O(1 ns) timing resolution in LAr-TPC

Based on MicroBooNE analysis for BNB events

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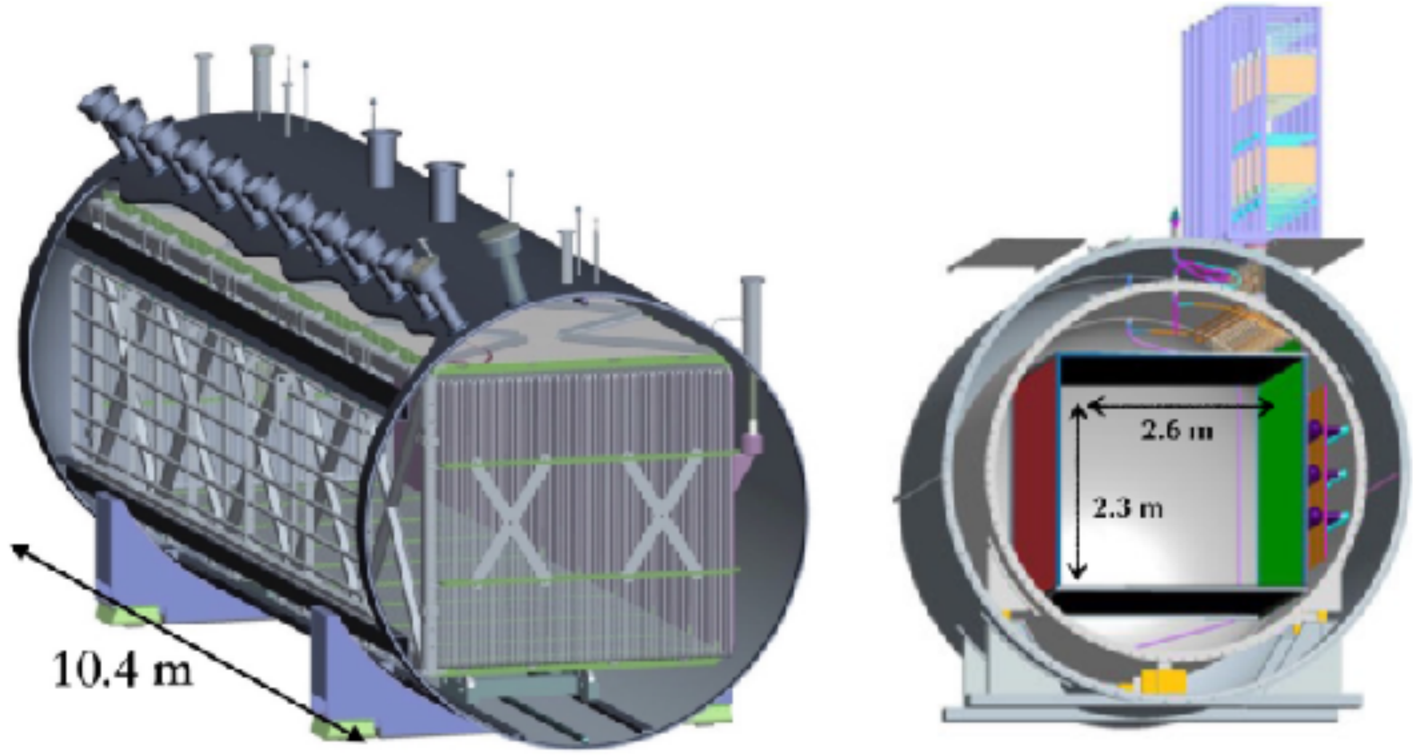
MicroBooNE and the Booster Neutrino Beamline

MicroBooNE [1] is a neutrino experiment located at Fermilab.
It collected data from 2015 to 2021, and, since 2018, it has been a part of the Short Baseline Neutrino (SBN) program.

To date, MicroBooNE has collected the largest dataset of neutrino interactions in the world.

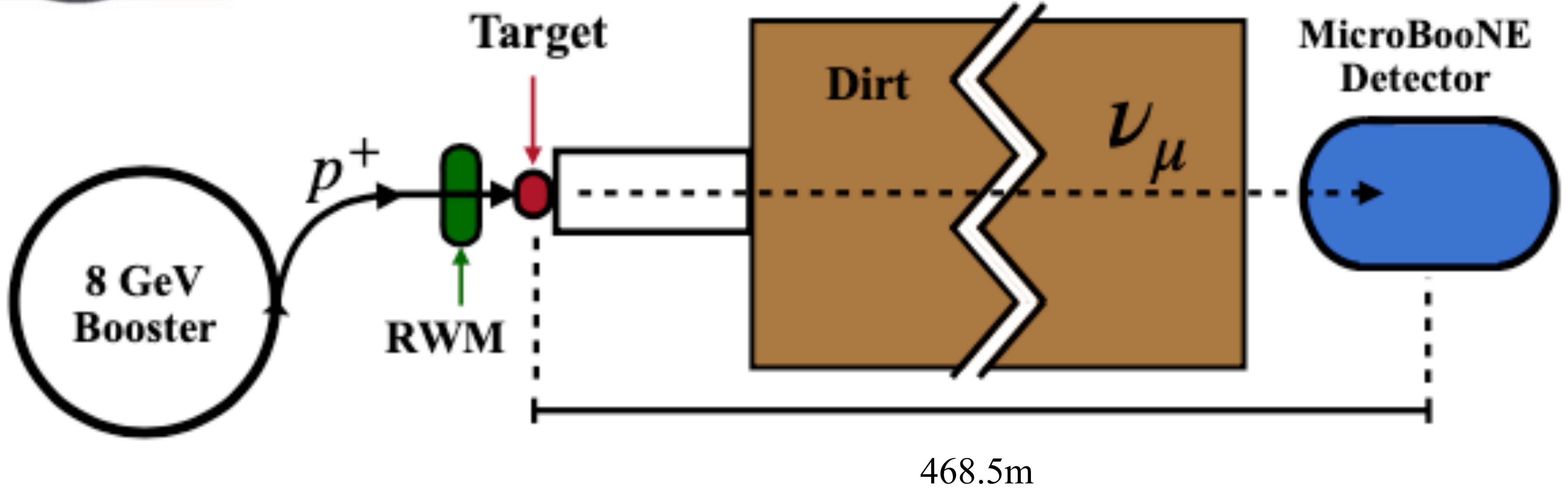


The MicroBooNE detector:

- LAr-TPC near the surface,
- on axis with the Booster Neutrino Beamline (BNB),
- 468.5 m downstream of the proton target,
- exposed to an off-axis component of the NuMI beam.

The Booster Neutrino Beamline (BNB)

- Main source of neutrino for MicroBooNE,
- 5 Hz average rate of proton pulses
  (7 pulses in a row at 15 Hz)[2].
  - 1.6 μs long proton pulses,
  - 81 bunches per pulse
    - 18.936 ns spaced [3] ,
    - ~2ns wide (⟨σB⟩≃1.308 ns * [4,5])



[1] R. Acciarri et al. (MicroBooNE Collaboration), Design and construction of the MicroBooNE detector, J. Instrum. 12, P02017 (2017).
[2] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration), Neutrino flux prediction at MiniBooNE, Phys. Rev. D 79, 072002 (2009).
[3] P. Abratenko et al. (MicroBooNE Collaboration) First demonstration of O(1ns)timing resolution in the MicroBooNE liquid argon time projection chamber Phys. Rev. D 108, 052010 (2023).
[4] M. Backfish, "MiniBooNE Resistive Wall Current Monitor", Fermilab TM-2556-AD, (2013), 10.2172/1128043
[5] M. Backfish, "Measuring the Bunch Length of the Booster Neutrino Beamline Beam". Fermilab, (2015)
[6] Bunch Rotation in the Booster Neutrino Beamline BeamsDoc 6904 available at https://beamdocs.fnal.gov/

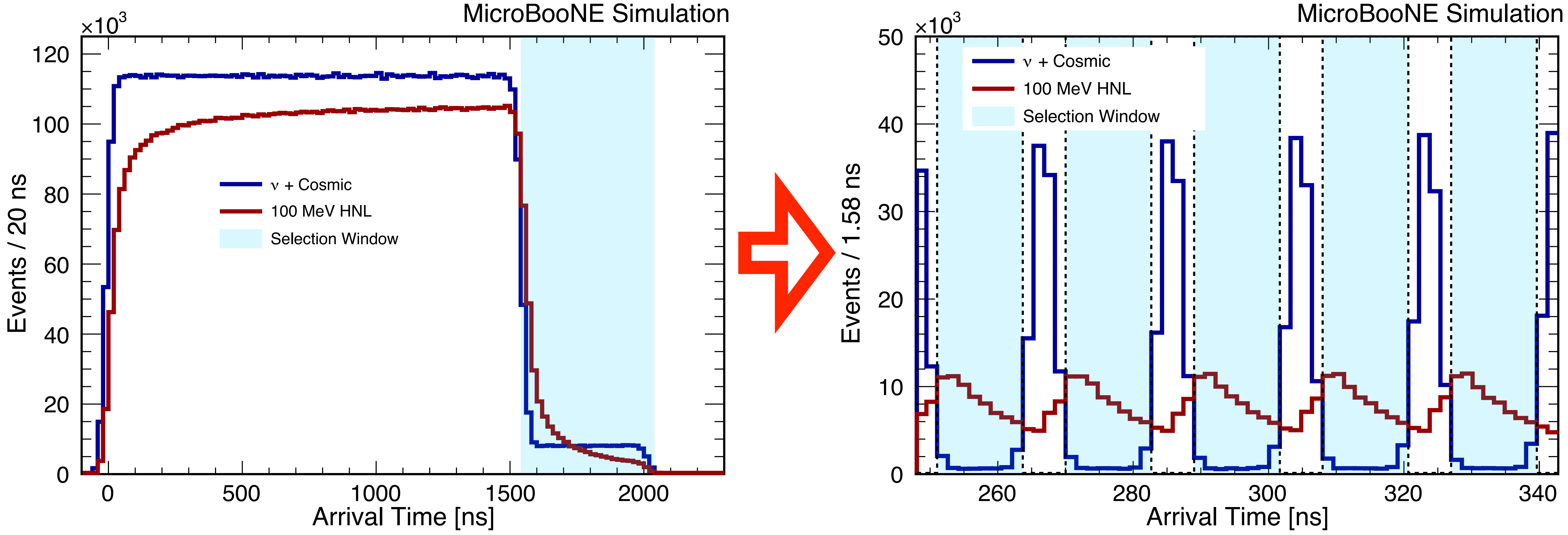
(*) For Booster bunch rotation off. When bunch rotation is on, ⟨σB⟩ increases [6].

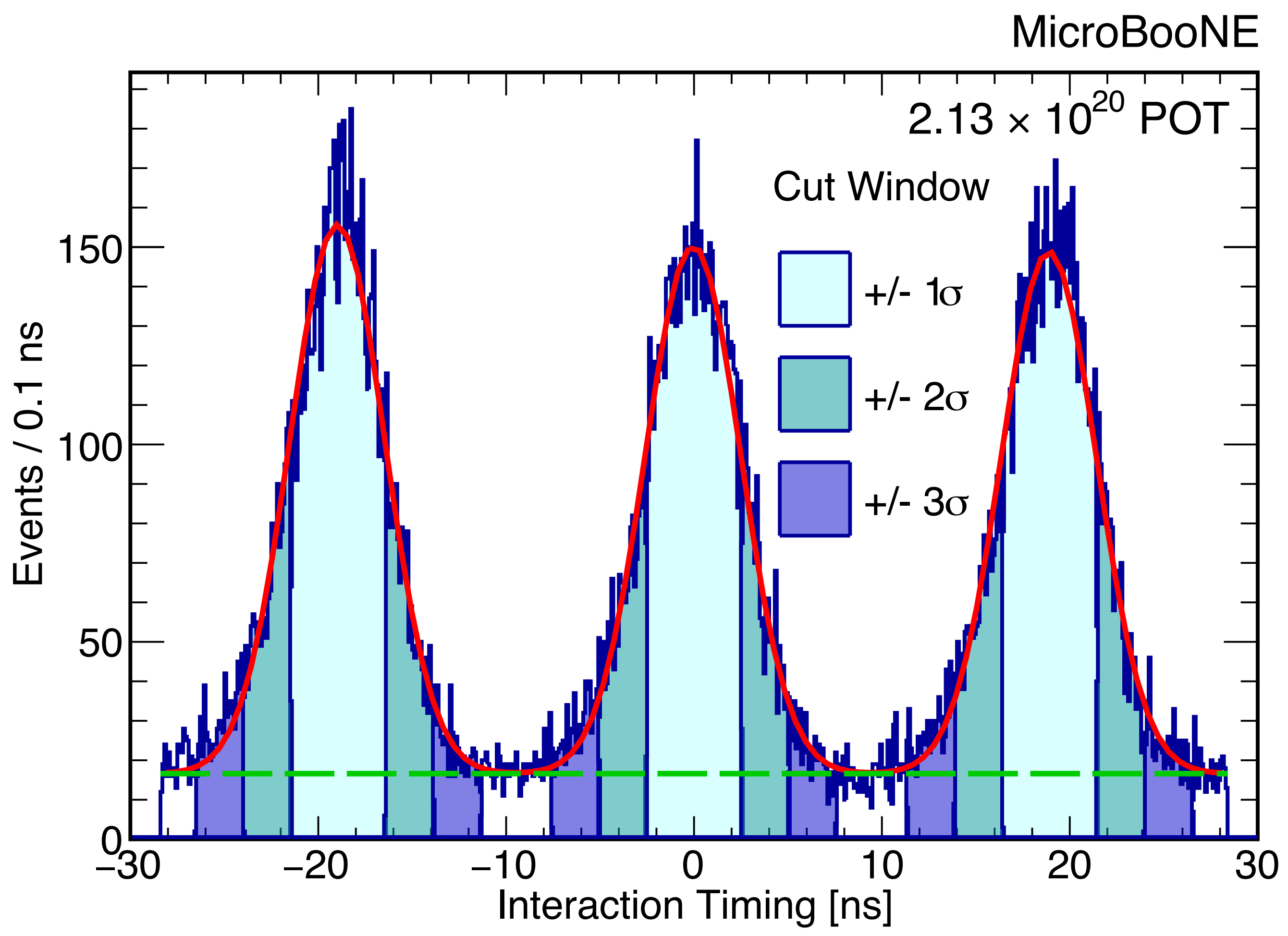
The role of O(1 ns) timing resolution in MicroBooNE's scientific goals

MicroBooNE's primary scientific goals are neutrino oscillation study and neutrino cross-section measurements, including investigating the MiniBooNE low energy excess [7].

Although MicroBooNE's surface location limits its capability for non-accelerator neutrino physics, the high statistic of neutrino beam interactions offers an ideal environment to search for Beyond the Standard Model (BSM) physics in the sub-GeV energy regime.

In this context, an improved timing resolution that can resolve the beam bunches ns substructure is a powerful tool to enhance MicroBooNE's ability to study neutrino interactions and search for beyond the standard model physics.





- The O(1 ns) timing resolution achieved in MicroBooNE [8] allows access to the BNB ns substructure, improving the performance of searches that exploit differences in time-of-flight (ToF) to detect long-lived massive particles that arrive at the detector delayed with respect to neutrinos.
- In addition, the BNB bunches resolution can improve the neutrino selection efficiency by adding the timing as a new tool for cosmic background rejection, orthogonal to existing techniques.

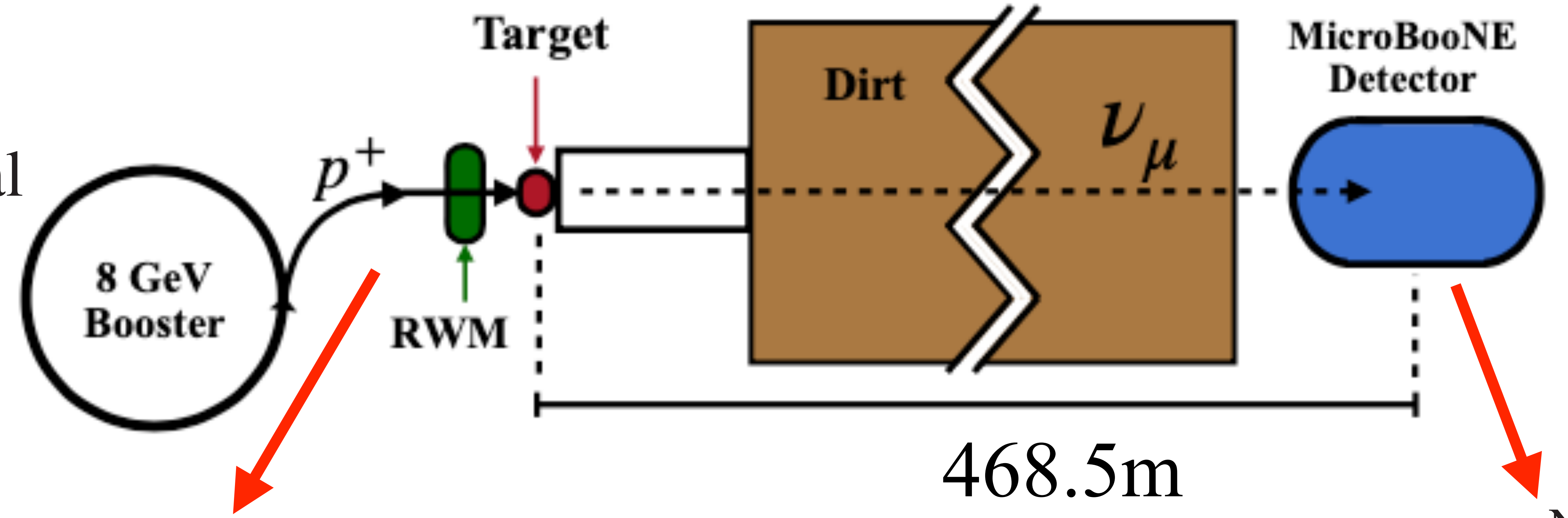
[7] A. A. Aguilar-Arevalo et al. (MiniBooNE Collaboration) Significant Excess of Electronlike Events in the MiniBooNE Short-Baseline Neutrino Experiment, Phys. Rev. Lett. 121, 221801 (2018)

[8] P. Abratenko et al. (MicroBooNE Collaboration) First demonstration of O(1 ns) timing resolution in the MicroBooNE liquid argon time projection chamber. Phys. Rev. D 108, 052010 (2023)

Strategy for achieving O(1 ns) timing resolution in MicroBooNE

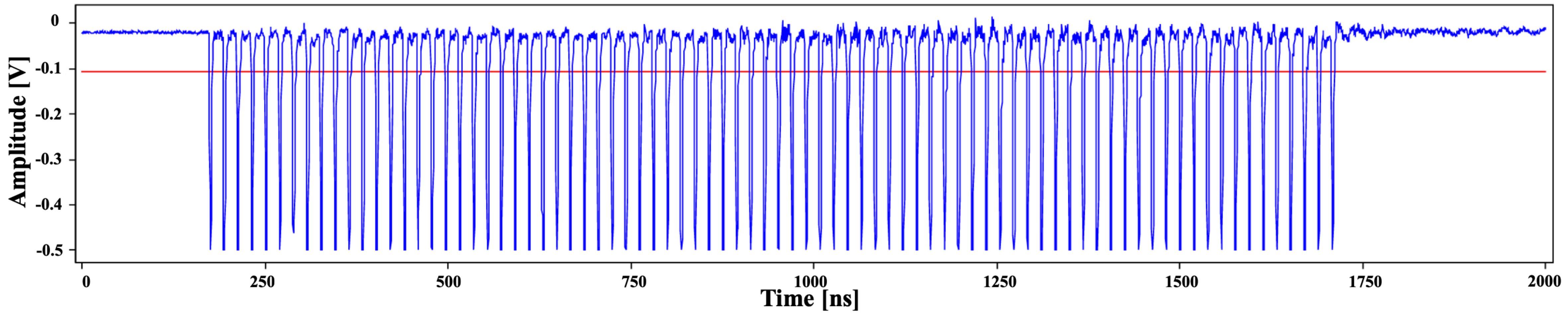
- **The timing resolution of the detector is evaluated by reconstructing the ns substructure of the beam pulse using the timing of the neutrino interaction events.**
- **The reconstructed neutrino arrival time at the upstream detector wall is compared with the proton pulse longitudinal profile.**

The RWM provides accurate longitudinal time profiles for the proton pulses.

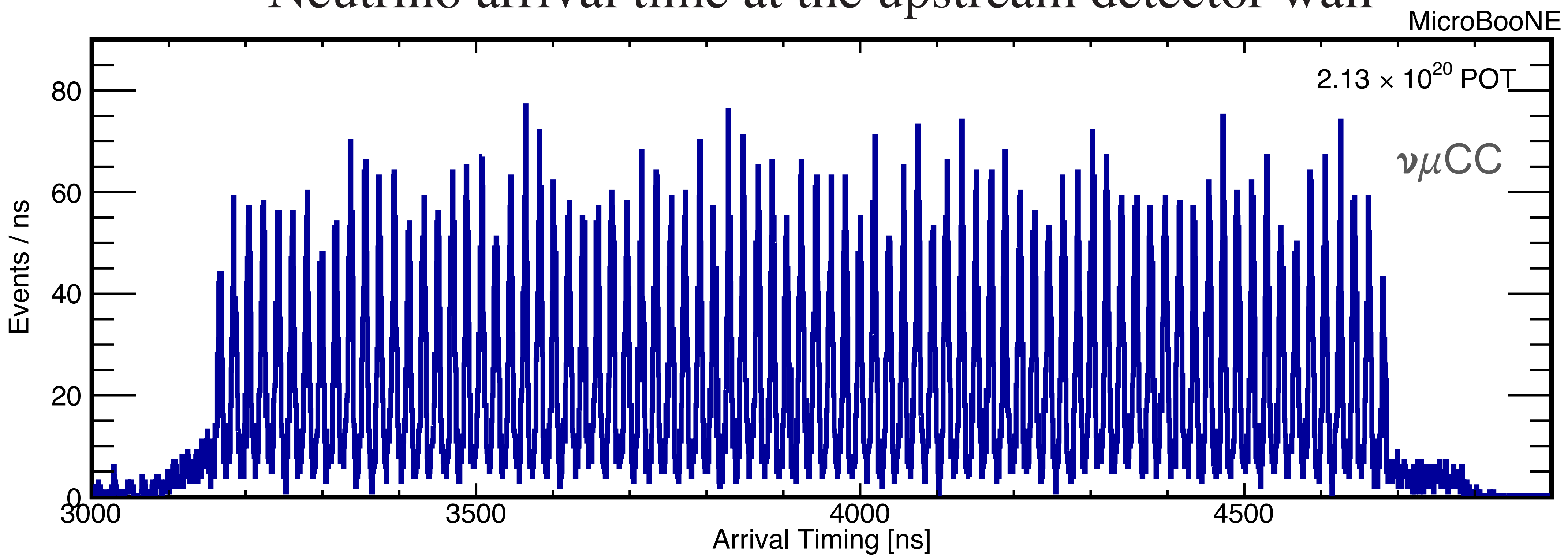


The neutrino arrival time at the upstream detector wall is reconstructed by combining light signals and reconstructed tracks in the MicroBooNE detector.

Proton pluses longitudinal time profiles from RWM



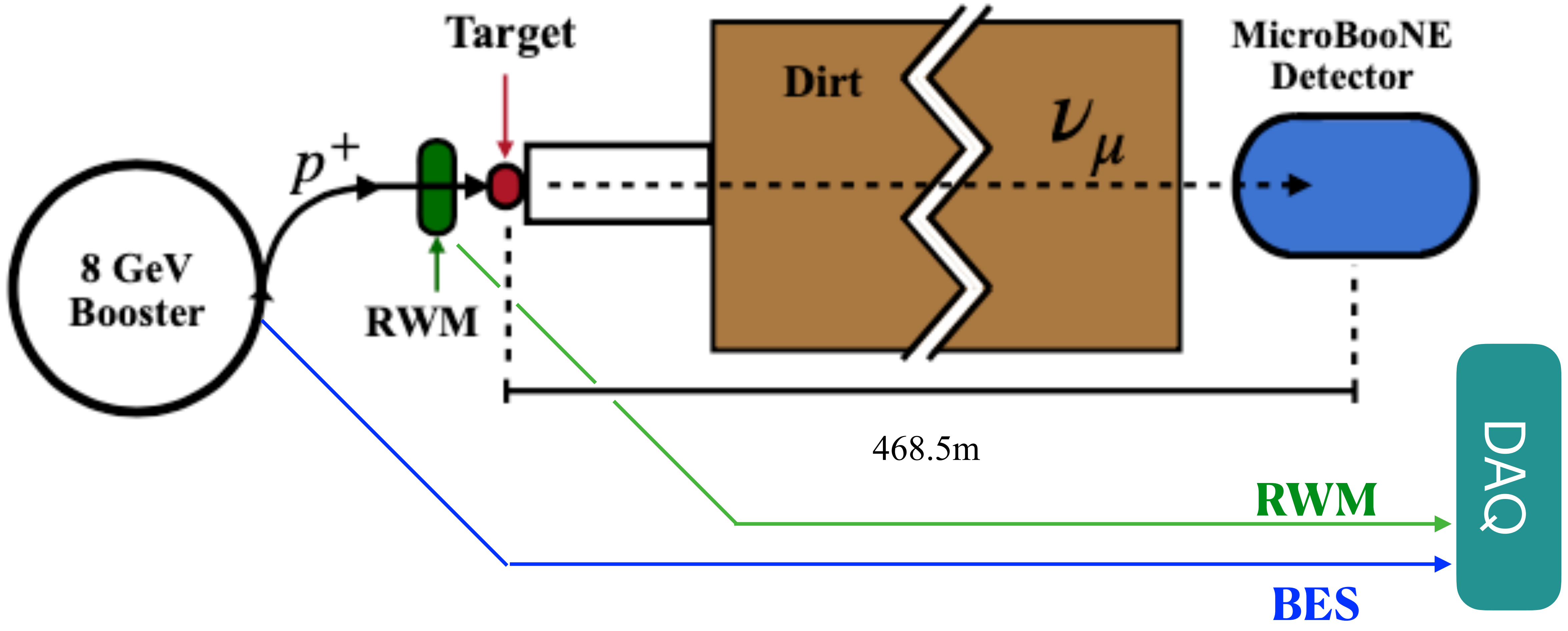
Neutrino arrival time at the upstream detector wall

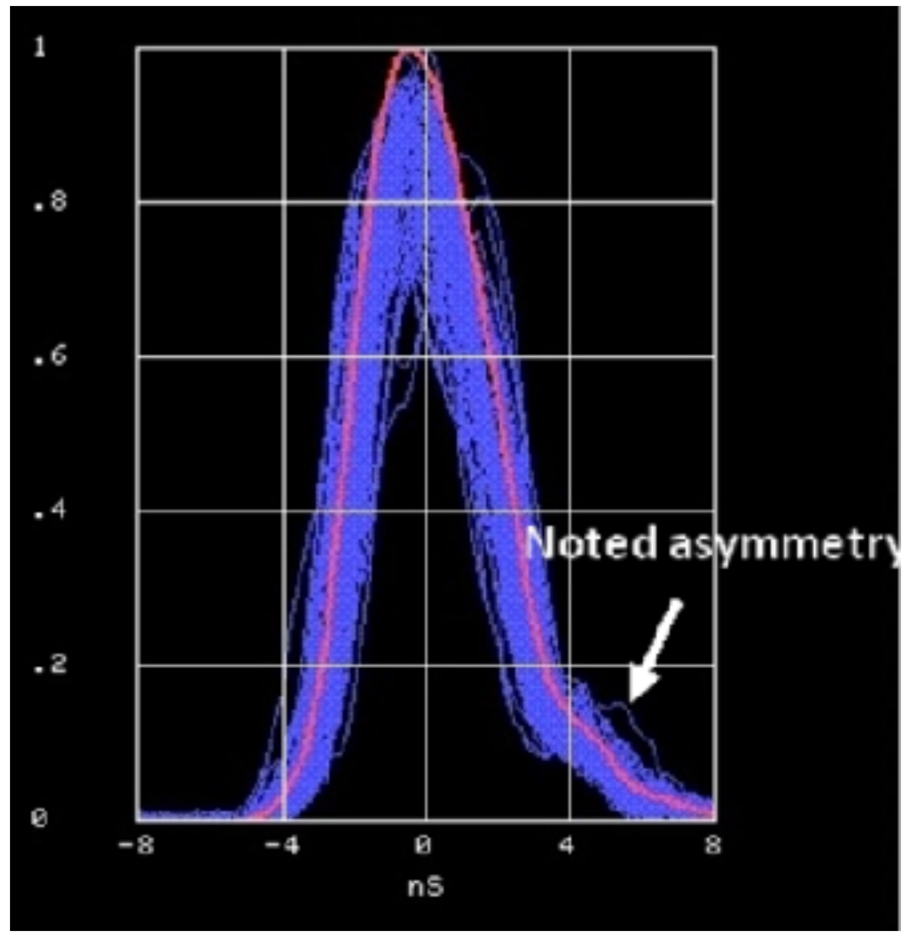


The resistive wall current monitor

A resistive wall current monitor (RWM) measures the proton's pulse longitudinal profile immediately before protons hit the target.

- the RWM waveforms are acquired with a relatively high rate: 2 GHz sampling frequency.
- the RWM readout response has been deeply characterized [9],[10], removing the smearing coming from cables and readout electronic

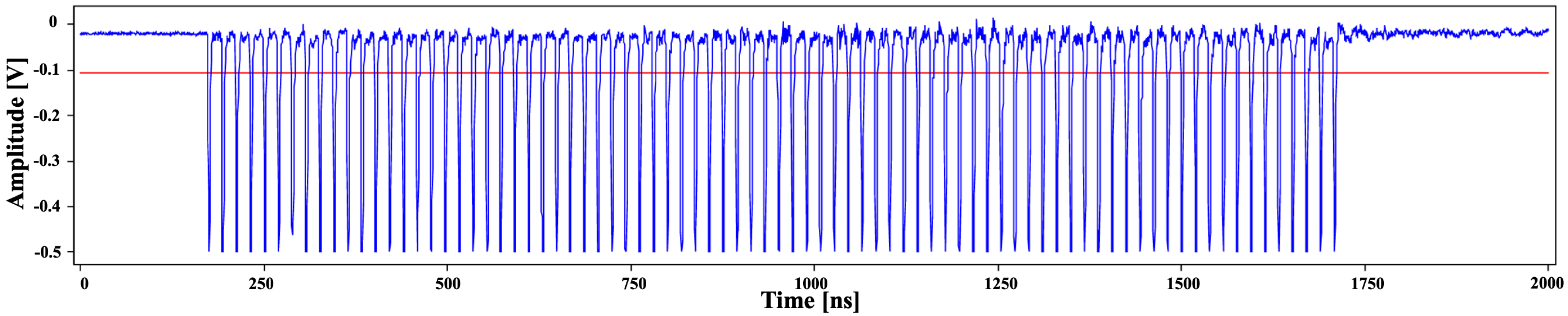




POT (e12)	σ (ns)	STD (ns)
.25 − 1	1.432	0.154
1 − 2	1.309	0.059
2 − 3	1.268	0.052
3 − 4	1.332	0.061
all	1.308	0.065

A thresholded logic pulse in coincidence with the beginning of the RWM waveform is sent to detectors for BNB trigger monitoring.

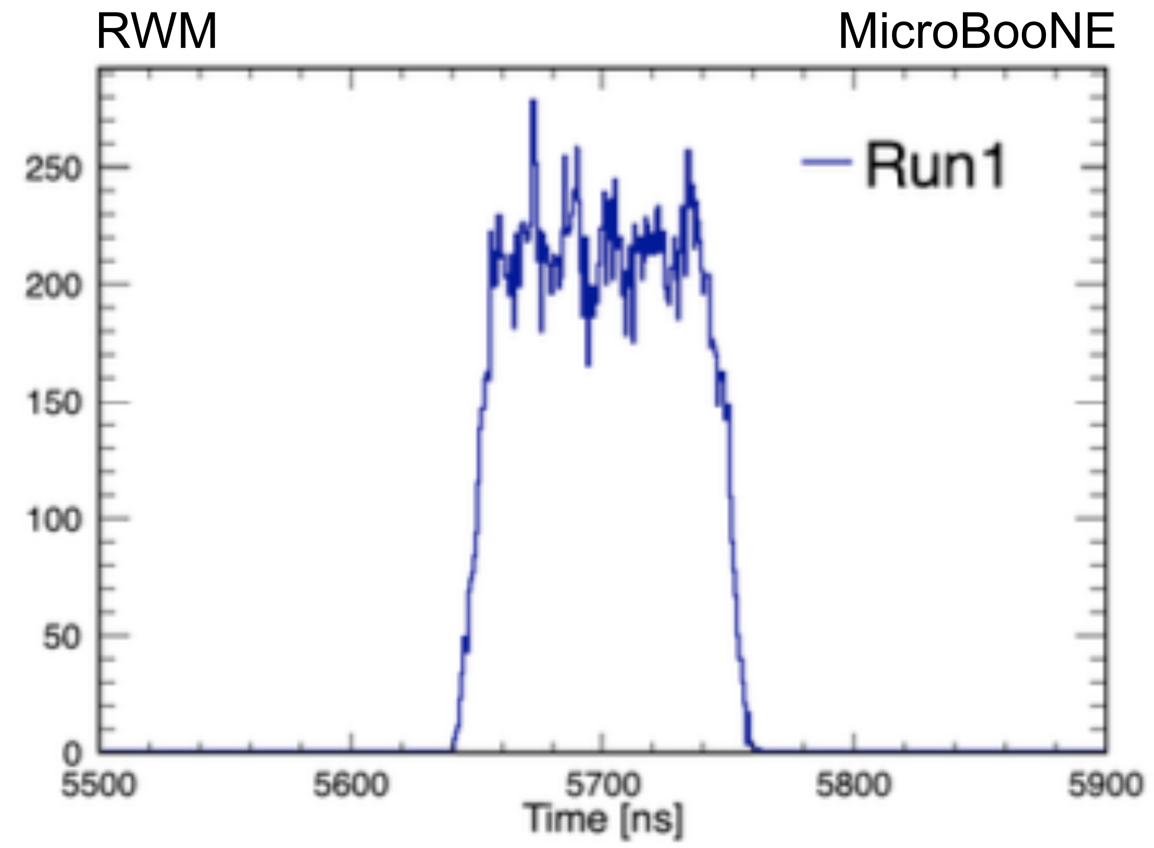
Trace of a single BNB RWM waveform. The red line shows the discriminator threshold.

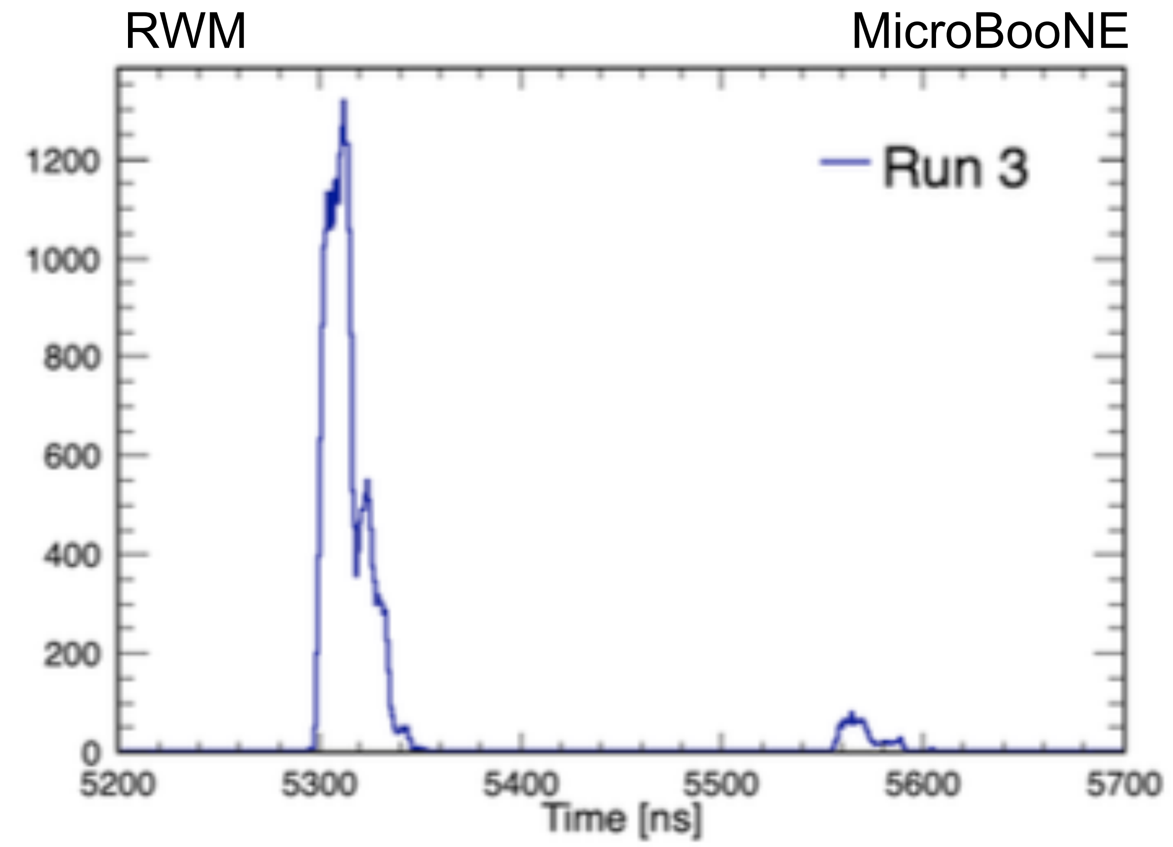


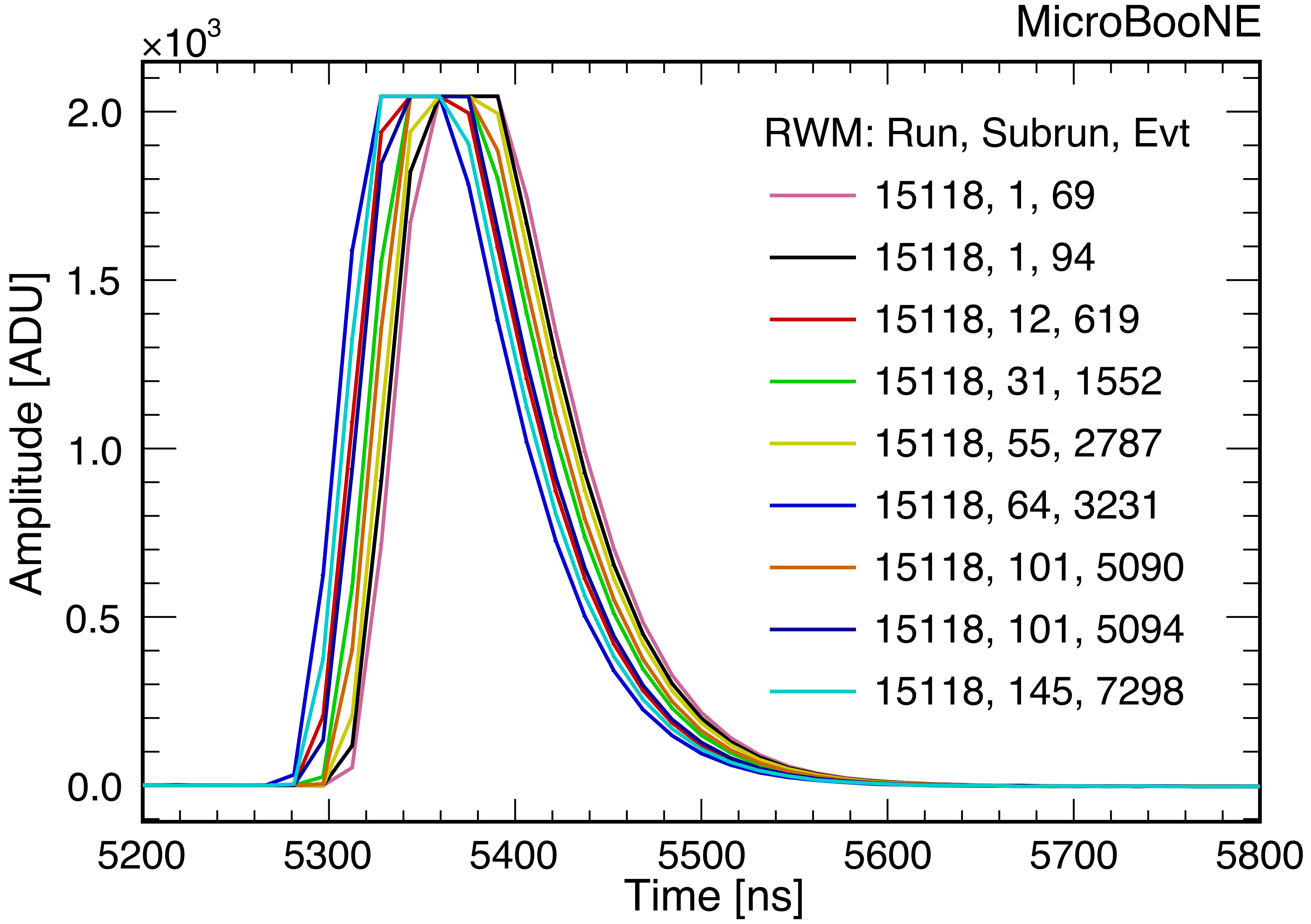
[9] M. Backfish, "MiniBooNE Resistive Wall Current Monitor", Fermilab TM-2556-AD, (2013), 10.2172/1128043
[10] M. Backfish, "Measuring the Bunch Length of the Booster Neutrino Beamline Beam", Fermilab, (2015)

RWM monitors the BNB trigger

- The BNB trigger is subject to a fluctuation of tens of ns with respect to the proton pulse extraction time.
- The RWM thresholded logic pulse is sent to detectors, where it is recorded for offline trigger monitoring
- In MicroBooNE the timing of the RWM logic pulse is used to remove the measured BNB trigger jitter.







RWM timing = rising edge half-height

At MicroBooNE the RWM logic pulse is recorded by the same electronic used for the PMTs, triggering on the BNB.

RWM waveform misalignment in time reflects the BNB trigger jitter.

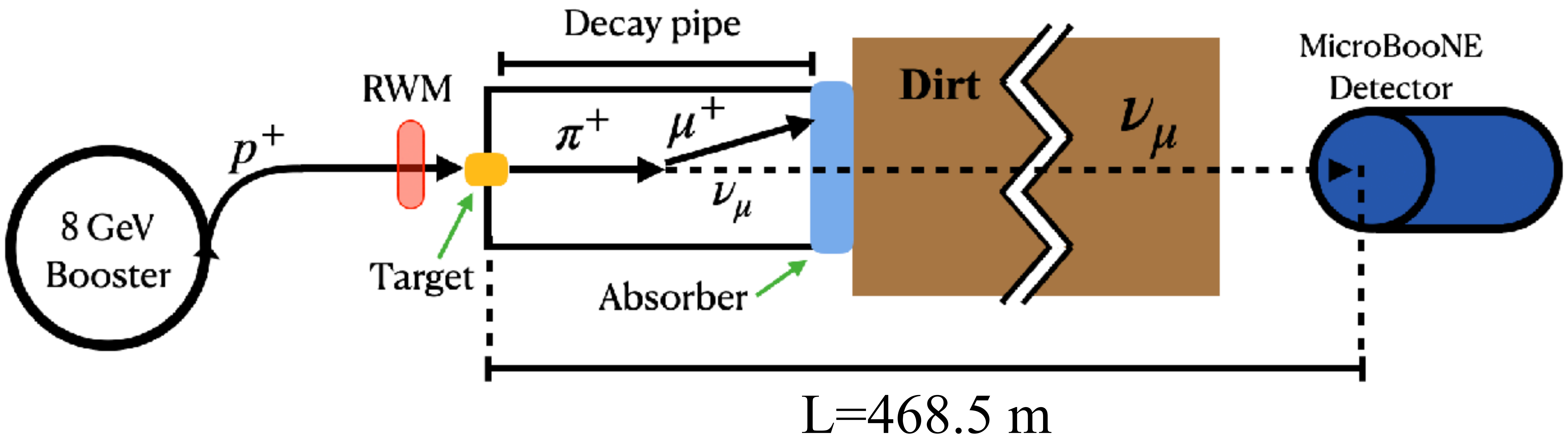
The distribution of the RWM timing gives good monitoring of the beam instrumentation conditions

Proposal to Accelerator Division for BNB monitoring improvement:

Recording the full RWM waveforms at the accelerator building, in a system synchronized with the SBN detectors (GPS/White Rabbit).

Neutrino time profile at the upstream detector wall

In the MicroBooNE analysis, the neutrino time profile at the upstream detector wall is assumed to be the same as the proton time profile provided by the RWM.



- Time for protons to hit the target,
- Propagation and decay of mesons,
- Neutrino travel time to the detector.

} Is treated as a constant offset for all the events.

- The main contribution to the propagation spread comes from the fraction of the full path (L) traveled by mesons before decaying.
- Based on their kinetic energy and the decay point they can affect the ToF of the full chain.

In MicroBooNE:

Based on a preliminary simulation, the typical delay caused by the fraction of the path traveled by mesons is $\ll 1\,ns$.

An appreciable effect may arise from events in the lower part of the neutrino energy spectrum.

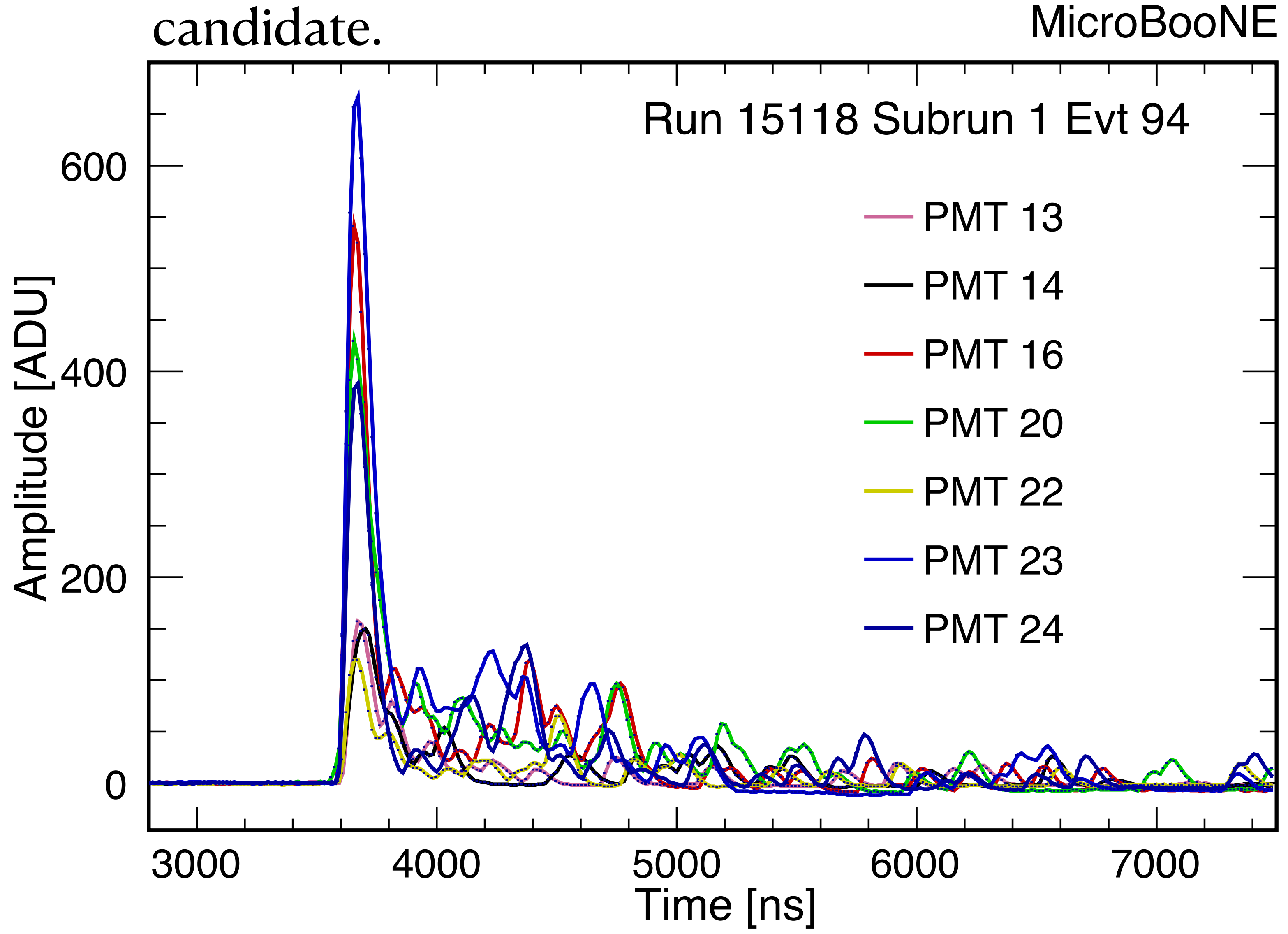
Photo Detection System

Liquid argon is a high-performance prompt scintillator with ~23% of the light emitted within a few ns.

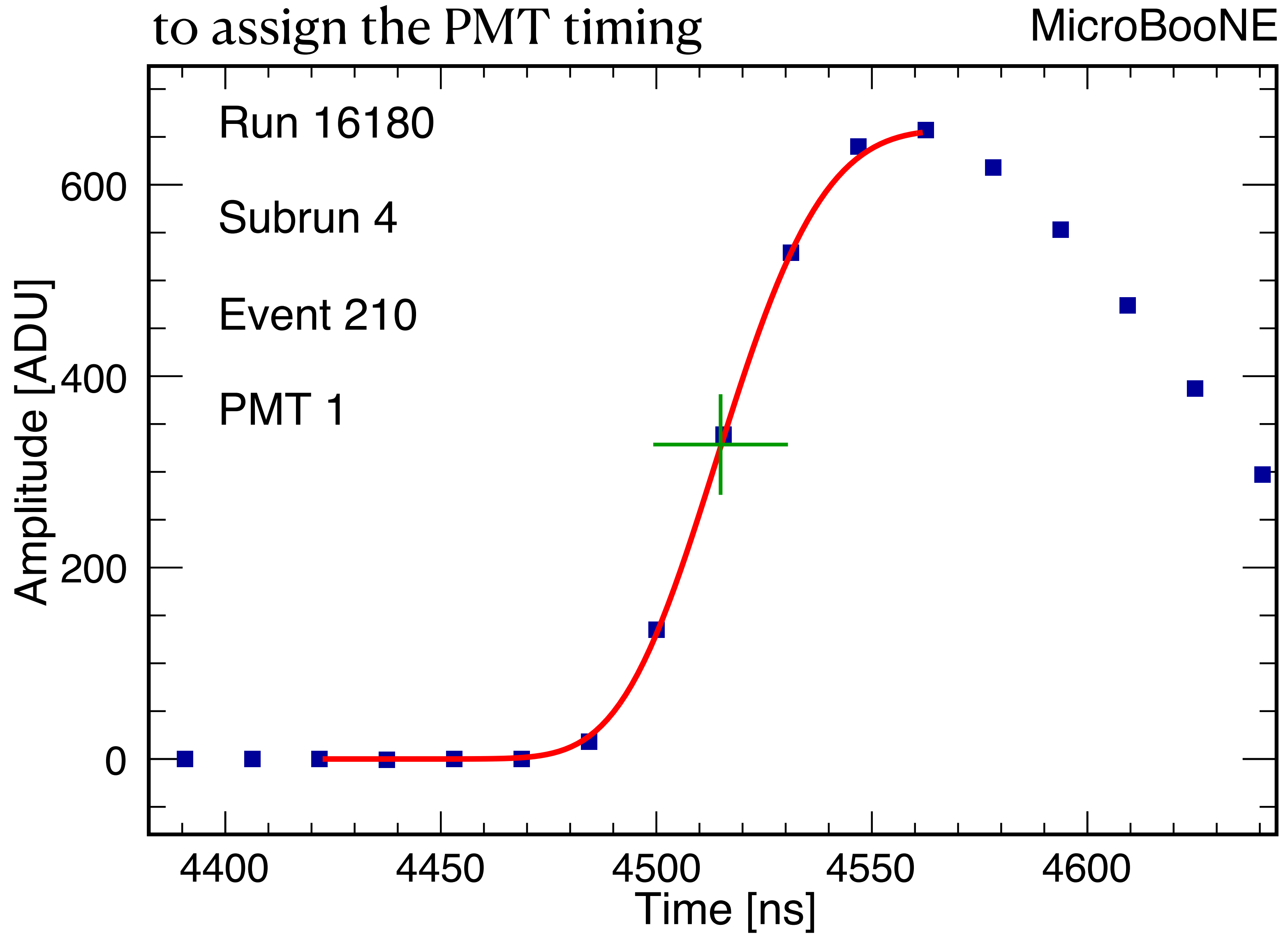
The photodetection system (PDS) provides the fastest response to interaction events in LAr-TPCs.

- The MicroBooNE detector is equipped with 32 PMTs.
- Waveforms are recorded in coincidence with the BNB trigger.
- The rising edge fit provides the PMT's signal timing.
  - The fitting method provides the timing of the pulse with an excellent precision: **0.2 ns** smearing.
- The median of the PMT's timing is used to assign the neutrino interaction timing.
  - Corrections for particle and light propagation are already applied.
  - Only waveforms with maximum amplitude (fast component) larger than 2 photons are considered

MicroBooNE PMT waveforms for a typical neutrino candidate.



PMT's plus fit. The rising edge half-height is used to assign the PMT timing

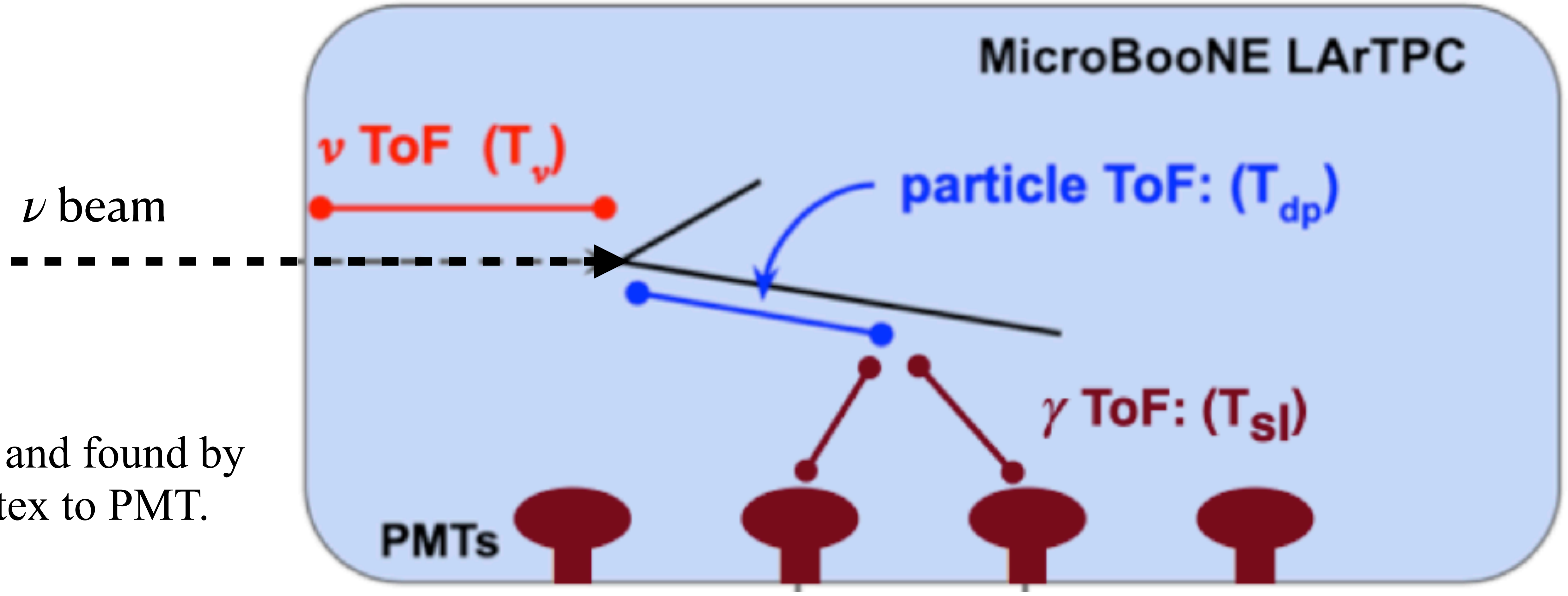


Particle/scintillation light propagation

Once neutrinos enter the detector, three processes impact the neutrino interaction time observed by PMTs.

- **Neutrino ToF inside the TPC:**
  from upstream detector wall to ν-vertex
- **Daughter particles ToF**
  from the neutrino vertex to a given space-point*
- **Scintillation light ToF**
  from the given space-point* to PMT

* The source of the first photons arriving to each PMT is located along the track and found by "minimizing" the daughter particle and scintillation light propagation from ν-vertex to PMT.



In MicroBooNE:

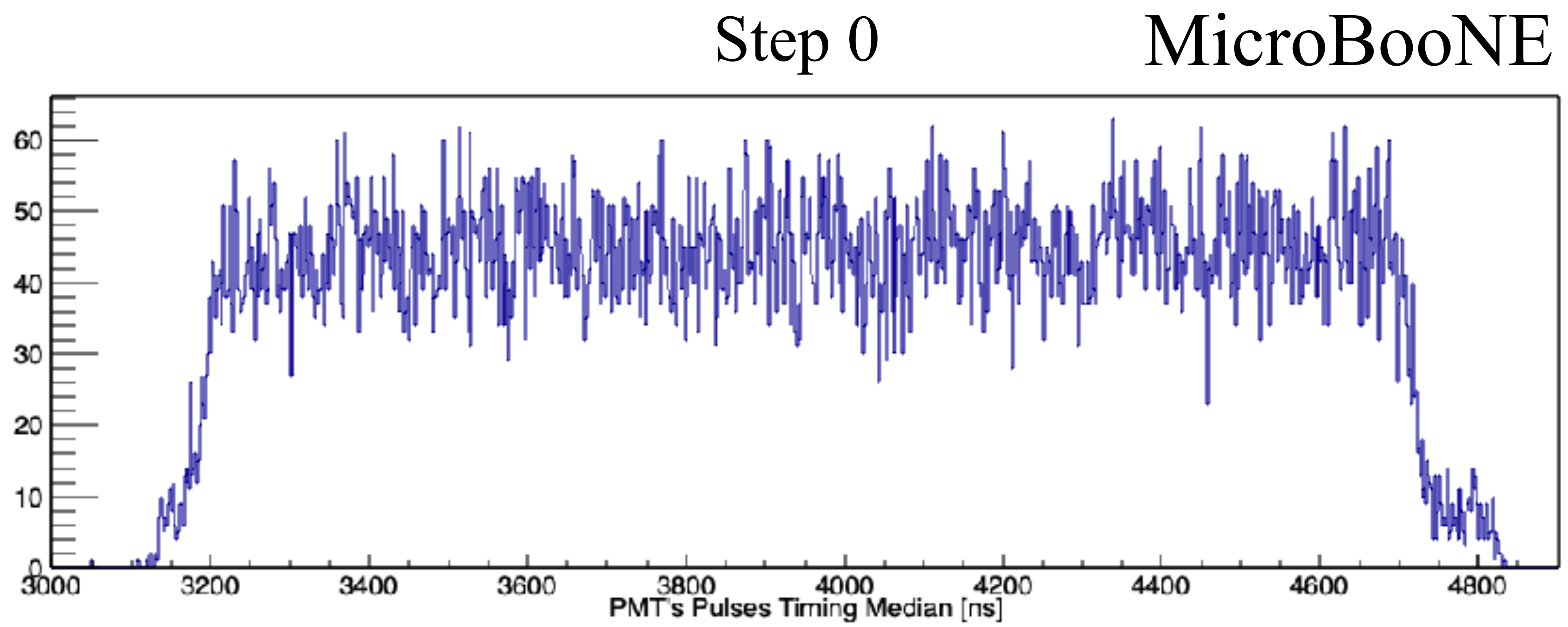
- The contributions of the three processes are obtained by leveraging the neutrino interaction vertex and the 3D track geometry provided by the TPC reconstruction.
- Daughter particles are assumed to travel at the speed of light in vacuum**
- Scintillation light propagation in Liquid Argon from [11]

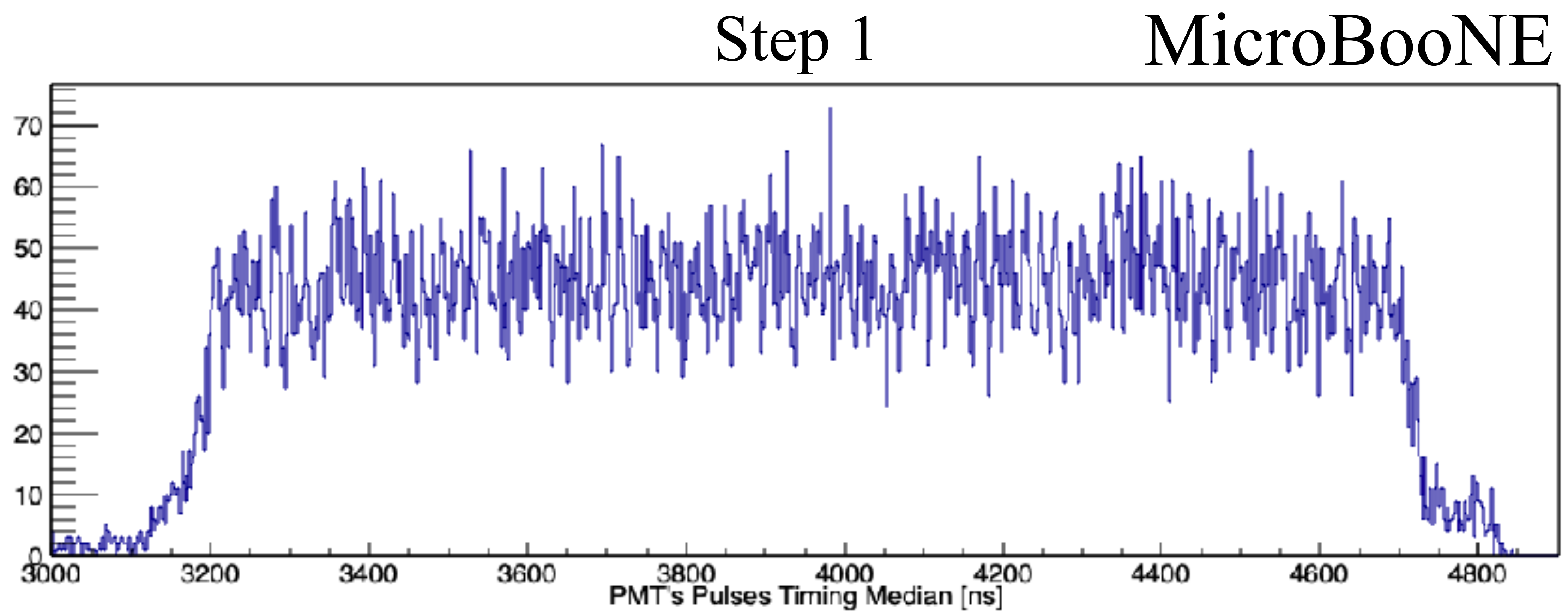
** Corrections based on empirical calibration are applied in MicroBooNE analysis to compensate for this approximation.

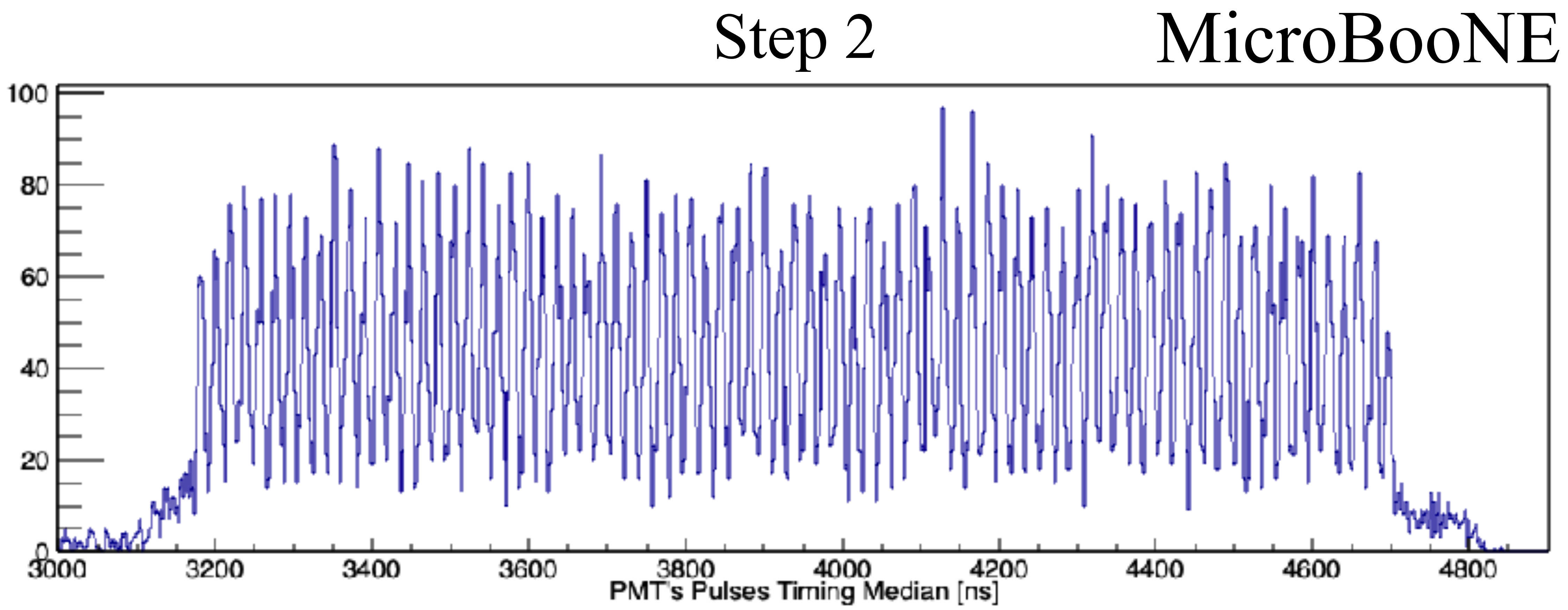
11 M. Babicz et al., A measurement of the group velocity of scintillation light in liquid argon, J. Instrum. 15, P09009 (2020).

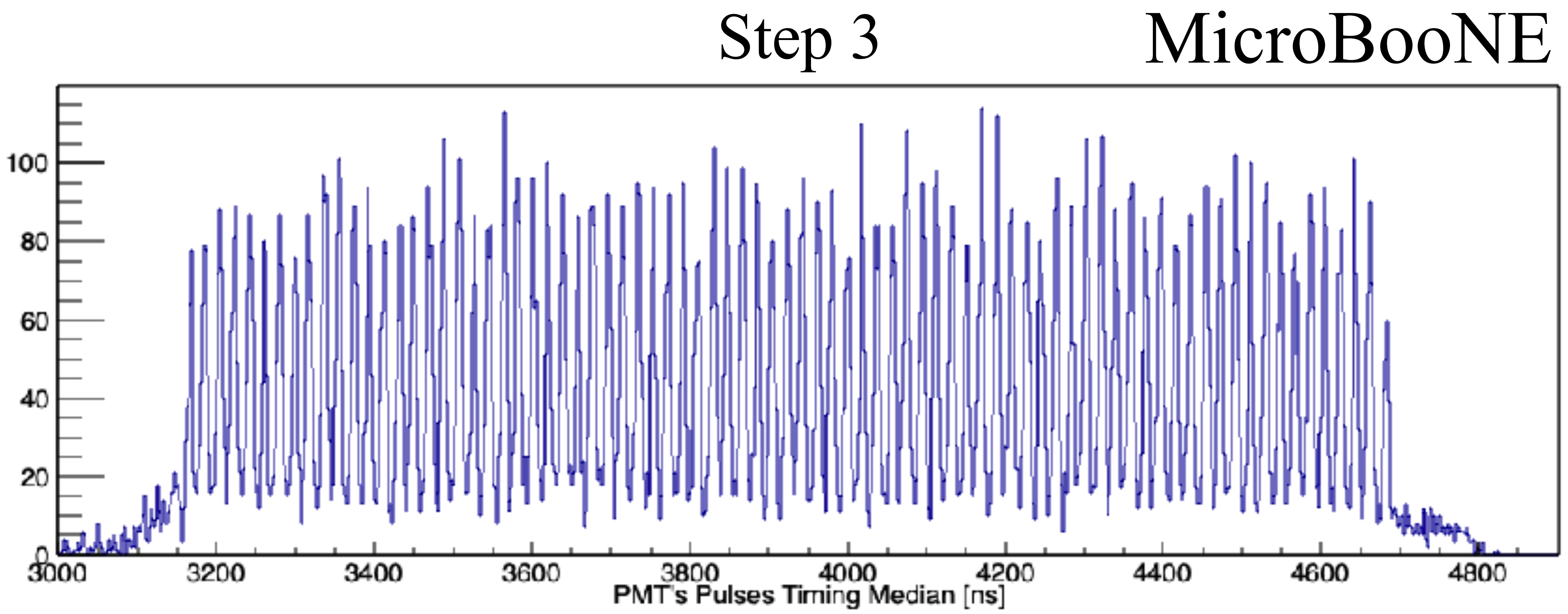
Beam pulse reconstruction steps [0, 1, 2, 3, 4]:

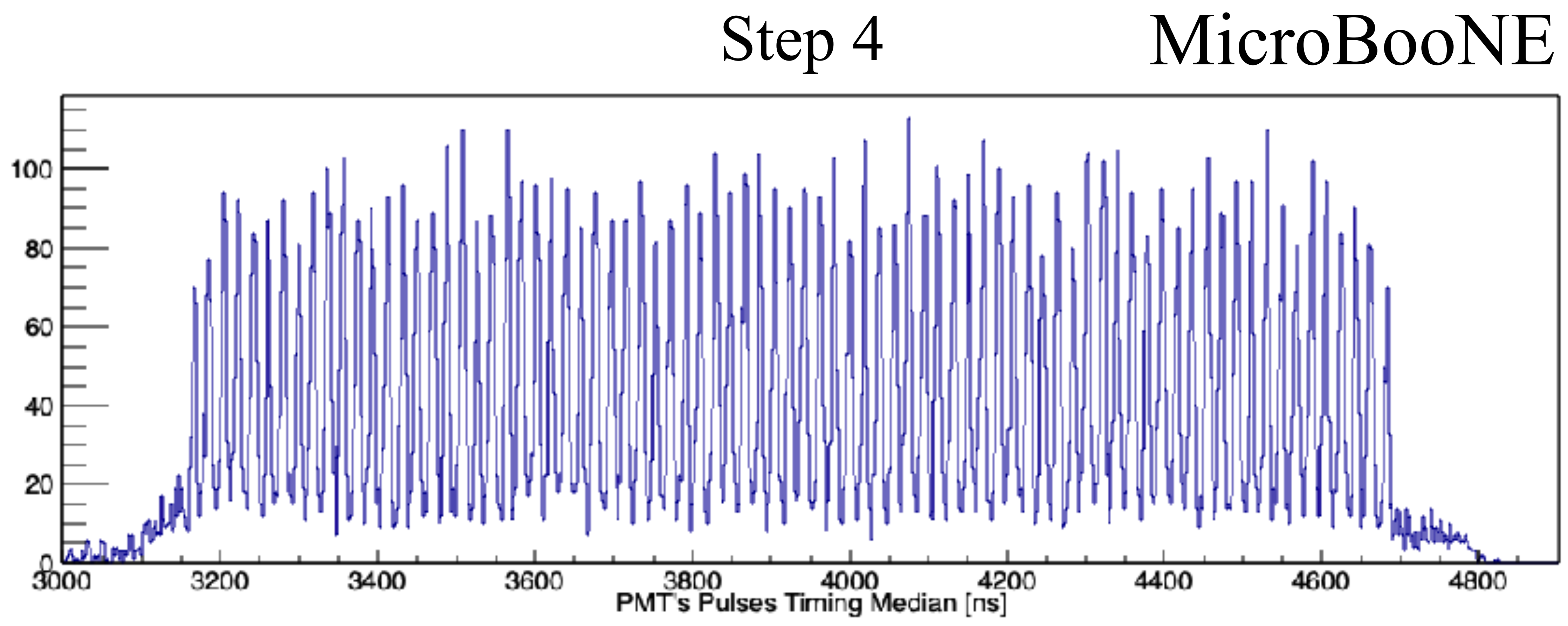
- **Step 0:** PMTs give a prompt signal,
  - Fit resolution : σ_{fit} < 0.2 ns
  - t = Median of PMTs
- **Step 1:** RWM removes the BNB tigger jitter,
  - Trigger jitter is 10s of ns
- **Step 2:** ν ToF inside the TPC,
  - Up to 33 ns
- **Step 3:** daughter particles and scintillation light propagation time,
  - Up to 50 ns

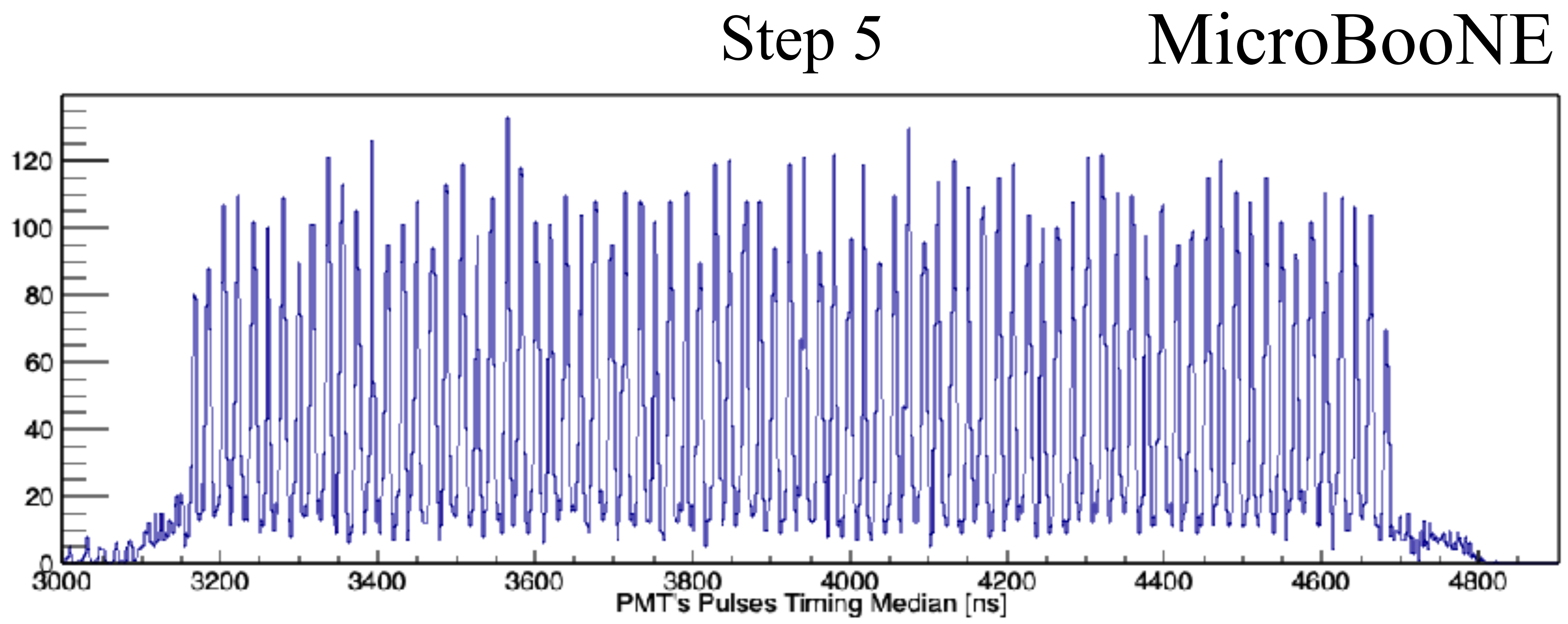












The dataset used in this analysis is an inclusive selection of ν_μCC iteration candidates from MicroBooNE's BNB, Run3 (2016-17)

Beam pulse reconstruction steps [4,5]:

- **Step 4:** PMT why PMT offset removal
- **Step 5:** Empirical calibration for propagation corrections

Reconstruction step summary

Steps:	Bunches width:
0. PMTs median	-
1. Trigger→RWM	-
2. ν ToF inside the TPC	σ = 4.7 ± 0.2 ns
3. ν-vertx to PMTs propagation	σ = 3.08 ± 0.04 ns
4. PMT by PMT offset	σ = 2.99 ± 0.04 ns
5. Empirical calibration	σ = 2.53 ± 0.02 ns

MicroBooNE timing resolution [8]

Neutrino interaction time resolution in BNB events:

- Gaussian fit gives $\sigma = 2.53 \pm 0.02$ ns
- The intrinsic beam spread is $\sigma_B = 1.308$ ns is subtracted

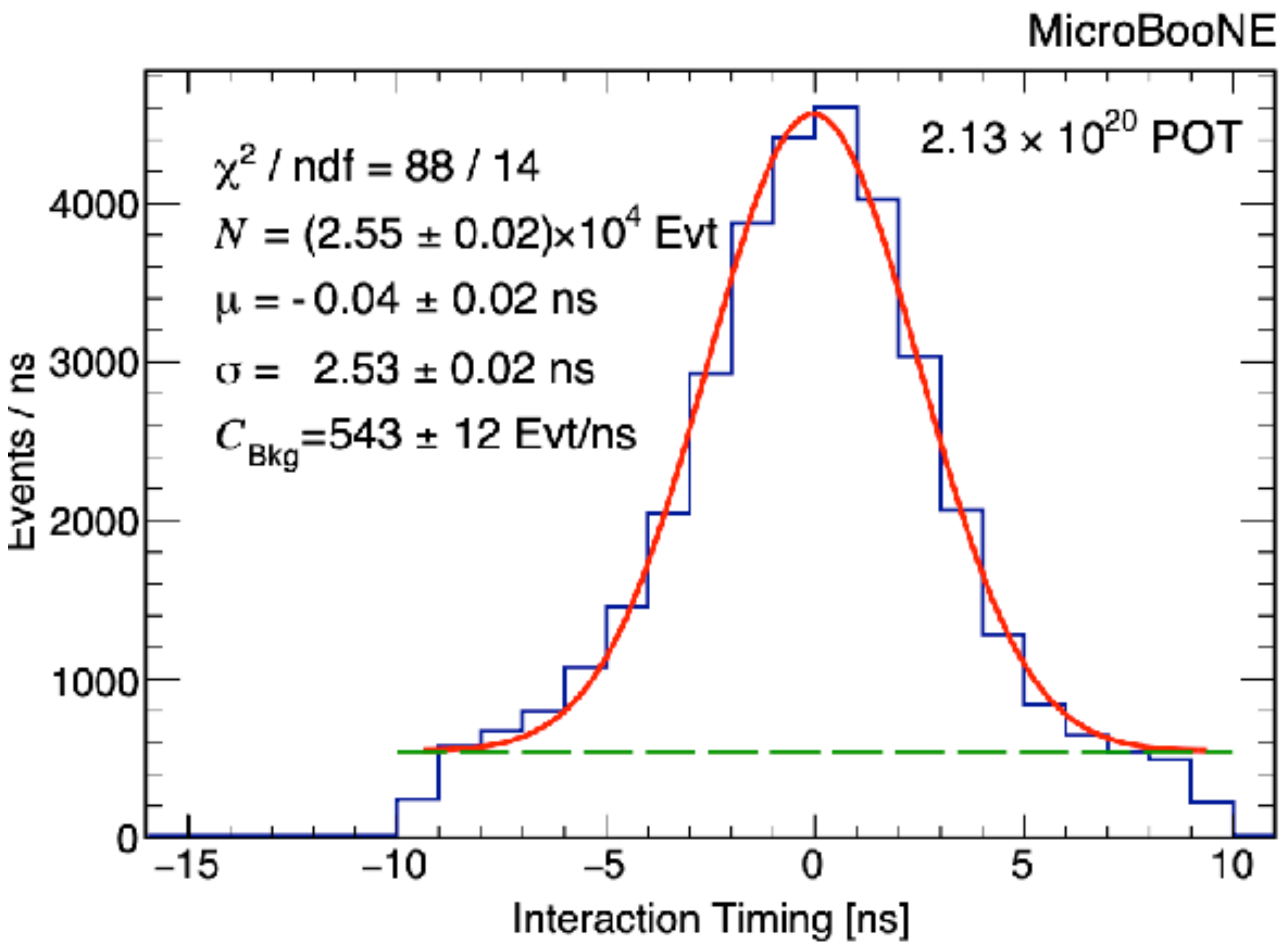
Overall resolution: 2.16 ± 0.02 ns.

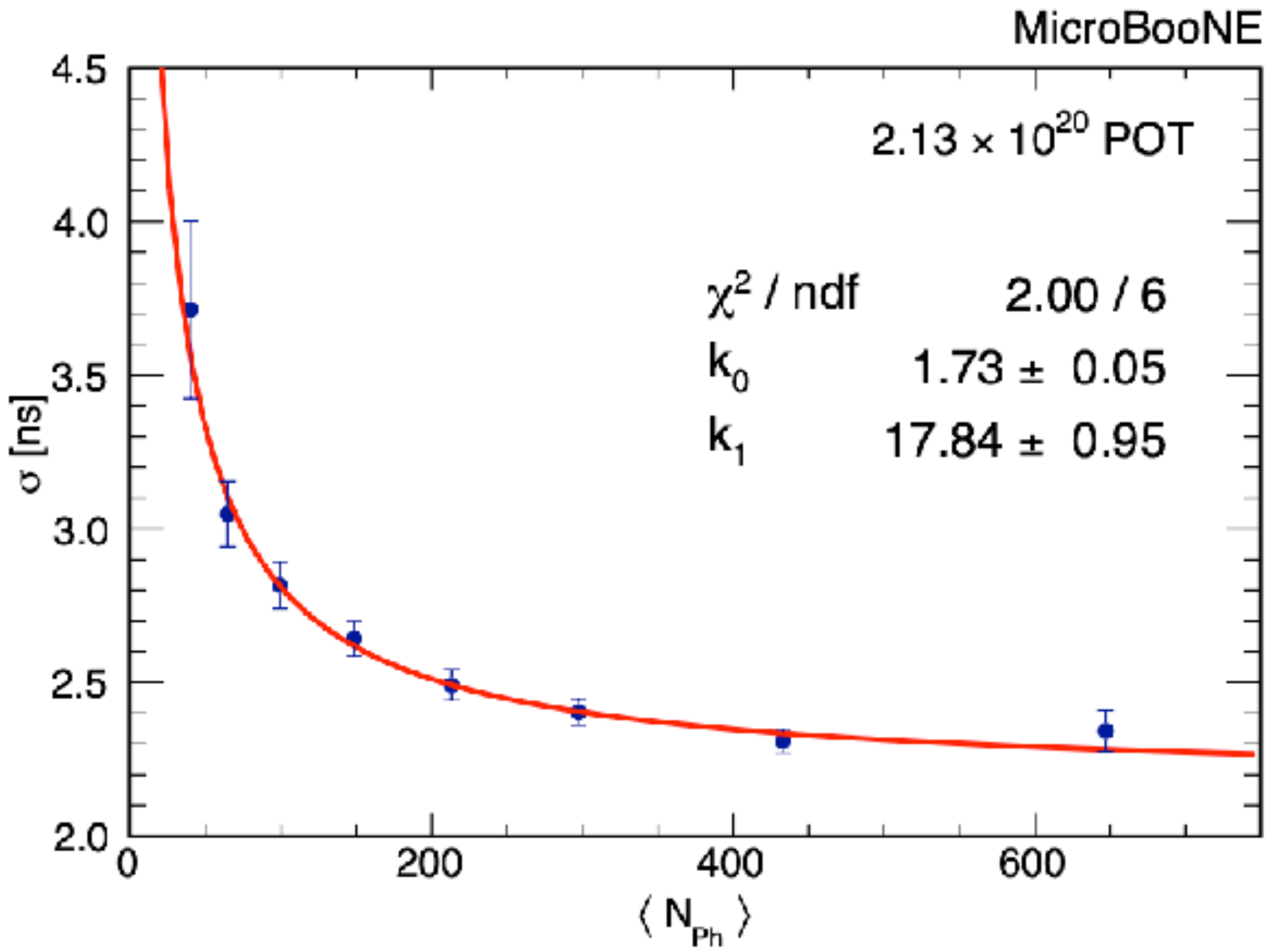
Detector intrinsic time resolution for neutrino interactions:

- Superimposed peak split by the number of photons detected.
- BNB intrinsic spread is subtracted
- Fit of the resolution vs. number of photons detected

$$\sigma\left(\langle N_{Ph}\rangle\right) = \sqrt{\langle\sigma_{BNB}\rangle^2 + k_0^2 + \left(\frac{k_1}{\sqrt{\langle N_{Ph}\rangle}}\right)^2},$$

Detector intrinsic resolution k0 = 1.73 ± 0.05 ns



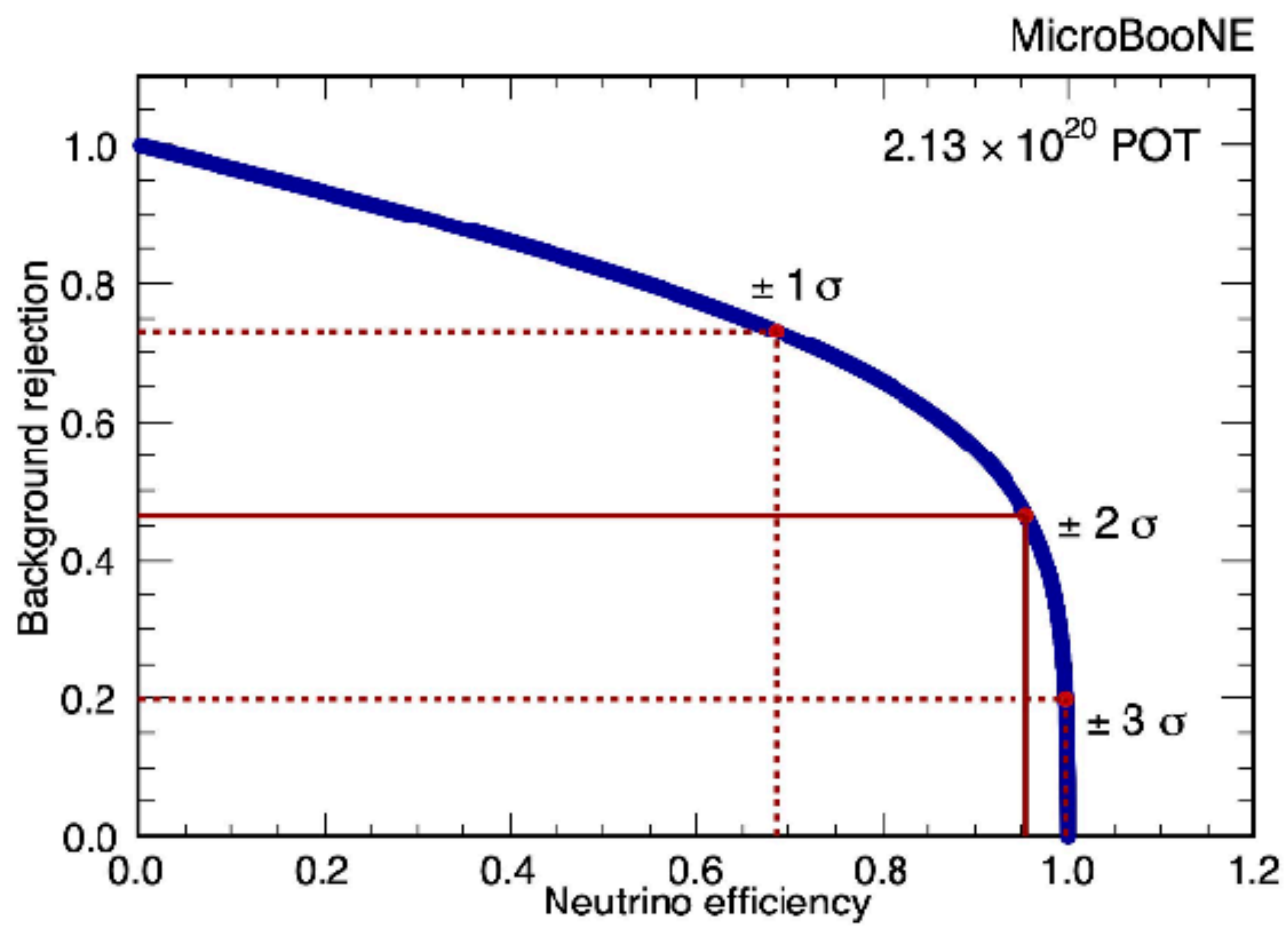


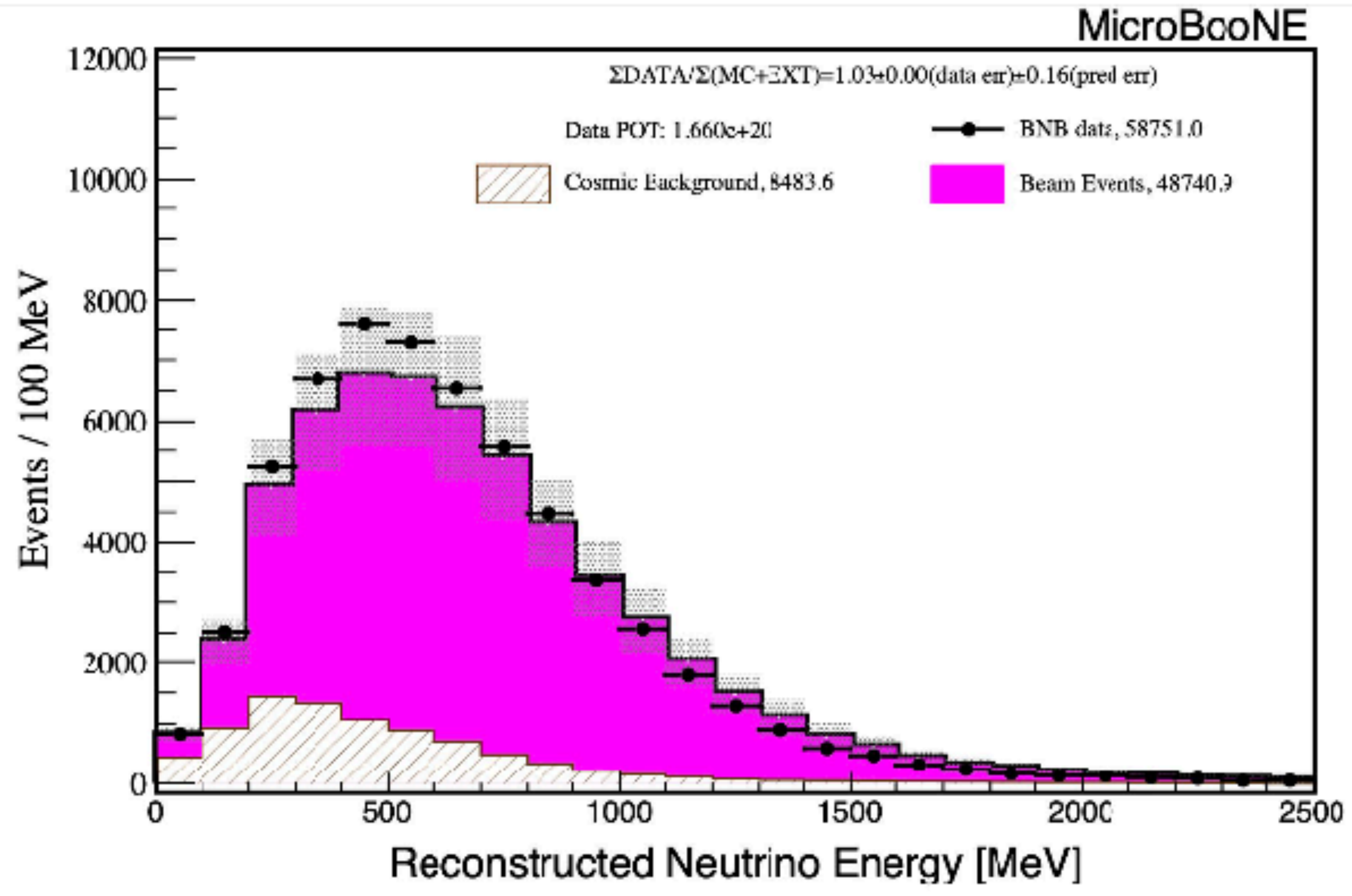
[8] P. Abratenko et al. (MicroBooNE Collaboration) First demonstration of O(1 ns) timing resolution in the MicroBooNE liquid argon time projection chamber. Phys. Rev. D 108, 052010 (2023)

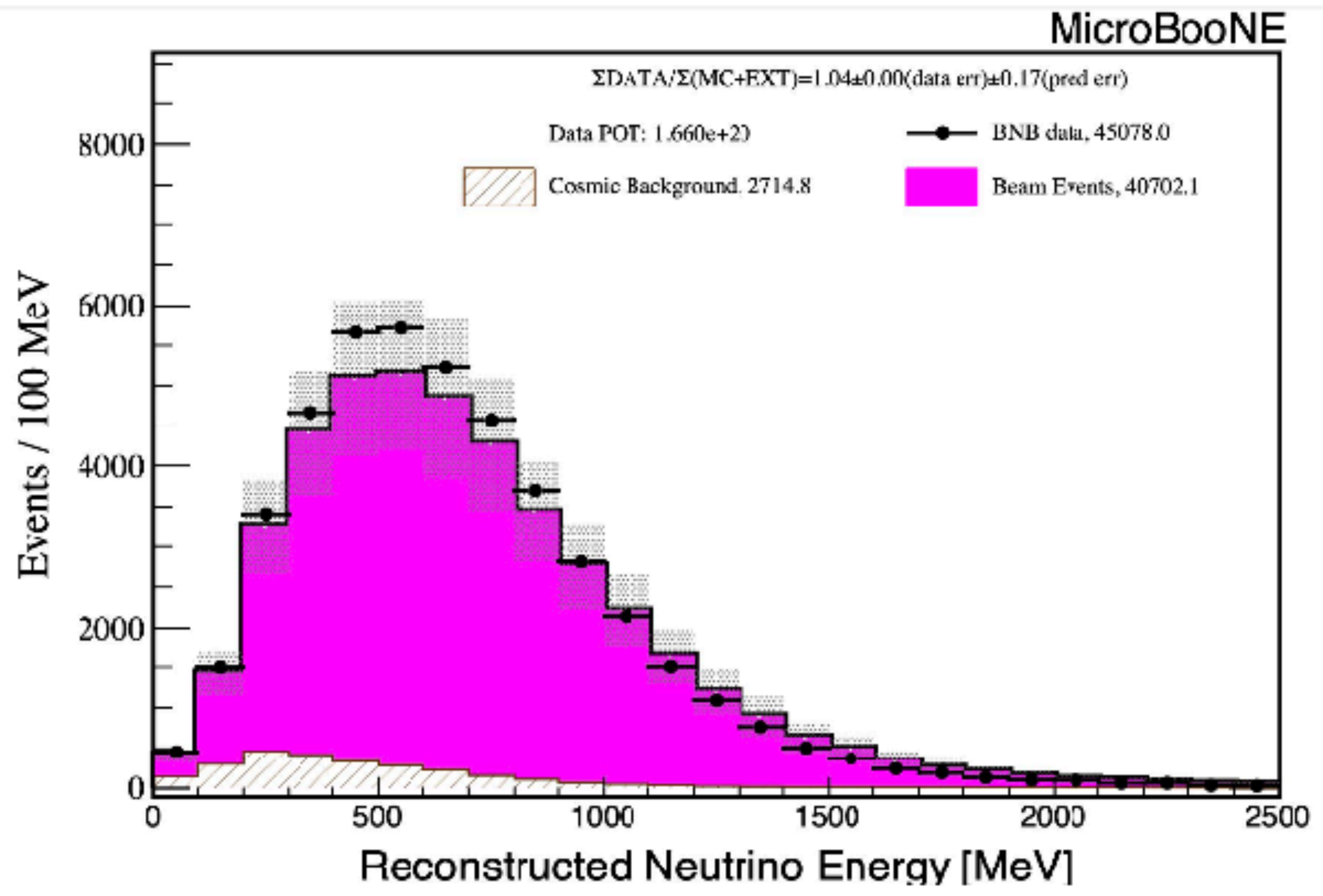
Application I: cosmic background rejection

Initial implementation of using the timing to improve the cosmic background rejection has been implemented in MicroBooNE's inclusive single photon LEE analysis [12]

- removes cosmic background at the "preselection" (pre-BDT) stage
- With 5 ns cut cosmic backgrounds reduced by ~50% with less than 10% signal efficiency loss
- Completely orthogonal and complementary to other, topology-based cosmic removal methods







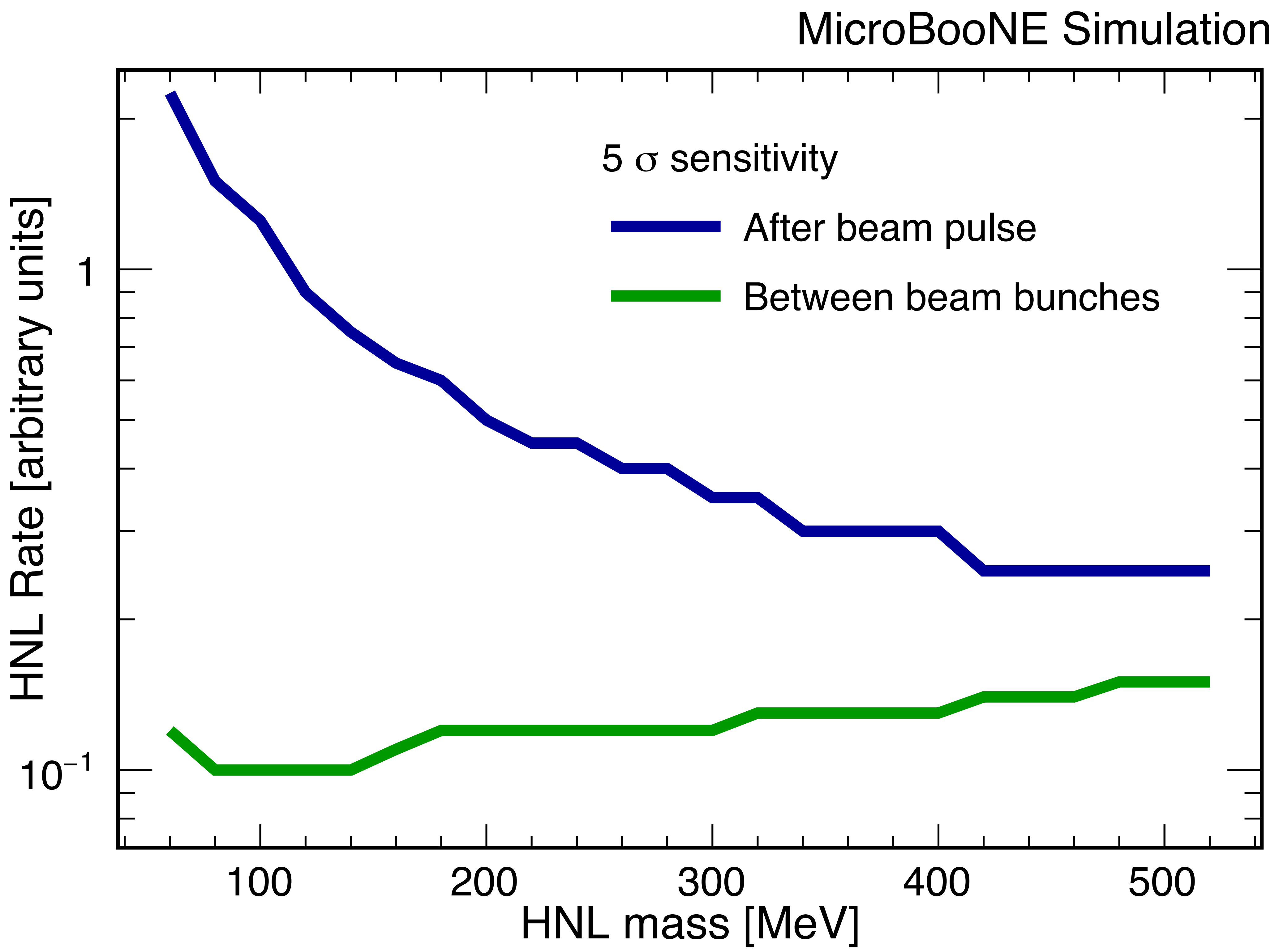
[12] MICROBOONE-NOTE-1102-PUB

Application II: HNL search improvement

The capability of MicroBooNE to access the beam substructure enables the investigation of events between bunches, offering significant improvements for long-lived massive particle searches in the 10s to 100s MeV range.

A sensible improvement in HNL search is obtained, especially for lower masses.

This is shown through lines of 5σ sensitivity*** using only events after the beam pulse (blue line) compared to only events between beam bunches (green line), as a function of the HNL mass [8].



***An Asimov sensitivity calculation is used to compute the sigma sensitivity

[8] P. Abratenko et al. (MicroBooNE Collaboration) First demonstration of O(1 ns) timing resolution in the MicroBooNE liquid argon time projection chamber. Phys. Rev. D 108, 052010 (2023)

Summary

MicroBooNE demonstrates to be capable of achieving an O(1 ns) timing resolution for the reconstruction of $\nu\mu$CC interaction time.

This result allows for the resolution of the pulse time structure of the BNB that, in turn, introduces a new powerful handle for physics measurements:

- new cosmic rejection method
- searches of BSM particles such as HNLs that have a longer ToF and reach the detector delayed with respect to neutrinos

Some steps have still room for improvement and the next SBN LAr-TPC experiments can take advantage of the microBooNE experience to improve the timing resolution:

- RWM waveform recording
- Propagation of particles and scintillation light inside the TPC

Room for trigger monitoring improvements

MicroBooNE experience:

At MicroBooNE the RWM logic pulse is recorded by the same electronic used for the PMTs, triggering on the BNB.

RWM waveform misalignment in time reflects the BNB trigger jitter.

The distribution of the RWM timing gives good monitoring of the beam instrumentation conditions:

- From MicroBooNE Run 1 to MicroBooNE Run 3, there was a substantial change in the spread of the RWM timing, from 100 ns to 10 ns → switching BNB trigger from $1F to BES, and beam signals transmission moved form copper to fibers.
- During MicroBooNE Run 3, the RWM timing distribution shifted of ~200 ns → hardware component replacement in the beam instrumentation.

Most of the RWM waveform information is lost since the signal arriving at the building of the detectors is the thresholded logic pulse.

Recording the full RWM waveforms at the accelerator building, in a system synchronized with the SBN detectors (GPS/White Rabbit) would be a useful tool for the SBN program.

- Accessing the full RWM waveform would be a useful tool to improve the beam timing information and for monitoring bunch shape stability

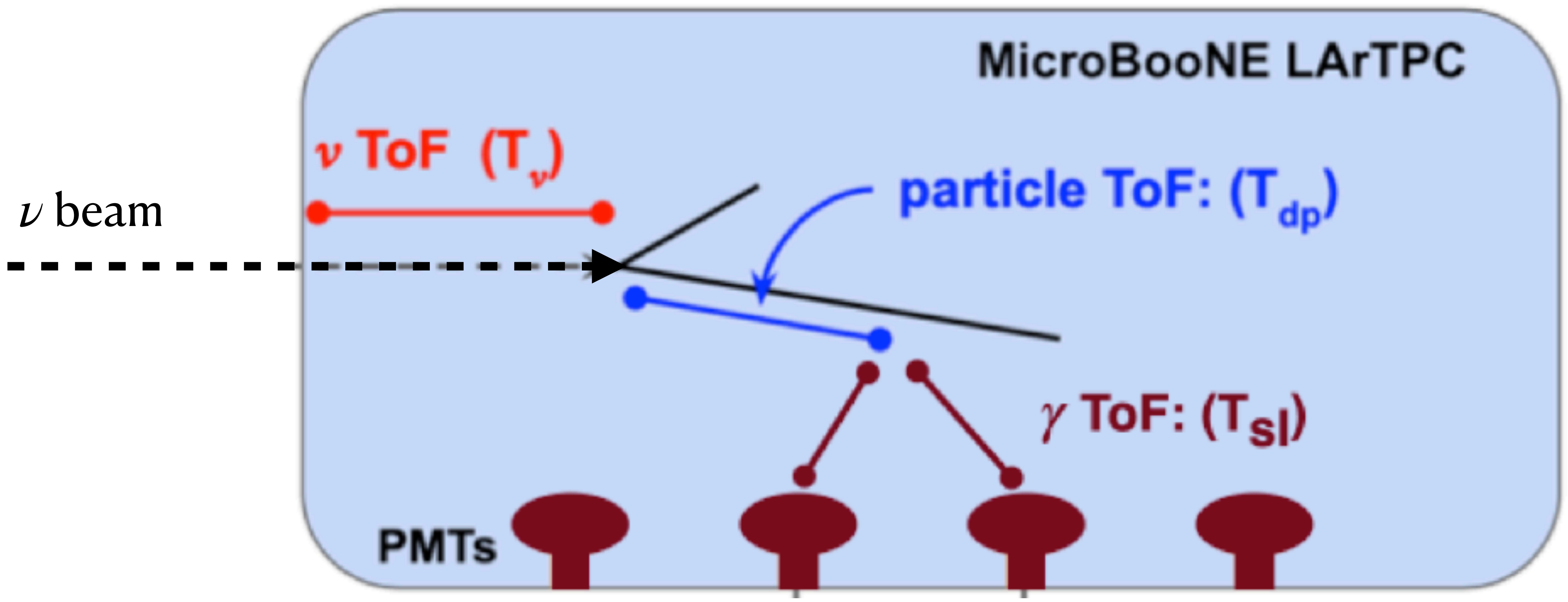
There is evidence that the first bunch shape is not stable. A first pulse smaller than usual can affect the logic pulse generation.

- The RWM waveform recorded in a synchronized time frame at the accelerator building would improve the trigger monitoring stability compared to the logic pulse that need to travel to the detector building.

Room for improvements

The model used to determine the propagation of daughter particles and scintillation light inside the TPC includes approximations limiting the performances of the reconstruction:

- Daughter particles are assumed to travel at the speed of light in vacuum → PID combined with kinetic energy information would improve the reconstruction of the daughter particle propagation time
- A geometrical calculation is used to get the first photons' arrival time on the PMTs → a library for the photons arrival time combined with the prediction of the light yield would improve the localization of the photons source to which the timing is associated.



The literature contains conflicting values for the speed of scintillation light in liquid Argon.

A measurement in a large LAr-TPC would be interesting for comparison and useful for timing purposes.