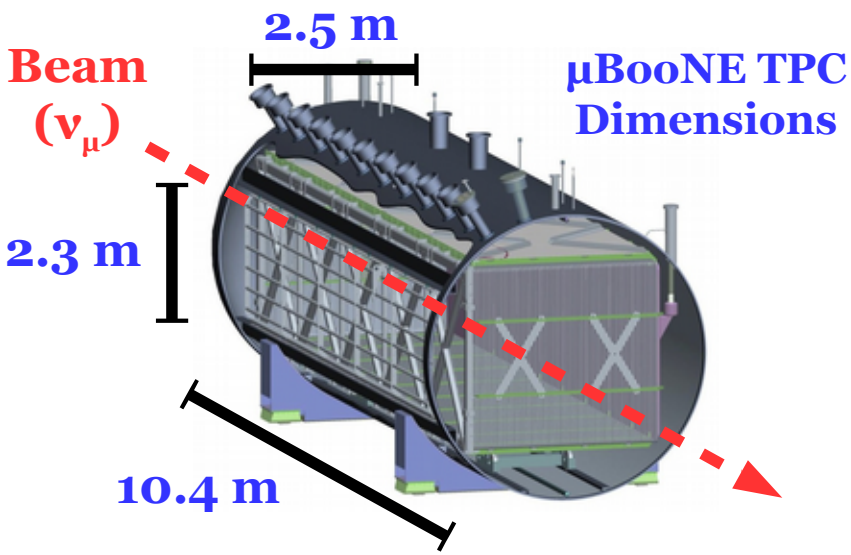
- SBN Program: three *LArTPC* detectors @ FNAL BNB
  - **Same beamline as MiniBooNE (BNB)**, but with e/γ discrimination
  - SBND (Short Baseline Near Detector): provides flux/xsec constraint
  - MicroBooNE/ICARUS: measure <u>oscillated</u> neutrino rate



Installation Phase | **Operating 2015-2021** | **Commissioning Phase**

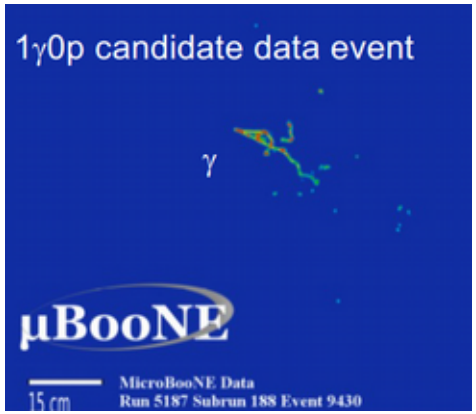
MicroBooNE (μBooNE)

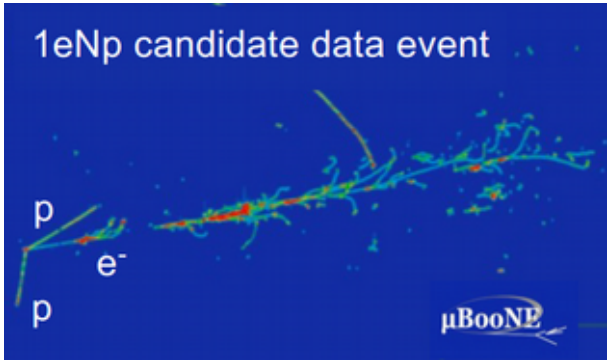
- MicroBooNE: "Micro Booster Neutrino Experiment"
- Notable details:
  - Taking data between 2015 and 2021
  - Cold (in LAr) front-end electronics (same for SBND, but not ICARUS)
  - UV laser calibration system
- Physics goals:
  - **Investigate MiniBooNE low-energy excess (LEE)**
  - Measure first low-energy ν-Ar cross sections
  - Key step for SBN Program
  - R&D for Deep Underground Neutrino Experiment (DUNE)

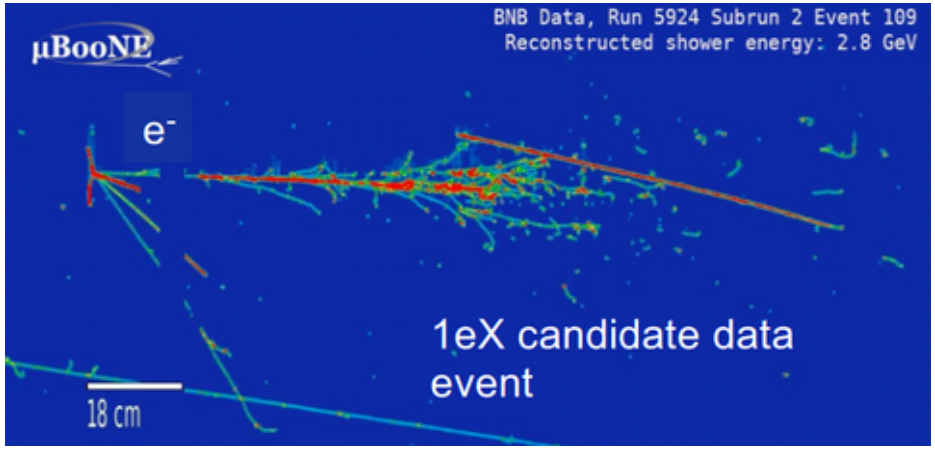


MicroBooNE LEE Analyses

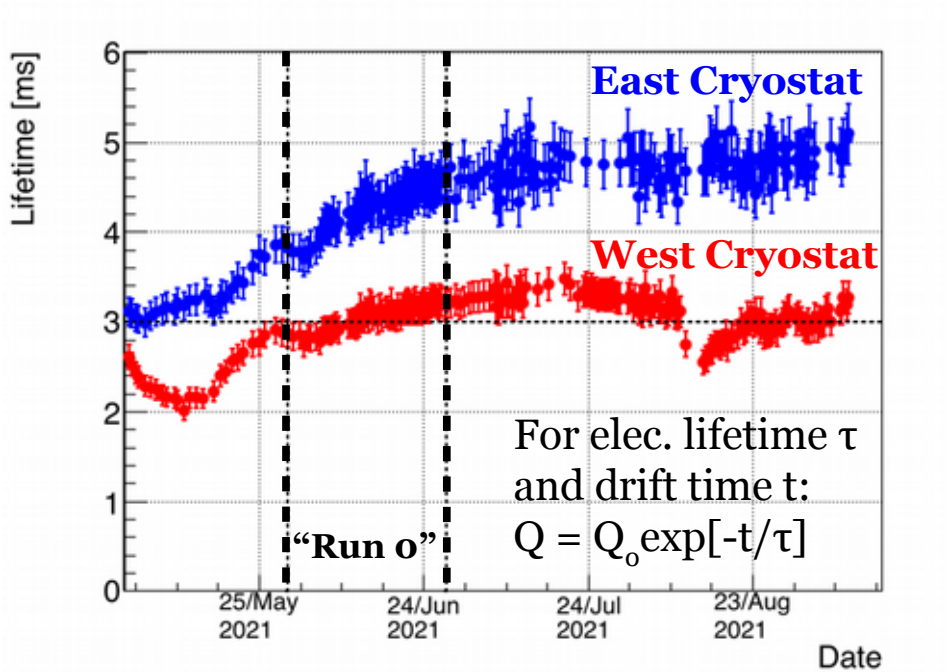
- Two distinct LEE approaches:
  - ν_e analyses (three in total):
    - MiniBooNE-like final state (1eNp/1e0p)
    - Quasi-elastic kinematics w/ ML (1e1p)
    - All ν_e final states (1eX)
  - Single photon production (1γ1p/1γ0p)
- Expect first public LEE results to come out soon







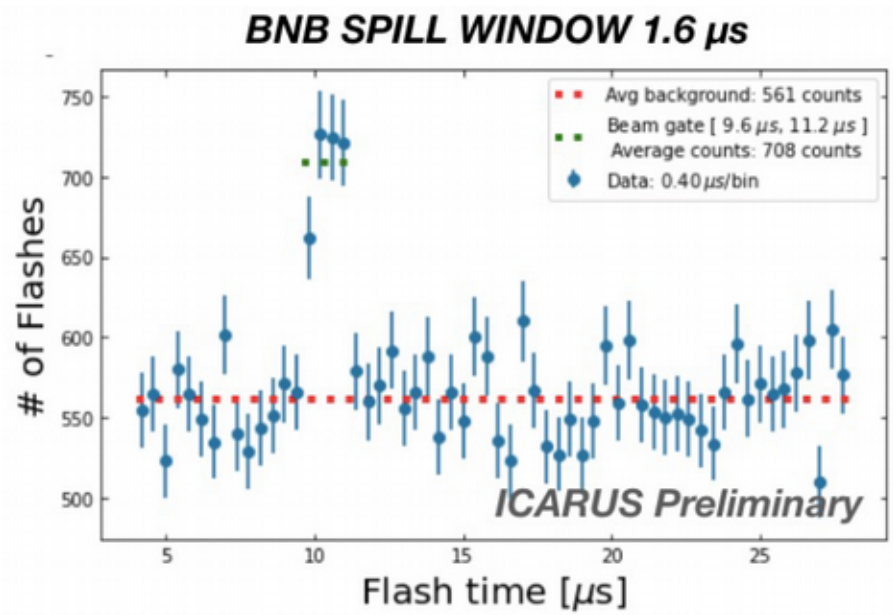
ICARUS Status



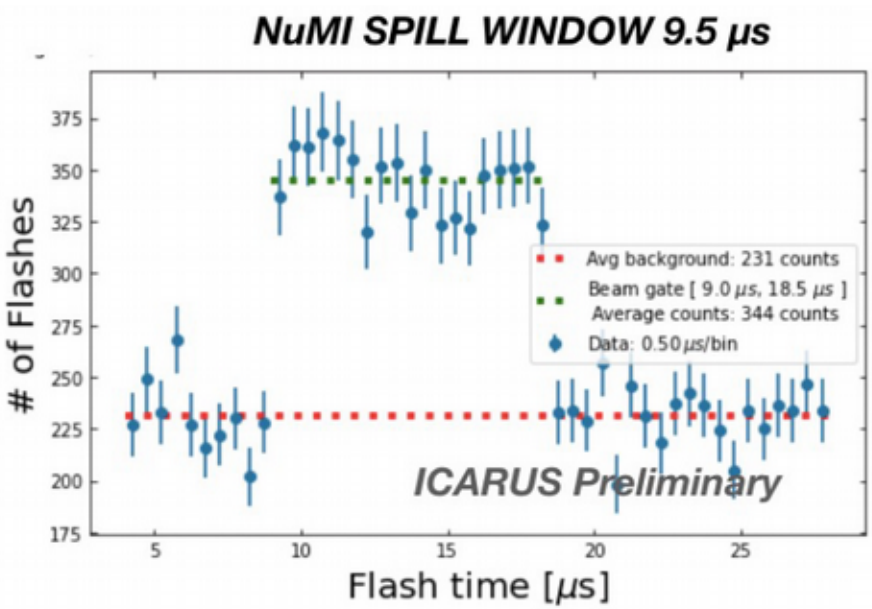
- ICARUS began commissioning in 2020, collecting first neutrino data in June 2021; transitioning to physics data collection in **October 2021**
- Stable noise levels (S/N > 10), good electron lifetime (> 3 ms)
- Expected BNB/NuMI rates observed via light flashes in PMTs

ICARUS Status

BNB: Booster Neutrino Beam



NuMI: Neutrinos at the Main Injector



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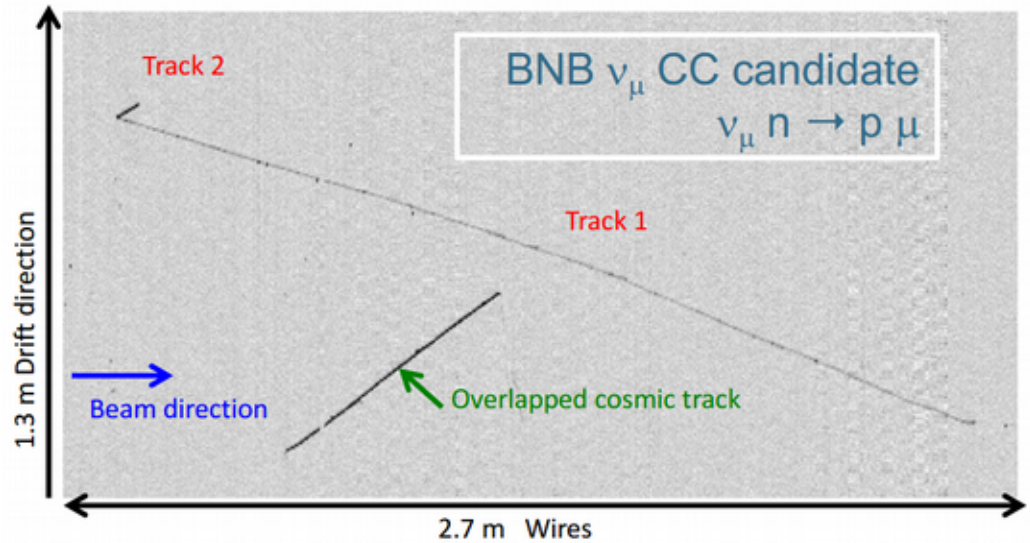
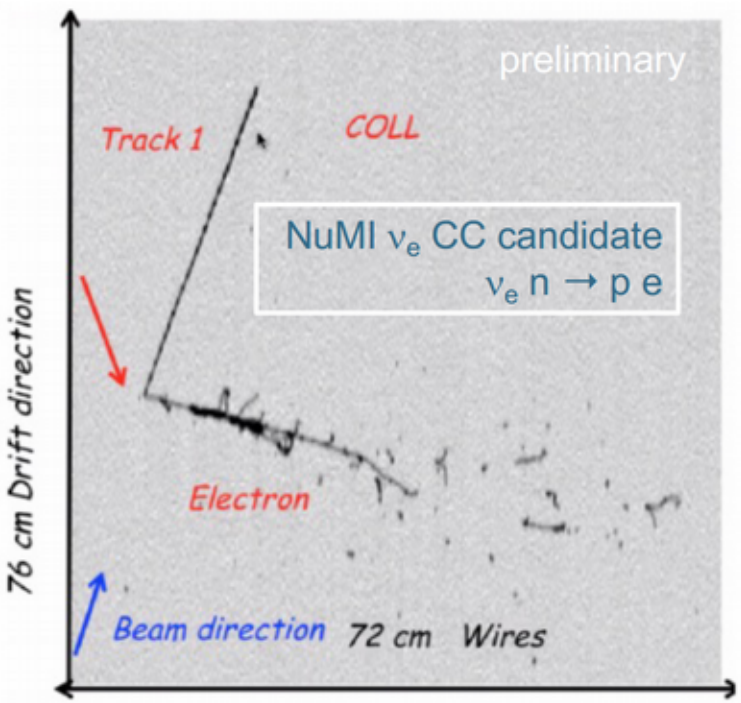
- Expected BNB/NuMI rates observed via light flashes in PMTs

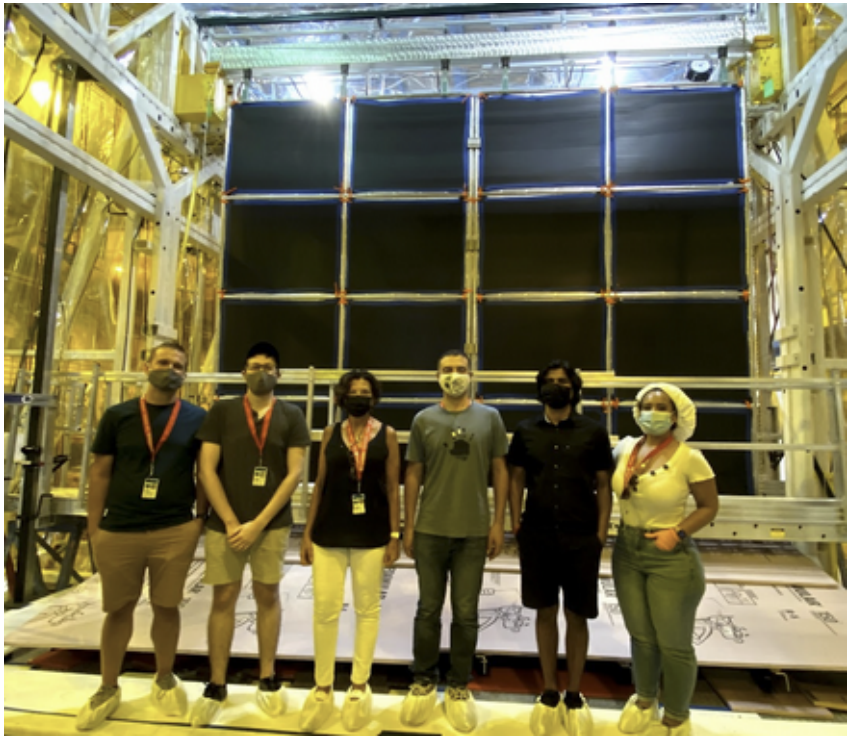
First Neutrinos at ICARUS

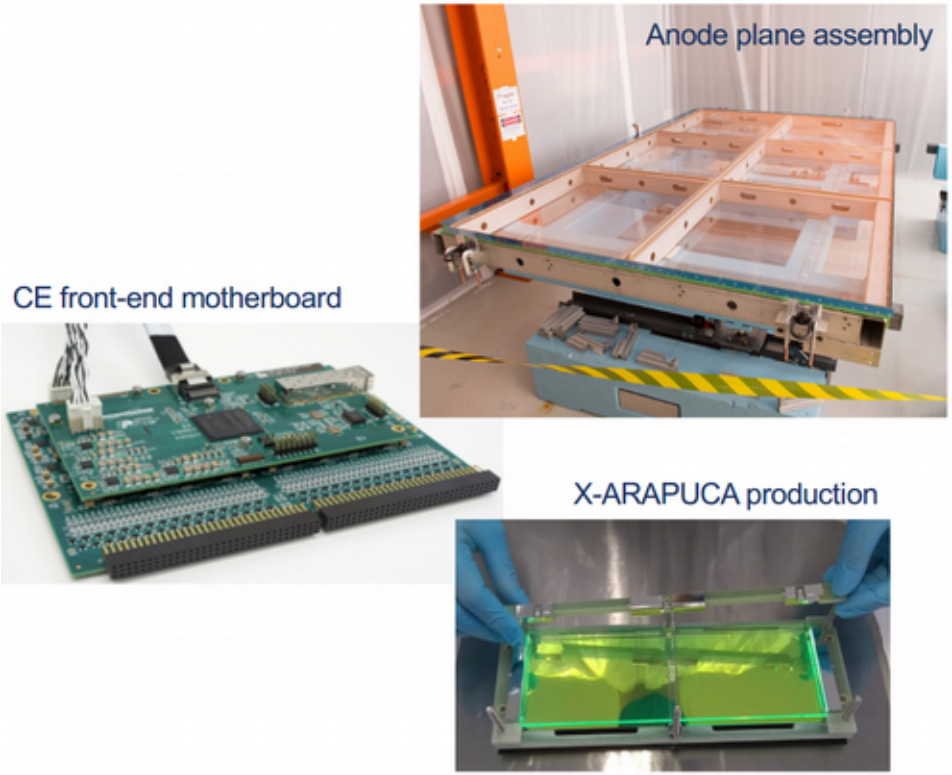




- ICARUS was the primary BNB user @ FNAL during the full month of June 2021 ("Run 0")
- 27.8×10^{18} POT from BNB and 52.0×10^{18} POT from NuMI were collected

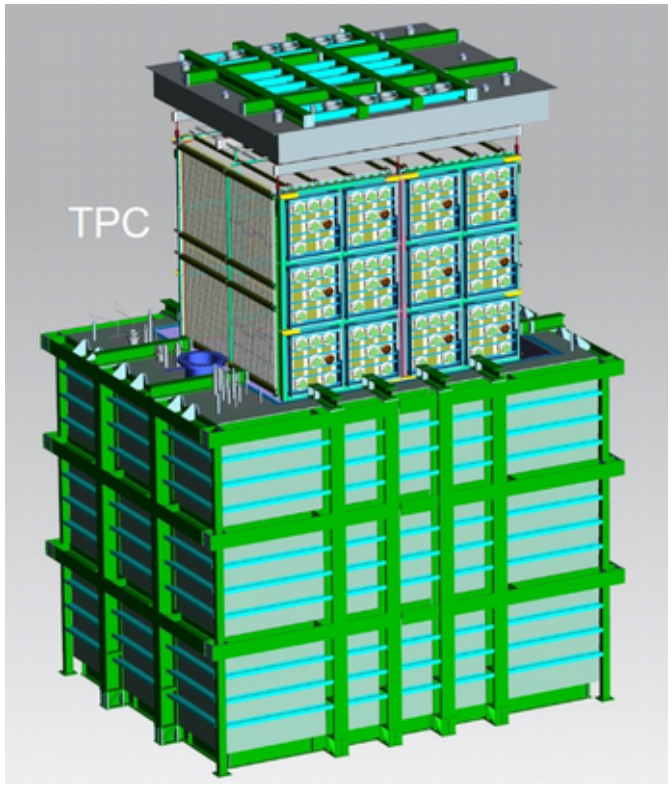
SBND Status

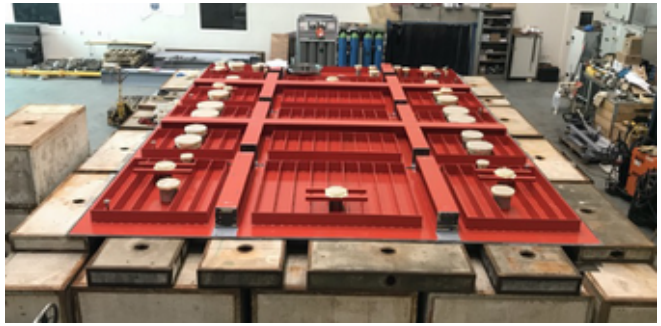


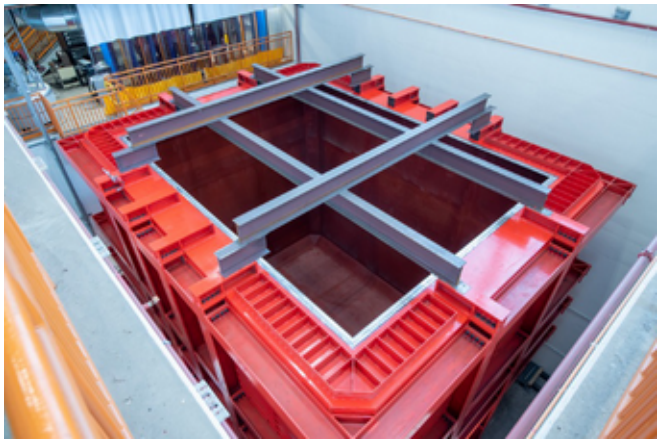


- Cathode installed in TPC; rest of components ready at FNAL
- Warm outer vessel installed in building; cryostat top fabricated and cryogenics/cryostat installation in progress
- SBND ready for cold commissioning by end of **2022**

SBND Status







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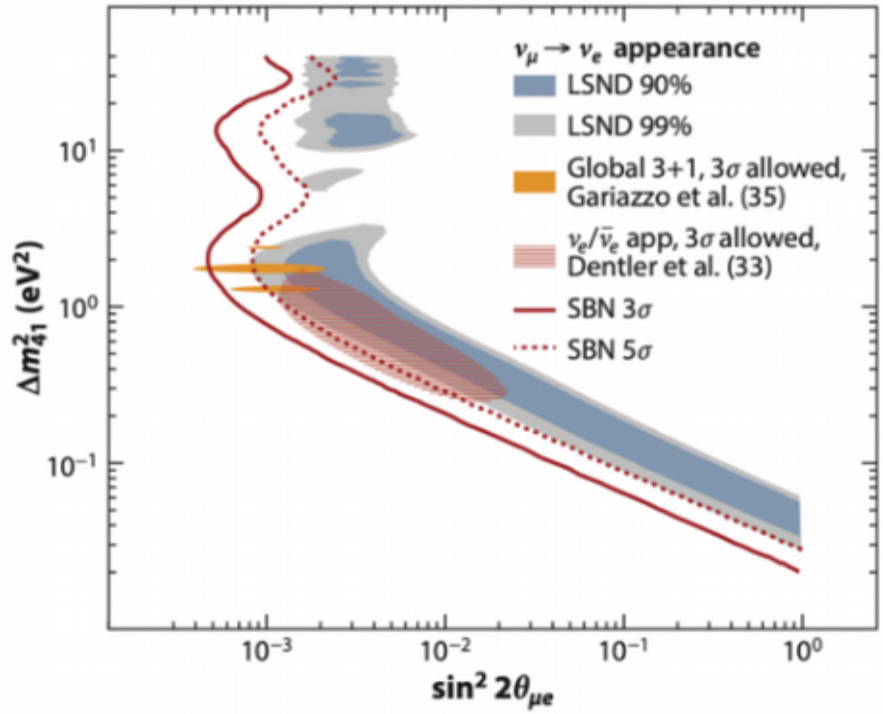
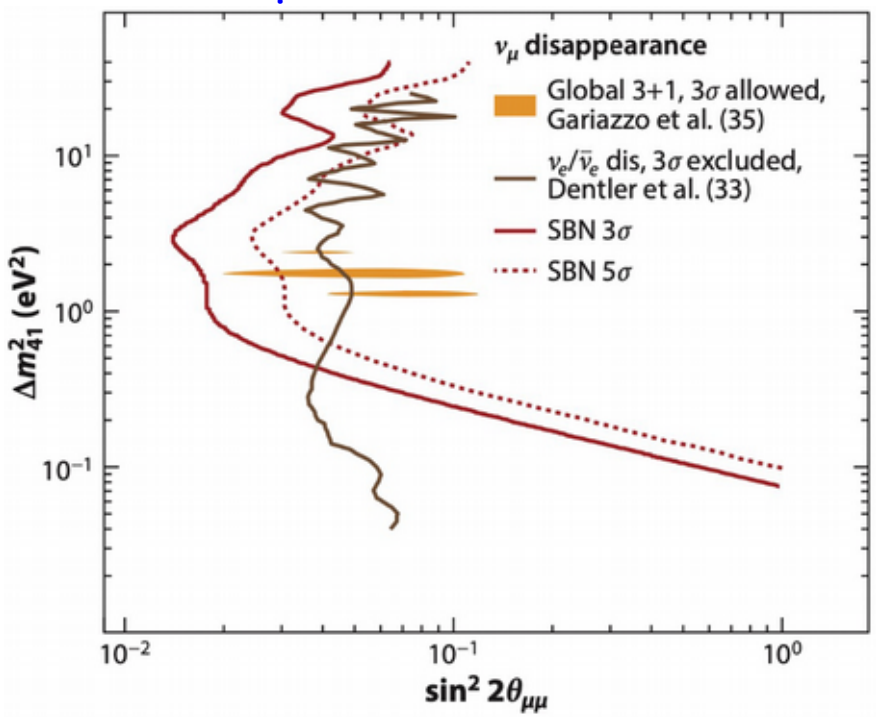
SBN Sensitivity

ν_e Appearance



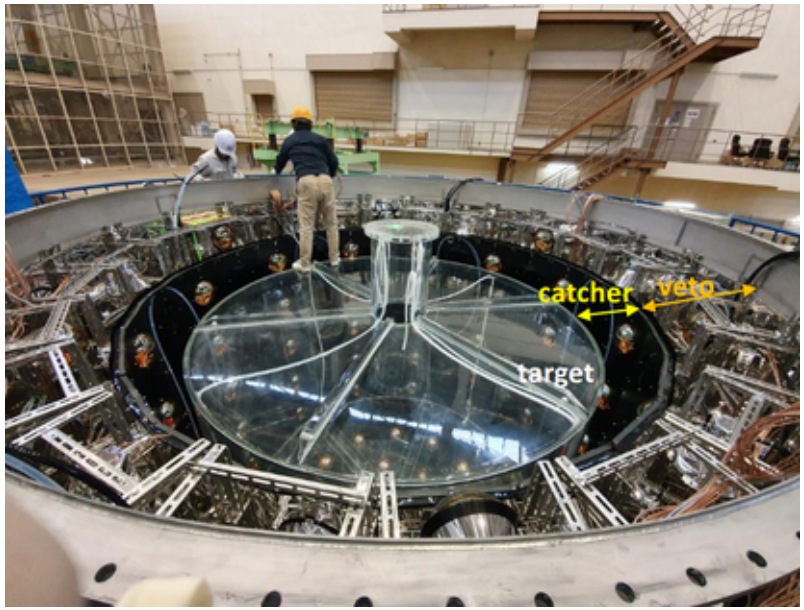
ν_μ Disappearance

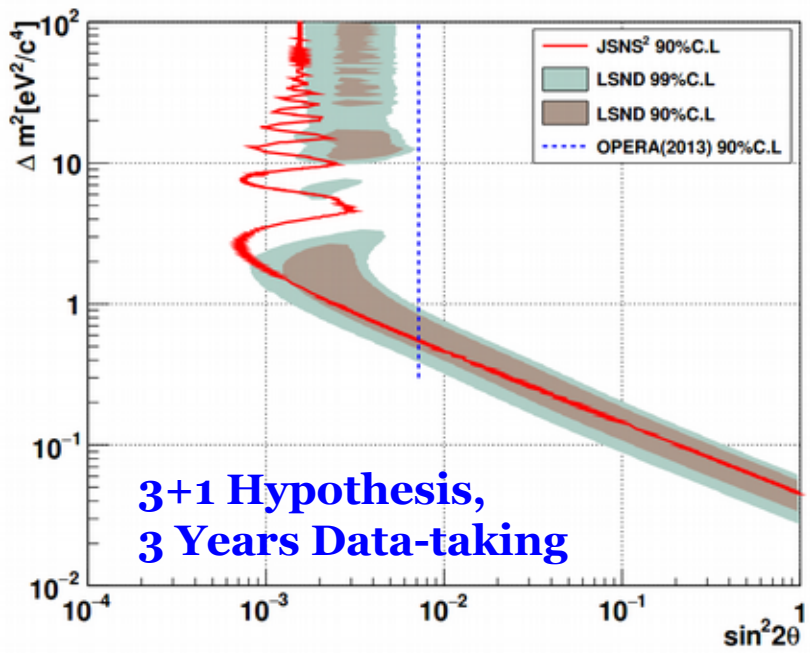


- Reflects **2-3 years** of neutrino-mode data-taking at **ICARUS and SBND** (double dataset for MicroBooNE)
- *SBN only probe of both ν_e appearance and ν_μ disappearance at same experiment*

Beyond SBN

JSNS^2





- JSNS^2: J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source – liquid scintillator w/ Gd-doping
- **Direct test of LSND anomaly:** nearly identical source (μ DAR), target (liquid scintillator), and baseline (~25 m)
  - First data collection in **June 2020, first half of 2021** (analysis ongoing); upgrade planned w/ more data-taking starting in **2023**

Summary

- Accelerator neutrino experiments have much to say about potentiality of sterile neutrinos
  - Previous anomalies:
    - LSND
    - MiniBooNE
  - Running/upcoming experiments:
    - MicroBooNE
    - SBN Program (SBND and ICARUS joining MicroBooNE)
    - $JSNS^2$
- Given experimental landscape, next few years should be very exciting for this topic!

Thanks!