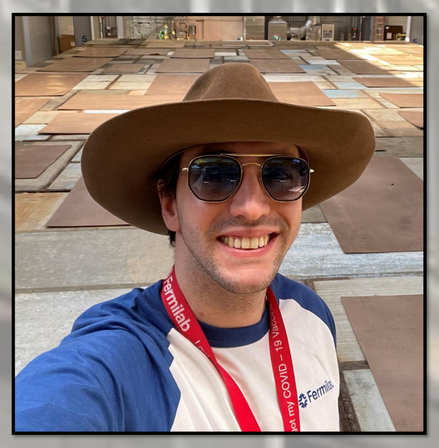

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# Cosmic Background Rejection of the ICARUS experiment at Fermilab

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## #1 Cosmic Background at the ICARUS detector at Fermilab

The ICARUS-T600 is a LArTPC with a total mass of 760 tons of liquid argon, located at Fermilab along the Booster Neutrino Beam (BNB) at 600 m from the neutrino source, and 6° off-axis the Neutrino from the Main Injector (NuMI) beamline. ICARUS will search for evidence of sterile neutrinos within the Short-Baseline Neutrino program. In addition it will perform measurement of neutrino cross-sections with the NuMI beam and Beyond Standard Model searches.

Being installed at shallow depth, ICARUS is exposed to a large flux of cosmic rays, which, if in time with the neutrino beam, could determine an event trigger, and, eventually, they could mimic a neutrino interaction.

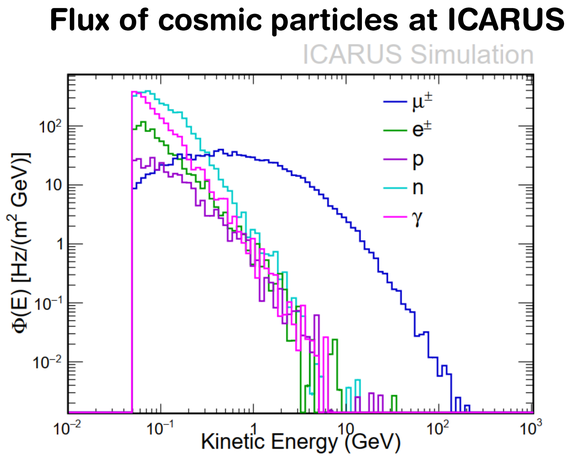
The expected rates of cosmic ray induced events and neutrino interactions are:

- 1 $\nu$ every 180 / 53 spills for BNB (1.6 $\mu s$) / NuMI (9.6 $\mu s$);
- 1 cosmic $\mu$ every 55 / 6 spills for BNB (1.6 $\mu s$) / NuMI (9.6 $\mu s$).

The cosmic induced background can be distinguished in two main categories:

- **In-Time interactions**: cosmic particles entering the detector during the beam spill;
- **Out-of-Time interactions**: cosmic particles crossing the detector read-out window.

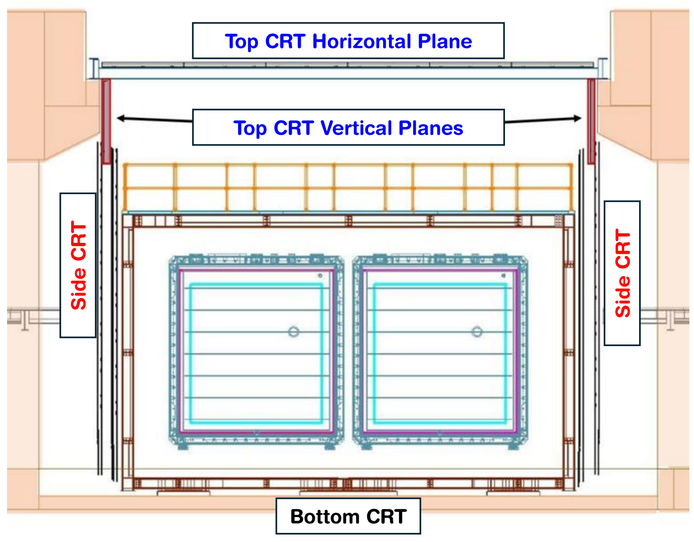
**Flux of cosmic particles at ICARUS**




To mitigate the cosmic ray flux, a 3 m **concrete overburden** is installed above the ICARUS apparatus. A Cosmic Ray Tagger (**CRT**)system surrounding the detector allows to detect muons reaching the TPC.

**ICARUS Simulation**

| Particle | No OB [Hz] | With OB [Hz] |
|---|---|---|
| $\mu^{\pm}$ | ~17100 | ~12800 |
| p | ~50 | 0.1 |
| $\gamma$ | ~100 | <<0.1 |
| n | ~1400 | 6.8 |

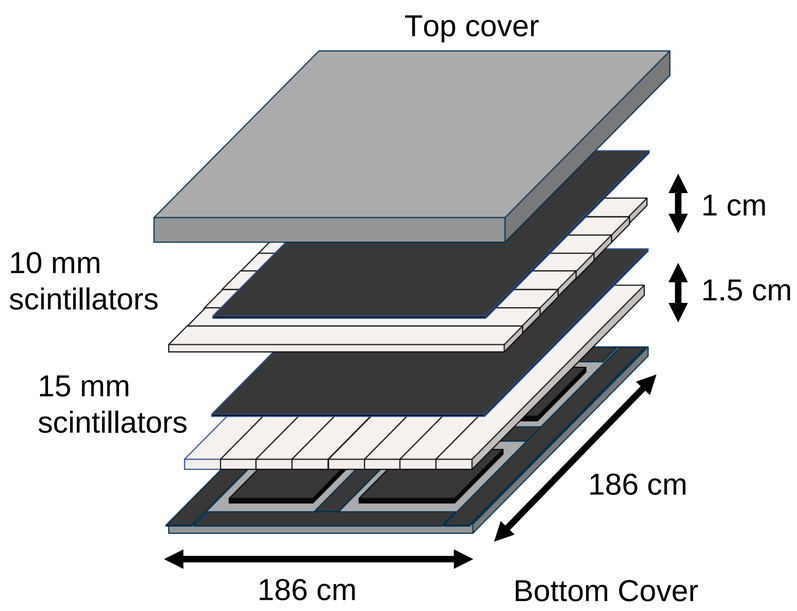



The CRT system is designed to provide a $\sim 4\pi$ coverage of the TPC. It is divided in: **Bottom CRT**, **Side CRT** and **Top CRT**.

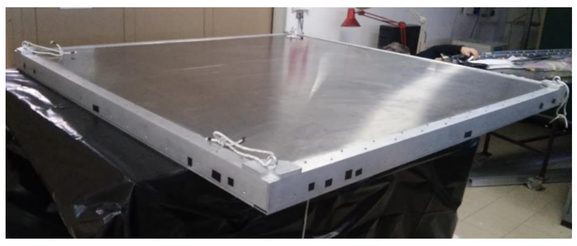
The CRT provides spatial (~cm resolution) and timing (~ns resolution) coordinates of the particle crossing points.

## #2 The Top CRT

- It is composed of 39 vertical modules and 84 horizontal modules, intercepting **80% of the incoming CR $\mu$ flux**.
- Hodoscope module consisting of 2 orthogonal layers of scintillator bars. Each layer consits of eight 23 cm wide bar. The scintillator layers are encased in Al boxes.

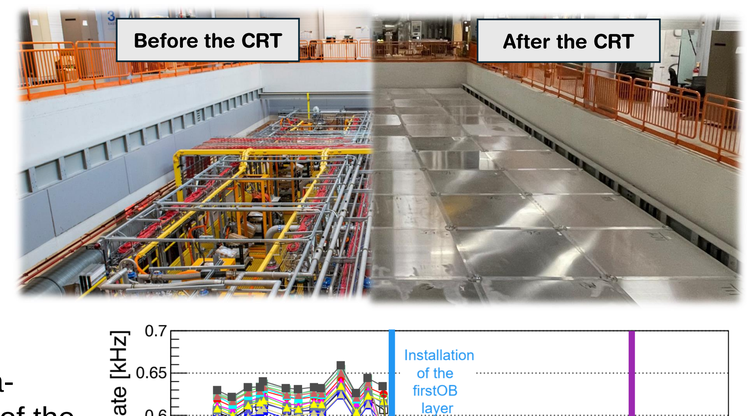



- Scintillation light is collected by two WLS fibres per bar each read-out at one end by one SiPM.
- The CRT trigger is provided by coincidence signals on both (AND) scintillation layers.

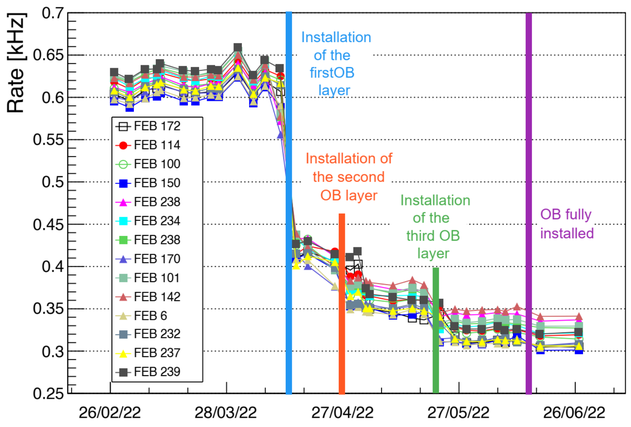


## #3 CRT Commissioning

- The commissioning of the CRT was completed in spring 2022.

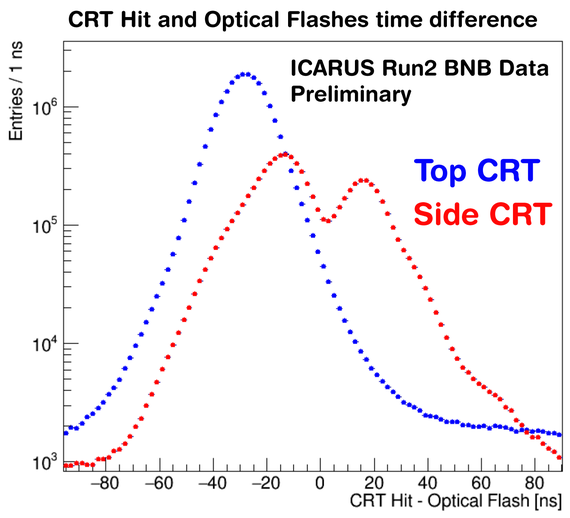



- The CRT system was in data-taking during the installation of the concrete overburden.
- The rate measured by Top CRT horizontal modules decreased from ~ 600 Hz/module to ~ 330 Hz/module, in agreement with the expected cosmic muon rate (~ 100 Hz/$m^2$).




## #4 CRT-PMT Matching

- The timing resolution of the CRT system (~ns) and of the Photo-Detection System (<ns) and their synchronization by means of the global event trigger, determines the possibility to associate each reconstructed **Optical Flash with one or more CRT hits** using only **timing** information.

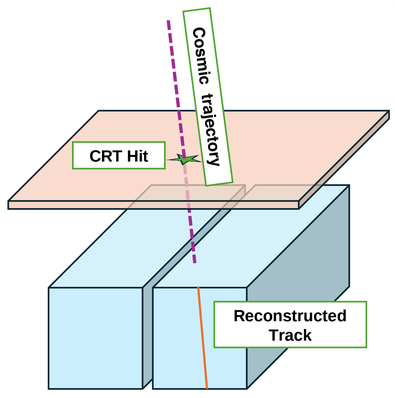



- By selecting events with optical flashes in time with the beam spill and not matched with any CRT hit we can determine an enhanced sample of fully contained neutrino interactions, effectively **suppressing the In-Time cosmic induced background**.

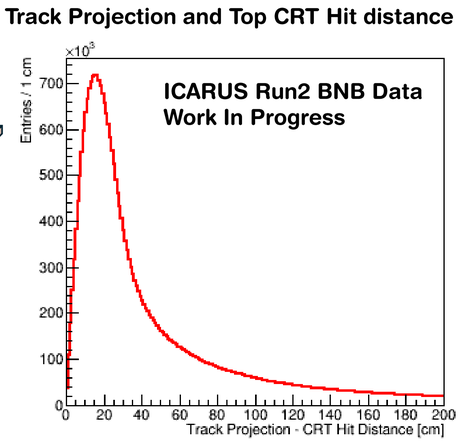
| Classification | NuMI [%] OnBeam | NuMI [%] OffBeam | BNB [%] OnBeam | BNB [%] OffBeam |
|---|---|---|---|---|
| No CRT match | 39.0 | 12.7 | 32.4 | 12.3 |
| 1 Entering from Top | 34.4 | 62.8 | 46.5 | 63.4 |
| 1 Entering from Side | 10.7 | 10.5 | 8.5 | 10.5 |
| 1 Entering from Top 1 Exiting from Side | 2.5 | 4.7 | 3.6 | 4.8 |
| 1 Exiting from Top | 2.0 | 0.5 | 1.3 | 0.5 |
| 1 Exiting from Side | 5.6 | 1.9 | 2.5 | 1.8 |
| Others | 5.8 | 6.9 | 5.3 | 6.7 |

## #5 CRT-TPC Matching

- The **rejection of the Out-Of-Time cosmics** can be achieved by associating the TPC reconstructed tracks with the CRT hits.
- The **CRT-TPC matching** is performed using spatial information: the reconstructed tracks are projected onto the CRT planes and the spatial distance between the projection and the CRT hit is used for the classification.

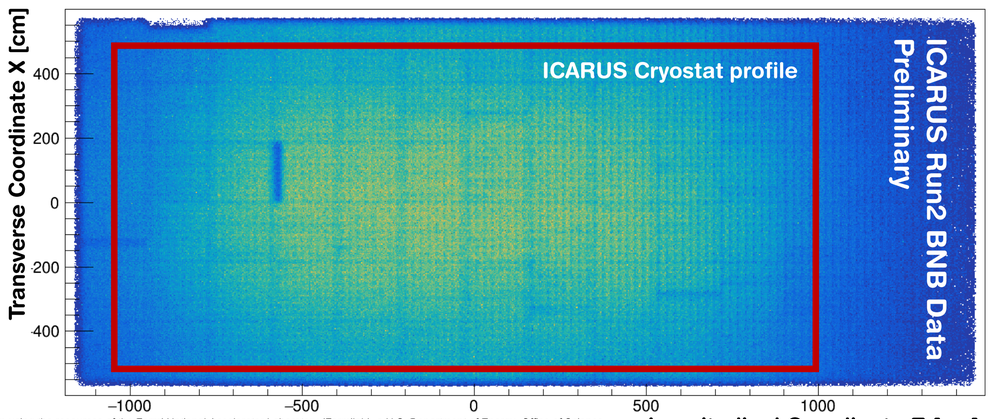



**Track Projection and Top CRT Hit distance**




**Distribution of Track Projections for CRT-Track matches with distance < 30 cm**

- A large dataset of > 10 milion TPC reconstructed tracks from ICARUS Run 2 was used to perform a **«cosmic tomography»** of the Top CRT.

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