ICARUS and the Fermilab Short Baseline Neutrino Program

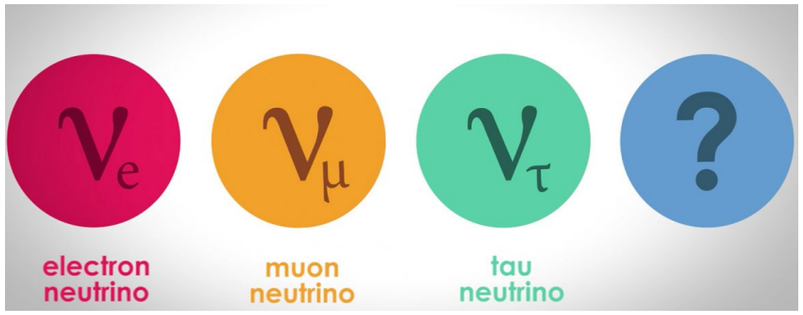
Minerba Betancourt on behalf of ICARUS and SBND Collaborations

XXIX International Conference on Neutrino Physics

June 22- July 02, 2020

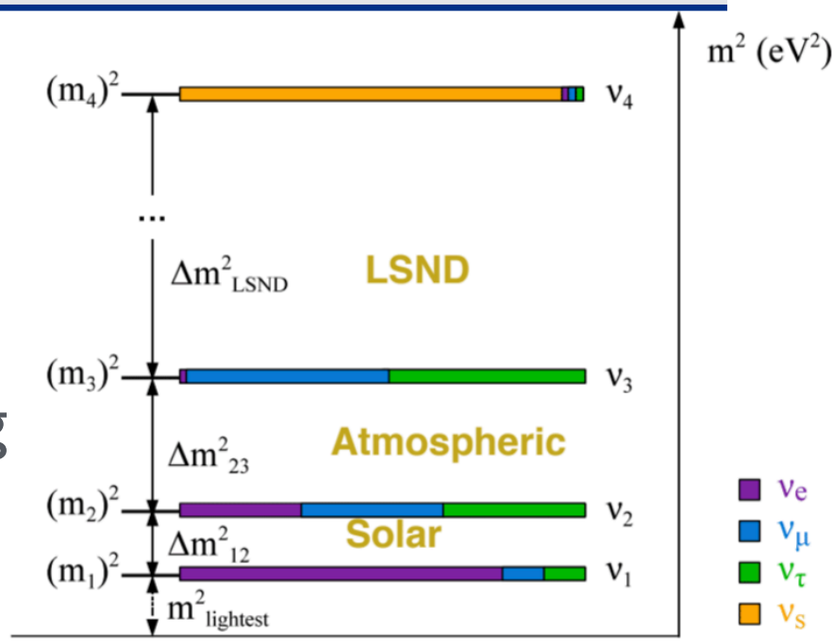
Short-Baseline Neutrino Anomalies

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



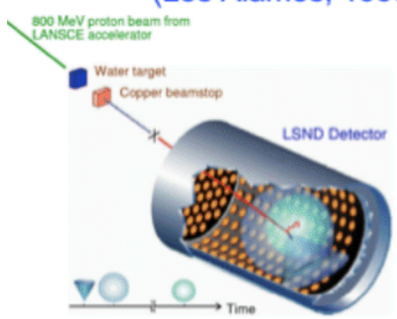
Experiment	Type	Channel	Significance
LSND anomaly	DAR accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8 σ
MiniBooNE anomaly	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 σ
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8 σ
GALLEX/SAGE	Source – e	ν_e disappearance	2.8 σ
Reactors anomaly	β decay	$\bar{\nu}_e$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



Sterile Neutrino Physics Scenario

Low energy $\overline{\nu}_\mu$ beam from a decay-at-rest pion beam (Los Alamos, 1993-1998)



LSND

Baseline 30 m

E= [20 – 50] MeV

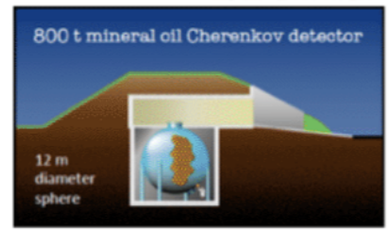
L/E ≈ 1 m/MeV

PRD 64 (2001) 112007

167 tons liquid scintillator

Decay in flight neutrino source (Booster Neutrino Beam - Fermilab)

L/E similar to LSND



800 tons mineral oil

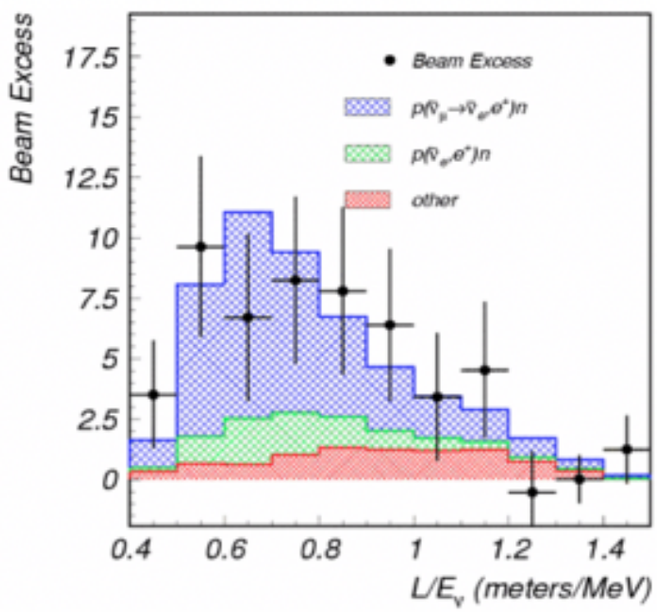
MiniBooNE

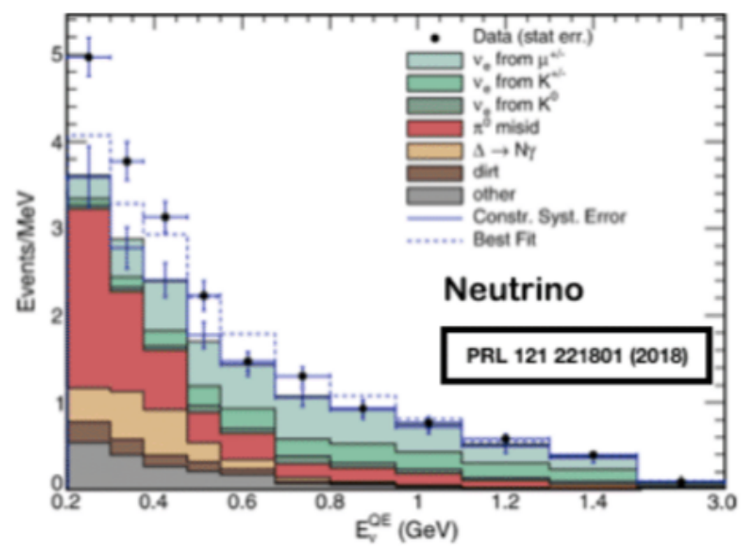
Baseline 540 m

E=[0 - 2] GeV

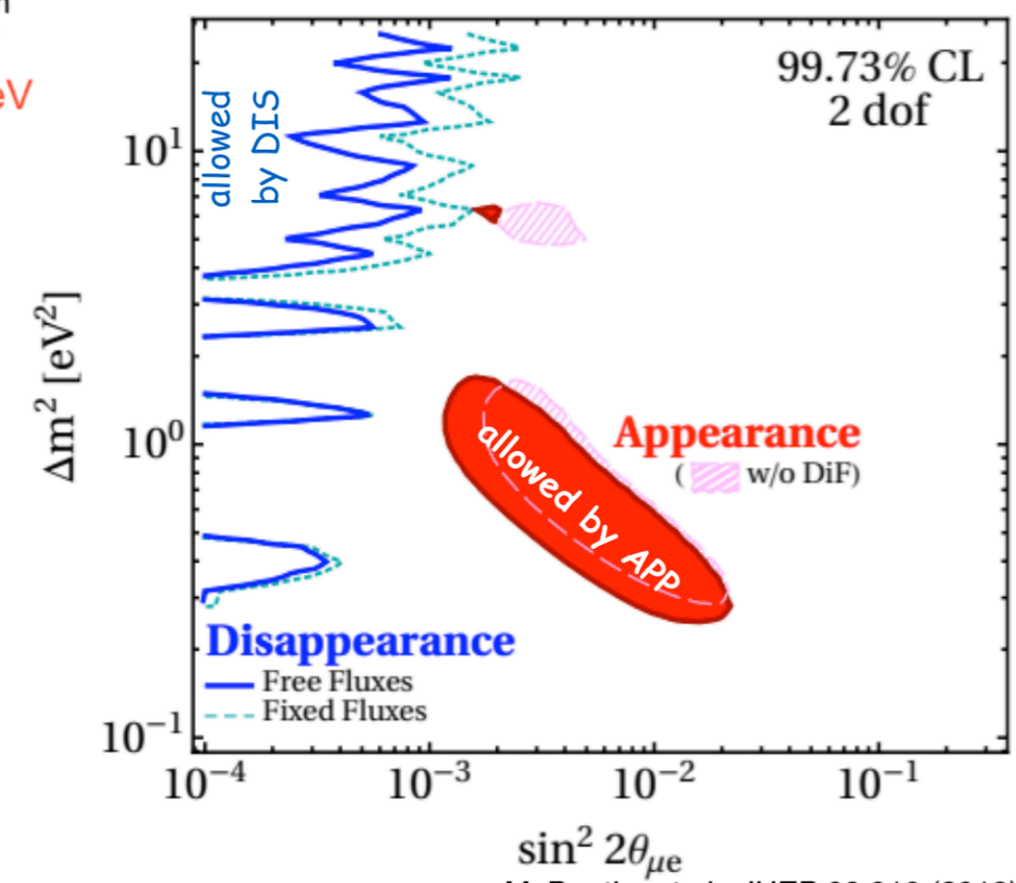
L/E ≈ 1 m/MeV

Tension between ν_e appearance and ν_μ disappearance results





PRL 121 221801 (2018)

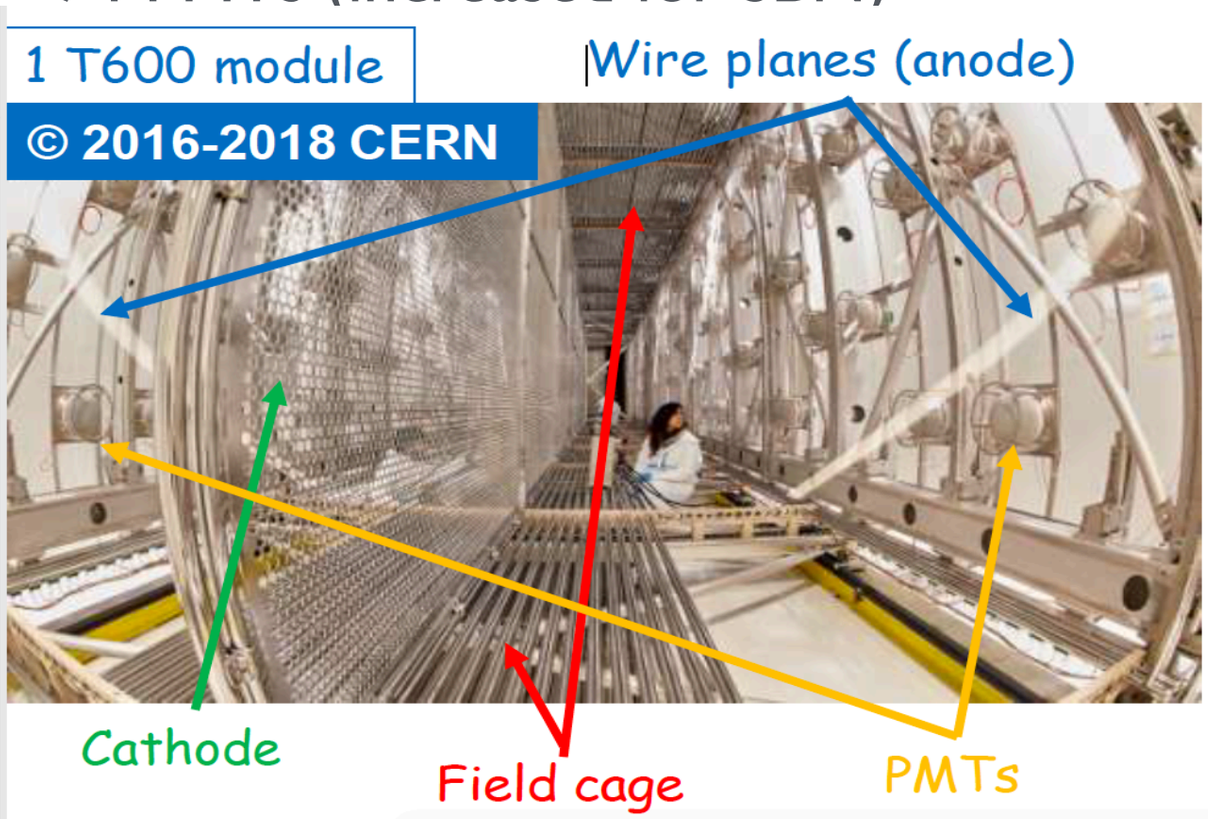


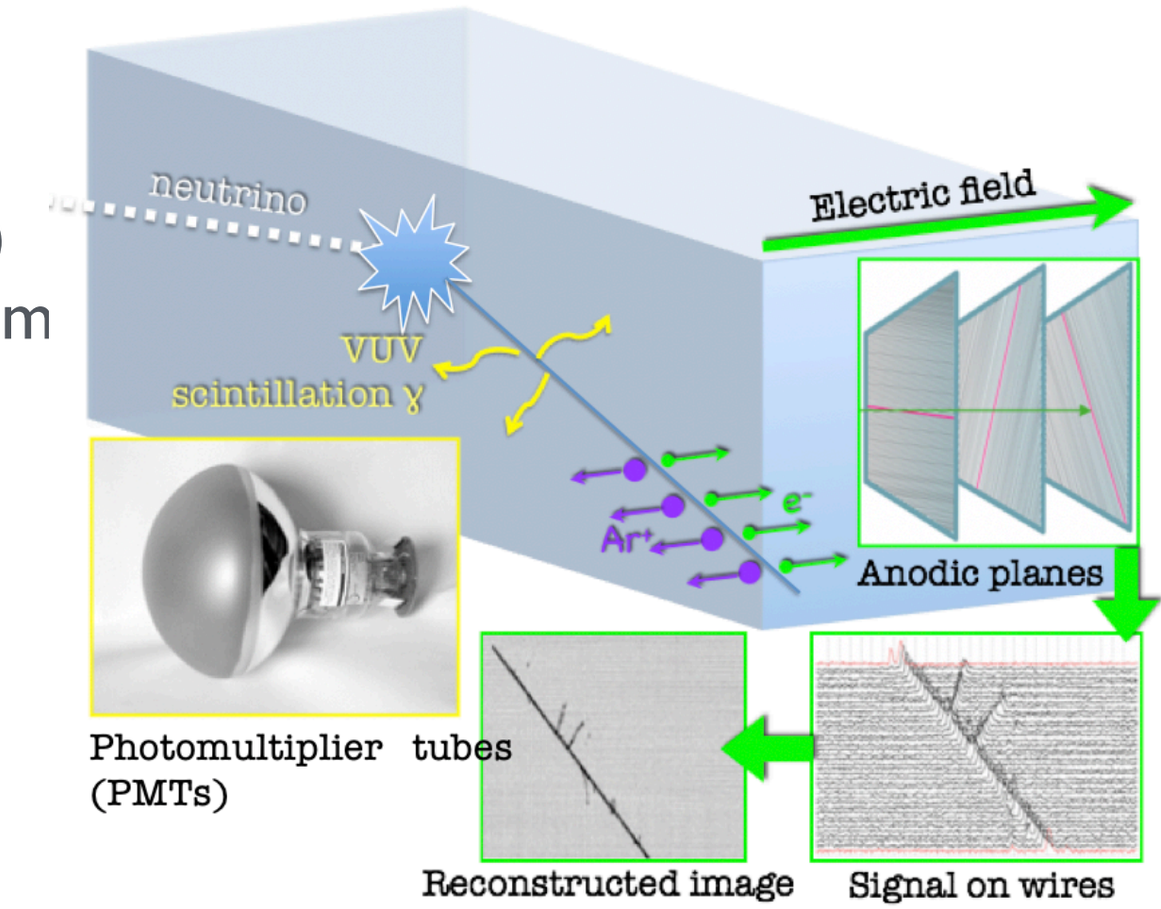
M. Dentler et al., JHEP 08:010 (2018)

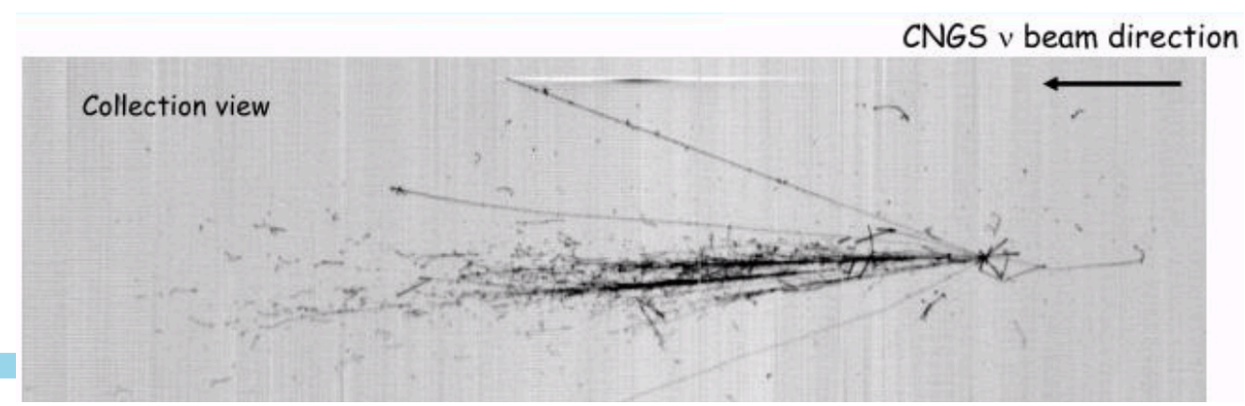
- Sterile neutrino scenario is far from understood:
  - No evidence in ν_μ disappearance experiments (NOvA, MINOS/MINOS+)
  - No precise indication from recent $\overline{\nu}_e$ flux measurement at reactors

ICARUS (Imaging Cosmic And Rare Underground Signals)

- Liquid argon technology for ν physics was proposed by C. Rubbia [CERN-EP/77-08]
- Many years of R&D at INFN/CERN culminated in first large-scale experiment at LNGS underground labs
- 2 TPCs per module with central cathode, 1.5 m drift, E_D=500 V/cm, Δt~1 ms
- 3 readout wire planes (2 induction+collection) per TPC, ~54000 wires at 0, ± 60 degrees, 3 mm pitch and a continuous read-out
- 74 PMTs (increased for SBN)



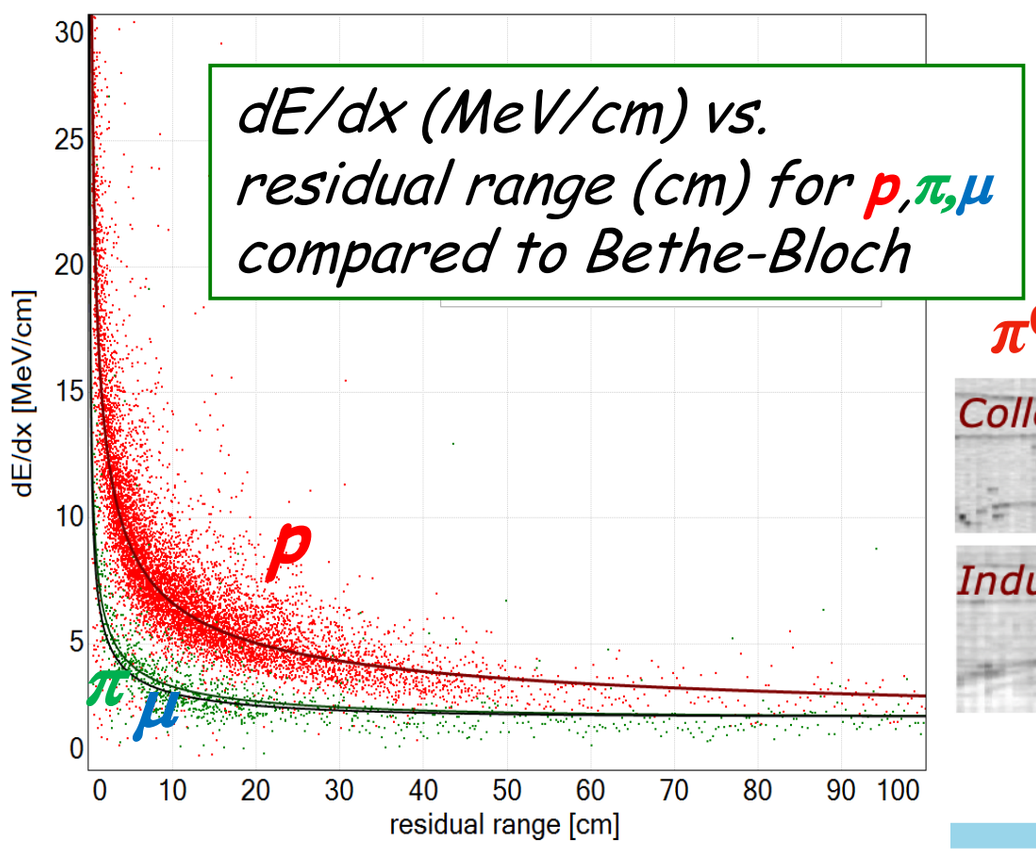


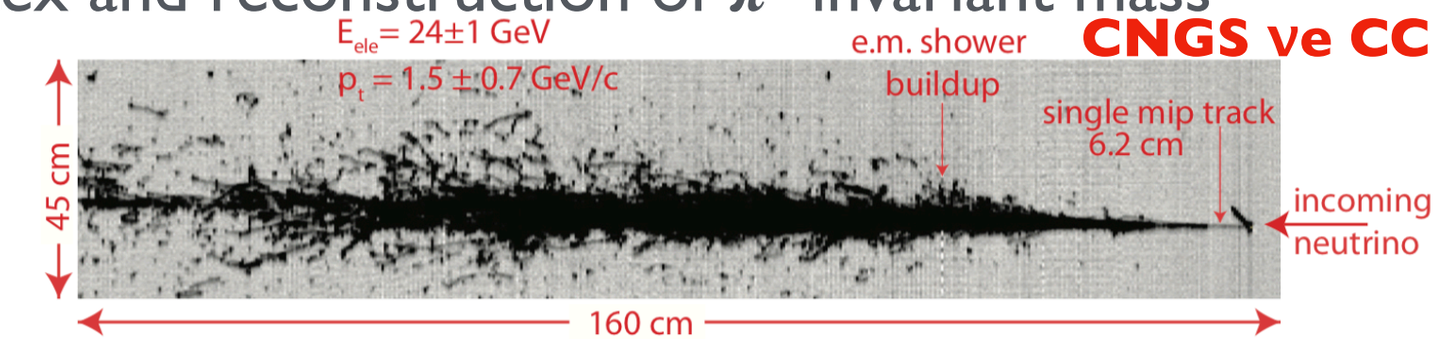


LAr-TPC: an ideal detector for ν physics

- Tracking device: precise 3D event topology with ~mm^3 resolution for ionizing particle
- Excellent calorimetry and particle identification
- Remarkable e/γ separation: ν_e CC event separation from NC background with π^0
  - Calorimetric accuracy and fine sampling allow measuring dE/dx on each wire, γ conversion gap from primary vertex and reconstruction of π^0 invariant mass

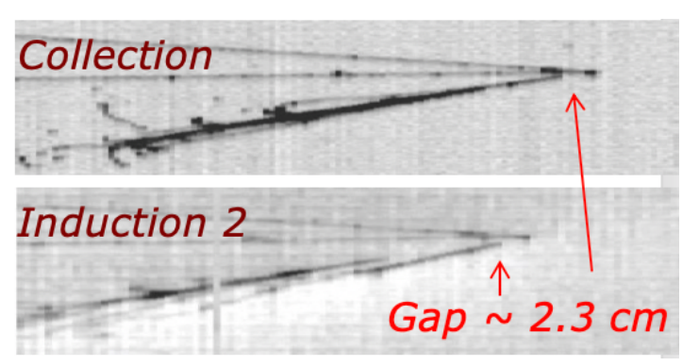
AHEP (2013) 260820

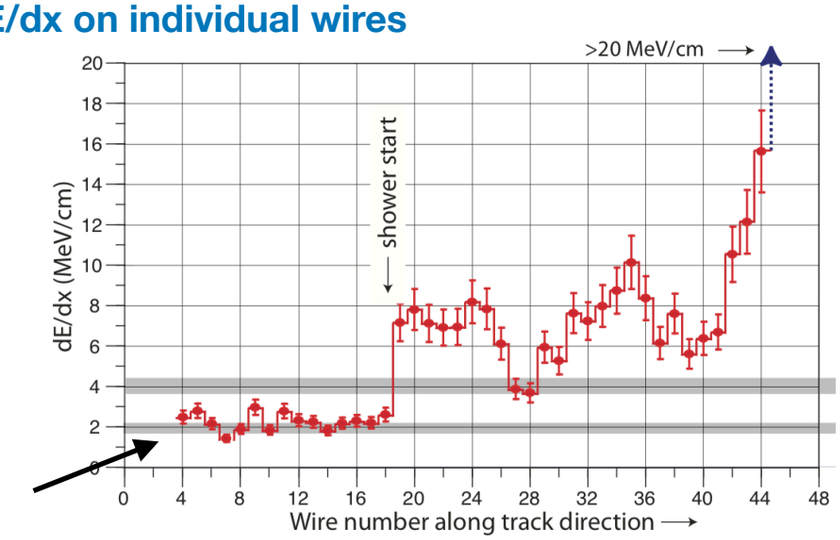




Evolution in collection view from single mip to EM shower is evident from dE/dx on individual wires

π^0

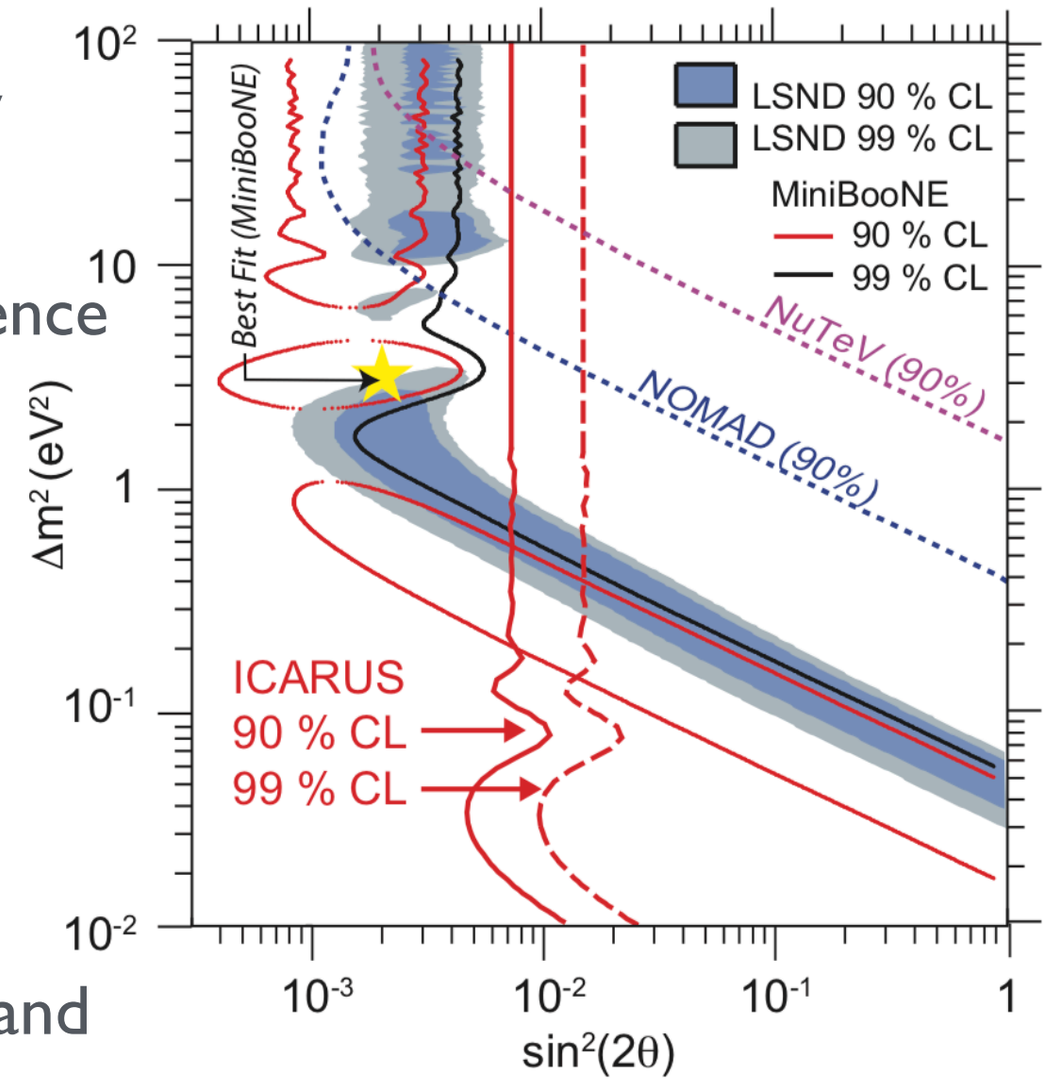




Single mip

ICARUS Search for Sterile Neutrinos at CNGS

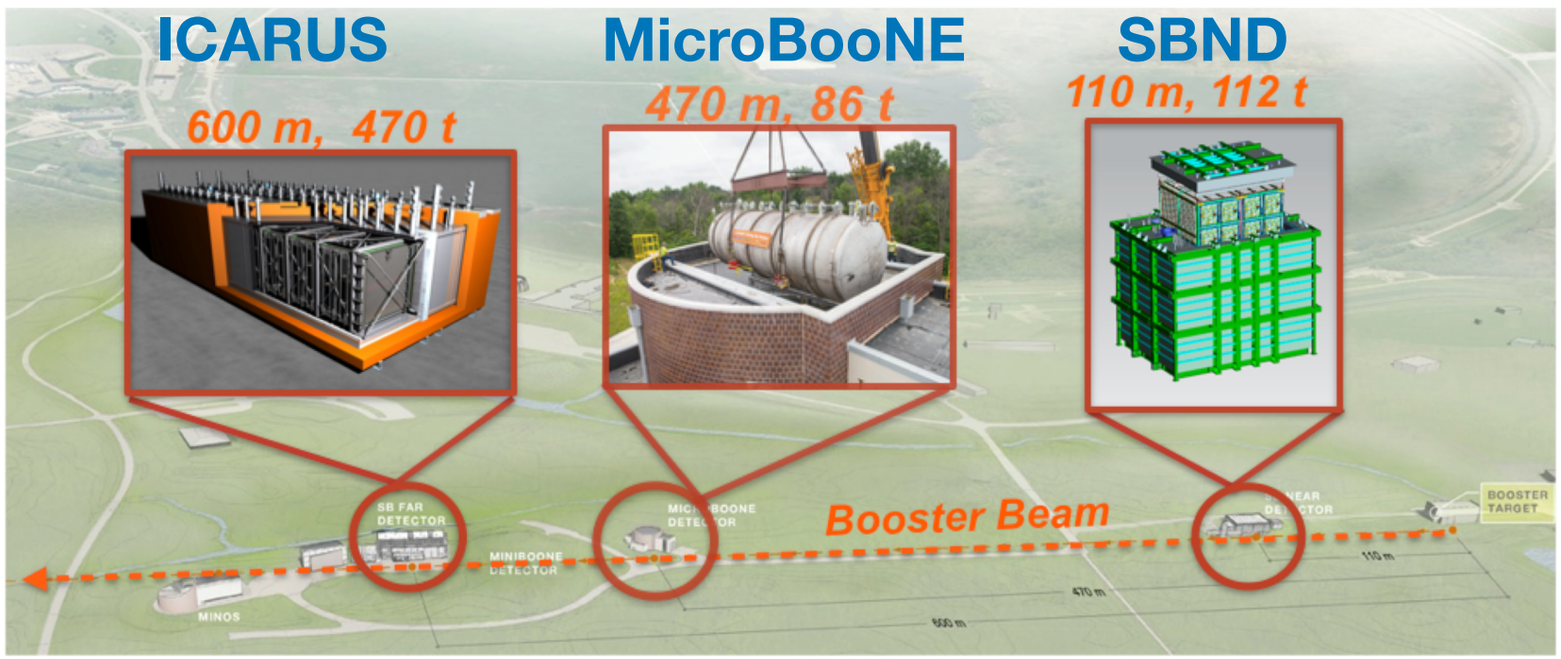
- ICARUS searched for sterile ν oscillation through ν_e appearance in the CNGS beam
- L/E ~36 km/GeV, far from LSND value ~1km/GeV
- 7.9e19 POTs analyzed (~2650 ν interactions)
- Expected ~8.5 ± 1.1 ν_e background events in absence of anomaly, mostly from intrinsic ν_e beam contamination
- Estimated ν_e identification efficiency ~74% with negligible background from misidentification
- 7 events observed -> no evidence of oscillation
- Constraining LSND to a narrow region at $\sin^2 2\theta \sim 0.005$, $\Delta m^2 = 0.5 eV^2$
- Similar result by OPERA with same CNGS beam and different detection techniques



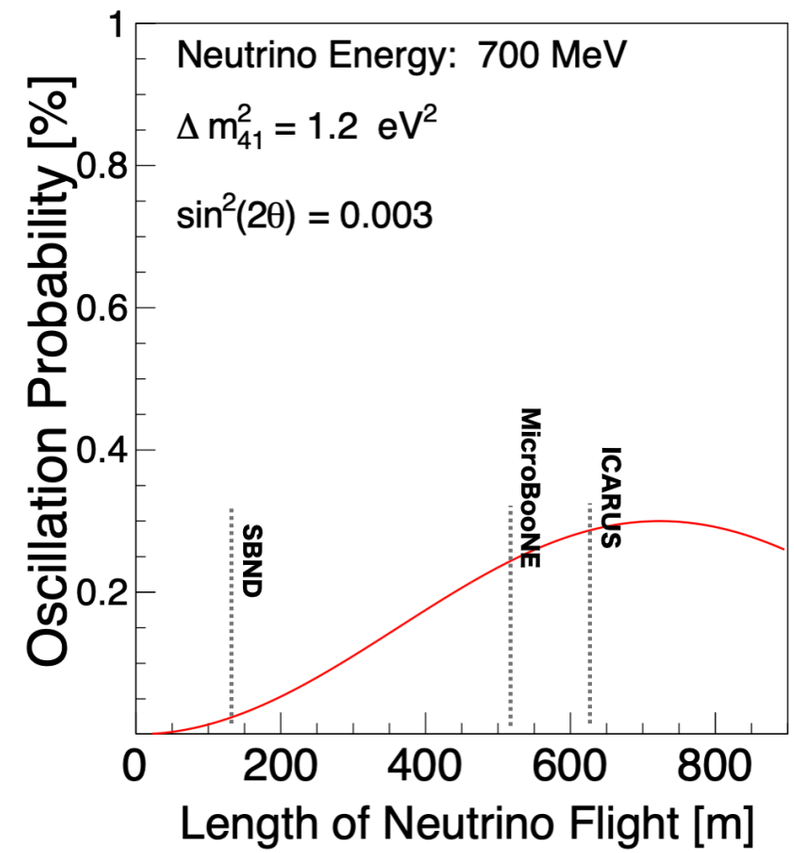
EPJ C(2013) 73: 2599

Short Baseline Program (SBN)

- LArTPC detectors at different baselines from Booster neutrino beam searching for sterile neutrino oscillations measuring both appearance and disappearance channels with three detectors



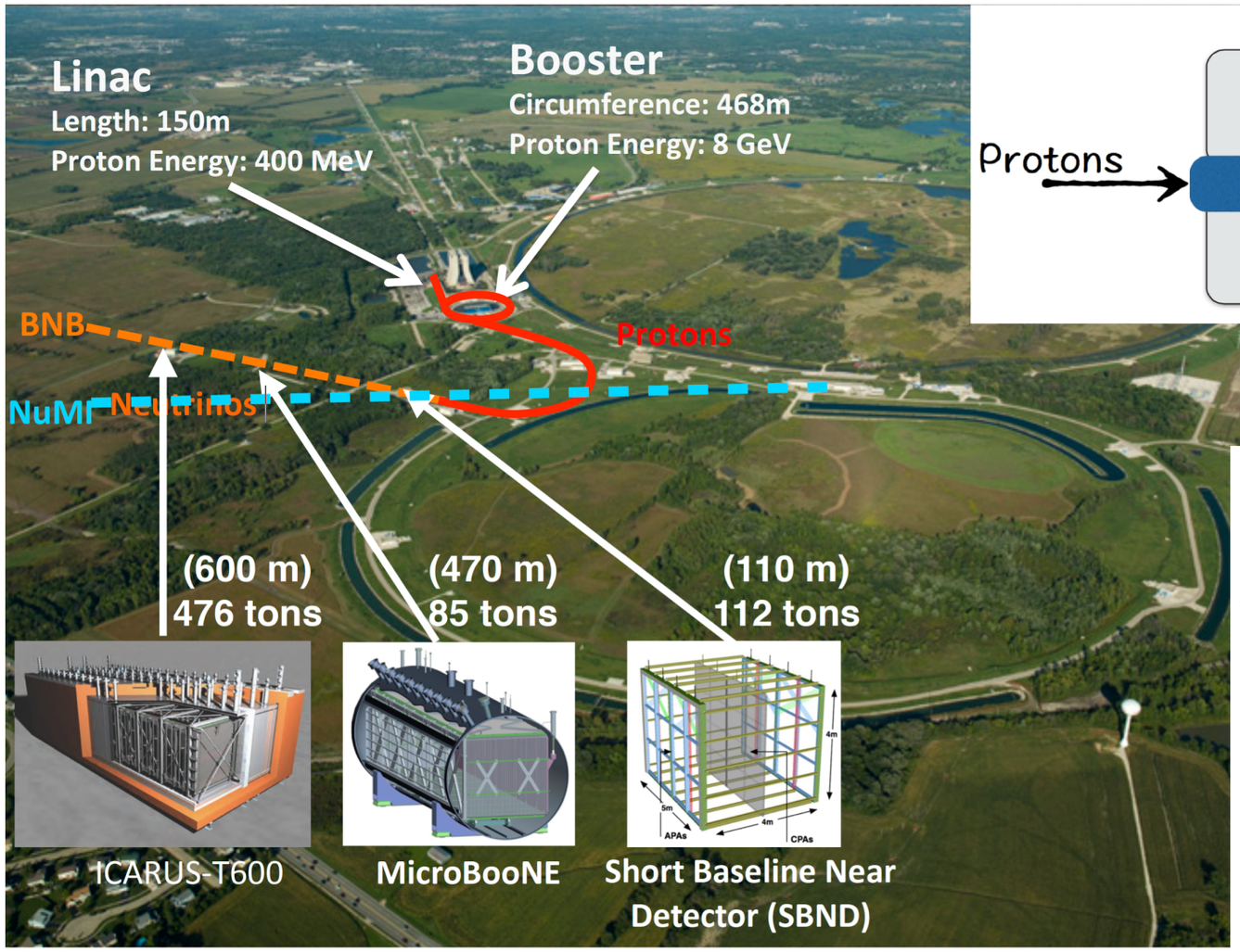
arXiv:1503.01520

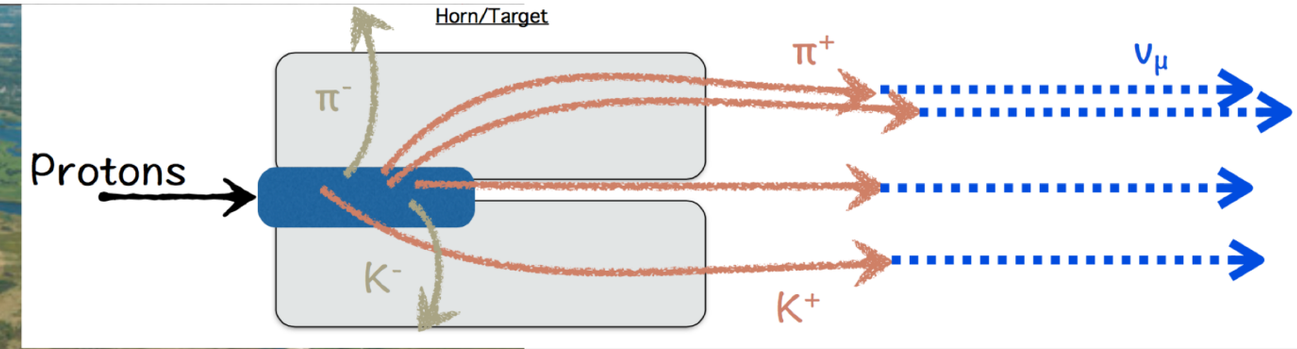


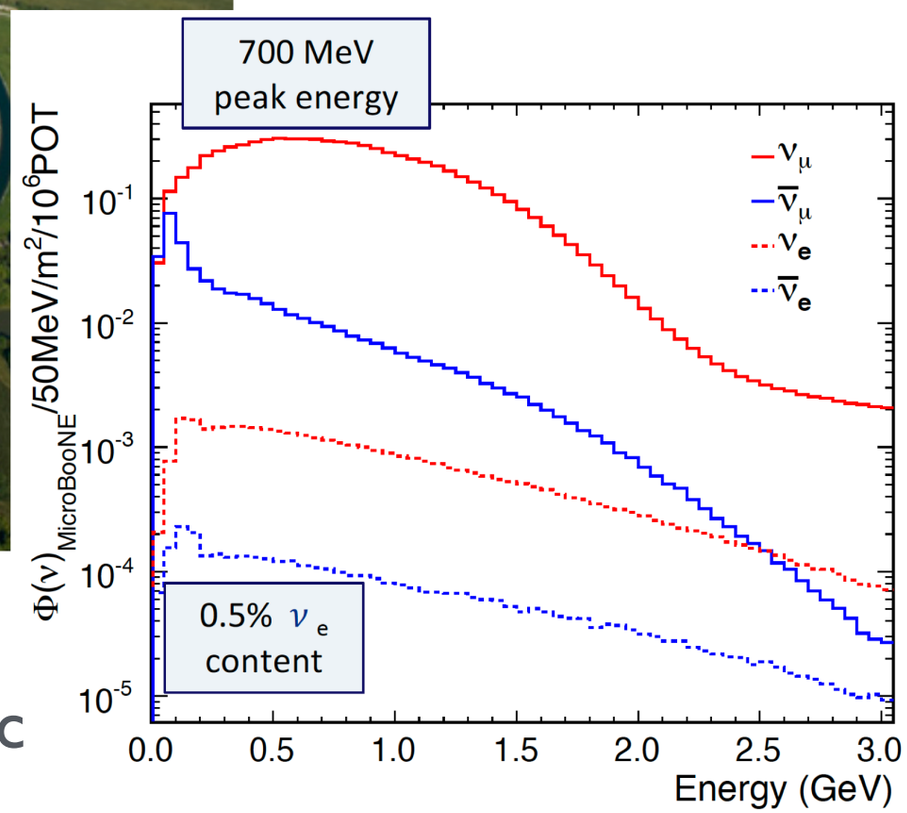
- Measure neutrino cross sections on liquid argon
- Same detector technology and neutrino beamline: reducing systematic uncertainties to the % level
  - A detection technique providing an excellent neutrino identification to reduce the backgrounds

See talk by Georgia Karagiorgi: Neutrino Oscillation in MicroBooNE

LAr TPC facility on the Neutrino Beams at Fermilab





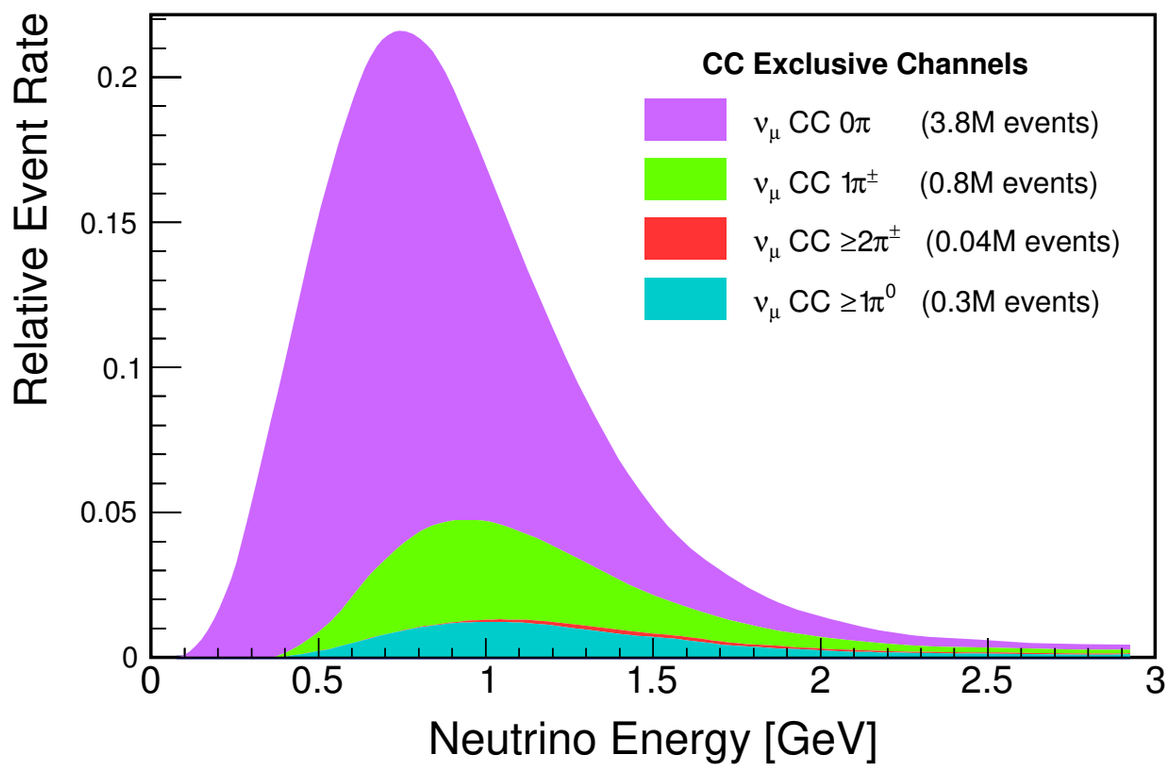


- Rates at SBND:
  - From Booster: 0.22 Hz (ν) and 0.07 Hz cosmic
- Rates at ICARUS:
  - From Booster 0.03 Hz (ν) and 0.11 Hz cosmic
  - From NuMI: 0.014 Hz (ν) and 0.08 Hz cosmic

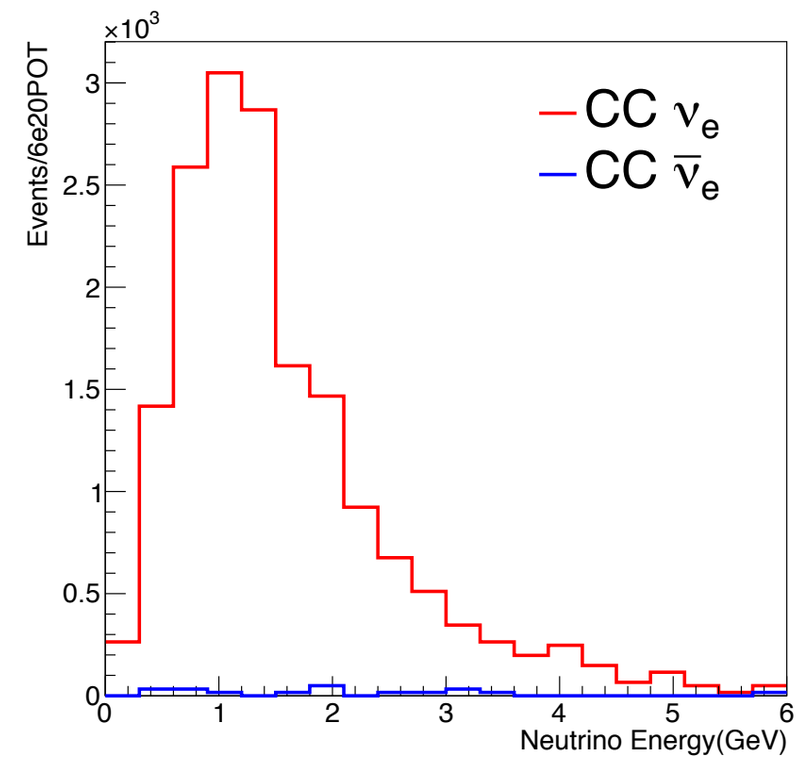
Neutrino Interactions at SBN

- High statistics precision measurements of neutrino argon cross sections in the DUNE energy range
  - SBND will have the word's highest statistics cross section measurements on argon
  - ICARUS will have high statistics electron neutrino cross section measurement using the NuMI off axis

ν_μ from the Booster at SBND



ν_e from the NuMI off axis at ICARUS



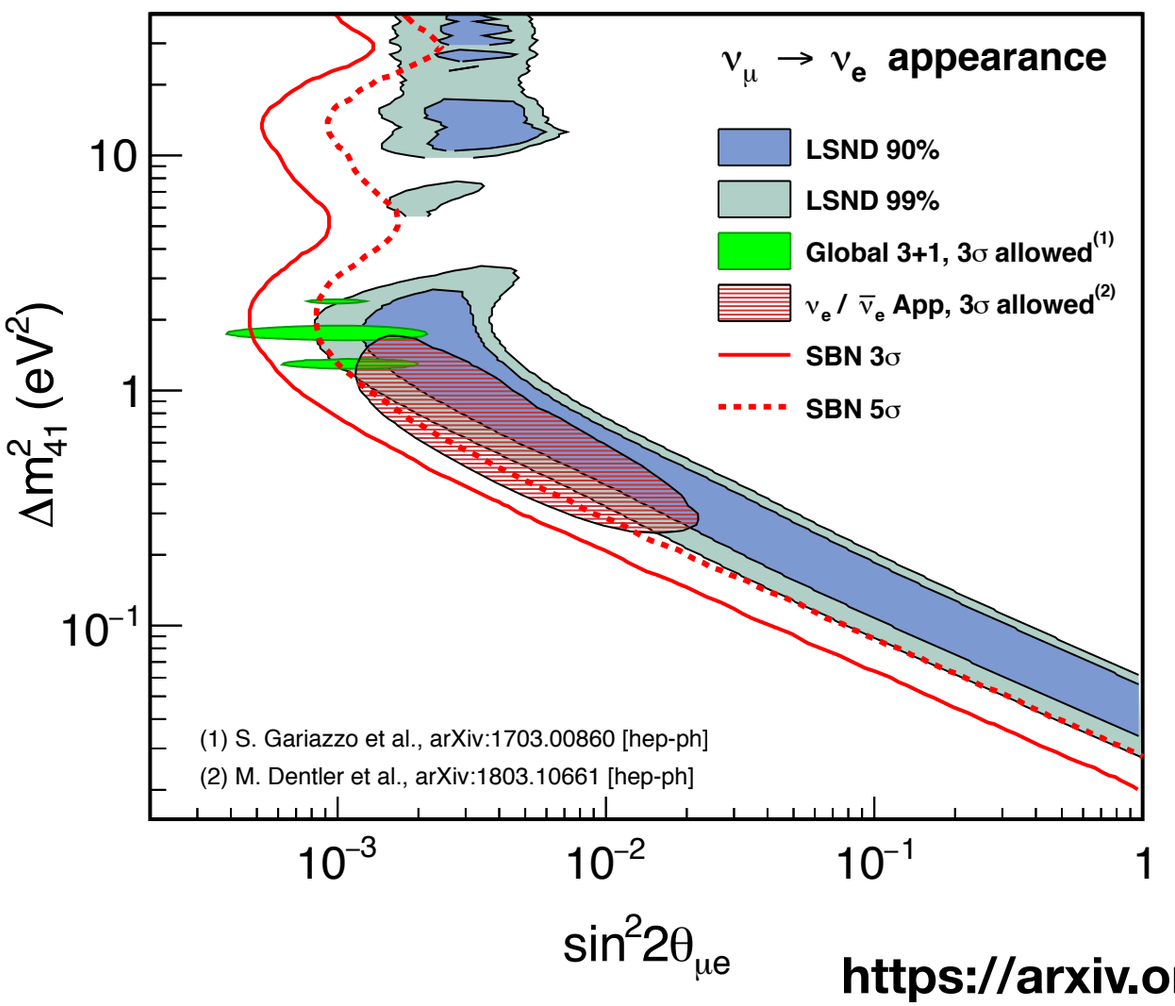
Ryan Howell and Bruce Howard, poster # 263, poster session #3

- Rich BSM searches: Neutrino tridents, dark matter, millicharged particles…

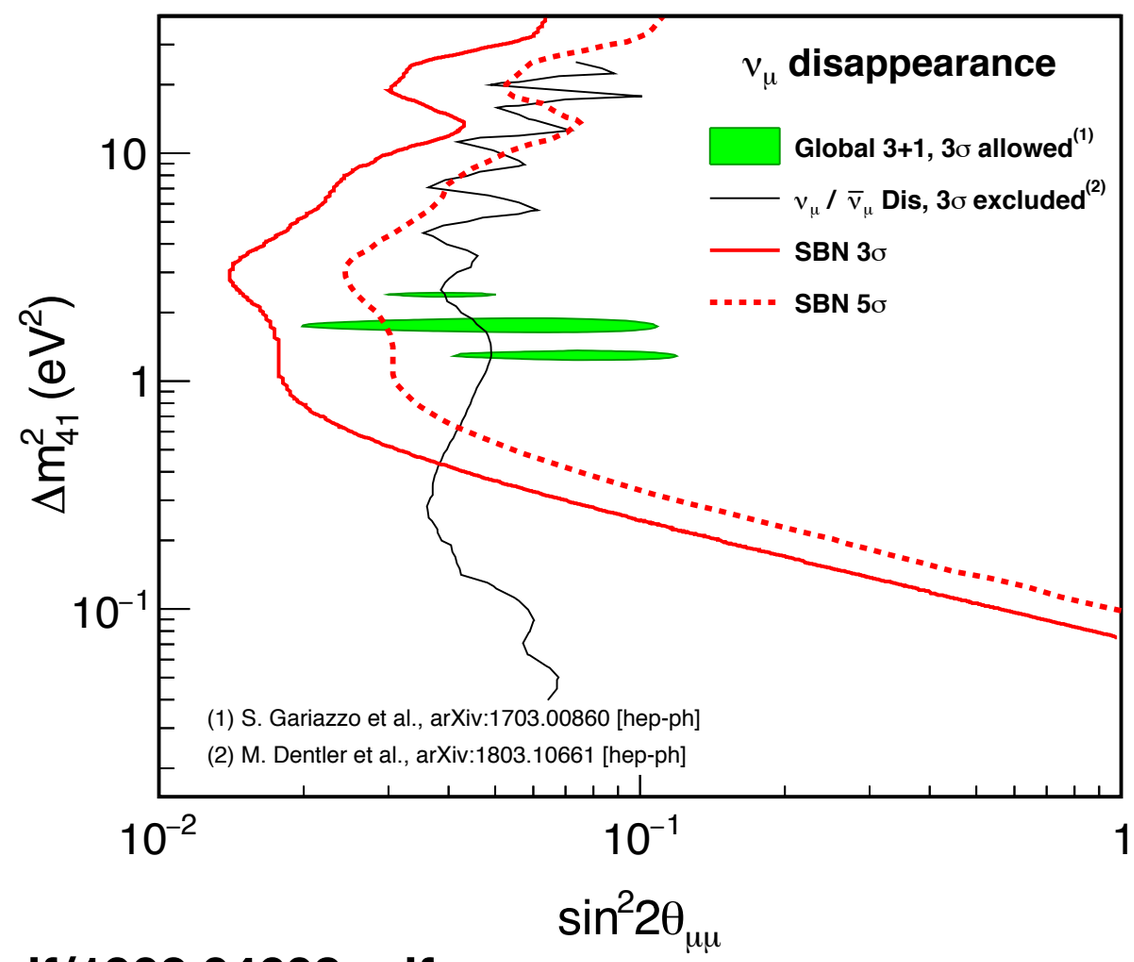
Sensitivity of SBN program

- Searches for both ν_e appearance and ν_μ disappearance

ν_e appearance



ν_μ disappearance



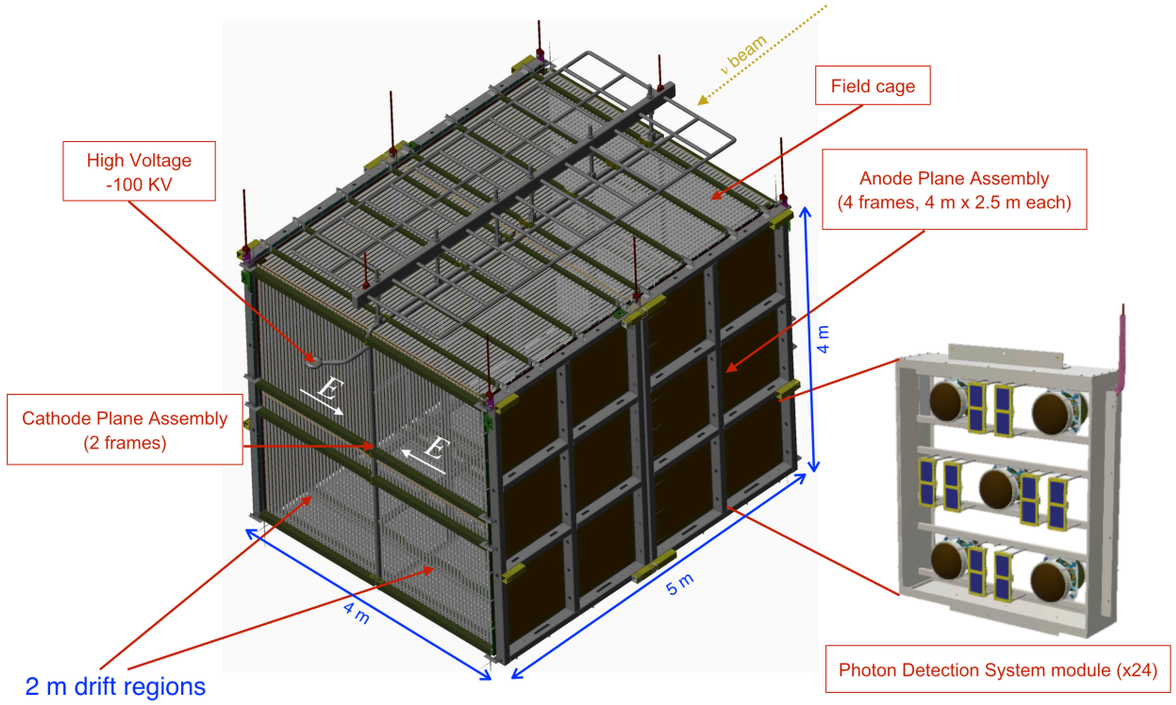
https://arxiv.org/pdf/1903.04608.pdf

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

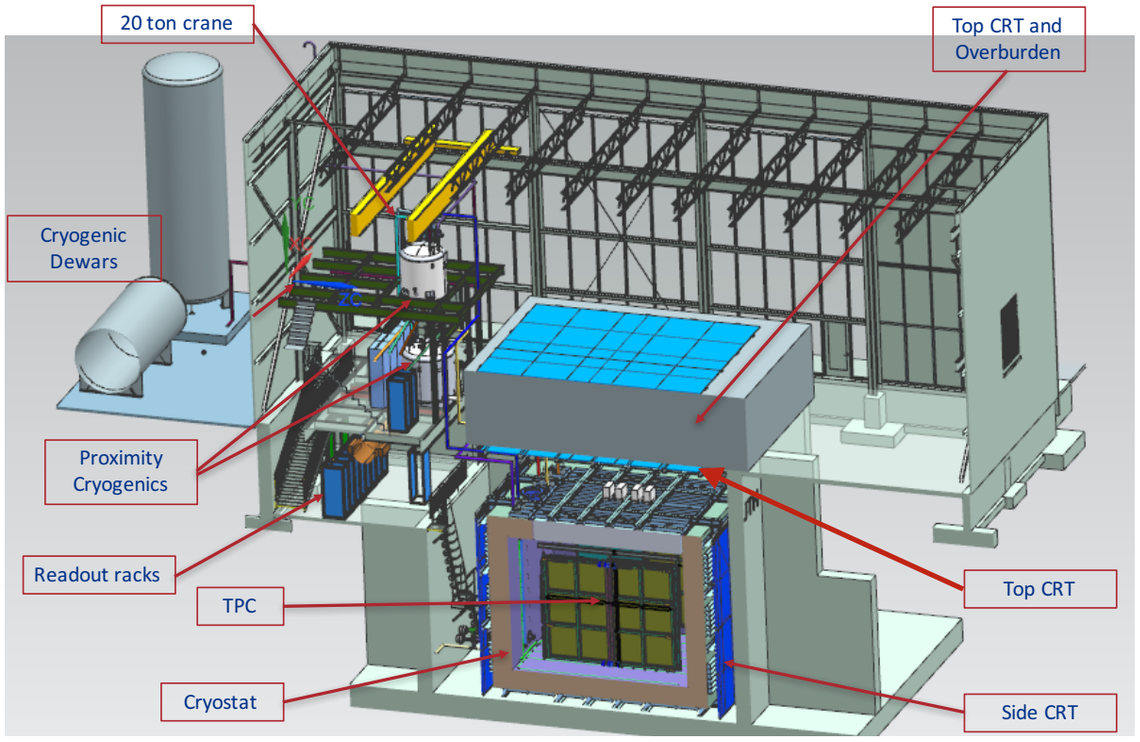
Jacob Larkin, poster #423 poster session 3

Guanqun Ge, poster #87, poster session 4

SBND Experiment



New LAr TPC detector, common design elements to ICARUS and DUNE

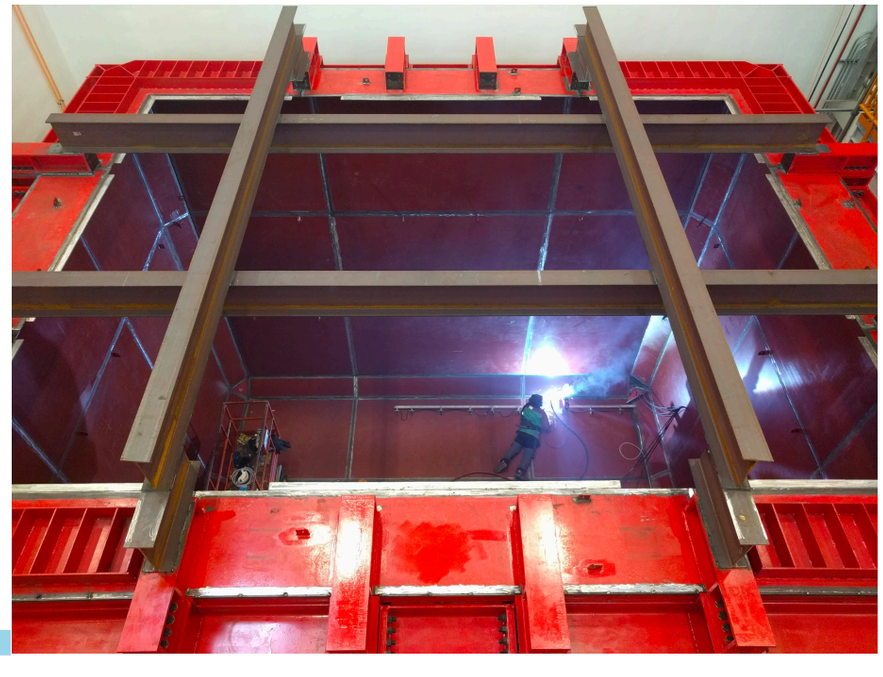


Status on SBND Construction

- Production of major TPC components and readout electronics is complete and components have been delivered to FNAL
- TPC assembly in progress
- PMT system is complete and has been tested
- Bottom CRT installed September 2019
- Proximity cryogenics and supporting infrastructure has been installed
- Cold electronics and readout electronics ready for installation

Bottom CRT installed

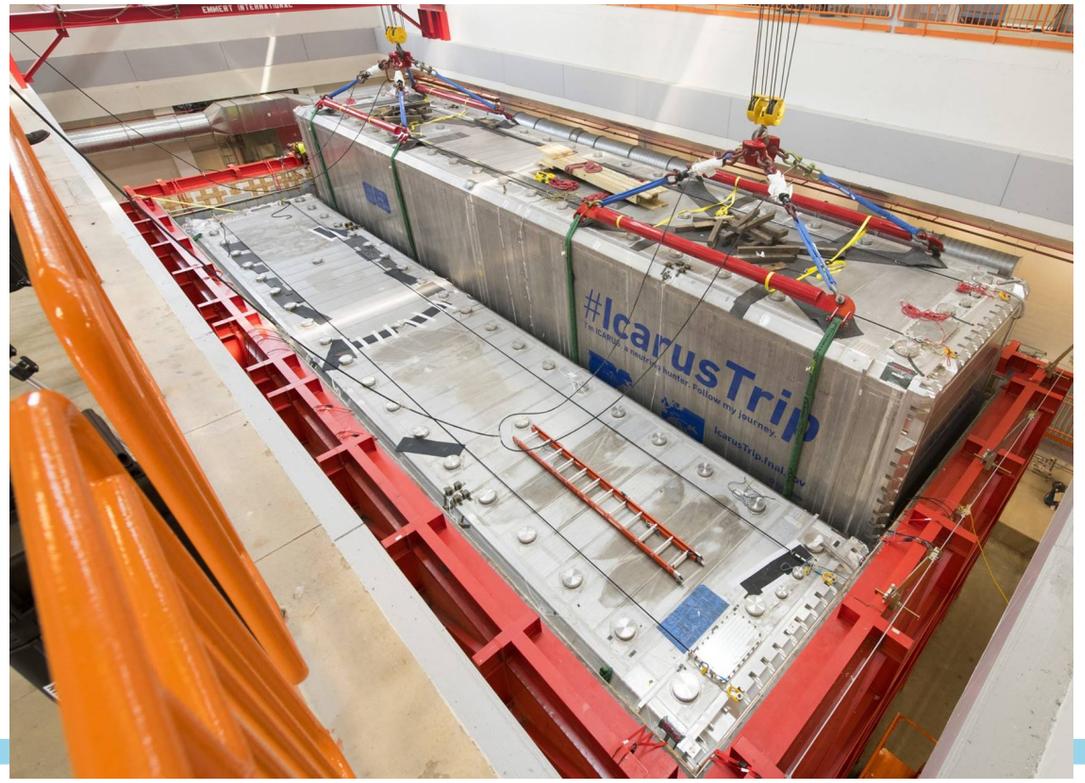
Cryostat warm structure installed



Cathode assembly frame

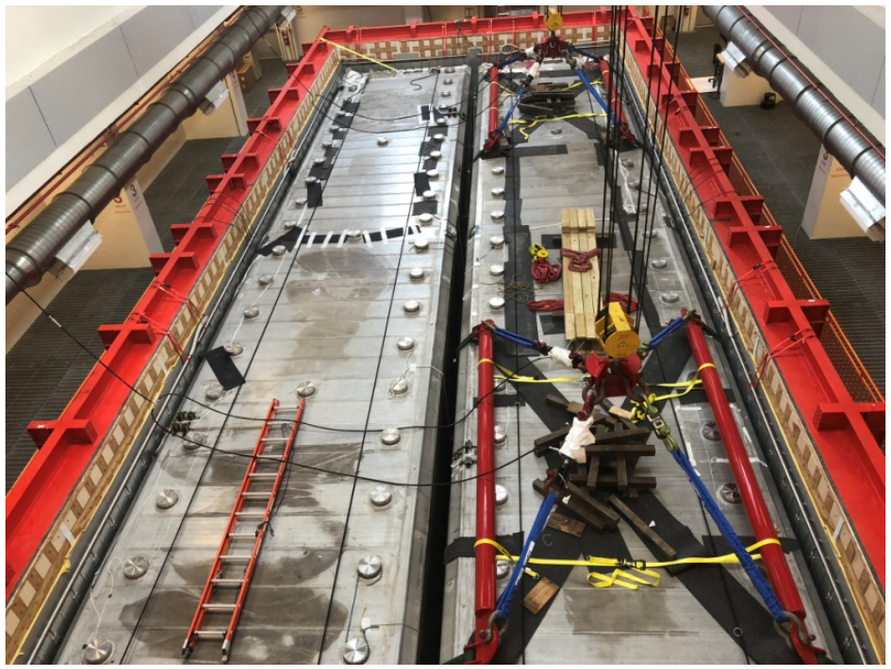
ICARUS at FNAL

- Several technology improvements were introduced, aiming to further improve the achieved performance at LNGS run:
  - New cold vessels, with a purely passive insolation
  - Renovated LAr cryogenics/purification equipment
  - Improvement of the cathode planarity
  - Upgrade of the PMT system: higher granularity and ns time resolution
  - New faster, higher-performance read-out electronics
  - Cosmic ray tagger system to correlate muons with TPC signals and 3m of concrete overburden

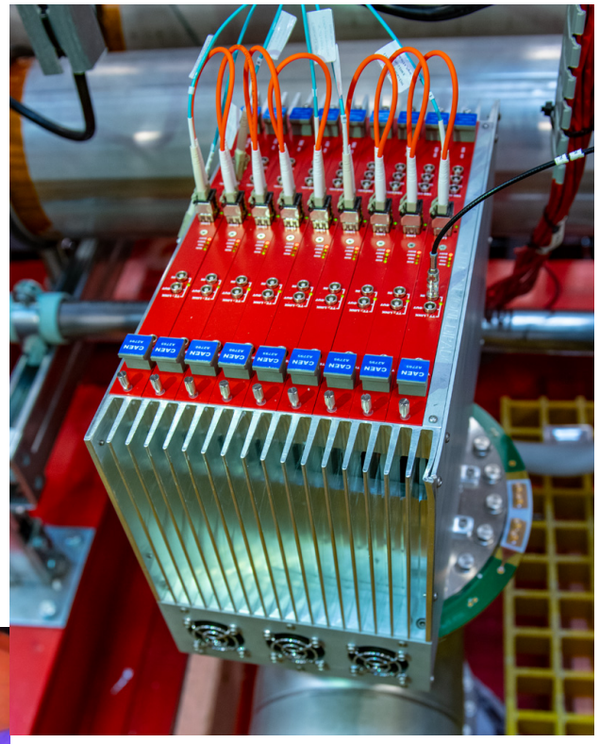


Status on ICARUS Installation

Placement of ICARUS inside the warm vessel after the overhauling at CERN (August 2018)

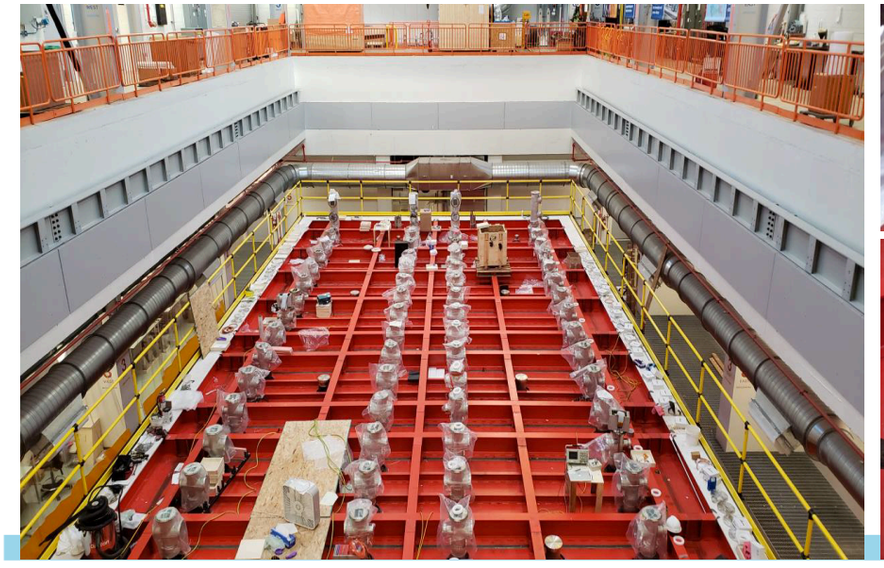


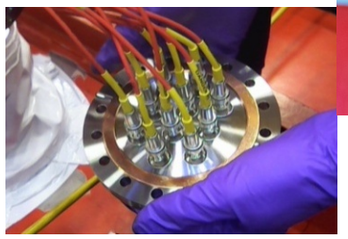
All TPC readout electronics installed and tested

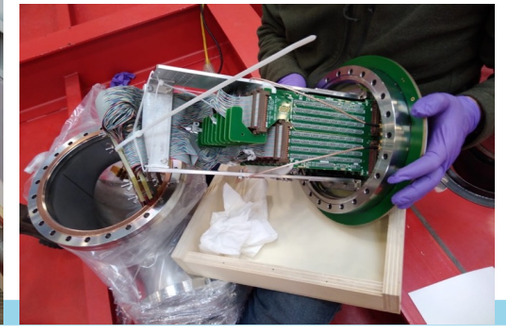


All cryogenic equipment installed, welded and tested (May 2019)

Feedthrough TPC/PMT/laser flanges installation (December 2018)

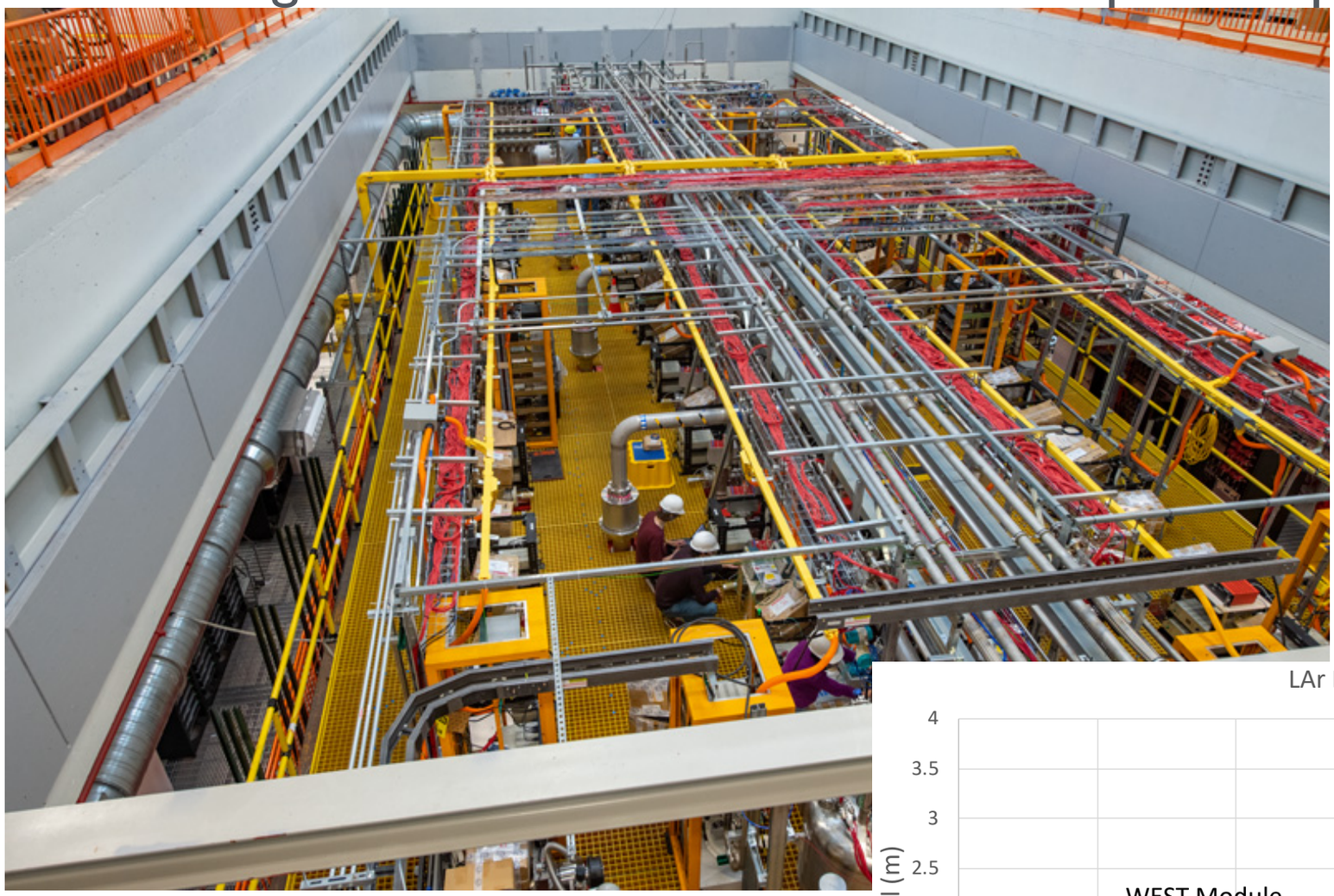


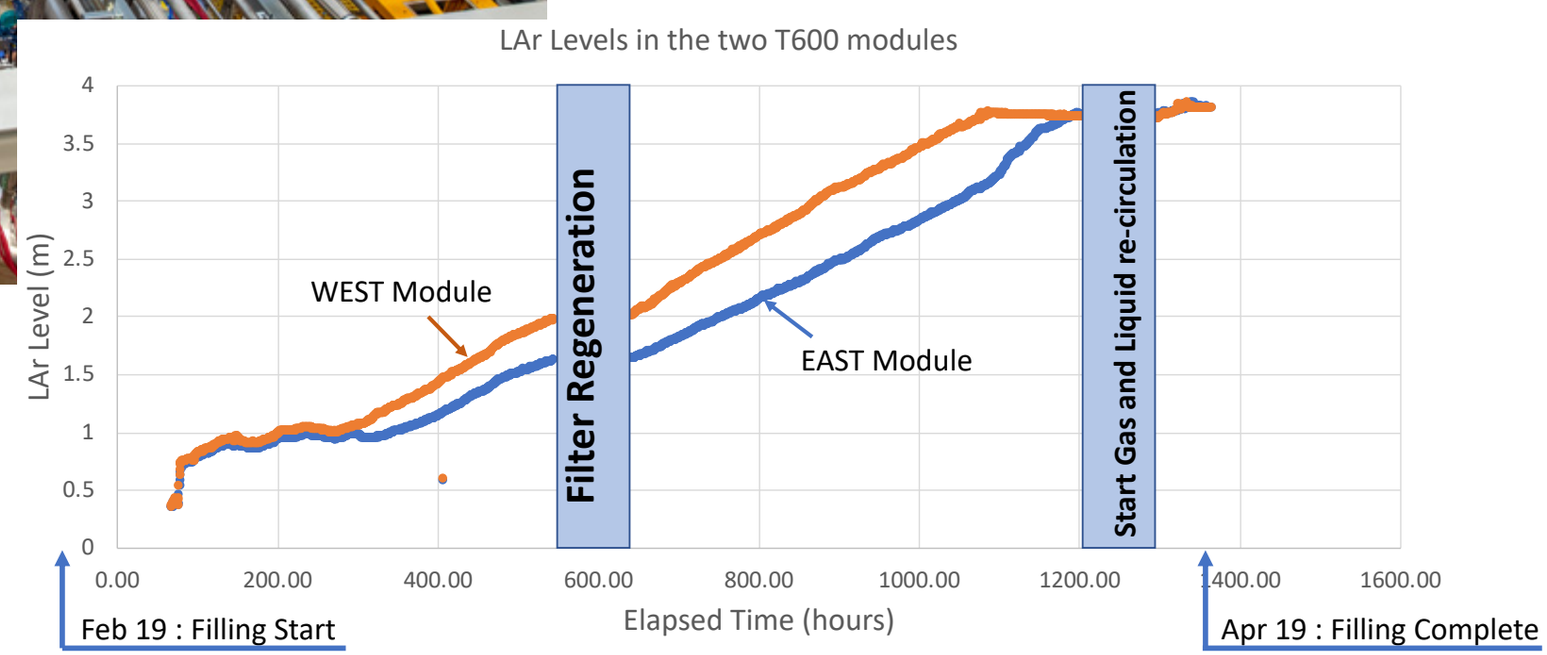




Status on ICARUS Installation

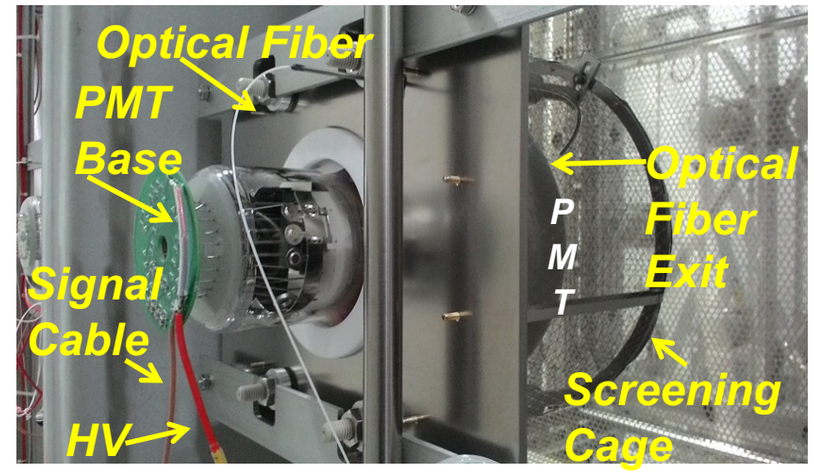
- LAr filling started on Feb19-2020 and completed Apr 19-2020





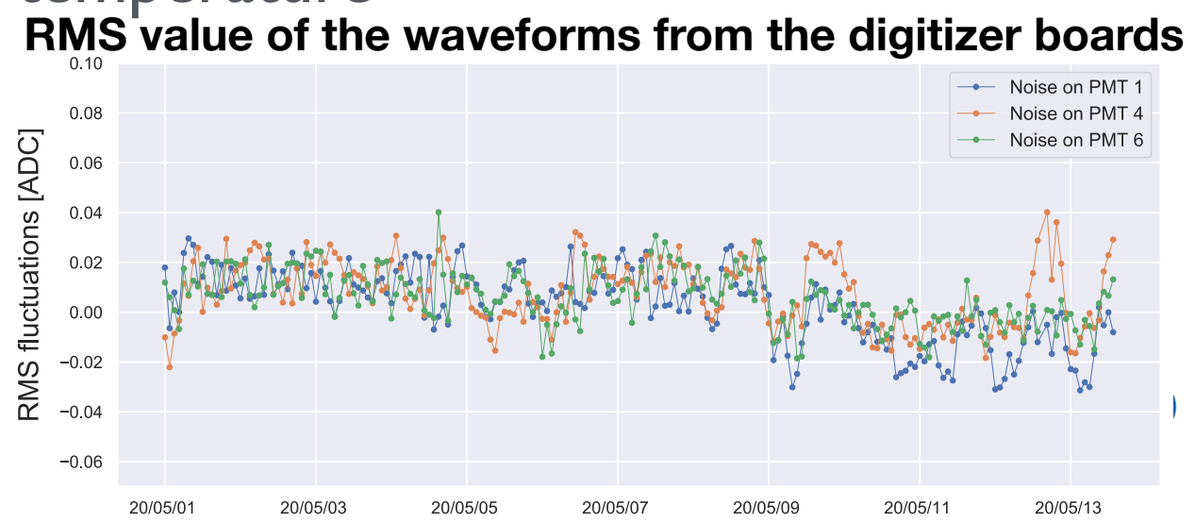
Light Collection System Upgrade (PMT)

- ICARUS at SBN has 360 PMTs 8" (5% photocathode coverage of TPC wire area, 15 phe/MeV) that provides:
  - Precisely identify the time of occurrence of any ionizing event in TPC with ns resolution
  - Localize events with <50 cm spatial resolution
  - Give event topology for selection purposes
    - Sensitivity to low energy events (~100 MeV)



https://arxiv.org/abs/2006.05261

- The system was completed in 2019 and is now ready for operation
- Commissioning of the system is in progress:
  - Activation of all the 360 PMTs
  - Calibration of the system at the LAr temperature

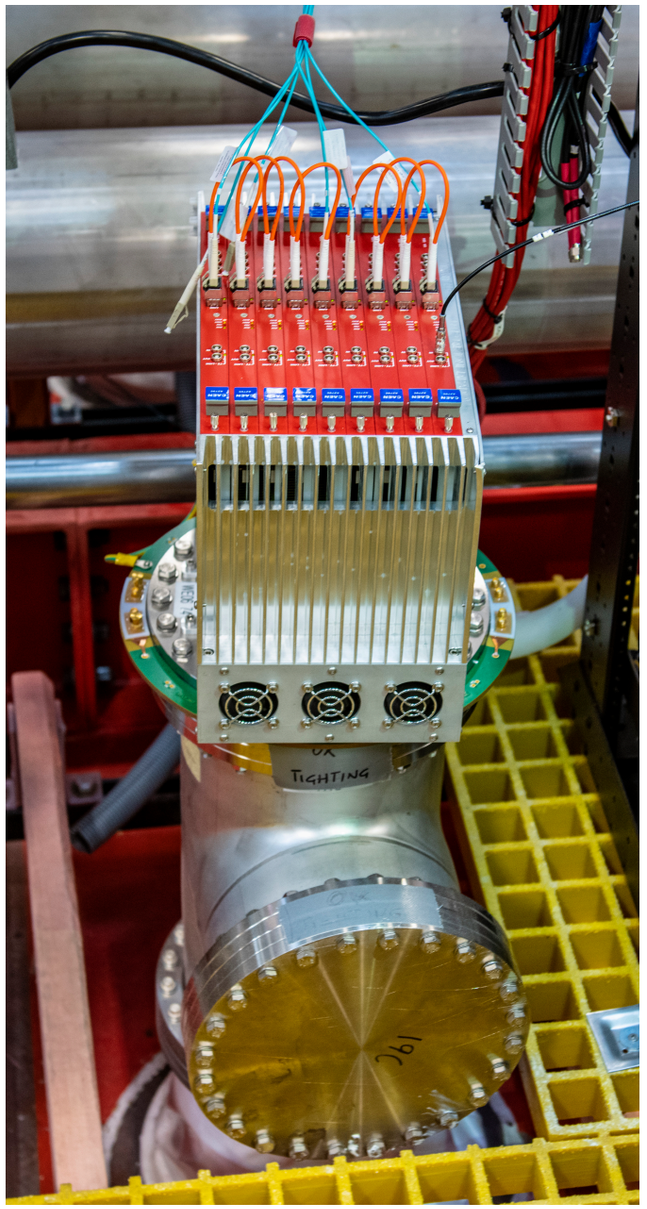


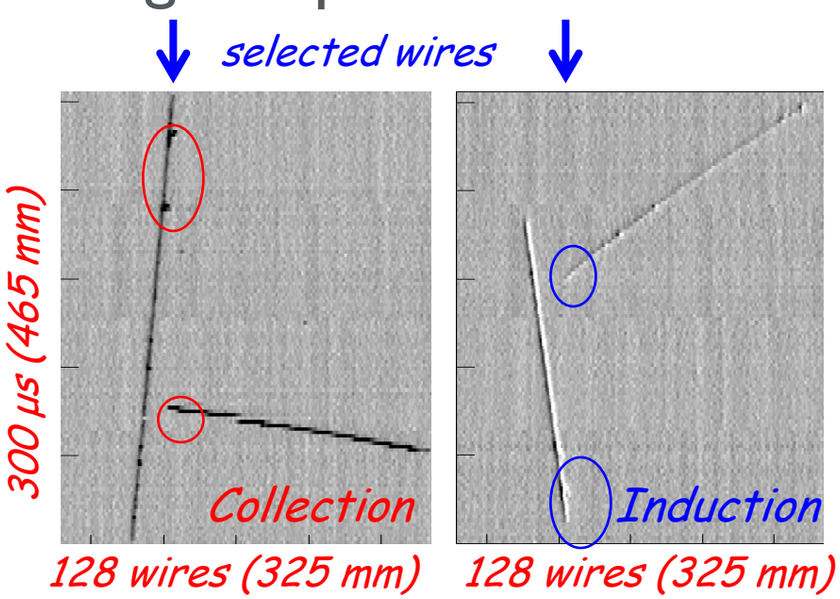
Animesh Chatterjee, poster #240, poster session 4

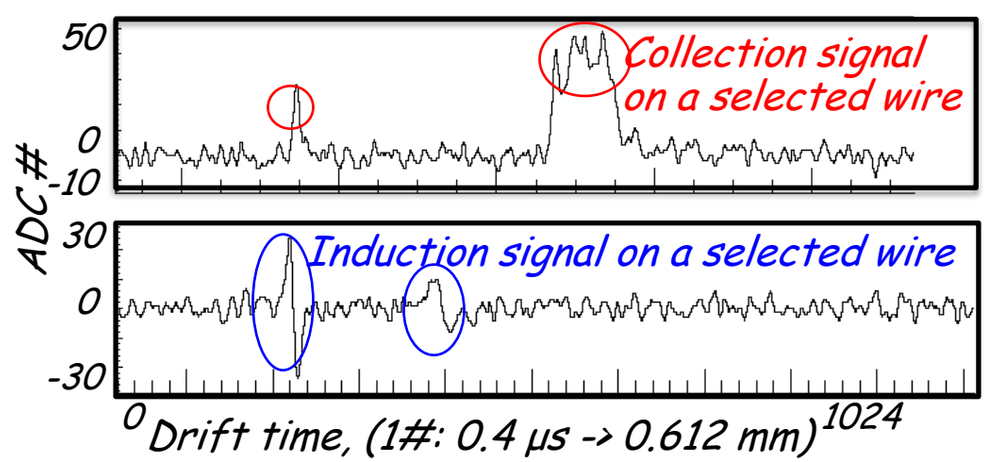
TPC Readout Electronics Upgrade

Reside outside the cryostat

- New TPC readout electronics
  - A front-end based on analogue low noise/charge sensitive pre-amplifier
  - More compact layout: both analog+digital electronics in a single flange
  - Lower noise ~1200 e- equivalent (~20% S/N improvement w.r.t LNGS)
  - Shorter shaping time ~1.5 μs matching e- transit time between wire planes providing a better hit position separation
- Full electronic chain has been tested with cosmic at CERN
- Single mip track event



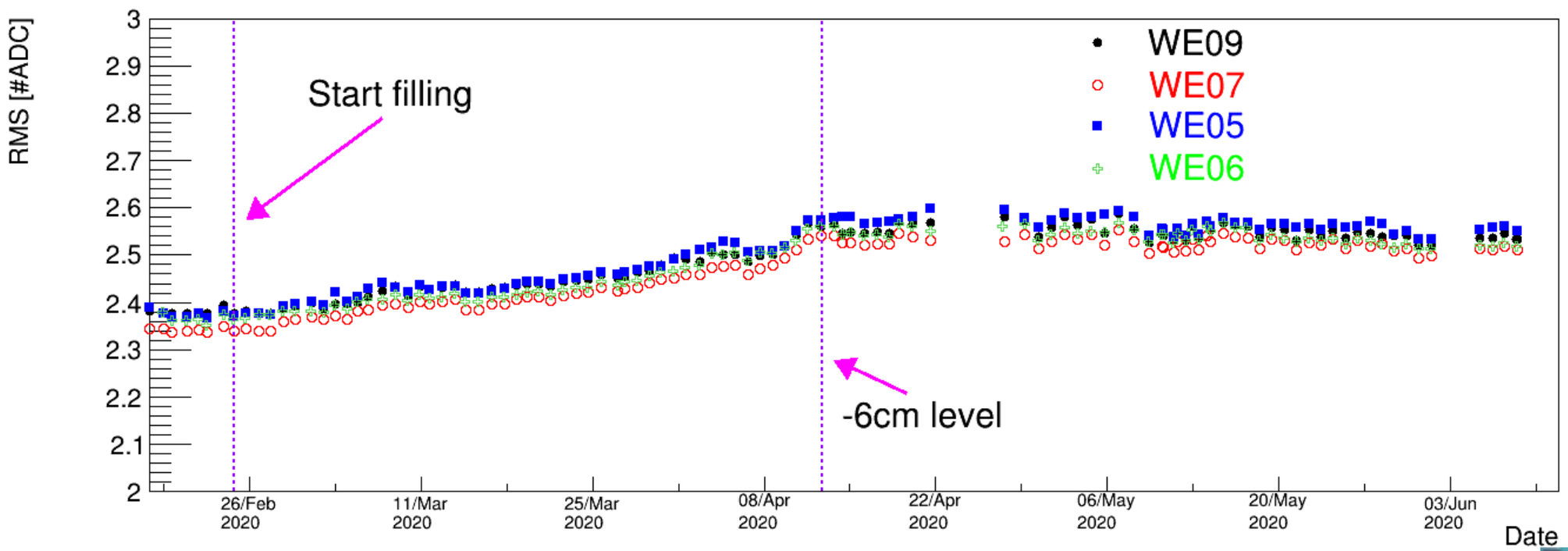


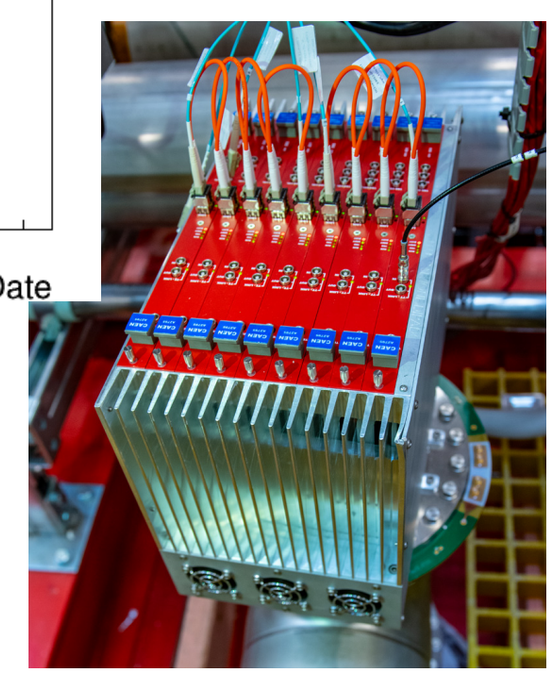


Fermilab

TPC Readout Electronics Commissioning

- Ten mini-crates are connected to external pulser to monitor the noise during the filling period
- Variations of the intrinsic noise level during the filling
  - After coherent noise removal





- A steady increase in the noise due to the TPC wire capacitance changes during the LAr filling

New Cosmic Ray Tagging System (CRT)

- CRT surrounds the cryostat with two layers of plastic scintillators (~1000 m^2)
- Provides spatial and timing coordinates of the track entry point
- Match reconstructed CRT hits to activity in the TPC
- Few ns time resolution allows measuring direction of incoming/ outgoing particle propagation via time of flight
- Three subsystems providing ~95% tagging efficiency:
  - Bottom, side and top CRT
- Commissioning of the two walls with cosmic is ongoing

Bottom CRT: installed

Top CRT: modules ready

Side CRT: partially installed

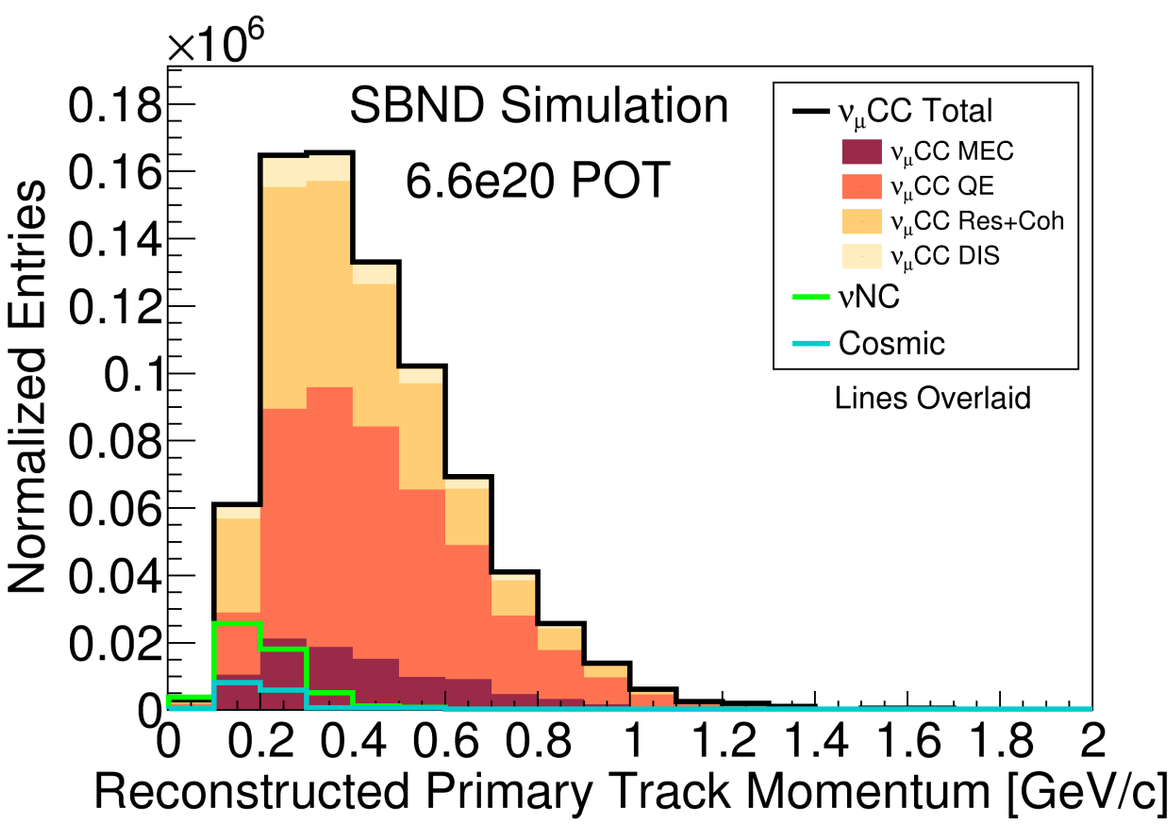
Chris Hilgenberg, poster #225, poster session 1
Tyler Boone, poster #229, poster session 1

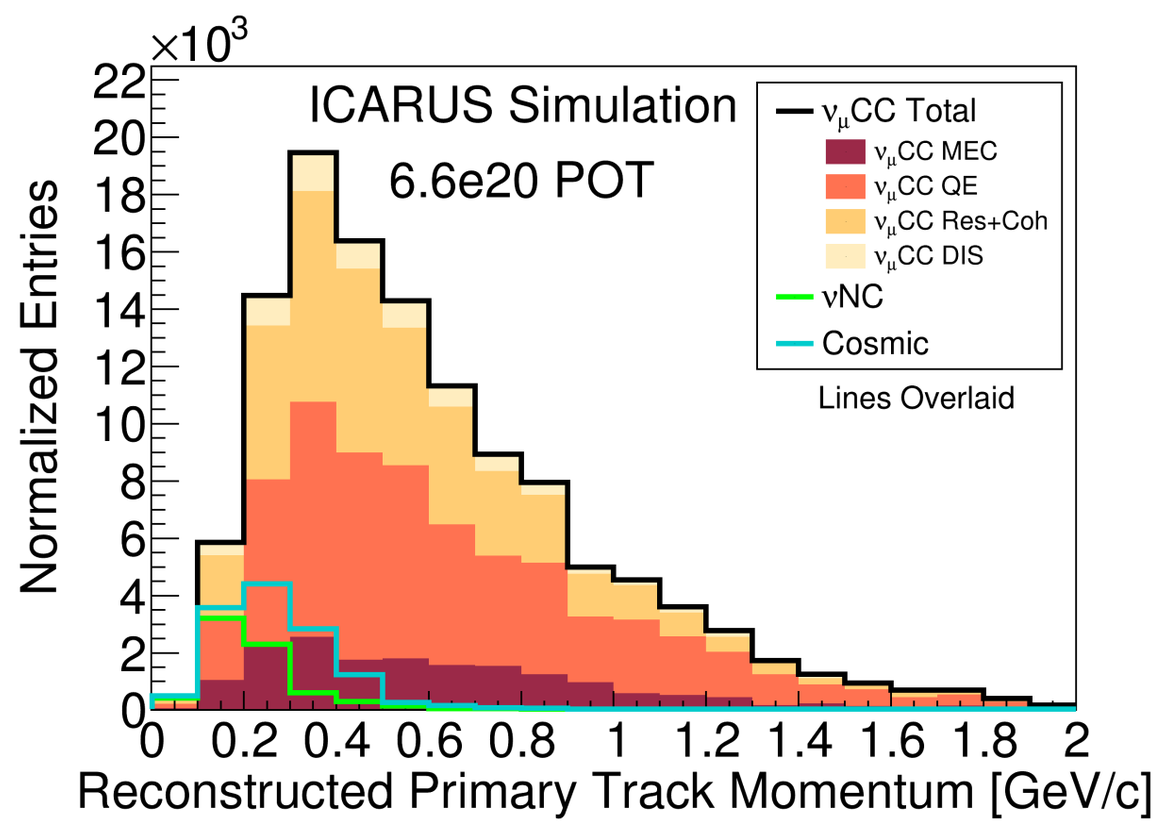
Event Selection and Reconstruction

- Full MC simulation is available for the SBN detectors
- The neutrino event selection and reconstruction is being developed with common tools for the TPC, the PMTs and the CRT, including background from cosmic and from the beam

Detector	N spills per ν	N spills per cosmic μ in spill	Total cosmic μ per drift
SBND	25	300	3
ICARUS	170	53	11

- Considering ν_μ CC contained events and rejecting cosmic rays using PMT and CRT reconstruction tools

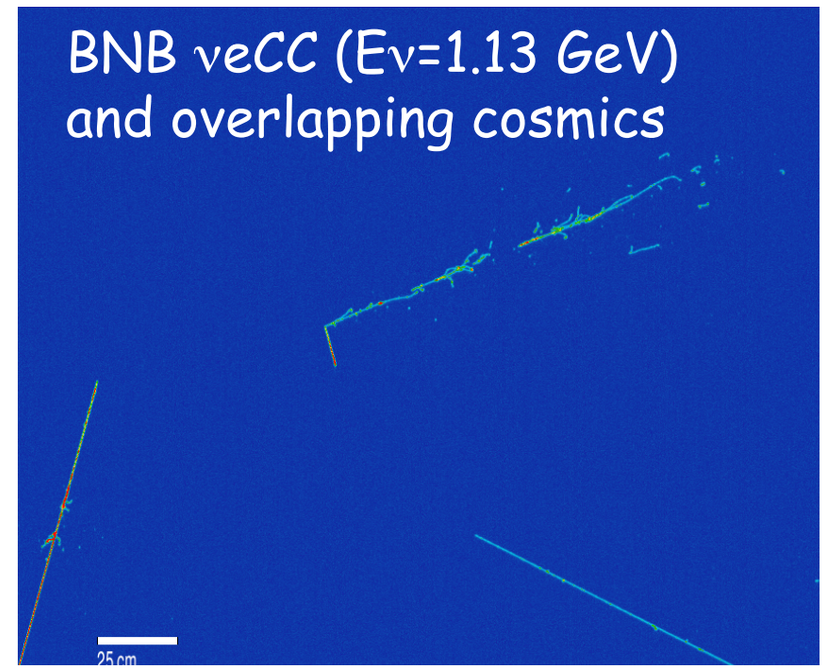


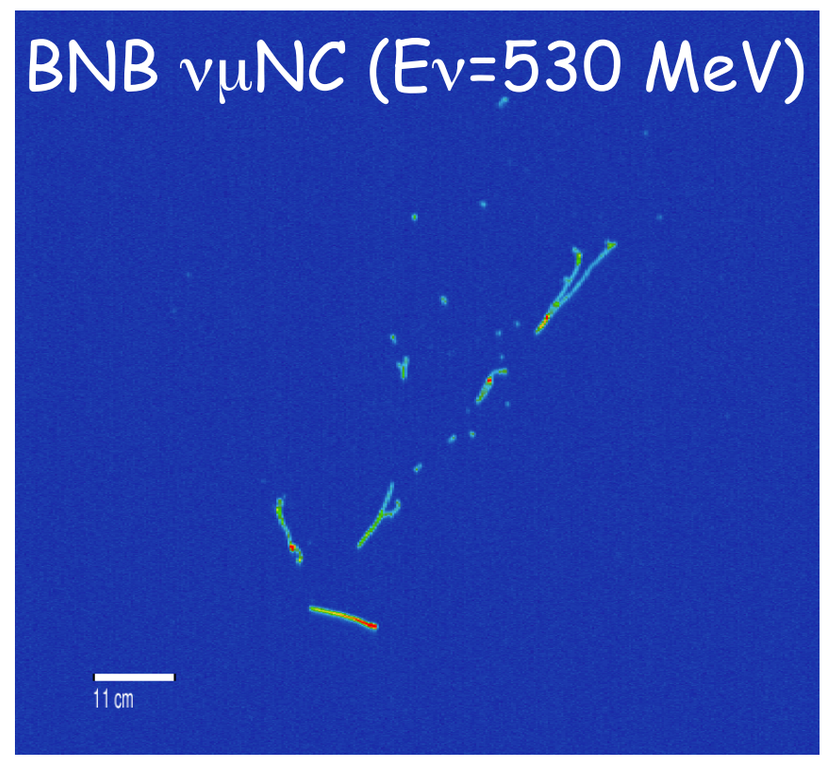


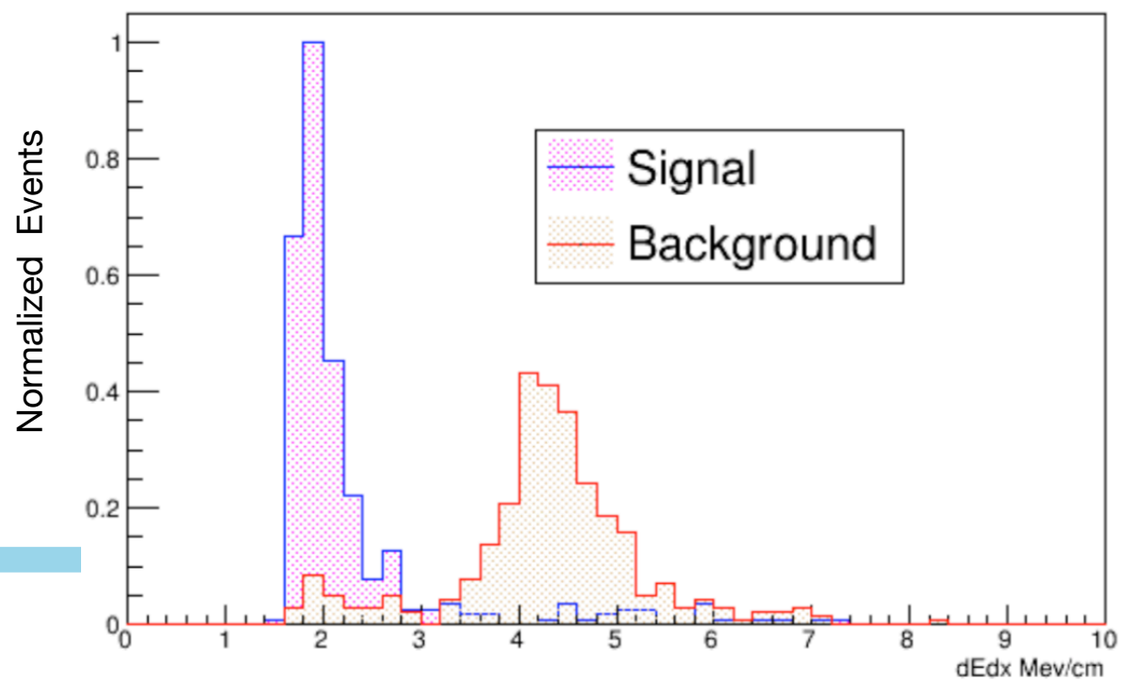
Gray Putnam, poster #443, poster session #3

Event Selection and Reconstruction

- e-γ separation based on the ionization density at the beginning of the shower
  - e-showers are expected to start with 1 m.i.p. ionization density
  - γ-showers should start with 2 m.i.p. from pair conversion
- Promising results with the present stage of the reconstruction tuning:
  - ~90% electron efficiency
  - ~90% γ rejection for well reconstructed ν vertex







Summary

- The SBN program will perform a world-leading search for eV-scale sterile neutrino by looking at both appearance and disappearance channels
- High precision measurements of neutrino-argon cross sections
- Rich physics program of BSM physics
- SBND construction is well on its way, all the components ready for assembly and installation
- After an extensive refurbishing, ICARUS installation at FNAL in the SBN far site has been completed
- ICARUS cooling down, filling and cryogenic commissioning was just completed this May 2020
- Starting the commissioning of ICARUS at FNAL
- ICARUS data taking for physics expected by beginning of next year
- The SBN oscillation program will begin when SBND is operational

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