# ICARUS
## Towards the Physics Run

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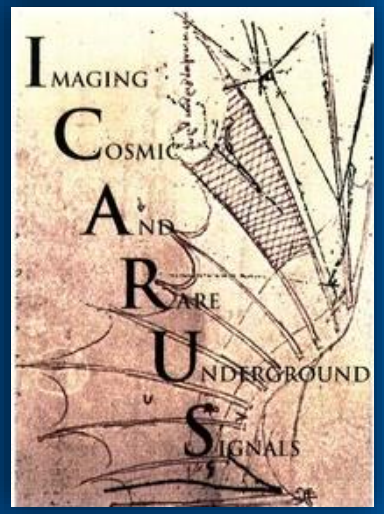
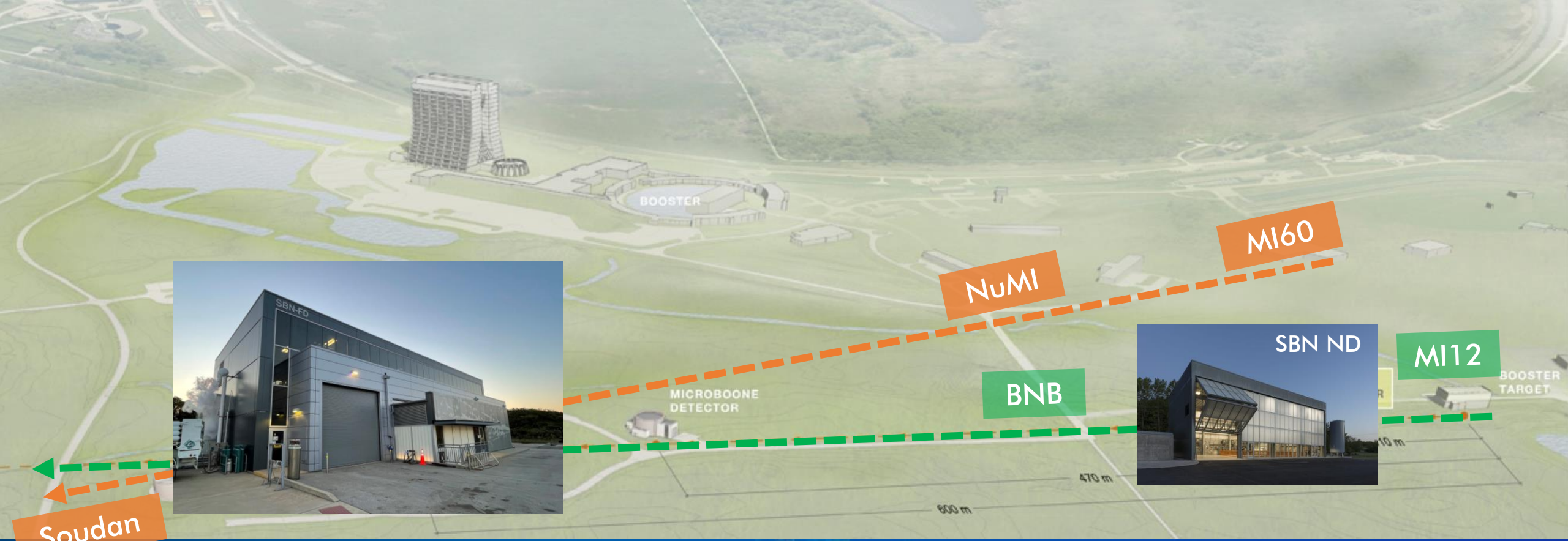
(INFN and University of Bologna)
On behalf of the ICARUS Collaboration

FNAL 55° Annual Users Meeting

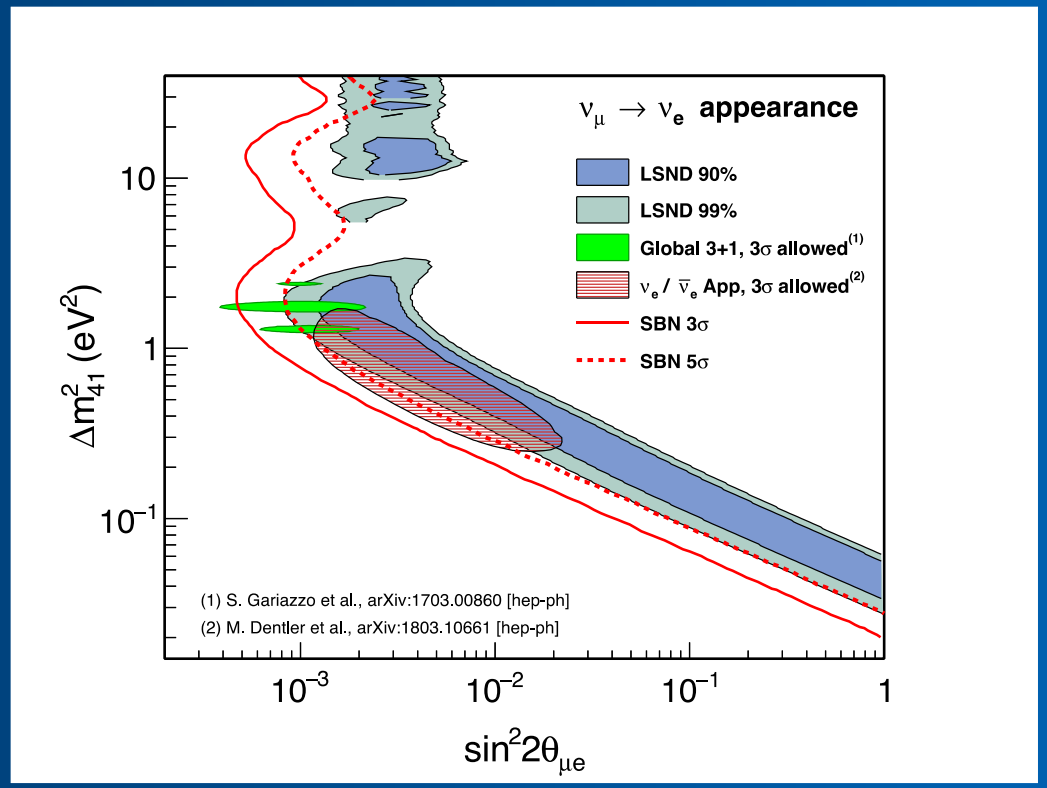


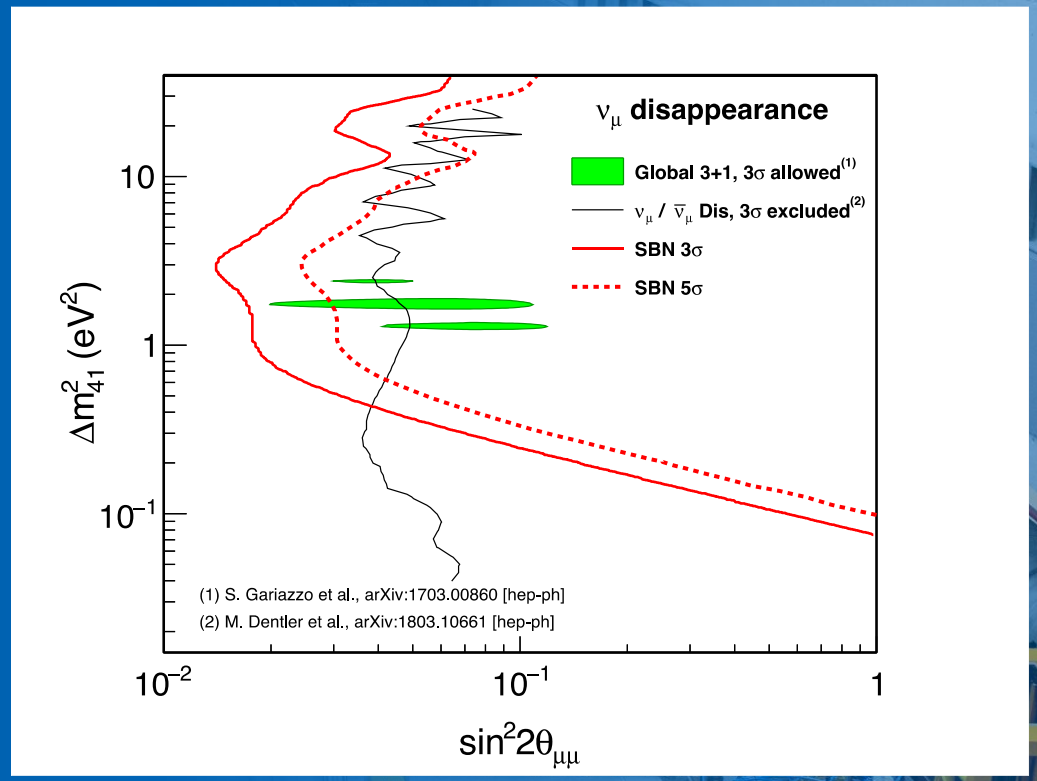



ICARUS is the Far Detector in the Short Baseline Neutrino Program (SBN) at FNAL.
SBN consists of three liquid argon TPCs (LArTPCs) sampling the same neutrino beam (BNB) at different distances, searching for sterile neutrino oscillations at the ~eV$^2$ mass scale.

It is also located 6 degrees off-axis on NuMI beam, accessing the electron-neutrino rich component of the spectrum.
NuMI grants ICARUS the access to a rich physics program including the study of the Neutrino-4 anomaly, ν-Ar cross-section measurements and rich BSM searches (Higgs portal scalars, neutrino tridents, light dark matter, …).

# SBN Program



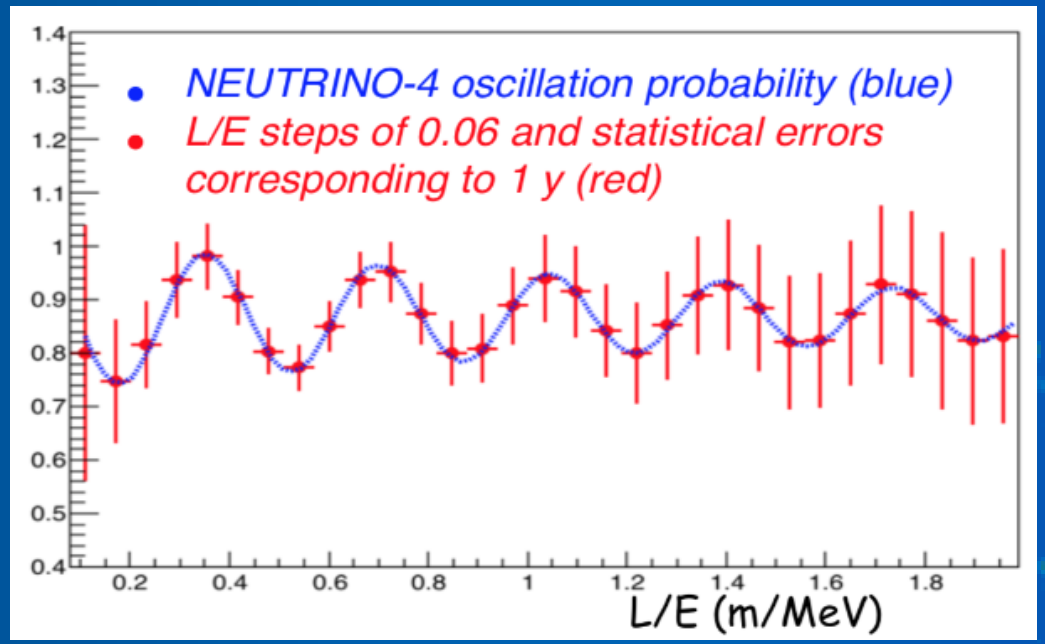




The SBN program will test the light sterile neutrino hypothesis, providing a definitive coverage of the LSND/MiniBooNE anomaly parameter space in 3 years.

SBN will probe simultaneously both the $\nu_e$ appearance and the $\nu_\mu$ disappearance channels.

# Neutrino-4 oscillation signal

- The Neutrino-4 collaboration claimed a reactor neutrino disppearance signal with a modulation with L/E ~1-3 m/MeV.
- ICARUS can confirm or refute the Neutrino-4 anomaly by means of two different channels:
  - $\nu_\mu$ disappearance channel from BNB focusing on QE contained $\nu_\mu$CC;
  - $\nu_e$ disappearance channel in the NuMI beam, selecting QE contained $\nu_e$CC.
- By complementing these channels with off-beam sample, ICARUS can observe such a modulation in less then one year.




*$\nu_e$ survival probability and ICARUS measurements, assuming 1 year data taking for Neutrino-4 best fit*

# ICARUS first life

The Liquid-Argon Time Projection Chamber:
a new concept for neutrino detectors (C. Rubbia)

16 May 1977

First test runs at Pavia

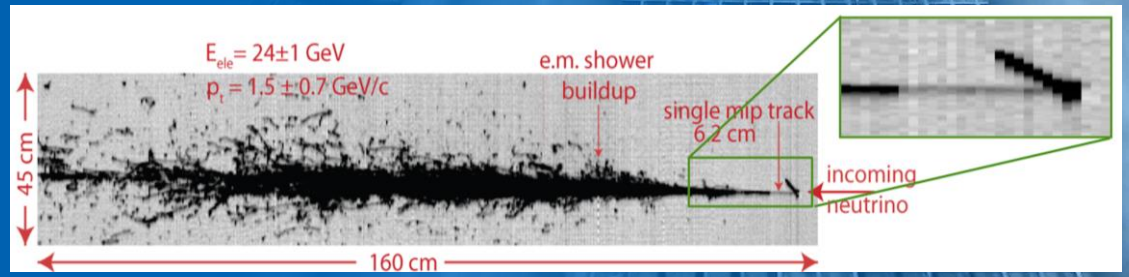
2001

ICARUS T600 begins operations at Gran Sasso

2010

ICARUS ends operations at Gran Sasso

2014



# ICARUS T600

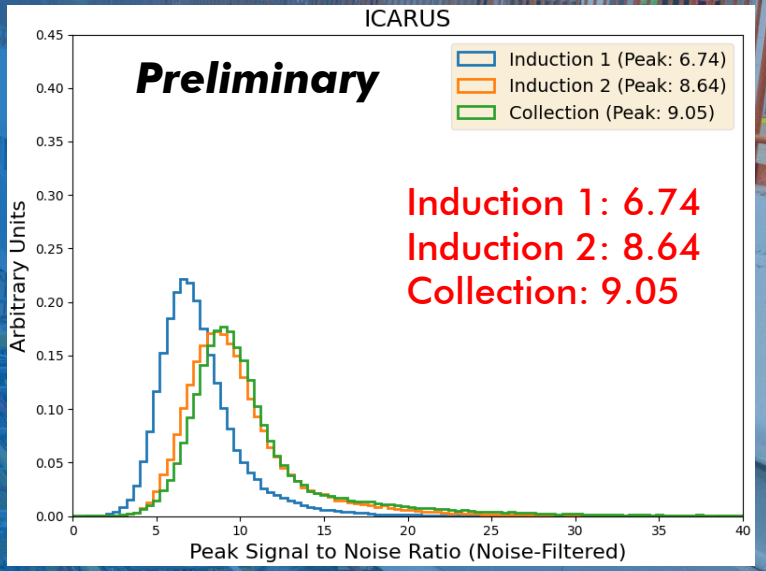
- Total mass of 760 t of Lar, active mass of 476 t.
- Two identical cryostats (T300 modules).
- Each module is divided in 2 TPCs with 1.5 m drift, 3 wire planes and a common 75kV cathode.
- Fully instrumented with 360 PMTs coated TPB.
- Almost fully covered by a Cosmic Ray Tagging System (CRT).
- 3 m concrete overburden.

# TPC upgrades

Upgrade of the warm TPC readout electronics:

- new front-end based on analogue low noise/charge sensitive pre-amplifier;
- more compact layout of analog and digital electronics in a single flange;
- shorter signal shaping time (~1.3 μs).

*S/N after coherent noise removal*



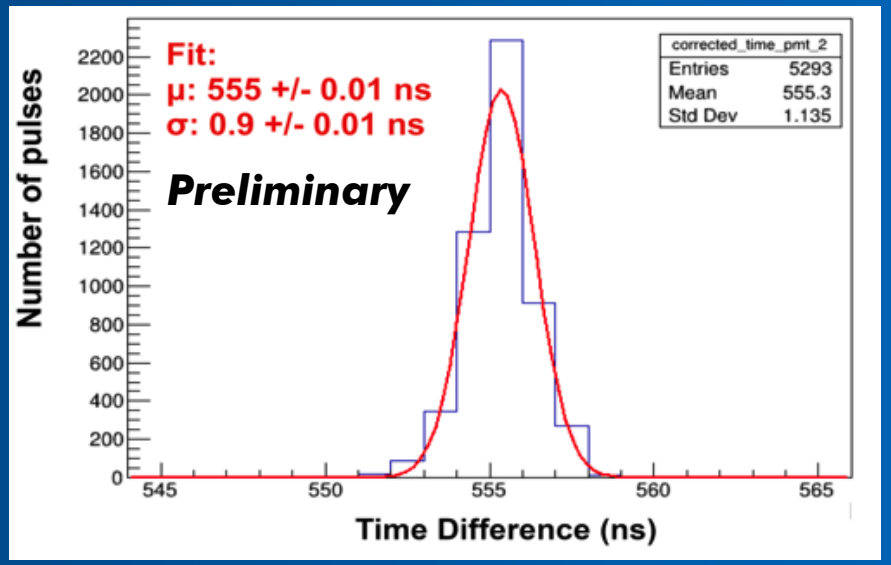

# Light collection system upgrades

Increased coverage of the detector surface with 360 8” PMTs (5% photocathode coverage of the TPC wire area) provides:

- ns event timing resolution;
- <50 cm event spatial resolution.

The PMT light detection system is working smoothly and all the gains have been equalized.

*Distribution of time difference between PMT signals and trigger time*




*Hamamatsu R5912-MOD*

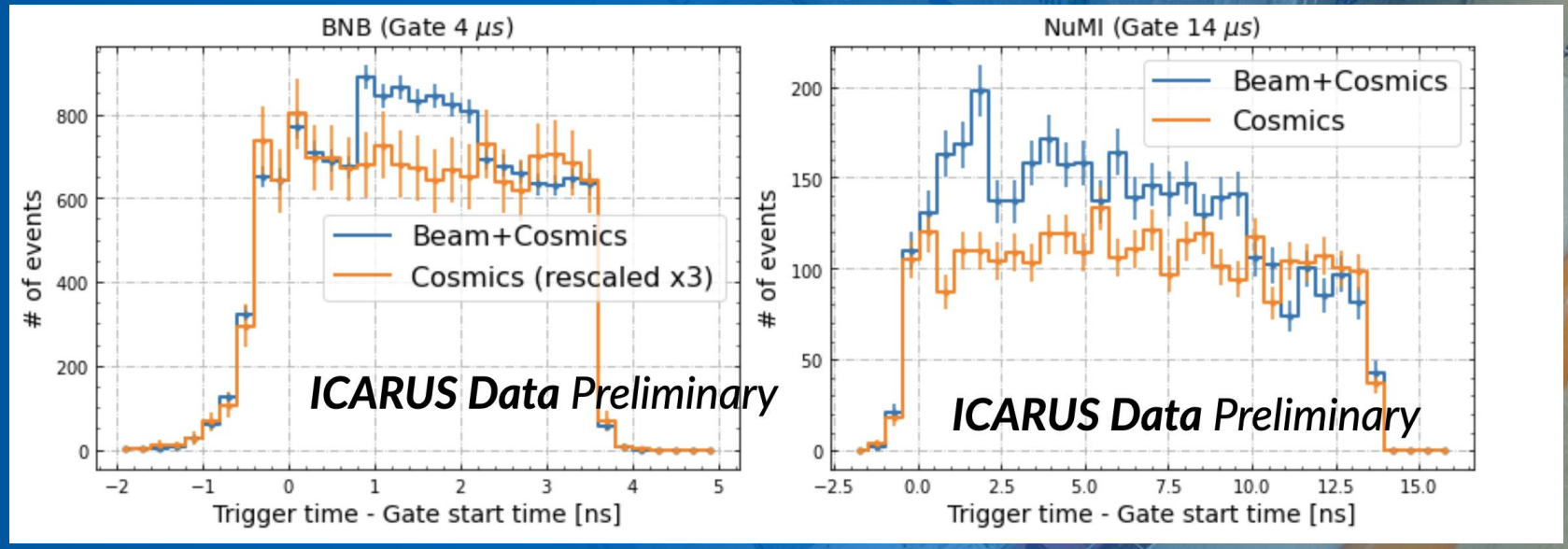
*PMT supporting system*

# Trigger

- The main ICARUS trigger signal is generated by majority of discriminated PMT pair signals in coincidence with BNB and NuMI beam spill gates (1.6 and 9.5 μs respectively).
- The current trigger requirement is 400 ADC/13 pe threshold for PMTs digitization and majority of 5 pairs.

- Correct timing of beam signals was verified by looking for excess PMT light over the cosmic background rate in minimum-bias runs.

*Excess of PMT flashes in the BNB (left) and NuMI (right) gates*



# Cosmic Background

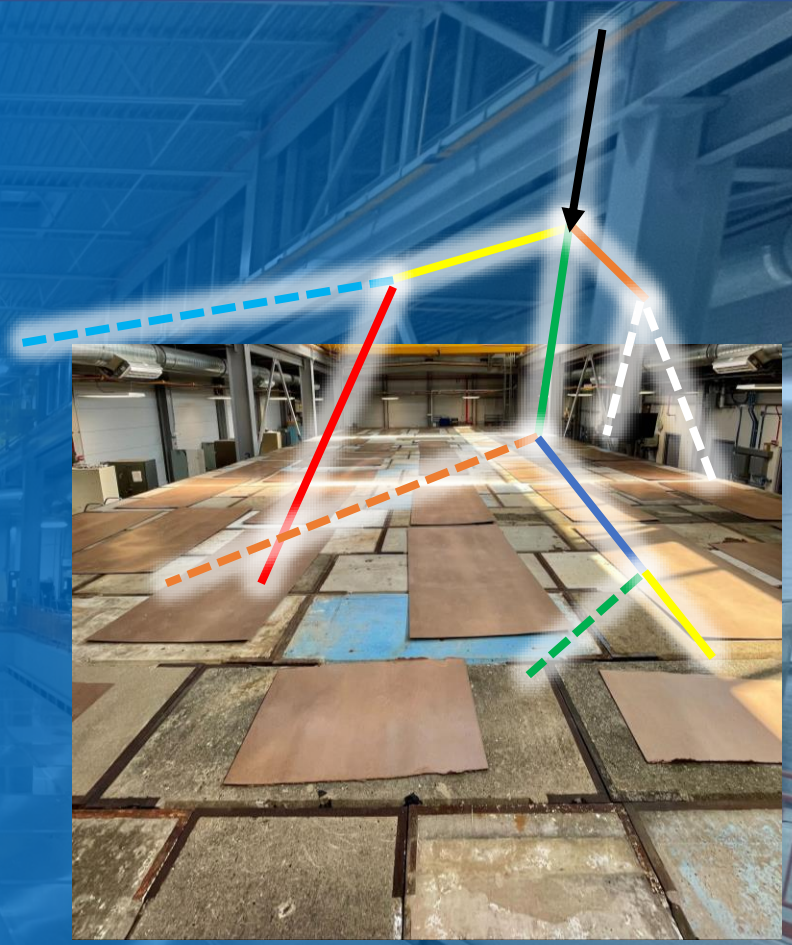
ICARUS is on the surface and thus exposed to a huge cosmic activity.
Cosmic activity can be divided in:

- In-time: cosmic particles entering the detector during the beam spill.
- Out-of-time: cosmic particles crossing the detector during the drift time.

Without shielding, ICARUS would be overwhelmed by the hadronic and soft energy component of the cosmic background.

In order to mitigate as much as possible the contribution of the cosmics, ICARUS is instrumented with:

- 3 m concrete overburden (6m water equivalent);
- A $4\pi$ coverage of the detector with Cosmic Ray Tagging modules (CRT):
  Bottom CRT, Side CRT and Top CRT.

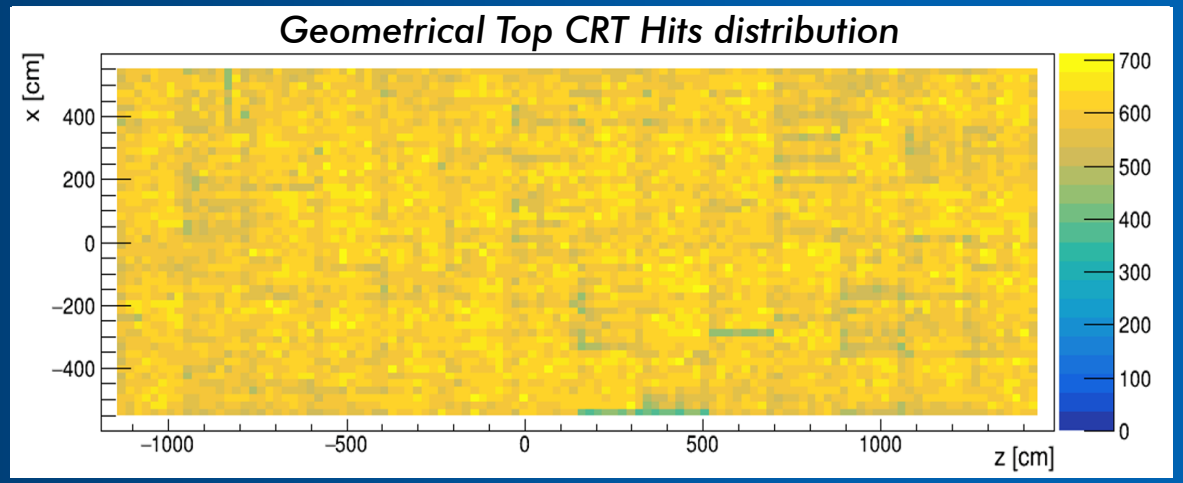


*Expected number of particles crossing the active Lar during the drift time*

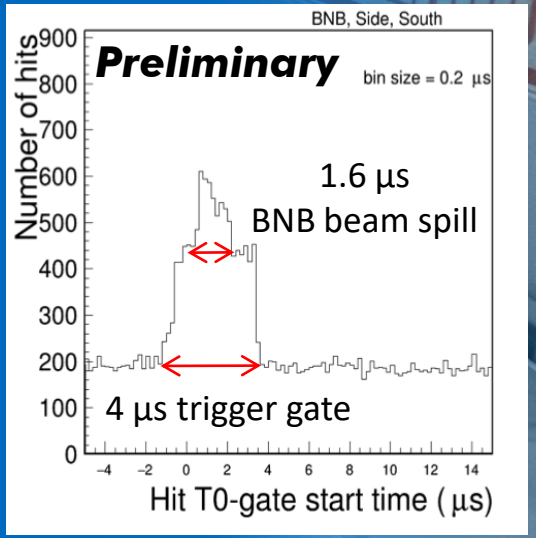
| Particle | Without OB | With OB |
|---|---|---|
| $\mu^{\pm}$ | 15.5 | 11.5 |
| $p$ | $< 0.045$ | $\ll 0.001$ |
| $\gamma$ | $< 0.01$ | 0 |
| $n$ | $< 0.45$ | $\ll 0.01$ |

# Cosmic Ray Tagger (CRT)

- The CRT system is composed of plastic scintillator bars readout by SiPMs.
- Side CRTs have been repurposed from MINOS modules.
- Top CRT modules were assembled at LNF (Italy) and installed by end of December 2021.
- The system provides spatial (~cm) and timing (~ns) coordinates of the track crossing point.

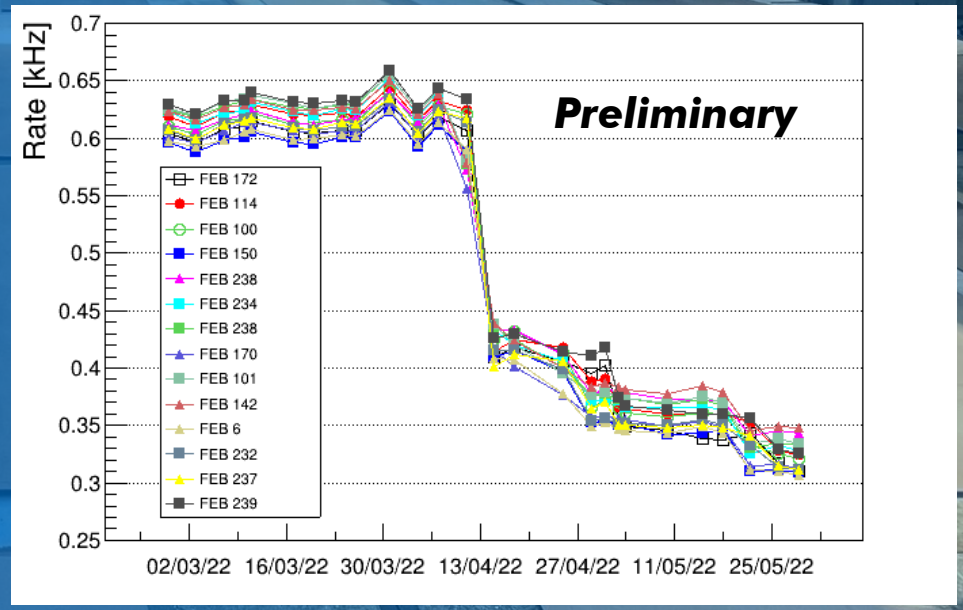



*Excess CRT activity during the beam gate for the south wall*



# Overburden

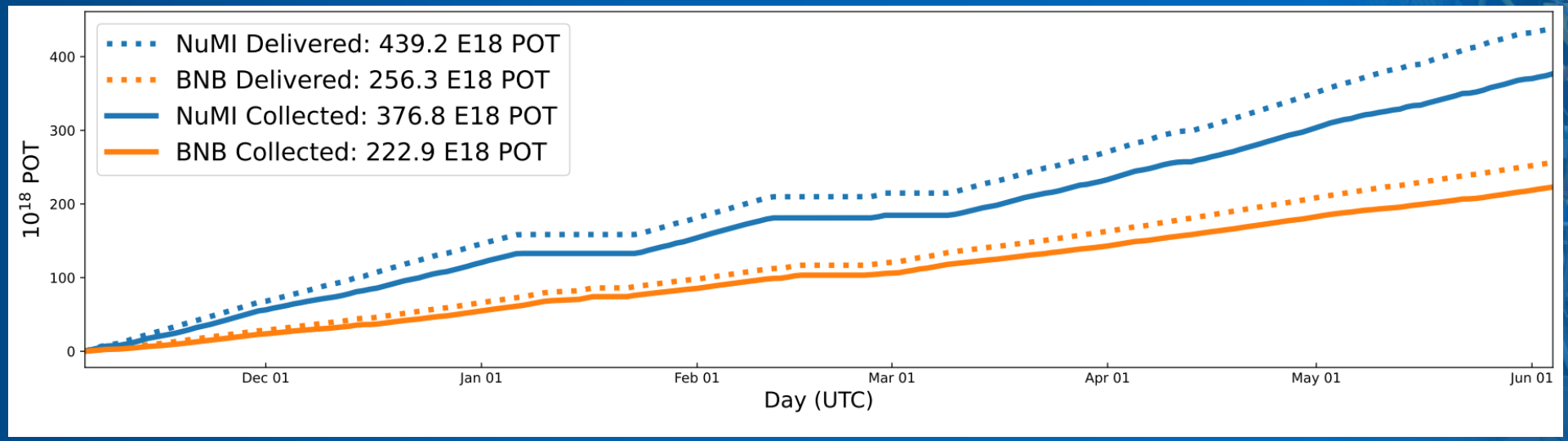
- The overburden is composed of three layer of concrete blocks of 1m height each. The total mass of the three layer is 5 million pounds.
- The installation of the last concrete block was completed June 7.
- The reduction of the cosmic rate is sensible: horizontal Top CRT modules rate decreased from 600 Hz to 330 Hz, in agreement with the expected cosmic rate after the removal of the soft energy component.



# Commissioning

- The detector is in nominal operating conditions since August 28th 2020, 24/7 shifts since February 14th 2020 (remote only since March 17th 2020).
- Steady data taking with neutrino beams since March 2021, in parallel with commissioning activities. First BNB neutrino full time (24/7) neutrino run May 31st - June 27th 2021.
- Top CRT was fully integrated in the data taking since February 2022.
- The commissioning phase of the detector was succesfully concluded by the end of May 2022.
- The physics data taking began June 7th, after the completion of the concrete Overburden.

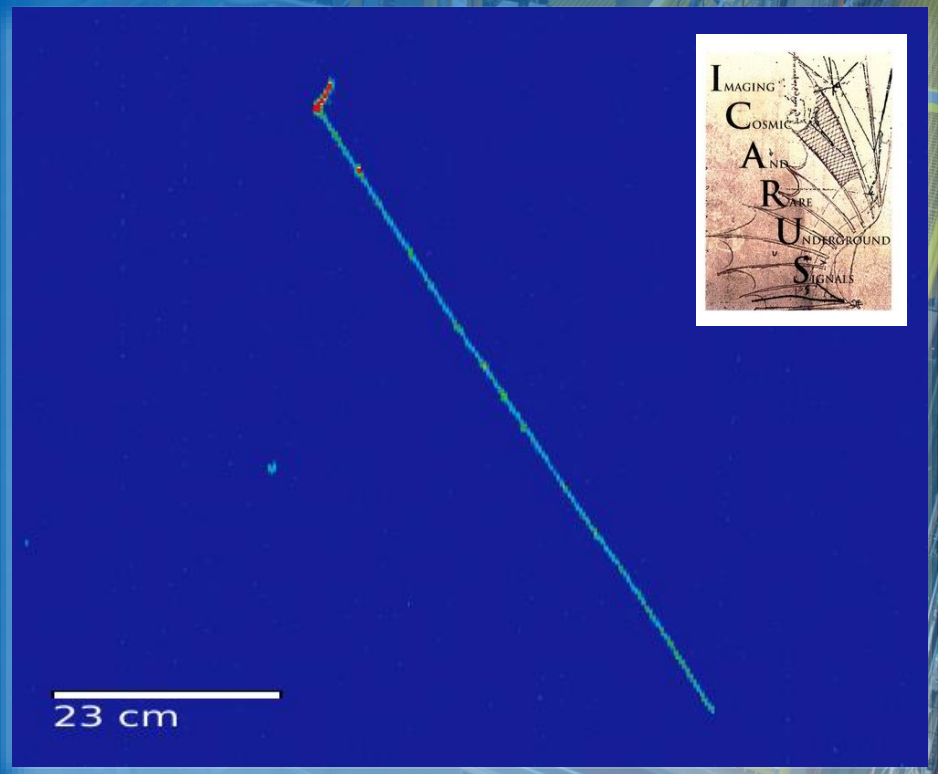
*ICARUS POT collection on BNB and NuMI during the Commissioning phase*



# ICARUS@FNAL First Neutrinos

ICARUS has been collecting beam data since 2021.
A visual event scanning campaign has been performed to create a neutrino candidates dataset.


$\nu_\mu$CC with hadronic activity from BNB



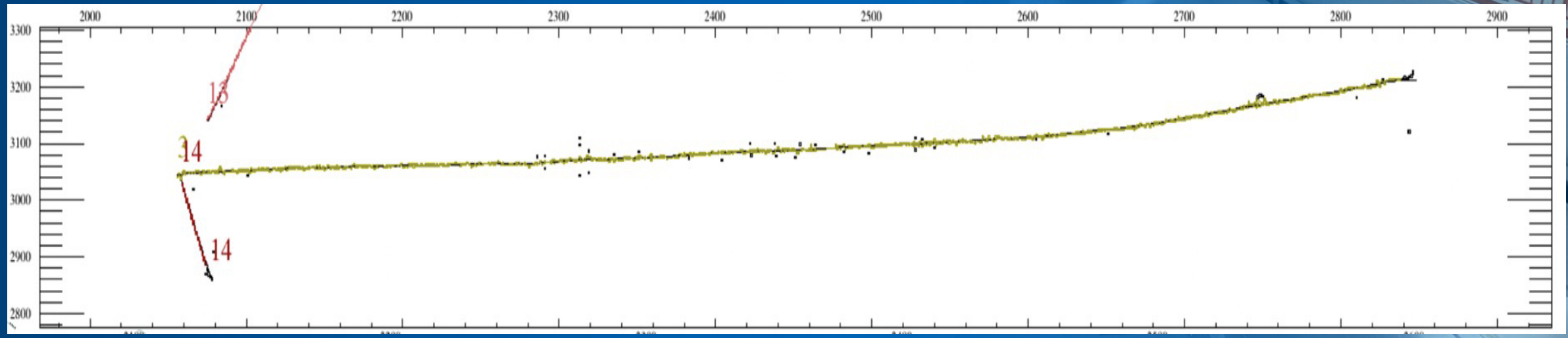

QE like $\nu_\mu$CC from BNB

# TPC event reconstruction

The default reconstruction uses Pandora (github.com/PandoraPFA), a pattern recognition software integrated in LArSoft:

- clusters the signals from the wire planes into reconstructed particles in 3D;
- reconstructs vertex;
- forms reconstructed particles hierarchy;
- provides a classifications of the particles as track-like or shower-like.

*Sample data event selected by visual scanning with reconstruction overlaid*



# Conclusions

- ICARUS completed its commissioning phase by the end of May 2022.
- The Overburden installation was completed by June 7 2022.
- ICARUS Run 1 started and it will cover a 40-days period until the beam summer shutdown (July 10 2022). The detector will contineously take data both on the BNB and NuMI beams.

May 05 2021: «ICARUS gets ready to fly»

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ICARUS gets ready to fly

May 20, 2021 | Brianna Barbu

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*The ICARUS detector, part of Fermilab's Short-Baseline Neutrino Program, will officially start its hunt for elusive sterile neutrinos this fall. The international collaboration led by Nobel laureate Carlo Rubbia successfully brought the detector online and is now collecting test data and making final improvements.*

When teams began cooling the ICARUS neutrino detector and filling it with 760 tons of liquid argon in early 2020, few people knew how much the world would change in the two months that the fill would take.

"In an ideal world, as soon as the filling is complete and the cryogenic plant is stabilized, then we can activate the detector and start looking for particle tracks basically immediately," said Angela Fava, the ICARUS commissioning coordinator and deputy technical coordinator.

# Conclusions

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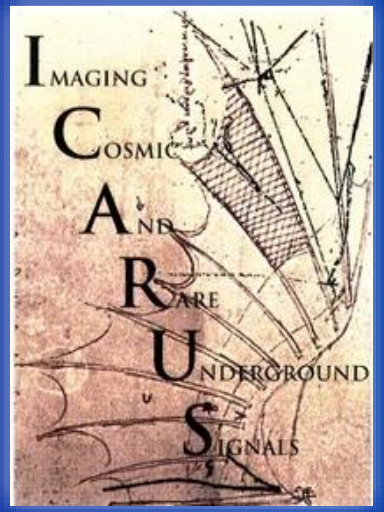
May 05 2021: «ICARUS gets ready to fly»


June 2022:
ICARUS starts Physics Data taking



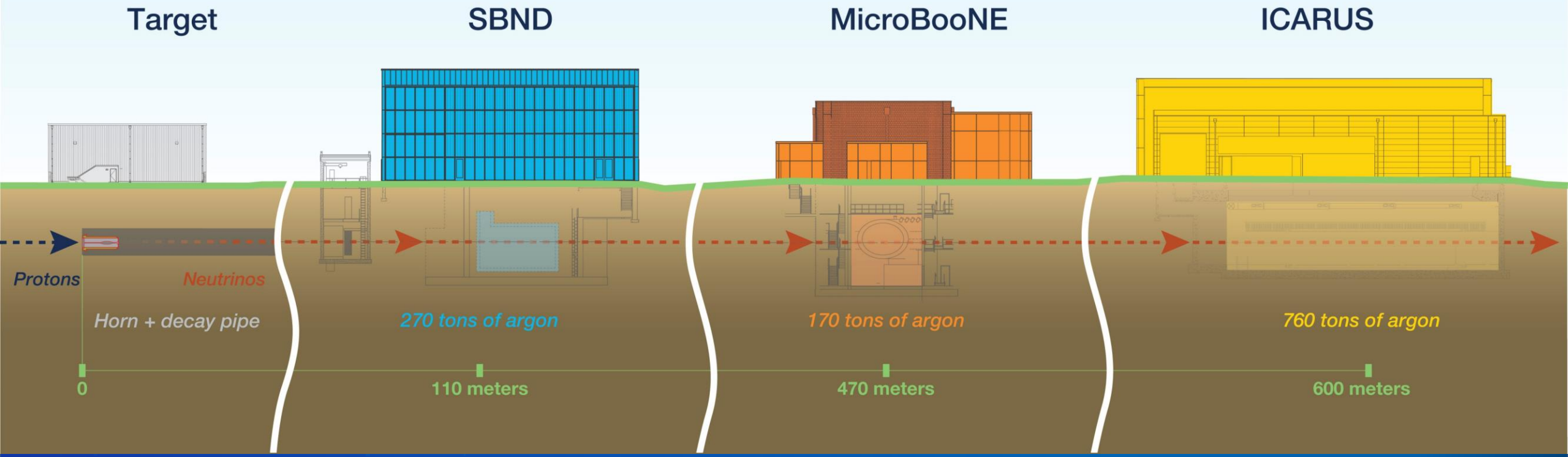


# Thank you!

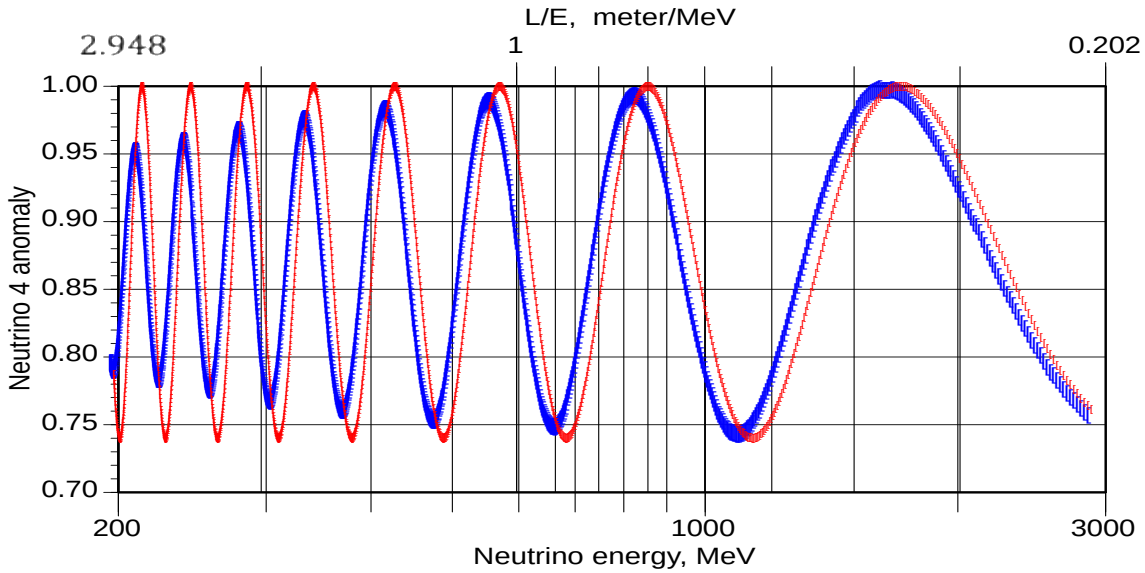
## Stay tuned… more to come!

# Backup

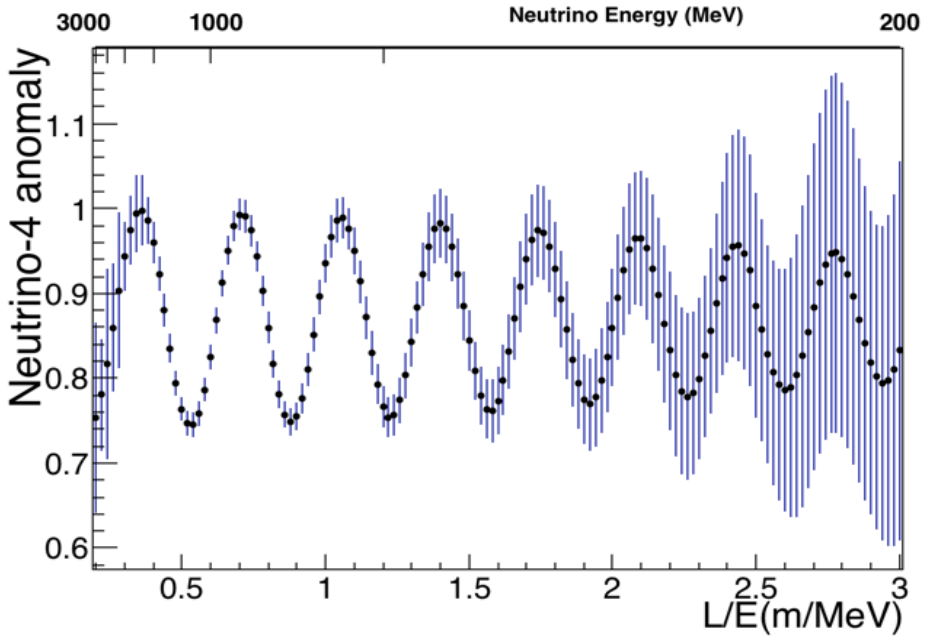
# Short-Baseline Neutrino Program at Fermilab



# Neutrino 4 - anomaly

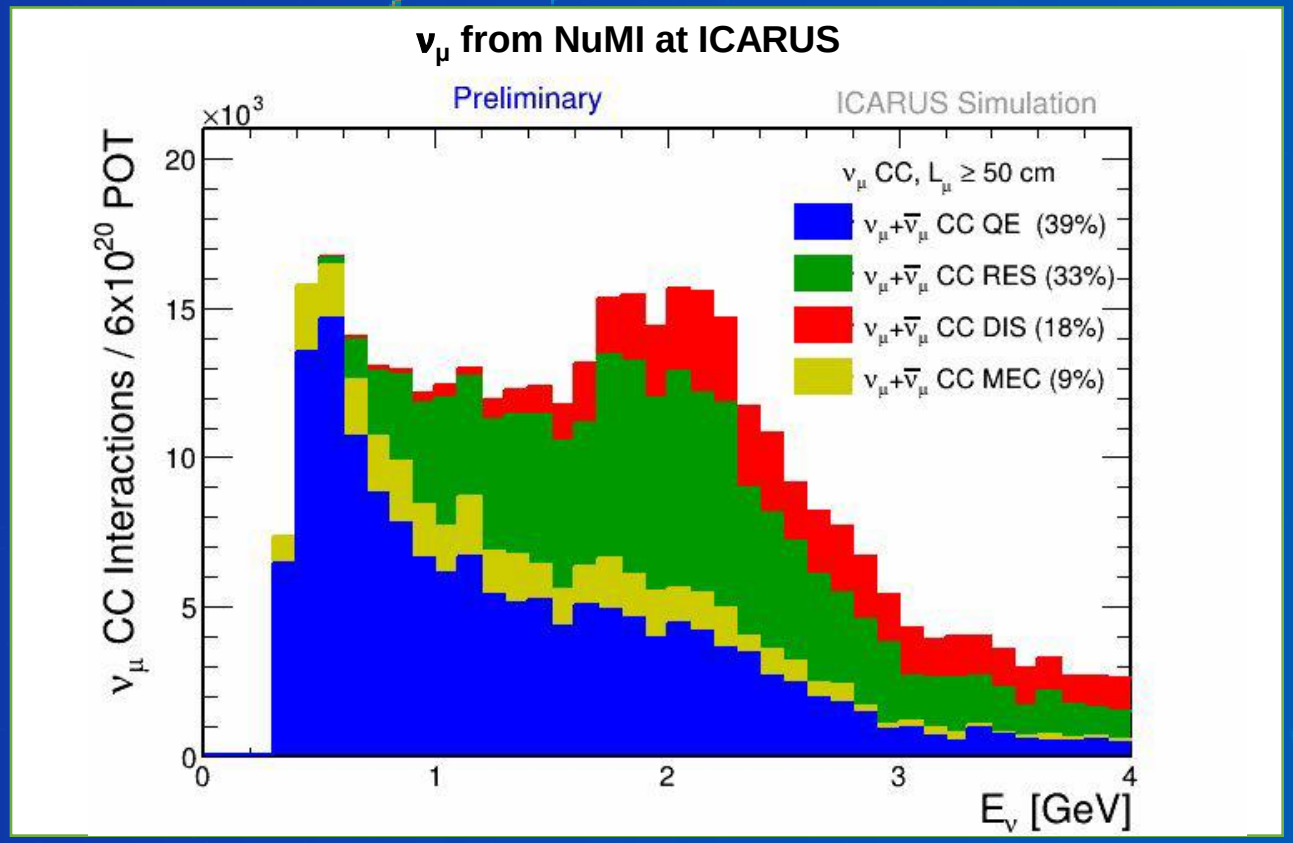


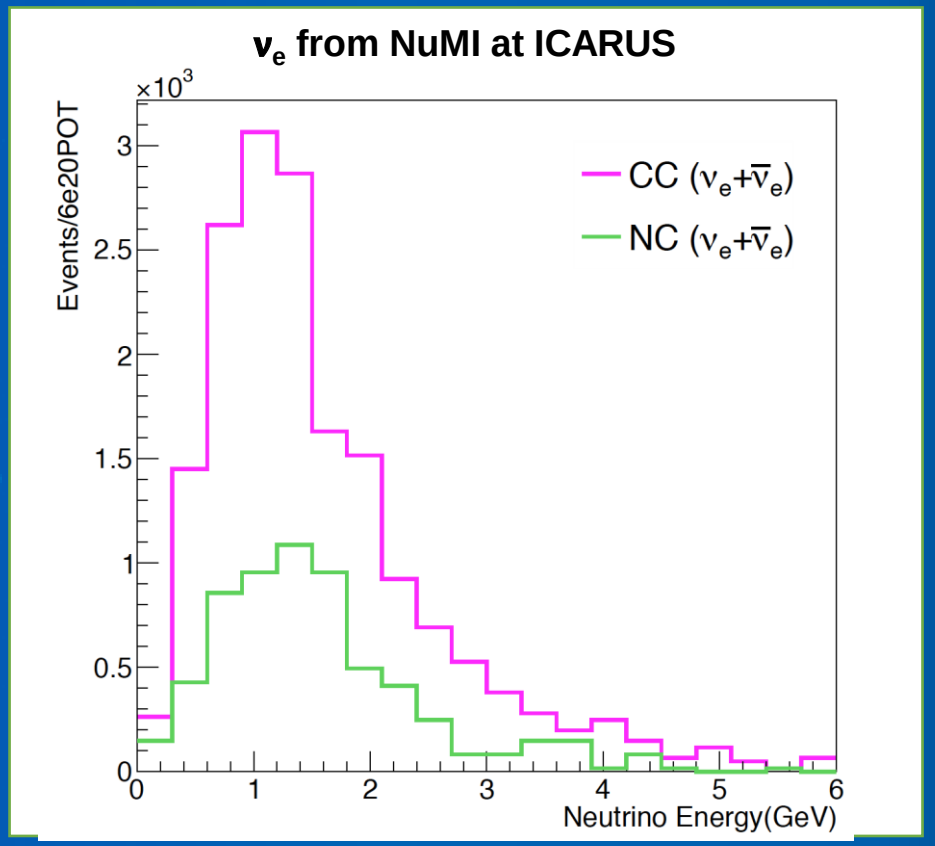

**Expected Neutrino-4 disappearance signal for L averaged position (blue) and at center (red)**




**Survival oscillation probability in 3 years for Neutrino-4 best fit (only stats)**

# Physics searches with NuMI



# ICARUS new life

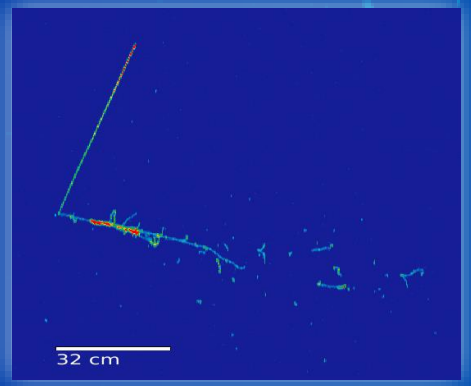
ICARUS undergoes refurbishment at CERN

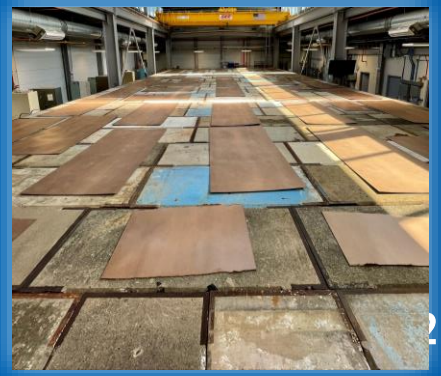
ICARUS moves to its new home at Fermilab

ICARUS starts taking data: first neutrinos at FNAL

The overburden is completed:
ICARUS starts Run 1

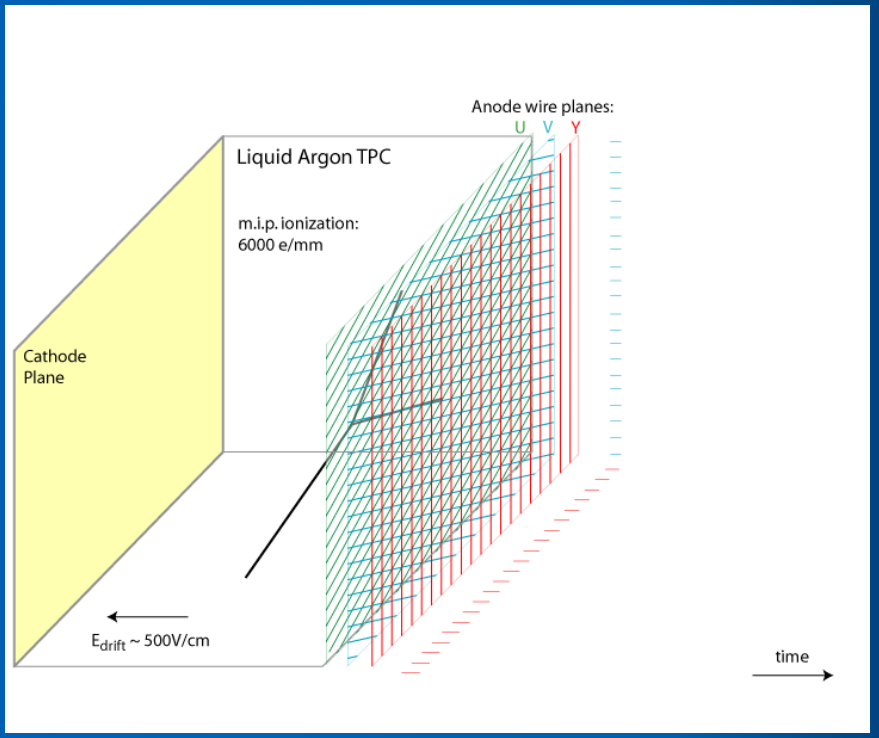
2015 2017 2020 2021 June 2022

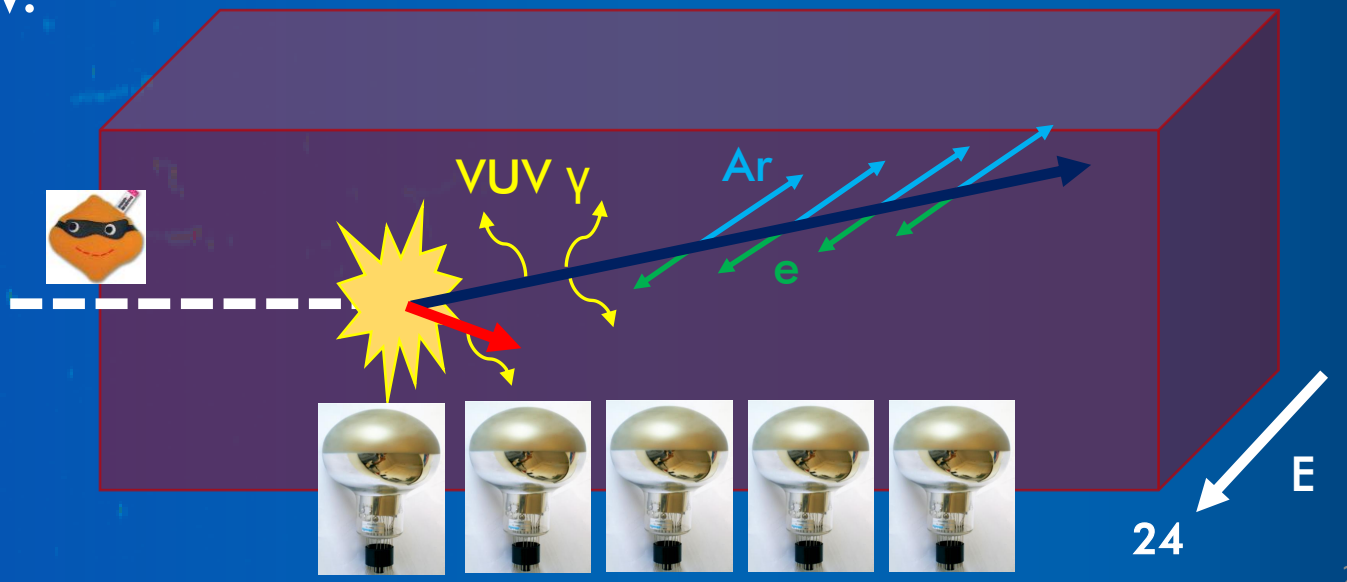



# LArTPCs

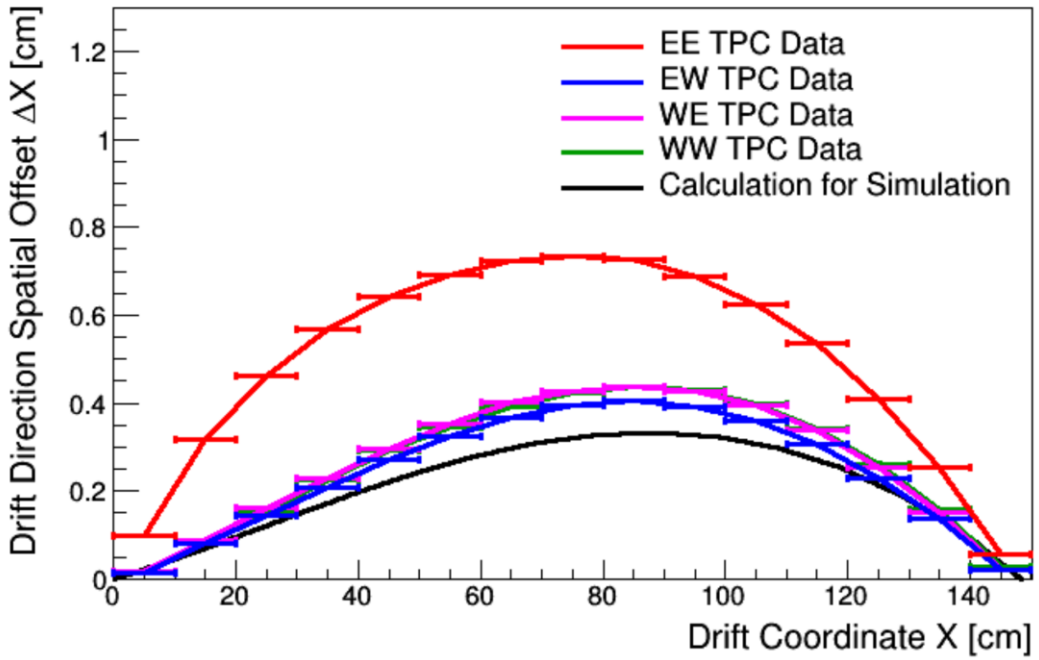
- ICARUS pioneered the LArTPC technology. The detector is a massive and homogeneous target with excellent tracking and calorimetric capabilities.
- Scintillation light:
  128 nm wavelength, 40k ph/MeV.
- Ionization electrons:
  42k e/MeV, drifted by E towards the anode plane in 0.96 ms.



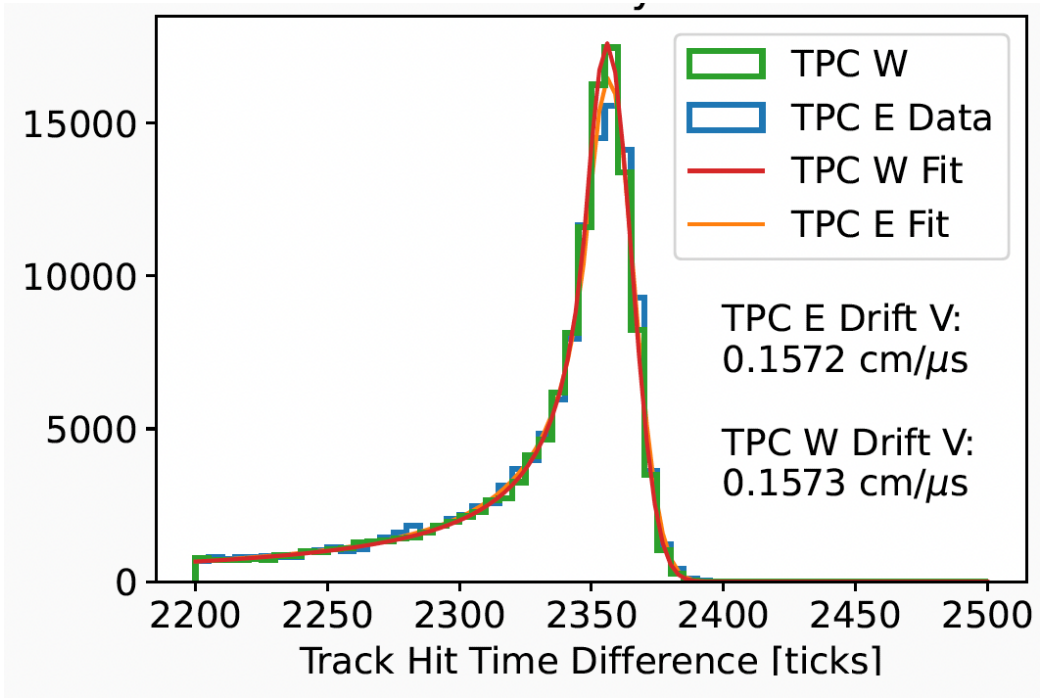



# TPC performance

**Spatial distortions in drift direction due to space charge**



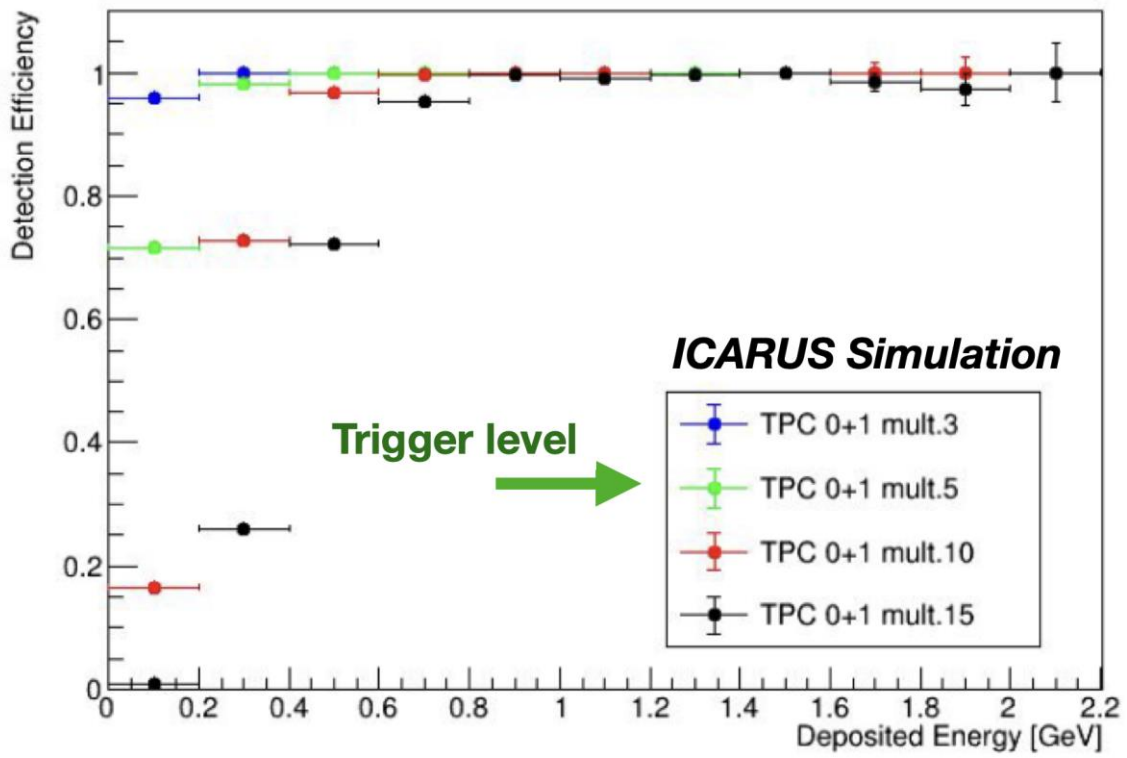

**Drift velocity in West cryostat**



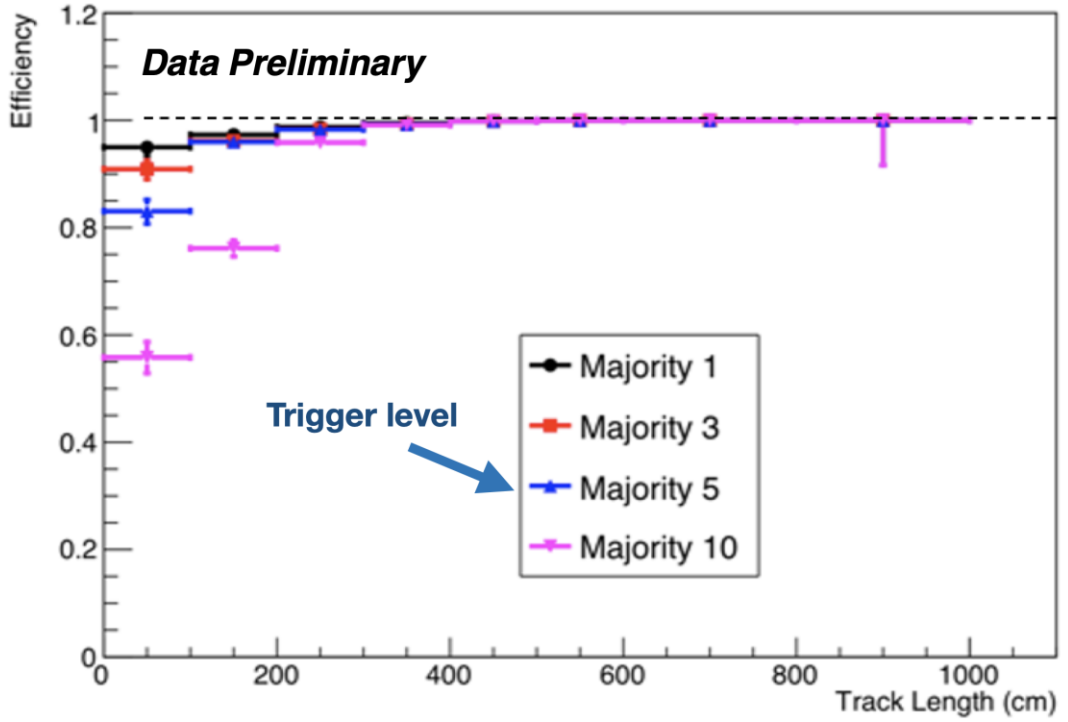

- Space charge effects (SCE) measured using anode-cathode-crossing cosmic muon tracks, looking at spatial distortions in drift direction. Good agreement with simulation, apart from one TPC where E field distortions associated with a possible field cage short are being investigated.

# Trigger efficiency studies

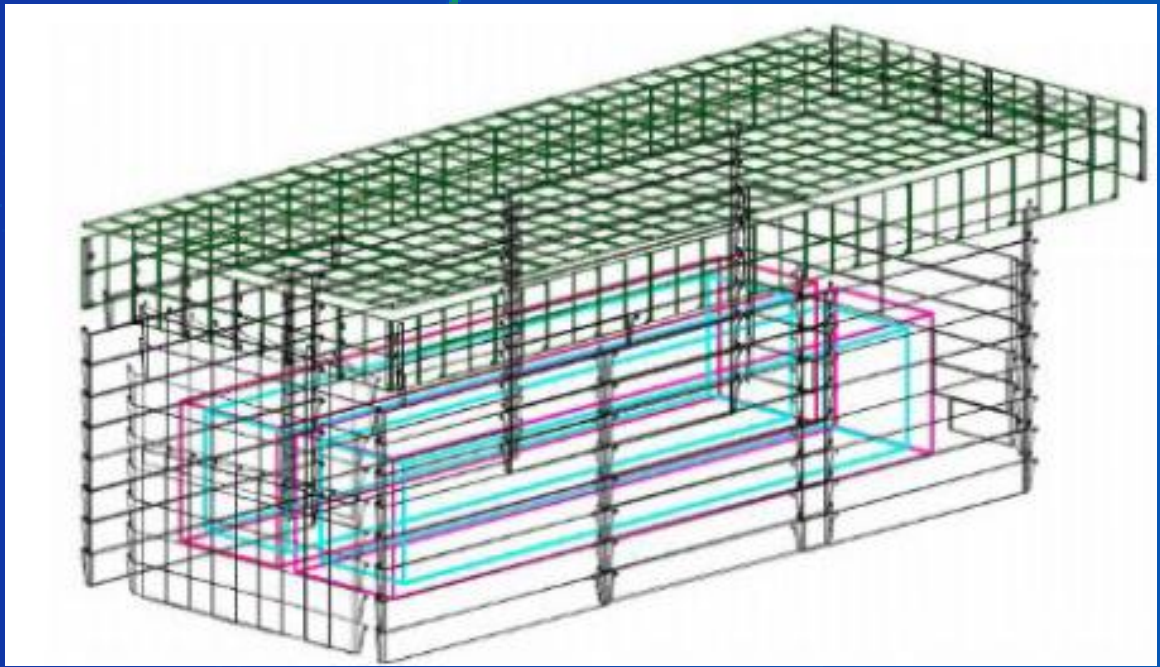
**Trigger efficiency on $\nu_\mu$CC from MonteCarlo**




**Trigger efficiency measured on crossing cosmic μ**



# CRT - Backup



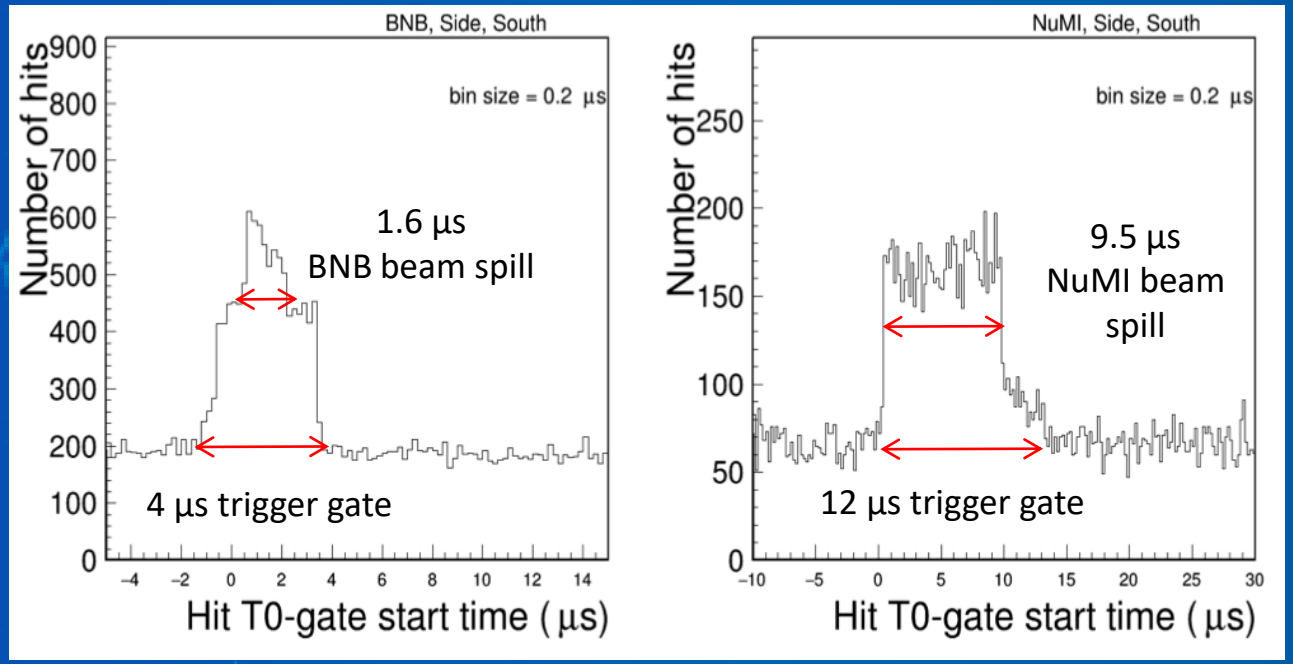
Bottom CRT

- Modules repurposed from the Double Chooz experiment.
- Two layers of parallel scintillator strips.
- Modules are composed of 32 strips, each 5 cm wide.
- Readout by a 64-pixel multi-anode PMT.

# Cosmic Ray Tagger (CRT)

## Side CRT

- Side CRTs have been repurposed from the MINOS modules.
- 20 parallel scintillator strips per module readout by SiPMs.
- Double layer X-X configuration, with the exception of the (upstream) south wall (X-Y).

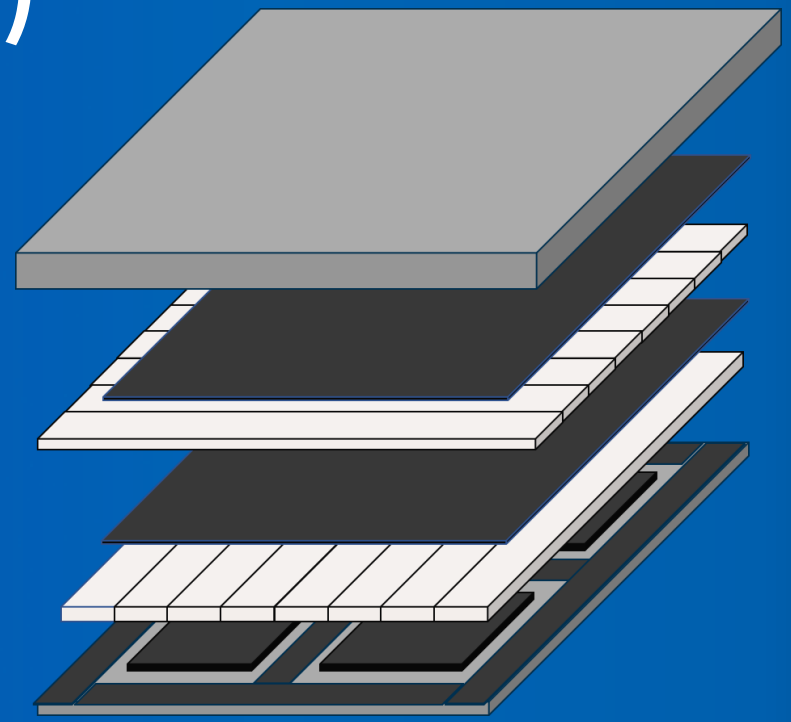


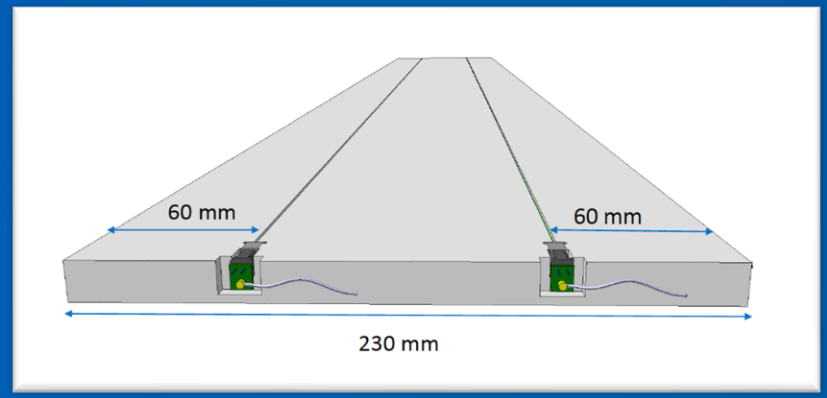

*Excess CRT activity during the beam gate for the south wall*

# Cosmic Ray Tagger (CRT)

## Top CRT

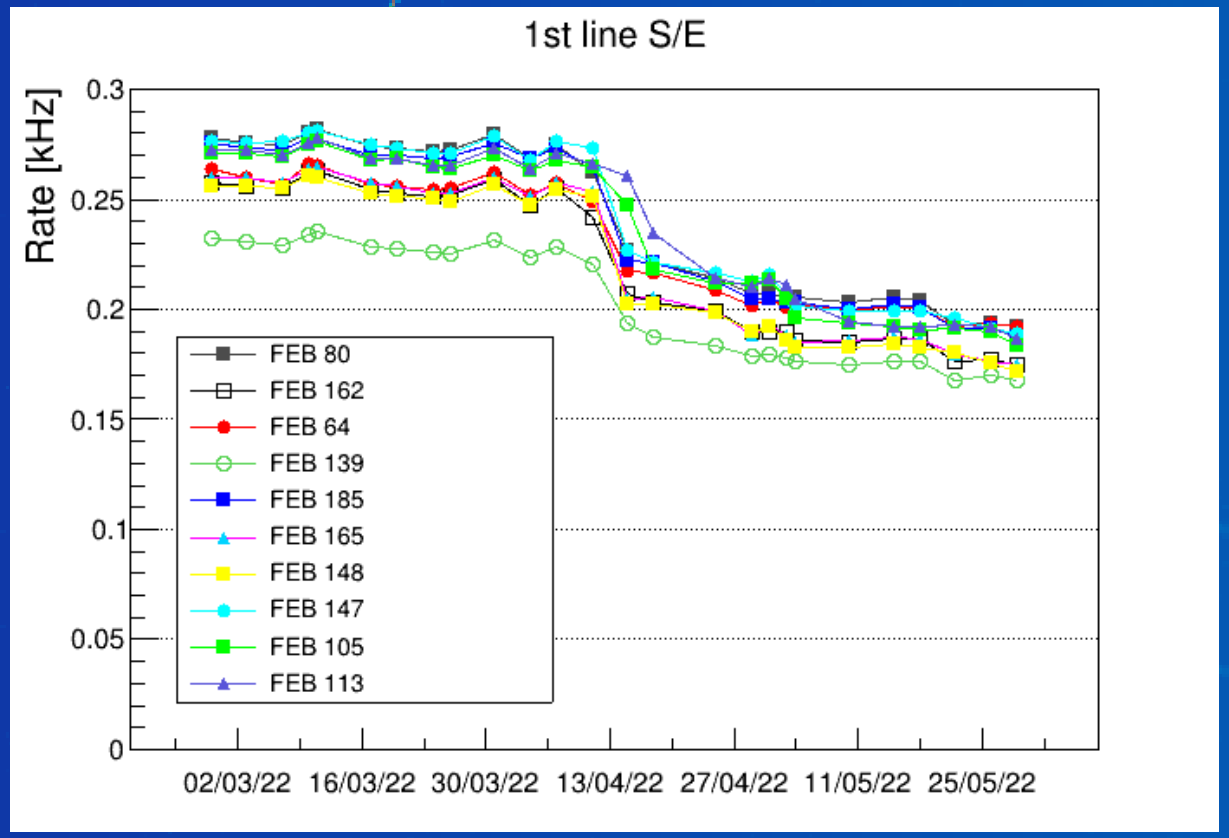
- The Top CRT is composed of 39 vertical modules and 84 horizontal modules covering ICARUS surface and tagging alone 80% of the incoming cosmic muons.
- Each module is an hodoscope consisting of 2 orthogonal layers of eight 23 cm wide scintillator bars, readout on one end by one SiPM.
- The Top CRT modules were assembled and tested at the Frascati National Laboratories. The modules were shipped to FNAL during the pandemic and they were fully installed by December 2021.



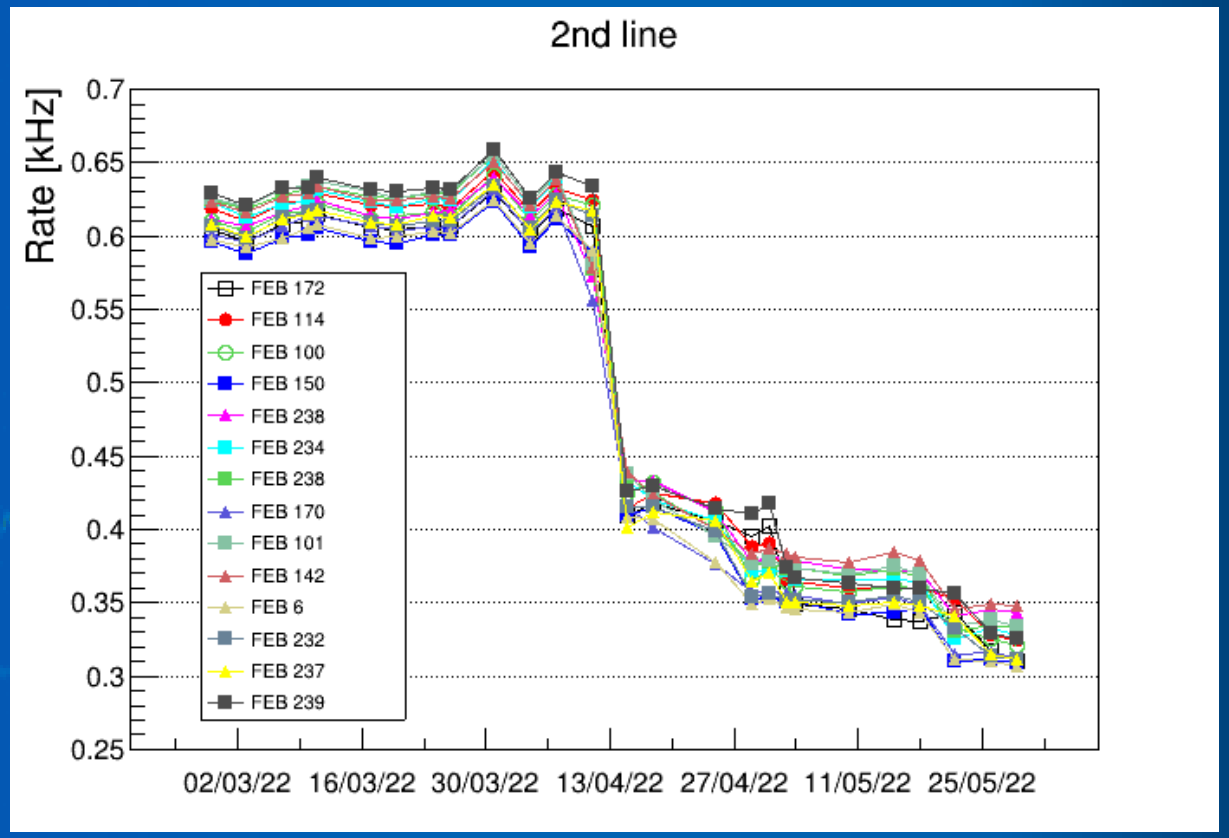


# Top CRT rates vs time

*Vertical Top CRT rates*




*Horizontal Top CRT rates*



# Track reconstruction: MC/Data comparison