Light Detection and Cosmic Rejection in the ICARUS LArTPC at Fermilab

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LIDINE 2023

Imaging Cosmic And Rare Underground Signals

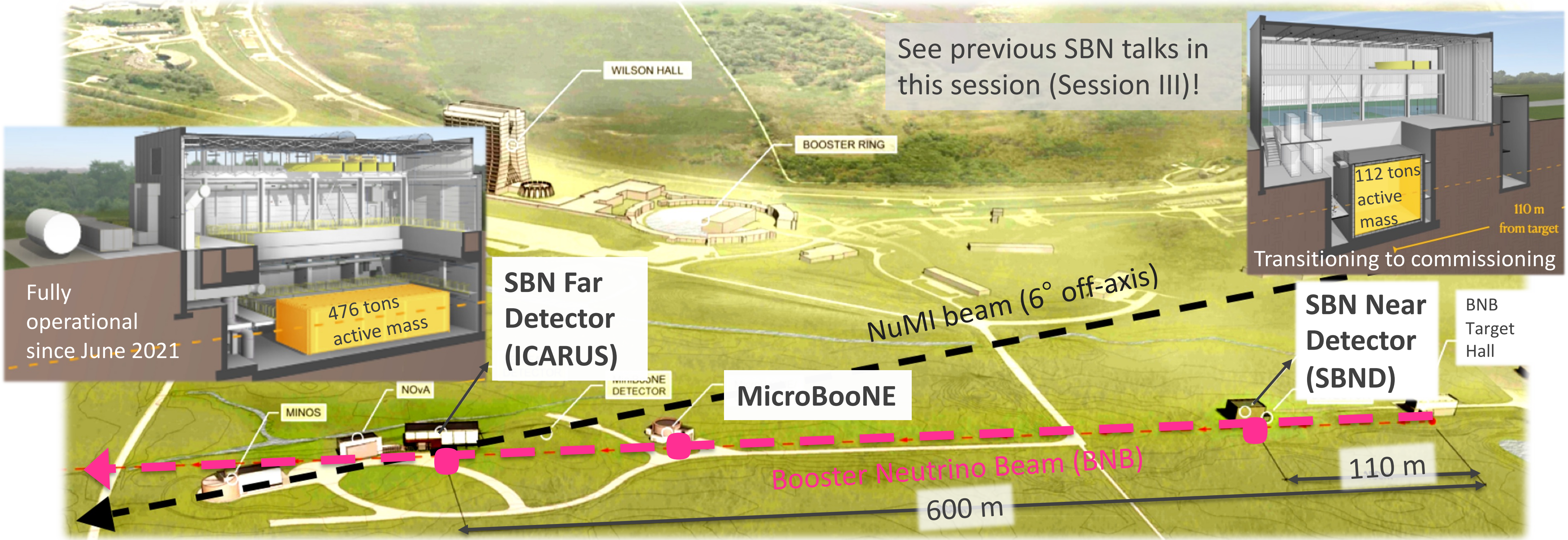
SBN Program

Outline

1. Introduction to ICARUS
2. ICARUS light detection system
3. ICARUS external tagging system
4. Cosmogenic background mitigation

ICARUS in the Short Baseline Neutrino (SBN) Program

- ICARUS is a Liquid Argon Time Projection Chamber (LArTPC) operating at Fermilab as the far detector in the SBN Program
  - Collects neutrinos both from the Booster Neutrino Beam (BNB) and Off-Axis from the Neutrinos at the Main Injector (NuMI) beam



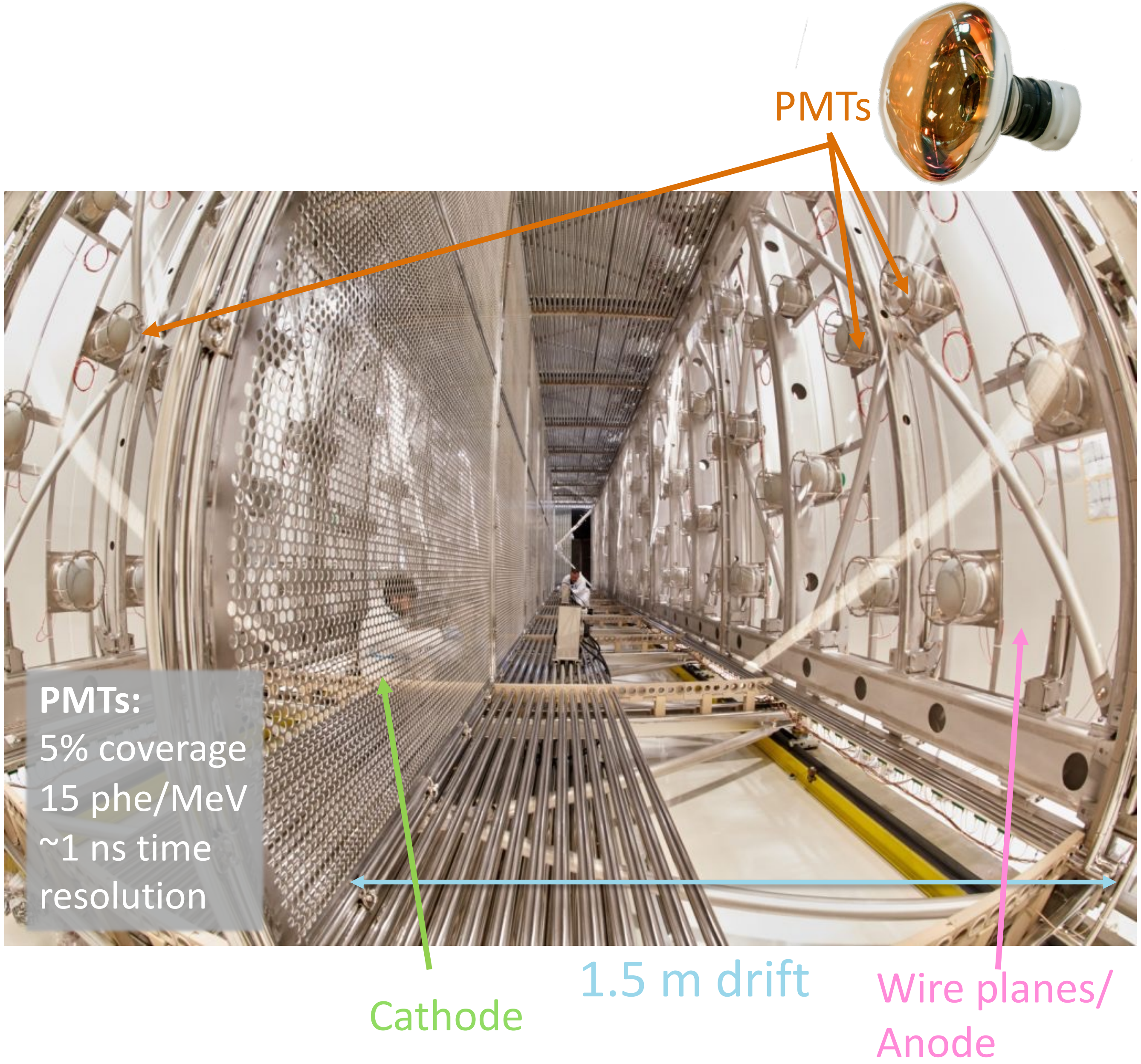
The ICARUS-T600 Detector

- First operated at Gran Sasso Underground Laboratory, Italy for 3 years as the first large scale LArTPC
  – 760 tons Liquid Argon; 3.6 x 19.6 x 3.9 m^3, 1 mm^3 spatial resolution
- Shipped to CERN for upgrades
  ✓ New TPC electronics
  ✓ New light collection system
- Now operating on the surface at Fermilab, exposed to a high flux of cosmogenic particles
  – 3-meter concrete overburden
  – **~13 cosmic muon tracks occur per triggered event in the 1 ms TPC drift readout**

One of the ICARUS TPCs being lowered into the cryostat at FNAL, c. 2018

ICARUS light detection system

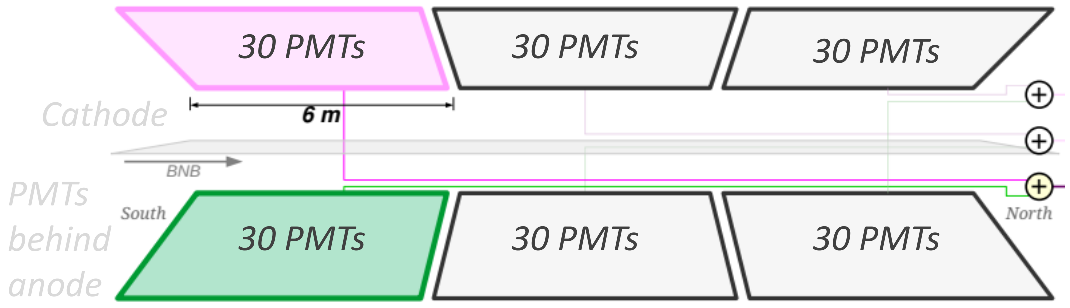
- 360 8” Hamamatsu R5912-MOD Photomultiplier Tubes (PMTs) for new optical detection system mounted behind the TPC wire planes
  - Coated with a wavelength shifter (tetraphenyl butadiene) to convert VUV photons to visible light
- Detects scintillation light from charged particles interacting in the Liquid Argon
  - Use the fast scintillation light to reconstruct the position of event along the charge drift direction
  - Used for the trigger of the full detector
    - Charge drift time in the LAr is ~ ms
    - PMTs response time is ~ ns



View inside one of the ICARUS TPCs while receiving upgrades at CERN

Eur. Phys. J. C 83:467 (2023)

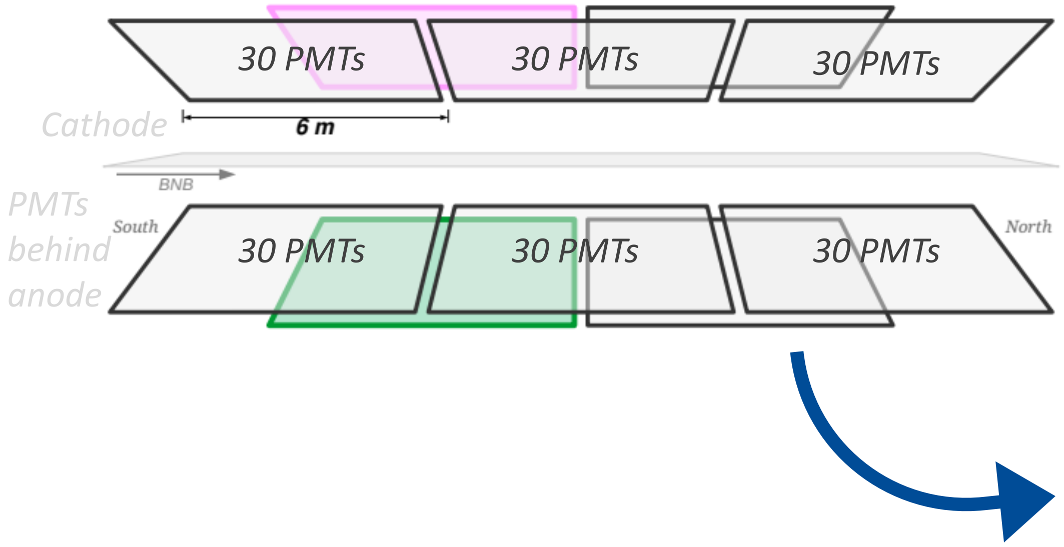
ICARUS light detection system as detector trigger

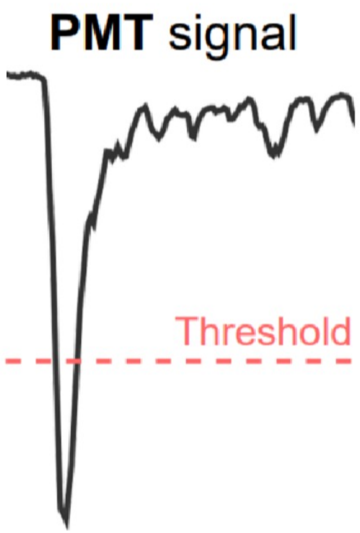


1. PMT signals (LVDS) are digitized and discriminated in pairs

Ex. 1.6 μs for BNB

ICARUS light detection system as detector trigger

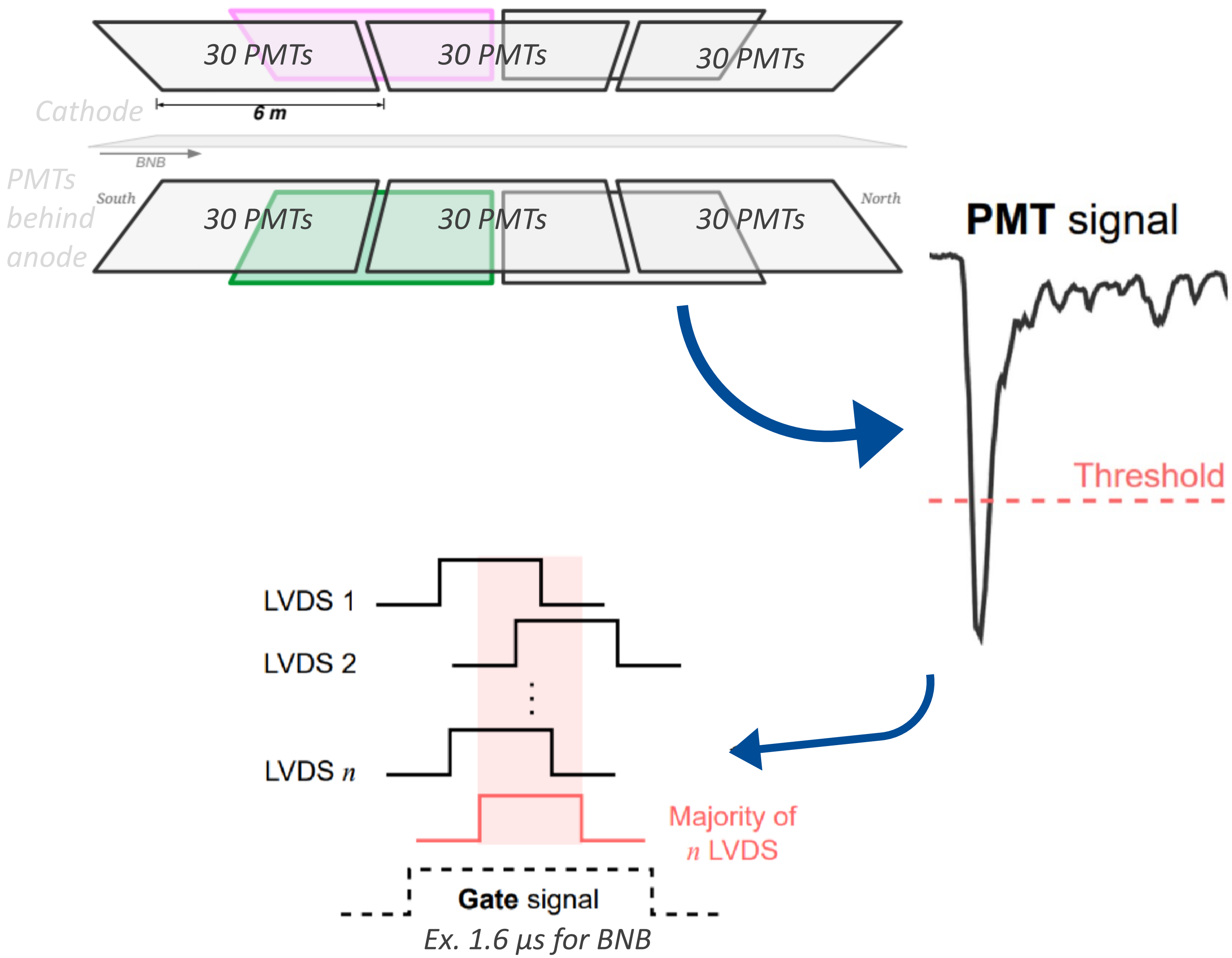




1. PMT signals (LVDS) are digitized and discriminated in pairs

2. Look for at least 5 pairs of PMT signals above a set threshold (Majority Logic) within a 6-meter longitudinal slice (30 PMTs x 2 sides of cathode)

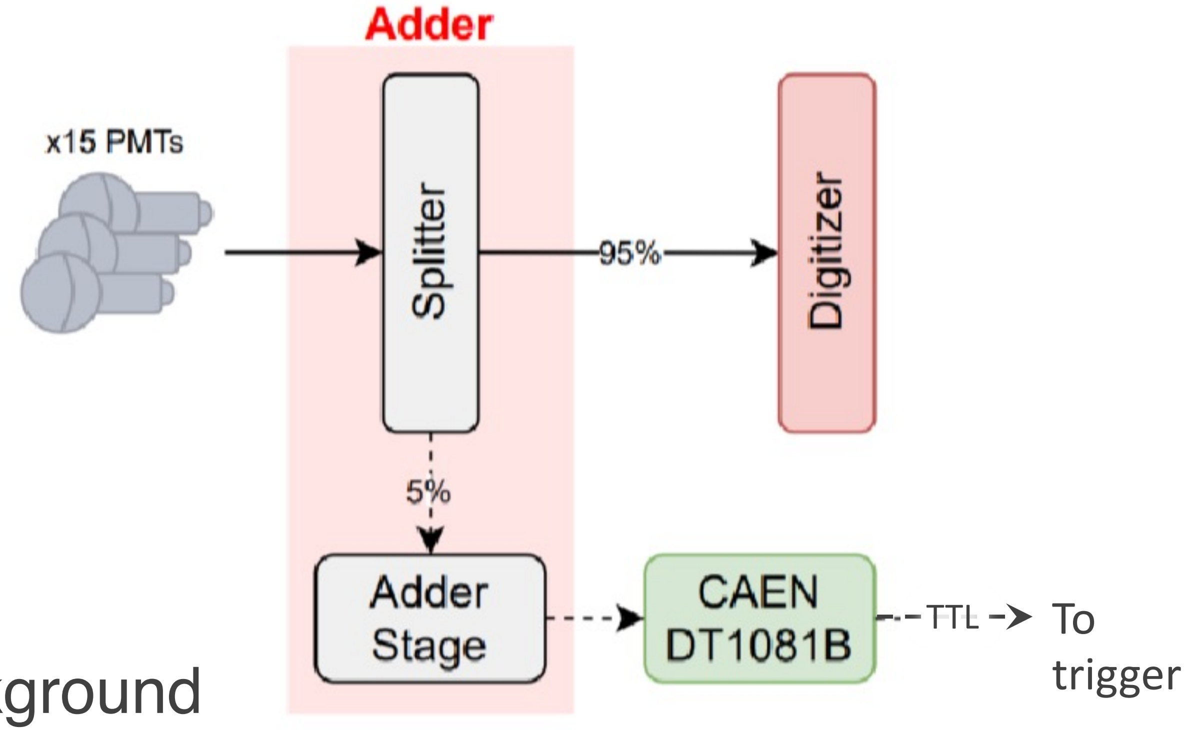
ICARUS light detection system as detector trigger



1. PMT signals (LVDS) are digitized and discriminated in pairs
2. Look for at least 5 pairs of PMT signals above a set threshold (Majority Logic) within a 6-meter longitudinal slice (30 PMTs x 2 sides of cathode)
3. A global trigger signal is produced when enough PMT light is detected in coincidence with BNB/NuMI beam spills (1.6/9.6 μs)

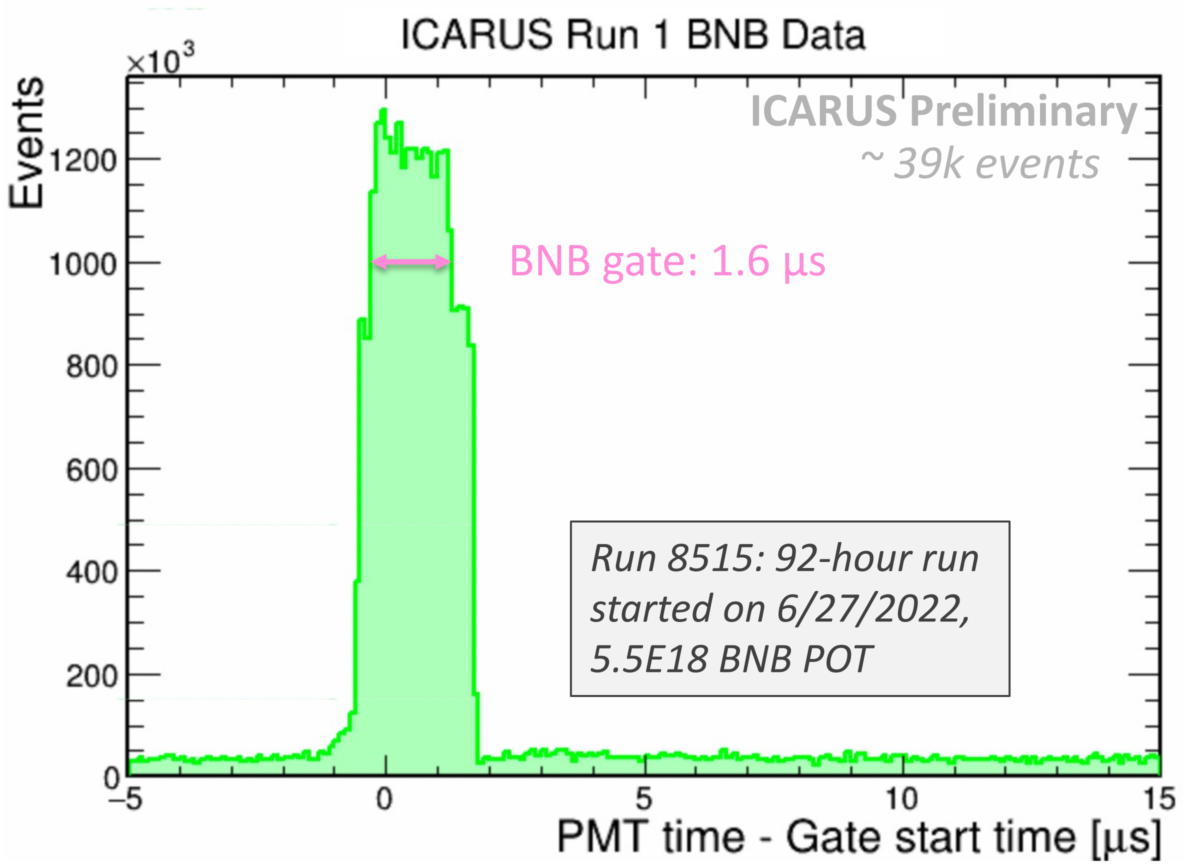
ICARUS trigger system status and updates

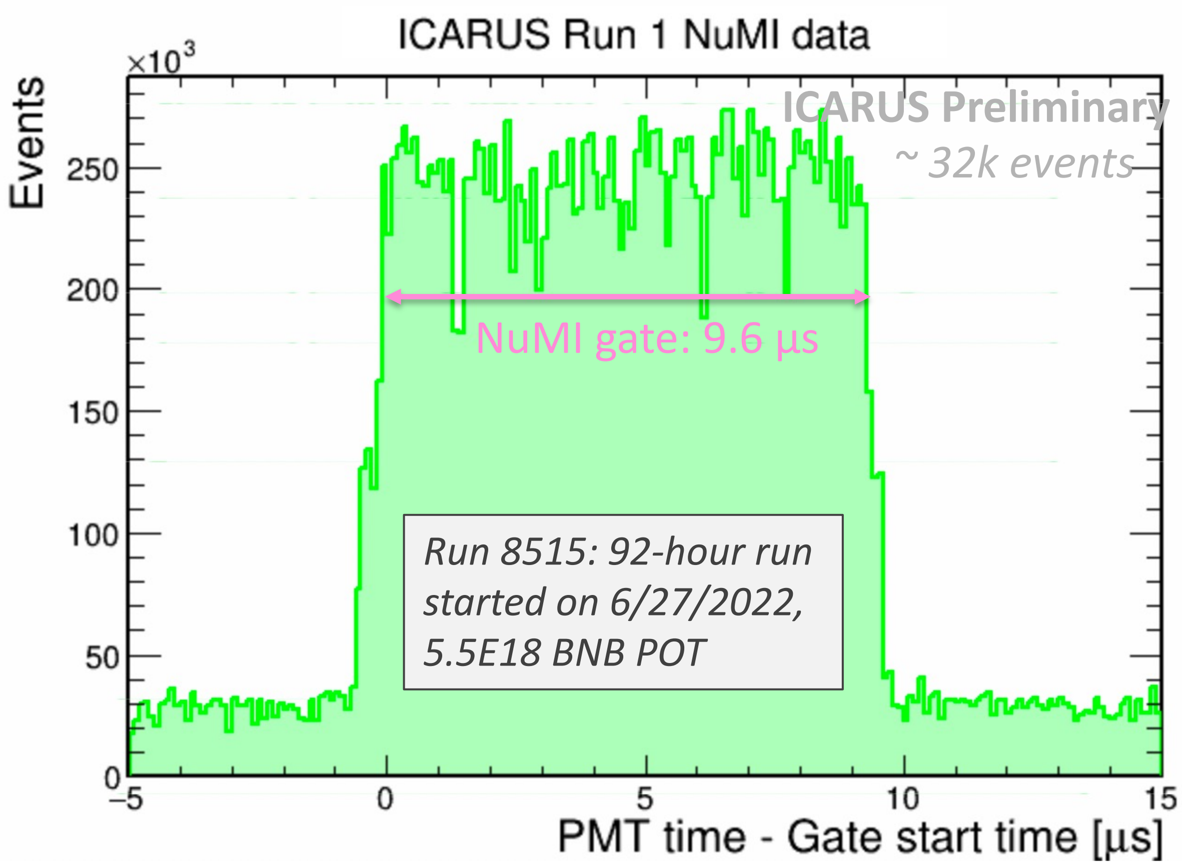
- Trigger rate ~ 0.7 Hz (0.3 Hz BNB, 0.15 Hz NuMI, 0.25 Hz off-beam)
- Trigger efficiency is under investigation on data (full detection efficiency above 200 MeV deposited energy)
- Lower efficiency for low energy cosmic rays
- Motivates a complementary system based on *Adder* boards
  - Analog sum of 15 PMTs
  - Can help identify events with plenty of light but not enough fired PMTs
  - *Work is ongoing*
- Additional triggers exist for cosmogenic background studies for neutrino oscillation searches and calibration
  - Without any request on scintillation light (Minimum bias)
  - Outside of beam spills (Off-Beam)



PMT signal timing

- Distribution of PMT scintillation signal timing with respect to the opening of the neutrino beam gates shows excess PMT light over the standard cosmic background rate, demonstrating the trigger performance





Cosmogenic background reduction

- Cosmic rays collide with Earth's upper atmosphere and produce a shower of particles
- These particles can interact and mimic our neutrino signal
- ICARUS employed two techniques to mitigate the cosmogenic exposure
  1. Install a 3-meter-thick concrete overburden
  2. Cosmic Ray Tagger (CRT) to surround the detector and tag incoming charged particles

ICARUS Geometry

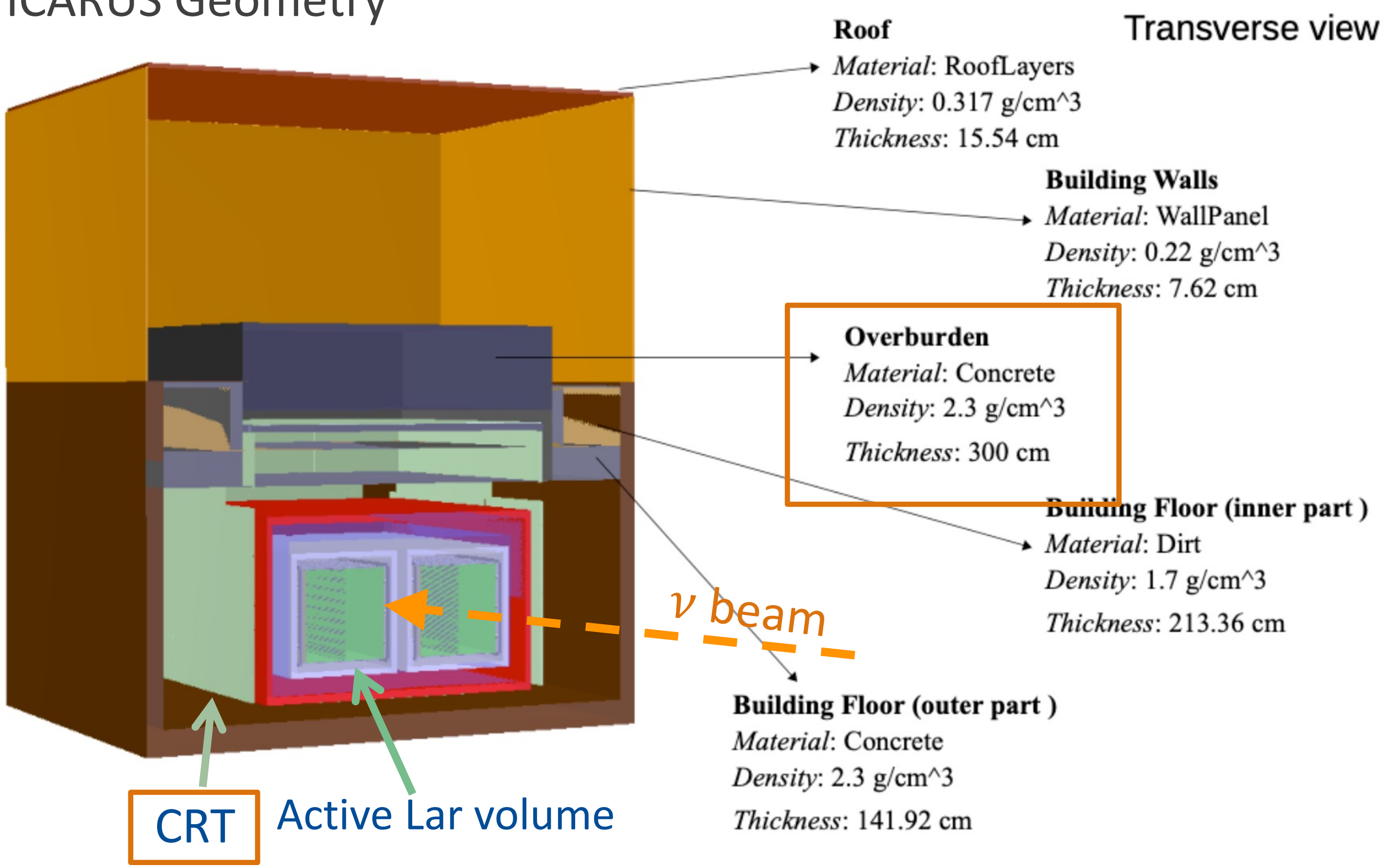
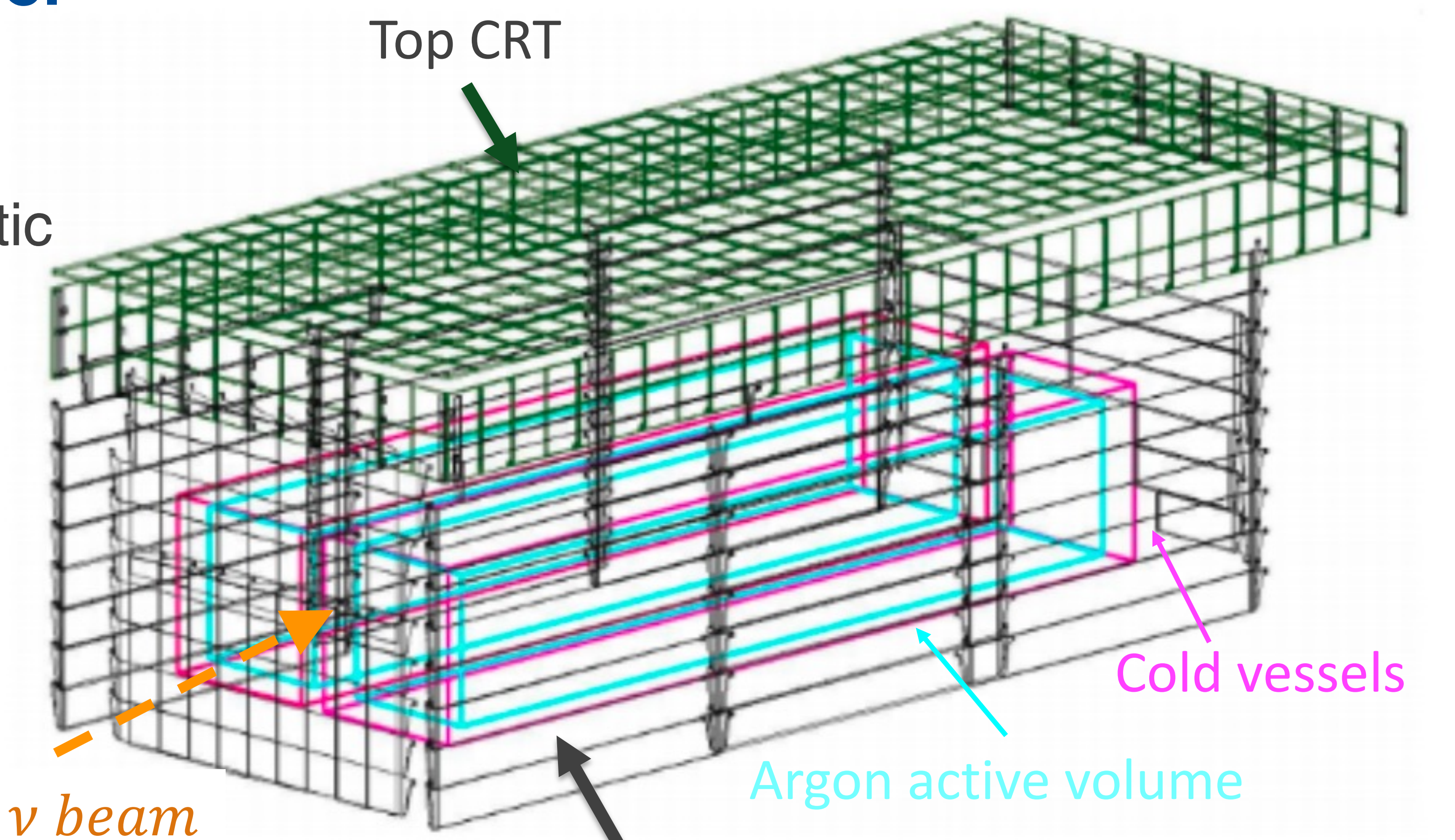
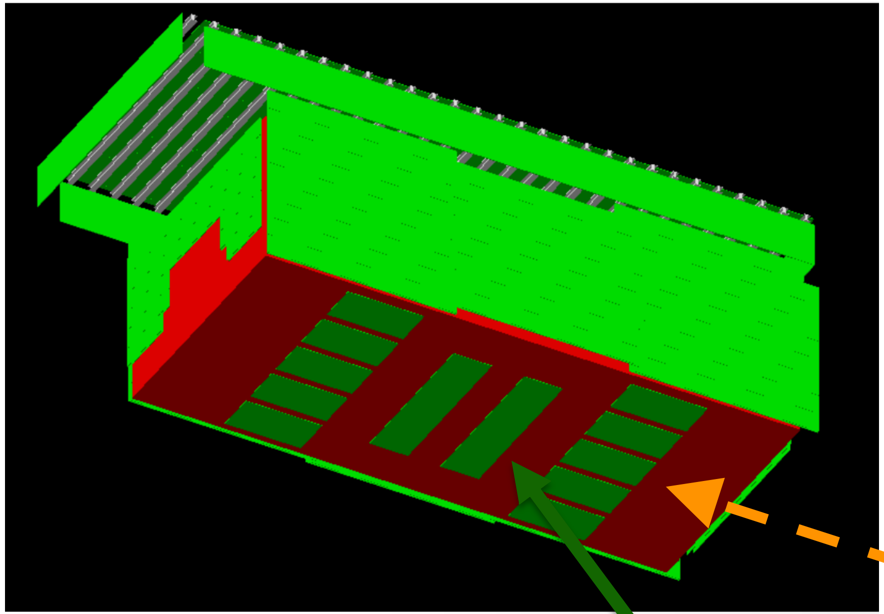


Figure: ICARUS detector hall (transverse view). Image Credit : Marta Torti and Alessandro Menegolli

ICARUS Cosmic Ray Tagger

- Surround detector medium (~1,000 m^2 coverage) with 2 layers of fiber embedded plastic scintillator

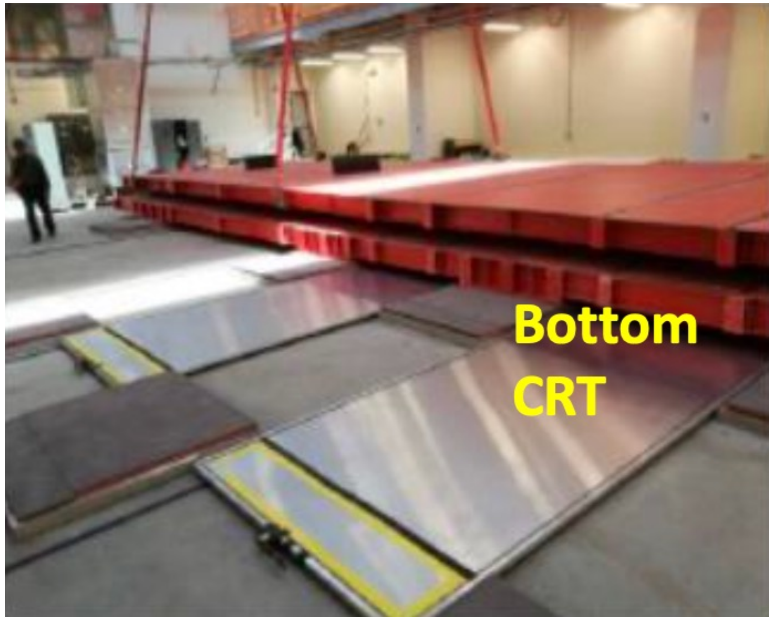




3 Cosmic Ray Tagging (CRT) subsystems

- New scintillator modules
- Silicon photomultiplier (SiPM)-based readout

- Repurposed MINOS modules
- SiPM-based readout



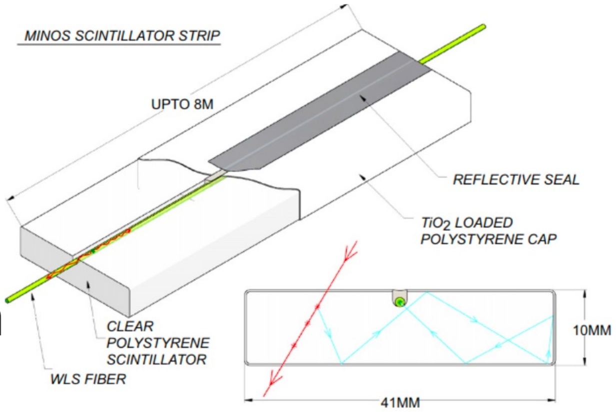
- Repurposed Double Chooz modules
- Photomultiplier tube (PMT)-based readout

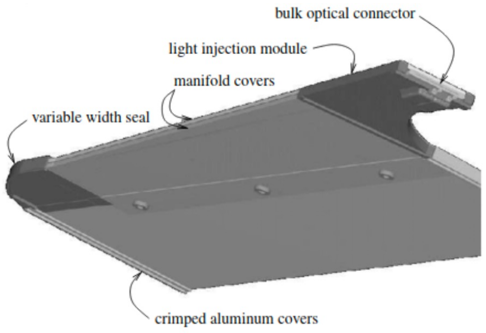
CRT light detection system

- Top and Side CRT subsystems use Silicon photomultipliers (SiPMs) to readout each scintillator strip

Side CRT Design

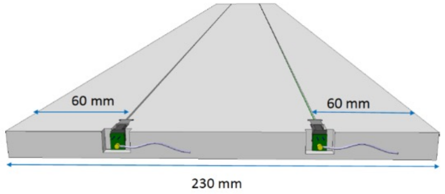
- New optical readout system with SiPMs designed by CSU
- 93 modules, each with 20 strips of scintillator embedded with wavelength shifting fibers
- Fibers are collected into snouts on the end of the modules with SiPM mounted

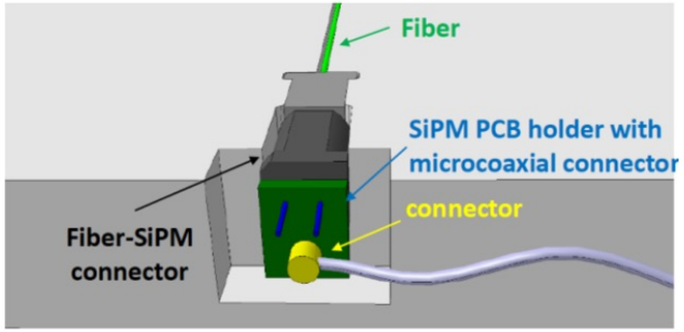




Top CRT Design

- New design by CERN/INFN
- 16 strips per module (double layered: 8X and 8Y), 123 modules
- Two fibers per scintillator strip readout at single end



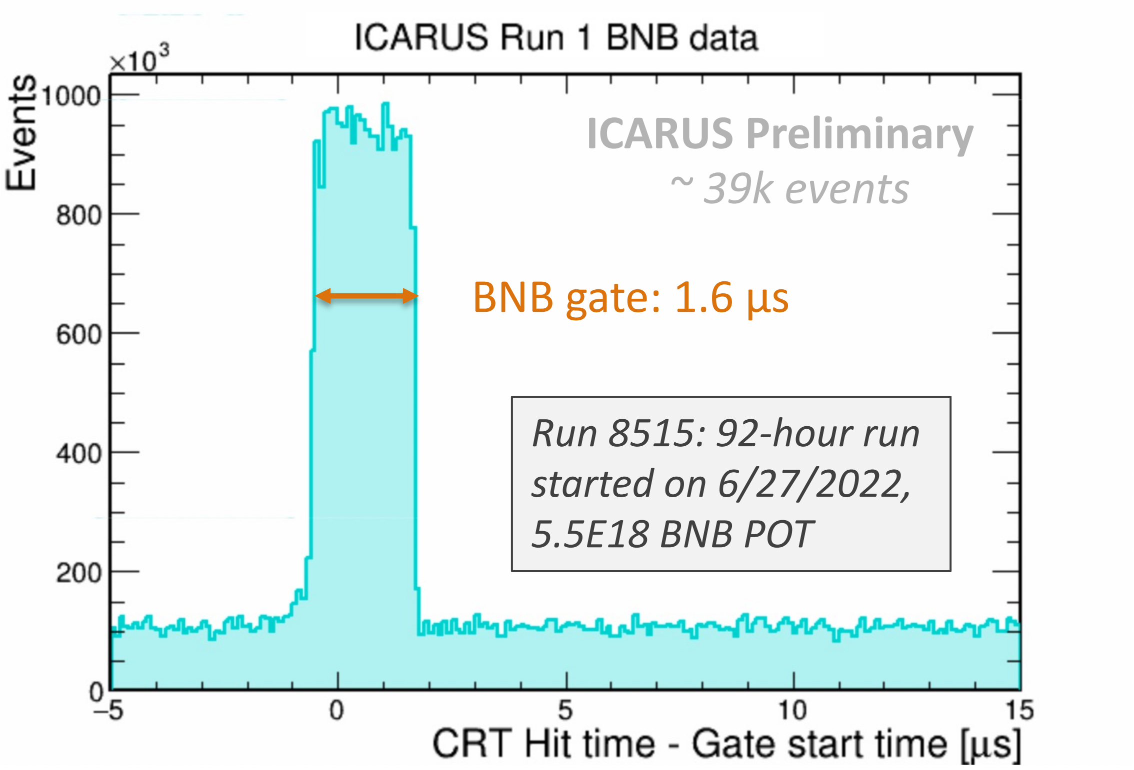


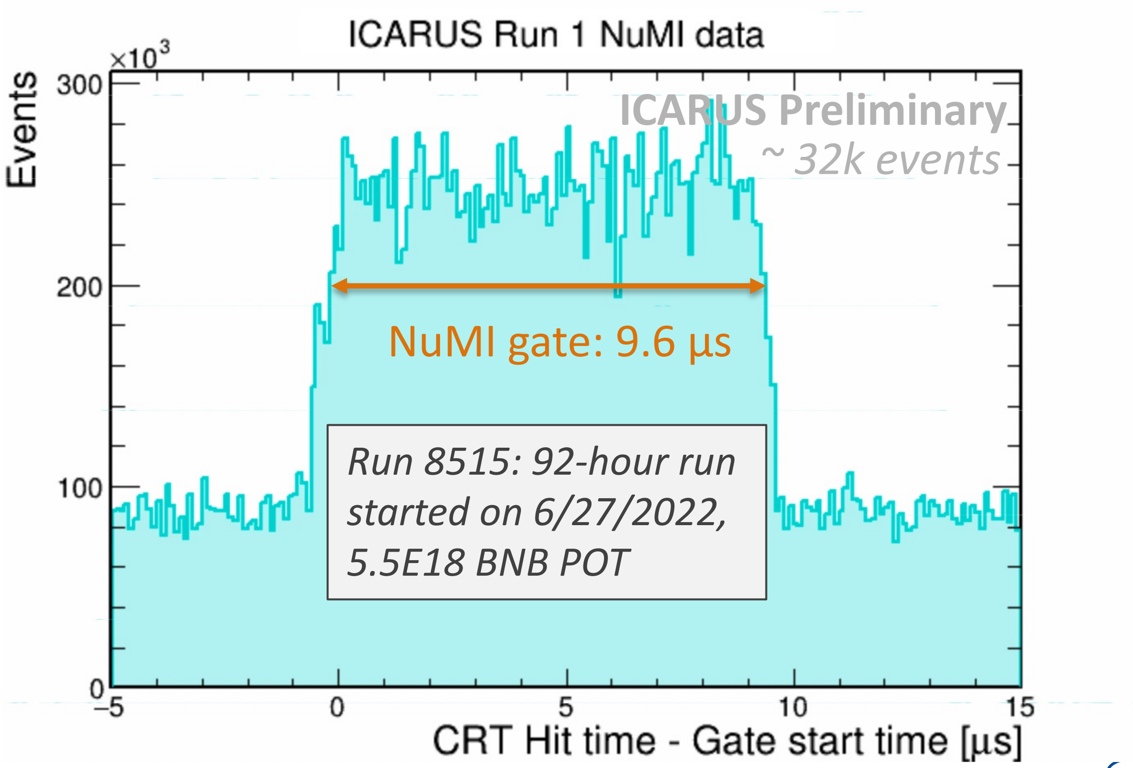
CRT Front-End Boards (FEBs)

- We use the CAEN A1702 32-channel Silicon Photomultipliers Readout Front-End Board to provide readout and digitization of our CRT Signals
- Provides amplification and shaping of SiPM signals with a configurable discrimination threshold (0-50 photoelectrons)
- Allows for triggering on an external signal or coincident signals in adjacent channels
- Two counters for timing
  - T0: Pulse per second (PPS) resets every second to produce absolute timestamp of every CRT interaction over threshold
  - T1: provides a time reference to the beam timing inside the CRT system
- Each FEB has a resolution of ~2.3 ns

CRT Hit timing

- We perform timing corrections to adjust the absolute CRT Hit time for light propagation, cable delays and time walk with amplitude
- Looking at the CRT timestamp with respect to the opening of the neutrino beam gates, we see excess hits associated with the BNB and NuMI beams

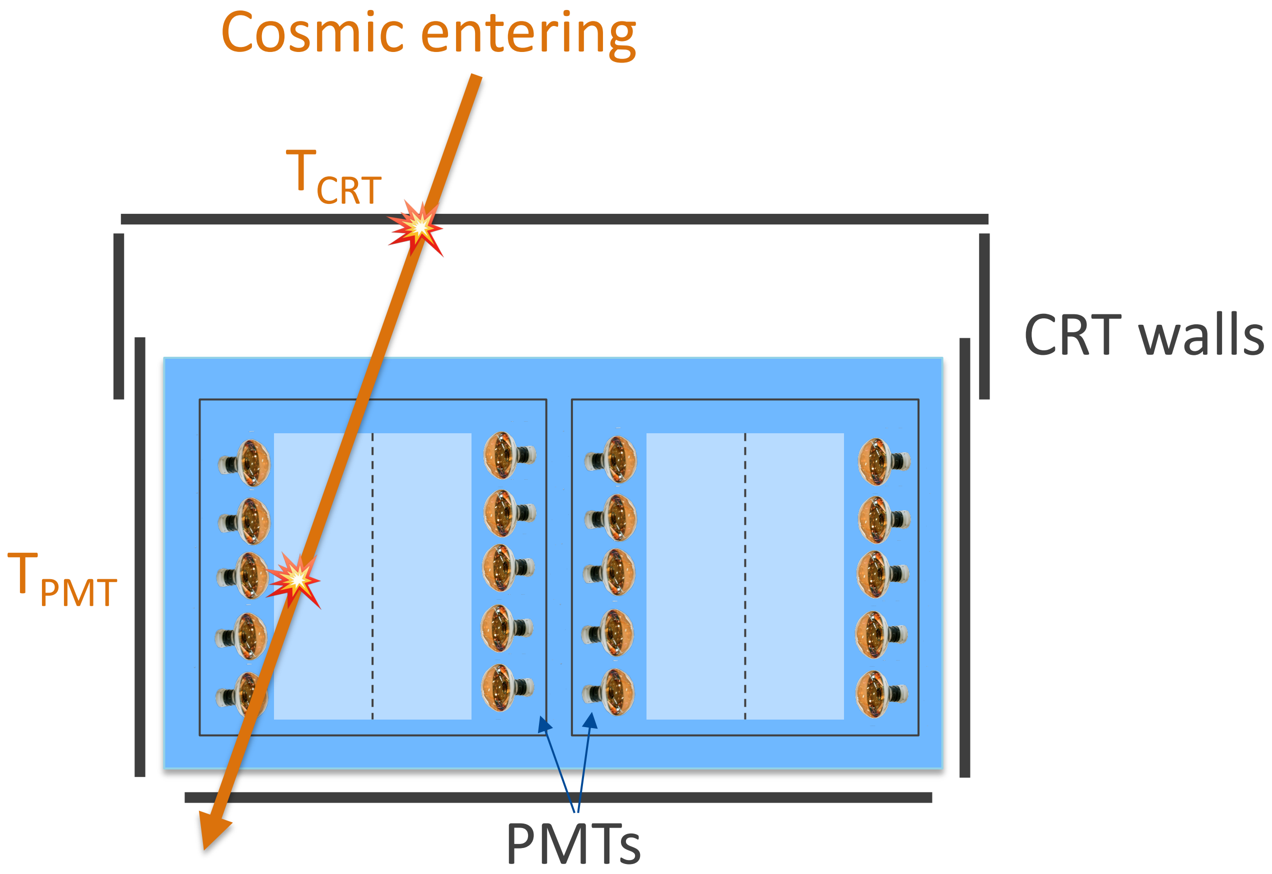




CRT-PMT Matching

- Uses time information from CRT Hits and PMT signals to distinguish between tracks entering and exiting the ICARUS cryostat
  - Cosmic tracks entering the TPCs will hit CRTs first

    $T_{CRT} - T_{PMT} < 0$



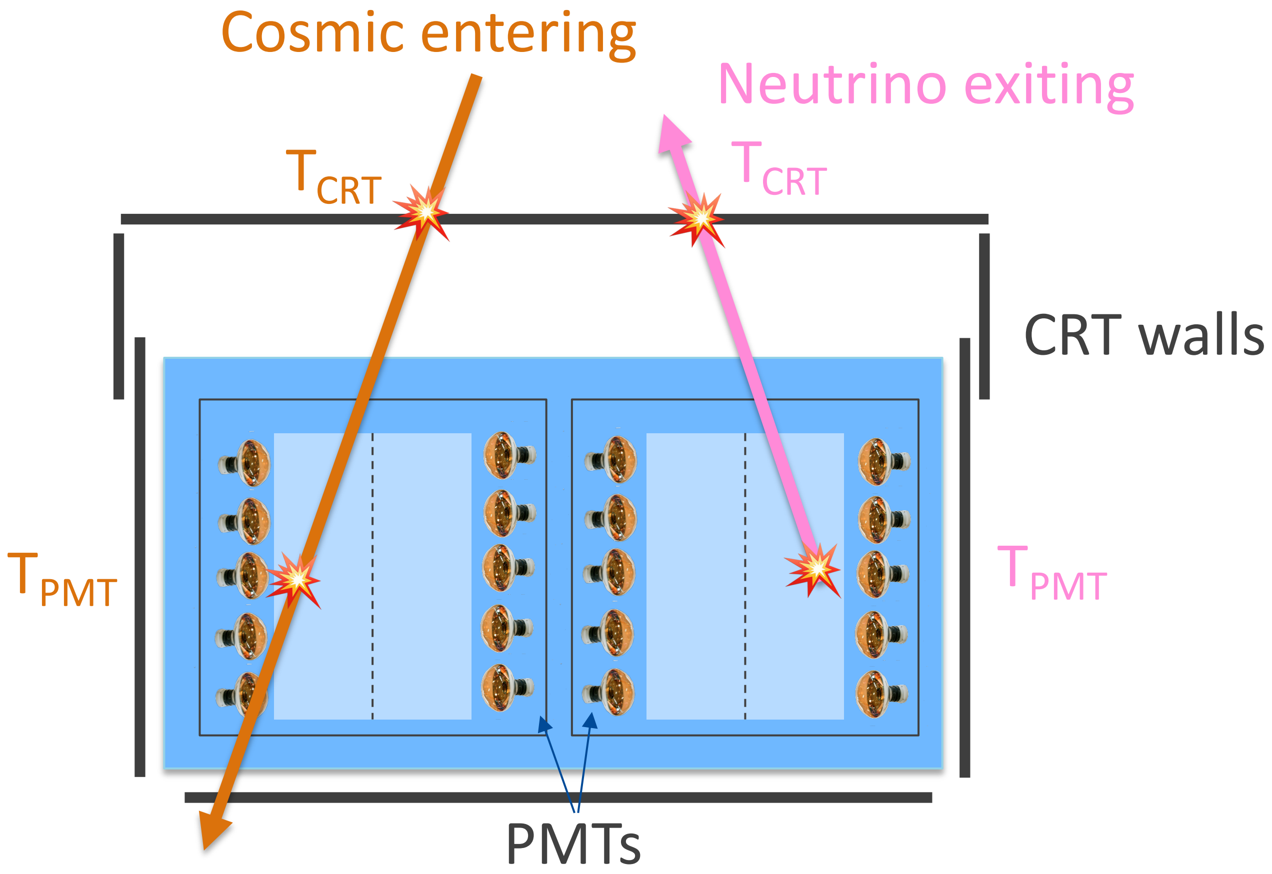
CRT-PMT Matching

- Uses time information from CRT Hits and PMT signals to distinguish between tracks entering and exiting the ICARUS cryostat
  - Cosmic tracks entering the TPCs will hit CRTs first

    $T_{CRT} - T_{PMT} < 0$

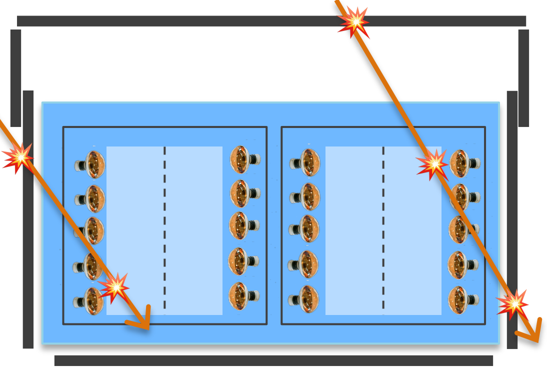
  - Neutrino interactions with tracks leaving the TPC will hit the PMTs first

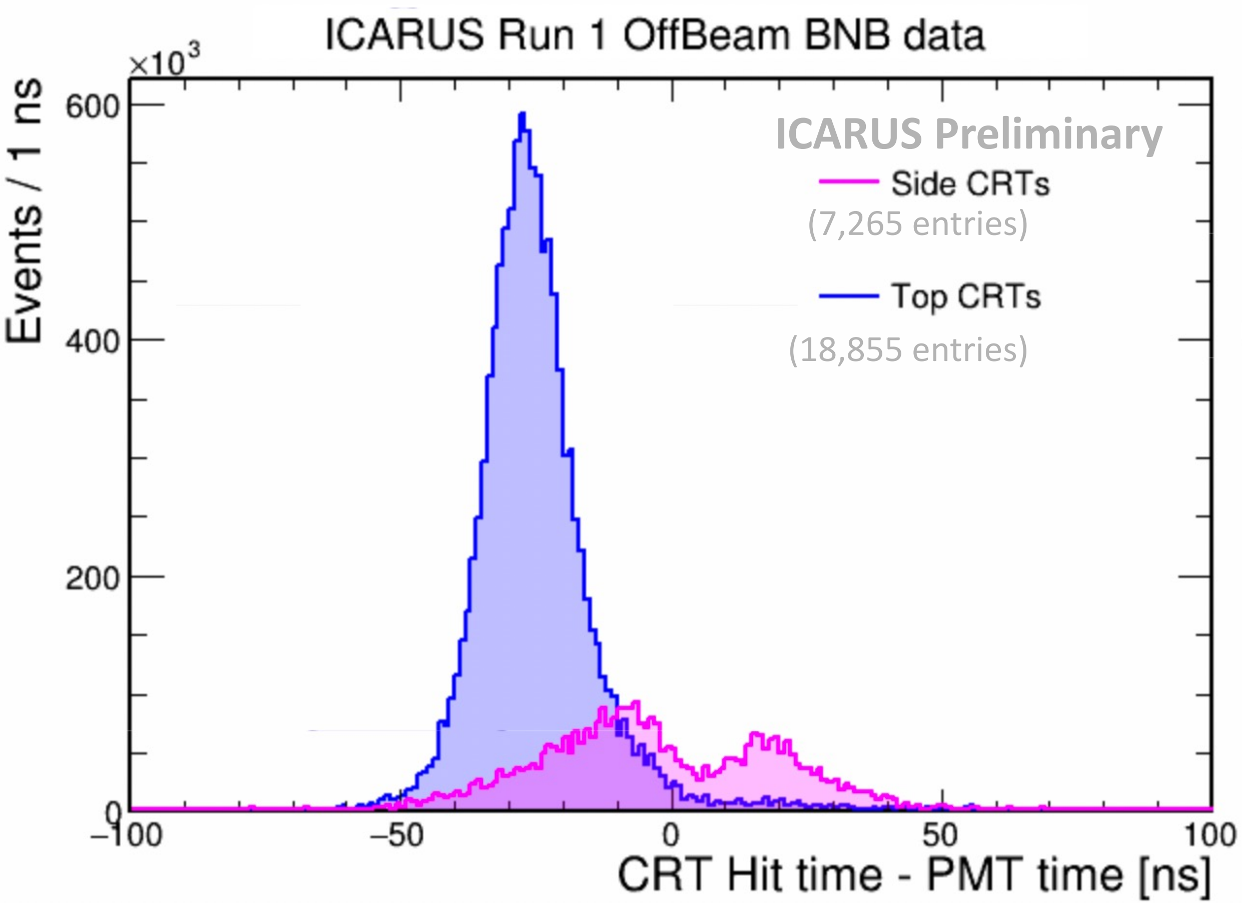
    $T_{CRT} - T_{PMT} > 0$

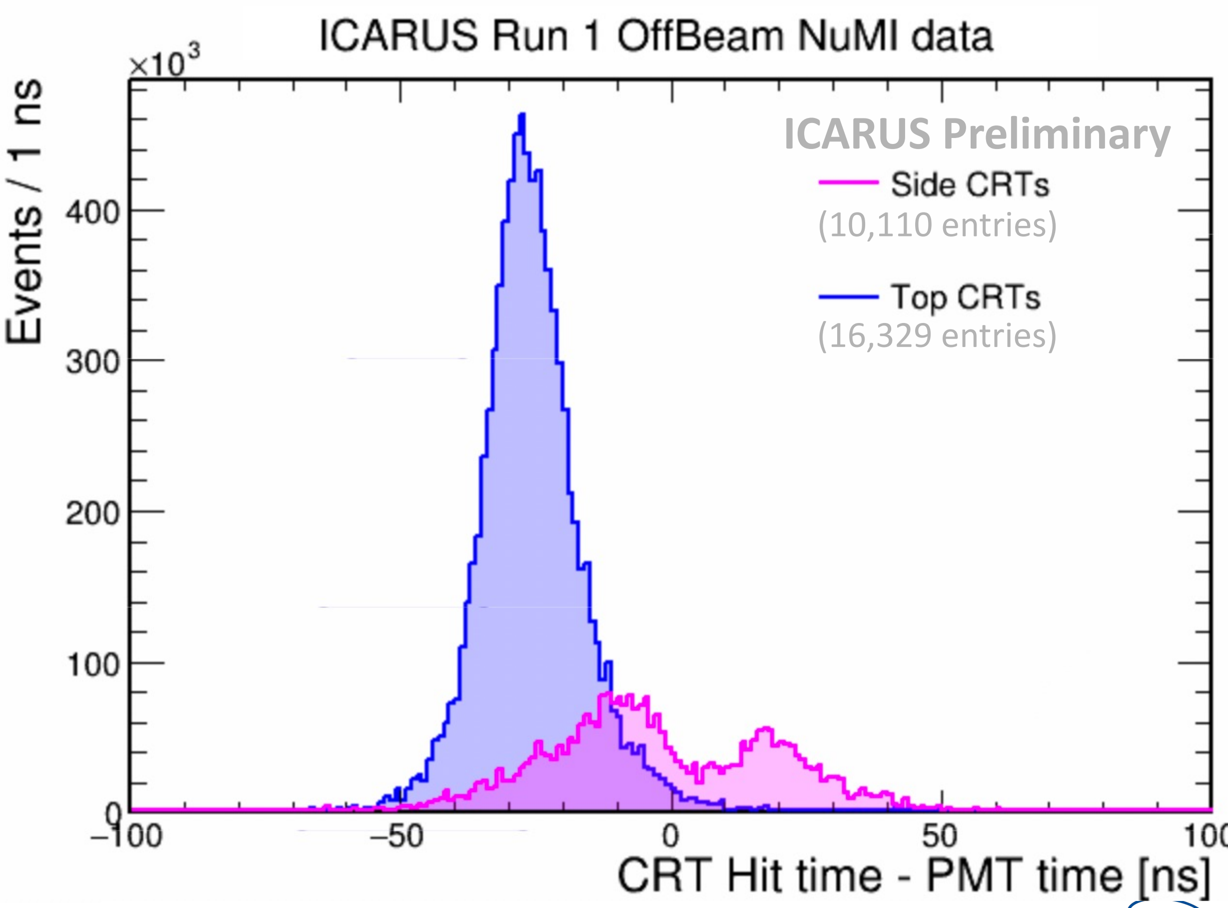


CRT Time – PMT time with off-beam data

- Using the nanosecond-scale synchronization of the CRT and PMT subsystems, we can associate PMT signals to CRT hits to distinguish between tracks entering or exiting the ICARUS detector







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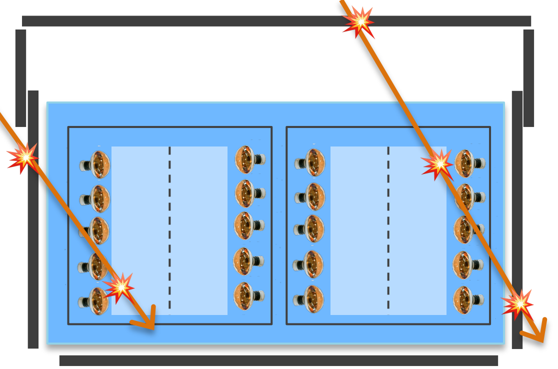
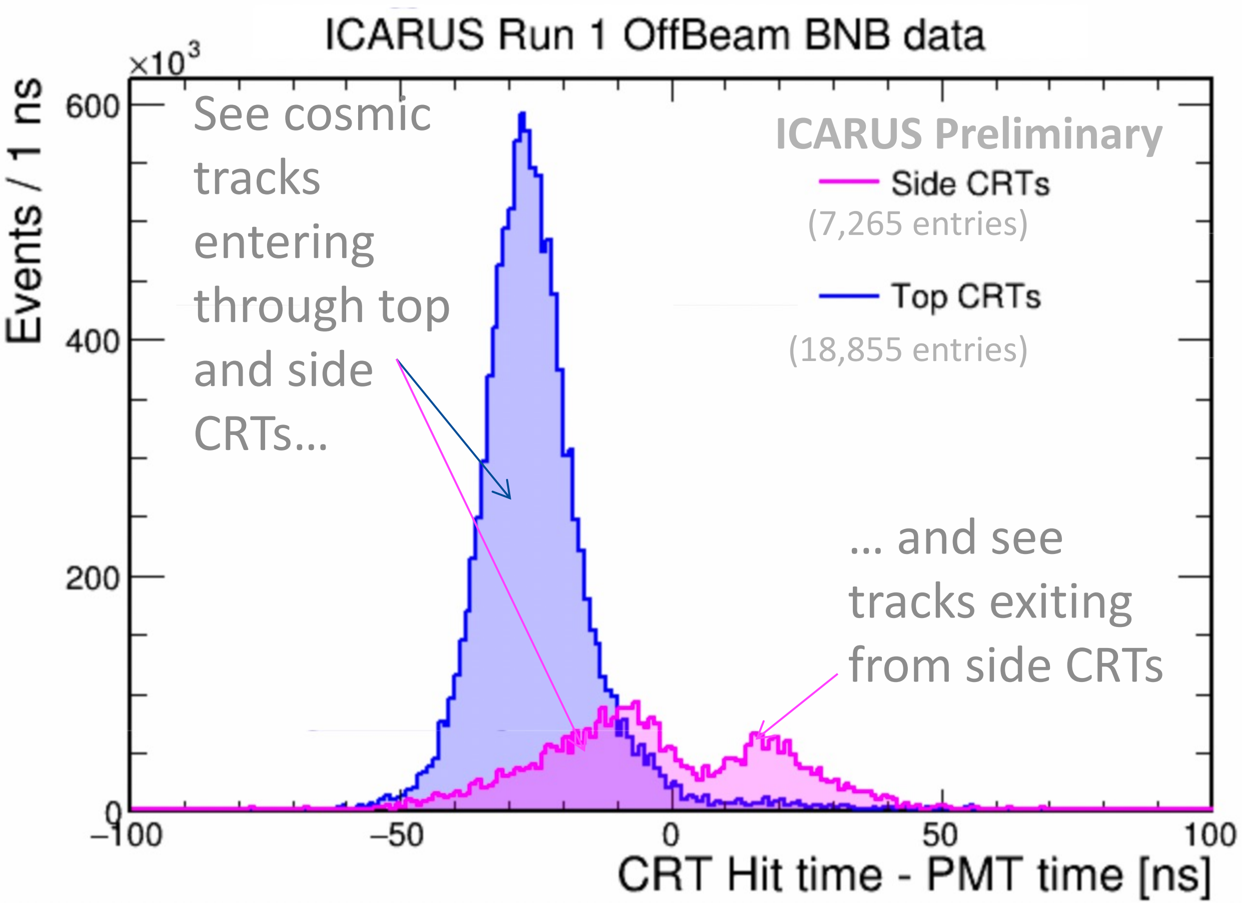
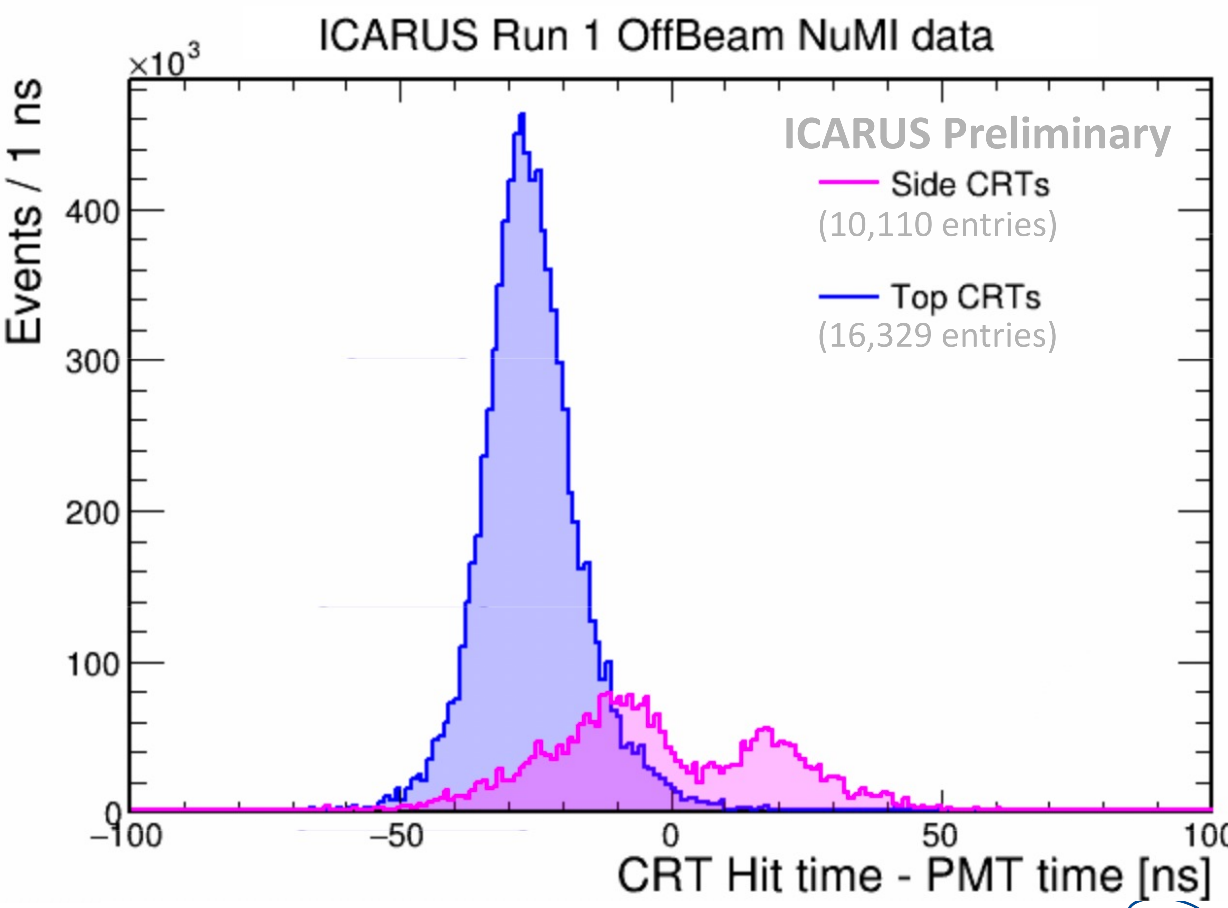
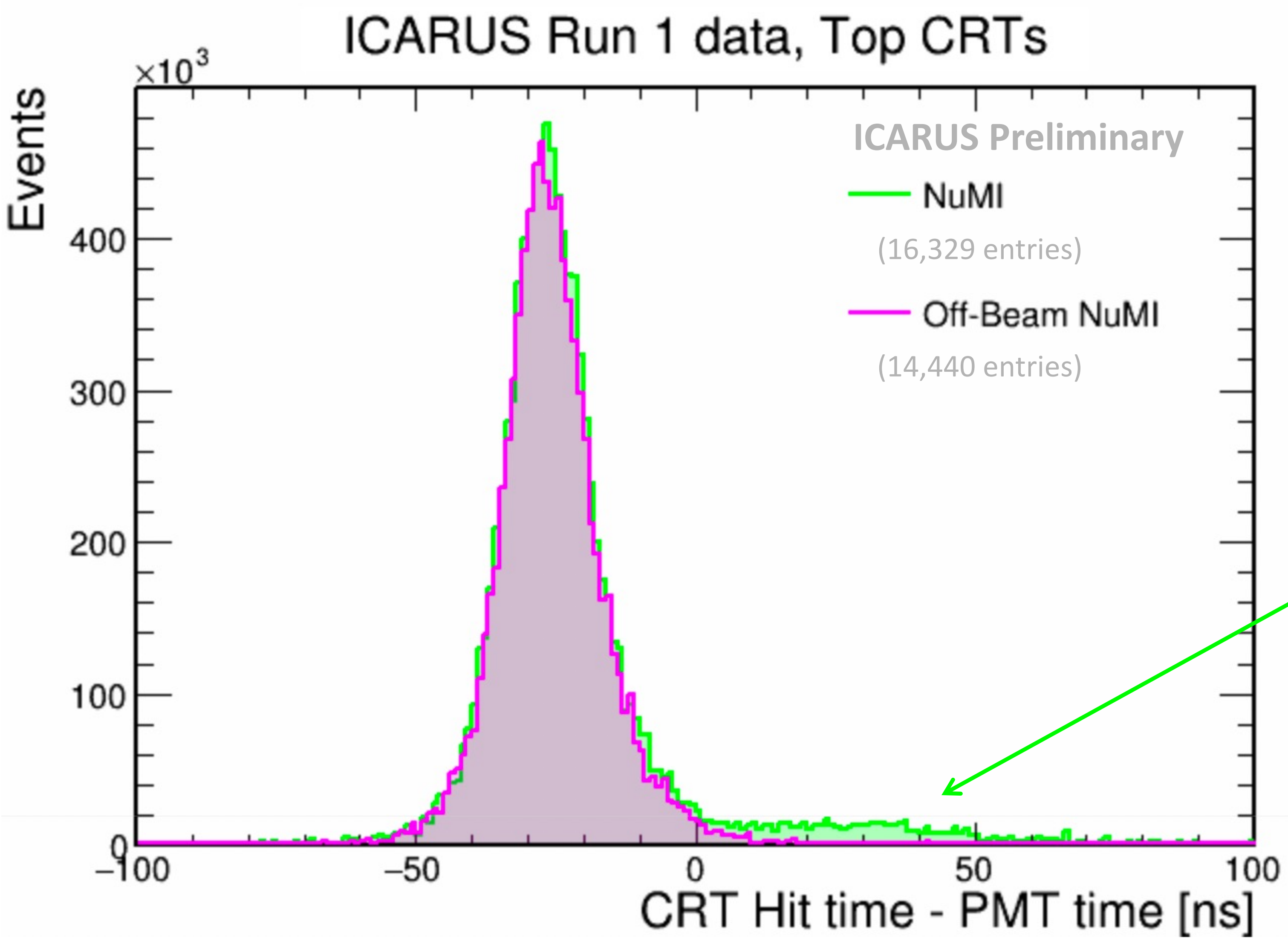
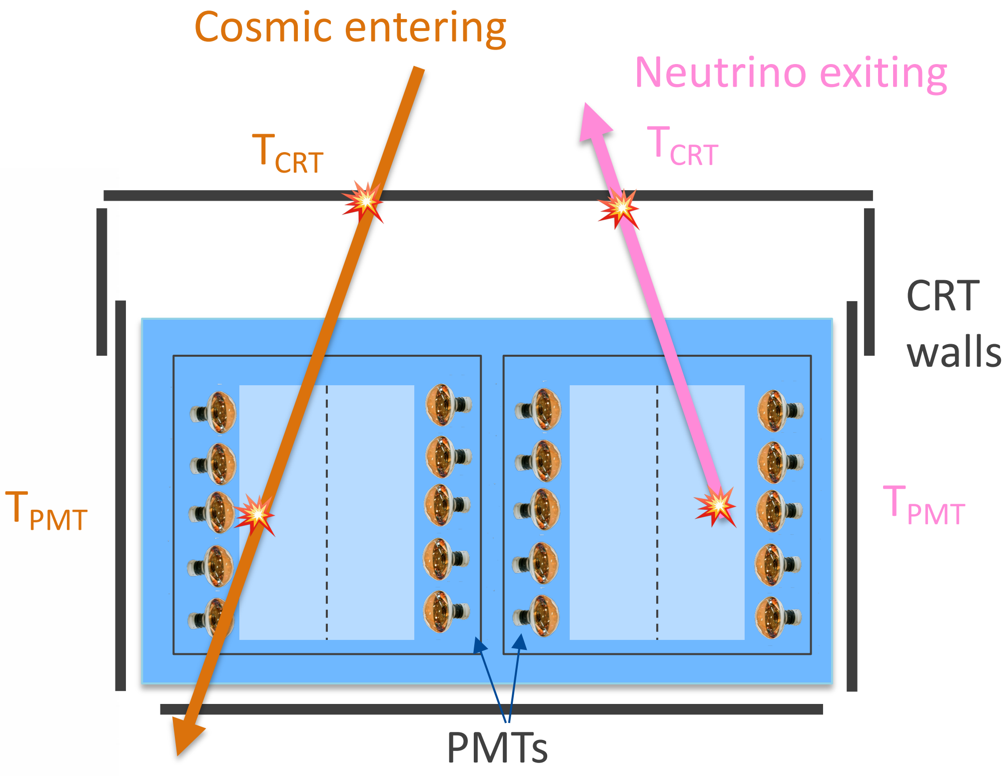






CRT Time – PMT time with beam data



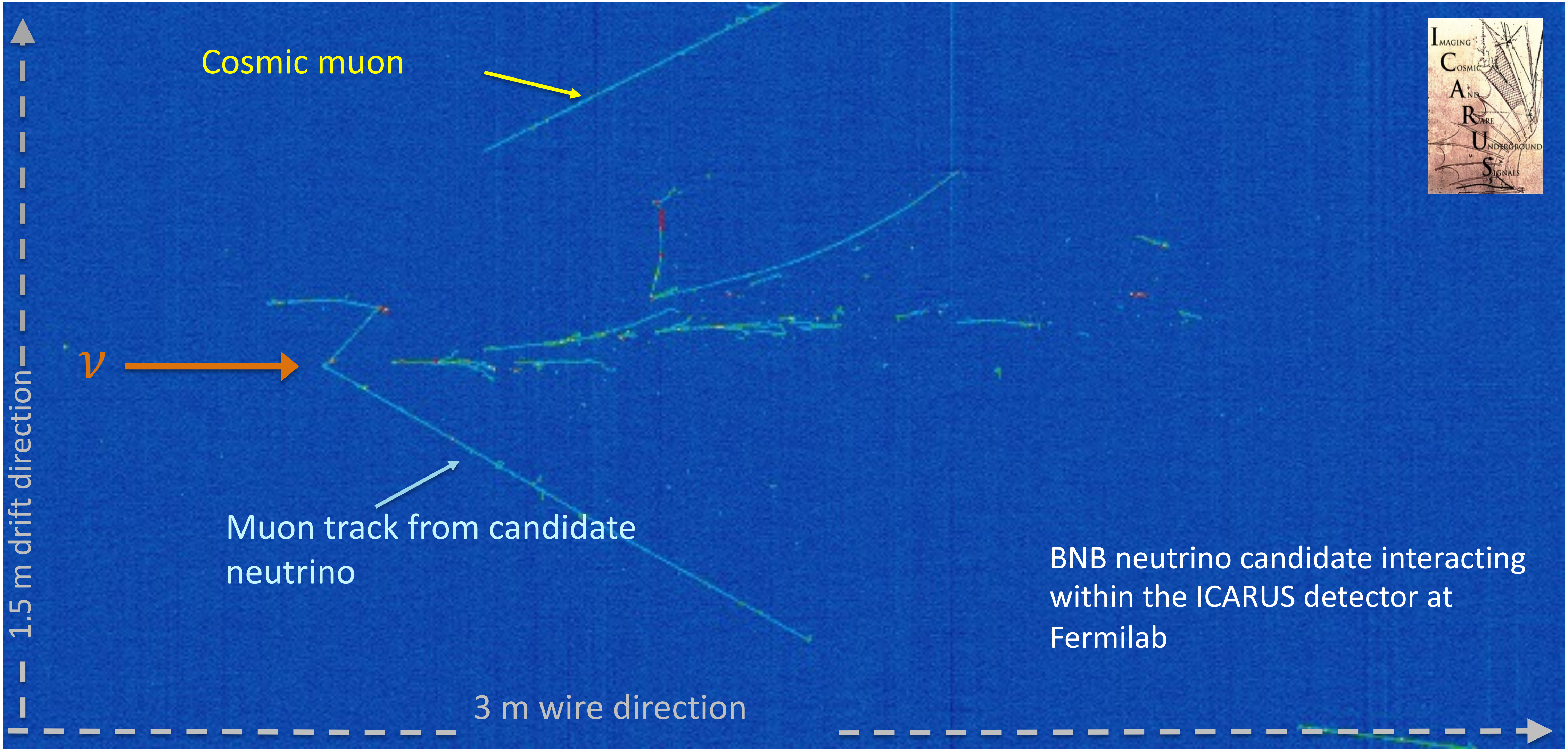


- Comparing the off-beam and on-beam distributions, we can see a clear effect from tracks "exiting" the detector through the top CRTs

Summary

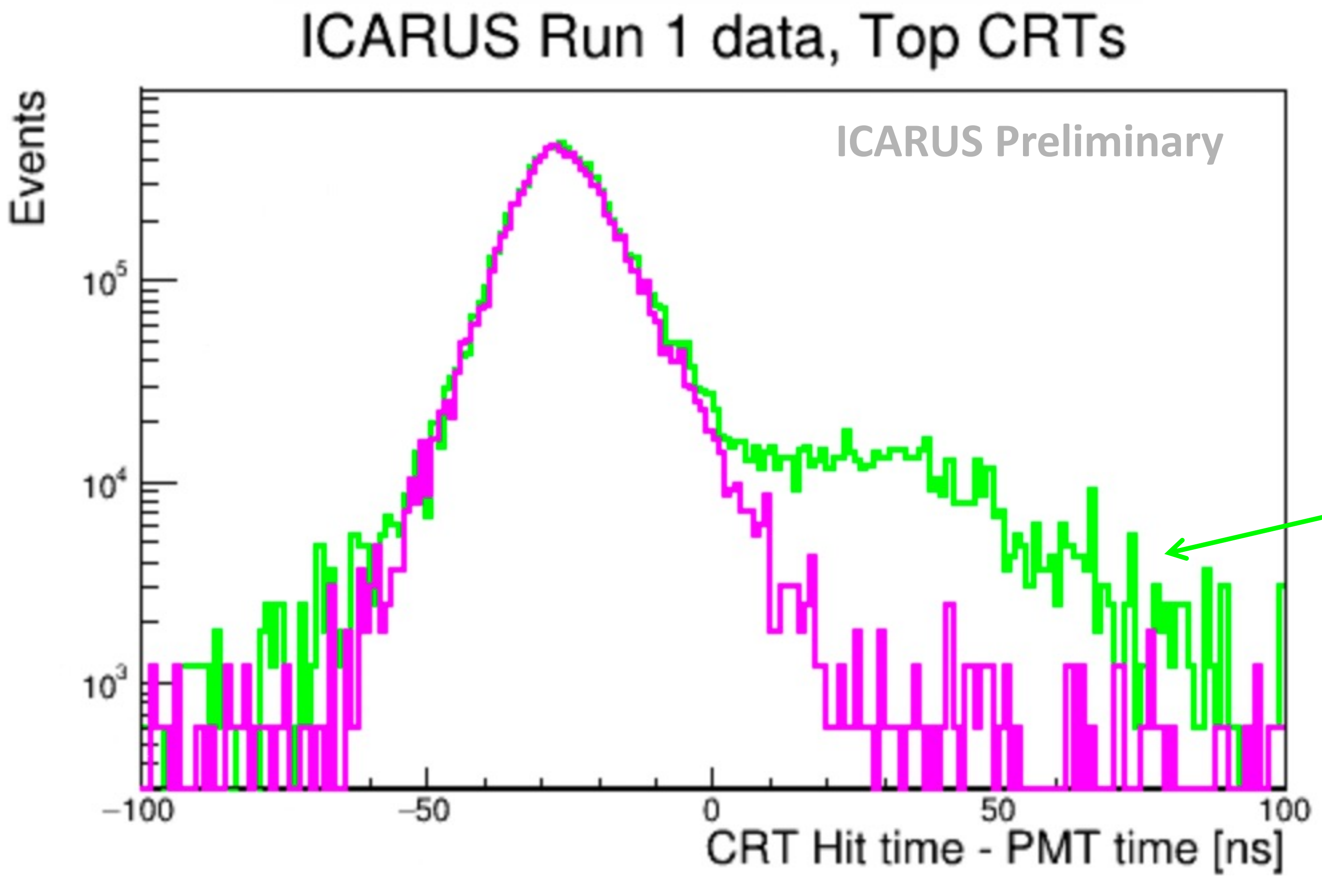
- ICARUS uses light detection in Liquid Argon with the PMT system to identify the interaction time of events, help reconstruct positions of interactions and to generate the trigger for the full detector
- The timing in ICARUS is synchronized across CRT and PMT systems with ~ ns precision, allowing us to perform additional event selection/cosmic rejection
- Stay tuned for exciting physics!

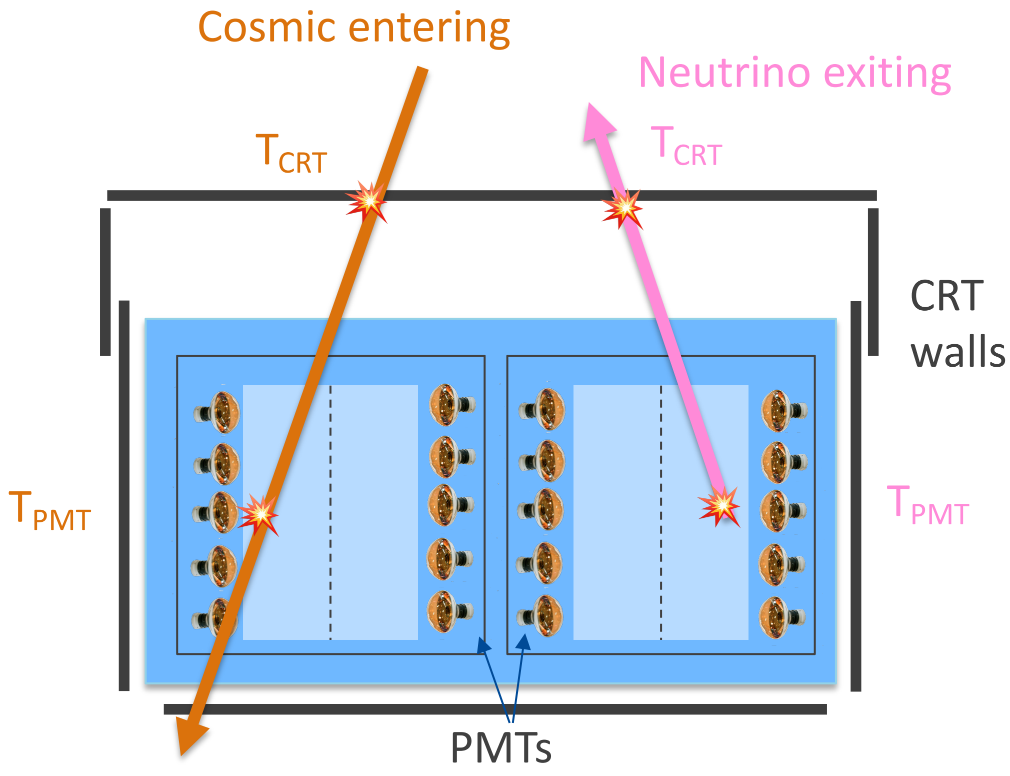
Thanks for listening!



Backup

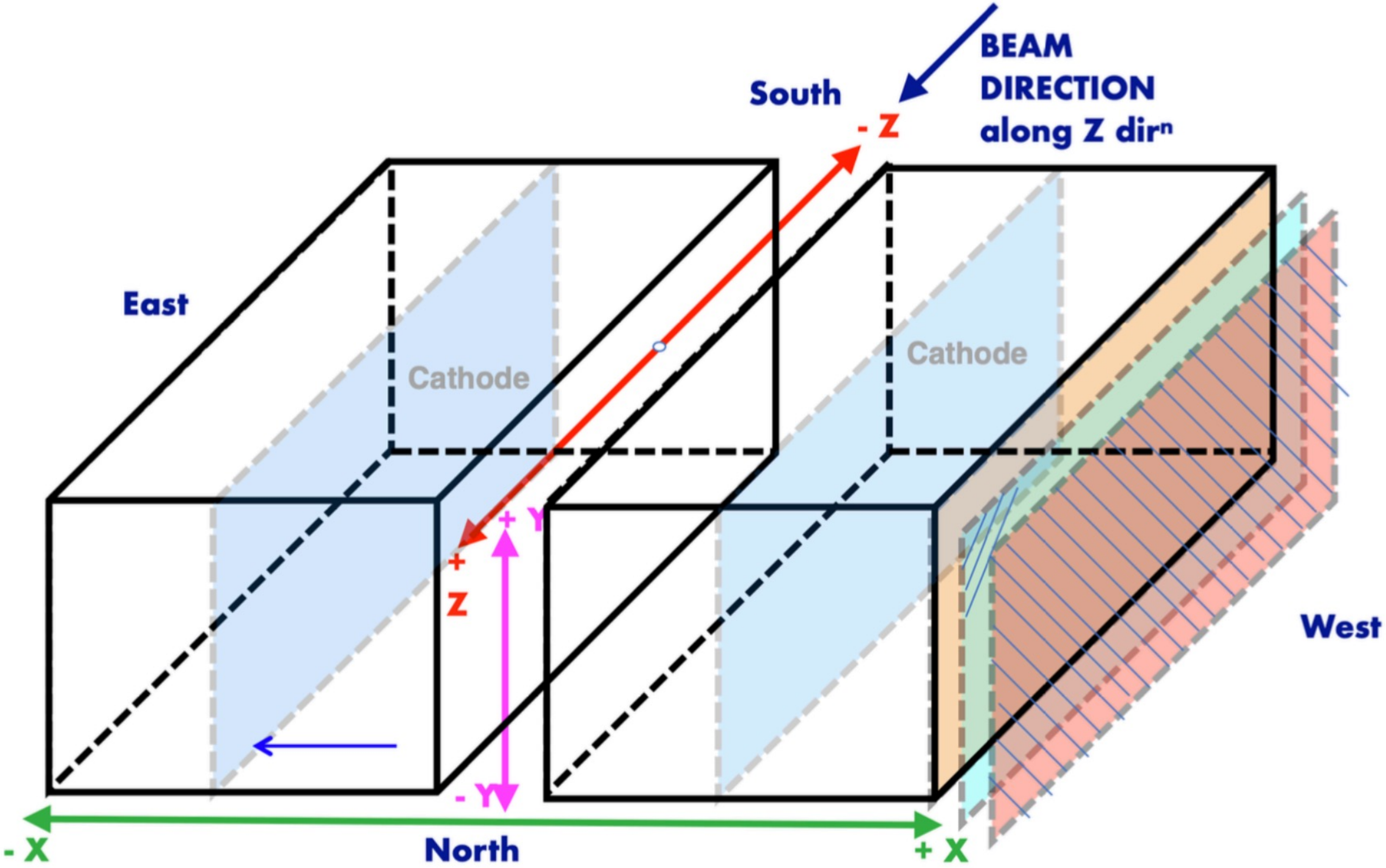
CRT Time – PMT time with beam data



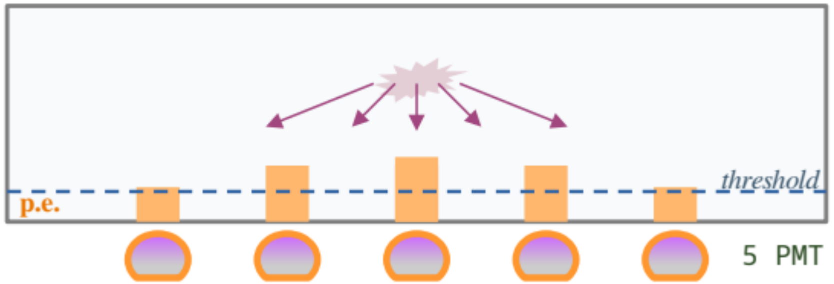


- Comparing the off-beam and on-beam distributions, we can see a clear effect from tracks "exiting" the detector through the top CRTs

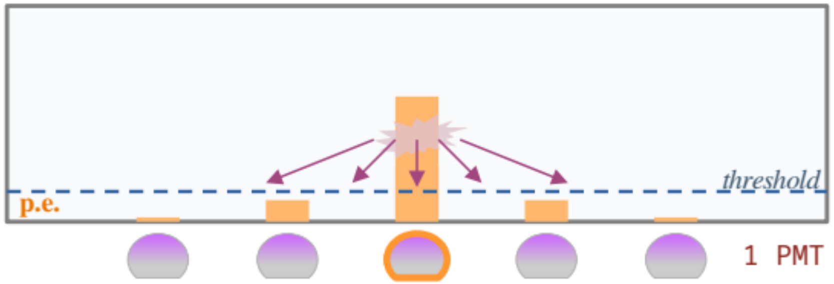
Two ICARUS TPCs



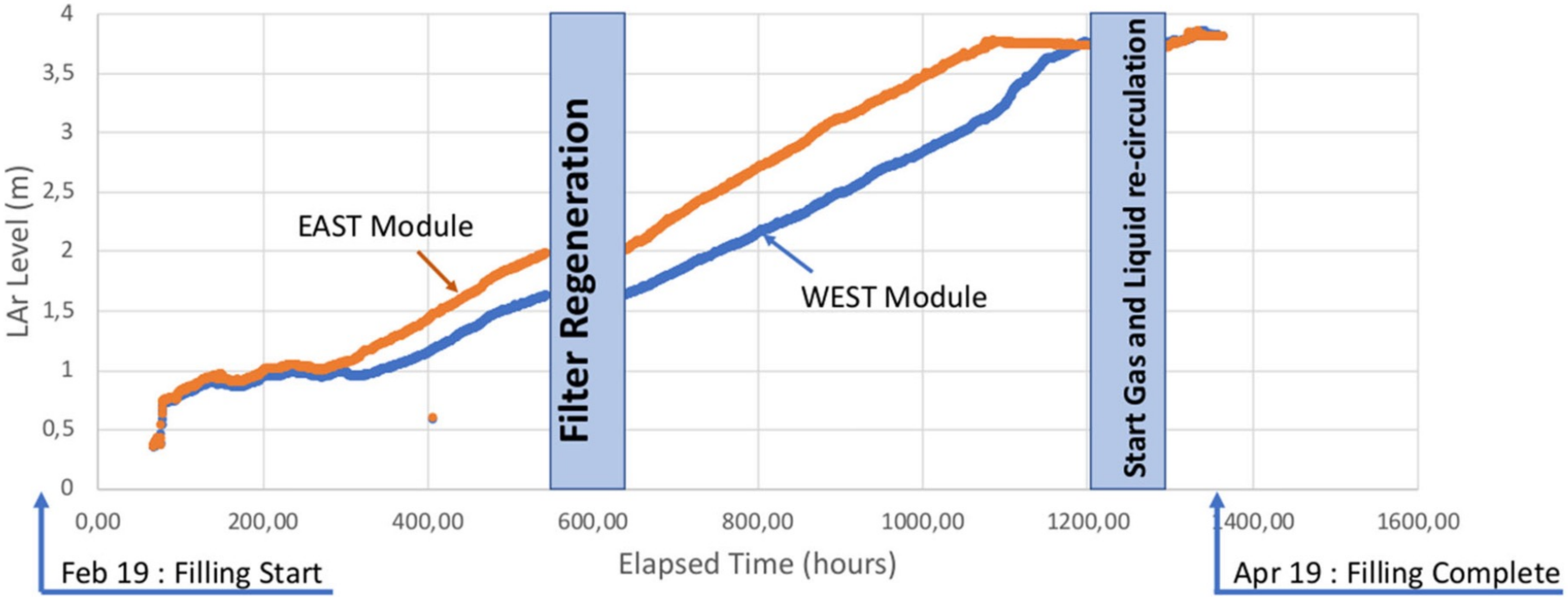
Example of case where adder could improve detector efficiency



Average position of flash with enough light should be able to give flashes on multiple PMTs



.. but if flash occurs too close to the PMT plane, it might only go above threshold on one PMT but still have a significant signal


4
3,5
3
2,5
2
1,5
1
0,5
0
LAr Level (m)
EAST Module
WEST Module
Filter Regeneration
Start Gas and Liquid re-circulation
0,00
200,00
400,00
600,00
800,00
1000,00
1200,00
1400,00
1600,00
Elapsed Time (hours)
Feb 19 : Filling Start
Apr 19 : Filling Complete

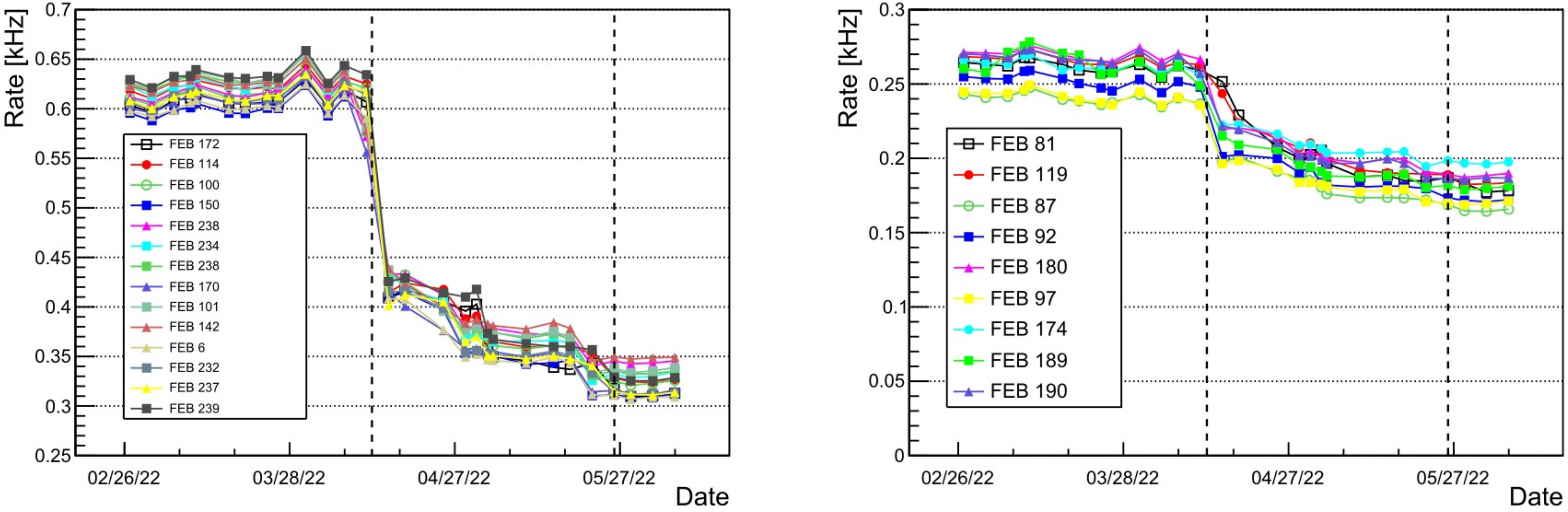
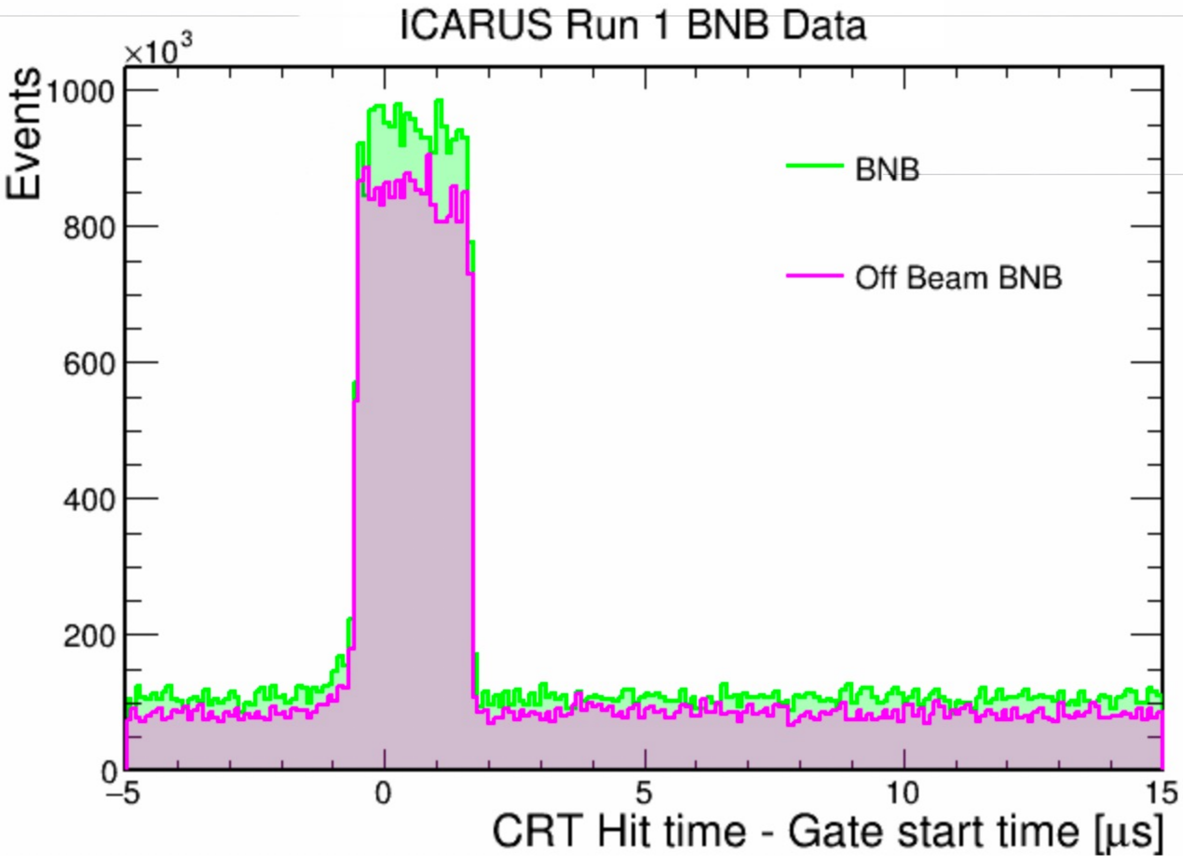
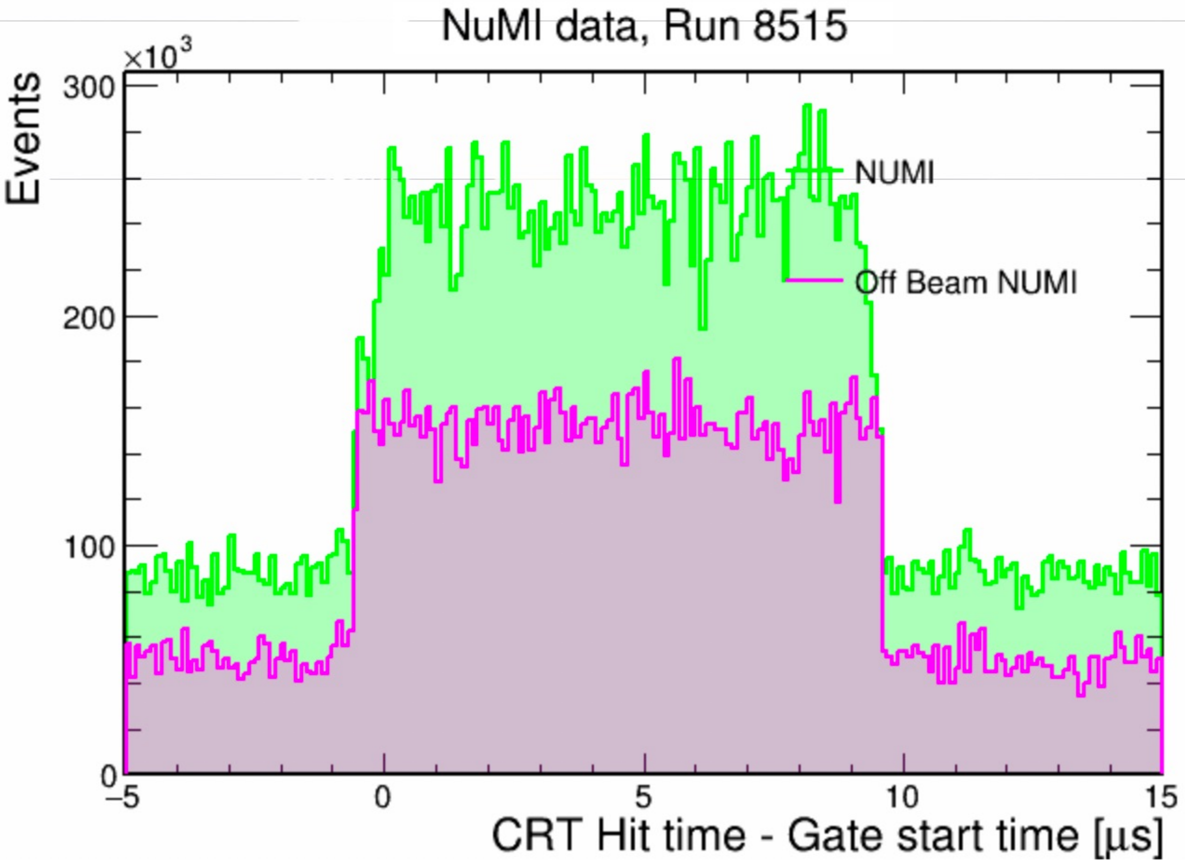


Fig. 23 Cosmic ray rates as a function of time for a set of Top CRT horizontal (left) and vertical (right) modules. Numbers in the legend indicate the module's Front End Board and the black dot lines indicate the beginning and the end of 3 m overburden installation over the displayed modules: the rates reduced from 610 (260) Hz before to 330 (180) Hz after the installation of the overburden for the horizontal (vertical) modules


ICARUS Run 1 BNB Data
×10^3
Events
1000
800
600
400
200
0
−5
0
5
10
15
CRT Hit time - Gate start time [µs]
BNB
Off Beam BNB


NuMI data, Run 8515
×10^3
Events
300
200
100
0
−5
0
5
10
15
CRT Hit time - Gate start time [µs]
NUMI
Off Beam NUMI

Side CRT optical readout system

- Two layers ("inner" and "outer" layers) of 173 repurposed MINOS scintillator modules
  - Each module has 20 strips of scintillator embedded with wavelength shifting fibers
  - Fibers are collected into snouts on the end of the modules
- New optical readout design with SiPMs
  - Modules previously readout by PMTs
  - Optically combine two fibers onto a single SiPM to optimize light yield and have complete active coverage of the fibers