Performance of the ICARUS Trigger System at the Booster and NuMI Neutrino Beams

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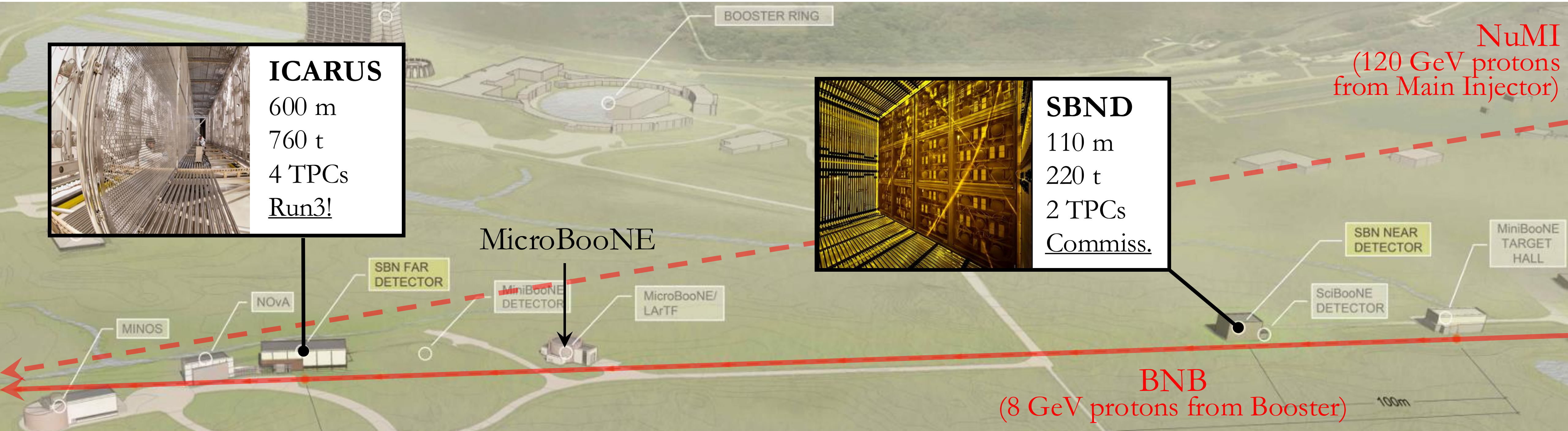
Short Baseline Neutrino Program

Several anomalies were observed at neutrino oscillation experiments (LSND, MiniBooNE), which might be explained with an additional **sterile neutrino** state.

SBN aims at studying anomalous neutrino oscillations at short baselines, using Liquid Argon TPC (**LArTPC**) detectors along the Booster Neutrino Beam (**BNB**):

- measuring ν_μ-disappearance and ν_e-appearance within the same experiment, covering at 5σ the parameter regions allowed by LSND/MiniBooNE;
- ICARUS also collects neutrinos from the Main Injector (**NuMI**) off-axis, for cross-section and BSM studies.



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See **M. Artero**'s talk on first **ICARUS** physics **results tomorrow**!

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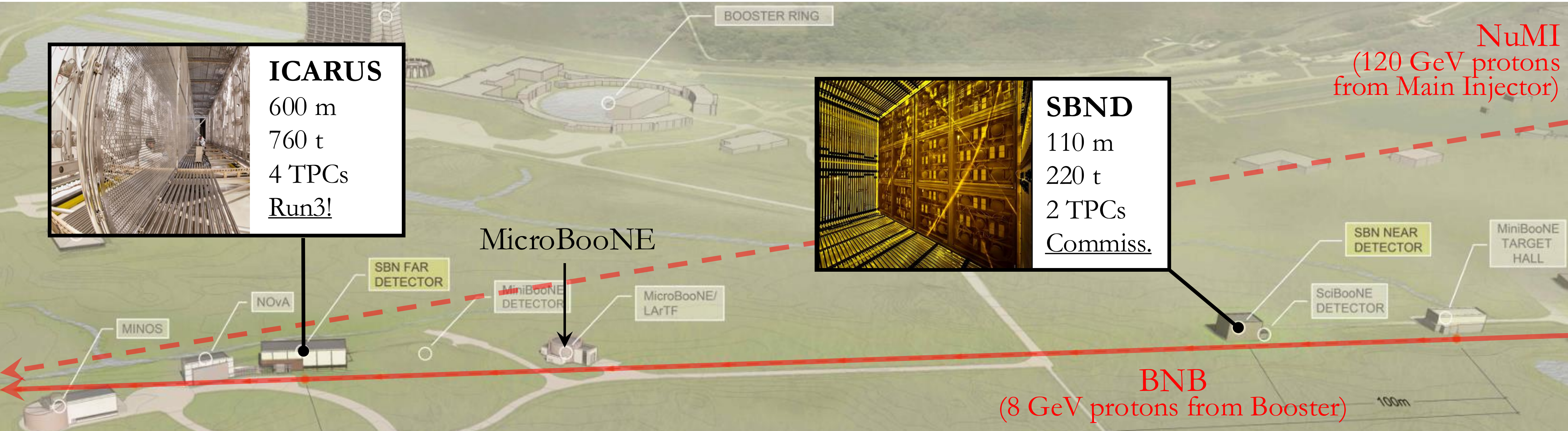


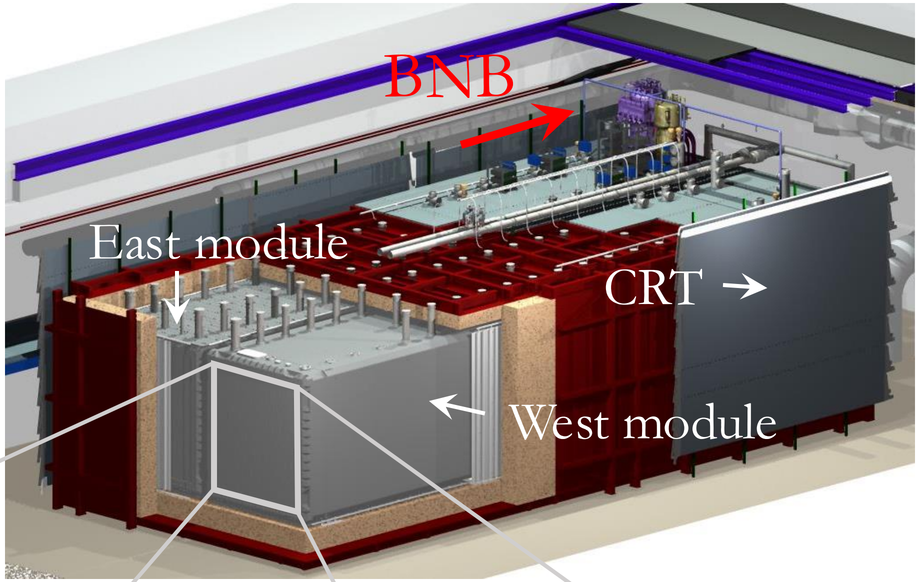
The ICARUS Detector

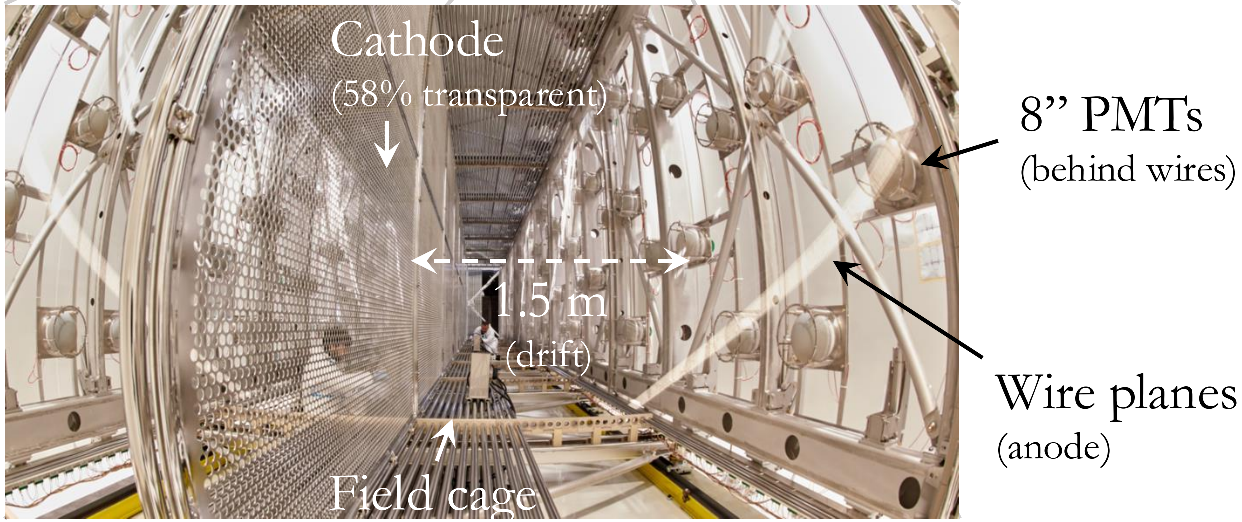
After underground operation at LNGS and overhauling at CERN/INFN, ICARUS is taking data at FNAL:

- first large-scale LArTPC detector, with 476 t of active liquid argon;
- two identical **modules**, each housing two TPCs separated by a shared cathode (uniform 500 V/cm field);
- four anodic wire planes with three views each for 3-d. imaging;
- 360 8" **PMTs** (90 per TPC) behind the wires to collect scintillation light (~20,000 γ/MeV at 500 V/cm).

At FNAL, ICARUS operates at the **surface**:

- enclosed in a ~4π Cosmic Ray Tagger (**CRT**) based on plastics scintillators;
- ~3-m concrete overburden reduces cosmic ray flux.





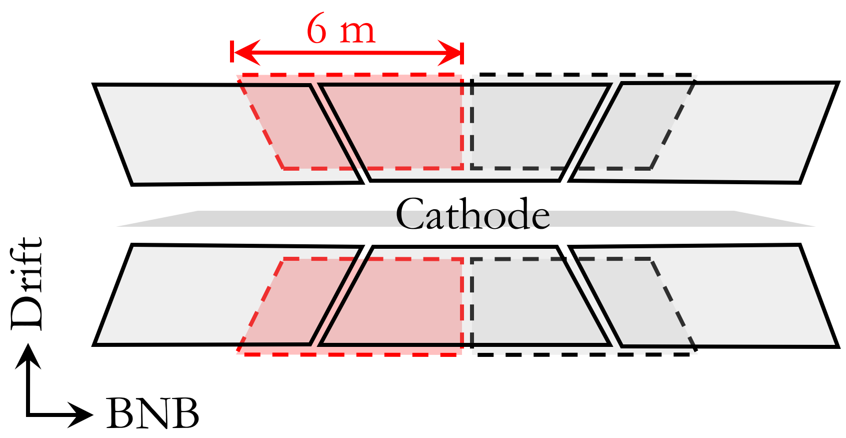
The ICARUS Trigger

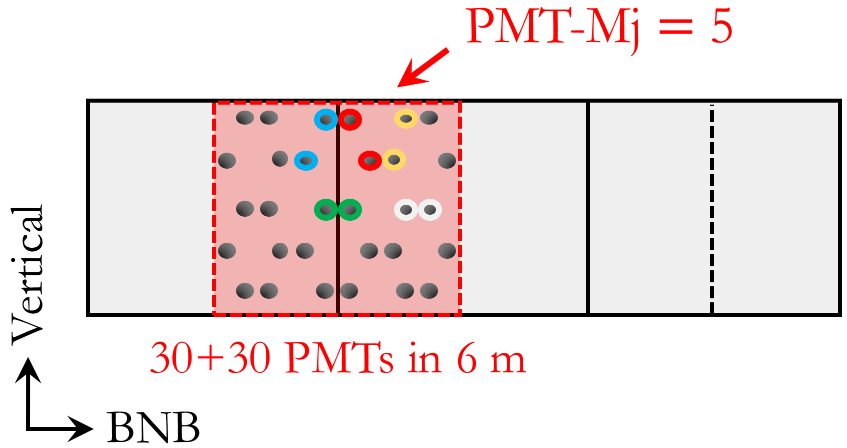
The ICARUS trigger is **online** and fully implemented on hardware, based on FPGA programmable logic:

- ✶ **interactions** from ~GeV neutrinos are on average contained in ~4-m longitudinally;
- ✶ each module is sliced in three side-by-side 6-m **windows** (Run1), plus two additional overlapped windows (Run2 – now);
- ✶ each window contains 60 PMTs (30 per TPC, front-facing), discriminated with a 13 PEs threshold and paired (OR) into digital LVDS signals.

A **global trigger** is issued when there are at least 5 PMT-pairs over threshold in a window (**PMT-Majority** trigger, Mj = 5) in coincidence with BNB or NuMI, and TPCs/PMTs/CRTs are all readout.

ICARUS module





Trigger Menu

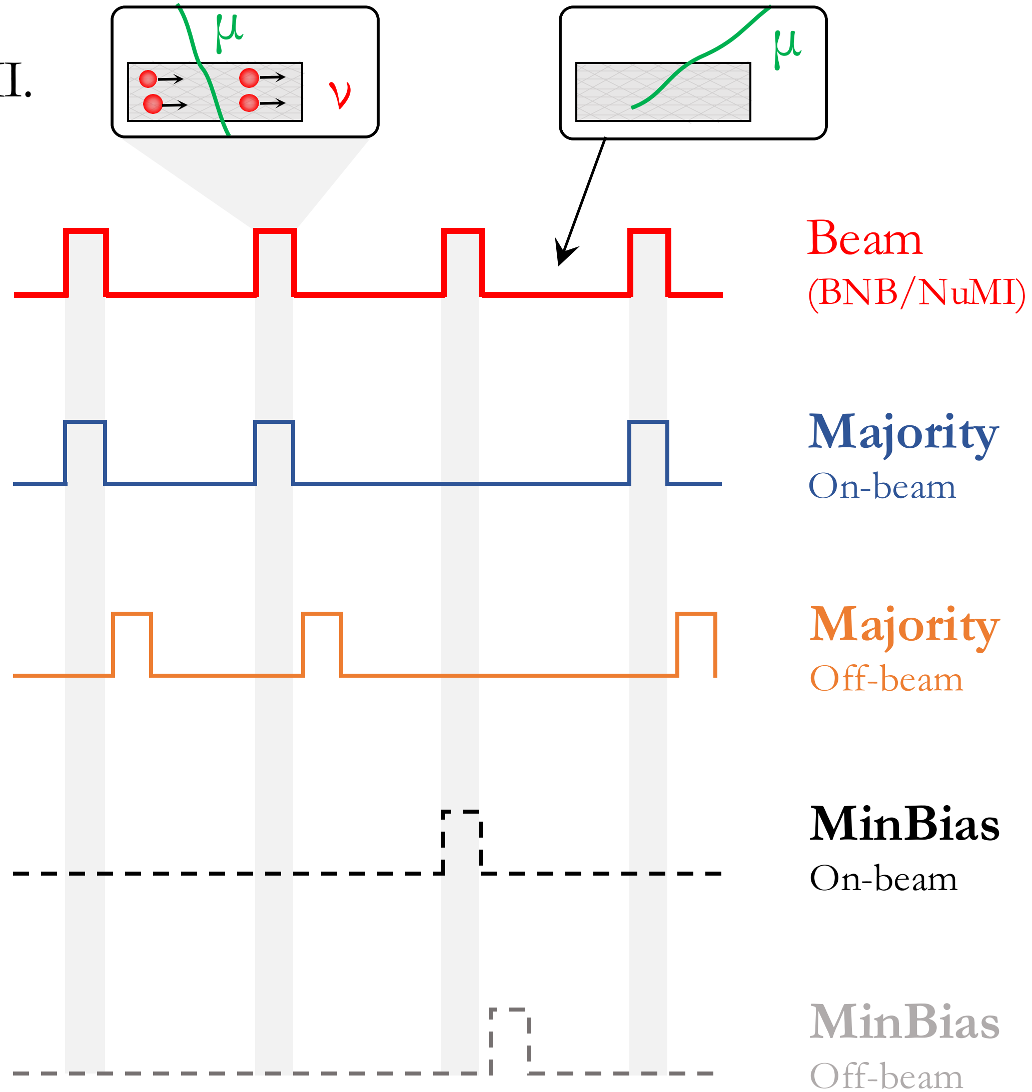
Several triggers are routinely collected with both BNB and NuMI.

As just described, PMT-Majority triggers are collected based on scintillation light:

- **on-beam**, in coincidence with BNB and NuMI spills (trigger for beam physics);
- **off-beam**, in between spills (background statistics).

Minimum Bias triggers are collected when there is a gate, regardless of the scintillation light, on and off-beam:

- this is done every ~20 gates (**prescale** factor, varying for different streams);
- useful for trigger efficiency, calibrations, and detector physics studies.



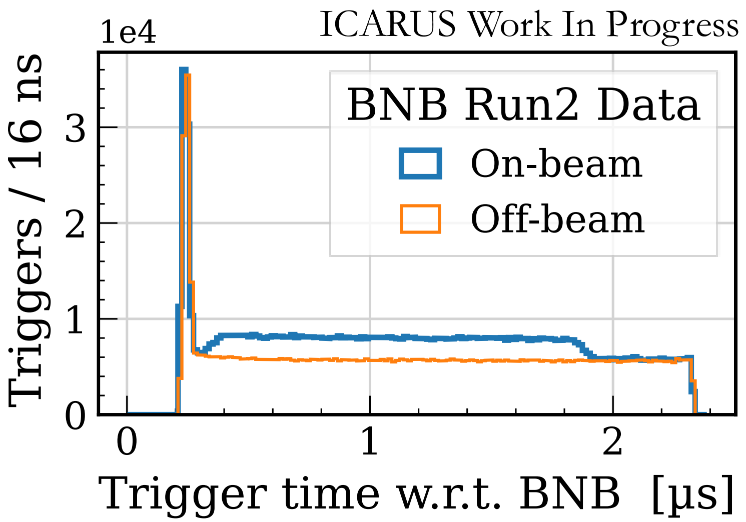
Operation of the Trigger

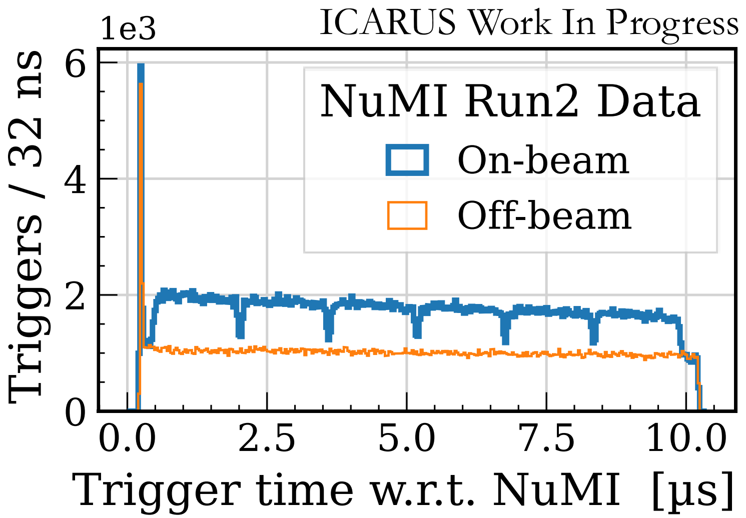
The ICARUS trigger is designed to **select physical interactions** within the BNB and NuMI beam spills:

- it rejects ~97% of spills, either empty or with negligible activity;
- **beam**-related activity (neutrinos, beam-halo, dirt) is an evident excess in the on-beam data with respect to the off-beam data;
- the **structures** of BNB (1.6 μs spill) and NuMI (9.5 μs spill, 6 batches) are visible: the proton-bunches sub-structure can be further reconstructed with PMTs and accelerator signals.

The trigger system enabled stable ICARUS operations:

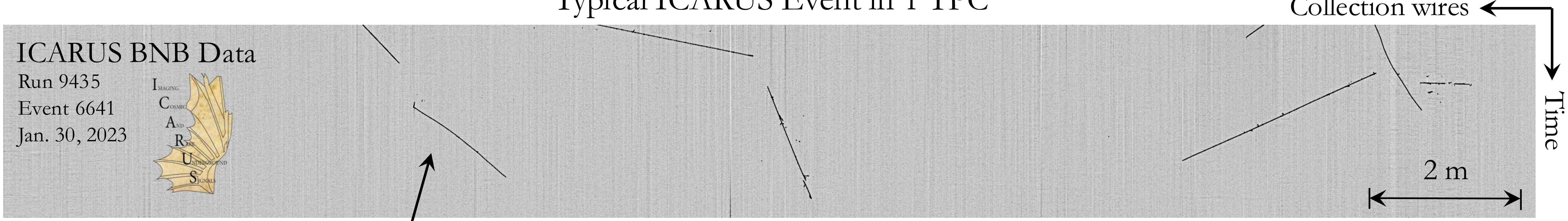
	Trigger	BNB [POT]	NuMI [POT]
Run1	Mj-5 (3 windows)	$0.41 \cdot 10^{20}$	$0.68 \cdot 10^{20}$
Run2	Mj-5 (5 windows)	$2.05 \cdot 10^{20}$	$2.74 \cdot 10^{20}$

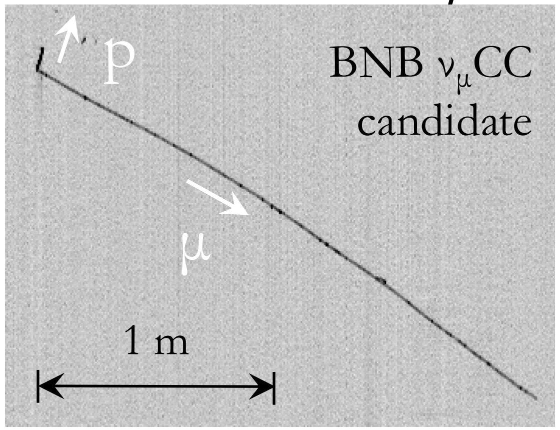




Cosmic Rejection

Typical ICARUS Event in 1 TPC





ICARUS, at the surface, is interested by ~11 kHz of cosmic rays crossing the detector during the drift of ionization electrons in beam events:

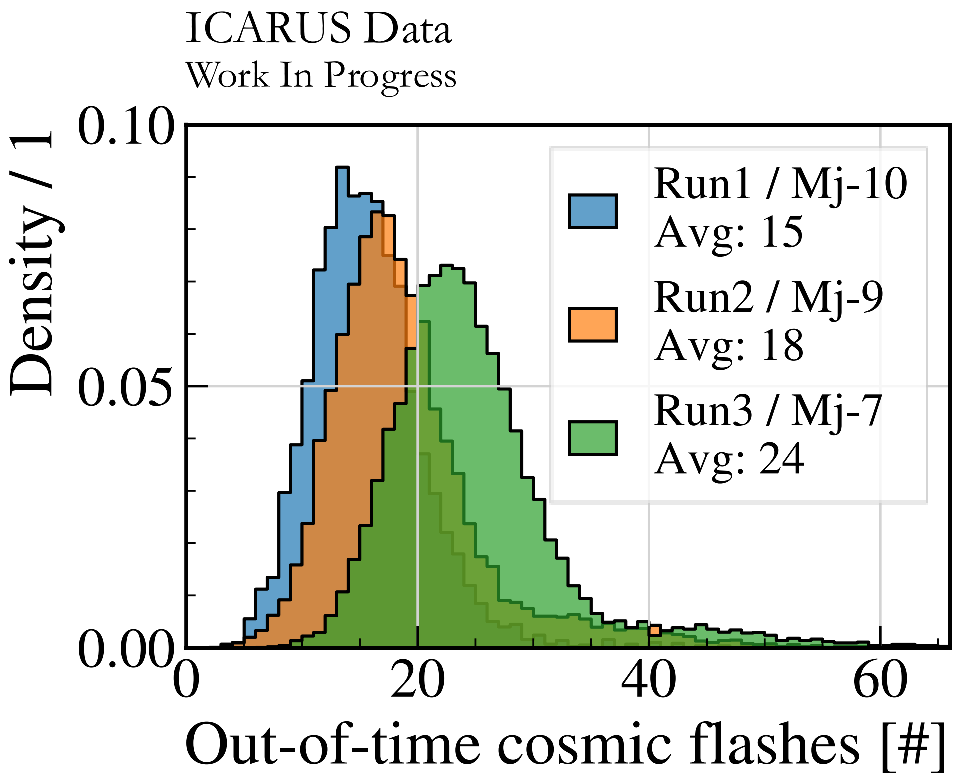
- during the ~1 ms electron drift in 1.5 m, o(10) cosmic rays are acquired in the whole detector per event;
- we can **tag cosmics** with light (TPC charge to light matching), **but** avoiding to acquire light continuously for 2 ms…

Cosmic Rejection

A "**flash**" is a cluster of PMTs fired in a 1 μs window

…to improve cosmic background rejection without saturating the DAQ, additional "**out-of-time**" **triggers** are collected:

- using a **tighter** PMT-Mj condition in a 2 ms window around the BNB / NuMI beam spills;
- when fired, 10 μs **PMT waveforms** are readout in the corresponding cryostat (180 PMTs), to tag crossing cosmics.



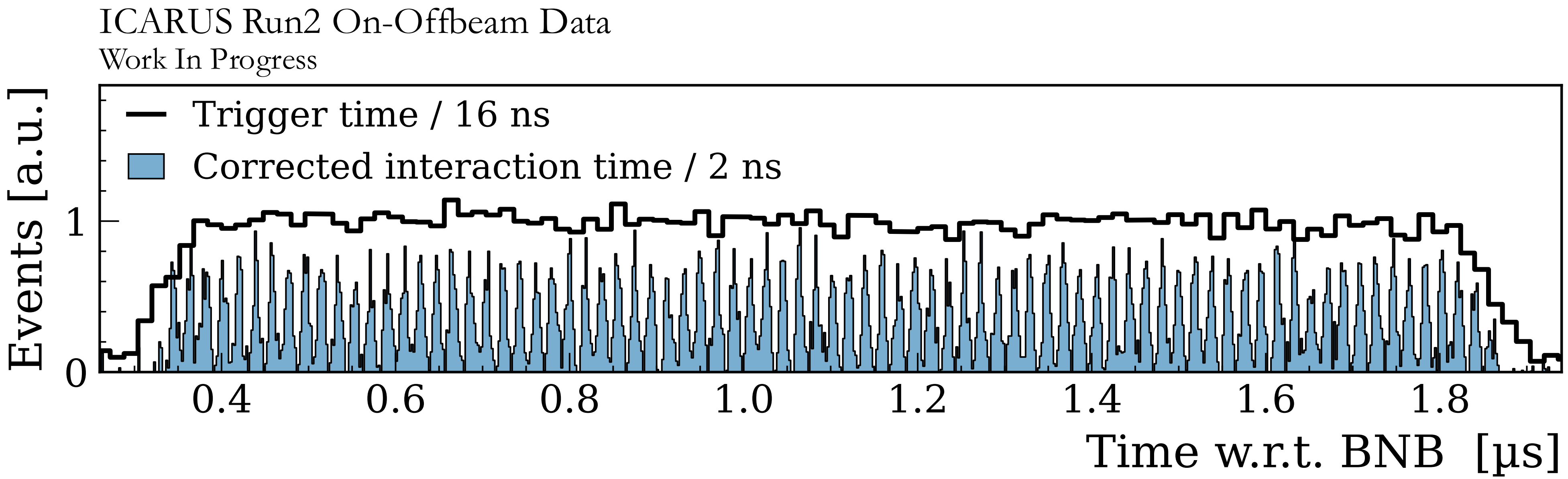
As of the latest physics runs:

- from Mj-10 in Run1, the requirements are lowered to Mj-7 in the latest physics runs (Run3): cosmic background rejection using light can be sensibly **improved**;
- the "out-of-time" trigger rate in Run3 is ~10 kHz, approaching the physical rate for cosmic rays at the surface.

Cosmic Rejection

Cosmic rejection can be enhanced also through **precise** interaction **timing**:

- the trigger provides timestamping with o(25 ns) resolution;
- the proton-bunches **sub-structure** of the beams can be reconstructed with light only with o(3 ns) resolution, using the average rise-time of the first PMTs in the two side-by-side TPCs;
- **PMTs** are calibrated with < 1 ns precision, the hardware trigger time jitter is removed by using signals from Fermilab accelerators and the time of flight is corrected by using the weighted-average position of fired PMTs;
- a time-based cut in-between **neutrino bunches** is being developed to reject cosmics (and select neutrinos or BSM signals).

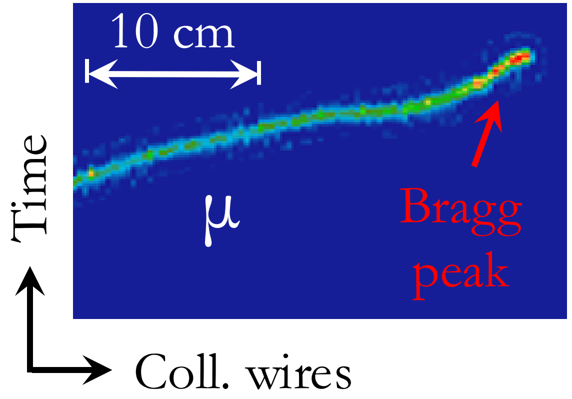


Study of the Trigger Performance

*arXiv:2407.12969

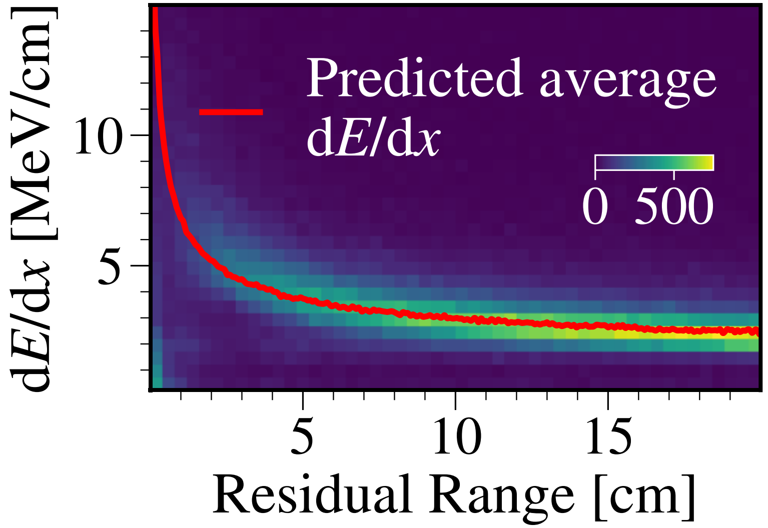
The trigger efficiency is studied with **cosmic muons**:

- using off-beam **minimum bias** data, collecting all the gates independently of the presence of scintillation light;
- time is assigned to cosmic ray particles with the **CRT**, matching in space hits on the scintillators with tracks in the TPCs;
- the trigger logic is **emulated**, starting from the collected PMT waveforms.



Muons **stopping** in the detector fiducial volume are selected:

- stopping muons are in topology and energy similar to BNB charged-current ν_μ interactions;
- their energy can be precisely measured from the residual range;
- **selection** is based on topology and calibrated* calorimetry (Bragg peak).



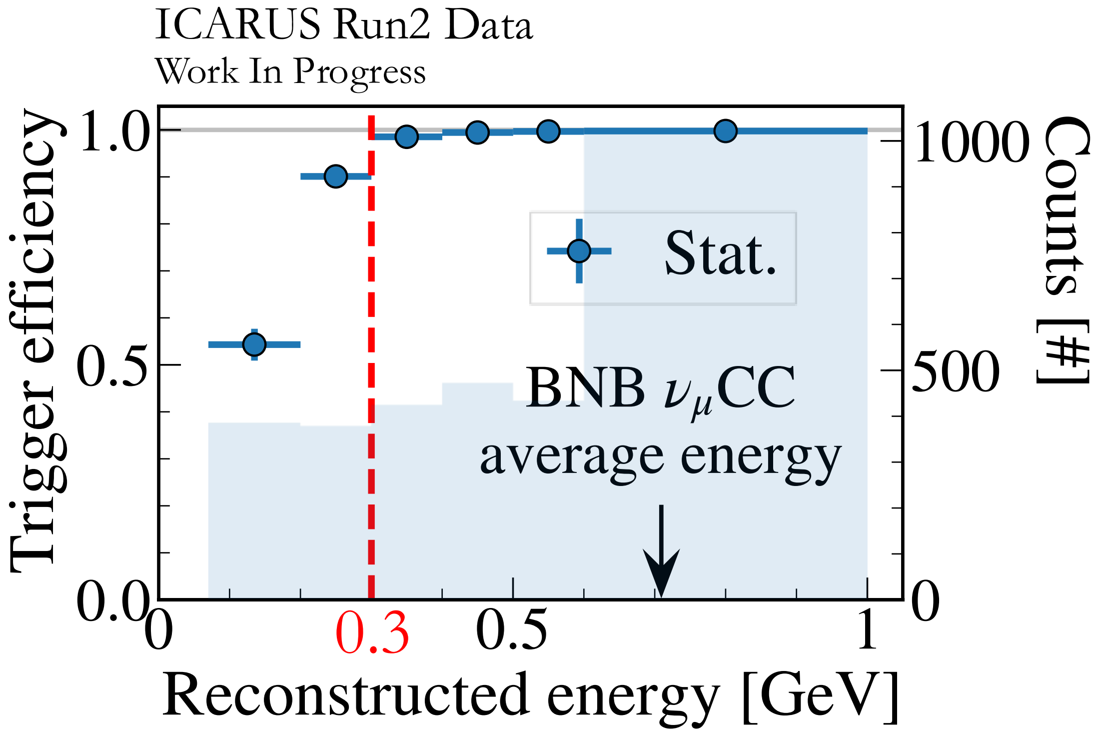
Study of the Trigger Performance

The Run2 trigger **efficiency** saturates at ~300 MeV (muon energy reconstructed from range):

- in Run2, we request at least 5 PMT-pairs in one of five overlapped 6 m-windows;
- most of **BNB** charged-current interactions occur where the trigger is fully efficient (also from **NuMI**, at higher energies).

This result only relied on **cosmic** stopping **muons**:

- for these, we reconstruct the energy precisely and easily;
- neutrinos have a different topology, developing longitudinally (based on MC, efficiency would be 15% higher < 200 MeV);
- systematic uncertainties are being finalized (~10% < 200 MeV).



Adders

“**Adder**” electronic boards were recently introduced for a complementary trigger system:

1. signals from 15 contiguous PMTs (in a 3-m longitudinal window) are split into 95%/5% components;
2. the 95% components are digitized and used for triggering with the usual PMT-Majority logic;
3. the 5% components from 15 contiguous PMTs are summed up analogically.

An **Adder trigger** is fired when there is <u>at least one Adder signal</u> going over threshold:

- ✶ can recover lower-energy events closer to the PMTs, where fewer PMTs collect more light;
- ✶ adders, based on **collected** light, are **complementary** to the multiplicity-based logic of the PMT-Majority trigger.

Plenty of light, high multiplicity.

Cathode

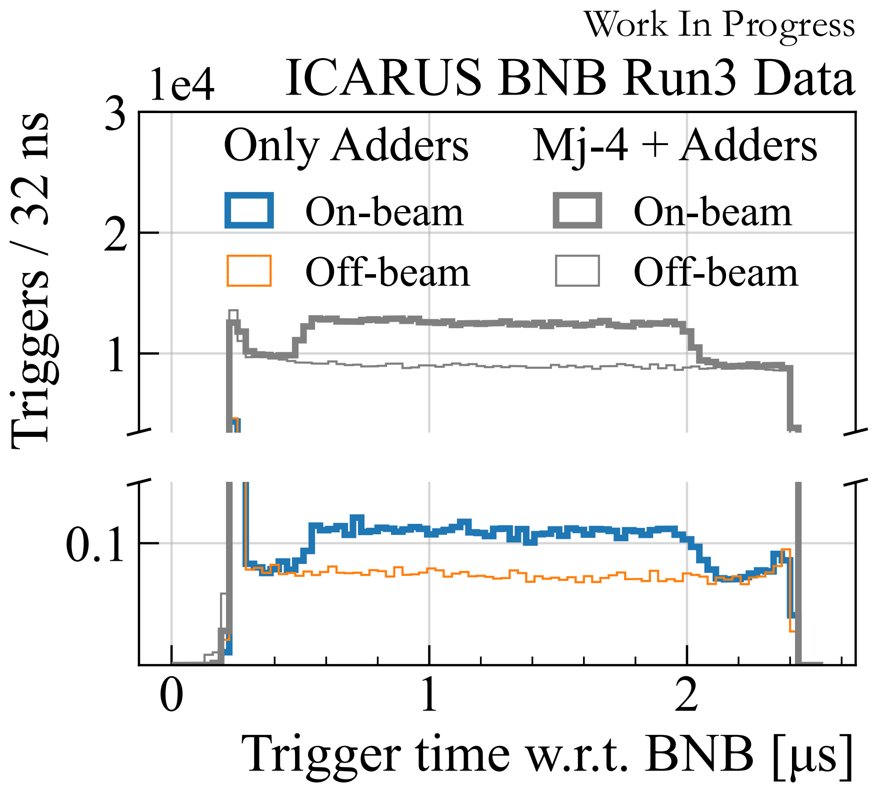
PMTs
behind anode

Plenty of light, lower multiplicity.

Trigger Performance in Run3

The trigger was **upgraded** for Run3 (Mar. 2024 – Jul. 2024), introducing the Adders in **OR** with the improved PMT-Majority logic:

- ✶ Adder trigger: at least one Adder signal above a 50 mV threshold;
- ✶ PMT-Majority trigger: the threshold was lowered from 5 to **4** PMT-pairs for collecting beam events, to further improve the efficiency;
- ✶ the two trigger sources can be **distinguished** at hardware level.



Looking at the **Run3** trigger time profiles:

- ✶ lots of **neutrinos** were collected with the Adders, on top of the well-performing PMT-Majority trigger;
- ✶ Adders alone are responsible for ~8 – 10% of the triggers, further improving the trigger efficiency at low energy.

Conclusions

✶ The **SBN** program at Fermilab aims at definitively resolving the sterile neutrino puzzle, using short-baseline LArTPC detectors along the BNB;

✶ **ICARUS** (SBN far detector) just completed its third physics run, collecting > 4 (6) $\cdot 10^{20}$ POT with BNB (NuMI);

✶ The ICARUS **trigger**, based on the multiplicity of PMTs, was **characterized** with cosmic muons and is fully efficient > 300 MeV;

✶ A **complementary** system based on the analog sum of light signals was developed and **implemented**, showing promising results.

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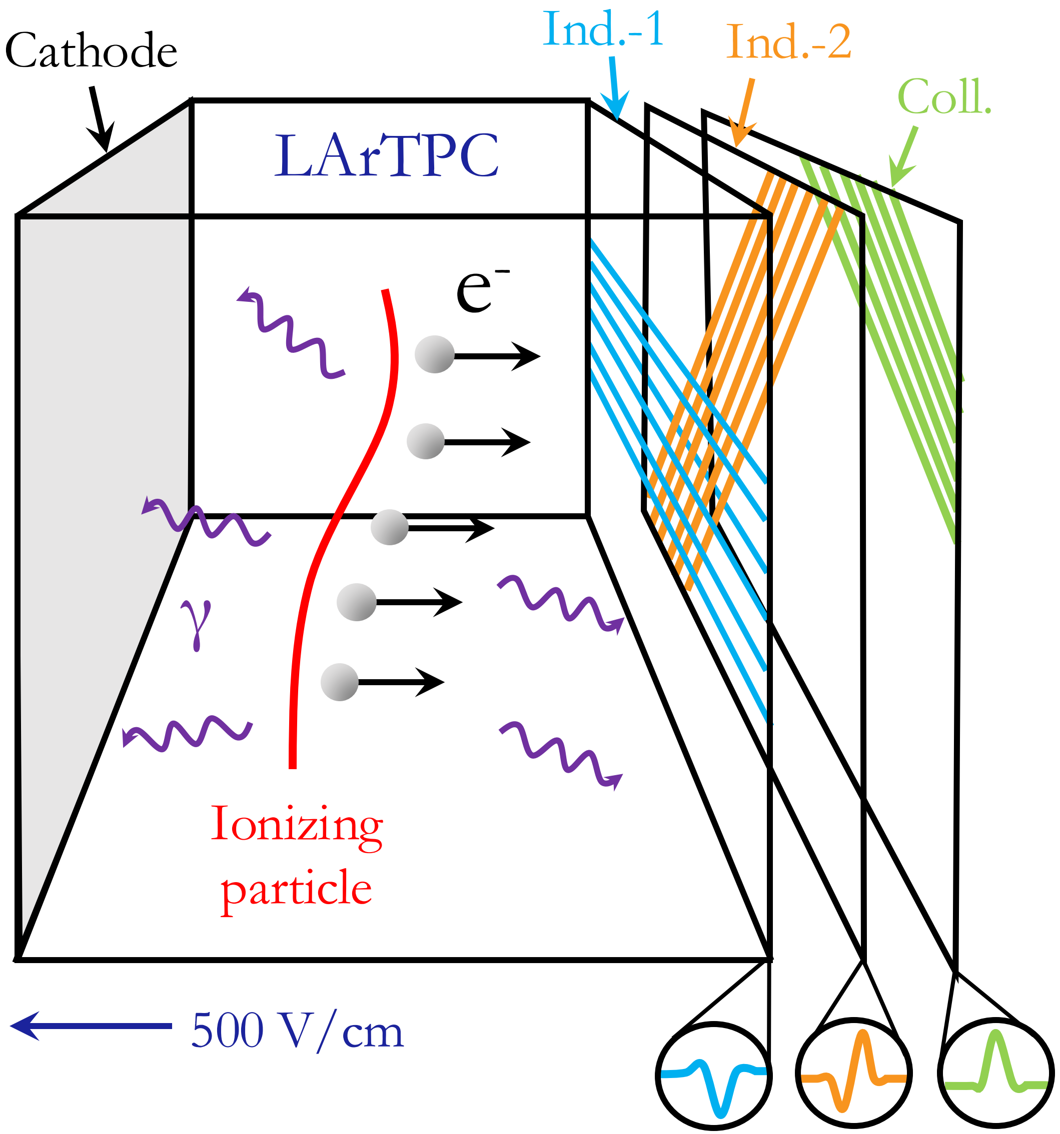
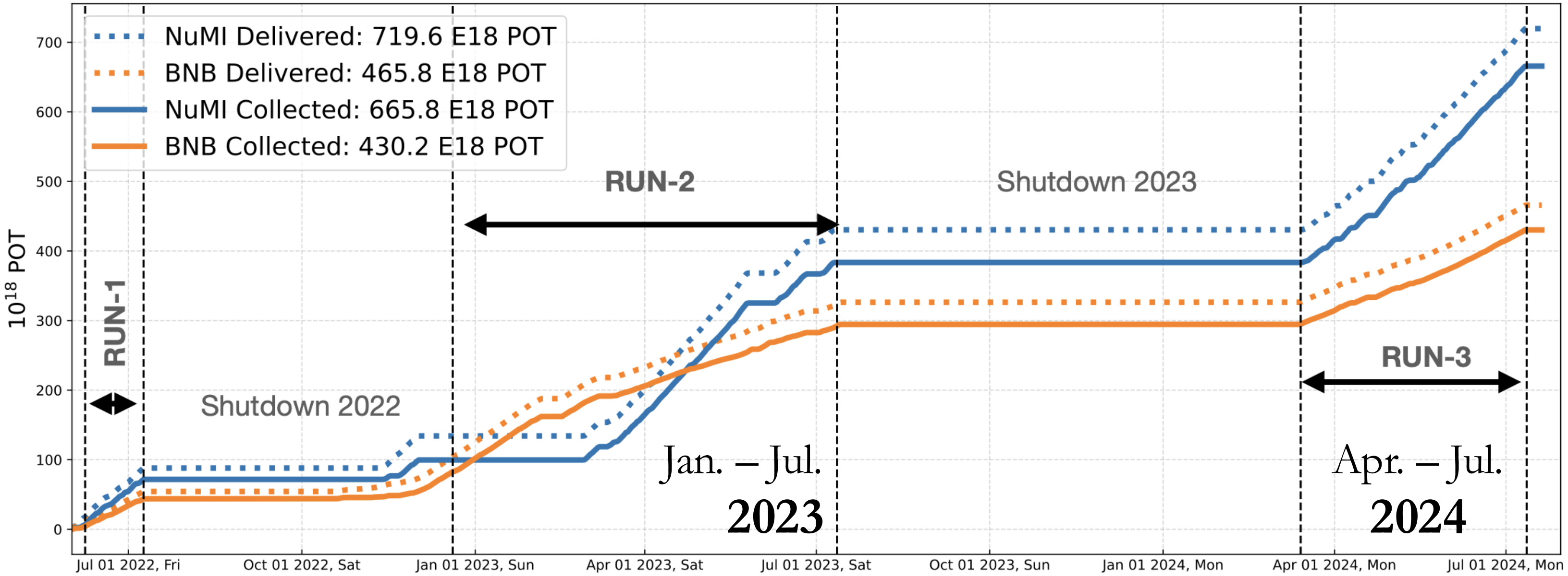
Backup

Liquid Argon Time Projection Chamber



ICARUS Timeline

ICARUS at the Fermilab Short-Baseline Neutrino program: initial operation. *Eur. Phys. J. C* **83**, 467 (2023).



Jun. – Jul. **2022**

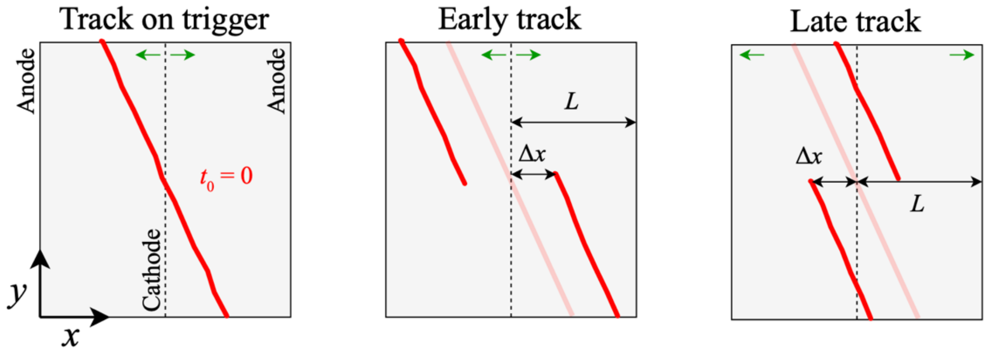
(Unbiased) Cosmic Muon Timing

Neutrino events are collected (by design) at the trigger time.

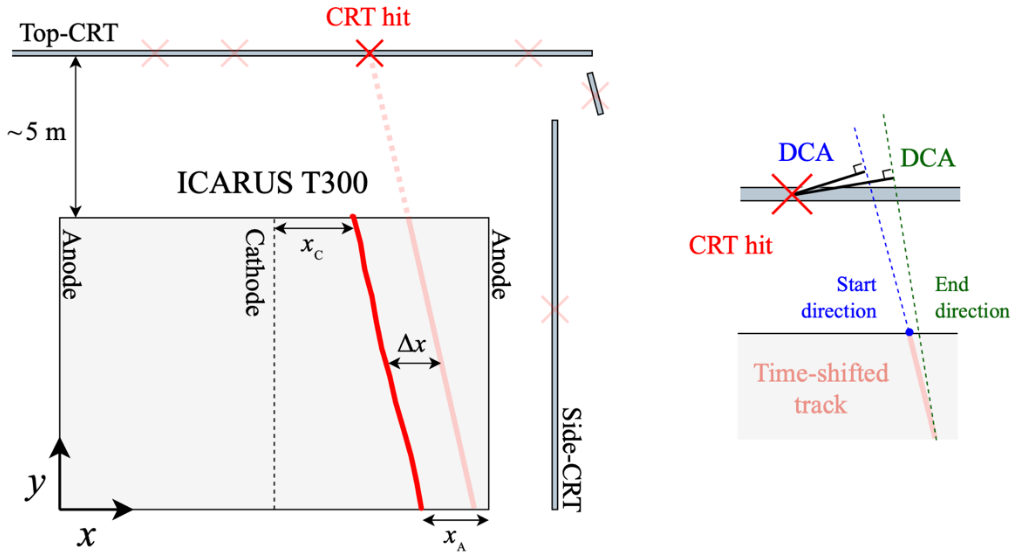
For **cosmic muons**, timing is not trivial:

- to avoid biasing the trigger efficiency estimation, PMTs **cannot** be used for timing (as one would do normally);
- the TPC can be used for timing from charge only for cathode-crossing tracks, using stitching at the cathode (µs-time resolution, orientation bias for the selected tracks, dependent on detector effects);
- the CRT provides a fast and precise determination of cosmics' crossing times.

Timing with **TPC** for cathode-crossers



Timing from **CRT**



Trigger Efficiencies