Resolving the HL-LHC beam bunch structure with fast timing

7th Forward Physics Facility Meeting

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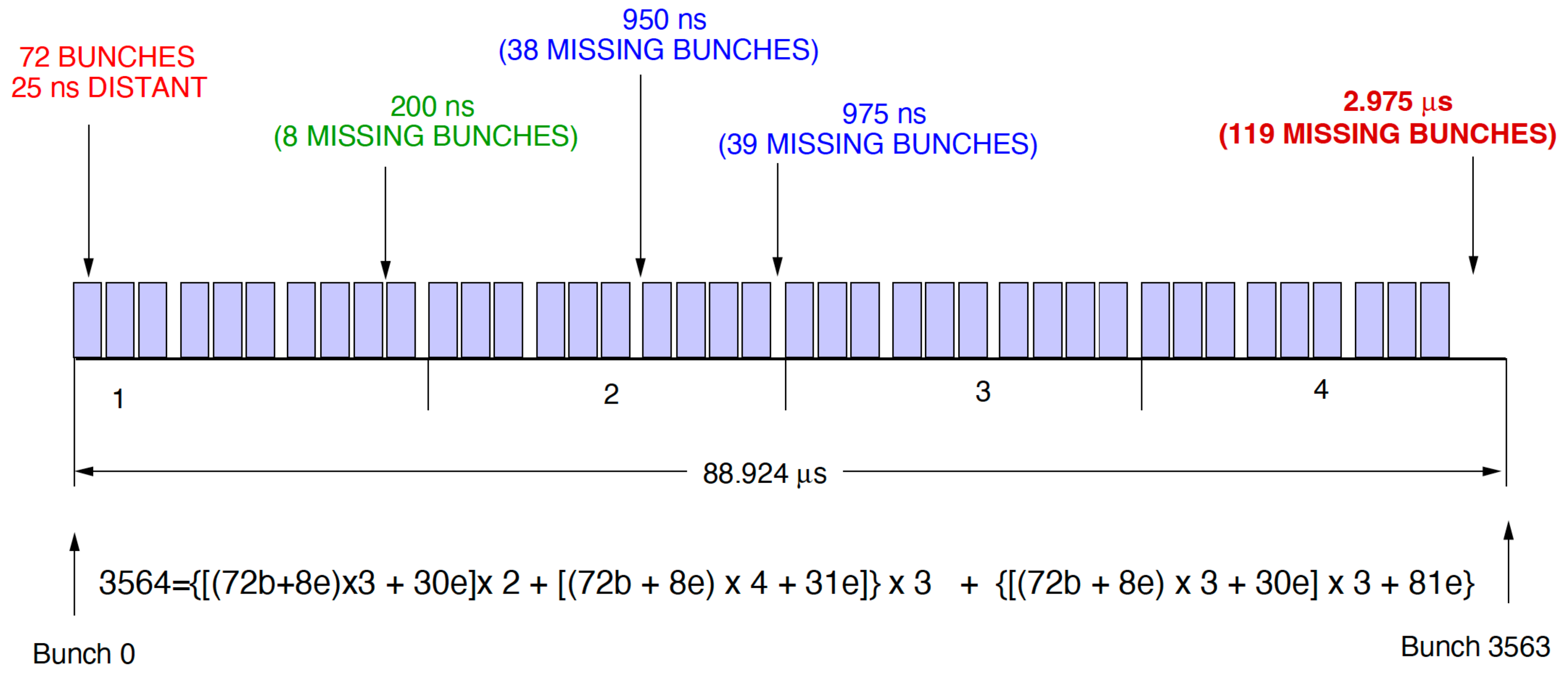
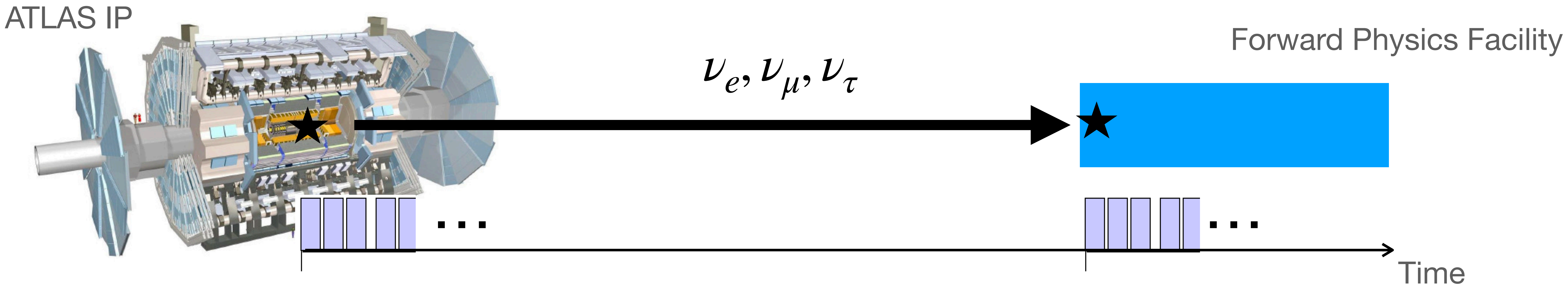
Beam timing @ HL-LHC

- HL-LHC will feature proton bunches in a 40MHz structure (25ns spacing).
- 3564 total bunches, ~2800 with protons.
- Large gap marks the end of a full orbit (89us), used to reset the bunch counters.

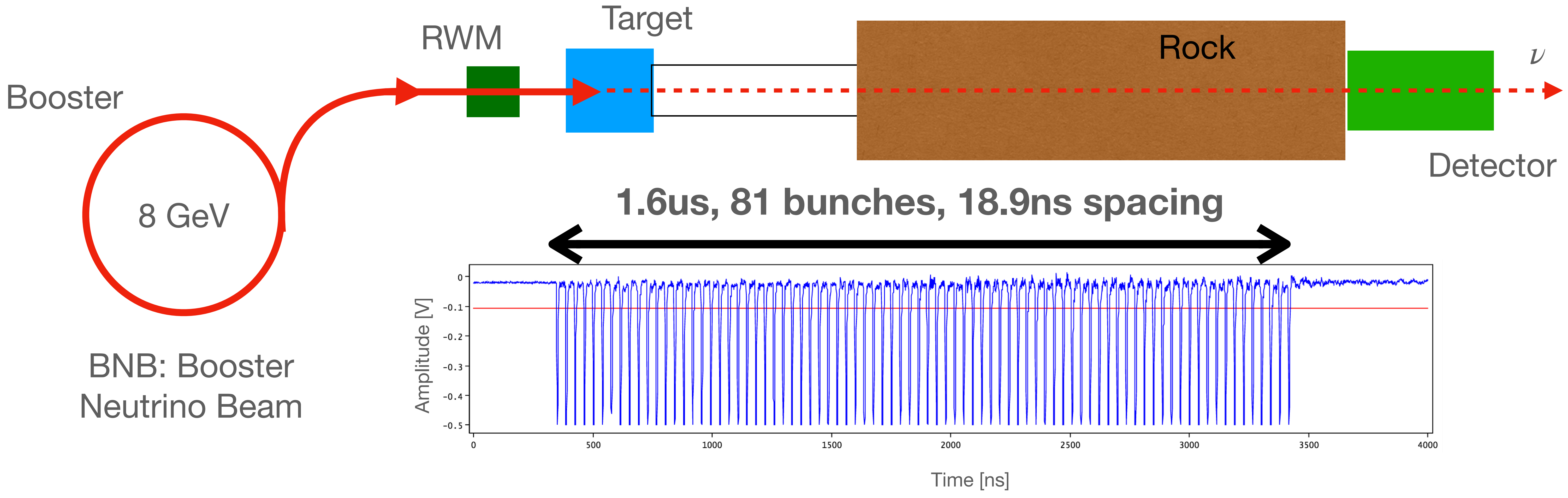




Neutrinos inherit the proton beam time profile: propagation (incl. meson decays) only adds constant offset!

Fast timing as a powerful selection tool, tagging beam-synchronous interactions (neutrinos) vs slower heavy BSM particles (e.g: HNLs)

Neutrino beam(s) @ Fermilab



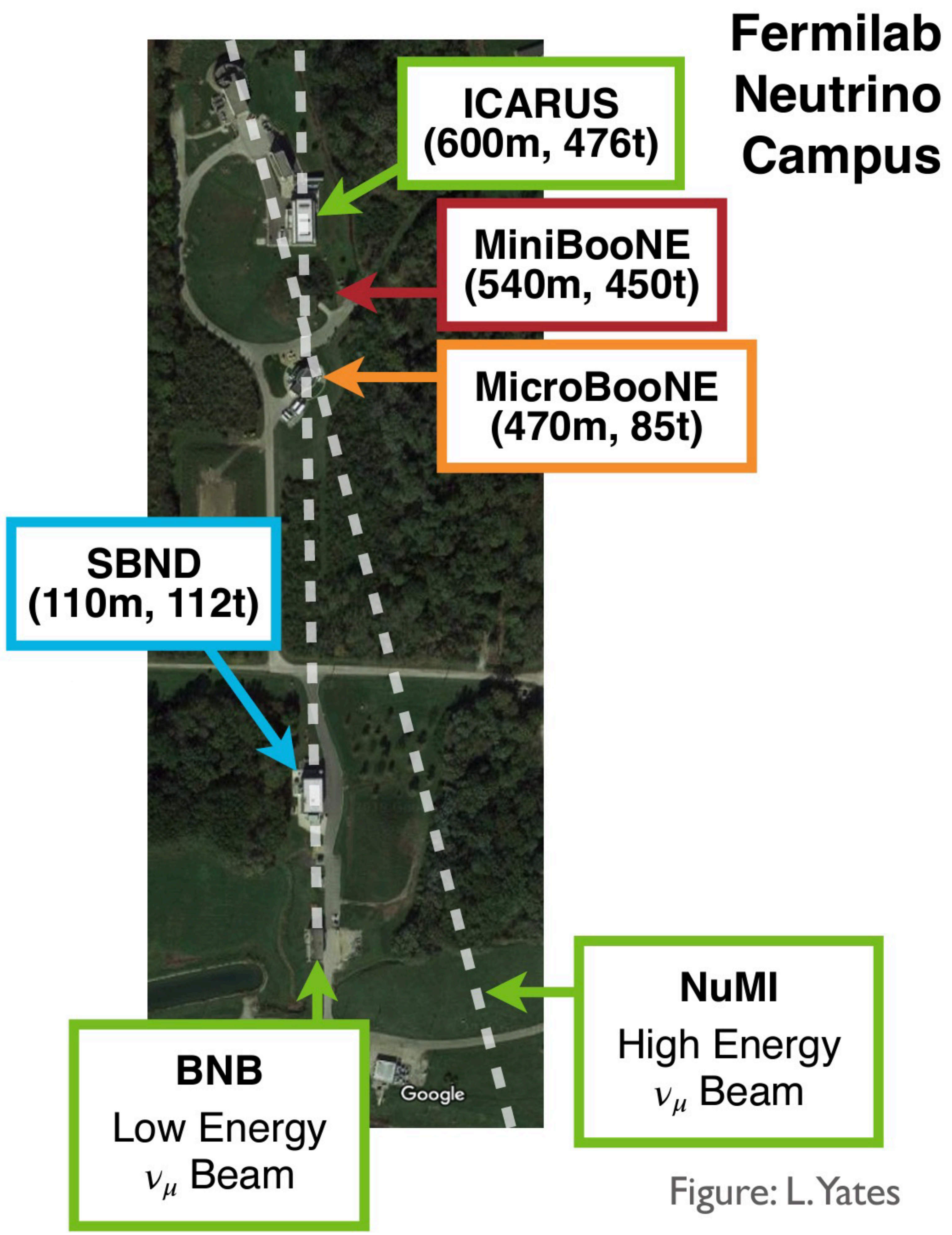
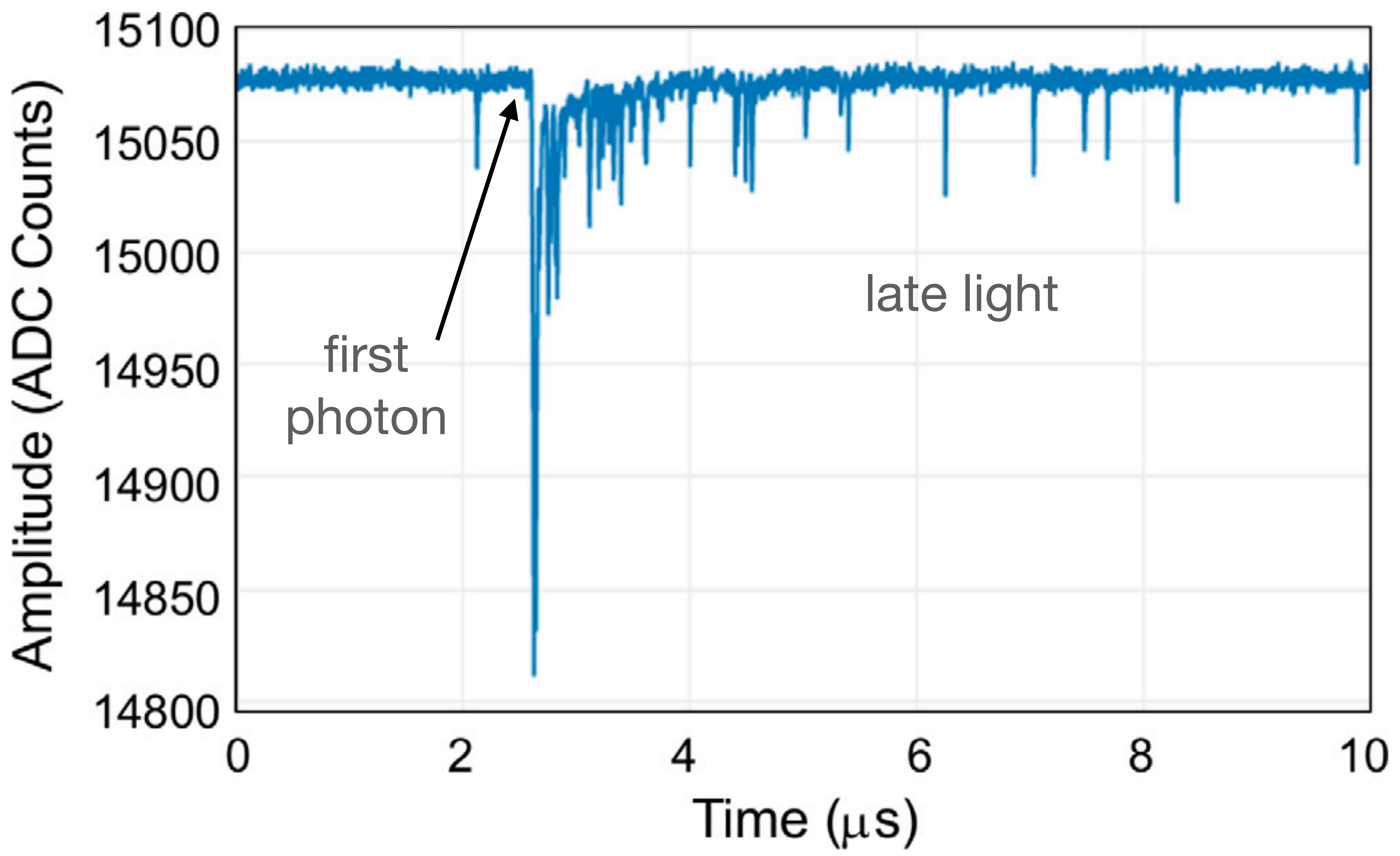


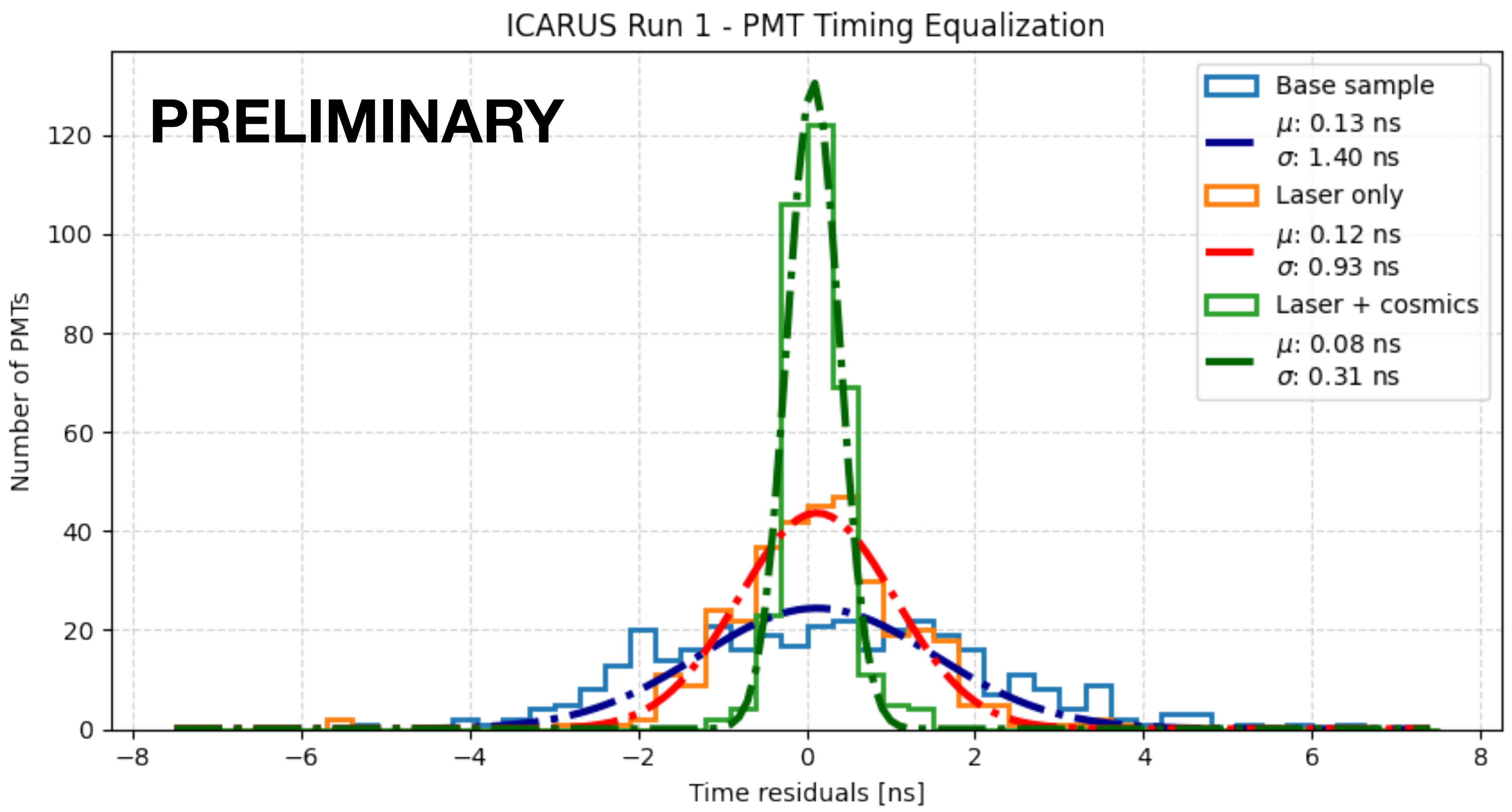
Figure: L.Yates

- Neutrino beam spills at Fermilab have a similar timing structure to LHC, with a slightly shorter spacing (~19ns).
  - BNB: 1.6us spill, 81 bunches, 18.9ns spacing (52.8 MHz)
  - NuMI: 11.1us spill, 486 bunches, 18.8ns spacing (53.1 MHz)
- Past and current experiments, including LArTPCs such as MicroBooNE and ICARUS, have been able to resolve the bunch structure with timing.

Fast timing in LArTPCs

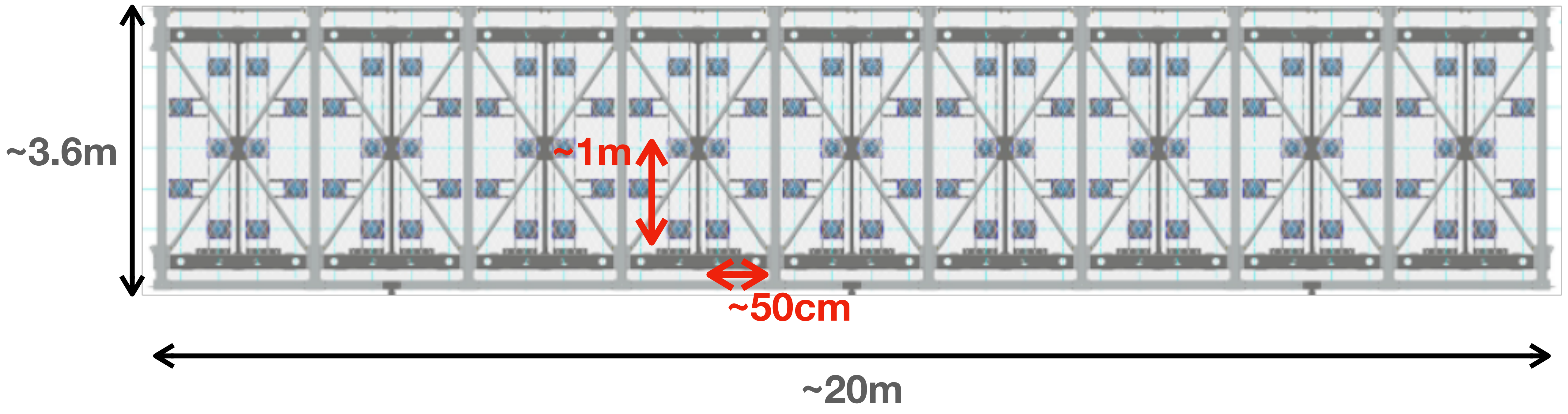
- Fast scintillation component in LAr is $\tau = 6$ ns, but this is not limiting the time resolution.
- Recorded signals are time series made of n scintillation photons, each independent. The *first photon* defines the pulse time.
- The time resolution improves ~ τ/n picking the first photon in the time series.
- MicrooBooNE recently achieved O(ns) timing resolution.
- ICARUS relative calibration down to ~300 ps using laser system and cosmic muons.

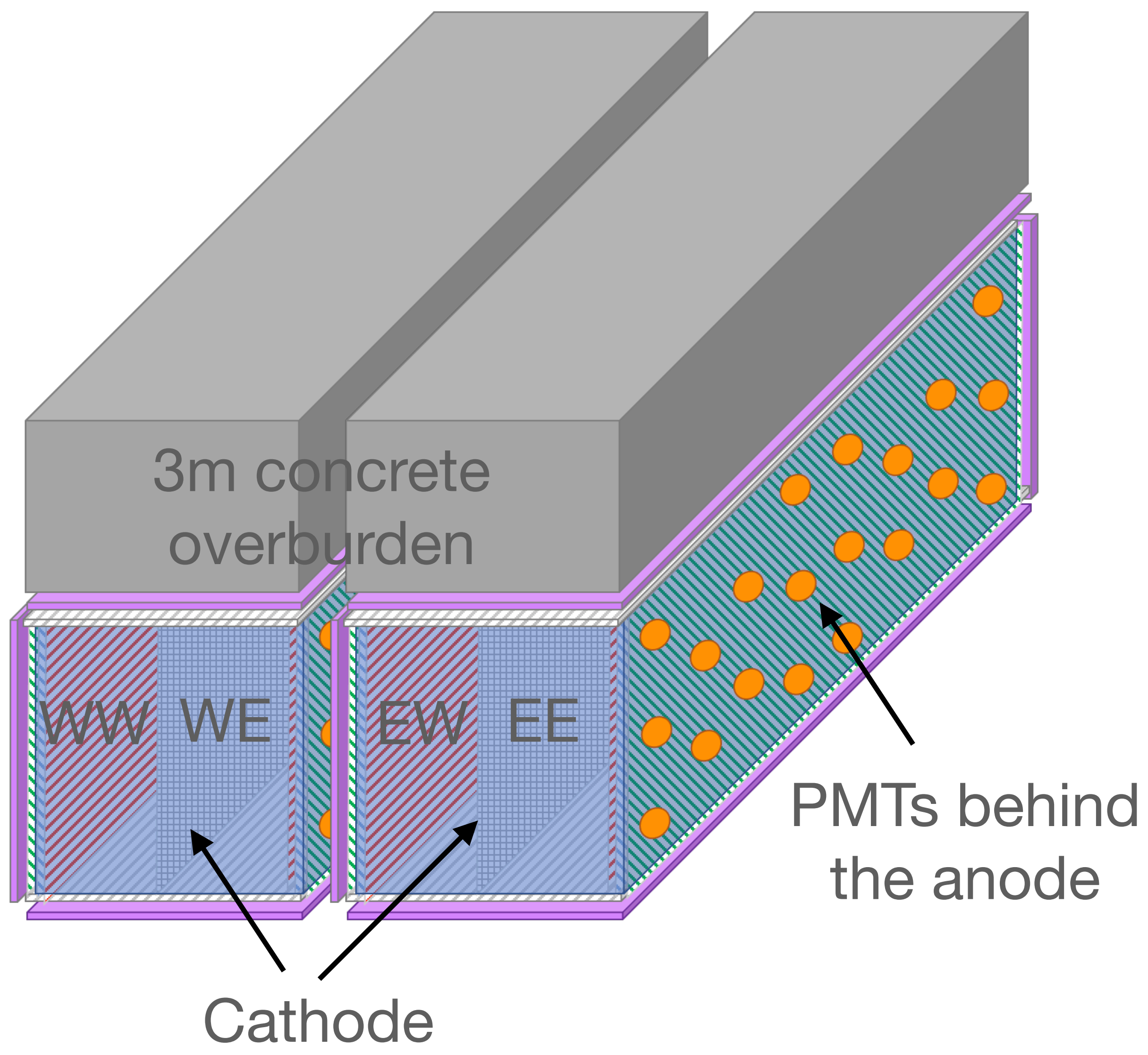




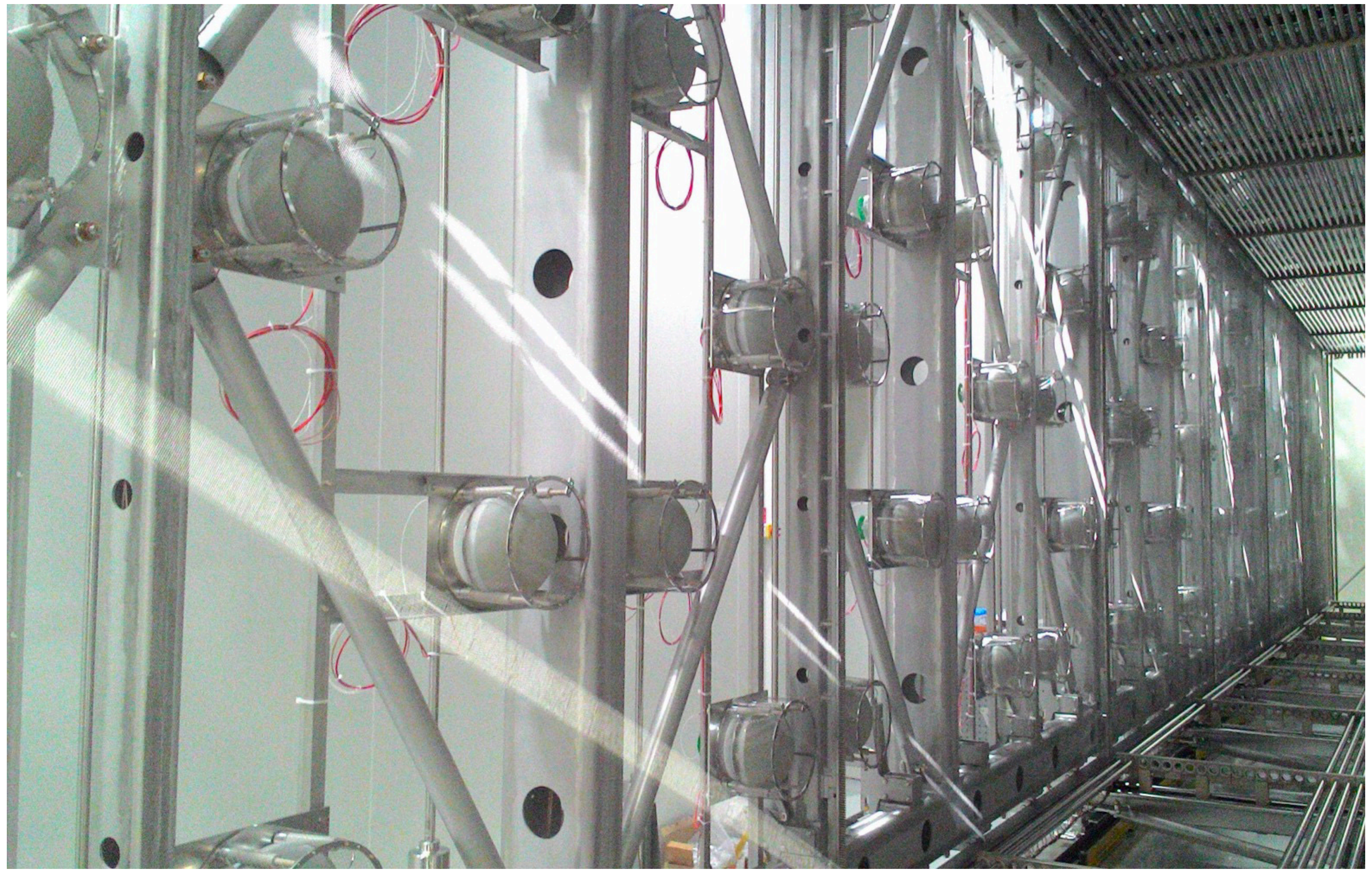
ICARUS T600

- ICARUS @ Fermilab is currently the largest liquid argon detector in operation (~476 active tons).
- Each cryostat with 2 TPCs sharing the same cathode.
- 360 Hamamatsu R5912-MOD 8” PMTs mounted behind the anode wires. PTB coating for 128nm sensitivity.
- Placed in a “honeycomb” structure on the four “walls” (90 per wall, 180 per cryostat).

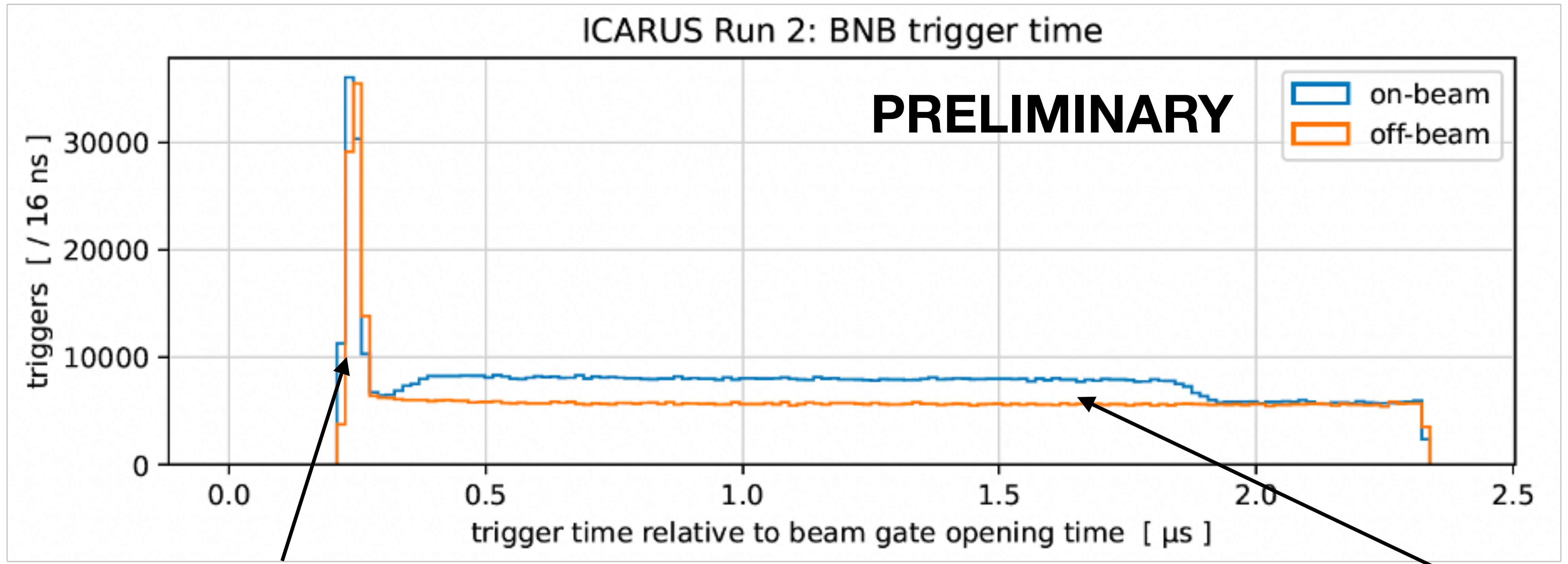


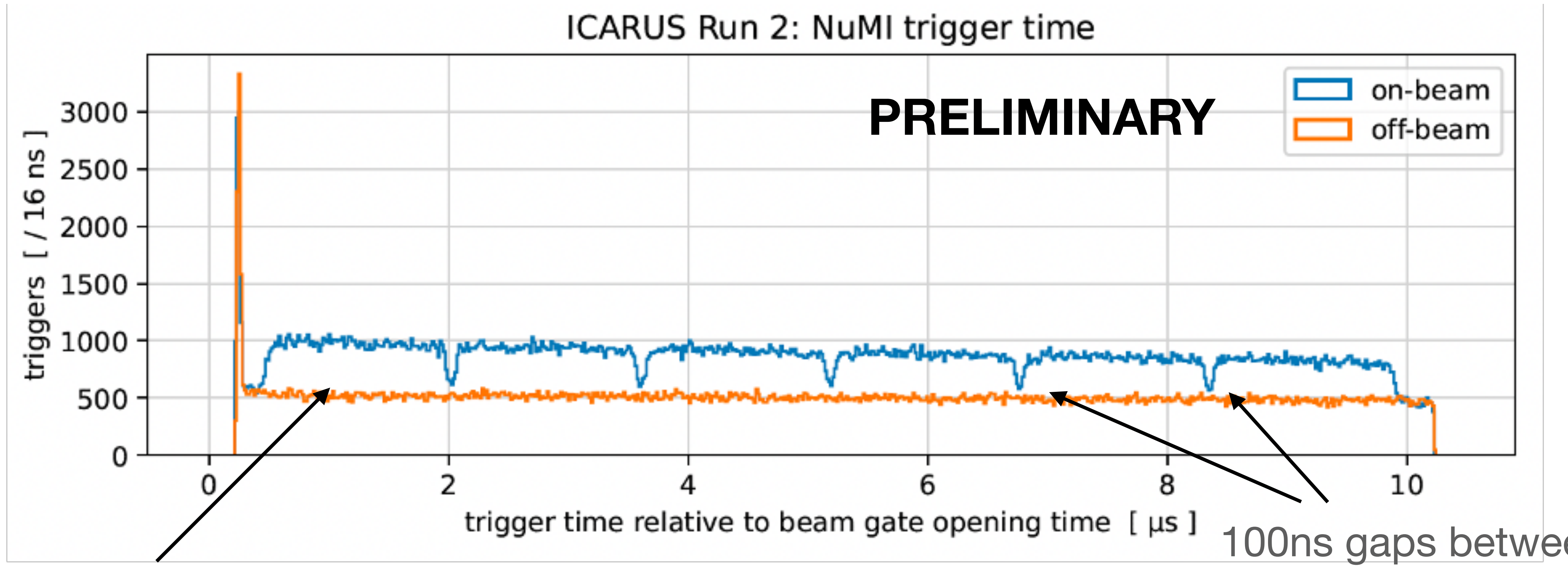


“Honeycomb” PMT pattern on one of TPC walls



Why isn't the trigger time enough?





Late light from cosmics right before the beam gate

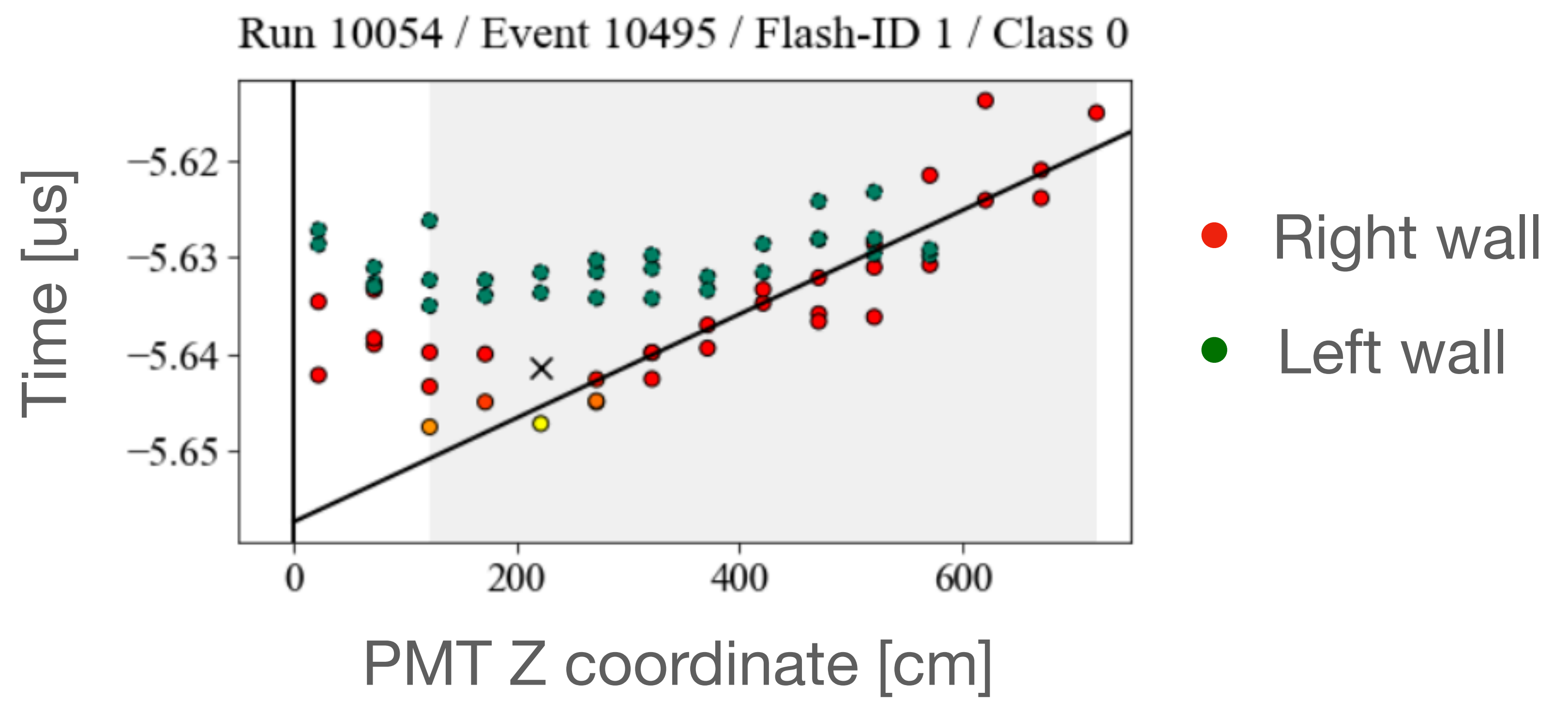
Beam excess

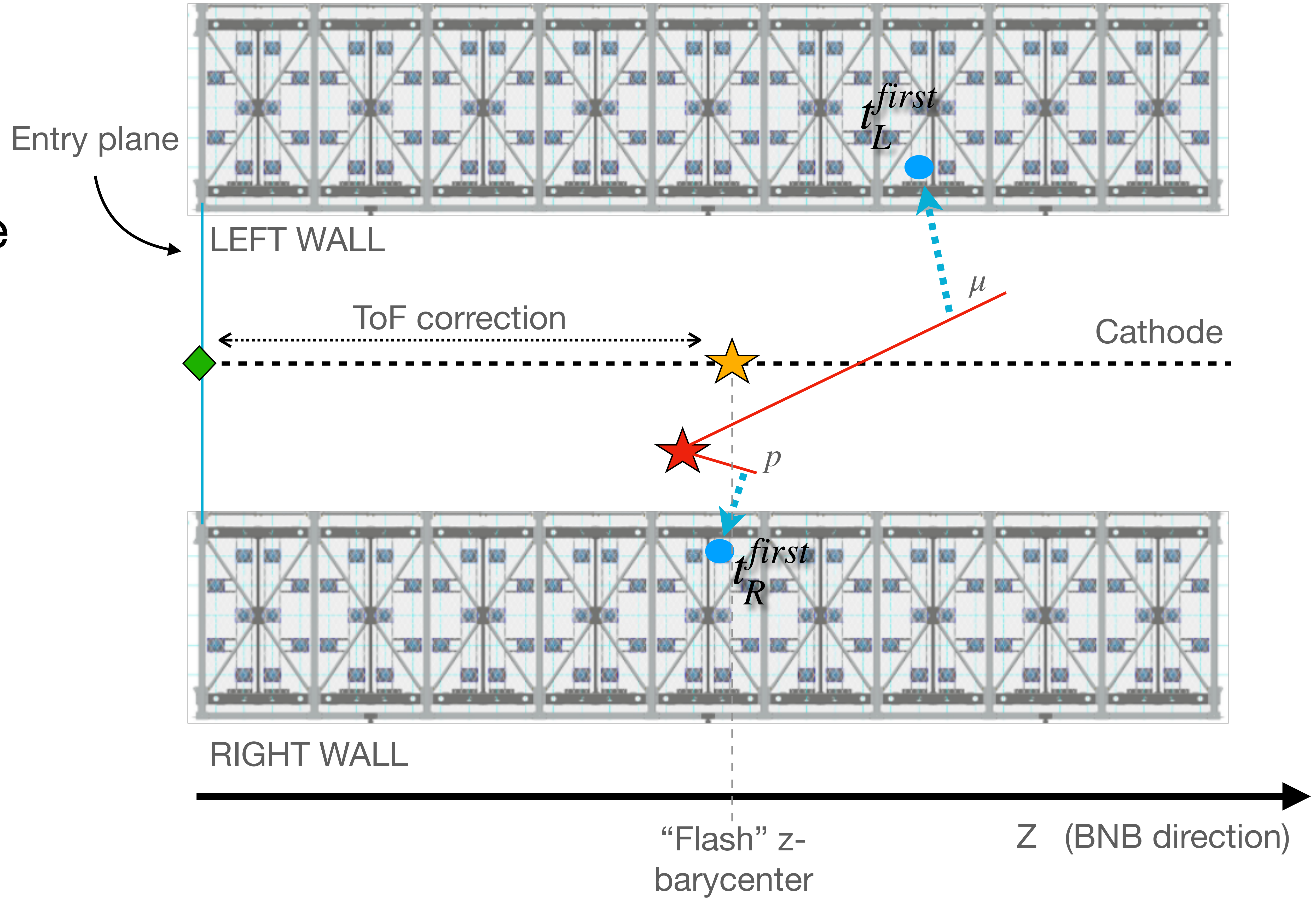
100ns gaps between NuMI batches

- The ICARUS global trigger timestamp jitter (25ns, 40 MHz clock) is too large to be able to see the beam bunch structure.
- However, CAEN V1730 digitizers have a 2ns (500 MHz clock) sampling time, and they timestamp at 125 MHz (8ns jitter). This is good enough to see the ~20ns gaps among individual bunches.
- <u>Strategy</u>: compare neutrino times from PMT pulses with an external accelerator signal, both digitized by the same boards to avoid jittering.

Event timing

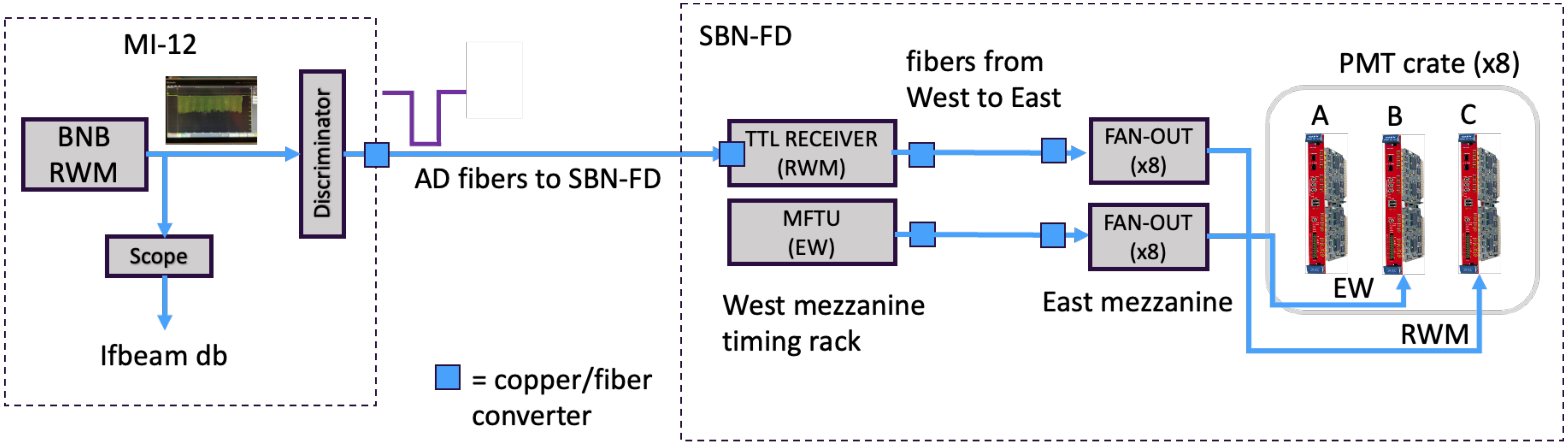
- Neutrino events happen anywhere, smearing out the timing profile. Events must be compared at the same distance from source.
- Event times are estimated with information from PMTs only. For each scintillation event:
  - Mean time between the first pulses on the two walls (t_L^{first}, t_R^{first}) as the "neutrino time". This removes dependency on the (x,y) position in the cryostat.
  - Time-of-flight (ToF) correction from the z-barycenter of the light to the entry plane.
- Charge information from the TPC can improve the vertex estimation and ToF correction.





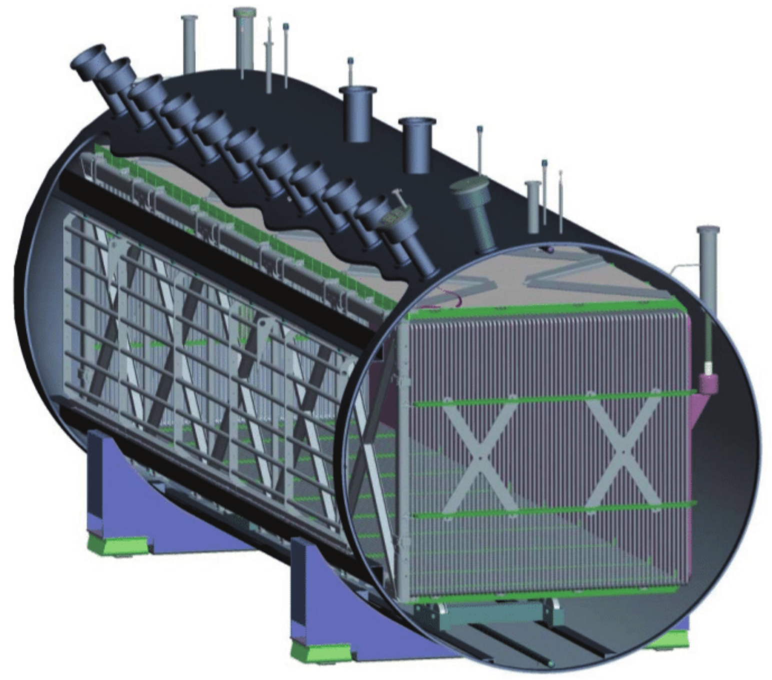
Beam reference signals

- Fermilab Accelerator Division (AD) provides ICARUS beam-synchronous reference signals via White Rabbit for trigger and timing.
- A discriminated copy of the RWM signal is also provided on fiber to be digitized alongside PMT signals. RWM = protons smashing on the target (~time of the spill = first bunch).
- This provides a free-of-jitter reference time for the beam spill.



Reconstructing the structure

- MicroBooNE recently published their results.
    - PMTs on one wall only, TPC information used to constrain the event.



ICARUS result is coming soon….

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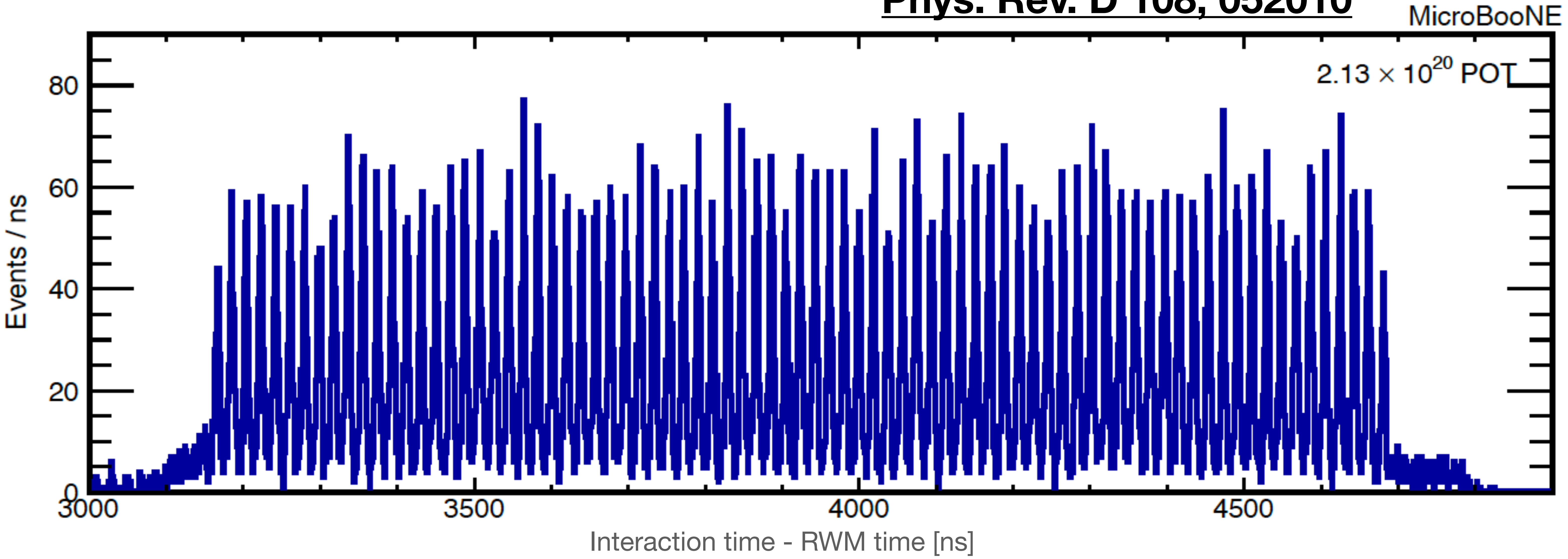
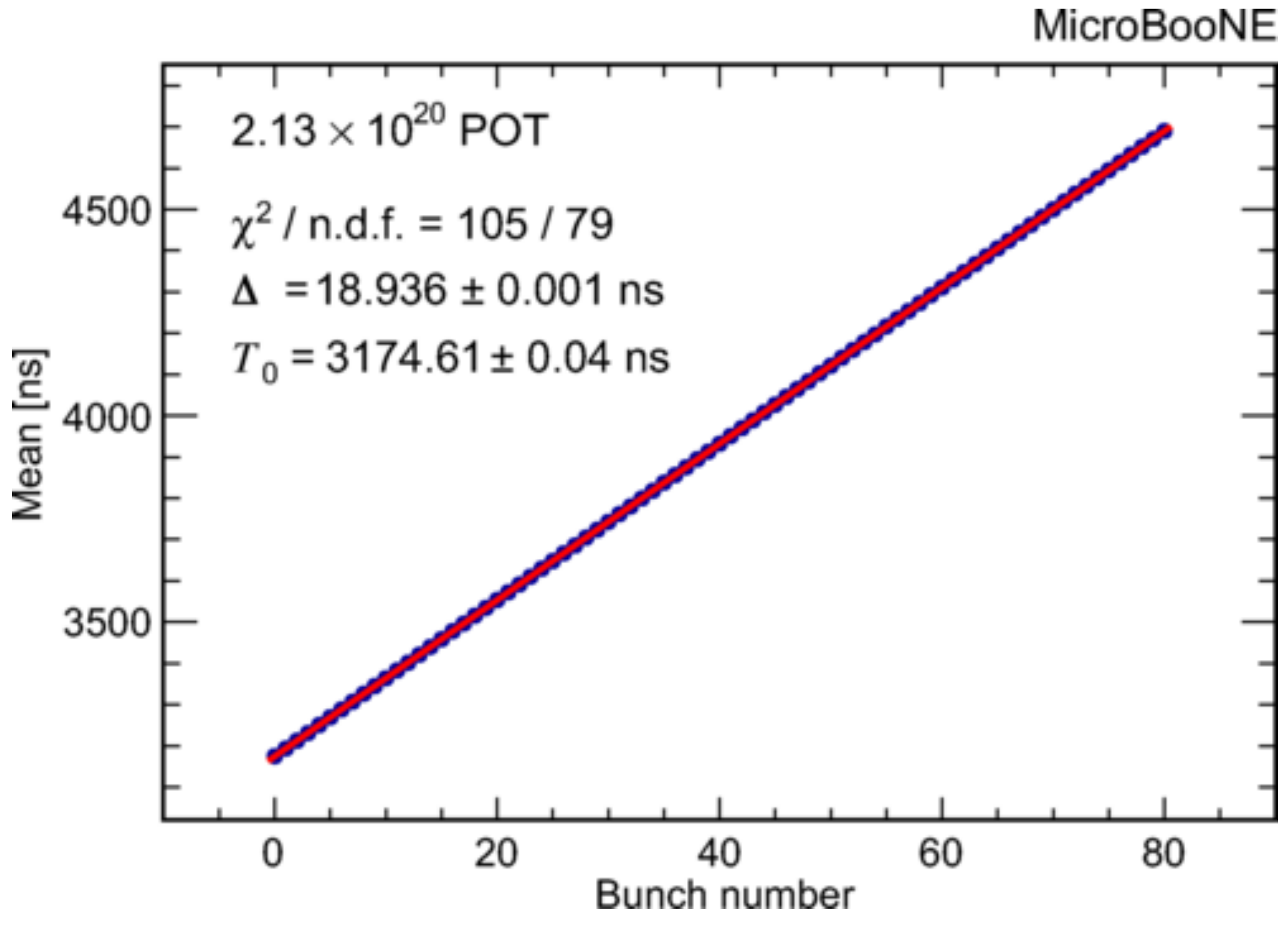
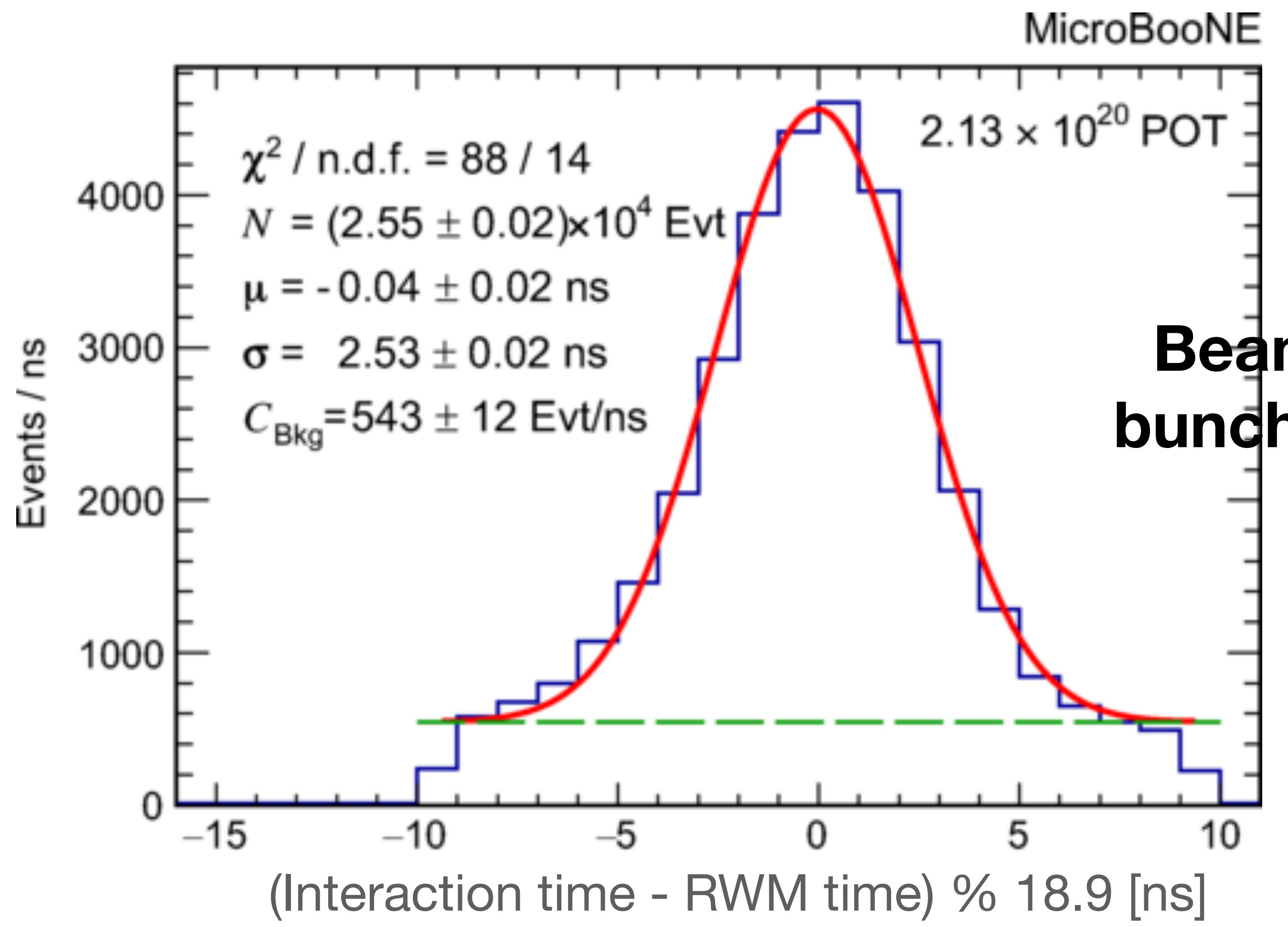






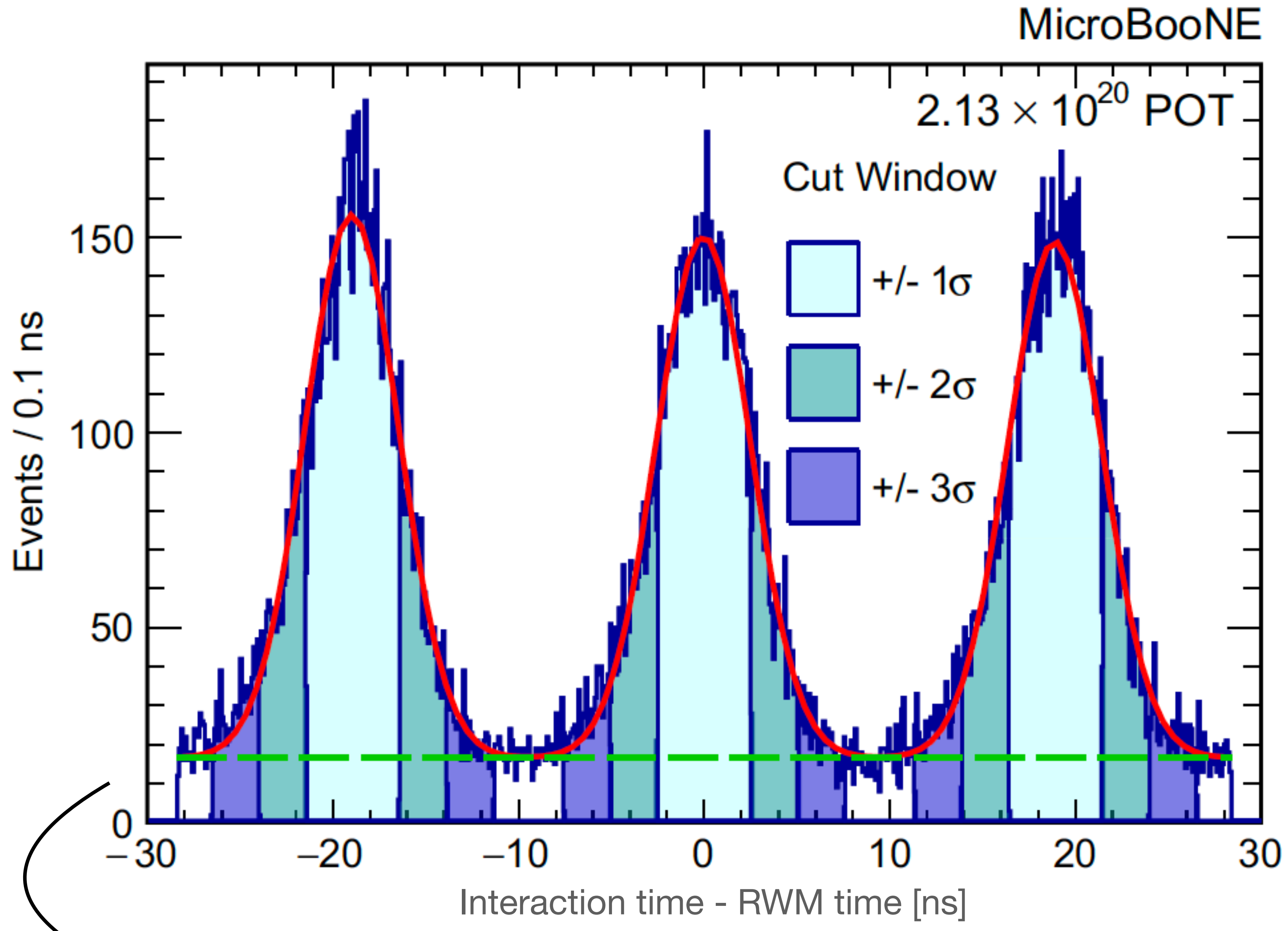
Beam intrinsic bunch RMS ~1ns

Physics opportunities

Phys. Rev. D 108, 052010

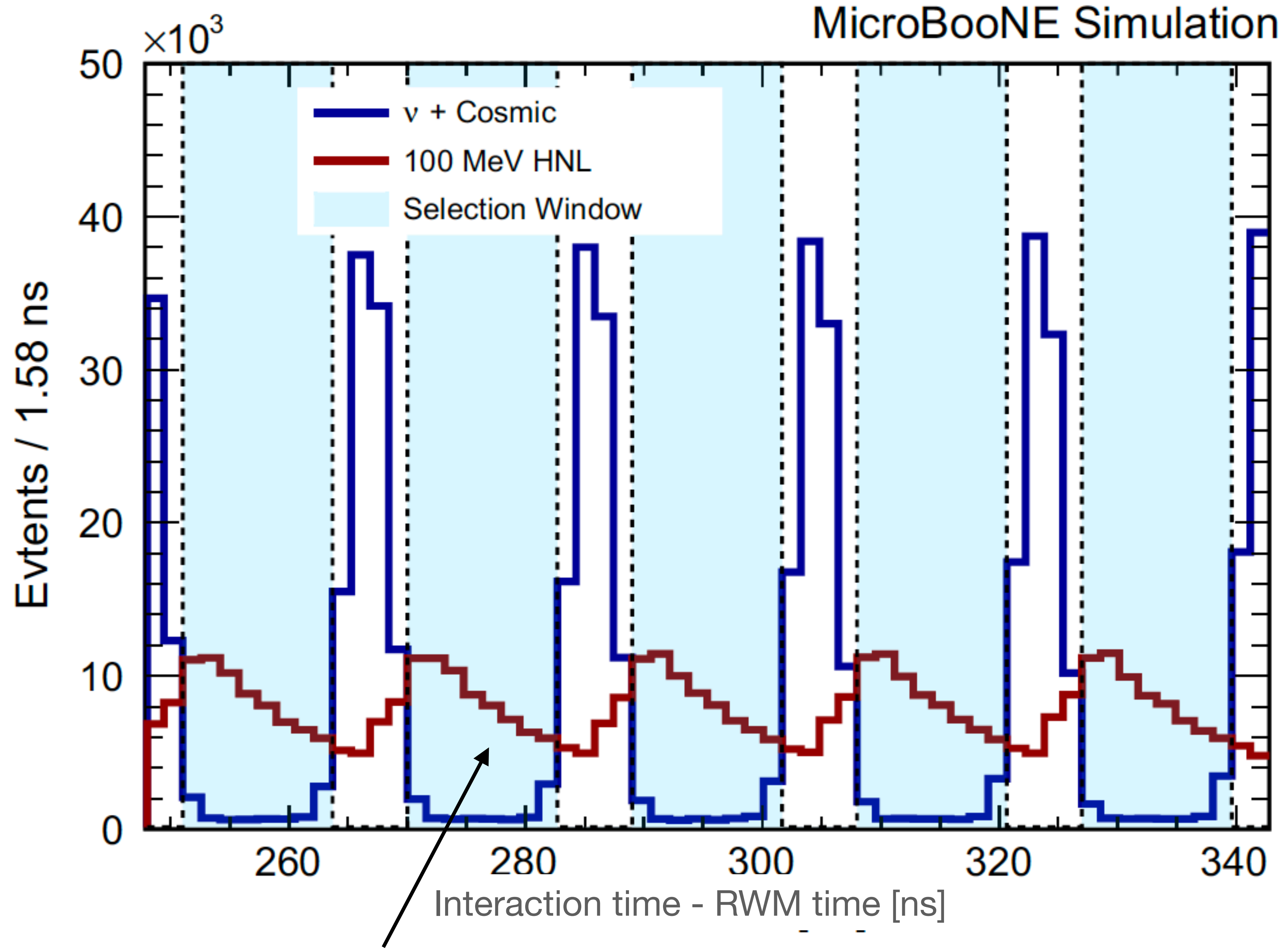
- Bunch identification is a powerful tool to reject backgrounds or look for new (heavier) particles.
- Physics opportunities by correlating FPF events with collider events should be considered!

Rejection of residual cosmic background



Residual background (30%) reduced to 10% with $\pm 1\sigma$ cut around each peak

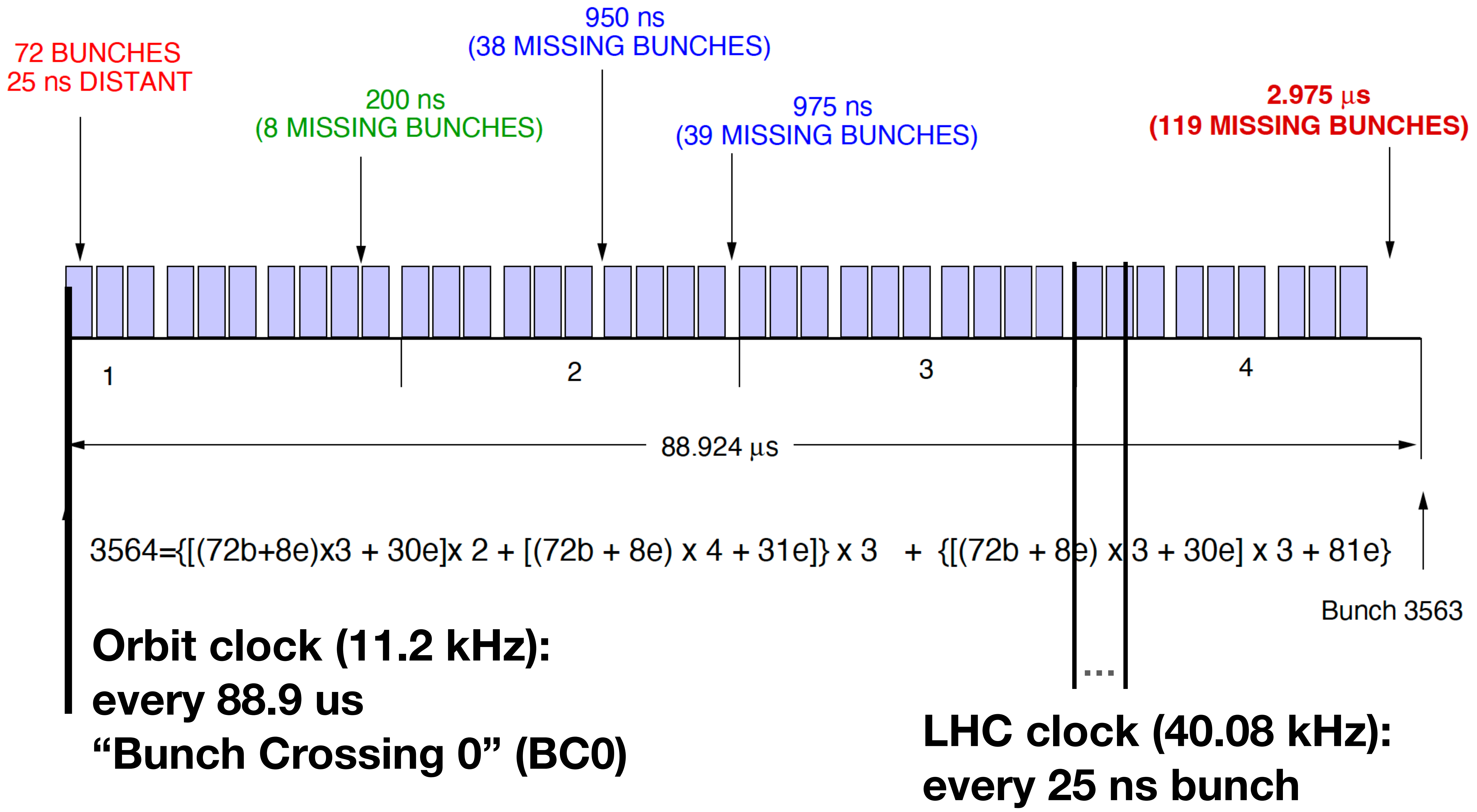
Simulation of νs + 100 MeV HNLs time profile



HNLs are massive so they are delayed w.r.t. nearly-massless neutrinos

Fast timing with FLArE @ FPF

- Fast timing with FLArE is expected to achieve O(ns) resolution, like other LArTPCs.
- LHC provides primarily two beam-synchronous signals to experiments:
  1. the bunch clock (40.08 MHz)
  2. the orbit clock (11.2 kHz)
- No showstoppers in resolving the bunch structure in FLArE!
  - 25ns are easier than 18.9ns!



We will work with BNL ATLAS colleagues to understand how best to utilize the BCID for trigger and analysis.

Summary

- LArTPCs have recently demonstrated O(1ns) timing resolutions.
- Successful identification of 52.81 MHz BNB spill bunch structure at past (MicroBooNE) and current (ICARUS) experiment at Fermilab.
- LHC proton beam structure shares similarities with Fermilab neutrino beams (25ns vs 18.9ns spacing).
- LHC reference signals provide opportunities for analogous timing techniques.
- Fast timing in FLArE is feasible and can provide enhanced capabilities for neutrino selections and BSM searches (e.g. HNLs).

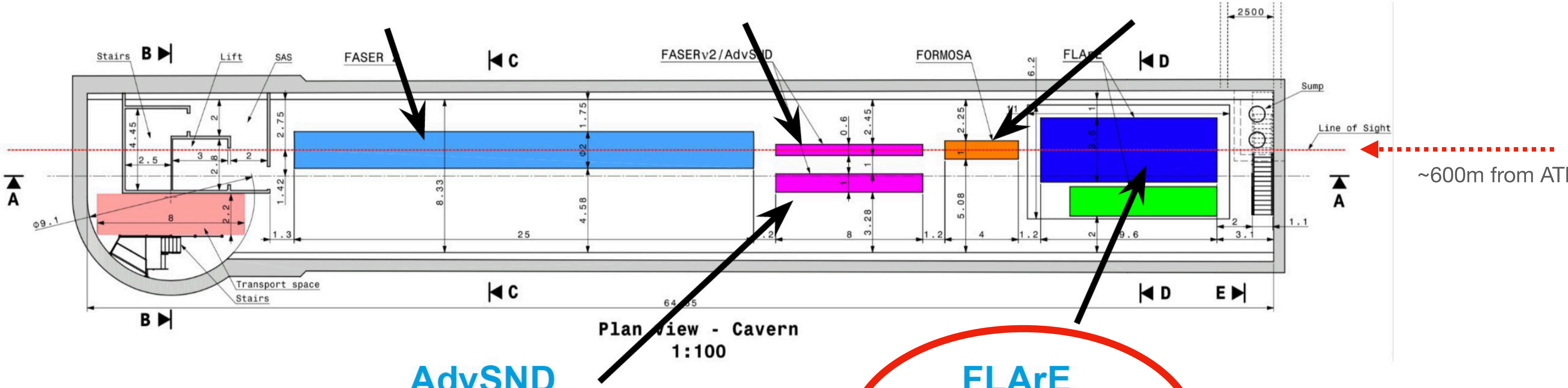
Backup

FLArE @ Forward Physics Facility

FASER2
magnetized spectrometer
for BSM searches

FASERv2
emulsion-based
neutrino detector

FORMOSA
plastic scintillator array
for BSM searches



~600m from ATLAS IP

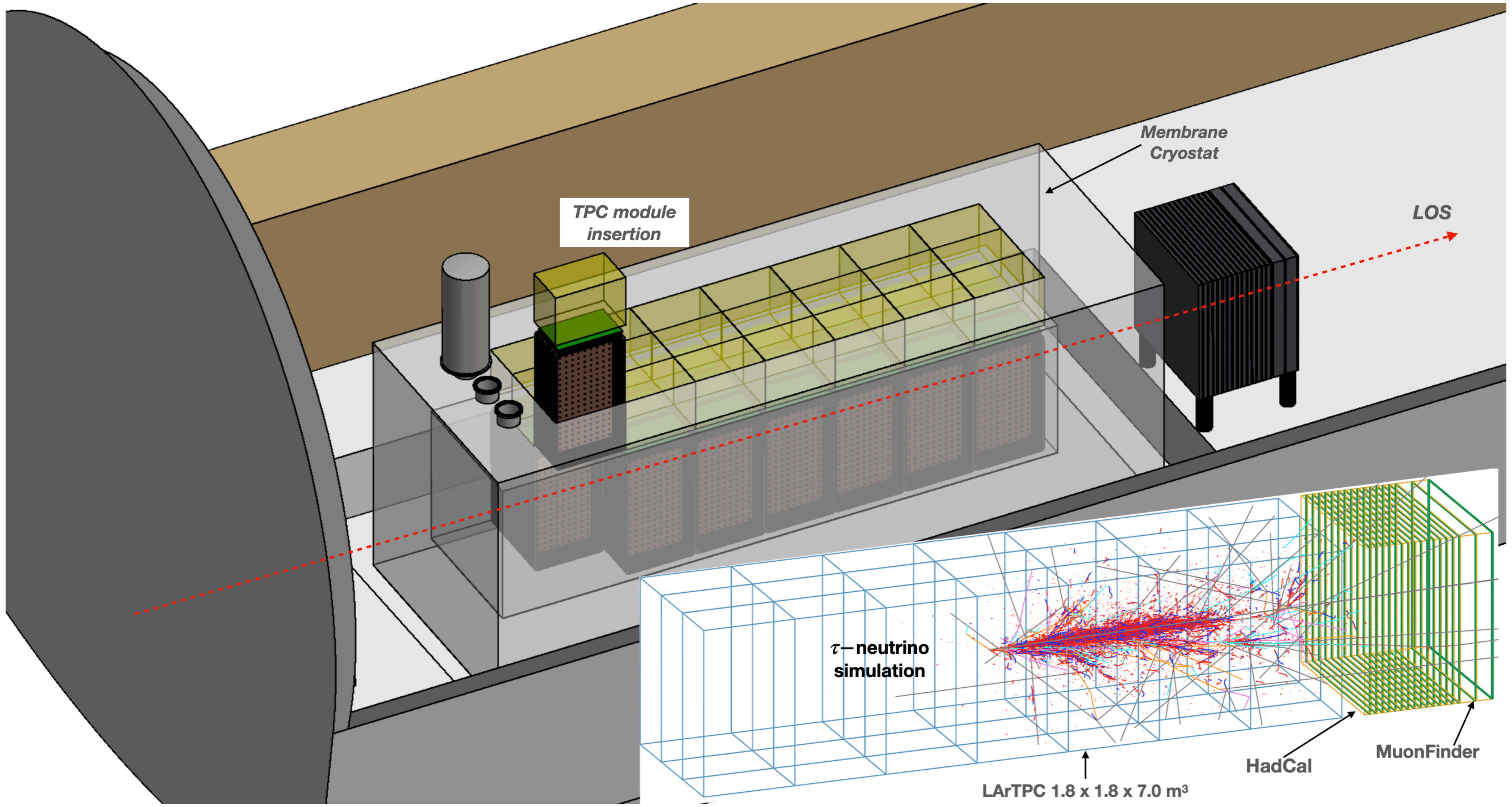
AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

FPF covers η > 5.5,
experiments on
LOS cover η ≳ 7

Modular TPC

https://www.osti.gov/biblio/1972463

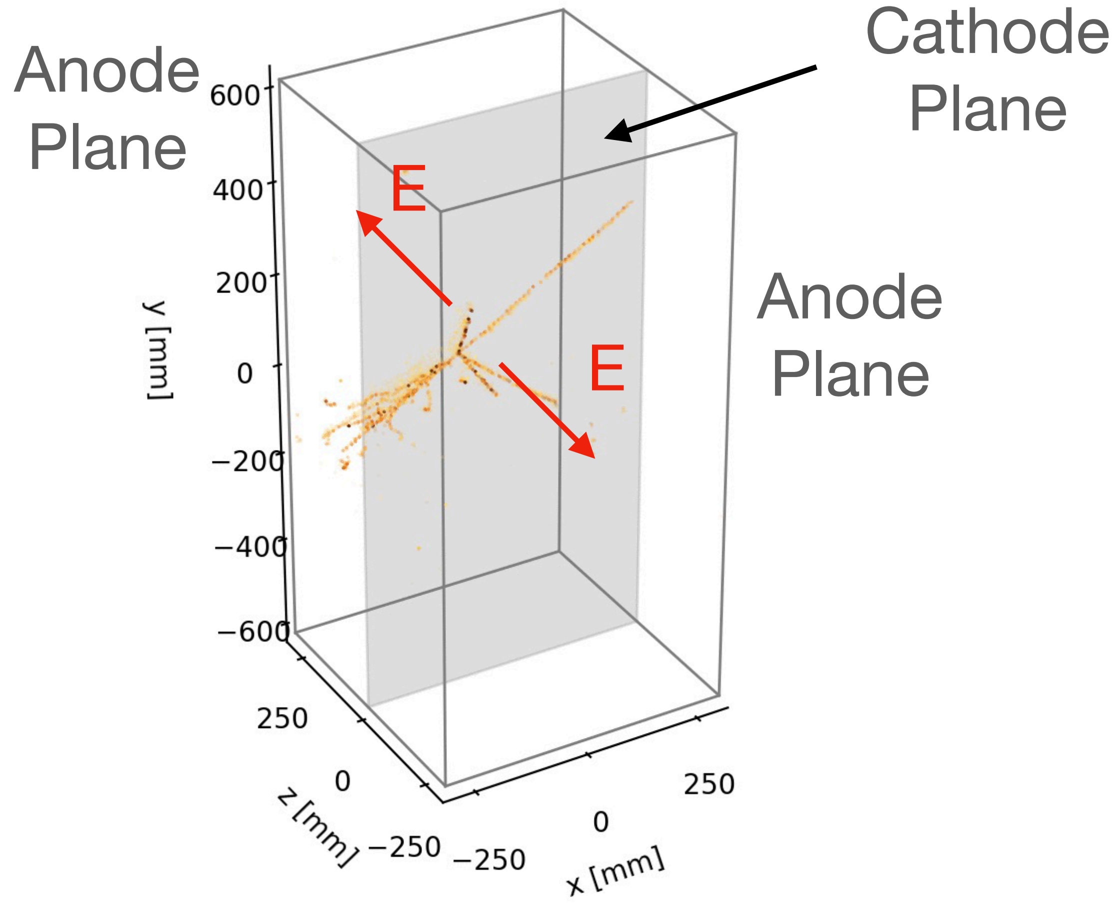


Inspired by the DUNE near detector concept

https://doi.org/10.3390/instruments5040031

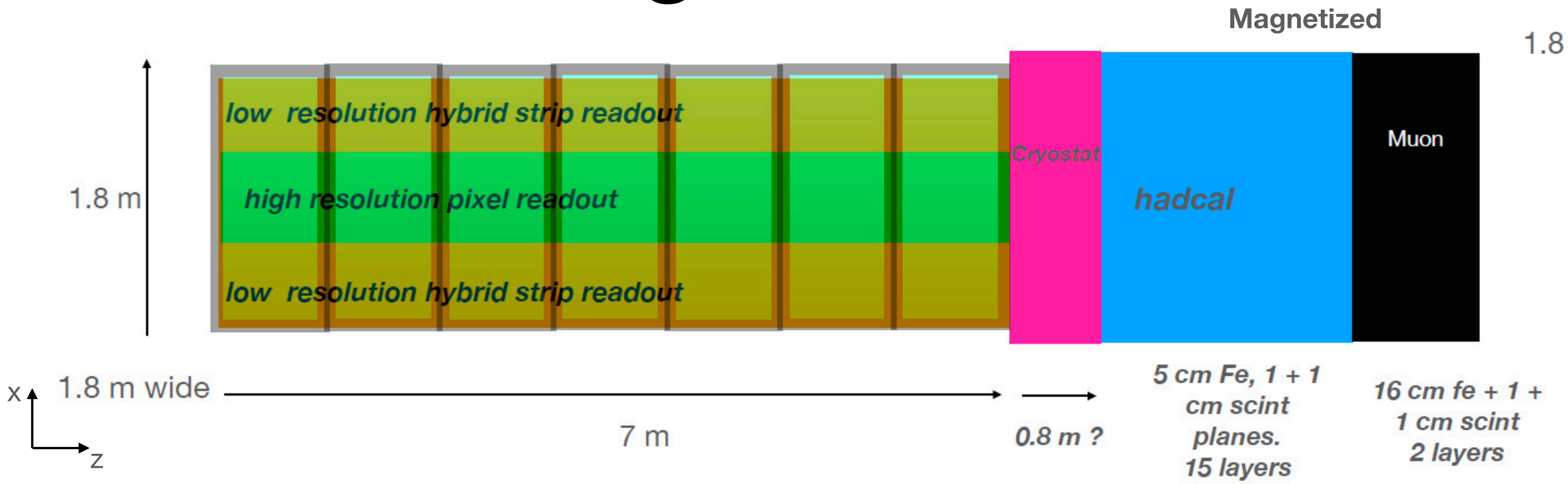
Lawrence Berkeley National Laboratory
University of Bern

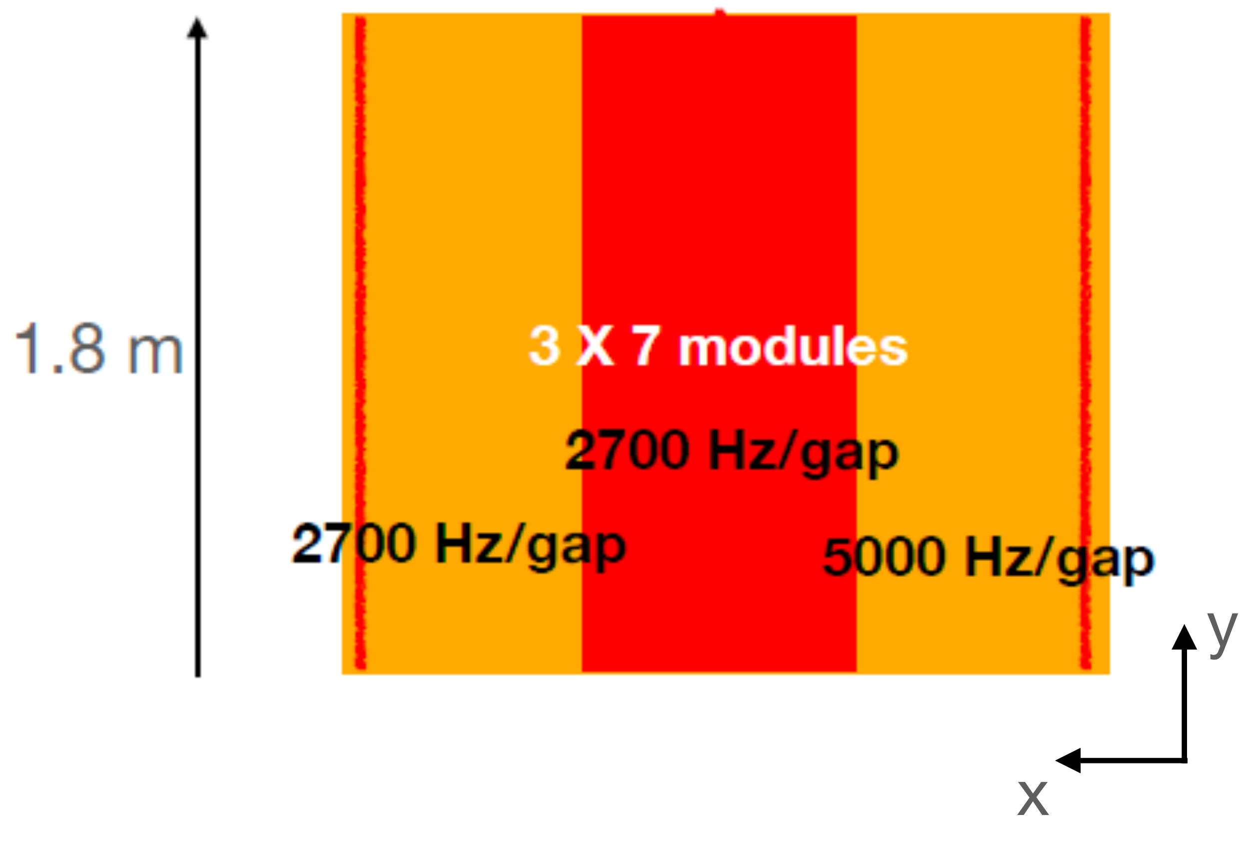
Each module is a “mini” TPC, with a cathode plane in the middle



- FLArE is a modular LAr TPC: segmentation for light collection (trigger) and reducing space charge intensity from muon rate with small drift gap (30cm).
- Taking full advantage of **recent R&Ds in LAr technologies**!

Detector design





None of this has been optimized yet – all numbers are preliminary!

- Conceptual Design is **3 x 7 vertical TPC modules** with 0.3 m gap. Each module is then 0.6 m X 1.8 m X 1 m. Orientation of drift is completely open for discussion to get < 1 mm space point resolution.
- Simulations show **reasonable containment of neutrino events** in LAr and total energy measurement.
- Pixel-based anode → very high number of channels. Reduce channel count by using **strip-based or wire anodes in non-fiducial region**. Fiducial mass is 10 tons, total active mass is ~30 tons.
- Magnetized hadron/muon calorimeter downstream.