



# The Short Baseline Neutrino Program at Fermilab

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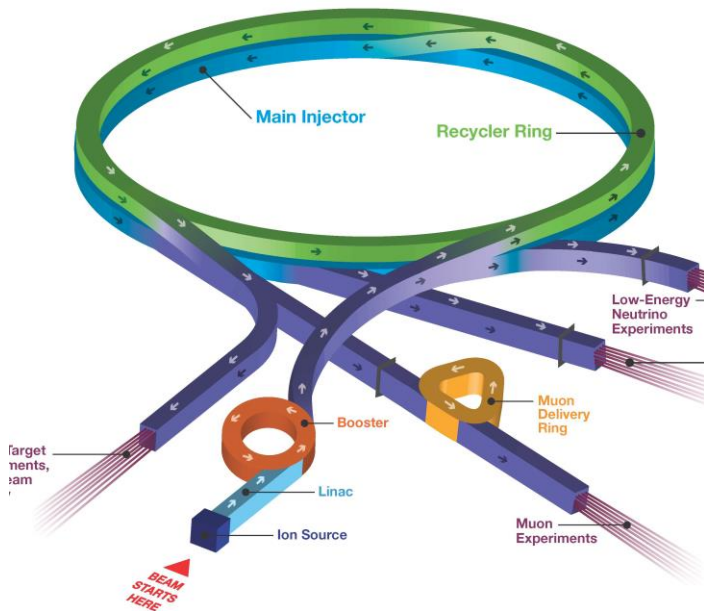
M. Bonesini Nufact 21



# FERMILAB NEUTRINO EXPERIMENTS



Fermilab Accelerator Complex



- Proton accelerator complex feeds multiple horn-focused neutrino beamlines
- **Booster Neutrino Beam (BNB):**
  - Neutrino energy  $\sim 700$  MeV
  - **MiniBooNE, SBN (SBND, MicroBooNE, ICARUS)**
- **NuMI Beam:**
  - Wideband, tunable beam, neutrino energy peaks between 3 and 12 GeV depending on tune
  - MINERvA
  - MINOS/**MINOS+**, NOvA (off-axis), FDs in Minnesota
- **LBNF Beam:**
  - Future wideband beam
  - DUNE, FD in South Dakota

# The puzzling picture of short baseline $\nu$ oscillations

Three independent classes of anomalous experimental results in the last 20 years, not fitting into the “standard” landscape of 3-flavour  $\nu$  mixing:

- **disappearance** of anti- $\nu_e$  detected from near-by nuclear reactors;
- **disappearance** of  $\nu_e$  from intense calibration sources in solar  $\nu$  experiments;
- **appearance** of  $\nu_e/\bar{\nu}_e$  in  $\nu_\mu/\bar{\nu}_\mu$  beams at particle accelerators.

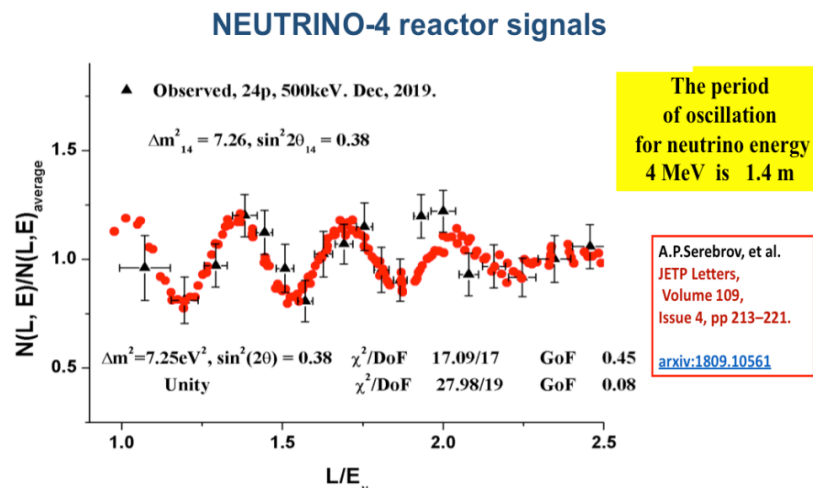
Experiment	Type	Channel	Significance
LSND	DAR accelerator	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	3.8 $\sigma$
MiniBooNE	SBL accelerator	$\nu_\mu \rightarrow \nu_e$	4.5 $\sigma$
		$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	2.8 $\sigma$
GALLEX/SAGE	Source – e capture	$\nu_e$ disappearance	2.8 $\sigma$
Reactors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



Each possibly explained by nonstandard “sterile” neutrino state(s) driving oscillations at  $\Delta m_{\text{new}}^2 \approx 1 \text{ eV}^2$  and relatively small  $\sin^2(2\vartheta_{\text{new}})$ , but no model so far successful in fitting all experimental results at once.

# Neutrino-4 oscillation signal

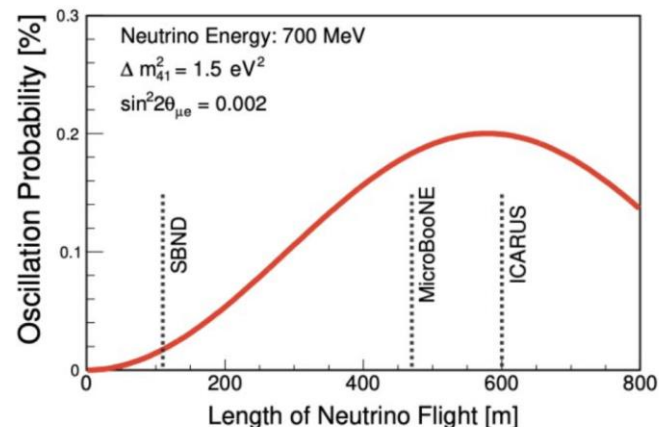
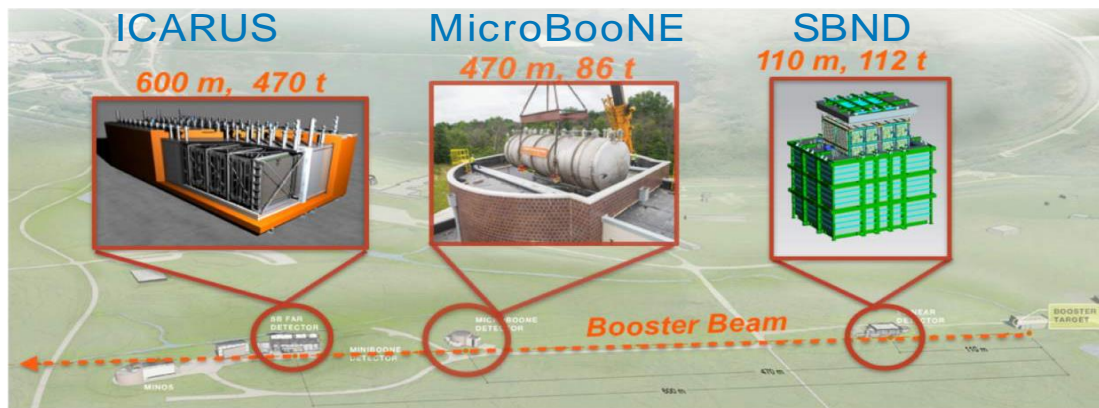
- The Neutrino-4 collaboration, at SM-3 reactor (Russia), claimed a neutrino disappearance signal with a clear modulation with  $L/E \sim 1-3$  m/MeV
- ICARUS alone (before SBND starts taking data at the end of 2022) can confirm or refute the Neutrino-4 oscillation signal
- ICARUS will be able to test this oscillation hypothesis in the same  $L/E$  range in two independent channels, with different beams:
  - Disappearance of  $\nu_\mu$  from the BNB beam, focusing the analysis on quasi-elastic contained  $\nu_\mu$ CC interactions.  $\sim 11500$  such events are expected in 3 months run
  - Disappearance of the  $\nu_e$  component in the NuMI beam, selecting quasi-elastic  $\nu_e$ CC events with contained EM showers.  $\sim 5200$  events expected per year
- The study of these channels, complemented with a beam-off sample, would allow to observe or reject a modulation as observed by Neutrino-4 in less than one year



# Short Baseline Neutrino Program at Fermilab

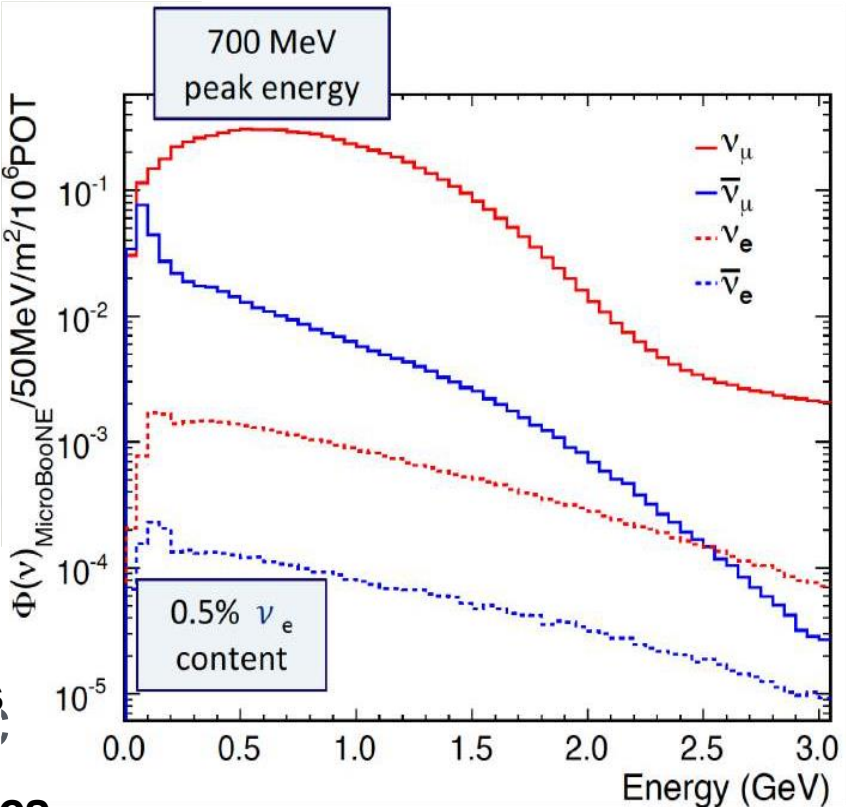
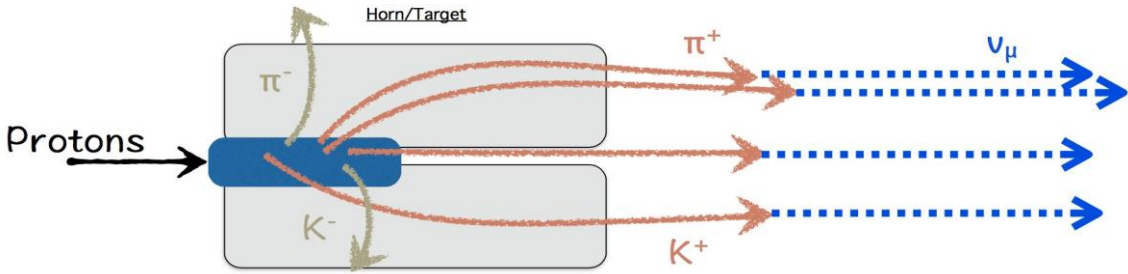
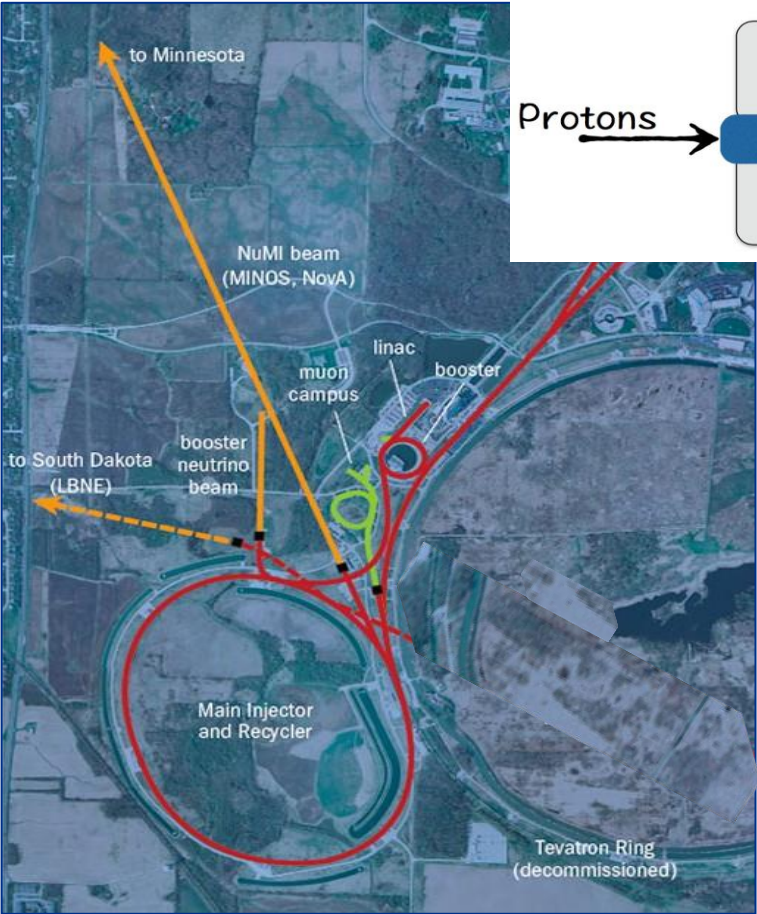
Program aimed at definitely solving the “sterile neutrino puzzle” by exploiting:

- the well characterized FNAL Booster  $\nu$  beamline;
- three detectors based on the same liquid argon TPC technique.
- MicroBooNE has just completed its physics programme, with an emphasis on Low Energy Excess search



- Millions/year events in SBND at low energy ( $<1 \text{ GeV}$ ) from BNB beam
- Hundred thousands/year events in ICARUS at higher energy ( $>1 \text{ GeV}$ ) from NUMI

# The Booster Neutrino Beam (BNB)

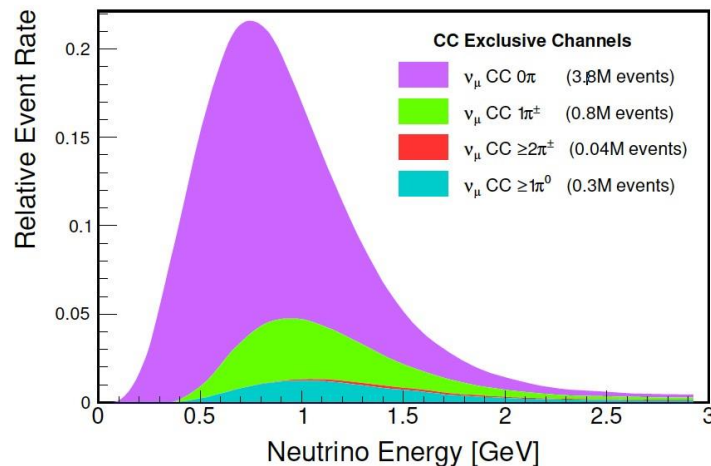


- **SBND:** BNB @ 0.25 Hz, 0.03 Hz cosmics,
- **ICARUS:** BNB @ 0.03 Hz, 0.14 Hz cosmics'
- **NUMI** @ 0.014 Hz, 0.08 Hz cosmics

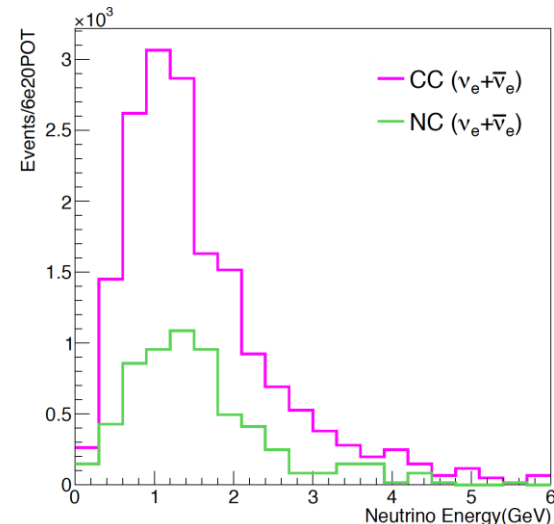
# Neutrino interactions at SBN

- High statistics precision measurements of neutrino Argon cross sections in the DUNE energy range.
  - SBND: world's highest statistics cross section measurements on Argon,  $\sim 7$  million  $\nu_\mu$  and  $\sim 50,000$   $\nu_e$  in 3 years
  - ICARUS: high statistics electron neutrino cross section measurement using the NuMI off axis,  $\sim 10^5$  events/year
  - MicroBooNE is now delivering the first results on cross section measurements

$\nu_\mu$  from the Booster at SBND



$\nu_e$  from the NuMI off axis at ICARUS

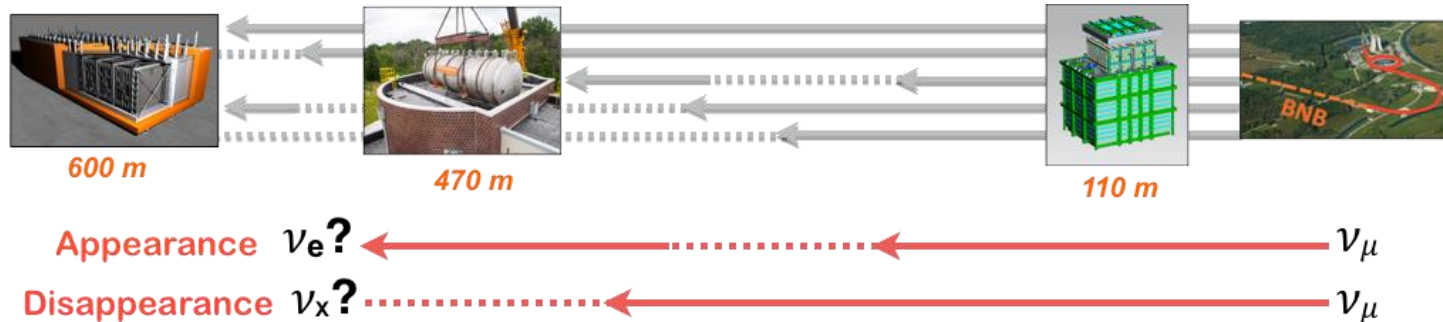
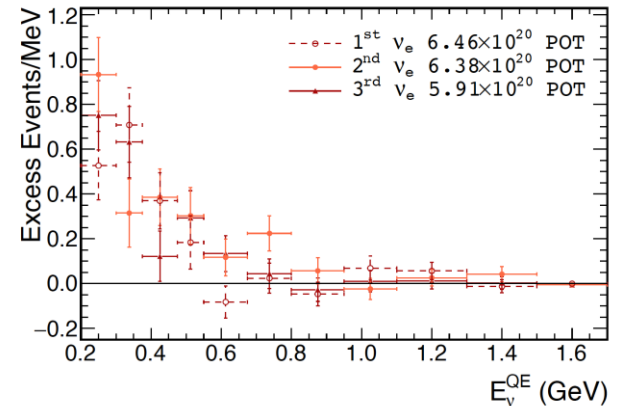


- Rich BSM searches: neutrino tridents, dark matter, millicharged particles...  
EX: MicroBooNE heavy neutral lepton search *Phys. Rev. D* 101, 052001 (2020)

# SBN goals

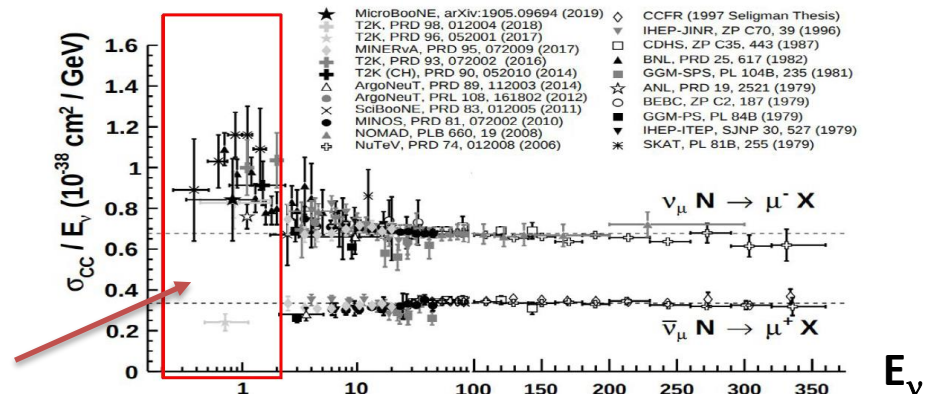
Phys. Rev. D 103, 052002 (2021)

- **MicroBooNE**  
Understand the nature of the MiniBooNE “low energy” excess anomaly
- **SBND + ICARUS**  
Search for short baseline oscillations both in appearance and disappearance channels.



## ○ Lay the ground for future long baseline program

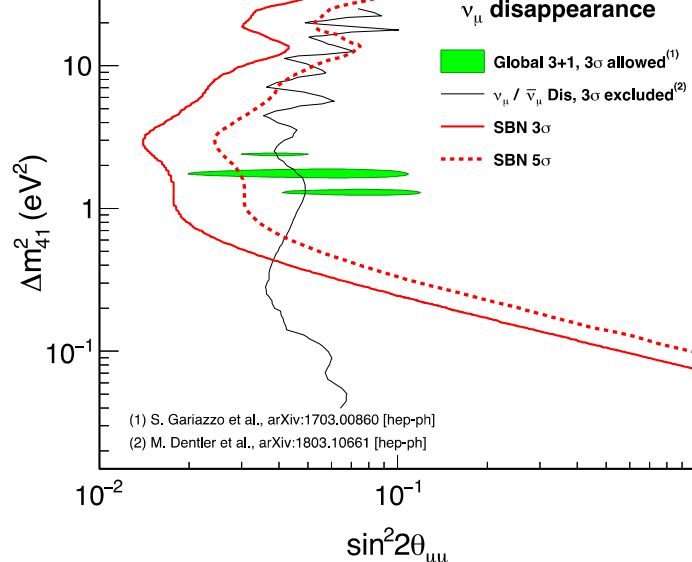
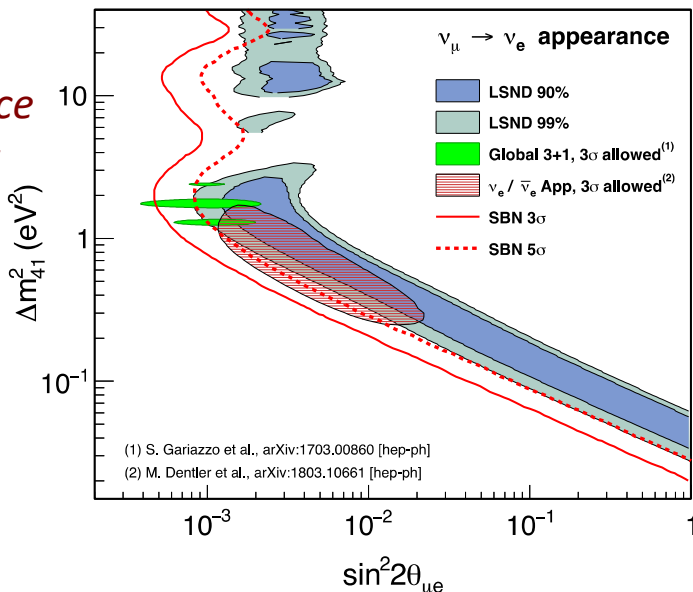
- Further develop LAr-TPC detector technology
- Measure  $\nu$ -Ar cross sections at energies (up to few GeV) relevant to DUNE



# SBN expected sensitivities for 3 years (6.6 10<sup>20</sup> pot)

- SBN will provide a conclusive verification of the sterile neutrino hypothesis
  - The combined analysis of near and far detector data will allow to cover the currently allowed parameter region with 5 $\sigma$  sensitivity both in appearance and disappearance channels, in 3 years of data-taking (6.6 10<sup>20</sup> pot):
    - ✓ Using the same detector technology will greatly reduce the systematic errors: SBND (near detector) will provide the “initial” beam composition and spectrum
    - ✓ The great  $\nu_e$  identification capability of LAr-TPC will help reduce the backgrounds

*SBN appearance sensitivity*



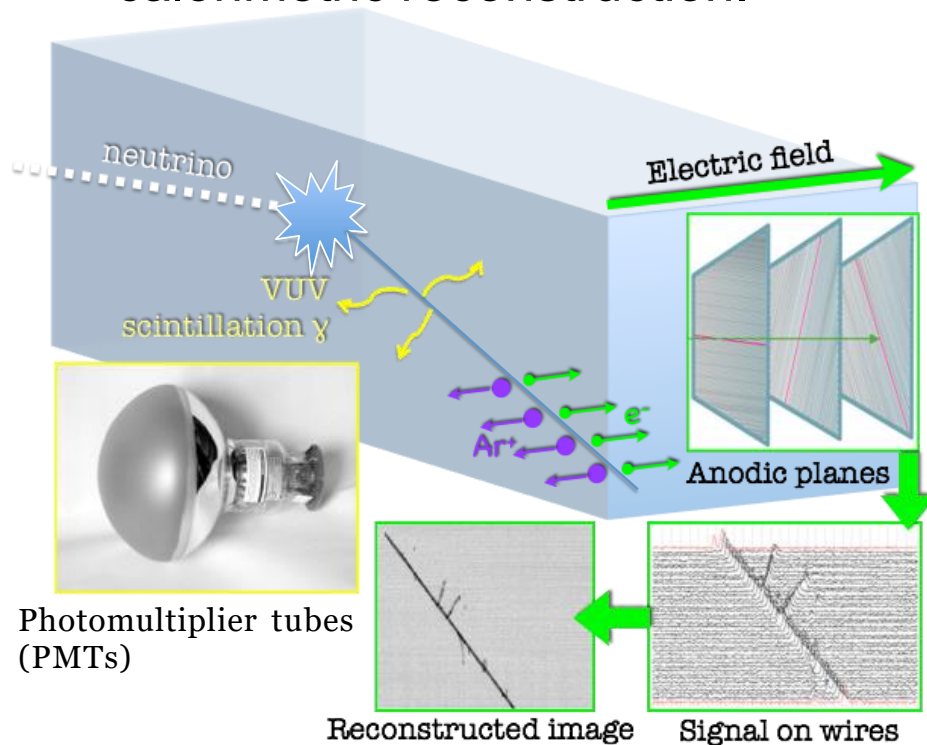
*Annual Rev. Nucl. Part. Sci. 2019.69:363-387*

*SBN disappearance sensitivity*



# Liquid Argon TPC detection technique

- Ideal technique for neutrino and rare event physics, first proposed by C. Rubbia and pioneered by the ICARUS collaboration.
- Homogeneous target that combines large mass with accurate spatial and calorimetric reconstruction.



## $\lambda = 128$ nm scintillation light:

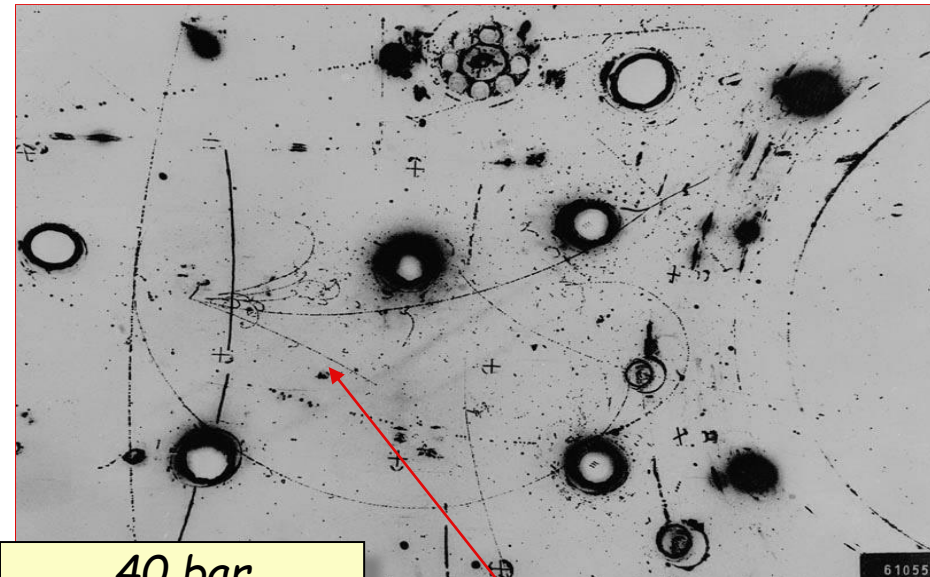
40000  $\gamma$ /MeV wo electric field.  
Response time  $\sim 6$  ns  $\div$  1.6  $\mu$ s,  
provides useful signals for  
timing/ triggering

## Ionisation electrons:

42000  $e^-$ /MeV.  
Drifted (E) toward planes of wires  
on which they induce a signal.  
Response time = drift time ( $\sim$  ms).

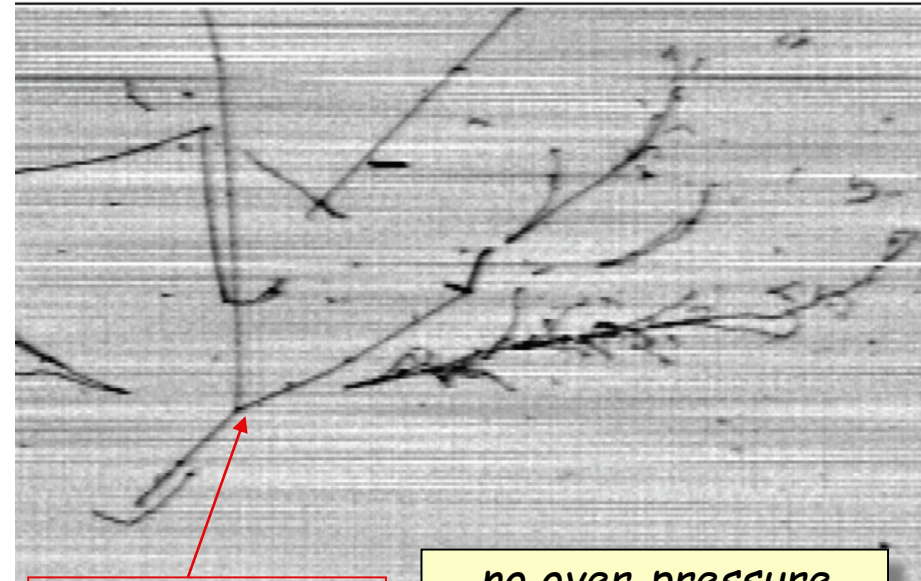
3D image reconstruction by combining coordinates on different wire planes at the same drift time.

# An "electronic" bubble chamber



40 bar  
pressure  
Pulsed  $\approx 1\text{ms}$

Bubble diameter  $\approx 3\text{ mm}$   
(diffraction limited)



"Bubble" size  
 $3 \times 3 \times 0.3$   
 $\text{mm}^3$

no over-pressure  
Continuously  
sensitive

## Heavy freon (Gargamelle)

Sensitive mass	3.0 ton
Density	$1.5\text{ g/cm}^3$
Radiation length	11.0 cm
Collision length	49.5 cm

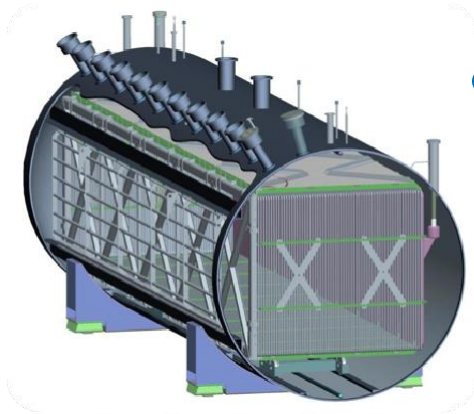
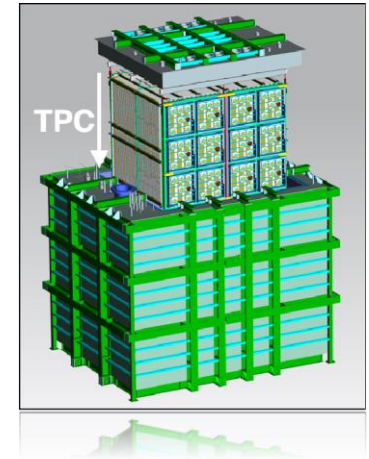
## Liquid argon

Sensitive mass	Many kton
Density	$1.4\text{ g/cm}^3$
Radiation length	14.0 cm
Collision length	54 cm

# The SBN detectors

## SBND construction/installation

- 260 t of LAr (112 t active), 110 m from target.
- 2 TPCs with 2 m drift
- 120 8" PMTs (96 coated with TPB), 192 X-ARAPUCA modules, TPB coated reflector foils on the cathode.
- 4 $\pi$  CRT (cosmic ray tagger) coverage

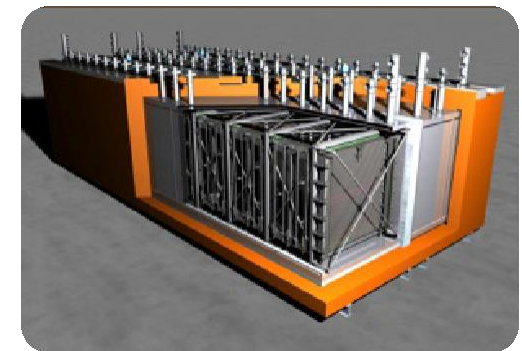


## MicroBooNE physics run completed

- 170 t of LAr (87 t active), 470 m from target.
- 1 TPC with 2.5 m drift.
- 32 8" PMTs on acrylic support coated with TPB.
- Top and side CRT.

## ICARUS commissioning

- 760 t of LAr (476 t active), 600 m from target.
- 4 TPCs with 1.5 m drift.
- 360 8" PMTs coated with TPB.
- Almost full CRT coverage.



# MicroBooNE status



- Currently the world's longest running liquid argon TPC (2015-present)
- Sits on BNB (on-axis), NuMI (off-axis)
- Analysis of high statistics data and long-term operational experience is informing the future LAr neutrino program
  - More than 33 papers, 56 public notes so far!
- Physics run complete, R&D program now underway
- On the cusp of releasing a series of first results addressing the anomalies seen in prior short-baseline neutrino experiments

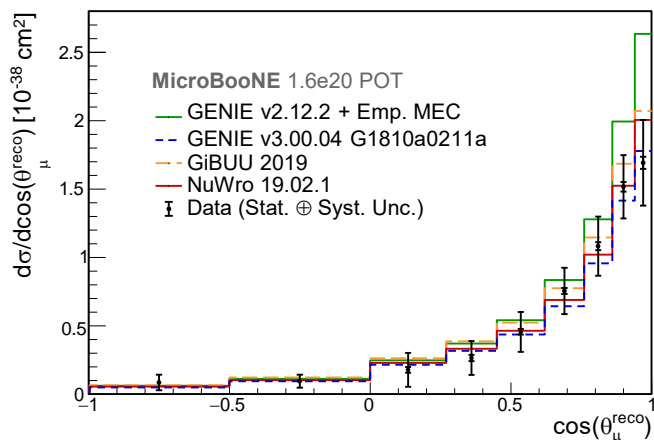


Future sterile-related analyses include:  $\nu_{\mu}$  disappearance, combined BNB + NuMI analysis in MicroBooNE, increased statistics (2x), combined SBN analysis with SBND and ICARUS

# MicroBooNE is now producing the world's first high statistics measurements of $\nu$ -Ar interactions

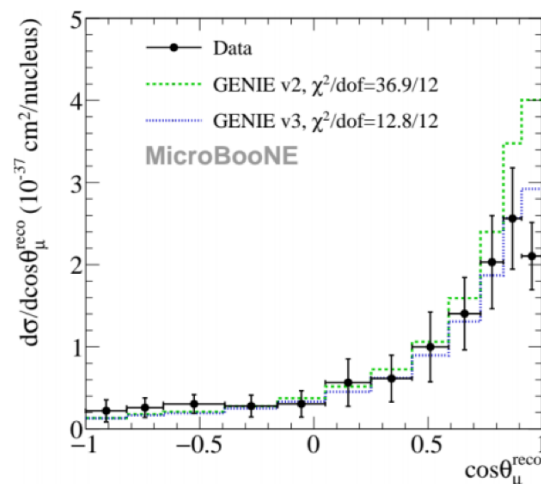
- Enables in depth studies of both inclusive channels and exclusive final states

Phys. Rev. Lett. 123, 131801 (2019)



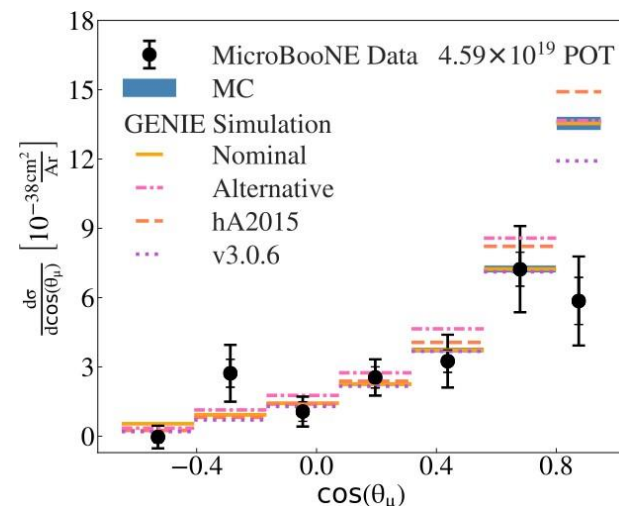
**CC Inclusive**  
Inclusive  
Some deficit

Phys. Rev. D 102, 112013 (2020)



**CC0 $\pi$ Np**  
More exclusive  
Turnover in data

Eur. Phys. J. C 79 673 (2019)  
Phys. Rev. Lett. 125, 201803 (2020)

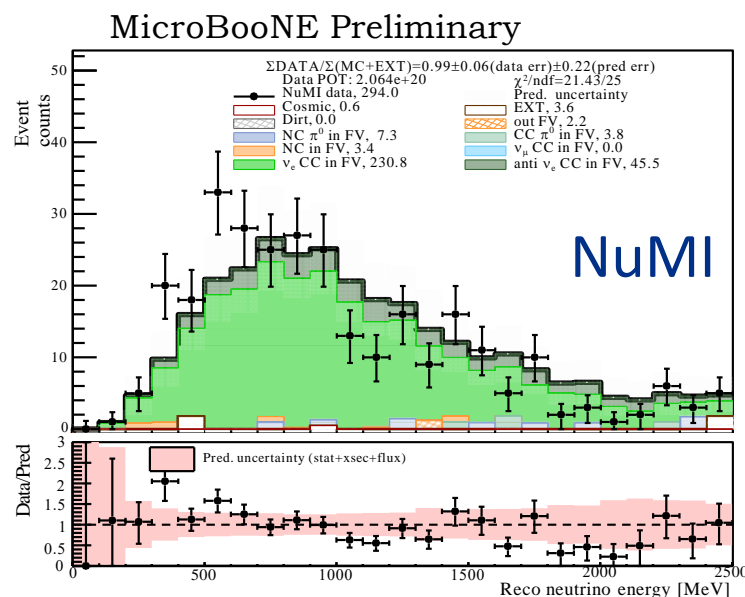
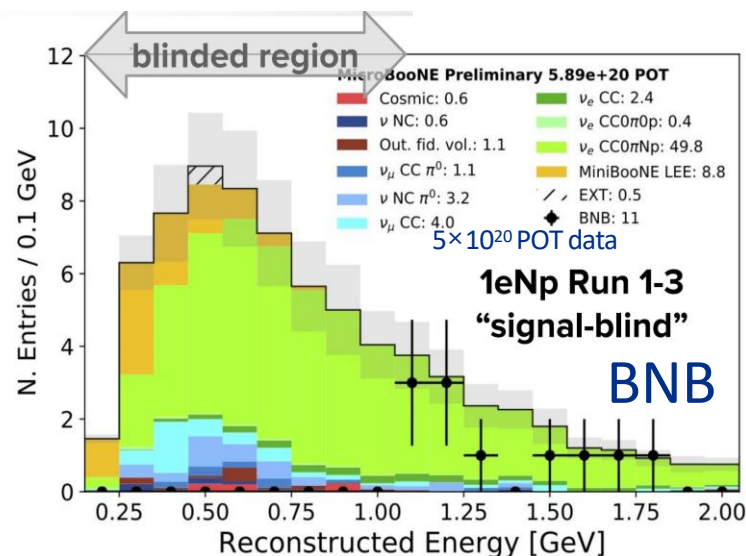


**CCQE-like**  
Even more exclusive  
Even more deficit

# Prospects for MicroBooNE Low-Energy Excess (LEE) Search

- The first LEE results based on  $6 \times 10^{20}$  POT data are imminent.
  - Results will be released in phases as the analysis are completed
- Next-generation reconstruction tools show improvements in  $\nu_e$  reconstruction allowing more sensitive tests of the SM and MiniBooNE anomalous event excess.
- Additional stats from the analysis of the full  $13 \times 10^{20}$  POT dataset will enable MicroBooNE to reach the ultimate sensitivity on the LEE search.

From Neutel 2021

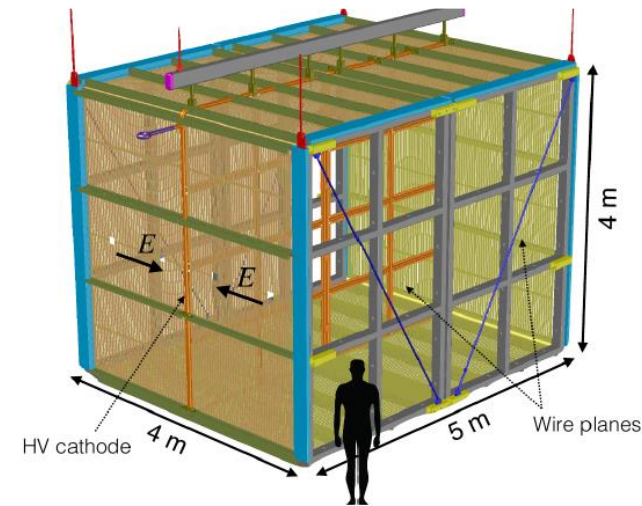


# SBND at Fermilab

- SBND will further constraint the intrinsic beam content of BNB by **measuring the un-oscillated neutrino fluxes**, essential for performing simultaneous appearance and disappearance fits.
- Analysis beyond the standard model: heavy neutrinos, neutrino tridents, dark matter, dark neutrinos. Modifications to neutrino oscillations: Lorentz and CPT violation, decaying sterile neutrinos ...

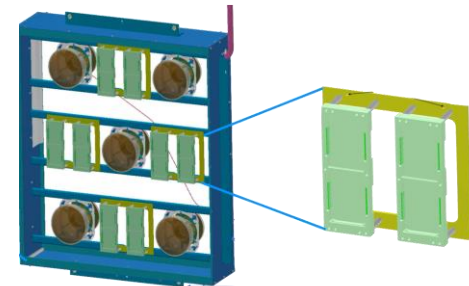
## Time Projection Chamber

- Single phase LAr TPC, with 112 tons active mass
- 5m x 4m x 4m active volume
- One central cathode plane assembly (CPA)  
[divides detector in two drift volumes;  $\tau_{\max} \sim 1.28$  ms]
- Two anode plane assemblies (APAs)
- 3 wire planes (vertical,  $\pm 60^\circ$  to vertical), wire pitch  $\sim 3$  mm
- Field cage to maintain 500 V/cm drift field
- UV laser calibration system



## Photon Detection System

- Modular detection system behind APAs
- 24 photon detection modules (PDS)
  - 5 PMTs, 80% total with WLS shifter
  - 8 X-ARAPUCA photon traps instr. with SIPM
- Reflective foils behind CPA mesh



## Cosmic Ray Tagger

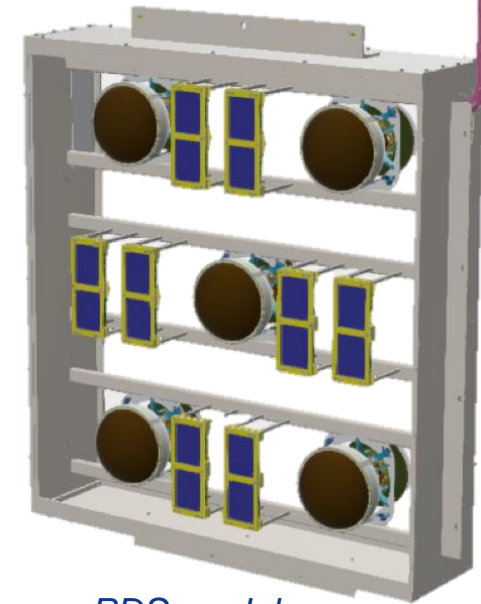
- Every side of the detector will be covered by planes of extruded scintillator strips

# SBND light detection system

- PMTs:
  - tested at LANL in the Coherent Captain Mills experiment;
  - PMTs delivered to FNAL and passed reception tests



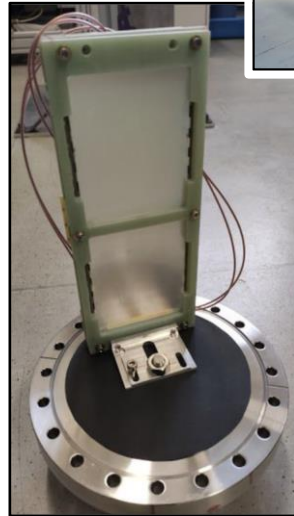
*PMTs being tested at LANL*



*PDS module*



*SiPM cold test*

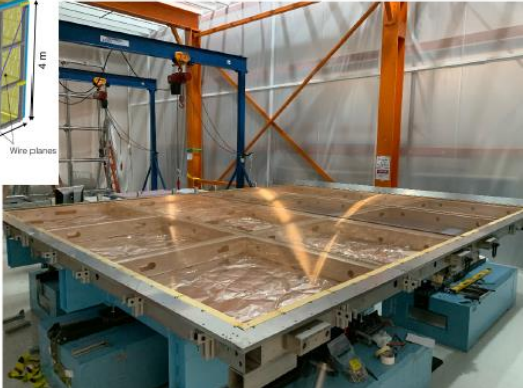
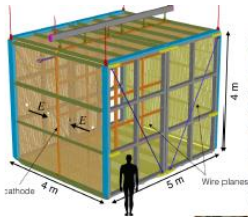
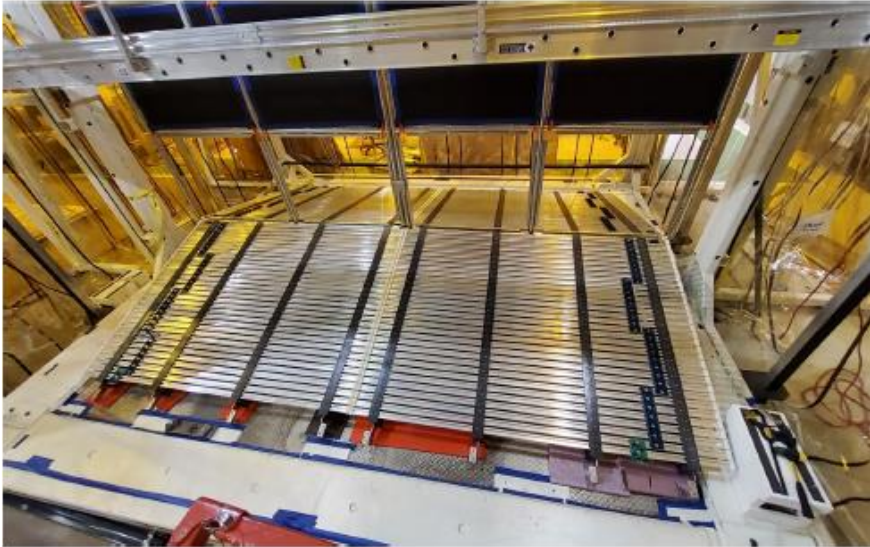


*X-ARAPUCA*

- X-ARAPUCAs:
  - Module production completed at UniCAMP and delivered to FNAL
  - test stands at FNAL for mass testing of SiPMs and for readout development/test.
- TPB coated reflector foils on the cathode:
  - at FNAL, to be installed when CPA ready

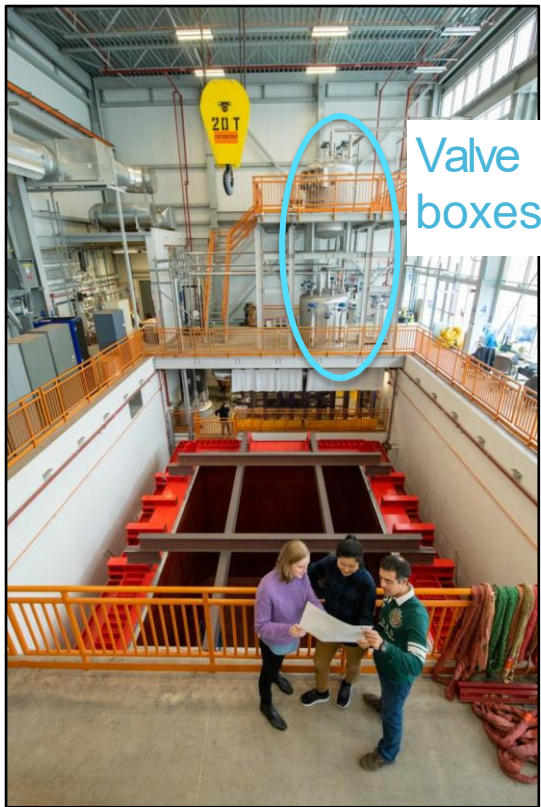
# SBND TPC Installation status

- Cathode plane assembly (CPA) recently installed
- First APA plane is already on-site, mechanically and electrically coupled. Ready for installation in September
- Bottom field cage just installed

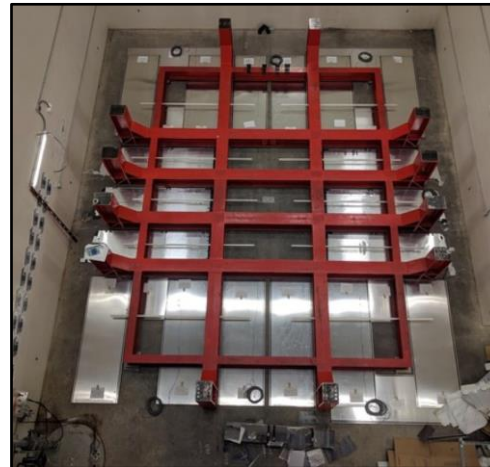


# SBND installation status

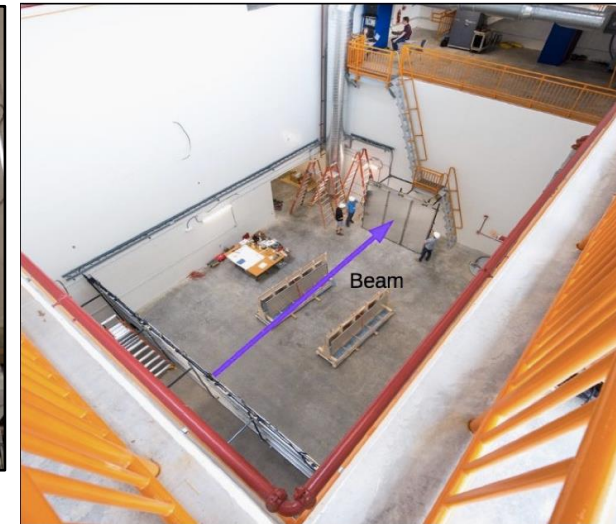
- CRT system:
  - Panels constructed
  - Bottom panels installed
  - Beam measurements in pit



*Warm outer vessel in the pit*



*Bottom CRT*



*BNB measurement with CRT*



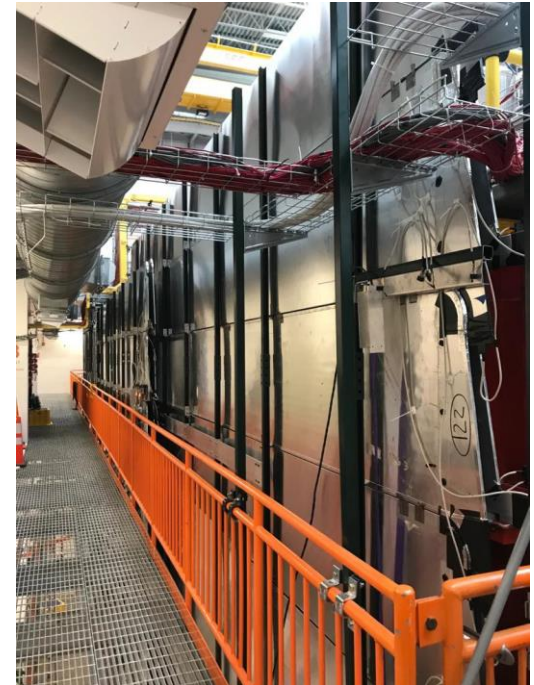
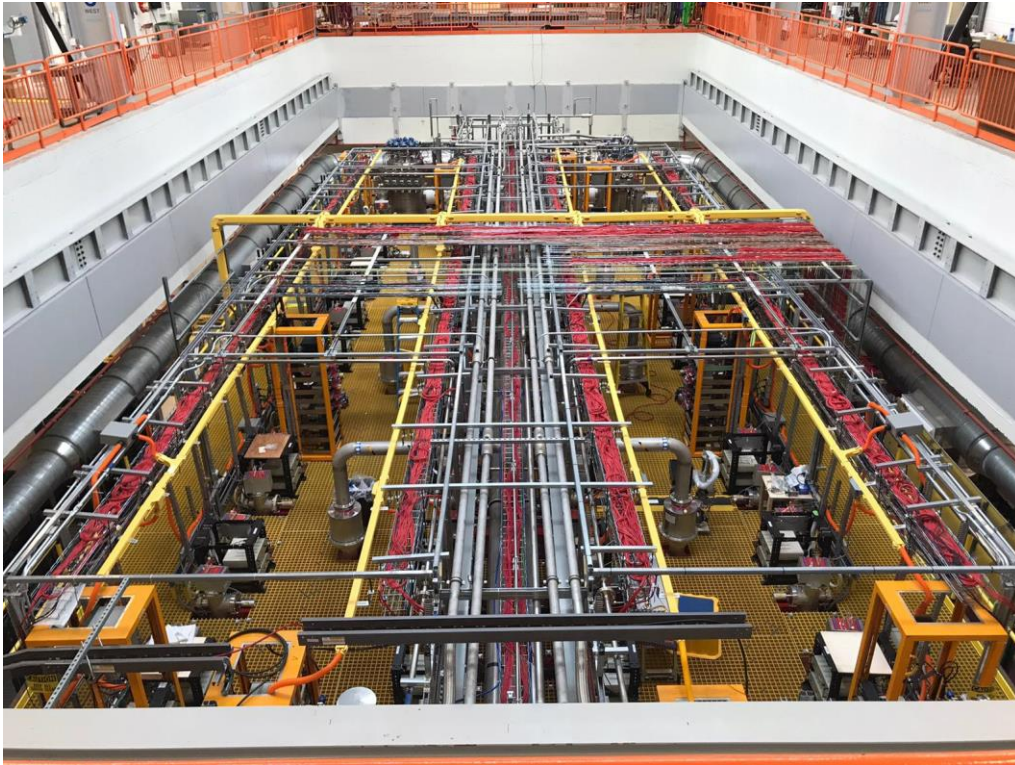
*Top cap \_ part 1*

- Cryostat/cryogenics:
  - Warm outer vessel installed.
  - Cryostat material at FNAL.
  - Top cap fabrication finalizing at CERN.
  - Cryogenics installation ongoing

# Status of Icarus detector

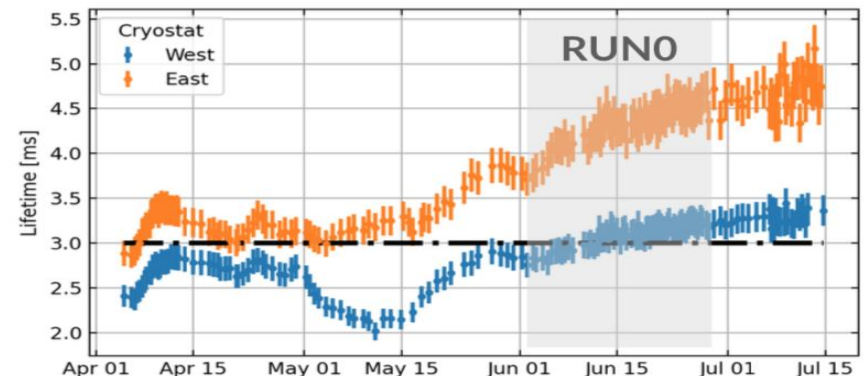
See M. Torti talk

- TPC, PMT, trigger and DAQ installation activities completed, with latest achievements during Covid-19 restricted operations.
- Bottom CRT and side CRT installation is completed.
- 24/7 shifts since February 14<sup>th</sup> 2020. Remote only shifts since March 17<sup>th</sup> 2020.



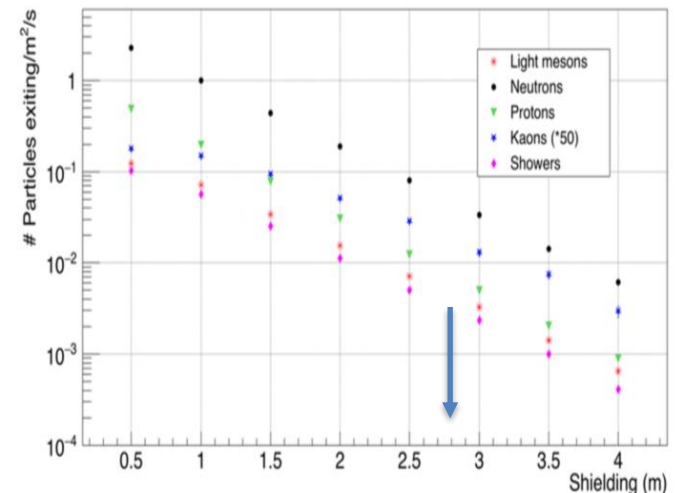
# Activation and commissioning of Icarus detector

- TPC wire planes and cathode HV to nominal voltages on Aug 27<sup>th</sup> 2020.
  - HV stable at -75 kV, without glitches or issues.
  - No significant currents on wire bias, except for 2 groups of Induction-2 wires of West module at 0 V (instead of -30 V).
- All PMTs switched on (3 out of 360 not working).
  - Calibration of gain with laser and fine tuning based on counting rates.
- All side CRT wall sections integrated into the readout.
- Cosmic-ray interaction events regularly collected with random 5 Hz trigger for calibration purposes. Dedicated runs for specific commissioning tasks (investigation of TPC noise, PMT calibration, DAQ upgrades/longevity tests, etc).
- The Liquid Argon purity level is continuously monitored by measuring the signal attenuation along the drift direction along crossing cosmic muon tracks. The electron lifetime reaches up to ~4.5 (~3) ms in the East (West) Cryostat, allowing efficient signal detection over the full LAr volume



# Cosmic-ray background mitigation: CRT

- With the presence of the overburden, primary cosmic muons will be the dominant component of cosmic rays producing background in ICARUS:  $\sim 11$  muon tracks will hit the TPC active volume in the  $\sim 1$ ms drift window
- To tag charged cosmic rays and determine unambiguously the position and timing of each ionizing events, ICARUS will use
  - A much improved **light detection system** (see next slide)
  - A **cosmic ray tagger (CRT)** surrounding the T600 with a double layer of scintillator bars ( $\sim 1000$  m<sup>2</sup>) equipped with optical fibers driving light to SiPM for readout.
- Tags incident cosmic or beam-induced muons with high efficiency, 95%, giving spatial and timing coordinates of the track entry point
- Reconstructed CRT hits are matched to the activity in the LAr TPC volume: CRT - PMT, CRT - TPC matching
- Installation of the Top CRT is planned to take place during the summer shutdown, to be followed by the installation of the overburden at the beginning of the next neutrino run



*Particles in LAr from primary hadrons as a function of overburden thickness*

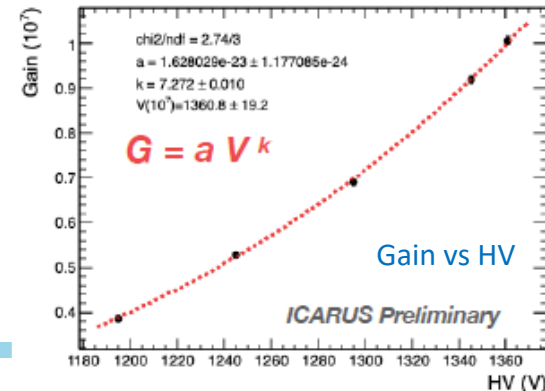
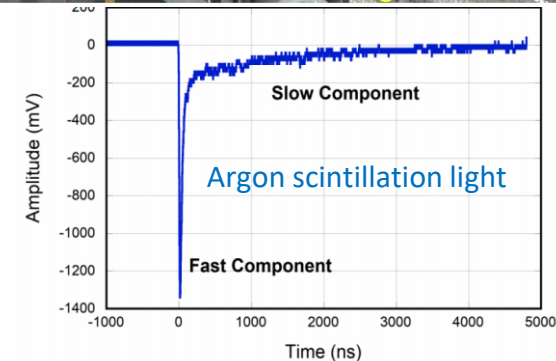
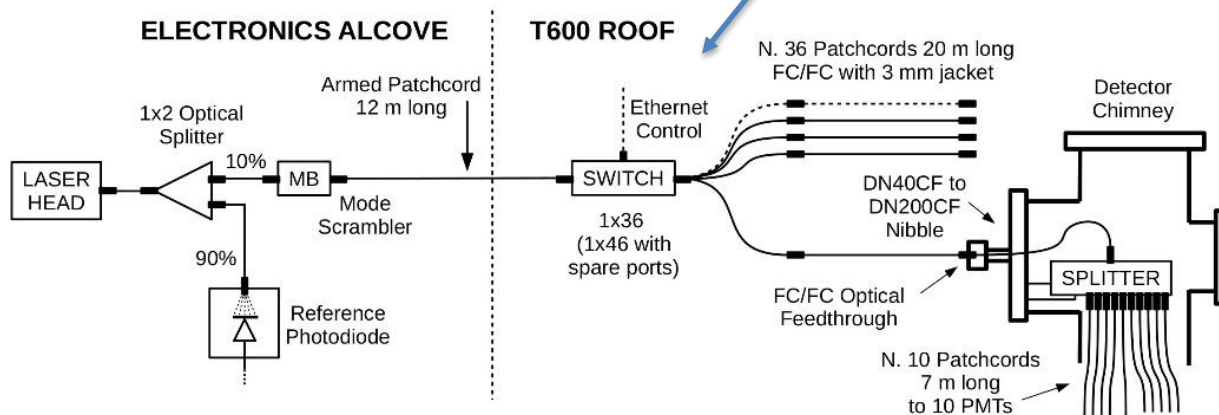
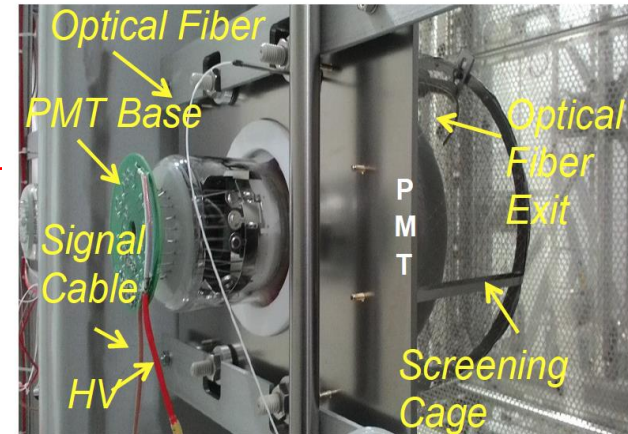
# Upgrade of the light collection system

ICARUS@SBN exploits 360 PMTs (5% coverage, 15 phe/MeV). This system will allow to:

- Precisely identify the **time of occurrence** ( $t_0$ ) of any ionizing event in the TPC with ns timing resolution
- **Localize events** with <50 cm spatial resolution and determine their **rough topology** and for selection purposes
- Generate a **trigger signal for read-out**
  - Sensitivity to low energy events ( $\sim 100$  MeV)

The system was completed in 2019 and activated after the LAr filling in 2020:

- Transit time resolution  $\sim$ ns, dark rate <5kHz, QE  $\sim$ 12%
- Stable gain ( $10^7$ @87K) to detect single p.e.
- PMTs gain/timing calibration in cryogenic environment performed with laser system flashed on each PMT by dedicated optical fibers



# Upgrade of the TPC read-out system

ICARUS electronics at LNGS was based on:

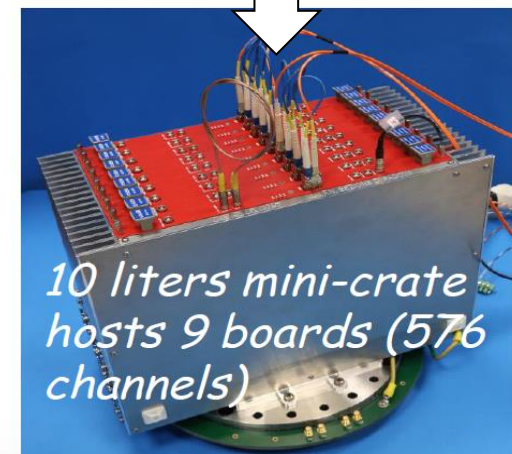
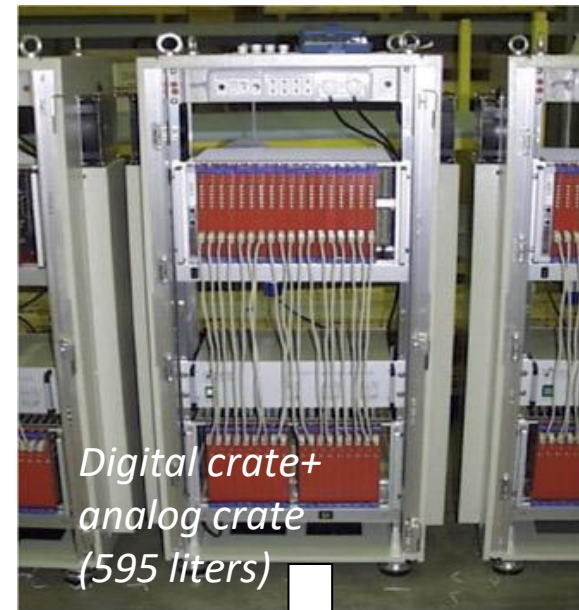
- "warm" low-noise front-end amplifier
- Multiplexed 10-bit ADC
- Digital VME module for local storage, data compression, trigger information

Performances proved adequate for track reconstruction and MCS measurement:

*S/N~9 in Collection, resolution  $\sigma_y \sim 0.7$  mm along drift*

However, in view of the SBN experiment some components were modernized and improved:

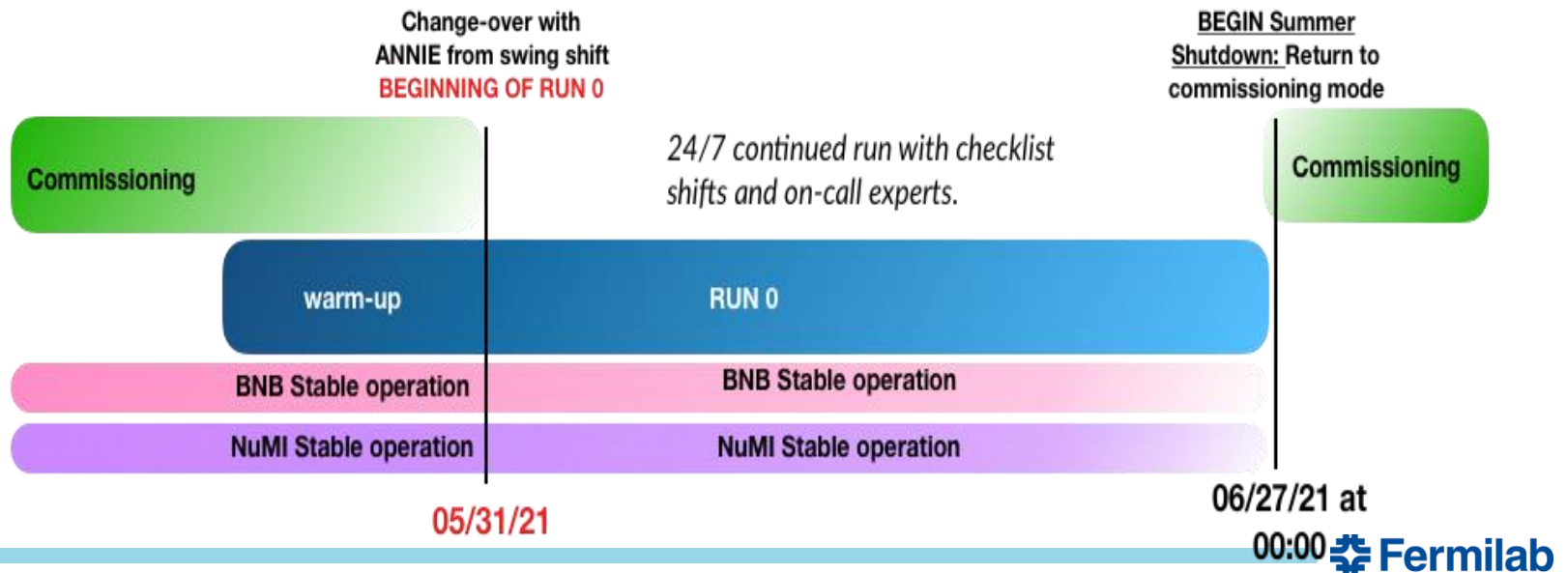
- Serial 12-bit ADC, fully synchronous in the whole detector -> *~20% improvement in MCS resolution*
- Serial bus architecture increases bandwidth to ~10 MHz
- More compact layout: both analog+digital electronics hosted on a single flange



# ICARUS RUN 0: May 30 - June 27

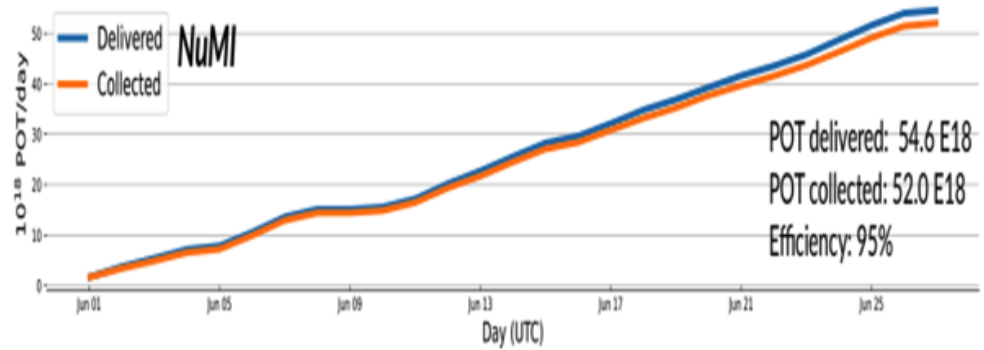
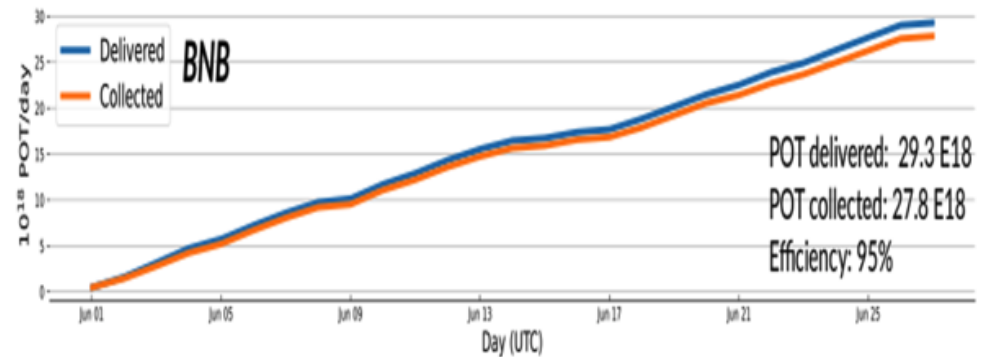
## ➤ Goals of the ICARUS RUN

- ✓ Certify the readiness of the detector for physics quality data with TPC and PMT and operate as primary BNB user in stable mode and with minimal downtime;
- ✓ Verify the possibility to run the detector in remote mode, with a limited on-site presence
- ✓ Test DAQ with different triggers for both BNB and NuMI beam and prepare the infrastructure for next run on fall.
- ✓ Accumulate a good quality data samples to tune the reconstruction of neutrino and cosmic candidates, perform dedicated detector and trigger efficiency studies.



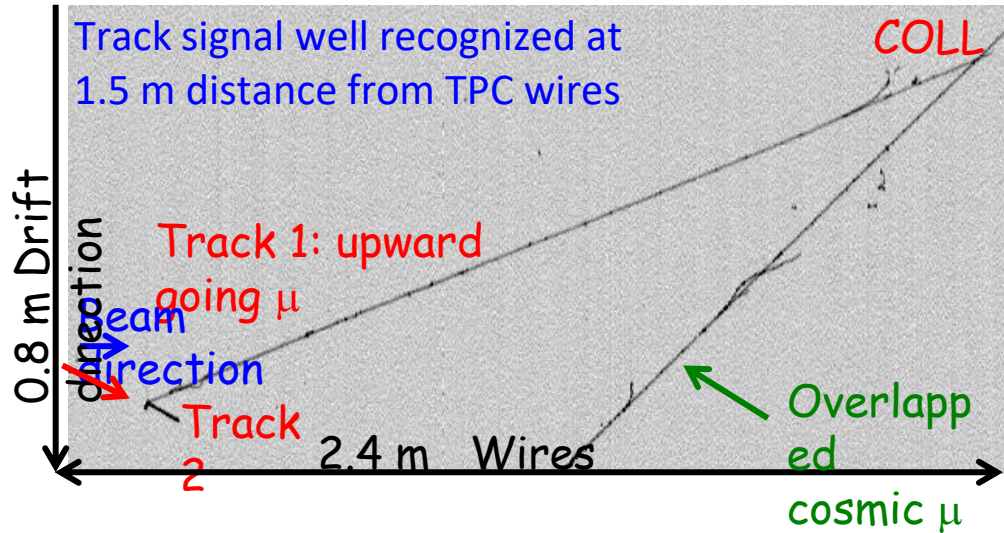
# RUN Run 0: collected data

- Two main triggers used to collect both BNB and NuMI beam events:
  - “Minimum Bias trigger”: data are recorded for every beam spill received;
  - “Majority trigger”: hardware Majority Mj of pairs of discriminated PMT signals (10 phe threshold) in coincidence with the beam spill duration, Mj level: 5, 10.
- ✓ Collected pot: 27.8 E18 (BNB), 52.0 E18 (NuMI) with ~ 95 % efficiency.
- ✓ A part of collected runs was also filtered & visually scanned: 254  $\nu_{\mu}$  CC and 15  $\nu_e$  CC gold event sample to be used for the tuning of the event reconstruction software.
- ✓ Cosmic rays data samples separately collected with the same trigger logics used for the RUN 0.



# BNB $\nu_\mu$ CC candidate, $e^-$ lifetime $\tau \sim 2.7$ ms

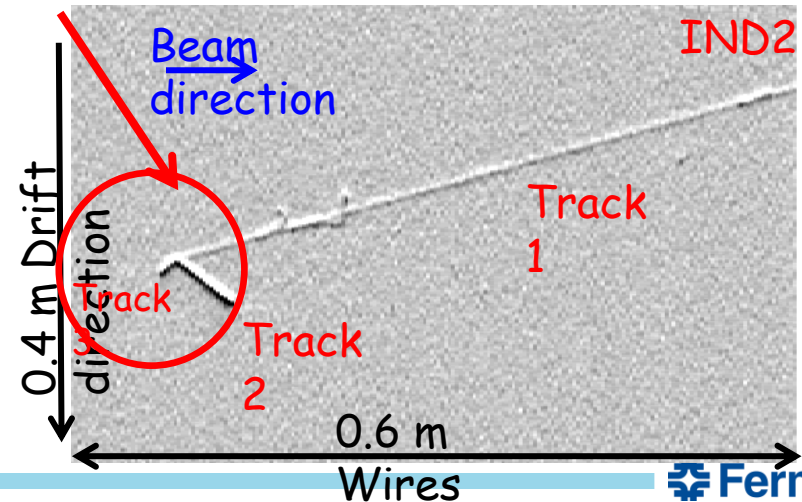
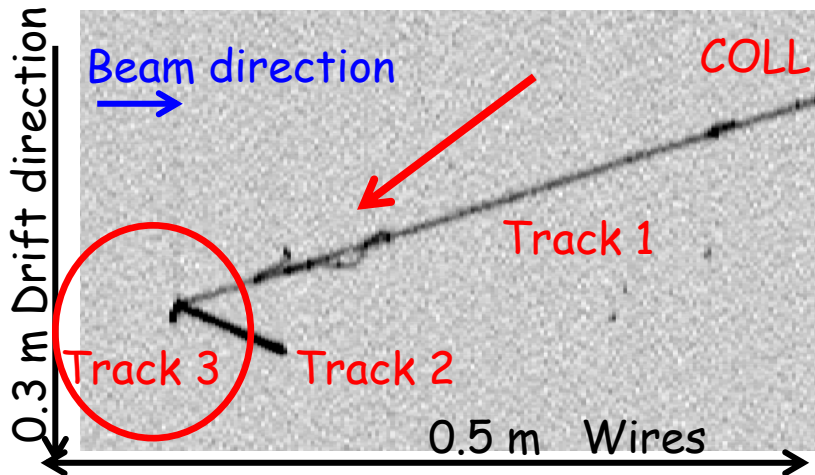
## Cathode



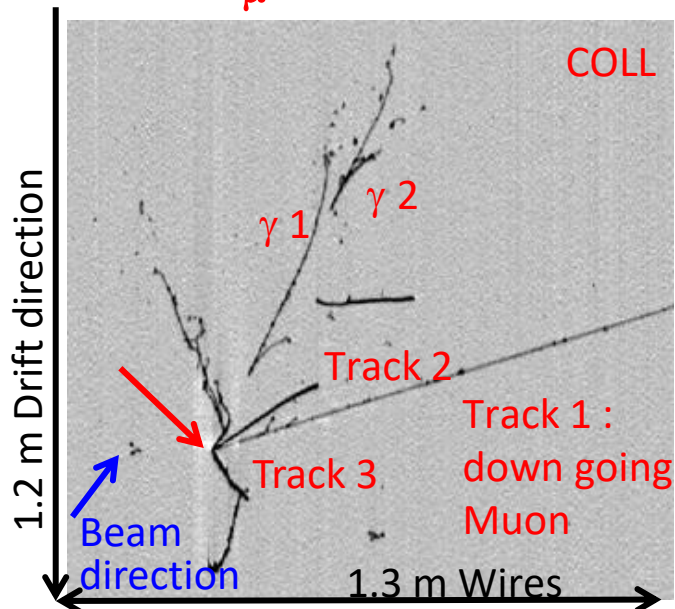
Three particles produced at vertex located at center of the TPC (red arrow and circles):

- ✓ Track 1 m candidate crossing the cathode and exiting through top wall  $L = 5.5$  m;
- ✓ Track 2 downward going stopping proton candidate  $L = 10$  cm;
- ✓ Track 3 (visible in the zoom) downward going stopping proton candidate  $L = 2$  cm.

## Zoom views of vertex: more details



# NuMI $\nu_\mu$ CC candidate, $e^-$ lifetime $\tau \sim 3.2$ ms



➤ Five particles produced at primary vertex (indicated by red arrows),  $E_{\text{DEP}} \sim 2.5$  GeV:

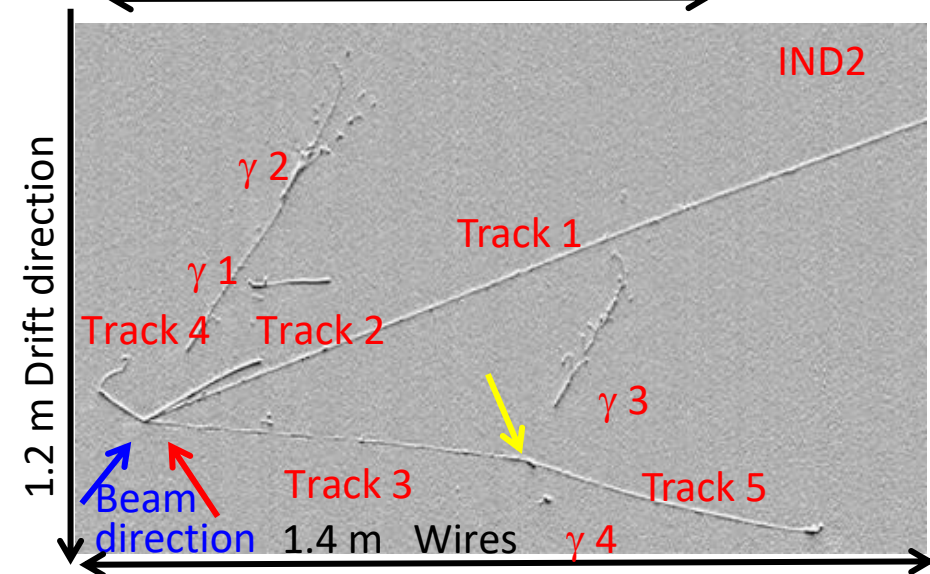
✓ Track 1: downward going  $\mu$ , crossing the cathode and exiting downstream,  $L = 4.2$  m,  $p \sim 1.3$  GeV/c by MCS;

✓ Track 2: upward going  $p$  candidate,  $L = 31$  cm;

✓ Two photons  $\gamma_1, \gamma_2$  are pointing to primary vertex,  $E_1 \sim 200$  MeV,  $E_2 \sim 240$  MeV and converting at 18 cm, 58 cm distance respectively;

✓ Track 3: hadron that produce a secondary vertex (yellow arrow) where a short proton, another hadron (Track 5) and two photons  $\gamma_3, \gamma_4$  are also clearly visible;

✓ Track 4: charged pion with visible Michel electron produced in  $p \rightarrow \mu \rightarrow e$  decay chain.

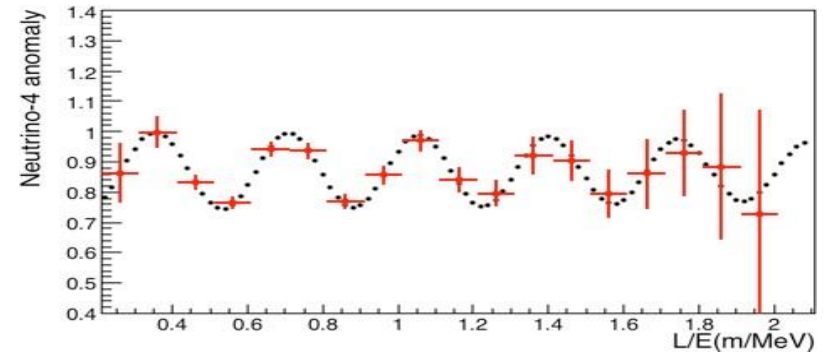


# Icarus data taking: next goals

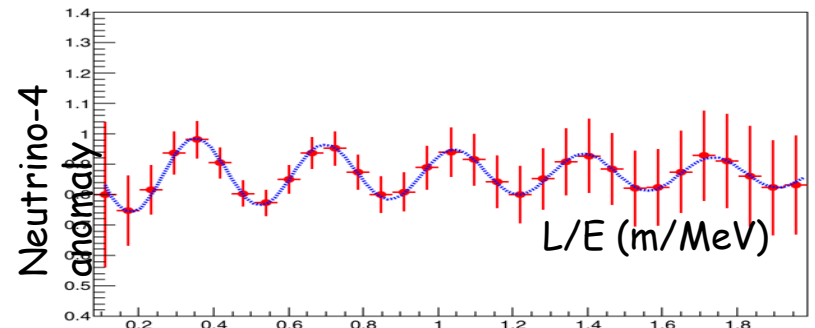
- Data taking resumes early October
- Main goal of this initial one-year ICARUS data taking: definitive verification of the recent claim by NEUTRINO-4 reactor experiment both in the  $\nu_\mu$  channel with the BNB and in the  $\nu_e$  channel with NUMI:

- Survival  $\nu_\mu$  oscillation probability for Neutrino-4 anomaly (black) for the best fit ( $\Delta m^2_{N4}=7.25 \text{ eV}^2$ ,  $\sin^2 2\theta_{N4}=0.26$ ), and expected corresponding ICARUS measurement for 3 months of BNB (red).
- Survival  $\nu_e$  oscillation probability for Neutrino-4 anomaly (blue) for the best fit ( $\Delta m^2_{N4}=7.25 \text{ eV}^2$ ,  $\sin^2 2\theta_{N4}=0.26$ ), and expected corresponding ICARUS measurement for 1 year of NuMI (red).

Survival probability of  $\nu_\mu$  from the BNB beam



survival probability of  $\nu_e$  from the NuMI beam



# Conclusions

- The **SBN Program at Fermilab** is proceeding well to:
  - an exciting search for neutrino oscillations over short baseline addressing the sterile neutrino puzzle;
  - make high precision measurements of  $\nu$ -Ar cross sections;
  - develop LAr-TPC technology & expertise in preparation for DUNE.
- **MicroBooNE** is now producing high statistics measurements of  $\nu$ -Ar interactions and is getting closer to start releasing the first results on the low energy excess, based on  $6 \times 10^{20}$  POT.
- Despite the challenges posed by the Covid-19 pandemic:
  - the **Icarus** detector was activated in August 2020 and is now in commissioning phase, expected to be completed early in the Fall 2021. RUN-0 done; data taking resuming early October
  - assembly and installation of the **SBND** detector are progressing and will finish by 2022

I would like to thank E. Worcester, D. Mendez, A. Fava, V. Pandey, V. Maddage, A. Menegolli, B. Wilson and V. Paolone for suggestions and the generous loan of transparencies and the organizers of NUFACT21 for support and understanding