Reconstruction of the BNB and NuMI Neutrino Bunch Structure with ICARUS

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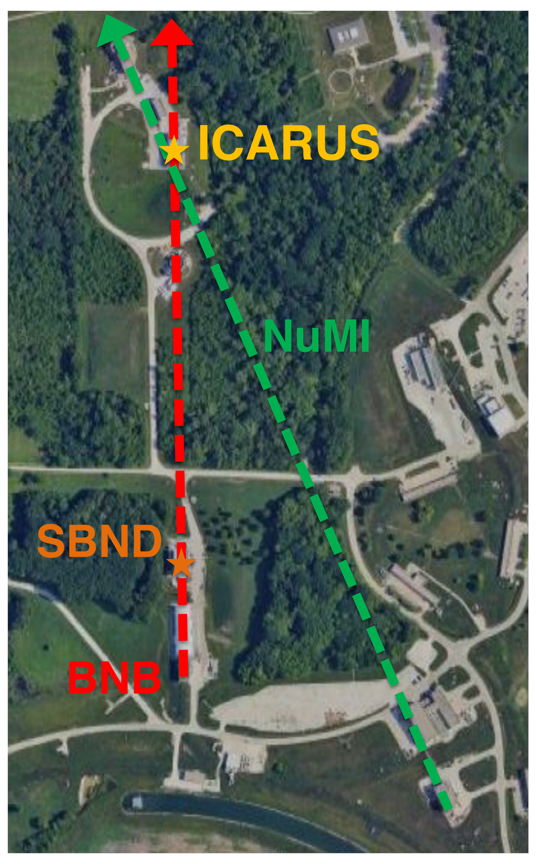
ICARUS is the Far Detector of the Short Baseline Neutrino (SBN) program

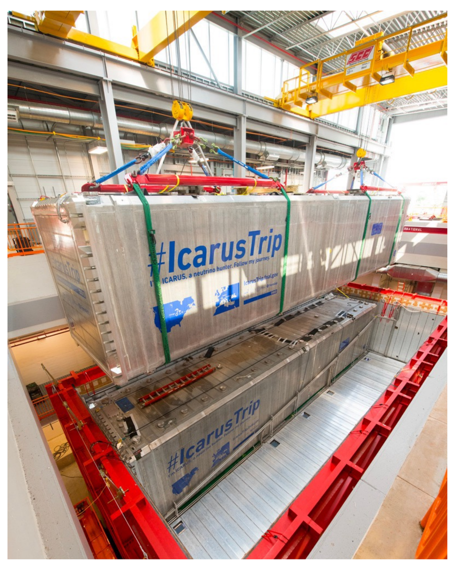
ICARUS is currently the largest **liquid argon** detector in operation (~476 active tons).

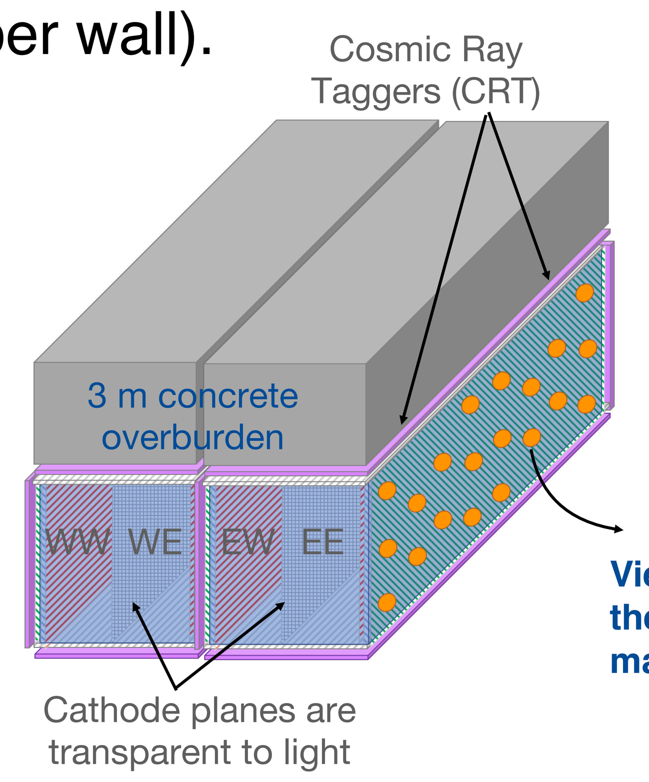
It sits on-axis on the Booster Neutrino Beam (**BNB**) and 6° off-axis from the Neutrinos at the Main Injector (**NuMI**) beam.

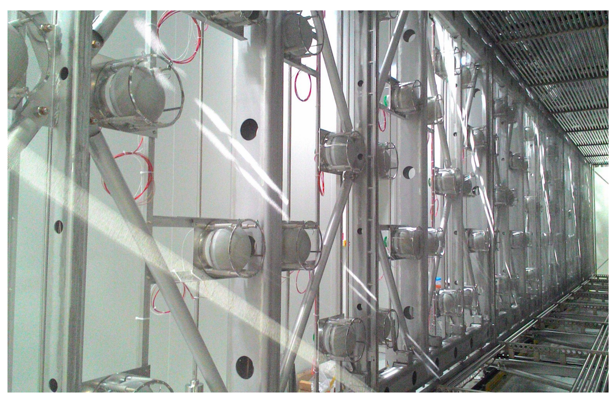
It is divided into 2 modules, each hosting 2 TPCs that share the cathode plane.

Light is read out via **360 TPB-coated PMTs** (8" Hamamatsu R5912-MOD), mounted on "honeycomb" structures behind the anode wires (90 PMTs per wall).



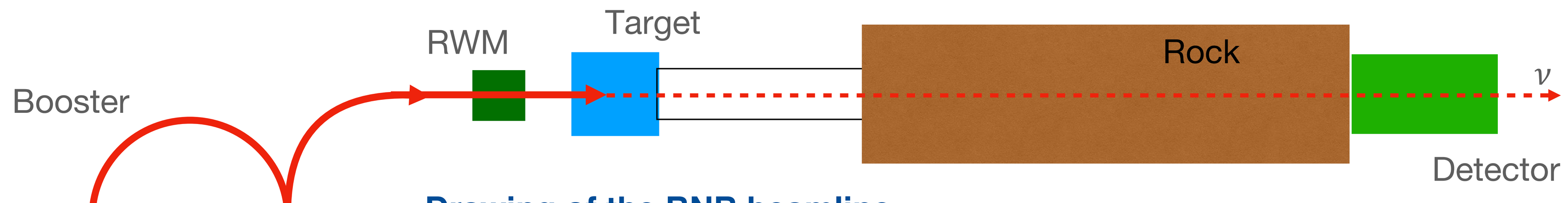






View of one PMT "wall" from inside one of the ICARUS modules. Light reflection makes the anode wires visible in the photo.

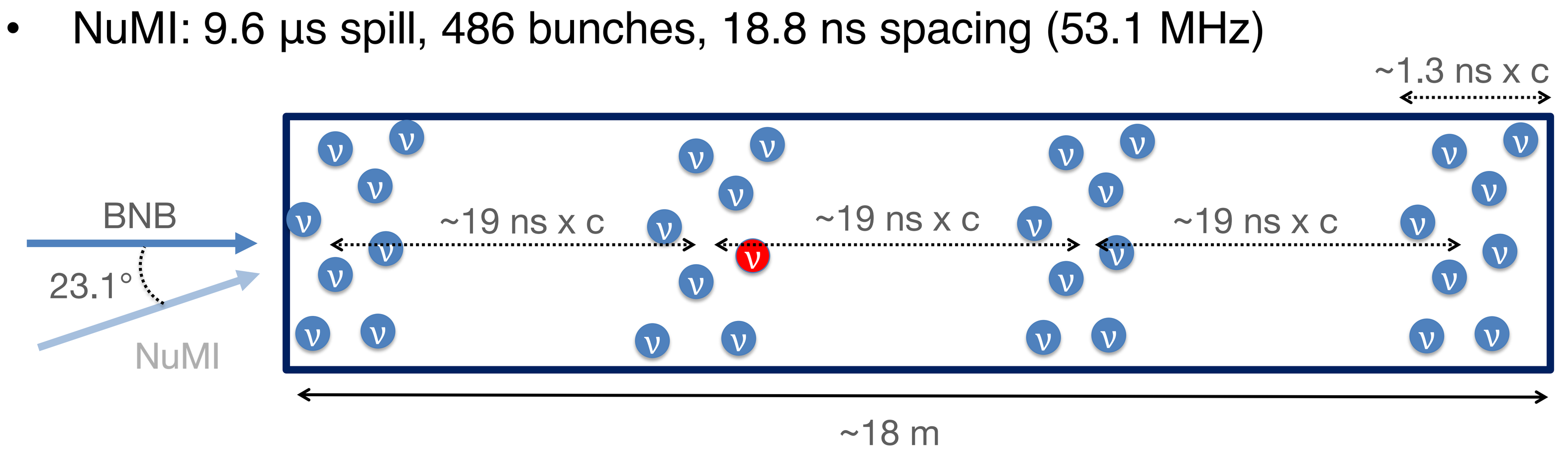
Neutrinos inherit the time profile of their parent proton bunches



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.

Neutrino propagation (including meson decays) only adds a constant offset, so the **time profile** of the bunches is preserved:

- 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)



Visualizing the bunch structure from the few detected neutrinos across many spills requires two steps:

1. Compute neutrino times at the same **reference plane** (eg. entry plane), accounting for their **time-of-flight** (ToF).
2. Accumulate spills on top of each other by measuring the time relative to an **accelerator-synchronous signal** (e.g. RWM).

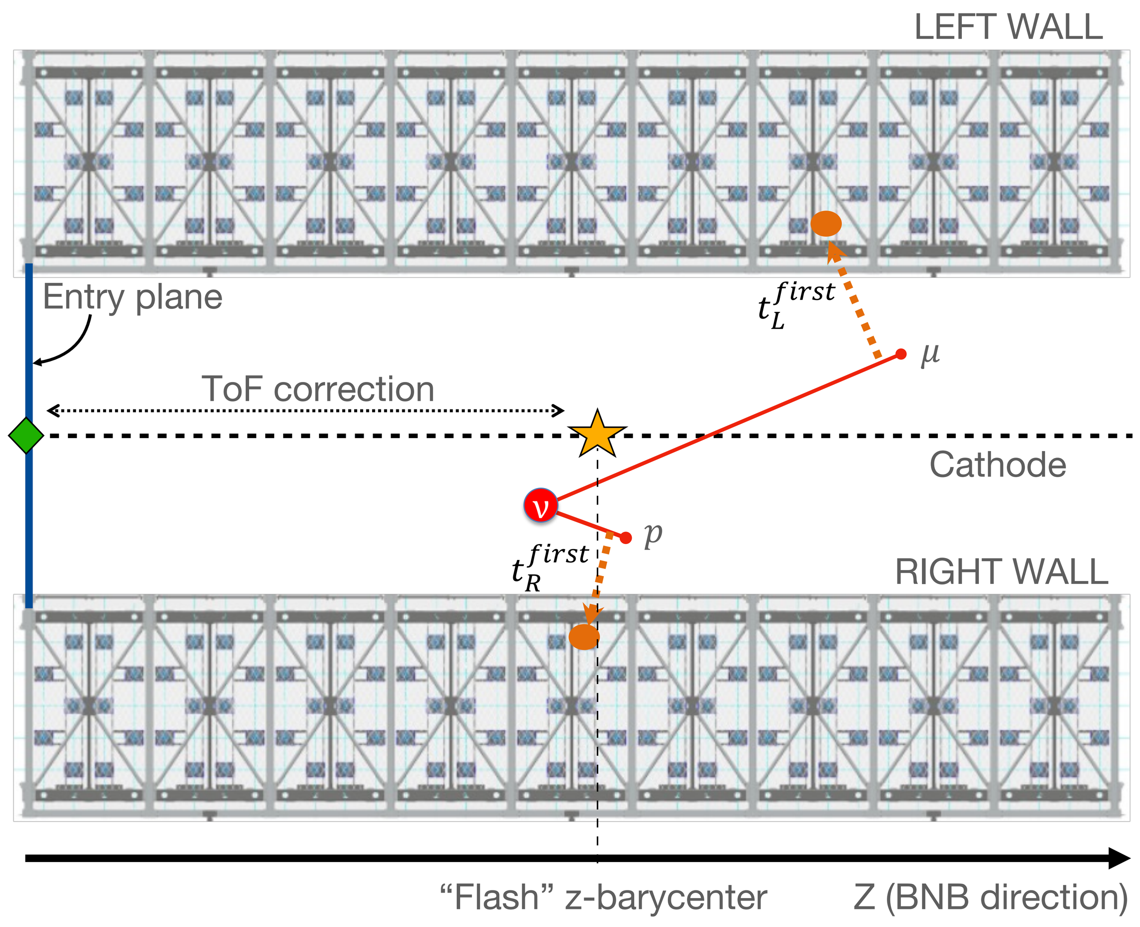
Neutrino interaction times and positions are estimated using only optical information

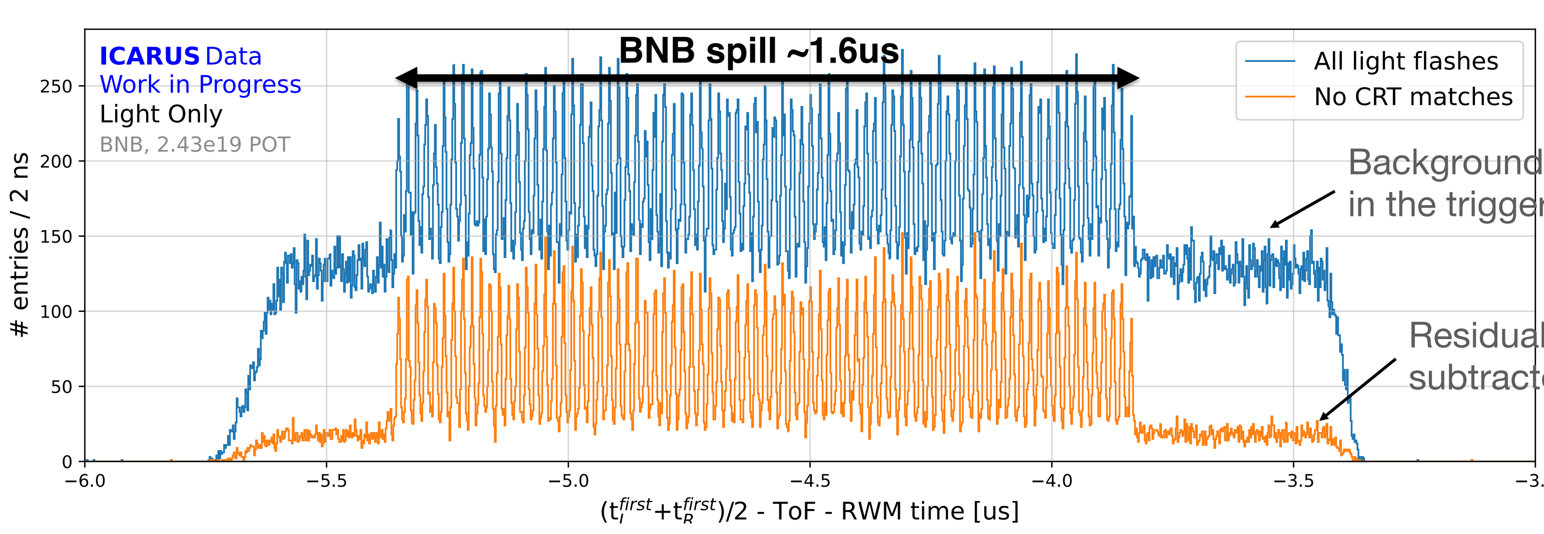
The large number of PMTs on both sides of the modules allow to reconstruct the time of any scintillation event and provide its location across the length of ICARUS.

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.

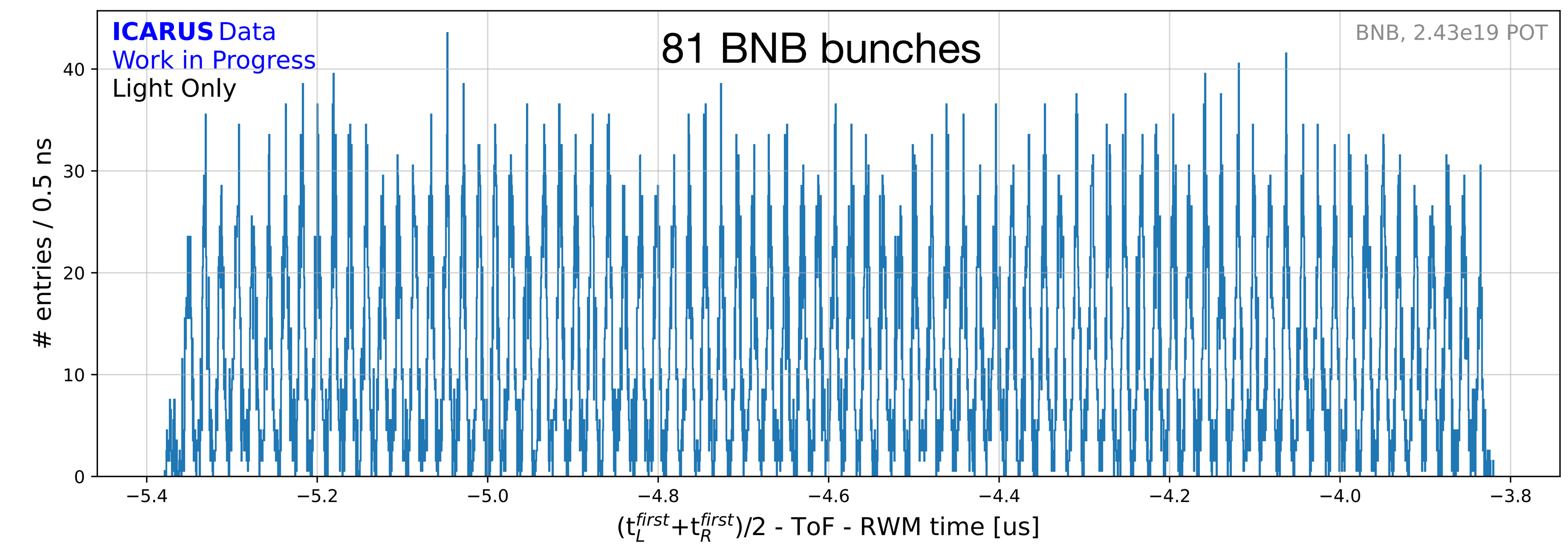
No charge information is currently used.



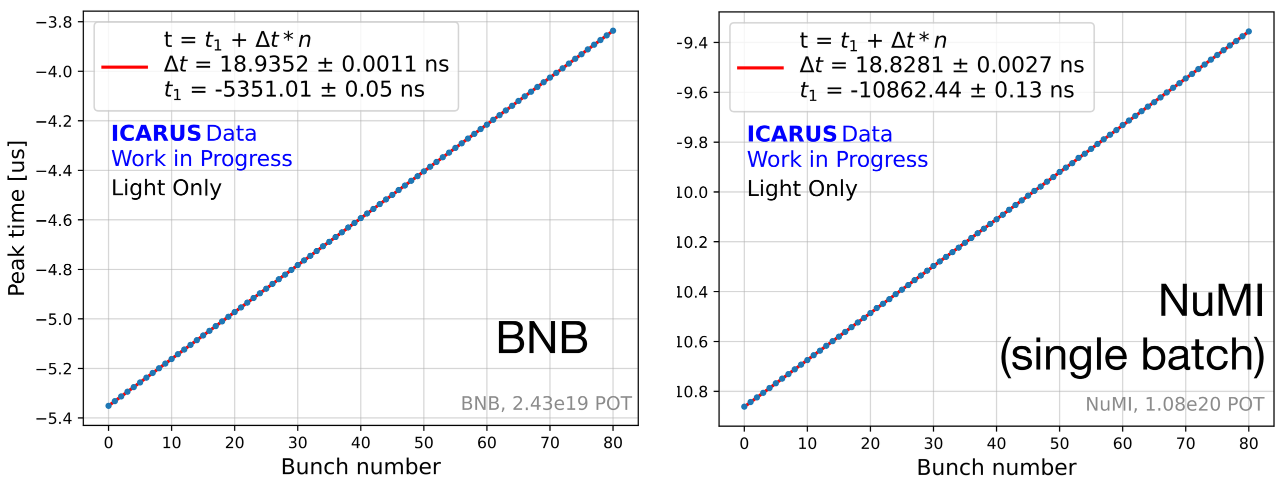


Cosmic Ray Taggers (CRT) are used to **remove cosmics**. Any light flash that matches any activity in the taggers is rejected.

BNB and NuMI bunch structures have been reconstructed in ICARUS data!

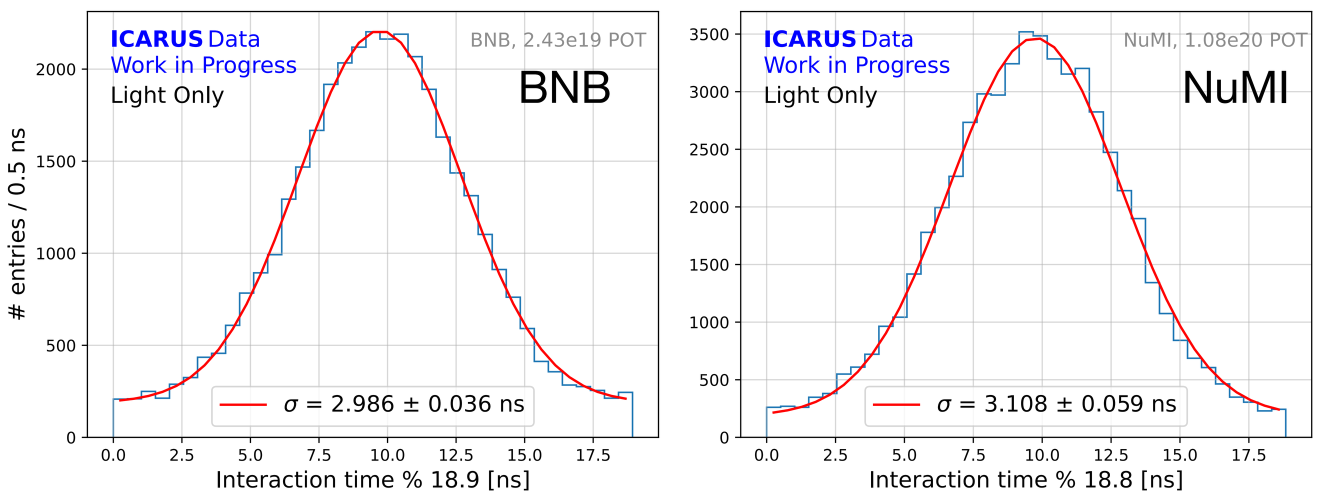


Despite the simple extraction method, the bunch structure has a **high S/N ratio**. Bunch width resolution is currently **~3 ns**, but improvements are expected once charge information is added.



After fitting the bunch structure, the spacing between the bunches can extracted by plotting the peak positions:

BNB: **18.935 ± 0.001 ns**
NuMI: **18.828 ± 0.003 ns**



Superimposing all the bunches allows to evaluate the shape of the average bunch and determine its width:

BNB: **2.99 ± 0.04 ns**
NuMI: **3.11 ± 0.06 ns**

These are expected to improve with better event reconstruction.

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