The Cosmic Ray Tagger system of the ICARUS detector at Fermilab

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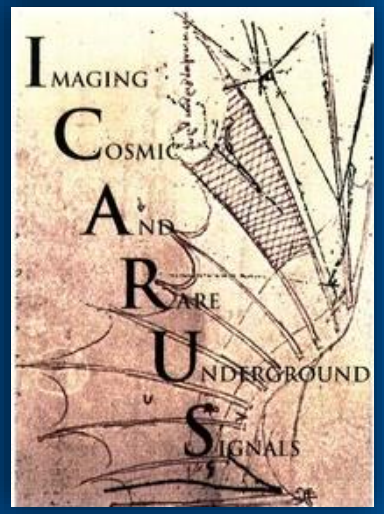
On behalf of the ICARUS Collaboration



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ICARUS at FNAL

ICARUS-T600 is a self-triggering LArTPC composed of two identical modules (T300). ICARUS is the Far Detector of the Short-Baseline Neutrino Program (SBN) at Fermilab and it is operating at surface level.

See L. Pasqualini talk
"Short–Baseline neutrino oscillation searches with the ICARUS detector"

Cosmic background

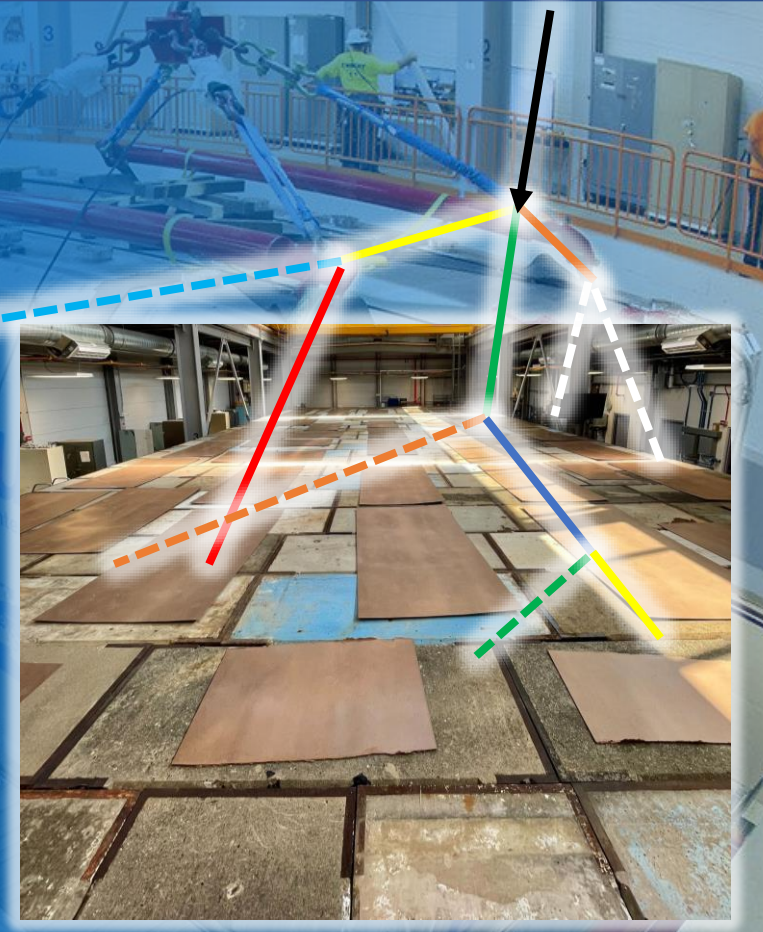
ICARUS is on the surface and thus exposed to a huge cosmic activity.
Cosmic activity can be divided in:

- 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:

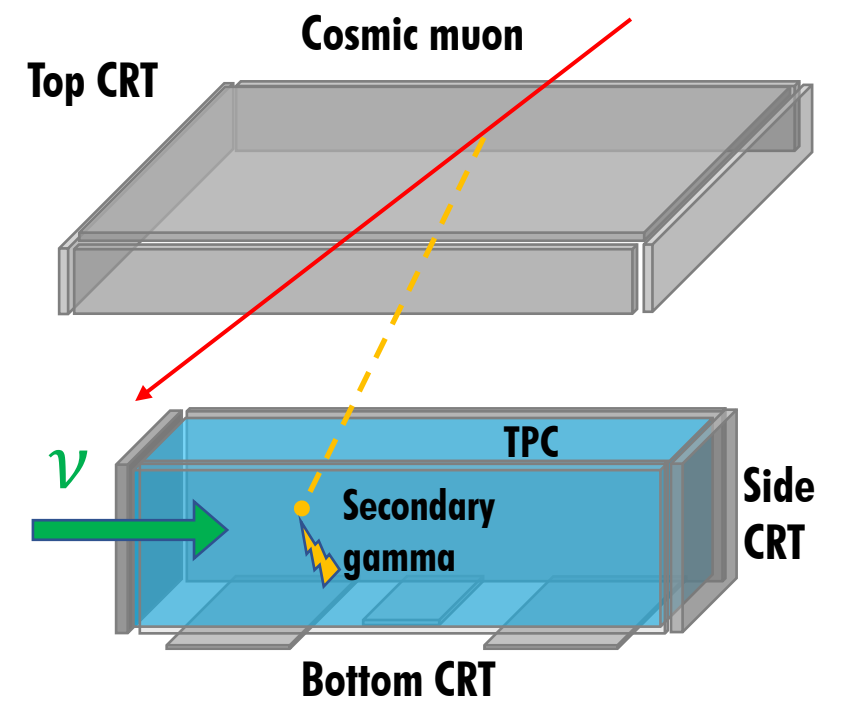
- 3 m concrete overburden (6m water equivalent);
- A 4π coverage of the detector with Cosmic Ray Tagging modules (CRT):
  Bottom CRT, Side CRT and Top CRT.



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	$\ll 0.001$
γ	< 0.01	0
n	< 0.45	$\ll 0.01$

Cosmic Ray Tagging system

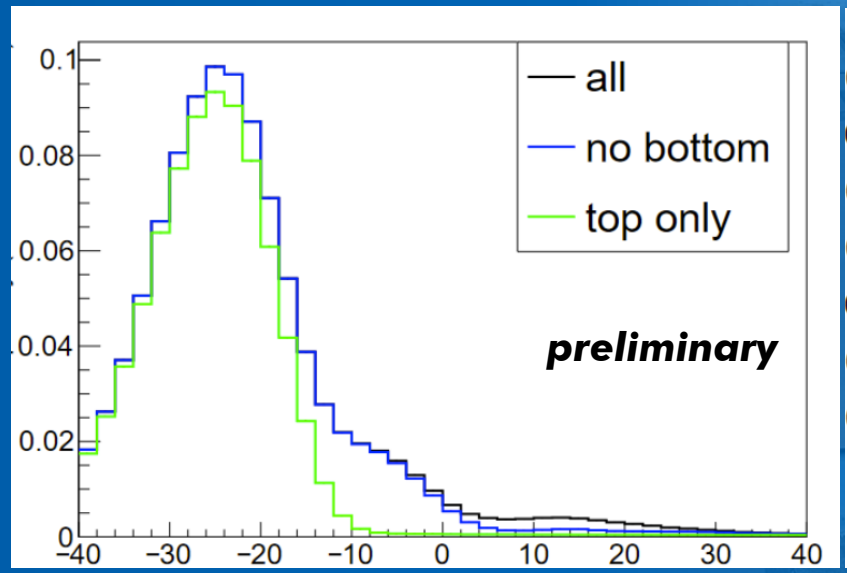


Rapresentation of the full CRT System

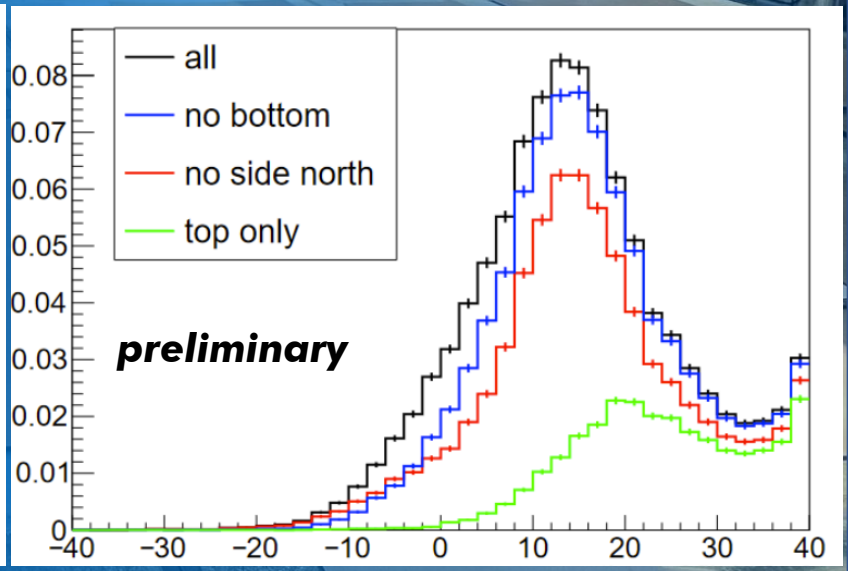
- ICARUS will have to identify O(10^6) neutrino interactions in 211 s of beam time amongst 11 kHz cosmic ray events.
- The external CRT system will provides spatial (~cm) and timing (~ns) coordinates of the track crossing point.
- The CRT system will intercept 95% of cosmic or beam-induced muons.

- CRT Hit – PMT flash matching will determine if the muon was exiting or entering the TPC.

Cosmogenic muons



BNB induced muons

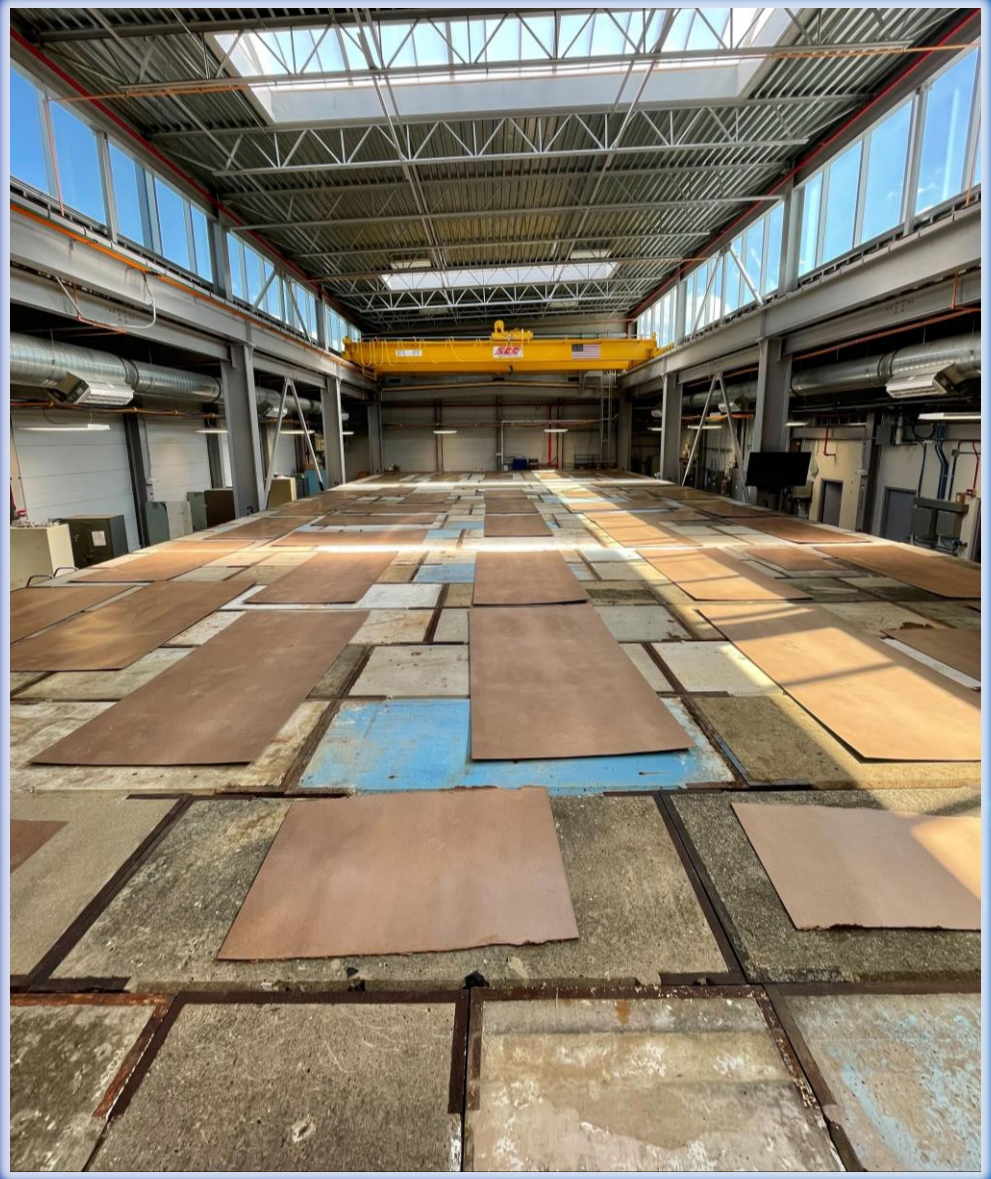


The Overburden/1

Deployment of the first OB block

- The overburden is composed of three layer of concrete blocks of 1m height each. The total mass of the three layer is 2.3 million tons.
- The installation of the last concrete block was completed June 7.

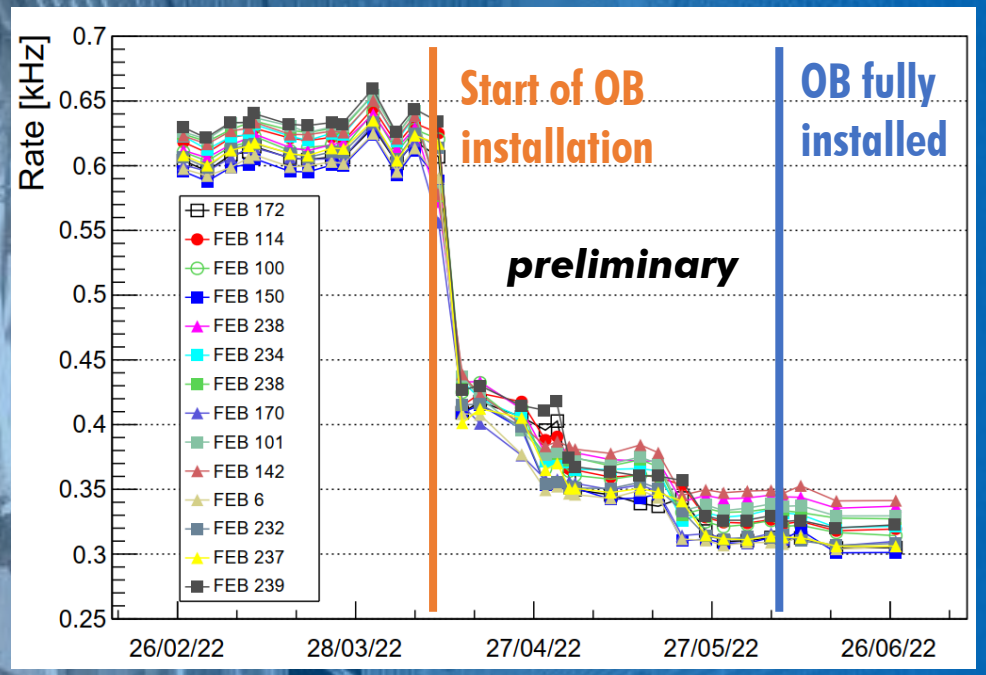
The Overburden/2

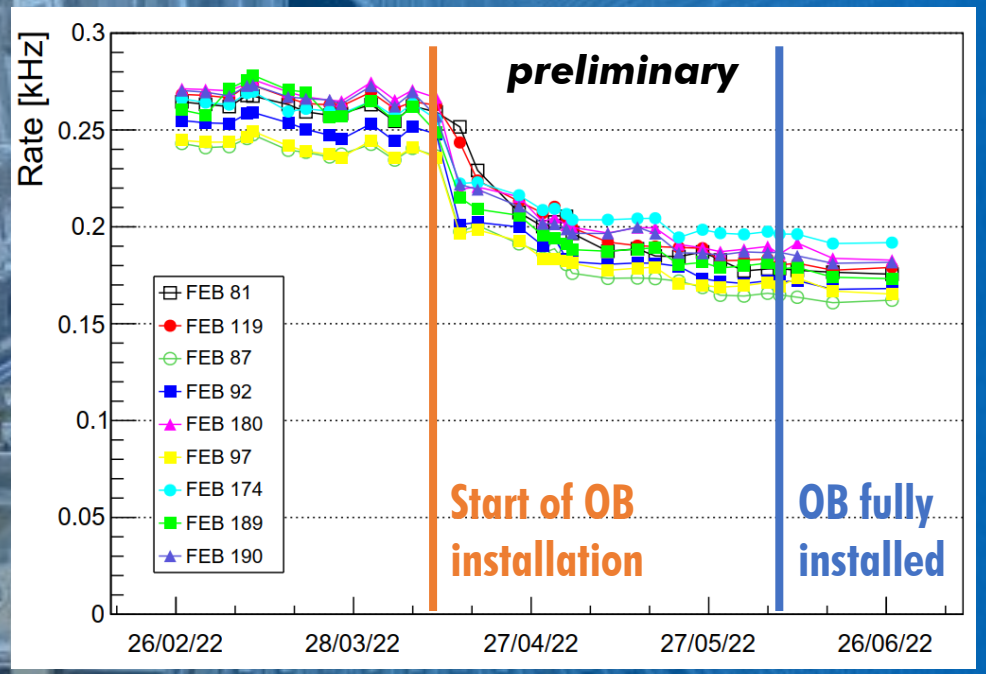


Picture of the OB after completion

Side view of the OB and installation of the last concrete block

The Overburden/3

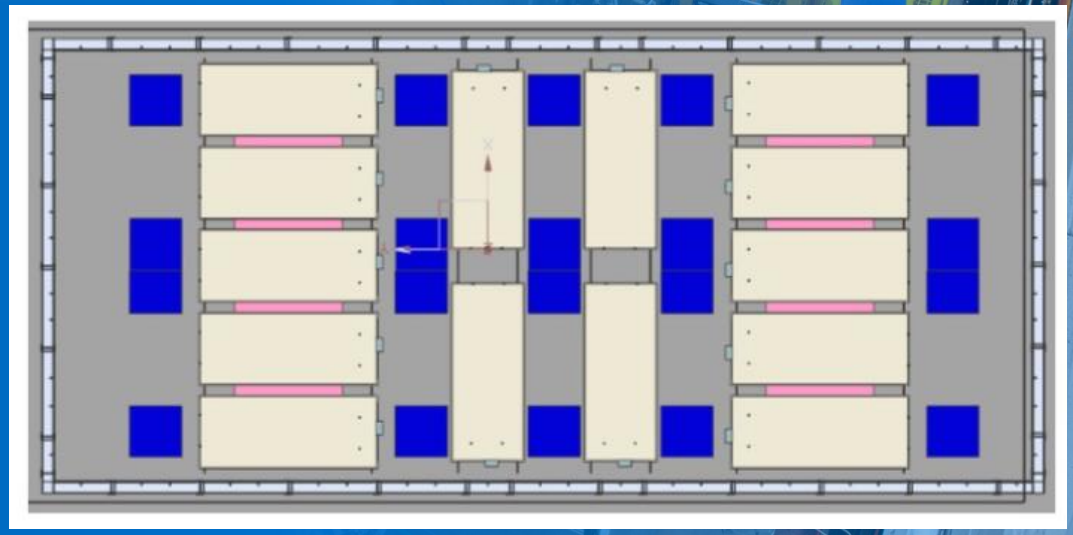




- The overburden is composed of three layer of concrete blocks of 1m height each. The total mass of the three layer is 2.3 million tons.
- The installation of the last concrete block was completed June 7.
- The observed reduction of the cosmic rate is from 600 (250) Hz to 330 (180) Hz for horizontal (vertical) Top CRT modules, in agreement with the expected cosmic rate after the removal of the soft energy component.

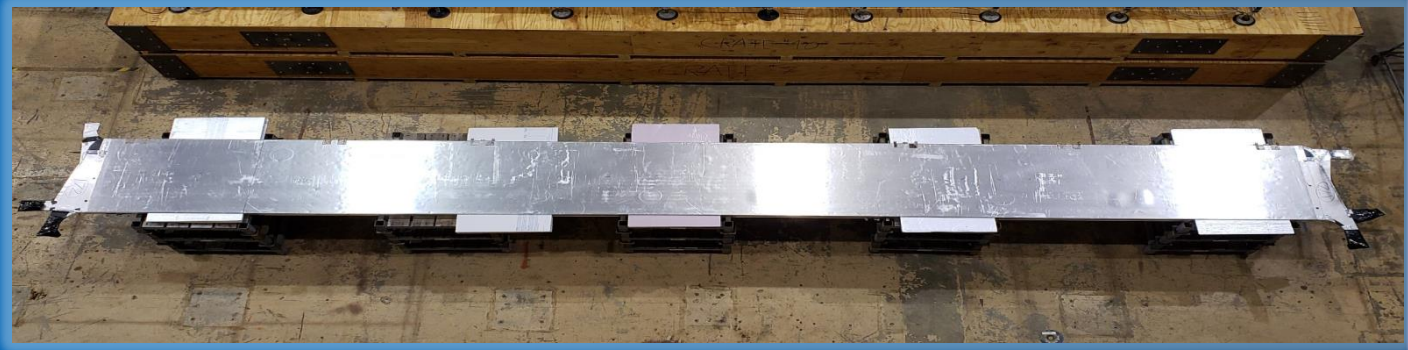
Bottom CRT

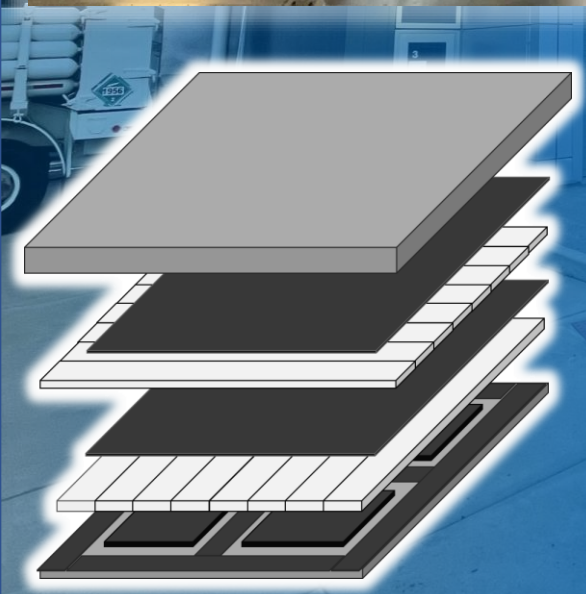
- Modules repurposed from the Double Chooz experiment.
- Two layers of parallel scintillator strips.
- Modules are composed of 32 strips, each 5 cm wide.
- Readout by a 64-pixel multi-anode PMT.
- 14 modules were installed in summer 2017 underneath the warm vessel.

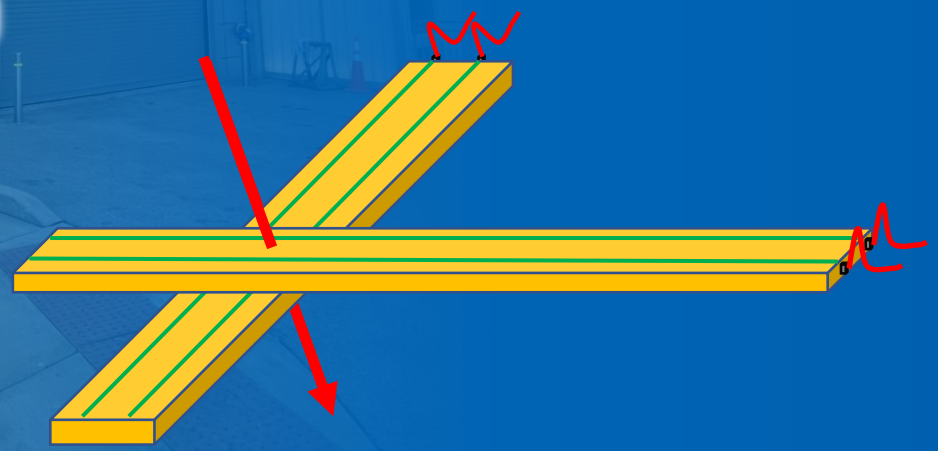


Side CRT

- Side CRTs have been repurposed from the MINOS modules.
- 20 parallel scintillator strips per module readout by SiPMs.
- Double parallel layer configuration, with the exception of the upstream wall which exploits two perpendicular layers.





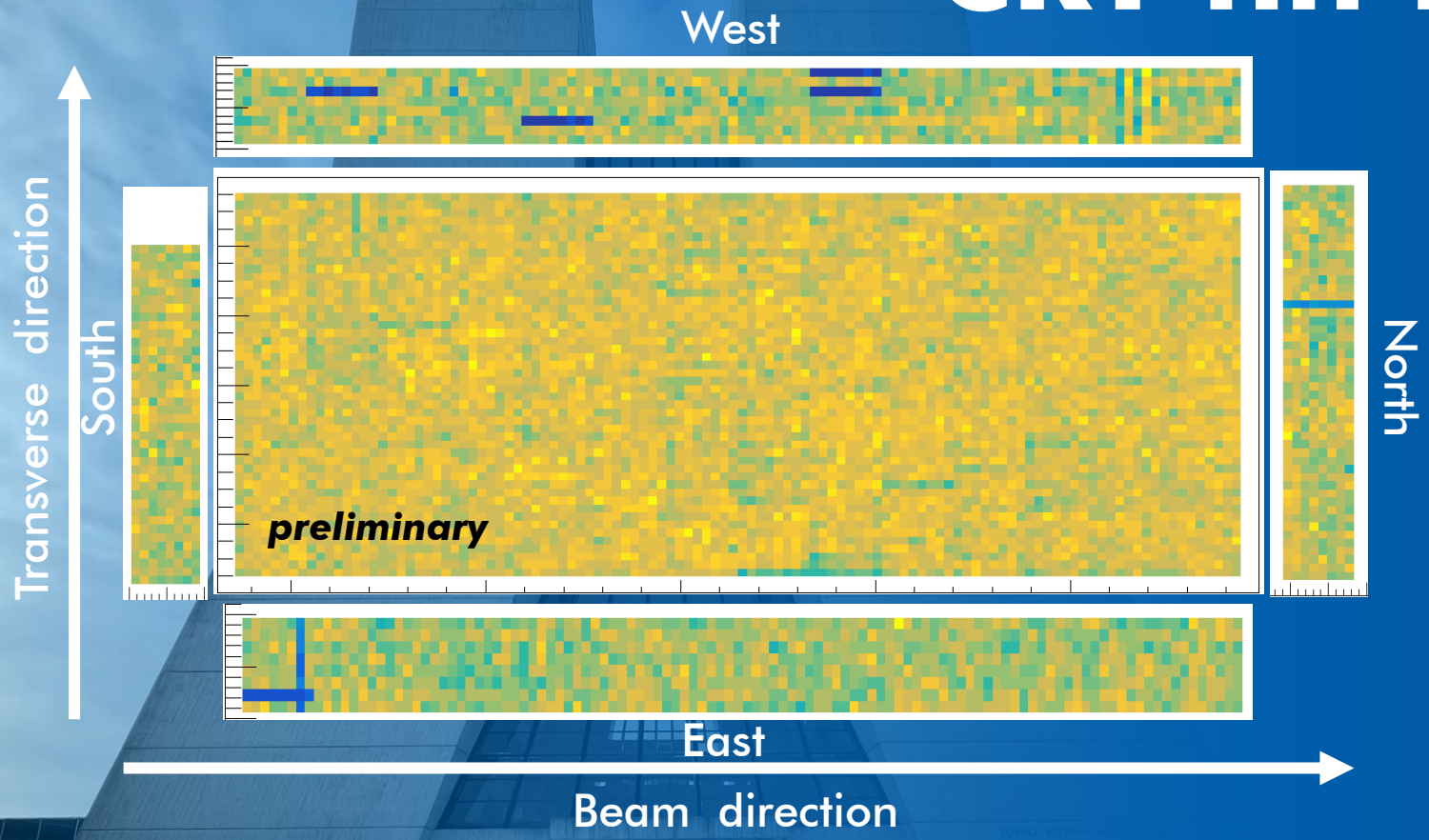


Top CRT

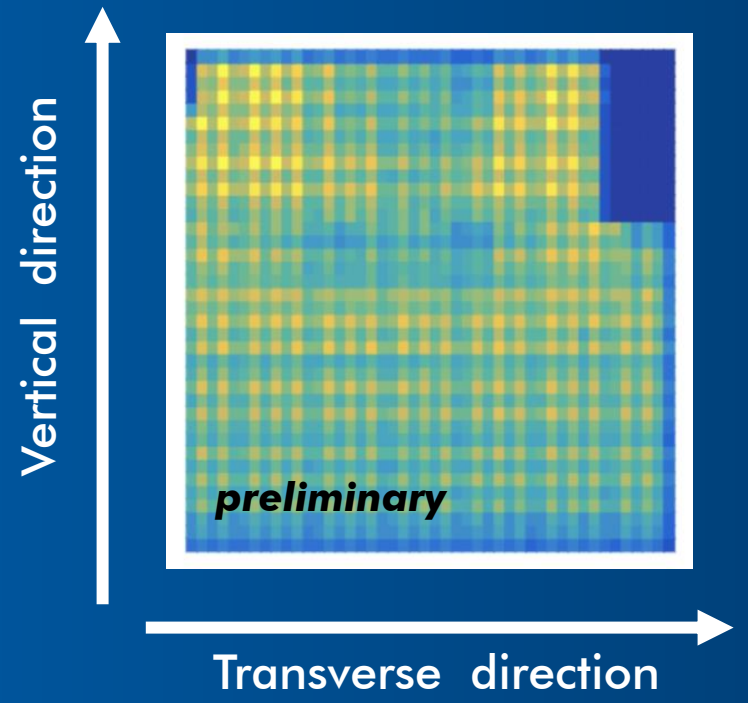
- The Top CRT is composed of 39 vertical modules and 84 horizontal modules covering ICARUS surface and tagging alone 80% of the incoming cosmic muons.
- Each module is an hodoscope consisting of 2 orthogonal layers of eight 23 cm wide scintillator bars, readout on one end by one SiPM.
- The Top CRT modules 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.

CRT hit reconstruction

CRT hit reconstruction for the whole Top CRT



CRT hit reconstruction for the south (upstream) Side CRT wall



- Side CRT hit reconstruction is performed by looking for coincidences between the outer and inner planes of CRT modules within a 150 ns window.
- Due to the different internal triggering logic, the Top CRT hit reconstruction is performed by selecting the triggering channels in each layer and mapping them in the detector coordinates.

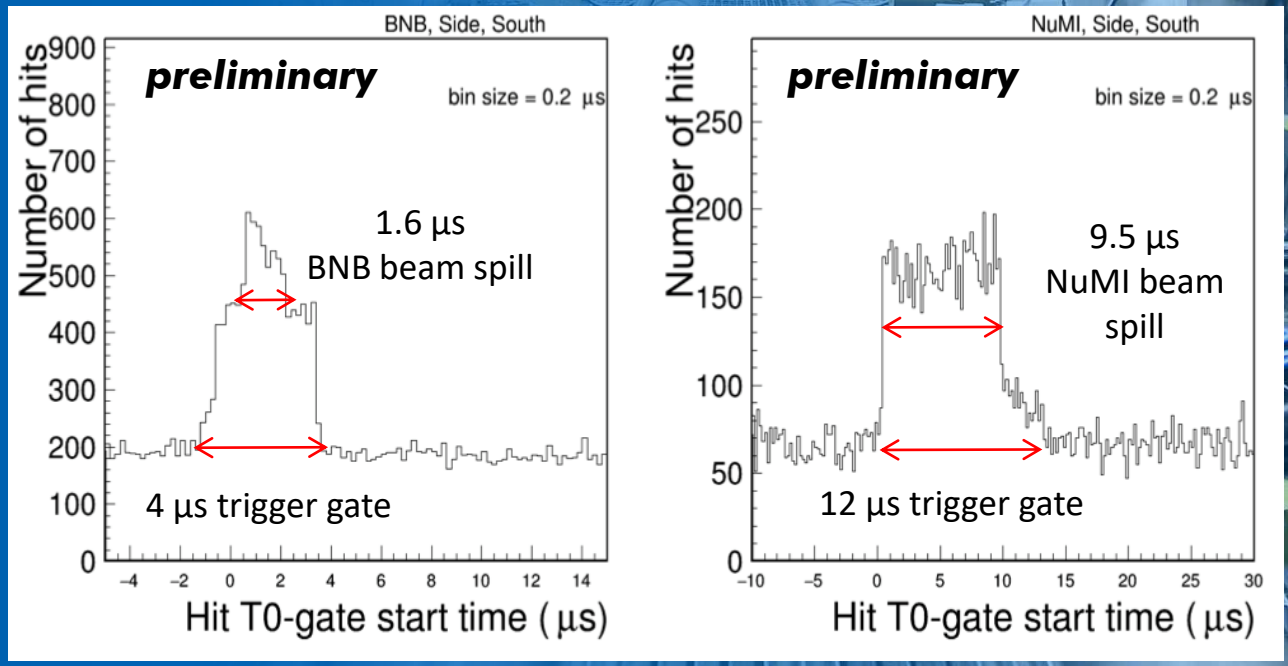
CRT timing signals

- The Front End Board is common to all the CRT modules and it is instrumented with two indipendent counters (T0 and T1) with 1 ns precision.

- The two counters can be reset by means of two logical signals:
  -> T0 is reset with a PPS signal provided by the White Rabbit (used to generate the Global Timing of the hit)
  -> T1 is reset with the Global Trigger provided by the trigger crate.

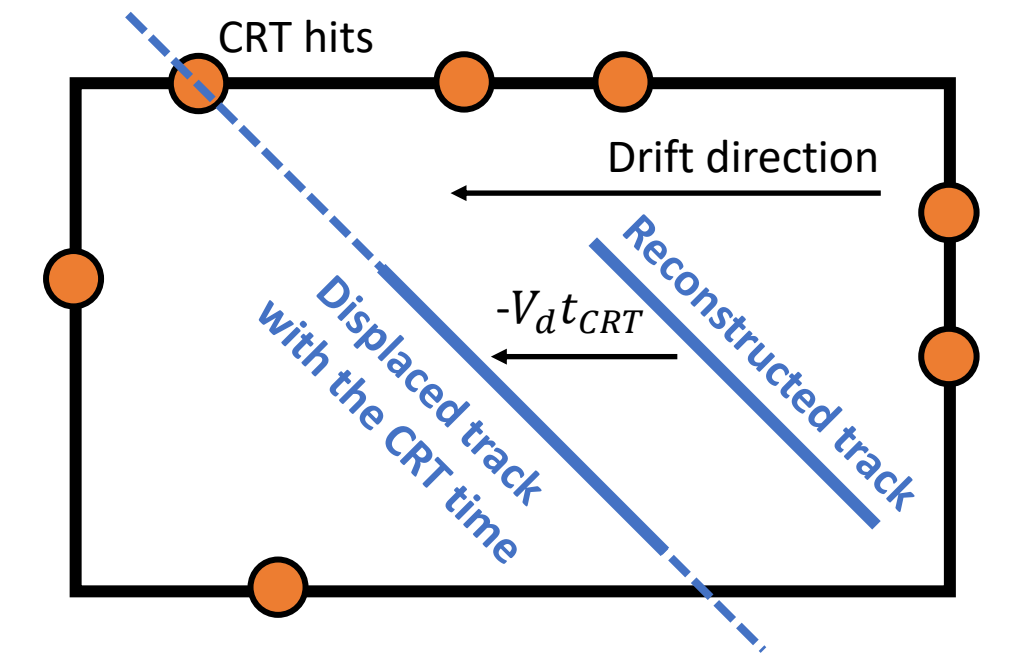
- The correct timing of the CRT system has been verified by observing the excess of CRT hits due to *rock muons* (from neutrinos interacting in the rock) in time with the beam spill gates.

Picture of the commercial FEB used by the CRT system

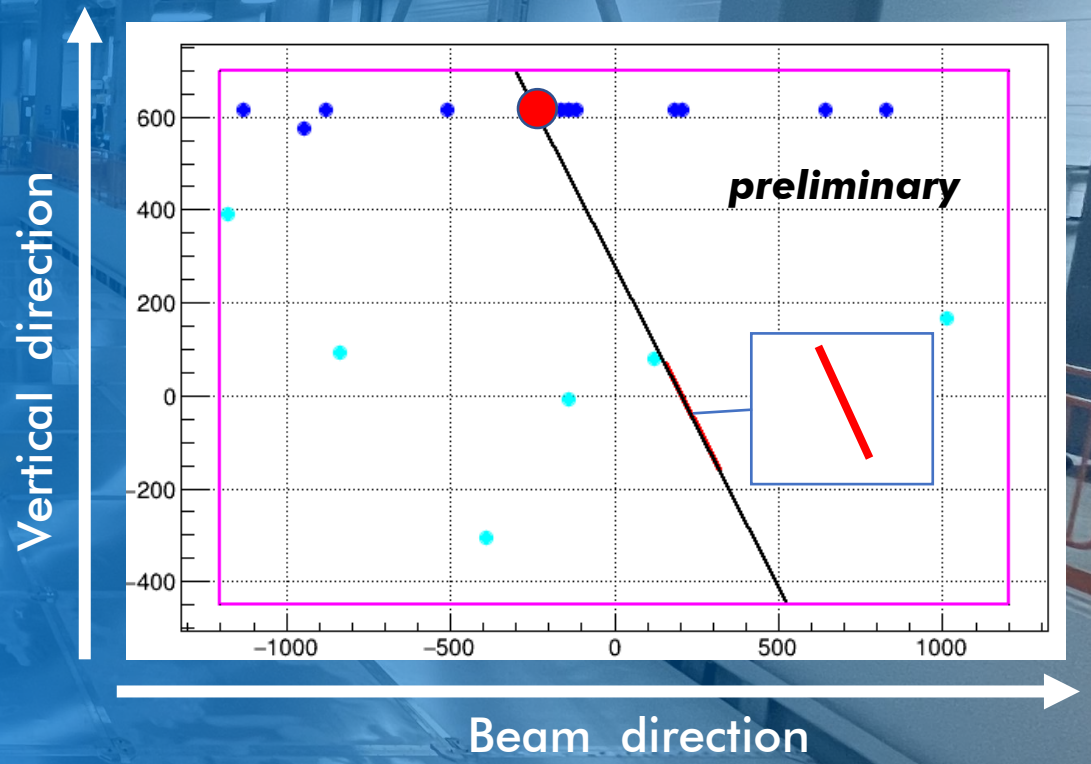


Excess CRT activity during the beam gate for the upstream wall

CRT to TPC matching



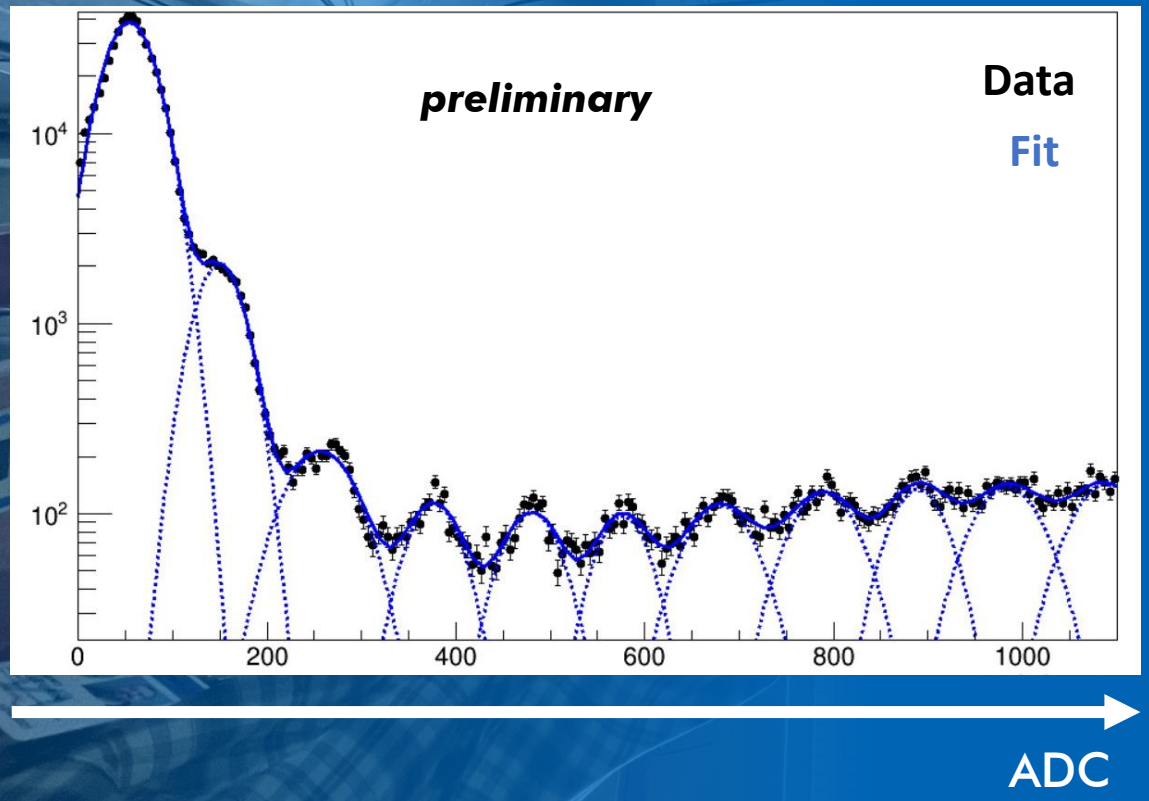
TPC track (red) matched with a Top CRT Hit (red dot)



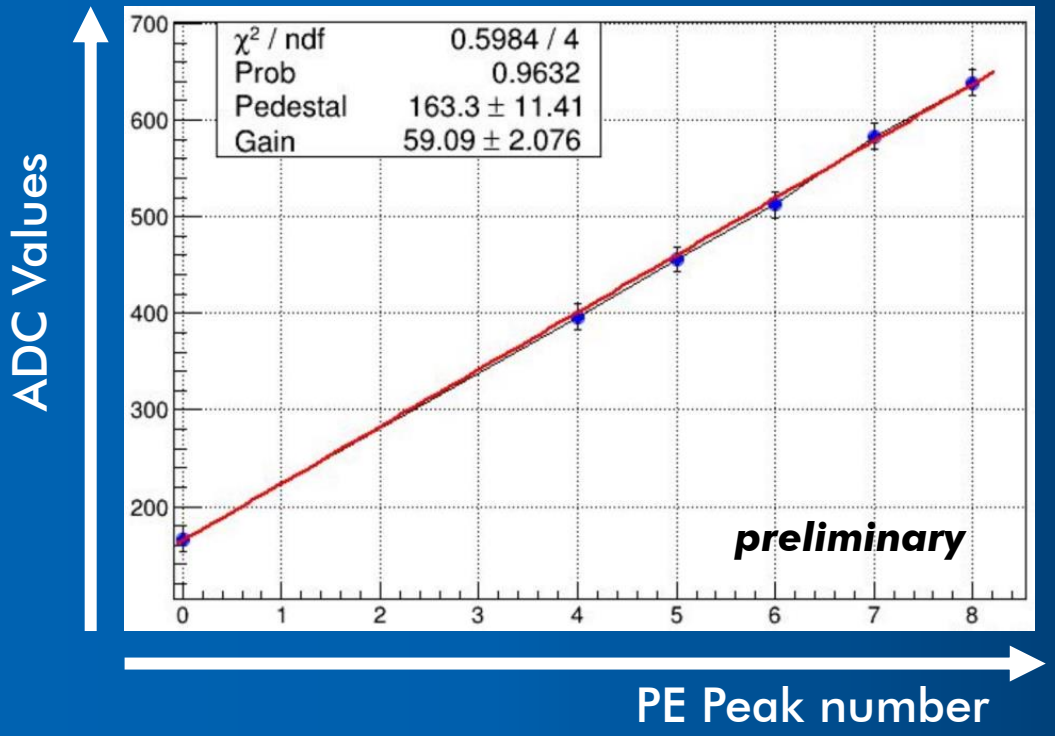
- Current CRT to TPC matching algorithm tries to match the closest CRT hit to the projection of the track on the CRT planes.
- In order for the track to be correctly matched, its position has to be corrected for its drift time. Currently the algorithm is being validated using cathode crossing tracks for which the time of the crossing particle is precisely known.

Calibration

ADC spectrum of one Top CRT channel



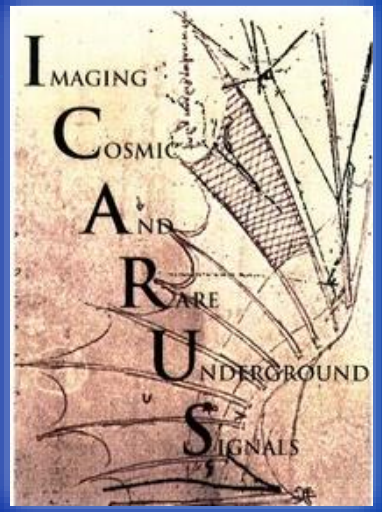
Gain fit on a Side CRT channel



- The CRT channel-to-channel calibration is obtained by fitting the lower range of the ADC spectra and evaluating the SiPM gain as the distance of consecutive single Photo-Electron (PE) peaks.
- Calibration results are used to confirm stability of the CRT system and to perform the conversion between ADC and PE.

Conclusions

- The Cosmic Ray Tagger system is fully installed and commissioned and it is currently actively taking data during Physics Run 1 of the ICARUS detector.
- The last layer of the concrete overburden has been installed on June 7th 2022.
- Cosmic rejections tools for the analysis are currently being validated using the data acquired during the commissioning phase.



Neutrino

Thank you!

Stay tuned… more to come!