Brookhaven National Laboratory

LIDINE 2024 Light Detection in Noble Elements

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Calibration and Timing Performance of the Light Detection System in the ICARUS Detector

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on behalf of the ICARUS collaboration

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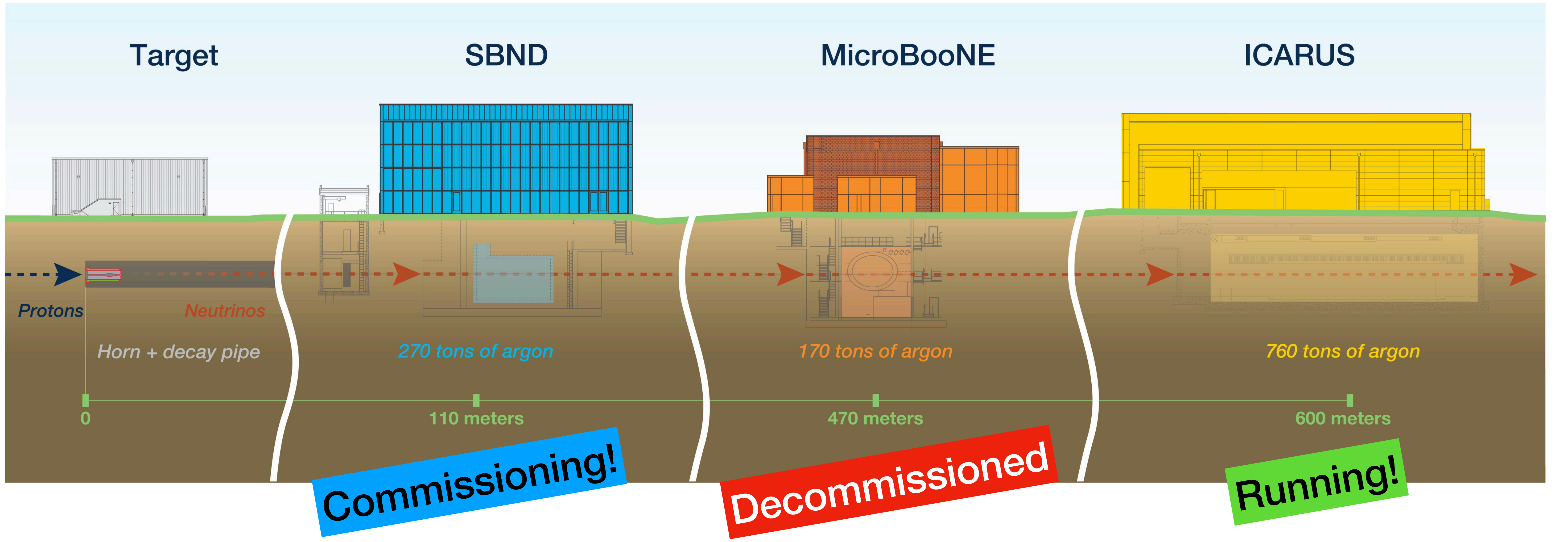
Imaging Cosmic And Rare Underground Signals

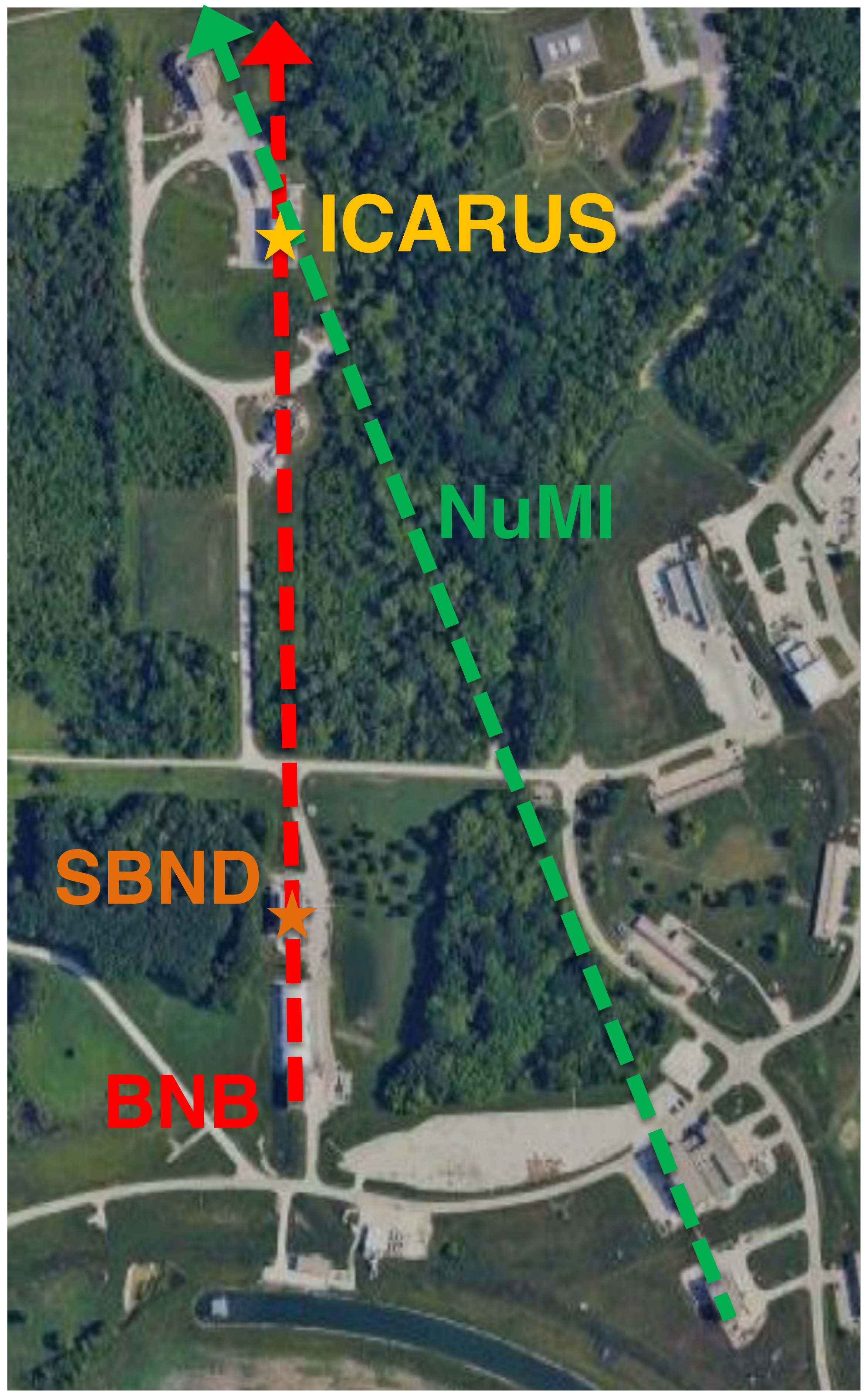
SBN Program

ICARUS @ Fermilab

ICARUS is the Far Detector of the **Short Baseline Neutrino (SBN) program**, sitting 600 m on-axis on the Booster Neutrino Beam (**BNB**) and 6°off-axis from the Neutrinos at the Main Injector (**NuMI**) beam.

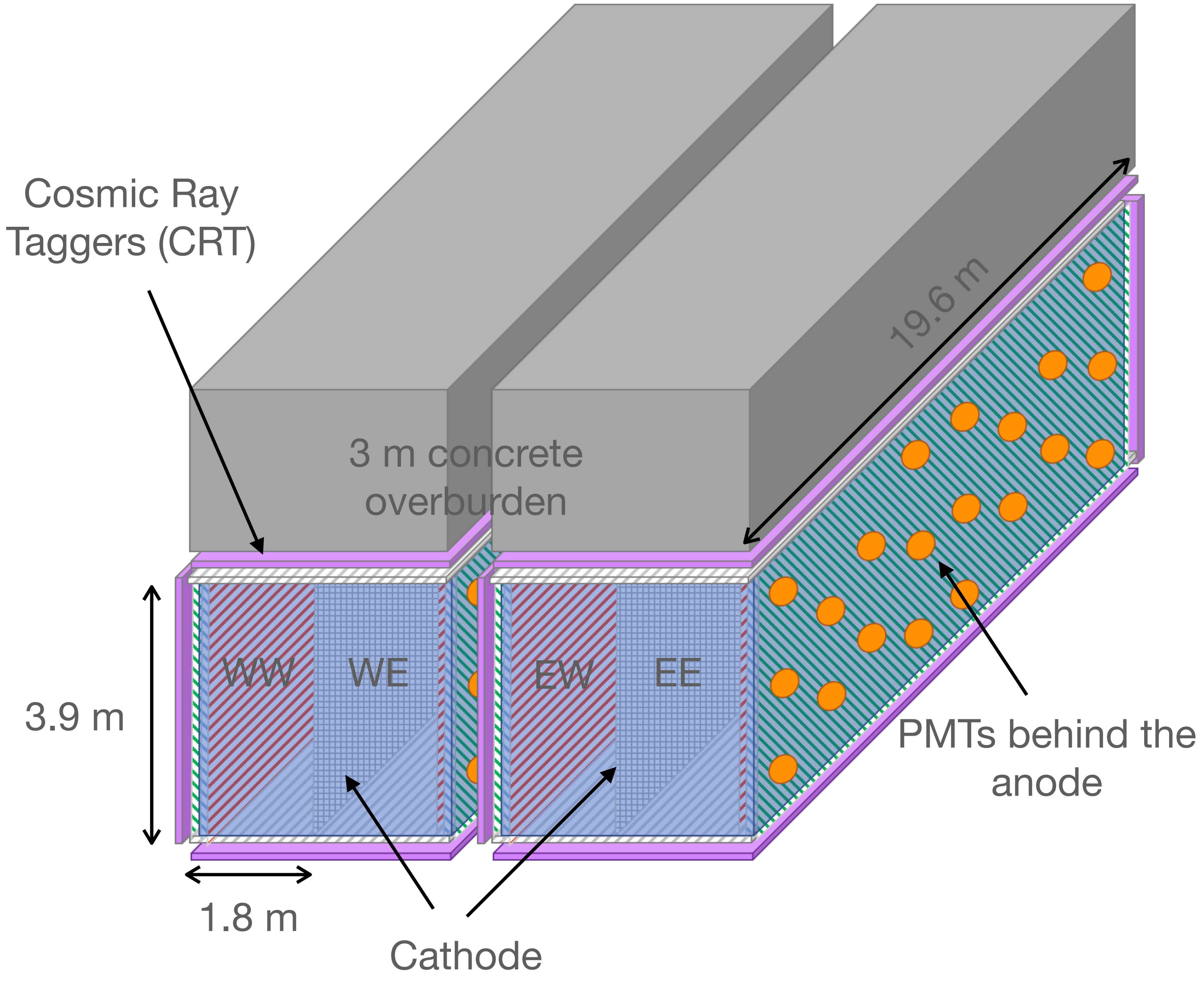
ICARUS recently concluded its third physics run in July 2024.





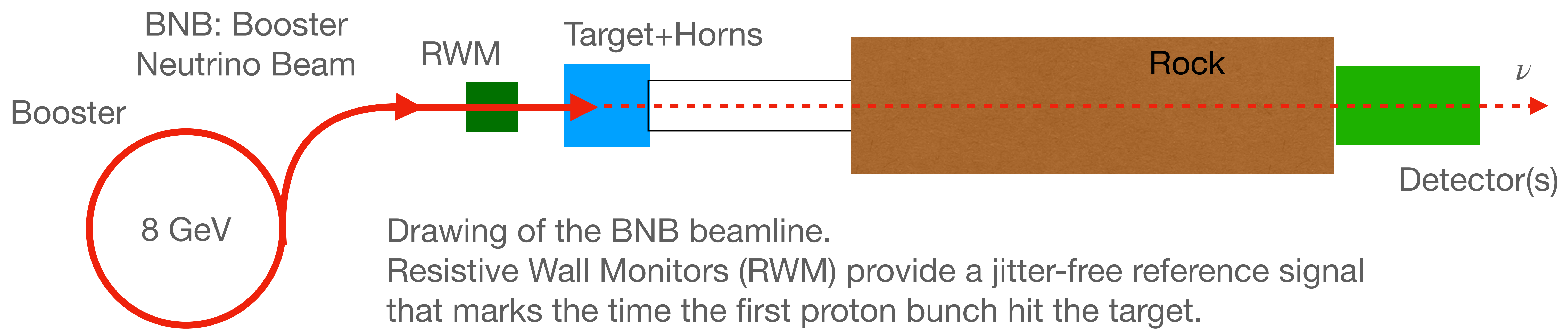
ICARUS LArTPCs

ICARUS is the **largest liquid argon detector** currently in operation (~476 active tons).
It's divided into 2 modules, each hosting 2 TPCs that share a central cathode plane.



https://doi.org/10.1140/epjc/s10052-023-11610-y

Neutrino beam timing

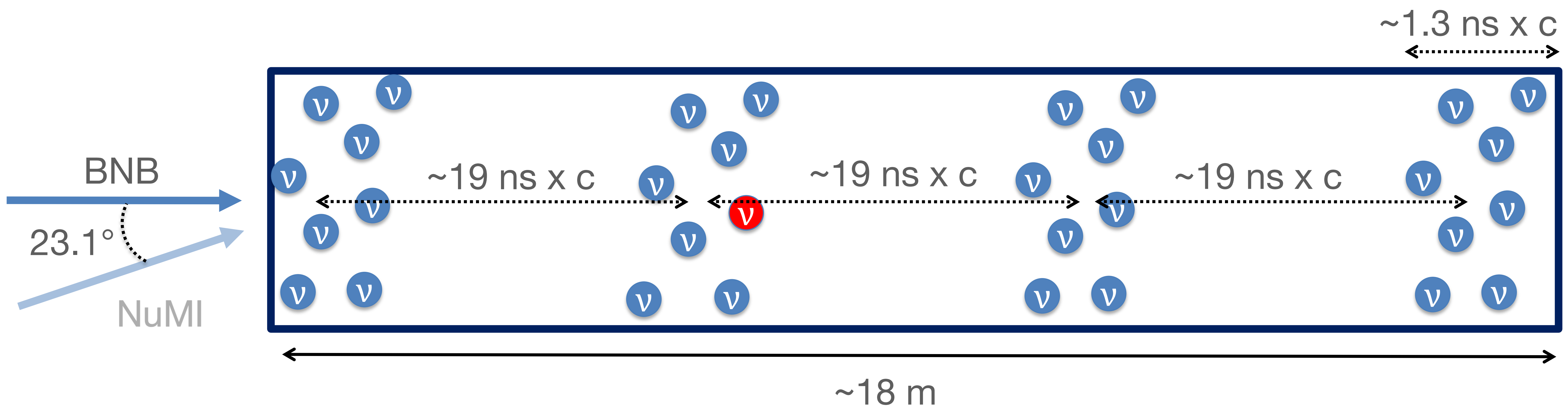


Drawing of the BNB beamline.
Resistive Wall Monitors (RWM) provide a jitter-free reference signal that marks the time the first proton bunch hit the target.

Beam timing:

- BNB: 1.6 μs spill, 81 bunches, 18.9 ns spacing (52.8 MHz)
- NuMI: 9.6 μs spill, 486 bunches, 18.8 ns spacing (53.1 MHz)

Neutrino propagation (+ meson decays) only adds a constant offset, so neutrinos inherit the **time profile of the proton bunches.** Precise event timing allows to tag neutrinos directly with no use of charge!



BNB bunches crossing ICARUS

Achieving this goal requires a relative and absolute calibration strategy towards **O(ns)** resolution!

- **Overview of the Light Readout System**
- Laser Calibrations
- Cosmics Calibrations
- Beam Event Timing
- Summary

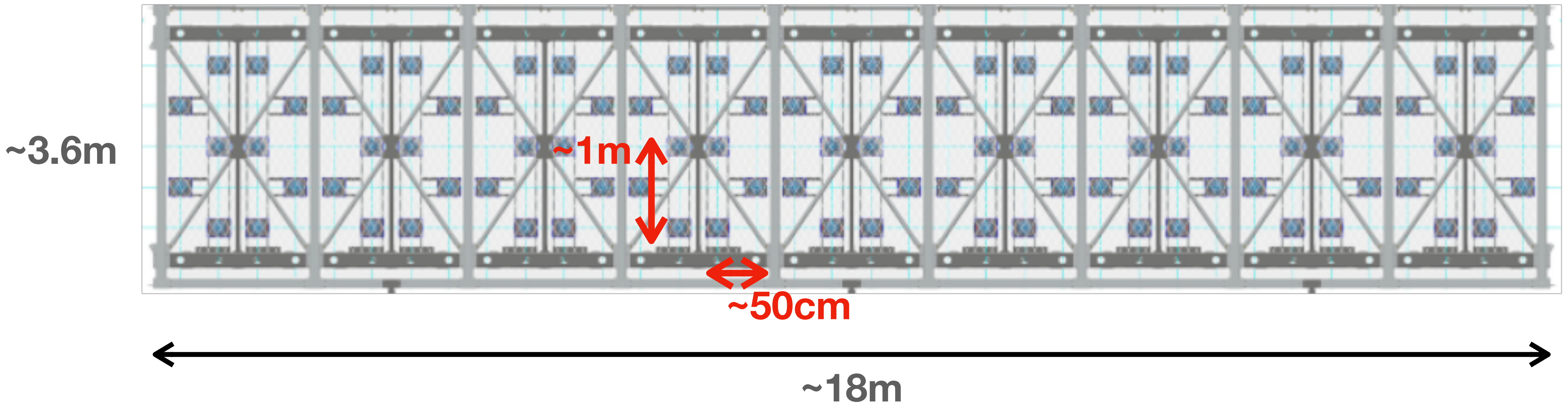
ICARUS light detection system

360 Hamamatsu R5912-MOD 8” PMTs mounted behind the anode wires.

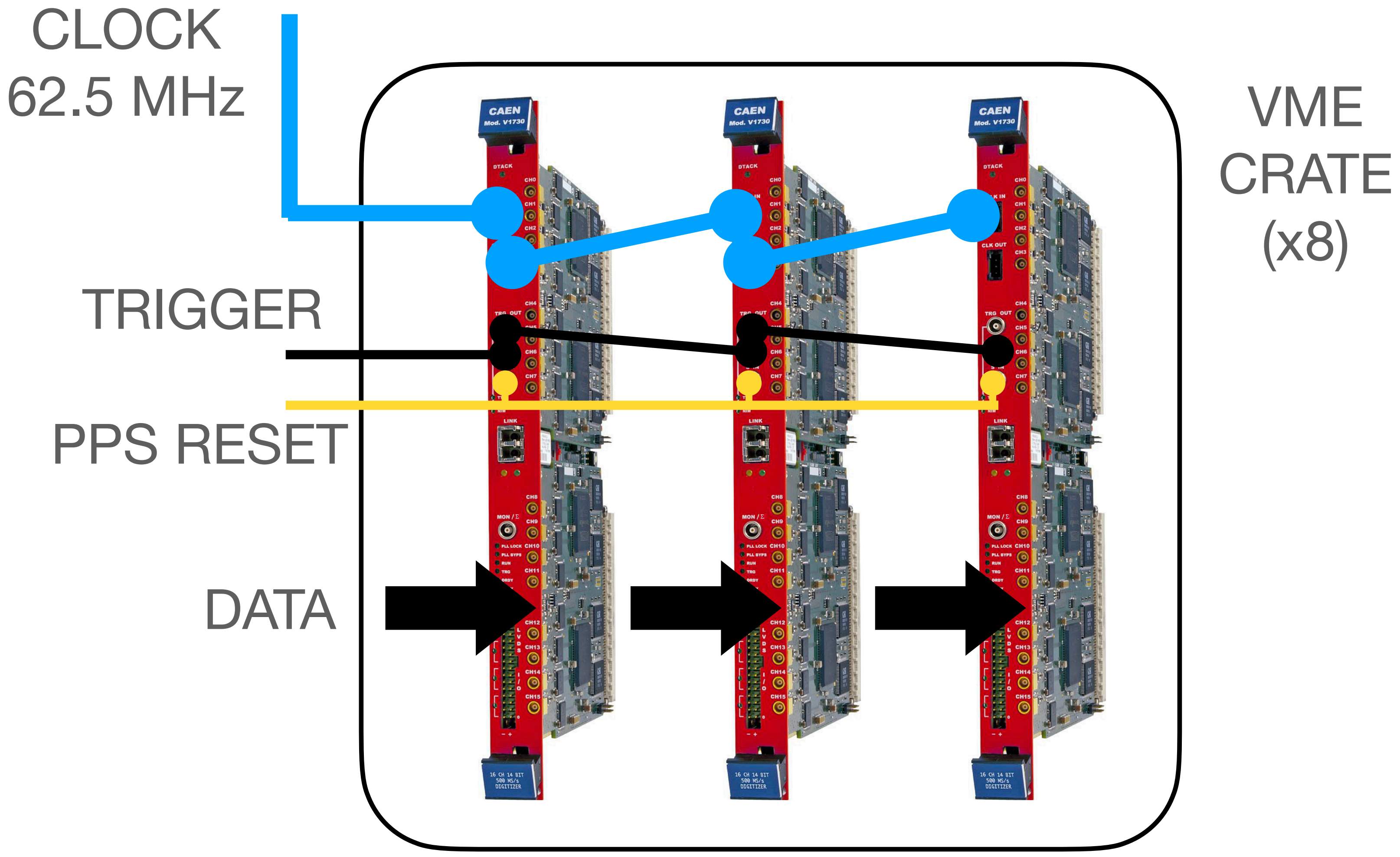
TPB coating for 128nm sensitivity.

Placed in a **“honeycomb” structure** on the four TPC “walls” (90 per TPC wall, 180 per module).

24 **CAEN V1730B** digitizers (500 MSa/s), 15 PMTs + 1 spare channel per board.



“Honeycomb” pattern on one wall



Timing Calibration Strategy

GOAL: Instantaneous signals should be reconstructed as simultaneous by all the PMTs in the same module.

ICARUS currently uses **three levels** of timing corrections/inter-calibrations deployed at different stages of the optical data flow:

1. **Hardware Synchronization**: removes jitters between the CAEN V1730 readout boards and the trigger hardware.
2. **Laser Calibrations**: cancels differences in the PMT transit and readout times (e.g: voltage applied, fiber delays).
3. **Cosmics Calibration**: further equalization of the PMT times using downward-going cosmic muons.

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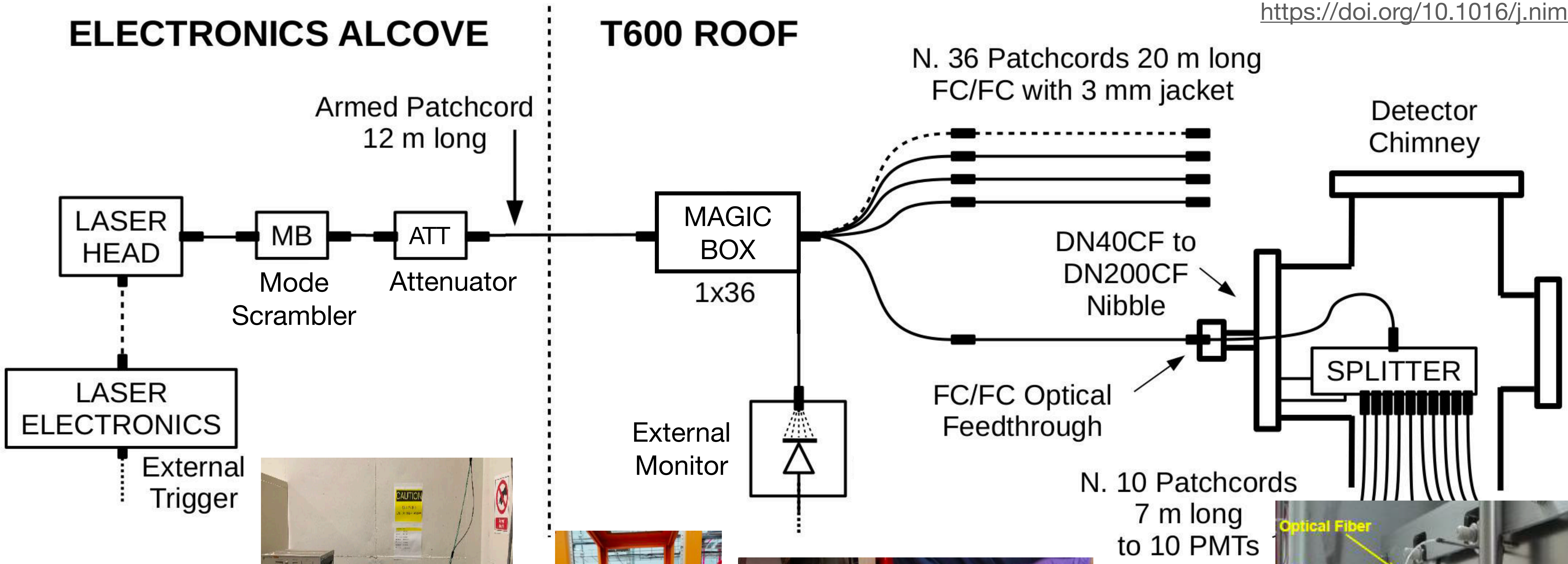
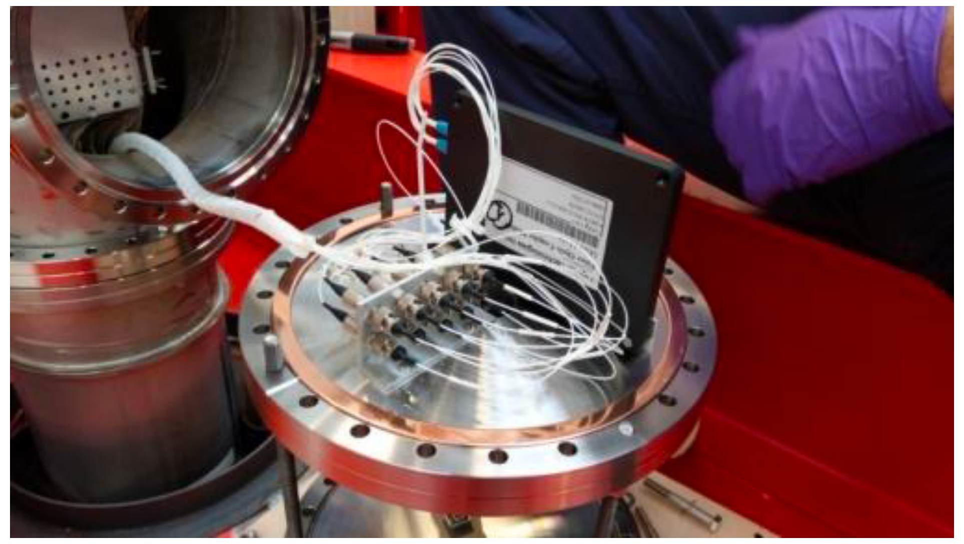
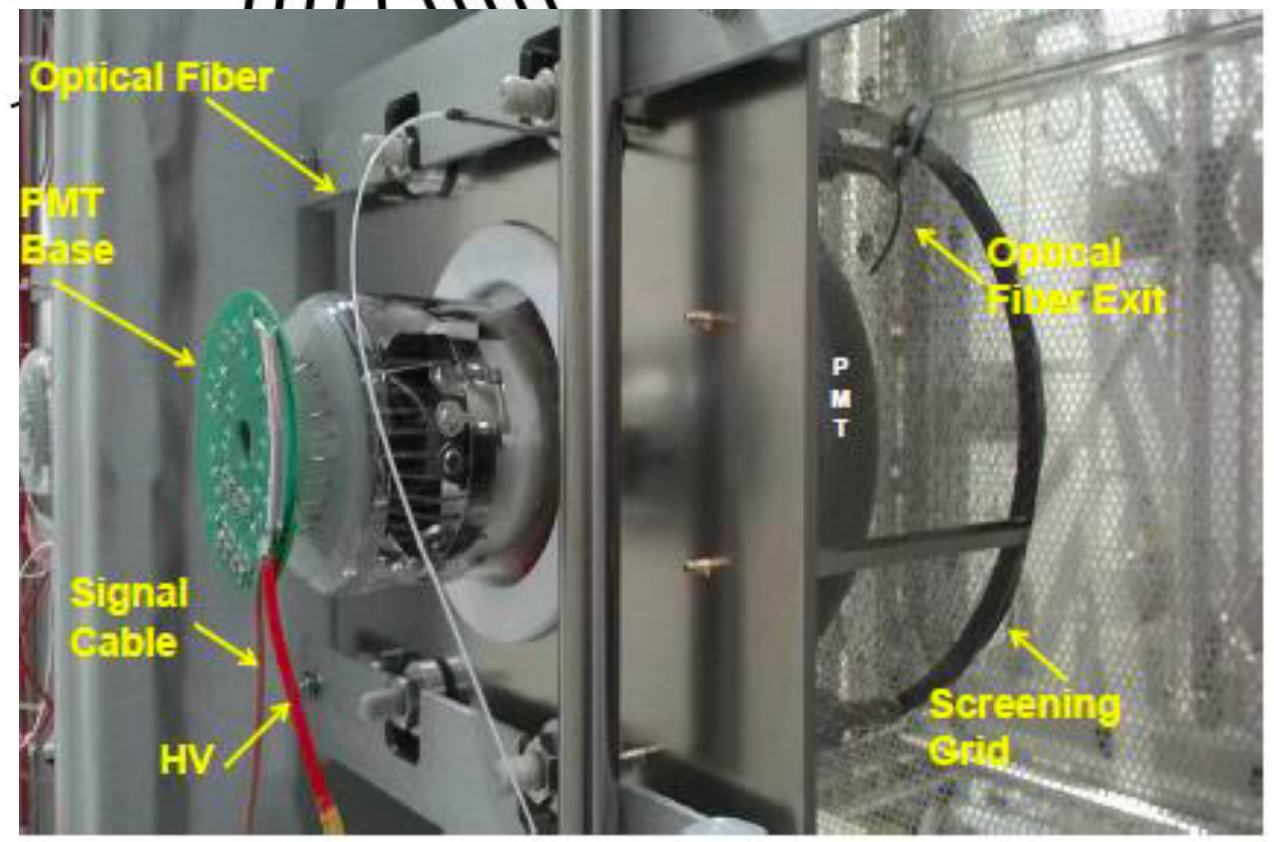
Overview of the laser system

https://doi.org/10.1016/j.nima.2024.169670

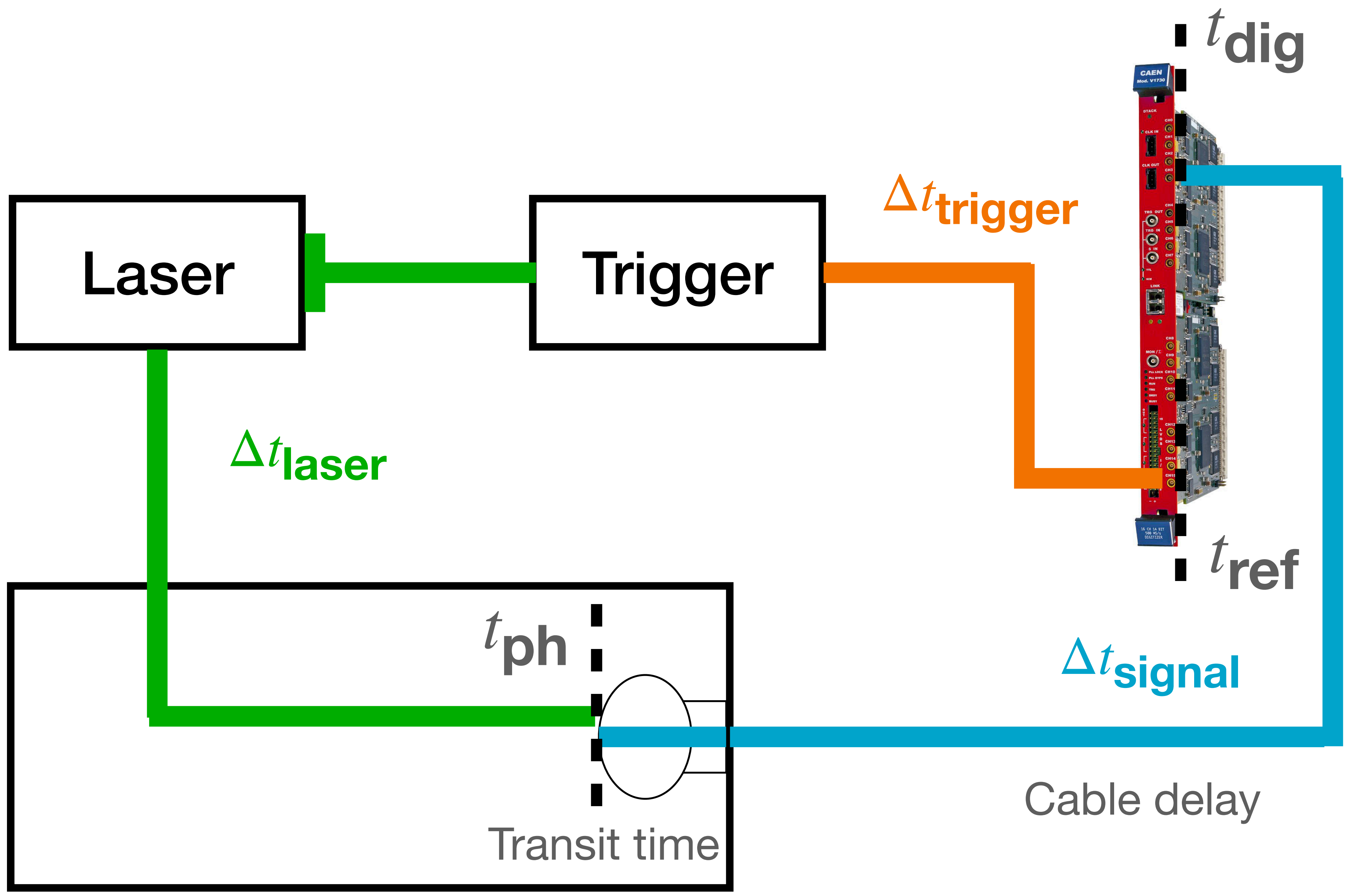






Signal propagation delays

Measuring **signal delays** between light hitting the photocathode (t_{ph}) and its signal being digitized (t_{dig}) using **instantaneous laser pulses** ($\lambda = 405$ nm, FWHM 60 ps) sent to each PMT.



$$\Delta t_{\text{signal}} = t_{\text{dig}} - t_{\text{ph}}$$

$$\Delta t_{\text{meas}} = t_{\text{dig}} - t_{\text{ref}}$$

$$\Delta t_{\text{signal}} = \Delta t_{\text{meas}} + \Delta t_{\text{trigger}} - \Delta t_{\text{laser}}$$

Time difference between signal and reference

(These are well-known and measured beforehand)

Laser calibrations

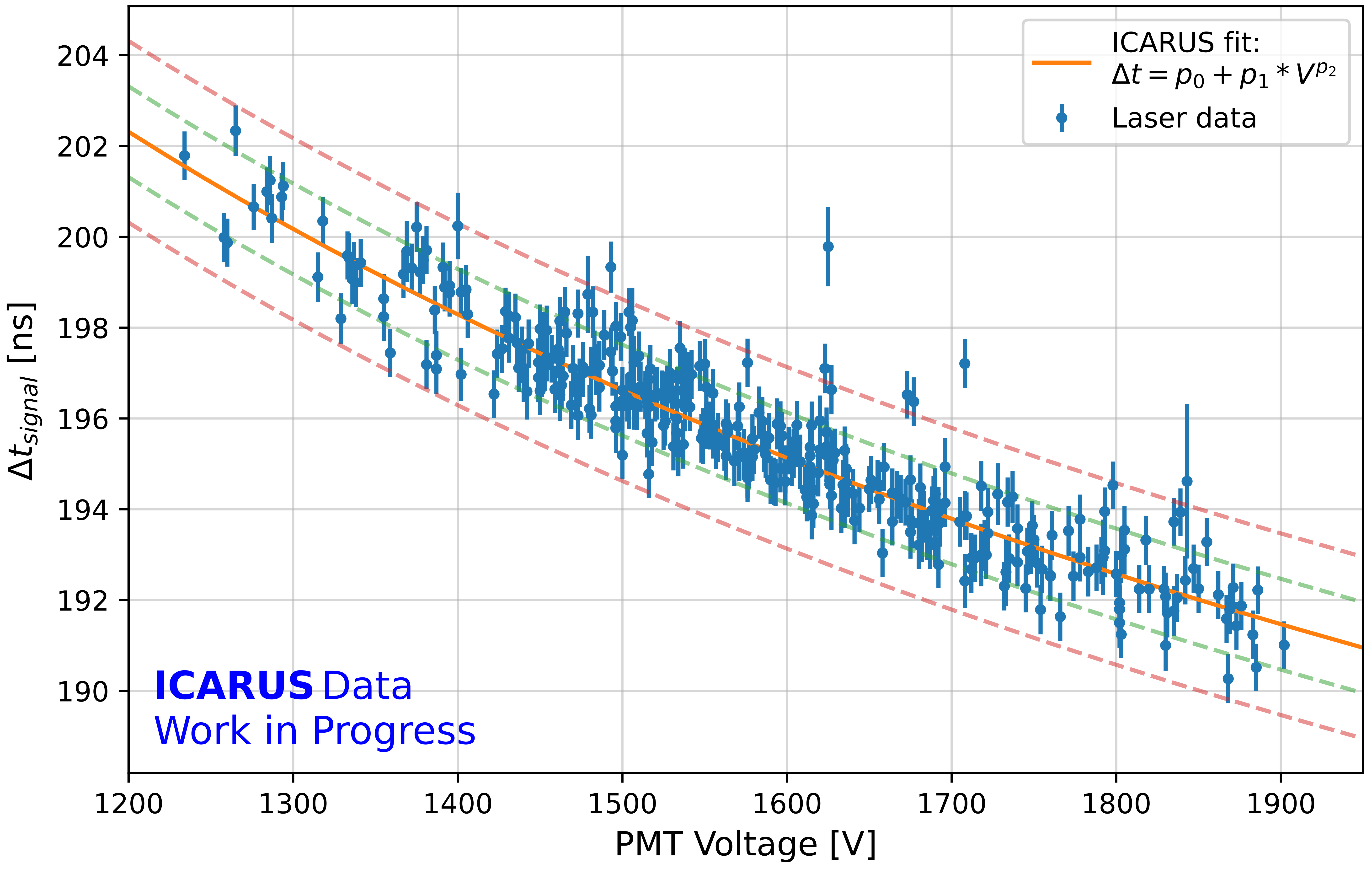
Delays are **O(200ns)**: 38 m of the signal cables.

Voltage differences produce ~10 ns spread (electron transit time).

These delays are stored in a database and **subtracted** to correct the digitized pulse times:

$$t^c_{\text{dig}} = t_{\text{dig}} - \Delta t_{\text{signal}}$$

PMT signal delays as a function of applied HV



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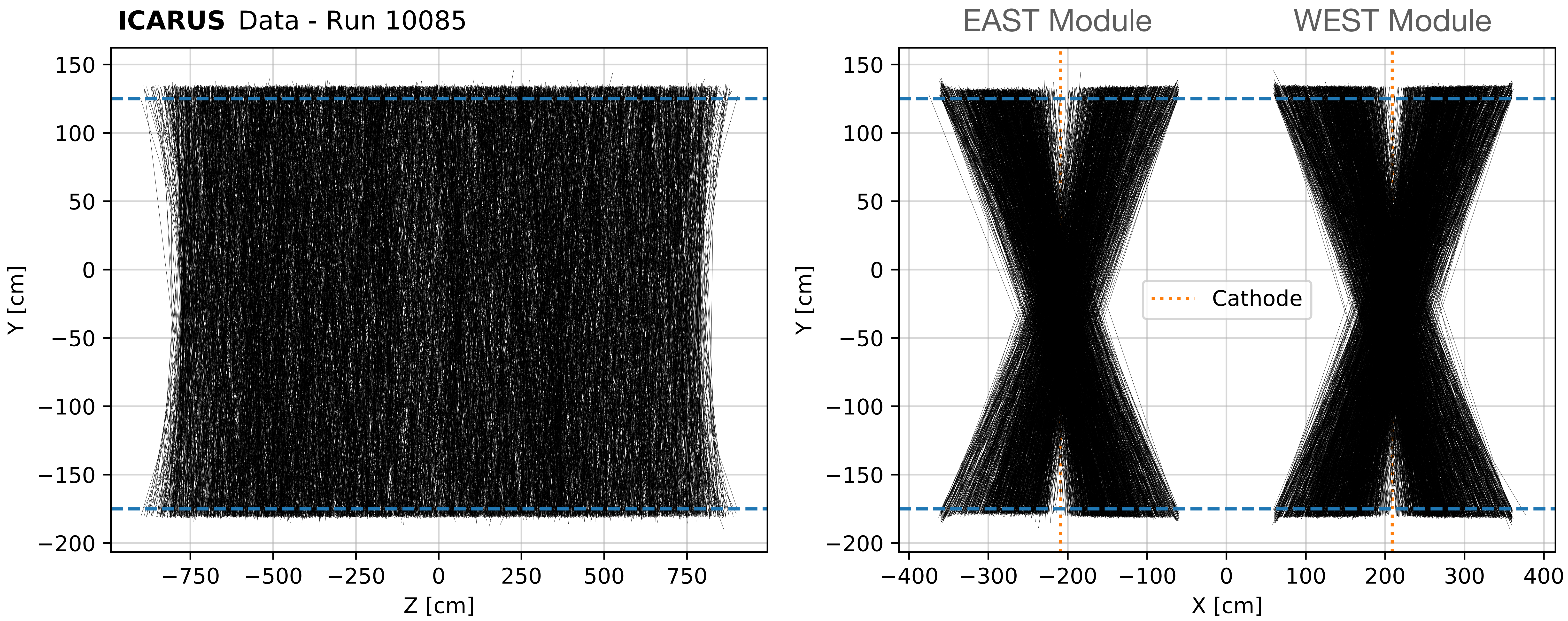
Calibration with cosmic tracks

Laser light is point-like and shines on a specific spot on the photocathode according to the PMT. Also, 5-7% of PMTs do not see direct laser light.

IDEA: Use **downward-going muon tracks** that shine uniformly on the PMTs, spatially constrained by TPC (or CRT) reconstruction. Happening all the time: no need of special runs!

Selection example:

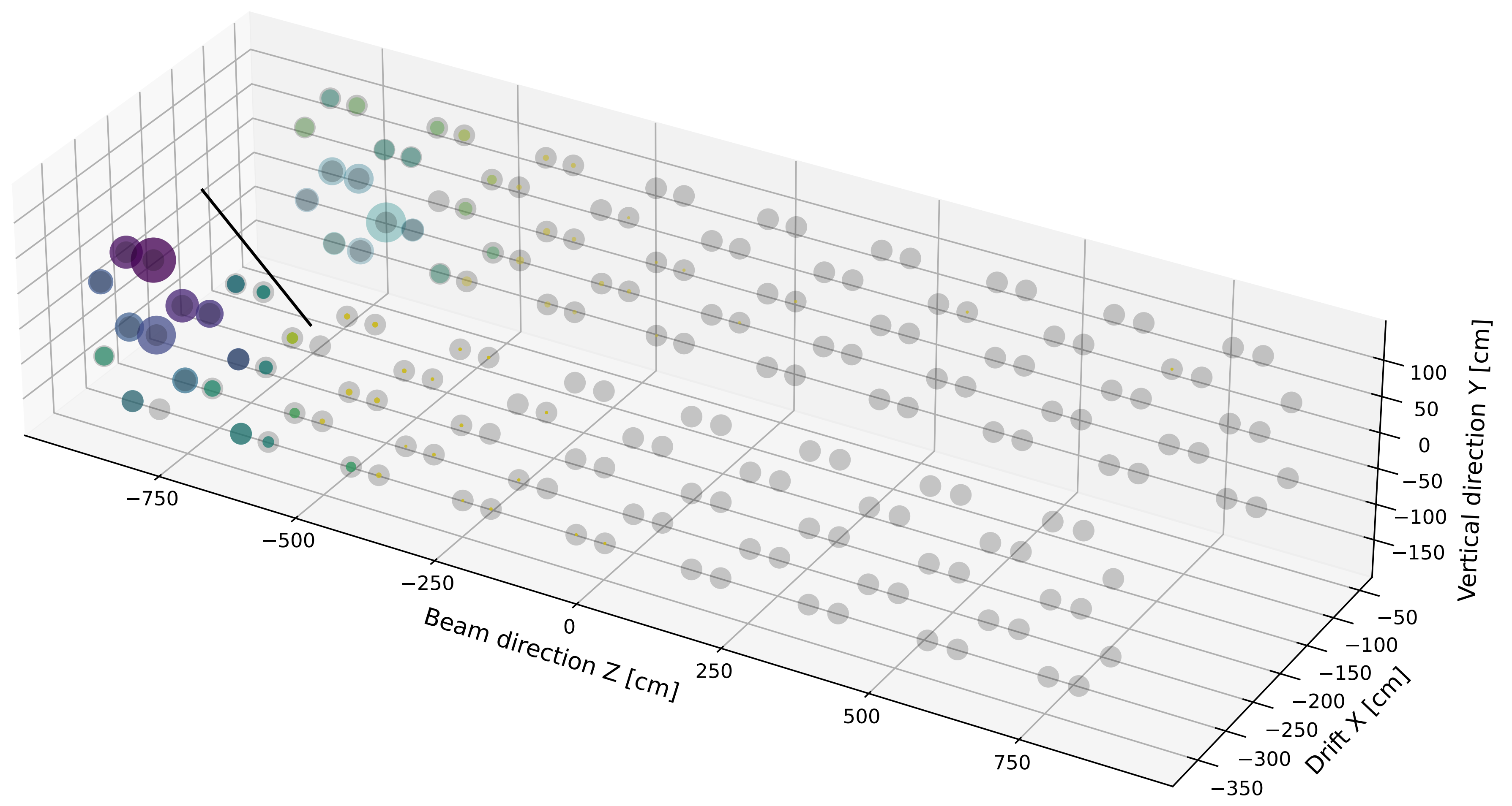
- Cathode crossing tracks
- Verticality with cuts on start/end positions
- Matched with a scintillation "flash" (charge vs light barycenter)

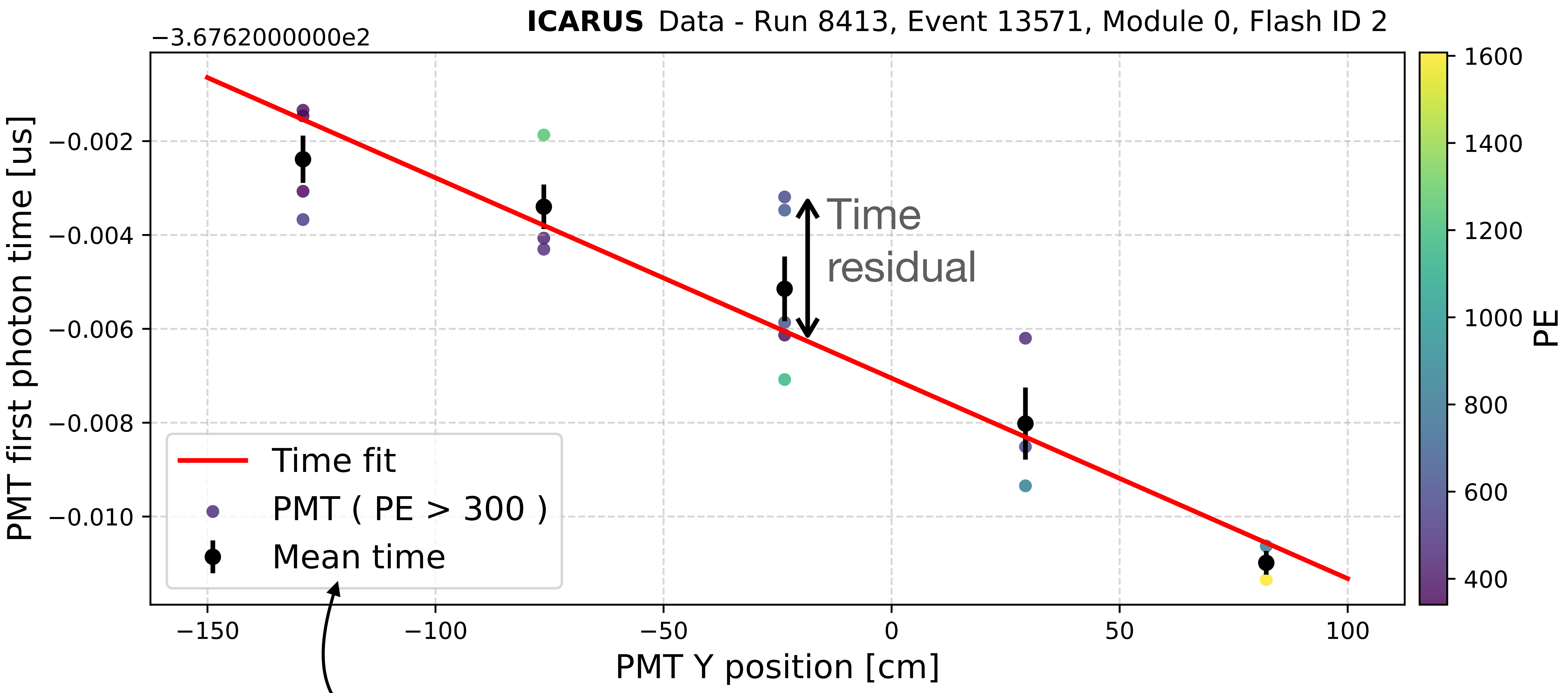


Timing with cosmics

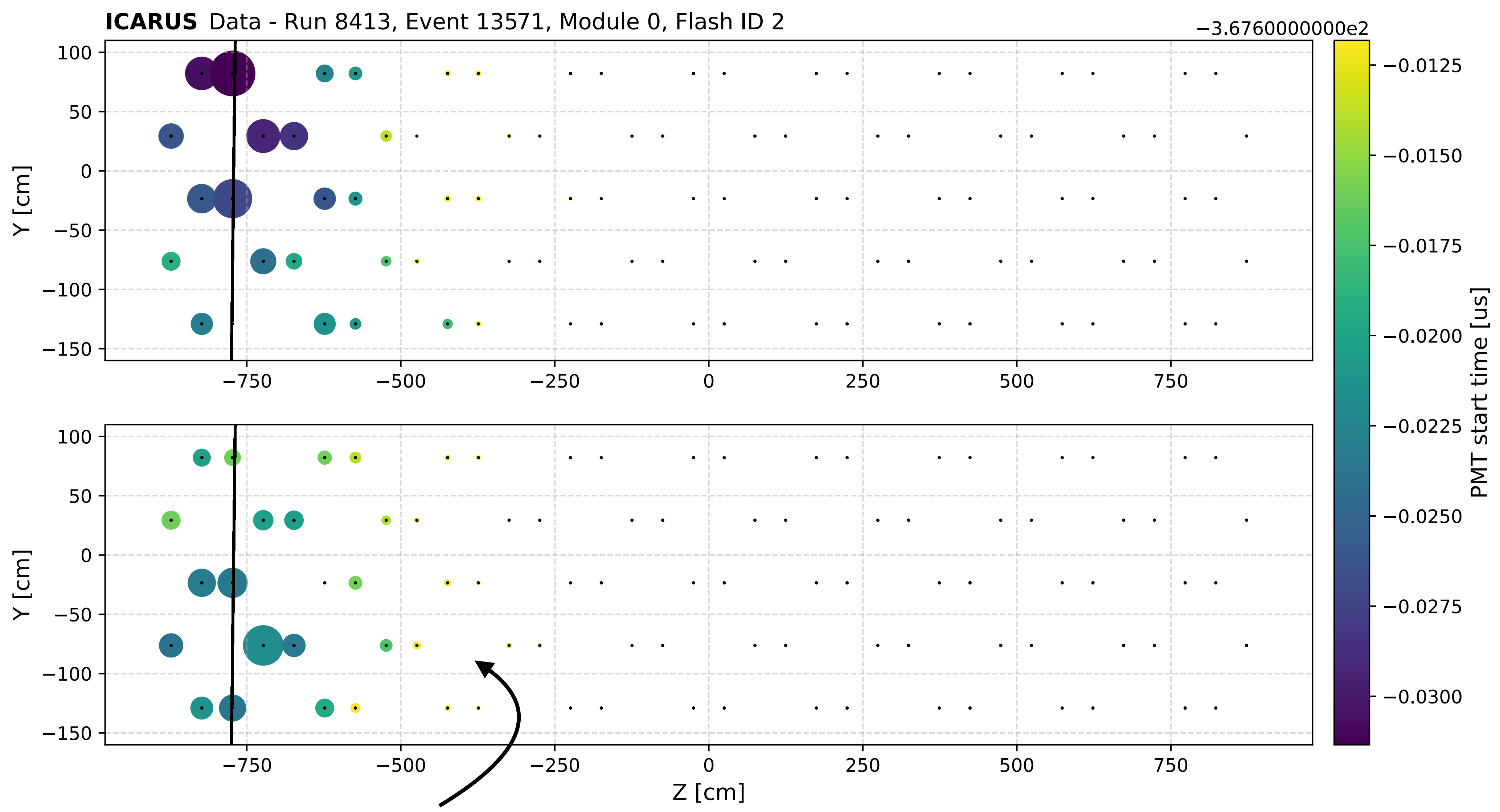
Comparing with the track, a **linear relationship** is expected between PMT y-coordinate and time.

Deviations are due to z-position w.r.t the track or x-coordinate if track is closer to one wall.





Mean between PMTs at the same quota on both wall removes x-dependence

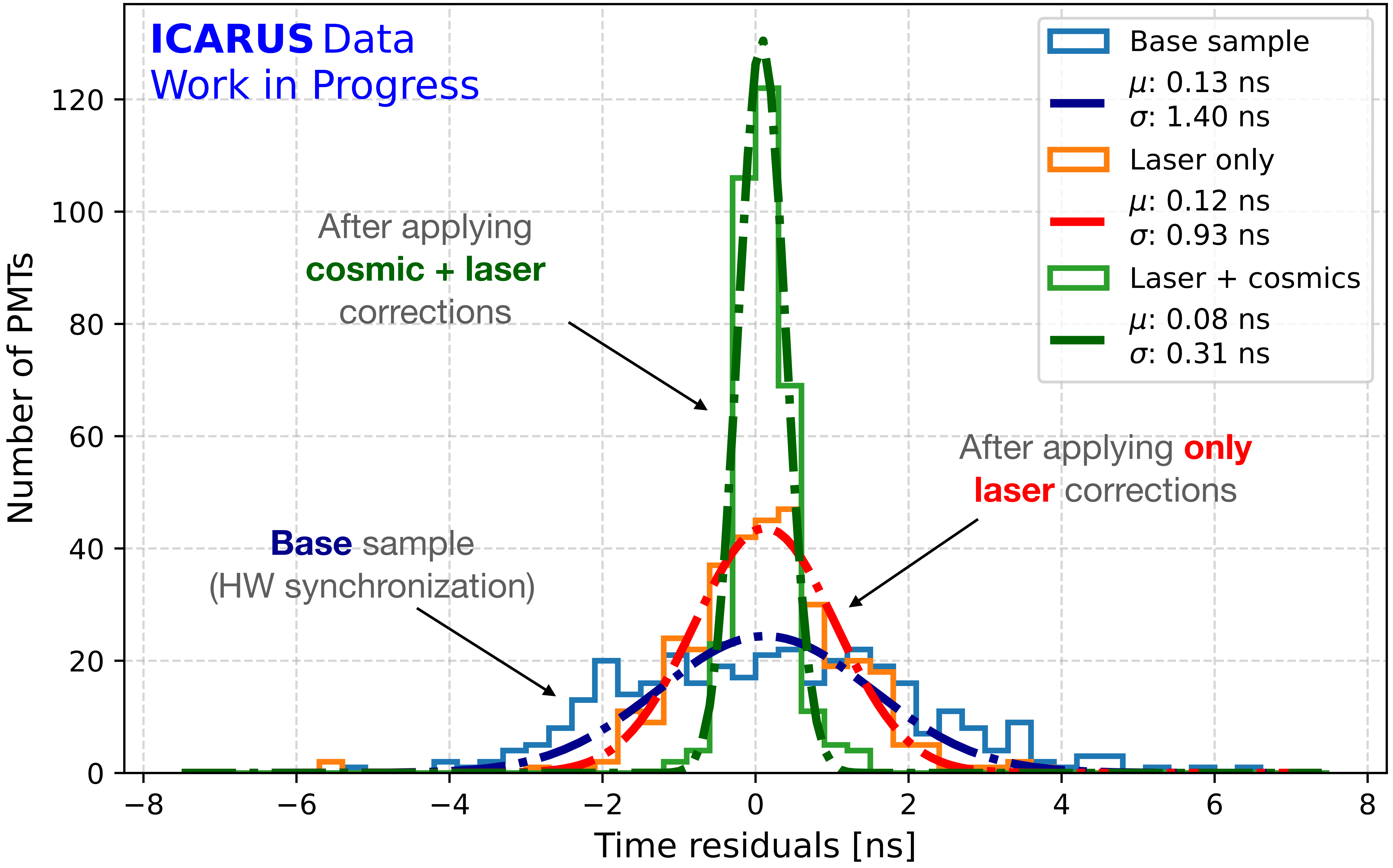


Cut on PE allows to exclude PMTs that are not in front of the track (z-dependence)

Post-calibration time residuals

The **mean of the distribution of time residuals** for each PMT is used to correct its digitized pulse times.

After corrections, an independent samples shows an **inter-calibration well below <1 ns!**



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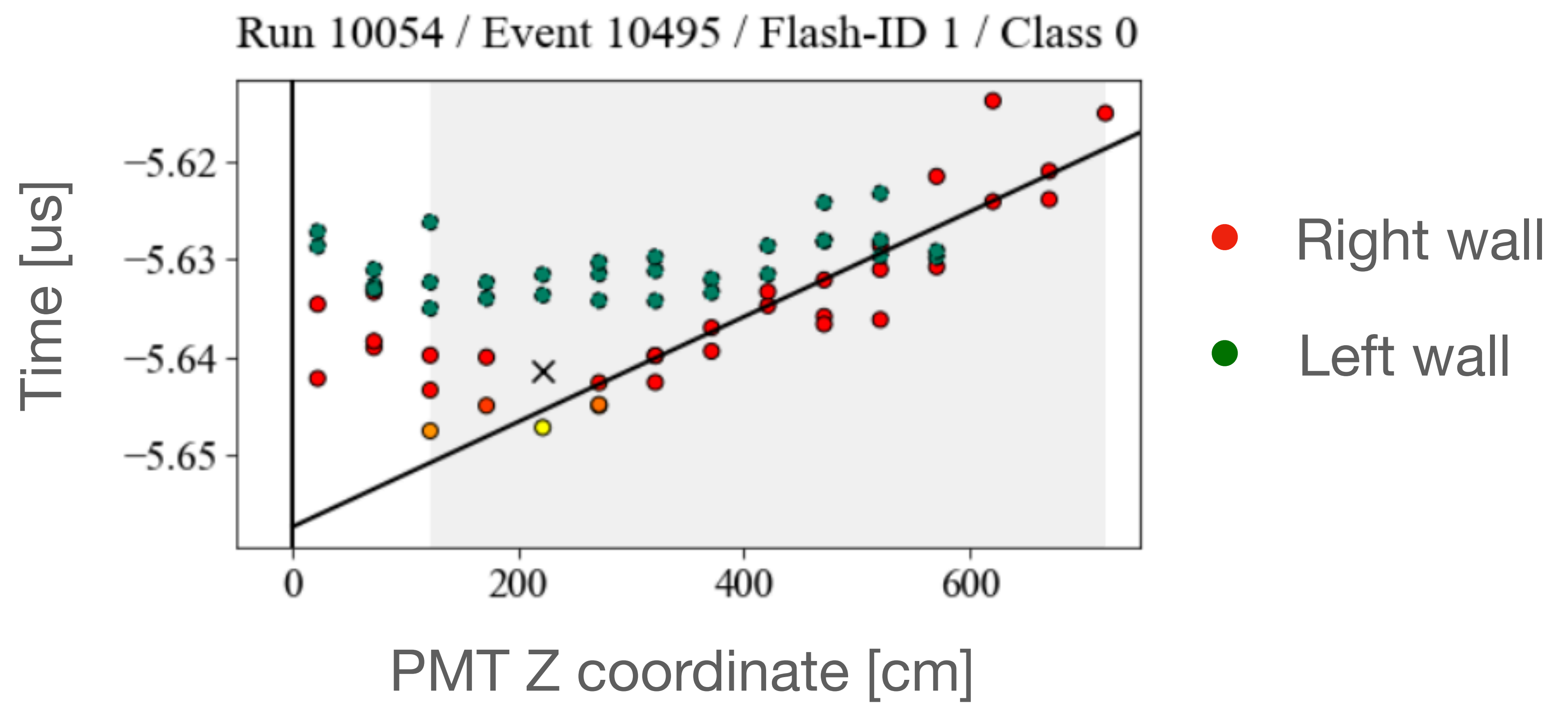
Event timing

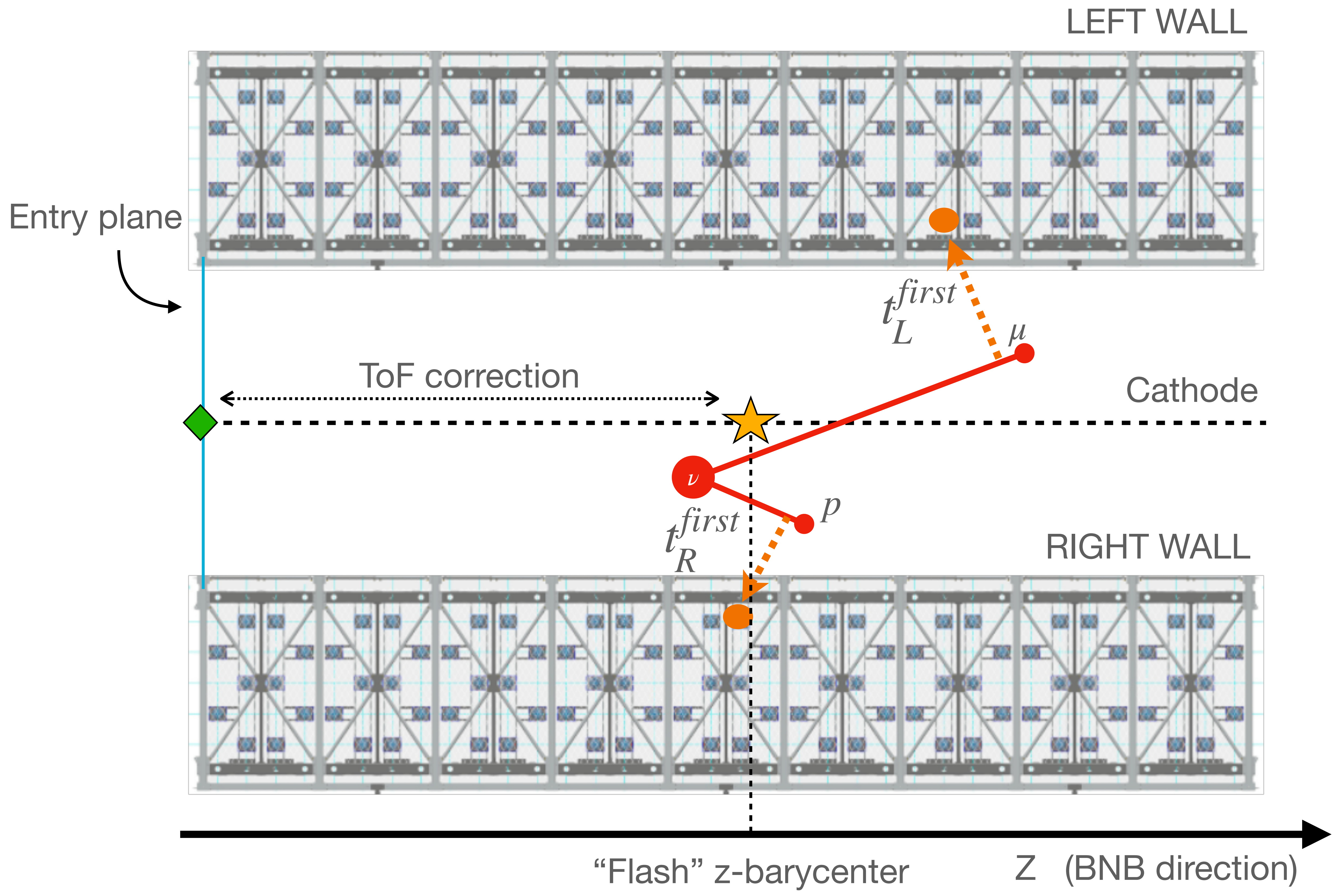
Light-only reconstruction

The dependency on the (x,y) position is removed by taking the mean between the **first PMT times on opposite walls** of the module.

A **time-of-flight** (ToF) correction is applied using the barycenter of the flash of light.

No charge information is currently used.

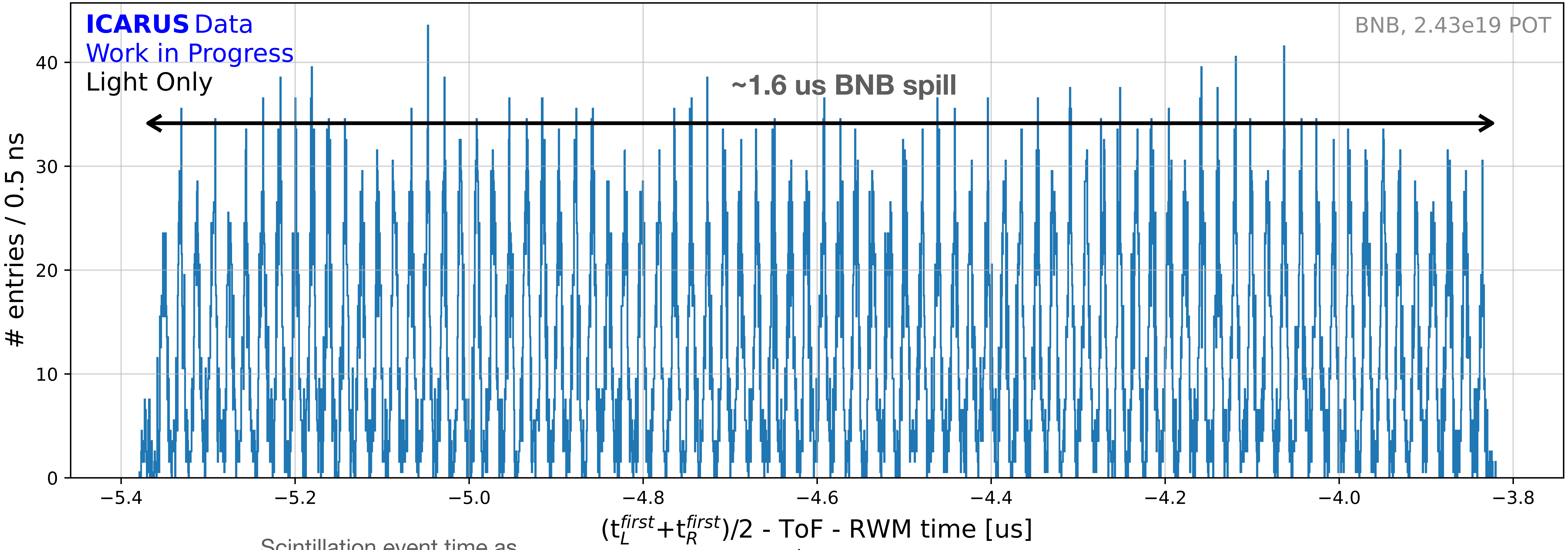




BNB bunch structure

Light-only reconstruction

(After subtracting cosmics)



Scintillation event time as mean between first PMT times on opposite walls

Time-of-flight correction from light barycenter

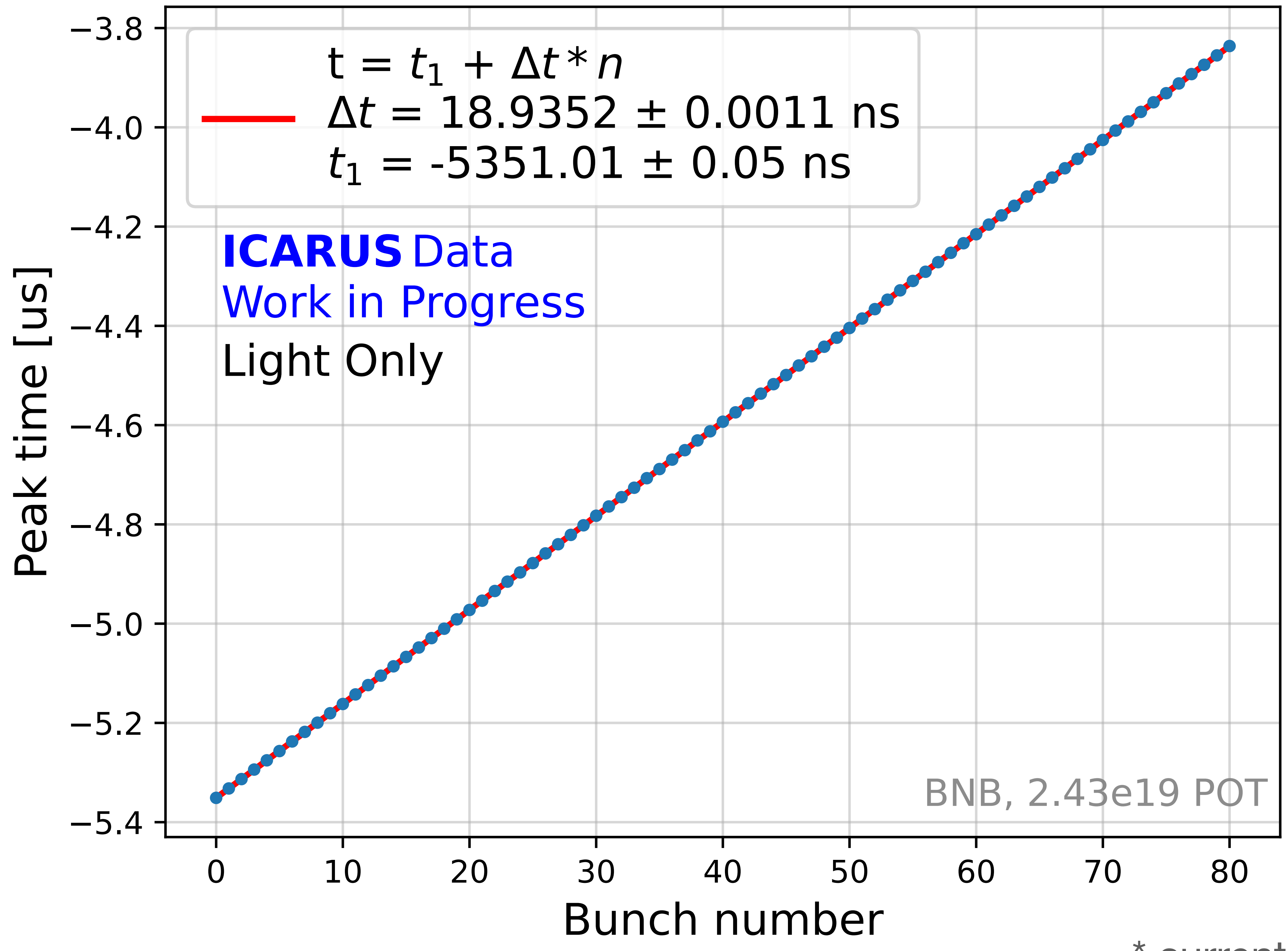
Synchronous to accelerator cycle

BNB bunch timing

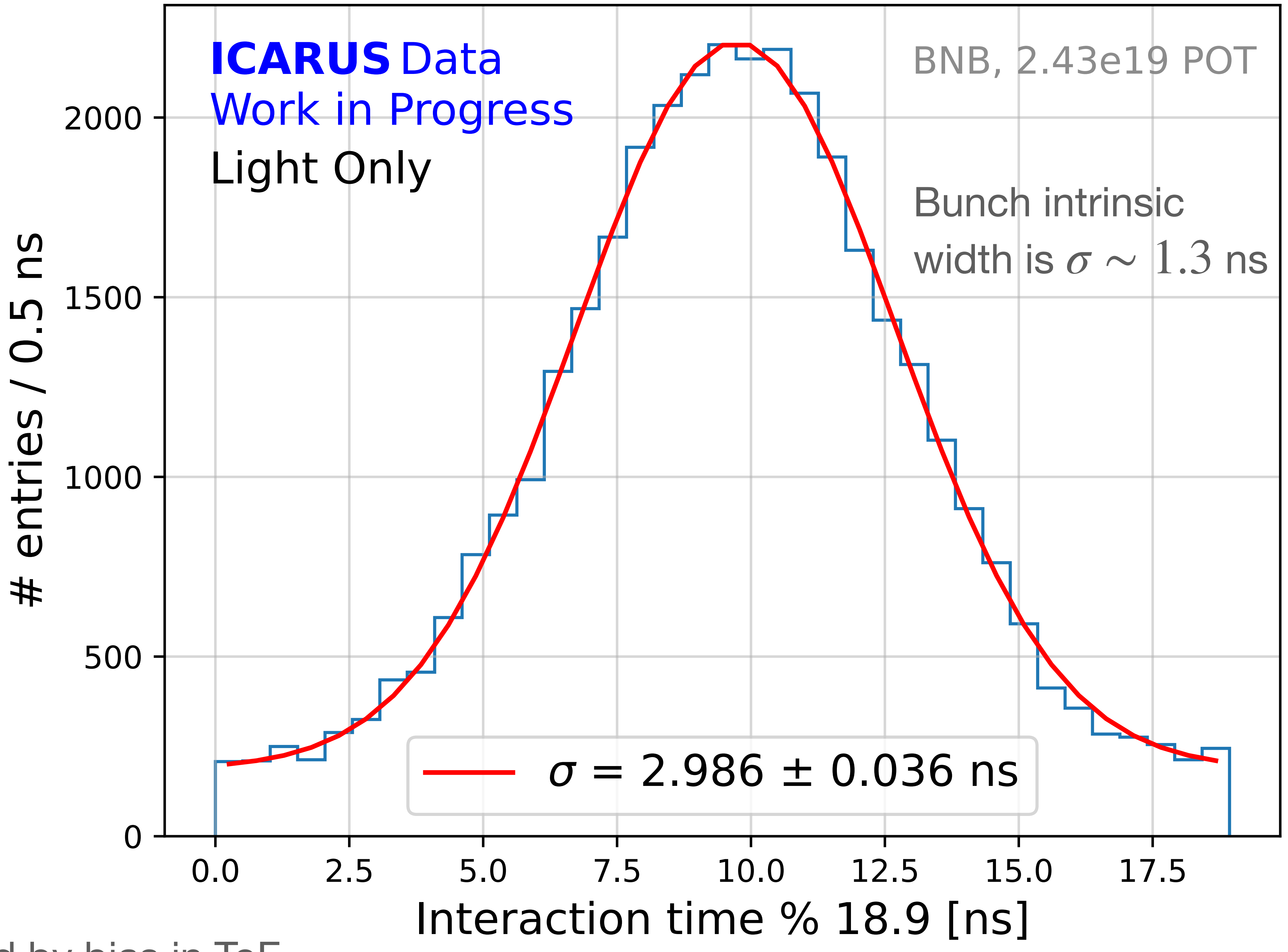
Light-only reconstruction

Similar results for NuMI!

After fitting the bunch structure, the **spacing** between the bunches is 18.935 ± 0.001 ns (52.8 MHz).



Superimposing all the bunches the **average bunch width** is $\sigma = 2.99 \pm 0.04$ ns.*



* currently dominated by bias in ToF correction using only light barycenter

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Summary

ICARUS has developed multi-stage strategies for both **relative and absolute timing calibrations** of its light readout system.

Laser and cosmic calibrations inter-calibrate the PMTs, refining timing to **sub-nanosecond synchronization** across the system.

Interaction times are realigned with the beam, allowing the **bunch structure** to be directly observed with only optical data.

This precise timing framework will be vital for effective background rejection and enhancing the **event selection for neutrinos and BSM searches with NuMI beam**.

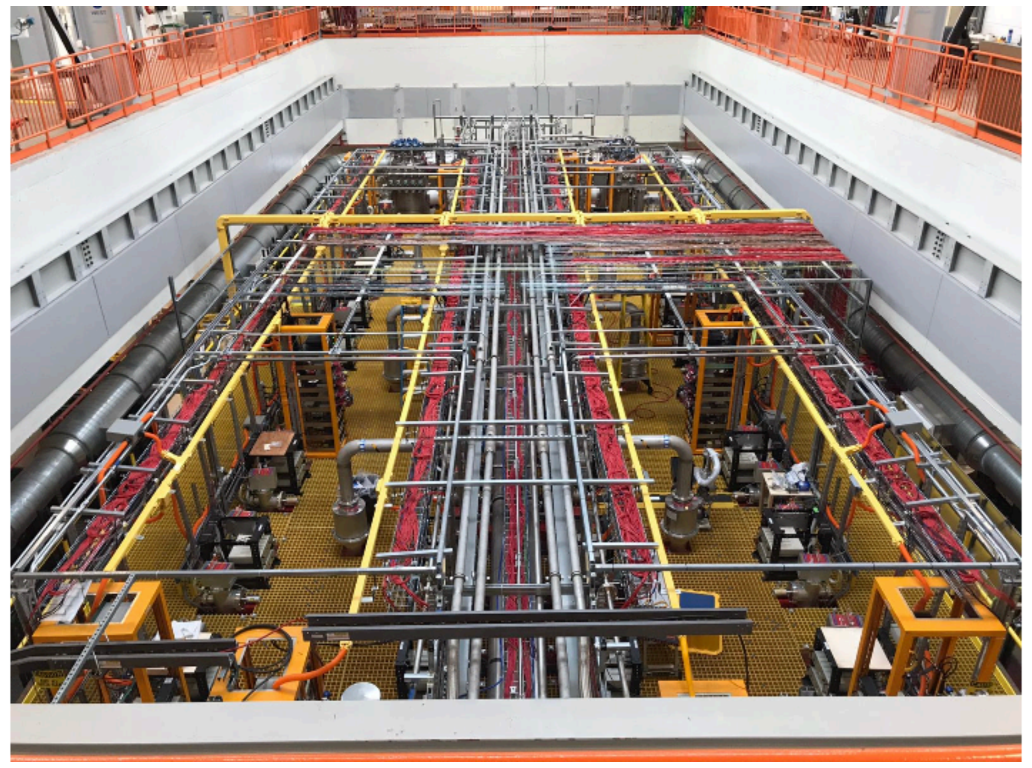
Thank you!

This document was prepared by ICARUS using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, Office of High Energy Physics HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359

ICARUS timeline

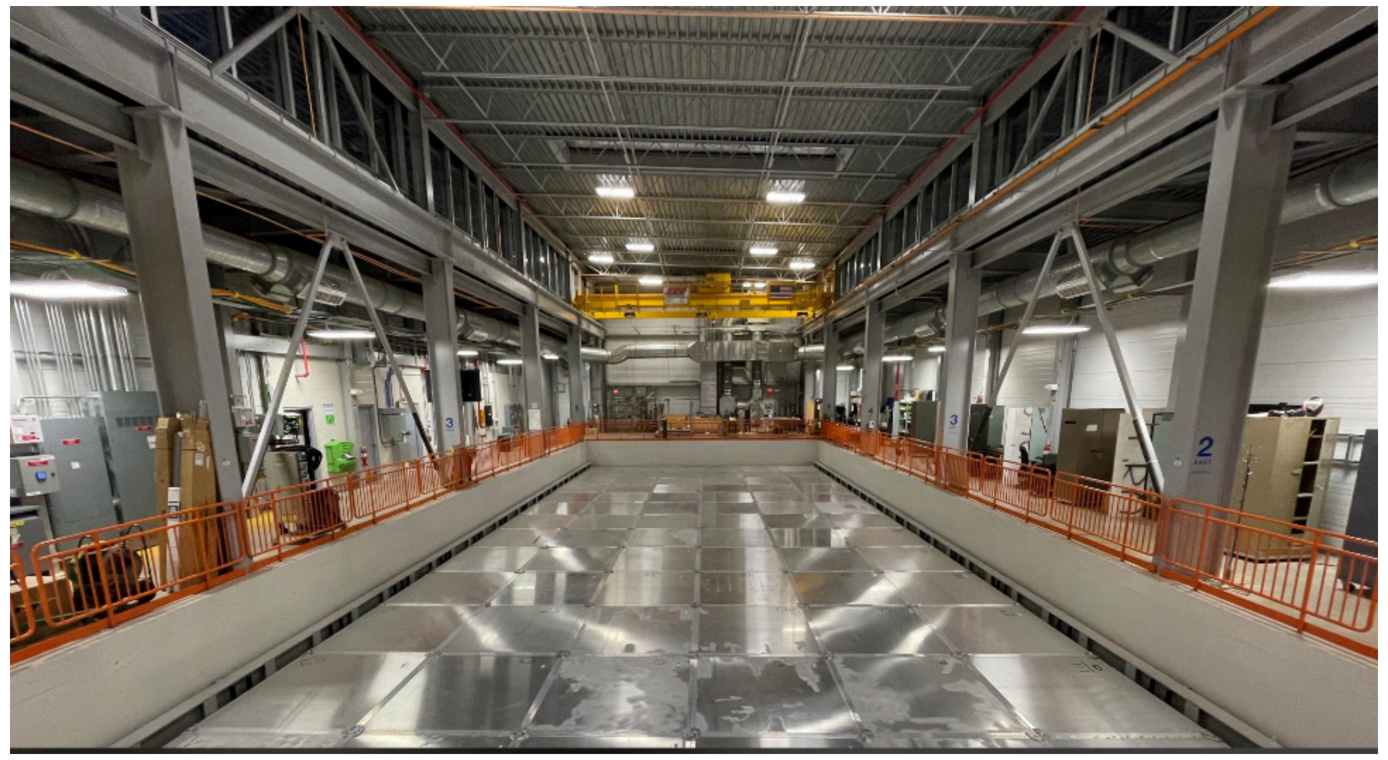
2018

ICARUS modules shipped from CERN to Fermilab



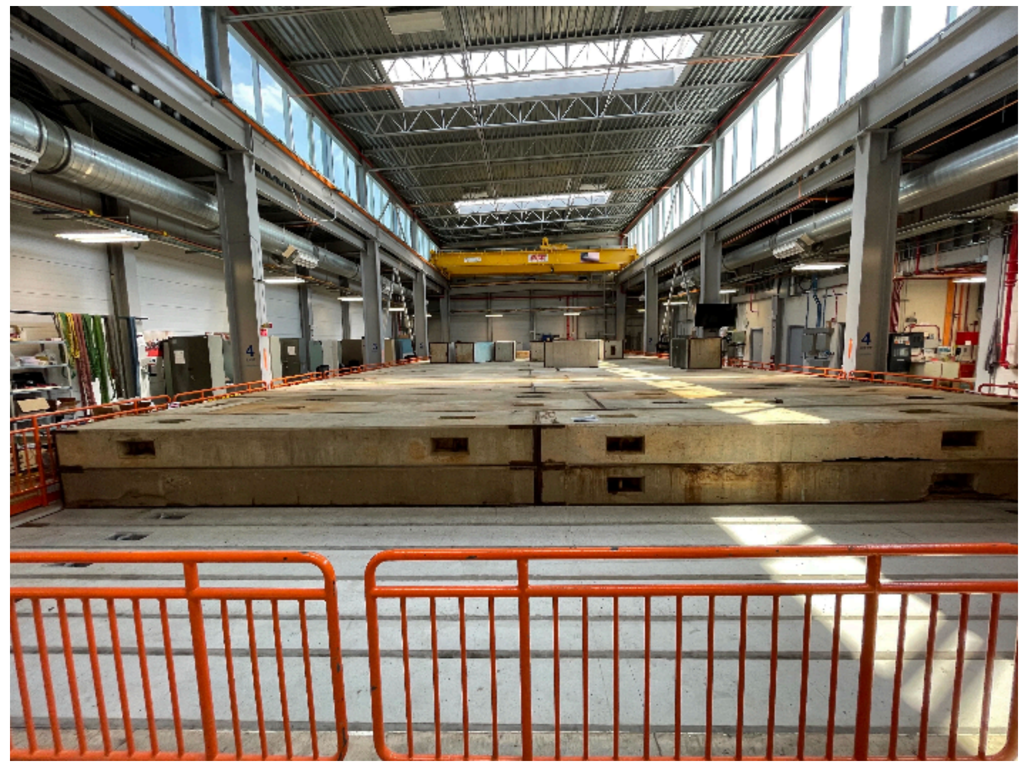
Sep 2020

Detector activation, Begin of commissioning activities.



Dec 2021

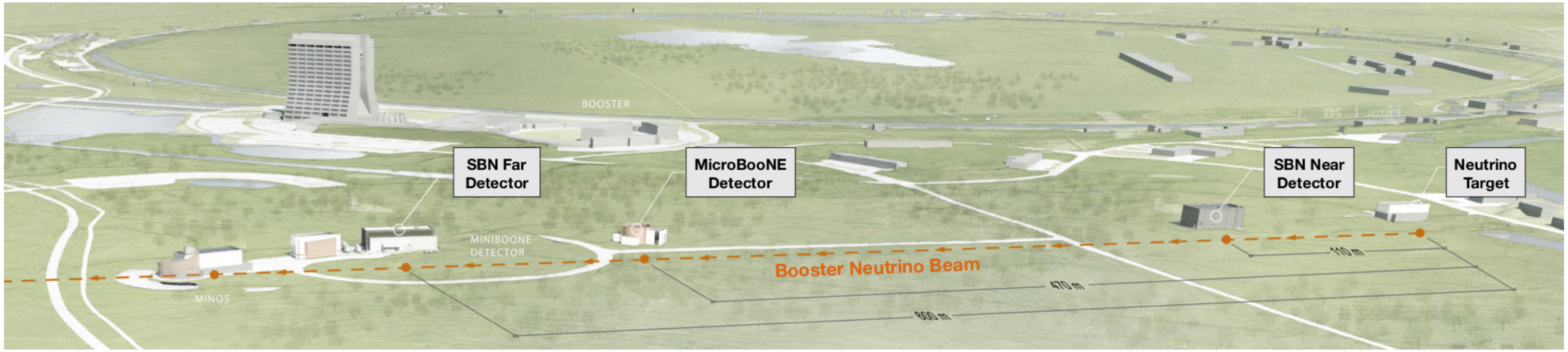
Installation of the Cosmic Ray Tagger (CRT) system. End of commissioning activities.



May 2022

Overburden installation completed. Begin of Physics runs.

ICARUS physics goals



The ultimate goal for ICARUS is to provide oscillated neutrino spectrum as Far Detector of the Short Baseline Neutrino (SBN) Program and **measure ν_μ disappearance + ν_e appearance** with two detectors to resolve the **sterile neutrino puzzle**. While SBND progresses through commissioning, ICARUS has been pursuing **single-detector physics**:

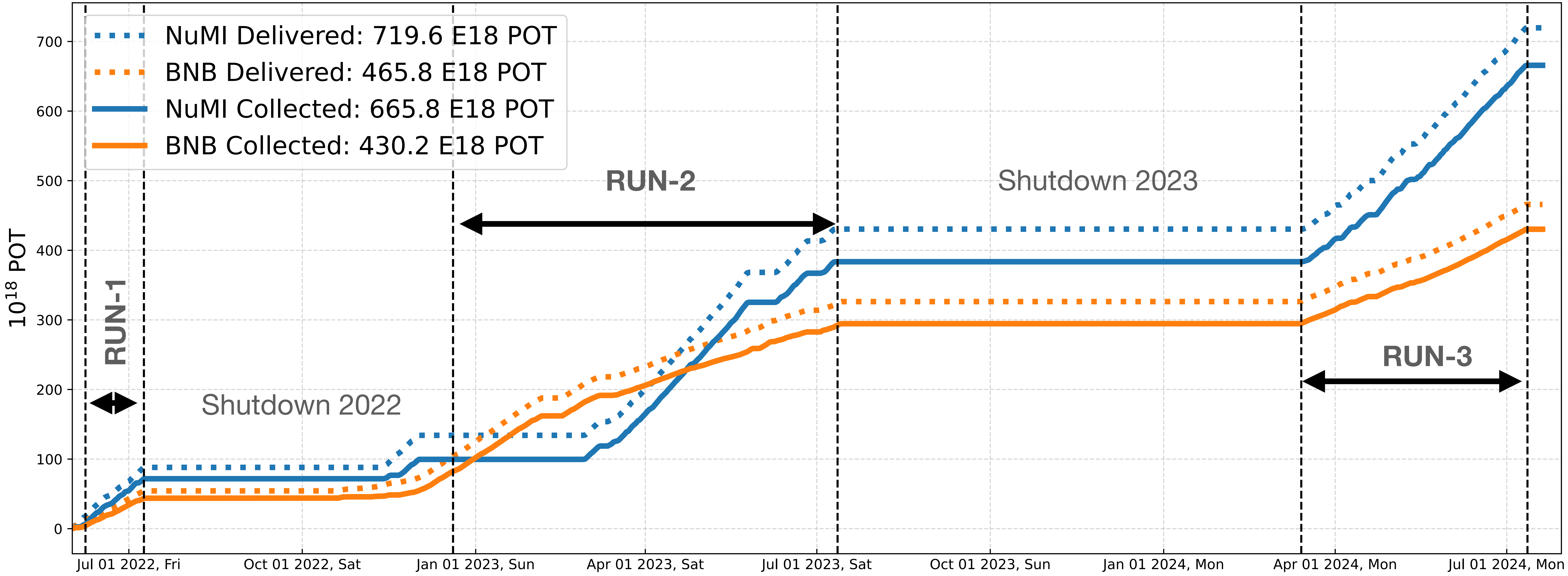
- ν_μ disappearance with BNB + ν_e disappearance with NuMI (Neutrino-4 claim).
- $\nu_{\mu,e} - Ar$ cross-section measurements with NuMI.
- Sub-GeV BSM searches with NuMI.

See Neutrino2024's talk for recent updates on these topics!

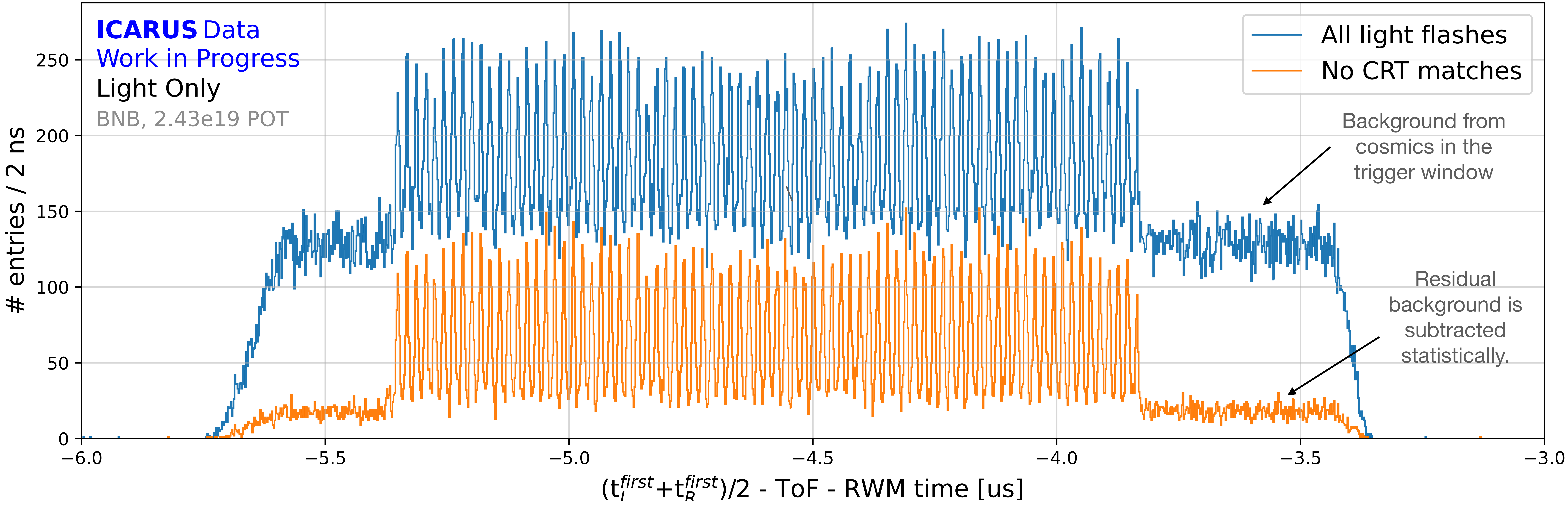
ICARUS POT

Total BNB POT: 3.9×10^{20} (FHC)

Total NuMI POT: 3.4×10^{20} (FHC), 2.8×10^{20} (RHC)



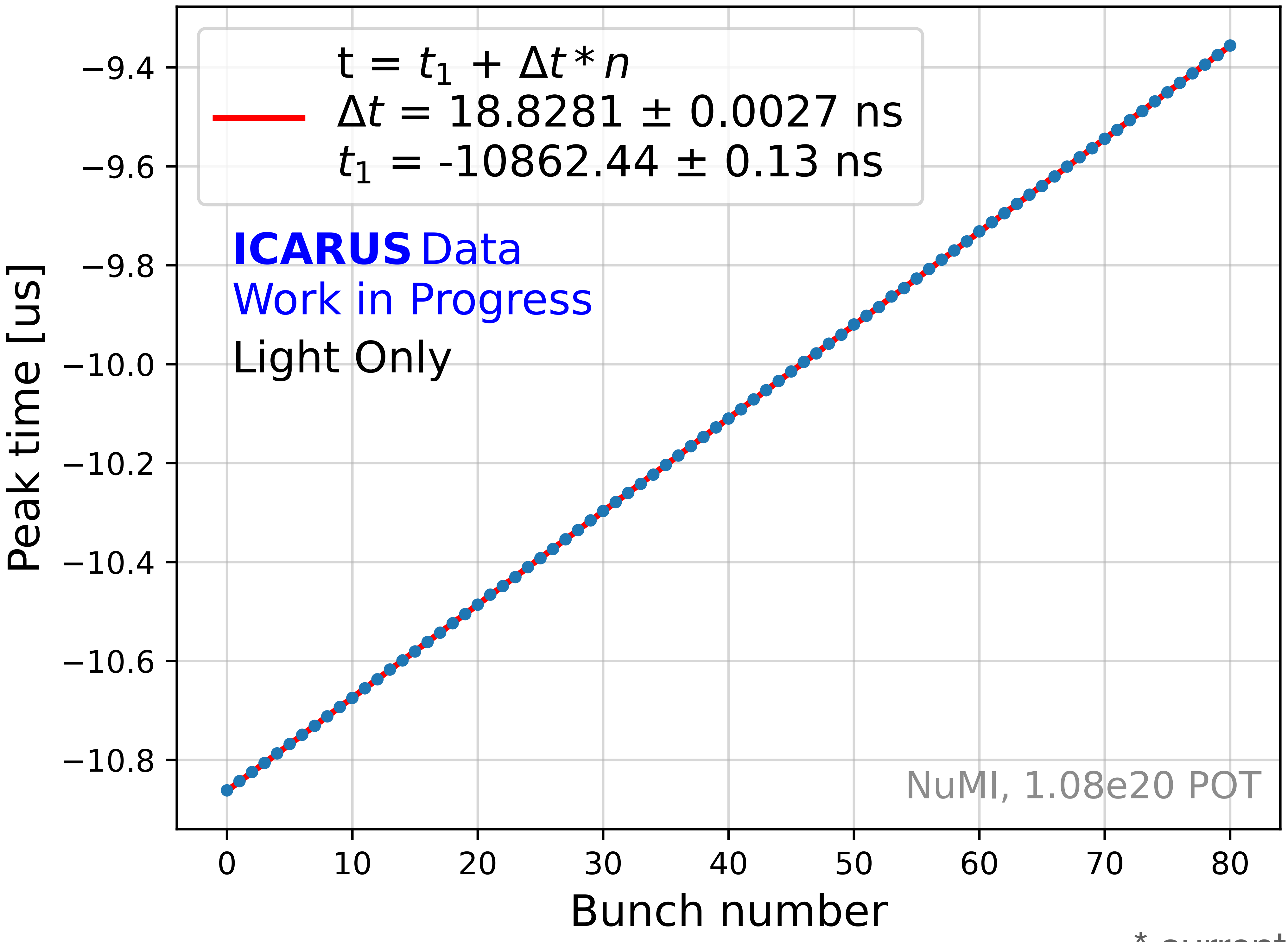
Cosmic background rejection



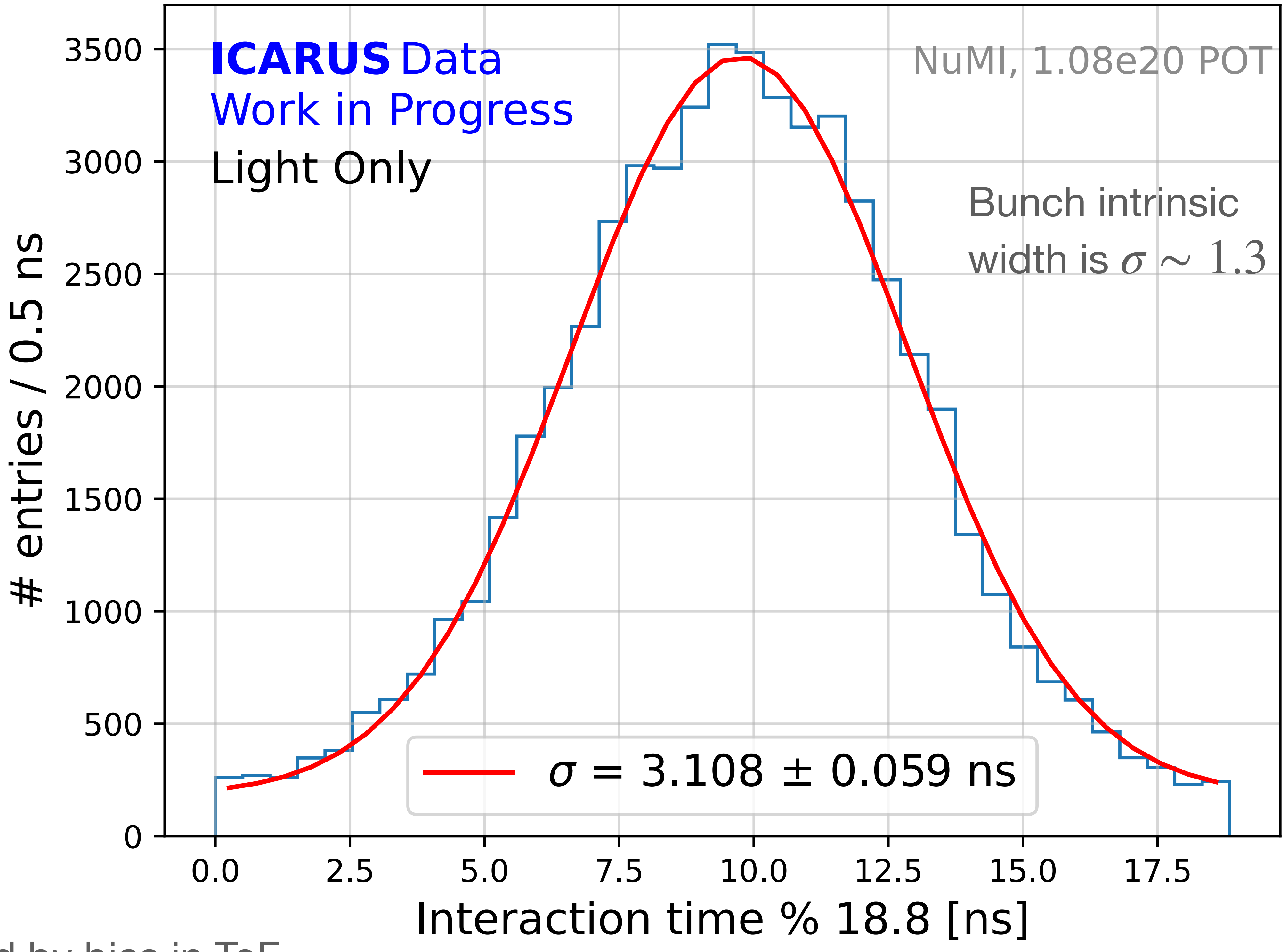
NuMI bunch timing

Light-only reconstruction

- After fitting the bunch structure, the **spacing** between the bunches is 18.828 ± 0.003 ns (53.1 MHz).



Superimposing all the bunches the **average bunch width** is $\sigma = 3.11 \pm 0.06$ ns.*



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